

**INTELLIGENT LASER CLADDING CONTROL SYSTEM DESIGN AND
CONSTRUCTION**

by

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B.Sc.(Control.Eng.)

April,1989

**A thesis submitted for the degree of Doctor of Philosophy of the
University of London and for the Diploma of Membership of Imperial
College**

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To:

My dear wife - Liu Zhu

ABSTRACT

Since the first industrial application of laser cladding (surface coating) in 1981, many problems have been found in industry applications for producing consistent, good quality product. This thesis reports the author's work on the investigation of possibilities in controlling the process for industrial applications. The project, funded by British SERC, Quantum Laser Corp. (USA), British Council (Technical Cooperation Department) and Chinese Government, involves industrial laser cladding process problems study, laser cladding controllability analysis, control system design, in-process quality inspection systems development, "smart" laser cladding equipment development and on-line adaptive laser cladding control techniques development.

The thesis is divided into four parts.

Part 1. Literature review: Identify the operating conditions and industrial practice for laser cladding by both experimentation and review of previous work. Also identify general developments and techniques for the in-process sensing and controlling of process parameters for laser materials processing.

Part 2. Development of laser cladding control system hardware: Design, construction and tests of closed loop control systems for the principle operating parameters. This includes the development of an on-line closed loop laser power controller for higher power CO₂ lasers, the development of a closed loop powder flowrate controller, the development of self-cleaning "smart" dome with spherical laser nozzle, the development of an automatic "smart" laser shutter controller, a closed loop nozzle/workpiece standoff controller, an automatic 3 axis CNC laser cladding workstation and all necessary interfaces for the supervisory "intelligent" laser cladding control.

Part 3. Development of in-process quality inspection system: This includes non-contact clad dilution sensing, non-contact clad uniformity and operating stability sensing and non-contact clad bead profile/thickness sensing.

Part 4. Development of adaptive laser cladding control techniques: This includes the laser cladding optimization techniques, rule based adaptive laser cladding control technique which could self-optimize the closed loop control characteristics for an unknown or partially known process, a knowledge based information processing technique which combines the fuzzy logic with expert system for the real time diagnosis and logical control of complicated or indefinite processes such as laser cladding.

ACKNOWLEDGMENTS

It is with great pleasure and deep gratitude that the author acknowledges his supervisors **Dr. H.D. Hibberd, Senior Lecturer , Deputy director of Center for Robotics and Automated Systems**, and **Prof. W.M. Steen, Director of Laser Laboratory, Materials Science Department (now Chairman of Advanced Manufacturing Research Centre, University of Liverpool)** for their invaluable guidance and criticism, and continuous support and encouragement throughout the course of this work and preparation of this thesis.

I feel compelled to record my indebtedness to **Dr. J.C Allwright, Senior lecture at Control System Section, Department of Electrical Engineering, Imperial college**, who had been my supervisor and friend during my first two year PhD research. His keen interest and excellent suggestions involving the theoretical analysis of the adaptive laser cladding control algorithm are very helpful.

Appreciation goes to **Dr. V.M.Weerasinghe, Research Assistant at Imperial College**, for his help in the laser cladding operation, process understanding and many other aspects during this research work.

Thanks are also due to:

Mr.P. Williams, electrical technician at the laser laboratory, Mr.R.Stracey, mechanical technician at the laser laboratory, Mr. C.S. Raves, Mr. A.E.Field, mechanical technicians at Robotics centre, Imperial college, Mr. Q. Rafiq from Dept. of Elec. Eng. and Mr. S.Plant, technician at laser group, Liverpool University for their assistance and help throughout the project.

Staffs in the store of Electrical Engineering department, store, workshop and photograph room in Material Science department for many friendly helps.

Dr. D.J. Brookfield, Dr. I.Owen and Prof. Escudier from Liverpool University for their kindly criticism and valuable suggestions.

All members of laser group for providing a stimulation academic environment and many productive discussions. Among those **Dr. Shah, Dr. Z.D.Chen, Mr.W.O'Neill, Mr.H.Y.Zheng, Mr.R.Akhter and Mrs. H.Garnett** are worth mentioning.

Chinese government, British Council, SERC, Quantum Laser Corp. for the

financial support to this work.

My parents for their understanding , encouragement and for all they have endured during this work.

My wife deserves my very special thanks for her love, care and support, which made this work possible and worthwhile.

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GENERAL INTRODUCTION

It's nearly three decades since the first laser was demonstrated. The rapid development of lasers and their applications has shown their increasing influences in the modern world. The use of lasers for holography, illumination, recording, printing, alignment, communication and metrology is already part of life today. The use of the lasers for medical surgery, materials processing (fabrication), nuclear fusion research and Star Wars are all becoming familiar to us. Laser materials processing, which started in 1965 with the drilling of diamonds for wire dies, now covers cutting, welding, drilling, soldering, alloying, cladding, annealing, hardening etc. as summarized by Arata^[1] in Fig.1.

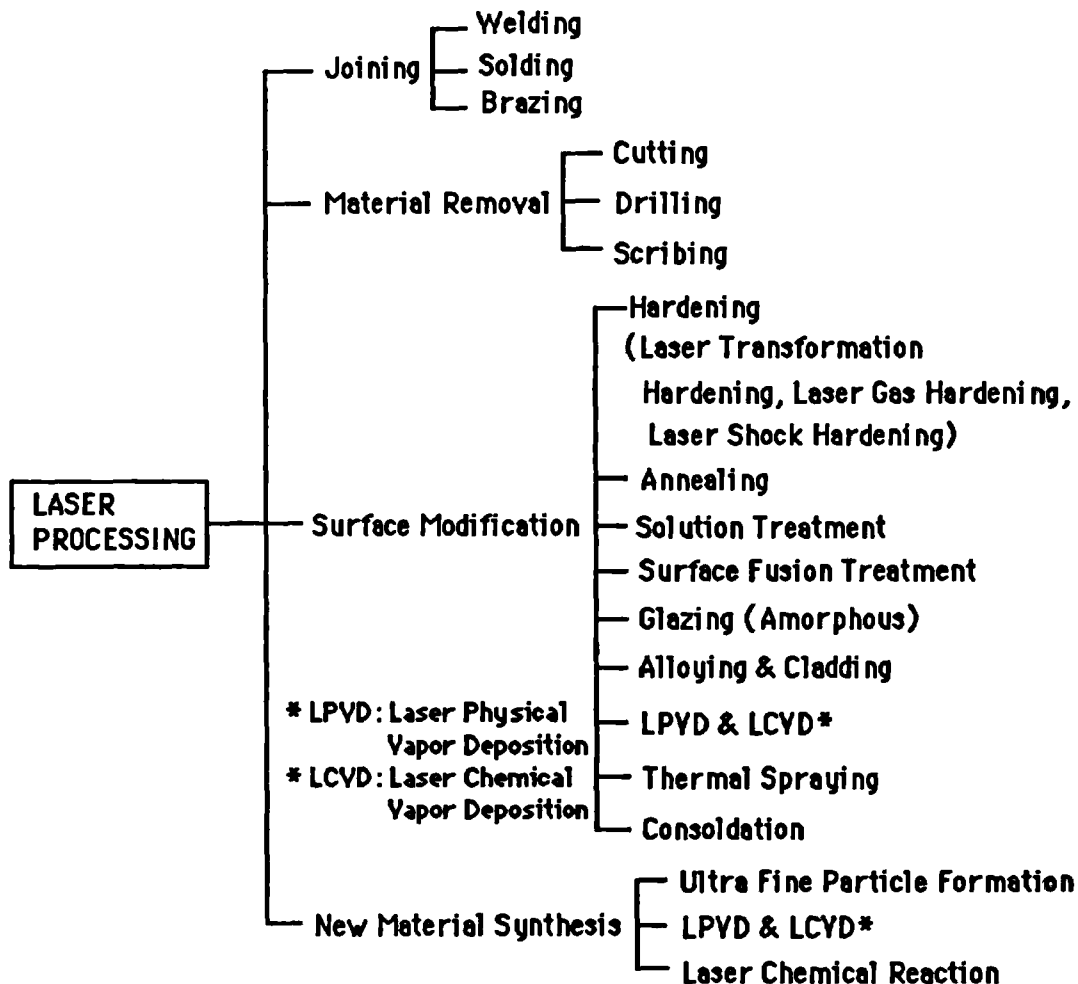


Fig. 1. Laser applications in materials processing^[1].

Many novel applications are being reported every year. The high power intensity, coherent and monochromatic light beams of lasers are recognized to be superior to orthodox

tools for materials processing. They are chemically clean, with no combustion or ion bombardment problems, and the heat can be highly localized, thus minimizing thermal damage. They are also ideally adaptable to automation. There are now approximately 400 companies providing goods and services to a laser materials processing industry, estimated to exceed \$385 million in annual sales internationally and expected to increase by 25% in the next few years[2].

With the increased use of lasers in industry, the need to combine them with intelligent machinery for high quality products becomes apparent. Laser cladding is one of the processes which demands such further development.

1. PROBLEM DEFINITION

Laser cladding is a method of coating a layer of new material onto the substrate surface of the existing products by laser fusion in order to improve material surface properties such as wear resistance, corrosion resistance, thermal resistance etc. Therefore the body of a product can be made of low cost materials while the desired surface property can be achieved by using laser cladding technique. Fig.2 illustrates a typical process for laser cladding where a powder feeder was used to supply the coating material to the laser (an infrared beam produced by a CO₂ laser) generated melt pool on a continuous moving substrate. Other techniques for the supply of coating material in laser cladding include wire feeding and preplacing powders on the substrate. An area of clad can be achieved by overlapping the single clad track as shown in Fig.3.

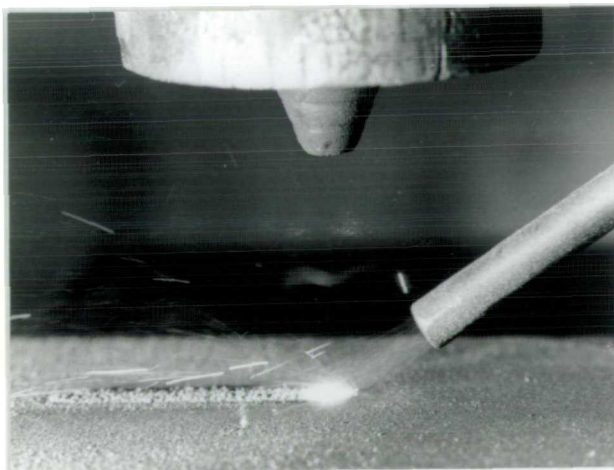


Fig.2. A typical laser cladding process using powder feed. (Photographed by Weerasinghe)

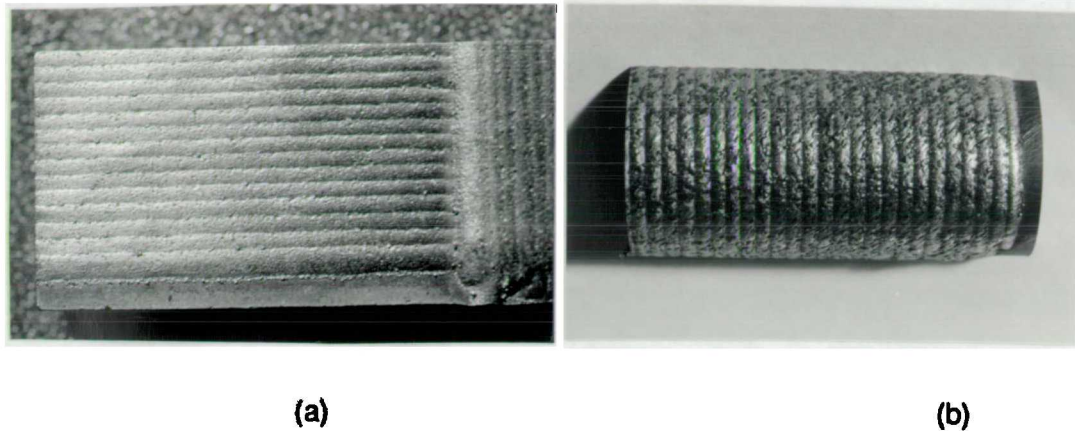


Fig. 3. Area of clad achieved by overlapping of single clad track. a). on flat plate (Courtesy of Weerasinghe), b). on a mild steel rod. (stainless steel clad on mild steel substrate)

Since the invention of the laser cladding technique in 1976, much research has been carried out to explore the applications of the process and improvement of clad quality. Some industries have already started to investigate the use of technique for production (See Chapter 2). However, many problems still remain unsolved which prevent the effective application of laser cladding technique in industry. Among those the following were studied in this thesis for the powder feed laser cladding:

a). Determination of optimum operating parameters for a given cladding requirement

Laser cladding like other materials processing involves many parameters as shown in Fig.4.

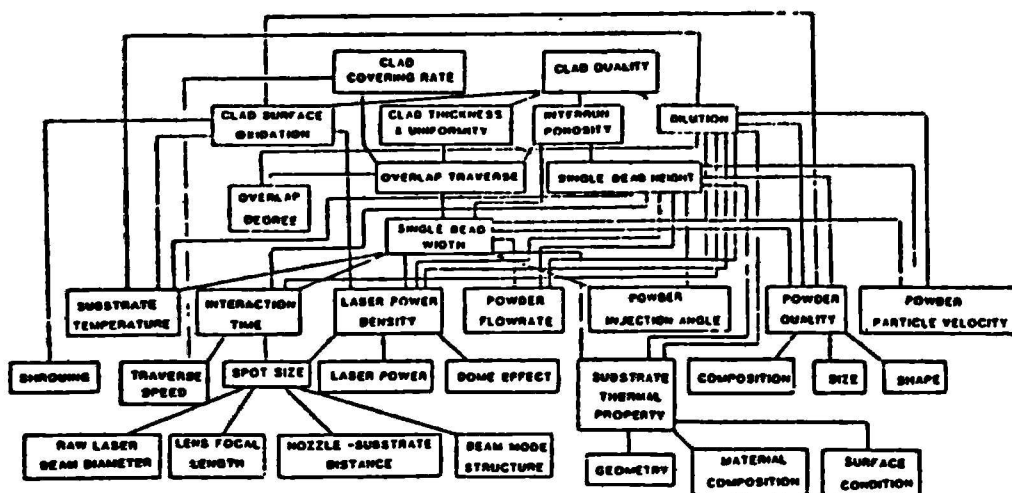
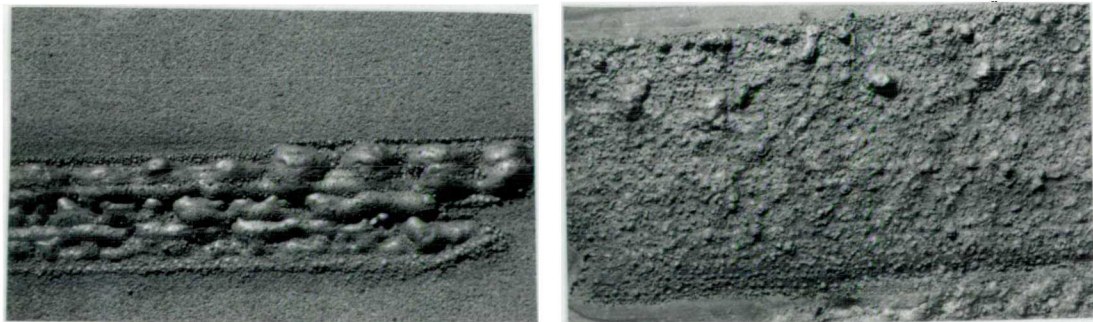


Fig.4. Powder feed laser cladding interrelations

Same operating parameters may not guarantee the same clad quality since any differences in materials surface condition, laser/powder alignment (for powder feed laser cladding) and laser beam quality can affect the assumed relationships. Current laser cladding practices are mainly based on prior experience and trial error. The processing quality is strongly dependent upon the operator skills. As the experience accumulated is usually limited to a certain working condition and environment, the operation flexibility and product accuracy as well as repeatability can not be ideally realized. Therefore, a better method is required to determine the optimum operating parameters more efficiently and more precisely under various operating situations in the industrial environment.

b). On-line recognition and prevention of the faulty clad

Faulty clad such as shown in Fig. 5. can be produced for various reasons in production. For example improper gas flow, poor beam mode, powder/beam misalignment, improper operating parameters or even defects on the substrate can all produce faulty products. It is desirable that the faulty clad can be recognized during production so that poor products can be recorded and further damages prevented. To locate the causes of these faults in order to correct them is often a very difficult task, since many factors can contribute to a problem and the possibilities of their individual contributions vary with different situations. It is essential, therefore, to have a system that can discover the faulty clad during processing and diagnose the problem to locate the causes so that action can be taken in time to prevent further damages.



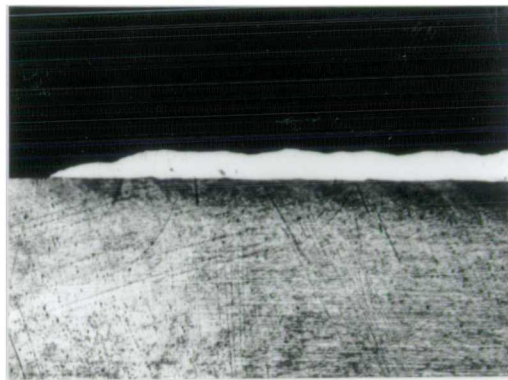
(a)

(b)

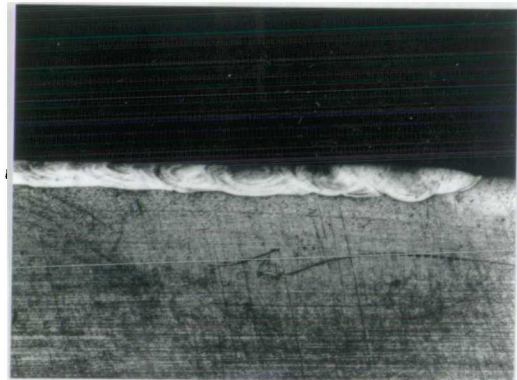
Fig. 5. Examples of faulty clad: a). non-uniform and discontinuous; b). high dilution and poor surface finish.

c). Maintaining a consistent clad quality throughout the process time

In laser cladding, parameters such as substrate temperature and material absorptivity to the laser beam may not be constant. They varies continuously during processing. These changes could lead to an undesired change of clad quality. Fig.6. shows an example of the problems seen in the continuous laser cladding of mild steel rod (250 mm long and 25mm diameter) with 316 stainless steel powder. It shows the dilution (degree of clad mixing with substrate material) varied, from zero at the start, to greater than 50% at the finishing point caused by substrate temperature rise during cladding process. An on-line feedback control system is therefore required to continuously vary the operating parameters (traverse speed, laser power, powder flowrate) to compensate for these undesired process variations.



Start



Finish

Fig. 6. Transverse section of a continuous spiral clad of 316 steel on a 25mm mild steel rod showing increasing dilution due to the substrate heat accumulation during processing.

All the above mentioned problems were not tackled before and they became the principle subjects of study in this thesis.

2. OBJECTIVES OF THE PROJECT

The objectives the project is to design and construct an intelligent laser cladding control cell for solving the above mentioned problems. Several stages were involved to achieve the final objective. These are:

- a). Laser cladding automation. This includes the development of a 3 axis CNC work station and computer controlled laser, and powder feeder operation.
- b). Development of closed loop control systems for principle operating parameters: laser

power, powder flowrate, traverse speed, traverse position and nozzle/workpiece distance. This will reduce the the possibility of poor clad produced by unstable operating parameters and guarantees the accuracy, repeatability of these parameters.

c). Development of in-process sensors for process quality inspection. This includes melt pool stability sensor development, clad dilution sensor development and clad thickness/bead profile sensor development.

d). Development of techniques for laser cladding optimum operating condition setting.

e). Development of adaptive control algorithms for closed loop clad thickness, bead width and dilution control.

f). Development of a technique for real time process diagnose and decision making.

g). The design of intelligent supervisory laser cladding control software to coordinate various sub-systems.

The structure of the intelligent laser cladding control system constructed is shown in Fig.7. with the first level dealing with the feedback control for laser power, powder feeder, CNC table, nozzle workpiece distance and laser shutter operation, and the secondary level for process monitoring and supervisory control of various parameters.

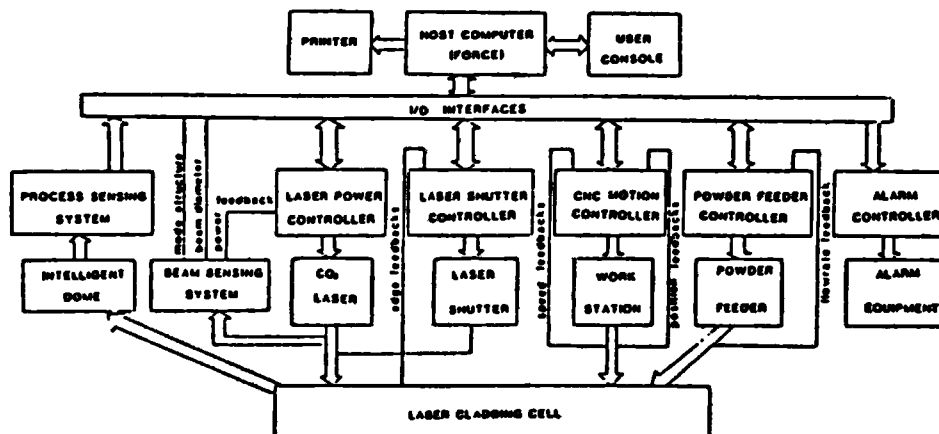


Fig. 7. Hierarchy of the intelligent laser cladding control system.

In the diagram, DDC is Direct Digital Control and SCC is Supervisory Computer Control.

3. THESIS ARRANGEMENT

The thesis is divided into 4 parts. Part 1 is literature review. It studies laser properties, laser cladding processes and previous efforts on the development of laser materials processing control systems. Part 2 reports the work on the development of an automatic laser cladding workstation and closed loop control of various operating parameters. In Part 3, in-process sensor development will be described. In Part 4, development on the supervisory laser cladding control techniques will be described.

PART 1

LITERATURE REVIEW

Three chapters are included in this part providing fundamental backgrounds of the high power lasers, laser cladding processes and previous efforts on the development of control systems for laser materials processing. Through these studies the following questions should be better understood:

- 1). What are the industrial high power lasers ?
- 2). How are these lasers working ?
- 3). What properties does a laser beam have ?
- 4). What are the factors affecting the laser beam quality and how do they affect it ?
- 5). How is laser cladding performed ?
- 6). What is the quality requirement of laser cladding ?
- 7). What is the advantage of laser cladding over the conventional cladding techniques?
- 8). What is the mechanism of powder feed laser cladding ?
- 9). What are the parameter relationships in laser cladding and how do various factors affect its quality ?
- 10). What have been done before to improve laser cladding quality
- 11). What have been done before to monitor and stabilize the laser beam ?
- 12). What is the automation situation in the current industrial laser processing systems ?
- 13). What are the state of art developments for intelligent laser materials processing control systems ?
- 14). How the problems were approached by other workers for the control of laser materials processing ?

Some experimental work by the author for the study of powder feed laser cladding process is also included in this part.

CHAPTER 1

LASER FUNDAMENTALS

In this chapter some basic phenomena and properties of laser beam together with its operating principles are studied. Since laser is a very important element in laser cladding process, an understanding of lasers and its behavior will help to understand the problems of the laser cladding process and its quality control requirements.

1.1 LASER OPERATING PRINCIPLES

1.1.1. Stimulated emission

A particle in an electro-magnetic field can have the following responses:

a). Absorption. A particle can only absorb the electro-magnetic energy and raise its energy level (Fig.1.1.a) if the external energy source satisfies Boltzmann's equation:

$$\Delta E = hc/\lambda \quad (1 - 1)$$

where: ΔE is the energy difference between two energy levels of the particle, c is the speed of light, λ is the wavelength of the external electro-magnetic field and h is Planck's constant (6.6×10^{-27} erg. sec).

b). Spontaneous emission. A particle in its upper energy level can release (or emit) its energy spontaneously in the form of an electro-magnetic wave (Fig.1.1.b). The wavelength of the emitted wave will also observe Boltzmann's equation.

At energy equilibrium the probabilities of absorption and spontaneous emission are equal.

c). Stimulated emission and population inverse. An atom in the upper energy level can also give up its energy and emit a photon when it is exposed to an electro-magnetic wave of the same wavelength as that of the energy level difference in the particle satisfying the Boltzmann's equation. The emitted wave from the particle will have the same wavelength as the stimulating field and will oscillate in the same phase as well as travelling in the same direction as shown in Fig.1.1.c. As a result the electro-magnetic wave is "amplified" with the same beam property. This phenomena was defined as "stimulated emission" by Albert Einstein [3].

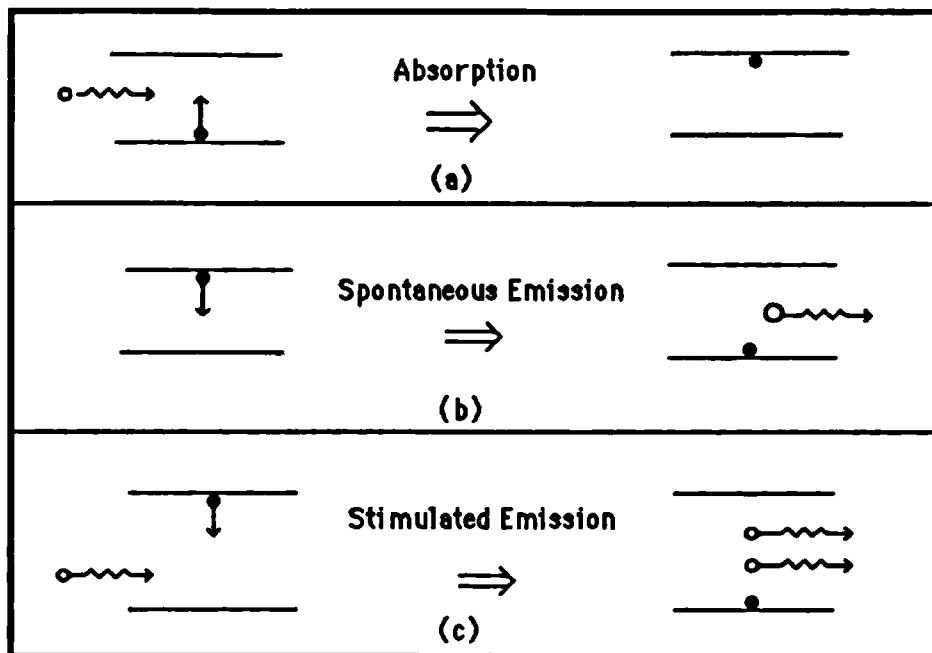


Fig.1.1. Behaviors of the particles in an electro-magnetic field.

However the stimulated emission can not result in a 'lasting' action unless there is a state of *population inverse* in the media, i.e. the number of particles at upper energy level N_2 is greater than that in the lower level N_1 .

A laser beam can be generated if a medium is excited to its upper energy level to give a state of population inverse. Then laser action starts by the initial spontaneous emitted beam and subsequent stimulated emission and light amplification in the cavity. The beam wavelengths of lasers beam are from ultraviolet to far infrared while its predecessor, the MASER, produces microwaves. The acronym of LASER stands for the Light Amplification by Stimulated Emission of Radiation.

1.1.2. Operating conditions of practical lasers

In order to generate a laser beam in practice the following elements must exist:

1). **Active medium.** A material such as CO₂ gas in CO₂ lasers must exist which can provide suitable energy levels for interaction with radiation.

2). **Power supply.** Some form of energy is required to raise the energy level of the medium to create the state of population reverse and this can be done by:

a). Auxiliary light sources.

b). Plasma generation. By placing two electrodes on both side of medium, when an electric current is discharged through the medium, a high energy plasma is generated which emits radiant energy over a wide range of wavelength, some of which is then absorbed by the

medium to raise its energy level. The electric discharge may be DC, AC or RF.

c). **Direct electron excitation:** When energetic electrons are injected into the medium through electrodes the electrons collide with ground state atoms and raising them to higher energy level.

d). **Resonant transfer of energy:** Electrons excite one of the gases to higher energy level by collision. These excited gas molecules then collide with molecules of another gas and transfer the excitation energy to the second gas.

e). **Chemical energy.** Several chemicals are mixed together for an reaction resulting in the rise of particles to their upper energy levels.

3). **Resonant cavity:** To achieve a continuous beam without continually dependent on a spontaneous emission to initiate lasing, an optical cavity with feedback end mirrors is required. A very basic resonant cavity consists of a tube for laser medium and two parallel mirrors (one with total reflection and the other with partial transmission) at the ends of laser tube with a distance of:

$$L = q(\lambda/2) \quad (1-2)$$

where L is distance between the two mirrors and λ is laser beam wavelength and q is an integer called cavity mode or longitudinal laser mode.

Practical lasers use spherical or confocal mirrors instead of plane mirror since plane parallel mirrors require exact angular alignment which is difficult to achieve.

Several basic cavities can be linked together in series to increase the power level of the lasers.

1.2. INDUSTRIAL LASERS

Lasers can be classified according to the lasing material into gas lasers such HeNe lasers, liquid lasers such as Dye lasers, solid state lasers such as Ruby laser and semiconductor lasers such as diode lasers. However not all lasers can be used in industry for materials processing. The most commonly used lasers for industrial materials processing applications are CO₂ gas lasers, Nd-YAG lasers, Nd-Glass lasers, Excimer lasers and sometimes Ruby lasers for their high power beam outputs. The recent developments have also shown the potential of high power CO lasers for materials processing.

1.2.1. CO₂ gas lasers

CO₂ lasers, invented in 1964 by Patel^[4], are considered as possessing highest

efficiencies (approximately 10 %) for the conversion of electrical to optical energy^[5]. This property, together with ease of operation at high power levels in both continuous wave (CW) and pulsed configurations, has made CO₂ lasers widely applicable as a heat source in the laser processing of materials.

CO₂ lasers use molecular vibrations of carbon dioxide as the lasing mechanism. Generally, a mixture of carbon dioxide, nitrogen and helium gases are used, the nitrogen is active in the excitation process to increase the excitation efficiency and helium which comprises about three quarters of the total gas mixture acts as an internal heat sink. Sometimes a small amount of oxygen is added to reduce contamination from carbon monoxide and carbon produced in the excitation and depopulation processes. The 10.6 μm infrared beam output enables the CO₂ laser to process variety of materials although with difficulties for highly reflective materials such as copper, silver and gold.

There are 4 major designs of CO₂ lasers. These are:

- . *Slow axial gas flow with axial discharge.* The slow flow design (Fig.1.2a) relies on thermal conduction for the cooling of the gases and consequently the cross-sectional area of the discharge region is limited; relatively narrow bore tubes must be used. Roughly 50-70 watts of power per meter of tube length can be obtained from this type of design. The output power of this type of laser is generally below 1 kW [5].

- . *Fast axial gas flow with axial discharge.* The fast flow (about 60m/s) designs (Fig.1.2b) use convection cooling so that much larger discharge cross sections can be achieved. Hence, the power per unit length is much higher, typically 600W/m. The output power of this type of laser is around 2 kW [5].

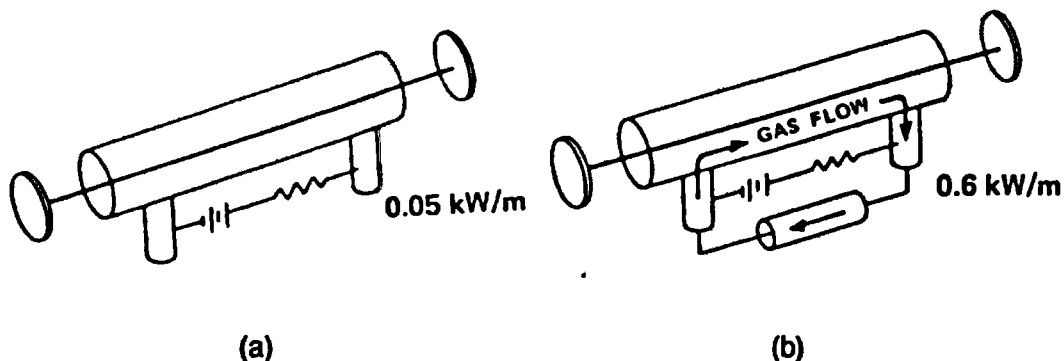


Fig. 1.2. Axial flow CO₂ lasers^[6]. a). Slow axial flow, b). Fast axial flow.

The gas pressure in the laser cavity is usually below atmospheric pressure for the above two types.

- . *Fast transverse gas flow with transverse discharge.* This type of laser (Fig.1.3) can generally produce higher power levels than the axial flow version. The electrical discharge is applied transverse to the optical axis and a blower is used to circulate gas rapidly transverse to the long dimension of the laser cavity. This permits operation at relatively high gas pressures (several atmospheres) with voltage of less than 100kV. As a

result the power per unit length is greatly increased , typ. 2500w/m. The usual power output of this type of laser is between 2.5-20kw.

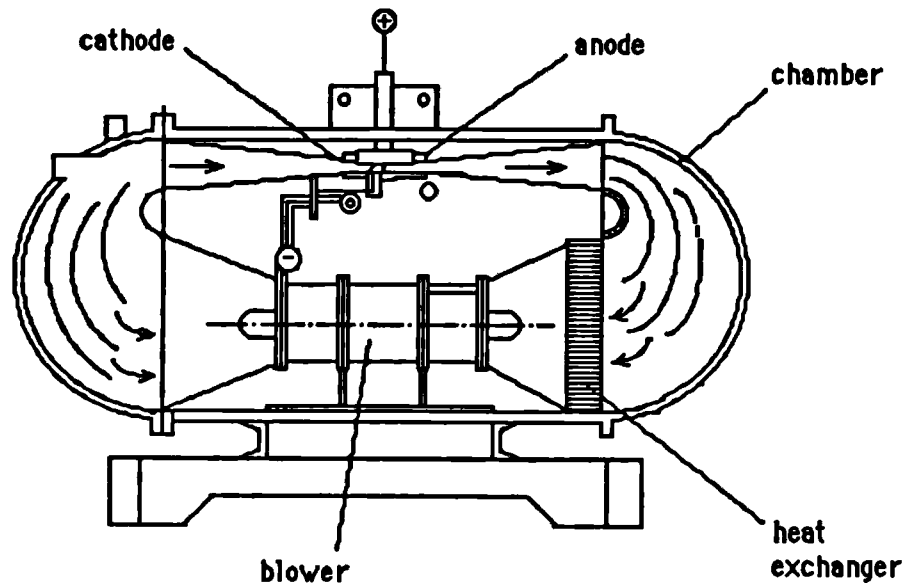


Fig. 1.3 . Transverse flow CO₂ gas laser illustration [7].

. *AC or RF-excited CO₂ lasers.* Although 99% of the commercial CO₂ lasers are DC excited, recent development of CO₂ lasers using low or high frequency voltages (10kHz to 100MHz) are becoming more noted. For DC excited lasers the discharge electrodes are all pin types, which results in inhomogeneous discharge distribution in the laser resonator with brighter lighting near the electrode where the discharge is compressed [8]. This results in the instabilities of high powered CO₂ laser power and transverse density distribution. While using AC or RF excitation the electric power is capacitively coupled into the discharge which electrode mounted just outside on glass tube as shown in Fig.1.4. The discharge is transverse to optical axis of laser, with a separation of electrode with a distance of only the diameter of laser tube. One of the advantages of AC or RF excited CO₂ lasers is that the discharge is very stable and homogeneous. 1500w CW RF-excited CO₂ laser has been reported by Trumpf GmbH & Co. West Germany[9].

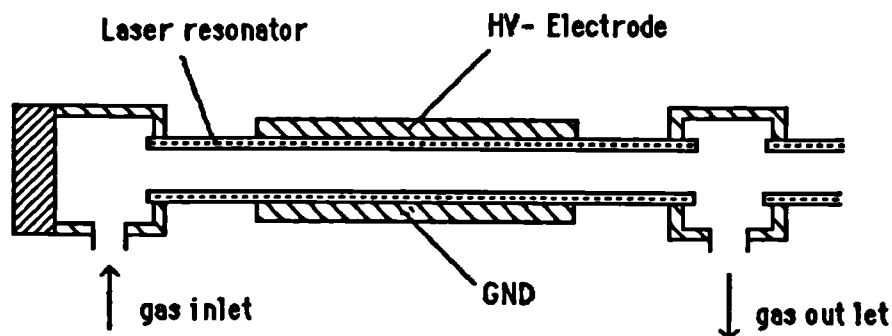


Fig. 1.4 RF-excited CO₂ laser illustration [9].

Other types of CO₂ lasers such as small sealed off and waveguide lasers are also used in industry.

CO₂ lasers dominant the laser market for industrial use with their applications from cutting, welding, soldering, drilling to various surface treatment processes.

1.2.2. Nd-YAG solid state lasers

This laser employs neodymium (Nd) as the lasing material doped in a YAG (yttrium-aluminum-garnet) crystal. Excitation is by one or two krypton or xenon lamps. The wavelength is 1.06 μm , which is close to visible spectrum that conventional optics can be used for lasers and windows. One of the advantages of this type of lasers is that it is relatively easy to guide the beam in optical fibres. The Nd-YAG laser is the most widely used of all solid-state lasers for materials processing. It is available in both pulsed and CW configuration, but in most applications pulsed operation is preferred. The average power of the Nd-YAG laser range from few watts to several hundred watts; the peak power at the switching mode can be kilowatts at kilohertz rate. Typical applications of Nd-YAG lasers in industries are marking, scribing (e.g. thick or thin film resistor trimming), cutting and hermetic seam welding of thin materials.

1.2.3. Nd-Glass solid state lasers

The Nd-Glass laser utilizes neodymium as the lasing material, but the host material is glass. The beam wavelength is 1.06 μm . Nd-glass laser material can be fabricated in a variety of sizes and shapes including rods with length of up to 2m and slabs with diameter of around 10 cm. More than one laser head can be operated from the same power supply, typically two, in an alternating fashion. However, because of the low thermal conductivity of glass compared to that of YAG, cooling is a problem which tends to limit operation to a maximum repetition rate of around 2 Hz. The average power of this type of laser is small but the peak power of the laser pulse can reach 10^{12} - 10^{13} W. Again the optical fiber can be used for flexible beam guide.

Due to the poor thermal characteristics of glass this laser is used in pulsed mode mainly for spot welding and hole piercing.

1.2.4. Excimer gas lasers

Excimer lasers use excited noble gas-halide molecule as a lasing medium and can only produce short pulses because the lifetime of the excited state is very short. Pulse durations are of order of tens of nanoseconds and intensities are very high. In contrast with most lasers, the excimer operates in the ultraviolet range of the spectrum (0.193-0.351 μm). It is in this range where the reflectivity of many metals strongly decrease. The average

power of the excimer laser is generally small, typically 10-200w^[10]. Applications of Excimer lasers are mainly in semiconductor industry: fabrication of premium solar cells, doping, etching, photolithography and laser chemical vapor deposition. Recent applications have show a great potential for surface treatment and thin materials micro-machining^[11].

1.2.5. Ruby solid state lasers

Ruby lasers contain triply-ionized chromium, Cr³⁺, in crystalline aluminum oxide as host. Commercial products are restricted to low repetition rate pulsed operation, usually less than 1HZ with average power of 100J. The normal pulsed operation is actually an envelope of random spikes and particularly suited to drilling applications. In fact, hole-drilling by a ruby laser was the first material processing industrial application of lasers. The ruby laser may have advantages in some specialized processing, either by virtue of significantly increased absorption at its wavelength (0.694μm) or because short wavelengths allow for tighter focusing. Today the role of ruby laser in material processing is being overshadowed by its applications in other fields such as diagnosis.

1.2.6. CO gas Lasers

The CO laser beam is produced by the vibration-rotation transitions in the ground electronic state of CO molecule by electrical excitation with continuous beam power up to hundreds of Kilowatts and pulsed of order of kilojoules at electrical efficiencies (defined by the ratio of optical output/electrical input) in the range from 20-50%^[12,13]. The output wavelength of CO laser beam is around 5μm. Although there has been no commercial CO lasers available, the potential of using CO laser for materials processing can be seen to be great.

In laser cladding CO₂ lasers are used predominantly because of their high power levels available and the capability for continuous beam output.

1.3. PROPERTIES OF LASER LIGHT

It is the unique properties of laser beam that offers the advantages over the previous heat sources for materials processing. This section outlines some of the properties of laser beam that are relevant to laser materials processing.

1.3.1. Monochromaticity

One feature of the laser beam is its monochromaticity or to be precise narrow spectral line width. This enables the laser beam to be focused to a tiny spot (near the size of

wavelength) with very high intensities due to the elimination of chromatic aberration in laser optical systems. Actually the beam wavelength or frequency is broadened by the Doppler shifts

$$\Delta f = c/2L \quad (1-3)$$

where c is speed of light and L is the length between two end mirrors in laser cavity.

A characteristic wavelength λ is normally used to describe the mean wavelength of output of a laser corresponding to a particular transition. Fluctuations in the length of cavity (due to, for example, the thermal expansion) will result in the change in wavelength according to Eqn.(1-2).

1.3.2. Collimation

Most cavity optics designs produce near parallel beams with only a few milli-radian divergence thus the laser beam can travel a long way without losing its compactness and focusability. Even for a truly parallel beam there will be some divergence due to diffraction. The angle of beam divergence due to diffraction is defined as:

$$\theta = k\lambda/d \quad (1-4)$$

where d is distance, λ is wavelength, θ is the angle of divergence and k is a constant which equals 1.22 for an uniform beam and $2/\pi$ for Gaussian beam. Table 1.1 lists some typical beam divergence angle for industrial lasers.

Laser	CO ₂	Ruby	Nd-glass	Nd-YAG
Div.angle (mrad)	1-4	1-10	0.25-10	2-20

Table 1.1. Typical beam divergence angle for some industrial lasers^[54].

The beam divergence angle affects the effective beam diameter at the work place for materials processing. When a flying optics laser robot or gantry type CNC motion system are used the change of laser beam length could bring a change of the spot size. Therefore this is a factor to be concerned in the CNC laser system design.

The beam divergence angle tends to increase with increasing power output of the laser. The divergence of multi-mode laser is higher than single mode lasers. Divergence is also dependent on the laser mirror. For example, divergence for spherical mirror > that for plane mirror.

1.3.3. Coherence

Coherence is used to describe different parts of an assembly of electromagnetic waves which are in phase with one another. Spatial coherence is a term which describes the phase relation in plane perpendicular to the direction of beam propagation while temporal coherence describes the phase relation in the direction of beam axis. The spatial coherence represents the transverse beam intensity distribution stability in the beam propagation and temporal coherence represent the beam spectral width stability which affects beam focusing quality. A laser beam is basically both spatial coherent and temporal coherent which means both transverse beam profile and beam wavelength will not change in the beam propagation, nor with time.

1.3.4. Polarization

A laser beam is usually polarized but may have a varying plane of polarization. Since a polarized laser beam can reduce power losses at beam reflection mirrors which are used to guide the laser beam to the workstation in materials processing, some lasers are deliberately polarized (usually linearly polarized) before they come out of the front window of the laser cavity by using Brewster mirror or polarizing lenses. The absorptivity of a polarized beam is direction dependable and hence a stable plane of polarization is normally engineered by an internal "roof top" mirror which favors one polarization plane. Since the cavity is an amplifier, this plane is strongly favored and the stimulated emission phenomenon ensures that the plane of polarization is maintained. In practice most laser beams are strongly polarized because of the multiple reflection from the angled beam reflection mirrors. The polarized laser beam may produce different effect of processing for different traverse directions. Most cutting lenses are fitted with depolarizers, which split the beam into two parts and phase shift one part by $\lambda/2$ causing the polarization plane to rotate.

1.3.5. Mode structure

Energy Stored in a laser resonator has spatial variations in both directions perpendicular to the laser beam axis and along it. The former is described by transverse mode and the latter by longitudinal mode.

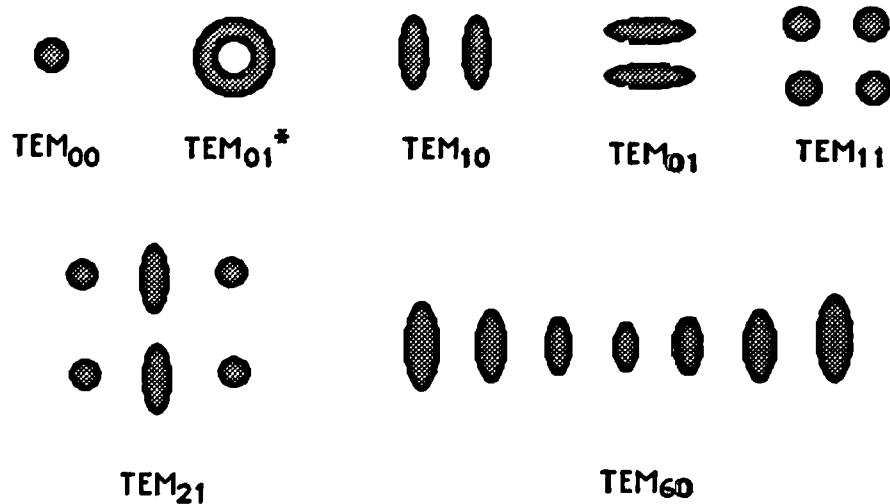


Fig. 1.5. Examples of laser beam transverse mode^[15].

a). **Transverse mode:** Since laser light is composed of electro-magnetic waves, the spatial distribution of laser beam resonating within a laser cavity is controlled by laws governing electric and magnetic fields in reflecting cavity. Each allowable distribution of an electromagnetic field across the laser beam axis is called a Transverse Electromagnetic Mode (TEM_{mn}). It defines the power density distribution across the beam. A laser may operate in one or many TEMs at the same time. Fig.1. 5 gives some of the laser transverse modes in which TEM₀₀ mode or Gaussian mode produces the smallest diameter and lowest divergence beam and TEM₀₁* mode or doughnut mode is a superposition of like modes (TEM₀₁ and TEM₁₀) rotated by 90 degrees. High order modes and multimode laser operations can increase the output power but decrease the coherence (see below) and increase the divergence^[14,15].

The intensity profiles of a TEM₀₀ mode can be expressed mathematically as:

$$I = I_0 \exp(-2x^2/r^2) \quad (1-5)$$

where I_0 is the intensity at the centre, x is the distance from the centre and r is the beam radius.

b). **Longitudinal mode.** Longitudinal mode of laser is the number of half wavelengths between the two end mirrors of laser cavity. It decides the frequency of beam oscillation and spectrum width (or line width) as from the following:

$$f_n = n(c/2L) \quad (1-6)$$

$$\text{and } f_{n+1} = (n+1)(c/2L) \quad (1-7)$$

$$\Delta f = c/2L$$

where f_n is the beam oscillating frequency at mode n and f_{n+1} is that at mode $n+1$. Δf is the frequency shift. c is the speed of light and L is the length between two mirrors.

In laser cutting, welding, drilling and soldering a Gaussian beam mode is desirable to achieve smallest focus spot while in laser surfacing such as transformation hardening, glazing, cladding and alloying higher mode is desirable and usually defocused wider uniform beam is used in these applications. Factors that affect laser mode structure include the geometry of the laser cavity and optics, the gain of laser cavity, homogeneity in the laser medium and the pumping power.

1.3.6. Beam waist, radius, near field, far field and focusing properties.

The minimum laser beam width before any focusing optics is called beam waist. Laser beam begins to diverge only after the beam waist. Usually the beam waist of the laser is at the laser output window of the laser cavity. The size of beam waist can be calculated theoretically from [15]:

$$w_0 = (\lambda b/2\pi)^{1/2} \quad (1-8)$$

where

$$b = [2/(R_1 + R_2 - 2L)] [L(R_2 - L)(R_1 - L)(R_1 + R_2 - L)]^{1/2} \quad (1-9)$$

and R_1 is the radius of curvature of the front window of laser cavity and R_2 is the radius of curvature of the back end mirror of the laser cavity and L is the length of the laser cavity.

Near field of laser beam is defined as the section of beam length which satisfies [15]:

$$L_f \leq d^2/\lambda \quad (1-10)$$

Here, L_f is the distance from the laser output window, d is the beam width at the output aperture, or beam waist in cavity, if known., λ is the wavelength of the laser beam.

Far field of laser beam satisfies [15]:

$$L_f \geq 100d^2/\lambda \quad (1-11)$$

The beam radius, w , as a function of propagation distance, Z , at far field (see bellow) is given by:

$$w = w_0 [1 + (Z\lambda/\pi w_0^2)^2]^{1/2} \quad (1-12)$$

Between near field and far field is gray field. These are illustrated in Fig.1.6

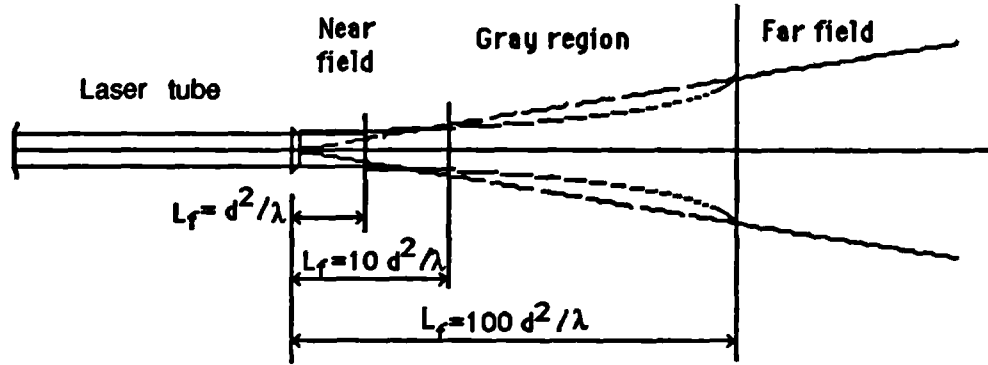


Fig. 1.6 Illustration of near field and far field of laser beams^[15].

There are also definitions for near field and far field^[2] as

$$\text{Near field: } L_f \leq 10d^2/\lambda \quad (1-13)$$

$$\text{Far field : } L_f > 10d^2/\lambda \quad (1-14)$$

This definition eliminates the need of a gray field. Laser beam divergence property is different for near field and far field. At far field the beam divergence is a constant while at near field the beam divergence is more complex. The phase front in the near field especially at the beam waist is planar while the phase front in the far field is usually curved. This could affect the focus quality.

Diffraction limited spot size at the focus of a lens with focal length, f , is:

$$r_s = 1.4f\lambda/D \quad (1-15)$$

where r_s is the spot size of the focused laser beam, f is the lens focal length and D is the diameter of the lens. The depth of field at focus is :

$$z = \lambda f^2/D^2 \quad (1-16)$$

These show that although the use of a shorter focal length lens gives a smaller spot size as desired for cutting etc., the depth of field will be reduced as a result and the beam divergence will be faster after the focal point. These are not usually desired in laser materials processing. In practice since laser power, mode, lens aberration and beam transaction will all affect the effective focusing, the spot size is usually bigger than the theoretical one. For a low order mode beam from a CO₂ laser typical focused spot size is about 100 μm ^[13].

1.4. CO₂ LASER MECHANISMS

The CO₂ lasers are studied more in this review because they are used predominantly in laser materials processing including laser cladding. CO₂ laser works on the transitions between various vibrational and rotational states of gas molecules. The vibrational levels of CO₂ can be described by 3 fundamental modes. I.e. symmetric stretching mode, bending mode and asymmetric stretching mode as shown in Fig.1.7.

C O C	DEFINITION
	Symmetric Stretching Mode (SSM)
	Bending Mode (BM)
	Asymmetric Stretching Mode (ASM)

Fig.1.7. Illustration of CO₂ molecule vibration modes.

Vibrational state is defined by the notation (n_1, n_2^l, n_3) where n_1 , n_2 and n_3 are the number of quanta at frequency ν_1 , ν_2 and ν_3 separately possessed by the molecule. The superscript l represents the quantum number of degenerate vibration which takes the value $l = n_2, n_2-2, \dots, 0$.

n_1 is the quantum level of excitation of the symmetric mode;

n_2 is the quantum level of excitation of the bending mode;

n_3 is the quantum level of excitation of the asymmetric mode.

A series of rotational levels are superimposed on each of those vibrational states. These are labeled j .

The mechanism of CO₂ (plus N₂ and He gases) laser action is governed by the following four processes:

1). Vibrational excitation of N₂ molecules by electron impact during discharges: Initially about 20-30% of N₂ molecules are vibrationally excited by direct electron excitation. I.e.

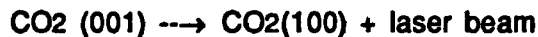


2). Vibrational energy transfer from the vibrationally excited nitrogen molecules to the asymmetrical vibration of CO₂ molecules: Since there is a close match of N₂ ($\nu=1$) to 001 state of CO₂ and higher level of N₂ to higher level ($00n$) of CO₂, the effective

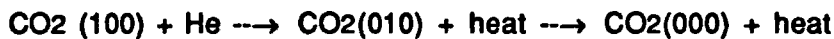
resonance collision transfer between them results in the rise of CO₂ energy level to 001 with average transition time of 10⁻⁴s. i.e.



3). Stimulated transfer of quanta (laser emission) from the asymmetrical value of vibration to the symmetrical vibration of carbondioxide molecules: If there is sufficient energy in the 001 level then the CO₂ starts decaying from 001 state to 100 state resulting in the near 10.6μm laser radiation with average transition time of 10⁻⁶s. i.e.



4). Depopulation of the lower laser level of carbon dioxide to the ground state by thermal relaxation: The CO₂ molecules in 100 level will further decay to lower levels (010 and 000) by non-radiative process. The primary effect of He is to help the relaxation of 100 to 010 and 000 levels while essentially unaffected the population in 001 level. He gas also helps to lower the gas kinetic temperature. The transition time in this process is about 10⁻⁷ to 10⁻⁵ s. The reaction can be expressed as:



The whole process of CO₂ laser generation can be described in Fig. 1.8.

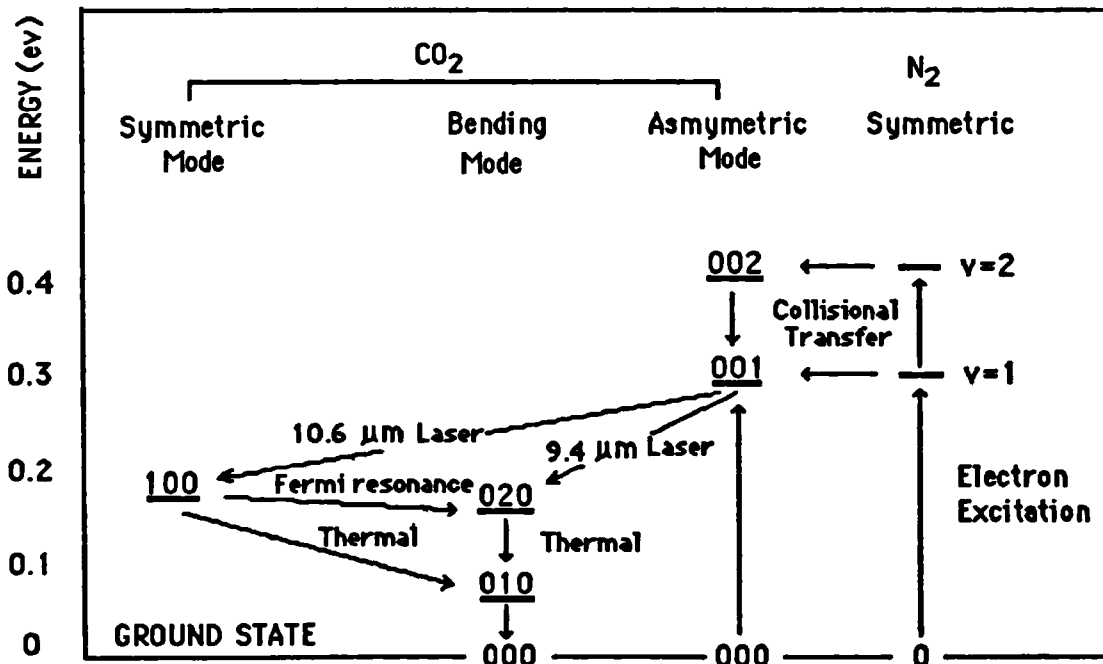
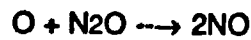
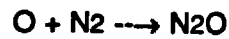
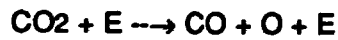


Fig.1.8. Illustration for CO₂ laser working principles.

Reactions in the media also produce CO, O₂, N₂O and NO as described by the following^[137]:



1.5. FACTORS THAT AFFECT CO₂ LASER BEAM QUALITY

Studies made by a number of workers have shown that many factors can affect the CO₂ laser beam quality. These factors include gas flowrate, gas pressure and mixture, tube current and bore diameter, tube wall temperature and stability of gas plasma.

1.5.1. Effect of gas flowrate on beam quality

The gain of the laser amplification was found^[16] to increase by increasing the gas flowrate as shown in Fig. 1.9. This is due to a). rapid cooling of gas mixture by convection so that relaxation can be performed easier; b). removal of dissociation products such CO by convection. Since CO ($v=1$) energy level closely matches that of N₂ ($v=1$) metastable state, a strong quenching of N₂ energy by CO can readily occur resulting in a decrease of pumping rate of 001 CO₂ upper level by N₂ ($v=1$)^[17].

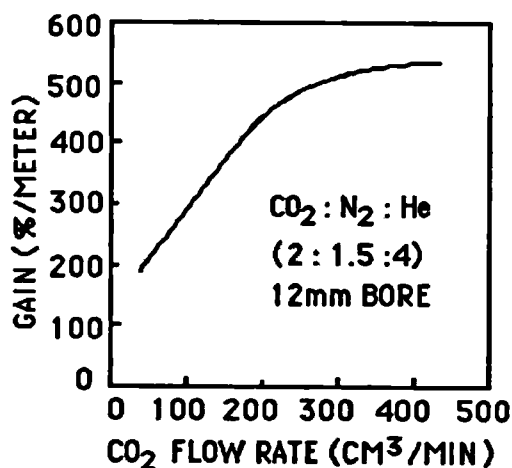


Fig. 1.9. Gas flowrate effect on the gains of the laser beam^[16]

1.5.2. Effect of gas pressure and mixture ratio on beam quality

Experiments by Cheo^[16] has found that at low pressure the gain will increase when gas

pressure increases. However for CO₂ and He there is a point above which gain will reduce when pressure increases as shown in Fig.1.10a and b. For He the gain saturates at a certain level as shown in Fig.1.10.c. This is probably because at lower pressure the increase of gas pressure increases the number of molecules in the medium and thus increase the probability of gas collision for energy transfer. However if there are too many ground state molecules the probability of population inversion will decrease which reduces the probability of stimulated emission. The gas mixture ratio was also found to affect the gain of amplification^[18]. A ratio of CO₂: N₂: He = 1:1:8 was believed to be appropriate for efficient lasing action.

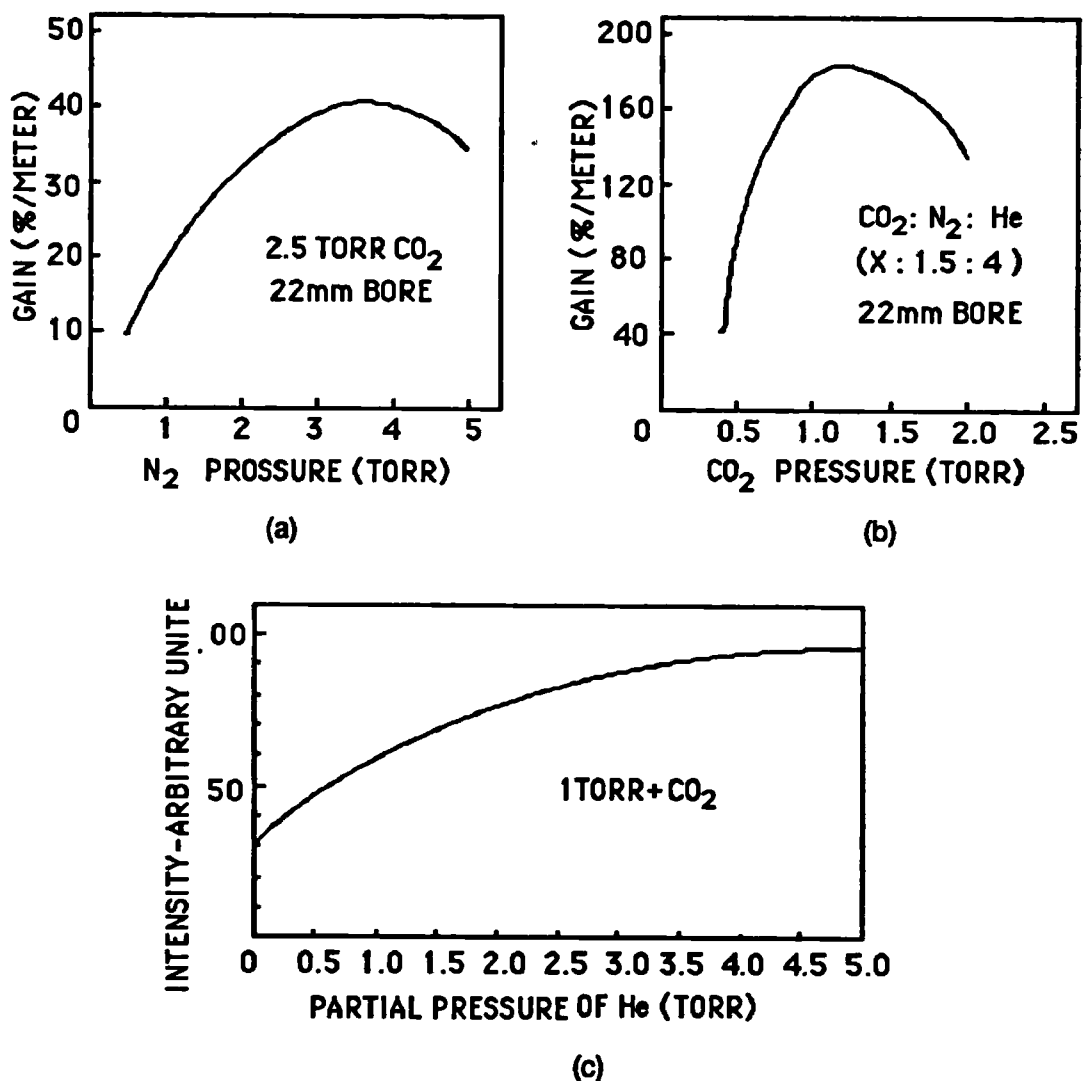


Fig. 1.10. Effect of gas pressure on the gains of laser beam ^[16].

1.5.3. Effect of tube current and bore diameter on beam quality

The gain of the beam amplification was also found to reduce slightly with increasing tube current (Fig. 5.11a) although beam power will increase with increasing tube current^[15].

The system gain is also inversely proportional the bore diameter of the laser tube (Fig.1.11b) . This is because the reduction of bore size will increase the gas flowrate for a constant supply of gases^[19] .

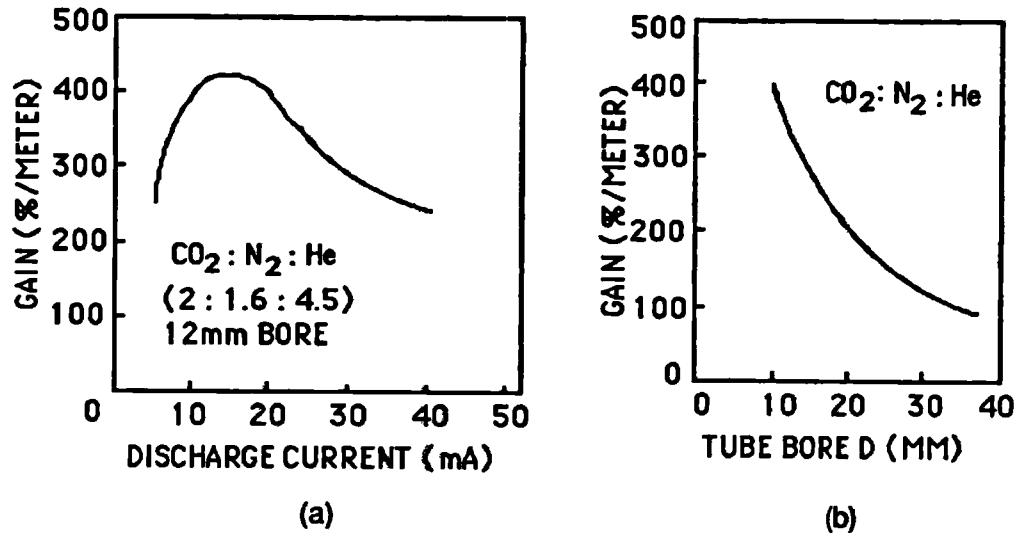


Fig. 1.11 Effect of tube current and bore diameter on laser beam gains^[19]

1.5.4. Effect of wall temperature on beam quality

The gain of the laser transition has found to increase linearly with decreasing wall (tube) temperature over the range from 20°C to 100°C^[16] as shown in Fig. 1.12. The temperature rise in the laser tube mainly affects the relaxation of 100 to 010 and 010 to ground state since they are thermal process.

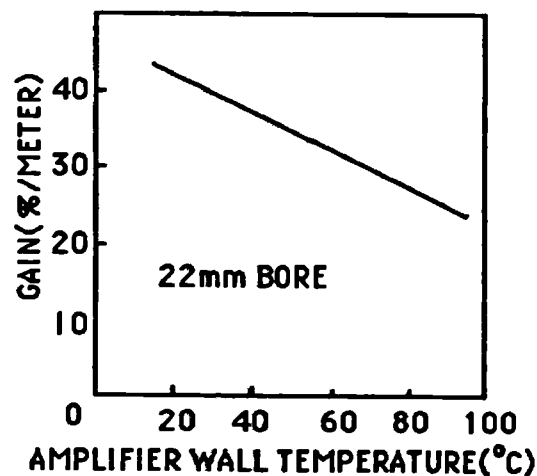


Fig. 1.12. Effect of wall temperature on the laser beam gains.^[18]

1.5.5. Effect of plasma fluctuations on beam quality

Fluctuations of electron density of the plasma generated in laser tube can cause considerable fluctuations in laser output power, and frequency as well as voltage and current in the laser tube^[20]. The frequencies of plasma fluctuation was found to be proportional to gas pressure and tube current^[20].

1.5.6. Effect of optical cavity geometric stability on laser beam quality

Both laser power and beam direction have been found to be effected by the length of resonator, mirror curvatures and alignment of mirrors in the cavity ^[21]. The geometry of laser cavity can again be affected by the laser tube temperature, plasma stability, cooling system stability or even laser power stability. Therefore a natural feedback loop could be formed in the laser cavity resulting periodical fluctuations of laser beam or related phenomena (See Chapter 5).

1.6. SUMMARY

A review has been given in this chapter about laser beam property and factors affecting the CO₂ laser beam quality. It can be seen from the above study that laser can provide a high intensity, flexible, clean heat source for materials processing but beam quality has to be carefully monitored and controlled so that the energy it provides is uniform and stable. The effect of laser beam quality on the quality of laser cladding will be studied in the next chapter.

CHAPTER 2

LASER CLADDING PROCESS DESCRIPTION AND PARAMETER RELATIONSHIPS

2.1 INTRODUCTION

In order to control the laser cladding process it is necessary to know what the process requires, how it is performed, what parameters are involved in the process and what their relationships are, as well as the various factors influencing clad quality. This chapter studies the previous work on the cladding process development. The emphasis is on the general features of the process and parametric relationships rather than the metallurgical and physical achievements of the process such as the application of a new material. Some new experiments made by the author are also included in this chapter. These experiments verified some of the previous results. From these experiments we also found that clad thickness reduces as laser power increases at low powder flowrate; dilution increases linearly with increasing laser power and decreases linearly with increasing powder flowrate. These relationships have not been noted before.

2.2 DEFINITION AND THE OBJECTIVES OF LASER CLADDING

Laser cladding is a process whereby a new material with the required property is fusion bonded on the surface of a substrate by laser irradiation to achieve one or more of the following:

- a). Improving surface wear resistance of the material. For example the cladding of Wallex 6PC on mild steel substrate.
- b). Creating a thermal barrier on the material surface. For example the cladding of zirconia, alumina on Udimet 700 alloy or AISI 4140 steel substrate.
- c). Corrosion resistance. For example the cladding of stainless steel or ceramics on mild steel substrate.
- d). Change of magnetic property or electric property of the material surface. Such as the cladding of austenitic stainless steel on cast iron substrate.
- e). Other benefits from surface property improvement.

The ideal laser cladding process requires:

- a). Minimum mixing between the clad and substrate so that the clad properties are not altered by the alloying of substrate materials.
- b). Minimum heat effect on the substrate.
- c). No process defect such as cracks, porosities, distortion, oxidation, micro

segregation or poor bonding etc..

d). uniform clad deposit

The laser cladding as an industrial process requires further:

e). repeatability of the products.

f). productivity, efficiency and economy of the process

2.3 METHODS OF LASER CLADDING

2.3.1. Wire feed laser cladding

Wire feeding was the first reported laser cladding technique which was patented by Gnanamuthu in 1976^[22]. The method is described in Fig.2.1.

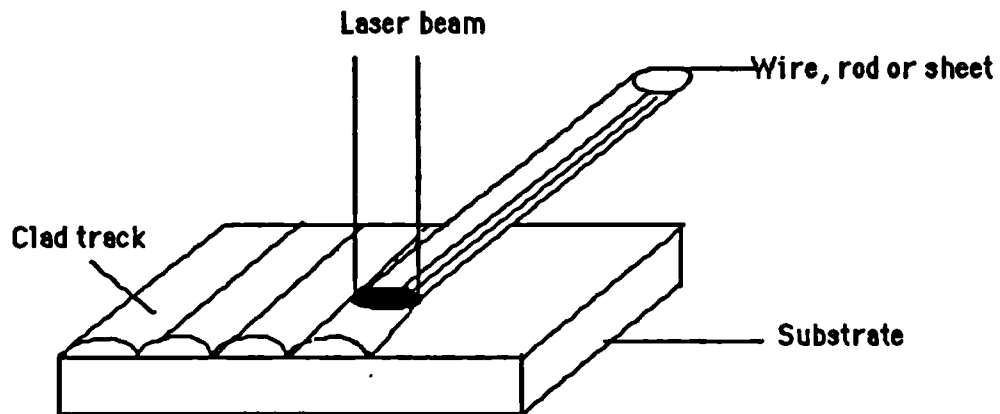


Fig.2.1 Illustration of wire feed laser cladding.

When the clad material in the form of wire or rod or ribbon was fed to a point under the laser beam in contact with the substrate surface, part of laser beam impinged directly on the cladding material to melt it and part of the beam impinged on the adjacent surface area of the substrate to improve flow of molten metal thereon. By the subsequent withdrawing of laser beam, resolidification of the melted material forms a fusion bond clad on the substrate. Many materials have been deposited this way, the patent reported, including Manganese phosphate on AISI 4815 steel substrate, Cast Stellite Alloy No.1 on AISI 4340 steel substrate and AISI 304 stainless steel on AISI C1018 substrate. The laser beam was 1-20 kW with a circular or non-circular beam shape. Beam diameter on the substrate was varied from 0.0635-2.54 cm with resulting 4.495-77.5kW/cm² power density. The traverse speed of substrate relative to the laser beam was between 0.211-2.11cm/sec. A better fusion bond and thicker clad layer comparing with conventional coating methods was reported to be achieved.

The difference between wire feeding laser cladding and laser soldering is that a thin layer of substrate melts as well in laser cladding to achieve a fusion bond while in laser soldering only the applied material is melted.

The advantage of this method is that a neat working environment can be achieved and clad material can be fully used since there will be no waste of clad material if they are completely melted. However due to the shadowing effect of the wire the coupling of laser beam to the workpiece was not very efficient [23]. Also it needs very precise feeding location in order to produce smooth material transfer. These conditions make the wire feeding process less popular than other methods discussed below.

2.3.2. Preplaced powder laser cladding

Cladding can also be performed by first preplacing a powder bed on the substrate surface and then fusing it down using a laser beam as shown in Fig.2.2.

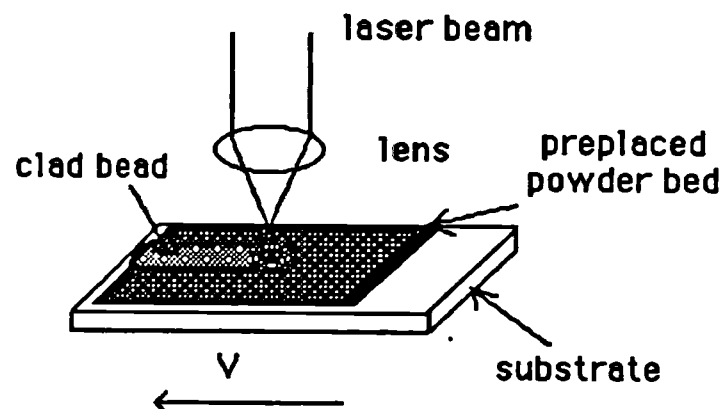


Fig. 2.2 Illustration of preplaced powder laser cladding process

The method was first reported in Gnanamuthu's patent in 1976 where Nickel powder was spread on the AISI 1080 steel substrate and scanned by a laser beam to form a clad bead. The technique was later put to industrial use by Caterpillar Tractor Co. for the coating of an engine valve by stellite 6 (Co base alloy) in 1977 [24]. The earliest university based study of laser cladding was started by Steen and Courtney in 1979 at Imperial College [25], where a 2 kW CO₂ laser was used to clad preplaced stellite12 powder on Nimonic75 substrate.

The powder bed can be preplaced on the substrate in one of the following forms:

1. loose powder (first reported by Gnanamuthu, 1976) which can be placed on a flat surface with a powder thickness of more than 0.5mm.
2. powder with a binder (first reported by Rocca et al, 1977 [26]) which can be

placed on the surface of any shapes. However often this results in increased porosity or surface roughness of the clad due to the ejection of vapor from the binder [27].

The main advantage of the preplaced powder method over the wire feeding is that the efficiency of coupling of the laser beam to material is increased. However since extra work is required to preplace powders the production cycle becomes long. Also as Powell pointed out[28] that although sound deposits could be produced over a wide range of processing parameters, there remains some difficulties in obtaining a reproducible thickness of powder bed and uniform clad over large areas. It is also difficult to achieve overlapping passes for uniform clad thickness using this method.

2.3.3 Powder feed laser cladding

In order to overcome the problems caused by the above two methods continuous powder feeding techniques were developed for laser cladding as shown in Fig. 2.3.

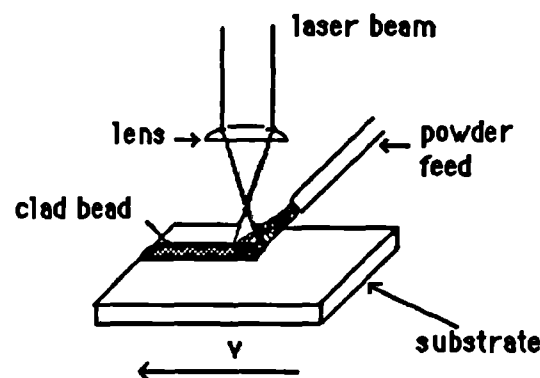


Fig. 2.3. Powder feed laser cladding

The first reported work on continuous powder fed cladding was by Clarke et al in 1979 at Imperial College[29]. The powder feeder used was a modified oxyacetylene torch with a funnel for powder flow as shown in Fig. 2.4. The powder was brought down to workpiece by gravity of powder and blown Argon gas. The laser beam first passes through the powder cloud and generates a melt pool on the substrate, the incoming powder will then be trapped in the pool and melted forming a fusion bonded clad layer.

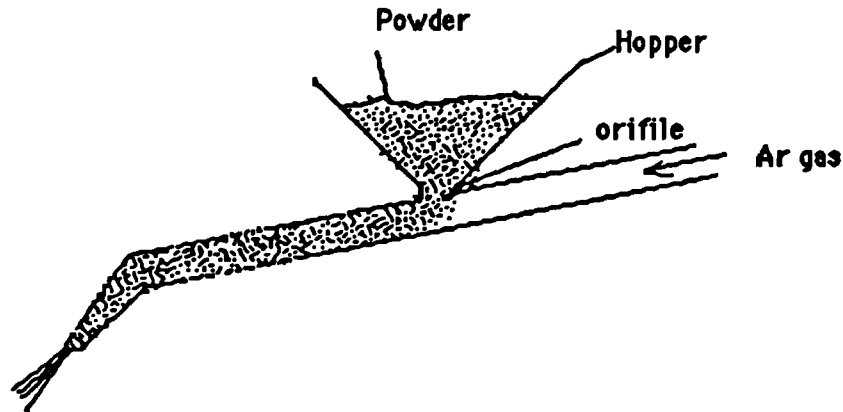


Fig.2.4 Gravity and Pneumatic driven powder feeder^[29].

Since powder can be fed to the laser generated melt pool during processing, any shape of substrate and overlaps of clad tracks can be performed to obtain uniform areas of clad. The process was soon adopted in industrial production by Rolls Royce in 1982 for hardfacing of turbine blade shroud interlocks^[30]. 85% reduction on the production cost over the previously used TIG welding technique was reported.

The powder feeding technique was further developed at Imperial College by Weerasinghe and Steen using a screw feed powder feeder in 1983.^[31]

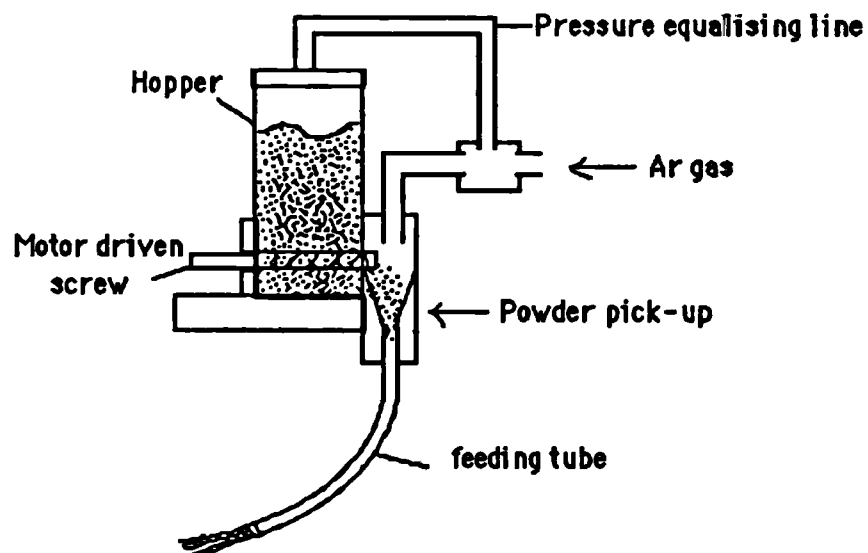


Fig.2.5. Screw powder feeder^[31,50].

It offers the advantages of a controllable powder feedrate (therefore controllable dilution and the deposit thickness) over wide range and uniform powder flow. The powder feeder developed by Weerasinghe is shown in Fig.2.5.

Takeda et al [32] has used multi-hopper single feed tube for the cladding of mild steel with Fe-Cr-Ni powders. These feeders can deliver pre-determined ratio of Cr, Ni and Fe into the same feed tube as shown in Fig.2.6a so that the clad composition and property can be easily controlled. Also studied by Takeda et al was a multi-hopper multi-tube feeding system as shown in Fig. 2.6b. The system was developed to enable the deposition of brittle hardfacing alloys with a soft 'buffer' layer in a simultaneous operation to eliminate hardfacing alloy cracking by plastic deformation of buffer layer. The results of feeding pure nickel powder to the front of the melt pool and a nickel based hardfacing alloy to the rear of melt pool showed that a clad "sandwich" could be produced though with considerable mixing of the two layers.

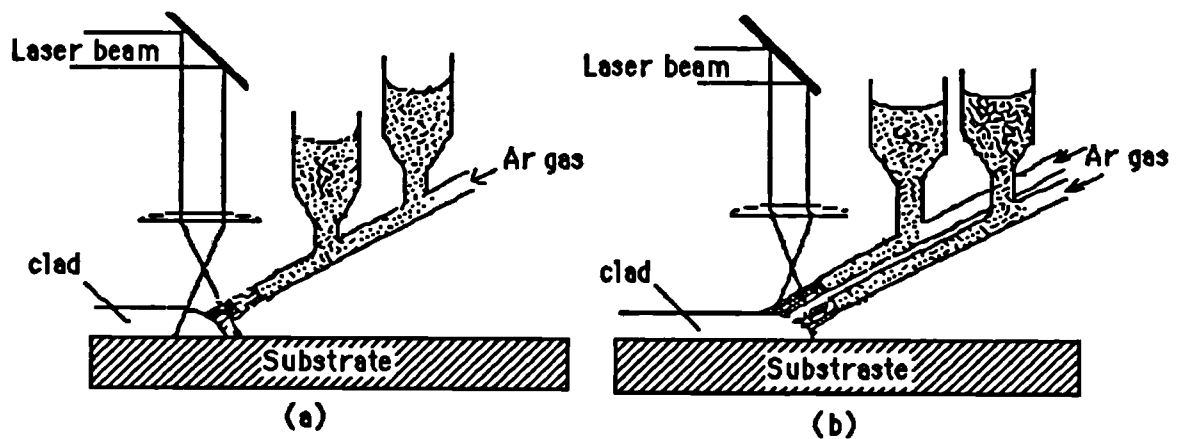


Fig. 2.6. Multi-hopper powder feed laser cladding. a). single feed tube; b). multi feed tube.[32]

In order for the powder feeding system to be omni-directional a coaxial laser/powder feed cladding system was developed by Tucker et al in 1984 [33]. The system as shown in Fig.2.7 was claimed, apart from the advantages of omni-directionality, to be more energy efficient in transferring heat to the substrate via direct particle heating than other particle injection techniques.

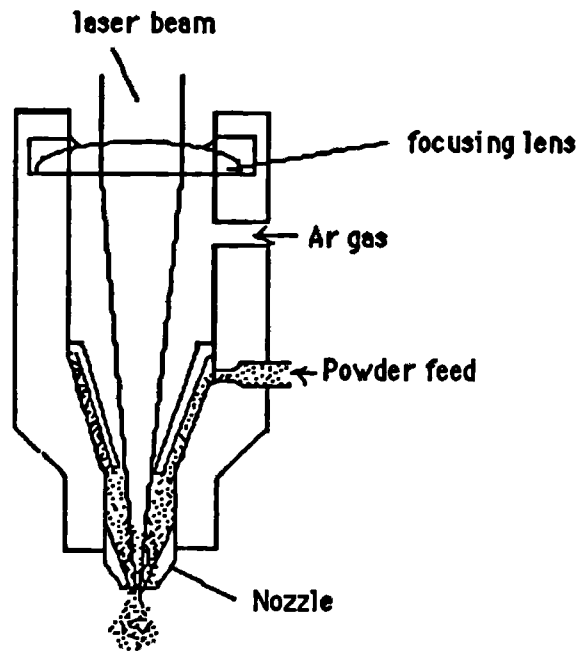


Fig.2.7 Coaxial powder feeding [33].

The major advantages of the blown powder cladding technique are that the process is a non-contact one and is not restricted to the shape and size of substrates. Clad tracks produced can be more uniform and overlapping to produce a layer of clad with uniform thickness is possible. At the same time the beam/material coupling efficiency is higher than that for the wire or rod cladding. One disadvantage of powder blown cladding is that some of the powders can bounce off from the substrate surface resulting in powder waste and possible pollution to the operating area. However much of this powder can be reclaimed since it will probably not have even be heated.

2.4. PREVIOUS DEVELOPMENTS FOR THE IMPROVEMENT OF CLAD QUALITY AND OPERATING EFFICIENCY

2.4.1 Vibro laser cladding

Powell [28] noted that in the cladding of hardfacing materials on a substrate, stress induced cracking and porosity were the major problems encountered in producing undiluted deposits. A vibro-laser cladding technique was then developed by Powell and Steen^[27]. The cladding was carried out simultaneously with ultrasonic vibration of the substrate by Lead-Zirconate-Titanate piezo-electric crystals with a frequency of 25kHz and associated amplifiers. This was reported to be able to reject pores and give rise to stress relief to the clad so that the incidence of cracking and population of pores were much reduced. The

process was later patented by Control Laser Ltd. in 1982 [34].

2.4.2 Substrate shot blasting and use of dome

Reducing the surface reflectivity of the substrate has been shown to help beam coupling and hence processing rate by Weerasinghe and Steen [31]. They used shot blasting to avoid surface contamination and increase surface roughness for enhanced beam coupling. Also an optical reflecting dome device similar to that patented by BOC for arc welding was developed by Weerasinghe as shown in Fig 2.8. This device was also patented for laser heat treatment by La Raca. By using the dome in the process, beam power coupling has increased to about 90% from the previous 30% to 60%, and oxidation and porosities in the clad were much reduced [31].

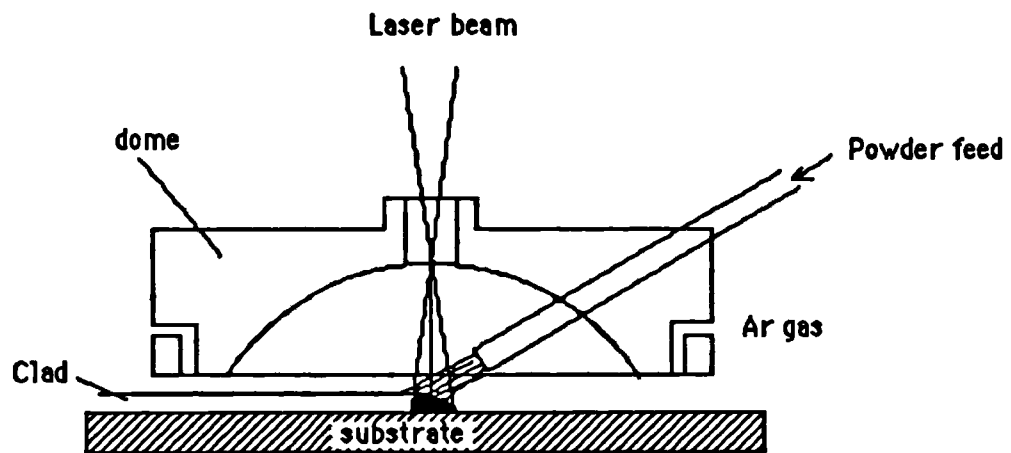


Fig. 2.8. Optical dome for beam recycling and process shrouding.[31, 50]

2.4.3. Laser beam homogenizing for uniform beam profile

Usually a defocused CW CO₂ laser beam (200W - 20kW) is used for laser cladding , which moves relative to the substrate at speed of 5-25 mm/s producing a clad track width between 1-8 mm. The problem of non-uniform distribution of laser beam energy across the beam diameter (Gaussian or doughnut or other Irregular shape as shown in Fig. 2.9.a and b.) prevents further increase of spot size or power level without creating dilution at the central part of clad track. The clad bead produced using a defocused beam should preferably have spherical cap shape (Fig.2.9.c).

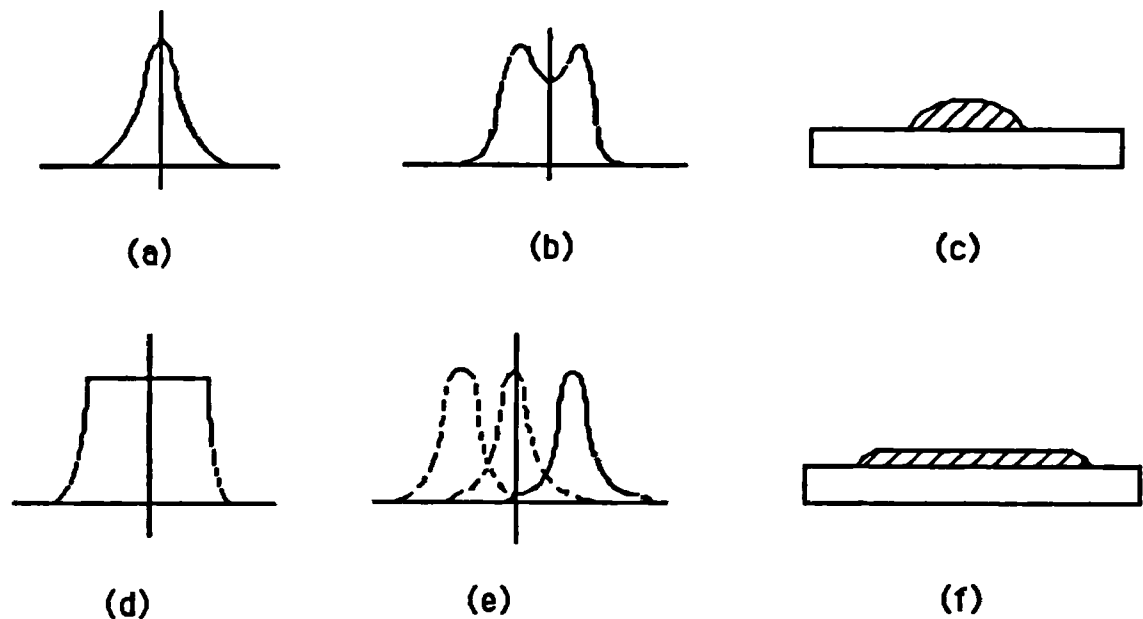


Fig. 2.9 Laser beams used in laser cladding and typical clad bead shapes produced. a). Gaussian beam; b). doughnut beam ; c). spherical bead shape; d). top hat beam produced by optical integrator; e). beam produced by optical oscillator; f). flat bead shape.

The development of optical integrators in 1980 by Dourte et al [35] homogenized the beam energy by superimposing many parts of beam intercepted by a segmented mirror (Fig. 2.10), so that a "top hat" square beam was produced (Fig. 2.9.d), by using which single clad track width of 12.7 mm has been reported to be achieved [36] with a wider top flat bead shape (Fig. 2.9. f).

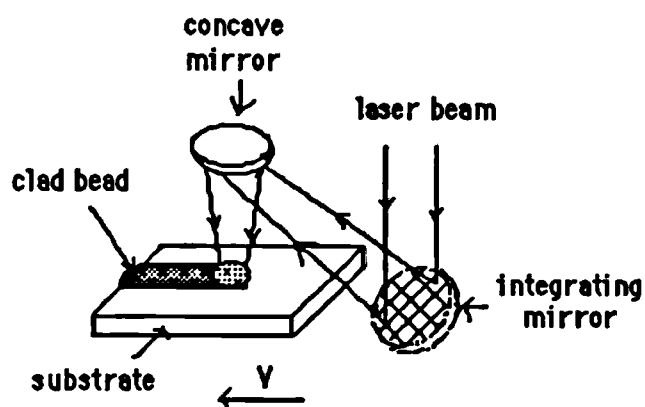


Fig. 2.10 . Use of optical integrator for laser cladding^[52].

An alternative method of achieving large single track clad is the use of a linear beam Oscillator (Slusher, 1983 [37]) which provides an uniform linear heat source with both frequency and amplitude adjustment (Fig. 2.11). The shapes of the beam and clad bead

produced are shown in Figs. 2.9.e. and f. The bead track width produced using this method has been reported to reach 12.7 mm with masks for a preplaced bed [36].

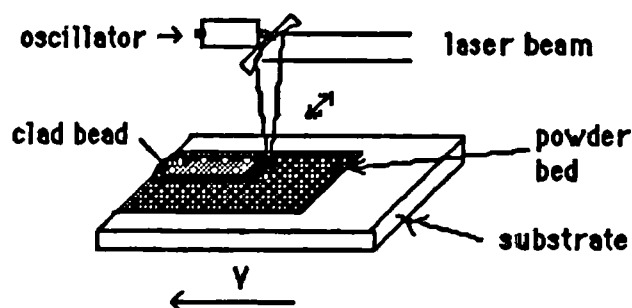


Fig. 2.11. Use of oscillated beam for laser cladding.

Other techniques developed recently for the reshaping of laser beam for surface treatment include the use of cylindrical lenses^[38] which was reported to be able to produce "top hat" laser beam with variable spot size and cylindrical mirror beam shaping device producing rectangular beam^[176].

2.5 APPLICATION OF LASER CLADDING IN INDUSTRY

The industrial applications of laser cladding techniques can be traced back to the early 1977^[24] when Caterpillar Tractor Co. used preplaced powder laser cladding for engine valves. The first powder feed laser cladding applications in industry was from 1981 by Rolls-Royce, cladding on turbine blade shroud interlocks^[30]. A list of some of the commercial laser cladding applications was made by Eboo and Lindemanis^[39] as shown in Table. 2.1.

<u>Company</u>	<u>Component</u>	<u>Cladding material and method</u>
Rolls- Royce	Turbine blade shroud interlock	Tribaloy/Nimonic (powder feed)
Pratt & Whitney	Turbine blade shroud interlock	PWA 694/Nimonic (preplaced chip)
GE	Proprietary	Reverse machining with Ti (powder feed)

Combustion engineering	Offshore drilling & production parts, valve components, boiler firewall	Stellites, Colmonloys and other alloys, including carbide, (powder feed)
Fiat	Valve stem, valve seat, aluminum block	CrC2, Cr, Ni, Mo on cast Fe (preplaced powder)
General Motors	Automotive	Cast iron systems
Rockwell	aerospace	T-800, stellites, (powder feed)
Westinghouse	Turbine blades	Stellites, Colmonloys (preplaced bed, and powder feed)
NRL	Proprietary	Multiple alloys, (powder feed, preplaced beds)
<u>Quantum Laser Corp.</u>	<u>Variety</u>	<u>powder feed</u>

Table 2.1 commercial applications of laser cladding (after Ref.39).

Most of the above industrial laser cladding systems are automated processes. The setting of the operating condition is, however, based mainly on experience.

2.6. ADVANTAGES OF LASER CLADDING OVER THE CONVENTIONAL CLADDING TECHNIQUES

Previous methods for local area cladding of an alloy material onto the surface of a substrate include:

1). Oxyacetylene torch cladding or braze welding: In this method a neutral oxyacetylene flame is used to weld down a bare cast filler rod onto the substrate. Usually low melting point alloys are coated onto the relatively high melt point substrate so that low dilution can be achieved.^[40, 41]

2). Plasma Transferred Arc cladding or fusion welding: In this technique coaxial powder is blown into a plasma arc generated between the tube electrodes and the

workpiece^[42]. Dilution is relatively high in this process if the workpiece surface melts, otherwise only a liquid/solid bond is formed.

3). Thermal spray cladding. This technique can be performed in 3 ways, in which the powder is melted and then blown into a solid substrate:

a). Oxyacetylene flame spray, where oxyacetylene gas is used as fuel source. The coaxial powder is blown into the flame and is melted. The molten powder then strikes and sticks to the surface^[43].

b). Induction fusion, which is coating by high power eddy current produced from induction machine. A preplaced powder coating is melted by induction heat onto the substrate surface^[44].

c). Vacuum furnace fusion. The sample previously coated by plasma or oxyacetylene methods is placed in a vacuum furnace and heated up for consolidation ^[45].

Most of these conventional processes use sources of highly variable power level such as flame or electrical sources or an overall heating of the substrate such as in vacuum furnace fusion. As a result, excess heat is normally directed to the workpiece being coated and the microstructure thereof is often adversely affected so that additional heat treatment is subsequently necessary ^[24]. A non-uniform clad surface may be produced due to the irregularities in the deposition rate and lack of the full ability to control its placement. The rate of deposition is also slow because of the low power produced by conventional sources.

Since the laser beam offers well defined spot size and high density power, cladding can be performed much more quickly with less total heat input so that dilution and heat affected zone can be reduced. Also high melting point material can be clad which was difficult with conventional methods. Steen ^[46] made a comparison of laser cladding and conventional coating methods as shown in Table 2.2.

The advantages of laser cladding can then be summarized as follows:

1. Smaller heat affected zone (HAZ) is produced because of the localized high density energy of laser beam.
2. Higher melting efficiency i.e. 35%-60% of the total available energy is utilized compared to 5%-25% for the conventional methods^[47].
3. Lower dilution is possible because of the accurate control of laser power input.
4. Homogeneous and uniform clad layer can be produced with refined microstructure due to the high turbulence and high cooling rate of the melted materials^[48].
5. Thick layer of alloy can be clad onto a substrate
6. Smoother clad surface can be achieved.
7. Clad rate can be increased
8. More flexible and easy for automation.

However as described in the General Introduction, there are also many problems of laser

COMPARISON OF CLADDING PROCESSES

PROCESS	ADHESION		QUALITY	EFFICIENCY		DISTORTION	FLEXIBILITY		SURFACE FINISH
	INTERFACE BOND S=Solid L=Liquid		DILUTION	DEPOSITION RATE	MIN THICKNESS	HEAT SPOT SIZE	APPL. TO AUTOMATIONS	APPL. TO INTERNAL	
	Clad subs		%	lb/hr	IN	IN		L=Large Only	
FLAME SPRAY	L	S	1-10	1-6	1/32	1			S
FUSEWELD	S/L	S	1-30						S
OXYACET + ROD	L	L	15-25						
M.M.A	L	L	"	5-25	$\frac{1}{8}$	$\frac{1}{2}$			
TIG	L	L		1-6	$\frac{1}{8}$	$\frac{1}{2}$		L	
GTA, TIG	L	L	10-20	1-8	3/32	$\frac{1}{2}$		L	
PLASMA TR ARC	L	L	5-25	1-15	1/16			L	
PLASMA SPRAY	L	S	5-30	1-15	1/32	$\frac{1}{2}$		L	S
PLASMA SPRAY	L	L	5-30					L	S
SAW	L	L	10-50	10-60	$\frac{1}{8}$ -5/16	2			
PLASMA + FNC	L	S/L	1-30						S
ROLL BONDING	S	S	0						(S)
EXPLOSION	S	S	0		$\frac{1}{8}$			L*	(S)
DETONATION	S	S	0		1/64				S
ELECTROPLATE	S	S	0		10^{-5}				S
PVD	S	S	0		0				S
CVD	S	S	0		0				S
ION PLATING	S	S	0		0				S
SLM LASER	S/L	L	0-90 Controll able	1-10	1/64	1/100 - $\frac{1}{2}$ Controll- able			S if correct

Table 2.2. Comparison of cladding processes[46].

cladding. It requires that operating parameters be carefully selected and precisely controlled in order to achieve the desired repeatability and quality of the laser cladding products.

2.7. PRINCIPLE PARAMETERS INVOLVED IN POWDER FEED LASER CLADDING

The following parameters are often concerned in laser cladding:

i). **Laser Power (P)** : Laser beam is the heat source for laser cladding. It decides the amount of heat input to the process. If it is too high, over heating, excessive melting may be resulted. If it is not enough, no fusion bond can be achieved. In current laser cladding practice the laser power is pre-selected (usually maximum power is used) and fixed during process. The Laser power used in cladding is usually between 1 and 15kW. This level is generally available from CO₂ lasers, which are used predominantly in laser cladding.

ii). **Beam spot size (D) and Power density (I_o)** : Spot size is defined as the laser beam diameter at the interaction surface. Since a defocused laser beam is used in laser cladding, the spot size is usually bigger than the focused laser beam size which could be less than 0.1 mm. The spot size in laser cladding can be determined from geometric ray diagrams as:

$$D = D_b Z / f \quad (2-1)$$

where D = spot size (mm)

D_b = Laser beam diameter at the lens (mm)

Z = laser nozzle standoff (mm), when laser focus is at the end of the nozzle.

f = focal length of the focusing lens (mm)

The spot size in laser cladding usually varies between 3 and 15mm depending on the power level and application involved.

Laser power density can then be derived from laser power and spot size as (for circular beam):

$$I_o = 4P / (\pi D^2) \quad (2-2)$$

iii). **Laser beam mode structure (TEM_{mn})**: As discussed in Chapter 1 the spatial profiles of laser beam are usually represented by TEM_{mn} (Transverse Electromagnetic Mode). For example TEM₀₀ represents a Gaussian profile while TEM₁₀ (Fig. 2.9a) represents a doughnut profile (Fig. 2.9b). For laser cladding, a "top hat" beam (Fig. 2.9d) or its nearest form such as doughnut beam was found to be the most suitable.

iv). **Powder flowrate (M):** Powder flowrate in laser cladding is defined as the mass of powder flow in a unit time, usually expressed in g/s or g/min. The flowrate decides the amount of clad deposit to be fused on the substrate. Non-uniform flowrate will result in non-uniform clad. Chapter 6 will discuss more on the powder feeding principle and the development for closed loop powder flowrate control.

v). **Traverse speed (V):** Traverse speed is an important parameter in laser cladding. It is the relative motion speed between substrate to be clad and laser beam. It affects clad deposition rate and deposit thickness. The usual traverse speed used in laser cladding is from 2 to 25 mm/s.

vi). **Clad bead width (W), height (H) and Aspect ratio (A):** A typical cross section of single bead clad produced by powder fed laser cladding is shown Fig. 2.12. with clad bead width and height defined in the picture.

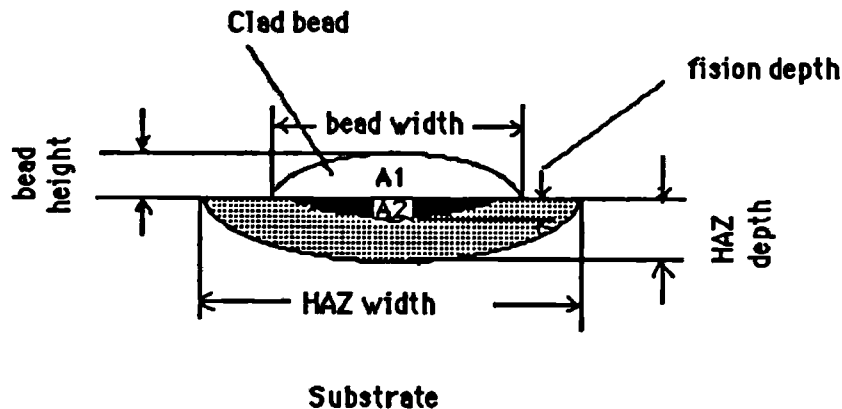


Fig. 2.12. Description of clad parameters.

The aspect ratio of clad bead is defined as:

$$A = W/H \quad (2-3)$$

where A is aspect ratio, W is bead width (mm), H is bead height (mm).

The clad bead width is closely related to spot size and also affected by traverse speed and mode structure. The usual bead width is from 2mm to 14mm. Clad bead height decides the clad thickness deposited and is affected by many parameters among them traverse speed and powder flowrate are dominant. The usual clad height produced is from a few microns to up to several millimeters. Aspect ratio is usually required to exceed 5 for overlapped laser cladding in order that good overlapped clad is achieved.

vii). **Dilution (DI) and fusion depth:** Dilution in laser cladding (DI) was defined by the percentage change of dominant clad element by the pollution of substrate material. This

can be express either by [49]:

$$D_1 = \frac{P_p(\%X_{p+s} - \%X_p)}{P_s(\%X_s - \%X_{p+s}) + P_p(\%X_{p+s} - \%X_p)} \quad (2-4)$$

where D_1 = dilution degree
 P_p = density of melted powder alloy
 P_s = density of substrate material
 $\%X_p$ = weight percent of element X in the powder alloy
 $\%X_s$ = weight percent of element X in the substrate
 $\%X_{p+s}$ = weight percent of element X in the total overlay

or [50]

$$D_1 = \frac{A_2}{A_1 + A_2} \quad (2-5)$$

where A_2 is cross section area of clad bead below the substrate surface and A_1 is cross section area of clad above the substrate surface as shown in Fig.2.12. Dilution is of constant concern in laser cladding practice, since any excessive dilution can alter the desired clad material property. It is difficult to achieve a fusion bond to the substrate and not to contaminate the clad material. Dilution can happen if there is too much heat input or too little clad powder or an unexpected surface temperature rise.

Fusion depth is defined as the maximum melt depth into the substrate. The same fusion depth may give a different dilution if clad bead dimensions are altered.

viii). **Heat Affected Zone (HAZ):** Heat affected zone is defined as that part of the substrate area beneath the clad bead in which the structure is different from the unaffected substrate as shown in Fig. 2.12. Heat affected zone, or HAZ, is often the cause of cracking due to hardening mechanisms such as martensite transformations in steels. The extent of the HAZ also indicates surface distortion and residual stress in laser cladding [51]. The HAZ is unavoidable in laser cladding since it is a result of heat diffusion from the molten clad material [51]. It can increase in size for continuous laser cladding, especially for overlapped cladding of small parts. In overlapping the HAZ structure of prior tracks may be tempered by subsequent passes. The HAZ can often be evaluated by is the width and depth.

ix). **Degree of overlap (λ) and clad thickness (h):** Degree of overlap is defined as the ratio of the part of clad overlapped, to the overall clad bead width. Sometimes an overlap index is used which is defined as:

$$\lambda = \frac{h}{l} \quad (2-6)$$

where i is overlap index and j is degree of overlap.

In laser cladding constant clad bead width and constant overlap degree is required so that uniform overlapped clad thickness can be maintained provided that the clad height is constant. The degree of overlap is usually between 50% and 75%.

x). **Interrun porosities and Interface porosities:** Porosities in laser clad include interrun porosity (Fig.2.13a), internal porosity and interface porosity (Fig.2.13b). Internal and interface porosities are rare and usually material dependent, as apposed to process dependent. They may be due to dissolved gas, or boiling reactions. Interrun porosities are often seen in cladding practice and may be avoided by proper arrangement of operating parameters.

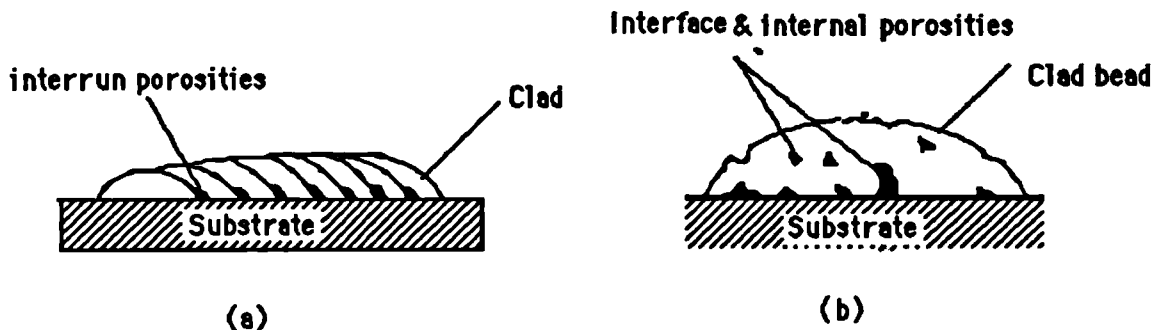


Fig.2.13. Porosities in laser cladding. a). Interrun porosities, b). interface and internal porosities.

A good clad should have no porosities. It is found that ^[50] if the degree of overlap is less than 75% and at the same time the aspect ratio of the single clad bead is greater than 5, then interrun porosity can generally be avoided.

xi). **Clad coverage rate (C):** Clad coverage rate or clad rate is the area to be clad in unit time expressed in mm^2/s . Maximum clad coverage rate is required in laser cladding. As will be seen later faster speed does not also mean higher clad rate. It is affected by a number of factors (see section 2.9.2.13).

xii) **Powder catchment efficiency (η_m):** Not all the powder fed to the process can be caught for clad formation, usually 30% to 40% of powder fed is used for actual clad formation. Powder fails to be caught due to a mismatch in powder jet size and melt pool size (which depends on many factors) and also powder ricocheting off the melt pool. The ratio of powders used for clad formation to the total powder flowrate is defined as the powder catchment efficiency (η_m). Maximum powder efficiency is required in laser cladding. However it is always affected by many factors as discussed later.

However it is always affected by many factors as discussed later.

A block diagram of the principle parameter relationships for powder fed laser cladding is shown in Fig.4 in General Introduction.

2.8. POWDER FEED LASER CLADDING MECHANISMS

Three basic physical phenomena have been found to be involved in laser cladding. They are beam absorption, heat transfer and mass transfer. In this section only the process with blown powder is discussed. The mechanisms for preplaced powder is different from the powder blown process. Detailed description on preplaced powder process can be found in Ref.52 and 53.

2.8.1. Beam absorption mechanism

When the laser beam strikes a solid material, the energy transfer of laser photon with the material will observe Boltzmann' relation as shown in Eqn.(1-1). A material can only absorb light energy if the wavelength of the incident light satisfies Eqn.(1-1) for the internal energy level of the material. Although each atoms of an element in the material has its own specific energy levels, when the density of the material is dense enough so that they interact with each other as in solids or liquids, the energy levels of the bulk are no longer those of individual atoms or molecules, but broaden and merge into a nearly continuous band, consisting of a large number of closely spaced energy levels, such a combination can exist for almost any wavelength and the material can be opaque to the beam --- *absorption*.

Generally, bound electrons respond only weakly to the external electromagnetic wave and mainly affect its phase velocity. Free electrons such as in metals and conductors, are able to accelerate and to extract energy from the field more efficiently. However, since the external field is periodically changing its direction, the oscillating electrons re-radiate their kinetic energy (reflection) unless they undergo frequent collisions with the atoms or lattice phonons and other electrons as in metals, thus heat is generated --- *light/heat conversion*.

Since the mean free time between collisions of electrons in a conductor is of order of 10^{-19} second, we can therefore regard the optical energy as being instantaneously turned into heat at the point of interaction at which the light is absorbed [54].

The light intensity penetrating into the material surface at depth, z can be expressed as [55]:

$$\Phi(z) = I_0 (1-r) e^{-\theta z}$$

(2-7)

where $\Phi(z)$ is the power density at depth, z (mm), I_0 is the incident laser power density (W/mm^2), r is the reflectivity of the material surface and θ is the absorption coefficient (mm^{-1}) which depends on material properties and wavelength of the incident beam. For metals, θ is of order of 10^5cm^{-1} . Therefore the absorbed energy is deposited in a layer about $0.1 \mu\text{m}$ thick^[55] -- skin depth.

In the powder blown laser cladding process, some of the laser beam will be intercepted by the powder cloud and lose some of its energy. The rest of the beam will pass through the powder cloud and reach the substrate. The amount of laser beam energy being absorbed and converted to thermal energy depends on the wavelength of the incident beam (reflectivity generally increases for conductors when the wavelength increases, Fig.2.14), angle of incidence and beam polarization (Fig.2.15), laser beam intensity (Fig.2.16), material surface conditions (rougher surface can usually cause some of the reflected beam scattering among the bumps of the surface therefore the absorptivity increases; surface oxidation and absorbant coating can also increase the absorptivity of the material As shown in Fig. 2.17, surface temperature and conductivity of the material(generally the increase of surface temperature will increase the absorptivity, especially when the material is melted; high conductivity material will usually have a higher reflectivity to infrared laser beams as shown in Figs 2.18a. Metals are all poor absorber for CO₂ laser beam. The higher the conductivity of a metal the more it reflects as shown in Fig.2.18.b.). The powder shadowing effect also contributes to the laser power loss as shown in Fig. 2.19. The increase of powder flowrate will decrease the beam absorption.

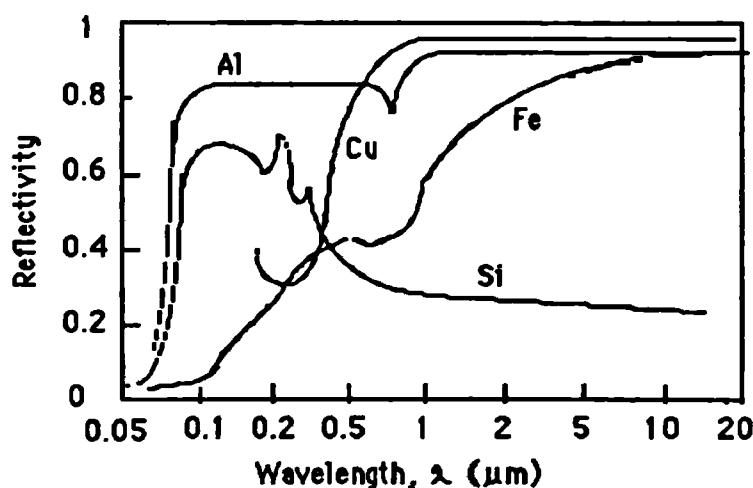


Fig. 2.14. Effect of beam wavelength on R. [54, 56]

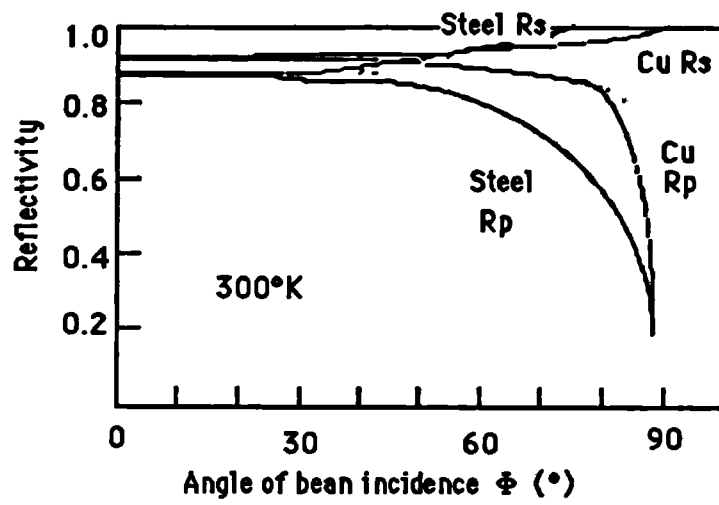


Fig.2.15. Effect of beam incidence angle on R.[57, 58]

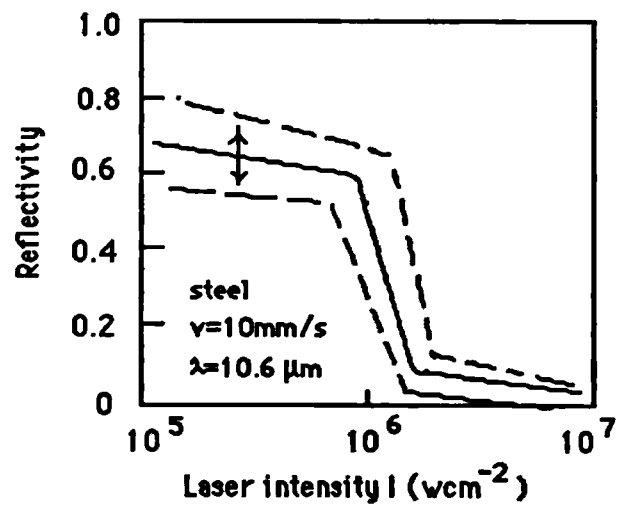


Fig. 2.16. Effect of beam intensity on R. [59]

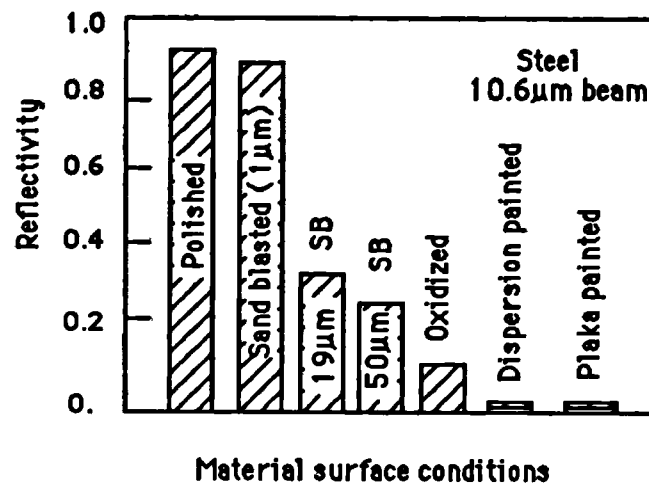


Fig. 2.17. Effect of surface condition on R.^[57]

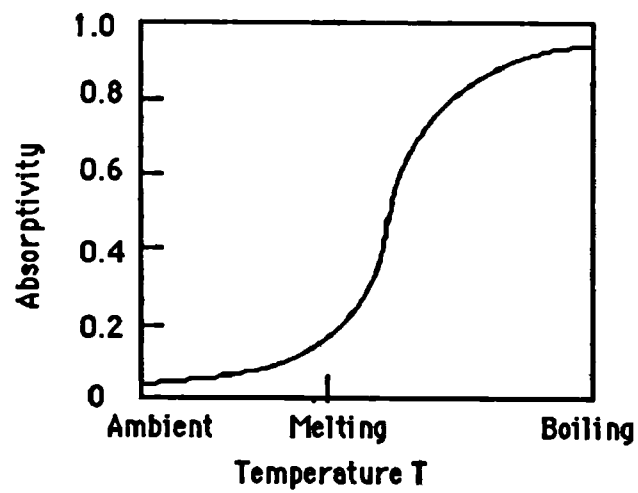


Fig.2.18. a. Effect of surface temperature on absorptivity. ^[56]

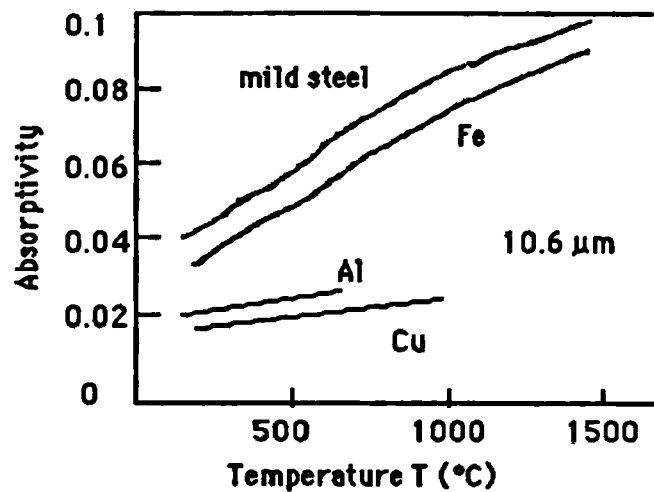


Fig.2.18.b. The effect of materials and surface temperature on absorptivity .[58]

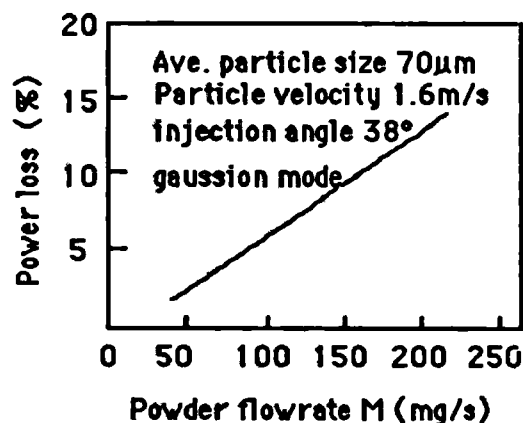


Fig. 2.19. Powder "shadow" effect on the beam material coupling efficiency. [60]

It has been found [47] that the absorptive characteristics of the molten surface in laser cladding can radically change due to the formation of drossy films (slag), such that , a significant portion of optical energy is reflected away. Discontinuous or patchy surface film formation during laser processing can cause variation in laser coupling efficiency during the course of laser cladding causing non-uniformity and variation of the thickness of clad or the contour of the fusion develop (bead profiles).

The reflection losses dominate many laser processing applications and are often the primary limiting factor to the overall efficiency of the conversion of laser radiation to heat in metallic systems. In laser cladding usually 30-65 percent of the laser beam is reflected. The use of a reflective dome in laser cladding can generally increase the absorptivity since

the reflected beam is recycled back to the workpiece. The coupling efficiency has been reported to increase to about 90% by using the dome [31,50]. (A problem was found later due to the contamination by powders and fume during laser cladding. An improvement was made in this thesis to solve this problem).

2.8.2. Heat transfer mechanisms

It has been found [31,50] that the powders arriving at the substrate surface were not melted. Therefore unless there is a initial melt of substrate, powders can not be caught and no clad is formed. On the other hand if there is too much melting of the substrate the incoming powders will alloy into the substrate melt pool which is also not desired in laser cladding. The ideal laser cladding requires the minimum amount of substrate to be melted and yet a fusion bond to be formed between the clad and the substrate. This is decided by both the amount of heat absorbed and by the thermal properties of the substrate, including its geometry and temperature. The basic heat transfer in laser cladding can be divided in three stages:

1. generating a thin "wet" melt pool on the substrate surface;
2. melting the trapped powders to form a deeper melt pool;
3. resolidification after laser beam moves away.

In the substrate "wetting" process, the surface temperature rise is mainly decided by the power density, substrate material thermal property and traverse speed. The powders only act as a "shadow effect" since they will bounce off from the surface until a melt on the substrate is generated to cause sticking. Many heat transfer models which were used for laser surface hardening and melting can be used to approximately describe the substrate temperature rise on the substrate. A rule of thumb formula given by Ready^[54] for a uniform beam interacting for time t_p with constant intensity I_0 is as follows.

$$\Delta T = 2(1-r)I_0 t_p^{1/2} / [\pi \rho C_v K]^{1/2} \quad (2-8)$$

- where
- ΔT = surface temperature rise (K)
 - r = surface reflectivity
 - C_v = specific heat of the substrate (J/gK)
 - K = thermal conductivity of the substrate (W/mmK)
 - I_0 = input power density = $4P/\pi D^2$ (W/mm²)
 - t_p = beam/substrate interaction time before the substrate melts
 - ρ = density of the material (g/mm³)

Once the substrate starts to melt, powders will be trapped in it and a melt pool will be generated. The heat transfer becomes more complex at this stage because not only is heat transfer by conduction to the surrounding solids (including resolidified clad with different thermal properties) but also by convection in the melt pool as well as to the new powder

arriving in the pool. The materials "melt up" for new powders instead of "melt down" for more substrates such as in preplaced powder method. However if powder flowrate is too low or clad material has high thermal conductivity and diffusivity the excessive heat will sometimes also melt down into the substrate as shown in Takeda's experiment^[32], Fig.2.20.b.

A heat balance in the melt pool has been derived by Steen^[61] for laser cladding which can be stated as:

Laser power absorbed = heat to melt arriving powder + convected energy + conduction loss

in which the radiated heat loss and heat for 'wetting' the substrate surface are neglected since they are usually small compare to the others.

This relationship has been expressed by Steen^[61] as :

$$\frac{4P(1-r)w \, dx}{\pi D^2} = M\eta_m (C_p T + L_a)w \, dx + v_c w \delta h \rho_p C_p \frac{dT}{dx} \, dx + q_c w \, dx \quad (2-9)$$

where M = powder flowrate (kg/s)
 η_m = powder catchment efficiency
 L_a = latent heat of the clad material (J/kg)
 w = width of the clad track (m)
 x = distance in clad direction (m)
 C_p = specific heat of powder (J/kgC)
 v_c = convective velocity (m/s)
 δh = thickness of convected layer (m)
 ρ_p = density of the melt material (kg/m³)
 q_c = Heat conducted away from the pool (w/m²)

Thus surface layer temperature of the melt pool, T, is given approximately by a relationship of the form:

$$T = \left[\frac{\frac{4P(1-r)}{\pi D^2} - q_c - v_c \rho_p \delta h C_p \frac{dT}{dx}}{M \eta_m C_p} - L_a \right] \quad (2-10)$$

Cracks and porosities can affect the pool temperature significantly, since the thermal

diffusivity is changed in a substantial way.

Mazumder and Kar^[62] found that the cooling rate of the melted material in laser cladding is of order of 10^3 °K/sec. This means melted material starts to cool down to resolidify even within the beam material interaction time (normally 0.2 ~ 2.5 sec). This suggests that a resolidified clad may be formed underneath the top molten layer. An experiment discovery of the shape of solid/liquid interface in the beam-material interaction zone using hammer decant method was made by Weerasinghe^[50], which is shown in Fig 2.20 a. A similar shape was also obtained by Takeda et al ^[32] (Fig.2.20 b).

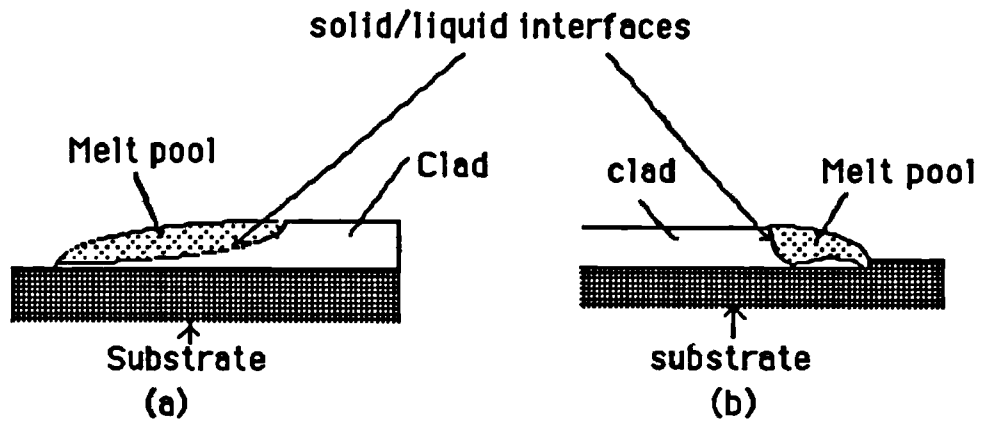


Fig.2.20. Melt pool shapes in laser cladding by powder feed method. a). from Weerasinghe's experiment. b). from Takeda and Steen's experiment.

This solid/liquid interface was described mathematically by Steen^[61] as:

$$x = \left[\frac{SA \sqrt{\alpha V} L^n w_{pp}}{M \eta_m} \right]^{\frac{2}{2n-1}} \quad (2-11)$$

and

$$y = \frac{M \eta_m x^n}{V_{ppw} L^n S} \quad (2-12)$$

or

$$y = B \sqrt{\alpha t} \quad (2-13)$$

where x is the distance from the leading edge of the clad

y is the melt depth at distance x

n is a constant between 0.5 and 1.

α is the effective diffusivity of the liquid clad

S is bead cross section shape factor

L is length of the melt pool

$B = 2 \operatorname{erf}^{-1}(T^*)$ and $T^* = (T_m - T_o) / (T_1 - T_o)$,

where T_m is the melting point of the clad, T_o is the initial temperature and T_1 is the melt pool temperature.

The most significant point in this qualitative calculation, as Steen suggests, is that a resolidified layer forms almost immediately after forming the fusion bond and only the shape of leading edge of the clad affects the probability of dilution. In an other words, dilution is generated mostly at the initial laser "wetting" process rather than the subsequent heat conduction stages. However this heat dissipation of the clad can cause a degree of heat affected zone (HAZ), which is undesired in laser cladding. Also problems like temperature build up and workpiece distortion are all part due to the heat accumulation. The surface tension of the molten material and the way the material is built up make the clad bead profile a spherical cap shape for defocused beam cladding. However if operating parameters are not chosen properly the bead profile can change to some undesired shape^[31].

2.8.3 . Mass transfer mechanisms

Mass transfer by turbulent convection has been found to exist in the melt pool. The force for the turbulent motion was found^[32] to be caused mainly by surface tension. An experiment made by Takeda and Steen^[32, 61] using embedded marker has shown that the average material traverse speed in the clad melt pool is about 48-80mm/s. This suggests that the uniform mixing in the melt pool of the clad is possible. This also suggests that if there is a melt of substrate in the melt pool the clad layer could be uniformly contaminated or alloyed. A mathematical model has been developed by Mazumder and Kar^[62] to describe this process (discussed later), in which both laser power and powder flowrate as well as the initial pool temperature have been found to affect the mass diffusion rate of the clad material.

2.9. PARAMETER RELATIONSHIPS IN POWDER FEED LASER CLADDING

The parametric relations in laser cladding can be classified into theoretical models which deal with ideal situations and experimental models obtained under real operating conditions through statistical analysis.

2.9.1. Theoretical models

The modelling of laser material processing was pioneered by Steen in 1976 for the calculation of surface temperatures in modelling the stationary Laser Chemical Vapor Deposition (LCVD) of cobalt oxide on glass substrate using finite difference methods [63]. However, only few models were developed for laser cladding process.

1. 3-D finite difference heat transfer model. A three dimensional finite difference model has been developed by Weerasinghe and Steen for laser cladding [50, 64] (1983). The model was based on an original moving source laser heating model developed by Mazumder and Steen [65] (1980) and subsequently improved by Henry et al [66] (1982). The object of the model is to obtain clad bead dimensions (width and height) resulting from a given set of process and operating parameters. The required input parameters include traverse speed, laser power, beam diameter, powder flowrate, melting point of substrate/clad, density of substrate/clad, average surface reflectivity, ambient temperature, specific heat of the clad, diameter of the powder cloud, and melt pool elongation factor etc. The model is based on the energy balance for different elements as described below.

$$\begin{aligned}
 &-(\alpha/\delta x)(\partial T/\partial x)WP - (\alpha/\delta y)(\partial T/\partial y)NP - (\alpha/\delta z)(\partial T/\partial z)HP + \\
 &+ (\alpha/\delta x)(\partial T/\partial x)PE + (\alpha/\delta y)(\partial T/\partial y)PS + (\alpha/\delta z)(\partial T/\partial z)PL + \\
 &+ [(Vmd/\delta z)(T_{part} - T_p - La/C_p) + V/\delta x(T_w - T_p)] = 0
 \end{aligned} \tag{2-14}$$

and for surface elements

$$K\delta x\delta y (\partial T/\partial z)HP = P_o (K,I) \tag{2-15}$$

where K = Thermal conductivity
 α = Thermal diffusivity
 C_p = Specific heat
 La = Latent heat
 T = Temperature
 T_{part} = Temperature of particles falling onto surface element (K,I)
 Vmd = Powder volume flow rate per unit area.
 V = Traverse speed
 P_o = Absorbed heat from laser irradiation
 W, E, N, S, H, L, P as located in Fig. 2.21.

The solution of the equation was obtained numerically on a computer using FORTRAN language. However a trial and error method must be used in the calculation of the solutions, since the bead geometry and the boundary conditions are both interrelated.[50]

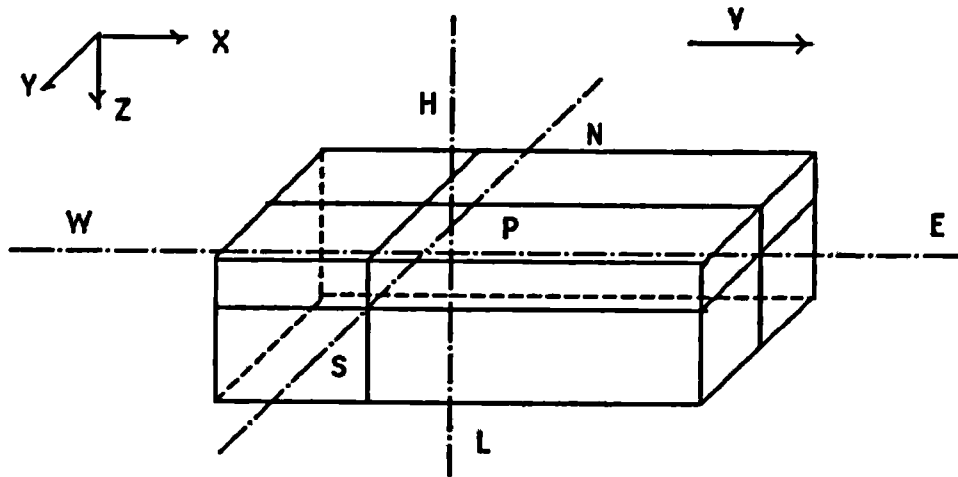


Fig. 2.21. An elemental control volume in Weerasinghe's model [50].

2. Two dimensional heat and mass transfer model. Another model developed by Chande and Mazumder [67,68] (1985) for powder injection laser alloying includes the effect of mass transportation in the melt pool was used to estimate the solute content of the resolidified material. Since the difference of laser cladding to laser alloying is the degree of dilution, the model could also be used for the cladding process to evaluate the degree of dilution. The model (two dimensional) can be written as:

$$(1/Pe)(\partial^2 C^*/\partial x^{*2} + \partial^2 C^*/\partial y^{*2}) - (u^* \partial C^*/\partial x^* + v^* \partial C^*/\partial y^*) = \partial C^*/\partial t^* \quad (2-16)$$

with boundary conditions:

$$\begin{aligned} \partial C^*/\partial x^* &= 0 \text{ for } x^*=0, \\ \partial C^*/\partial y^* &= -j^* \text{ for } y^*=0, x^* \leq x^*_{sl}, \\ \partial C^*/\partial x^* &= \partial C^*/\partial y^* = 0 \text{ at the solid-liquid interface.} \end{aligned} \quad (2-17)$$

where $C^* = (C - C_o)/(C_i - C_o)$ (dimensionless)

$X^* = x/d$ //

$y^* = y/d$ //

$t^* = t u_o/d$ //

$u^* = u/u_o$ //

$v^* = v/u_o$ //

$j^* = j/[D_c(C_i - C_o)/d]$ //

D_c = solute diffusivity in the molten pool (m^2/s),

C = concentration of the solute (kg/m^3),

u and v were local components of liquid velocity field in the x and y directions (m/s).

s_l = surface location of melt front,
 j = powder injection flux ($\text{kg/m}^2\text{s}$),
 C_i = a reference concentration (kg/m^3),
 C_o = original concentration (kg/m^3),
 d = beam spot size (m),
 V = traverse speed,
 $Pe = Vd/D_c$ is Peclet number for mass transport.

Numerical solutions were obtained to describe the solute distributions in the alloying track.

3. One dimensional heat and mass transfer model at a nonequilibrium cooling rate.

Mazumder and Kar (1987) [62] have developed another one dimensional model for laser cladding which considered both energy transport and mass transport at a nonequilibrium cooling rate. The model can be described as:

1). Energy transport

Region 1 (solid substrate)

$$\partial^2 T_1 / \partial x^2 = (1/\alpha_1) \partial T_1 / \partial t; \quad t \geq 0 \quad -\infty < x \leq 0 \quad (2-18)$$

Region 2 (solidified clad)

$$\partial^2 T_2 / \partial x^2 = (1/\alpha_2) \partial T_2 / \partial t; \quad t \geq 0 \quad 0 \leq x \leq S(t) \quad (2-19)$$

Region 3 (liquid clad)

$$\partial^2 T_3 / \partial x^2 = (1/\alpha_3) \partial T_3 / \partial t; \quad t \geq 0, S(t) \leq x < \infty \quad (2-20)$$

with boundary conditions:

$$\begin{aligned}
 T_1(-\infty, t) &= T_1(x, 0) = T_0 \\
 \partial T_1 / \partial x &= (k_2/k_1) \partial T_2 / \partial x \quad \text{at } x=0 \\
 T_1(0, t) &= T_2(0, t) \\
 T_2(x, t) &= T_3(x, t) = T_m \quad \text{at } x=S(t) \\
 k_2 \partial T_2 / \partial x - k_3 \partial T_3 / \partial x &= \rho L_a dS/dt \quad \text{at } x=S(t) \\
 T_3(\infty, t) &= T_3(x, 0) = T_f \\
 S(0) &= 0
 \end{aligned} \quad (2-21)$$

2). Mass transport

$$\frac{\partial C}{\partial t} - \frac{\gamma \sqrt{\alpha_3}}{\sqrt{t}} \frac{\partial C}{\partial x} = D_m \frac{\partial^2 C}{\partial x^2} \quad (2-22)$$

where γ is the root of transcendental equation:

$$\frac{T_m - T_0}{1 + \text{Erf}(\gamma)} + \frac{T_m - T_f}{1 - \text{Erf}(\gamma)} = \sqrt{\pi} \rho \frac{\alpha_3}{k_3} L_a \gamma e^{\gamma^2} \quad (2-23)$$

and the boundary conditions:

$$C(x,0) = C(\infty,t) = C_0 \quad (2-24)$$

and

$$D_m \left(1 + \frac{\gamma \sqrt{\alpha_3}}{\sqrt{t}} \beta\right) \frac{\partial C}{\partial x} = \frac{\gamma \sqrt{\alpha_3}}{\sqrt{t}} (k_e - 1) C \quad \text{at } x = 0 \quad (2-25)$$

where

T_1, T_2 and T_3 are temperatures of regions 1,2 and 3, respectively.

α_1, α_2 and α_3 are thermal diffusivities of the regions 1,2 and 3.

k_1, k_2 and k_3 are thermal conductivities of regions 1, 2 and 3.

$S(t)$ = location of solid-liquid interface at time t

T_0 = ambient temperature

T_m = melt point of the clad material

T_p = mean temperature of melt pool

ρ = density of the clad melt

L_a = latent heat of clad material

C_0 = initial concentration of solute in the liquid phase

D_m = mass diffusion coefficient

k_e = equilibrium partition coefficient at the solid-liquid interface

β = λ/D^* where λ is the interatomic spacing and D^* is the interdiffusivity.

From this model both the change in melt depth and clad composition can be evaluated.

2.9.2. Statistical models and experimental parameter relationships

Because of various assumptions for the validity of the calculations, the theoretical models are mostly used for predicting a new processing applications while experimental relationships are often used for actual processing practice. In this section, such relations are studied for the blown powder process. They are mainly taken from the work of Steen et al^[60], Weerasinghe^[50] and Takeda et al^[51].

2.9.2.1. Relationships for clad bead width

The following relationships have been found through experiments:

- a). Bead width decreases linearly with increasing traverse speed (Fig.2.22.b);
- b). Bead width increases with an increase in beam diameter;
- c). Bead width increases with increasing laser power (Fig.2.22a);
- d). Bead width decreases *slightly* with increasing powder flowrate;
- e). Bead width increases with increasing substrate surface temperature;
- f). Bead width increases with reducing powder particle size.

An experiment made by Weerasinghe ^[50] has shown that when substrate increases from room temperature to 700°C the clad bead width is nearly doubled.

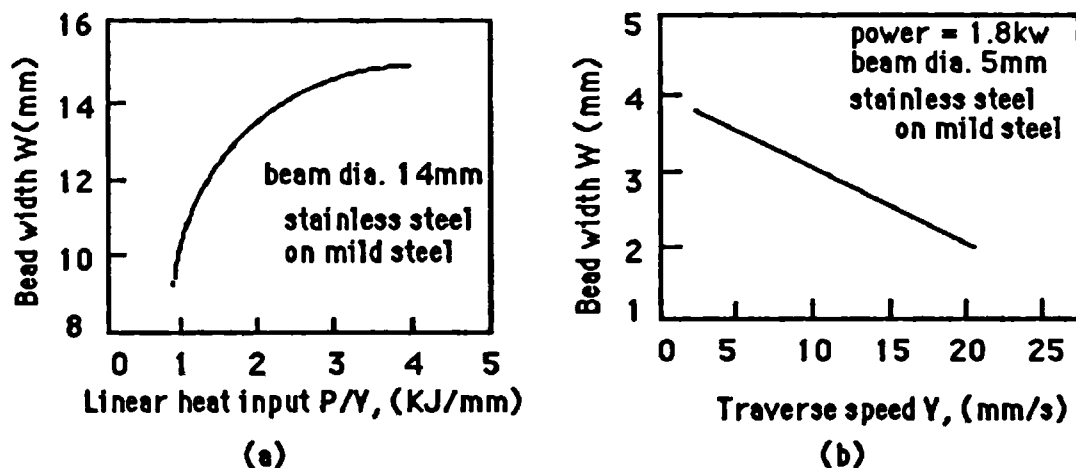


Fig. 2.22 . Effect of operating parameters on clad bead width. a). linear heat input effect on bead width ^[46], b). traverse speed effect on bead width^[50].

One statistical relationship found by Steen et al^[60] to relate the bead width to substrate traverse speed at constant laser power is:

$$W = D'(1-bV)$$

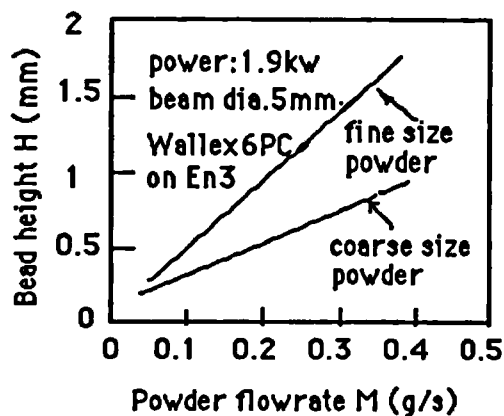
(2-26)

where V is the traverse speed (mm/s), b and D' are parameters depending on other factors, D' is approximately equal to the beam spot size. For a particular set up and materials applications D' and b can be found experimentally. It was generally agreed that the bead width can be considered to be independent of powder flowrate.

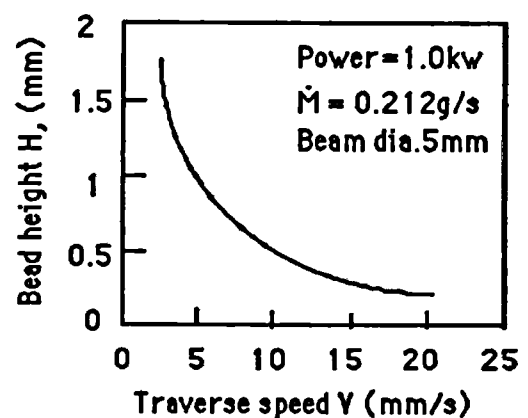
2.9.2.2 Relationships for clad bead height

Experiments have shown the following:

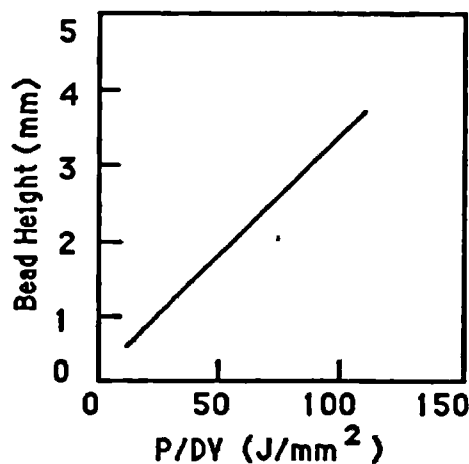
- a). Bead height increases linearly with increasing powder flowrate (Fig. 2.23a);
- b). Bead height decreases hyperbolically with increasing traverse speed (Fig. 2.23b);
- c). Bead height is not so much affected by laser power and beam diameter^{1,31};
However bead height decreases with increase P/DV ratio (Fig. 2.23c);
- d). Bead height decreases with increasing particle size (Fig. 2.23a);
- e). Bead height increases with increasing substrate temperature^[50].



(a)



(b)



(c)

Fig. 2.23. Parameter relationships for bead height. a). powder flowrate effect on bead

height [48, 60]; b). traverse speed effect on bead height [50]; c). specific energy density effect on bead height[51].

Steen et al^[60] have proposed a statistical relationship for the clad bead width as a function of powder flowrate and substrate traverse speed (V) as :

$$H = aM/V \quad (2-28)$$

where H = clad bead height (mm).
 M = powder flowrate (g/s).
 a = a parameter depending on laser power, mode structure, surface condition and other factors.

2.9.2.3. Parameter relationships governing the aspect ratio of the clad bead

The following was found by Takeda^[51]:

- Aspect ratio increases with increasing traverse speed (Fig.2.24b).
- Aspect ratio decreases with increasing powder flowrate.
- Aspect ratio decreases with increasing laser power (Fig.2.24a).
- Aspect ratio Increases with increasing spot size.

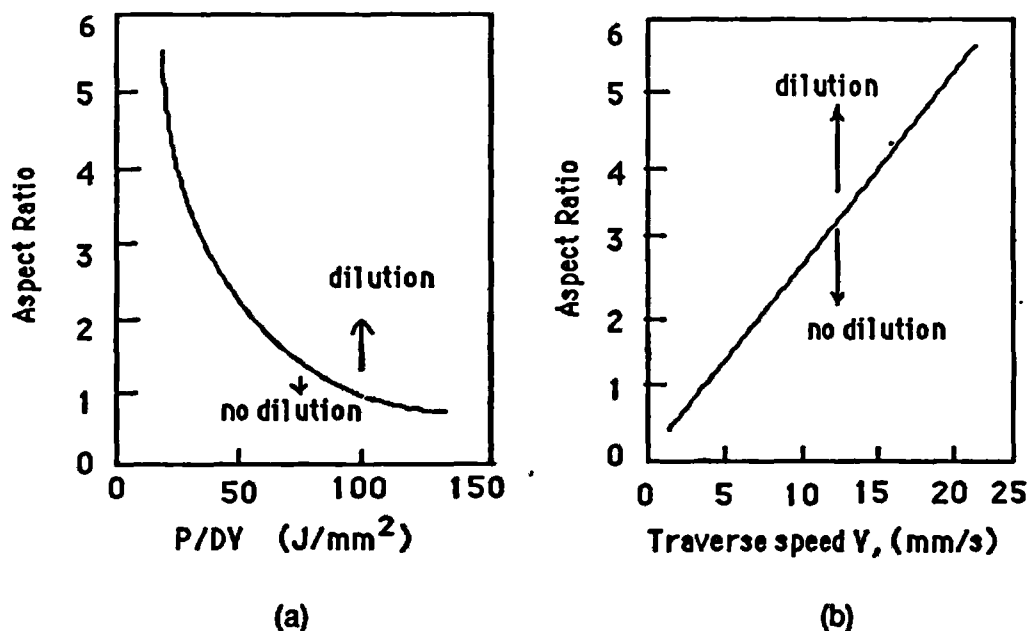


Fig. 2.24 . Effect of linear heat input and traverse speed on clad aspect ratio^[51]

A statistical relations can be derived from Eqns.(2-27) and (2-28) as:

$$\begin{aligned}
A &= W/H \\
&= D(1-bV)/(aM/V) \\
&= DV(1-bV)/(aM)
\end{aligned}
\tag{2-29}$$

2.9.2.4. Parameter relationships for dilution

Previous experiments has found the following:

- Dilution increases with increasing laser power.
- Dilution decreases with increasing powder flowrate
- Dilution is relatively independent of traverse speed.
- dilution increases with decreasing of spot size

Experiments and some theoretical calculations by Steen et al ^[60] have found the following constraints for avoiding excess dilution:

$$P/(DM) \leq K_m \tag{2-30}$$

where K_m is a factor depending on other processing conditions. Table 2.3 lists the experimental values of K_m for some materials.

Table 2.3. Dilution parameters K_m for various materials ^[60].

Cladding materials (mild steel substr.)	Maximum value of K_m to avoid significant dilution J/g.mm
Wallex 6PC (Cr- based hardfacing alloy)	2500 (multiple track, 50% overlap) 3000 (single track)
Colmonoy 52M (Ni- based hardfacing alloy)	2000 (single track)
316 stainless steel	2300 (single track)

Takeda^[51] has found that the fusion depth has the following relationship with other process parameters:

$$\text{Fusion depth} = C_p P(1-C_m M)/D(1-C_v V) \tag{2-31}$$

where C_p , C_m and C_v are constants which can be determined through experiments.

2.9.2.5. Parameter relations dominating the size of Heat Affected Zone

Experiments by Takeda^[51] have shown that:

- a). HAZ width and depth reduce with the reduction of spot size
- b). HAZ width and depth reduce with increasing traverse speed (Fig.2.25)
- c). HAZ reduces with increasing powder flowrate.
- e). HAZ is relatively independent of particle size.

HAZ is mainly produced by thermal diffusion while dilution is produced by initial melting. .
No statistical relations were given.

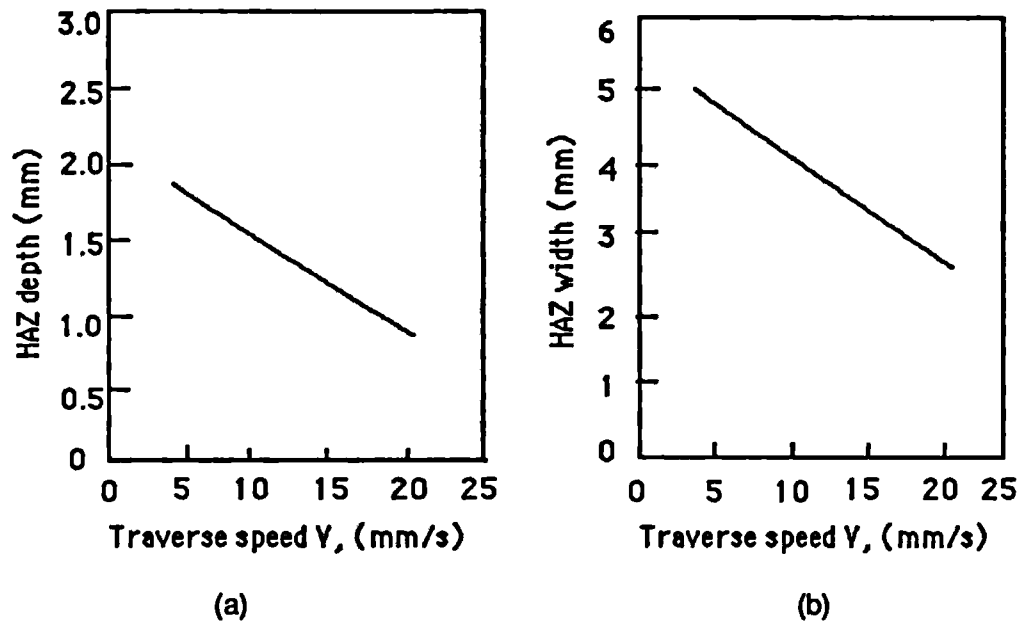


Fig. 2.25. Traverse speed effect on HAZ ^[51]. a). Speed effect on HAZ depth , b). Speed effect on HAZ width.

2.9.2.6. Parameter relationships for clad thickness of an overlapped area

Experiments by Weerasinghe^[50] showed that:

- a). Clad thickness over an area increases with increasing single track bead height.
- b). Clad thickness over an area increases with increasing degree of overlap.

An experiment made by Nurminen and Smith ^[48] showed that different shielding gas will also affect clad thickness uniformity. If power density is 10^3 - 10^4 W/cm², Argon gas is reported to be better than helium for the clad uniformity. The steady state relationship between area clad thickness, h and single bead clad height, H and overlap factor, i, has been found by Weerasinghe ^[50] to be :

$$h = - 1.8 H \ln(i) \quad (2-32)$$

(see Fig.2.26). No transient relationships are given in the literatures.

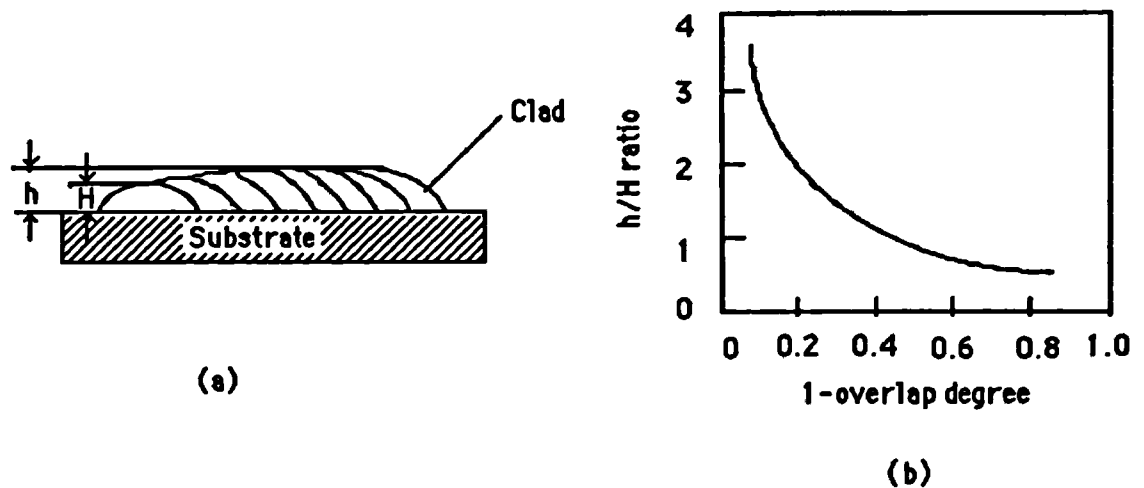


Fig. 2.26. Relationship between of clad thickness and single bead height. a). geometric illustration. b). experimental relation [50].

2.9.2.7. Factors that affect clad porosities

The interrun porosity for the defocused beam method is affected by the degree of overlap and aspect ratio of the single clad track. Experiments have shown [31,60] that if the following conditions are satisfied interrun porosities can generally be avoided:

- a). $Asp \geq 5$
- b). $i \geq 30$ (2-33)

For cladding using optical integrators or line scanners, the interrun porosity is decided by the side angle of the single clad bead since the bead is not circular shape. If the side angle $> 120^\circ$ then interrun porosity free clad can be obtained [49]. Interface porosity can be caused by sharp differences of the melting points of the clad and substrate materials. The higher the clad material melting point the more likely will be the interface porosity.

2.9.2.8. Factors that affect clad bonding conditions

Clad bonding may fail if:

- a). there is not enough laser power to generate a initial "wet" substrate. This is decided by the ratio of laser power to powder flowrate i.e.

$$P/M \geq K_{min} \quad (2-34)$$

where K_{min} is the minimum value required.

b). different thermal expansion rate of clad material and substrate material. On cooling the bond may break.

c). If melting point of clad is much lower than that of substrate, the clad may be vaporized. [69]

2.9.2.9. Factors that affect clad homogeneity

Since the melt pool in laser cladding is highly turbulent (shown experimentally by Takeda[32] and Steen[61], and theoretically by Chan[70]). Mass diffusion (mainly eddy diffusion) and convective flow dominate the mass transportation in the molten pool. However if beam-material interaction time is not sufficient to allow for this mass transportation, ie. traverse speed is too high, then non- homogeneity of clad may occur [31,61]. i.e. for homogeneous cladding, the traverse speed must satisfy the relationship:

$$V \leq V_{max} \quad (2-35)$$

where V_{max} is the maximum allowed traverse speed for a homogeneous clad.

2.9.2.10. Factors that affect clad surface oxidation

The degree of oxidation of the clad depends on activity of the elements in the clad material with oxygen, the oxygen content of the shroud gas and the clad material, also if the surface temperature is too high then the hot clad may emerge from the shrouded region. Since there is not a perfect shrouding system, oxidation will always occur in laser cladding to some extent especially for overlapped cladding since the surface temperature may build up to very high values.

2.9.2.11. Factors that affect clad cracking

In solidifying and cooling a liquid molten pool on an externally cool substrate considerable residual stresses build up. Cracking will occur if there is insufficient ductility in the clad layer. This is particular relevant to hard materials [31]. The differences of the linear heat expansion coefficients of the clad material and substrate material may also contribute to the cracking on cooling.

2.9.2.12. Factors that affect substrate distortion

Substrate distortion is common in cladding processes due to the reasons stated above (2.9.2.11). Those processes which heat up the entire workpiece, e.g. vacuum fusion, suffer least from distortion, while those with thermal gradients usually distort. The laser process thus is vulnerable to distortion. One of its potential virtues is that in laser cladding only small areas may be clad, as in the Rolls Royce shroud interlock, hence distortion is minimum.

2.9.2.13. Parameter relationships for clad coverage rate

For overlapped cladding the clad coverage rate is decided by single clad bead width, degree of overlap and traverse speed, which can be expressed as :

$$\begin{array}{lll} C = iWV/2 & \text{for one directional feed} & (2-36) \\ \text{and } C = iWV & \text{for omnidirectional feed} & (2-37) \end{array}$$

If by substituting Eqn (2-26) the above two equations become:

$$\begin{array}{lll} C = iD(1-bV)V/2 & \text{one directional feed} & (2-38) \\ C = iD(1-bV)V & \text{omnidirectional feed} & (2-39) \end{array}$$

2.9.2.14 Factors that affect powder catchment efficiency

Powder catchment is a important concern in cladding applications. Normally only 30% of powder can be used for the clad bead formation [51]. Takeda has made a series experiment to study various factors affecting powder catchment efficiency, through which he has found the following:

- a). Powder catchment decreases with increasing traverse speed (Fig. 2.27a,b);
- b). Powder catchment decreases with increasing powder flowrate (Fig. 2.27a);
- c). Powder catchment increases with increasing spot size (Fig. 2.27b);
- d). Powder catchment increases slightly with the increase of laser power;
- e). Powder catchment increases linearly with increasing feed angle (Fig. 2.27c).
- f). Highest powder catchment can be obtained if feeding central axis was aligned to the centre of laser beam interaction region compare to other positions.

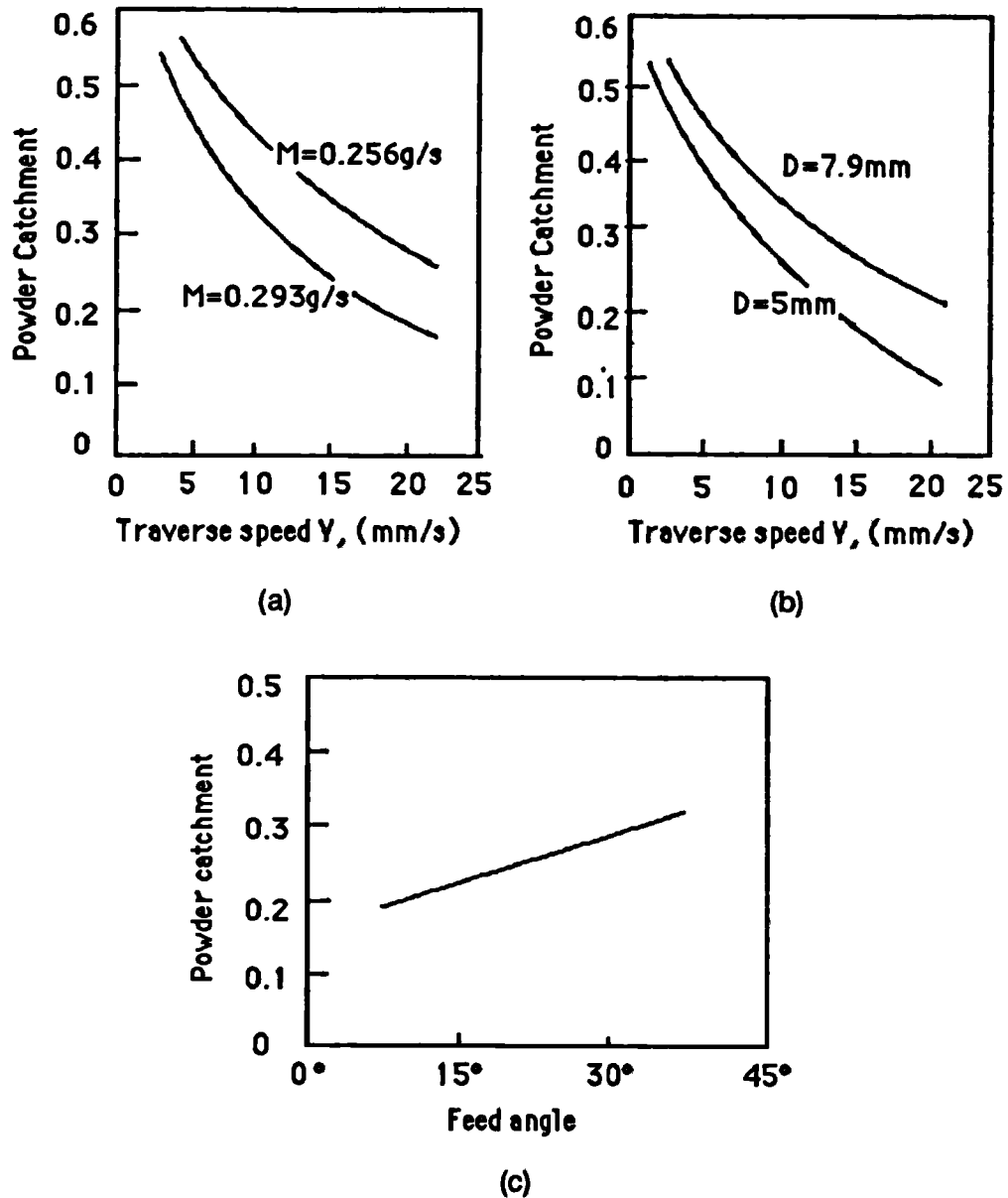


Fig. 2.27. Various factors affecting powder catchment efficiency^[51].

2.10. EXPERIMENTS BY THE AUTHOR FOR THE STUDY OF LASER POWER AND POWDER FLOWRATE EFFECTS ON CLAD QUALITY

Experiments were made to verify some of the results obtained from previous workers and to study the effect of laser power variation and powder flowrate variation on dilution and bead dimensions, which were not given by the previous work. The clad material used in this experiment is 316 stainless steel and substrate is mild steel.

2.10.1. Effect of laser power and powder flowrate on dilution

An experiment was made to produce single clad tracks by using different laser power and powder flowrate. The sample was cross sectioned and the dilution was measured using Eqn.(2-5) with a microscope. The results are plotted as shown in Fig. 2.28. and Fig.2.29, from which we can see that dilution increases linearly with increasing laser power and decrease linearly with increasing powder flowrate.

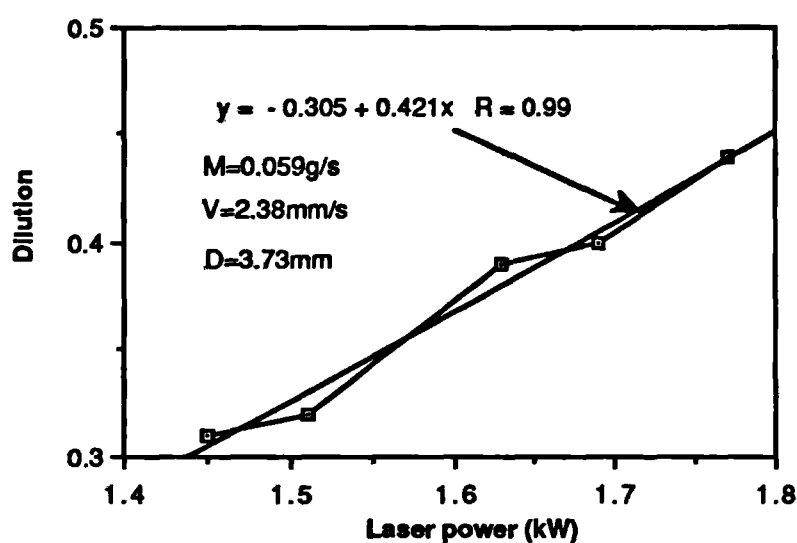


Fig. 2.28. Effect of laser power on dilution with LS curve fit.

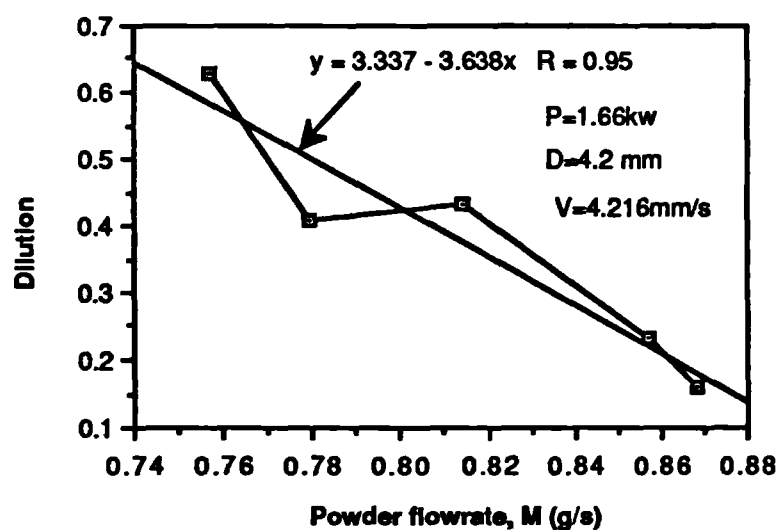


Fig. 2.29. Effect of powder flowrate on dilution with LS curve fit.

A statistical relationship for dilution can be found in the form of :

$$\text{Dilution} = cP - d_m M \quad (2-40)$$

where c and d_m are two constants which can be determined through experiments. For example, in sample 1 (Fig. 2.28), $c=0.421$ and $d_m=0.593$; in sample 2 (Fig. 2.29, $c=2.01$ and $d_m=3.638$. In both cases c and d_m have the same order of magnitude. The reason that the values of c and d_m are different in the two cases is probably because the operating conditions are different and the surface conditions of the two samples are different. (Sample 2 was shot blasted while sample 1 was as received).

2.10.2. Effect of laser power and powder flowrate variations on clad bead width

In the above experiment clad bead width was measured and relationships with laser power and powder flowrate were plotted as shown in Fig. 2.30 and Fig. 2.31. From these diagrams it can be seen that at low laser power level, clad bead width increases linearly with increasing laser power and saturates at a certain value. Clad bead width decreases linearly with increasing powder flowrate.

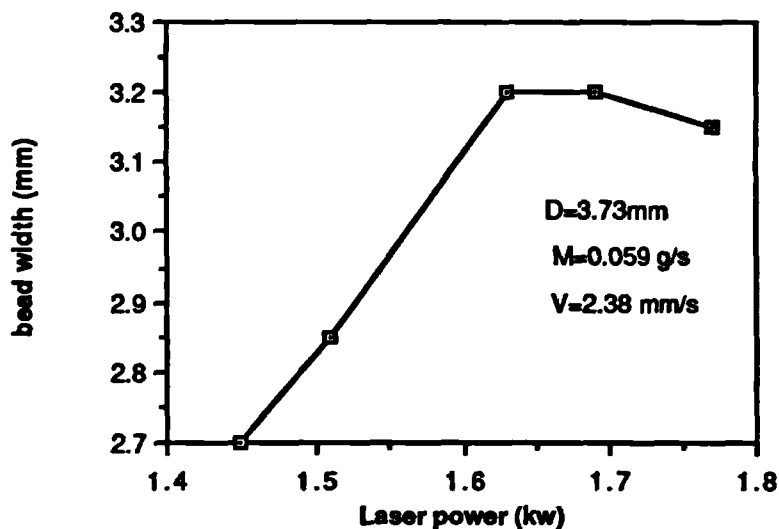


Fig.2.30. Effect of laser power on clad bead width.

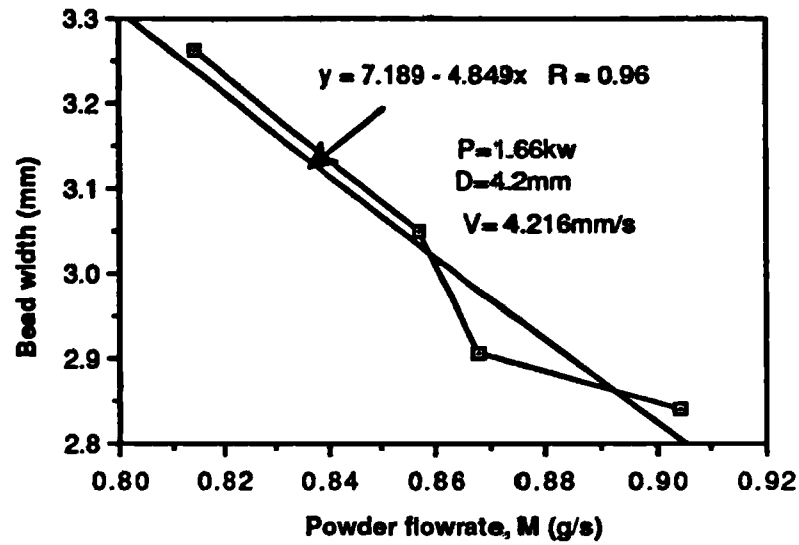


Fig. 2.31. Effect of powder flowrate on clad bead width with LS curve fit.

From these results the equation for clad bead width Eqn.(2-26) can be extended to include laser power and powder flowrate to be :

$$W = D'(K_1P - K_2M - bV) \quad P \leq P_1 \quad (2-41)$$

$$W = D'(K_1P_1 - K_2M - bV) \quad P > P_1 \quad (2-42)$$

where P_1 is the saturation laser power, K_1 and K_2 are coefficients which can be found by experiment. The reduction of bead width by the increasing of powder flowrate probably is due to an increase of shadow effect.

2.10.3 Effect of laser power and powder flowrate on bead height

The linear increase of bead height with powder flowrate is well known. However the linear decrease of the bead height with increasing laser power at low powder flowrate has not been previously noted. Fig. 2.32 shows this relationship through the above experiment. At low powder feedrate, the increase of laser power will increase the dilution instead of clad bead thickness. However a separate experiment has shown that the increase of laser power has led to a linear increase of the clad thickness. Since the change of laser power changes the slope of the H-M relationship [50] the equations for clad bead height could be modified as:

$$H = (a + K_3P)M/V \quad P/DM \geq K_m \quad (2-43)$$

$$H = (a - K_4P)M/V \quad P/DM < K_m \quad (2-44)$$

Where K3 and K4 are coefficients which can be determined through experiments.

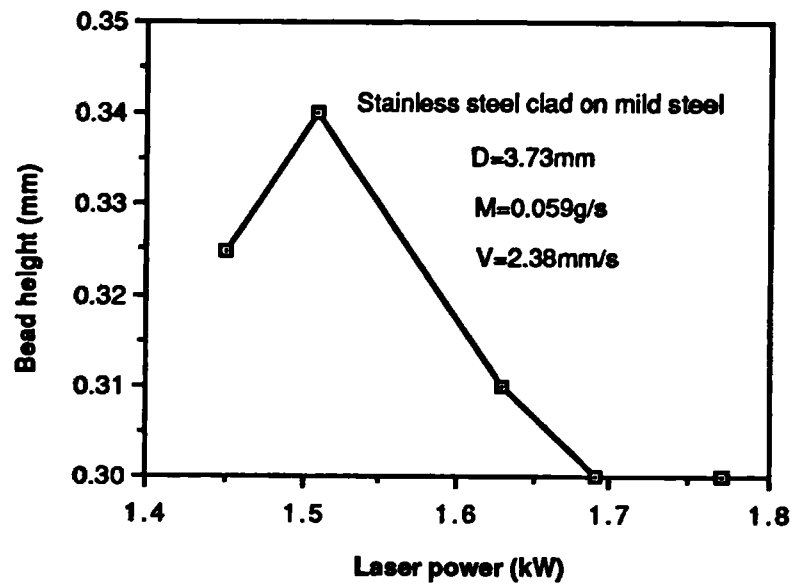


Fig. 2.32. Effect of laser power on clad bead height.

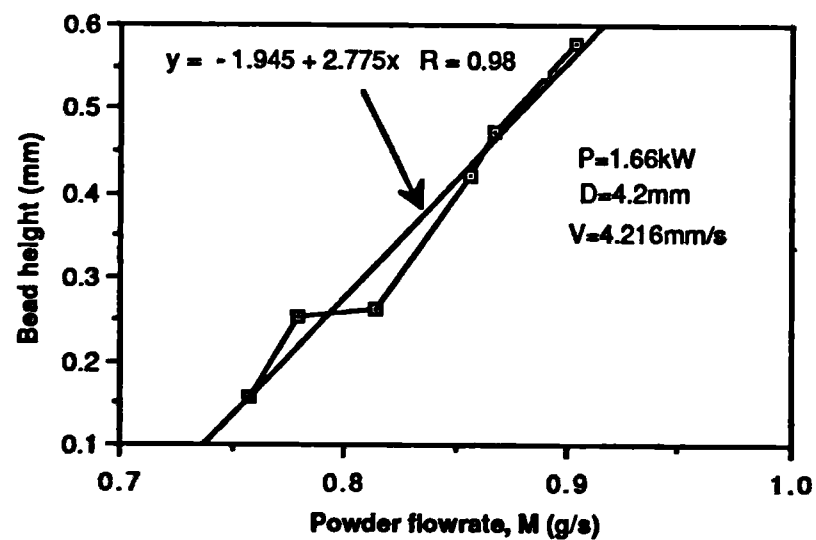


Fig. 2.33 Effect of powder flowrate on clad bead height.

2.11. DESCRIPTION OF EQUIPMENT USED IN THE LABORATORY FOR LASER CLADDING AT THE START OF THE PROJECT

The project concentrated on the blown powder laser cladding process. The equipment available at the start of the project consisted of a 2kW continuous wave CO₂ laser, a powder feeder, a hydraulic manually operated single axis linear motion table and a stationary beam focusing head together with a cladding dome. This is illustrated in Fig.2.34

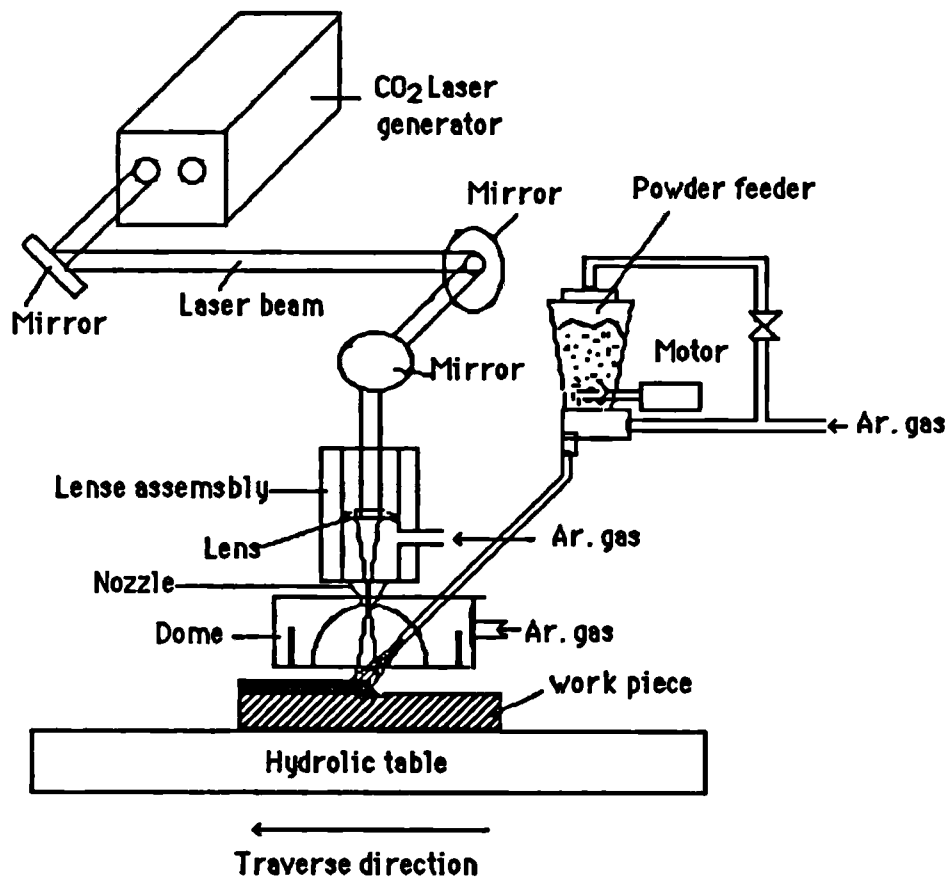


Fig.2.34 Laser cladding arrangement at Imperial College at the start of the project.

2.11.1. The BOC 901 2kW CO₂ laser used in the project

The laser used was an early version of the BOC 901 fast axial flow CO₂ gas laser manufactured by Control Laser Ltd. (Fig.2.35.). A mixture of CO₂, N₂ and He gases with a ratio of roughly 1:1:8 (5%-10% : 10%-14% : 75%-85%) is supplied to the laser discharge tubes (4 identical in series folded in the middle) with a pressure of around 45 mBar regulated, the pressure of the tubes being pumped to vacuum before the gas is

supplied. In the *purge* mode new gas is supplied continuously while in the *recirculating* mode the used gases are filtered, cooled and recirculated back to the discharge tubes via a catalytic convecter for CO & oxides of nitrogen with a cycle time of about 15-30 seconds. An electric power supply provides around 30kV discharge voltage to the tubes with current varying between 0 to 150mA for each tube. The laser power produced can be varied from 1kW to 2kW through a remotely operated potentiometer. The power reading is from a flowing water calorimeter which sits in front of the output window of the laser cavity. This power reading is however only available when the laser is not used for processing since the whole laser beam is required for the power measurement. The beam diameter produced is about 22 mm with a transverse mode of TEM₀₁* which has doughnut shape with a shallow in the middle. The wavelength of laser beam is around 10.6 μm which is in far infrared region. The laser beam can be directed to the workpiece through a series gold coated copper mirrors when the laser shutter is open; otherwise the laser beam is directed to the calorimeter. A 0.9 mW HeNe laser is used for laser beam alignment. The HeNe laser has a beam of 0.6328 μm in wavelength which is visible red light, and the diameter is around 2mm. Two water cooling systems are circulated in the laser generator with flowrate of 450gals/hr and temperatures below 20°C. The primary cooling circuit is used for cooling the cathode box, heat exchangers, gas recirculating system, the blower and vacuum pump. The secondary water circuit is used to cool all the mirrors, the output window and supply for calorimeter. A schematic diagram of the laser is shown in Fig. 2.36.

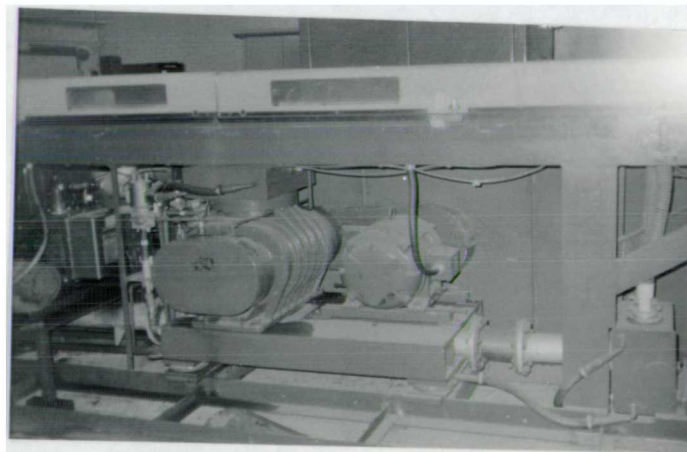


Fig.2.35. Model BOC 901 2 kW CO₂ laser used in the project.

2.11.2 Powder feeder

The powder feeder used is the screw feed version designed by Weerasinghe and made at Imperial College as shown in Fig.2.37.

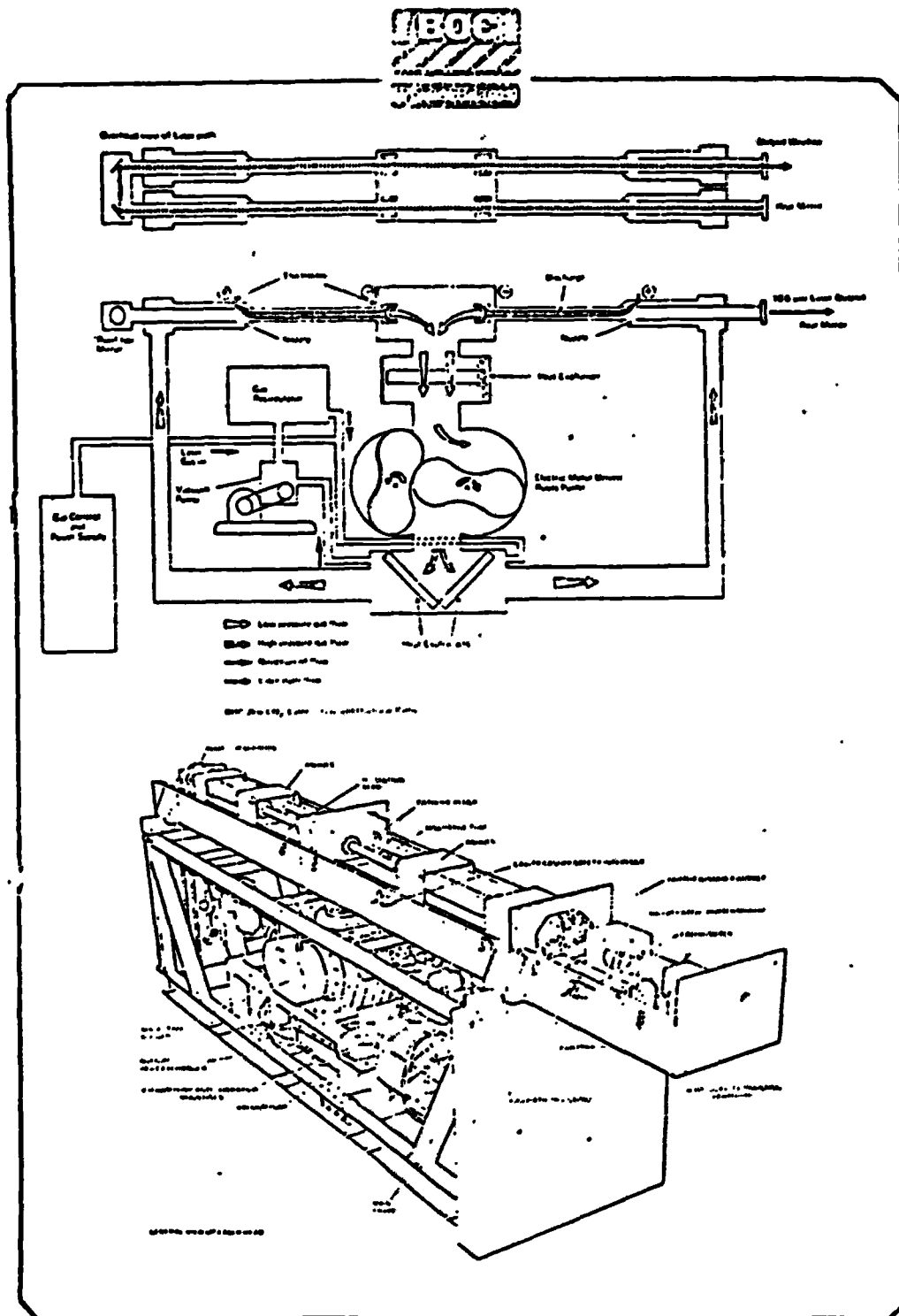


Fig.2.36. Schematic diagram of the Control Laser BOC 901 2kW CO₂ laser [137].

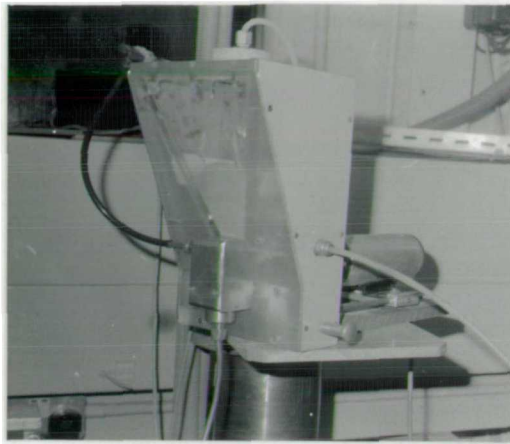


Fig. 2.37. Powder feeder used in the project.

It requires the size of powder material to be around $60\mu\text{m}$ and the gas supply flowrate of approx. 1.5-7 Litre/min. Ar gas was used throughout the experiment. The feed screw (commercial double flute twisted drill) is rotated by a DC motor which is controlled through Electric Craft manual speed controller model E-552-M. The screw rotating speed was between 200 to 2000 rpm. The powder flowrate was calibrated by weighing the powder for a flow of about 30 seconds. A copper pipe of 3 mm internal diameter was used to feed the powder to the workpiece.

2.11.3. Lens assembly operating head

A lens in a cylindrical lens holder is used to focus the laser beam. For laser cladding a long focal length lens (120mm, 150mm) was preferred. The lens used for this project was a 35mm diameter, 150 focal length KCl lens. A nozzle with lens protection gas (usually Ar) was used in the assembly to protect the lens from being overheated and contaminated by the beam reflection or hot particles or smoke during processing. The nozzle used was made of flat ended brass with central hole size about 2mm diameter. The flowrate of the coaxial lens protection gas is required to be kept low so as not to disturb the powder injection system. The distance between lens and nozzle can be adjusted by placing different spacers in the lens holder. A dome is usually used to provide gas shrouding and recycling of optical energy. The mechanical assembly used for lens holding, gas protection and nozzle assembly are called the operating head.

2.11.4. Workpiece traverse table

A hydraulic work table with manual operation (Fig. 2.38) was used in the laboratory for general laboratory study of laser treatment of small samples. Only one directional

continuous motion was possible with the other axis being traversed by a hand wheel. The speed of the workstation was between 0.1mm/s to 150mm/s. The table speed measurement was conducted by a timer fixed on the workstation which recorded the time laps for the table to traverse 100 mm distance.

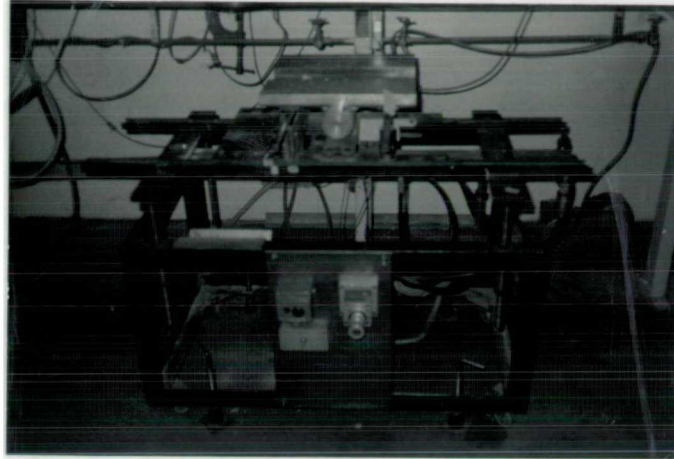


Fig.2.38. Hydraulic traverse table in the laboratory.

2.11.5. LBA

A Laser Beam Analyzer (LBA), which was invented at Imperial College and commercialized by ALL Monchen Ltd. (West Germany) was used to check mode structure of the laser beam since the oscilloscope display of the LBA output will give a beam transverse power intensity distribution.

2.12 POWDER FEED LASER CLADDING OPERATING PROCEDURES

The usual procedure for laser cladding operation can be summarized in the following 8 steps, which mainly refer to the system used at Imperial College at the start of the project. Cladding system in other places may require fewer steps according to their level of automation and quality of equipment.

Step 1. Start the laser. This includes the turning on the water, gas and electric supply to the laser in a set sequence.

Step 2. Laser beam alignment. A 0.9mW HeNe laser was used to align the laser to the guiding mirrors.

Step 3. Lens fitting and beam focus location. The lenses are usually plano-convex. The

convex side is required to face the incoming beam. Spacers was used to position the lens for the required distance to the nozzle which is about the focal length of the lens. The focal point of the actual laser beam is required just below the nozzle. The method used to find the laser focal position was to move a metal piece up/down under the nozzle while firing the laser onto it until a blue plasma is generated, which is proximately the focal point.

Step 4. Nozzle alignment. Cladding experience has shown that nozzle clipping is a frequent cause of cladding failure. This means nozzle alignment is very important for successful cladding. The alignment was performed at Imperial College by adjusting the last reflecting mirror until the HeNe laser beam comes to the centre of nozzle and checking the results by using paper marks. Many other methods could be used in commercial processes^[118].

Step 5. Powder feeder and workpiece preparation. The workpiece usually requires shot or sand blasting on the surface to be clad to increase the absorptivity. Gas supply and powder supply are required for the operation of powder feeder.

Step 6. Nozzle/substrate distance setting. Since this distance decides the spot size of laser beam on the substrate surface . It needs precisely set and maintained during process. Spacers were used for the set of nozzle substrate distance. For a spot size of 5mm diameter, and using 150 focal length lens a distance of 35mm is required between the nozzle and workpiece for an un-focused beam of 22mm diameter.

Step 7. Powder feeding alignment and dome fitting. It is required that the powder is fed to the melt pool for the maximum powder catchment efficiency. This was performed by first adjusting the feeding tube position (bending the copper feeding tube) so that the fed powder meets the HeNe laser beam on the workpiece and recheck it by making a melt spot at the workpiece surface using CO₂ laser and aligning the powder feeding to the spot by the assistant of torch light. Since the powder feeding alignment has a significant influence on the cladding quality, usually a trial run of one track clad was conducted to make sure the powder feeding was perfectly aligned. An optical reflective dome can be fitted for process shrouding and recycling the laser beam.

Step 8. Operating parameters selection and processing operation. The operating parameters in laser cladding include laser power, powder flowrate, cladding speed and overlap traverse (if overlap is required). The value of operating parameters are required differently for different material applications and cladding requirements. Normally the power density required for laser cladding is between 10 to 1000W/mm² and interaction time is between 0.1 to 1 second ^[59]. These two parameters can be used to decide the laser power and traverse speed range for a given spot size. For most of current laser cladding practice, laser power is fixed to the maximum and powder flowrate adjusted by trial and error so that a smooth fusion bond achieved and no apparent heat effect on the substrate. Cladding speed is set usually between 1 to 25mm/s and again trial and error is used to find a suitable

clad bead (wide and uniform clad). Further cladding operation will mainly base on previous experience. The clad quality strongly depends on the skill and experience of the operator.

Since the equipment was manually, open loop operated, precise values of the laser power, traverse speed, powder flowrate and overlap traverse had to take a long time to achieve. For example, for a laser power set of, say 1.8kW, the procedure required is to tune up the current potential meter on the remote control box so that a reading from the calorimeter reaches 1.8kW. However this reading will soon drop down due to the laser tube temperature rises and other effects until a new equilibrium is reached. This usually takes several minutes. The power was therefore required to be readjusted (increased again). This cycle repeats several times until the stabilized reading of 1.8kw is obtained. The similar problems exist to the powder flowrate and traverse speed setting where the settings have to readjust several times to obtain a precise value. However many laser cladding systems in commercial have a CNC motion control system of 2 to 6 axis, the setting of traverse speed and overlap traverse can be made automatically. It is unfortunate that no existing powder feeding system for laser cladding is closed loop controlled. Weighting the powders for a period of time was used at almost all laser cladding workshops for powder flowrate measurement. It is therefore difficult to achieve a precise cladding requirement with high repeatability.

2.13. SUMMARY

A study of the laser cladding process and its previous developments were given. From this review it can be seen that:

1). Laser cladding is a relatively new process with powder feed cladding as the most advanced form, which still needs further development such as on-line process quality control.

2). Factors involved in laser cladding are numerous and some are difficult to quantify such as beam mode structure, materials surface condition etc.. The principle operating parameters in laser cladding are laser power, beam spot size, powder flowrate, traverse speed and overlap traverse. Their stability, their relationships together with other process conditions (beam/powder alignment, materials physical properties, shrouding effect, substrate temperature etc.) decide the clad quality. The process relationships are complex multi-variable and non-linear. Although some theoretical and experimental relationships were developed, many are dependent on various assumptions. The process dynamics was not available.

3). Previous laser cladding practice was basically experience based. Therefore the quality of the process is strongly dependent upon the operator skills and equipment used.

4). There is a possibility of drifting of clad quality from the desired during processing either because of unstable operating parameters or because of other operating condition changes such as substrate temperature rise.

5). Current equipment used for laser cladding in the laboratory was mamnual, open loop operated. Much work has to be done to innovate the experiment equipment for the development of automatic, Intelligent work cell.

CHAPTER 3

PREVIOUS EFFORTS AND STATE OF ART DEVELOPMENTS FOR LASER MATERIALS PROCESSING CONTROL

Although no previous work could be found for the control of laser cladding process, a study of some relative developments such as laser beam sensing, industrial laser robot or CNC laser systems and control methods used for other laser processes like laser cutting and welding can be beneficial to the development of laser cladding control system. Therefore a review is given in this chapter on the general development of the laser processing automation and quality control instead of restricting to laser cladding process alone.

3.1. LASER BEAM SENSING AND CONTROL TECHNIQUES

Three key parameters of a laser beam are necessary to know in laser materials processing. These are (particularly for continuous laser):

- . Laser power
- . Beam diameter
- . Transverse beam profile (or mode structure)

The methods to measure these parameters can be generally divided into two groups. i.e. off-line methods and on-line methods.

3.1.1 Off-line techniques

Off-line methods for laser parameter measurement are the methods which use the whole laser beam for the measurement. In such a case laser beam cannot be used for processing during the measurement. The commonly used techniques for the off-line beam parameter measurement are listed in Table 3.1

Among these methods water flow calorimeter is the most popular device used for high power CO₂ laser power measurement. Pyroelectric and thermopile beam power meter are often used for the measurement of lower power lasers (below 1kW). Pyroelectric sensor arrays, photo diode arrays, thermo-resistor arrays and thermopile arrays are the most popular commercial instruments for the off-line beam diameter and profile measurement but only suitable for measuring the laser beam with power less than 1 kW. Beam printing on a piece of perspex is often used in practice as an easy, quick way of checking the beam profiles.

Table 3.1. Off-line techniques for laser beam measurement

Method	Principle	beam profile	beam power	characteristics	References
Water flow Calorimeter	Thermal	N	Y	Low sensitivity	54
Thermal resistor array	Thermal	Y	Y	≤ 1 kW	75
Pyro-electric sensor array	Optical	Y	Y	IR beam only ≤ 1 kW	73, 76
Thermal pile	Thermal	Y	Y	≤ 1 kW	72
Photodiode array	Opto-electric	Y	Y	Visible beam only ≤ 50 W	77, 177
Heating plate & use of microphone	Photo-acoustic	N	Y	Pulsed or chopped beam only	187
Photon drag	Momentum trns.	Y	Y	High power pulsed only	182, 183
Acrylic print	Thermal damage	Y	N		179
Spherical cone	Thermal	N	Y	Use focused beam	88, 180
Heating plate & use thermal couple	Thermal history	Y	Y	Unfocused beam	181
Nipkow disc	Beam sampling	Y	Y	Unfocused	184
u/v screen	Fluorescent	Y	N	Low power beam	
Drill metal	Thermal damage	Y	N	Focused beam	
Charring wood	Thermal damage	Y	N		
Photography	Thermal Image	Y	N	Low power beam	185, 186
Silican vidicon	Video Image	Y	N	Low power beam	178
Print paper	Thermal	Y	N	Low power beam	184
Burning metal foil	Thermal print	Y	N		185
Ge-Cu Hg-Cd-Te sensor	Quantum	N	Y	Low power beam	

3.1.2. On-line techniques

Unlike the off-line methods the on-line method uses only a small fraction of laser beam for the measurement and the beam information can be available continuously even when laser beam is used for processing. The disturbances of the sensing technique to the beam is usually negligible. The commonly used techniques for the on-line beam monitoring is summarized in Table 3.2.

Table 3.2. On-line techniques for laser beam monitoring

Method	Principle	Beam profile	Beam power	Charactor-istics	References
Multifacet rotating mirr.	Beam sampling	Y	Y	Continuous beam only	78, 79
LBA	Beam sampling	Y	Y	Continuous IR beam only	80, 81
Chopper Blade	Beam sampling	Y	Y	Continuous beam only	84
Hollow needle	Beam sampling	Y	N	Continuous beam only	85
Beam splitter	Beam splitting	Y	Y	Off-line meter can be used	86, 195
Partial trans-mit back end mirror	Beam splitting	Y	Y	Off-line meter can be used	87, 88
Transparent flat plate	Beam scattering	N	Y	Fast resp.	89
moving wire resistance	Thermal	Y	Y	continuous beam	193
Thermopile mirror	Thermal	Y	Y	continuous beam	194
Thermocouple mirror(s)	Thermal	N	Y	Position dependent	191, 192
Acoustic mirror	Photon-stress	Mode	Stability	Fast resp.	84, 90
Gas pressure	Thermal	N	Y	Pulse beam	189
Gas acoustic	Thermal	N	Y	cont. beam	190
Gas temper-ature	Thermal	N	Y	Pulsed beam	188

The techniques for on-line laser beam monitoring can be classified into 7 groups: beam scanning sampler, beam splitter, beam scatter, thermal mirror, thermal gas chamber, thermal wire and acoustic mirror. These will be briefly discussed in the following:

1). **Beam scanning sampler** : This technique uses a wire or needle to scan over the laser beam to abstract a small fraction of beam for measurement. This technique can be used for the measurement of both raw and focused beam. The direct information from this kind of instrument is the laser beam intensity distribution. However because of the restriction of the sampling rate this kind of instrument is only suitable for continuous laser beam. Four different instruments can be found using beam sampling technique:

a). *Multifacet rotating mirror*. This device was developed by Jupner (Germany)^[78,79]. It uses a mirror-wheel with eight mirror stripes arranged spoke-like at an angle of 45 degree to the beam axis. At any time only one of the mirror stripes is in the area of the transmitted beam. This mirror reflects a small fraction of laser beam at an angle of 90 degree onto 3 pyroelectric detectors on the resolution axis. The signals are then fed to a micro-processor for digital analysis and video display. Since 24 lines of signal can be obtained for each revolution of the wheel 3-D image of the beam mode can be obtained.

b). *Laser Beam Analyser (LBA)*. It was developed at Imperial College (UK) by G.C. Lim and W.M.Steen in 1982^[80]. By reflecting a fraction (0.8%) of laser beam with a fast rotation needle to two (x and y) pyroelectric infrared detectors, the laser beam profile can be obtained by displaying the sensor output on an oscilloscope^[81] (Fig. 3.1).

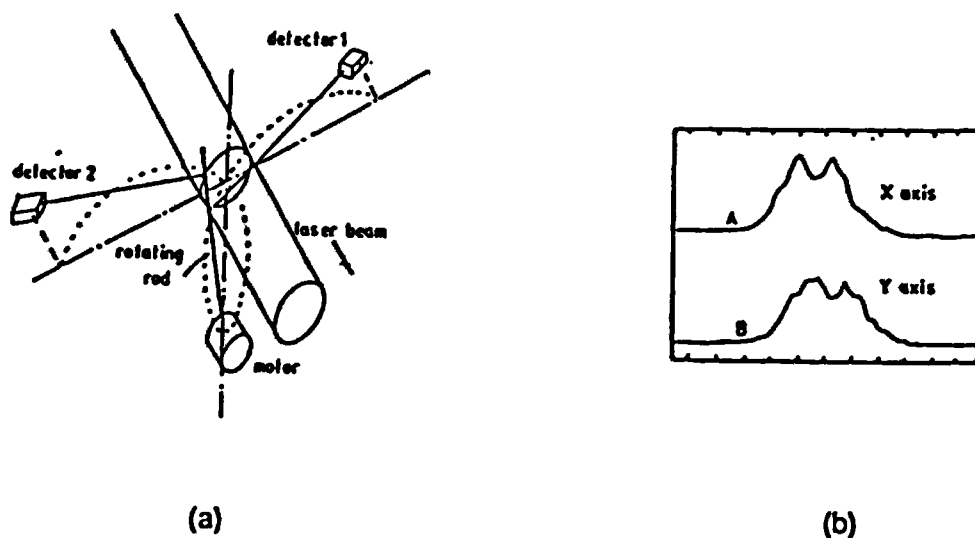


Fig. 3.1. Illustration of LBA for laser beam monitoring^[81]. a). Operating principle; b). Typical output from the LBA showing a near TEM₀₁⁺ mode pattern.

It is now manufactured by ALL Monchen Lt.d (West Germany) and A-B Lasers Inc. (U.S.A)^[82]. Recently G.C.Lim (Amada Laser, USA) has reported a computer beam analysing system for LBA in which beam power, beam width, beam center, peak power positions and symmetry of beam along the beam axis are analysed and displayed from a computer screen while the laser is being used^[83]. This upgraded PC based Laser Diagnose System (LDS) is also commercially available from ALL Monchen Lt.d.

c). *Chopper blade laser beam sampler.* This was developed at Combustion Engineering Industrial Lasers Inc. (USA) by P.D.Austin in 1986 ^[84]. The system developed consists of mode viewing and power sensing two parts. The mode viewing was realized by deflecting a small portion of laser beam (less than 1%) with a high speed (2400rpm) aluminum chopper to a luminescent phosphorus plate, which again being photographed by a CCTV camera and displayed on a TV screen. Another chopper using two polished nickel blades is rotated across the laser beam and deflect a fraction (less than 1%) of beam to a concave mirror which focuses the sampled laser beam onto a thermopile network. The thermopile network then converts the laser heat energy to an electrical signal which is proportional to laser power.

d). *Hollow needle beam sampler.* This was developed at Fraunhofer-Institute of Laser Technique (West Germany) by E.Beyer et al in 1986^[85]. This device was developed especially for monitoring of focused laser beam, although it can also be used to monitor the raw laser beam. The working principle of this device is as shown in Fig.3.2. in which laser beam is sampled through a hollow rotating needle and reflected inside the needle down to a pyroelectric sensor for measurement; to get the whole beam profile the needle also moves linearly perpendicular to the beam in such a way that each cut line through the beam profile is detected with every rotation of the needle. As a result the whole beam can be sampled in a very short time (9 sec. typ.) and 3-D beam profile obtained.

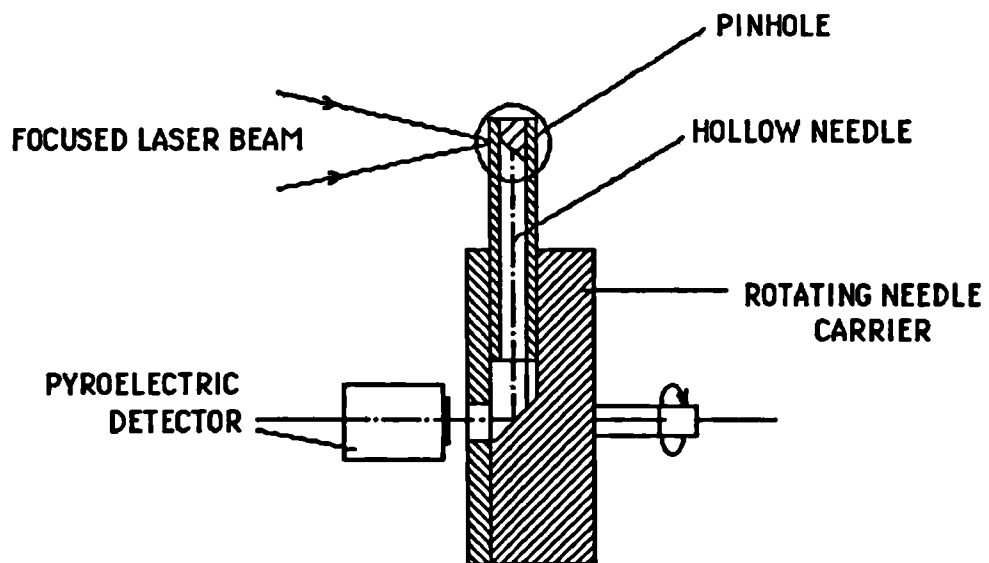


Fig.3.2. Hollow needle beam sampler^[85].

2). **Beam splitter:** Instead of scanning over the laser beam which only works with continuous laser beam, some device can be used to split the laser beam, so that a fraction of laser beam is directed to the beam sensor continuously. A convenient feature of this type of instrument is that most of the off-line beam measuring instruments can be used for on-line beam monitoring. Two typical ways of splitting the laser beam are by partial transmit mirror and acoustic diffraction grating.

a). *Partial transmit mirror for beam splitting.* An instrument was developed at Electrotechnical Laboratory (Japan) by M. Ikeda et al in 1986 [86]. The device uses partial transmitted beam splitter (Silicon wafer coated with gold for 10^{-3} % power transmission) and a reflecting prism for beam sampling. The transmitted signal is directed to a second silicon wafer for further damping and then to a HgCdTe infrared sensor for measurement. The horizontal sampling is obtained by rotating the shaft encoder incorporated prism and the vertical sampling is achieved by rectilinear motion of prism and sensor together. 200x200 points in cross section of a beam are reported to be obtained in this device.

b). *Partial transmission back end mirror.* Two examples of Instrument based on this principle can be found:

i). Developed by Delta Developments (USA) an instrument which simultaneously monitors both the pulse shape and average power of high-power CO₂ lasers (1986) [87]. The monitor measures the laser power output through a 1%- transmitting mirror at laser's non-output end. A wedged beam splitter routes the bleed power to two detectors: a pyroelectric, for waveform monitoring; and a platinum, resistance bolometer which senses average power. The signal strength was reported to be independent of beam size and position due to the precise optical arrangement of diffusers and lenses. The method is now widely used on recently produced lasers.

ii). Use of integrating sphere with partial transmission back end mirror. This device was developed by Drenker et al at Fraunhofer Institute of Laser Technology, West Germany (1988)[88]. The device consists of a pyroelectric detector and a thermopile mounted to an integrating sphere. The part of laser beam escaped from the partially transmitting rear mirror was collected by a focusing mirror and directed to the integrating sphere for multi-reflection which guarantees that the intensity of the radiation impinging on both detectors is proportional to the entire beam power. Signals of both detectors are electronically corrected and combined to a single output signal which is proportional to beam power over a band width of 300kHz.

c). *Acoustic beam splitter.* The technique, as reported by Neckel et al [195], employs an ultrasonic diffraction grating generated in the air path across a laser beam (Fig. 3.3). A very small fraction ($\sim 10^{-7}$) of the main beam is diffracted through a small

angle ($\sim 2^\circ$) on either side. A MCT detector was used to scan the diffracted laser beam to obtain CO₂ laser beam profiles and power. The advantage of the method is that the sensing is non-contact. However as the laser beam diameter increases, the problem of the acoustic wave attenuation becomes apparent. Non-uniform acoustic amplitude across the beam results in a non-uniform beam splitting fraction.

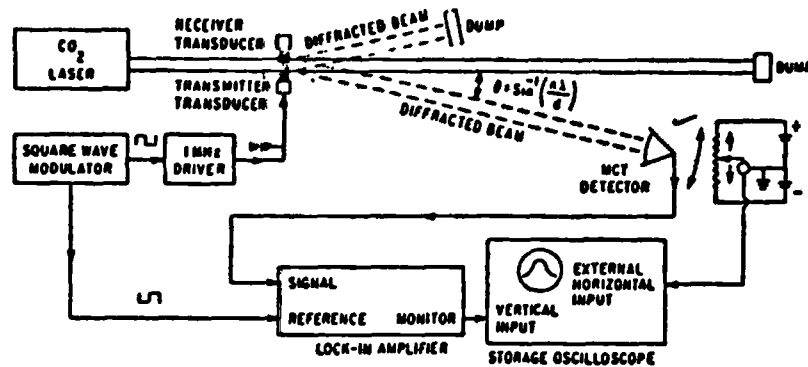


Fig. 3.3. Illustration of acoustic beam splitter for in-process beam monitoring^[195].

3). **Beam scatter:** A transparent flat plate was used by T.G.Crow (U.S army)^[89] in the laser path. 4 photo-diodes was attached to the sides of the plate to catch the scattered laser beam and the signals were summed up to obtain the average laser power through calibration. Only visible beam can be monitored using this particular device but the principle could be used to detect laser beams in other spectrum if different sensors are used.

4). **Thermal mirror:** Several instruments have been developed based on this principle (See Table 3.2). By placing thermal couple or thermal-pile or thermal resistor arrays at the back of laser mirror(s) laser power or beam profile can be determined without disturbing the laser beam. These techniques require the redesign or modification of existing laser mirrors.

5). **Thermal gas chamber:** This technique is based on the fact that gases in the path of a laser beam can be heated and expended by laser. The change of gas temperature or pressure can be detected by either a temperature detector or a pressure sensor or a microphone. This requires that laser beam is pulsed or chopped or the gas density is modulated for effective sensing. Since little energy is used for heating up the gas the sensing does not disturb the use of laser for other purpose. Several different instruments have been developed based on this principle as shown in Table 3.2.

6). **Thermal wire:** This was invented in Japan where a thermo-resistive wire was scanned across the laser beam so that the change of the resistance by laser heating can be

detected to relate to laser beam power and possible beam profile.

7). **Acoustic mirror.** This technique was developed at Imperial College (U.K.) by V.M.Weerasinghe and W.M.Steen in 1985 [90] and patented by Quantum Laser Co. (U.S.A). By placing an acoustic transducer at the back of normal beam guiding mirror(Fig.3.4), various changes of laser beam can be detected including power density and wander. One of the advantages of the system is its response to very high frequency changes of laser beam (up to 2MHZ), which could be employed for monitoring the pulsed laser beam as well. Also because the monitoring is non-intruding it can be used to monitor very high powered laser beams where the beam sampling technique may be a problem. However, it is difficult with this device to provide individual information on laser beam profile, diameter, and laser power. The response characteristics of the system may enable the method to be used as a good device for laser beam alarms.

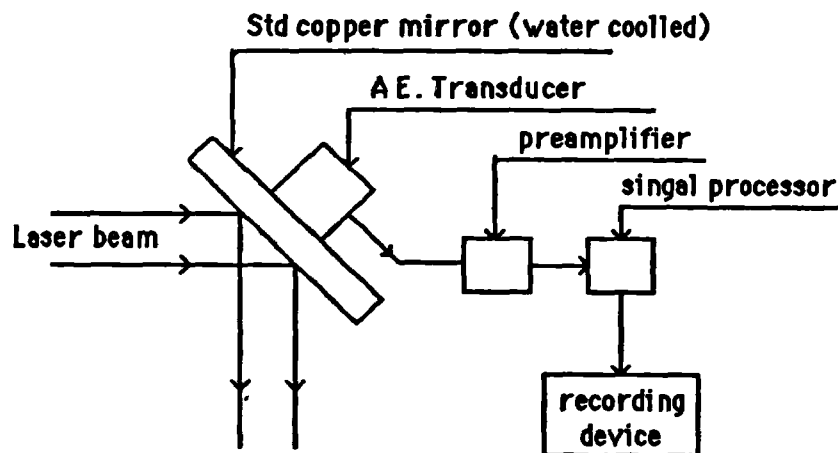


Fig. 3.4. Acoustic mirror for beam sensing [90].

A summary and comparison of the laser beam monitoring techniques can also be found in the work of Steen[90] and Kong[91].

3.2. LASER POWER CONTROL TECHNIQUES

Although many techniques have been developed for in-process laser beam monitoring, most of the present industrial lasers are still open loop controlled. I.e. setting the laser power by controlling the amount of electrical power input to the excitation system with human as feedback sensor (reading the power meter) and controller (adjusting the power setting so that the reading is as desired). Often laser power is set before the processing starts and left unchanged. There are however several reports on the development of feedback laser power control where a closed loop structure is used so that laser power can be maintained to the desired level automatically. Most of control systems developed are for

very low power lasers. Little are reported for the closed loop control of high powered lasers.

1). Olympus Optical Company Ltd has reported an idea of controlling of laser power by using a polarization-sensitive output coupler for low powered linearly polarized laser beam for medical surgery applications.^[92] When a polarized laser beam strikes on an external polarizing coupler (germanium or zinc selenide plate) placing at Brewster's angle to the optical axis, the laser beam will transmitted through the plate without loss. However if the plate rotates perpendicular to the optical axis with an angle, the p components of the beam will decrease and s components increase causing the reduction of laser beam transmitted. The power is thus varied from 100% at 0° angle to 20% at 90° angle. The reflected beam is dumped to a water jacket.

2). Cambridge Research Instrumentation Inc. has introduced a laser power stabilizer for the controlling of low power HeNe, HeCd, Argon or Nd:YAG lasers (spectrum from 350 to 1150 nm. with power level less than 10 watts) in 1985 ^[93]. The device uses a Pockel cell, photodiode beam sensor and electronic servo. The laser beam was reported to be stabilized to 0.05% rms. However 20% to 30% of the laser beam is used for sensing if polarized laser beam is used.

3). Combustion Engineering Ltd. (U.S.A.) has reported a new development on the closed loop control of high powered A.C exited CO2 laser beams^[84] (1986), where chopper blades were used to deflect a portion (less than 1%) of laser beam onto a concave imaging mirror. The thermopile network is then used to convert the laser heat energy to an electrical signal used as an input to the closed loop power electronics. Since the temperature within the beam diagnostic system enclosure is subject to temperature fluctuations, a second thermopile network, not exposed to the laser beam input, is used as reference to compensate for temperature drifts and excessive heat within the enclosure. The output from the closed loop power electronics is then used to control the A.C. voltage applied to the four discharge channels. The result is enhanced light output stability and repeatability. No system performance was reported.

3.3. METHODS OF COUPLING OF LASERS WITH MOTION MACHINERY AS INDUSTRIAL TOOLS FOR AUTOMATIC LASER MATERIALS PROCESSING

The current industrial laser materials processing systems are mainly characterized by the combination of CNC motion systems or Robot arms with laser devices. The motion control systems provide the traverse of workpiece relative to the laser beam while laser provides a highly concentrated energy. The basic design points in the CNC laser processing systems were suggested by Steen and Li^[94] to be:

a). Positioning accuracy. Since the beam diameter is usually around 0.1 mm or less, the positioning accuracy of the motion system must be in the same magnitude.

b). Constant beam centering: The beam must be fairly precisely centered on the focusing optics and exit nozzle. Failure to do this can seriously affect processing performance in processing dependent on fine focus such as laser cutting and welding. This point is important particularly when moving beam option is selected.

c). Minimum number of mirrors: Number of mirrors should be kept to a minimum due to mirror losses (approximately 1-2%/mirror), alignment and mirror maintenance.

d). Constant beam path length: Because of the slight beam divergence a change of beam path (as in gentry flying optics system) may lead to a change of beam diameter which might affect process quality.

e). Safety: Whatever machine arrangement is used it must have built in protection for user, beam delivery system and process.

The automated laser systems can be generally classified into the following three types^[94-99]:

- . Stationary beam, parts moving
- . Stationary parts, beam moving
- . Hybrid systems

This is illustrated in Fig. 3.5.as summarized by Steen and the author^[94].

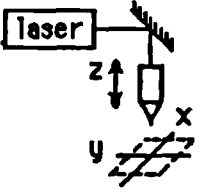
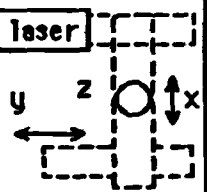
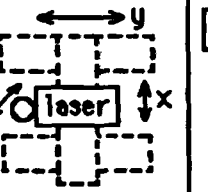
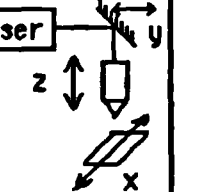
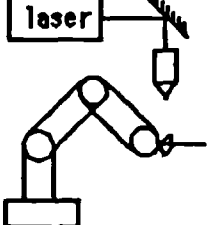
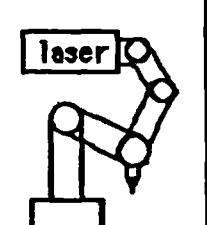
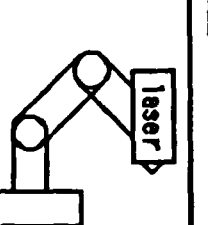
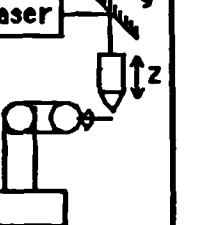
STYLE	MOVING WORKPIECE	MOVING OPTIC	MOVING LASER	HYBRID
CARTESIAN GANTRY TYPE				
ARTICULATED ROBOT STYLE				

Fig. 3.5. A Summary of various laser/robot systems^[94].

3.3.1 Stationary beam, parts moving systems

The configuration of this type of system was first adopted in industry by using the existing NC X-Y tables and milling machine table while the laser beam was guided down to the work station through a series of fixed reflecting mirrors and focusing lens. Rotation and tilted tables were also used for different applications. Later (late 70's) the industrial robot was employed to move the parts so that three dimensional parts can be processed (Fig.3.6) . Since it is usually difficult to maintain the constant speed for multi-axis robot and not possible to process large, heavy or flimsy parts. This type of system are not widely used in industry, but are frequently used in research centers for day to day change application studies. The advantage of moving parts system is its low cost, flexibility and easy to start. It is very suitable for research centers and small laser job shops where 2 axis CNC x-y table is usually used. The examples of this type of system used in industry are: 3 axis CNC laser machines at Grumman Aerospace Corp and U.S Air Force ^[100] and a 3 axis CNC laser workstation at Bramah Engineering Ltd (Sheffield,U.K)^[101].

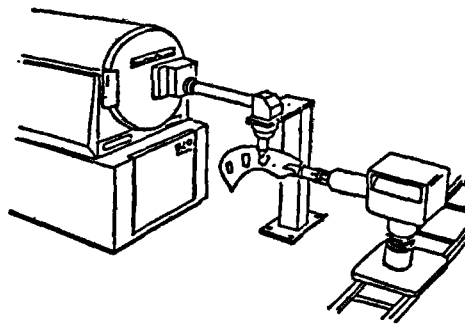


Fig. 3.6. Illustration of stationary beam parts moving system^[95].

3.3.2. Stationary parts, moving beam

This was initiated when industry wanted to process very large heavy parts such as car and large plates. The system mentioned above had proved to be very inefficient for this type of application. There have been 5 techniques being studied and used in industry for flexible beam guide:

- 1). Moving laser head
- 2). Industrial robot arm moving flexible beam guide
- 3). Articulated laser robot with built-in beam guide by reflecting mirrors
- 4). Gentry fly-optics laser robot
- 5). Fibre optics integrated laser robot

1). *Moving laser head* . The first and easiest way to move the laser beam was to mount the whole laser body (laser head) on a programmable moving table (often gentry type). This can be 2 (X-Y) or 3 axis (X-Y-Z). The lasers used in this type of configuration are usually small and rigid such as Nd-YAG, Nd-Glass, Excima and very low powered CO₂ lasers . The applications of this type systems are only restricted to two dimensional work pieces processing but very large and heavy workpiece can be processed. One such example is the BOC "Falcon S" optical line-following machine using Ferranti MF400 CO₂ laser [102].

2). *Moving flexible beam guide by conventional laser robot*. If 3 dimensional heavy workpiece laser processing is required or high power lasers are used, the above mentioned methods are no longer suitable. One way of avoiding this is to use commercial industrial robot to move a flexible beam guide with multiple mirrors. One example of such system is Ferranti Laserflex^[96], which used A5EA robot to move a flexible beam guide for laser cutting.

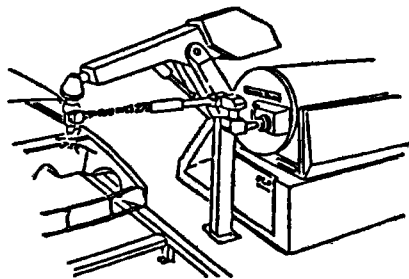


Fig. 3.7. Moving flexible beam guide by conventional robot^[97].

3). *Articulate laser robot*. By fixing the reflective mirrors at the turning points of a industrial robot and by assembling the focal lens and processing head (nozzle assembly etc.) at the end of the robot arm an articulated laser robot can be made. The laser beam can then be guided through the robot and processing head to the workpiece. This type of system was first used in medical laser surgery and later adopted for high power lasers to use in industry. The advantages of this type of laser robots are that they are easy to transfer from place to place and very flexible to guide high power laser beams to any reaching 3 dimensional space. The robot used are usually 5 axis (XYZAB) and sometimes 6 to 9 axis depending on the applications. It is very suitable for industrial laser processing (e.g. cutting and welding) of heavy, but not very large, 3 dimensional workpiece in production line, and several such laser robots can be stationed at one working spot for either different processing or efficient handling. The disadvantage of this type of configuration is that the reaching distance is limited by the length of articulated robot arm and difficult to achieve

required moving smoothness over length at high speed , which will be overcome by introducing the gantry type laser robot discussed in the following. One example of such system used in industry is Toshiba (Japan) FBG laser machining robot with 6 joints, 8 degree of freedom, which can deliver a CO₂ laser of 1.2kw, pulse mode beam with traverse speed of 12m/min and position accuracy of 0.3mm for laser cutting^[103].

4) *Gantry type Flying optics.* The gantry type laser systems were developed only recently in which gantry frames are used for the long distance linear traverse with optics attached to the ends while the rotating axes use robot arm with flexible optics. Usually 3 to 6 axis are used. Such flexible laser beam guide systems are very suitable for heavy industry laser materials processing like car industry, aerospace industry and ship industry. Large , heavy 3 dimensional workpiece processing can be easily realized with this type of system and smoother path on straight line path can be achieved. The disadvantage of this type of system is that they are expensive and also beam length changes as optics move resulting in the slight change of beam spot size. As a result they are mainly used in heavy industries. An example of such system is the 5 axis moving optics laser robot with capacitive autofocus system developed by Rofin-Sinar (U.S.A), which has traverse speed up to 10m/min with position accuracy of 0.02mm for 3-D laser cutting ^[104] . Another example of such system is Renault RL5, a 5 axis laser robot developed by Renault Automation for 3-D laser cutting in automobile industry ^[105], which can provide traverse speed up to 300m/s with position accuracy of 0.01mm.

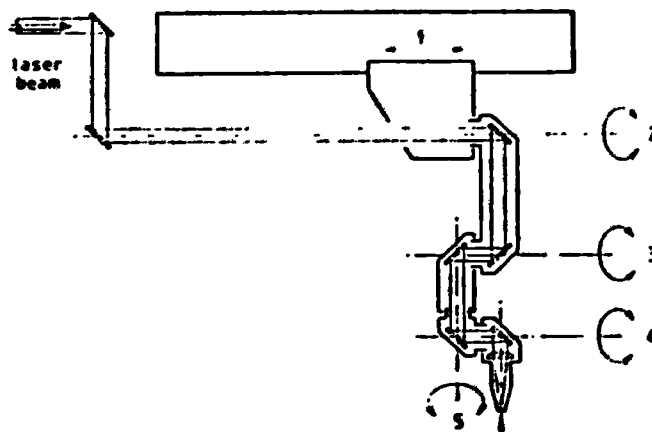


Fig. 3.8 Gantry type flying optics^[105].

5). *Optical fiber integrated beam guide.* This is the most flexible and low cost method of guiding the laser beam for 3 -D processing . Any type of industrial robot can be used with little modifications, since the beam can be transmitted through optical fibers directly to the processing head mounted on the robot gripper. However the current optical

fiber laser robot system only available for Nd-YAG, Nd-Class and very low powered CO₂ lasers^[106]. Because special material is required to transmit CO₂ laser beam, the cost for CO₂ optical fiber laser robot is very high and many problems still exist. An example of such system is developed by Permalux Laser system AB, Sweden ^[107] where 0.2 and 0.5 mm diameter quartz fibre with peak transmission for 1.06 μ m was used to guide 25 W and 150 W Nd.YAG laser through a Seiko D-tran XY-3000 4 axis (XYZA) industrial robot, which has maximum speed of 1000mm/s and position accuracy of 0.03mm. The laser robot was built for welding applications.

Some laser robot use the combination of the above techniques. For example a five axis laser robot developed and used in Volkswagen production line is the combination of articulated 3 axis robot arm and a 2 axis CNC system to move the Ferrenti 400W CO₂ laser generator for 3-D cutting of car body ^[102].

3.3.3. Hybrid systems

This is the most commonly used laser materials processing system in industry. From the simple CNC X-Y table plus Z axis laser operating head movement to the more complicated robotic system such as X-Y table plus 3 axis (Z,A,B) laser beam guides and X plus 5 axis laser robot. The systems of this type are generally more flexible than other type of systems. Most laser job shops use this structure and single purpose laser processing machines mainly use this structure. They are generally more stable and reliable than other type of machine since the most commonly used linear movement is achieved by CNC X-Y tables. The only disadvantage of this type of system is that the heavy, large workpiece are difficult to process. The examples of this type of systems are: a five axis laser robot consisting of a 3 axis laser operating head (z plus two rotational axis) and a CNC x-y table developed at Prima Progetti SpA (Italy) for cutting and trimming applications ^[108]; A five axis laser robot developed by University of Lulea (Sweden) consisting of 3 axis (linear, tilting and rotation) beam handling robot arm and a CNC x-y table to combine 2 CO₂ laser beams (Spectra Physics 973 and Rofin-sinar RS-500) to a single workstation for butt welding of sheet metals ^[109].

It can be seen from the above survey that method 1 (using stationary beam and moving parts) has very small application window in industry but can be used in research centers for development purpose; method 2 (moving beam with stationary workpiece) is generally used in heavy industry where constant moving of large, heavy workpiece is difficult; method 3 (hybrid system) is the most promising structure for small or middle scale laser systems. Although there have been many automated materials processing systems used in industry, few are reported for laser cladding.

3.3.4. Programming methods for NC or CNC workstations

There are mainly 3 methods currently used in laser processing practice for parts programming^[94].

1). NC language programming. Most CNC workstations use NC language for parts programming. This requires the precise location of processing dimensions beforehand. Usually only numerical numbers are accepted. Few systems accept variables, logic loop conditions and mathematical formulas.

2). Manual teach programming. It is a very difficult task using NC language for complicated programming requirement. For example, 3-D processing is virtually impossible to program using NC languages. Therefore some manual teach techniques are used, where the end effector of laser robot is guided by hand or digitized wheeler to traverse along the required 3-D path while CNC machine memorized the traversing position and stores them as feed demands. Any error generated by manual teach will however faithfully reproduced in the following processing.

3). CAD programming. When CAD system is integrated in CNC system the original programming language is replaced by handing graphics and marking of dimensions and processing directions. The CAD will change the graphics into the executable motion commands.

For these commercial CNC systems once the program is loaded into the machine, operating parameters such as speed and position can not be altered during processing. Therefore process has to be performed with prefixed parameters and moving patterns.

3.4. RECENT DEVELOPMENTS FOR ADVANCED AUTOMATED LASER PROCESSING SYSTEMS

The demand for high production rate in industry has led to further developments on process automation . These include constant nozzle/workpiece distance servoing, seam tracking, cutting line searching, automatic beam alignment, automatic nozzle alignment etc. This section studies the development in this area.

3.4.1. Nozzle Standoff Sensing. Control Techniques

The requirement of nozzle standoff and orientation control is more delicate because any slight change of them will change the beam density and the processing quality affected. This task is further complicated in laser processing by the influences of laser beam and laser

generated material melting, radiation and plasma. Early height sensing devices were simple in design, using a tactile (contacting) sensor to determine and control the nozzle/substrate distances. Also for laser cutting some "ride on" laser nozzle assembly using floating z axis with bearings "sitting" on the workpiece. Recent developments have introduced some non-contact height sensing and control devices. These include devices using capacitive proximity sensor and laser diode projection LCD height sensor.

1). *Capacitive nozzle* . The technique was patented by Rofine-Sinar, Hamberg, West Germany for autofocusing in laser cutting . A collar shape capacitive sensor was fitted to the nozzle to detect the distance between the nozzle and workpiece. The signal was then feedback to a servo control system to maintain the nozzle stand off with a accuracy of 0.2mm.^[110] There are two restrictions for the the application of this type of system.

a). The workpiece must be conductor so that it forms part of capacitor.

b). It can only be used for laser cutting. In laser welding or other surfacing process, plasma generation or material melt pool will prevent the normal function of the sensing. This is because capacitive sensors are subject to changes in the dielectric constant of the space between the sensor and the workpiece. Therefore metal vapor, steam, small metallic parts, or other objects entering this space can all change the field affecting the operation.

2). *Laser diode probe*. An optical height sensor consisting of a laser diode and an optical position sensitive device (PSD) was developed by Mitsubishi Electric Co. In Japan in 1985 for laser cutting ^[111]. The wavelength of laser diode is $0.83\mu\text{m}$. The change of the reflected beam position on the PSD is proportional to the absolute distance. The signal is fed to a servo controller for height control with an accuracy of 0.5mm. One problem of the system is that the sensing range is limited by the size of the PSD and the sensitivity is affected by surface roughness, inclination and reflectivity of the workpiece (The spot size falling on the PSD is affected).

Other methods include inductive, feeler, pressure etc. as summarized by Steen et al^[94].

3.4.2. Powder Flowrate Sensing

Powder feeding has been used in laser cladding and laser alloying for providing new materials. One method has been reported to use acoustic sensor for powder flowrate sensing^[112] in laser cladding applications. The technique was first proposed by Arrington in 1981^[113] and then developed at Imperial College by Weerasinghe and Steen in 1983. They found that the TMS value of the signal from the acoustic sensor attached to the feed tube is related to powder flowrate as:

$$TMS = kM^a$$

(3 - 1)

where M is powder flowrate and a is a constant to be calibrated through experiments. The signal is also proportional to the square of gas pressure.

3.4.3. Seam tracking

There have been 3 reports on the development of seam tracking system for laser welding process although many have been developed for traditional welding seam tracking.

1). *Optical probes for automatic seam tracking:* A Diffracto Model 600 optical probe was reported to be used by General Motors Co.(U.S.A,1986) on a five axis laser welding robot to locate the position of a joint by focusing a near infrared light beam on the car body and triangulating the detected reflection [114]. No image processing is required. In practice, first the X actual position is detected in reference to the position of rear window opening with a longitudinal movement. The Y actual position is detected by scanning along the Y axis, and when the trench is found, its depth is measured. The variations in X,Y,Z as

$$X = X + \Delta X$$

$$Y = Y + \Delta Y$$

$$Z = Z + \Delta Z$$

(3 - 2)

are measured and used by the welding robots to contour the welding path.

2). *Acousto-optical scanning sensors for automatic seam tracking:* This was achieved by Pennsylvania State University (USA) in 1987 [115] where a acousto-optic device was used to diffract the scanning laser beam with controlled RF drive frequency over the seam 0.250 inches ahead the weld spot and spaced 0.750 inches apart at rate of 1kHz. The reflected beam pattern was detected by linear CCD sensors. The signals were fed to two robot servo controllers (with coarse loop controlling robot end effector and fine loop controlling mirrors) which updated the contouring position at rate of 200Hz which was claimed to be 7 times faster than the ARC welding seam tracking system (30Hz max). The accuracy of the tracking was reported to be within 0.005 inches.

3). *Beck reflection pressure sensor for automatic seam tracking:* A seam tracking system is being developed at Imperial College and the University of Liverpool[116] by scanning a back reflection pressure sensor across the seam ahead of nozzle and updating the contouring position accordingly. The advantage of this method is that the sensing is independent of laser beam reflection and part surface conditions. However the scanning speed is restricted by the response of the sensor at high traverse speed. Therefore the system could be used for low speed laser welding applications.

3.4. 4. Automatic beam alignment

The beam alignment involves the beam alignment within the laser optical cavity mirror alignment and nozzle alignment.

1). *Automatic laser optical cavity alignment*: This was reported recently, [117] that an active mechanical stabilization system was used by Coherent Ltd. to continuously optimizes resonator mirror alignment by monitoring laser power through a photodiode for a 25w ion laser (not used for materials processing). The alignment of laser cavity via the rear-mirror controls is maintained by a feedback system, which is optimized and controlled by a sophisticated phase-sensitive digital detection electronics.

2). *Automatic mirror alignment*: This is being developed at Imperial College and Liverpool University where four acoustic sensors are placed at the back of mirrors to determine the beam position on the mirror^[118]. Experiments have found that maximum rms value of the sensor output can be obtained when the laser beam strikes on the mirror corresponding to the centre axis of the sensor, and the magnitude reduces as the laser beam move out of the centre. X and Y coordinates of mirror are then adjusted until the beam is in the centre i.e. signals from all four sensors are equal. This system is still in its development stage but the alignment control potential has been recognized.

3). *Automatic nozzle alignment*: The importance of nozzle alignment are becoming well recognized in practice^[119]. The nozzle alignment is being developed at both Liverpool University and Imperial College, where a thermocouple is used attaching to the nozzle and traverse the nozzle by two computer controlled stepper motors relative to beam in all 4 directions until thermal couple gets hot (beam clips the nozzle). The centre of nozzle can then be located as the half the extreme traverse used and thus beam is positioned to the centre.

3.4.5. Self-searching cut contours

A self-teaching CNC parts programming technique for laser cutting has been reported by Mitsubishi Electric Co. (1987) [120], which consists of a laser diode and a PSD sensor. The focused low power laser beam from the laser diode scans over the cutting line marked by marker tapes and generates CNC programs from the obtained information to follow the cut line automatically.

3.5. DEVELOPMENTS FOR OPTIMUM MATERIALS PROCESSING CONDITION SETTING

Much research has been directed to the optimization of processing parameters. These were developed to prevent the production of poor quality components because of the improper operating parameters used. The methods used are experience based using data or knowledge bases.

1). A software package has been developed by CEN/CEA, France [121] using Pascal language to optimize laser cutting operating conditions (laser power, cutting speed etc.) to minimize Heat Affected Zone (HAZ) and cut dross under different material composition and parts thickness. Artificial intelligence and statistics were used in the development of the software.

2). A software was developed by Welding Research Institute of Osaka University (Japan) for optimum operating condition setting in steel hardening by the combination of theoretical models and experimental data base [122].

3). Also developed by Welding Research Institute of Osaka University was a CAM software for laser welding using Prolog language to support engineers to make decisions against weld cracks [123].

Although they are all off-line programs they could help operators to solve many problems in production and reduce the probability of the faulty products.

3.6. STATE OF ART WORK ON PROCESS QUALITY SENSING AND CONTROL FOR LASER MATERIALS PROCESSING

Activities in process sensing and control developments only started recently. These include laser cutting control, laser welding control, laser transformation hardening control and laser soldering control etc.

3.6.1. Laser cutting process sensing and control techniques

4 different approaches have been made for laser cutting in-process monitoring or/and control. They are:

1). *Vision system for laser cutting process monitoring.* A vision method was developed

at Technical University of Denmark (1987) [124] to view the emitted light image at the cut point from the upper side of the workpiece. Different image pattern were matched for different cutting quality. In case of slow cutting rates, the light emission from the cut kerf was varying, both in spatial distribution and intensity, while in case of correct or too high cutting rates, the emission was relatively stable. Three types of image has been collected: a). self-burning, where image is irregular shape, b). good cut, where image is narrow dark; c). no penetration, where image is very bright.

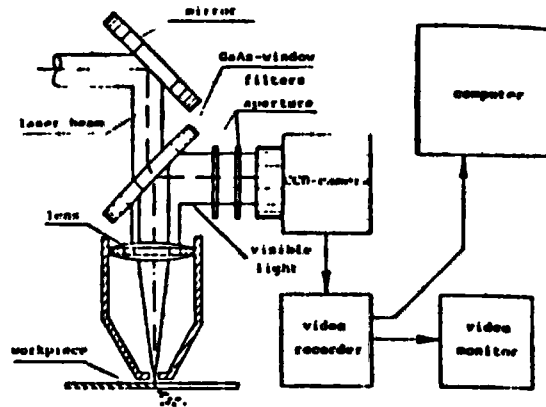


Fig. 3.9. In-process laser cutting monitoring using CCD camera^[124].

2). *Pyroelectric sensor for laser cut quality monitoring.* Also reported by the Technical University of Denmark [124] for in-process laser cutting quality sensing was to use pyroelectric sensor underneath the workpiece to view the angular distribution and relative intensity of laser light passing through the cut kerf (Fig.3.10). Relationships between cut quality (good, acceptable, poor) and sensor response were found through experiments.

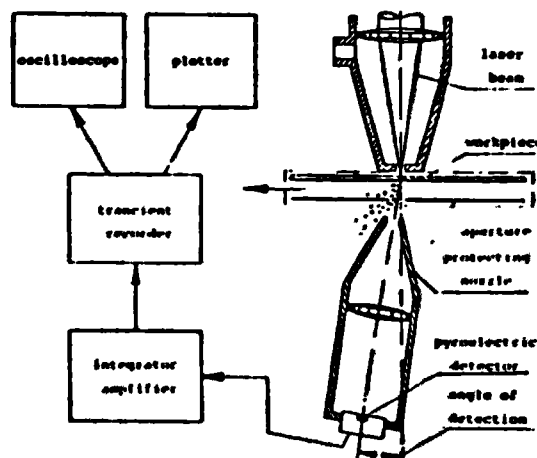


Fig. 3.10. In-process laser cutting monitoring by pyroelectric sensor.

3). *Coordinated laser cutting control.* A coordinated laser cutting control system was developed by Mitsubishi Electric Co.(Japan) to keep the ratio of cutting speed and laser power constant^[125]. This is especially beneficial at the corner where the cutting speed is very low. If laser power was not reduced, the tip of corner may get melt off owing to overheating and much dross will hung on the bottom surface of sheet metal.

4). *Feed back Laser cutting control.* A "smart" laser cutting system was developed by ETCA, France ^[126,127], where a video camera was used under the workpiece to look at the spark cones produced in laser cutting. The cone angle and symmetry were believed to be related to kerf width and cut quality . Operating parameters (cutting speed, assist gas pressure and laser power) were varied when the cone pattern deviates from the normal record. The amount and sequence of parameter variation were searched using on-line trial and error. Several diagnostic rules were developed. For example, if no cone is present, then the laser beam has not penetrated the material (power density too low, beam extinguished etc.). If molten material is dripping, then the cutting speed is too slow, or gas-assist is inadequate. If the cone shape is unstable, then the beam power density is too low. If cone angle is very narrow, then gas assist is excessive. Cases of near-ideal cone shape are not readily analyzed by the human eye, but video systems can solve the trajectories of individual molten droplets in the cone. No control system effects were reported.

3.6.2. Laser welding process sensing and control techniques

Five reports obtained in this aspect are:

1). *Acoustic probe for keyhole stability sensing* : By placing a steel plate above the welding workpiece and attaching a piezoelectric sensor to the steel plate (probe), the laser generated material vaporization stability can be detected, which was related to welding quality by Jon ^[196].

2). *Acoustic mirror for keyhole stability sensing.* The use of acoustic mirror for welding process key hole monitoring has been developed at Imperial College ^[128], where an acoustic sensor was placed at the back of the nearest laser mirror to the workpiece. Back reflection of laser beam from the weld pool can thus be picked up by the sensor and was related to the key hole generation and weld quality. Since the signal can also be affected by the stability of laser beam. Differentiation between laser beam fluctuation and back-reflected laser beam is necessary for the effective process monitoring.

3). *Pyroelectric sensor for weld penetration detection.* A pyroelectric sensor was used under the workpiece to detect the temperature of the workpiece, which was related to the weld-penetration depth^[116].

4). *Laser projection for weld pool stability sensing:* Laser optics method was

developed by Fraunhofer-Institute für Lasertechnik (West Germany)^[129] for plasma fluctuation as well as welding surface rippling detection, where an Ar laser is projected onto the melting pool and two photo detectors are used one for reflected Ar laser beam from the melt pool and the second for plasma light emission. The reflected laser beam intensity fluctuation frequency was found to correlate to weld ripples as well as plasma density fluctuation frequency which correlates to the signal detected from the second photodiode.

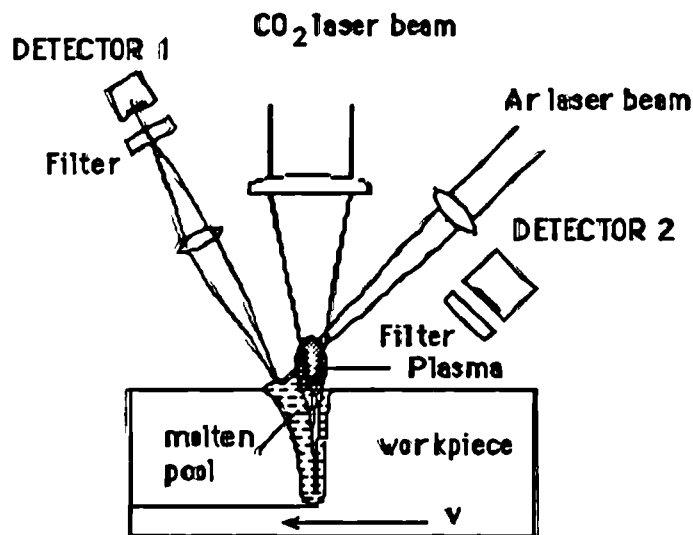


Fig.3.11. Optical weld quality sensing^[129] .

5). *Temperature sensor probe for welding quality control*: A production floor quality control of laser welding against defective parts was reported by Spectra Physics in 1987^[132], where the welding spot temperature was monitored. If there is any defect in the parts the detected temperature signal will be out of normal operating window. The system will then rejected the parts to eliminates the faulty products.

3.6.3. Laser transformation hardening process sensing and control techniques

The methods used in laser transformation hardening sensing and control are:

1). *Acoustic transformation hardening sensing*: Rawlings R.D and Steen W.M reported a technique to monitor the size of heat affected zone, materials transformation and on-set of surface melting by using an acoustic transducer attached to the workpiece during hardening process^[133]. The ring down frequency and RMS value of the transducer has been found to be able to relate to the process qualities. Although the same technique has been tried as reported by Rawlings and Steen for laser cladding, the signals were overwhelmed by the powder injection so that the process sensing was not successful. However the use of acoustic

sensor for powder flowrate sensing was then suggested (Later developed by Weerasinghe and Steen).

2). *Transformation hardening control*: A feedback control system for on-line transformation transformation hardening control is reported by FLE University, West Germany [134], where surface temperature and reflected laser beam from the surface were on-line monitored with a Kleiber pyrometer and the signals were fed to a Micro-computer to adjust laser power in order to maintain constant surface temperature during hardening operating.

3.6.4. Laser surface melting process sensing

An application of acoustic sensors was made by US National Bureau of Standards for in-process detection of solidification stresses for laser melting process.[135]

3.6.5. Laser soldering process sensing and control

A "smart" laser soldering system using NdYAG laser has been reported by Vanzetti Systems (U.S.A)[136], where the thermo profile of each joint is monitored and compared the signature against previously stored in memory, and use it to turn off the laser at the proper instant. Poor joints can be detected and printed out using the system.

3.7. SUMMARY

A review of previous developments on laser processing automation and quality control was presented in this chapter, from which it can be seen that:

1). The in-process laser beam monitoring for laser beam profile tends to be matured but closed loop laser power control has been mainly restricted to low powered lasers and AC excited CO₂ laser. Further development is required for the closed loop control of DC excited CO₂ laser and other high power lasers.

2). Computer programmable multi-axis laser materials processing systems are already becoming commercial available, which use either robot integrated flexible beam guide, or flying optics gentry system or hybrid robot/CNC system. However most systems have to be operated with pre-programmed commands. The configuration for the ability of in-process variation of parameters such as speed and position (which are required for the more intelligent systems) are not possessed by most of the systems.

3). Nozzle/workpiece distance control is only restricted to laser cutting process where no foreign material such as clad or powder interference nor plasma generation.

4). Powder feeders are open loop manually operated in laser materials processing applications. The stability of the powder feeding system therefore can not be guaranteed.

5). In-process sensors development and process quality control is still in R&D phase.

6). No previous effort has been made for the in-process monitoring and control of laser cladding process.

Generally speaking the industrial laser materials processing systems are becoming more intelligent and reliable. Laser cladding is a relatively new process. Although it has been automated in the basic version (CNC Motion control or Robotics integrated system) in industrial applications such as in Rolls Royce and Quantum Laser Ltd, many developments are needed to make the process more flexible and reliable, which is the object of this thesis.

PART 2

SYSTEM HARDWARE DEVELOPMENT FOR INTELLIGENT LASER CLADDING CONTROL

In this part, 3 chapters are included describing the author's work on the hardware development for an intelligent laser cladding cell. i.e. laser cladding automation, on-line closed loop laser power control and on-line closed loop powder flowrate control. According to the control system requirement the general laser cladding control system hardware structure was designed as shown in Fig. 7 in the General Introduction and Fig.8 on the next page .

In laser cladding, unsatisfactory products can often be produced because of unstable operating parameters such as laser power, powder flowrate, traverse speed, nozzle/substrate distance etc. These factors can however be much reduced if the key parameters are closed loop controlled. Although CNC laser workstations have been used in many production lines, the closed loop control of laser power (DC excited CO₂ laser), powder flowrate and nozzle standoff (in the case of powder feed laser process) were not conducted or not reported before.

The object of this part of development is to automate the laser cladding process and to realize the closed loop control of the above mentioned key operating parameters. Other unstable factors such as beam absorption stability, and powder feed alignment were also be improved by the innovation of cladding dome.

CHAPTER 4

LASER CLADDING AUTOMATION

4.1 INTRODUCTION

The first and fundamental step toward the intelligent laser cladding control is the process automation. Since the existing equipment in the laboratory for laser cladding was manually operated (See Chapter 2), much work has to be done to innovate the equipment so that they can be suited for the intelligent system development. In this chapter, work is described on the development of:

a). A 3-axis hybrid structured (moving both part and laser optics) CNC laser cladding workstation with closed loop position and speed control. It has the feature that after the part programming is loaded into the controller for operation both speed and position can still be altered instantly from the supervising computer during processing - a feature that most existing CNC laser processing systems do not have. This feature is required for the supervisory laser cladding control where traverse speed has to be varied during processing to compensate for the undesired process changes.

b). A self-cleaning laser cladding dome with a spherical nozzle, which was designed to improve the consistency of the laser beam light recycling, powder feed alignment and for in-process sensor integration.

c). An automatic laser shutter controller with in-process workpiece edge sensing.

d). A closed loop laser nozzle/substrate distance controller through in-process height sensing.

e). Necessary interfaces between various system elements for supervisory laser cladding control.

4.2. 3 AXIS HYBRID CNC LASER CLADDING WORKSTATION CONSTRUCTION

The CNC laser cladding workstation was developed to consist of a CNC x-y table (which moves the workpiece under the laser beam), CNC z axis moving optics (which controls the laser beam focus and beam spot size on the workpiece by changing the nozzle/workpiece distance), and interfaces for the computer operation of other system elements such as laser and powder feeder.

4.2.1 X-Y table and z axis moving optics preparation

A). X-Y table

A 2 axis aluminum linear traverse (250mmx280mm) table was supplied by Control Laser Ltd which has two permanent magnetic DC motor/tachos coupled to the stainless table lead screw through a pulley/belt mechanism with primary gear of 14 teeth and secondary gear of 28 teeth. In order to use this table as part of CNC workstation, work was carried out to add the follow to it:

- . Two 1000 line incremental shaft encoders with line drivers (Supplied by Electric Craft Ltd), direct coupled to the lead screw shaft through flexible couplings, as table position feedback elements.

- . Mechanical safety limit switches for all 4 directions with normally close (fail safe) configuration. Two of these limit switches were also used as datuming switches for CNC control.

- . Protection bellows to cover the exposed lead screws and aluminum top cover sheets were used to prevent hot dust falling on the bellows.

- . Lockable, rigid, multi-way connectors to replace flying leads for electrical connections.

- . An adjustable drill stand was used to support X-Y table and a platform was made on the collar of the drill stand for the mounting of powder feeder.

B). Z axis moving optics

The z axis moving optics was also supplied by Control laser LtdL , which consists of a 45° adjustable mirror, lens holder and nozzle assembly. The lens assembly can be moved up and down through a rack and pinion mechanical system. In order that this z axis can be controlled by CNC controller, work was carried out to add the following to it:

- . A permanent magnetic DC motor/tacho with 6000RPM maximum speed (purchased for Electric Craft) directly coupled to the pinion. The selection of motor was to maximize the speed since load required is very small because of the high gear ratio (1/100).

- . A 1000 line incremental shaft encoder with line driver (from Electric Craft) linked to the motor through a coupling.

- . Safety Limit switches in both directions of the z axis with one of them as datuming switch.

- . Lockable, rigid, multiway connectors for electrical connections.

The electrical and mechanical details of the workstation can be found in Appendix A. Fig. 4.1. shows the upgraded workstation.

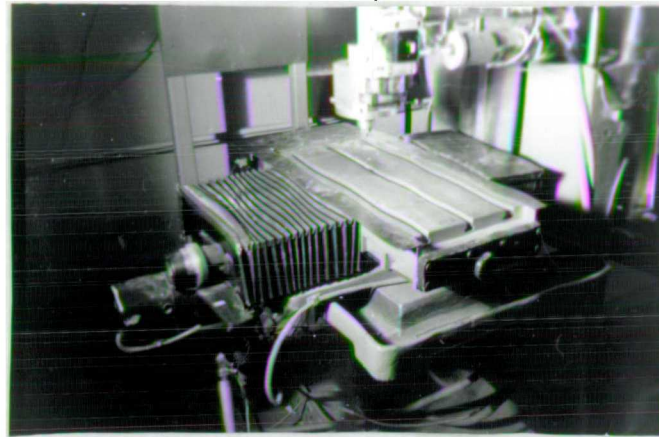


Fig. 4.1 The upgraded workstation for CNC laser cladding.

4.2.2. CNC motion control system construction and optimization

The structure of the constructed CNC motion control system is shown in Fig. 4.2.

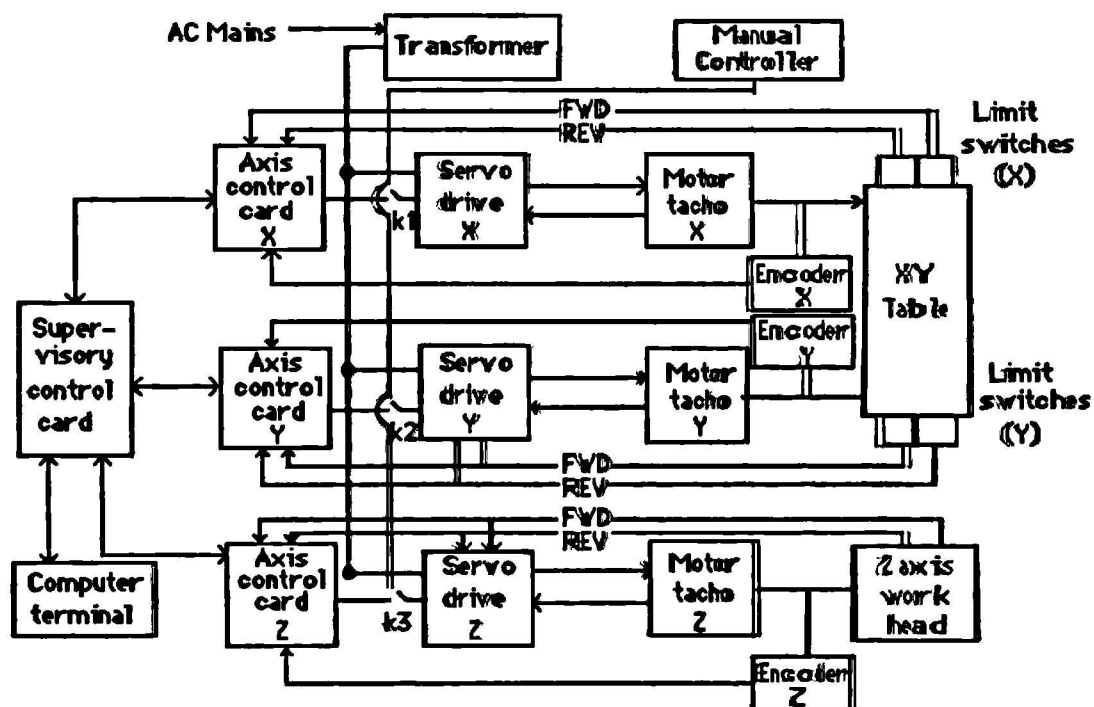
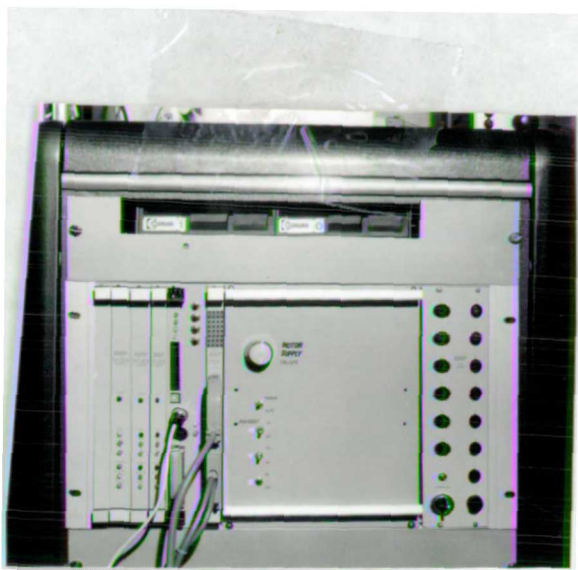
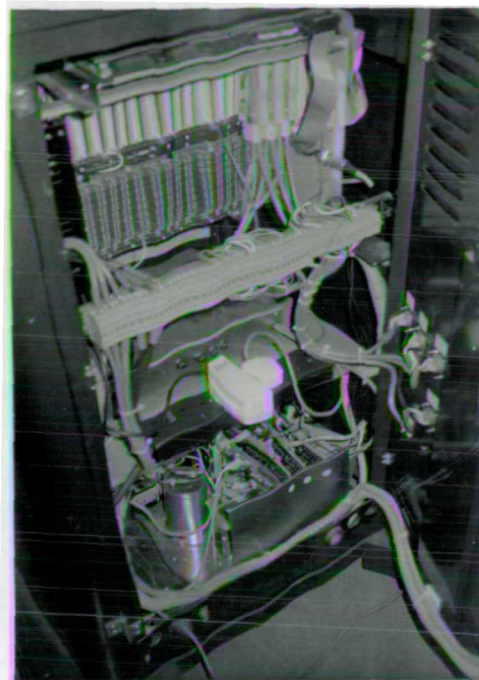


Fig. 4.2. 3 axis CNC workstation structure.

A 19" standard system cabinet was used to house a 3 axis servo amplifier (from Electric-Craft Ltd.), 3 micro-processor based servo control cards (From RDP Project



(a)



(b)

Fig.4.3. CNC motion control system cabinet. a).front, b).back.

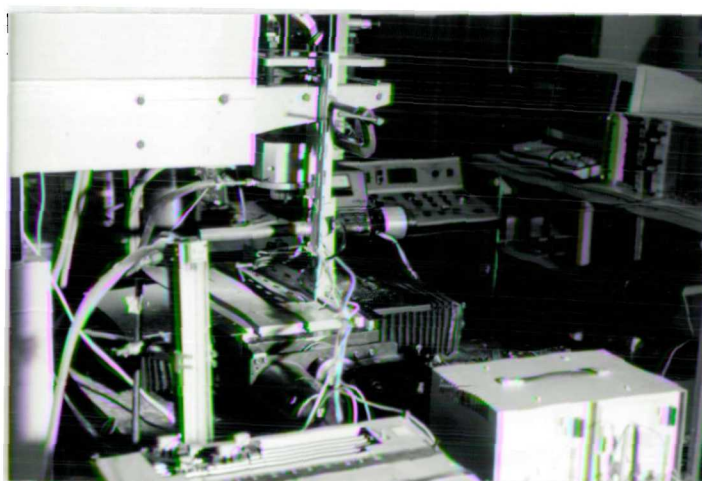


Fig.4.4. CNC laser cladding workstation at work for red cladding.



(a)



(b)



(c)



(d)

Fig.4.5. CNC motion control system peripherals. a).PSU. b).Manual controller. c).Operator console. d). Portable emergency stop.

Ltd), a micro-processor based motion supervisory control card (tailor made by MCT Ltd), an auxiliary DC power supply unit (for encoder and limit switch power supply) and the front operating panel made. Terminal blocks were used in the cabinet for the distribution of electric signals. Self-locking connectors were used to communicate to the workstation through screened multi-way cables. A separate system power supply unit was built to contain a transformer, an auxiliary 24V DC power supply for system safety interlocks. A 3 axis manual speed controller for laser workstation and a portable safety stop unit were also developed. A computer terminal was used to communicate to the motion controller through RS232 link. All the motion control system elements were linked together as shown in Fig. 4.2. The completed CNC motion control system is shown in Figs 4.3 to 4.5.

The motion control system uses Control BASIC language developed by MCS Ltd. specially for this project. The motion control program can be down loaded into the 4k memory in the supervisory motion control card. The speed and position can be instantly altered while moving through system supervisory computer or a computer terminal.

The motion control characteristics were optimized through experiments and theoretical analysis (Appendix A).

4.2.3. CNC motion control system performance

The evaluation and test of the CNC motion control system were conducted in the following aspects:

a). Position control accuracy: Experiments found that the steady state position control errors were around 10 and 20 encoder pulses for x-y table and z axis respectively. i.e. 0.05mm for x-y table and 0.01mm for z axis. This was probably due to the backlash of the lead screw/rack or the dead band of the motor response. Nevertheless the control accuracy is adequate for laser cladding and most of laser materials processing applications.

b). Speed control accuracy: The actual workstation speed was measured from tachometer output when a constant speed control was applied from the CNC programming. The two values showed a difference of 0.6% for x-y table and 0.4% for z axis, i.e. a 0.06mm/s deviation at speed of 10mm/s for x-y table and 0.04mm/s deviation at constant speed of 10mm/s for z axis, which is probably due to the inaccuracy of the tacho constant.

c). Repeatability. The repeatability of the position control was tested for the x and y axes by mounting a pen on the nozzle mount and drawing squares on the table 100 times continuously and read encoder pulses from the computer at the same time. There was no visible shift on the y axis but the position reading from the computer after 100 repeats shifted 0.05 mm from the start point. However the repeatability on x axis was not very good and this was found to be due to a loose encoder coupling and a failure on the encoder

amplifier. After repairing this the repeatability on the x axis was as good as the y axis. Similar experiments were made for the z axis and the shift from the start point was only 0.01 mm (computer digital reading), which is within the control accuracy.

d). Maximum and minimum speed. The speed capability was tested by using the forced output from the motion controller which can generate either +10V or -10V to the servo drive thus a maximum speed was achieved which was found by the motion controller speed readings to be 150mm/s for both x and y axis and 50mm/s for z axis. The minimum speed for x-y table has achieved 0.05mm/s and 0.01mm/s for z axis.

e). Accelerations. Since acceleration can be defined by the control software, different accelerations can be used to arrive at a speed as shown Fig. 4.6. This is useful when slope in and slope out is required in the laser materials processing applications. The experiment found that the maximum acceleration was around 200mm/s² for x-y table at the maximum speed beyond which large following error was resulted.

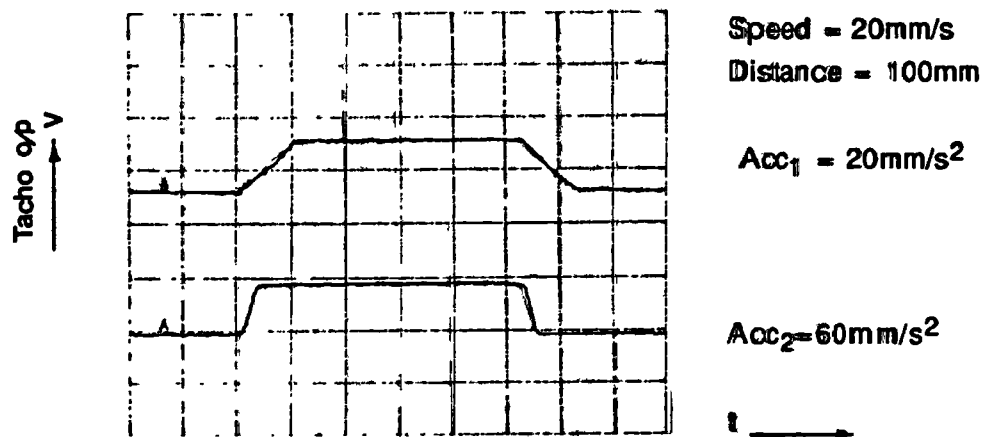
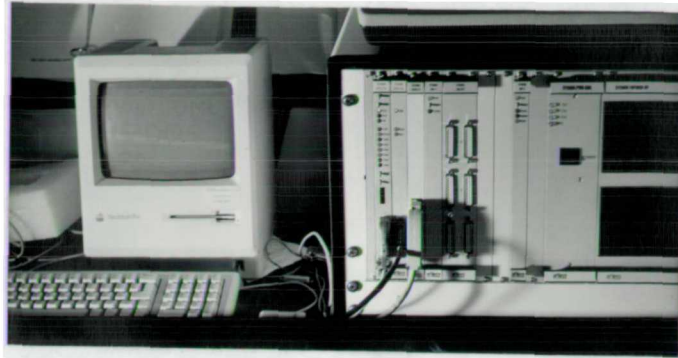


Fig.4.6. The controlled speed profile of the CNC system (measured from tacho).

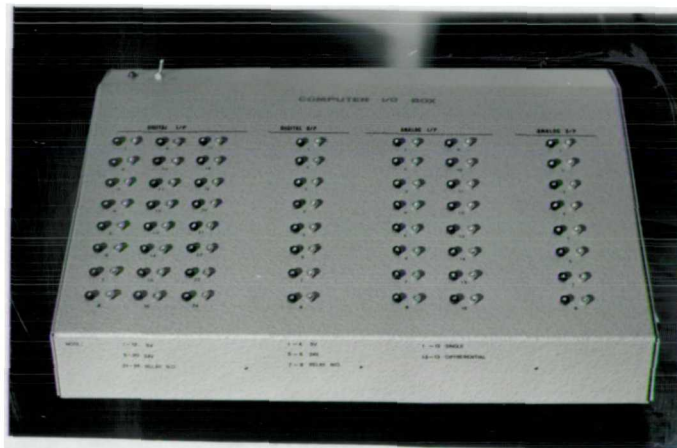
4.2.4. Interfaces for laser, powder feeder, system supervisory computer and sensing systems

To integrate laser and powder feeder operation, a digital I/O card (supplied by RDP Ltd.) was installed in the motion control cabinet and appropriate interfaces were made for both powder feeder driver and laser manual operating unit. Since the digital card provides open collector outputs an additional power supply was made to pull up the output voltage for triggering the control relays. The programming of the laser shutter and powder feeder operation with CNC motion control was achieved through the supervisory control card. This allows the coordination of laser shutter and powder feeder operation to the motion control automatically and with precise timing.

The system supervisory computer was purchased which is a VME bus micro-computer



(a)



(b)

Fig. 4.7. System supervisory computer and control interfaces. a). VME bus computer and operator console. b). System interface box.

multi-task operating system. 12 channel A/D, 2 channel D/A, 8 channel RS232 boards were purchased and installed to the computer. The communication of the system supervisory computer to the CNC control unit was by a serial link (RS232). Since the parts programming can be made off-line and down loaded to the on-board memory of the motion control card and the communication is by ASCII code, the supervisory computer can use any language to adjust the motion parameter on-line during processing. The communications of supervisory computer to power feeder and laser were through either D/A board (for open loop control) or RS232 (to the automatic closed loop controllers, which will be described in the next two chapters). An easy used interface box was made (Fig.4.7b.) for the communication of supervisory computer to other parts of the system such as sensing system (through A/D converter). Under this configuration the whole laser cladding operating can be programmed through the system supervisory computer enabling the automation and coordination of the process.

4.3. DEVELOPMENT OF A SELF-CLEANING "SMART" DOME FOR LASER CLADDING

A self-cleaning "smart" laser cladding dome (Fig.4.8) was designed and realized as part of intelligent laser cladding system.

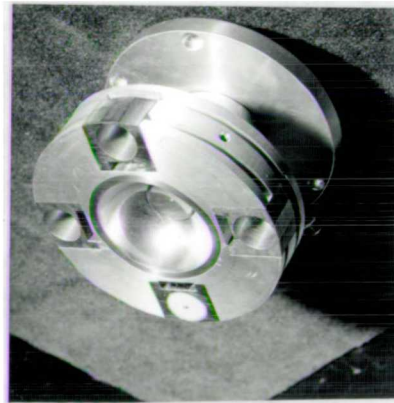


Fig.4.8. Self-cleaning "smart" laser dome with sensor integration.

It has the following improvements over the previous dome:

1). **Aerodynamic cleaning for constant dome reflectivity.** Approximately 40% of the laser power is lost through the surface reflection in laser cladding on mild steel

if a dome is not used. Similar problems exist for other laser processes as well. The use of an optical dome was first suggested by La Rocca of Fiat, Italy [141] and later by Weerasinghe of I.C. U.K.[50]. However using a dome for laser cladding or alloying by the powder feeding method introduces a new problem, that of contamination of the dome surface by the powder and fume generated from the process. This occurs after a short running time, thereby reducing its efficiency substantially. To solve this problem, a self-cleaning reflector-nozzle was designed with adjustable air gap (Fig. 4.9) which by deflecting a high speed film of gas to the wall of the dome prevents powder dust and fume settling on the surface . The dome itself was made of brass of spherical shape with the internal wall highly polished. This design ensures that the main reflection from the melt pool (located at the centre of the sphere) is back to the pool. Fig. 4.10 compares the experimental results of cladding using dome with and without self-cleaning function. The improvement is apparent.

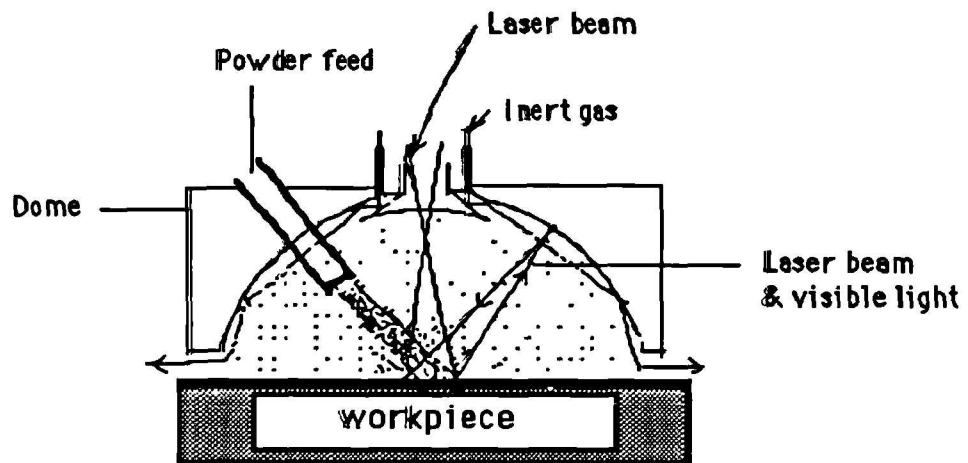


Fig. 4.9. Self-cleaning, laser light recycling dome operating principle.

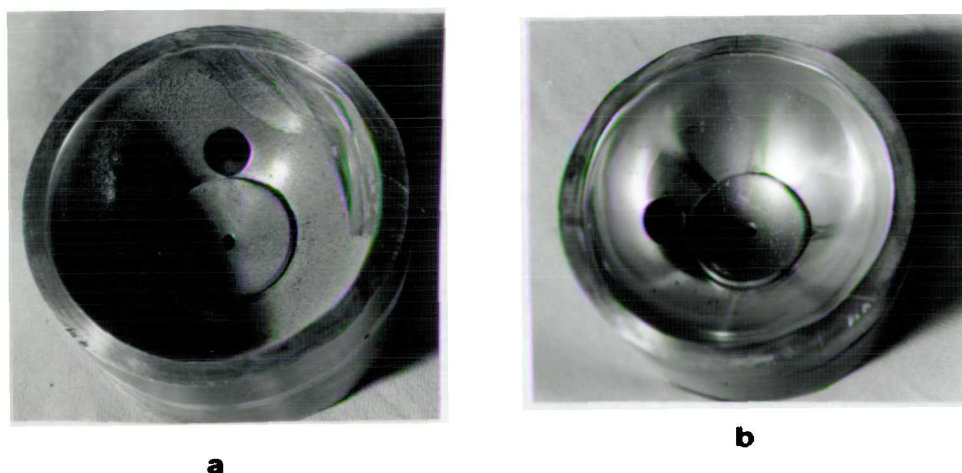


Fig. 4.10. Comparison of the dome with and without self-cleaning. a). continuous running for 1 minute without self-cleaning. b). continuous running for 3 minutes with

self-cleaning.

2). **Self-cleaning gas for process shrouding and dome cooling.** The self-cleaning function discussed above was found also helps for process shrouding and cooling of dome. Previous method used for process shrouding can be summarized in Figs. 4.11

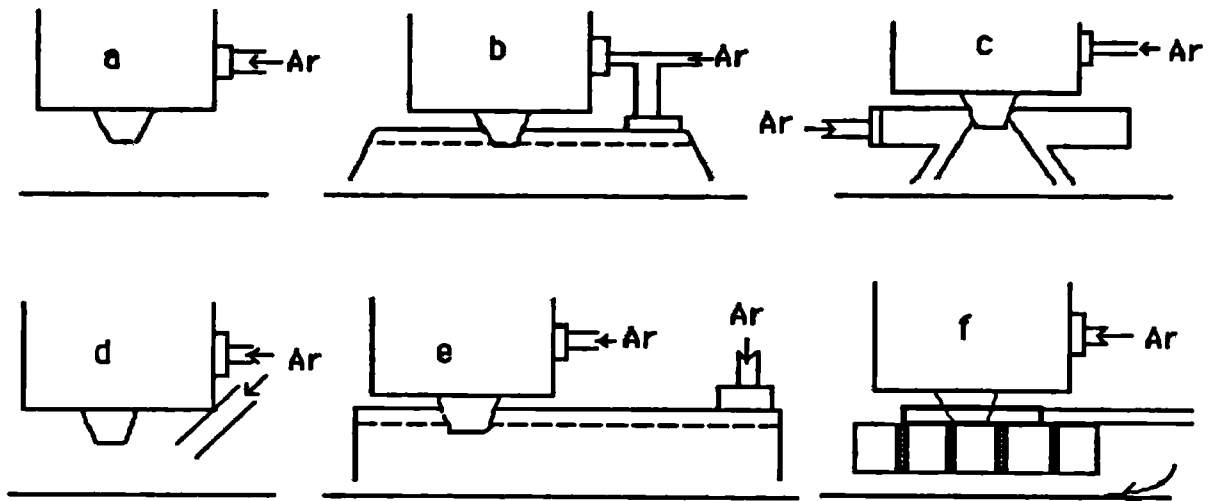


Fig. 4.11. Shrouding techniques for laser processing. a) coaxial jet, b). dish, c). double cone, d). side nozzle, e) trailing, and f) turbine.

1). Coaxial jet (Fig.4.11a). Inert gas is blown out from the laser nozzle to the laser processing area. This can disturb the powder feeding and therefore not applicable for laser cladding.

2). Dish shroud [142]. (Fig.4.11b). This method was reported to be more effective.

3). Cone shroud [143] (Fig.4.11.c). Reported to be effective.

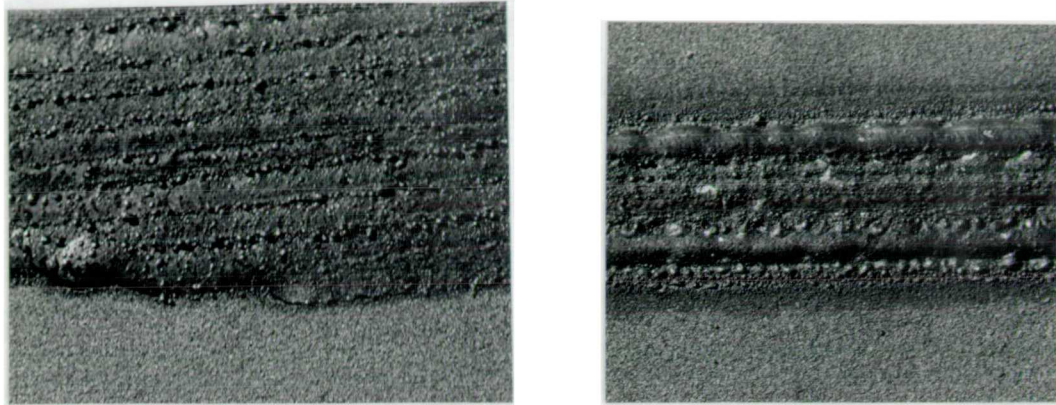
4). Side jets [144] (Fig.4.11d). This is often used. It covers very small area. The hot surface may still get oxidized when moves out of the spot. Not applicable to laser cladding since it disturbs the powder feed.

5). Trailing jets (Fig.4.11e). It is often used for high speed traverse workpiece.[145]

6). Turbine shroud [146] (Fig.4.11f). Needs a driving system.

For the dome developed, the cleaning gas used in the dome forms a thin wall of gas surrounding the work area and also it creates a relative high pressure zone inside the dome, which prevents the air coming in. This gives a shrouding function. The use of inert gases such as Argon or Nitrogen for cleaning gas makes this shrouding effective. Fig. 4.12

compares the clad result with and without shrouding. A highly oxidized clad was observed without the shrouding. When N₂ gas was used as dome cleaning gas, the oxidation was greatly reduced.



a). With shrouding

b). without shrouding

Fig.4.12. Comparison of laser cladding results with and without gas shrouding effect.

The cleaning gas used in the dome was found also helps to reduce the temperature rise rate of the dome. The experiment has shown that when the cladding run continuously for 1 minute without gas, the dome temperature had risen to 120 °C, while with gas the dome temperature had risen to 40°C for two minutes continuous cladding.

3). Fixed angle powder injection. In previous laser cladding practice, the angle of powder feeding varies between experiments, because there had been no facilities to guarantee this angle for all the experiments. This reduces the repeatability of the processing and experiments, since powder feed angle has an influence on the clad results (see chapter 2). On the dome developed a port was provided for powder feeding, which is a fixed 55° to the horizontal and intercepts the laser beam at a point 5mm below the bottom edge of the dome. This high angle feeding has proved to be more efficient in powder catchment. [50]

4). In-process sensor integration. Various in-process sensors (described in Part 3 of this thesis) are fitted to the dome on an instrumented collar in which infrared distance sensors, dilution sensors, edge detectors and scanning profile sensors are incorporated. Also channels are provided for water cooling and gas cooling of the sensors.

5). Spherical nozzle for beam recycling. Instead of using "top hat" or cone shape nozzles as used in previous laser materials processing practice, a spherical end nozzle was designed to enhance the laser beam recycling by reflecting the laser beam back to the melt

pool again (Fig. 4.13). By slightly changing the shape of nozzle end it could be used for pre-heating and post heating as the previous dome did [50].



Fig. 4.13. Discription of the spherical nozzle for beam recycling and pre/post heating.
a). ordinary nozzle. b) spherical nozzle.

6). Safe operation. This is a common feature of all types of domes used in laser cladding since it effectively covers the process area and will shield the operators from scattered laser reflection reducing the need for more complex safety arrangements.

4.4. DEVELOPMENT OF IN-PROCESS EDGE SENSING AND AUTOMATIC LASER SHUTTER CONTROLLER

The automatic "smart" laser shutter control was designed and realized to switch on/off the laser beam to the workpiece by self-detecting the workpiece edges using four proximity switches.

The sensing part of the automatic laser shutter control unit was developed to consist of four non-contact infrared proximity sensors located around the centre of nozzle in +x, -x, +y, -y directions as shown in Fig. 4.14. The sensors will give a logic 1 signal (high) to indicate the sensing point is on the workpiece and a logic 0 (low) to indicate the sensing point is not on the workpiece surface. 2 methods were investigated for the laser shutter control using these sensors:

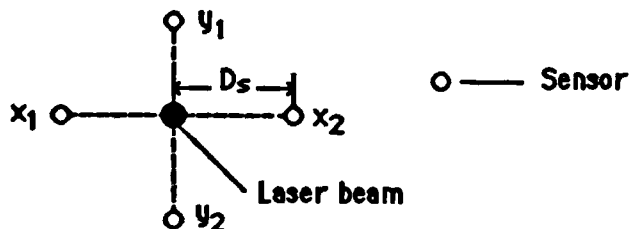


Fig. 4.14. Arrangement of edge detectors.

4.4.1 Hardware method

Assuming a rectangular workpiece and alignment of the detectors as shown in Fig. 4.15. As the workpiece traverse relative to the laser beam 16 possible situations will be produced which is shown in Fig. 4.15 and Table 4.1. According to this table, if there are two or more than two sensors indicating a logic "high", the centre point will be on the workpiece. Only when there is one sensor is "on" and rest of three are "off", the centre point is "off" the surface.

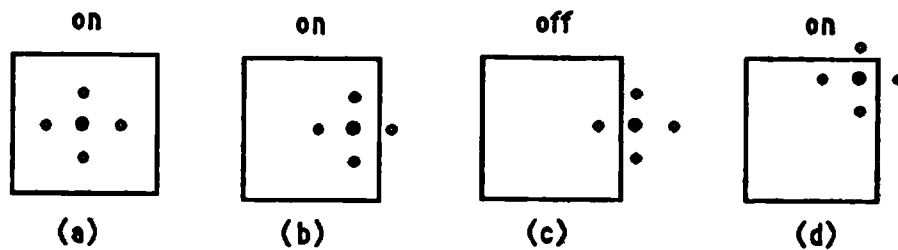


Fig. 4.15. Edge sensing possibilities.

Table 4.1. Edge sensing logic truth table.

X_1	X_2	Y_1	Y_2	Laser state	X_1	X_2	Y_1	Y_2	Laser state
0	0	0	0	off	1	0	0	1	on
0	0	0	1	off	1	0	1	0	on
0	0	1	0	off	1	0	1	1	on
0	0	1	1	on	1	1	0	0	on
0	1	0	0	off	1	1	0	1	on
0	1	0	1	on	1	1	1	0	on
0	1	1	0	on	1	0	0	0	off
0	1	1	1	on	1	1	1	1	on

This logic can be expressed using Boolean logic expressions as:

$$\begin{aligned}
ON_{centre} &= X1 \cdot X2 + X1 \cdot Y1 + X1 \cdot Y2 + X2 \cdot Y1 + X2 \cdot Y2 + Y1 \cdot Y2 \\
&= X1 \cdot X2 + (X1+X2) \cdot (Y1+Y2) + Y1 \cdot Y2 \quad (4-1)
\end{aligned}$$

$$OFF_{centre} = \overline{ON_{centre}}$$

Here "+" represents logic "OR" and "." represents logic "AND". The top bar "-" represents "NOT" logic. The laser shutter should be switched on if

$$ON_{centre} = "1"$$

and shutter switched off when:

$$OFF_{centre} = "1"$$

$$\text{or} \quad ON_{centre} = "0"$$

where ON_{centre} and OFF_{centre} are two Boolean variables representing the state of laser shutter. A stand alone automatic laser shutter controller was developed (Fig. 4.16) according to the above analysis. The controller modulates the proximity sensors with 10kHz frequency and filters the received signal with a band pass filter so that the influence of thermal radiation from the melt pool can be eliminated (see section 4.6.1). The received sensor signal was converted to DC signal by using sample and hold circuit and digitized to switching signals using comparators and Schmitt trigger, where the sensor signal was compared to an adjustable reference logic level. If the sensor signal is higher than the reference level the logic will be "0" otherwise it is "1". If the plate is not flat, the edge threshold can be set at the lowest point of the workpiece so that any point below that will be considered as "off". LED indicators and four logic output ports were provided so that it can be fed to computer for programmable shutter operations. NAND gate IC's were used to realize the control logic and generate the laser shutter command signals. A timer was used to record the laser beam "on" time to a accuracy of 0.01s as an additional function of the controller. The control output from the controller was sent to the laser manual operating unit where an interface was made for the external control of the laser shutter.



Fig.4.16. Laser shutter controller.

4.4.2. Software method

The above mentioned control logic can also be achieved using computer software. However it can be noted that the above logic method has some weakness in that if either the sensors are not aligned with the workpiece or the workpiece is irregular shape, the method may give a wrong interpretation of the true state. This can be eliminated by using a second shutter control approach: The computer continuously samples the outputs from the sensors in the leading direction of the motion. Suppose the centre of nozzle moves relative to the workpiece in +x direction with speed V. The computer will look at the +x sensor continuously or using hardware interruption. If the sensor is triggered "ON" the computer will record the position and when the nozzle moves further a distance equal to the sensor/nozzle centre distance (D_{sn}), (obtained either by reading the position buffer of the CNC motion control unit or set software timer to D_{sn}/V). The laser shutter can then be triggered to switch on. Similarly when the leading sensors have indicated that the centre point is about to fall off the surface, the computer will switch the laser shutter off at the appropriate time. Shutter control when workpiece moves in directions rather than X/Y can be realized in a similar way except that the position of laser beam relative to the edge has to be calculated using vector calculations.

4.5. DEVELOPMENT OF IN-PROCESS DISTANCE SENSOR AND CLOSED LOOP NOZZLE STANDOFF CONTROL

Automatic maintenance of the laser nozzle to workpiece height during processing is particularly necessary when processing of non-flat workpiece. Previous methods of surface height following cannot be used either because the distance between the nozzle and substrate (usually 35mm for cladding) is much greater than the sensor range (for example for capacitive or inductive sensors) or because the powder feeding to the melt pool prevents any coaxial approach for the height sensing. This section introduces a new method for automatic height following. It has shown an accuracy of around $\pm 0.05\text{mm}$ for steady state position control and approximately $\pm 0.1\text{mm}$ for dynamic slope following at the traverse speed of 0.1 to 30mm/s which covers the traverse speed used for most laser cladding practice.

4.5.1. Distance sensor development

The sensor consists of an infrared transmitter (peak wavelength $0.8\ \mu\text{m}$) and an infrared detector (spectrum from $0.5 - 1.2\ \mu\text{m}$) arranged as shown in Fig.4.17. When the distance of the sensing face from the reflective surface changes the amplitude of the received signal will change as shown in Fig. 4.18 .

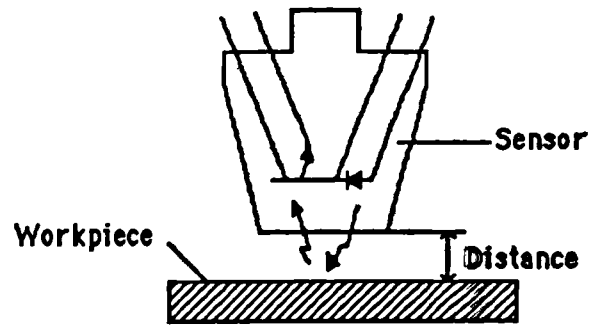


Fig. 4.17. Infrared distance sensor.

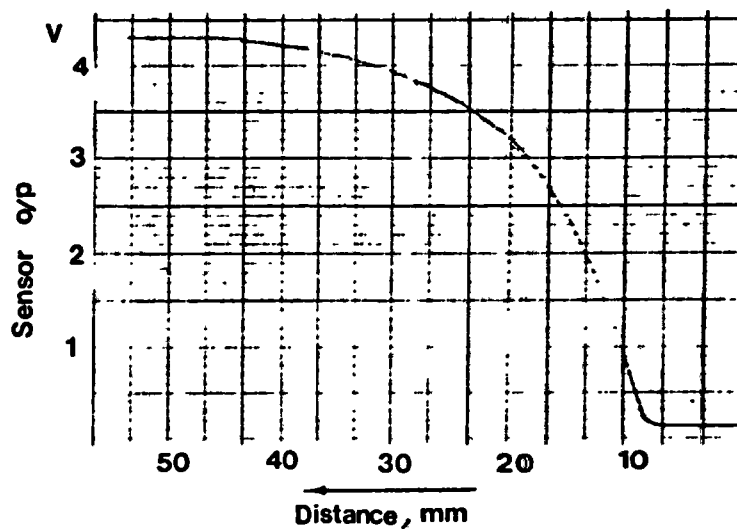


Fig.4.18. Sensor response to distance change of a mild steel surface.

The following effects were examined on the sensor and appropriate measures were taken to optimize the sensing:

a). Surface condition and materials effects. Although the sensor will have a different sensitivity for different materials and surface conditions due to the reflectivity change, when the material surfaces were shot blasted, as they always are for laser cladding, the difference between the material is very little as shown in Fig.4.19. However it is still recommended to calibrate the sensor for different substrate materials. Surface oxidation was found to have a marked effect on the sensor (See chapter 9) response. This requires that a good process shroud should be used so that surface oxidation is minimum.

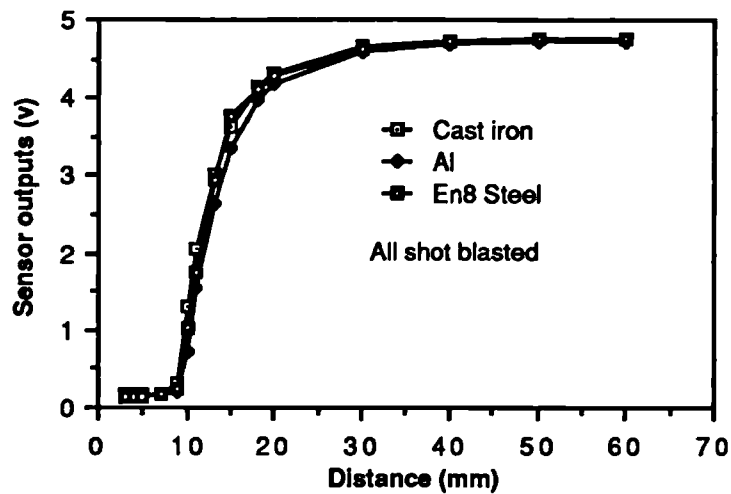


Fig.4.19 Infrared distance sensor response to different materials (shot blasted).

b). Powder particles effect. Loose particles on the substrate surface were found to affect the sensing accuracy. This effect however could be eliminated by injecting a weak gas flow at the sensing point to clean the particles. Low pass filter was used to reject the single particle induced pulse on the sensor.

c). Background light effect. Although CO₂ laser beam (10.6 μ m) does not affect the sensing, the thermal radiation from the melt pool can have a strong influence on the sensing. This is shown in Fig.4.20 . The low temperature thermal radiation from other parts of the clad workpiece will have little effect on the sensing since the spectrum of this radiation will generally be beyond 1.2 μ m. The reflectivity change due to the substrate surface temperature rise is very little since the reflectivity dependence on temperature mostly happens near and above melting point. An experiment was made to investigate this possible effect where a mild steel plate was heated by a flame torch while the distance sensor was placed above the plate. There was no change of the sensor signal when temperature was below 350°C.

In order to cut off the noise generated from the melt pool light and other ambient light. The sensor was modulated by pulsing the transmitted signal with high a frequency of 10kHz and at the receiver a narrow band pass filter was fitted to allow only the signal with the frequency identical to the transmitting frequency to pass. The modulated signal is then demodulated to a DC voltage signal by a synchronized sample and hold circuit. Low pass filter was used after this point to reject particle induced noise. The modulated distance sensing showed no effect from the melt pool thermal radiation as shown in Fig. 4.21. The signal received at the non-transmitting period could also be used to monitor the melt pool stability if a separate sample and hold circuit is synchronized to take the radiated signal only. This provides an additional feature of the sensor.

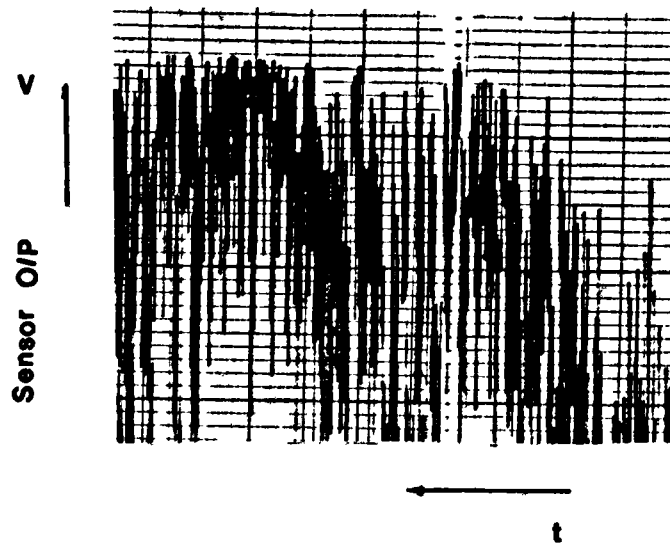


Fig. 4.20. Melt pool radiation effect on the un-modulated sensor.

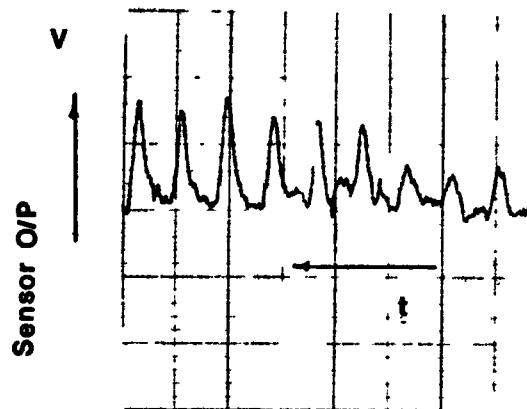


Fig.4.21. Sensor response independent of melt pool radiation after the signal conditioning (It shows the response to clad profiles).

d). **Sensor Linearization.** The response of the sensor to distance changes is a non-linear relationship. This provides a non-uniform sensitivity within the sensing range (10 to 50mm). Two solutions were found to linearize the sensing:

1). By restricting the operating zone. As can be seen in Fig.4.22, the sensor's effective response can be divided into 4 linear zones each has a different sensitivity. However only A, B and C zones can be used while the sensitivity in zone D is too low. This approach may limit the sensor applications and provide difficulties for display and calibration.

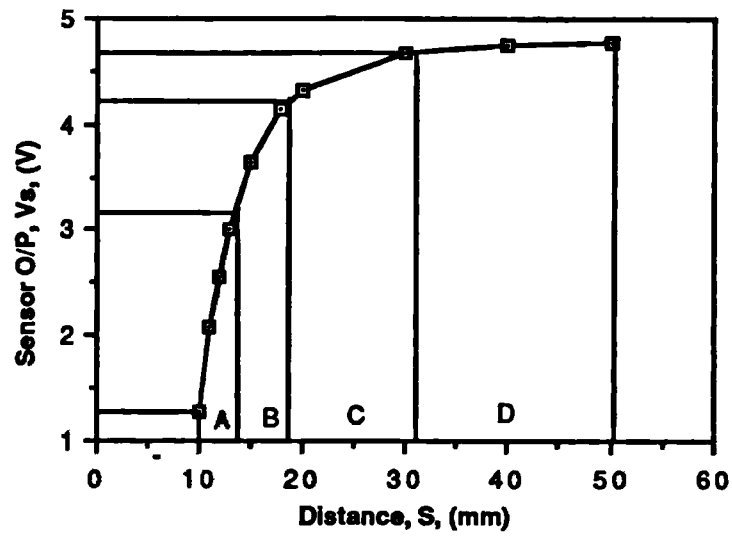


Fig. 4.22. 4 linear zones divided for the distance sensor

2). By electronic signal processing. From the sensor response curve we can see that it looks very much like an exponential curve. Actually when an exponential function as in Eqn. (4-2) was used with proper parameter values the calculated curve fitted the experimental response quite closely. (Fig.4.23)

$$V_{sz} = V_o [1 - e^{-\alpha(z-z_o)}] \quad (4-2)$$

where V_{sz} is the sensor output voltage and z is the distance, α and z_o are two constant.

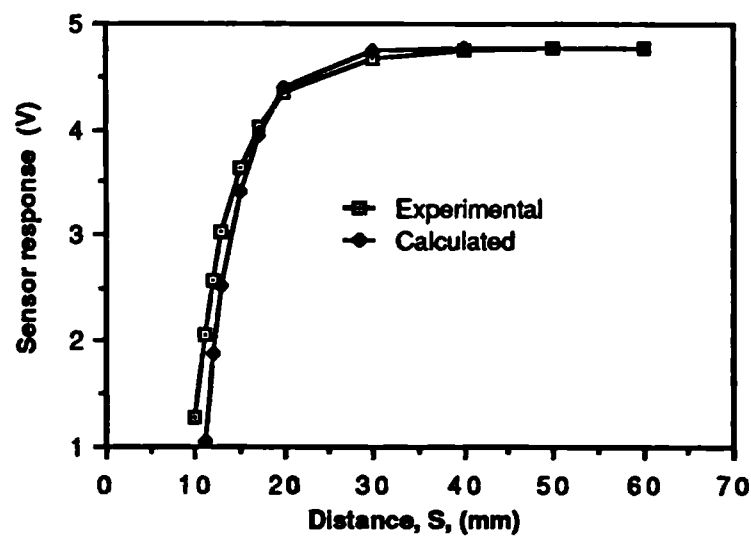


Fig.4.23 Approximation of the sensor response with an exponential function $V_{sz} = V_o[1 - e^{-\alpha(z-z_o)}]$, where $V_o=4.773$, $\alpha = 0.25$ and $z_o = 10\text{mm}$.

This allows us to linearize the response by the following transforms:

$$\begin{aligned}
 V_{sz} &= \ln(V_0) - \ln(V_0 - V_{sz}) \\
 &= \ln(V_0) - \ln [V_0 - V_0 + V_0 e^{-\alpha(z-z_0)}] \\
 &= \ln(V_0) - [\ln(V_0) - \alpha(z-z_0)] \\
 &= \alpha z - \alpha z_0
 \end{aligned}
 \tag{4-3}$$

which has a linear relationship with the distance z . This transformation was realized with electronics hardware (V_0 was taken as the sensor output for infinite distance). The response of the linearized signal is shown in Fig.4.24 with a comparison to the original signal. The average sensitivity has become 150mv/mm over the sensing range is (10mm-50mm). The sensing resolution for shot blasted surface was found to be 0.05mm and grounded surface of 0.02mm.

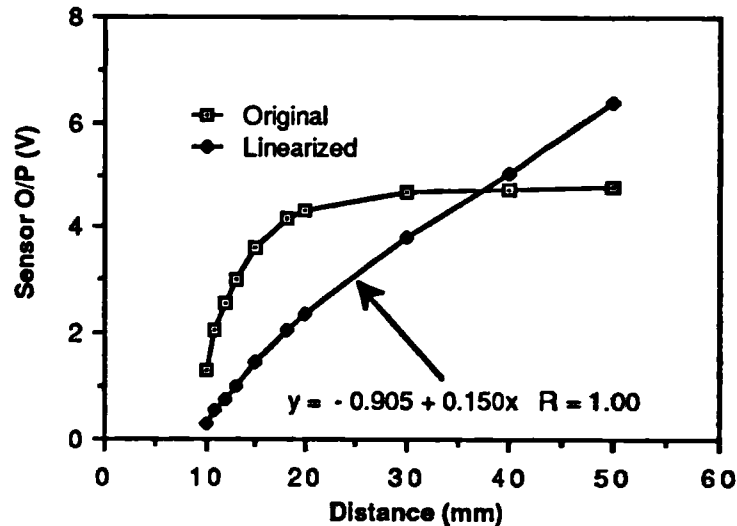


Fig. 4.24. Response of the linearized sensor with comparison to the original sensor response.

4.5.2. Closed loop laser nozzle standoff control

The closed loop control of distance between laser nozzle and substrate surface was achieved by placing the sensor next to the nozzle (off axis) either by leading the traverse direction (a delay circuit is required) or parallel to the traverse direction. The distance sensing signal was then fed to a proportional control electronics device made for this purpose, which compares the reference signal set by a potentiometer to the feedback signal and the error was amplified to within $\pm 10v$ and sent to the z axis servo amplifier which controls the z axis motor and laser work head movement. This arrangement is shown in Fig.4.25.

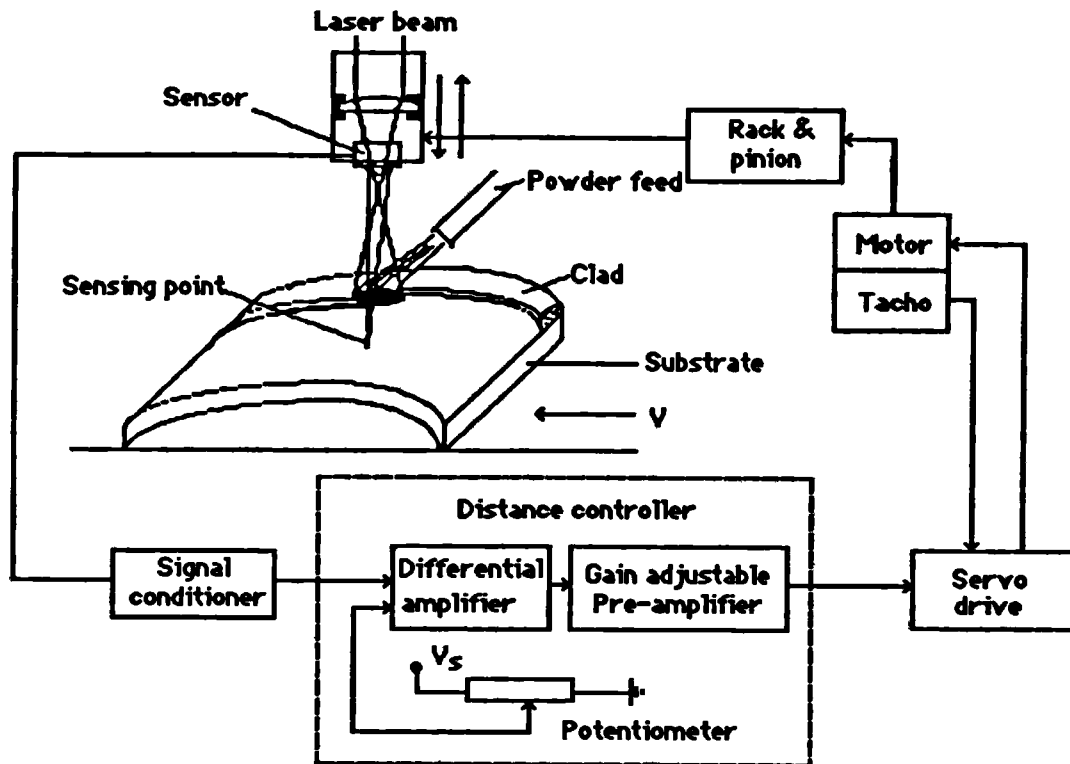


Fig. 4.25. Closed loop distance control in laser cladding.

4.5.2.1. Closed loop laser nozzle standoff control optimization

The DC motor driving the z axis can be described by the following two equations:

$$T_z = K_t I \quad (4-4)$$

$$V_i - IR = K_{zv} \omega \quad (4-5)$$

where T_z : Torque on the motor shaft (NM)

V_i : Input voltage (V)

K_t : Torque constant (NM/I)

K_{zv} : Voltage const. (Vs/rad)

I : Armature current (A)

R : Armature resistance (Ω)

ω : Angular velocity of the motor shaft (Rad/s)

Since the motor was coupled to the mechanical load of the z axis through a rack and pinion with a gear ratio of $K_{gz} = 1/100$, the torque T_z can be expressed as:

$$T_z = J \frac{d\omega}{dt} + T_s \quad (4-6)$$

where

T_s : Static load due to friction etc.

J : Combined moment of inertia of motor and load. In this case:

$$J = J_r + K_g z^2 J_l \quad (4-7)$$

where J_r is inertia of the motor and J_l is the inertia of the load

$$J_l = W_z r_p^2 / e \quad (4-8)$$

where W_z is the weight of the load (about 10kg), r_z is the radius of the pinion (9mm) and e is the rack and pinion efficiency (0.93). The pinion inertia and gear inertia are ignored here in the calculation since they are small compared to the load inertia. Therefore the total inertia reflected at the motor end will be:

$$\begin{aligned} J &= J_r + K_g z^2 J_l \\ &\approx 0.000037 + 10^{-4} \times 10 \times 9^2 \times 10^{-6} / 0.93 \\ &\approx 0.000037 \text{ (kgm}^2\text{)} \\ &= J_r \end{aligned}$$

Combining Eqns.(4-4), (4-5), (4-6), we obtain:

$$\tau_m \frac{d\omega}{dt} + \omega = \frac{1}{K_{zv}} V_i - \frac{1}{K_t K_{zv}} T_s \quad (4-9)$$

where τ_m is mechanical time constant of the load motor and is defined by:

$$\tau_m = \frac{J R}{K_t K_{zv}} \quad (4-10)$$

Since $J \approx J_r$ in our case, we can take $\tau_m = T_{zm}$, which is mechanical constant of the z axis motor.

The Laplace transform of the equation (4-9) is:

$$\omega(s) = \frac{K_{zm} V_i(s) - (R K_{zm} / K_t) T_s(s)}{1 + s T_{zm}} \quad (4-11)$$

where K_{zm} is the gain of the motor and is defined as:

$$K_{zm} = 1/K_{zv} \quad (4-12)$$

When motor shaft is aligned properly with the pinion shaft the magnitude of T_s becomes very small and can usually be neglected. Eqn. (4-11) becomes:

$$\omega(s) = \frac{K_{zm}V_1(s)}{1 + sT_{zm}} \quad (4-13)$$

or the transfer function of the z axis motor/mechanical system becomes:

$$\frac{\omega(s)}{V_1(s)} = \frac{K_{zm}}{1 + sT_{zm}} \quad (4-14)$$

The tachometer can be described as:

$$V_{zp} = K_{zp} \omega \quad (4-15)$$

or the transfer function for tachometer is:

$$\frac{V_{zp}(s)}{\omega(s)} = K_{zp} \quad (4-16)$$

where $V_{zp}(s)$ is the laplace transform of speed feedback voltage V_z , K_{zp} is the z axis tachometer constant. The servo amplifier can be expressed as:

$$V_{zm} = K_a e_{zp} = K_a (V_{zc} - V_{zp}) \quad (4-17)$$

where V_{zm} is the voltage output to the motor from the servo amplifier, K_a is the gain of the servo amplifier, V_{zc} is the control input to the servo amplifier from the height tracking electronics, e_{zp} is the error signal generated by the difference of the V_{zc} and V_{zp} . The transfer function for this expression is:

$$\frac{V_{zm}(s)}{e_{zp}(s)} = K_a \quad (4-18)$$

The linear speed of the z axis can be expressed as:

$$V_z = K_{zl} \omega \quad (4-19)$$

z axis. The transfer function for this relationship is:

$$\frac{V_z(s)}{\omega(s)} = K_{z1} \quad (4-20)$$

The linear position of laser work head Z_1 is the integration of the linear speed V_z and so the the transfer function for this process can be expressed as:

$$\frac{Z_1(s)}{V_z(s)} = \frac{1}{s} \quad (4-21)$$

The distance sensing can be expressed as:

$$Z_f = K_f Z_2 = K_f(Z_1 - Z_w) \quad (4-22)$$

where, Z_w is the Laplace transform of the workpiece surface position, Z_f is the voltage output of the sensor and K_f is the transducer constant which is about 0.15 in our case. Z_2 is the distance between the sensor and the workpiece. The transfer function for this is then:

$$\frac{Z_f(s)}{Z_2(s)} = K_f \quad (4-23)$$

The height tracking controller was designed as a proportional control which can be described as:

$$V_{zc} = K_c e_z = K_c(Z_r - Z_f) \quad (4-24)$$

where V_{zc} is the control output voltage from the controller to the servo amplifier and Z_r is the height requirement set by a potential meter and K_c is the gain of the controller. e_z is the difference between the required distance Z_r and the actual distance Z_f . The objective is to find an optimum K_c so that the closed loop control has the best characteristics and stable.

The block diagram of the overall height tracking system can then be obtained as shown in Fig. 4-26.

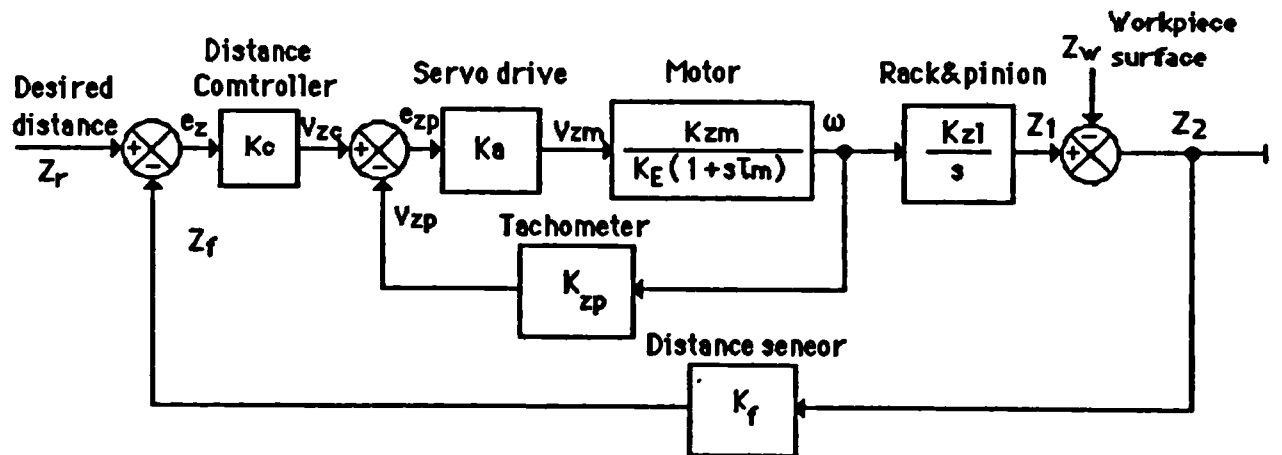


Fig.4.26. Block diagram of the closed loop distance control system.

From this diagram the transfer function between e_z and Z_1 can be obtained as:

$$G_o(s) = \frac{K_z}{s(1+s\tau)} \quad (4-25)$$

where $K_z = \alpha K_c K_a K_{zm} K_{zi}$ (4-26)

$\alpha = 1/(1+K_a K_{zm} K_{zp})$ (4-27)

$\tau = \alpha T_{zm}$ (4-28)

For the ease of analysis, the block diagram was converted to its equivalence as shown in Fig.4.27c from which we can see that Z_w factor does not contribute to the closed loop system characteristics.

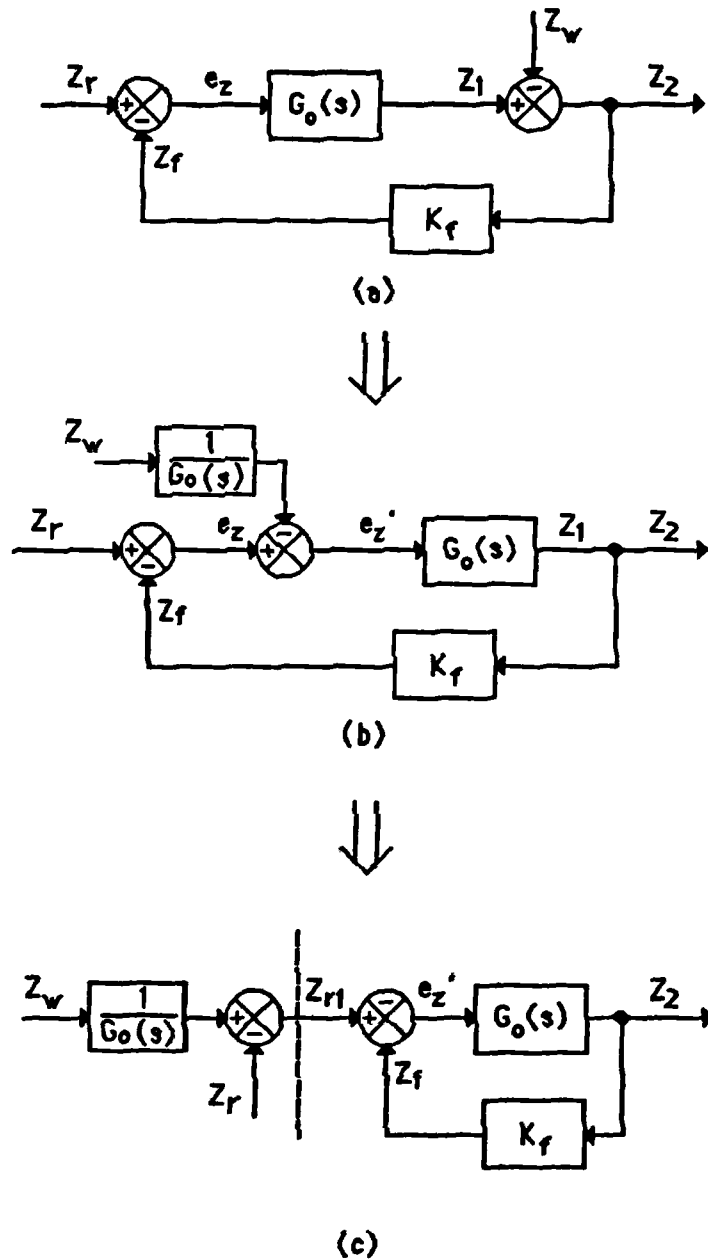


Fig. 4.27. The conversion of the block diagrams for their equivalence.

The closed loop transfer function for the system in the converted form can be derived from Fig.4.27 c as :

$$G(s) = \frac{K_z}{\tau s^2 + s + K_f K_z} \quad (4-29)$$

which is a second order system. The characteristic equation is:

$$s^2 + 2\zeta\omega_n s + \omega_n^2 \quad (4-30)$$

where the ζ is a damping factor which can be expressed as:

$$\zeta = \frac{1}{2\sqrt{K_f K_z}} \quad (4-31)$$

ω_n is the natural frequency of the closed loop system, which can be expressed as:

$$\omega_n = \sqrt{\frac{K_f K_z}{\tau}} \quad (4-32)$$

The optimum closed loop characteristic of the second order system can be achieved if $\zeta = 1/\sqrt{2}$, i.e.

$$K_z = 1/(2\tau K_f) \quad (4-33)$$

This gives us the solution for the optimum control gain K_c by combining Eqns. (4-33), (4-26), (4-27), (4-28):

$$\begin{aligned} K_{copt} &= \frac{K_z}{\alpha K_a K_m K_z} = \frac{1}{2\tau \alpha K_a K_m K_z K_f} = \frac{1}{2\alpha^2 T_m K_a K_m K_z K_f} \\ &= \frac{(1 + K_a K_m K_p)^2}{2K_a K_m K_z K_f T_m} \end{aligned} \quad (4-34)$$

For the constructed z axis moving optics the parameters can be found (see Appendix A) to be:

$$\begin{aligned} K_a &= 10 \\ K_m &= 1/K_z v = 1/(5.85 \text{ v/rpm}) = 171 \text{ rpm/v} \\ K_{z2} &= 600 \text{ rpm/v (the gain of the inner loop)} \\ K_{zp} &= (K_a K_m - K_2)/(K_a K_m K_2) = 0.00108 \text{ v/rpm} \\ K_{z1} &= 0.5 \text{ (mm /srpm)} \\ K_f &= 0.15 \text{ v/mm} \\ T_m &= 13.5 \text{ ms} = 0.0135 \text{ s} \end{aligned}$$

Therefore

$$K_{copt} = \frac{[1 + 10 \times 171(\text{rpm/v}) \times 0.00108 (\text{v/rpm})]^2}{2 \times 10 \times 171(\text{rpm/v}) \times 0.5(\text{mm/rpms}) \times 0.15(\text{v/mm}) \times 0.0135(\text{s})}$$

$$= 2.34$$

4.5.2.2. System performance

The system performance was assessed in the following aspects:

1). **Step response:** The theoretical settling time T_{st} (when the response is within 2% of the steady state value) for the closed loop system to a step response is:

$$T_{st} = 4 / \zeta \omega_n = 8\tau = 0.038\text{sec} = 38 \text{ ms}$$

The experimental closed loop response to a step change of was recorded by using a chart recorder as shown in Fig.4.28. The response time according to this experiment was about 45 ms. The deviation of the experimental response value from the theoretical one was probably because of the response delay by the recording device plus the imperfectness of the step input demand.

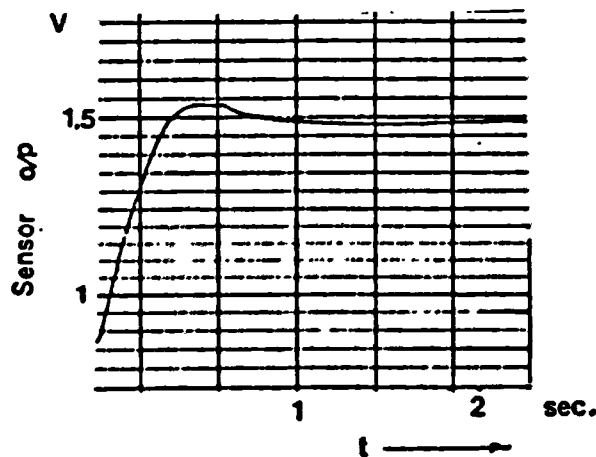


Fig.4.28. Step response of the closed loop distance control

2). **Stability.** The root locus for the closed loop system was plotted as shown in Fig.4.29 from which we can see that the system will remain stable for any value of K' , where $K' = K_z K_l / \tau$, and there will be an overshoot when K' exceeds $1/4\tau^2$. However since

there may be some non-linearities in the real system, experiments were made to operate the distance control at different distance levels within the sensing range and the system was found to be always stable.

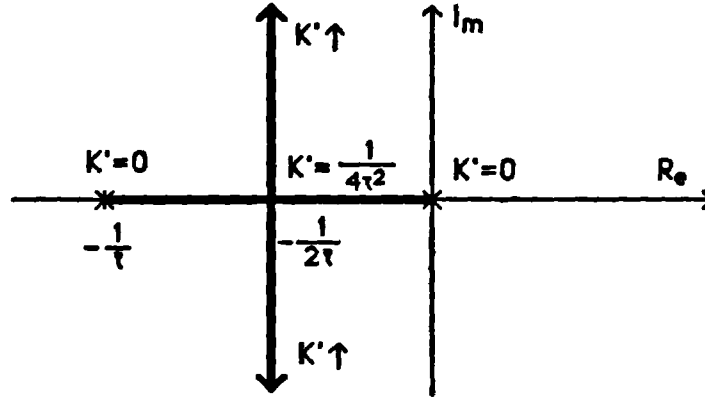


Fig.4.29 The root locus for the closed distance control system

3). **Steady state error and control accuracy.** The error function $e_z(s)$ can be found from Fig 4.27a. to be:

$$\begin{aligned} e_z(s) &= Z_r(s) - Z_f(s) \\ &= Z_r(s) - K_f[Z_1(s) - Z_w(s)] \\ &= Z_r(s) - K_f G_o(s) e_z(s) + K_f Z_w(s) \end{aligned} \quad (4-35)$$

Therefore $e_z(s)$ can be expressed as:

$$e_z(s) = \frac{1}{1 + K_f G_o(s)} [Z_r(s) + K_f Z_w(s)] \quad (4-36)$$

The steady state error in time domain can then be expressed as:

$$\begin{aligned} \lim_{t \rightarrow \infty} e_z(t) &= \lim_{s \rightarrow 0} s e_z(s) = \lim_{s \rightarrow 0} s \frac{1}{1 + K_f G_o(s)} [Z_r(s) + K_f Z_w(s)] \\ &= \lim_{s \rightarrow 0} \frac{s^2(1+\tau s)}{s(1+\tau s) + K_f K_Z} [Z_r(s) + K_f Z_w(s)] \end{aligned} \quad (4-37)$$

For a step input of $Z_r(t)$ with a magnitude of Z_r (a constant), while Z_w is kept constant, the term $Z_r(s) + K_f Z_w(s)$ becomes:

$$Z_r(s) + K_f Z_w(s) = Z_r/s \quad (4-38)$$

Therefore the steady state error becomes zero according to Eqn. (4-37).

Similarly if there is a step change in Z_w , the distance following control steady state

error also becomes zero. Apparently the steady state error for speed control and acceleration control are all zeros (since $L[dZ_r/dt] = sZ_r(s) - Z_r(0)$). However the following error for a ramp input will not be zero. The steady state error for a ramp input $Z_r = K_{or} t$ (v) or $(Z_r(s) = K_{or}/s^2)$ with ramping slope K_{or} , while Z_w is kept constant, becomes:

$$ess_{Z_r} = K_{or}/(K_z K_f) = K_{or}/(K_f/2\tau K_f) = K_{or} 2\tau = 2\alpha T_{zm} K_{or} = 0.01 K_{or} \text{ (sec)}$$

where ess_{Z_r} is the steady state error for ramp function Z_r and K_{or} has the unit of v/sec. For example the distance following error for a ramp input $Z_r = 0.1t$ (v) will be $0.001v$ which is equivalent to $0.006mm$. Similarly the steady state error for a ramp function in $Z_w = K_{ow} t$ will be K_f times of steady state error for Z_r ramp. i.e.

$$ess_{Z_w} = K_f ess_{Z_r} = 0.0015 K_{ow}$$

where ess_{Z_w} is the steady state error for a ramp change in Z_w and K_{ow} is in the unit of mm/sec. For example when substrate surface height changes in $Z_w = 2t$ (mm), the following error will be 0.003 mm. However the actual control accuracy is limited by the sensing accuracy and becomes 0.05 mm for shot blasted surface.

4). Distance following when there is a step disturbance on the nozzle/workpiece distance: Fig.4.30 shows the system response when there is a change of the nozzle/substrate (grounded mild steel) distance for as small as $0.2mm$. The closed loop system immediately changes the z axis position so that the nozzle/substrate distance is maintained as the previous value despite the changes of substrate.

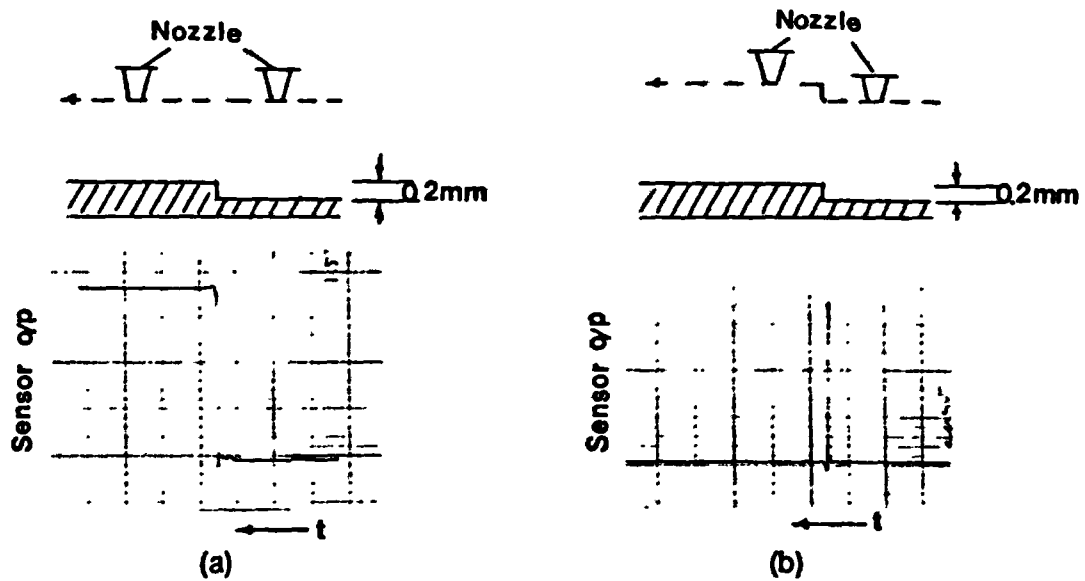


Fig. 4.30 . Control effect for a step change in the substrate. a). Uncontrolled, b). controlled.

5). Distance following when there is a continuous height variation. When the substrate/nozzle distance changed continuously from 20 to 20.3 mm over a length of 150mm at a speed of 12mm/s (in the range used for laser cladding) the uncontrolled and controlled responses are shown in Fig.4.31. The maximum control error is 0.08mm.

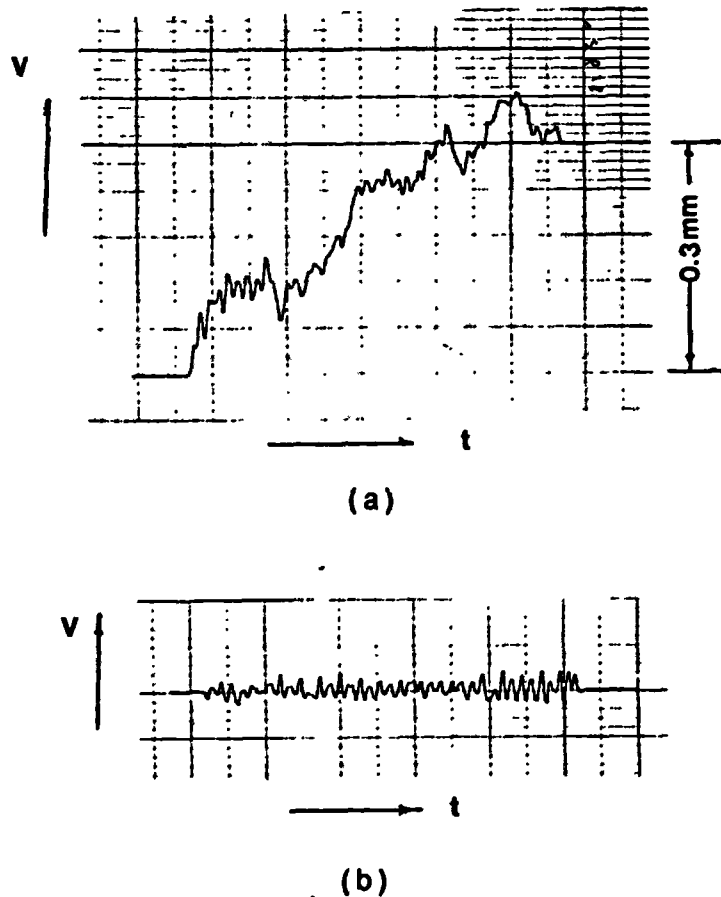


Fig.4.31. Slope following control effect. a), Uncontrolled response, b).controlled response.

An alternative way for the distance control could be the use of present sensor or a pneumatic distance sensor to scan over the sample prior to processing and record the z position in the computer memory as a "learning process" so that a program can be generated according to this recording. This is however an off-line method.

4.6. SUMMARY

A CNC laser cladding workstation has been developed with closed loop traverse speed control, closed loop position control, automatic laser shutter control, automatic height following and self-cleaning "smart" dome. The programming language used in the system is

CONTROL BASIC - a high level scientific programming language which allows the part programming to use variables and scientific calculations as well as conditional loops while most of commercial NC stations used only numerical data and set commands. With the system built the cladding speed can be instantly varied during processing which satisfies the requirement for further development on the intelligent laser cladding control system. The approaches of aerodynamic dome cleaning and off-axis nozzle standoff control for laser cladding process are suggested and realized.

Since any instability of the laser power and powder flowrate rate or the continuous rise of surface temperature during laser cladding can all affect prescribed clad quality, further development of closed loop control of these parameters is necessary. The following chapters will discuss these aspects.

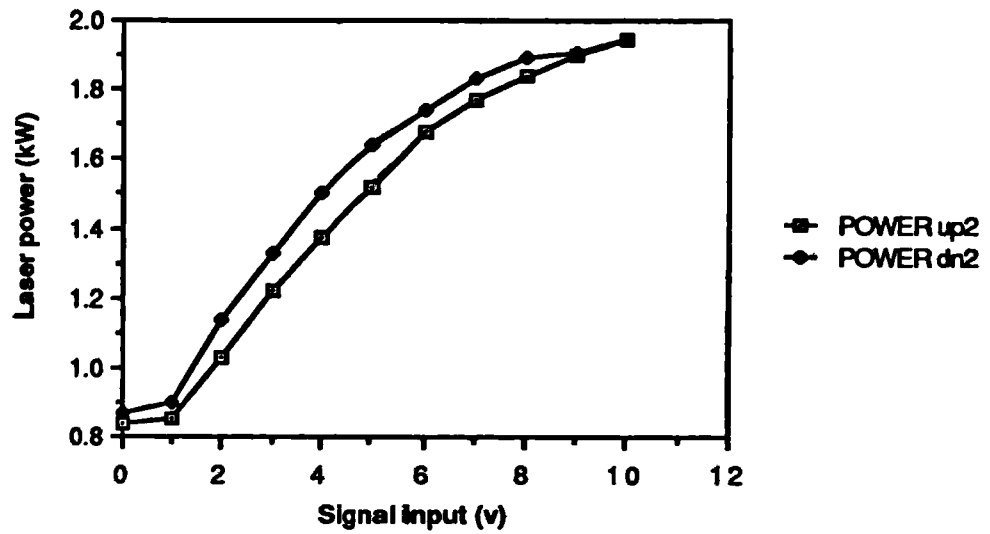
CHAPTER 5

ON-LINE CLOSED LOOP LASER POWER CONTROL

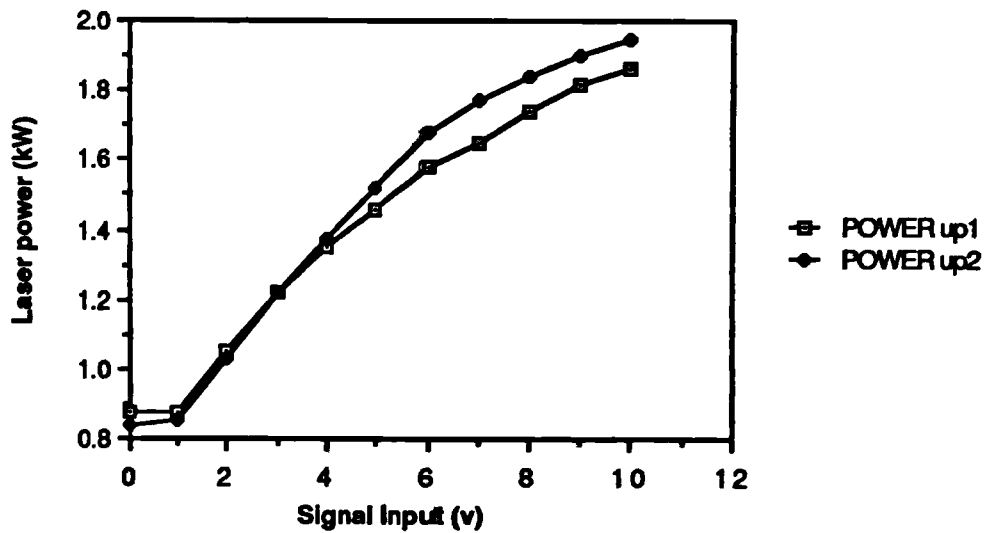
5.1 INTRODUCTION

Laser power stability plays a very important role in the materials processing quality as discussed in Chapter 2. However since laser power, beam diameter, power distribution and their repeatability can be affected by many factors including discharge current, plasma density and uniformity, gas mixture and pressure, gas flowrate, wall temperature, cavity alignment, cavity mirror condition as well as feedback radiation both internal and external to the cavity (See Chapter 1), the process quality can be affected unless laser beam is stable. Although much has been done on in-process beam monitoring (see Chapter 3), little has been reported on the closed loop control of high power DC excited CO₂ lasers which are used predominantly in laser materials processing including laser cladding at the present time.

Four problems were studied in this chapter: power stability, repeatability, response time and start up time. As will be seen in this chapter that the laser power of high power CO₂ lasers can be fluctuating a great deal (30 to 100 W) during processing. The start up time was also very long (typically 45 minutes). Apart from these, repeatability of the set laser power and response time required to change to a new steady laser power level were also not satisfactory for real time process control. Fig. 5.1 shows the experimental recording of the repeatability of the open loop 2kW CO₂ laser used in the project. Although the same current demands were used the corresponding laser power (steady state response) will not be the same for either incremental/decreasing or incremental/incremental sequence of variation despite all the other external conditions (cooling water flowrate, gas pressure and ratio etc.) were kept undisturbed. Fig. 5.2 shows the laser power response to a step change in the demand , which demonstrated that the laser (BOC 901) has a settling time of about 7 minutes due to the wall temperature effect (increase of power leads to an increase of tube temperature which reduces the laser power until a new thermal equilibrium is reached) . These characteristics mean the use of the existing open loop system for on-line process control is inadequate where an accurate power value and fast response are required.



(a)



(b)

Fig. 5.1. Steady state response repeatability of the open loop operated laser. a). Laser power was increased and then decreased. b). Laser power was increased to its highest level and the procedure was repeated after half an hour. An average of 20 minutes interval was used for each point taken.

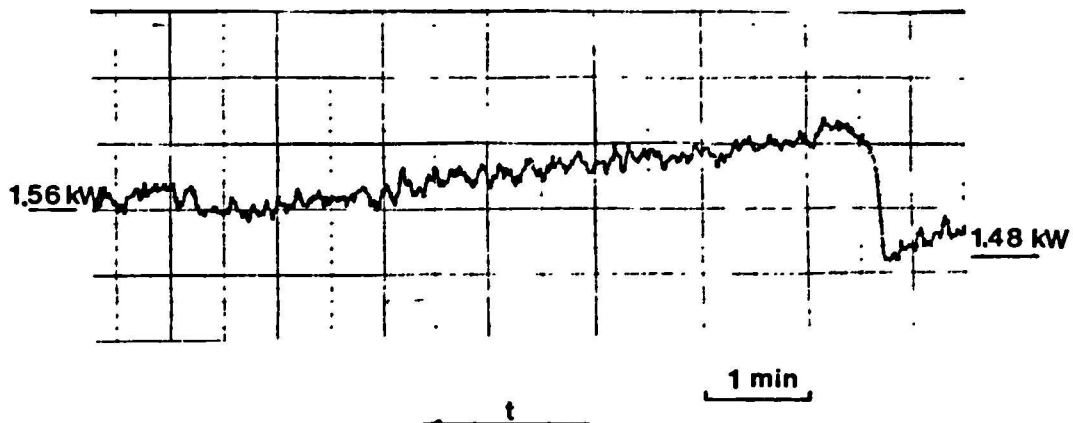


Fig. 5.2. Response of the laser power to a step change in the power setting potentiometer for the present open loop operated CO₂ laser. A response time of 7 minutes is clearly shown.

Work is described in this Chapter on the development of an in-process laser power + beam diameter measurement device and closed loop laser power controller based on LBA beam sampling for DC excited high power CO₂ laser. The laser under study is a 2kW BOC 901 Fast Axis Flow laser supplied by Control Laser Ltd. The system developed has shown a substantial improvement on the beam quality in the four aspects mentioned above.

5.2. LBA SIGNAL CONDITIONING FOR IN-PROCESS LASER POWER AND BEAM DIAMETER MEASUREMENT

The typical responses obtained from LBA for the CO₂ laser beam at two different power levels are shown in Fig. 5.3 from which we can see that higher laser power will generally produce higher magnitude on the signal outputs.

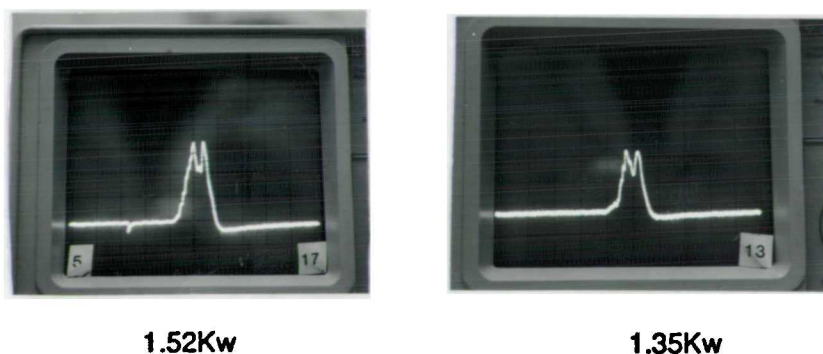


Fig. 5.3. LBA outputs for the present laser beam.

It is these signals that were used in this work to abstract the laser power and beam diameter information.

5.2.1 In-process beam power meter development

Lim and Steen stated in their paper^[80] that the output magnitude of the signal from the LBA is linearly proportional to the beam intensity crossing the beam. This led us first to try to relate the integral of the LBA signals to the laser power measured by a water cooled cone calorimeter. The correlation is shown in Fig. 5.4. Also tried is the relation of RMS (Root Mean Square) value of the LBA outputs to the laser power read from the water cooled cone calorimeter. The correlation is shown in Fig. 5.5, which shows better linear relationship at higher laser power level which is the level often used in practice.

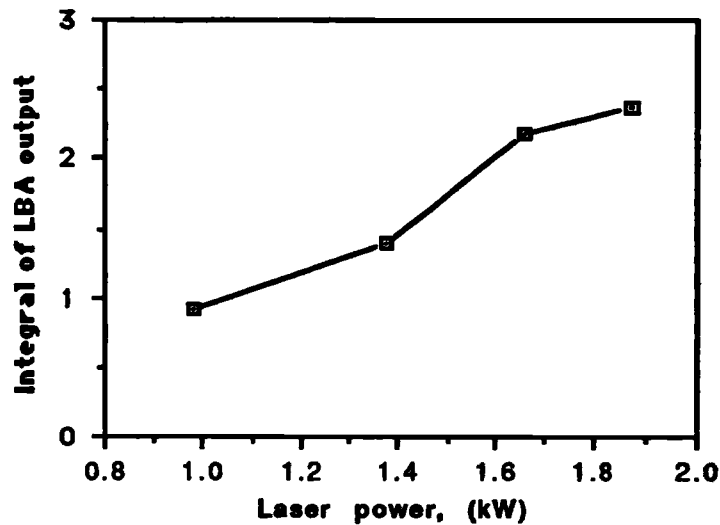


Fig. 5.4. Correlation of Integral of LBA signal to the laser power measured by the calorimeter.

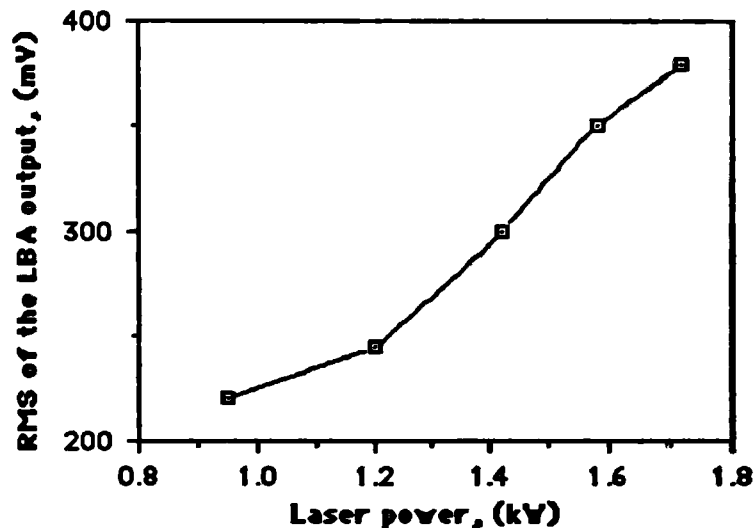


Fig. 5.5. Correlation of RMS value of the LBA signal to the laser power measured by the calorimeter.

A digital on-line laser power meter was thus made (Fig.5.6) which takes LBA output as input. The signal is then amplified or attenuated (controlled from the front panel) and converted to RMS DC voltage with tunable time constant. After this, the signal is low pass filtered and sent to a digital LED display. At the same time two analog outputs are provided: one is within 200mV for analog laser power recording; the other output is the amplified power signal (between 0 - 5V DC) which can be fed to a computer via A/D converter. The calibration of the power meter was done by adjusting the calibration potentiometer with water cool cone calorimeter as a standard. With such device the laser power can be displayed digitally and continuously recorded through a recording device even when the laser beam is being used for processing.

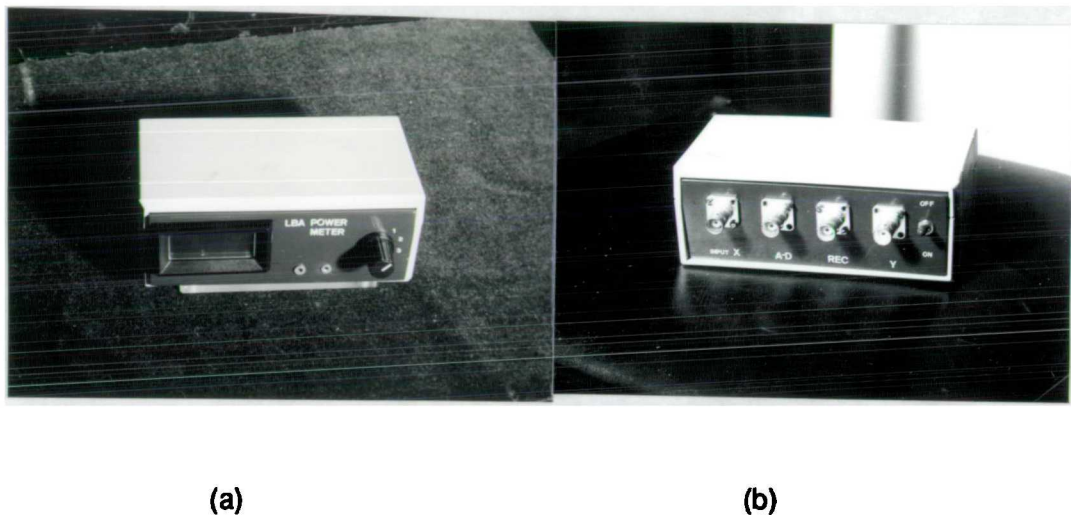


Fig. 5.6 In-process laser power meter . a). Front, b). Back.

The power meter was further improved (Version 2) by taking the two orthogonal outputs from the LBA at the same time and the average of these two signals were used for laser power measurement. Such a configuration was used to prevent possible error of the single channel signal version when there is a misalignment of the LBA and laser beam. When two signals are used the misalignment may be averaged out. (With the LBA located near the output window alignment is unlikely to fluctuate.)

The evaluation of this power meter was considered from the following 3 aspects:

1). Meter Response time. The response time of the LBA power meter is continuous tunable from about 200ms to approximately 4 seconds by RMS time constant adjustment. In order that the power reading is not too "noisy" for digital display and closed loop power control application, the time constant was set at the time of experiment to be 1.5 seconds. Experiment was made to examine the step response of the power meter. This was done by

instantly removing the laser beam from the LBA (through switch off laser power supply). The response of the LBA power meter is shown in Fig.5.7. with a comparison to the water flow calorimeter response. A significant improvement in response time was demonstrated. Also a pure time lag of the water flow calorimeter was observed.

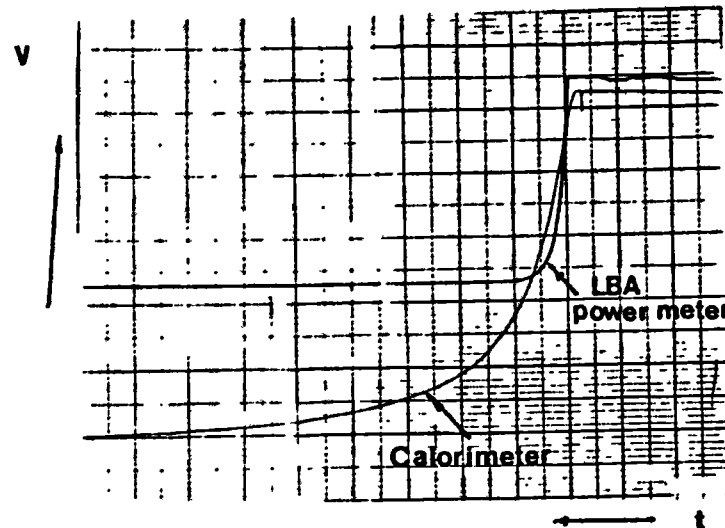


Fig. 5.7. Responses of the power meters to the instant removal of the laser beam.

2). Sensing repeatability: The experiments were carried out by setting the beam power for certain values at different time (The flowing cone calorimeter was taken as standard) and the power output measured by the calibrated power meter was recorded as shown in Table 5.1 which shows the sensing repeatability within 10 watt for kilowatt power readings.

Table 5.1 Repeatability of the power meter at different power levels

Power meters	Read out (kW)			
Calorimeter reading	1.61	1.72	1.80	1.91
LBA power meter reading (1)	1.612	1.723	1.804	1.915
LBA power meter reading (2)	1.610	1.722	1.801	1.913
LBA power meter reading (3)	1.615	1.726	1.806	1.917

3). Sensitivity. The digital display of the power meter has a total range of 0-9.999 kW (can be switched to 0-9.999w, 0-99.99 kW etc. for different applications), the display resolution can be seen to be 0.01% of the total measuring range. The change of 1 W in power will produce a 1.4mv change on the analog output of the power meter which is detectable by most of volt meters and A/D converters.

5.2.2. In-process beam diameter meter development

Laser beam diameter has several definitions. For TEM₀₀ mode the beam diameter was defined theoretically as the distance across the centre of the beam for which the irradiation equals $1/e^2$ (or 0.135) of the maximum radiance^[15] as shown in Fig.5.8a. The area inside a circle of this size centered on the beam centre will contain 86.5% of the total energy of the Gaussian beam. Such a definition for the diameter of Gaussian beam is because the radiance of such beams drops off away from the centre and the exact edges cannot be theoretically or even experimentally located. There are other definitions for the TEM₀₀ mode beam diameter including the $1/e$ points, the points at which radiance is $1/2.7$ of the maximum value, or the diameter of a circle that contains a 65.5% of the total beam energy or power. For higher order mode beam the mathematical description of the profile is more complicated and the profile edges are much sharper as shown in Fig.5.8b. The boundaries between laser beam and non-radiance area can be more easily recognized. There is little difference between the true start of the beam edge and $1/e^2$ point. Some definitions such as the width within which 85% or 90% of total power is contained also exist. However in practice laser power may fluctuate while the actual beam width remains unchanged. The use of the above definition may lead to some misinterpretation that the diameter is fluctuating. Therefore in the development of beam diameter meter the actual beam width (starts and finishes from just off zero) was considered as beam diameter. It contains nearly 100% of the total beam. In cases of high power laser beam application for materials processing a fraction (10% or 15%) of laser beam on the edge may still produce a non-negligible effect. Therefore the beam width (zero start) may be more practical to represent the beam diameter of especially high order mode beams for the practical estimation of spot size produced on the workpiece.

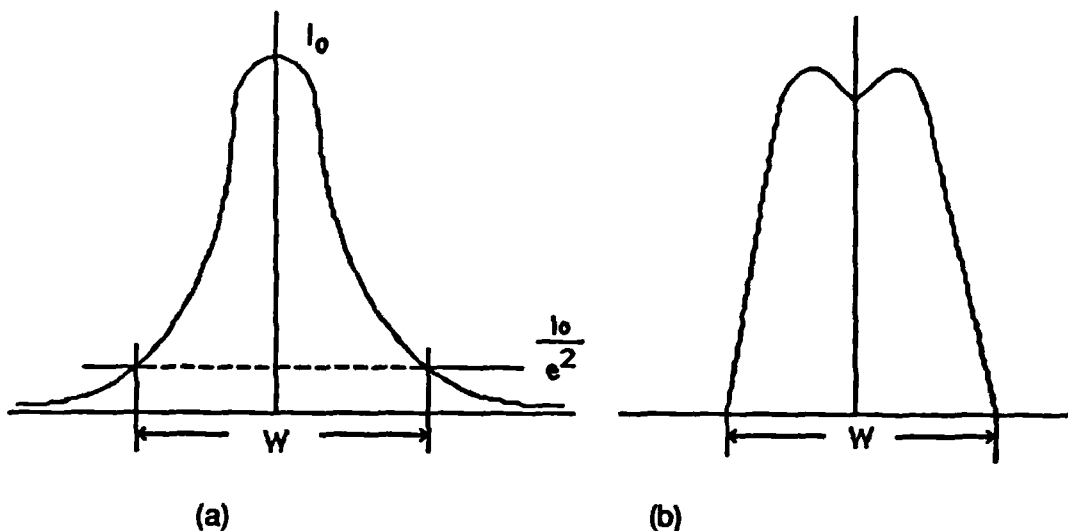


Fig. 5.8. Illustration of beam diameter W for TEM₀₀ mode and higher order mode (I_0 is the peak beam intensity).

It has been found by Lim and Steen [80] that the time the LBA needle scans across the beam (with constant speed) is proportional to the beam width. For LBA model 2 (motor speed 1800rpm and rotating needle of 90mm in length) which was used in the experiment, 0.1ms correspond to 2.4 mm. This result was used for the present design of in-process diameter meter which gives beam width digital read out continuously. The instrument consists of a high pass filter, a signal amplifier, a digitizing circuit to change the sampled signal profile into switching signal to trigger a timer (using a D/A converter, since analog output is required for the closed loop control purpose) and both digital (7 section LED read out) and analog outputs (0-5V) were provided. The signal were calibrated using the above data through a calibration potentiometer in the diameter meter. Fig.5.9 shows the relation of the meter analog output to the beam diameter values measured by calculating the beam width through oscilloscope mode display. A linear relationship is demonstrated.

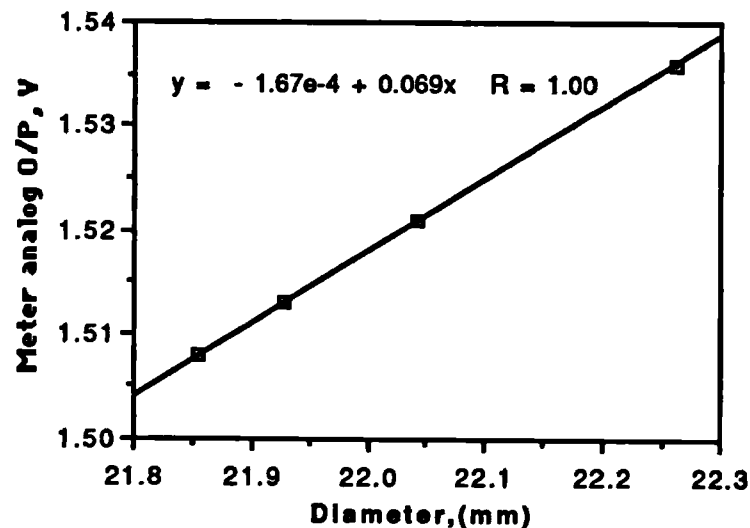


Fig.5.9. Relationship of the analog output of the diameter recording device to the beam diameter value.

An application of the beam diameter recording device for the monitoring of the variation of the laser power with beam width was made as shown in Fig.5.10, which indicates that the beam width increases with laser power.

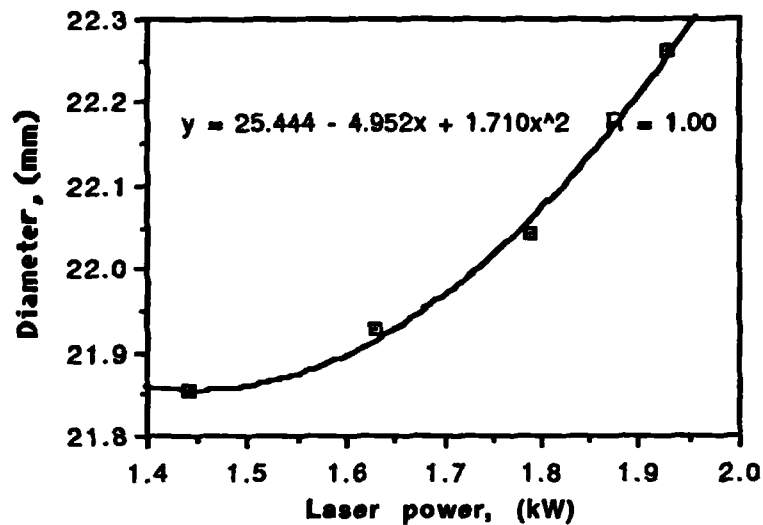


Fig. 5.10 Recording of beam diameter variation as the beam power changes.

5.3. ON-LINE CLOSED LOOP LASER POWER CONTROLLER DEVELOPMENT

In this section the development of an on-line closed loop laser power controller for high power DC excited CO₂ lasers will be described. It contains four subjects: laser dynamic model identification, closed loop power control configuration, controller instrumentation and control system performances.

5.3.1 Laser dynamic model identification

In order to control the laser power it is necessary to know the basic dynamics and input-output relationships of the laser. Although there have been many models for CO₂ lasers, most of them concern the gain of the laser cavity instead of relating the current setting to the output laser power. Therefore some experiments were made to determine the dynamic and steady state relationships by using system identification technique.

a). Steady state response

The steady state response of the laser was examined by varying the voltage control setting on the manual laser operating unit and record the laser power readings from both the

new power meter and calorimeter. The purpose of this experiment is to see the linearity of the input/output relation. This is shown in Fig. 5.11, which demonstrates some non-linearity.

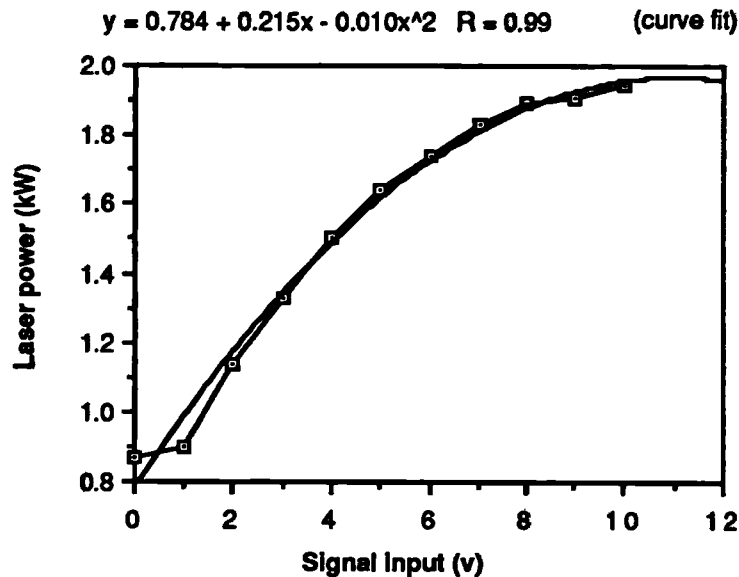


Fig. 5.11. Steady state responses of the BOC 901 CO₂ laser and least square curve fit using least square curve fitting algorithm.

This gives a steady state relations:

$$P(t) = P_0 + K_{p1} u(t) - K_{p2} u(t)^2 \quad (5-1)$$

where $P(t)$: laser power (Kw)

$u(t)$: control input (V)

K_{p1} and K_{p2} are two constants which are 0.215 and 0.01 respectively according to the above experiment.

P_0 : Pseudo-offset laser power. This is the power when control demand voltage at the power setting potentiometer is zero. $P_0 = 0.784$ according to the above experiment (slightly different from the true offset power because of the curve fit).

The open loop control gain which is defined by the derivatives of the laser power reading to the control input can be found for this laser to be:

$$K_{po} = dP/du = K_{p1} - 2K_{p2} u(t) \quad (5-2)$$

where K_{po} = open loop laser power control gain (W/V)

This shows that the open loop control gain of this laser depends on the control input. i.e. K_{po} reduces as the control input increases. However since K_{p1} is much larger than K_{p2} as

shown in the experiment, this non-linearity effect may not be significant.

b). Transient response

The step response experiment was made by suddenly varying the control input to a different value (step change) and recording the transient behaviour of the laser power variation using the power meter developed. The purpose of this experiment is to find the dynamic behaviour of the laser power response to its control demand. This is shown in Fig. 5.12.

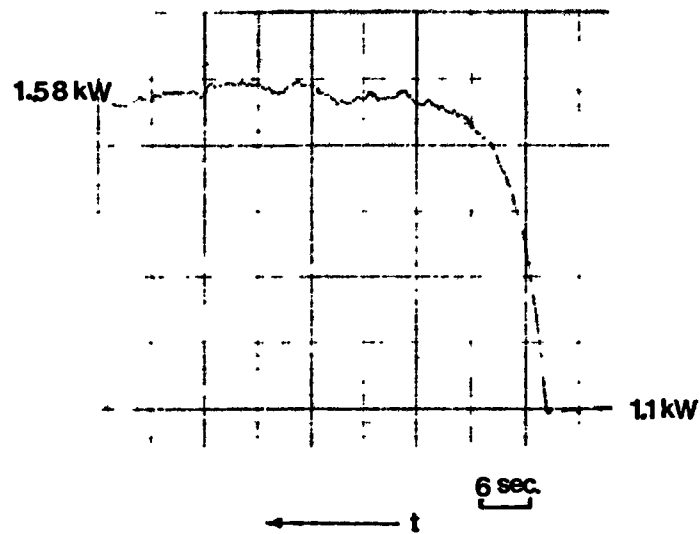


Fig. 5.12. Step response of the open loop CO₂ laser.

The response can be seen to be an exponential relationship: i.e.

$$P_v = (P_{v1} - P_{v0})(1 - e^{-t/T}) + P_{v0} \quad (5-3)$$

$$\text{or } \Delta P_v = (1 - e^{-t/T}) K_v u(t) \quad (5-4)$$

where P_v : the recorded laser power from power meter (V)

$u(t)$: power control input, (V)

P_{v0} : offset laser power expressed in voltage (measured with power meter)

P_{v1} : steady state power level after change (V)

ΔP_v : a change of P_v . i.e. $\Delta P_v = P_v - P_{v0}$ (V)

T : response time constant, which is defined as the time required for the response to reach 63.2% of the steady state value. It can be seen to be around 5 seconds in this case (including the power meter) if the further decay of laser power due to the temperature effect is neglected.

K_v : is the open loop control gain for the converted voltage laser power representation. K_v is defined at the working point (P, u) as:

$$K_v = \Delta P_v / \Delta u \quad (5-5)$$

where Δu is the change of control input. For this experiment K_v was found to be 0.2. This value can be different at different laser power levels as studied in the steady state response experiment. A more general expression of this value will be similar to Eqn.(5-2). i.e.

$$K_v = K_{v0} - K_u u(t) \quad (5-6)$$

where K_{v0} is the open loop gain when $u=0$ and K_u is the coefficient for non-linear effect. Therefore the transient response of laser power to a control input considering the non-linear effect would be:

$$\Delta P_v = K_{v0}(1-e^{-t/T}) u - K_u(1-e^{-t/T}) u^2 \quad (5-7)$$

c). Experimental model and transfer function of laser response

An experimental mathematical model of the laser under study can be found by combining the steady state response and transient response. i.e. to convert Eqn.(5-7) into a more general differential equation:

$$A_p \frac{dP_v(t)}{dt} + B_p P_v(t) + P_0 = K_{v0} u(t) + K_u u(t)^2 \quad (5-8)$$

where A_p and B_p are two coefficients.

If only the small variation of signal around a working point is concerned the non-linear term could be ignored and the approximated model becomes:

$$A_p \frac{d[\Delta P_v(t)]}{dt} + B_p \Delta P_v(t) = \Delta u(t) \quad (5-9)$$

where $B_p = 1/K_v = 5$ and $A_p = B_p T = 25$ sec, according to the above experiment.

Note that the parameters A_p and B_p are constants only when the control variation or any disturbance is in the small neighborhood of the normal working point (P, u). The open loop transfer function of the CO₂ laser can thus be obtained from Eqn.(5-9) for the small signal variation as:

$$G_p(s) = \frac{\Delta P_v(s)}{\Delta u(s)} = \frac{K_v}{(Ts + 1)} \quad (5-10)$$

where $G_p(s)$ = the small signal disturbance transfer function of the CO₂ laser in frequency domain.

$\Delta P_v(s)$ = Laplace transform of $\Delta P_v(t)$.

$\Delta u(s)$ = Laplace transform of $\Delta u(t)$.

5.3.2 Closed loop laser power control algorithms design

The objective of the closed loop laser power controller design is to force the actual laser power to be the same as the demand value under various undesired disturbances. These disturbances may be the laser tube temperature instability, gas pressure instability, optical mirror instability etc. According to this requirement the control system must form a negative feedback loop as shown in Fig. 5.13, where the unknown block is the laser power controller to be designed.

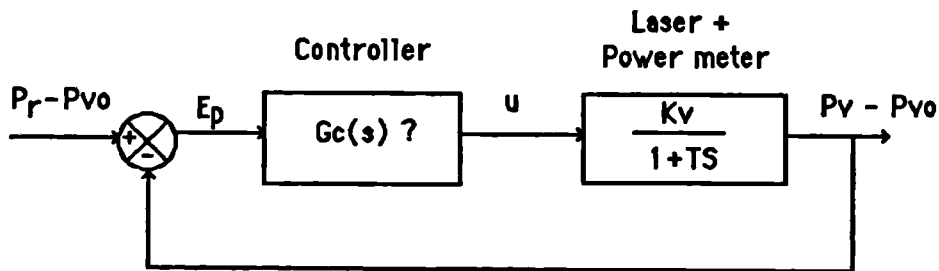


Fig. 5.13 Closed loop laser power control loop configuration, where
 P_r : the demanded laser power converted to a voltage signal (v)
 P_{vo} : the off-set laser power level converted to a voltage signal (v)
 P_v : actual laser power measured by the power meter (v)
 E_p : differences between the demanded laser power and actual laser power (v)
 $G_c(s)$: transfer function of the closed loop laser power controller to be designed.

The design objective is to find how $u(t)$ should vary with E_p so that $P_r - P_v = 0$ and system is stable and has satisfactory dynamic performance. It can be shown in the following that a proportional controller can not satisfy the control requirement.

According to the definition of the proportional control the control signal is proportional to the error between the reference value and the feedback signal. i.e.

$$\begin{aligned} u(t) &= K_p E_p(t) \\ &= K_p [P_r(t) - P_v(t)] \end{aligned} \quad (5-11)$$

or on the S plane:

$$u(s) = K_p E_p(s) \quad (5-12)$$

where K_p is proportional control gain. $u(s)$, $Pr(s)$, $P(s)$ and $Ep(s)$ are the Laplace transform of $u(t)$, $Pr(t)$, $P(t)$ and $Ep(t)$ respectively. The proportional controller is:

$$G_c(s) = K_p \quad (5-13)$$

The steady state closed loop control error to follow a step change in $Pr(t)$ using proportional control will be:

$$\begin{aligned} \lim_{t \rightarrow \infty} E_p(t) &= \lim_{s \rightarrow 0} S E_p(s) = \lim_{s \rightarrow 0} S [Pr(s) - P(s)] = \lim_{s \rightarrow 0} \frac{S Pr(s)}{1 + K_p G_p(s)} \\ &= \lim_{s \rightarrow 0} \frac{(1+TS)Pr}{1+TS + K_p K_v} = \frac{Pr}{1+K_p K_v} \end{aligned} \quad (5-14)$$

where the step input of $Pr(t)$ in frequency domain is $Pr(s) = Pr/s$ and Pr is the magnitude of the step function input. This calculation demonstrates that proportional control will always give a steady state control error. If however an integral term is added to form a PI control, i.e.

$$u(t) = K_p E_p(t) + K_i \int E_p(t) dt \quad (5-15)$$

or on the S plane:

$$u(s) = (K_p + K_i/s) E_p(s) \quad (5-16)$$

where K_i is the integral control gain, the closed loop steady state error will become zero as shown below:

$$\begin{aligned} \lim_{t \rightarrow \infty} E_p(t) &= \lim_{s \rightarrow 0} S E_p(s) = \lim_{s \rightarrow 0} S [Pr(s) - P(s)] = \lim_{s \rightarrow 0} \frac{S Pr(s)}{1 + G_p(s)(K_p + \frac{K_i}{s})} \\ &= \lim_{s \rightarrow 0} \frac{S(1+TS)Pr}{TS^2 + (1+K_v K_p)S + K_v K_i} = 0 \end{aligned} \quad (5-17)$$

In order to decrease the system response time and improve the closed loop stability, a derivative term should also be added to form a PID control:

$$u(t) = K_p E_p(t) + K_i \int E_p(t) dt + K_d (dE_p(t)/dt) \quad (5-18)$$

$$\text{or on the S plane: } u(s) = (K_p + K_i/s + K_d s) E_p(s) \quad (5-19)$$

where K_d is the derivative control gain.

5.3.3. Closed loop laser power control parameters selection

The PID control was realized using a commercial programmable digital PID controller (ECA40d from Satt control Lt.d), which has the sampling rate of 200ms. The analog signal from the laser power meter is sampled by the controller and this signal when changed to a digital correspondence is compared to the demanded laser power level set from the front panel of the controller. The difference is used to generate a PID control output which is then converted to analog voltage for the variation of laser power through an interface box made for this purpose. The control loop is shown in Fig. 5.14.

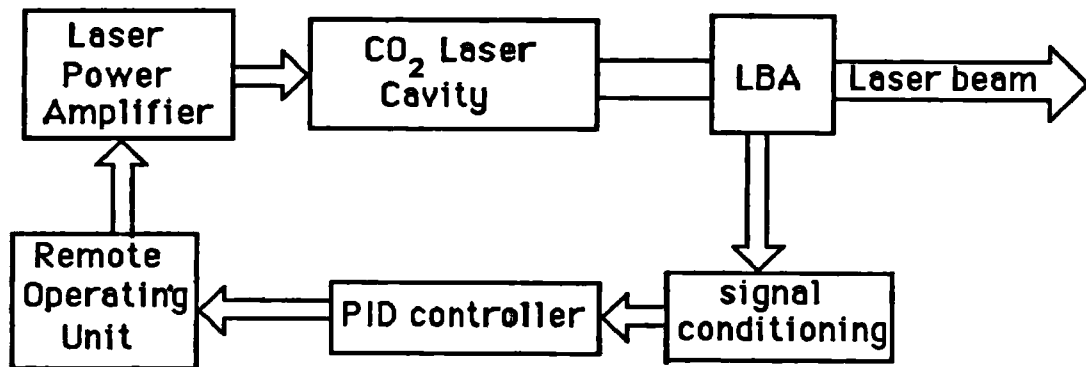


Fig. 5.14. Control loop for CO2 laser power

Since the use of digital controller has introduced in the system both digital and analog signals, the closed loop block diagram expressed in frequency domain has become as shown in Fig.5.15.

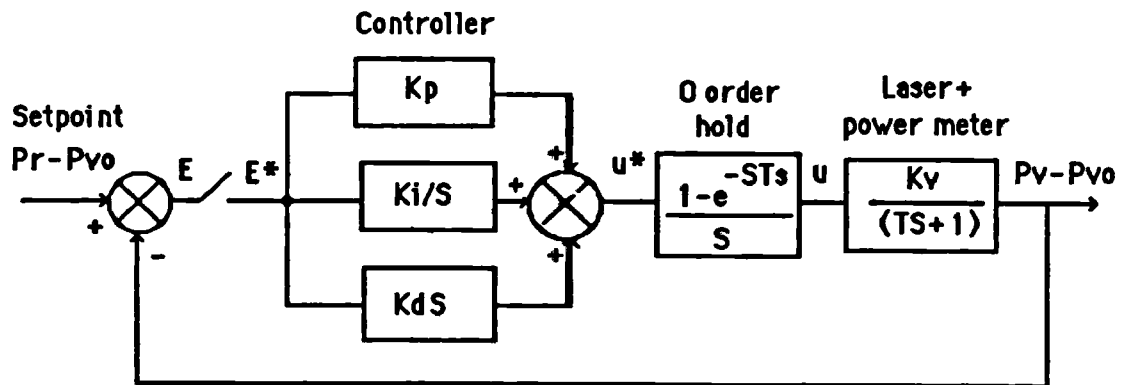


Fig. 5.15. Block diagram of the closed loop laser power control system in frequency domain where E^* and u^* are the digital correspondence of the analog signal.

The digital PID control algorithm can be described as :

$$u_{i+1} = K_p (e_i + T_d \frac{e_i - e_{i-1}}{T_s} + \frac{T_s}{T_i} \sum_{j=1}^i e_j) \quad (5-20)$$

where $e_i = P_r - P_i$, is the error signal (difference between the set power P_r and the actual power P_i) at iteration i .

e_{i-1} = error signal at iteration $i-1$

u_{i+1} = PID control output for the next iteration.

T_s = the sampling period which is the time intervals between i and $i-1$ iteration. For the present controller $T_s = 200\text{ms}$.

K_p = proportional control gain to be set.

T_i = integral term time constant to be set, $T_i = K_i/K_p$

T_d = derivative term time constant to be set, $T_d = K_d/K_p$

The selection of PID control parameters is critical to the success of closed loop control. For example, if K_p is set too high the system will oscillate while too low the value will result in the slow control response. A proper setting of Integral time constant T_i will improve the control accuracy. However if it is set too low the system will become unstable. A proper selection of T_d parameter will reduce the response time and increase the system stability. A wrong selection of the parameter can also lead to the instability of the system. Since the real laser has some non-linearity, purely rely on the self-tuning function of the controller may not give a satisfactory response.

The PID control parameters for this particular laser were therefore set experimentally using Ziegler and Nichol's Ultimate method^[145], which can be stated as follows:

1. Set $T_i = \infty$, $T_d = 0$.
2. Slowly increase K_p until system starts to oscillate.
3. Record the proportional control gain for this oscillation which is defined as the ultimate gain K_{max} .
4. Record the oscillating period which is defined as ultimate period P_u .
5. Then the "optimum" (with 1/4 overshoot) PID control parameters can be calculated as:

$$K_p = 0.6K_{max}, \quad T_i = 0.5P_u, \quad T_d = P_u/8 \quad (5-21)$$

The ultimate gain K_{max} was found to be 1.65 and the ultimate period P_u was found to be approximately 2.7 seconds in the experiment. The PID parameters thus were derived using Eqn.(5-20) as:

$$K_{p1} = 0.6K_{max} = 0.6 \times 1.65 = 0.99 \text{ (dimensionless)}$$

$$T_{i1} = 0.5P_u = 0.5 \times 2.7 = 1.35 \text{ s}$$

$$T_{d1} = P_u/8 = 2.7/8 = 0.34 \text{ s}$$

Ziegler et al [145] have shown that the process with such control parameters will be stable. However since the process dealt with has some non-linear factors and the change of the gas pressure, gas flow, tube temperature can all lead to the change of the system characteristics (See chapter 1), the selection of control parameters as such may lead to the instability of the system in some circumstances (such as the increase of gas flow). Also the experimental results of the control system using the above control parameters have shown a "noisy" laser power response. Therefore the final selection of proportional gain K_p was a reduction of the experimental one in order to increase the robustness of the system and the derivative time constant T_d was selected slightly higher to further increase the stability of the system and response rate, while integral time constant T_i was selected a little lower than that from the Ziegler's method for a better control accuracy and a reduction of small noise. Such consideration gives the "optimum" control parameters as:

$$K_p = 0.86, \quad T_i = 1.1\text{s}, \quad T_d = 0.7\text{s}$$

The stability of the closed loop system using such control parameters were examined. For the convenience of analysis the expression of the system transfer functions in Fig.4.15 was converted into discrete form by using z transformation. For PID controller the conversion can be made as follows:

$$Z(K_p) = K_p \quad (5-22)$$

$$Z(K_i/S) = \frac{K_i T_s (z+1)}{2(z-1)} \quad (5-23)$$

$$Z(K_d S) = \frac{K_d (z-1)}{T_s z} \quad (5-24)$$

The z transformation for zero order hold (introduced by the digital controller) and laser can be found as follows:

$$Z\left[\frac{1-e^{-Ts}}{s} \frac{K_v}{TS+1}\right] = \frac{z-1}{z} Z\left[\frac{K_v}{s(TS+1)}\right] = \frac{K_v(1-e^{-Ts/T})}{z-e^{-Ts/T}} \quad (5-25)$$

The closed loop control system block diagram on z -plane can therefore be obtained as shown in Fig. 5.16.

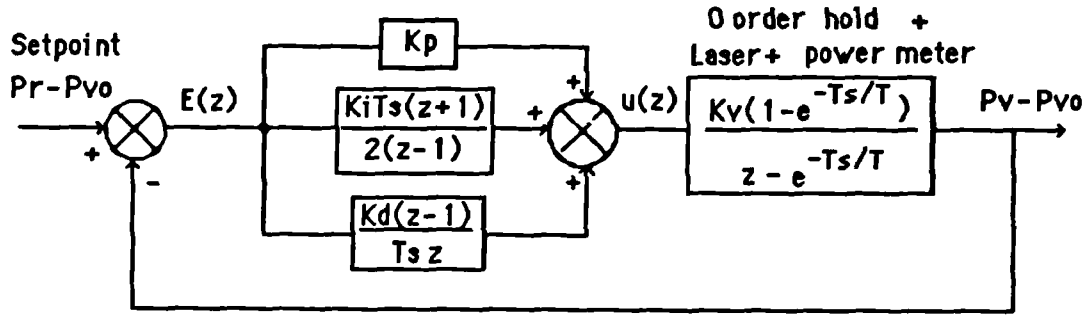


Fig.5.16. Block diagram of the closed loop laser power control system in z domain.

The open loop forward transfer function $G_o(z)$ can then be found to be:

$$\begin{aligned}
 G_o(z) &= \frac{(K_i T_s^2 + 2K_d + 2K_p T_s)z^2 + (K_p T_s^2 - 2K_p T_s - 4K_d)z + 2K_d}{2T_s z(z-1)} \\
 &\quad \times \frac{K_v(1-e^{-Ts/T})}{z-e^{-Ts/T}} \\
 &= \frac{K_v[(K_i T_s^2 + 2K_d + 2K_p T_s)z^2 + (K_p T_s^2 - 2K_p T_s - 4K_d)z + 2K_d](1-e^{-Ts/T})}{2T_s T z(z-e^{-Ts/T})(z-1)}
 \end{aligned} \tag{5-26}$$

where $T=5, T_s=0.2, K_v=0.2, K_p=0.86, K_i=K_p/T_i = 0.86/1.1=0.78$
 and $K_d=K_p T_d=0.86 \times 0.7 = 0.602$

Substituting these values into Eqn.(5-26) the open loop forward transfer function on z-plane can be found to be:

$$G_o(z) = \frac{0.004(1.579z^2 - 2.72z + 1.204)}{z^3 + 1.96z^2 + 0.96z} \tag{5-27}$$

The closed loop characteristic equation which is defined as:

$$1 + G_o(z) = 0 \tag{5-28}$$

can be found to be:

$$z^3 - 1.95z^2 + 0.95z + 0.005 = 0 \tag{5-29}$$

Using bilinear transformation:

$$z = \frac{1+r}{1-r} \quad (5-30)$$

The closed loop characteristic equation on r-plane can be found after a considerable amount of algebra to be:

$$3.895 r^3 + 5.015r^2 + 0.085r + 0.005 = 0 \quad (5-31)$$

The Routh array for this equation can be obtained after some calculations to be:

r^3	3.895	0.085	(5-32)
r^2	4.015	0.005	
r^1	0.08	0	
r^0	0.005		

which shows that there are no sign changes in the first column and therefore the closed loop control system is stable according to Routh-Hurwitz criterion^[146].

Since the sample and hold introduced by digital controller does not change the steady state error^[147], the closed loop system steady state error for a step function input will be zero as proved in Eqn.(5-17).

In order to operate the system properly other parameters like engineering unit conversion (calibration), upper limit, lower limit etc. were also set. For this particular laser, the maximum laser power is 2kW and minimum is 1kW. Since the laser power supply will switch off automatically if any of the tube current is over 150mA, a upper limit for the control output was also set so that this limit can not be exceeded.

5.3.4. Closed loop laser power control system performances

Experiments were made to examine the closed loop control system performance and comparisons with the open loop system were made.

a). Laser power stability

A comparison of the controlled and uncontrolled power output is shown in Fig. 5.17.

The uncontrolled signal showed a $\pm 15\text{W}$ power variation with a systematic power oscillation of around 60 s /cycle. The oscillation frequency was found to increase with increasing power and reduce with time from start up Fig.5.18. This effect has also been observed with the acoustic mirror beam detector^[90]. The reason for the open loop laser power fluctuation may be associated with the cavity wall temperature stability. Since a disturbance (rise for example) of laser power will introduce a disturbance (rise) in wall temperature of the laser cavity which will again vary slightly the cavity dimension as well as molecule relaxation rate. These disturbance could lead to a change (reduction) of laser power. When laser power reduces the above effect would become just the opposite. The process continuous until an equilibrium state of temperature is achieved. Since the temperature variation is slow, the cycling period is thus very long. This point was further verified by attaching a thermal couple to the laser tube. The measured wall temperature showed a similar oscillating pattern (Fig.5.19). These power variations are almost eliminated with the closed loop power control leaving a small ripple of around $\pm 4\text{w}$. For 2kW laser operation, this means a 0.2% deviation. Other factors affecting the power stability such as gas pressure can all be compensated by the closed loop power control (Fig.5.20).

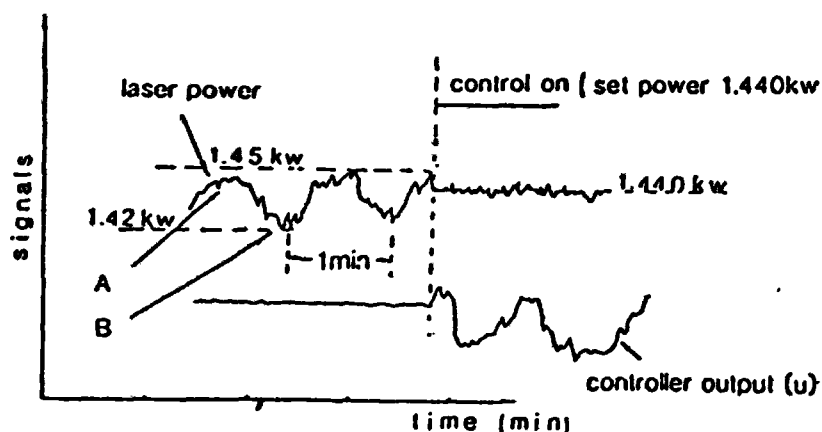


Fig. 5.17. Comparison of the laser power stability with and without closed loop control.

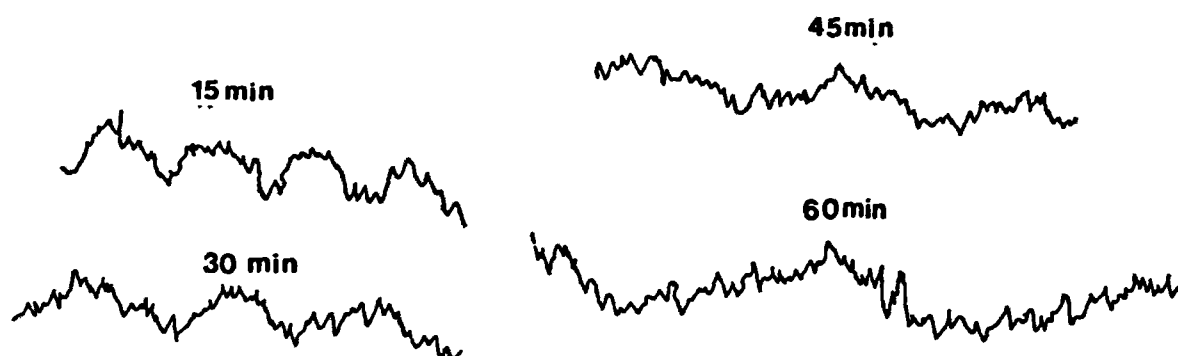


Fig. 5.18. Laser power fluctuations at different times from start up.

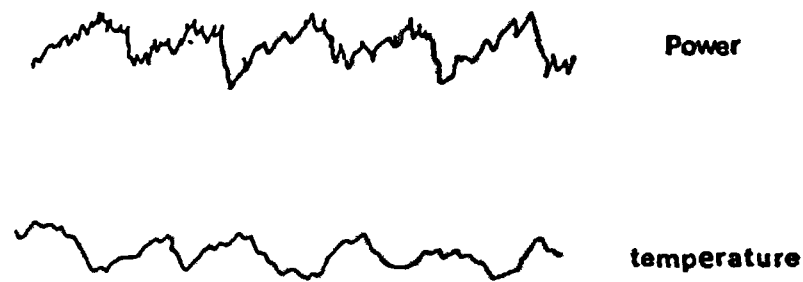


Fig.5.19. Correlation of the cavity wall temperature to the laser power fluctuation.

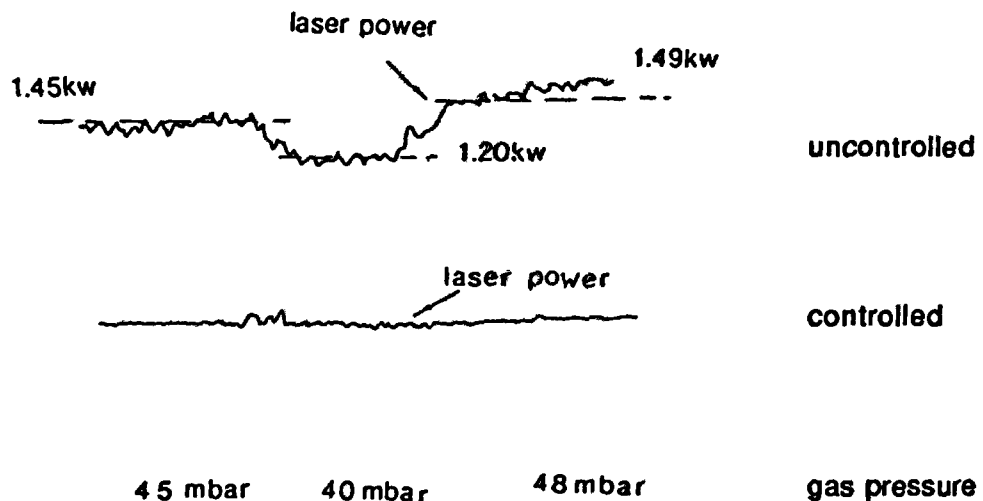


Fig. 5.20. Effect of cavity pressure stability on laser power for open loop and closed loop system.

b). Laser start up performance

For high power CO₂ lasers the start up time could be as long as 45 to 60 minutes, which means only after this warm up period can the laser be used because of the instabilities of both laser power and beam mode structure during this period. With the closed loop control this time has been reduced to less than 1 minute as shown in Fig.5.21. and Fig.5.22. The mode of the laser beam was also stabilized by the power control (Fig. 5.23). This is an unexpected result. In order to explain this, an experiment was made to determine if there is a relationship between the laser power level and the mode structure. These results are shown in Fig. 5.24. from which we can see that the beam mode could change as the laser

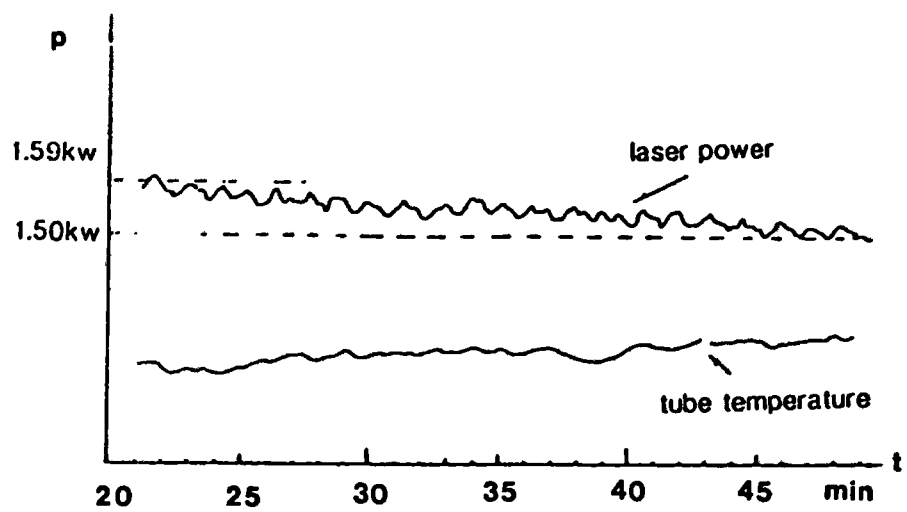
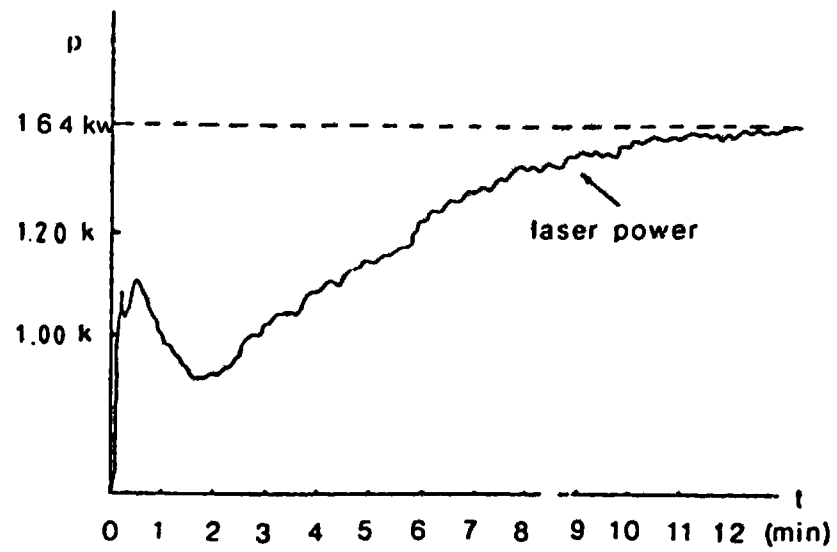


Fig.5.21. Laser start up beam power behaviour without closed loop control.

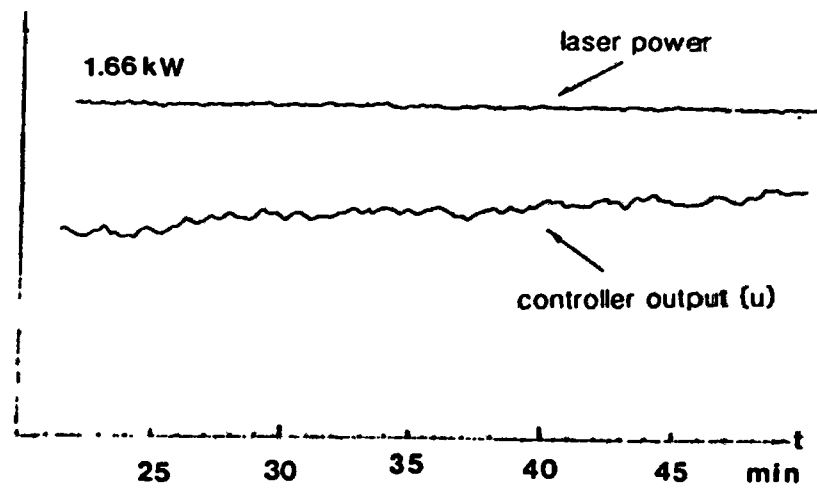
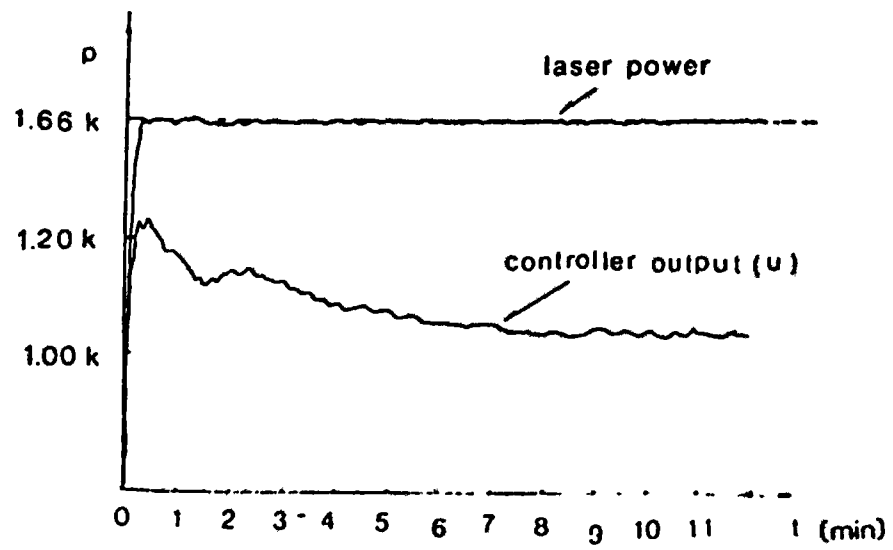
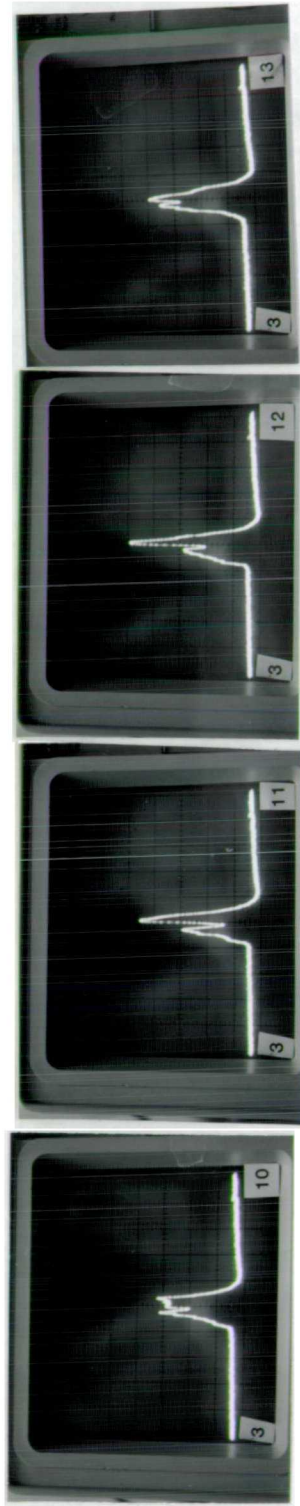
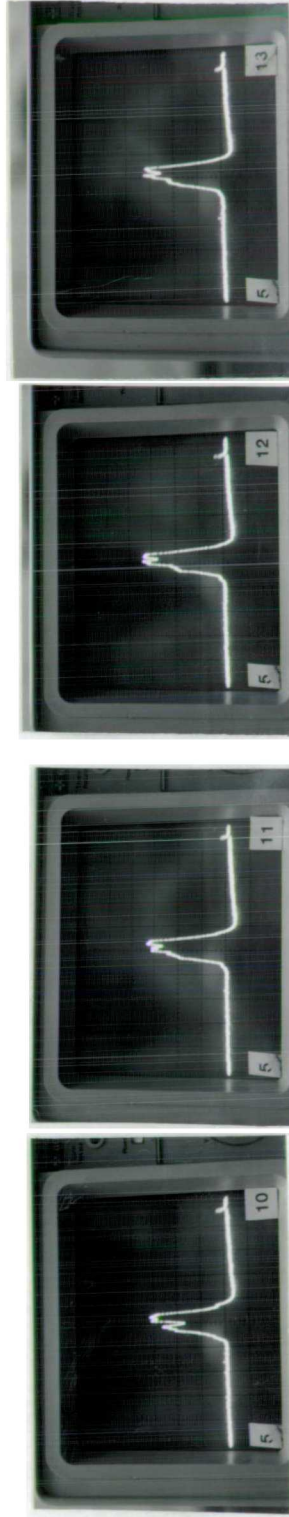


Fig.5.22. Laser start up beam power behaviour with closed loop control.



(a)



(b)

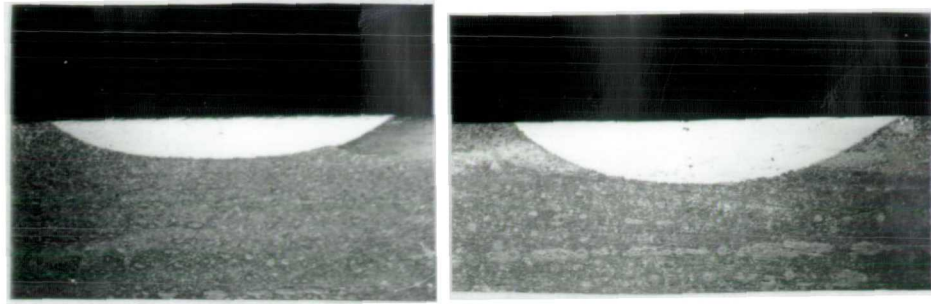
Fig. 5.23. Laser beam mode at state up. a). Without closed loop power control. b). With closed loop power control.
(Photographs taken at every 4 minutes from the start up)



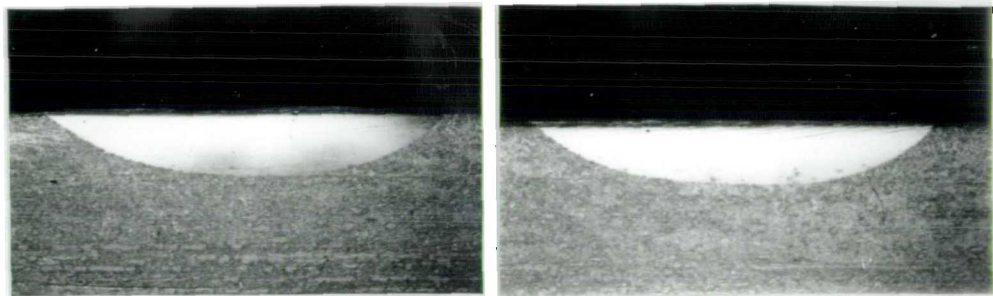
1.45kW



Fig.5.24. Laser power effect on the beam mode.

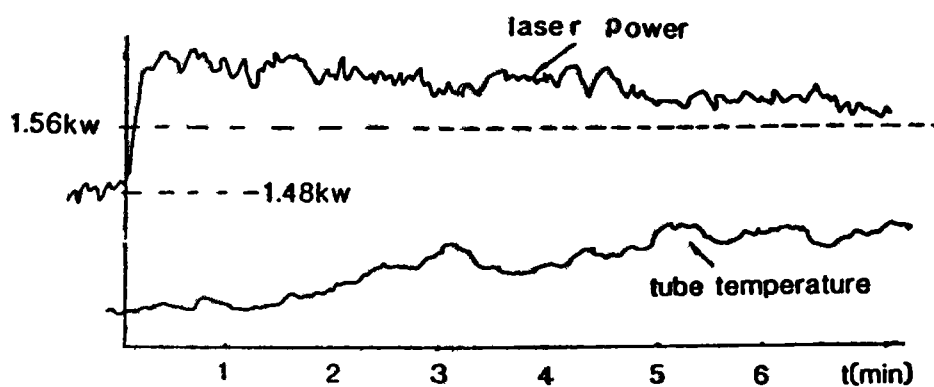


a

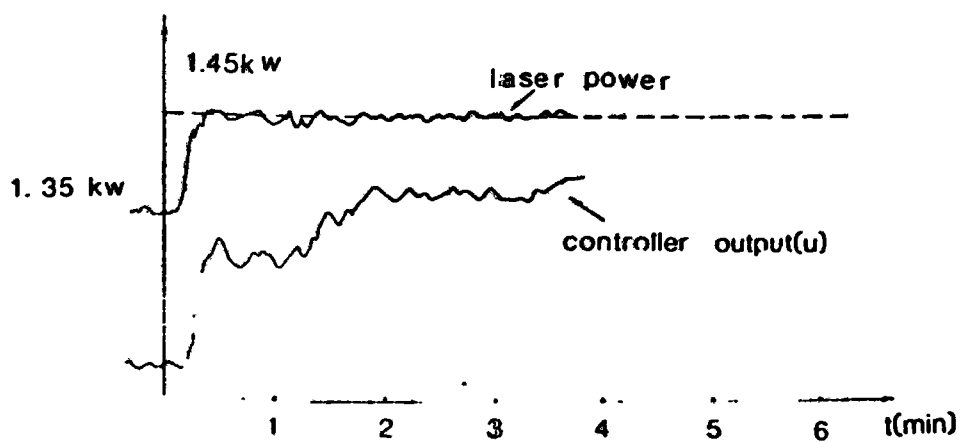


b

Fig.5.25. Comparison of material hardened depth using the laser beam at the start up period. a). Without power control. b). With closed loop power control. The samples on the right hand side were produced 5 minute later than the those on the left.



(a)



(b)

Fig.5.26. Laser power response to a step change in the power demand. a).Without control. b).With control.

power changes . The reason for this may be that the temperature of the laser cavity stabilizes at different power levels and therefore the optical cavity dimension could also be different for each power level. A fluctuation of beam intensity profiles could lead to the fluctuation of laser power as well. When this fluctuation is detected by the closed loop system it will be stabilized by the closed loop power control. In order to examine the possibilities of using the laser immediately after start up, materials surface hardening was performed 1 minute after the switching on of laser HT. The result is shown in Fig. 5.25 in which the processing using the closed loop controlled laser showed an uniform depth while using the open loop uncontrolled laser the uniformity is poor. In production this reduction of start up time and energy consumption could be significant in terms of efficiency, productivity and economy.

c). Response time

The step response of the closed loop system is shown in Fig. 5.26 (b) in which laser power arrives to the second stable level in less than 4 seconds while for the same step demand change the open loop controlled system took 7 minutes (Fig.5.26.a) because of the temperature effect just referred to. The response shows a near optimum control characteristic (little slower than the optimum response but overshooting is avoided). The time constant is shown about 1.5 seconds which may be slow for adaptive control of fast processing applications like cutting a thin sheet. The response time of the closed loop system could be decreased by reducing the RMS time constant in the power meter and the use of faster PID controller.

d). Effect of laser shutter operation

Since the LBA is located between the output window and the shutter box (Fig.5.27) there is no effect on the laser power sensing and control system by operating the shutter. The only way in which an effect might be expected is if the calorimeter heats up (for example a failure in the water supply to the calorimeter) in which case the back reflected signal from the nearby calorimeter beam dump would tend to make the controller reduce the laser power -- an advantageous result for safety.

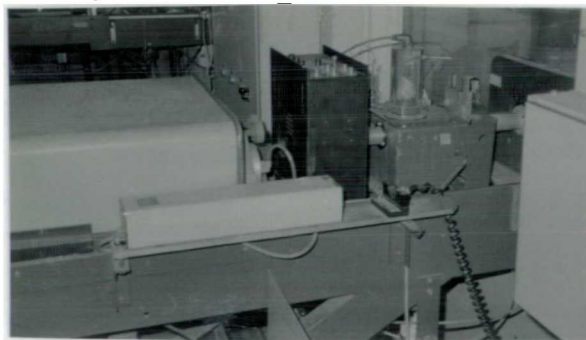


Fig. 5.27. Position of the LBA for in-process beam sampling.

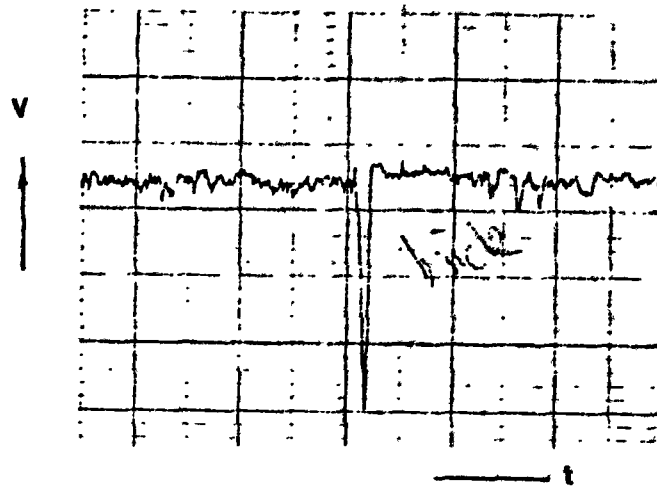


Fig.5.28. Laser beam back reflection from a fire brick at a distance of 2 feet from the laser output window.

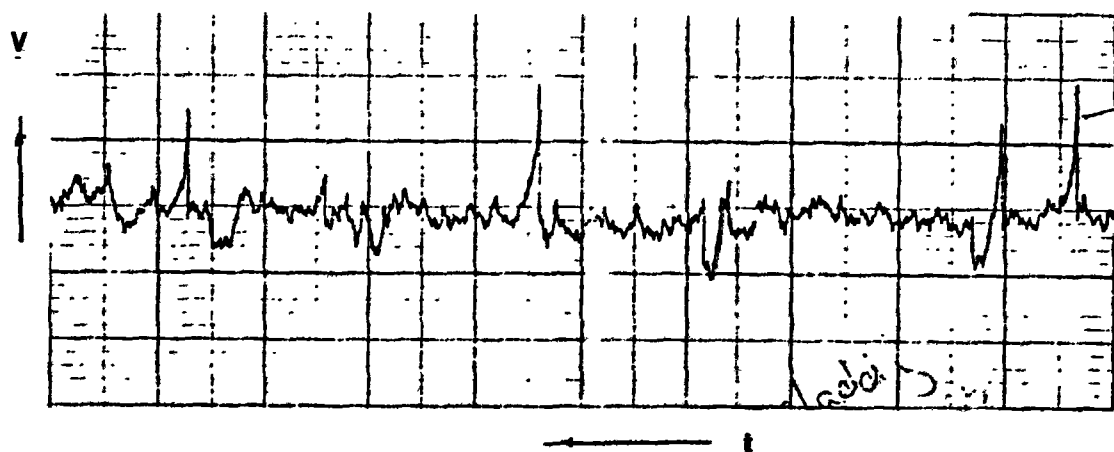


Fig. 5.29. Laser beam back reflection from the workstation 2 meters away from the LBA when performing laser cladding.

e). Effect of back reflection from the workpiece

If LBA is placed near to the beam interaction process then a back reflection signal was observed as shown in Fig.5.28 where a fire brick placed 2 feet from the LBA was heated by the laser. This signal would interfere with the control action and thus the LBA should be placed at a distance from the working area. In this study no effect was observed when cutting at a distance of 5 meters from the LBA. However a signal was observed when working at a distance of 2 m from the workpiece (Fig.5.29). To prevent the back reflected signal affecting the beam power sensing, proper shaping of the rotating needle in the LBA may be necessary. It is worth noting that the back reflected laser beam may re-enter the laser cavity and to be amplified to cause a laser power fluctuation. Using the closed loop power controller these back reflection caused power fluctuation could also be compensated for.

5.4. SYSTEM INSTRUMENTATION

An instrument was made which incorporated PID programmable controller, laser power meter (with two channel averaging) and beam diameter meter in one unit together with DC power supplies, I/O port for signal recording, and digital 7 section LED displays for both laser power and beam diameter. This is shown in Fig. 5.30.



Fig. 5.30. Closed loop laser power controller instrument.

It takes signals from LBA and gives a control output to laser remote operating unit. The following additional features are also included in the instrument:

- 1). **Fault alarms:** If the present power deviation from the required value exceeds the preset values (programmable) the unit will give alarms by flashing the display.

2). Upper and lower limits setting: The upper and lower laser power limits can be set by a hand held programmer. This is to prevent the power demand exceeding the capability of the laser or processing requirement.

3). Manual/Auto selection: For "manual" operation power value can be set in the front operating panel with open loop control while digital power display gives the actual power reading. For "auto" operation the set power will be followed by closed loop power control.

4). Remote operation and host computer communication. The power demand can be set from the remote port by a voltage signal. The unit will allow the power to follow the remote power setting continuously. RS232 serial communication was also provided for host computer communication and control.

5.5 SUMMARY

An on-line closed loop laser power control unit has been developed for high power DC excited CO₂ lasers. The following were achieved using the controller.

a). The system has improved laser beam stability to enable power to be maintained within $\pm 0.2\%$ representing around $\pm 4\text{W}$ at 2kW beam, while the previous performance had a $\pm 15\text{W}$ slow fluctuation. Any instability of the laser system can be automatically compensated (such cases of laser instability happen especially for very high power lasers or high power lasers operating at lower laser power level). This will reduce the possibility of the laser fluctuation effect on the materials processing quality.

b). The system has improved the repeatability and response time. The open loop lasers usually need quite a long time to settle (5-10 minutes) to achieve a steady value of a new power level while the closed loop system reduces this to 1-4 seconds. These enable the laser power to be the same as required during materials processing. The possibilities to achieve a high quality materials processing product can thus be increased.

c). A substantial reduction of laser start up time by the unit has been achieved from a previous 40 to 60 minutes with an temperature effect of more than two hours, to less than 1 minute by using this unit. This allows significant saving in laser gases, energy and labour previously used during the start up period.

d). Communication between laser power controller and system supervisory computer is provided and therefore the on-line variation of laser power for adaptive feedback process control becomes possible.

e). Both digital display and continuous analog recording of the laser power and diameter during materials processing can be achieved using the instrument developed.

CHAPTER 6

POWDER FEEDER MODELLING AND CLOSED LOOP POWDER FLOWRATE CONTROL

6.1 INTRODUCTION

As discussed in Chapter 2, the stability of the powder feeder operation has a profound effect on the processing quality such as clad thickness and dilution or even the success of the cladding. However most powder feeders used in laser cladding and alloying applications are manually open loop operated and the average flowrate is usually determined by weighing the powders flowing out of the feeder tube for a period of time and then dividing the powder weight by the time. By using this method, not only that the accurate setting of powder flowrate to a given value took a long time but also the operating stability and repeatability can not be guaranteed because of the open loop control. Fig. 6.1 shows an experimental result of powder feeding repeatability by the open loop operation. It can be seen from this experiment that setting the powder flowrate according to a pre-calibrated speed control may not be very reliable. Also that the powder flowrate can still drift from its desired values even if a constant motor speed is used because of the change of the powder level in the hopper or other influences. Fig. 6.2 shows an experimental record of the powder flowrate for the same feeder taken at different times when the motor speed and gas supply settings were kept for the same values.

These experiments may not represent the instabilities for all powder feeders, but at least they demonstrated that open loop powder feeding could result in fluctuations of powder flowrate even if the control settings are kept constant. These instabilities will affect the process quality. In order to overcome these a closed loop powder flowrate control system is required.

This chapter describes author's work on the modelling of a screw feed powder feeder and on the development of a closed loop powder flowrate control system. As will be seen later that the controlled system has demonstrated an expected improvement on the powder feeding stability.

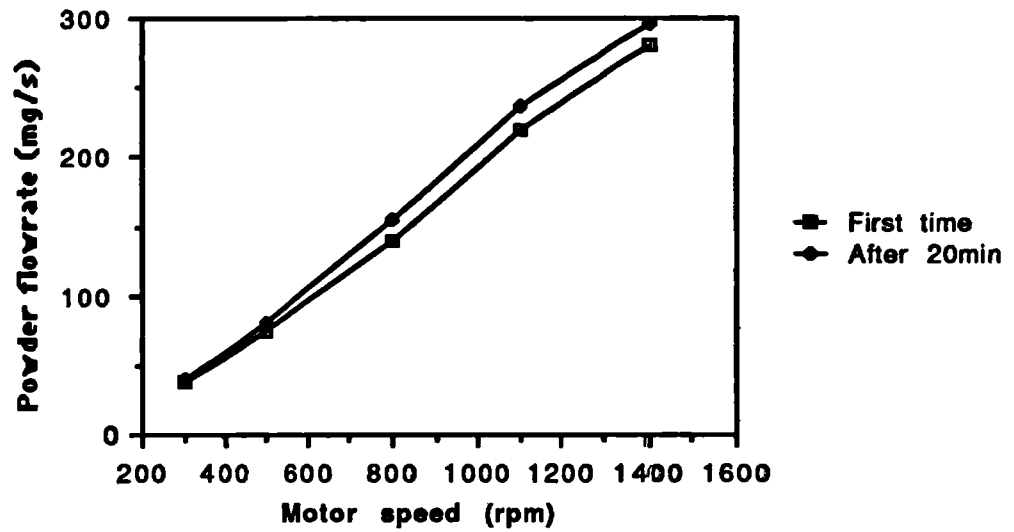


Fig. 6.1. Repeatability of the open loop powder feeder system. (The motor speed setting was from a remote control port by applying accurately measured voltage.)

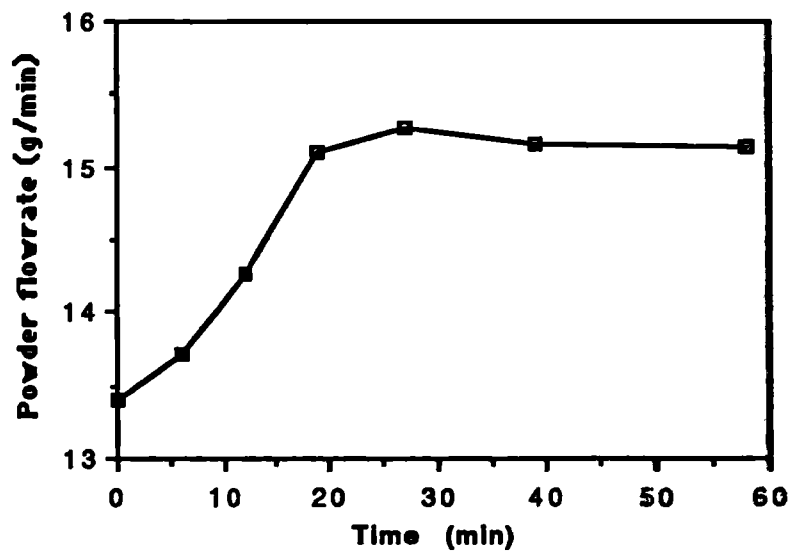


Fig. 6.2. Stability of powder feeding for a feeder used in laser cladding. About 30 minutes is required for the powder feed to become stable.

6.2 POWDER FEEDER MODELLING

The powder feeder under study was a laboratory model developed by V.M.Weerasinghe at

Imperial College (See Chapter 2.). It consisted of a powder hopper, motor driven feed screw (commercial double twist drill) and a pneumatic powder conveying tube (copper tube with 5mm internal diameter). The pressure of the hopper and that of the conveying tube are equalized by an equalizing gas tube line. The motor (Permanent Magnetic DC motor) was controlled by a manual motor speed controller (Electric-Craft Model:E-652-M) which consisted of a speed setting potentiometer and servo amplifier with tacho feedback from the the motor. An analog meter displayed the motor speed in RPM. Generally the powder flowrate was quite uniform over a certain range of operating speed after some initial "warm up" time (around 20 to 40 minutes as shown in Fig. 6.2) and the relation between the speed and flowrate is linear in that operating range (Fig.6.1). If the conveying pressure is set properly the powder driven out from the hopper by the screw (rotating anti-clockwise) will flow continuously through the tube without blocking and powder dripping. The powder flowrate characteristics will depend on a number of parameters including feeder screw speed, powder level in the hopper, conveying gas flowrate and pressure, conveying tube length, diameter and angle etc. A study of these factors will be helpful for the effective and correct use of powder feeders and control system development. The modelling of the powder feeder was divided into two parts: screw feed process and pneumatic powder conveying process.

6.2.1 Modelling of screw feed process

The screw driven powder feed process is basically a servomechanism process. The elements involved are a servo drive, a DC motor directly coupled to a feed screw and powders in the hopper as well as the dynamic gas pressure difference between the hopper and outlet of the feed screw (Fig.6.3).

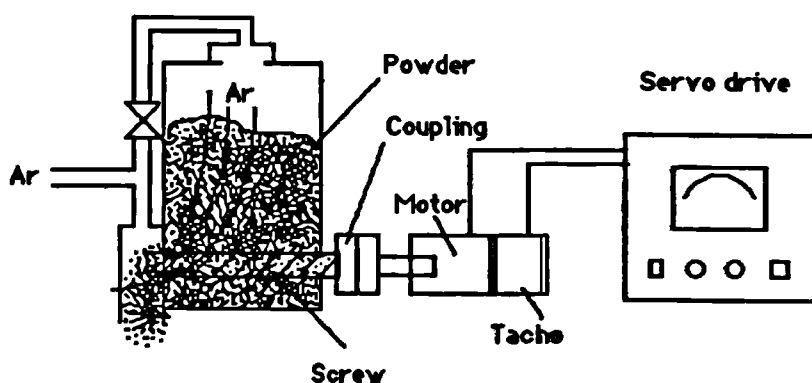


Fig.6.3. Screw feed process of the powder feeder.

Suppose the powder has an uniform size and always fills the screw thread either by weight or by compression of the hopper gas pressure and that there is no sticking of the powder on the feed screw or slippage; Then the amount of powder (in weight) being driven

out by the twin fluted screw (Fig.6.4) per revolution will be:

$$m_1 = \rho 2A_d r \quad (6-1)$$

where m_1 : The powder mass flow per revolution of feed screw rotation (g/rev)

r : Lead of helix of the drill (mm), which is defined as the distance measured parallel to the drill axis between corresponding points on the leading edge of a flute in one complete turn.

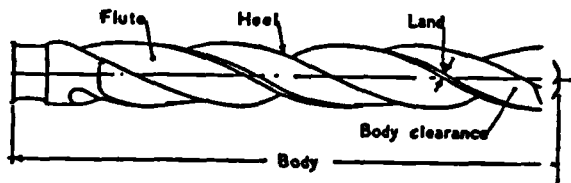
ρ : Density of the powder in the hopper, (g/mm³). This value is different from the specific weight of the powder material. Actually ρ depends on hopper elevation, acceleration (if it is mobile one), void factor (ratio of the space of air to that of solid), particle size, viscosity of the powder, powder level in the hopper and hopper gas pressure etc.

A_d : Area of the one flute in a cross section of the drill as shown in Fig. 6.4. A_d is found to be roughly equal to 1/4 of the total cross sectional area of the drill. Thus

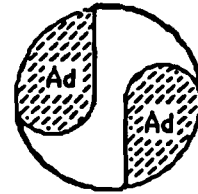
$$2A_d \approx A_s/2 = \pi D_d^2/8 \quad (6-2)$$

where A_s = cross sectional area of the drill (mm²)

D_d = diameter of the drill (mm)



(a)



(b)

Fig. 6.4. Illustration of the twist drill. a). side view, b). cross sectional geometry.

Therefore Eqn. (6-1) can be rewritten as:

$$m_1 = \pi \rho D_d^2 r / 8 \quad (6-3)$$

When the screw is continuously rotated by a motor, powder flowrate can be expressed as:

$$M = m_1 V_{mr} \quad (6-4)$$

where V_{mr} : motor speed (rev./s)

M : powder mass flowrate (g/s)

However this linear relationship between flowrate and motor speed only exists if the assumptions made above are true. When either there is sticking of the powder to the screw (when very fine powder is used) or the flute are not filled (when motor speed is too fast causing centrifugal effect) the relationship fails, which will generally result in the saturation or even the reduction of powder feedrate. Thus either too fine or sticky powder cannot be fed effectively using this type of powder feeder unless a propeller or fluidized screw or additional vibrating device is used [50,148] and powder feed can only be used below certain speeds. Since the end of screw shaft is enclosed in a bush with a fine clearance, the powder used for feeding can not be too large (not exceeding the size of bush/screw clearance), which would otherwise result in the "squeeze" of powders against the bush and screw leading to a mechanical damage to the powder feeder if the powder used is very hard. When hopper gas pressure is much higher than that at the powder pick-up, there is also a possibility that the powder is driven through the drill flutes by gas flow, which depends on the void factor of the powder material (decided by particle size, shape also the gas pressure).

The mathematical modelling of the motor driven screw feed process can be carried out as follows:

1. Motor dynamics (See Chapter 4):

$$\tau_m \frac{d\omega}{dt} + \omega = \frac{V_m}{K_{vm}} - \frac{R}{K_t K_{vm}} T_s \quad (6-5)$$

where ω : Angular velocity of the motor shaft (Rad/s).

τ_m : Mechanical time constant of the motor (s)

K_{vm} : Voltage constant (Vs/m)

K_t : Torque constant (Nm/A)

R : Armature resistance of the motor (Ω)

V_m : DC voltage applied to the motor (V)

T_s : Static (or Load) torque on the motor shaft (Nm), which depends on the powder weight in the hopper and therefore varies during feeding.

2. Tacho relationship:

$$V_p = K_p \omega \quad (6-6)$$

where V_p : Tacho voltage output (V)

K_p : Tacho constant (V s/m)

3. Servo amplifier relationship:

$$V_m = K_a (V_c - V_p) \quad (6-7)$$

where V_c : Applied voltage to the servo drive (volts)
 K_a : Servo drive control gain

By solving Eqns.(6-5), (6-6) and (6-7) the screw speed (in Rev/s) can be derived as:

$$\begin{aligned} V_{mr} &= \omega(t)/(2\pi) \\ &= (1/2\pi)[\alpha K_a K_{m1} V_c - (\alpha R K_n / K_t) T_s(t)] [1 - e^{-t/(\alpha \tau_m)}] \end{aligned} \quad (6-8)$$

where $K_n = 1/K_{vm}$ and $\alpha = 1/(1 + K_a K_n K_p)$.

By combining Eqn.(6-4) and (6-8) a dynamic model for screw powder feed can be found to be:

$$M = (1/2\pi)\alpha K_n m_1 \rho [K_a V_c - (R/K_t) T_s(t)] [1 - e^{-t/(\alpha \tau_m)}] \quad (6-9)$$

where M = powder mass flowrate

From this model we can see that both static and dynamic powder flowrate can be affected by the load in the hopper, which in turn will be affected by the level of the powder and the stability of hopper gas pressure (as additional load on the screw shaft). These factors are actually changing during processing and therefore change the powder flowrate progressively. Without closed loop control with powder flowrate feedback this change will remain uncorrected.

Eqn.(6-9) can be further simplified as:

$$M = [K_{vc} V_c(t) - K_{ts} T_s(t)] (1 - e^{-t/\tau}) \quad (6-10)$$

$$\text{where } K_{vc} = (1/2\pi)\alpha K_n m_1 \rho K_a \quad (6-11)$$

$$K_{ts} = (1/2\pi)\alpha K_n m_1 \rho R/K_t \quad (6-12)$$

$$\tau = \alpha \tau_m \quad (6-13)$$

Performing the Laplace transform on Eqn.(6-10), a frequency domain expression of the screw feed process can be obtained as:

$$M(s) = \frac{K_{vc}}{\tau s + 1} V_c(s) - \frac{K_{ts}}{\tau s + 1} T_s(s) \quad (6-14)$$

where $M(s)$, $V_c(s)$ and $T_s(s)$ are the frequency correspondence of $M(t)$, $V_c(t)$ and $T_s(t)$ respectively. It is worth noting that both K_{vc} and K_{ts} can be affected by the change of ρ which could be affected by a number of factors as mentioned above, one of which is the stability of gas flow rate. Fig.6.5 shows this effect on the flowrate when $V_c(s)$ was kept

unchanged.

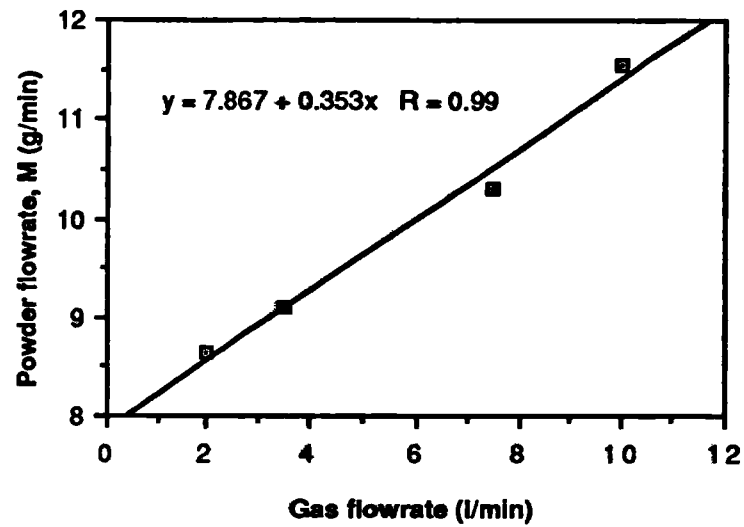


Fig. 6.5. Effect of gas flowrate on powder flowrate when the setting for motor was kept constant.

6.2.2. Modelling of pneumatic powder conveying process

Suppose a constant flow of gas with a flowrate of Q_g is supplied to a conveying tube which has an internal diameter of D_t and length of L_t with an overall height of the tube of H_t , as shown in Fig. 6.6

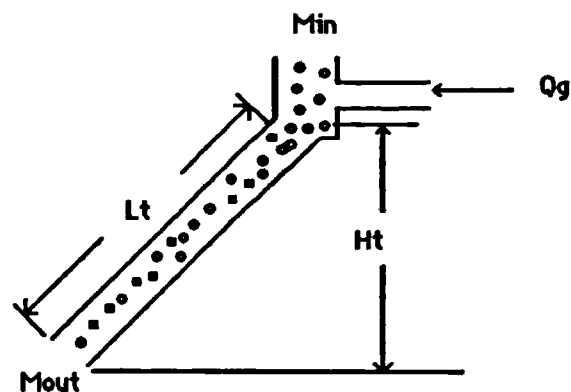


Fig. 6.6. Illustration of pneumatic powder conveying.

The points of interest for powder flowrate control are:

1). How much the gas flowrate is required so that there is no settling of powders in the conveying tube?

2). What is the relationship between the powder flowrate at the end of the feed tube and that coming into the tube ?

a). Minimum gas flowrate for non-settling powder flow

In the pneumatic conveying process it is important that powder does not settle in the pipe, as this would lead to build-up of material or even blocking the feed tube which would destroy the required uniform powder feed. The appropriate gas velocity relative to the particles required to avoid powder settling is called the fluidizing velocity which is given [154] as:

$$U_m = (\rho_s - \rho_g) g \frac{D_s^2 \epsilon^3}{180 \mu \lambda^2 (1-\epsilon)} \quad (6-15)$$

where U_m : fluidizing velocity of the gas relative to the particles (m/s).

ρ_s : powder material density (kg/m³)

ρ_g : gas density (kg/m³)

g : gravitational constant (9.8m/s²).

D_s : average diameter of the powder particle(m)

λ : a shape factor of the powder (which changes the non-spherical powder shape into a spherical powder equivalent. For spherical powder $\lambda = 1$).

μ : coefficient of viscosity (Ns/m²)

ϵ : void fraction which is defined as:

$$\epsilon = \frac{A_t - A_{pm}}{A_t} \quad (6-16)$$

where A_t is the tube cross sectional area;

A_{pm} is the maximum expected cross sectional area occupied by the powders in the tube. A_{pm} can be related to powder flowrate and mean particle velocity as:

$$A_{pm} = \frac{M_{max}}{\rho_s U_{smin}} \quad (6-17)$$

where U_{smin} is the minimum expected average velocity of the powder travelling in the tube, m/s. (The average particle velocity is defined here as $(U_{st} - U_{so})/2$, where U_{st} is the average particle velocity at the exit point of the tube and U_{so} is the average particle velocity at the entrance of the tube.)

Mmax is the maximum powder mass flowrate expected to be used for the process, g/s

Therefore given the required mass flowrate, particle traverse velocity and tube diameter, the minimum gas velocity required can be calculated using Eqns. (6-15), (6-16) and (6-17). The corresponding gas flowrate required can then be decided as:

$$Q_{gmin} = \epsilon A_t U_{gm} \quad (6-18)$$

where $U_{gm} = U_m + U_{smin}$ is the average gas velocity across the tube.

For example, to calculate the minimum gas flow for powder feeding of 316 stainless steel of average size of 60 μ m spherical powder with feed tube diameter of 3mm and known^[50] that: $M_{max} = 0.35\text{g/s}$, $U_{smin} = 0.2\text{m/s}$

The following can be calculated:

$$A_t = \pi D_t^2 / 4 = 7.065 \text{ mm}^2$$

$$A_{pm} = M_{max} / (\rho_s U_{smin}) = 0.21875 \text{ mm}^2$$

$$\epsilon = (A_t - A_{pm}) / A_t = 0.969$$

Since $\lambda = 1$, $\mu = 1.7 \times 10^{-5} \text{ mms}$, $g = 9.8 \times 10^3 \text{ mm/s}^2$, the minimum gas velocity required can be calculated using Eqn.(6-15) to be $U_m = 2.7\text{m/s}$ which agrees with the experimental data from Ref.50. The required gas flowrate can be calculated using Eqn.(6-18) to be: $Q_{gmin} = 1.191 \text{ litre/min}$.

b). Relationship between powder flowrate at tube entrance and that at tube exit

Suppose the gas velocity has exceeded U_m so that there is no powder blockage or powder settling in the tube. Then because of the conservation of mass, the relationship between the powder flowrate at the exit of the feed tube and that give by the screw feed into the tube can be found to be:

$$\begin{aligned} \text{Change of mass in the tube} &= \int_t^{t+\Delta t} (M_{in} - M_{out}) dt \\ &= \int_t^{t+L_t / U_{pm}} (M_{in} - M_{out}) dt \quad (6-19) \end{aligned}$$

where

M_{in} : Powder mass flowrate into the feed tube

M_{out} : Powder mass flowrate at the exit of the feed tube

L_t : Length of the tube.

U_{pm} : The average particle velocity across the tube within the time interval concerned.

An equilibrium of the powders kept in the tube can be achieved (the change of mass in the tube = 0) when M_{in} is kept as constant for longer than Δt time. i.e. when $t' > t + \Delta t$ the average mass flowrate on both ends should be equal assuming no further smoothing in the tube. This steady state relationship can be expressed using a unit step function " $u(t)$ " as:

$$M_{out} = M_{in} u(t - L_t / U_{sm}) \quad (6-20)$$

where the unit step function is defined as:

$$u(t) = \begin{cases} 1 & t \geq 0 \\ 0 & t < 0 \end{cases} \quad (6-21)$$

It can be seen that the screw feed powder flow will have a pure delay time of L_t / U_{sm} before the change is reflected at the process end of the feed tube. This suggests that the shortest possible tube length should be used for laser cladding processes with a consideration for adaptive control in order to reduce the response time of the actual powder flowrate to the control settings. It can be seen that the average powder flowrate at steady state is independent of particle velocity. However the instant powder flowrate could be affected by the particle travelling speed since faster particle velocity will result in less powder accumulation in the feed tube causing an instant increase of the powder flowrate at the exit of the feed tube.

6.3. IN-PROCESS CONTINUOUS POWDER FLOWRATE SENSING

The in-process powder flowrate sensing was achieved by using a compact pressure sensor attached to the powder pick-up as illustrated in Fig. 6.7. The sensing element of the pressure sensor is a 0.1" square silicon chip with integral sensing diaphragm and four piezoresistors arranged in a bridge. When pressure is applied to the diaphragm it causes it to flex, changing the resistance, which results in an output voltage proportional to the pressure when an excitation voltage is applied to the device. Two complimentary outputs are provided in the sensor so that the difference between them can be used as differential outputs for better sensitivity. The sensitivity of the sensor is 6.67mV/p.s.i with 10V power supply. The response time of the sensor is 1ms. For the present application the differential value of the pressure between "no powder flow" and "there is powder flow" was abstracted through electronic conditioning circuits. This can be expressed as:

$$V_{mf} = K_{mf} (P_{ms} - P_{mo}) \quad (6-22)$$

K_{mf} : Sensitivity of the sensor

P_{ms} : pressure when there is powder flow

P_{mo} : pressure when powder flowrate is zero.

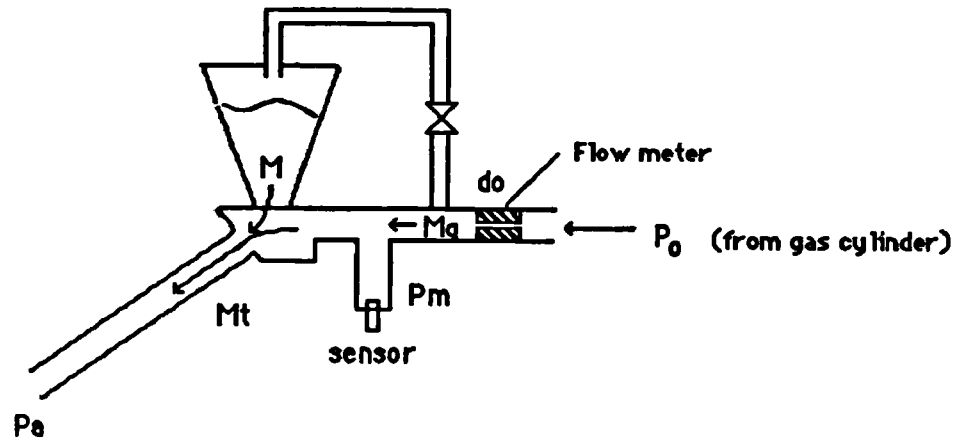


Fig. 6.7. powder flowrate sensing arrangement

6.3.1 Principle of the flowrate sensing

Considering the sensing set up as shown in Fig. 6.7. a constant gas flow Q_g is supplied to the conveying tube through a flow meter orifice with the up stream connected directly to the compressed gas bottle through a high pressure gas regulator generating a choked condition at the flowmeter orifice. The gas flowrate at this condition can be found as [150]:

$$M_g = C_D \frac{\pi d_o^2}{4} \left[\frac{\gamma}{R} \left(\frac{2}{\gamma+1} \right)^{\frac{\gamma+1}{\gamma-1}} \right]^{1/2} \frac{P_0}{\sqrt{T}} \quad (6-23)$$

where M_g = Gas mass flowrate for pneumatic conveying

C_D = Coefficient of discharge, which is a constant for a gas.

P_0 = Gas pressure before it comes through the orifice.

d_o = Diameter of the orifice.

γ = Ratio of specific heat at constant pressure and volum = C_p/C_v .

The choked condition can be satisfied so long as:

$$P_0 \gg P_m \quad (6-24)$$

where P_m is the pressure on the down stream side of the flowmeter.

When there is powder flowing in the conveying tube, the powders will occupy a portion of space in the pipe thus reducing the effective tube cross sectional area causing more resistance to the gas flow. At steady state the amount of gas coming through the flowmeter orifice to the conveying area must be equal to the amount of gas exiting from the feed tube. This can only be maintained when there is a higher pressure difference between the two ends of the conveying tube than when there is no powder so that the gas can travel faster in a narrower path. Since the gas pressure at the exit of the feeding tube is atmospheric pressure, the increase of pressure difference results in the pressure rise at the sensing area. More powder being present in the pipe will lead to higher resistance to the flow resulting in a higher pressure being built up in the sensing area and vice versa. The quantitative analysis of this can be made as follows:

The energy loss of the gas in the conveying tube can be contributed by elevation (potential energy of the gas), friction (with tube wall and particles) and drag force (for the conveying of the particles). The pressure drop of the gas in the tube due to these factors can be expressed approximately as:

$$\Delta P_t = \rho_g g H_t + 2\rho_g C_f U_{gm}^2 L_t/D_t + C_d \rho_g U_{gs}^2/2 \quad (6-25)$$

The first term on the right hand side of this equation is the pressure drop due to elevation; the second term, the friction; and the third term acceleration.

C_f is a friction factor, the value of which depends on whether the flow is turbulent or laminar. Since the gas flow speed used for powder feeding is between 2.7m/s to 6.8m/s [50], the Reynolds number of gas flow can be calculated using $Re = \rho_g U_g D_t/\mu$ to be between 476 and 1200 which means the gas flow is laminar and therefore $C_f = 16/Re$. i.e.

$$C_f = \frac{16\mu}{\rho_g U_{gm} D_t} \quad (6-26)$$

where U_{gm} is the average gas velocity in the conveying tube which is higher than when there is no powder presents in the tube because of the reduction of the effective flow area. U_{gm} can be approximately expressed as:

$$U_{gm} = \frac{Q_g}{A_t - \frac{M}{\rho_s U_{pm}}} \quad (6-27)$$

U_{gs} is the gas velocity relative to the particle velocity, which can be expressed as:

$$U_{gs} = U_{gm} - U_{pm} \quad (6-28)$$

where $U_{pm} > A_t \rho_s / M$.

C_d is drag coefficient which equals $14/Re$.

Since the gas pressure drop due to elevation of the tube is usually small compared with the other two, it can be dropped from the above equation. The amplitude of the second term of Eqn.(6-25) is more than $2L_t/D_t$ times larger than the third term. If $L_t \gg D_t$ which is true for most of cladding applications, the acceleration effect can also be neglected leaving only the friction term. Therefore the pressure drop in the pipe can be expressed approximately as:

$$\Delta P_{gs} \approx \frac{16\mu L_t}{D_t^2} \left(\frac{Q_g}{A_t - \frac{M}{\rho_s U_{pm}}} \right) \quad (6-29)$$

Using Taylor series expansion and ignoring the higher order terms, a linear relationship can be obtained as:

$$\Delta P_{gs} \approx \frac{16\mu L_t Q_g}{D_t^2 A_t} \left(1 + \frac{1}{A_t \rho_s U_{pm}} M \right) \quad (6-30)$$

with the condition that $A_t > M/(\rho_s U_{pm})$ which can always be observed so long as there is no blocking of the feed tube by powder.

Since $A_t = \pi D_t^2/4$, Eqn. (6-30) can also be expressed as:

$$\Delta P_{gs} \approx \frac{64\mu L_t Q_g}{\pi D_t^4} \left(1 + \frac{4}{\pi D_t^2 \rho_s U_{pm}} M \right) \quad (6-31)$$

If we define:

$$K_u = \frac{4}{\pi D_t^2 U_{pm}} \quad (6-32)$$

and

$$\Delta P_0 = \frac{64 \mu L_t Q_g}{\pi D_t^4} \quad (6-33)$$

which is the gas pressure when there is no powder flow., then we have:

$$\Delta P_{gs} \approx \Delta P_0 (1 + K_u M / \rho_s) \quad (6-34)$$

Since the gas pressure at the exit of the feed tube is atmospheric, the gas pressure drop is actually the gas pressure at the powder pick-up or inlet of the feed tube. The differential sensory signal for actual flowrate detection therefore is:

$$\begin{aligned} V_{mf} &= K_{mf} (P_m - P_{m0}) \\ &= K_{mf} (\Delta P_{gs} - \Delta P_0) \\ &= K_{mf} K_u \Delta P_0 M / \rho_s \end{aligned} \quad (6-35)$$

$$\text{or} \quad V_{mf} = K_{vm} M \quad (6-36)$$

where $K_{vm} = K_{mf} K_u \Delta P_0 / \rho_s$ in which, ΔP_0 and K_u are determined by Eqns.(6-32) and (6-33).

From Eqns.(6-32) to (6-36) we can see that:

- 1). Sensor signal is approximately linear to the powder flowrate.
- 2). If gas flow is controlled to be constant (or used in the choked condition) during powder feeding the sensing is stable with constant sensitivity.
- 3). Sensing sensitivity is proportional to the tube length.
- 4). The volumetric flowrate is independent of material type but can be different if particle size changes.

6.3.2. Sensing experiments

1). M-V_{mf} relation: The voltage output from the sensor has been found experimentally to have a linear relationship to the powder mass flowrate as shown in Fig. 6.8. This agrees the theoretical analysis as in Eqn.(6-36).

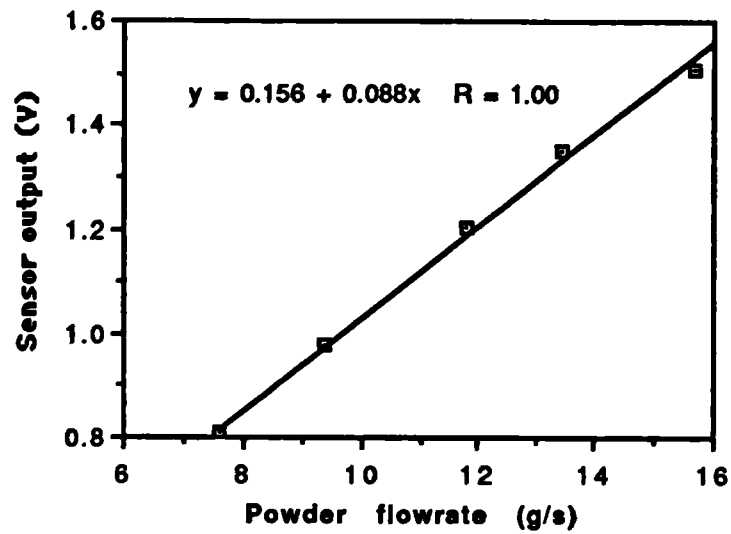


Fig.6.8. Pressure sensor output and powder flowrate relationships.

2). Gas flowrate (Qg) or ΔP_o effect: When gas flowrate was varied the sensitivity of the sensing was found to increase with increasing gas flowrate and the linearity of the sensing was preserved except when gas flow rate was too low as shown in Fig.6.9, bottom curve.

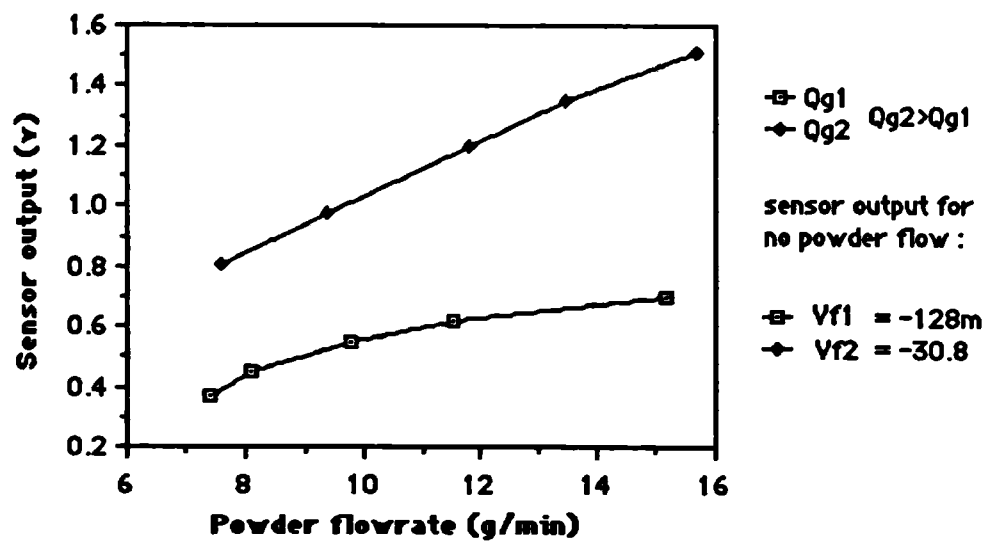


Fig. 6.9 Effect of gas flowrate on the flowrate sensing

3). Powder feed tube length (L_f) effect: When the powder feed tube length was increased from $L_{t1} = 12\text{cm}$ to $L_{t2} = 54\text{ cm} = 4.5 L_{t1}$, the sensitivity of the flowrate sensing increased about 4.5 times, while the response time was reduced 4.5 times. In the early theoretical analysis for powder flowrate effect on the gas pressure, the steady state response was assumed. I.e. if there is a change of powder flowrate it will be uniformly distributed through out the feed tube. This actually requires some time to establish and this time is approximately $\Delta t = L_f/U_{pm}$. This relation enables us to evaluate the average powder particle velocity by recording the response time of the sensor to a step powder flowrate change. For this experiment the response time for 12cm tube is about 0.2 second. Therefore the average powder particle speed is 0.6m/s. If the particle velocity at the end of the tube, U_p , is twice the average powder particle velocity (assuming uniform acceleration), U_p can be found approximately to be 1.2m/s which agrees with experiment data [50].

4). Hopper powder level effect. Although the change of hopper powder level changes the actual powder flowrate no visible effect on the sensing has been found from the experiment.

5). Gas temperature effect. Although powder collisions (particle/particle, particle / tube wall) in the feed tube can introduce additional heat in the gas, the actual gas temperature rise is very little (within 1°C) due to the continuous gas flow. No visible effect on the sensing and powder flowrate has been found in the experiment. In practical laser cladding, the feed tube can be heated up by the process induced heat which will affect the feed quality. This effect could be reduced by additional water cooling of the feeding tube. No experiment was made for the verification of this point.

6). Powder materials effect. A comparison of powder flowrate monitoring for feeding of aluminum powder and 316 steel powder was made as shown in Fig.6.10. The sensitivity was only slightly changed while the linearity is satisfactory, despite the fact that the powders had different sizes and densities.

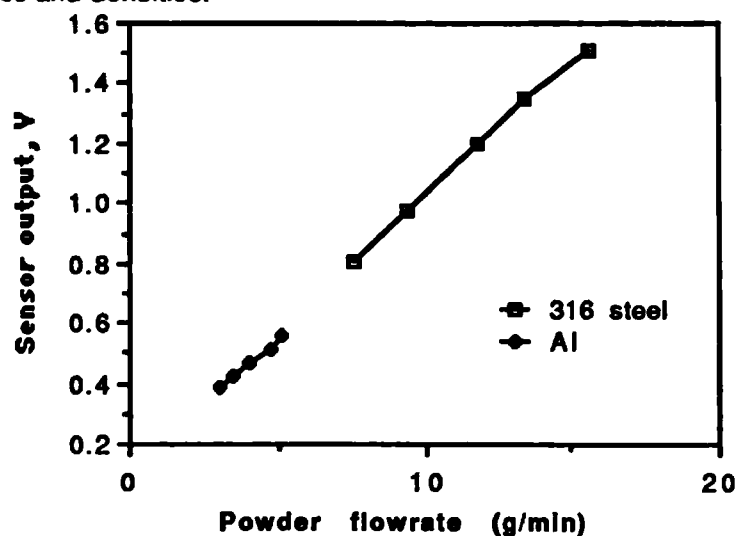


Fig. 6.10. The effect of different materials on the flowrate sensing.

6.3. CLOSED LOOP POWDER FLOWRATE CONTROL

6.3.1. Powder feeder open loop step response experiment

The step response of the powder flowrate was made by recording the flowrate sensor output when a step change in the feeder control input was introduced. It is intended for the identification of process dynamics for the closed loop control. The open loop step response of the powder feeder including the sensing device is shown in Fig.6.11. from which it can be seen that:

a). The dynamic behaviour of the powder feed exhibited a first order response characteristics.

b). There is a pure time lag (around 20ms) between the step input (voltage signal applied to the powder feeder motor) and flowrate response (detected by the flowrate sensor developed), which may be the time for pressure propagation. Actually the pressure propagation in a pipe line can be modeled as a first order system with a pure time lag^[147].

c). The open loop flowrate response time for the powder feeder tested was found to be about 2 seconds. The time constant is about 0.6 second and the over all open loop gain, K_o , including the sensing system is 1.5

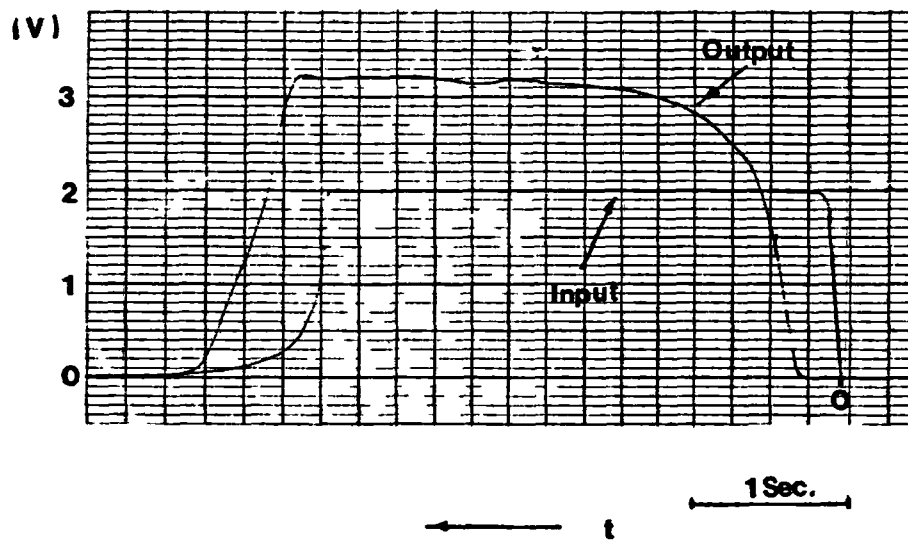


Fig. 6.11. Step response of the powder feeder (including the effect of sensor and recording device which has response time of around 200ms as shown in the step input curve).

6.4.2. Closed loop powder flowrate control algorithm design and realization

Since the process to be controlled is type-0 system, for the similar reason as that in laser power control, powder flowrate control cannot be realized by a proportional control which will introduce a steady state error. An integrating term must be introduced. Also because of the existence of some "lag" in the open loop response, a derivative term should also be introduced for powder flowrate control. Thus a three term PID control strategy was chosen.

The closed loop powder flowrate control was realized by feeding the flowrate sensing signal (after pre-amplification and conditioning) to a programmable digital self-tuning PID controller (Satt Control Model ECA40d) and the output voltage from the controller was used to control the feeder motor speed and therefore the flowrate. This arrangement is shown in Fig. 6.12.

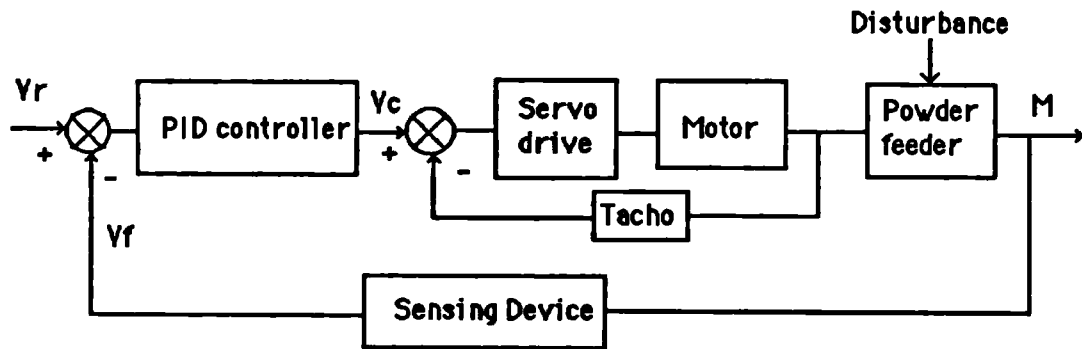


Fig. 6.12. Closed loop powder flowrate control arrangement.

The settings of PID parameters were established using the self-tuning function of the controller but the proportional control gain was further reduced to increase the robustness of the system. The control parameters were determined to be:

$$K_p = 0.23, \quad T_i = 1.1 \quad T_d = 0.3$$

The performance of the closed loop system was examined in the following aspects:

1). **System stability:** The stability of the system was examined using the similar method as that used for laser power control analysis and the system was proved to be stable. Since the gain of the process transfer function may change during processing, experimental stability examination was also made. The powder flowrate level was set at different levels for closed loop control and no system oscillation was observed.

2). **Step response characteristics.** The response of the powder flowrate to a step

change in the demand value was made by first using "manual" control to make a difference between the actual value to the desired one and change over to "auto" control. The response is shown in Fig.6.13.

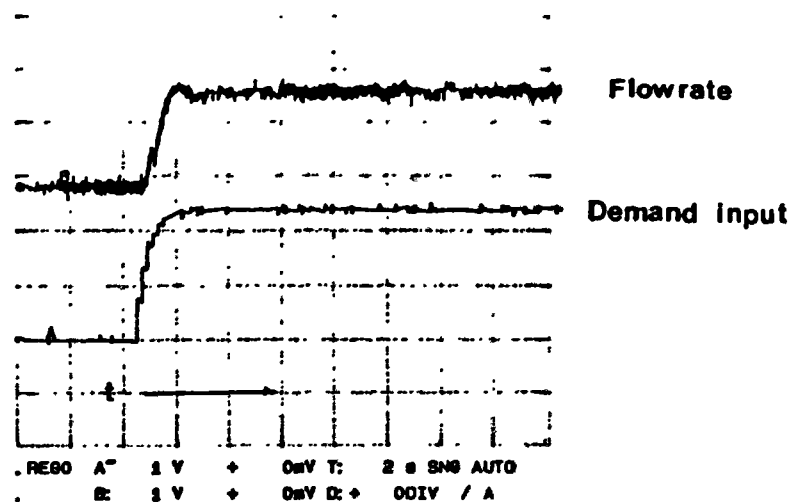


Fig.6.13. Step response of the closed loop powder flowrate control

3). Steady state error and control accuracy: Although theoretical steady state error is zero for step function input the actual closed loop control steady state error was found to be restricted by system sensing and control accuracy, which is about 2% of the operating range.

4). Powder feeding quality improvement: By using the closed loop control system the powder flowrate was maintained to the same level through out the feeding time despite the changes in the powder level in the hopper. The flowrate stability was much improved as shown in Fig. 6.14.

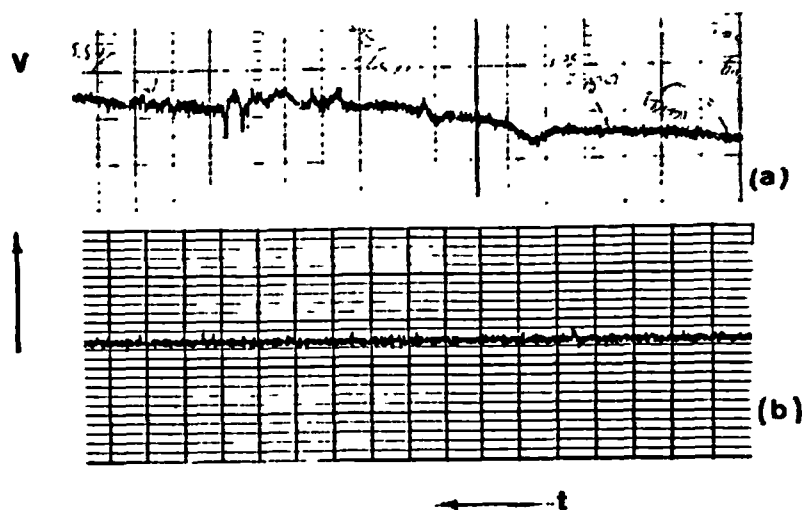


Fig.6.14. Comparison of the powder feed stability with (b) and without (a) closed loop control.

loop control.

5). Powder flowrate deviation alarms and analog/digital communication for remote computer setting of the demanded flowrate were provided.

6). Both demanded powder flowrate and actual powder flowrate can be digitally displayed.

The instrumentation of the powder feeder controller was realized as shown in Fig. 6.15.

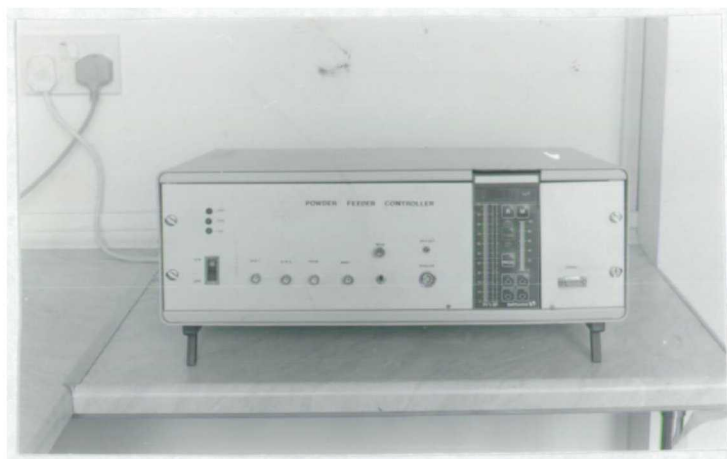


Fig. 6.15. Powder feeder controller made in this project.

6.5. SUMMARY

Powder feeder using motor driven screw feed and pneumatic conveying was studied. The dynamic modelling of the powder feeder was investigated. A closed loop system for the controlling the powder flowrate was developed, which enables the powder feed to be stable and repeatable eliminating problems associated with a poor powder feed which affected the laser cladding (and laser alloying) quality.

In addition, a preliminary study on the continuous particle velocity sensing was also made where two pressure sensors were used one at the present position and the second mounted on the feed tube. The natural fluctuations of the powder flowrate was found to create similar patterns on both sensors but with a time difference between them. Therefore a cross correlation of the two sensory signals could possibly be used to evaluate the particle velocity continuously. The closed loop control of this parameter could be performed by varying the gas flowrate according to the sensory signal. Since the variation of gas flowrate also varies the powder flowrate, the control of these two parameters at the same time is a multi-variable system control problem. This could be the subject of future work.

PART 3

IN-PROCESS LASER CLADDING QUALITY INSPECTION

In this PART, three in-process clad quality sensing techniques were investigated: clad uniformity sensor, dilution sensor and clad bead profile sensor.

The clad uniformity sensing (Chapter 7) was achieved by using an opto-electric sensor detecting the thermal radiation from the clad melt pool during processing. The signal responses were found to be able to indicate the changes of process quality such as clad uniformity, clad bonding property etc. Some correlation between the clad volume and the signal response was also found. This sensor is suitable for in-process clad quality inspection and process failure alarms.

The detection of dilution or the contamination of clad by substrate (Chapter 8) was achieved by generating a magnetic field on the clad and detecting the change of magnetic strength using a inductive sensor. This change of magnetic field was related to the change of material reluctance and conductivity caused by material contamination or dilution. A method was developed to eliminating the effect of sensor/workpiece distance. This sensor was developed for the on-line monitoring and feedback control of clad dilution.

The clad bead profile sensing (Chapter 9) was achieved by scanning the clad track with an infrared distance sensor so that clad bead width, height, aspect ratio and bead symmetry can be found. this sensor was developed for the on-line monitoring and feedback control of clad bead width, height and clad thickness.

CHAPTER 7

IN-PROCESS CLAD UNIFORMITY AND OPERATING STABILITY MONITORING

7.1 INTRODUCTION

Although a laser cladding process can be operated fully automatically with the systems described in Part 2, a poor clad can still be possible if the operating conditions (laser power, spot size, powder flowrate, traverse speed, degree of overlap, powder feed/laser alignment, powder particle travelling speed, powder feeding angle, laser beam mode and nozzle gas flowrate etc) are not set properly or there is an operating failure such as nozzle clipping or lens cracking or there is a change of workpiece conditions such as substrate temperature rise or defect in substrate surface (bump or distortion etc). Therefore it is necessary to know the end effect of laser cladding during processing so that problems can be found on-line. This Chapter provides the author's work on using a photo-diode for melt pool stability monitoring so that unsatisfactory clad can be recognized during processing. Experiments have indicated that poor clad bonding, substrate defects, overlap performance, clad roughness and system failure could all lead to certain changes of the state of the melt pool and the sensor responses. A theoretical study was made to explain the experimental phenomena. Finally the use of sensor for on-line clad quality assurance will be described .

7.2 SENSING PRINCIPLES

The arrangement for the in-process melt pool stability monitoring is shown in Fig.7.1. where a photo-diode with cylindrical light shield was placed about 2 feet away from melt pool to detect the light intensity emitted from the melt pool during laser cladding. The current leakage of the sensor, when reverse biased, will increase proportionally to the incident light strength in its spectrum range (0.4 to 1.25 μm). The response time of the sensor is 250 ns. The sensor signal was then amplified and converted to voltage for recording.

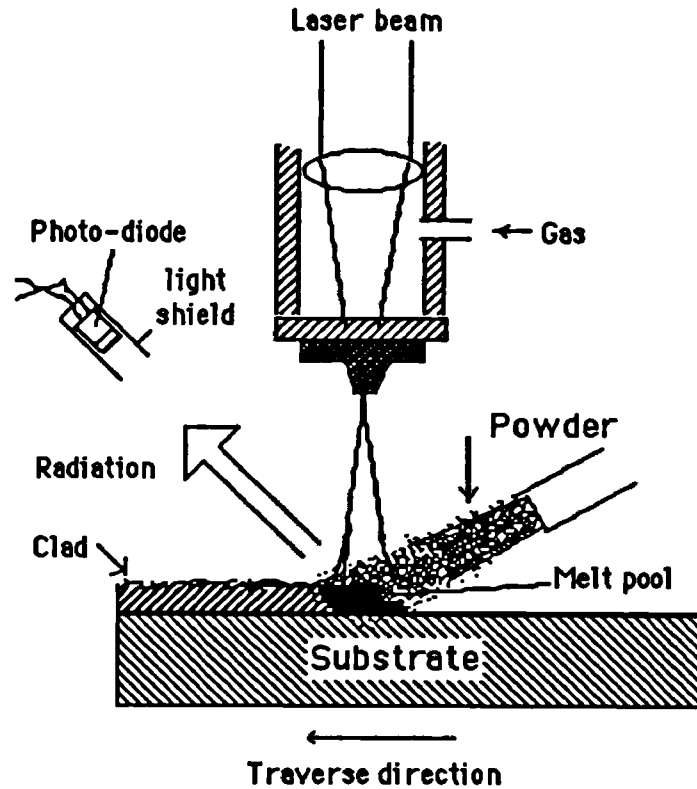


Fig. 7.1. Schematic diagram of the process sensing arrangement.

During laser cladding the materials in the melt pool will become "red hot" and radiate electromagnetic waves observing Stefan-Boltzman's equation^[155]:

$$W_t = \epsilon \alpha_s T^4 \quad (\text{Watts}) \quad (7-1)$$

where T is the average molten pool temperature (K), W_t is the radiated energy in Watt, ϵ is emissivity of the melted materials and α_s is Stefan-Boltzman constant ($5.67 \times 10^{-8} \text{m}^{-2} \text{K}^{-4}$). The wavelength at which the intensity is strongest is related to temperature by Wien's Displacement Law^[155]:

$$\lambda_{\max} T = C \quad (7-2)$$

where $C=2897.6$ and $\lambda_{\max}$ is wavelength in μm . The relationship of temperature and the radiation wavelength for a black body is shown in Fig. 7.2

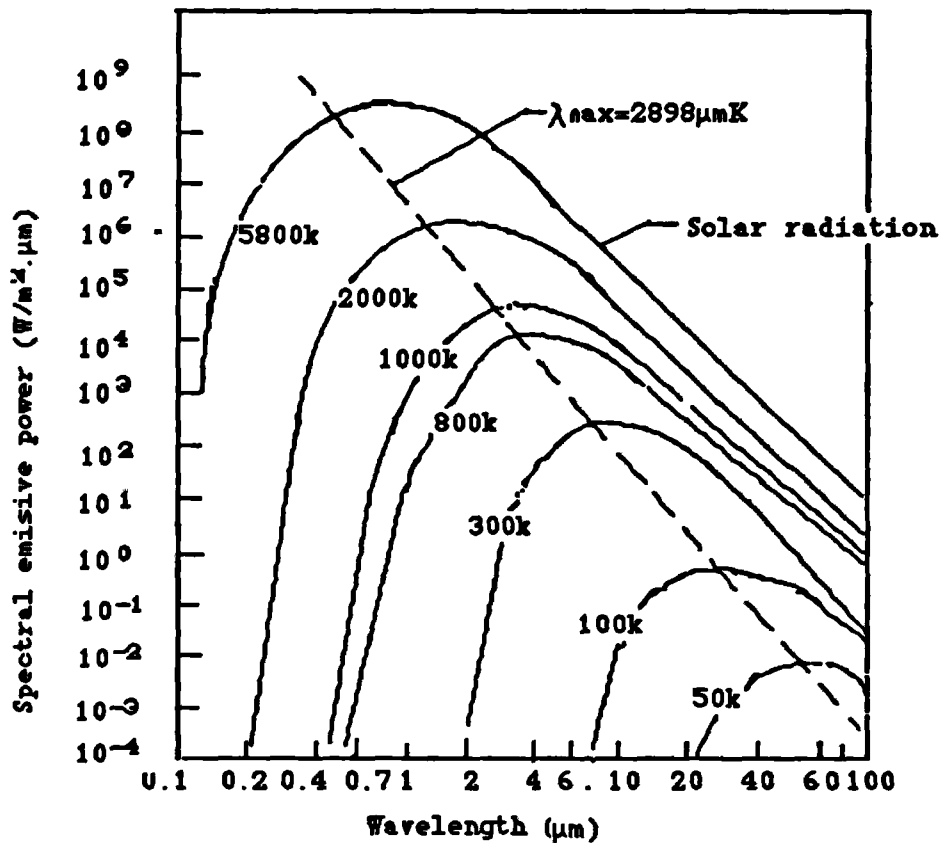


Fig. 7.2 Spectral blackbody emissive power^[155].

Since most materials for laser cladding process have their melting point over 800°C the wavelength radiated will include visible light (0.4 to $0.7\mu\text{m}$). It is this light that the sensor detected.

The sensor response spectrum is shown in Fig.7.3, which clearly indicates that neither the $10.6\mu\text{m}$ CO₂ laser beam nor the infrared thermal radiation from the workpiece surface rather than that from the melt pool can generate a response on the sensor since they are outside the response spectrum of the sensor. Direct ambient light (such as the room light, sun light) effect on the sensor was also prevented by the use of a light shield sleeve. Since usually the level of ambient light reflection from the workpiece surface is much weaker than that from the melt pool, and the use of a shielding sleeve restricted the view window of the sensor to only a small area around the melt pool, the ambient light reflection effect on the sensor could also be ignored. Therefore the sensor signal is only decided by the melt pool radiation.

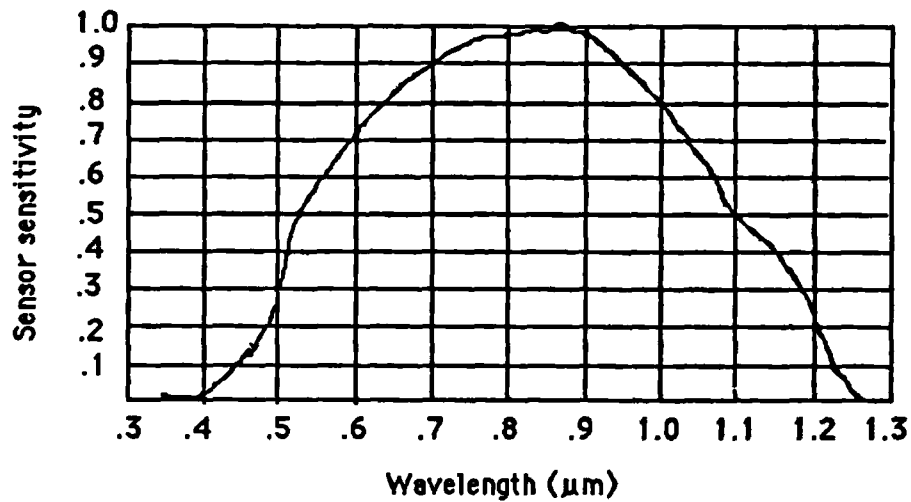


Fig. 7.3 Spectral response of the photo-diode used in the experiment^[156].

The sensor response to the melt pool thermal radiation is dependent upon melt pool temperature, shape and size. It also dependent on the distance between the sensor and the melt pool as well as the view angle of sensor. These relationships can be expressed as^[150]:

$$V_{ps} = K_s \epsilon A_p \cos(\alpha) T^4 / d_s^2 \quad (7-3)$$

where V_{ps} = the sensor output (Volts)

K_s = a sensor constant decided by the sensitivity of the sensor, amplification gain of the signal conditioner, shielding factor of the sensor, size of the sensitive area of the sensor and absorptivity of the sensor

ϵ = the emissivity of the molten material in the melt pool

A_p = the effective melt pool area exposed to the sensor

α = the angle of sensor relative to the normal of the workpiece surface

T = the average pool temperature

d_s = the distance between the sensor and melt pool.

Therefore any changes of the state of melt pool such as temperature, size, shape and emissivity etc. (caused, for instance, by the change of clad quality) can be reflected in the sensor signal output. "Signatures" corresponding to different clad quality can then be recorded and used to compare with the actual responses during processing to diagnose the problems of the cladding process.

7.3 SENSING EXPERIMENTS

A series of experiments were made to investigate sensor responses to various cladding conditions and clad quality variations. In these experiments 316 stainless powder was used

to clad on mild steel substrate with Control Laser 2kW CO₂ Laser.

7.3.1. Sensor responses to operating parameter changes and clad deposition variations

In these experiments clad parameter (bead width, height and dilution) was varied by changing the principle operating parameters: laser power, traverse speed, powder flowrate, powder particle travelling speed, and overlap degree each at a time. The sensor responses to these variation were recorded on a chart recorder during processing. When laser was not fired on the workpiece, the sensor output was zero.

1). **Response to laser power variation.** At normal powder flowrate (0.2 to 0.4g/s), when laser power was increased, the average level of the sensor output was also increased as shown in Fig. 7.4 (a). However at low powder flowrate (<0.15g/s), the increase of laser power did not increase the sensor response and sometimes decreased the sensor response.

2). **Response to traverse speed variation.** When traverse speed was reduced, the sensor output had increased as shown in Fig. 7.4 (b).

3). **Response to powder flowrate variation.** At low and moderate powder flowrate (0.15 to 0.3g/s) when powder flowrate was increased, the sensor output had increased as shown in Fig.7.4 (c). However at higher powder flowrate, the increase of powder flowrate did not increase the sensor response.

4). **Response to a variation in the degree of overlap.** When the degree of overlap was increased, the sensor response had increased as shown in Fig. 7.4 (d).

5). **Response to powder particle travelling speed variation.** When powder conveying gas flow was decreased, the average sensor output had increased as shown in Fig. 7.4 (e).

6). Unless there is a change of clad dimension or clad quality the operating condition changes did not generate a change on the sensor response.

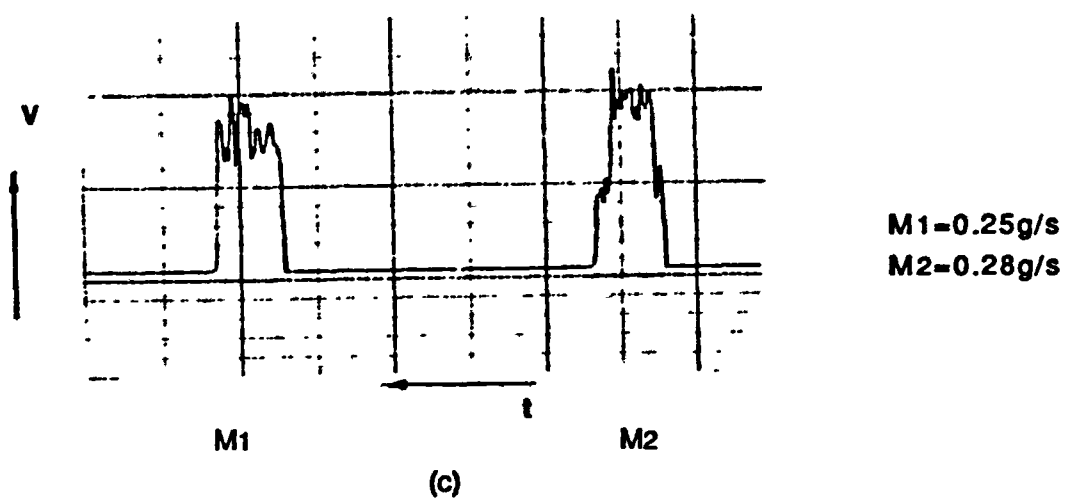
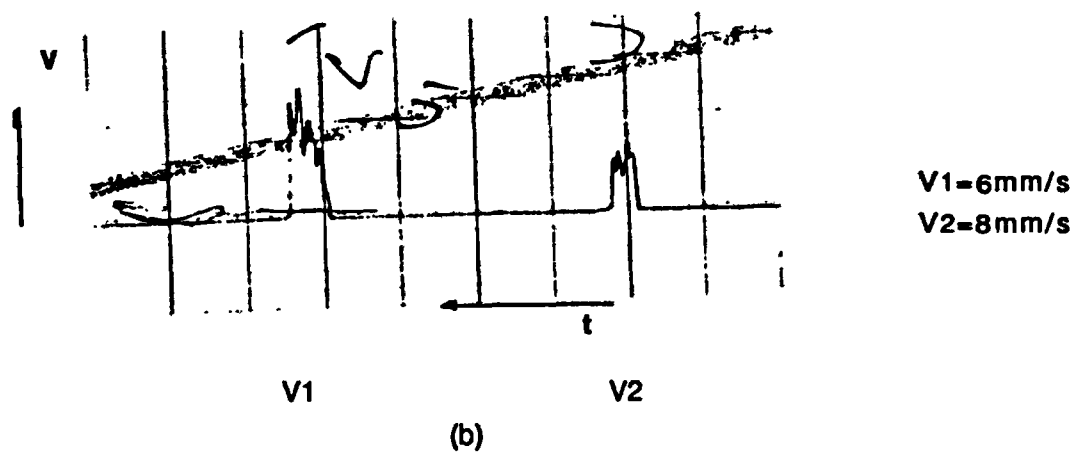
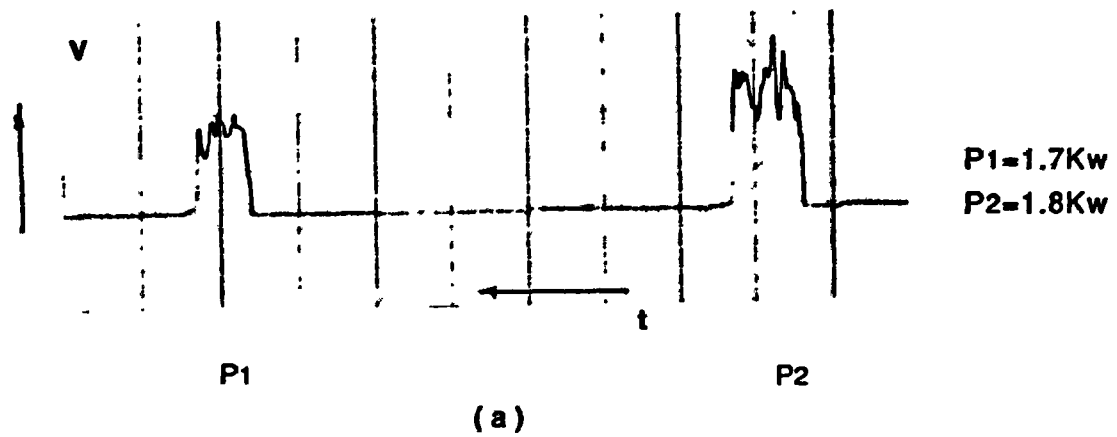


Fig. 7.4. a. b. c. Sensor responses to cladding condition changes.

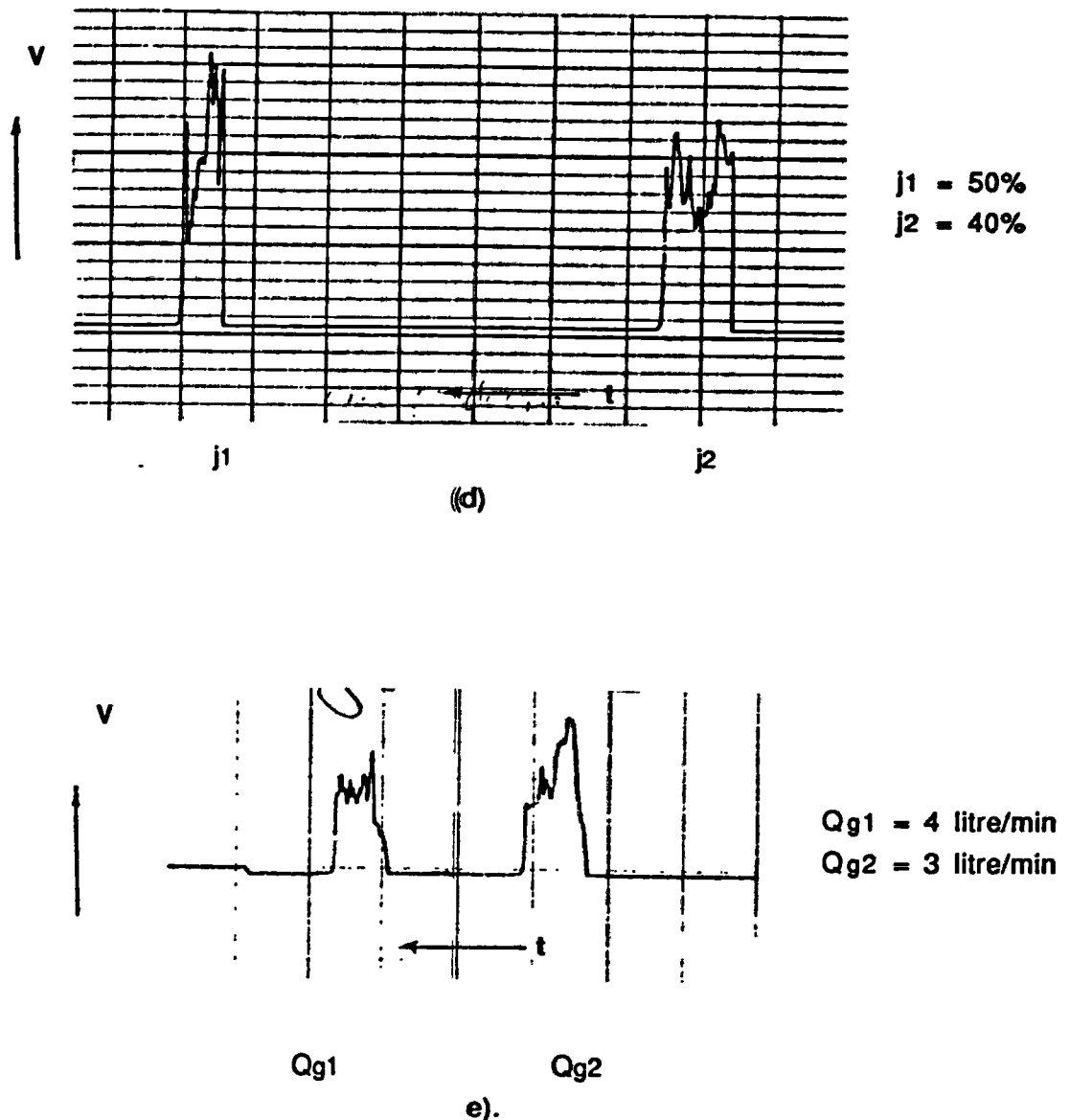


Fig. 7.4.c.d. Sensor responses to cladding condition changes.

It is known (See Chapter 2) that:

- a). The increase of laser power will slightly increase both clad bead width and clad thickness if there is a sufficient powder flow; The increase of laser power will reduce the clad thickness and increase the dilution when the powder feed is not sufficient.
- b). The increase of traverse speed will decrease both clad thickness and width.
- c). The increase of powder flowrate will generally reduce dilution and increase clad thickness. However if the powder flowrate is too much the clad bead would not be properly formed and clad bead width and height may get saturated.
- d). The increase of the degree of overlap will increase clad thickness.
- e). The reduction of powder travelling speed will increase the powder catchment and therefore increase the clad thickness.

Therefore the experimental results have indicated that when the clad thickness and width increase the sensor response will increase. For the materials used the increase of dilution could reduce the sensor response.

Fig. 7.5. shows the sensor responses to laser irradiation on substrate only, for single clad bead and 100% overlapped clad. The increase of clad thickness was clearly reflected by the increase of sensor response.

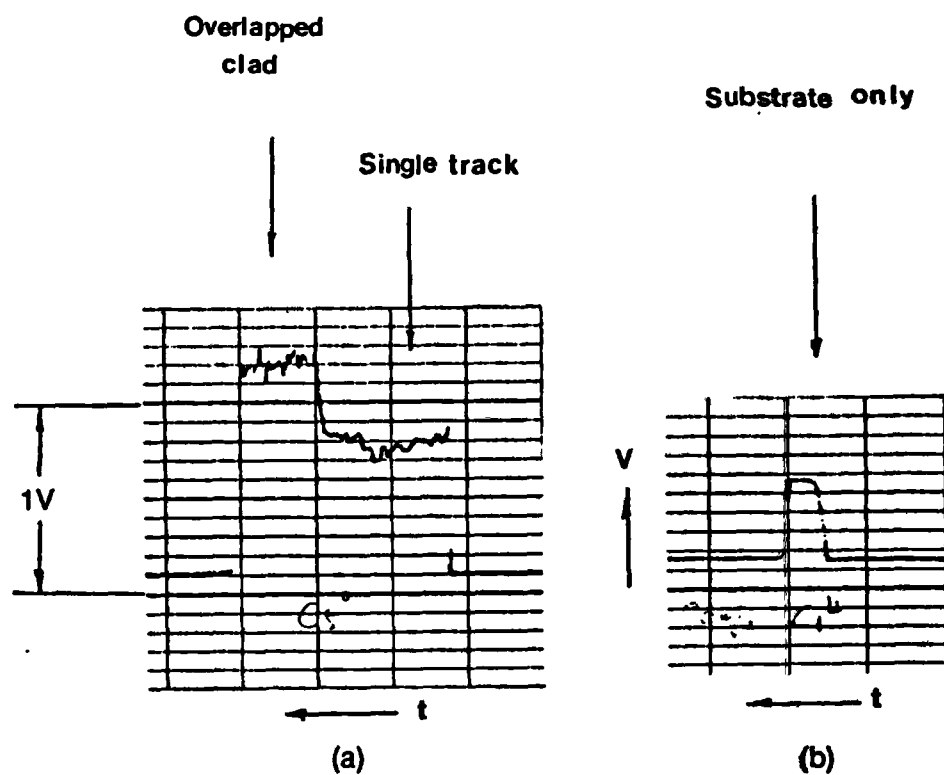
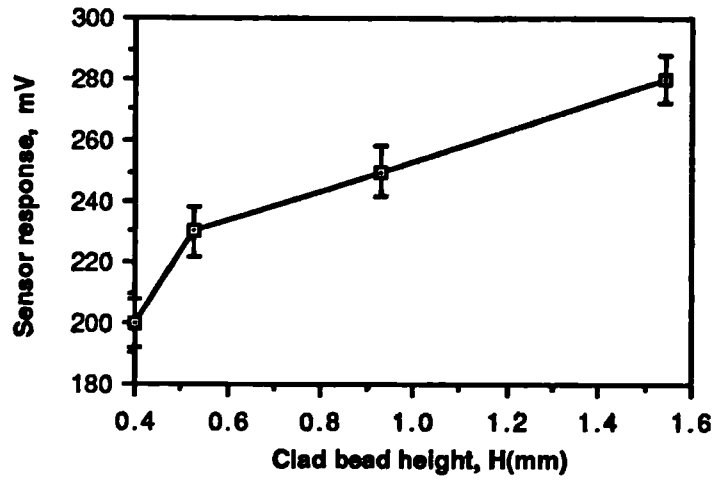
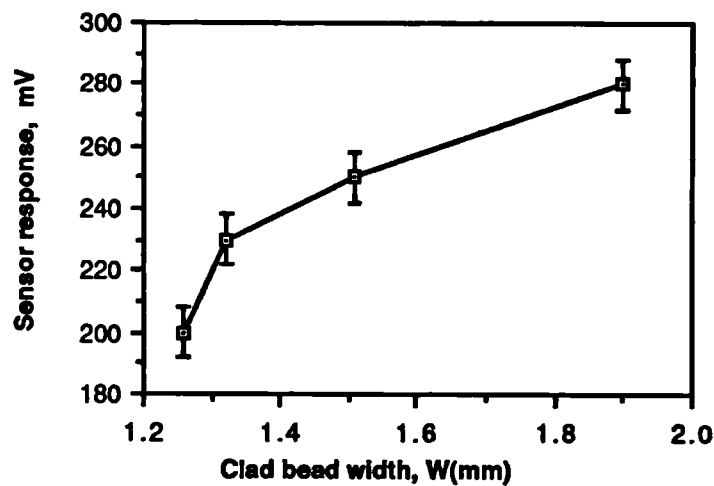


Fig. 7.5. Sensor response to melted substrate (no powder feed) radiation(b), single clad and 100% overlapped clad (a).

An experimental relationship between the sensor output and clad thickness and width is shown in Fig.7.6.



(a)



(b)

Fig.7.6 Variation of sensor response to clad bead height (a) and width (b) changes.

7.3.2 Clad roughness and faulty clad detection

In these experiments faulty clad beads were produced deliberately by varying substrate conditions, powder feed gas flow, nozzle gas flow, nozzle clipping and also accidental influences from system failure (such as lens cracking). Sensor responses to the faulty clad thus produced were recorded.

1). **Clad roughness detection:** By the examination of samples produced the above and many other experiments, it was found that the rougher clad will produce rougher sensor response and smoother sensor response can generally indicate a smoother clad. A typical comparison is given Fig. 7.7. where (a) corresponds to a rough clad and (b) corresponds to a smooth clad.

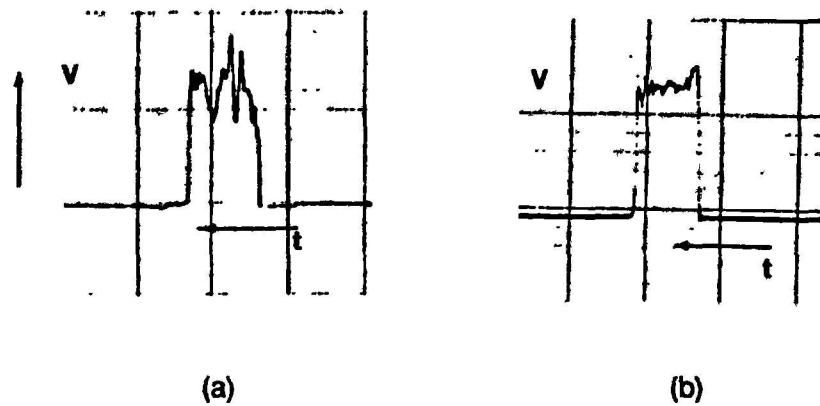


Fig.7.7. Comparison of sensor responses to a rough clad (a) and a smooth clad (b).

2). **Detection of faulty clad caused by substrate defect.** Experiment was made to produce a defective substrate by creating two melted spots on the substrate by laser prior to the cladding and then passing the clad track over them. The clad produced (on rod) is shown in Fig. 7.8a where a faulty clad at the point with defective substrate is apparent. The sensor response to these faults is shown in Fig.7.8.b. where the high magnitude pulses were produced at the faulty part of the clad bead.

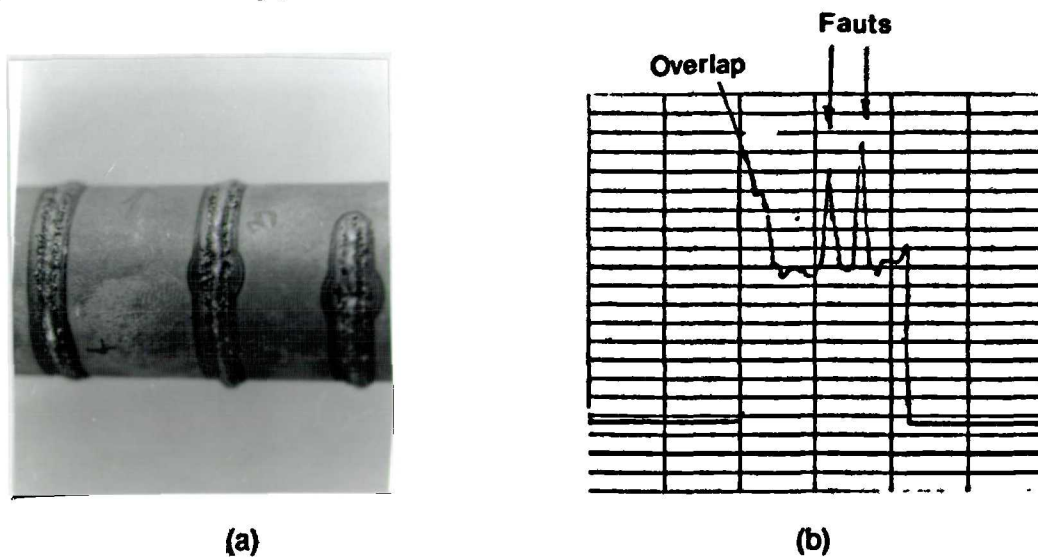


Fig.7.8. Sensor responses to a faulty clad caused by substrate defect. a). Clad track produced; b). Sensor response.

3). **Detection of faulty clad caused by powder feed failure and lens cracking.** When gas supply to the powder delivery system stopped causing a blockage of the powder feed tube so that powder flowrate reduced to zero. At the same time the laser lens also cracked therefore the laser power density on the workpiece was also reduced. The sensor response in this case is shown in Fig. 7.9. where the slope down indicates the reduction of clad material and laser power density.

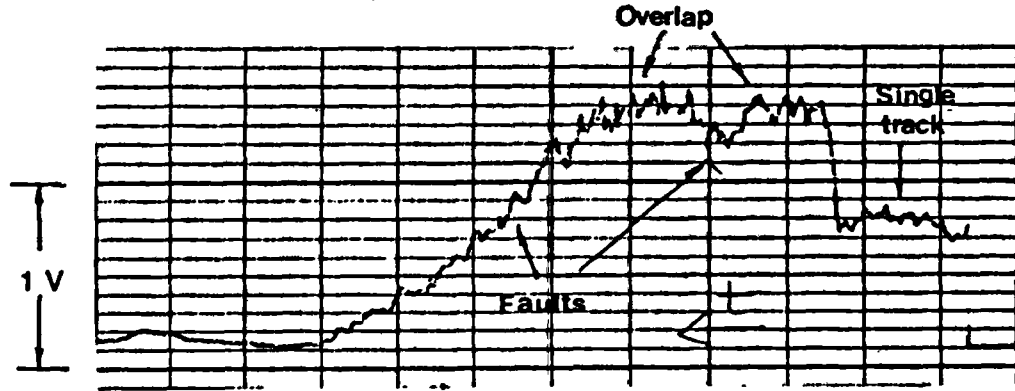


Fig. 7.9. Sensor response to faulty clad resulting from powder feed failure and lens cracking.

4). **Detection of poor clad bonding.** When the gas supply to the nozzle is unstable and there is a nozzle clipping, the clad appearance was very rough and bonding was poor (clad could be knocked off easily). The sensor response to this situation is shown in Fig. 7.10.

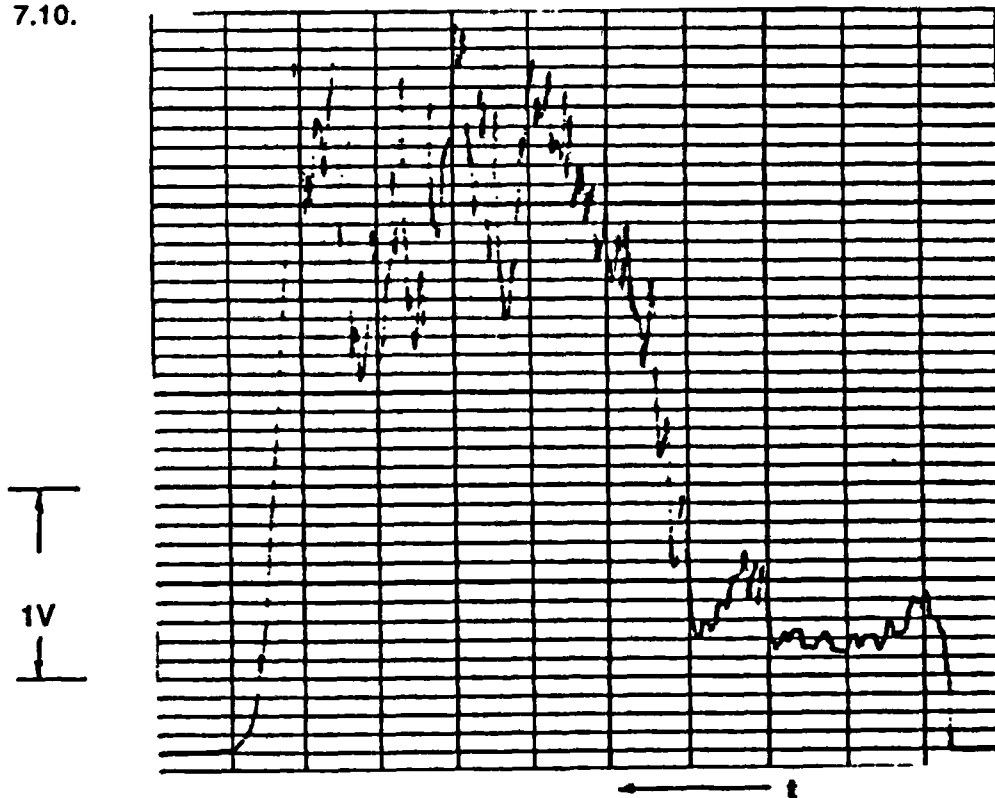


Fig.7.10. Sensor response to poorly bonded clad.

7.4 THEORETICAL ANALYSIS AND DISCUSSIONS

Since the molten pool temperature, shape, size and even the emissivity of the molten material can all contribute to the sensor response as shown in Eqn.(7-3), in order to explain the above observations it is necessary to investigate various factors affecting these parameters.

1). **Molten pool temperature.** A heat balance on the molten pool can be expressed as:

$$Q_a = Q_m + Q_{cd} + Q_{cv} + Q_{rd} \quad (7-5)$$

where Q_a = absorbed power from the incident beam (W).

Q_m = power used for melting powder and substrate surface + power used to heat up melt pool above the melting point (W).

Q_{cd} = Conducted loss from the pool during beam/material interaction (W).

Q_{cv} = surface convection loss to the air (W) .

Q_{rd} = radiated heat loss (W)

Q_a can be expressed as:

$$Q_a = \eta_c P \quad (7-6)$$

where η_c is the absorptivity of the materials to the laser beam with additional powder cloud effect (see Chapter 2).

It has been shown by Steen and Takeda^[61] that the clad molten pool is quite turbulent and heat flowrate in the pool is about 40 times faster than that by conduction. Therefore it is acceptable to consider the the average molten pool temperature as the pool temperature and Q_m can be expressed as:

$$\begin{aligned} Q_m = & \mu_p M [C_p(T - T_{p0}) + L_p] + M_s [C_s(T - T_{s0}) + L_s] \\ = & (\mu_p M C_p + M_s C_s) T + \mu_p M [L_p - C_p T_{p0}] + M_s [L_s - C_s T_{s0}] \end{aligned} \quad (7-7)$$

where M = powder feedrate (g/s)

C_p = specific heat of the clad powder (J/gK)

T = average melt pool temperature (K)

T_{p0} = powder temperature before reaching the melt pool (K)

L_p = latent heat of the clad material (J/g)

μ_p = powder catchment efficiency

M_s = melted substrate material in unit time (g/s)

C_s = specific heat of the substrate material (J/g K)

T_{so} = substrate surface temperature before laser irradiation (K)

L_s = latent heat of the substrate (J/g)

The conducted heat loss can be expressed by Fourier equation [157] as:

$$Q_{cd} = A_m k_c (dT/dz)_{av} \quad (7-8)$$

where **k_c** = thermal conductivity of the molten material

A_m = area of the solid/liquid interface in the molten pool

(dT/dz)_{av} = average temperature gradient at the solid/liquid interface. Steen has shown that [61] **(dT/dz)_{av}** is proportional to traverse speed. i.e.

$$(dT/dz)_{av} = a'V + b' \quad (7-9)$$

where **a'** and **b'** are two constants. Thus Eqn.(7-8) can be expressed as:

$$Q_{cd} = A_m k_c (a'V + b') \quad (7-10)$$

The heat loss convected to the air can be expressed using Newton's equation [157]:

$$Q_{cv} = h_c A' (T - T_a) \quad (7-11)$$

where **h_c** = convective heat transfer coefficient

T_a = air temperature.

A' = melt pool surface area.

The radiated heat loss can be expressed using Stefan-Boltzman equation

$$Q_{rd} = A' \epsilon \alpha T^4 \quad (7-12)$$

Since **Q_{cv}** and **Q_{rd}** are much smaller comparing with other losses [61], their contribution to pool temperature can be ignored. The heat balance on the melt pool can therefore be expressed as:

$$\begin{aligned} \eta_c P &= (\mu_p M C_p + M_s C_s) T + \mu_p M (L_p - C_p T_{po}) + M_s (L_s - C_s T_{so}) + A_m k_c (a'V + b') \\ &= (\mu_p M C_p + M_s C_s) T + H_p M + H_s M_s + A_m k_c (a'V + b') \end{aligned} \quad (7-13)$$

where **H_p** = $\mu_p (L_p - C_p T_{po})$

H_s = $L_s - C_s T_{so}$

Therefore the pool temperature can be expressed as:

$$T = \frac{\eta_c P - H_p M - H_s M_s - A_m k_c (a'V + b')}{\mu_p C_p M + C_s M_s} \quad (7-14)$$

It should be noted that M_s and A_m are not independent parameters. They are dependent on laser power and powder flowrate etc. For the same amount of laser power more powder flowrate would generally lead to less M_s and A_m because of less dilution. When powder flowrate is constant, the increase of laser power would usually produce the opposite effect. Therefore it could say that M_s and A_m are dependent on dilution.

2). **Molten pool size.** Steen has shown [61] that the length of melt pool can be related to the operating parameters as: $L = (\eta_c P - \mu_p H_m M) / k_c B W V$, where B is a constant and $H_m = \rho_p C_p T_m + L_p$ with T_m as the melting point of the powder. The melt pool size (pool surface area) can therefore be found to be:

$$A' = k' WL = k' ((\eta_c P - \mu_p H_m M) / k_c B V) \quad (7-15)$$

where A' = melt pool surface area

k' = a positive constant.

Therefore the experimental observations can be explained as follows:

a). When traverse speed increases both melt pool size A' and pool will reduce as the result of less beam/material interaction time, which causes less powder to be entrapped in the pool thus the heat in the melt pool is easier to be dissipated into the cooler substrate. As a result the sensor response should decrease as shown in Eqn.(7-3). This agrees with the experiments. The direct consequences of the increase of traverse speed is the reduction of clad bead width and height. Since the melt pool starts to resolidify even within the beam/material interaction time, more molten volume in the melt pool would require more time to cool down because of the resolidified hot thermal barrier material under the melt pool. Therefore we can say that the increase of clad bead height or width should lead to an increase of sensor response. This conclusion is not restricted a particular materials used.

b). In the experiment, since the clad material used has much less thermal conductivity ($k_c=13.4\text{W/m.K}$) than that of the substrate material ($k_c=60.5\text{W/mK}$), the sensor response for the overlapped clad would impede the normal flow of heat to the highly conducting substrate which could otherwise dissipate it quickly. As a result the melt pool temperature is higher than that for the single track cladding. This is also indicated in Eqns.(7-14) and (7-15). Therefore if clad material has lower thermal conductivity than that of the substrate the overlapped clad should produce higher sensor response than the single bead clad under the same operating conditions. Similarly, if the substrate material

is more thermal conductive than the clad material, the clad melt pool temperature should be higher than that of substrate melt pool temperature under the same operating conditions. This agrees with the experiment. Note that although substrate material has higher melting point than that of clad material (mild steel 1810°K and stainless steel 1670°K) the light intensity emitted from stainless steel is still higher because of less thermal conductivity.

c). If there is an occlusion or a poor bond or porosities or other similar default of clad, the heat will remain at the surface longer (reflected in the Eqns.(7-14) and (7-15) as an increase of k_c). Thus the sensor response is stronger.

d). For a certain amount of laser power it will melt certain amount of materials which are clad + substrate. If clad material feed is inadequate, melt pool will have more substrate materials (dilution). Therefore M_s and A_m will increase. If the substrate material has higher thermal conductivity, increase of dilution would increase the thermal conductivity of the melt pool material and the temperature gradient at the solid/liquid interface, which would cause the heat to be dissipated more quickly resulting in a reduction of the sensor signal.

e). The increase of powder particle velocity reduces the powder catchment (See Chapter 2), which would produce the similar sensor responses as for the reduction of powder flowrate.

f). When laser power increases and there is sufficient powder flow, it would produce thicker clad resulting an increase of the sensor signal. However if the powder feed is not sufficient, the increase of laser power would melt more substrate instead, causing higher dilution and the possible reduction of clad thickness (See Chapter 2 experiments by the author). In this case the sensor response may decrease for the same reason as that discussed in (d).

7.5 IN-PROCESS LASER CLAD QUALITY ASSURANCE

From the above study it can be seen that it is possible to use the system for in-process cladding monitoring. The sensing system not only is able to tell us "*whether*" something is wrong by comparing with a pre-recorded processing "signature", but also possible to assess "*how much*" the process deviates from the requirement by more detailed quantitative analysis. In this section mathematical analysis of the sensor signal will be discussed so that faulty clad can be detected.

7.5.1. Signal averaging for clad thickness assessment

Since the sensor signal is generally noisy, the representation of the level of response

for clad thickness assessment and process monitoring requires the averaging of the sensor response over a period of time.

The average of the sensory signal can be found using

$$S_a = \frac{1}{n} \sum_{i=1}^n S_i \quad (7-16)$$

where S_a is the average of the sensory signal, n is the number of samples made by a micro-processor for averaging and S_i is the sensory signal. Experiments found that the clad roughness caused signal oscillation is between 5 and 30Hz. Therefore if the sampling rate is 15 to 70Hz (according to Shannon sampling theorem), 15 to 70 points are required for the averaging period of 1 second which was found to be sufficient for the average signal level representation. A linear relationship may be found between clad thickness and sensor average signals when clad thickness is above certain level as shown in Fig.7.6.

7.5.2. Standard deviation for clad roughness assessment

Since rougher clad produces rougher sensor response, the clad uniformity can be estimated by calculating standard deviations of the sensor signal from its average value. The standard deviation σ can be calculated using:

$$\sigma = \sqrt{\frac{\sum_{i=1}^n (S_i - S_a)^2}{n-1}} \quad (7-17)$$

The higher the value σ is the rougher the clad would be .

7.5.3. Quality control band for on-line clad quality assurance

From the experiments it can be found that "good" clad will produce smooth, leveled sensor signal while faulty clad or "poor" clad will produce either heavy fluctuated sensor response or too much deviation from the "normal" response line. While the signal smoothness can be analysed by standard deviation calculation, the average magnitude of the sensor signal can be obtained by the signal averaging and compared with "Quality Band" as shown in Fig.7.11 for on-line clad quality assurance. Different degree of band can be used to classify whether clad is "very good" or "good" or "OK" or "bad" .

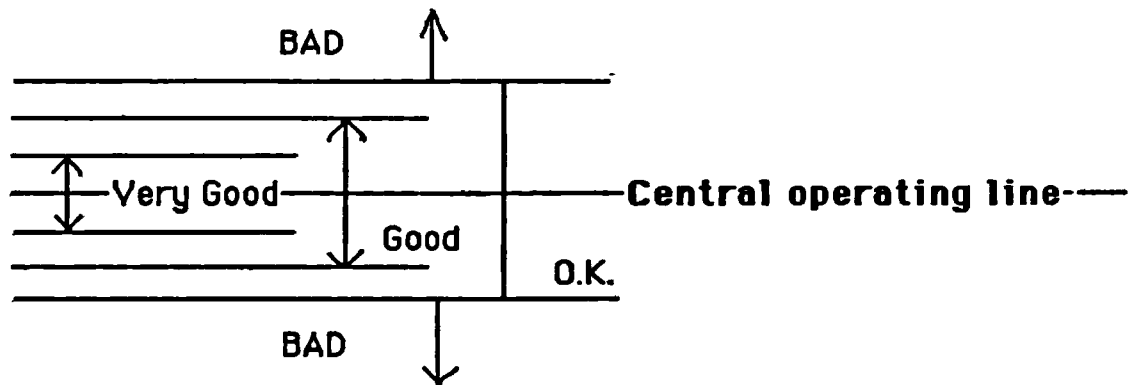


Fig.7.11 The quality control zones/lines of laser cladding operation.

The values of the these zones/lines were found for the materials studied to be:

- a) **"very good" zone:** 10% deviation from the central operating line (the sensor average for a good clad). In this zone, the clad results will be uniform and consistent.
- b). **"good" zone:** 20% deviation from the central operating line. In this zone. all clad results are acceptable but some variation of clad parameters may result. The clad surface may be rougher.
- c). **"OK" zone:** 30% deviation from the central operating line. Clad is rough and poor but could be controlled to become accepted, since there is no serious fault in the clad.
- d). **"bad" zone:** deviation beyond 30% from the central line. If the sensor signals fall into this zone, it indicates a system failure or uncontrollable clad faults. Alarm should be given in this case. ‡

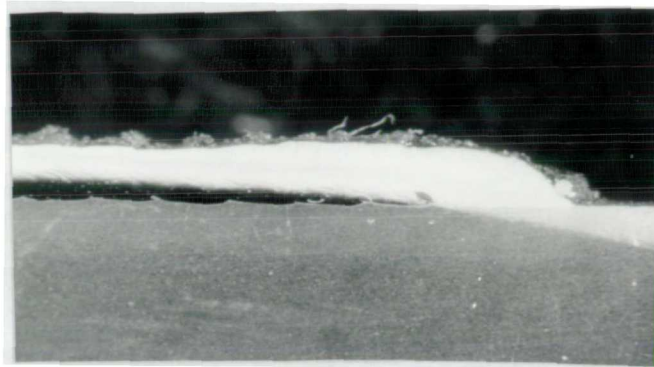
7.5.4. Faults diagnosis rules

The following rules could be used for laser cladding faults diagnosis concerning the cladding of less thermal conductive material on more thermal conductive substrate (More is included in Appendix C):

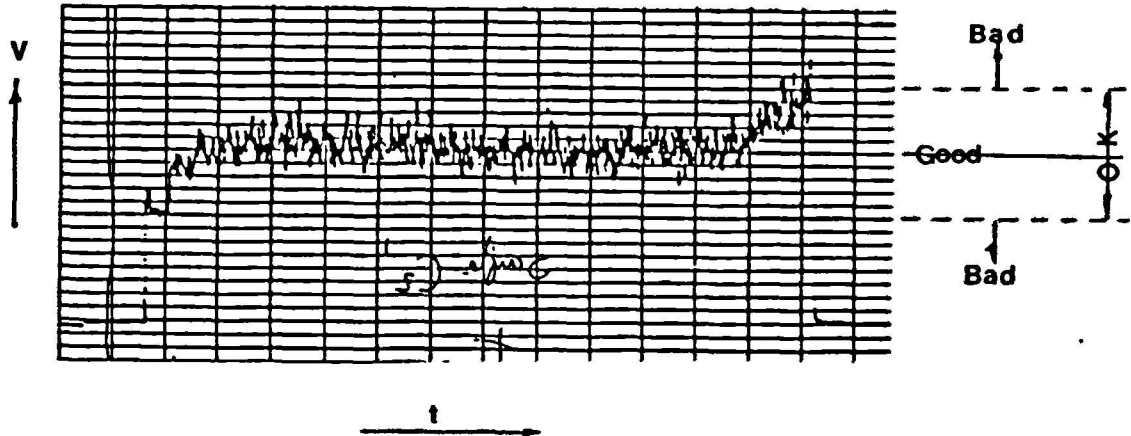
- 1). If the average signal is above the upper limit (30% line) of the operating band and there is a frequent heavy oscillation of the signal, then the clad is possibly not bonded properly or there are porosities or there may be some system failure.
- 2). If the occurrence of the pulse is infrequent (once or twice in the given period) then it is very likely that there are some clad surface craters (vaporization of clad material) or substrate defects or clad cracks.
- 3). If the average signal is below the lower operating limits then possibly there is powder supply failure or lens cracking.

7.5.5. Application examples

1). **Continuous monitoring of overlapped rod clad quality.** Fig 7.12b shows the sensor response for the continuous spiral laser cladding of 316 stainless steel on En8 mild steel rod. The rising of the sensor signal on the right indicates the growth of clad thickness at the end of the clad track (Fig.7.12 a). The laser cladding operation can therefore be stopped for simple quality control since the average of sensor signals had risen beyond the band upper acceptable limit which was set 30% of the central line (1.5V).



(a)



(b)

Fig.7.12. Continuous monitoring of laser rod cladding. a). sample appearance. b). Sensor response.

2). **Comparison with operating band for faulty clad recognition.** For faulty clad recognition, the quality band was defined as 30% tolerance. The normal operating line was obtained by recording the sensor response level for the acceptable clad. In this experiment the central line was defined as 750mV and the upper acceptable band limit was

therefore 975 mV and lower acceptable band limit was 525mV. Fig.7.13 shows the sensor responses for clad quality.

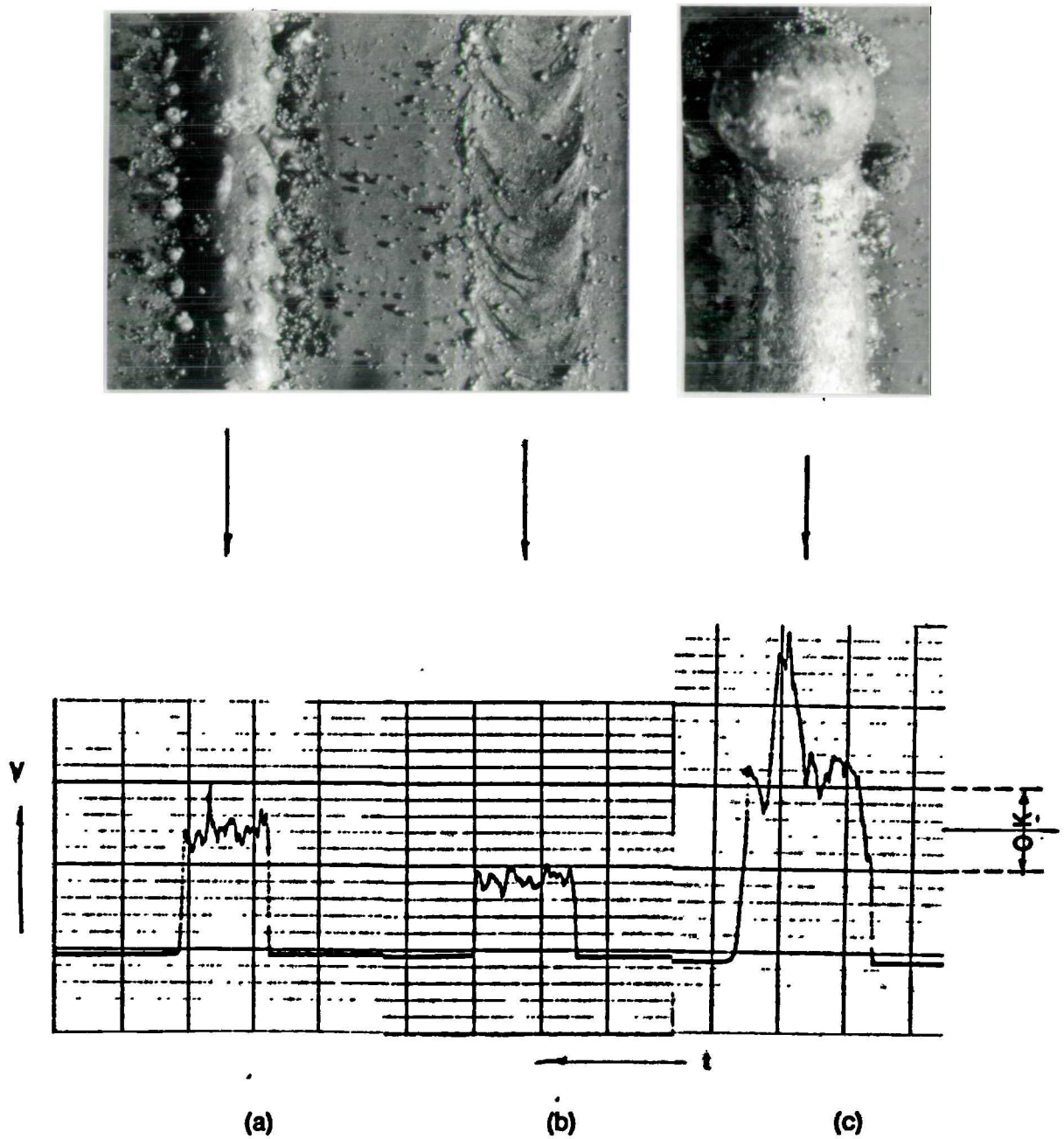


Fig. 7.13. Faulty clad recognition by using quality control band. a). Acceptable clad; b). No powder stick (powder particle velocity too high). c). Over thick and traverse fail.

7.6. CONCLUSIONS

An opto-electric sensing technique for the in-process monitoring the clad quality has been developed which has the following features:

- 1. Low cost**
- 2. Fast response**
- 3. In-process, non-contact**
- 4. Multi-information**
- 5. Compact**

Experiments and theoretical study have found that the sensor could detect the clad roughness, clad thickness or volume variation or a faulty clad caused by poor operating conditions or defective substrate. Mathematical representation of the signal and diagnostic rules were developed together with the introduction of quality control lines , which enables the clad quality to be determined on-line.

CHAPTER 8

ON-LINE DILUTION SENSING

8.1 INTRODUCTION

Dilution is of constant concern in laser cladding. To achieve a good fusion bond without creating any dilution requires the careful arrangement and precise control of operating parameters (See Chapter 10 for the optimum clad condition setting). Dilution could also vary during processing due to, for example, the substrate temperature rise (See General Introduction). Therefore it is necessary to know the level of dilution during processing so that the adaptive process control to maintain the dilution level can be implemented (Chapter 11 will discuss the adaptive laser cladding control law development). This chapter describes the author's work on the development of a dilution sensor. The dilution sensing was achieved by using an electro-magnetic transducer which generates alternating electromagnetic field on the clad surface and detects the magnetic flux change caused by clad dilution - a contamination of clad by substrate material. Both theoretical and experimental study were made to optimized the sensing. A new method was developed to reduce the effect of air gap between the sensor and clad surface so that the sensing can be used on-line.

Alternative methods of determining the level of dilution in laser clad layer are available, but they cannot be used on-line:

1. By using scanning electron microscope (SEM) to analyse the clad composition and then compare it with the un-contaminated clad material. This requires the special preparation of the sample (cross sectioning, polishing, moulding and gold plating etc.) and the sample must be placed in a special vacuum chamber for testing.

2. By using optical microscope to examine the cross section of clad bead and calculating dilution as the ratio of clad bead area under the substrate line to the total cross section bead area (See Chapter 2 for dilution definition). This again needs the preparation of the sample (cutting, polishing and etching etc.).

The method described in this Chapter was developed to enable the information on clad dilution to be obtained both durring processing and off-line.

8.2 SENSOR DESIGN AND THEORETICAL ANALYSIS

It is known that the melt pool in laser cladding is highly turbulent (See Chapter 2), thus the contamination of clad is homogeneously distributed on the clad track [62]. Table 8.1 gives the experiment results of the clad surface composition change when there is an on-set of the dilution (for 316 stainless steel clad on En8 mild steel substrate). These changes would change the magnetic and electric properties of the clad. Table 8.2 lists the relative permeabilities of selected materials and the effect of the "impurities".

Table 8.1 Clad surface composition analysed by Scanning Electron Microscope.

	pure melted powder	with 13% dilution	with 42% dilution	En8 steel substrate
Fe	67.203	71.912	81.601	97.625
Cr	17.457	15.411	9.719	0
Ni	12.156	10.906	7.245	0.07
Mo	2.201	0.491	0	0
Si	0.429	0.479	0.355	0.11
Mn	0.346	0.229	0.338	0.63
S	0.044	0.572	0.725	1.256

Table 8.2 Relative permeability of the selected materials.

Substance	μ_r	Substance	μ_r
Lead	0.999983	Cobalt	250
Copper	0.999991	Nickel	600
Air	1.00000	Mild steel (0.2c)	2000
Aluminum	1.00002	Iron(0.2 impurity)	5000
Stainless steel	1.005-10.0	Purified iron	200000

Although the effect of materials composition on the magnetic and electric properties is

complicated. If the materials used for the clad and that for the substrate have a distinct difference in these properties as they often do (such as the cladding of 316 steel which is non-ferrous on mild steel which is ferrous, or the cladding of ceramics which is insulator on steel alloys which is a conductor), then the contamination of the clad by the substrate could alter the magnetic or the electric properties significantly as will be seen later in this Chapter. If these changes can be detected, then the clad dilution could be evaluated. An electro-magnetic transducer was therefore developed for the non-contact sensing of the clad surface magnetic and electric property change. The sensing principle can be described as follows.

Consider a transducer configuration as shown in Fig. 8.1. with primary winding of N_p turns and second winding N_s turns.

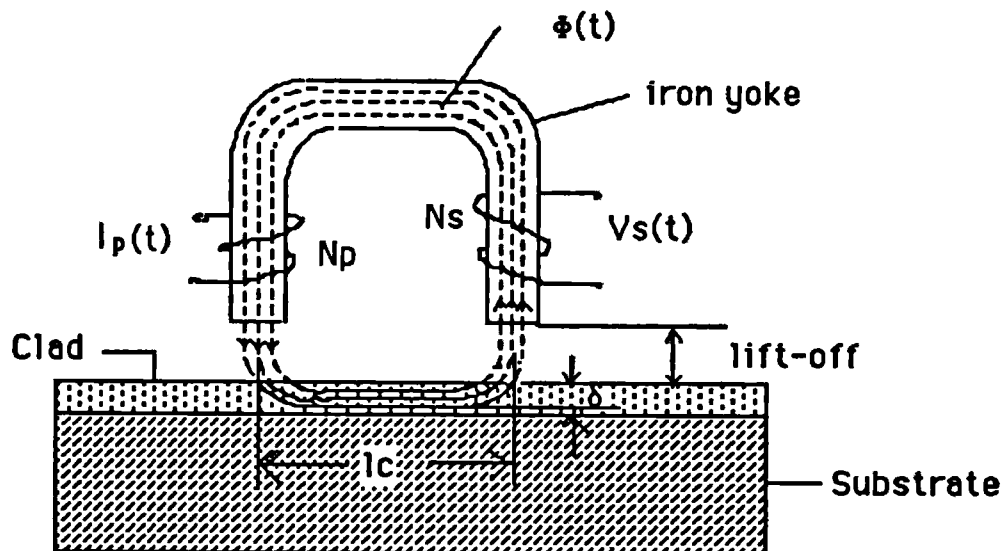


Fig.8.1. Basic transducer configuration for dilution sensing.

Applying Ampere's law to the magnetic loop, we have

$$N_p I_p(t) = [\Phi(t)/\mu_0](R_{tr} + R_g + R_c) \quad (8-1)$$

- where
- $I_p(t)$ = the time-varying current input in the transmitter
 - $\Phi(t)$ = the magnetic flux of the loop
 - μ_0 = permeability of the vacuum
 - R_{tr} = reluctance of the transducer body
 - R_g = reluctance of the air gap
 - R_c = reluctance of the clad material.

The reluctance of a material in the magnetic path can be found as:

$$R_i = l_i / \mu_{ri} A_i \quad (8-2)$$

where l_i = the length of the magnetic path through object i
 A_i = the cross area of the magnetic path through object i
 μ_{ri} = the relative permeability of the object i

The induced voltage on the secondary winding (magnetic field detector) according to Farady's law will be:

$$V_s(t) = N_s \frac{d\Phi(t)}{dt} = \frac{\mu_0 N_s N_p dI_p(t)/dt}{R_{tr} + R_g + R_c} \quad (8-3)$$

where $V_s(t)$ is voltage induced on the secondary winding.

If the penetration depth of the magnetic field to the sample surface is small enough so that $A_{clad} \ll A_{trans}$, where A_{trans} is the area of the magnetic poles of the transducer facing the sample surface, and since the core for the transducer is made of pure iron which has high permeability, from Eqn. (8-2) we can see that the reluctance of the transducer R_{tr} is very small compared to that of air gap and clad surface and R_{tr} and therefore R_{tr} can be neglected in Eqn. (8-3) leaving the effect of air gap and clad surface only. The voltage induced on the secondary coil becomes:

$$V_s = \frac{\mu_0 N_p N_s dI(t)/dt}{R_g + R_c} \quad (8-4)$$

The reluctance of air gap, R_g , and sample surface, R_c , can be expressed respectively as:

$$R_g = 2d / A_g \mu_0 \quad (8-5)$$

$$\text{and} \quad R_c = l_c / \mu_c A_c \quad (8-6)$$

where d = the sensor distance from the clad surface (m)
 A_g = the area of the transducer poles (m^2)
 μ_c = relative permeability of the clad track (dimensionless)
 A_c = path area of the magnetic field in the clad track (m^2)
 l_c = path length of that magnetic fields passes in the clad track (m)

A_c is proportional to the penetration depth of the magnetic field to the clad which is decided by the following equation:

$$\delta = (\pi \mu_0 \mu_c \sigma f)^{-1/2} \quad (8-7)$$

where δ = the magnetic flux penetrating depth into the clad

σ = the conductivity of the clad

f = the exciting frequency for generating the magnetic field

This relationship suggests that the penetration depth can be controlled by the field exciting frequency: the higher the frequency is, the less depth of penetration will be. Table 8.3 gives the depth of penetration of the magnetic field at various frequencies calculated using Equation (8-7) for 316 stainless steel and En8 mild steel.

Table 8.3. Depth of penetration of the magnetic field for 316 and En8 steel at various frequencies.

f (kHz)	1	4	10	40	100	400	1000	4000
δ (mm) 316 steel	4.288	2.144	1.355	0.675	0.428	0.214	0.136	0.068
δ (mm) En8 steel	0.612	0.306	0.194	0.097	0.061	0.030	0.019	0.009

The material reluctance R_c is therefore proportional to $\sqrt{f}$.

If the exciting source is sinusoidal current with a frequency f , i.e.

$$I_p = I_m \sin(2\pi ft) \quad (8-8)$$

then the sensor response can be written as:

$$V_s = \frac{\mu_0 2\pi f N_p N_s I_m \cos(2\pi ft)}{R_g + R_c} \quad (8-9)$$

It can be seen that the sensor response includes the mixed information of both air gap (R_g) and sample surface property (R_c). This is the problem that previous electro-magnetic transducers face and there had been no appropriate solution to it. To separate these two signals, a new approach was made to use two different frequencies to excite the transducer alternatively as shown in Fig.8.2.

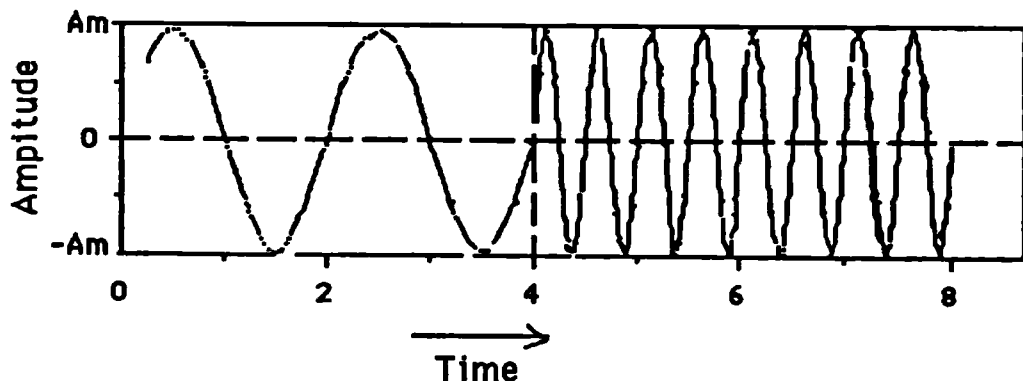


Fig. 8.2 Illustration of using two different frequencies alternatively for the transducer.

The sensor response to the second exciting source with frequency nf will be:

$$V_{sn} = \frac{\mu_o 2\pi nf N_p N_s I_m \cos(2\pi nft)}{R_g + R_c \sqrt{n}} \quad (8-10)$$

If peak demodulation (only the maximum positive amplitude of the received signal in each cycle is sampled) is used for the signal conditioning (RMS could also be used for the signal demodulation. The RMS value is $1/\sqrt{2}$ of the peak demodulation magnitude.), then Eqns. (8-9) and (8-10) will become time independent and can be expressed as:

$$V_s = \frac{\mu_o 2\pi f N_p N_s I_m}{R_g + R_c} = A' \frac{1}{R_g + R_c} \quad (8-11)$$

$$V_{sn} = \frac{A' n}{R_g + R_c \sqrt{n}} \quad (8-12)$$

Where $A' = \mu_o 2\pi f N_p N_s I_m$ is a constant if the principle exciting frequency f is fixed and a constant current source is used at the primary side. By solving the above two equations R_g and R_c can be obtained separately as:

$$R_c = \frac{A'}{\sqrt{n} - 1} \left(\frac{n}{V_{sn}} - \frac{1}{V_s} \right) \quad (8-13)$$

$$R_g = \frac{A'}{\sqrt{n} - 1} \left(\frac{\sqrt{n}}{V_s} - \frac{n}{V_{sn}} \right) \quad (8-14)$$

For example, if $n=4$, i.e. $f_2=4f_1$, then Eqns. (8-13) and (8-14) become:

$$R_c = A' \left(\frac{4}{V_{sn}} - \frac{1}{V_s} \right) \quad (8-15)$$

$$R_g = A' \left(\frac{2}{V_s} - \frac{4}{V_{sn}} \right) \quad (8-16)$$

which gives separated information on both sample surface property and air gap. Two conditions must be satisfied in order use the above formula:

- 1). The exciting source must be a constant current source.
- 2). The demodulator at the receiving end must have the operating bandwidth that

covers the frequencies the sensor works at.

Using this method, the sensor distance to the clad surface can be found from Eqn.(8-5) to be:

$$d = R_g A_g \mu_o / 2 \quad (8-17)$$

and the laser clad dilution could be evaluated using:

$$\text{Dilution} = \frac{R_c - R_{cp}}{R_{sp} - R_{cp}} \times 100\% \quad (8-18)$$

where R_{cp} = the reluctance of the non-contaminated clad
 R_{sp} = reluctance of the substrate material

These two parameters can be easily by placing the un-contaminated clad material and substrate under the sensor respectively so that the values can be calculated using Eqn. (8-13) or (8-16).

From Eqn.(8-18) it can be seen that:

- 1). For un-contaminated clad, $R_c = R_{cp}$ and therefore the calculated dilution becomes 0.
- 2). For totally contaminated clad, $R_c = R_{sp}$ and therefore the value of the calculated dilution becomes 100%.
- 3). If R_c falls between R_{sp} and R_{cp} , then the value of calculated dilution is between 0 to 100% no matter whether $R_{sp} > R_{cp}$ or $R_{cp} > R_{sp}$. The nearer the value of R_c is to R_{sp} the higher the dilution will appear. This dilution representation may not correspond to the actual degree of dilution since a linear relationships was assumed here. However an one to one map of the two should exist and if the calculated "dilution" can be maintained as a constant by feedback control (See Chapter 11) the actual dilution level should be kept as a constant as well.

The best sensitivity of the sensor for dilution measurement can be found, from the above analysis, in the cases of ferrous material clad on non-ferrous substrate or non-ferrous metal on ferrous substrate. This combination occurs in the majority of industrial cladding applications, since often iron or carbon steel are used as substrate, which are ferrous material while stainless steel, silicon carbide, silica etc. are used as clad material which are non-ferrous materials or at least of greatly different permeabilities to ferrous substrates. Thus the sensing technique could find its applications in most of the cladding

practice. Nevertheless, the sensing for non-ferrous material cladding could also give a fair result since dilution will change conductivity of the material, which in turn changes the reluctance of the clad. The better sensitivity could be obtained if the clad-substrate combination is one conductive, the other non-conductive.

A prototype transducer was made which consists of an electromagnetic field generator and a coaxial magnetic flux detector as shown in Fig. 8.3. The primary winding uses 0.2 mm copper wire for 350 turns and the secondary winding 400 turns using the same material. The coaxial configuration was chosen to reduce the edge effect and ensures better efficiency. The iron yoke has 2.5mm diameter. Shielding is employed to prevent environmental noise.

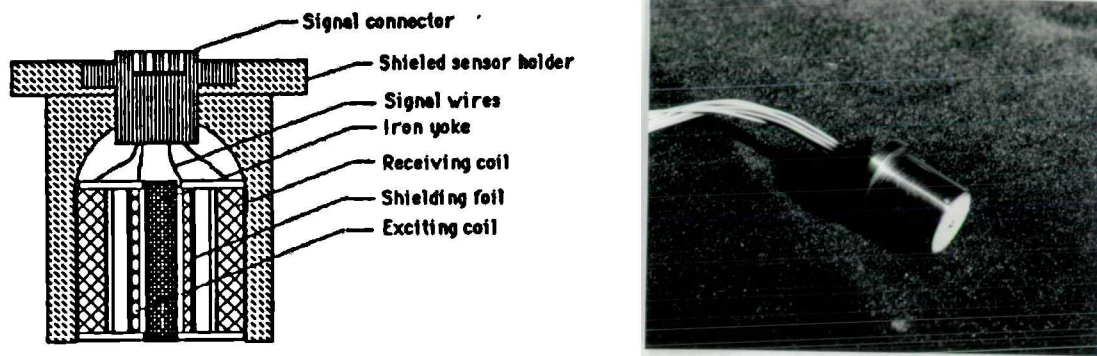


Fig.8.3. Prototype dilution transducer (left, schematic, dimension exaggerated; right, a photograph of the actual transducer).

8.3 SENSING EXPERIMENTS AND OPERATING OPTIMIZATION

Experiments were made on samples with 316 stainless steel clad on mild steel substrate using the developed dilution sensor. The exciting source was from a signal generator (Voltage source). The received signal was fed to RMS meter which produces output voltage proportional to the magnitude of the peak value. Effects of the signal source waveform, frequency, sensing distance etc. were examined.

Experiment 1. Sensor response with different exciting frequencies and waveforms. Fig. 8.4 shows the experimental sensor sensitivity (differences between 100% dilution response and 0% dilution) at various exciting frequencies with different waveforms (sinusoidal, square and triangular). The reduction of the sensor sensitivity at

high frequency was found due to the limited band width of the RMS meter used in the experiment as shown in Fig.8.5. The noise level of the signals was found below 0.1mV, which gives more than 240 : 1 signal to noise ratio. Also can be seen from Fig.8.4 that square wave exciting source produced most sensitive response. However since sinusoidal wave produces least waveform distortion at the receiving end as shown in Fig. 8.6, It is recommended that sinusoidal wave be used for the ease of signal processing such as peak demodulation.

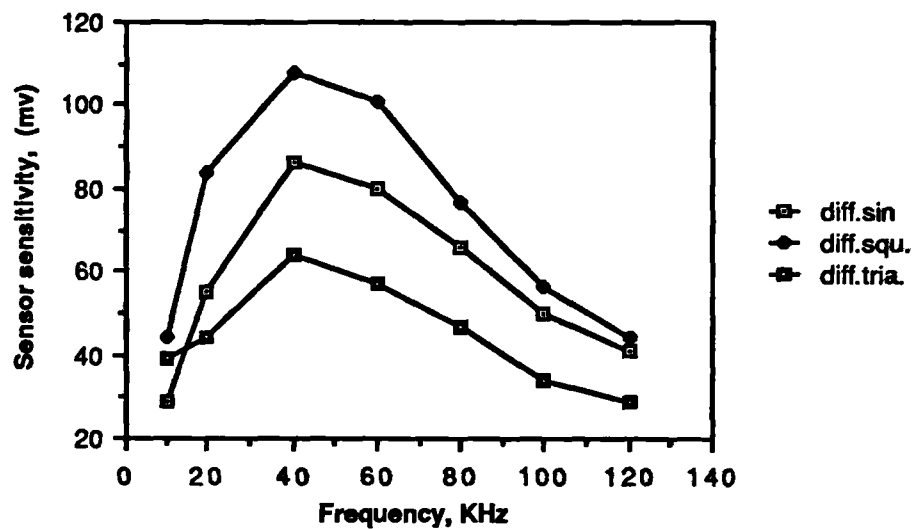


Fig. 8.4. Sensor response sensitivity at different frequencies and exciting waveforms.

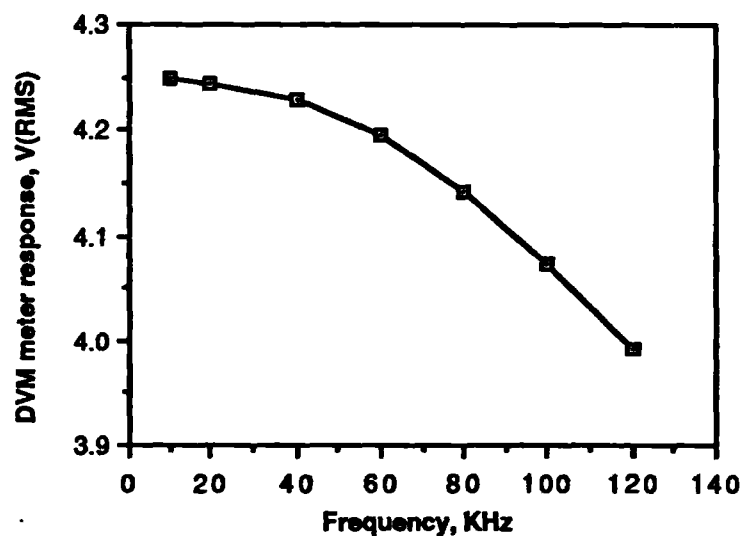
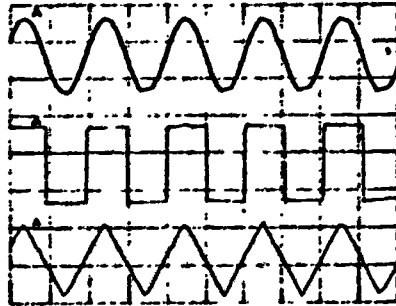
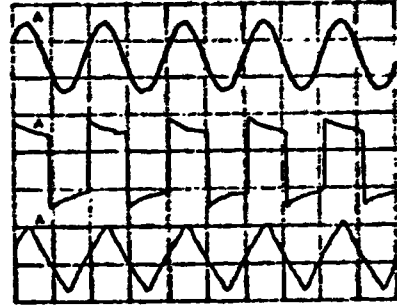


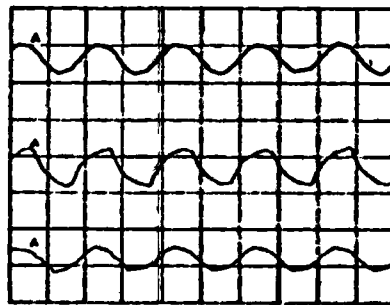
Fig. 8.5. RMS meter response curve to different frequencies.



(a)



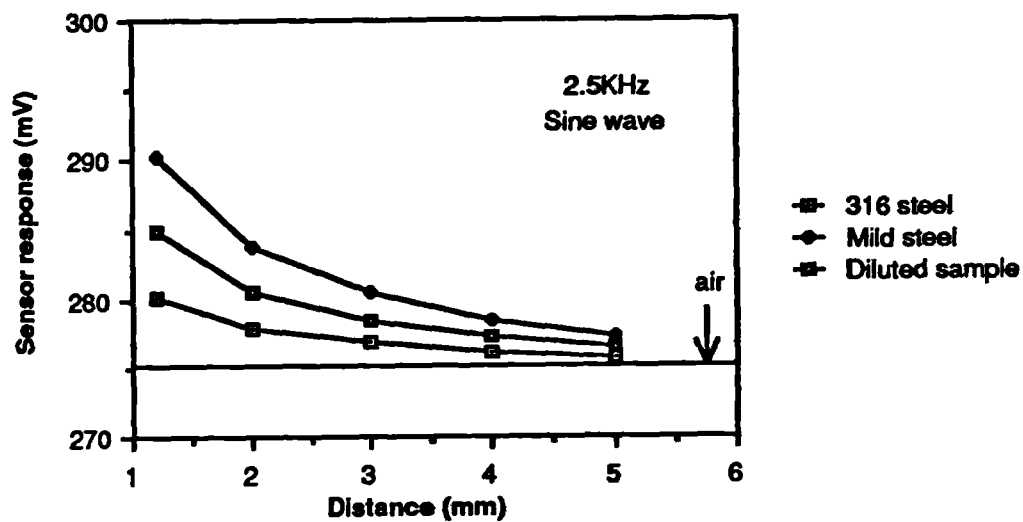
(b)



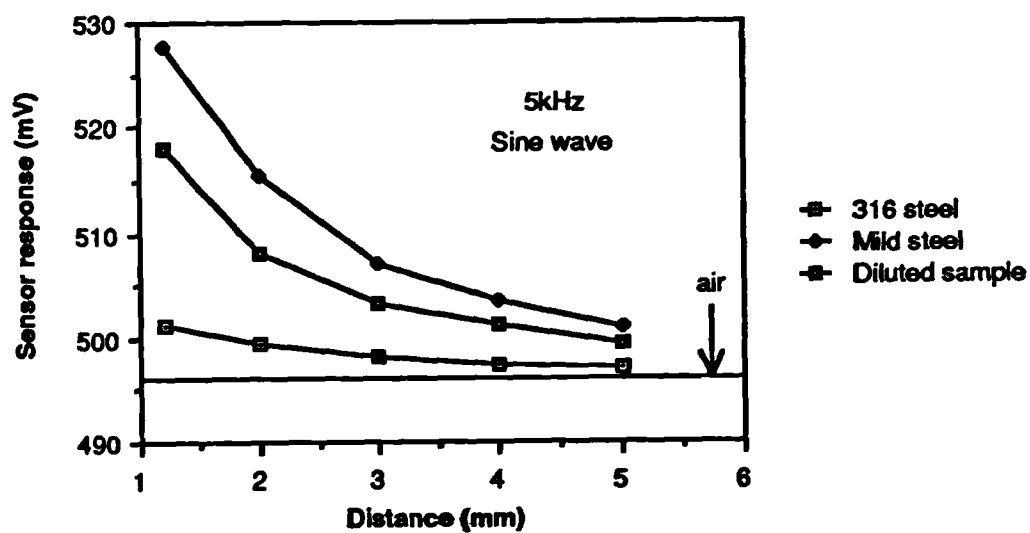
(c)

Fig. 8.6. Waveform comparison for dilution sensing. a). As generated from the signal generator; (b) Primary coil waveforms; c). Secondary coil waveforms.

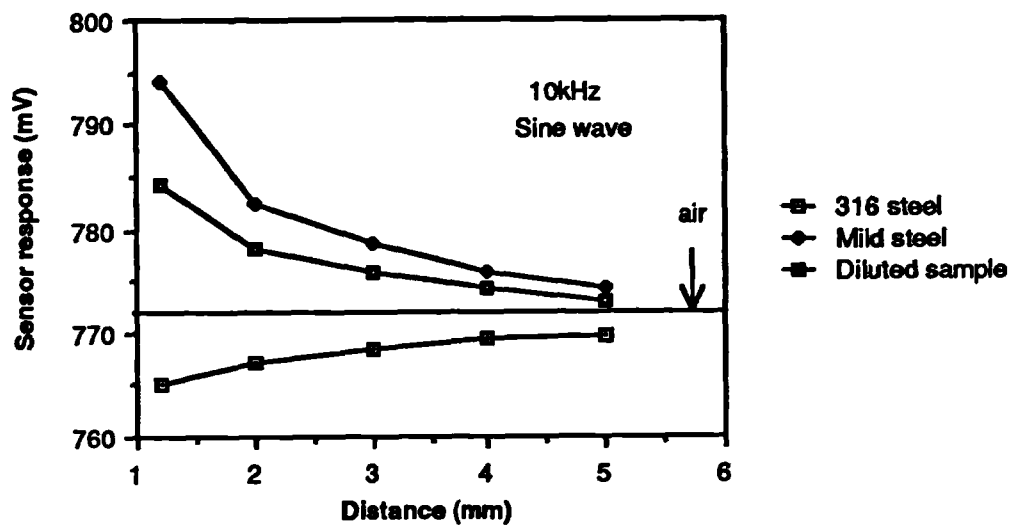
Experiment 2. Sensor responses at various distances and frequencies. In these experiments sinusoidal signal was used. 0.2 mm spacers were used to lift the sensor at different distances from the sensing object. At each specified distance different frequencies were used to generate sensor responses. The received signal was fed to a multimeter for RMS reading. The meter bandwidth was very limited as shown in Fig. 8.5. 316 steel, mild steel, and a 40-80% diluted sample were examined using the sensor. The response curves were plotted using Cricket Graph on Macintosh SE computer. These are shown in Fig.8.7.



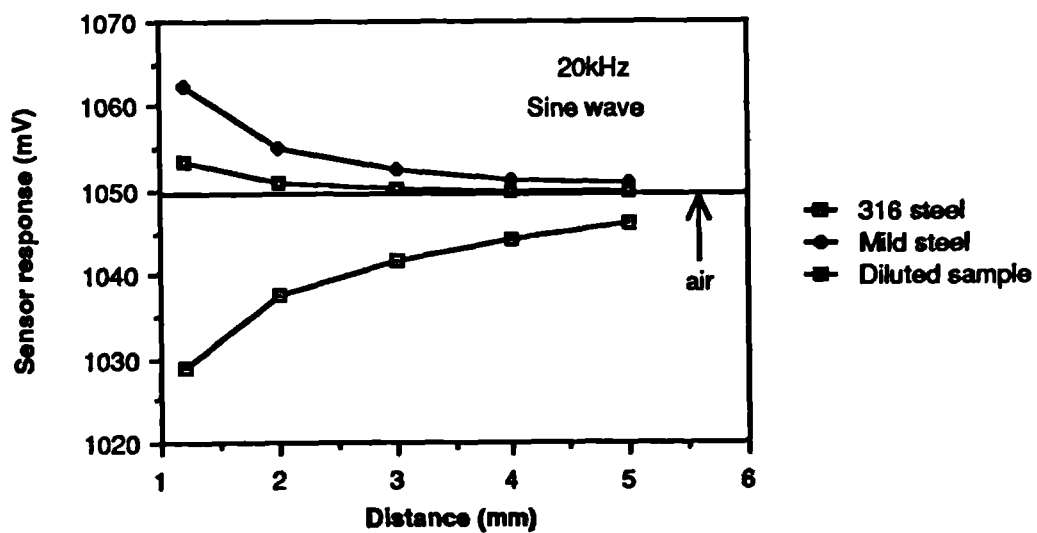
(a)



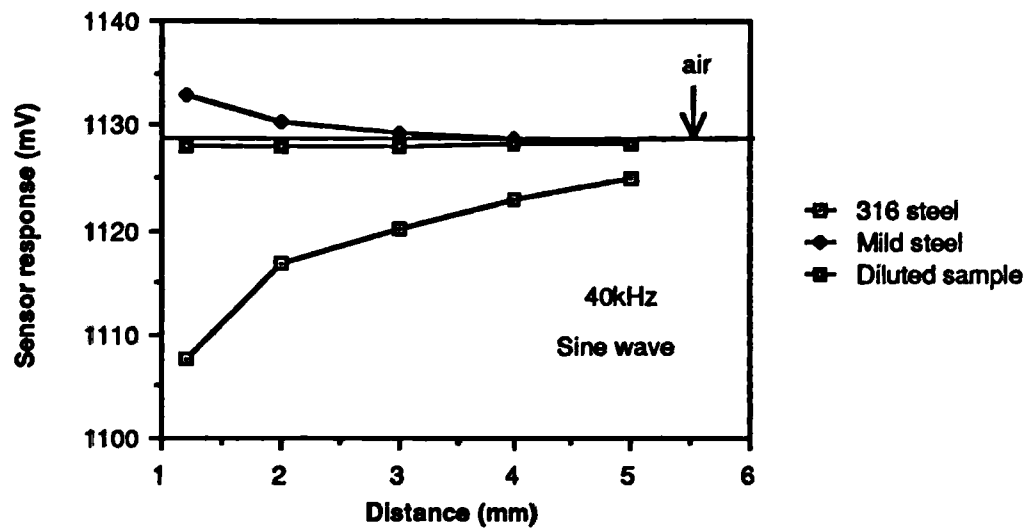
(b)



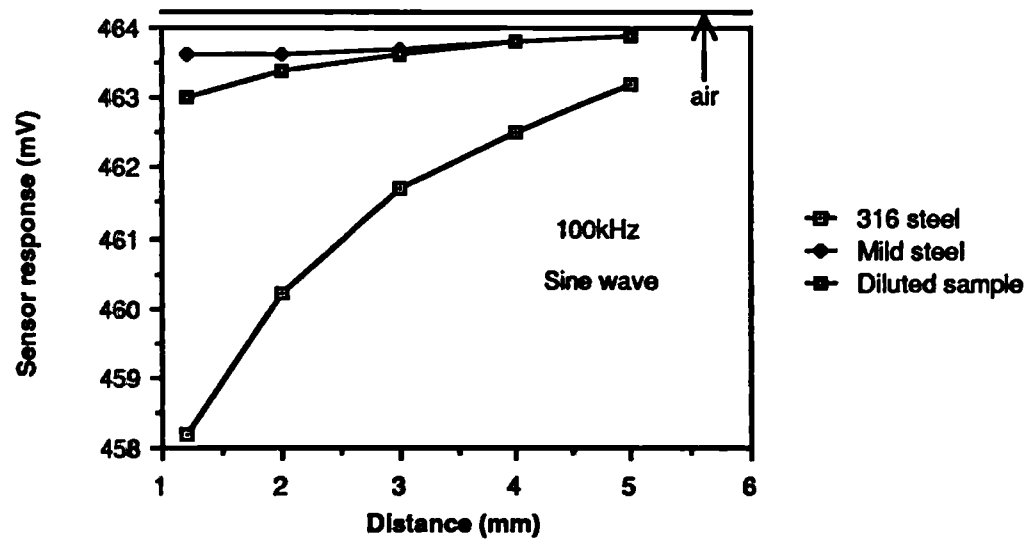
(c)



(d)



(e)



(f)

Fig.8.7. Distance effect on the dilution sensing at various frequencies. a). At 2.5kHz; b). At 5 kHz; c). At 10 kHz; d). At 20kHz; e). At 40 kHz; f). At 100 kHz.

From these experiments it can be seen that:

a). Sensing sensitivity (differences between the sensor response for substrate and that for undiluted clad) reduces as the distance increases, which is probably because the reduction of magnetic flux reaching to the tested samples at the farther distances, thus reducing the effect of the materials reluctance change on the sensor.

b). At low frequencies (such as 2.5kHz and 5kHz) the sensor response to non-diluted clad surface (316 steel) reduces as the distance increases -- similar to that for the diluted clad surface and substrate (mild steel). When the frequency increases above a certain level (10k, for example), the features of the distance effect for undiluted clad (non-ferrous) becomes opposite to that for diluted clad and substrate (ferrous) with the sensor response to the air as an asymptotical line in both cases. This is probably because at low frequencies the reluctance of all the tested materials including undiluted 316 steel clad are smaller than that of the air gap. As the sensing distance (air gap) increases, the originally lower reluctance materials in the magnetic path are replaced by the relatively higher reluctance air (R_g increases). Therefore the total reluctance in the magnetic path has increased which resulted in the reduction of the sensor response. At low frequencies there is also a possibility that the magnetic field has penetrated through the clad into the substrate (See Table 8.3) resulting in a reduction of the reluctance of the 316 steel clad which is about 2.2mm thick in this experiment. At higher frequencies, R_c may become bigger than R_g as in the case for 316 steel undiluted clad. The increase of the sensing distance has replaced the originally higher reluctance material in the magnetic path with lower reluctance air, which results in a reduction of the total reluctance in the magnetic path and therefore sensor response increases.

c). As frequency increases the sensor responses to the diluted clad approach to those to the substrate. This is probably because the high frequency had produced shallower penetration on the clad and that the clad dilution was not uniformly distributed across the clad and the surface part of the clad may have been diluted heavier due to the melt pool turbulence.

Experiment 3. Sensor response to continuous varying diluted clad. Fig.8.8 shows the sensor responses when scanned over a continuous varying diluted clad. The sample was produced by cladding 316 stainless powder on a En8 mild steel rod substrate. The change of clad dilution was caused by the substrate temperature built up during processing. The rise of the sensor signal clearly indicates the increase of the clad dilution. Fig. 8.9 shows the sensor responses to En8 substrate (100% dilution) and undiluted clad (2.2mm thick).

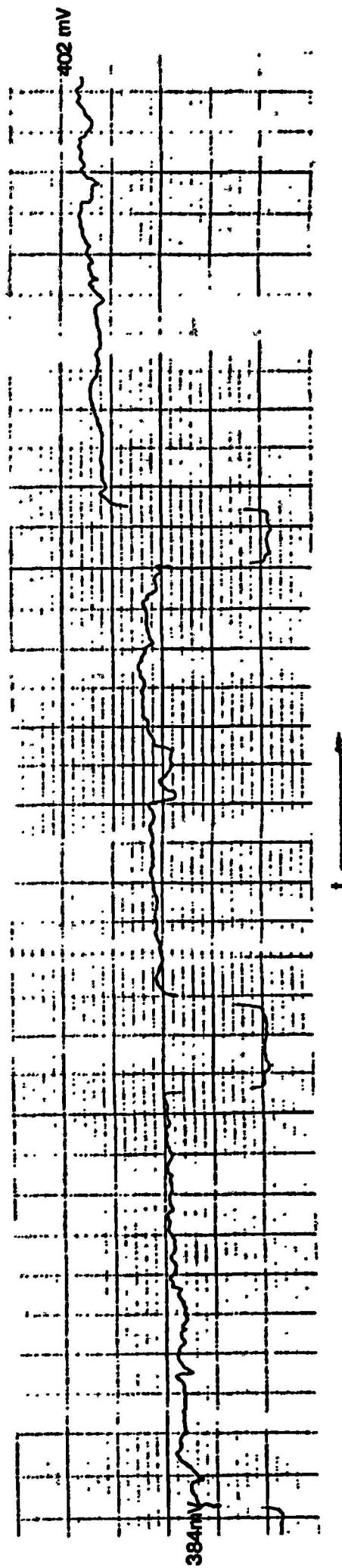
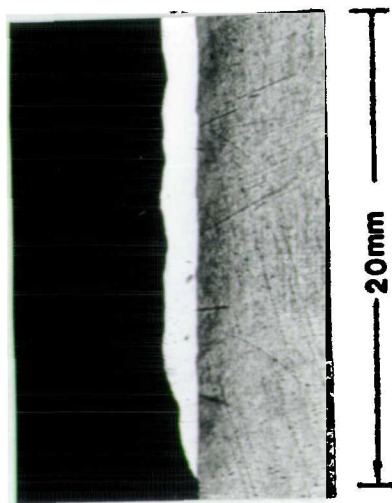
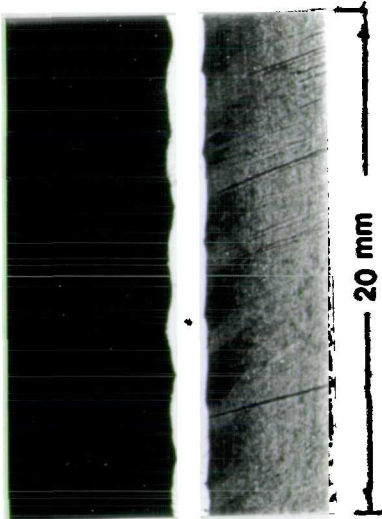
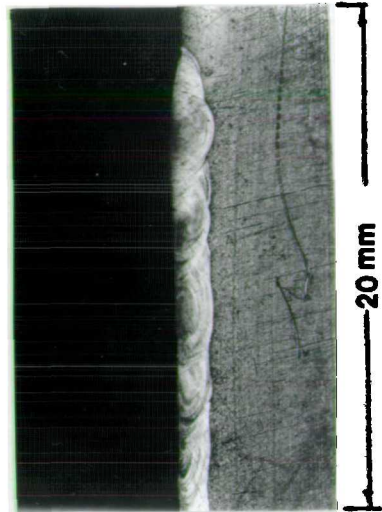


Fig. 8.8 . Sensor response to continuously varying diluted sample.

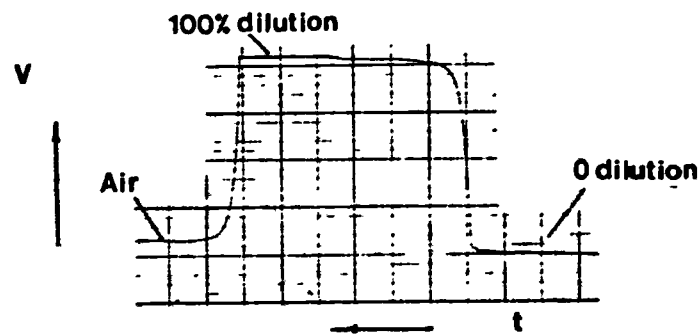


Fig. 8.9. Dilution sensor response to non-diluted clad and 100% dilution sample.

8.4 APPLICATION CONSIDERATIONS

The in-process dilution sensing arrangement is shown in Fig.8.10.

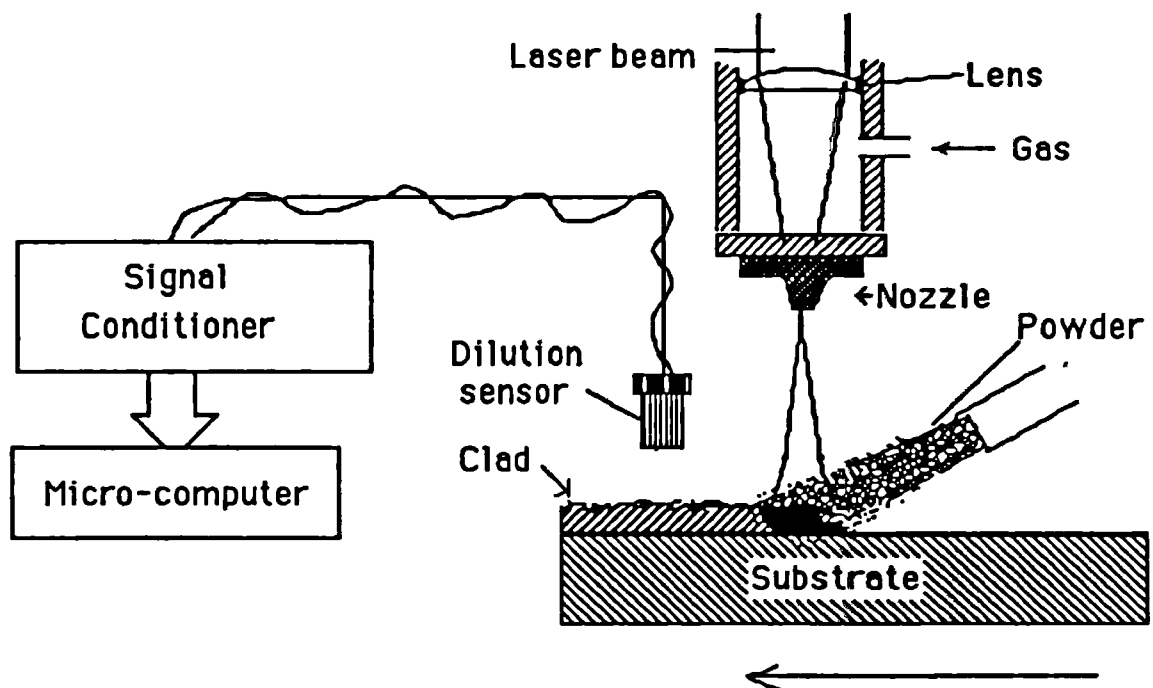


Fig. 8.10. In-process dilution sensing arrangement in laser cladding.

For the in-process dilution sensing the following factors should also be considered as well as the distance effect discussed in the previous sections.

a). Clad thickness effect. Careful selection of exciting frequency should be made so that the magnetic flux does not penetrate through the clad into the substrate. If this is satisfied the

variation of clad thickness should not affect the dilution sensing.

b). Temperature effect. A rise in environmental temperature (as it happens in laser processing) may lead to an increase in the resistance of the copper wire of the transducer coils. If voltage source is used instead of a current source, then for transmitter the most direct consequence particularly at low excitation frequency, will be a reduction of the transmitting current and hence the magnetic field. When a constant current source is used the temperature effect on the primary part can be eliminated. At high excitation frequencies, the inductive reluctance (which is unaffected by temperature) becomes the predominant part of the impedance, so variations in winding resistance have less effect. However a rise in clad temperature may change magnetic permeability of the clad layer. For diamagnetic materials like copper, the magnetic permeability is independent of temperature, while for paramagnetic material like Aluminum and 316 Stainless steel the permeability reduces as temperature rises. This relation can be expressed by Curie's law as:

$$\chi = C/T \quad (8-21)$$

where χ is susceptibility for paramagnetic material, C is Curie constant and T is temperature. The magnetic permeability of ferromagnetic material only reduces when the temperature is above the Curie temperature. For iron and mild steels the Curie temperature is 770°C, which is above the usual temperature of the resolidified clad. Therefore the only influence of the temperature is the change of permeability of the paramagnetic clad. However since the effect of the temperature on the conductivity of the materials have the similar relations to that for the permeability changes of paramagnetic materials. This can be expressed by Lorenz's law as:

$$\sigma = C_2/T \quad (8-22)$$

where C_2 is a constant relating to material properties. Considering the relations of reluctance R_c to μ_c ($=1+\chi_c$) and σ in Eqns. (8-6) and (8-7) and rearranging them as temperature dependent and temperature independent two parts, R_c becomes:

$$\begin{aligned} R_c &= l_c / (\mu_c w_c \delta_c) \\ &= l_c (\pi \mu_0 \mu_c \sigma f)^{1/2} / (\mu_c w_c) \\ &= [l_c (\pi \mu_0 f)^{1/2} / w_c] (\sigma / \mu_c)^{1/2} \end{aligned} \quad (8-23)$$

where w_c is the width of the magnetic path on the clad layer. By substituting μ_c and σ with the expressions in Eqns. (8-21) and (8-22), R_c becomes:

$$R_c = [l_c (\pi \mu_0 f)^{1/2} / w_c] [(C_2 T) / (C T)]^{1/2}$$

$$= [\mu_c(\pi\mu_o f)^{1/2}/w_c][C_2/C]^{1/2} \quad (8-24)$$

which shows that the temperature effect on the reluctance is cancelled because the temperature affects both permeability and conductivity in the same manner (here we assume $\mu_c \approx \chi$). The temperature rise can also change the magnetic penetration depth. If say the temperature rises from room temperature to 500C° both conductivity and permeability reduces about 20 times and therefore the penetration depth increases 20 times. This requires the control of exciting frequency so that the initial penetration depth is about 20 times less than that of cladded thickness so that even at high temperature the magnetic field will not penetrate to the substrate.

c). Signal conditioner design. In order that the system can work in real time, an instrument is required to generate 2 exciting frequency current source alternatively and the received signals should be decoupled to two channels for f and nf and converted to the demodulated signal. Synchronizing between transmitting and receiving is therefore required. A signal conditioner for this purpose was designed as shown in Fig. 8.10

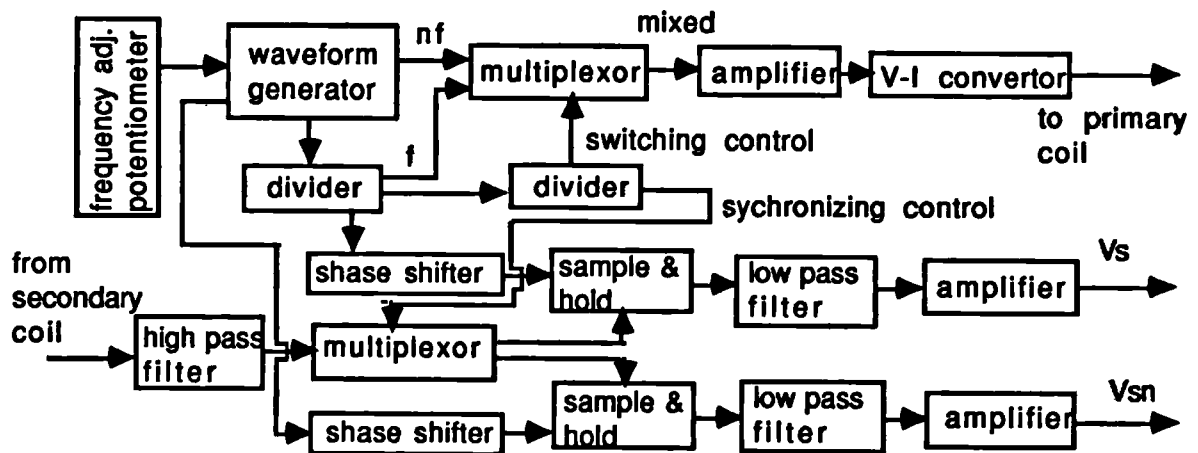


Fig. 8.11. Functional diagram of the clad dilution sensing signal conditioner.

In this diagram, two different frequency waveforms can be generated by one signal generator and a frequency divider. The switching between the two different frequencies can be realized by using analog switches (for sine wave) or a decoder (for square wave) logically controlled by a logic controller (a frequency divider). Then the signal may be amplified and converted to a current source to the transducer primary coil. At the receiving end high pass or band pass filters prior to signal splitting should be used to reduce the unnecessary noises. Analog multiplexor or use of logic controlled analog switches can be used to split the signals into high and low frequency two parts. The peak demodulation can be realized using a sample and hold circuit synchronized (logic controlled) by the shifting of primary pulses to 180° (use, for example, an inverter). The splitted signals will then pass through low pass filters and amplifiers providing recordable DC signals V_s and V_{sn} for computer analysis.

8.5 CONCLUSIONS

In-process dilution sensing was realized by using a developed electromagnetic transducer. Theoretical studies were made on the eliminating the effect of air gap (sensor/sample distance) for the non-contact dilution sensing application. Experiments were made on samples of 316 stainless steel clad on mild steel substrate. Various in-process application considerations were made and sensor signal conditioner was designed.

CHAPTER 9

IN-PROCESS CLAD BEAD PROFILE SENSING

9.1 INTRODUCTION

The studies made in Chapter 2 have shown that clad bead profile plays an important role in clad quality. For example, if the aspect ratio of the clad bead is lower than 4, the overlapped clad would have interrune porosities. The overlapped clad thickness and clad coverage rate are all dependent upon the dimensions of the single clad bead. Fig. 9.1 lists some of the bead profiles often found in practice, in which only type *a* is desired. While *b* although OK for single track cladding, may produce interrune porosities if tracks are overlapped. Bead type *c*, and *d* are considered to be poor clad beads and are to be avoided in practice.

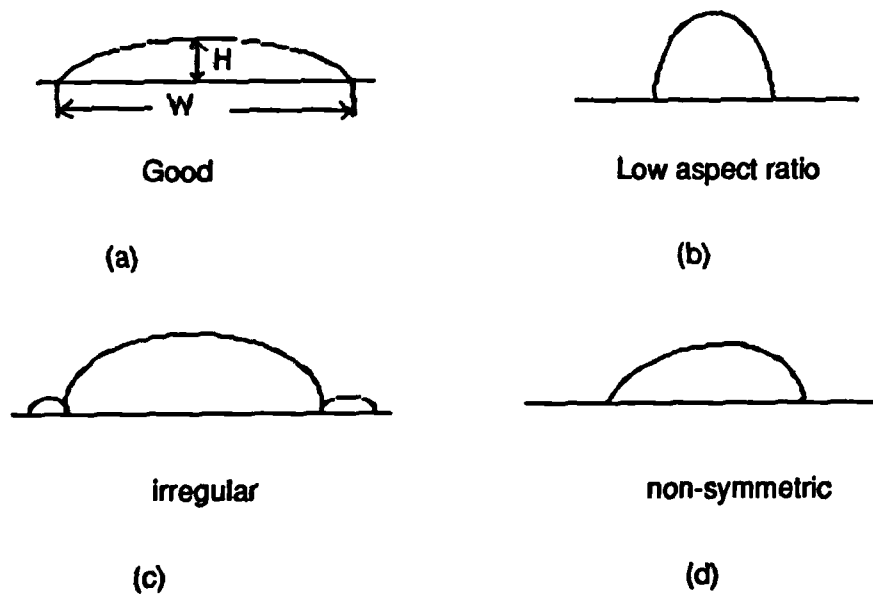


Fig. 9.1 Some clad bead profiles seen in practice.

Clad bead profile can be affected by many factors including traverse speed, powder flowrate, laser power, spot size, beam mode structure, powder feed alignment, powder feed gas pressure, nozzle gas pressure, substrate thermal property, powder property etc (see Chapter 2). It is often difficult to achieve a desired clad bead in practice and clad bead dimensions can deviate from the initial set values during processing because of the the substrate temperature rise (See General Introduction). In order to maintain the desired clad bead profile in-process sensing of the bead parameters is necessary. This chapter describes the author's work on the development of an in-process clad bead profile/clad

thickness sensing device and the associated parameter calculations. The use of the signals for on-line clad quality feedback control will be discussed in Chapter 11 and Chapter 12.

9.2. CLAD BEAD PROFILE SCANNER DESIGN

Clad bead profile can be characterized by its width, height, symmetry, aspect ratio etc. Several methods could be used to detect these parameters:

- 1). The use of a line scanning camera
- 2). The used of laser line scanner
- 3). The use of non-contact, fast response distance sensors and linear traverse device
- 4). The use of optical fibre arrays

Since method 3 is the most economic approach and the signal is easier to process, this method was investigated in the project.

The distance sensor selected for clad bead profile scanning experiment was the infrared sensor that was used for nozzle standoff control (See Chapter 4). This sensor has the following advantages:

- a). Fast response.
- b). Non-contact.
- c). Long sensing range (10-50mm).
- d). High accuracy (<0.1mm).
- e). Small in size and light in weight.

The development described in Chapter 4 has further improved the sensor so that it has the following additional features:

- f). Background noise immune.
- g). Linearized sensing relationship.

Since the sensor signal also depends on materials surface reflectivity it requires that the reflectivities of the clad bead and bulk substrate are relatively constant during processing. The factors that can possibly affect clad bead reflectivity during process are clad surface oxidation and temperature rise. The former can be reduced to minimum by using process shrouding (such as the use of dome) while the latter only starts to affect the sensing when surface temperature is over 400°C (See chapter 4) which is very unlikely for resolidified clad. The change of substrate surface reflectivity is not relevant to the clad bead sensing since the sensing parameters are only relative to lowest point of clad bead instead of comparing to the substrate. Therefore once calibrated for a material, the system requires no further in-process calibration.

The scanning device was realized using a small DC motor with a rotation/linear motion converting mechanism. An additional linear distance sensor was used to determine the infrared sensor position. A datum switch could be used providing the synchronizing signal for oscilloscope display. The designed bead profile scanning device is illustrated in Fig.9.2.

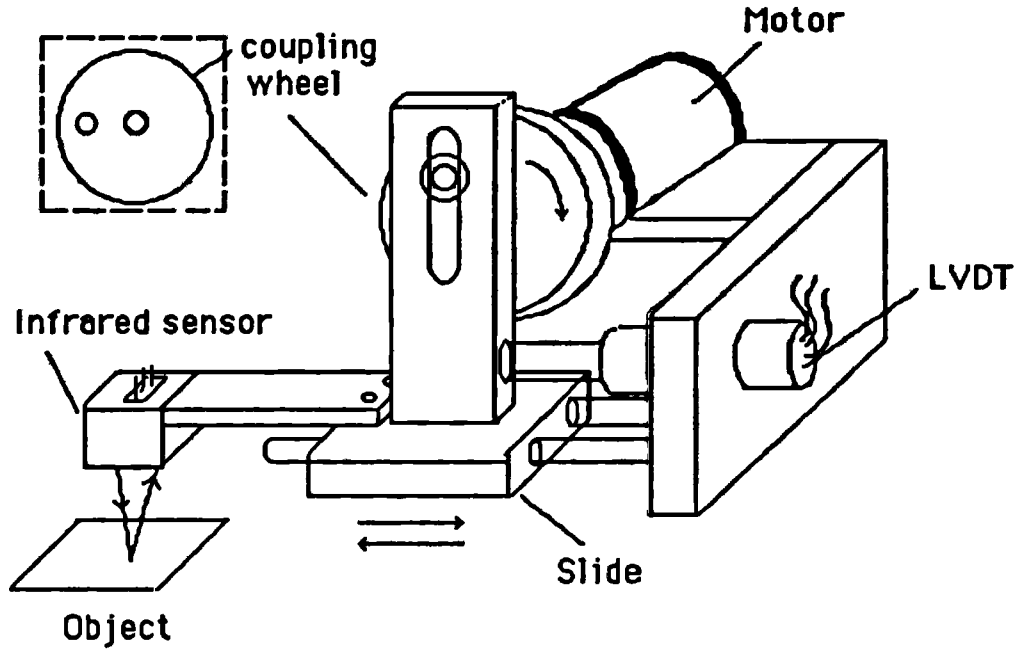


Fig. 9.2. Schematic diagram of the Infrared clad bead profile scanning device.

Suppose the motor rotates at an angular speed of ω and the distance between the coupling bearing centre and motor shaft centre is R then the linear traverse speed of the scanning sensor can be found to be:

$$V_{scan}(t) = \omega R \sin(\omega t) \quad (9-1)$$

where the V_{scan} is the linear scanning speed of the sensor. The position of the sensor, X , relative to one extreme of the traverse (datum point) at time t can be found to be:

$$\begin{aligned} X &= \int_0^t V_{scan}(z) dz = \int_0^t \omega R \sin(\omega z) dz \\ &= R [1 - \cos(\omega t)] \end{aligned} \quad (9-2)$$

where X is the sensor position at time t .

Suppose the infrared sensor scans at speed $V_{scan}(t)$ in both directions perpendicular to a clad bead which moves at speed V_{trav} and if V_m is the maximum traverse speed used for laser cladding and z_c (mm) is the length of clad allowed to pass for the period of one scan so that the clad bead height is relatively constant in this section, then motor speed required for the scan should be:

$$V_{motor} = \frac{30V_m}{z_c} \quad (\text{rpm}) \quad (9-3)$$

where V_{motor} : the motor speed in RPM required for scanning.

V_m : Maximum laser cladding traverse speed (mm/s)

z_c : The length of clad allowed to pass under 1/2 scan cycle (mm).

For example, the laser cladding of stainless steel to mild steel using a 2 kW laser requires the maximum substrate traverse speed of 24 mm/s and there is no apparent changes of clad bead profile with 1 mm length for normal laser cladding (with no setup faults such as powder feed misalignment etc.). Therefore $z_c=1$ mm, and $V_m = 24$ mm/s in this case. The required scanning motor speed for this application according to Eqn. (9-3) should be 720 RPM. Often laser cladding is operated at lower speed (5-8mm/s), which requires the scanning motor speed of 150 to 240 RPM.

A prototype clad bead profile scanner was made (Fig.9.3.) which has the linear traverse of 10mm and scanning rate of 0 to 6Hz.

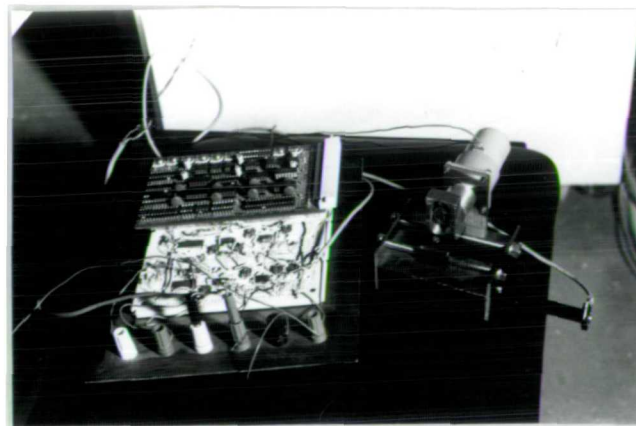


Fig. 9.3. The prototype clad bead profile scanner.

9.3 CLAD BEAD PROFILE SENSING EXPERIMENTS

Fig. 9.4 shows the scanner responses to two 316 steel clad beads on mild steel substrate. The differences in bead width and height are clearly indicated in the sensor responses.

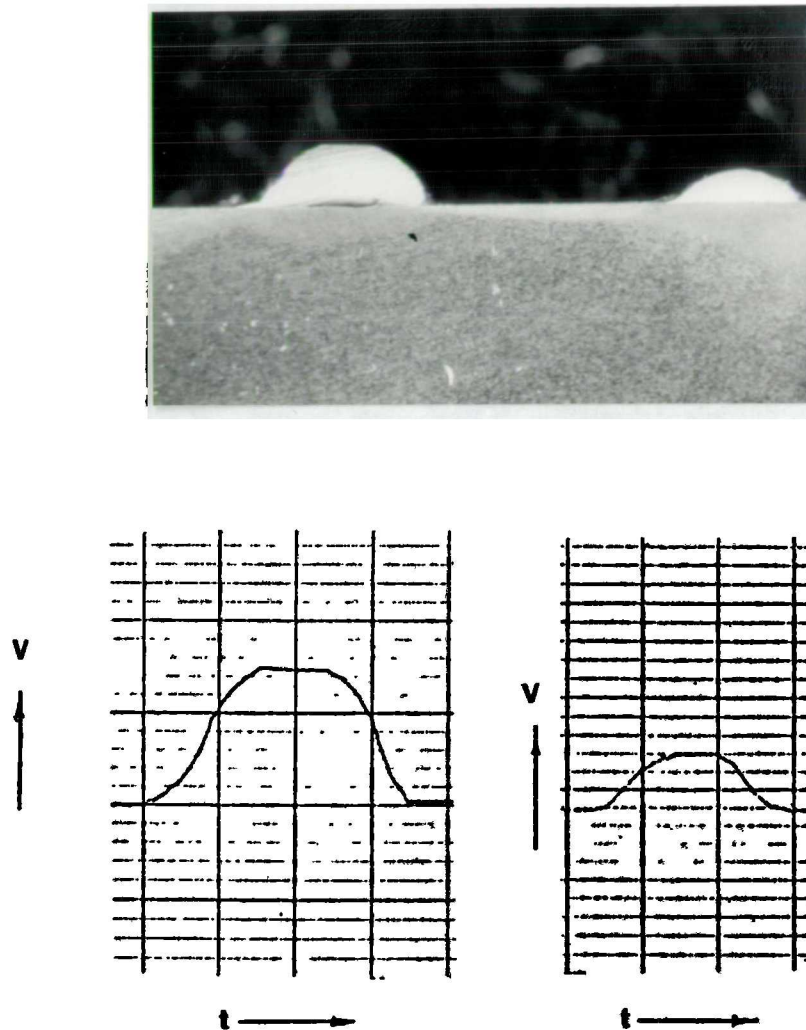


Fig. 9.4. Sensor responses to two different clad bead dimensions.

If the substrate near the clad bead is highly oxidized, the sensor response would be a different pattern as shown in Fig.9.5, from which the effect of oxidation can be easily recognized.

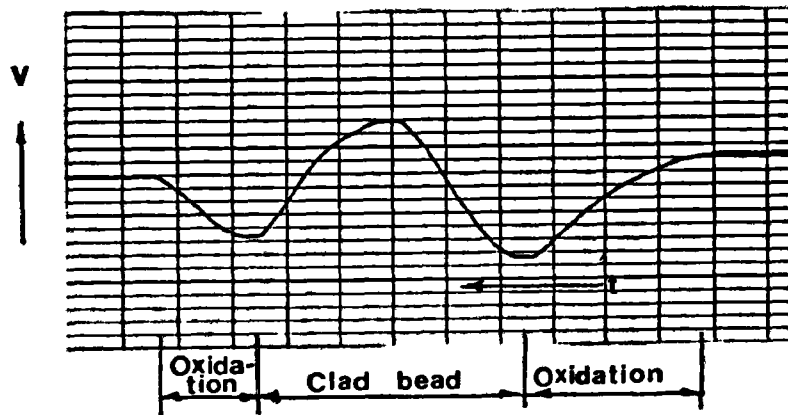


Fig.9.5. Sensor response to a clad bead with oxidized substrate near the clad bead.

When different scanning rates were used the sensor responses had little changes in magnitude and shape in the current range of the motor speed. The experimental curves are shown in Fig.9.6. in which the scanning rate was 0.5Hz, 1Hz, 2Hz and 4Hz respectively. The signal was recorded on a digital storage oscilloscope (HAMEG HM205-2) and plotted on a chart recorder (LINSEIS LS52-2).

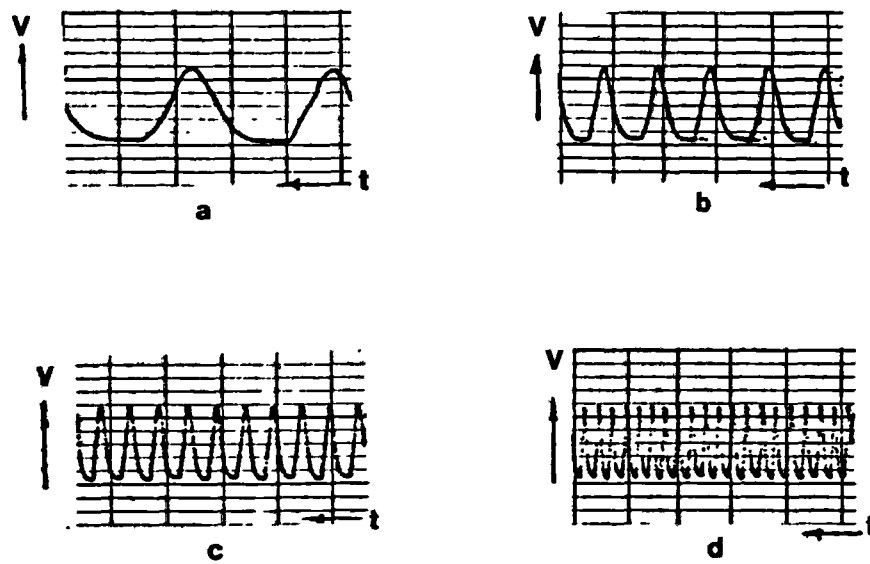


Fig.9.6. Sensor response to a clad at different scanning rates. a).0.5Hz; b).1Hz; c). 2Hz; d).4 Hz

A typical sensor response for a clad in one scanning cycle is shown in Fig.9.7, from which it can be seen that the sensing is direction independent.

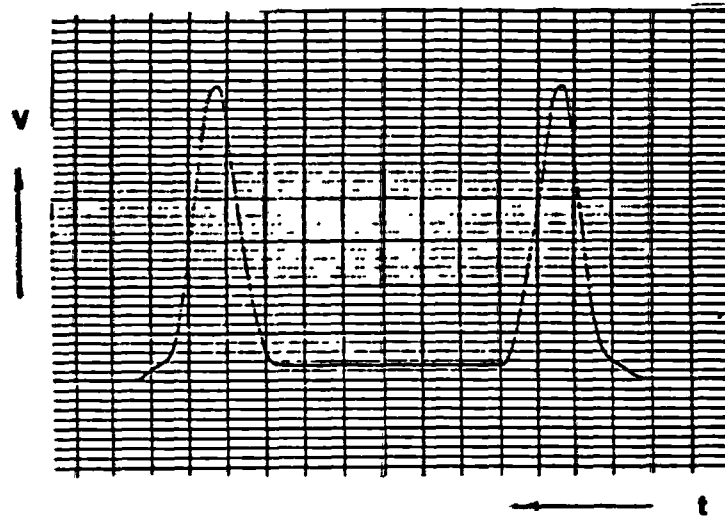


Fig.9.7. Typical sensor responses to a clad bead for one cycle of scanning.

When different substrate traverse speeds were used while scanning, no apparent affect can be seen on the sensor response for an uniformly laid clad (Fig.9.8). Therefore the sensing could be insensitive to substrate traverse speed.

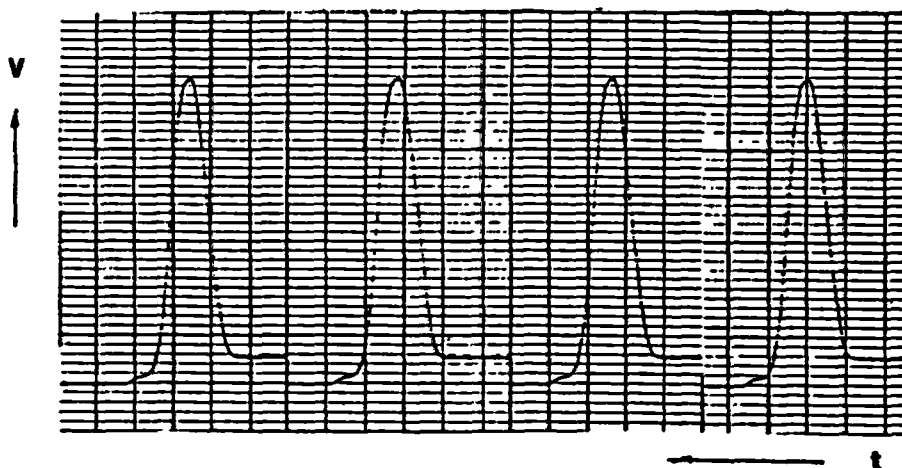


Fig. 9.8. Sensor response to a clad at different substrate traverse speed. (From left to right: 5mm/s, 10mm/s, 15mm/s, 20mm/s)

9.4. CLAD BEAD PARAMETER EVALUATION

In order to calculate clad bead parameters from the sensor signals the following studies were made.

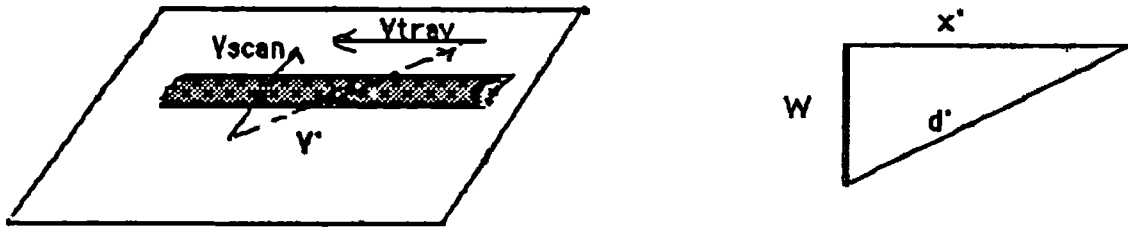


Fig. 9.9. Illustration for scanning sensing.

1). Clad bead width calculation: Clad bead width can be determined using:

$$W = x_2 - x_1 \quad (9-4)$$

where x_1 : Sensor position at the start point of clad bead to be scanned;
 x_2 : Sensor position at the finish point of clad bead scanned over;
 W : Clad bead width.

x_1 and x_2 can be determined using the additional sensor position sensor (LVDT for example) or by software or hardware timer with respect to the datuming switch. x_1 point occurs when the scanning sensor signal starts to rise and x_2 point occurs when the scanning sensor signal falls to the bottom again.

Two features can be found for the determination of this parameter using the sensor:

a). Clad bead width sensing is independent of substrate traverse speed so long as the scanning direction is perpendicular to it although the actual traverse of the scanning sensor over the clad bead is not perpendicular to the traverse direction (Fig.9.9). This is because the time the sensor spent over the clad is only determined by the speed that is perpendicular to the clad bead which is preset scanning speed.

b). Clad bead width sensing is also independent of the clad materials since only the starting and finishing points of clad bead are required.

2). Clad bead height calculation: Since the peak signal from the scanning sensor is the highest point of the section of clad it passes. If the scanning speed satisfies Eqn.(9-3) this

peak value can be considered as the highest point of the clad bead over its cross section, i.e. clad bead height. It can therefore be determined using:

$$H = \beta \text{ Max } (y_i \mid y_i \in Y) \quad (9-5)$$

where Y is the set of whole sampled data or recorded value of the scanning sensor in half of a scanning cycle and β is calibration factor of the sensing signal.

3). Bead symmetry determination : The symmetry of a clad bead can be found by locating the position of the clad peak, if it locates in the middle of the bead then it is symmetric. Otherwise it is not. The degree of symmetry can be determined using the following relation :

$$\text{Sym} = \left| 1 - \frac{2(x_p - x_1)}{x_2 - x_1} \right| \quad (9-6)$$

where x_p : Position of the scanning sensor at the peak point of the clad bead;

Sym: Symmetry of the clad bead which is between 0 and 1. The smaller the value of Sym the better symmetry the bead will be .

The inclination of the clad bead can also be determined using the following relationship:

$$\text{Inc} = \text{Sign} \left\{ 1 - \frac{2(x_p - x_1)}{x_2 - x_1} \right\} \quad (9-7)$$

where $\text{Sign}(x)$: a "sign" function which equals "1" when x is positive and "-1" when x is negative and "0" when $x=0$.

Inc: Inclination of the clad bead.

For example: if x_1 is the position for the left edge of the clad bead, then if $\text{Inc} = +1$ it means that the clad is not symmetric and inclined to the right. Similarly $\text{Inc} = -1$ indicates that the clad bead is un-symmetric and inclined to the left. Since these parameters are only related to the relative values of the sensor signals at the clad , the sensing is also independent of clad and substrate materials.

4). Aspect ratio calculation: After the clad bead width and height calculations, the aspect ratio of a clad can be calculated using its definition:

$$A = W/H \quad (9-8)$$

Where A is aspect ratio and W , H are clad bead width and height respectively..

5). Oxidation zone size evaluation, It was found that the oxidized part of the substrate is always darker than the rest part of the material, and the near to the clad the higher oxidation will be. As a result a progressive signal reduction on the sensor response will be

resulted when the sensor scans over the oxidation zone toward the clad bead. Once the sensor reaches the clad, the signal will start to rise. This enables us to distinguish the starting and finishing point of the oxidation zone from that of clad bead. i.e. the oxidation zone starts at the first negative signal slope and finishes at the start of the positive slope which is the start of clad bead. The sensor response for other side of the oxidation zone is just opposite. Similar formula to that used for the determination of clad bead width can be used for the calculation of the size of the oxidation zone so long as it still falls into the scanning traverse range.

6). Clad thickness sensing. The change of clad thickness can be detected in the same way as that for single bead height sensing. i.e. the differences between the highest magnitude and the lowest magnitude in the clad scan is considered as the clad thickness at the time of scanning. This can be expressed as:

$$H_i = \beta y_{\max} - \alpha y_{\text{sub}} \quad (9-9)$$

where H_i is the overlapped clad thickness for scan iteration i and $y_{\max}$ is the maximum point of the clad and y_{sub} is the sensor response for substrate. β and α are scanning sensor calibration factor for clad and substrate material respectively. If the sensor is kept stationary on top of the overlapped clad track then the fluctuation of the overlapped clad thickness can be detected continuously.

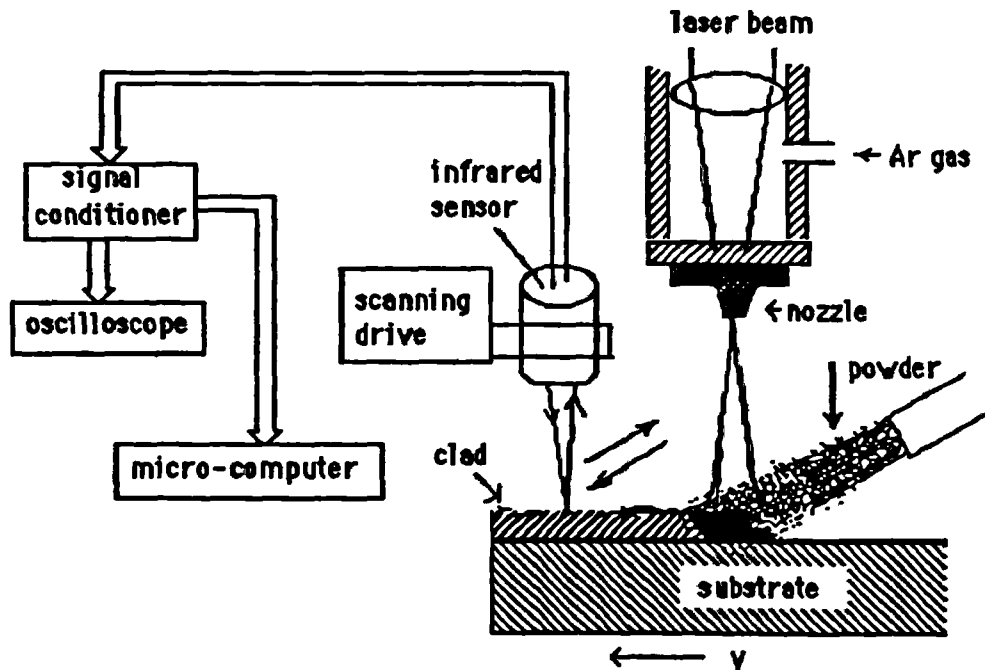


Fig. 9.10. Clad bead parameter sensing arrangement.

9.5 SUMMARY

A reflective infrared distance sensor was used for clad bead profile and clad thickness sensing because of its light weight, small size, fast response, low price, long sensing range and high sensitivities. The sensing arrangement for laser cladding is shown in Fig. 9.10. Experiment have found that the speed of traverse or scanning rate has little effect on the signal amplitude. Clad width, bead symmetry and size of HAZ sensing are independent of materials, surface condition and substrate traverse. However for sensing of the clad bead height and overlapped clad thickness the system needs calibration for each material. The influence of powder dust, and sparks generated from the process on the sensing system could be eliminated since the signal is pulse modulated (see chapter 4) the sensor is mobile, which reduces the possibility of catching the powder.

PART 4

DEVELOPMENT OF TECHNIQUES FOR INTELLIGENT SUPERVISORY LASER CLADDING CONTROL

Unsatisfactory clad can be produced if either the operating parameters are not selected properly such as powder flowrate too low , or the operating parameters are not stable such as laser power fluctuation, or there is a change of operating conditions such as surface temperature rise or there is a system failure such as nozzle clipping and beam/powder misalignment etc.. Not all these problems are controllable. For example, interface porosities are caused by the properties (oxygen content etc.) of the powder materials used which can not be controlled by the variation of operating parameters. The on-line controllable clad parameters are referred to those which can be changed by the variation of laser power, powder flowrate, traverse speed and overlap traverse. Therefore the direct controllable clad parameters are clad thickness, clad bead width, clad bead height, clad dilution. Other indirect controllable parameters could be interrun porosity (decided by the clad bead aspect ratio and the degree of overlap), overlapped clad uniformity (decided by the degree of overlap) and possibly the clad roughness (by the proper selection of operating zone and system setup) etc.

The task of the supervisory laser cladding control is to coordinate various sub-systems in the hierarchy so that the optimum operating condition is achieved and clad quality is maintained as the desired. This includes process optimization, closed loop control of the controllable operating parameters and diagnose the uncontrollable clad faults or system failures for process alarm. Since the system is multi-variable interactive, non-linear and there is no dynamic model of the process, many existing control techniques cannot be used for the analog feedback control. Also there could be many possibilities for a clad fault, the Boolean algebra can not be used for logical process control. Therefore some new techniques are required to "learn" the process for adaptive feedback control and to diagnoses the problems of a faulty clad from "indefinite" relationships for logical process quality control.

Three chapters are included in this part describing the techniques developed for supervisory laser cladding " total quality control".

Chapter 10 gives the research results for the development of methods for optimum laser cladding condition setting which could provide more economic, more accurate and less faulty clad operation, while the previous laser cladding practices were mostly based on trial and error.

Chapter 11 gives the research results on the development of new techniques for adaptive laser cladding feedback control as well as for the control of other similar processes .

Chapter 12 gives the research results on the development of a new information processing technique (the use of knowledge based relational matrices and inference engine) for laser cladding on-line faults diagnoses and quality control from both qualitative sensor and quantitative sensors. The general laser cladding supervisory control software structure is also included in Chapter 12.

CHAPTER 10

LASER CLADDING OPTIMIZATION

10.1 INTRODUCTION

The selection of operating parameters is critical to the success of laser cladding. An improper setting of these conditions will usually lead to process failure or poor clad quality. Therefore the optimization of laser cladding operating parameters is included as one of the objectives of laser cladding control. As introduced in chapter 2 the previous methods used to decide the operating parameters for a given processing requirement (clad thickness, dilution level, etc.) were mainly based on prior-experience or trial and error. Although some theoretical models could be used to estimate the possible results under certain operating conditions, the accuracy of correlation with the reality cannot be guaranteed due to the assumptions implicit in the models. Some workers have used data base or Artificial Intelligence methods for optimum operating condition setting in laser welding, laser cutting and transformation hardening process (See Chapter 3). Their results have shown certain improvements to the conventional methods for setting operating conditions. This chapter describes the author's work on the development of techniques and a software package for optimum setting of the laser cladding conditions at the start of cladding operation. The difference between the present method and previous methods in laser materials processing is that the present methods were designed to incorporate in-process sensors so that any incorrect estimation could be identified by an initial trial run and the system will "learn" the process and re-design its operating parameters. Thus the method is "on-line" and adaptive to many process variations such as different clad materials or use of different lasers. In this development statistical laser cladding correlations (See Chapter 2) were employed, since they firstly have more direct relationships and explicit expressions, and secondly because they were obtained by many experiments and could be closely fitted to the real processing conditions especially when on-line identification is used. The theoretical formulae obtained for laser cladding process optimization are independent of particular processes. Examples of the application of the developed methods and the examination of the process behaviors under various conditions (optimized and non-optimized) were made for a particular process: Cladding of Wallex 6PC material on EN8 mild steel using 2 kW CO₂ laser with corresponding process parameters obtained from Ref.60. All the calculated diagrams in this Chapter are refer to this particular process. The results have shown that the theoretical calculations are closely matched to the experimental observations.

10.2. PROBLEM DEFINITION

The problem of establishing the optimum conditions for the laser cladding process can be stated as:

For a given product specification such as clad thickness h , find the best group of operating parameters: traverse speed, V , powder flowrate, M , overlap degree, j , and laser power, P , so that the product can be produced with maximum coverage rate, minimum power and powder consumption, minimum dilution, free from interrun porosities and uniform overlapped clad surface. By using the relationships discussed in Chapter 2, the problem can be expressed mathematically as:

Objective:	Maximize $C = iWV$	(10-1)
Subject to:	$i = \exp [-h/(1.8H)]$	(10-2)
	$W = D'(1-bV)$	(10-3a)
or	$W = D(K_1P - K_2M - bV)$	(10-3b)
	$H = aM/V$	(10-4a)
or	$H = (a+K_3P)M/V$, when $P/(DM) \geq K_m$	(10-4b)
or	$H = (a-K_4P)M/V$, when $P/(DM) \leq K_m$	(10-4c)
	$DI = cP - d_mM$	(10-5a)
or	$P/(DM) \leq K_m$	(10-5b)
	$A = W/H \geq 5$	(10-6)
	$i \geq 0.25$	(10-7)
	$i \leq 0.5$	(10-8)
	$P_{min} \leq P \leq P_{max}$	(10-9)
	$V_{min} \leq V \leq V_{max}$	(10-10)
	$M_{min} \leq M \leq M_{max}$	(10-11)

with

- H = clad bead height
- W = clad bead width
- M = powder flowrate
- DI = degree of dilution
- h = overlapped clad thickness
- C = clad coverage rate
- i = overlap index = $1 - \text{degree of overlap}$
- V = traverse speed
- P = laser power

$a, b, c, D', d_m, K_1, K_2, K_3, K_4$ are process parameters decided through experiments (See Chapter 2) or on-line sensing.

$M_{min}, V_{min}, P_{min}, M_{max}, V_{max}$, and P_{max} are the lower and upper operating limits for M, V and P respectively.

In the above expressions Eqn. (10-1) is the optimization objective function.; Eqns (10-2) to (10-4a,b,c) are the conditions required to satisfy the clad thickness specification; Eqns (10-5a,b) are the conditions to satisfy dilution specification; Eqns (10-6) and (10-7) are the conditions to satisfy interrune porosity free clad requirement; Eqn.(10-8) is the condition for uniform overlap; and Eqns.(10-9) to (10-11) are the physical restrictions on the selection of operating parameters.

Several points are worth pointing out:

a). A higher laser power is not necessarily better. This is because a higher power than necessary will deliver extra heat to the process, resulting in a bigger heat affected zone, higher dilution and even vaporization of the clad. Also it increases the energy consumption rate and possibly may reduce the life of the laser. Actually laser power has to be in a fixed ratio with powder flowrate as shown in Eqns.(10-5a) or (10-5b).

b). It is not always true that the increase of traverse speed will increase clad coverage rate. Clad coverage rate C can be expressed in terms of l , D , V as:

$$C = lD'(1-bV)V \quad (10-12)$$

which is a quadratic relationship with V and the maximum clad coverage rate occurs at $V=1/2b$. For example, in the case of cladding of Wallex 6PC on mild steel substrate using 1.9kW laser and 5mm spot size, the variation of clad coverage with V will be as shown in Fig.10.1, where the process parameters D' and b are 5mm and 0.05 respectively^[60]. The maximum clad coverage rate occurs at $V=10\text{mm/s}$. As traverse speed exceeds this point clad coverage will be reduced.

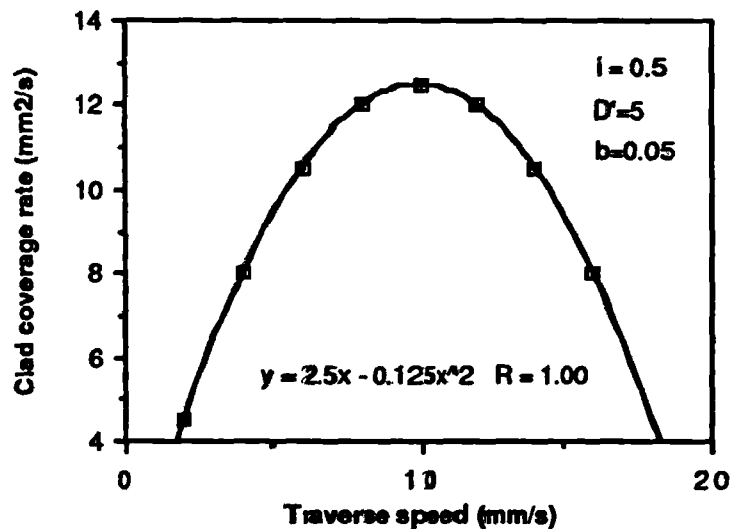


Fig. 10.1. Example of the effect of variation of traverse speed on C .

c). The same clad thickness can be achieved with different combination of traverse speed, degree of overlap and mass flowrate. These are indicated in Eqns.(10-3a) and (10-2). If higher traverse speed is selected (resulting in a reduction of bead width and thickness according to Eqns. (10-2) to (10-4a,b,c), powder mass flowrate has to be increased (with $A=W/H < 5$ to avoid interrune porosities) or degree of overlap has to be increased (with $i \leq 0.25$ to avoid interrune porosities). Therefore there is a need for optimization.

d). Operating laser cladding purely according to surface appearance and prior-experience is risky, since problems like dilution and interrune porosity are not obvious by clad appearance examination.

Therefore it is both necessary and possible to optimize the cladding operation.

10.3. PARAMETER SELECTION AND OPTIMIZATION

The degree of optimization for laser cladding is decided by the number of conditions and requirements given. More restrictions in specification will result in less freedom in selecting the operating parameters. The situations can be classified into the following 4 groups:

10.3.1. Direct calculation of operating parameters without optimization

Case A: If aspect ratio A , overlap index i (or degree of overlap $j=1-i$), clad thickness requirement h and dilution requirement D are given, which is often the case in current cladding applications, then the conditions define only one group of operating parameters to be used and optimization becomes impossible as will be seen below:

Cladding traverse speed V : This can be calculated from:

$$i = \exp [-h/(1.8H)]$$

$$A = W/H$$

and $W = D(1-bV)$

as :

$$V = \frac{W}{bD} - \frac{1}{b} = \frac{AH}{bD} - \frac{1}{b} = \frac{hA}{-1.8 \ln(i) bD} - \frac{1}{b} \quad (10-13)$$

Powder flowrate M : This can be calculated by combining Eqn.(10-13) and Eqn.(10-4a) as:

$$M = \frac{HV}{a} = \frac{hV}{-1.8 \ln(i) a} \quad (10-14)$$

or

$$M = \frac{HV}{a} = \frac{WV}{aA} = \frac{D(1-bV)V}{aA} \quad (10-15)$$

Laser power P: Laser power can be calculated from Eqn.(10-5a) as:

$$P = [DI + dmM]/c \quad (10-16)$$

or only the upper limit of laser power is calculated to prevent heavy dilution, using Eqn.(10-5b), as:

$$P \leq M_{im}(P_m, K_m D M) \quad (10-17)$$

For example, in the cladding of Wallex 6PC on mild steel substrate ($a = 20$, $b=0.05$, $K_m=2.5$)^[60] with a spot size of 5mm, overlap degree of 50% and the aspect ratio specified as 5, the calculated operating parameters using Eqns.(10-13) to (10-17) to satisfy a given clad thickness of, say, $h=1\text{mm}$ will be:

$$V = 2.3 \text{ mm/s}, \quad M = 0.159, \quad P \leq 1.98 \text{ k.}$$

with a resultant single bead dimension and clad coverage rate estimated using Eqns.(10-3a), (10-4a) and (10-1) as:

$$W = 4.40 \text{ mm}, \quad H = 0.81 \text{ mm}, \quad C = 7.95 \text{ mm}^2/\text{s}$$

which are reasonable values with comparison to the experimental data^[60]. It should be noted that, the clad thickness cannot be chosen at will. There is an upper limit for it (See section 10.4). For the above example if $h > 1.25\text{mm}$ then traverse speed has to be zero (Fig.10.2) if interrump free clad is to be produced .

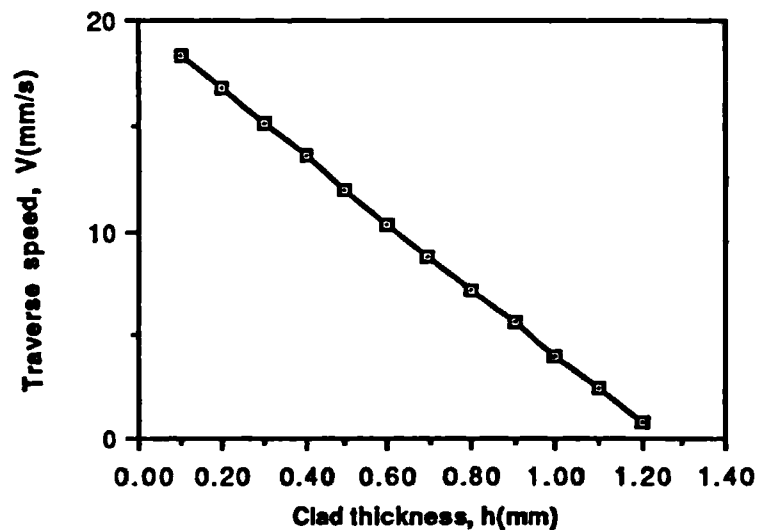


Fig. 10.2. Variation of traverse speed with clad thickness.

If P is not varied with M , as in most of current laser cladding practice, then it could result in a heavy dilution for certain clad thickness requirements. For the above example, if P is kept at 1.9kw, then dilution will appear if clad thickness requirement is either beyond 1mm or below 0.25 mm as shown in Fig. 10.3.

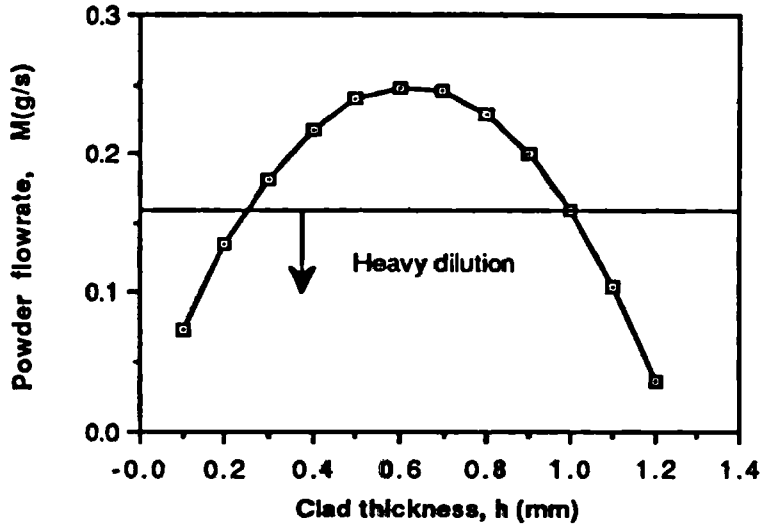


Fig. 10.3. Powder flowrate variation with clad thickness when P is kept constant.

Case B: If A , P and h are given then i , V and M can be found uniquely as:

Powder flowrate:

$$M = cP/bm \quad (10-18)$$

Traverse speed:

$$V = \frac{1}{2b} \left(1 + \sqrt{1 - \frac{4abAM}{D}} \right) \quad (10-19)$$

Overlap Index:

$$i = \text{EXP}\left(\frac{-hV}{1.8aM}\right) \quad (10-20)$$

Although the above non-optimized methods can provide required operating parameters with some considerations on clad quality to an extent, they usually can not guarantee a maximum clad coverage rate as shown in Fig. 10.4 for the above example.

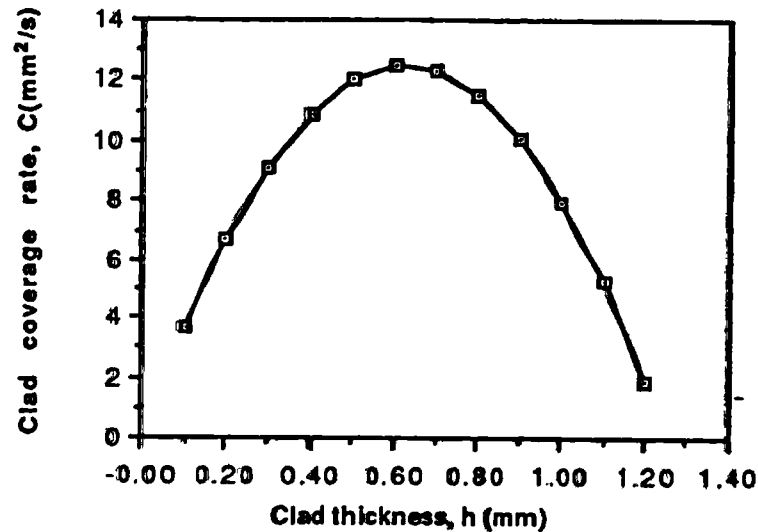


Fig. 10.4. Non-optimized clad coverage rate for different clad thickness.

10.3.2. Operating parameter selection to give an optimized clad thickness

This is the the situation when the clad thickness is not specified (which is true for some applications) but is allowed to be optimized within a range for maximum clad coverage rate. It allows a free choice of traverse speed, degree of overlap and powder flowrate under the quality control constraints. The given parameters are aspect ratio A and spot size D and the range of overlap index changes give in Eqns.(10-7) and (10-8). The ideal operating parameters and clad thickness can then be calculated in the following.

From the relationship:

$$C = iWV = iD'(1-bV)V \quad (10-21)$$

the maximum C can be found using differentiation method to occur at

$$i_{op} = i_{max} = 0.5 \quad (10-22)$$

$$V_{op} = 1/(2b) \quad (10-23)$$

so that

$$\begin{aligned} C_{max} &= 0.5 \times D'[1-b/(2b)] [1/(2b)] \\ &= 0.125D'/b \\ &= 0.125D/b \end{aligned} \quad (10-24)$$

The optimum clad thickness and powder flowrate can be found as:

$$\begin{aligned}
hop &= -1.8\ln(iop)Hop \\
&= -1.8\ln(iop)Wop/A \\
&= -1.8\ln(iop)D'(1-bVop)/A \\
&= -1.8\ln(0.5)D'[1-b/(2b)]/A \\
&= 0.623D'/A \\
&\approx 0.623D/A
\end{aligned}
\tag{10-25}$$

$$\begin{aligned}
Mop &= VopHop/a \\
&= -Vophop/[1.8\ln(iop)a] \\
&= -1/(2b) \times 0.623 D'/[1.8 \ln(0.5) A a] \\
&\approx 0.25 D/(abA)
\end{aligned}
\tag{10-26}$$

$$\begin{aligned}
P &\leq (P_{max}, KmDMop) \\
&= \text{Min}[P_{max}, 0.25KmD^2/(abA)]
\end{aligned}
\tag{10-27}$$

where iop : optimum overlap index
 Vop : optimum traverse speed
 C_{max} : maximum clad coverage rate
 hop : optimum clad thickness
 Mop optimum powder flowrate
 D : beam spot size

From the above relationships it can be seen that if clad thickness is not specified then optimum overlap degree is always 50%, optimum traverse speed is only decided by the process parameter b , and the optimum clad thickness is decided by spot size and aspect ratio.

For example, in the cladding of Wallex 6PC on mild steel substrate with beam spot size of 5mm and $P_{max}=2kW$ and $a=20$, $b=0.05$, $Km=2.5$ (from Ref.60). If aspect ratio is given as 5 then the optimum operating parameters and the optimum clad thickness will be:

$Vop(mm/s)$	$Mop(g/s)$	$Pop(kw)$	$iop(\%)$	$hop(mm)$	$C_{max}(mm^2/s)$
10	0.25	2.0	50	0.623	12.5

Different optimum clad thickness can be achieved with different aspect ratio specified. Fig. 10.5 shows the effect of aspect ratio variation on clad thickness for a spot size of 5. It reveals a small variation window (only when $h \leq 0.623D/5$).

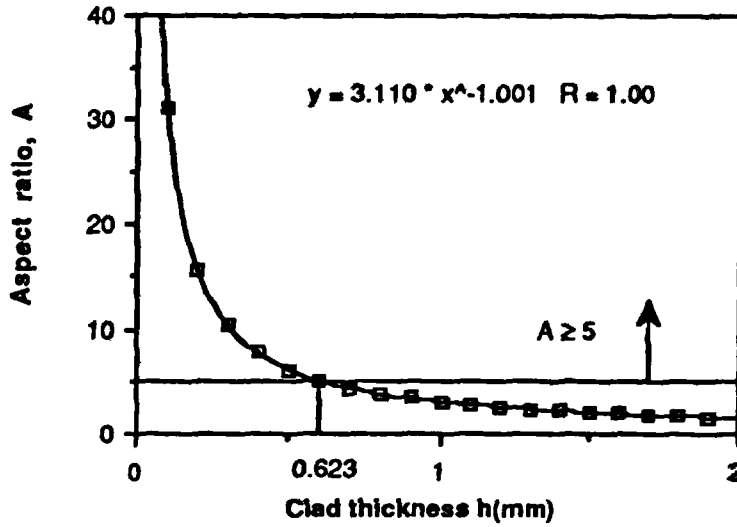


Fig. 10.5. Aspect ratio variation with optimum clad thickness for a beam spot size of 5mm.

10.3.3. Operating parameter optimization when clad thickness and aspect ratio are specified

In this case V and i are interrelated by Eqns.(10-2) and (10-4a) and A is taken as constant. The optimization problem can be stated as:

$$\begin{aligned} \text{Objective:} & \quad \text{Max} \quad C = iWV \\ \text{Subject to:} & \quad W = D'(1-bV) \\ & \quad A = W/H \\ & \quad i = \exp(h/1.8H) \end{aligned}$$

Substituting the constraints into the objective function gives:

$$C = D'V(1-bV) \exp\left(\frac{-hA}{1.8D'(1-bV)}\right) \quad (10-28)$$

By taking the derivative of C with respect to V arrives:

$$\frac{dC}{dV} = [D'(1-2bV) - \frac{hbAV}{1.8(1-bV)}] \exp\left[\frac{-hA}{1.8D'(1-bV)}\right] \quad (10-29)$$

From $dC/dV = 0$ we obtain:

$$2b^2V^2 - \left(\frac{hAb}{1.8D'} + 3b\right)V + 1 = 0 \quad (10-30)$$

which has a solution to be:

$$V = \frac{\left(\frac{hA}{1.8D'} + 3\right) \pm \sqrt{\left(\frac{hA}{1.8D'} + 3\right)^2 - 8}}{4b} \quad (10-31)$$

Since $h > 0$, $A > 0$ and $D' > 0$, we have

$$\frac{hA}{1.8D'} + 3 > 3 \quad (10-32)$$

and

$$\sqrt{\left(\frac{hA}{1.8D'} + 3\right)^2 - 8} > 1 \quad (10-33)$$

One of the solutions of Eqn.(10-31) is

$$V_1 = \frac{\left(\frac{hA}{1.8D'} + 3\right) + \sqrt{\left(\frac{hA}{1.8D'} + 3\right)^2 - 8}}{4b} > b \quad (10-34)$$

From

$$W = D'(1-bV)$$

If $V > b$ then $W < 0$, which is not desired. Thus $V_{op} \neq V_1$. Therefore

$$V_{op} = \frac{\left(\frac{hA}{1.8D'} + 3\right) - \sqrt{\left(\frac{hA}{1.8D'} + 3\right)^2 - 8}}{4b} \quad (10-35)$$

and

$$H_{op} = W/A = D'(1-bV_{op})/A \quad (10-36)$$

The optimum overlap index i_{op} can be derived as:

$$\begin{aligned} i_{op} &= \exp\left(\frac{-h}{1.8H}\right) \\ &= \exp\left(\frac{-hA}{1.8D'(1-bV_{op})}\right) \end{aligned} \quad (10-37)$$

Similarly the optimum powder flowrate M_{op} and laser power P_{op} can be obtained as:

$$M_{op} = \frac{H_{op} V_{op}}{a}$$

$$= \frac{-hV_{op}}{1.8Ln(i_{op})a} \quad (10-38)$$

and

$$P_{op} = \frac{d_m M_{op} + D_1}{c} \quad (10-39)$$

or

$$P \leq M_{im} (P_{max}, K_m D M_{op}) \quad (10-40)$$

For example, in the cladding of Wallex 6PC on mild steel using a 2kW laser, where $a=20$, $b=0.05$, $D=5$ (from Ref.60), the optimized operating parameters for a given clad thickness, say, 1mm will be:

$$V_{op} = 7.00 \text{ mm/s}, \quad M_{op} = 0.524 \text{ g/s}, \quad i_{op} = 0.425, \quad P_{op} \leq 2 \text{ kW}$$

The single clad bead dimension and clad coverage rate are:

$$W_{op} = 3.24 \text{ mm}, \quad H_{op} = 0.649 \text{ mm}, \quad C = 9.68$$

From this example it can be seen that the clad coverage rate has increased by more than 20% compared to the non-optimized case for the same clad thickness (If the un-optimized operating parameter uses an overlap of more than 50%, the difference of clad coverage rate between optimized and non-optimized will be even higher), which makes a significant difference in the production rate and energy savings. The variation of clad coverage rate with clad thickness under the optimized condition for the above example is shown in Fig.10.6. Figs. 10.7 and 10.8 give the variation of optimum powder flowrate and optimum traverse speed with clad thickness for the same cladding application, from which it can be seen that since A is required to be constant, increasing the clad thickness requirement can result in an increase of the bead width which forces the reduction of traverse speed. If however A is allowed to be selected under certain constraints ($A \geq 5$) the situation may become different (Section 10.3.4). Also since the constraints on the selection of overlap index were not considered in the above method, It could cause interrun porosity and non-uniform overlap as shown in Fig. 10.9 for the cladding of Wallex 6PC on EN8 mild steel substrate.

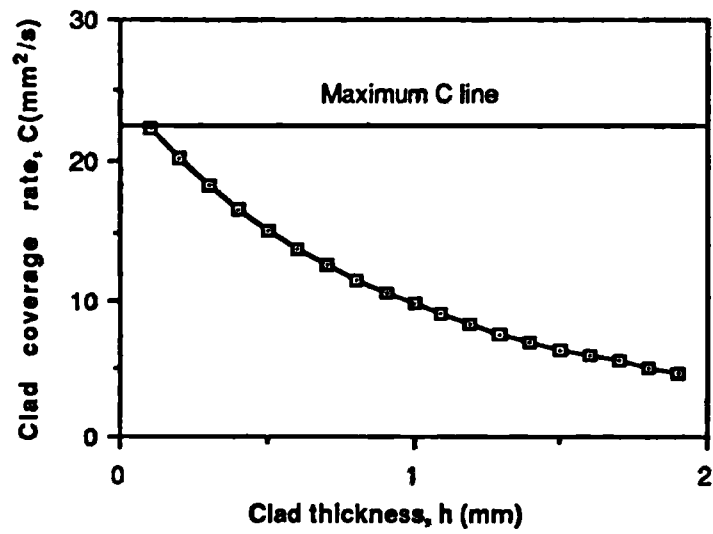


Fig. 10.6 . Clad coverage rate variation with clad thickness.

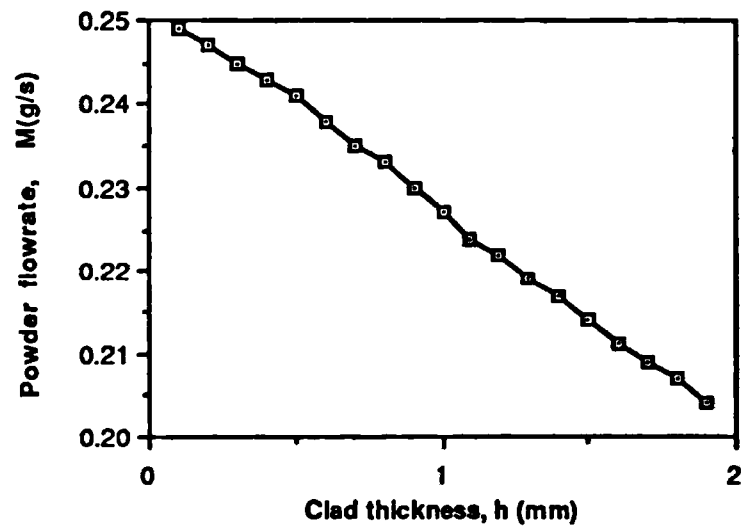


Fig. 10.7. Variation of optimum powder flowrate with clad thickness.

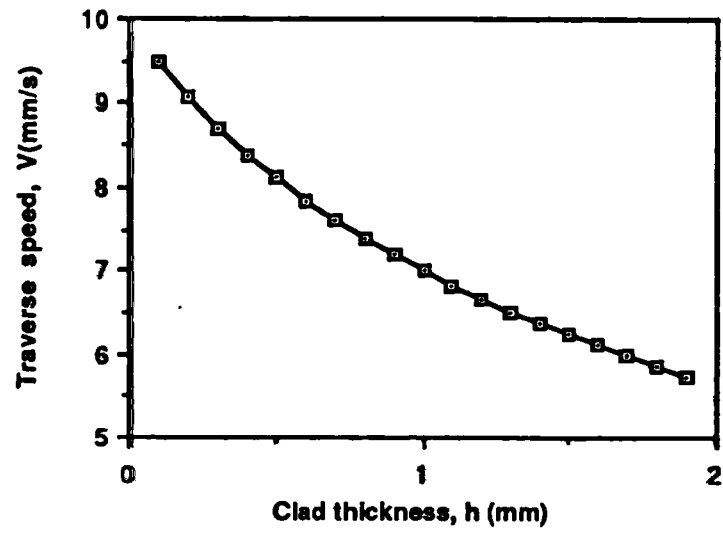


Fig. 10.8. Variation of optimum traverse speed with clad thickness.

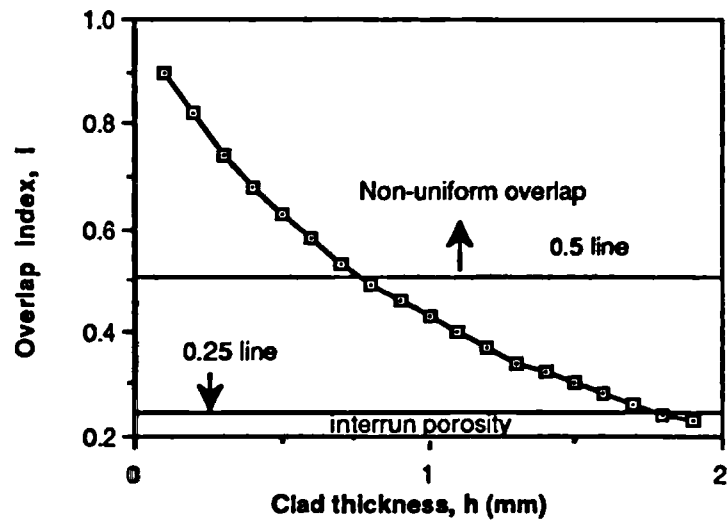


Fig. 10.9 Problems of optimization without considering I variation.

10.3.4. Laser cladding optimization for a given clad thickness requirement with additional constraints for overlap degree and aspect ratio

In the above optimization there is no limit on the i value selection, which could result in poor clad quality for certain clad thickness requirement. Also aspect ratio A is a fixed value in the above optimization. Further improved of the optimization can therefore be made to consider first the in-equality constraints:

$$0.25 \leq i \leq 0.5$$

as well as the other equality constraints to satisfy the clad thickness requirement. The optimization problem can be stated as:

$$\text{Maximize} \quad C = iD(1-bV)V \quad (10-41)$$

$$\text{Subject to} \quad i = \exp(-hV/1.8aM) \quad (10-42)$$

$$A = D(1-bV)V/(aM) \quad (10-43)$$

$$0.25 \leq i \leq 0.75 \quad (10-44a)$$

A slack variable x_1 is introduced so that Eqn.(10-44a) can be replaced by an equation :

$$i = (0.5+0.25)/2 + [(0.5-0.25)/2]\sin(x_1) \quad (10-44b)$$

The optimization problem can be rearranged as:

$$\text{Maximize} \quad C = iD'(1-bV)V$$

$$\text{Subject to} \quad g_1 = i - \exp \{-hA/[1.8D'(1-bV)]\} = 0$$

$$g_2 = i - 0.375 - 0.125 \sin(x_1) = 0$$

where g_1 and g_2 are the two constraint functions.

A necessary condition for the existence of the above constrained optimum is [165]:

$$\text{Det} \left[J_{x_1} \left(\frac{C, g_1, g_2}{x_1, i, V} \right) \right] = 0 \quad (10-45)$$

where J_{x_1} is the Jacobian matrix relative to x_1 , which can be found to be:

$$J_{x_1} \left(\frac{C, g_1, g_2}{x_1, i, V} \right) = \begin{bmatrix} \frac{\partial C}{\partial x_1} & \frac{\partial C}{\partial i} & \frac{\partial C}{\partial V} \\ \frac{\partial g_1}{\partial x_1} & \frac{\partial g_1}{\partial i} & \frac{\partial g_1}{\partial V} \\ \frac{\partial g_2}{\partial x_1} & \frac{\partial g_2}{\partial i} & \frac{\partial g_2}{\partial V} \end{bmatrix}$$

$$= \begin{bmatrix} 0 & D'(1-bV)V & D'(1-2bV)i \\ 0 & 1 & \text{Exp}\left[\frac{-hA}{1.8D'(1-bV)}\right] \frac{hAb}{1.8D'(1-b)^2} \\ 0.125\text{Cos}(x_1) & 1 & 0 \end{bmatrix} \quad (10-46)$$

Thus

$$\begin{aligned} \text{Det} [J_{x_1} (\frac{C, g_1, g_2}{x_1, i, V})] &= -0.125 \cos(x_1) \exp[\frac{-hA}{1.8D'(1-bV)}] \frac{hAbV}{1.8(1-bV)} + \\ &\quad + 0.125 \cos(x_1) D'(1-2bV) \\ &= 0.125 \cos(x_1) [1.8D'(1-bV)(1-2bV)i - \\ &\quad - hAV \exp(\frac{-hA}{1.8D'(1-bV)})] \\ &= 0 \end{aligned}$$

Situation 1: $\cos(x_1) \neq 0$, which is the case when i is inside the defined boundary.

$$1.8D'(1-bV)(1-2bV)i - hAbV \exp[\frac{-hA}{1.8D'(1-bV)}] = 0 \quad (10-47)$$

Combining Eqn.(10-47) with Eqns (10-42) and (10-3a) the following can be derived:

$$2b^2V^2 + (\frac{hAb}{1.8D'} + 3b)V + 1 = 0 \quad (10-48)$$

which is the same as Eqn.(10-30). It means that the formulae obtained for the unconstrained optimization in Section 10.3.3 can be used when i is inside (not including the boundary) the limited zone.

Situation 2: $\cos(x_1) = 0$

$$\text{i.e. } \sin(x_1) = \pm 1$$

From Eqn.(10-44) we have:

$$i = 0.5 \quad \text{or} \quad i = 0.25$$

which is the boundary of the non-equality constraints. In either case V_{op} can be found from Eqns.(10-2), (10-4a), (10-6) and (10-3a) as:

$$V_{op} = \frac{1}{b} (1 + \frac{hA}{1.8D'Ln(i)}) \quad (10-49)$$

and M_{op} and P_{op} can be found using Eqns. (10-15), (10-16) and (10-17). For example: in the cladding of Wallex 6PC on En8 mild steel substrate the variations of the optimum traverse speed, overlap index, powder flowrate and clad coverage rate with clad thickness can be calculated and plotted using Macintosh computer as shown in Figs.10.10 to 10.13, from which we can see that overlap index varies within the specification and at the same time the clad coverage rate is maximized.

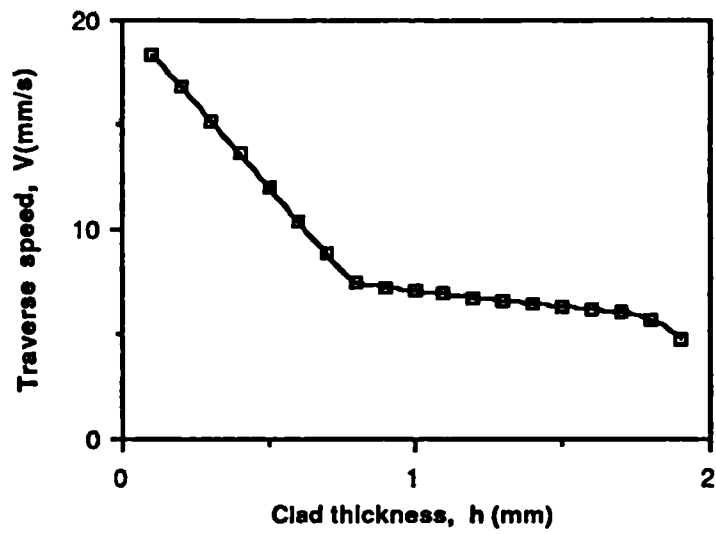


Fig. 10.10. Variation of optimum traverse speed with clad thickness under limited i selection.

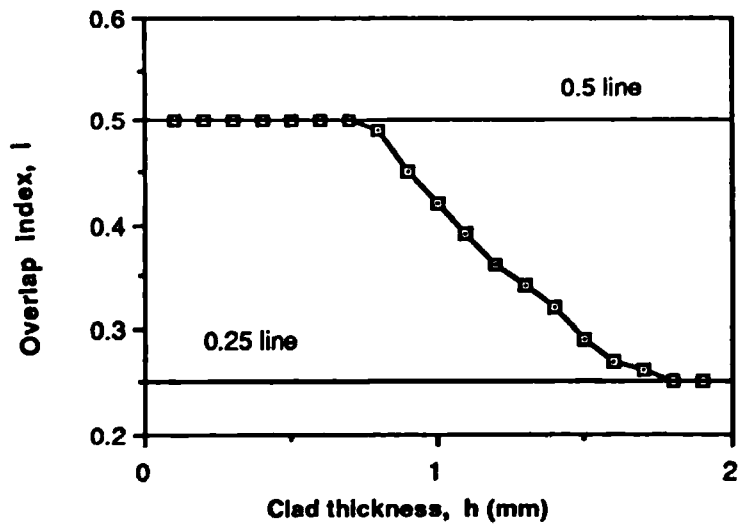


Fig. 10.11. Improvement of the overlap index selection.

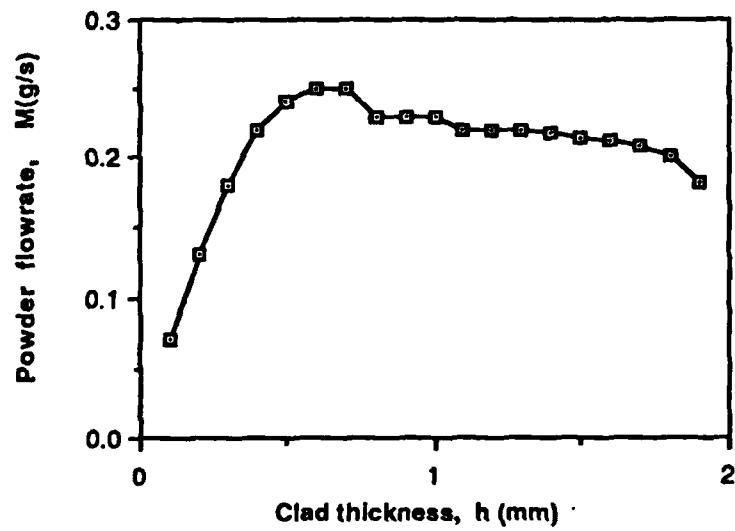


Fig. 10.12. Optimum powder flowrate variation with clad thickness under i constraint.

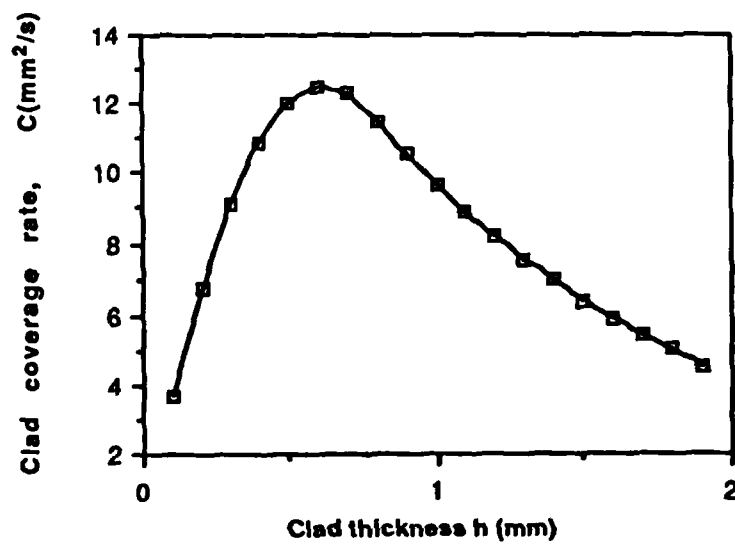


Fig. 10.13. Variation of optimum clad coverage rate with clad thickness under i constraint.

In the above optimization the aspect ratio, A , has been taken as a constant. Now we further extend the optimization so that A is also specified by an in-equality relationship:

$$A \geq 5$$

$$(10-50)$$

as required in the Problem Definition (Section 10.2). This can be considered in the optimization by introducing a second slack variable x_2 so that constraint (10-50) becomes.

$$g_3 = A - 5 - x_2^2 = 0 \quad (10-51)$$

where g_3 is the constraint function. Using the similar analysis as for i we arrive at:

When $h \leq 0.623 D/5 = 0.125D$

$$V_{op} = 1/(2b)$$

$$i_{op} = 0.5$$

otherwise A should be equal to 5 and Eqns. (10-37), (10-35) or (10-49) should be used.

M_{op} , P_{op} , W_{op} , H_{op} and C can be found using Eqns. (10-26), (10-27) and (10-24). Up to now all the constraints $\{i, A, h, D\}$ have been considered in the optimization apart from the machine limits which restrict the choice of clad thickness (This aspect will be discussed in the next section), which suggests that if the calculated i is within the constrained limits and A is equal or less than 5 then the optimization should let $A = 5$ and use Eqns (10-35) to (10-40); Otherwise Eqns (10-49) and/or (10-22) to (10-27) should be used. With such consideration the optimization for the cladding of Wallex 6PC on mild steel substrate ($a=20$, $b=0.05$ and $D=5$ [60]) was made and the results are shown Figs. (10-14) to (10-17), from which we can see that both i and A vary within the constraints and C is maximized.

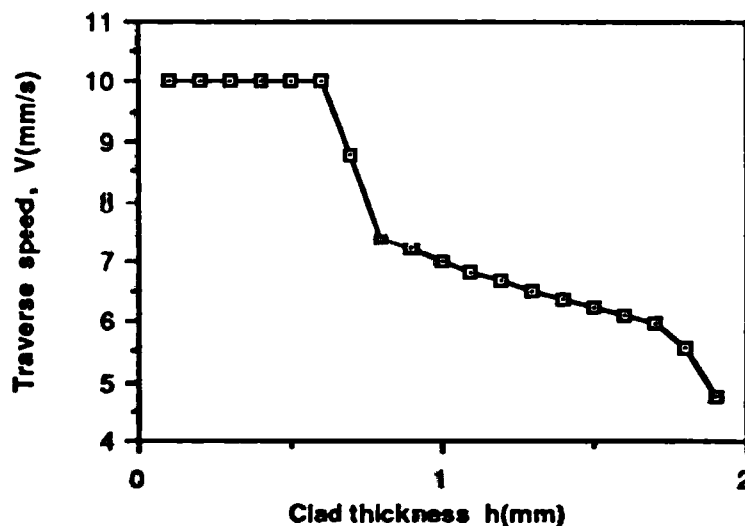


Fig. 10.14. Variation of optimum traverse speed with clad thickness under both i and A constraints.

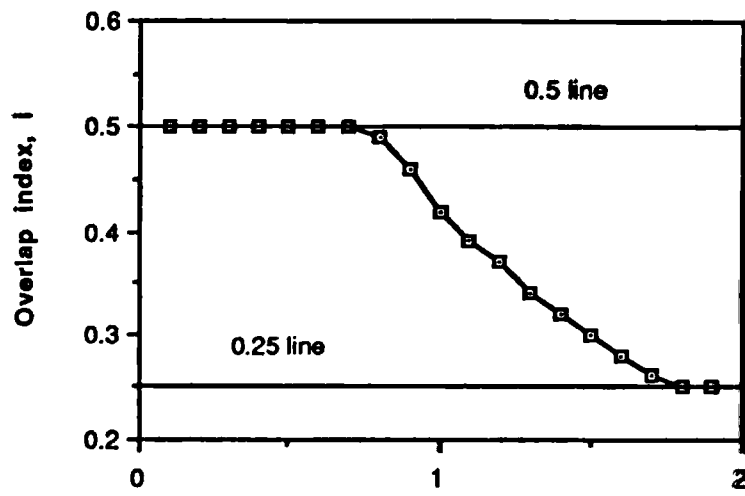


Fig. 10.15. Variation of optimum overlap index with clad thickness.

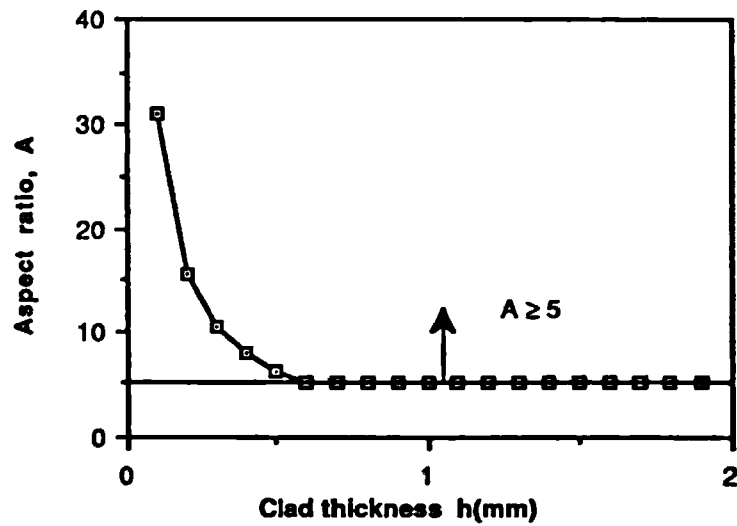


Fig. 10.16. Variation of optimum aspect ratio with clad thickness.

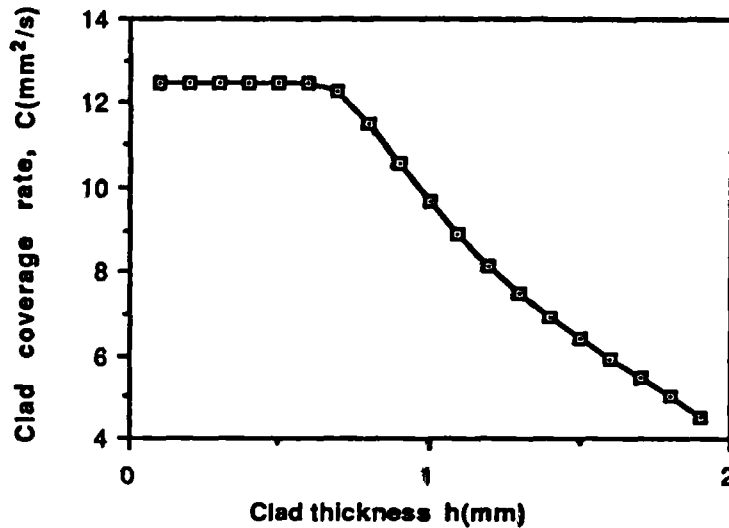


Fig. 10.17. Optimized clad coverage rate for different clad thickness.

10.4 OPERATING LIMITS CALCULATION

In the above calculations the limit and scope for the choice of the operating parameters were not given. In practice some of the values obtained above may not be able to be physically realized or not realistic. Thus the selection of clad thickness is also restricted by these limits. The purpose of calculating the operating limits not only lies in the need for consideration of the scope in selecting operating parameter and cladding requirement in laser cladding practice but also gives the envelope of the possible variations of operating parameters for on-line feedback control. The limits of operating parameters can be calculated as follows:

1). Maximum traverse speed V_{max}

From Eqn.(10-3a) we know that if $V \geq 1/b$ then $W \leq 0$ which means cladding is not possible. Therefore traverse speed must be less than this value:

$$V_{max} = 1/b + \delta \quad (10-52)$$

where δ is a tolerance value.

2). Minimum powder flowrate M_{min}

The minimum powder flowrate should be the bigger value between the lowest capable

powder flowrate of the powder feeder for stable feeding and that restricted for dilution requirement. i.e.

$$M_{\min} = \text{Max}[P_{\min}/(DK_m), M_{\min f}] \quad (10-53)$$

where $M_{\min f}$ is the lower limit of the powder feeder below which the feeding will not be stable.

3). Minimum traverse speed, maximum clad bead height width, $W_{\max}$ and the maximum and minimum clad bead height, $H_{\max}$ and $H_{\min}$

This value is decided by the aspect ratio and limited bead width. Since the lower the speed the higher will be the clad thickness while the maximum bead width is the laser spot size. Thus a higher value than a minimum allowed traverse speed will result in interrune porosities because of the poor aspect ratio. This limiting value together with the maximum clad bead height, $H_{\max}$, and maximum clad bead width, $W_{\max}$, can be found by solving the following equations:

$$W_{\max} = D(1-bV_{\min}) \quad (10-54)$$

$$H_{\max} = W_{\max}/A_{\min} \quad (10-55)$$

$$V_{\min} = a M_{\min}/H_{\max} \quad (10-56)$$

where $A_{\min}$ is the lower limit of the aspect ratio (usually = 5). $V_{\min}$ can be found to be:

$$V_{\min} = \frac{D - \sqrt{D^2 - 4abDM_{\min}A_{\min}}}{2bD} \quad (10-57)$$

and $H_{\max}$ and $W_{\max}$ can be calculated as:

$$W_{\max} = \frac{D}{2} + \sqrt{D^2 - 4abDM_{\min}A_{\min}} \quad (10-58)$$

and

$$\begin{aligned} H_{\max} &= W_{\max}/A_{\min} \\ H_{\min} &= a M_{\min}/V_{\max} \end{aligned} \quad (10-59)$$

4). Maximum powder flowrate, $M_{\max}$

The maximum powder flowrate is restricted by the aspect ratio required and the clad bounding condition as well as the upper limit of the powder feeding system. Therefore

$$M_{\max} = \text{Min}(H_{\max}V_{\max}/a, M_{\max f}, P_{\max}/K_m) \quad (10-60)$$

where M_{maxf} is the upper limit of the powder feeder and P_{maxl} is the upper limit of the power for the laser used.

5). Maximum and minimum laser power. P_{max} and P_{min}

In order to avoid dilution, the upper limit for laser power will be restricted to :

$$P_{max} = \text{Min}(M_{max}DK_m, P_{maxl}) \quad (10-61)$$

The minimum laser power is the power required to be able to generate a "wet" on the substrate within the traverse length of spot size at the slowest speed. Below this point no cladding is possible. The power required to melt the substrate at the lowest speed according to Ready's equation, (Eqn. (2-7) in Chapter 2) can be estimated as:

$$P_{min} = \frac{\pi T_{mt} D^2 C_v}{4(1-r)} \sqrt{\frac{2K_{th} V_{min}}{D}} \quad (10-62)$$

where T_{mt} = melting point of the substrate material ($^{\circ}\text{K}$)
 C_v = Specific heat of the substrate material ($\text{J/g}^{\circ}\text{K}$)
 K_{th} = Thermal diffusivity of the substrate material ($\text{W/mm}^{\circ}\text{K}$)
 D = laser spot size (mm)
 r = reflectivity of the material plus the powder shadow effect.

6). The maximum and minimum clad thickness. h_{max} and h_{min}

The restriction on the overlapped clad thickness is critical to the success of parameter optimization. If the requirement of clad thickness is beyond the capability of the machines or leads to poor clad quality, no optimization can be made. From the above calculations we have already obtained the restrictions for single pass clad bead for overlapping purposes. These are mainly due to the restrictions on the spot size and aspect ratio (for maximum bead height) and minimum powder flowrate and maximum traverse speed (for minimum bead height). The clad thickness selection should be within the capability of the cladding system and also satisfies the processing constraints. The maximum possible overlapped clad thickness can be found as:

$$\begin{aligned} h_{max} &= -1.8H_{max} \ln(i_{min}) \\ &= 2.49 H_{max} \\ &= 2.49 W_{max}/A_{min} \\ &= 2.49 D'/A_{min} \end{aligned} \quad (10-63)$$

The minimum overlapped clad thickness is limited by the minimum stable powder feed

rate and minimum stable laser power. (Many lasers do not work well at lower power levels.)

$$\begin{aligned}
 h_{min} &= -1.8H_{min}\ln(i_{max}) \\
 &= 1.25H_{min} \\
 &= 1.25 aM_{min}/V_{max} \\
 &= 1.25 abM_{min}
 \end{aligned}
 \tag{10-64}$$

For example, in the cladding of Wallex 6PC on EN8 mild steel with a fixed 1.9KW laser power and spot size of 5mm and knowing that $a=20$, $b=0.05$, $K_m=2.5$ (From Ref.60), if the minimum aspect ratio is required to be 4.5, then the operating limits or operating window for the process can be evaluated to be:

V (mm/s)	M (g/s)	W (mm)	H (mm)	h (mm)
2.6 - 17	0.15 - 0.82	0.75 - 4.35	0.18 - 0.97	0.22 - 2.42

These results agree with the experiments^[60].

10.5. PROCESS PARAMETER IDENTIFICATION

In the above analysis and optimization, it has assumed known process parameters a , b , D' , c and d_m . These parameters were decided by the physical properties of the cladding materials and process set-up conditions. They can be obtained through experiments and statistical analysis as has been done by Steen et al for the cladding of Wallex 6PC on mild steel^[60]. If the operating conditions change, such as a change of powder feeding angle, laser mode structure or cladding of a new material, the existing parameters may not be suitable. In this section various formulae were developed for the on-line identification of these parameters through in-process sensors.

10.5.1. Instantaneous approximation method

From relationship :

$$H = aM/V$$

"a" can be calculated from either single track experiment

$$a = HV/M$$

or multi-track (n tracks with different operating parameters) experiment

$$a = \frac{1}{n} \sum_{i=1}^n \frac{H_i V_i}{M_i} \quad (10-65)$$

where H and H_i are the bead height measured by the in-process sensors, V_i and M_i are traverse speed and powder flowrate used for producing these tracks. n is the number of point taken for the parameter evaluation.

From $W = D'(1-bV)$
the parameter D' and b can be obtained by using dual track experiments:

$$W_1 = D' (1-bV_1) \quad (10-66)$$

$$W_2 = D' (1-bV_2) \quad (10-67)$$

where W_1 and W_2 are the clad bead width measured by on-line sensors and V_1, V_2 are the traverse speeds used for producing these two tracks. Therefore D' and b can be calculated as:

$$b = \frac{W_2 - W_1}{W_2 V_1 - W_1 V_2} \quad (10-68)$$

and

$$D' = \frac{1}{2} \left[\frac{W_1}{1-bV_1} + \frac{W_2}{1-bV_2} \right] \quad (10-69)$$

From $DI = cP - dmM$
c and dm can be obtained by using dual track experiments:

$$DI_1 = cP_1 - dmM_1 \quad (10-70)$$

$$DI_2 = cP_2 - dmM_2 \quad (10-71)$$

as:

$$c = \frac{D_{I1} M_2 - D_{I2} M_1}{P_1 M_2 - P_2 M_1} \quad (10-72)$$

$$dm = \frac{1}{2} \left(\frac{cP_1 - D_{I1}}{M_1} + \frac{cP_2 - D_{I2}}{M_2} \right) \quad (10-73)$$

10.5.2. Least square regression method

This is a statistical method which uses a given equation to approximate the experimental data so that the square of the error of the function determined by the parameter from the

experimental data is minimum.

The error function for parameters D' and b can be expressed as:

$$\sum_{i=1}^n e_{wi}^2 = \sum_{i=1}^n (W_i - D' + D'bV_i)^2 \quad (10-74)$$

Minimizing the error function by taking the partial derivative with b and D' to zero we have:

$$\frac{\partial(\sum_{i=1}^n e_{wi}^2)}{\partial b} = 2D' \sum_{i=1}^n (W_i V_i - D'V_i + D'bV_i^2) = 0 \quad (10-75)$$

and

$$\frac{\partial(\sum_{i=1}^n e_{wi}^2)}{\partial D'} = \sum_{i=1}^n [(2bV_i - 1)(W_i - D' + D'bV_i)] = 0 \quad (10-76)$$

from which b and D' can be obtained as:

$$b = \frac{(\sum W_i)^2 - \sum W_i V_i}{\sum W_i [\sum V_i^2 - (\sum V_i)^2]} \quad (10-77)$$

$$D' = \frac{\sum W_i}{1 - b \sum V_i} \quad (10-78)$$

The error function for parameter a can be expressed as:

$$\sum_{i=1}^n e_{Hi}^2 = \sum_{i=1}^n (H_i - a \frac{M_i}{V_i})^2 \quad (10-79)$$

By taking derivative of the error function respect to " a " to zero we obtain:

$$\frac{d \sum e_{Hi}^2}{da} = 2 \sum \left(\frac{M_i H_i}{V_i} - a \frac{M_i^2}{V_i^2} \right) = 0 \quad (10-80)$$

i.e.

$$a = \frac{\sum \left(\frac{M_i H_i}{V_i} \right)}{\sum \left(\frac{M_i}{V_i} \right)^2} \quad (10-81)$$

The error function for c and dm can be obtained as:

$$\sum_{i=1}^n e_{Dli}^2 = \sum_{i=1}^n (D_{li} - cP_i + d_m M_i)^2 \quad (10-82)$$

The value of c and dm can be found through:

$$\frac{\partial \sum e_{Dli}^2}{\partial c} = 2 \sum (-P_i D_{li} + cP_i^2 + d_m P_i M_i) = 0 \quad (10-83)$$

and

$$\frac{\partial \sum e_{Dli}^2}{\partial d_m} = 2 \sum (M_i D_{li} - cP_i M_i - d_m M_i^2) = 0 \quad (10-84)$$

Solving the the equations we have:

$$d_m = \frac{\sum P_i^2 \sum M_i D_{li}}{(\sum P_i M_i)^2 + \sum P_i M_i \sum P_i D_{li} - \sum P_i^2 \sum M_i^2} \quad (10-85)$$

and

$$c = \frac{d_m \sum P_i M_i + \sum P_i D_{li}}{\sum P_i^2} \quad (10-86)$$

The experimental procedure for the on line process parameter identification using least square regression method can be summarized as:

- i). Clad n single tracks using different operating parameters P_i , M_i , V_i .
- ii). Record bead dimensions W_i , H_i and dilutions D_{li} for each operating parameter used.
- iii). Using the developed equations to calculate a, b, c, d_m and D' .
- iv). Examine the parameter fitness by calculating the corresponding standard error which is defined as:

$$\sigma = \sqrt{\frac{\sum_{i=1}^n e_i^2}{n-1}} \quad (10-87)$$

where σ is standard deviation of the identified parameters and e_i is the errors in the error function expressions in Eqn (10-74) for b and D' , Eqn.(10-79) for " a ", and Eqn. (10-82) for c and d_m .

The smaller this value is, the better the fitness will be the parameters to the assumed relationships . For example, to examine the deviation of parameter " a " as identified, σ_H can be calculated as:

$$\sigma_H = \sqrt{\frac{\sum_{i=1}^n e_{Hi}^2}{n-1}} = \sqrt{\frac{\sum_{i=1}^n (H_i - a \frac{M_i}{V_i})^2}{n-1}} \quad (10-88)$$

If s_H is within say 10% of the average H_i value, then we may accept the parameter, otherwise the identification is failed. It means the statistical expression for the process is not suitable.

10.6. COMPUTER PROGRAM REALIZATION

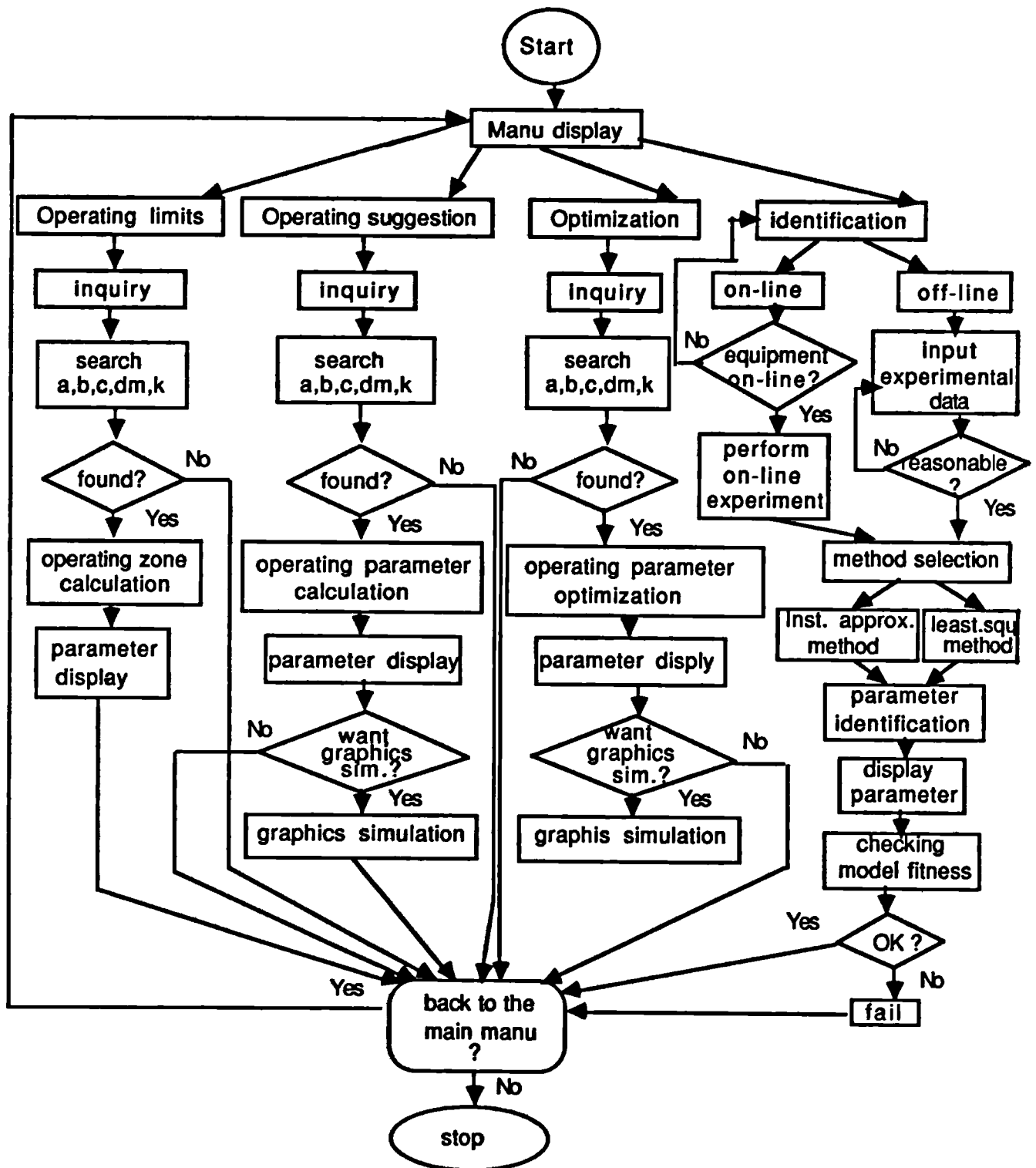


Fig. 10.18. Flow chart for laser cladding parameter optimization.

The overall algorithms were realized using BASIC language, which starts by asking questions from the user and then calculates and suggests either operating zones or the corresponding (not optimized) or the optimum operating parameters for the given cladding requirement. The process parameters a , b , c , d_m and K_m are stored either from previous collections in a data bank for the known process or derived from the on-line identification or by inputting experimental data by the user from the computer terminal. The flow chart of the computer software is shown in Fig. 10.18.

10.7. SUMMARY

An optimization technique and a software package for powder feed laser cladding process have been developed which has the following features:

- 1). Maximizing the cladding coverage rate.
- 2). Minimizing dilution. Actually the desired level of dilution could be achieved by using the technique -- an advantage for laser alloying.
- 3). Clad thickness is as desired.
- 4). Preventing interrune porosity through proper bead aspect ratio and degree of overlap.
- 5). Preventing non-uniform clad thickness due to improper overlapping.
- 6). The method is not restricted to a particular process such as laser power level or cladding materials.
- 7). Process parameters a , b , c , d_m , K_m etc. can be found or identified either by simple off-line experiments or on-line identification.
- 8). The operating zone or operating limits can be calculated to assist the parameter selection.

These developments have provided a more scientific way of selecting optimum operating parameters for a given cladding requirement, while previous approaches were based on experience and trial and error which would not be accurate and repetitive. Experimental data from Ref.60 were used to examine the developed formulae, which agreed with experiments closely. The optimum conditions set up using the developed methods however may be broken during processing because of surface temperature rise etc. The next chapter will investigate the methods to deal with this problem by using continuous on-line adaptive cladding process control.

CHAPTER 11

DEVELOPMENT OF ADAPTIVE LASER CLADDING CONTROL TECHNIQUES

11.1 INTRODUCTION

It is desirable that the required clad quality be maintained through out the processing time. This however can not be guaranteed due to various factors including substrate temperature rise, substrate thickness variation and beam mode structure variations. The change of process parameters a , b , c , d_m and D' by these factors will change the process relations and lead to the progressive deterioration of clad quality as discussed in the General Introduction. Therefore operating parameters have to be varied on-line to compensate for these changes. Since process parameters in laser cladding are inter-related (See Chapter 2), variation of one parameter (such as powder flowrate) will lead to a change of several clad parameters (such as dilution and clad thickness). Therefore several operating parameters have to be varied at the same time to achieve a desired control objective: maintaining the clad parameters (bead width, height or clad thickness and dilution) as the desired value through out the process. This chapter describes the author's work on the development of techniques for the supervisory feedback (adaptive) control of laser cladding. The methods developed are:

- 1). Adaptive control by continuous on-line identification and adjustment of operating parameters.
- 2). Adaptive control by rule based self-learning control law and quantitative sensory feedbacks.
- 3). Rule based adaptive control through qualitative sensor feedbacks.

11.2. ADAPTIVE LASER CLADDING CONTROL BY ON-LINE IDENTIFICATION

If the on-line identification and optimization introduced in Chapter 10 are continued during the process then the change of process parameters a , b , c , d_m can be detected and model values continuously updated provided the process models used are correct. Optimum operating parameters can be re-calculated. This on-line identification must however not to disturb the normal processing. i.e. the identification must use the existing process information from sensor feedbacks instead of going through a series controlled experiments as used in Chapter 10. This is because the deliberate generation of operating parameter changes for process identification can cause process disturbance and therefore the possible undesirable changes of clad quality. Other two problems of using the off-line optimization

technique discussed in Chapter 10 for on-line feedback control are:

a). The optimization will result in the change of both clad bead dimensions and overlap degree. If this is continued during processing, neither single bead dimensions nor the degree of overlap will be constant thus the overlapped clad cannot be uniform.

b). The h-H relationship used in the optimization is the steady state relation which requires 5 to 6 overlapped tracks to be reached. If the optimization is continued in between these tracks all the expected relations will be altered.

Thus the optimization is recommended for use at the start of the operation to determine the best ratio between overlap degree and single bead parameters (optimum clad bead width and height). The aim of the on-line adaptive control is to maintain these optimum conditions.

Suppose there is a process disturbance such as surface temperature rise, it will lead to a change of clad bead width, height and dilution, if the operating parameters are not changed accordingly. These varied process parameters (bead width, height and dilution) however can be detected by the in-process sensors to be:

$$W_{i+1} = W_i + \Delta W \quad (11-1)$$

$$H_{i+1} = H_i + \Delta H \quad (11-2)$$

$$D_{i+1} = D_i + \Delta D \quad (11-3)$$

where W_{i+1} , H_{i+1} and D_{i+1} are the present values of the clad bead width, height and dilution detected by in-process sensor; W_i , H_i and D_i are the previous corresponding clad parameters; and ΔW , ΔH and ΔD are the differences between the two values of the corresponding clad parameters. The task of the computer control is to identify the changes of the process parameters a , b , D' , c and d_m of the process model through the above detected changes and the known operating parameters (laser power, powder flowrate and traverse speed). This can be done by the modification of Eqns. (10-65), (10-4a), (10-69), (10-5a) and (10-73) without disturbing the process:

$$\begin{aligned} a_{i+1} &= (1/2) (V_i/M_i) (H_i + H_{i+1}) \\ &= (a_i + a_i H_{i+1}/H_i)/2 \\ &= (a_i/2) (1 + H_{i+1}/H_i) \end{aligned} \quad (11-4)$$

$$\begin{aligned} D'_{i+1} &= [1/(2(1-b_i V_i))] (W_i + W_{i+1}) \\ &= (D'_i + D'_i W_{i+1}/W_i)/2 \\ &= (D'_i/2) (1 + W_{i+1}/W_i) \end{aligned} \quad (11-5)$$

$$b_{i+1} = (1/V_i)(1 - W_{i+1}/D'_{i+1}) \quad (11-6)$$

$$\begin{aligned}
d_{mi+1} &= (1/2)[(c_i P_i - D_{li})/M_i + (c_i P_i - D_{li+1})/M_i] \\
&= (1/2)[2d_{mi} - (D_{li} + D_{li+1})/M_i] \\
&= d_{mi} - (D_{li} + D_{li+1})/(2M_i)
\end{aligned} \tag{11-7}$$

$$c_{i+1} = (D_{li+1} + d_{mi+1} M_i)/P_i \tag{11-8}$$

where a_{i+1} , b_{i+1} , c_{i+1} , d_{mi+1} and D'_{i+1} are the updated process parameters through in-process sensing and on-line identification. The new operating parameters V_{i+1} , M_{i+1} and P_{i+1} required to maintain the desired clad parameters can be obtained by using Eqns. (10-13), (10-14) , (10-16) and the above identified process parameters. i.e.

$$V_{i+1} = \frac{1}{b_{i+1}} - \frac{W_r}{b_{i+1} D_{i+1}} \tag{11-9}$$

$$M_{i+1} = \frac{H_r V_{i+1}}{a_{i+1}} \tag{11-10}$$

$$P_{i+1} = \frac{D_{lr} + d_{mi+1} M_{i+1}}{c_{i+1}} \tag{11-11}$$

where W_r , H_r and D_{lr} are the desired clad bead width, bead height and dilution as calculated from initial optimization (See Chapter 10); V_{i+1} , M_{i+1} and P_{i+1} are the new operating parameters to be used for the maintaining the required clad qualities. The closed loop configurations for this method is illustrated in Fig. 11.1.

A computer simulation of the above control method was made for the cladding of Wallex 6PC on En8 mild steel to study the control effect under the process disturbance of the surface temperature rise. From the fact that the surface temperature rise will lead to a increase of bead width, height and dilution^[50,197] (Also see Addendix B), the temperature effect was simulated by the continuous increasing of these parameters. i.e.

$$W_{i+1} = (D' + 0.05N)(1 - bV_i) \tag{11-12}$$

$$H_{i+1} = (a + 0.25N)M_i/V_i \tag{11-13}$$

$$D_{li+1} = (c + 0.002N)P_i - d_m M_i \tag{11-14}$$

where N is the number of iteration. If the process parameters changes are not detected by the controller, V_i , M_i and P_i will not be updated. Therefore clad bead width, height and dilution will increase progressively as in the case of surface temperature rise. What visible to the controller in the simulation were the changes of the clad parameters, W , H and DI . The controller had to figure out the inside changes of the process parameters a, b, c, d_m and D' using Eqns.(11-4) to (11-8) and worked out a new set of control demands: V_{i+1} , M_{i+1} and

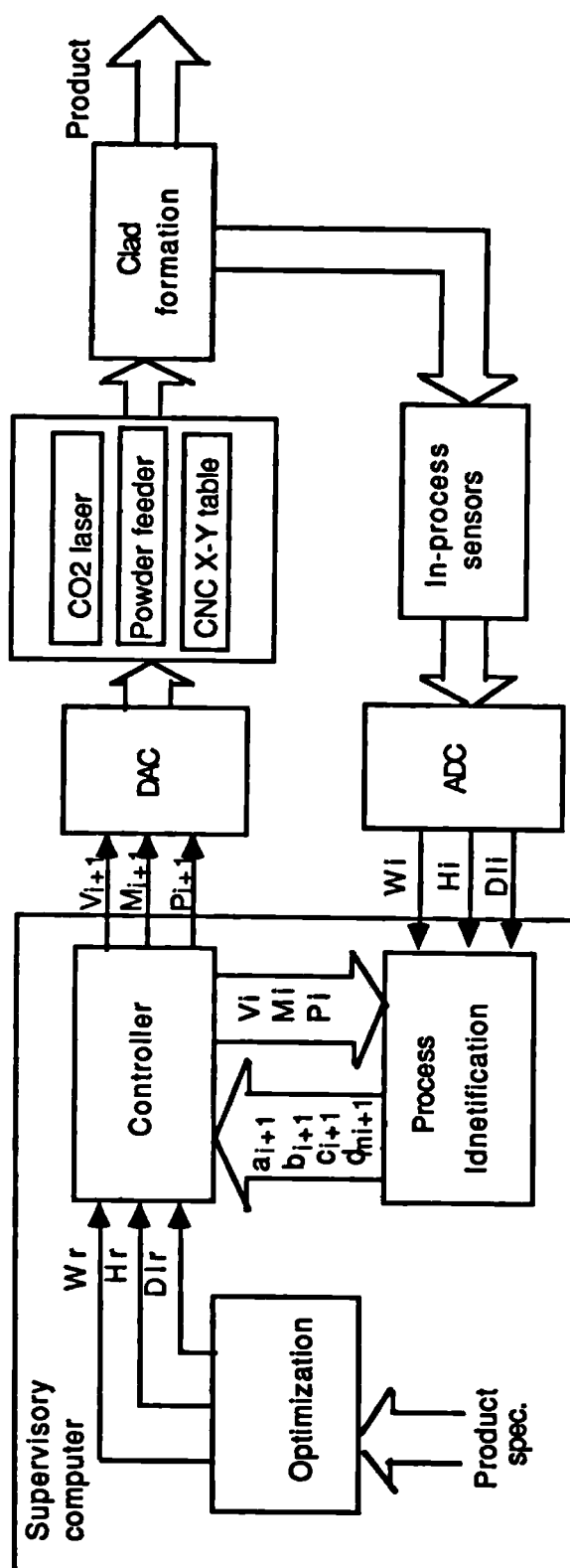


Fig. 11.1.1. Configuration for adaptive laser cladding control (method 1).

P_{i+1} using Eqns.(11-9) to (11-11) in order to keep clad bead width, height and dilution as the demanded values, W_r , H_r and D_{lr} . The control effects were such examined and the results are shown in Fig. 11.2 to Fig.11.4 where the desired clad parameters are:

$W_r = 3 \text{ mm}$
 $H_r = 0.7 \text{ mm}$
 $D_{lr} = 0.1$

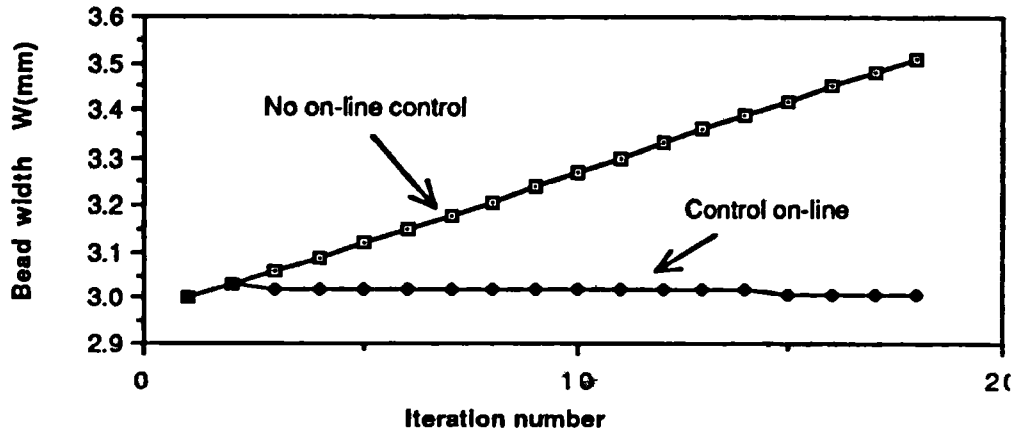


Fig. 11.2. Effect of the clad bead width control under surface temperature rise.

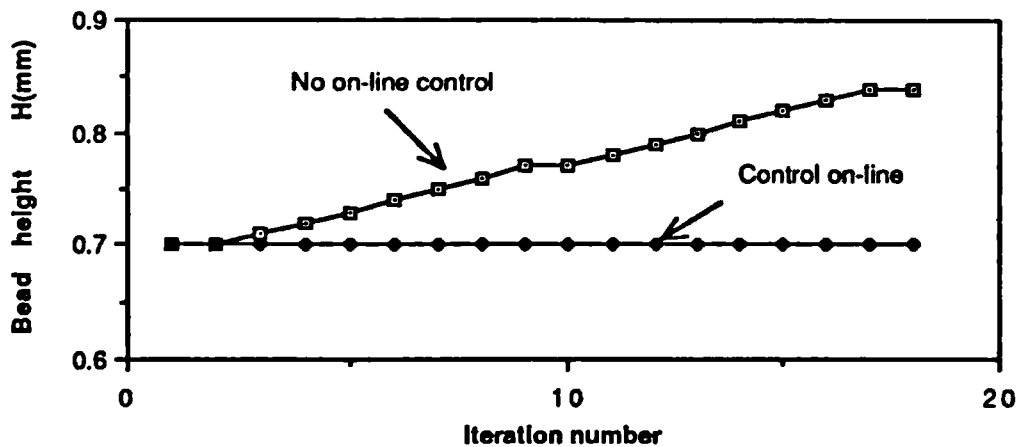


Fig. 11.3. Effect of the clad bead height (or clad thickness) control under surface temperature rise.

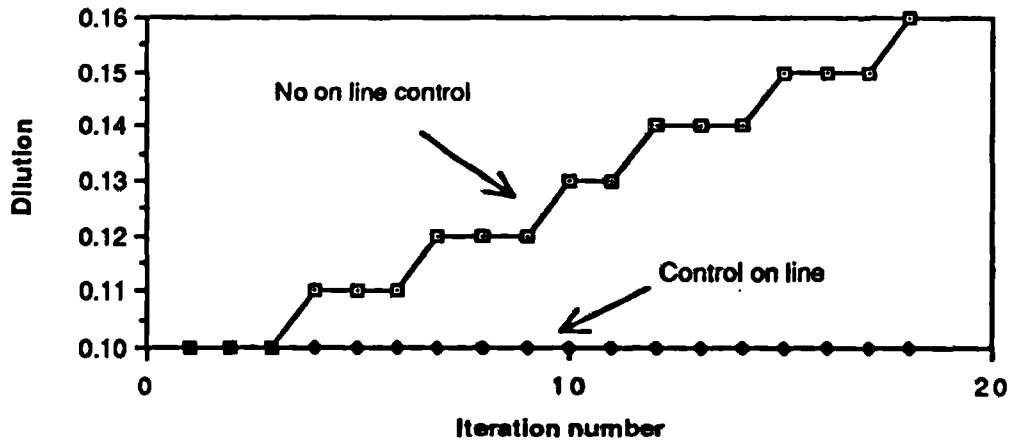


Fig. 11.4. Effect of the dilution control under the surface temperature rise.

From the above control results it can be seen that the temperature rise could be compensated for using the controller designed. Actually, during the control the traverse speed was increasing (Fig. 11.5a) and laser power was decreasing (Fig.11.5b) to compensate for the temperature rise effect. Powder flowrate was found not changed in this case. i.e $M = 0.28\text{g/s}$.

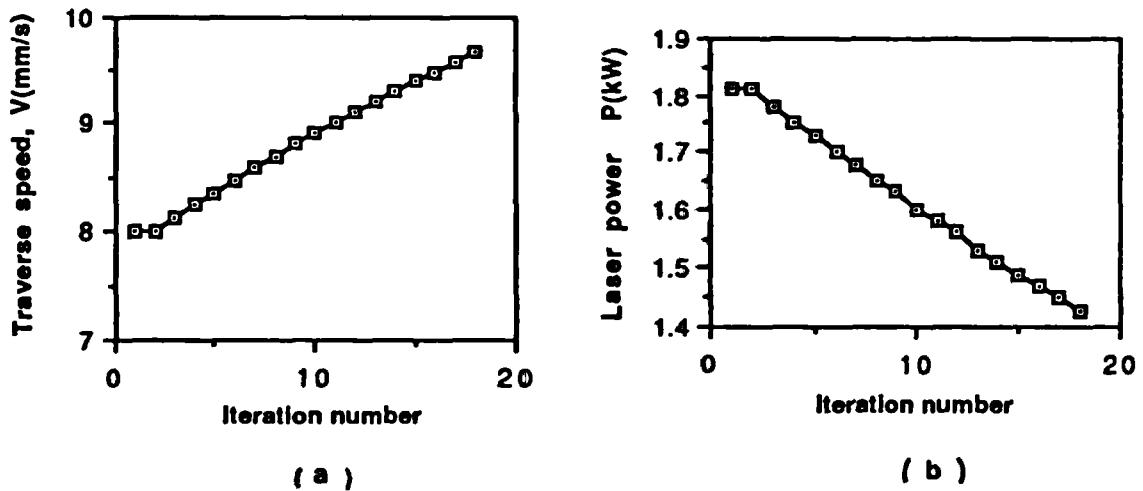


Fig. 11.5. Operating parameter variations during the control action.

A second computer simulation was made to examine the robustness of the designed controller. This was done by using different models for the process simulation from that used for control reference. In this case the process was simulated using a more interactive relationship (See Chapter 2):

$$W = D'(1-bV) + cP - dmM \quad (11-15)$$

$$H = a(1 + K_1P) M/V \quad (11-16)$$

$$DI = cP - dmM \quad (11-17)$$

while the controller were based on a different, simplified model:

$$W = D'(1-bV) \quad (11-18)$$

$$H = aM/V \quad (11-19)$$

$$DI = cP - dmM \quad (11-20)$$

where $a=20$, $b=0.05$, $c=0.12$, $dm=0.42$, $D'=5$ and $K_1=1.5$ [60] to simulate the cladding of Wallex 6PC or 316 steel on mild steel substrate. The demanded clad parameters were the same as in the first simulation experiment. The simulation results are shown in Figs.11.6 and 11.7. from which it can be seen that, despite the differences in the models used for control and that for the cladding process. The controller still could manage to keep the clad parameters as the desired values after a few control iteration.

The advantage of the controller is that the control action is fast (took less than 1ms computing time using PASCAL and 5ms using BASIC on an Opus PC-5 micro-computer) and adaptive (can follow the process changes). However since the controller requires a known process model (model parameters are not required to be accurate), if the fitness of the model is poor then the control accuracy may become poor as well, although this was not shown in the examples studied.

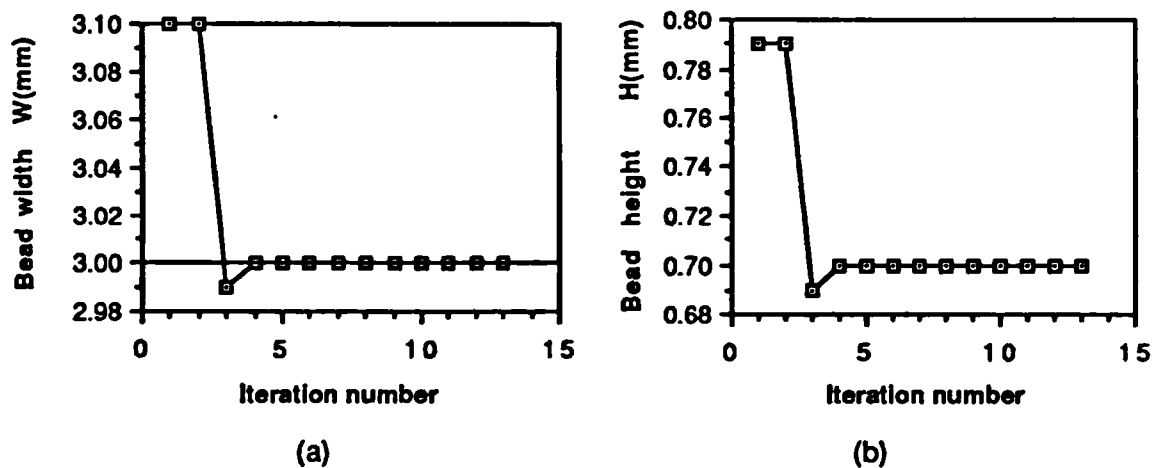
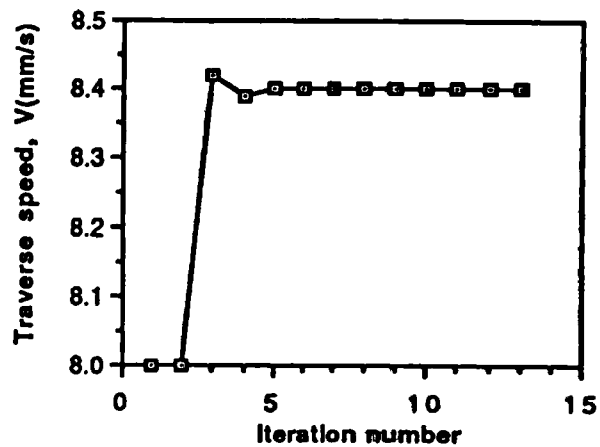
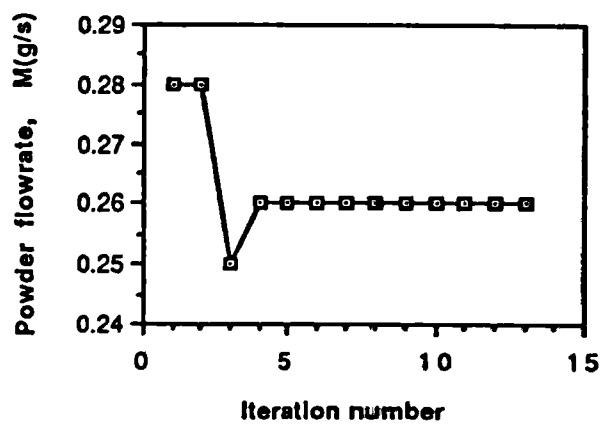


Fig. 11.6. The control effects for clad bead width (a) and height (b) when the control reference model used was not accurately representative of the real process.



(a)



(b)

Fig. 11.7. Operating parameter variations during the control action. a). Traverse speed. b). Powder flowrate. (Laser power also converges from 1.81kW to 1.74 kW in two iteration).

11.3 ERROR GENERATED SELF-SEARCHING ADAPTIVE LASER CLADDING CONTROL

A second adaptive control algorithm was developed which does not require a process model but uses the errors between the demand values and actual feedback signals to generate

a negative recursive feedback control action. The optimum control gains are searched for on-line adaptively according to the system performance and a series search rules. This method differs from previous adaptive control methods (such as model reference adaptive control, Kalman Sub-optimal adaptive control etc.) in that the process model is not required for the controller while the previous methods do. Therefore the inaccuracy of the model will not influence the control effects and the application of which may become more general. The control algorithm and adaptation rules will be described separately in the following.

11.3.1. Control algorithm development

Suppose the demanded clad parameters are $H=H_r$, $W=W_r$ and $DI = D_{lr}$. For some reasons (such as improper operating parameters or surface temperature rises) the actual process responses are different from the demanded an error between the two is generated:

$$EW = W_r - W_i \quad (11-21)$$

$$EH = H_r - H_i \quad (11-22)$$

$$EDI = D_{lr} - D_{li} \quad (11-23)$$

where W_i is the actual clad bead width measured at iteration i and E_w is the associated deviation from the demanded value W_r ; H_i is the actual bead height or clad thickness measured at iteration i and E_H is the associated deviation from the demanded value H_r ; D_{li} is the actual dilution measured at iteration i and EDI is the associated deviation from the desired value D_{lr} .

From the experiments and experience, we know that clad bead width can be varied by the variation of traverse speed V ; clad thickness can be varied by the variation of powder flowrate as well as traverse speed and dilution can be varied by the variation of laser power as well as powder flowrate. On the other hand variation of one parameter may lead to a change of several clad parameters. However since powder flowrate has only little influence on the clad bead width and traverse speed has little influence on the clad dilution (See Chapter 2), some of these interrelations may be decoupled. A multi-variable negative feedback laser cladding control algorithm was then designed as using the above knowledge:

$$V_{i+1} = V_i - K_v E_w \quad (11-24)$$

$$M_{i+1} = M_i + K_m V_i E_H \quad (11-25)$$

$$P_{i+1} = P_i + K_p EDI \quad (11-26)$$

where $K_v > 0$ is the bead width control gain, $K_m > 0$ is the bead height control gain and $K_p > 0$ is the dilution control gain. According to this control law, if bead width is higher than the demanded ($E_w < 0$) the traverse speed V will be automatically increased so that the bead width is reduced; On the other hand if the bead width is smaller than the demanded ($E_w > 0$)

then the traverse speed will be automatically decreased so that the clad bead width can be increased; If clad bead width is equal to the demanded ($E_w = 0$) then the traverse speed will be kept constant, i.e. no control action is taken. The disturbance of the clad bead width can come from various sources including the variation of other operating parameters (such as powder flowrate or laser power). All these disturbances can thus be automatically compensated. Similarly the powder flowrate and laser power will be adjusted until bead height and dilution are equal to the demanded. It is worth noting that the control law does not involve process parameters a, b, c, d_m and D' etc. Therefore these parameters do not have to be known.

The convergence property and system stability using the above control algorithms can be studied as follows:

1). Clad bead width control loop:

If we define

$$F(V_i) = V_i - K_v E_{wi} \quad (11-27)$$

then

$$\begin{aligned} ||F(V_m) - F(V_n)|| &= ||V_m - K_v E_{wm} - V_n + K_v E_{wn}|| \\ &= ||V_m - V_n - K_v (W_r - W_m) + K_v (W_r - W_n)|| \\ &= ||V_m - V_n + K_v (W_m - W_n)|| \end{aligned} \quad (11-28)$$

By substituting $W = D'(1 - bV)$ into the equation, we have:

$$\begin{aligned} ||F(V_m) - F(V_n)|| &= ||V_m - V_n + K_v [D'(1 - bV_m) - D'(1 - bV_n)]|| \\ &= ||V_m - V_n - K_v D' b (V_m - V_n)|| \\ &= ||(1 - K_v D' b) (V_m - V_n)|| \\ &= (1 - K_v D' b) ||V_m - V_n|| \end{aligned} \quad (11-29)$$

$$\text{If} \quad 0 \leq 1 - K_v D' b < 1 \quad (11-30)$$

$$\text{i.e. if} \quad 0 < K_v \leq 1/(D' b) \quad (11-31)$$

the operation $F(V_i)$ will become a contraction (See Appendix D) and the closed loop control system is therefore asymptotically stable according to Karlman-Bertram's theorem^[168].

2). Clad thickness control loop

The operation of the control loop can be defined as:

$$F(M_i, V_i) = M_{i+1} = M_i + K_m V_i E_{Hi} \quad (11-32)$$

Then

$$\begin{aligned} || F(M_m, V_m) - F(M_n, V_n) || &= || M_m + K_m V_m E H_m - M_n - K_m V_n E H_n || \\ &= || M_m - M_n + K_m V_m (H_r - H_m) - K_n V_n (H_r - H_n) || \end{aligned} \quad (11-33)$$

By substituting $H = aM/V$ into the equation gives:

$$\begin{aligned} || F(M_m, V_m) - F(M_n, V_n) || &= || M_m - M_n + K_m H_r (V_m - V_n) - K_m (a M_m - a M_n) || \\ &= || (1 - K_m a) (M_m - M_n) + K_m H_r (V_m - V_n) || \\ &\leq (1 - K_m a) || M_m - M_n || + K_m H_r || V_m - V_n || \end{aligned} \quad (11-34)$$

i.e.

$$|| F(M_m, V_m) - F(M_n, V_n) || \leq \begin{bmatrix} 1 - K_m a & K_m H_r \end{bmatrix} \begin{bmatrix} || M_m - M_n || \\ || V_m - V_n || \end{bmatrix} \quad (11-35)$$

If

$$|| 1 - K_m a, K_m H_r || < 1 \quad (11-36)$$

ie. if

$$(1 - K_m a)^2 + (K_m H_r)^2 < 1 \quad (11-37)$$

or

$$0 < K_m < 2a/H_r^2 \quad (11-38)$$

then the operation is a contraction and the closed loop control system is stable.

3). Dilution control loop

Let

$$F(P_i, M_i) = P_{i+1} = P_i + K_p E D i \quad (11-39)$$

Then

$$\begin{aligned} || F(P_m, M_m) - F(P_n, M_n) || &= || P_m + K_p E D i_m - P_n - K_p E D i_n || \\ &= || P_m - P_n + K_p (D i_r - D i_m) - K_p (D i_r - D i_n) || \\ &= || P_m - P_n - K_p (D i_m - D i_n) || \end{aligned} \quad (11-40)$$

By substituting the relationship: $D i = c P - d m M$ into the above equation arrives:

$$\begin{aligned} || F(P_m, M_m) - F(P_n, M_n) || &= || P_m - P_n - K_p (c P_m - d m M_m - c P_n + d m M_n) || \\ &= || (1 - K_p c) (P_m - P_n) + K_p d m (M_m - M_n) || \\ &\leq (1 - K_p c) || P_m - P_n || + K_p d m || M_m - M_n || \end{aligned} \quad (11-41)$$

If

$$|| 1 - K_p c, K_{pdm} || < 0 \quad (11-42)$$

i.e. if

$$0 < K_p < 2c/(c^2 + dm^2) \quad (11-43)$$

then the operation will be a contraction and the closed loop system is therefore stable.

Because of interactions between parameters, the three control loops should be applied simultaneously.

11.3.2. Rule based adaptive mechanism development

It has been shown in the above analysis that if the control gains K_v , K_m and K_p are within certain values the system will be stable. The stable zones depend on process parameters as well as demanded control variables. If these parameters are not known precisely then it is usually hard to decide what control gains should be used. Also even if the control gains are in the stable zone they can still be either too small (causing slow convergence) or too high (causing high overshoot). Therefore there is a need to find these control gains so that the closed loop control system will have the optimum response. In order that the both adaptive mechanism and feedback control algorithm are not dependent on the process parameters, a rule based or knowledge based adaptive control law was developed by the author to search for the optimum control gains on-line by examining the actual control system performances.

The diagnostic rules for recognizing the system dynamic performance and the decision rules to update the control gains were designed to be:

a). IF: the deviation of the actual process value and the demanded value is high and changes very little after a control iteration

THEN: the response is slow

b). IF: the response is slow

THEN : the corresponding control gain is too low.

Decision THEN : increase the corresponding control gain

c). IF: the deviation of the actual process value from the desired value is high and changes signs for the successive control iteration

THEN: the control response is either highly overshoot or oscillating

d). IF: there is either highly overshoot or unstable response

THEN: control gain is too high

Decision THEN: reduce the corresponding control gain.

e). IF: none of the above situation happens

THEN: system performance is "OK"

Decision THEN control gain is optimum and no variation is needed.

The above rules require that the process sampling period is longer than the system open loop process response time constant. It also requires that the stability characteristics of the closed loop system is monotone with respect to closed loop control gains. Laser cladding process satisfies these conditions. Since the above characteristics represent majority of the engineering control process thus it may have a more general significance.

Two problems have to be solved in realizing the above rules in practice.

a). How to evaluate the system performance in a scientific expression instead of declarative languages?

b). How much should the control gains be varied if necessary ?

These were studied as follows:

1). Diagnosis condition expressions

By examining various situations as shown in Fig.11.8, the diagnostic condition can be expressed quantitatively as follows.

a). Diagnosis for slow damping

The situation for the slow error reduction as shown in Fig. 11.8a can be expressed as:

$$1 \geq e_i / e_{i-1} > L_1 \quad 0 < L_1 < 1 \quad (11-44)$$

where e_i and e_{i-1} are the errors of the variable to be controlled at iteration i and $i-1$ respectively. L_1 is the minimum desired convergence rate defined by the user. If, say, L_1 is 0.4, then any error reduction rate below 60% is considered as slow and control gain will be increased by the controller.

b). Diagnosis for unstable oscillation

The situation for unstable oscillation (Fig.11.8.b) can be expressed as:

$$e_i / e_{i-1} \leq -1 \quad (11-45)$$

c). Diagnosis for excessive overshoot

Since a good response requires the overshoots to be less than 10% and overshoots are always associated with the change of the signs of the errors as shown in Fig. 11.8c , the excessive overshoot can be expressed as:

$$e_i/e_{i-1} < -0.1 \quad (11-46)$$

e). Diagnosis for optimum control performance

The optimum operating situation can be expressed as:

$$-0.1 \leq e_i/e_{i-1} \leq 0.4 \quad (11-47)$$

which requires that the error will be reduced at least by 60% after each control iteration and overshoot is less than 10%. The ideal response is as shown in Figs.11.8e and 11.8f.

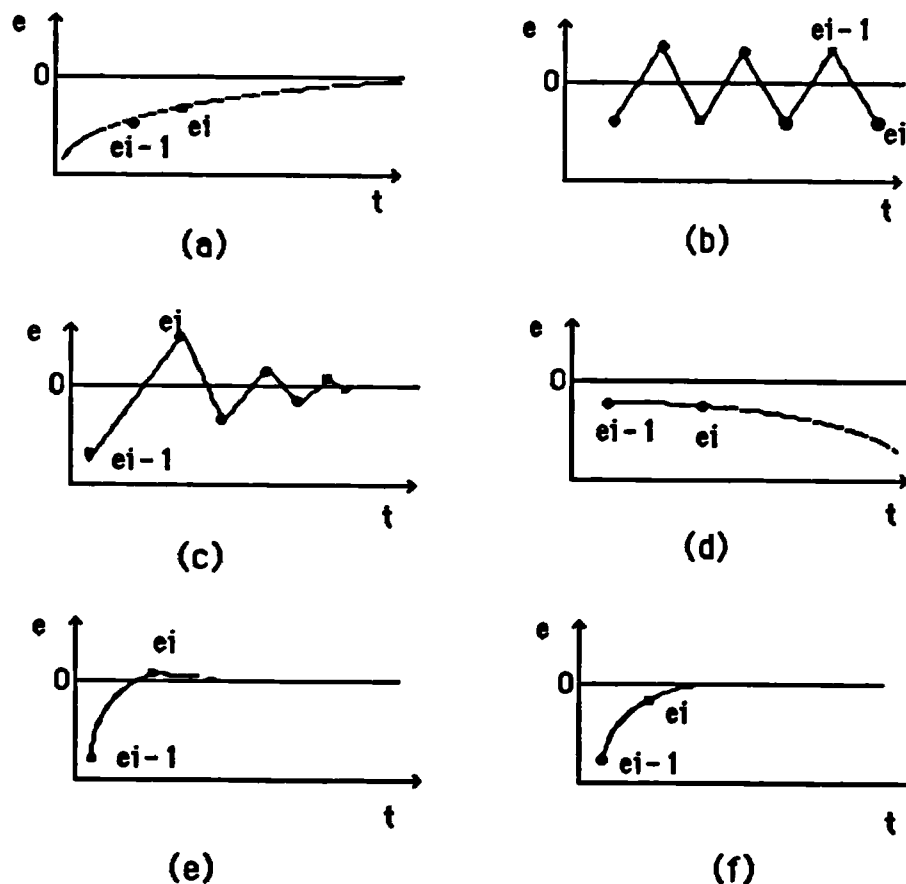


Fig. 11.8. Various features of the closed loop system. a). too slow. b). Oscillation. c). high overshoot. d). shoot off. e) and f). Good performances.

2). Optimum control gain searching

The variation of control gain is too much or inadequate can all delay the convergence rate and destroy the optimum system performance. The following rule based control gain search technique was developed by the modification of the Golden Ratio method^[162] (Also see Appendix E). The developed rule-based optimum gain search technique can be described as:

1). Start at any point K_i (control gain) and take this point as one of the boundaries of search zone and 0 as the other. i.e. the initial search zone is $(0, K_i)$. If the search zone is defined as $[x_1, x_2]$ with the present search point at x_0 , then $x_1=0$, $x_2=x_0=i$.

2). Examine the system performance for the control gain K_i using the above diagnostic rules.

a). If the gain is required to increase and $x_2=K_i$ then the procedure of search should follow:

$$\begin{aligned} K_{i+1} &= K_i + 1.618 (x_2 - x_1) \\ &= K_i + 1.618 (K_i - x_1) \\ &= 2.618 K_i - 1.618 x_1 \end{aligned} \quad (11-48)$$

forming a new search zone $x_1'=x_2$, $x_2'=K_{i+1}$ and $x_0'=K_{i+1}$. This is illustrated in Fig.11.9a.

b). If the control gain is required to decrease and $x_1 = K_i > 0$ then the search procedure should follow:

$$K_{i+1} = 0.618 K_i \quad (11-49)$$

forming a new search zone $x_1' = 0$, $x_2' = x_1$, $x_0'=K_{i+1}$. This is illustrate in Fig. 11.9b.

c). If the above situation does not occur and the system performance has the same feature for both K_i and K_{i-1} points as shown in Fig.11.9c and Fig.11.9d then the next search should be in the same direction. i.e.

If K_i needs to be increased, then:

$$\begin{aligned} K_{i+1} &= K_i + 0.618 (x_2 - x_0) \\ &= K_i + 0.618 (x_2 - K_i) \\ &= K_i + 0.618(0.382/0.618) (K_i - K_{i-1}) \\ &= 1.382 K_i - 0.382 K_{i-1} \end{aligned} \quad (11-50)$$

forming a new search zone: $x_1' = x_0$, $x_2' = x_2$ and $x_0'=K_{i+1}$.

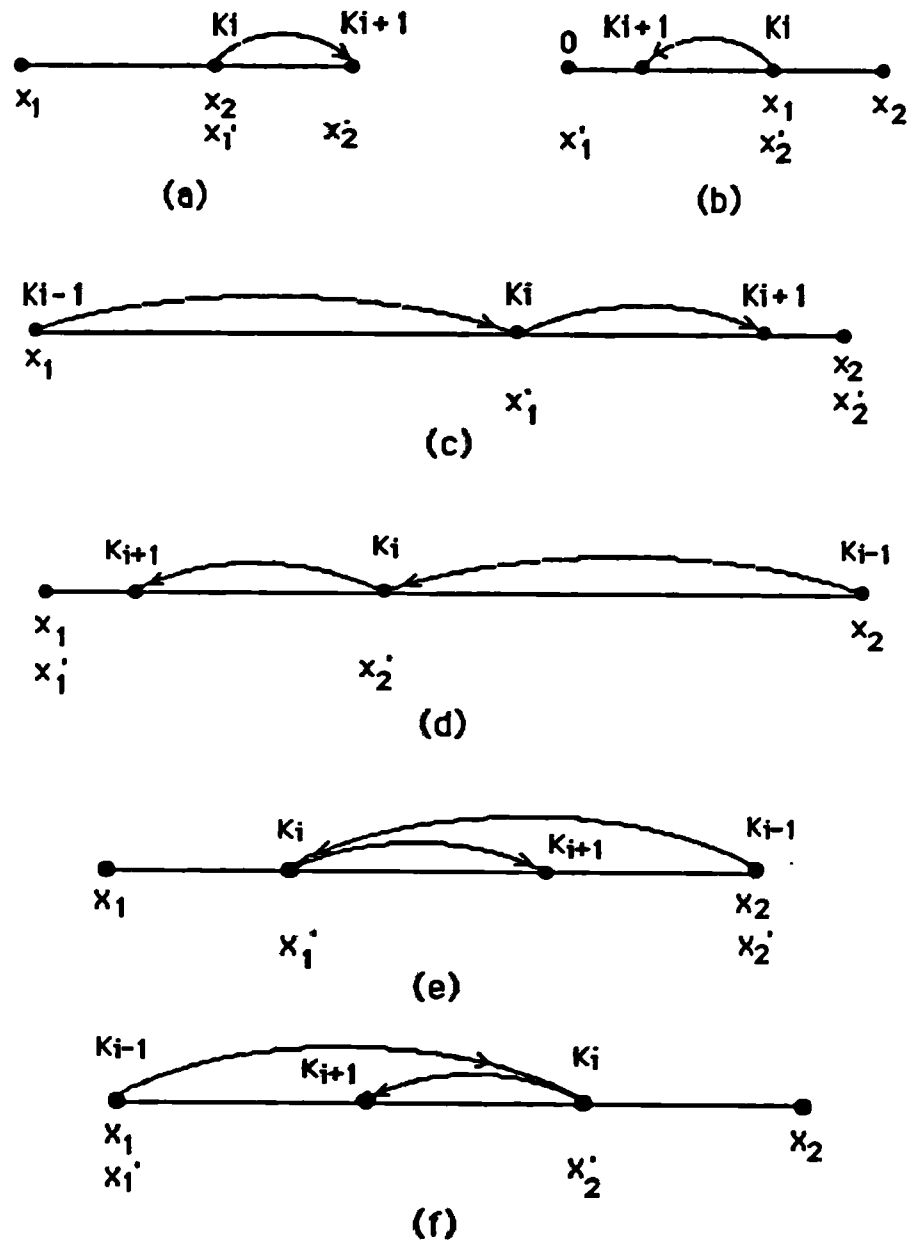


Fig. 11.9. Illustrations for optimum control gain searching.

If control gain needs to be decreased, then:

$$\begin{aligned}
 K_{i+1} &= K_i - 0.618 (x_0 - x_1) \\
 &= K_i - 0.618 (K_i - x_1). \\
 &= K_i + 0.618 (0.382/0.618)(K_{i-1} - K_i) \\
 &= 0.618K_i + 0.382K_{i-1}
 \end{aligned}
 \tag{11-51}$$

forming a new search zone: $x_2' = x_0$, $x_1' = x_1$ and $x_0' = K_{i+1}$.

In both cases the size of zone has reduced 0.618 times.

d). If situation b does not occur and the system performance has the opposite feature at K_i

and K_{i-1} (over tuned) then the next search should be in the opposite direction as shown in Fig.11.9e and Fig.11.9f. i.e. If the control gain needs to be increased, then

$$\begin{aligned} K_{i+1} &= K_i + 0.618 (x_2 - x_0) \\ &= K_i + 0.618 (K_{i-1} - K_i) \\ &= 0.382K_i + 0.618K_{i-1} \end{aligned} \quad (11-52)$$

forming a new search zone: $x_1' = x_0$, $x_2' = x_2$ and $x_0' = K_{i+1}$.

If the control gain needs to be decreased, then:

$$\begin{aligned} K_{i+1} &= K_i - 0.618 (x_0 - x_1) \\ &= K_i - 0.618 (K_i - K_{i-1}) \\ &= 0.382 K_i + 0.618 K_{i-1} \end{aligned} \quad (11-53)$$

forming a new search zone: $x_2' = x_0$, $x_1' = x_1$, $x_0' = K_{i+1}$.

In both cases the size of search zone has reduced 0.382 times.

The convergence of the search technique is apparent since the uncertainty zone is reduced at least 0.383 times for each iteration. For a constant process parameter the above procedure is enough to find the optimum control gain and is kept constant (self-tuning). However if the process parameter changes (as will do for laser cladding when surface temperature rises) the actual optimum point will be shifted. The optimum point after shifting may fall outside of the search zone again. If the search is looped in the already defined zone, the optimum point may never be found, although the control gain converges to a point. Therefore the search has to continued for the extension of the search zone if the search zone becomes very small and the optimum point is still not found (adaptive control). The rules required for the preventing of "dead loop" can be described as:

IF : the size of the search zone falls below a limit and control gain is still not satisfactory,

THEN: the size of the search zone should be expanded as:

$$\begin{aligned} x_1' &= x_1 - 1.618(x_2 - x_1) \\ &= 2.618x_1 - 1.618x_2 \end{aligned} \quad (11-54)$$

$$\begin{aligned} x_2' &= x_2 + 1.618 (x_2 - x_1) \\ &= 2.618x_2 - 1.618x_1 \end{aligned} \quad (11-55)$$

3). Combination of diagnosis and decision making

By combining the diagnostic rules and control gain modification decision making rules the self-searching adaptive mechanism can be summarized as follows:

Criterion 1.

IF $e_i/e_{i-1} < -0.1$ and $|e_{i-1}| > 0$

THEN Control gain K_i needs to be decreased

Case 1: If $x_1 = K_i$

then $K_{i+1} = 0.618 K_i$

and the search zone is updated to:

$x_1' = 0, x_2' = x_1, x_0' = K_{i+1}$.

Case 2: If case 1 does not occur and the search zone is too small. i.e.

$x_2 - x_1 \leq Z_{min}$

then $x_1' = 1.382x_1 - 0.382x_2$

and $x_2' = 1.382x_2 - 0.382x_1$

Case 3: If neither case 1 nor case 2 occur then:

$K_{i+1} = K_i - 0.618 (x_0 - x_1)$

and the search zone is updated to:

$x_2' = x_0, x_1' = x_1$ and $x_0' = K_{i+1}$.

Criterion 2.

IF $0.4 < e_i/e_{i-1} \leq 1$ and $|e_{i-1}| > 0$

THEN the control gain needs to be increased

Case 1: If $x_2 = K_i$

then $K_{i+1} = 2.618 K_i - 1.618x_1$

and the search zone is updated to:

$x_1' = x_2, x_2' = K_{i+1}$ and $x_0' = K_{i+1}$

Case 2: If case 1 does not occur and the search zone is too small. i.e.

$x_2 - x_1 \leq Z_{min}$

then $x_1' = 1.382x_1 - 0.382x_2$

and $x_2' = 1.382x_2 - 0.382x_1$

Case 3: If neither case 1 nor case 2 occur

then: $K_{i+1} = K_i + 0.618 (x_2 - x_0)$

and the search zone is updated to:

$x_1' = x_0, x_2' = x_2$ and $x_0' = K_{i+1}$.

Criterion 3

IF $-0.3 \leq e_{i+1}/e_i \leq 0.4$ (good performance) or $e_i = e_{i-1} = e_{i-2}$ (system saturated).

THEN $K_{i+1} = K_i$ and search zone unchanged.

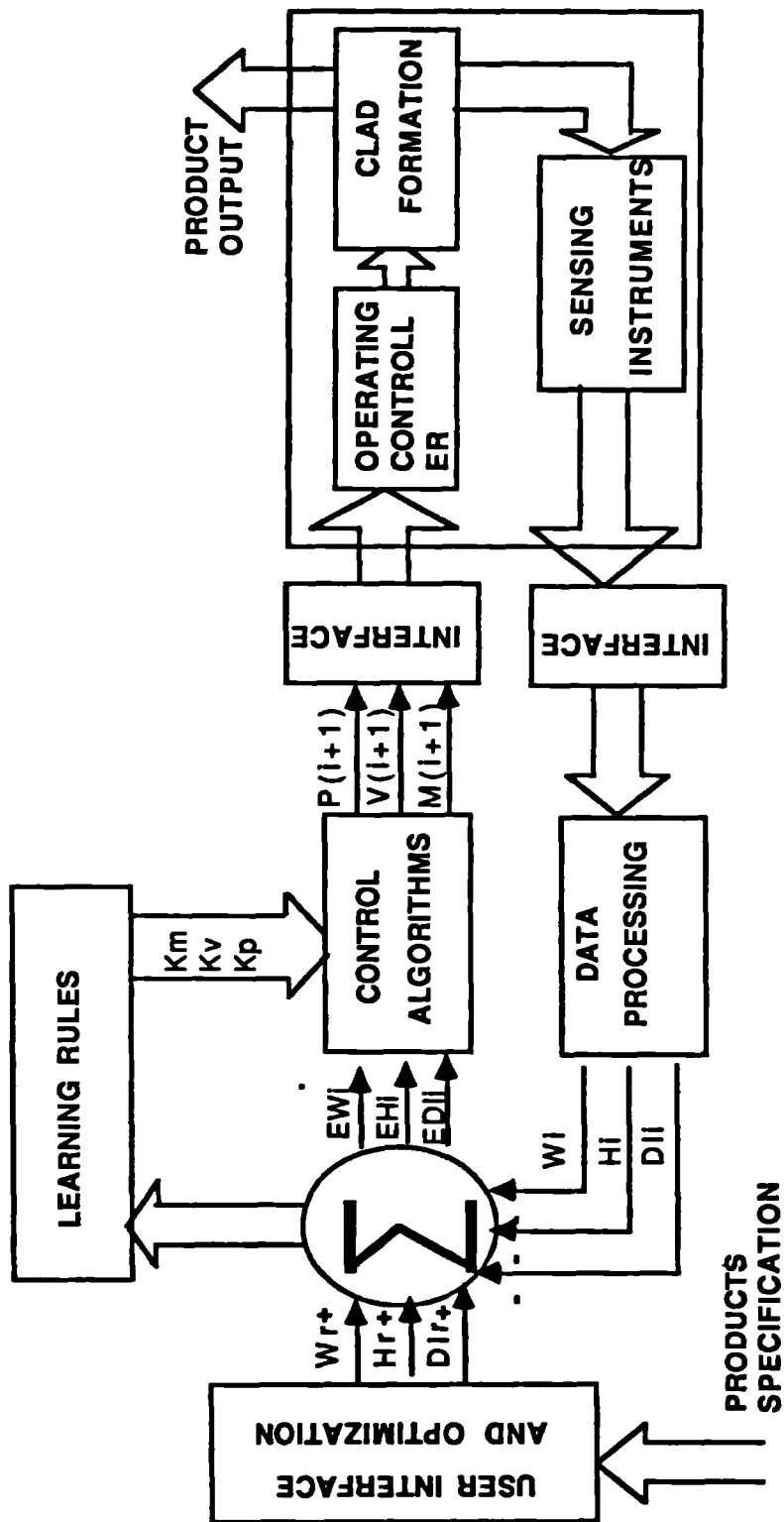


Fig.11.10. Adaptive laser cladding control configuration (method 2).

where Z_{min} is the minimum search zone, below which a zone expansion is required to avoid "dead loop". K_i , K_{i-1} and K_{i+1} are the control gains at the corresponding iteration. x_1 , x_2 and x_0 are the search zone lower, upper boundaries and interior point respectively. The above optimum control gain search should be applied to all the control loops in the system. The closed loop control system structure can be illustrated in Fig.11.10 . The method was programmed using BASIC and tested on Macintosh SE computer. The computation time required for one cycle is about 15ms. If pascal language is used the computing time would be less than 5ms for one cycle.

This adaptive control method is different from previous adaptive control methods in that:

- 1). Process model is not required for the design of controller. The system can "learn" the process and optimize the controller by rule-based adaption mechanism. Therefore the inaccuracy of the process model will not affect the adaptive control mechanism while previous methods are model dependent.
- 2). Self-tuning is fast, on-line and does not affect the normal control action while most of the previous self-tuning controllers need a generation of step response.
- 3). It is suitable for both linear and non-linear systems.
- 4). Very little knowledge is required to construct the control system. Processes like "black box" or "grey box" which could not be controlled before could now be possibly controlled using the method developed.

11.3.3. Computer control simulation

A simulation study was made to investigate the application problems of the rule-based adaptive control method described above. The process used for simulation was the cladding of Wallex 6PC on EN8 mild steel substrate, which can be described by:

$$W = D' (1-bV) \quad (11-56)$$

$$H = a M/V \quad (11-57)$$

$$DI = cP - dmM \quad (11-58)$$

where $D' = 5$, $b = 0.05$, $a = 20$, $c = 0.12$ and $dm = 0.42$ for the given materials^[60].

In the control simulation following considerations were also made:

- a). Each operating parameter has an upper and lower limit either because of the capability of the physical machine or because of clad formation requirement. For the present study the operating parameters were restricted to:

$$1kW \leq P \leq 2kW \quad (11-59)$$

$$\begin{aligned} 0.01\text{mm/s} \leq V < 20\text{mm/s} & \quad (11-60) \\ 0.01\text{g/s} \leq M \leq 5\text{ g/s} & \quad (11-61) \end{aligned}$$

b). The minimum search zones are defined for all the control gains to be:

$$Z_{\min} = 0.02 \quad (11-62)$$

The computer control simulation experiments were made to investigate the following aspects:

1). Fixed gain feedback control under improper initial operating parameters

In these experiments the control requirements were:

Desired bead width $W_r = 3\text{ mm}$
 Desired bead height $H_r = 0.7\text{ mm}$
 Desired dilution $D_{lr} = 0.1$

The initial operating parameters were randomly chosen as:

Group 1: $P_0 = 2\text{ kW}$,
 $M_0 = 0.2\text{ g/s}$
 $V_0 = 10\text{ mm/s}$

which produced an initial clad of $W_0 = 2.5\text{ mm}$, $H_0 = 0.4\text{ mm}$, $D_{l0} = 0.15$ from Eqns.(11-56) to (11-58).

Group 2: $P_0 = 1.6\text{ kW}$
 $M_0 = 0.4\text{ g/s}$
 $V_0 = 4\text{ mm/s}$

which produced an initial clad bead of $W_0 = 4\text{ mm}$, $H_0 = 2\text{ mm}$, $D_{l0} = 0.02$.

In both cases the clad parameters produced using the initial operating parameters were far from the desired values. However when feedback controls were applied (with control gains as: $K_v = 5$, $K_m = 0.05$, $K_p = 11$) the clad bead parameters all converged to the desired values as shown in Figs.11.11, 11.12 and 11.13. The variation of the operating parameters in the above control iteration are shown in Figs.11.14, 11.15 and 11.16 which have demonstrated the convergence values of $P = 1.81\text{ kW}$, $M = 0.28\text{ g/s}$ and $V = 8\text{ mm/s}$.

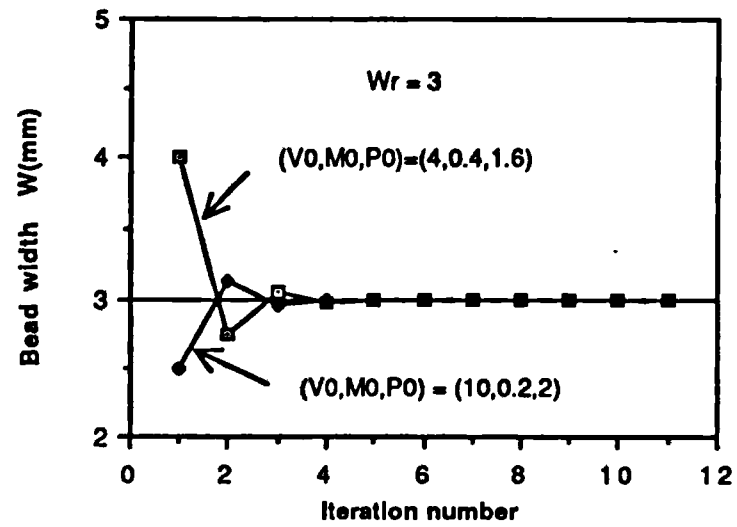


Fig. 11.11 Fixed gain feedback control effect (clad bead width loop).

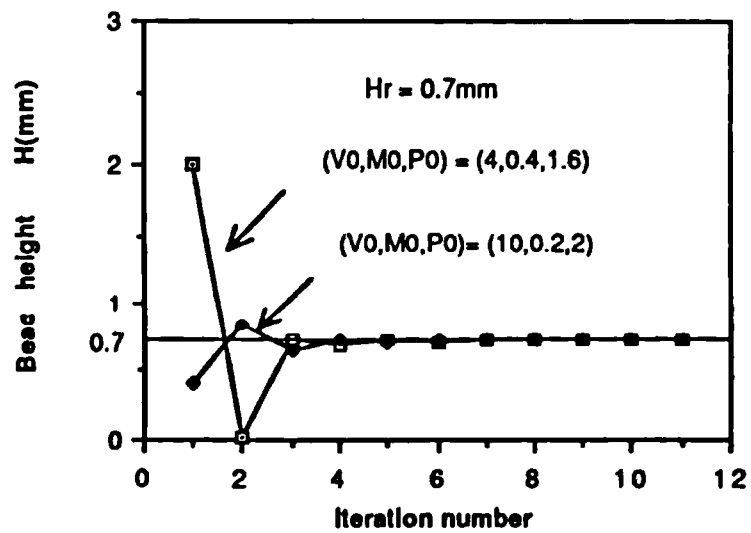


Fig. 11.12 Fixed gain feedback control effect (clad bead height loop).

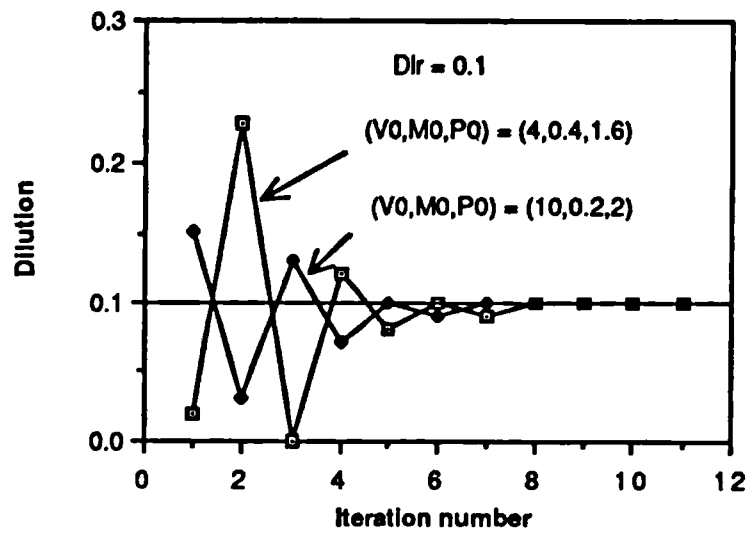


Fig.11.13 Fixed gain feedback control effect (dilution loop).

z

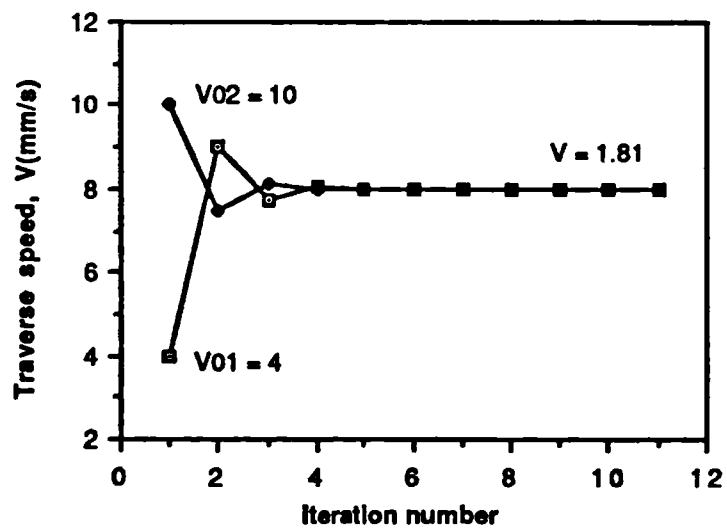


Fig.11.14 Behavior of the traverse speeds in the closed loop cladding control for fixed gain operation.

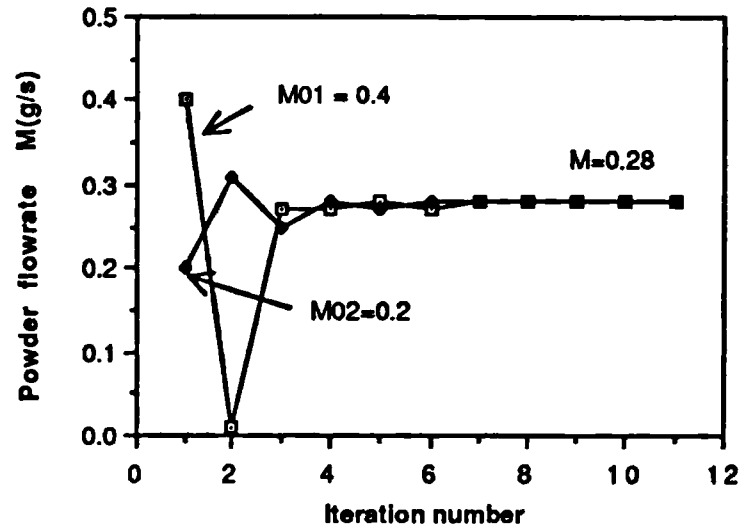


Fig.11.15 Behavior of the powder flowrate in the closed loop cladding control for fixed gain operation.

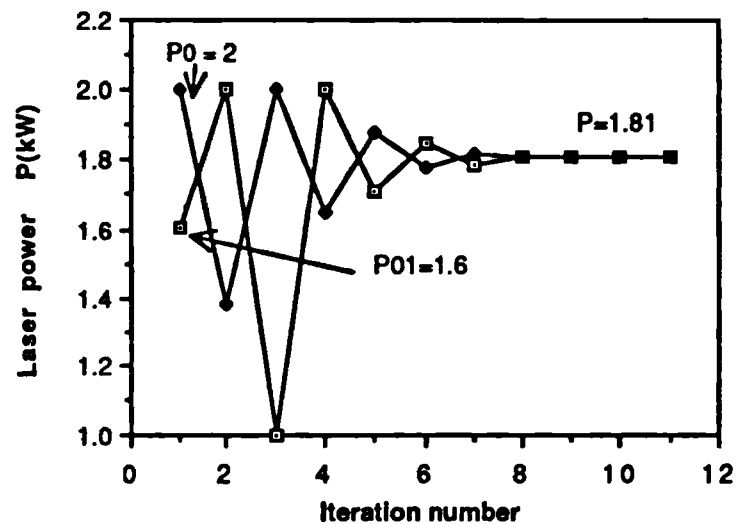


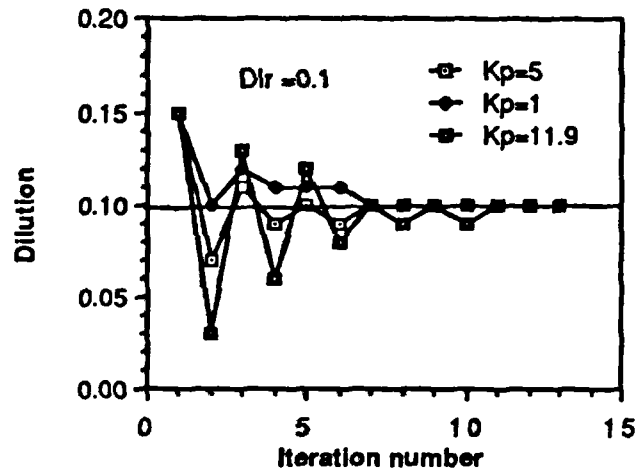
Fig. 11.16. Behavior of the laser power in the closed loop cladding control for fixed gain operation.

It can be seen from the above experiments that an improper selection of initial operating parameters could be automatically corrected to the ideal values if the control gains are chosen correctly.

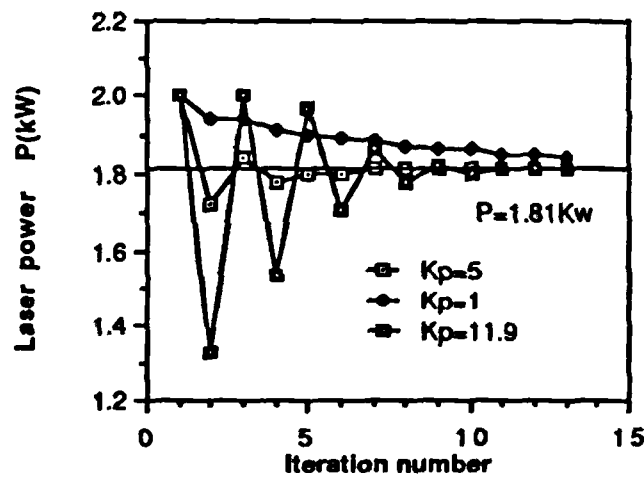
2). The effect of the control gains on the closed loop system performance.

The selection of the proper control gains are vital to the success of the closed loop

control. Either too high or too small control gains can all delay the system convergence rate or even lead to the instability of the closed loop system. These were examined as shown in Fig.11.17 and Fig. 11.18. In the experiments all the control loops were activated at same time with $V_0=10$, $M_0=0.25$, $P_0=2$, $K_v=5$, $K_m=0.05$ and K_p varied to different values.

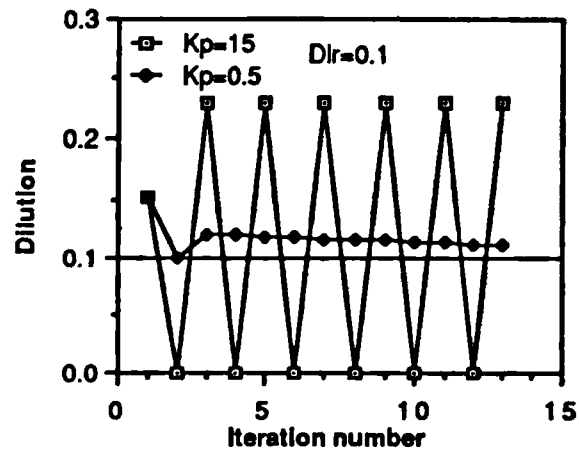


(a)

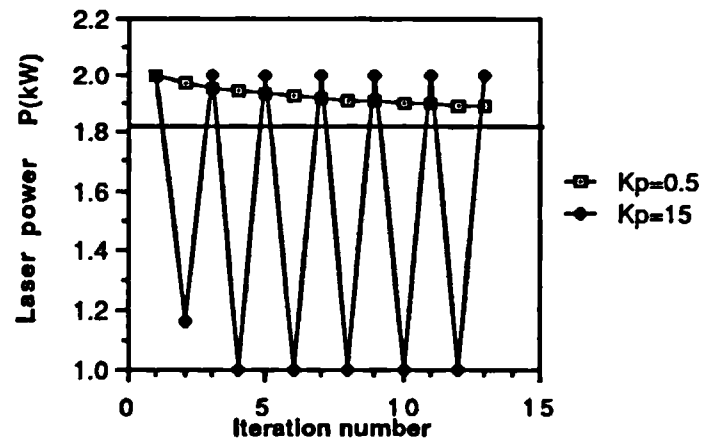


(b)

Fig. 11.17. Effect of different control gains on the closed loop system performance.
a). Dilution change under control action. b). Laser power changes during control.



(a)



(b)

Fig. 11.18. Effect of improper control gains on the closed loop system performance
a). Dilution changes. b). Operating parameter changes.

It should be noted that the parameter interaction due to the multi-variable feature of the laser cladding process can also affect the closed loop system performance. Fig.11.19 shows this effect for dilution control loop, where the initial operating parameters were $V_0 = 10$ mm/s , $M_0 = 0.2$ g/s and $P_0 = 2$ kW with control gains $K_v = 5$, $K_m = 0.05$ and $K_p = 11$. The multi-variable parameter effect in this case has created a lower convergence rate and higher overshoot of the closed loop system performance.

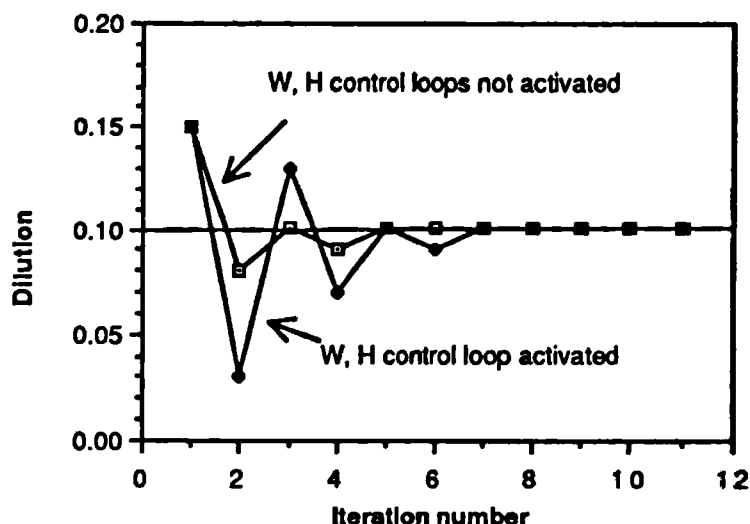
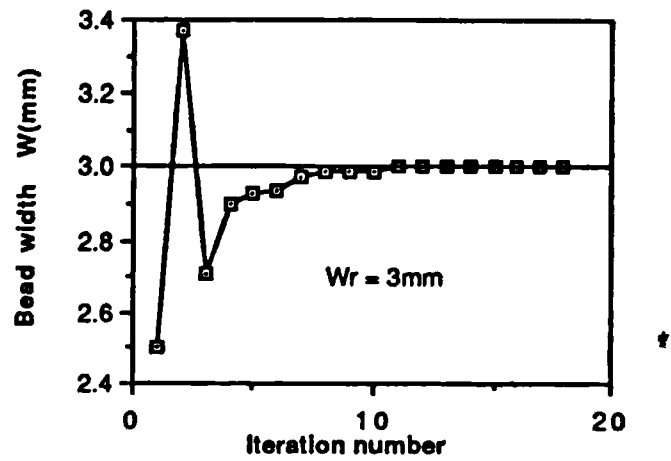


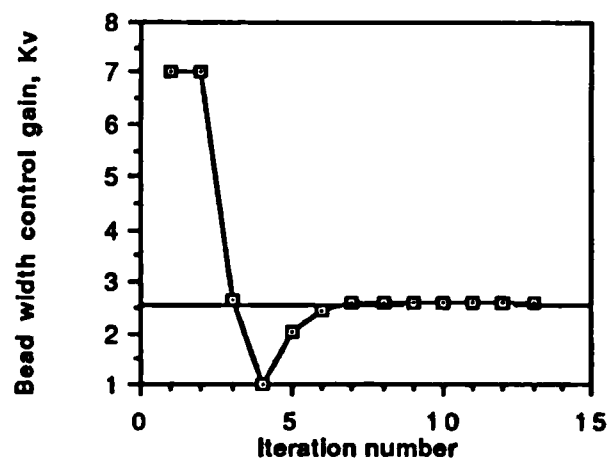
Fig.11.19 Effect of parameter interaction on the performances of the closed loop dilution control.

3.) Self-tuning control simulation

The above negative feedback control simulations have demonstrated that the difficulties in selecting proper operating parameters could be overcome by automatic adjusting of operating parameters according to the deviations of the actual process quality from the desired values provided the control gains are selected properly. The self-tuning mechanism was designed to solve the problems of selecting a set of control gains so that the feedback controls are guaranteed to converge and to operate in an optimum state. In the following experiments the initial operating parameters were chosen as: $V_0=10$ mm/s, $M_0=0.2$ g/s and $P_0=2$ kW. The initial control gains were chosen randomly as $K_v=7$, $K_m=0.1$ and $K_p=0.01$. The desired process response were $W_r=3$ mm, $H_r=0.7$ mm, $D_{lr}=0.1$. It should be noted that neither the initial operating parameters nor the system control gains were chosen correctly. The control system was asked to find both optimum control gains and correct operating parameters automatically during the feedback control actions. The control effects and control gain variations are shown in Fig 11.20 to Fig.11.22 . The behaviour of the corresponding operating parameters are shown in Figs.11.23 to 11.25.



(a)



(b)

Fig.11.20 Self-tuning laser cladding control, bead width control loop. a). Bead width response. b). Control gain variation.

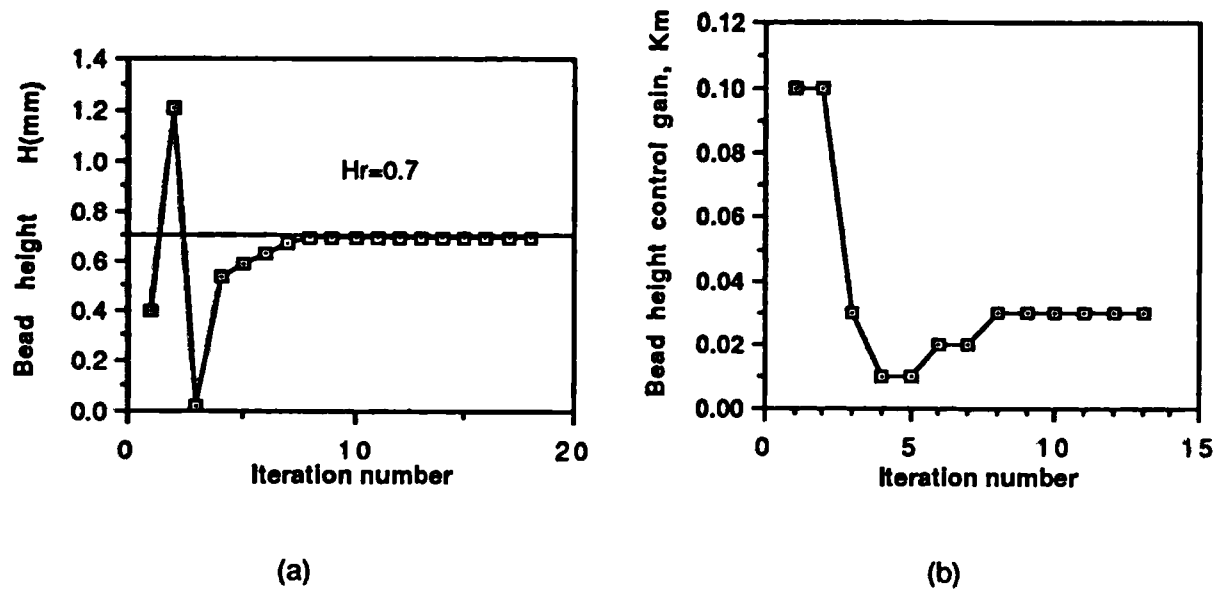


Fig.11.21. Self-tuning laser cladding control, bead height control loop. a). Clad thickness response. b). Control gain variation.

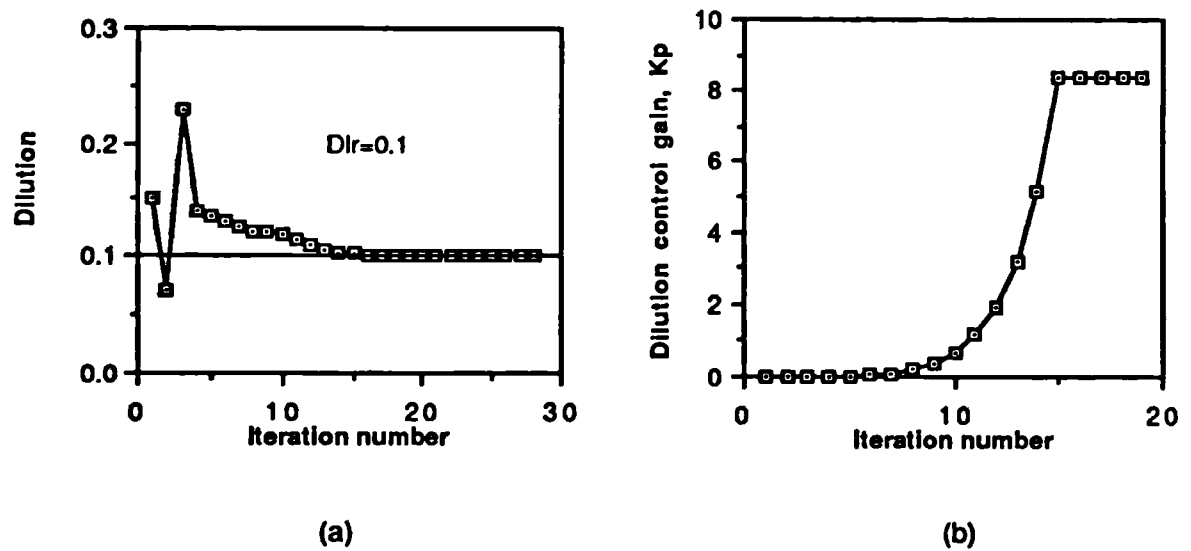


Fig. 11.22. Self-tuning laser cladding control, dilution control loop. a). Dilution response. b). Control gain variation.

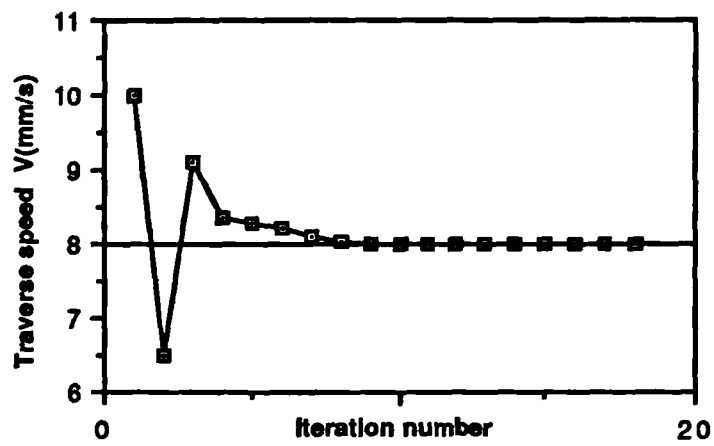


Fig. 11.23. Traverse speed variation during self-tuning feedback control.

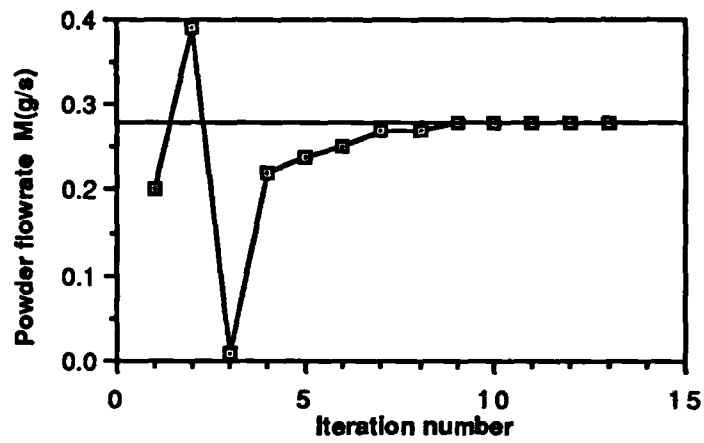


Fig.11.24. Powder flowrate variation during self-tuning control iteration.

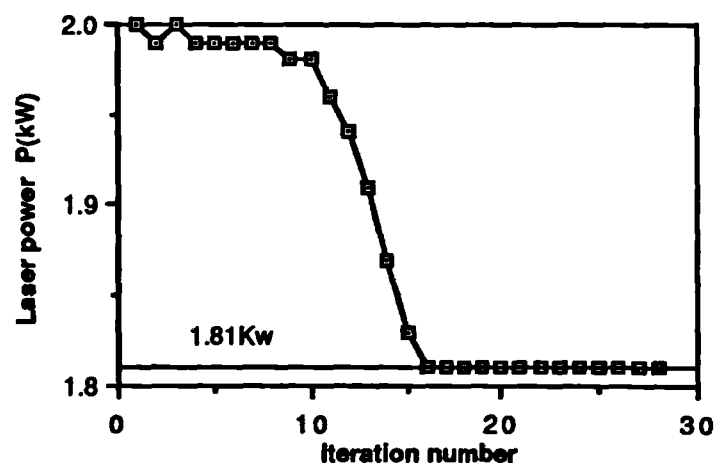


Fig.11.25. Laser power variation during self-tuning laser cladding control.

It should be noted that in the above experiments the closed loop control action started at the second iteration (one error signal needed) and the self-tuning (or adaptive) control started at the third iteration (two error signals needed). If the self-tuning was not switched on and only the initial control gains were used through out the control iteration, the process responses under the above starting conditions were found to be poor (Fig11.26) and even unstable (Figs.11.27 and 11.28).

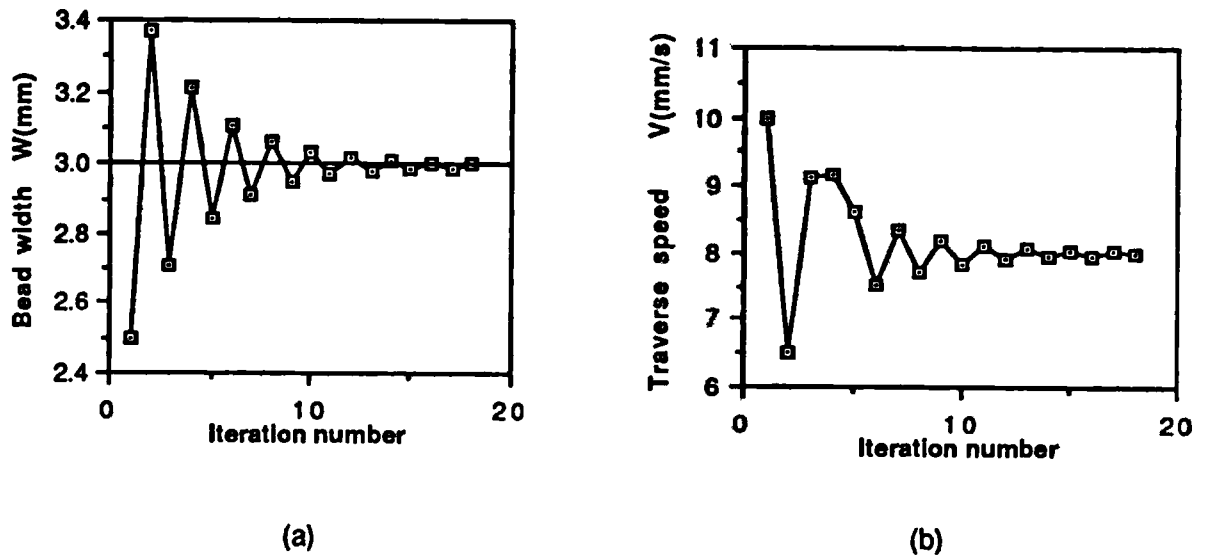


Fig.11.26. Clad bead width control without self-tuning. a). Bead width response. b). Traverse speed variation during control action.

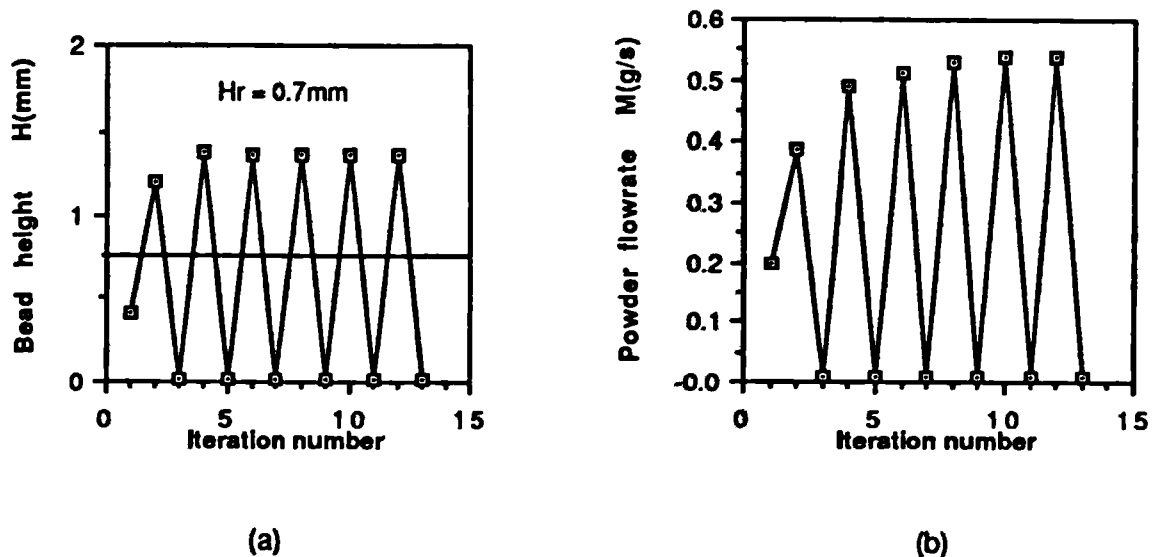


Fig. 11.27. Clad thickness control without self-tuning. a). Clad thickness response. b). Powder flowrate variation during control action.

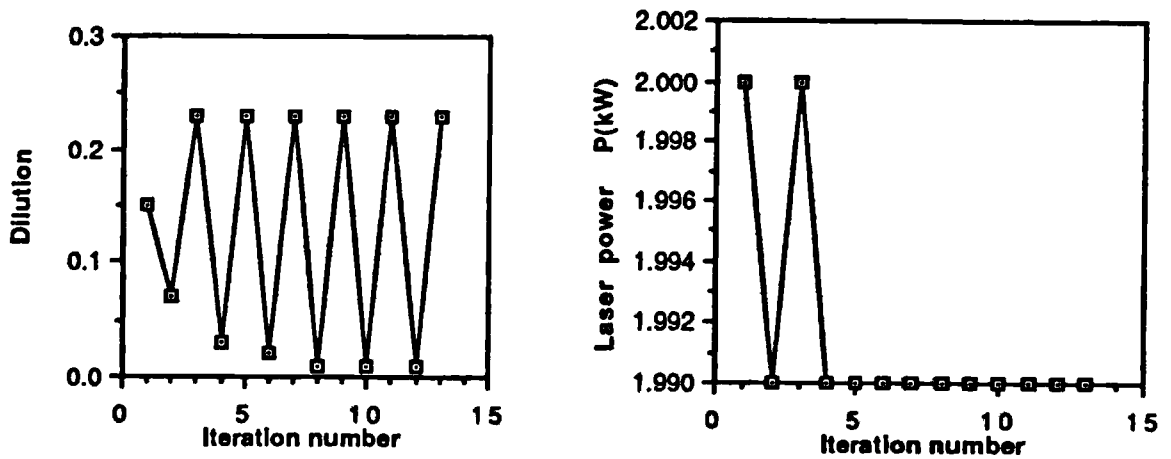


Fig.11.28. Dilution control without self-tuning a). Dilution response. b). Laser power variation during control action

4). Adaptive control to compensate for substrate temperature rise effect.

The situation of clad surface temperature rise was simulated as:

$$W = (D' + 0.08N)(1-bV) \quad (11-63)$$

$$H = (20 + 0.25N)M/V \quad (11-64)$$

$$DI = (c + 0.002N)P - dmM \quad (11-65)$$

where $D' = 5$, $b=0.05$, $c=0.12$, $dm = 0.42$ and N is the iteration number. As the iteration number increases (i.e. time increases) W , H and DI will increase as well. The increase rates of these parameters have been exaggerated to be very high to represent the worst case. In practice temperature effect is a very slow effect. The adaptive control in this situation was studied as follows:

Firstly, the system was operated with constant operating parameters $V=8$ mm/s, $M=0.28$ g/s and $P=1.81$ kW with initial control gains $K_v=K_m=K_p=0$ (open loop) and the control requirement $W_r = 3$ mm, $H_r=0.7$ mm, $DI_r=0.1$ mm. The temperature rise effect for this open loop control situation was then recorded.

Secondly, the system was re-started with initial operating parameters $V_0 = 10$ mm/s, $M_0=0.2$ g/s and $P_0=2$ kW. Then feedback control was activated with constant control gains $K_v= 5$, $K_m=0.05$ and $K_p=5$. The fixed gain feedback control for the temperature rise effect was recorded.

Thirdly, system started with improper initial operating parameters and control gains $V_0=10$ mm/s, $M_0=0.2$ g/s, $P_0=2$ kW, $K_v=1$, $K_m=0.01$ and $K_p=15$. Then, adaptive control

was switched on for the search of both optimum control gain and proper operating parameters so that the clad parameters were the same as the demanded. The control effects were recorded.

Figs.11.29 to 11.31 provide the comparison of the above results, which have shown that both optimum feedback control and adaptive control can follow process changes but adaptive control provided better control performances.

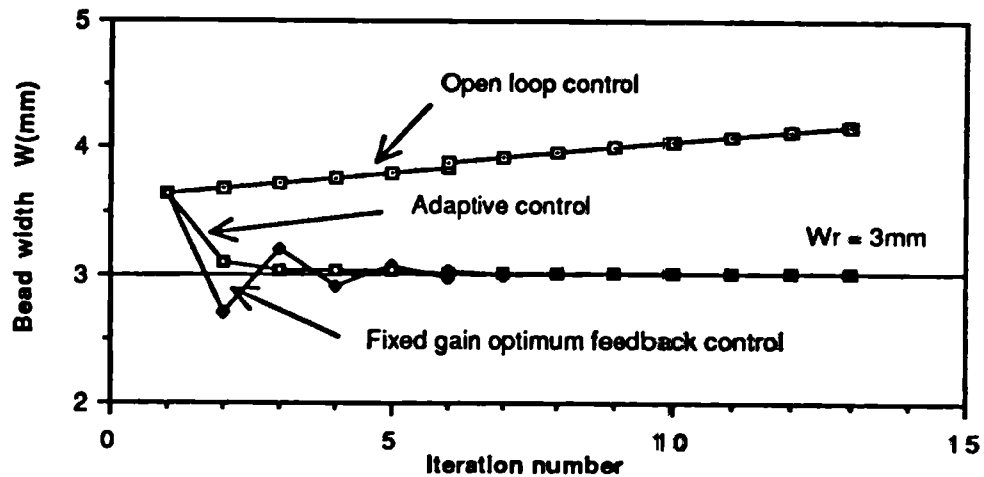


Fig. 11.29. Clad bead width responses under different control schemes, when there is a surface temperature rise.

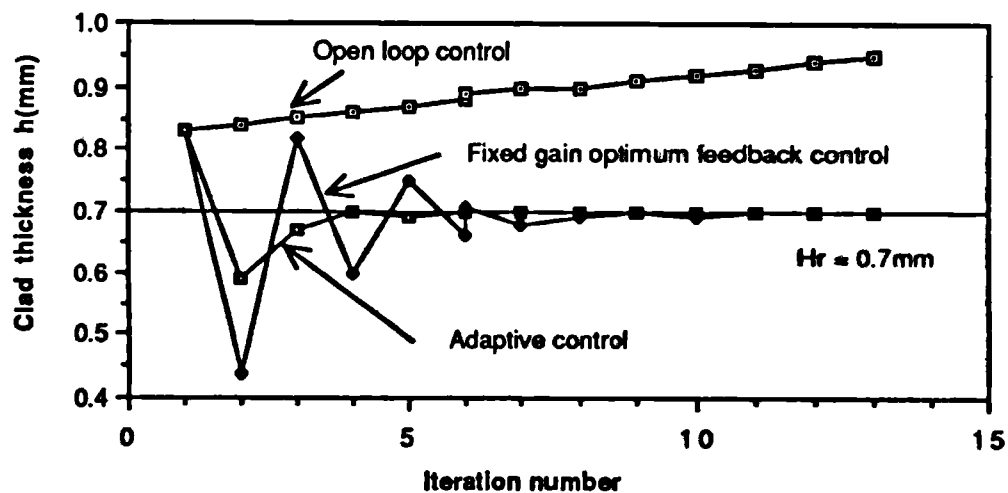


Fig. 11.30. Clad thickness responses under different control schemes when there is a surface temperature rise

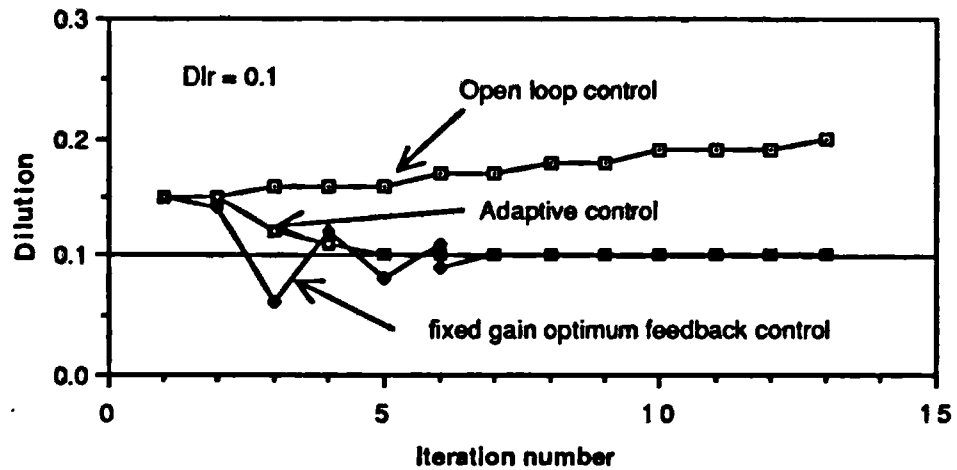


Fig.11.31 Dilution responses under different control schemes when there is a surface temperature rise.

In the closed loop control, the temperature rise was actually compensated for by the variation of operating parameters, which are shown in Figs.11.32 to 11.34.

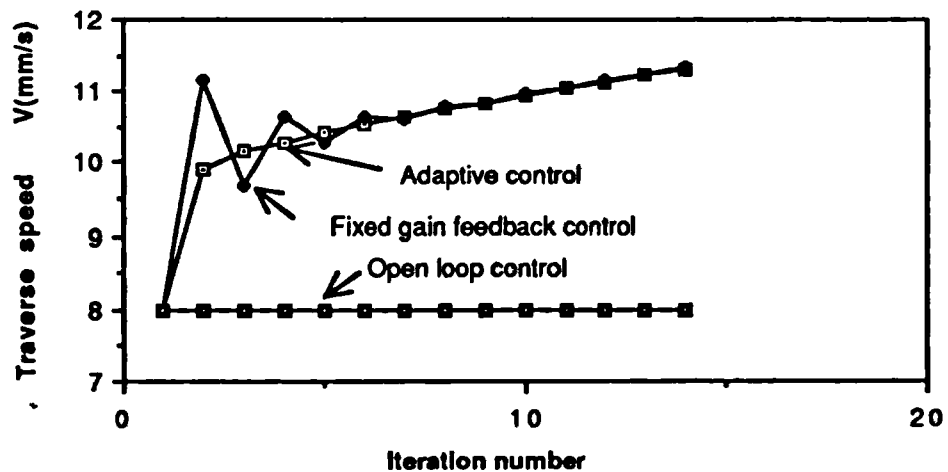


Fig.11.32 Traverse speed variations during the control action.

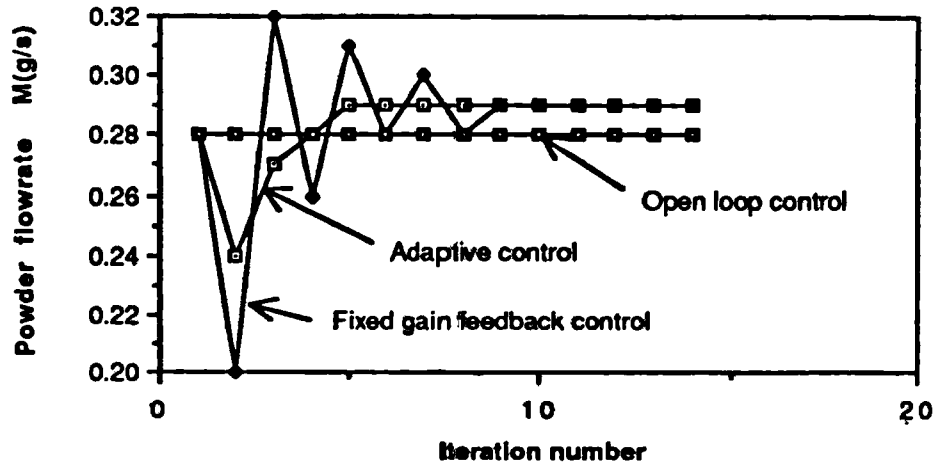


Fig.11.33. Powder flowrate variations during the control action.

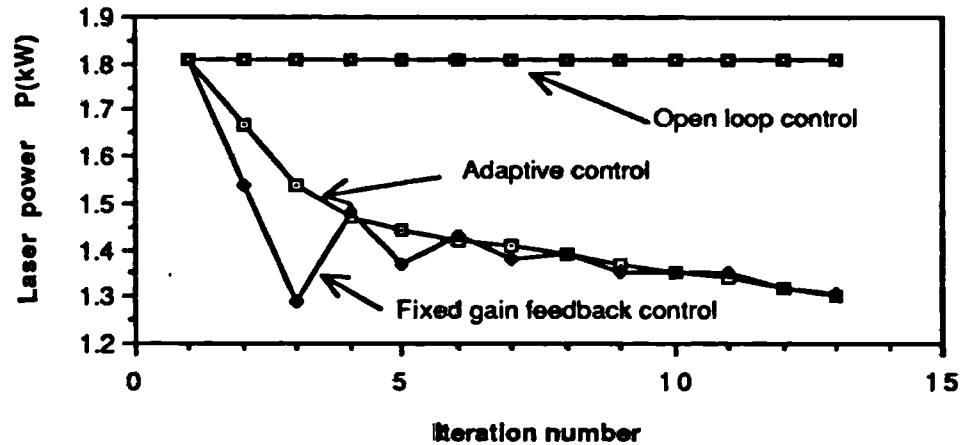


Fig.11.34 Laser power variations during the control action.

It can be seen that the temperature rise was compensated for by the increase of traverse speed, and the reduction of laser power. The variation of powder flowrate may not be significant for the compensation of temperature rise. This results agree with that by using the first method discussed in Section 11.2.

11.4 RULE-BASED ADAPTIVE LASER CLADDING CONTROL USING QUALITATIVE SENSOR FEEDBACK

The control technique discussed above requires quantitative sensors (dilution sensor and clad bead profile/ thickness scanner). In this section another approach is made to use a qualitative sensor (melt pool radiation sensor discussed in Chapter 7) for the clad quality feedback control and system failure alarms. A reduction in system hardware is beneficial if

clad quality can be maintained using this approach.

In Chapter 7, a single light intensity sensor was used to detect the visible radiation from the melt pool which was related to various process changes. This information could be utilized for the process feedback control as well as the monitoring and alarms as discussed in Chapter 7. The control objective in this case is to maintain the thermal radiation as constant, which may indirectly stabilize the melt pool and the clad parameters. Two parameters of the sensor signal: average magnitude and fluctuation magnitude were utilized in the process control. The control requires a prior-record of the signal signature for "good" clad and compares the detected signal to the ideal one during processing. Since the main reason for the continuous change of clad parameters is the clad substrate temperature rise (for small and medium samples) and from the study made for the above two methods we know that, these can be compensated for by the increase of traverse speed and the reduction of laser power. For the cladding of poor thermal conducting material (such as stainless steel, ceramics etc.) on good thermal conducting substrate (such as mild steel, cast iron, copper and Aluminum) the following rules could be applied:

1). IF the average value of detected signal is higher than normal line but below the 30% line and the standard deviation of the fluctuated signal is less than 30%.

THEN it is possible that the clad thickness and width are higher than the required values.

Decision: THEN Increase traverse speed until the signal comes back.

2). IF the average value of the signal is below the normal operating line but not below the -30% line and the standard deviation from the average is less than 30%.

THEN It is possible that there is a heavy dilution (0.8) or the clad thickness is too low (0.2),

Decision: THEN reduce laser power and reduce traverse speed or increase the powder flowrate.

3). IF the average value of the signal is above the 30% line and the standard deviation from the average is more than 30%

THEN It is possible that there is a poor clad bonding or porosities or system failure such as nozzle clipping and lens cracking.

Decision THEN stop the system and give alarm

4). IF the average value of the signal is below the -30% line and the standard deviation of the fluctuated signal is more than 30%.

THEN It is possible that there is a failure in the gas supply or powder feeder

Decision THEN stop the system and give alarms.

The adaptive feedback control method discussed in Section 11.3 could also be used for

this application. i.e. using deviation signal between the demanded and actual process response to generate a control command.

For example :
$$V_{i+1} = V_i + K_{v2}(S_r - S_i) \quad (\text{for both rule 1 and rule 2}) \quad (11-66)$$

$$P_{i+1} = P_i - K_{p2}(S_r - S_i) \quad (\text{for rule 2}) \quad (11-67)$$

$$M_{i+1} = M_i + K_{m2}(S_r - S_i) \quad (\text{for rule 2}) \quad (11-68)$$

where S_r is the melt pool radiation signal for a "good" clad and S_i is the actual signal response; K_{v2} , K_{m2} and K_{p2} are the control gains which could be optimized using the rule-based adaptive mechanism discussed in the last section. More will be investigated in the next Chapter on the use of knowledge based system for laser cladding faults diagnosis and quality control . The computing time for this method would be approximately the same as that for Method 2 (Section 11.3). i.e. 15ms using BASIC language and less than 5ms using PASCAL.

11.5. SAMPLING RATE CONSIDERATION

Almost all the diagrams in this chapter use "iteration number" as the unit for the horizontal axis. How long each iteration should take is decided by both the nature of the process and computing time for the control software. Since the steady state of operating parameters were used for the above developed methods and these conditions would required some time to establish (longer than the computing time for the control software), it is recommended that the sampling period is equal to or near the open loop system step response time constant (Some software waiting is required). Also since the dilution sensor and clad bead profile sensor are placed a distance behind the melt pool there is a sensor response delay to the control action. This requires the the sampling period even longer. If, say, the sensors are placed 20mm away from the melt pool the sensor response delay could be 2 seconds for the cladding speed of 10mm/s. In order to reduce this lag time the sensors are suggested to be as near as possible to the melt pool and cooling system may be required. The minimum sampling period for method 1 and 2 can be calculated using:

$$T_{sam} = T_{senm} + \text{Max}[T_{laser}, T_{feeder}] \quad (11-69)$$

where T_{sam} : Sampling period
 T_{senm} : Maximum sensing delay time
 T_{laser} : Laser power response time constant
 T_{feeder} : Powder feeder response time constant

For the equipment used in this experiment and the cladding traverse speed of between 1 and 24 mm/s :

$$T_{senm} \approx 2 \text{ s}, \quad T_{laser} \approx 1.5 \text{ s}, \quad T_{feeder} \approx 1.2 \text{ s}$$

Therefore the sampling period or the time for each control cycle should be 3.5 seconds. For the above mentioned slow speed laser cladding (typical 10mm/s) the continuous feedback control of clad quality to compensate for substrate temperature rise effect (which has a very slow change rate as well), the slow sampling rate would not affect the control accuracy of the control system. When traverse speed increases the effect of sensor delay will be further reduced. The sampling rate could therefore be further increased. From this study it can be seen that the closed loop laser cladding control using method one or method two may not be able to control the faster local clad fluctuations either because of the slow equipment response or because of the sensing delay. However the slow clad variation due to the temperature effect could be compensated for using the methods. It is also required that the closed loop control of system operating parameters (laser power, powder flowrate and traverse speed) should be used to achieve parameter accuracy and fast response.

Since method 3 uses melt pool information, which has no sensing delay, the sampling rate could be faster. Therefore some fast variations of the clad could be eliminated using method 3. However since the melt pool radiation sensor may not give the exact information on the clad bead dimensions, the accurate control of these parameters may require further investigation. Since traverse speed has the fastest response (few milliseconds), the variation of traverse speed for the control of clad bead width and clad thickness could be faster than the variation of powder flowrate. By examining the control effects of the 3 methods developed, in most cases traverse speed (instead of powder flowrate) was varied automatically to control the clad bead width and clad thickness while laser power was used to control clad dilution (since traverse speed has little effect on clad dilution.). Therefore the control loop for the of clad thickness and width could select a faster sampling rate. Especially for method 3, Shannon sampling theorem ($f_{sam} \geq 2 f_{max-of-the clad-fluctuation}$) could be used to decide the sampling rate. Dilution control however has to be slower unless laser power step response time can be further reduced.

For the reliability of sampled signal, it is required that several data to be taken for each point, so that filtering and smoothing can be made.

SUMMARY

Three techniques for supervisory laser cladding control have been developed:

The model based adaptive control method requires a known process model. If the models fit the real process closely the method can be applied. Two sensors are required for laser cladding control : dilution sensor and clad bead profile sensor.

The rule based self-searching adaptive feedback control method eliminated the need for a process model. Only the behaviors of the input/output parameters are needed. The control

gains can be self-optimized during process control. Two sensors are needed by the method for laser cladding process: dilution sensor and clad bead profile sensor. The method could be applied to many similar process where a model is not available or inaccurate. Both method 1 and method 2 could be used to search for the appropriate operating parameters for a given cladding requirement through on-line feedback control, eliminating the difficulties to decide the proper operating parameters in the previous practice.

The rule based control using single qualitative sensor provides an economic way for clad quality control. No knowledge of the process model is required and only one sensor is required. This method assumes that if the melt pool radiation is uniform, the clad should be also uniform. Further investigation is required to confirm this point.

CHAPTER 12

KNOWLEDGE BASED SYSTEM DEVELOPMENT FOR PROCESS FAILURE DIAGNOSIS AND QUALITY CONTROL

12.1. INTRODUCTION

The multi-variable adaptive control algorithms discussed in Chapter 11 were designed to maintain the clad thickness and dilution or melt pool stability by varying traverse speed, powder flowrate and laser power. However, in practice, many other problems can also occur such as poor bonding, porosity, cracks, hole burning, rough clad, non-symmetric clad bead etc. The causes of these problems may be straight forward or complicated. For example: if a clad surface is rough, the causes can possibly be unstable powder flowrate, bad mode structure, too low powder particle velocity too low, poor powder feed alignment etc. Many other clad phenomena can also be related to unstable powder flowrate, bad mode structure. In these cases the relationships are not a definite "Yes" or "No" or IF "this" THEN "that" form, but with a degree of certainty or probability. Some of these problems may not be corrected by the variation of operating parameters. The commonly used Boolean logic control (such as the use of PLC, ladder logic programming or using conditional switching programming techniques) could fail for the situation discussed, since they only deal with binary logic. Thus a new information processing technique is required. This Chapter describes the author's work on the development of a technique which combines the fuzzy logic with expert systems for "intelligent" laser cladding control. Using such a technique the causes of a complex problem could be diagnosed in real time and decisions made to correct it. Combining this technique with those developed in the previous chapters, would provide a total quality control strategy for the industrial laser cladding production.

Fuzzy logic was invented in 1965^[170] to represent and process the qualitative measures such as "Good", "Tall", "New" etc. These measures do not have sharply, precisely defined criteria of membership. Thus a concept of using a class with a continuum of grades of membership - a fuzzy set - to measure the state of an object was introduced. The rules for operating the fuzzy sets are called fuzzy logic (Max $\wedge$ Min law). Instead of saying the measure of an object is "Yes" (logic 1) or "No" (logic 0), in fuzzy logic a measure can be neither "Yes" nor "No" but something in between (represented by a number between "1" and "0") such as "possible" . But unfortunately it cannot represent the situation like " I do not know" . It also lacks the ability to "learn" from its mistakes.

On the other hand the representation and manipulation of qualitative information can also be achieved by a new branch of Artificial Intelligence (AI) - Expert systems - also known as

knowledge based systems. These are *sophisticated computer programs to solve problems efficiently and effectively in a narrow problem area. Like real human experts, these systems use symbolic logic and heuristic--rules of thumb--to find solutions. And like real experts, they make mistakes but have the capacity to learn from their errors.*^[171] The first prototype expert system is DENDRAL developed in 1971 for mass-spectrogram interpretation. Expert System development tools like PROLOG and LISP languages and Expert System shells are already commercially available. However most of them were designed for off-line applications. The advantages of the expert system over fuzzy logic are that it can handle incomplete information such "do not know" and have the capability to learn from its mistakes.

The technique developed and discussed in this chapter is similar to an expert system in that it can handle incomplete information and draw conclusion by using inferences from the known facts and a series "Rules" in the knowledge base, representing the relations between these facts and possible conclusions. It can also self-improve its performance by "learning", such that the more the system is used the better it behaves. It is also similar to fuzzy logic in that the manipulation of information is through arithmetic logical analysis. It possible to be embedded into other software for in-process diagnosis and decision making applications.

12.2. RELATIONAL MATRIX DEVELOPMENT FOR KNOWLEDGE REPRESENTATION

Imagine a relational network as shown in Fig. 12.1 where the transitions between states are indefinite (with certain possibilities).

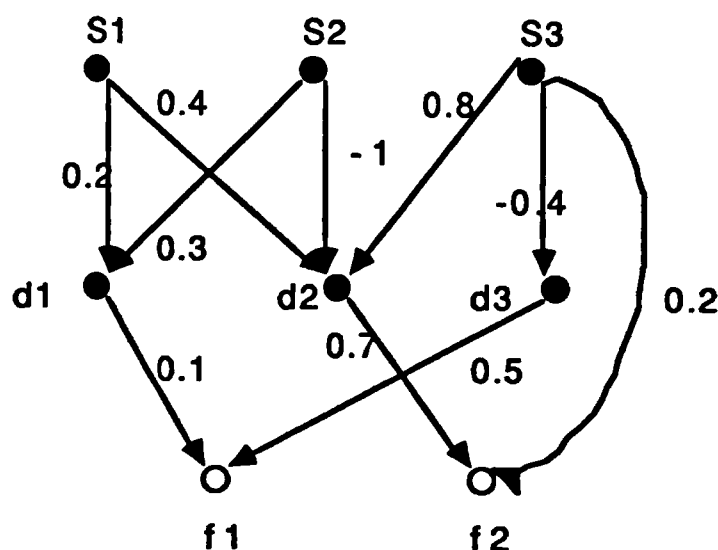


Fig. 12.1. An example of relational network with certainty factors.

The relationship can be represented using IF-THEN clause as used in most expert systems as:

Rule 1. IF S1 is true (S1=1),
THEN it is possible that d1 is true (confidence is 0.2) or d2 is true (confidence is 0.4).

Rule 2. IF S2 is true (S2=1),
THEN it is possible that d1 is true (confidence is 0.3) and d2 is impossible (full confidence).

Rule 3. IF S3 is true (S3=1),
THEN it is likely that d2 is true (confidence is 0.8) and it is very unlikely that d3 can happen (with confidence of 0.4) and it is possible that f2 is true (confidence is 0.2).

Rule 4. IF d1 is true (d1=1),
THEN there is some possibility that f1 is true (confidence is 0.1).

Rule 5. IF d2 is true (d2=1)
THEN it is very possible that f2 is true (confidence is 0.7).

Rule 6. IF d3 is true (d3=1)
THEN it may be that f1 is true (confidence is 0.5).

In this form of knowledge representation, the conditional part has to be a definite Boolean variable (true or false). If they are partially true or partially false as would be for d1, d2 and d3 then the above representation will fail. Thus an alternative way of representing complex relationships were introduced by the author i.e *Relational Matrix*.

To include the features of both Expert system and fuzzy logic, the **Relational Matrix** is defined here as a two dimensional matrix, R_{mn} which transfers one state vector $[x_1, x_2, \dots, x_m]^T$ to another state vector $[y_1, y_2, \dots, y_n]^T$ with certainty $-1 \leq r_{ij} \leq 1$. The states x_i or y_j themselves also have logic values in the form of a real number representing the degree of state certainty. For example, the above relational network can be represented using relational matrices such as:

$$R_{s-d} = \begin{bmatrix} 0.2 & 0.3 & 0 \\ 0.4 & -1 & 0.8 \\ 0 & 0 & -0.4 \\ 0 & 0 & 0.2 \end{bmatrix}, \quad R_{d-f} = \begin{bmatrix} 0.1 & 0 & 0.5 \\ 0 & 0.7 & 0 \end{bmatrix}$$

with the corresponding state vector represented as:

$$S = [s_1, s_2, s_3]^T, \quad D = [d_1, d_2, d_3, f_2]^T \quad \text{and} \quad F = [f_1, f_2]^T$$

where the superscript "T" represents the transpose of the corresponding vector. The simplification of the representation of relation using this technique is apparent compared to the IF-THEN rules. Although similar concept can be found in fuzzy mathematics, the relational matrix developed here however is slightly different from those used in fuzzy mathematics in that instead of using a number from 0 to 1 as a certainty factor, a number ranging from -1 to +1, was used with the negative representing the degree of impossibility and positive number for the degree of possibility while "zero" representing no relation or "do not know". This representation method extended the family of relationships in fuzzy logic to include "no relation" and "do not know" two situations. Another difference between the relational matrix defined here and that used in fuzzy mathematics is that: here the number of rows and the number of columns can be different and the states can have different meanings before and after transition, while in fuzzy mathematics the matrix must be a squared one and the states corresponding to rows must be the identical to that for columns. I.e. $S = D = F$ in the above example, which may be difficult to represent relationships in complicated situations unless S , D and F are combined to form a bigger matrix $[s_1, s_2, s_3, d_1, d_2, d_3, f_1, f_2, f_3]$ as in the above example. The flexibility and compactness of the present representation compared to the previous method can be clearly seen.

The states (nodes in the network) can be grouped into three categories in the Relational Matrix knowledge representation as shown in Fig. 12.2.

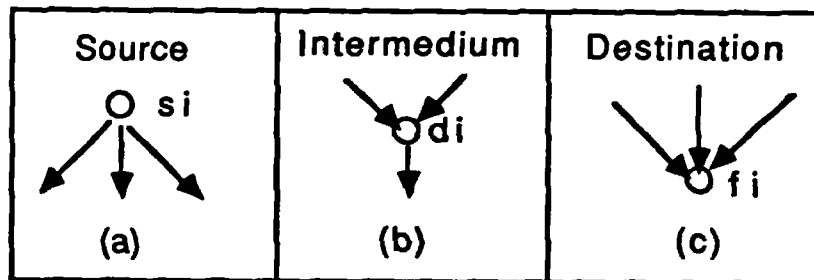


Fig. 12.2. Classification of information type in the knowledge network.

Group 1. Source attributes (S): These are the states which have only offspring. i.e. information is only flowing out from these attributes as shown in Fig. 12.2a.

Group 2. Intermediate attributes (D). These are the states which have both offspring and ancestors. i.e. information flows to it as well as flows out from it as shown in Fig. 12.2b.

Group 3. Destination attributes (F). These are the states which have only ancestors. i.e. information only flows into it. as shown in Fig.12.2c.

For process diagnosis and decision making the above definitions can be interpreted with more practical meaning as:

1. the source attributes --- sensory information;
2. the intermediate attributes --- diagnostic conclusions;
3. the destination attributes --- decisions made through the diagnosis.

Thus the known but indefinite relations between the sensory phenomena and its possible interpretation, as well as the various possibilities to correct the process behaviour can be represented using the technique developed.

It can be seen that, in the Relational Matrix representation of knowledge, the lengthy expression for a state is replaced by a single variable. For example instead of saying: IF the clad thickness is too high THEN reduce powder flowrate and laser power, we say IF s_1 then f_1 and f_2 . Such an expression avoids the participation of the physical expressions of state in the logic reasoning process thus the time used to reach a conclusion could be much reduced. The physical meanings to the state can however be filed in a separate place in the form of procedures or subroutines and can be accessed through their states when necessary. (Note that in most of expert systems, expression and relationships are mixed together).

12.3. INFERENCE ENGINE DEVELOPMENT FOR THE MANIPULATION OF THE RELATIONAL MATRICES

In order to draw useful information from the relational matrices an inference technique was developed which behaves in a similar way as forward chaining mechanism used expert systems but in a different form. The inference engine for analysing the relational matrices was designed as follows:

1. Obtaining the values of the source attributes (or sensor information) S by either off-line inquiry or on-line sensor sampling.
2. Using the known relational matrix R_{s-d} to infer the state possibilities of its immediate offspring D using:

$$D = R_{s-d} S \quad (12-1)$$

and compare the state values with the acceptance threshold, T_r (which is given by the user) and discard the states which do not satisfy:

$$D - T_r \geq 0 \quad (12-2)$$

3. If there are many intermediate layers then take the accepted D (denoted as D_a) as the source attributes and continue the process in step 2 until the destination states are reached.

4. The destination or final decision states can thus be inferred using:

$$F = R_d - f D_a \quad (\text{for single intermediate layer}) \quad (12-3)$$

or
$$F = R_{dn-f} D_{na} \quad (\text{for } n \text{ intermediate layers}) \quad (12-4)$$

5. If there are other items that have terminated (no further offspring) before the last matrix then the all the identical terminated states should be added together and compared with the acceptance threshold T_r so that the conclusion is made for those states which satisfy:

$$F - T_r \geq 0 \quad (12-5)$$

with the highest priority for the state with maximum positive value. ie.

$$f = \text{Max } (f_i) \quad i=1, 2, 3, \dots \quad (12-6)$$

where f is the final conclusion with the maximum probability.

For the above example: if

s_1 is true with certainty of 0.8. ($s_1=0.8$)

s_2 is false with certainty of 0.7 ($s_2=-0.7$)

s_3 is unknown ($s_3=0$)

then
$$S = [0.8 \quad -0.7 \quad 0]^T$$

If the acceptance threshold is 0.5 then the inference engine will arrive at a conclusion through the following process:

1.

$$D = \begin{bmatrix} d1 \\ d2 \\ d3 \\ f2 \end{bmatrix} = R_{s-f} S = \begin{bmatrix} 0.2 & 0.3 & 0 \\ 0.4 & -1 & 0.8 \\ 0 & 0 & -0.4 \\ 0 & 0 & 0.2 \end{bmatrix} \begin{bmatrix} 0.8 \\ -0.7 \\ 0 \end{bmatrix} = \begin{bmatrix} 0.2 \times 0.8 + 0.3 \times (-0.7) + 0 \\ 0.4 \times 0.8 + (-1) \times (-0.7) + 0 \\ 0 + 0 + 0 \\ 0 + 0 + 0 \end{bmatrix}$$

$$= \begin{bmatrix} -0.05 \\ 1.02 \\ 0 \\ 0 \end{bmatrix}$$

Since f2 is a terminated state, the further inference will exclude this parameter as source state. Also since $d1 < 0.5$, $d3 < 0.5$, these two states are also excluded for the further inferences. Thus the inference will be continued as:

$$F = \begin{bmatrix} f1 \\ f2 \end{bmatrix} = R_{d-f} \cdot d_2 = \begin{bmatrix} 0 \\ 0.7 \end{bmatrix} 1.02 = \begin{bmatrix} 0 \\ 0.714 \end{bmatrix}$$

Therefore a conclusion was made: there is a great possibility (0.714) that f2 is true under the condition given (Note that if in the D state assessment f2 is not zero then the f2 value in the D level should be added to the f2 value at the F level for a conclusion). Here f1= 0 means "not related",

It is possible that in the final conclusion set none of the states exceeds the acceptance threshold. In this case threshold should be decreased, or no action is taken, or choose the state with maximum value for execution so that the system can correct its behaviour later on (see next section). Note that the size of the matrices reduces after each transition because of the threshold selection, which means that the processing will proceed faster and faster. It is very rare that the full relational matrix is called.

The use of algebra for logic inference as described is different from the inference engines used in other expert systems where no arithmetic were involved. It also differs from the fuzzy logic analysis where Max-Min regulations are used.

12.4. LEARNING MECHANISMS DEVELOPMENT

If the Relational Matrices are not set properly the inferred results may be wrong. In order to prevent further mistakes a learning criterion was developed so that the system will improve the performance like a human being. The "punish and award" learning criterion was designed as:

1. IF there is no improvement after the manipulation of the decision fi is made by the system (same faults happen again) or the decision fi was proved to be wrong (by human check up).

THEN the corresponding entries leading to this decision in the relational matrices need to be reduced. i.e.

If $r_{ij} \geq -0.9$ and $r_{ij} \neq 0$ then let

$$r_{ij} = r_{ij} - 0.1 \quad \text{for all } j \text{ with non-zero ancestors,}$$

otherwise r_{ij} will not be changed.

2. IF there is an improvement after the manipulation according to the decision made by the system (faults disappeared).

THEN the corresponding entries in the relational matrices will not be altered if $f_i > t_r$, where t_r is the acceptance threshold. Otherwise

If $r_{ij} \leq 0.9$ and $r_{ij} \neq 0$ then

$$r_{ij} = r_{ij} + 0.1 \quad \text{for all } j \text{ with non-zero ancestors}$$

The recognition of the "improvement" can be made by recording the occurrence of the system problems as represented by S vector. If the same problems occurs (same states recalled), say, five times successively even after the control actions using the inference engine then the system performance is "bad". The correction of relational matrix is thus required.

For example, if the system performance has *not* been improved after the decision made in the above example then the corresponding entries in relational matrices R_{d-f} and R_{s-d} can be modified according to the learning process as:

$$R_{d-f} = \begin{bmatrix} 0.1 & 0 & 0.5 \\ 0 & 0.6 & 0 \end{bmatrix}, \quad R_{s-d} = \begin{bmatrix} 0.2 & 0.3 & 0 \\ 0.3 & -1 & 0.8 \\ 0 & 0 & -0.4 \\ 0 & 0 & 0.2 \end{bmatrix}$$

With such modification the future confidence for the same inference will be reduced, so that other conclusions can take the lead. Similarly if the corresponding factors in the relational matrices are increased the confidence for the same inference in the future will be increased as well.

12.5. KNOWLEDGE BASE DEVELOPMENT FOR LASER CLADDING QUALITY CONTROL

The first step in using the above described method for laser cladding process fault diagnosis

and correction is to establish the relational matrices. This requires experiences ("Rules of thumb") and many experiments. For diagnosis matrix, various relationships between the sensor signals and the possible problems needs to be established. Also the causes for this faults need to be related. For example an increase of brightness of the melt pool emitted light can be the result of increase of clad thickness due to the speed reduction (0.5) or overlaps (0.5), poor bonding (0.5), porosity (0.3), defect substrate (0.4) etc. In order to locate the true causes for the problem other information may also be required such as the signal fluctuation pattern etc.(See Chapter 7). To establish the decision matrix a knowledge of the factors which can correct the faults is required. For example interrune porosities can be avoided if a correct bead dimensions and degree of overlap are used. Therefore if there is an interrune porosity problem the degree of overlap should be decreased (0.8) or powder flowrate reduced (0.5) at the same time laser power should also be reduced in order to maintain the same level of dilution. A prototype knowledge base in the form of relational matrices for the laser cladding process was established (included in Appendix C). These were obtained by:

Process experience
Literatures survey
Discussions with experts

The sensors used are those discussed in Chapters 7, 8 and 9.

The faults set include : rougher clad, clad discontinuous, porosity, excessive oxidation, poor clad bounding etc.

The causes set include: shrouding failure, powder/beam misalignment, lens cracked, nozzle clipped, poor mode structure, laser power too low, powder too fine, powder flowrate too low, laser power too high etc.

The decision set include: reduce laser power, increase laser power, reduce traverse speed, increase spot size, stop operation and give alarm etc.

12.6. ILLUSTRATIVE EXAMPLE FOR ON-LINE CLAD FAULTS DIAGNOSIS AND QUALITY CONTROL

To demonstrate the use of the inference engine, for laser cladding process diagnoses and on-line decision making, part of the relational matrices was abstracted from the knowledge base (Appendix C) as shown in Fig. 12.3. where

s1 = very rough clad
s2 = clad discontinuous
s3 = bad laser beam mode
s5 = clad bead width too small
s6 = clad thickness too small
d1 = powder flowrate too high
d2 = powder particle traverse speed too low
d3 = bad mode structure

d4 = lens cracked
 d5 = nozzle gas pressure too high
 d6 = traverse speed too high
 c1 = condition 1: powder conveying gas pressure control not on-line
 c2 = condition 2: nozzle gas pressure control not on-line
 f1 = decrease powder flowrate
 f2 = Increase powder delivery gas pressure
 f3 = decrease nozzle gas pressure
 f4 = set alarm to indicate too high nozzle gas pressure
 f5 = set alarm to indicate too low powder delivery pressure

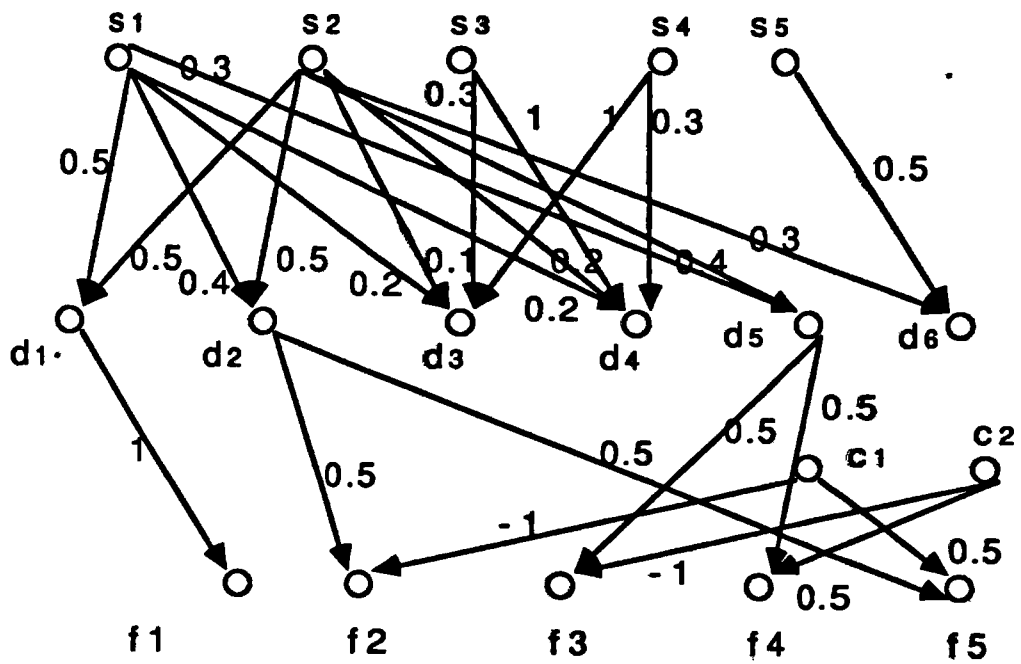


Fig. 12.3. A part of the knowledge network for laser cladding process.

The corresponding state vectors can be expressed as:

$$S = [s_1 \ s_2 \ s_3 \ s_4 \ s_5]^T, \quad D = [d_1 \ d_2 \ d_3 \ d_4 \ d_5 \ d_6]^T$$

$$F = [f_1 \ f_2 \ f_3 \ f_4 \ f_5]^T, \quad Dc = [d1 \ d2 \ d5 \ c1 \ c2]^T$$

The diagnostic matrix and part of the decision relational matrix can be expressed as:

$$R_{s-d} = \begin{bmatrix} s_1 & s_2 & s_3 & s_4 & s_5 \\ 0.5 & 0.5 & 0 & 0 & 0 \\ 0.4 & 0.4 & 0 & 0 & 0 \\ 0.2 & 0.1 & 0.3 & 1 & 0 \\ 0.2 & 0.2 & 1 & 0.3 & 0 \\ 0.3 & 0.4 & 0 & 0 & 0 \\ 0 & 0.3 & 0 & 0 & 0.5 \end{bmatrix} \begin{matrix} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \\ d_6 \end{matrix} \quad R_{d-f} = \begin{bmatrix} d_1 & d_2 & d_3 & d_4 & d_5 \\ 1 & 0 & 0 & 0 & 0 \\ 0 & 0.5 & 0 & -1 & 0 \\ 0 & 0 & 0.5 & 0 & -1 \\ 0 & 0 & 0.5 & 0 & 0.5 \\ 0 & 0.5 & 0 & 0.5 & 0 \end{bmatrix}$$

If the sensory feedback has found: $s_1 = \text{true}$, $s_2 = \text{true}$, $s_3 = \text{false}$, $s_4 = \text{false}$ and $s_5 = \text{false}$ i.e.

$$S = [1 \ 1 \ -1 \ -1 \ -1]^T$$

then the state of the diagnostic vector can be calculated using the inference engine as:

$$D = \begin{bmatrix} d_1 \\ d_2 \\ d_3 \\ d_4 \\ d_5 \\ d_6 \end{bmatrix} = R_{s-d} S = \begin{bmatrix} 0.5 & 0.5 & 0 & 0 & 0 \\ 0.4 & 0.5 & 0 & 0 & 0 \\ 0.2 & 0.1 & 0.3 & 1 & 0 \\ 0.2 & 0.2 & 1 & 0.3 & 0 \\ 0.3 & 0.4 & 0 & 0 & 0 \\ 0 & 0.3 & 0 & 0 & 0.5 \end{bmatrix} \begin{bmatrix} 1 \\ 1 \\ -1 \\ -1 \\ -1 \end{bmatrix} = \begin{bmatrix} 1 \\ 0.9 \\ -1 \\ -0.9 \\ 0.7 \\ -0.2 \end{bmatrix}$$

which means it is definitely (1) the powder flowrate is too high, and also possible (0.9) that powder particle speed is too low and nozzle gas pressure too high (possibility 0.7). Other causes are very unlikely. If the acceptance threshold is 0.5 then d_3 and d_4 will be discarded and the inference process will continue to the decision making. If conditions $c_1 = \text{true}$ and $c_2 = \text{true}$ (through initial user inquiries), then the decisions can be found as:

$$F = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \\ f_4 \\ f_5 \end{bmatrix} = R_{d-f} D_c = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 \\ 0 & 0.5 & 0 & -1 & 0 \\ 0 & 0 & 0.5 & 0 & -1 \\ 0 & 0 & 0.5 & 0 & 0.5 \\ 0 & 0.5 & 0 & 0.5 & 0 \end{bmatrix} \begin{bmatrix} 1 \\ 0.9 \\ 0.7 \\ 1 \\ 1 \end{bmatrix} = \begin{bmatrix} 1 \\ -0.55 \\ -0.65 \\ 0.85 \\ 0.95 \end{bmatrix}$$

i.e decrease powder flowrate (confidence =1). If the system performance is not changed then alarm to the user that powder gas pressure is too low (confidence = 0.95) or nozzle gas pressure is too high (confidence = 0.85). At the same time the corresponding entries in the relational matrices should be modified.

12.7. EXPERT SYSTEM IMBEDDED SUPERVISORY CONTROL SOFTWARE DESIGN FOR LASER CLADDING TOTAL QUALITY CONTROL

The overall supervisory laser cladding control software was designed to contain several modules as shown in Fig. 12.4 with imbedded micro-expert systems.

- 1). **INPUT MODULE** The task of this module is to sample the sensory signals, and then filter the data, calibrate them and send the results to the MONITORING MODULE and computer console.
- 2). **MONITORING MODULE.** The task of this model is to compare the sensory signal to the reference signals which represents the normal working conditions. If the deviation exceeds the threshold the corresponding problem will be sent to the micro-expert system for faults diagnosis and decision making as described in the previous section. At the same time the display on the computer console for the item will be flashing representing a problem.
- 3). **EXPERT SYSTEM.** The task of the expert system is to diagnose the causes for the problems identified in the MONITORING MODULE and measures taken for either direct control or alarms (with possible causes displayed) or recording for post-processing.
- 4). **CONTROL MODULE.** The task of the this module is to vary the operating parameters (laser power, powder flowrate, traverse speed) in an appropriate direction with an appropriate amount so that the errors will be reduced in the next cycling. This would use the techniques discussed in Chapter 11.

5). **OUTPUT MODULE.** The task of this module is to change the numerical physical unit of the calculated value to the appropriate signals for controlling the practical machines (CNC workstation, Laser and powder feeder). These include RS232 serial communications and D/A conversions.

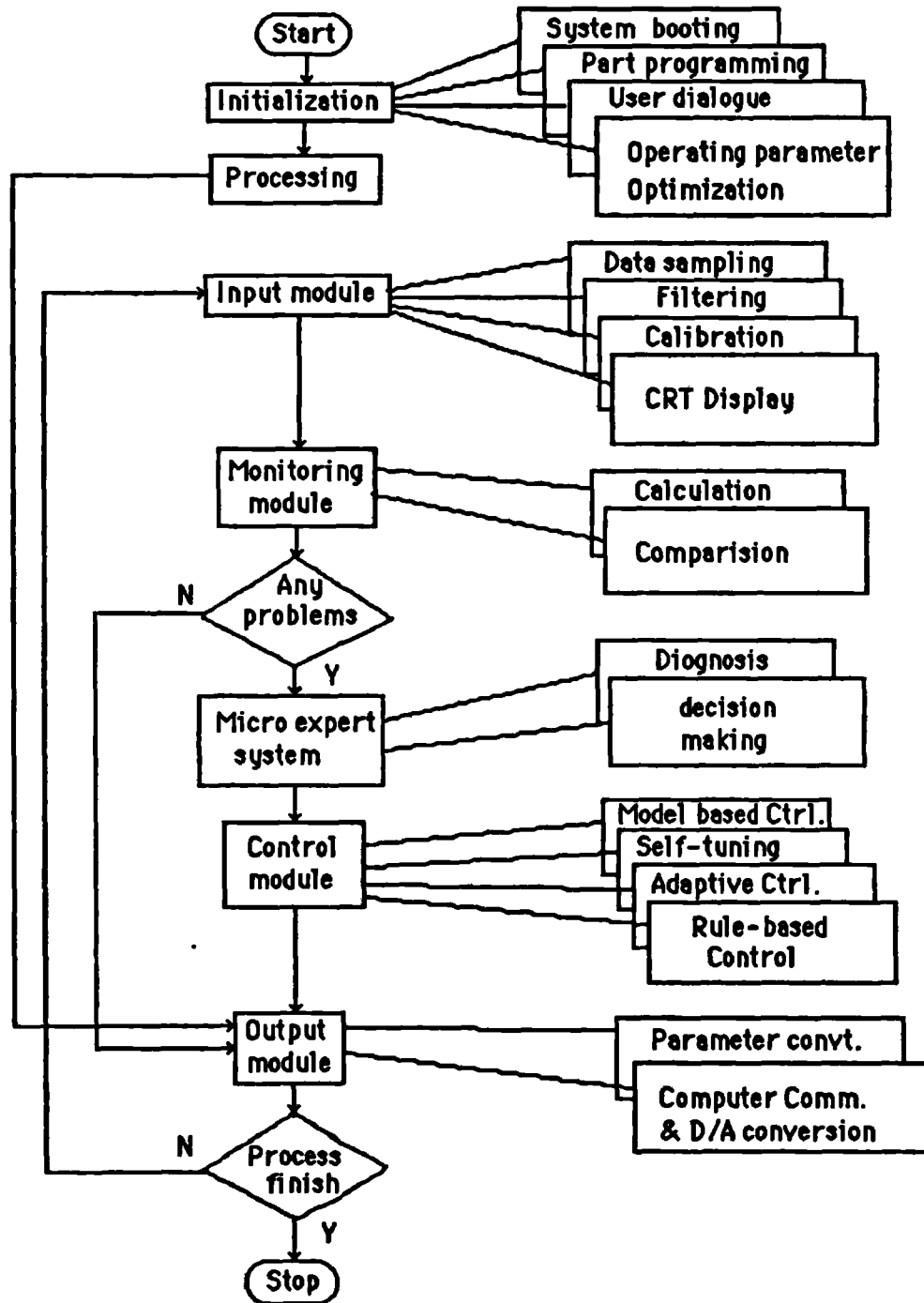


Fig. 12.4. Laser cladding supervisory control general software structure.

6). INITIALIZING MODULE. This module contains:

- a). System initializing (on boot for default values setting, interface initializing etc.);
- b). User dialogue for obtaining the operating requirement, materials properties etc.
- c). Operating parameter optimization (using techniques developed in Chapter 10).
- d). Parts programming (programming CNC moving pattern)
- e). Post processing inquiry (for relational matrix learning and updating)

The software was designed to be menu driven so that minimum explanation is required from the user. Part of the this software was realized using PASCAL language on the system supervisory computer (VME bus) by Mr. M. Hammarlund and Mr. P.J. Moody (from the Centre of Robotics, Imperial College) as their MSc theses.

12.8. SUMMARY

A new real time information manipulation technique was developed for laser cladding supervisory control. The advantages of the technique can be summarized as:

- 1. It can be easy to construct and can be embedded into many existing software.
- 2. It can be real time, on-line.
- 3. It considers the certainty factors for both state transition and attributes. Thus it is more flexible and realistic.
- 4. It is compact thus much less memory is required.
- 5. It separates the physical meaning of the variables from their logical relationships. Thus it is simple and faster for analysis.
- 6. It uses an arithmetic inference engine to manipulate relational matrices without involving the verbal expression of the rules themselves. Thus the speed is faster.
- 7. The structure is simple yet general, which could be used for other applications.

One disadvantage is that the size of the knowledge base is limited by the allowable size of matrices in the language and computer used.

Also in this chapter: A prototype data/knowledge base has been established; The application example for laser cladding system has demonstrated the possibilities of the using the technique for intelligent laser cladding process control; General intelligent laser cladding control system supervisory software structure is designed. Further application experiments are required to examine and verify the theoretical results discussed in this chapter.

CONCLUSIONS AND FUTURE WORK

Work has been reported in this thesis on the designing and construction of an intelligent laser cladding cell, which comprises of three aspects:

1. LASER CLADDING AUTOMATION.

The work done includes:

a). The construction of an 3 axis CNC laser workstation with closed loop distance and speed control. It combines 3-axis CNC motion control system with laser shutter control and powder feeder on/off control enabling automatic processing operation by computer programming. Instead of using NC language like many existing systems do, the developed system uses high level language (CONTROL BASIC) for parts programming, which provided higher flexibility. Also the traverse speed can be varied "on the fly" which is critical for adaptive laser process control applications.

b). Development of a sensor integrated, self-cleaning dome and a spherical nozzle . This was developed for laser beam recycling and process shrouding in laser cladding and alloying processes where powder feeding is used. The features of the developed dome different from the previous ones are aerodynamic cleaning, sensor integration and the use of a spherical nozzle. The pneumatic self-cleaning device guarantees the dome to be free from the powder contamination and provides additional shrouding and cooling effect. This was designed to reduce the effect of inconsistent beam reflection of the dome on the clad quality.

c). Development of an automatic laser shutter controller The controller uses 4 proximity sensors as edge detectors and by using logic circuit, laser beam can be switched on/off at appropriate place. Computer software control approach was also considered.

d). Development of a closed loop nozzle/substrate distance controller with off-centre infrared distance sensor feedback. Because of the powder feed and laser beam influence an off-centre (sensing point is on the side of the melt pool) sensing approach was used. The modulated and linearized sensing conditioner developed can extend the sensing and control range to 10 - 50 mm with 0.05mm accuracy and the sensing is independent of back ground noise influence including laser reflection and melt pool thermal radiation. However the change of the substrate surface oxidation may affect the control accuracy.

e). Development of an on-line closed loop laser power controller. It has reduced the laser start up time from previous 45 minutes to less than 1 minutes, response time from

previous 4-7 minutes to 1-4 seconds, beam stability from previous $\pm 15\text{W}$ fluctuation or more than 100 W power floating to $\pm 4\text{W}$ ripple (0.2% control accuracy). An additional effect of the closed loop laser power control is the stabilization of laser beam mode. The real causes for this have not been identified yet but it has been shown in the thesis that laser power level has some "link" with the beam shape possibly due to the temperature effect on the laser optical cavity. Along with the power controller an in-process beam diameter meter was also developed which enables digital display and continuous analog recording of beam width variation.

f). Development of powder feeder mathematical model and a closed loop powder flowrate controller. A mathematical model was developed for the screw feed, pneumatic conveying powder feeder, which allows better understanding and proper use of this type of feeder. The closed loop powder flowrate controller developed had improved powder feed stability, accuracy and repeatability.

2. IN-PROCESS CLAD QUALITY SENSING

Three types of in-process sensing techniques have been developed:

a). Thermal radiation sensing. By using a photo diode with an additional background noise shielding sleeve to look at the melt pool light radiation during laser cladding, some interesting information was obtained such as poor clad bonding, clad uniformity, substrate imperfection. Other system failures such as nozzle clipping, gas supply finishing can also be recognized by analysing the sensor signal "signature". Initial study has shown that the signal is closely related to melt pool stability and the amplitude of the signal could be related to the clad thickness.

b). Dilution sensing. Although electro-magnetic sensors have been used for non-destructive sensing in many fields they all depend on the air gap between the sensor and objects. A switching of transmitting frequencies was suggested in this thesis so that the distance and object properties can be separated. This enables the sensing technique to be used for non-contact sensing of moving objects. In the present application this was used to detect the clad reluctance change by the substrate contamination to indicate the degree of dilution.

c). Clad bead profile and clad thickness sensing. An infrared sensor and a scanning device was used for clad bead profile sensing. The sensor has the advantages of small size, light weight, low cost, fast response, long sensing range. The extent of surface oxidation was also recognized by the sensor. Since the sensing system uses infrared sensor it depends on material surface reflectivity, the calibrations for clad material and substrate materials distance sensing have to be made separately.

3. LASER CLADDING SUPERVISORY CONTROL

The supervisory laser cladding control techniques have been developed to solve three major problems raised in the General Introduction that of the determination of optimum operating parameters, maintaining the clad quality through out the processing time and in-process faults diagnoses and correction. These were treated in three different ways:

a). Laser cladding optimization technique. By using on-line identification and conditional optimization technique, laser cladding operating parameters can be optimized so that low dilution, good bonding, good clad bead profile, Interrun porosity free clad with desired clad thickness and maximum cladding coverage rate can be achieved. Various formulas were derived for process optimization operating zone calculation. A computer software was realized.

b). Adaptive control technique. A new rule based self-regulating and adaptive control technique was developed for the control of partially known and unknown process. The technique developed suits both single variable and multi-variable, both linear and non-linear processes. The simulated results for laser cladding process control have demonstrated its possibility for real applications.

c). Information manipulating technique. A new real time information manipulating technique was developed which combines fuzzy logic and an expert system to create relational matrices for the information representation and by using an newly developed arithmetic inference engine the information can be manipulated and conclusions made if the states of phenomena are known. A self-improving "punish and reward" learning feature was also incorporated in the system, so that the more the system is used the more accurate it will be. A prototype knowledge base was developed for laser cladding process and an example was give on the use of relational matrix and inference engine for laser cladding quality control.

The intelligent laser cladding control system hardware structure and software structure were designed and partially realized.

The 7 objectives listed in the General Introduction have so far been reached with supervisory laser cladding control techniques (d,e,f) to be further examined and verified through experiments.

FUTURE WORK:

The following work is suggested here for the further development:

- a). Instrumentation of magnetic dilution sensing device and conduct in-process sensing experiment.
- b). Study the sensor position and different material effects on the melt pool thermal radiation sensing to optimize the method and further confirmation of the clad thickness sensing using the sensor.
- d). Development of a computer controlled powder feeder control system, which closed loop controls both powder flowrate and particle speed.
- c). Implementation of laser cladding in-process faults alarm and diagnose system.
- f). Implementation of adaptive laser cladding control system.
- g). Data base and knowledge base perfection for laser cladding control and faults diagnosis.
- h). Application of laser cladding optimization software for different material combinations to verify and enrich the technique.
- i). Development of closed loop laser mode structure controller and ultra-fast laser power control technique.
- j). Development sensors that can give precise dilution and clad thickness information directly from clad melt pool.

Laser cladding has been used in industry for nearly 5 years for engineering parts hardfacing or creation of thermal barrier. The advantages of controllable, localized heat input for low dilution clad are well recognized. However the applications have been mainly restricted to local area coating of small parts like engine valve, exhaust valve etc. Large scale laser cladding still faces many problems. The advantages that laser cladding can offer over the conventional cladding techniques are its controlled fusion bound and flexibility thus complicated workpiece can be clad using lasers. In order that the clad quality can be maintained as the desired in production line for large scaled laser cladding applications, various process problems that industrial laser cladding would face need to be studied; techniques to select proper operating parameters need to be investigated, techniques for in-process clad quality sensing and control need to be developed. It is hoped that this thesis has contributed to this objective.

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APPENDIXES

Because of the restrictions on the thesis thickness, the size of the Appendix was cut down to contain only 6 sections which are closely relevant to or useful for the understanding of the main text. The following materials are excluded from the thesis.

- a). Tables of experimental data.
- b). Computer programmes for laser cladding optimization, adaptive laser cladding control, expert system and laser cladding supervisory control.
- c). Circuit diagrams for powder feeder controller, laser shutter controller, closed loop nozzle standoff controller, distance sensing signal conditioning, CNC workstation manual controller and various system interface circuits.
- d). Powder feeder modelling on the relationship between powder flowrate and powder particle travelling speed.
- e). Powder flowrate sensing when feed gas is turbulent.
- f). Clad quality sensing using pyro-electric sensor and acoustic sensor.
- g). Laser cladding control using temperature sensor feedback .
- h). Work in association with Dr. Weerasinghe on the use of acoustic sensor for powder hopper level sensing , the use of gas pressure sensor and gas jet/acoustic sensor for distance sensing.

Some of these may be published later. The author apologises for not being able to include the above mentioned materials in the thesis.

APPENDIX A.

CNC LASER CLADDING MOTION CONTROL SYSTEM OPTIMUM PARAMETER CONFIGURATIONS

A.1. X-Y TABLE MECHANICAL AND ELECTRICAL SPECIFICATIONS

The electric and mechanical characteristics of the x-y table are summarized as follows:

a). Motor/tacho Characteristics: Two identical permanent magnetic DC servo motors (Model SD125, supplied by CSR Inc.) with coaxial tacho-generators were used for x-y table. The specification of the motor is listed in Table A.1

Table A.1. x-y table motor/tacho specification (from CSR data sheet)

ITEMS	SYMBOLS	VALUES
Cont. Torque	T	9.7 lb-in
Nominal Speed	U	1978 RPM (for 50v supply)
Maximum Speed	U _{max}	3600 RPM
Torque Constant	K _t	2.1375 lb-in/A
Motor Constant	K _m	0.2415 N/Rad/s
Mech. Time Const.	T _{xym}	14.5 ms
Armature resistance	R	1.245 Ω
Speed constant	K _e	25.29 V/1000rpm
Moment of Inertia	J	0.00602 lb-in-sec ²
Maximum continuous current	I _{cmax}	4.54 amps
Maximum supply voltage	V _{max}	88 volts
Maximum power	P _{max}	3766 watts
Peak Torque	M _m	117.5 lb-in
Maximum ACC.	ACC _m	19500 Rad/Sec ²
Tacho constant.	K _g	0.0668 v/1000 RPM

The motor/tachos were connected to the x-y table lead screws through 1:2 (Kgr) belt/pulleys (motor side 14 teeth/rev, lead screw 28 teeth/rev)

b). Encoder Characteristics: Two identical encoders were used connecting to the x-y table lead screw through coaxial flexible couplings. The encoder (supplied by Electric Craft Ltd.) gives two channel (A and B with 90° phase shift) 1000 pulses/rev square wave TTL/line driver complementary outputs with zero index marks. 5V DC power supply is required for the encoder operation.

c). Limit/datuming switches: Four mechanical limit switches were installed at $\pm x$ and $\pm y$ table traverse ends with fail safe NC configuration. -x and -y limit switches were also used as datuming switches indicating the home position. +24V DC power supply were used for the limit switch control.

d). Table mechanical specification: Table lead screw has 5mm pitch (Pt). Aluminium table top weight is about 30 kg (Wt). Table traverse distance : x direction was 245mm; y direction was 280mm. Because of the fitting of bellows and allocation for the possible inertial overrun of the table at limit switches the actual table traverse at x direction between limit switches became 195mm and y direction of 240mm.

A.2. LASER WORK HEAD ELECTRICAL AND MECHANICAL SPECIFICATIONS

The mechanical and electrical characteristic of the z axis laser work head are summarized as follows:

a). Motor/tacho characteristics: The motor/tacho used for z-axis laser work head control was a small permanent magnetic DC servo motor with coaxial tacho-generator supplied by Electric Craft Ltd. Motor/tacho specification is listed in Table A.2.

Table A.2. z- axis laser work head motor/tacho specification(from EC data sheet)

ITEMS	SYMBLES	VALUES
Torque const.	Kt	0.056 Nm/A
Mech. time const.	Tzm	13.5ms
Moment of Inertia	Jr	0.000037kgm ²
Armature Resistance	R	0.8 Ω
Voltage constant	Kzv	5.85 V/krpm
Max speed	Uzm	6000 rpm
Peak torque	Mzm	1.0 Nm
Continuous power	Pct	80w
Continuous Stall torque	Mz	0.2Nm
Max. Input Voltage	Vimax	35.1VDC
Tacho constant	Kzp	14.2V/krpm

b). Encoder characteristics: The encoder used was the same type for x-t table fitted coaxial with the motor/tacho.

c). Limit switches: Two mechanical micro-limit switches were used at both ends of the z traverse ($\pm z$) with fail safe NC connection. -z end limit switch was also used as z axis

datuming switch. 24 v DC power supply was used for limit switch control.

d). Laser work head mechanical specification: The motor was coupled to the laser work head through a rack and pinion mechanism. The rack pitch $P_z = 2\text{mm}$ with 55mm traverse and the pinion has 1/100 gear ratio (KgZ) with 25teeth/rev.

A.3. SERVO DRIVE AND PSU SPECIFICATIONS

The servo drives and PSU provided the first loop servo control and power supply for the CNC motion control system. The electrical specifications of these units are given below.

a). Servo drive specification: The servo amplifiers were selected to meet the motor requirements. i.e. to allow the maximum motor capability to be used in terms of speed and torque. Since x-y table control motors require 88 volts x 4.54 amps drive and z axis motor requires 35 volts x 2.27 amps, a Pulse-width modulated 3 axis DC-servomotor Drive (PWM-4) supplied by Unimatic Engineers Lt.d was used. The servo-drive has the following features^[139]:

Max. continuous motor current (per axis)	12A
Max. motor supply voltage	100v DC
Overall frequency response	500Hz
Max. cont. power (per axis)	80w
Typical input voltage	$\pm 10\text{v}$
Power supply requirement	60V AC & 240V AC 50-60Hz

The inputs to the servo amplifiers include: $\pm 10\text{V}$ DC motion control signals from programmable servo controllers or manual speed controller; tacho-generator signal for speed feedback; Limits switches to stop the motion in the corresponding directions at limit position. The outputs from the servo drives are connected to the motor armature for motor speed and torque control. The adjustable parameters on the servo drive include: time constant, signal gain, tacho feedback gain, current limit and balance. Additional connections can also be made on the servo-drive to free the corresponding motor. The connection of servo drive with motors can form a motor speed servo control loop.

b). PCU specification: The power supply unit consists of a 3000VA 240VAC/60VAC isolating transformer, a +5VDC x 1A power supply for encoders, a +24VDC x 2A for Limit switches and safety interlock, and $\pm 10\text{VDC}$ x 1A power supplies for manual speed controller.

A.4. PROGRAMMABLE SERVO CONTROLLER DESCRIPTION

The programmable servo controller consists of two parts: axis controller module and supervisory control card. The axis control module controls the motion (position, speed and acceleration) for each axis while the supervisory control card coordinates axis cards for multi-axis interpolation (linear interpolation, circle and multi-axis speed, position control etc.).

a). Axis control module description: The micro-processor (6809 CPU) based axis control modules were supplied by R.D.Projects Ltd [138] which consists of 3 identical servo control 6U cards and a power supply card. The RDP axis module counts the input pulses (multiplied by 1,2 or 4 times by jumper selection) from the incremental encoder and converts them into a 32 bit 2's complement variable, representing the "Axis Position". A second 32 bit 2's complement number contains the position, in terms of encoder pulses, requested by the supervisory computer (through IEEE488 communications) using movement commands; this is referred to as the "Demand Position". Periodically the axis module compares the two and calculates the difference, generating the "Following Error". The following error multiplied by the axis "Servo Gain" determines the demand (between $\pm 10V$) to be applied to the motor amplifier. The axis module will interpolate along a requested path at a demanded speed with specified acceleration and deceleration phases (velocity profiling). The axis control module represents a proportional loop controller. Additional limit switch inputs, inhibit control inputs, jog inputs and break outputs are provided on each control module.

b). Supervisory motion control card description: The micro-processor based (68000 CPU) supervisory motion control 6U card was supplied by Motion Systems Ltd. The card provides linear and circular interpolation for multi-axis (up to 3 axis) operation through IEEE488 communication (up to 16 axis). The card can be configured and programmed from an external computer terminal through a serial link (RS232). An additional serial port is provided for print out of the program and other information. 4k memory was provided on the card so that system configuration parameters and application programs can be stored. One of the features of the card which is different from other NC system is that this card uses Control Basic language which allows variables, scientific calculations, logic analysis and loop conditions to be used in the parts programming. The motion speed can be varied "on the fly" during motion. The Control BASIC language has the features of BASIC language that can be used on both run mode (execute a single command directly) and program mode (run a set program).

A.5. MOTION CONTROL LOOP TUNING AND PARAMETER OPTIMIZATION

The servo control loops for one axis is shown in Fig.A.1; other axis is identical. Since there is no interaction between axis the system tuning and control parameter configurations

can be made separately for each axis which contain two control loops: speed control loop and position control loop. Therefore tuning of the system can be divided into 2 parts: servo drive tuning and axis control module configuration.

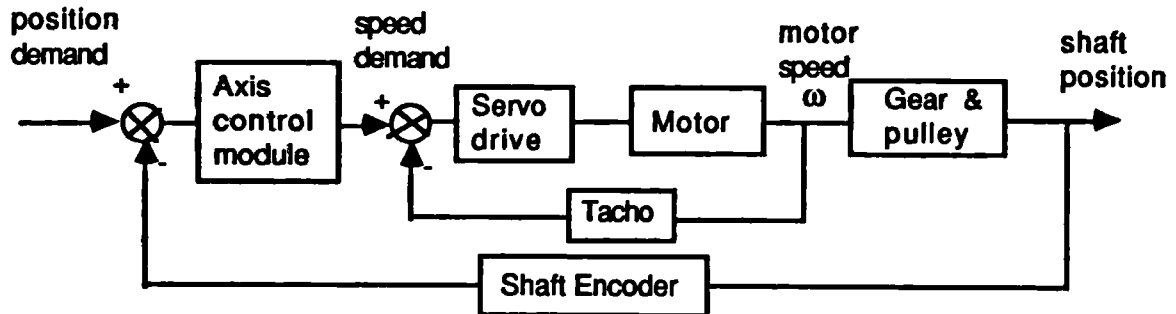


Fig. A.1. Control loops for CNC motion system (single axis)

a). Servo drive tuning: The tuning of servo drive decides the control characteristics of the speed control loop. An improper set up of parameter in this loop may lead to the system performance unsatisfactory. The tuning of servo drive parameters for this loop was performed by using step response method: closing the loop and connecting a the tacho signal to an oscilloscope while generating a step input to the servo amplifier. The variation of loop parameters was carried out with reference to the following diagrams (Fig.A.2).

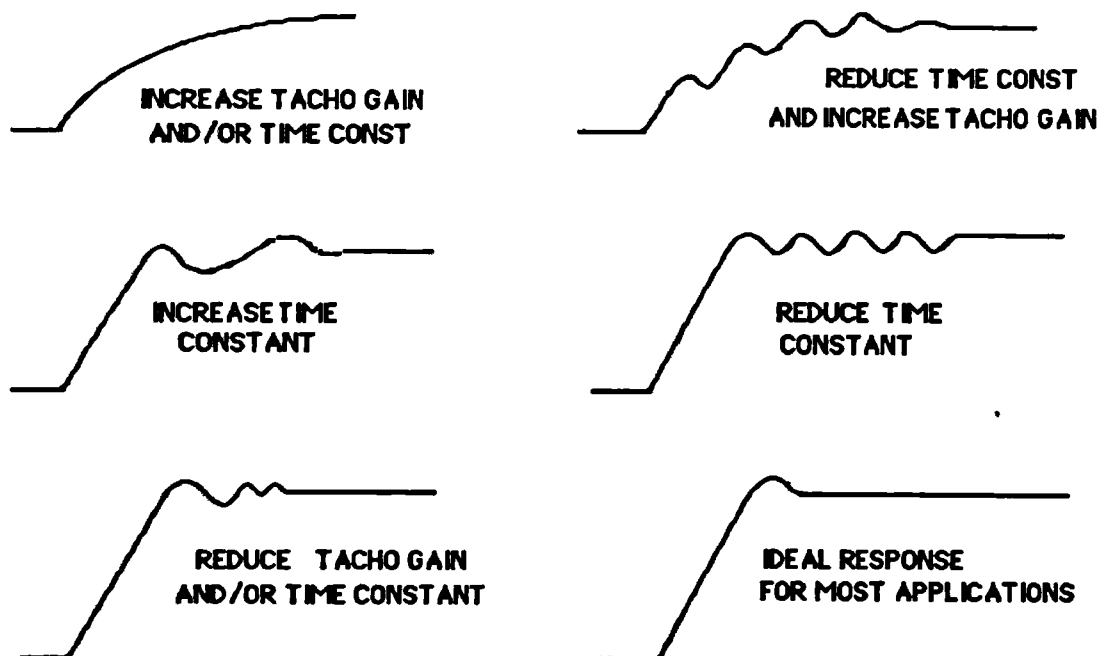


Fig. A.2. The step response method for optimizing the servo drive parameters^[139].

The optimized closed loop control gains were found to be $K_{cxy} = 5.5$ for x and y axis and $K_{cz}=3.2$ for z axis.

b). Parameter configuration for axis control cards: There are four set of parameters need to be configured on the axis control cards . These are:

i). Optimum sampling period: The optimum sampling period for a closed loop position was suggested by Koren [140] to be:

$$T_{sop} = 0.8 T_m \quad (A-1)$$

where T_{sop} : Optimum sampling period
 T_m : System mechanical time constant

Therefore the optimum sampling periods were selected for x-y and z axis to be:

$$\begin{aligned} T_{sopx,y} &= 0.8 T_{xym} = 0.8 \times 14.5\text{ms} = 11.6\text{ms} \\ T_{sopz} &= 0.8 T_{zm} = 0.8 \times 13.5\text{ms} = 10.8\text{ms} \end{aligned}$$

ii). Optimum proportional control gain: Since the closed loop position control system is a type 1 system, proportional control is sufficient to provide zero steady state position control error for a step input demand. The optimum proportional control gain were suggested by Koren [140] to be:

$$K_{op} = 1/[K_c K_e (T_{sop} + T_m)] \quad (A-2)$$

where

K_{op} : Optimum position control gain
 K_c : Speed servo loop gain
 K_e : Encoder constant (pulses/m)

Therefore the position control loop control gain can be set for x and y axes to be:

$$\begin{aligned} K_{opxy} &= 1/ [K_{cxy} K_{exy} (T_{sopxy} + T_{xym})] \\ &= 1 / [5.5 \times 0.2 \times (11.6 + 14.5)] \\ &= 0.03483 \end{aligned}$$

This value has to convert to the RDP card unit which has 0 for -10V and 32767 for + 10v D/A outputs. i.e. 1638 units/V. Thus the actual proportional gain for x and y axes is:

$$\begin{aligned} K_{optxy}^* &= \text{Int}(1638 \times K_{opxy}) \\ &= \text{Int}(1638 \times 0.0348) \\ &= 57 \end{aligned}$$

where Int is an integer truncation function.

Similarly the optimum proportional control gain for z axis was set to be:

$$\begin{aligned} K_{pz} &= 1/[K_{cz} K_{ez} (T_{sopz} + T_{zm})] \\ &= 1/[3.2 \times 2 \times (10.8 + 13.5)] \\ &= 0.00643 \end{aligned}$$

$$\begin{aligned} K_{pz}^* &= \text{Int}(1638 K_{pz}) \\ &= \text{Int}(1638 \times 0.00643) \\ &= 10 \end{aligned}$$

iii). Engineering unit conversion constants: Since the control cards control position and speed by the unit of encoder pulses. These have to be converted to engineering units for the convenience of operation. For the present application they were converted to mm for position and mm/s for speed.

For x and y axis encoders, Since

$$\begin{aligned} \text{Position resolution: } 1/K_{xy} &= \text{Lead screw pitch} / \text{Encoder lines} \\ &= 5 \text{ (mm/rev)} / 1000 \text{ (pulses/rev)} \\ &= 5 \text{ micron/pulse} \\ &= 0.005\text{mm/pulse} \end{aligned}$$

the engineering unit conversion constant (encoder constant) can be found to be:

$$K_{xy} = 200 \text{ pulses/mm}$$

For z axis since

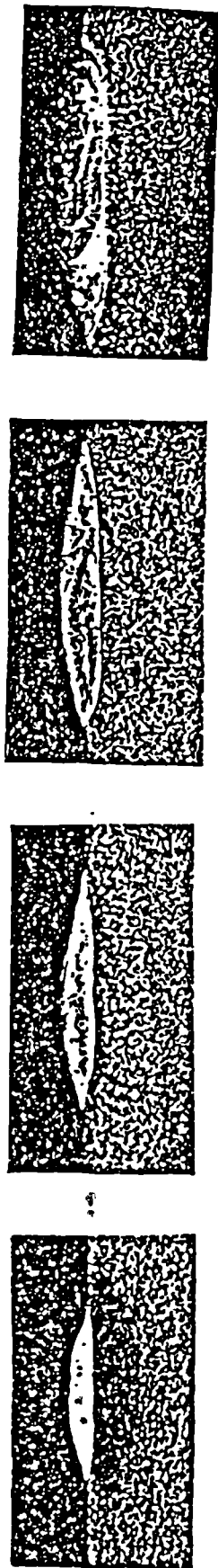
Linear position sensing resolution:

$$\begin{aligned} 1/K_{ez} &= \text{Gear ratio} \times \text{rack pitch} \times \text{No. of teeth per rev for the pinion} \\ &/ \text{Encoder constant} \\ &= 0.01 \times 2(\text{mm}) \times 25 / 1000 \\ &= 0.5 \text{ micron/pulse} \\ &= 0.0005\text{mm/pulse} \end{aligned}$$

the engineering unit conversion constant can be found to be:

$$K_{ez} = 1/0.0005 = 2000 \text{ pulses/mm}$$

iv). Software limits: Software limits were set 2 mm before the + direction mechanical limits: i.e. +193mm for x axis, +238mm for y axis and +53mm for z axis. The motion command will not be executed if the absolute positions exceed these values.



	R.T	200°C	400°C	750°C
Width(mm)	2.426	3.450	4.266	4.435
Height(mm)	0.319	0.493	0.601	0.785
Dilution	15%	40%	45%	50%

with all the other conditions (laser power, powder flowrate and traverse speed) same

APPENDIX B. Effect of Substrate Temperature on Single Clad Bead⁽¹⁹⁷⁵⁰⁾

APPENDIX C

KNOWLEDGE/DATA BASE FOR LASER CLADDING QUALITY CONTROL

Three types of relational matrices or tables are given:

1. Relational matrix for clad faults recognition.
2. Relational matrix for laser cladding problem diagnosis.
3. Relational matrix for laser cladding quality control decision making.

In the tables the following symbols are used:

Sa:	The signal average of the photo-diode melt pool thermal detector
Smax:	Upper limit in the quality control band using the thermal radiation detector
Smin:	Lower limit in the quality control band using the thermal radiation detector
σ:	Standard deviation of the thermal radiation sensor signals
σ_{max} :	Maximum allowed clad roughness expressed in standard deviation
Tsd:	Signal symptom lasting time
Tmax:	A time limit for the distinguish of temporary faults and lasting faults
H:	Clad bead height
Hr:	Desired bead height
W:	Clad bead width
Wr:	Desired bead width
Sym:	Clad bead symmetric parameter (See Chapter 9)
Asp:	Aspect ratio
Ar:	Desired aspect ratio
Xox:	Size of oxidation zone
Oxm:	Maximum allowed oxidation zone size
DI:	Dilution level
DIr:	Maximum allowed dilution

Table C.1. Relational matrix for clad faults recognition.

Sensor Clad signals faults	PHOTO-ODDE RADIATION DETECTOR						BEAD PROFILE SENSOR						DILUTION SENSOR	
	1 Sa>Smax	2 Sa<Smin	3 α>α _{max}	Tsd>Tmax			H>Hr	H<Hr	W>Wr	W<Wr	Sym>0.4	Asp<Ar	Xox>Oxm	Di>Dlr
				1	2	3								
poor bond	0.5	-0.6	0.5	0.3	0.3	0.3	0.3	-0.3	0.2	-0.2	0	0	0	-0.9
rough clad	0.3	0	1	0	0	0.3	0.2	0.2	0.2	0.2	0	0.2	0	0
disconti- nuous	0.3	0.3	0.4	0	0.2	0	0.3	0.3	0.3	0.3	0	0.3	0	0
surface oxidation	-0.2	0.2	0	0	0	0	-0.1	0.1	-0.1	0.1	0	0.1	1	0.3
porosity	0.4	-0.8	0.5	-0.2	0.2	0.2	0	0	0	0	0.2	0.6	0	0
clad deform	0.4	-0.7	0.2	-0.2	0.2	0.2	0	0	0	0	0.1	0	0	0.1
unsymmetric bead	0	0	0	0	0	0	0	0	0	0	1	0.1	0.1	0.1
hole	0.3	-0.3	0.3	-0.1	0.1	0.1	0.2	-0.1	0.1	-0.1	0	0	0	0
high dilution	-0.7	0.6	0	0	0.4	0	-0.2	0.2	0	0	0.1	0	0.2	1
high HAZ	-0.5	0.5	0	0	0.4	0	0	0.1	0.1	0	0.1	0	0.8	0.9
clad too thick	0.8	-0.8	0.2	0.2	0	0	1	-1	0.4	-0.3	0	0.3	0	-0.1
clad too thin	-0.8	0.8	0	0	0.2	0	-1	1	-0.1	0.1	0	-0.4	0	0.2
bead too wide	0.6	-0.6	0	0.2	0	0	0.1	-0.1	1	-1	0	-0.4	0.1	0
bead too narrow	-0.6	0.6	0	0	0.2	0	-0.1	0.1	-1	1	0	0.5	-0.2	0.1

Table C.2. Relational matrix for laser cladding problem diagnosis.

clad faults + causes / operating conditions	poor bond	rough clad	disconti- nuous	high oxidation	interrun porosity	clad deform	unsymetric bead	hole burning	high dilution	high HAZ	clad too thick	clad too thin	bead too wide	bead too narrow	no clad formation	LBA signal poor	nozzle hot
laser powder misalignment	0.6	0.4	0.4	0	0.2	0.1	0.7	0.1	0.3	0.3	-0.2	0.5	-0.3	0.5	0.4	0.1	0.1
nozzle/chipping	0.6	0.3	0.3	0	0.2	0.1	0.4	0.1	-0.1	0.1	0.2	0.5	0.3	0.4	0.5	0.1	0.9
lens cracking	0.6	0.2	0.2	0	0	0.1	0.1	0.1	0.3	0.3	0.5	0.6	0.6	0.2	0.7	0	0.2
poor beam mode	0.4	0.2	0.1	0.2	0.2	0.1	0.6	0.4	0.4	0.4	0.1	0.1	-0.2	0.3	0.2	0.9	0.1
laser power unstable	0.2	0.5	0.2	3	0	0.3	0	0.2	0	0	0.1	0.1	0.1	0.1	0.1	0.5	0
laser power too high	-0.8	0	-0.3	0.3	0	0	0	0.4	0.6	0.7	-0.4	0.1	0.2	-0.2	-0.4	0.3	0
laser power too low	0.7	0.3	0.3	-0.3	0	0	0	-0.4	-0.6	0.6	-0.3	0.3	-0.4	0.4	0.5	0.3	0
lens protecting gas too much	-0.1	0.3	0.4	0	0	0	0.2	0	0.2	0.1	-0.2	0.3	0	0.2	0.6	0	-0.2
dome d rty	0	0	0	0	0	0	0	-0.2	0.1	0.1	0	0.1	0	0.1	0.2	0	0.3
shroud fail	0	0	0	-0.9	0	0	0	0	0	0	0	0	0	0	0	0	0
faulty substrate	0.1	0	0.2	0	0	0.7	0.5	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0.1	0	0.1
substrate temperature too high	-0.3	0	-0.2	0.1	0	0	0	0	0.6	0.7	0.5	-0.2	0.5	-0.2	-0.2	0	0.2
powder feed unstable	0.2	0.1	0.3	0	0.4	0.7	0	0.1	0.2	0.2	0.2	0.2	0.1	0.1	0.1	0	0
powder flowrate too high	0.7	0.5	0.5	-0.1	0.6	0.3	0	0.3	-0.8	0.1	0.9	0.5	0.2	0.2	0.4	0	0
powder flowrate too low	-0.6	0	0	0.1	-0.6	-0.1	0	0.2	0.8	0.7	0.9	0.9	0.2	0.2	0.4	0	0
powder velocity too high	-0.2	0	0	0.1	-0.2	0.1	0	-0.1	0.2	0.2	0.8	0.5	0.2	0.4	0.8	0	0
powder velocity too low	0.6	0.4	0.4	-0.1	0.4	0.2	0	0.2	-0.2	-0.2	0.4	-0.3	0.2	0.1	-0.2	0	0
powder feed fa	0.4	0	0.3	0	0	0.3	0	0	0.5	0.5	0.3	0.7	-0.4	0.6	0.7	0	0
traverse speed too high	0.2	0	0.3	0.1	-0.1	0.1	0	-0.2	-0.1	0.1	0.9	0.7	-0.7	0.9	0.3	0	0
traverse speed too low	0	0	-0.3	0.1	0.4	0.2	0	0.2	0.1	0.6	0.8	0.7	1	0.9	0.4	0	0
traverse fail	0	0	0.3	0	0	0.6	0	0.3	0	0.3	0.7	1	0.5	1	-0.8	0	0
spot size too small	0.1	0	0.4	0	0.2	0.1	0	0.1	0.4	0.1	-0.2	0.2	-0.6	0.6	0.4	0.4	0
overlap too much	0	0.1	0.2	0	0.9	0.1	0.1	0.1	0.8	0.1	0.7	0.7	0	0	0	0	0
overlap too low	0	0.1	0	0	0.1	0	0	0.1	0	0	0.3	0.3	0	0	0	0	0

Table C.3. Relational matrix for laser cladding quality control decision making.

problems actions	laser/powder misalignment	nozzle/ clipping	laser cracking	poor beam mode	laser power unstable	laser power too high	laser power too low	laser power gas too much	laser protecting dirty	shroud fail	faulty substrate	substrate temperature too high	powder feed unstable	powder flow rate too high	powder flow rate too low	powder velocity too high	powder velocity too low	powder feed too high	traverse speed too high	traverse speed too low	traverse fail	spot size too small	overlap too much	overlap not enough	Qp not control- lable	Qnozzle not control- lable
alarm and stop oper- ating	0.8	1	1	0.4	0.4	0.2	0.2	0.5	0.4	0.6	0.3	0.3	0.4	0	0	0.3	0.3	1	0	0	1	0.5	0	0	0	0
recal- for post processing	0	0	0	0	0	0	0	0	0	0	0.7	0.4	0.5	0	0	0	0	0	0	0	0	0.2	0	0	0	0
increase P	-1	-1	-1	0	0	-1	1	0	0.3	0	0	-0.4	0	0.3	-0.3	-0.2	0.2	-0.8	0.1	-0.1	-1	0	0	0	0	0
reduce P	0.5	0.5	0.5	0	0	1	-1	0	-0.2	0	0	0.4	0	-0.3	0.3	0.2	-0.2	0	-0.1	0.1	0	0	0	0	0	0
increase V	0	0	0	0	0	0.2	-0.2	0	-0.1	0	0	0.6	0	0.2	0.2	0.2	0.2	0	-1	1	0	-0.8	0	0	0	0
reduce V	0	0	0	0	0	0.2	0.2	0.1	0.1	0	0	-0.6	0	-0.2	0.2	0.2	-0.2	0	1	-1	0	0.8	0	0	0	0
increase M	0	0	0	0	0	0.2	0.2	0.2	0	0	0	0	0	-1	1	0.6	0.6	0	0.3	-0.3	0	0	0.3	0.3	0	0
reduce M	0	0	0	0	0	-0.2	0.2	-0.2	0	0	0	0	0	1	-1	-0.6	0.6	0	0.3	0.3	0	0	-0.3	-0.3	0	0
increase I	0	0	0	0	0	0	0	0	0	0	0	-0.2	0	-0.1	0.1	-0.1	0.1	0	0.1	0.1	0	0	-1	1	0	0
reduce I	0	0	0	0	0	0	0	0	0	0	0	0.2	0	0.1	-0.1	0.1	-0.1	0	-0.1	0.1	0	0	1	1	0	0
increase Qp	0	0	0	0	0	0	0	0	0	0	0	0	0.3	0.2	-0.2	-0.5	0.5	0	0	0	0	0	0	0	0	0
reduce Qp	0	0	0	0	0	0	0	0	0	0	0	0	-0.3	-0.2	0.2	0.5	-0.5	0	0	0	0	0	0	0	0	0
increase nozzle gas	0	0.3	0.4	0	0	0	0	-0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
reduce nozzle gas	0	0	0.3	0	0	0	0	0.5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
alarm only	0.9	0.9	0.9	0.5	0.6	0.2	0.2	0.4	0.5	0.4	0.5	0.1	0.6	-0.1	-	0.5	0.5	-0.3	0.1	1	-0.3	0.5	5	0.5	0.5	5

APPENDIX D

BANACH CONTRACTION THEOREM AND KALMAN-BERTRAM STABILITY CRITERION

D.1 BANACH CONTRACTION THEOREM^[168]

The Banach's contraction theorem can be stated as:

For an operation $F(x)$, if

$$\| F(x_1) - F(x_2) \| \leq \alpha \| x_1 - x_2 \|$$

$$x_1, x_2 \in X \subset \mathbb{R}^n \text{ and } 0 < \alpha < 1$$

then there exists in the whole space, X , only one point, x_s , such that

$$x_s = F(x_s)$$

This point is called a fixed point of the operation $F(x)$ and operation itself is called contraction.

D.2. KALMAN-BERTRAM STABILITY CRITERION^[168]

The Kalman-Bertram stability criterion can be stated as:

If $F(x)$ is a contraction for all $x \in X$ then the system under such operation is asymptotically stable.

APPENDIX E

FIBONACCI SEARCH AND GOLDEN SECTION METHODS FOR OPTIMIZATION

Since the optimum control gain search method discussed in Chapter 11 for the adaptive control of laser cladding was developed by the modification of Golden Section method which is a special case of the Fibonacci method. Here these two methods are briefly described for the convenience of the reader who is not familiar with them. At the same time differences between the optimum control gain search and the Golden Section method will be given.

E.1. FIBONACCI SEARCH [161]

If the objective function $f(z)$ is unimodal in a search zone $[a, b]$, i.e. it has only one optimum point (Maximum or Minimum) in the zone then the search procedure will be:

1. Chose two points x_1 and x_2 in the zone $[a, b]$ so that

$$z_1 = a + (b-a) F_{n-2}/F_n \quad (E-1)$$

$$z_2 = a + (b-a) F_{n-1}/F_n \quad (E-2)$$

where n is the total iteration number required for search and F_i is the Fibonacci number which is defined as:

$$F_i = \frac{1}{\sqrt{5}} \left[\left(\frac{1+\sqrt{5}}{2} \right)^{i+1} - \left(\frac{1-\sqrt{5}}{2} \right)^{i+1} \right] \quad (E-3)$$

e.g. $F_0 = 1, F_1 = 1, F_2 = 2, F_3 = 3, F_4 = 5, F_5 = 8, F_6 = 13, F_7 = 21, F_8 = 34 \dots$

$$\text{i.e.} \quad F_n = F_{n-1} + F_{n-2} \quad (E-4)$$

2. Examine the objective function $f(z)$ at z_1 and z_2 and abandon the point which produces objective function further from the optimum (Maximum or Minimum). If, say, $f(z_1)$ is abandoned then the new uncertainty interval will be in $(z_1, b]$. It can be shown [163] that the new, reduced interval is

$$b - z_1 = a - z_2 = (b-a) F_{n-1}/F_n \quad (E-5)$$

3. Continue the procedure in the new, reduced interval for the following $n-1$ step. The interval reduction rate for each new step i can be shown to be:

$$F_n - (i+1) / F_n - (i-1) \quad (E-6)$$

i.e. the final interval will be (when $i=n$)

$$(b-a) / F_n \quad (E-7)$$

If, say, $n=11$ then $F_{11} = 144$. According to Eqn.(E-7) the interval will be reduced to <1% of the original size.

In this method, the number of search step has to be pre-determined, which also defines the search accuracy. This condition is eliminated by the modified Fibonacci search (Golden section search).

E.2. GOLDEN SECTION METHOD [162]

Since the interval reduction rate in the Fibonacci search can be expressed as:

$$F_{n-(i+1)} / F_{n-(i-1)} = F_{i-2} / F_i \quad (E-8)$$

it can be seen that when $i > 4$ the ratio is very close to 0.382. Actually, when $i \rightarrow \infty$ the ratio is 0.382.

If this ratio is used for the reduction of search zone then the search interval will be reduced to $(0.618)^n$ of the original size after n steps. This number 0.618 or 0.382 was considered as "magic" number for the ancient Greeks and was used for the gold separation, architecture design etc. The procedures for the modified Fibonacci search can be summarized as:

1). For an interval $[a, b]$ the first two points to be examined are:

$$z_1 = a + 0.382(b-a) = 0.618a + 0.382b \quad (E-9)$$

$$z_2 = b - 0.382(b-a) = 0.382a + 0.618b \quad (E-10)$$

2). Abandon the points which is further from the optimum point (Maximum or Minimum) and reduce the search interval to:

$[a, z_2]$ if z_2 is abandoned

$[z_1, b]$ if z_1 is abandoned

3). Continue the search until the optimum is found.

If, say, 6 steps are used then the interval will be reduced to $(0.618)^6 = 0.05 = 5\%$ of the original size. i.e the zone size is reduced in the rate of 0.382.

The adaptive optimum control gain search method developed in Chapter 11 differs from the Golden Section method in the following aspects:

i). The objective function for optimum control gain search is not a maximum or minimum problem as used in the golden search method. A series of diagnostic rules were used instead.

ii). The adaptive control gain search requires the search of the optimum point in an indefinite zone while the Golden Section method requires a pre-defined search zone.

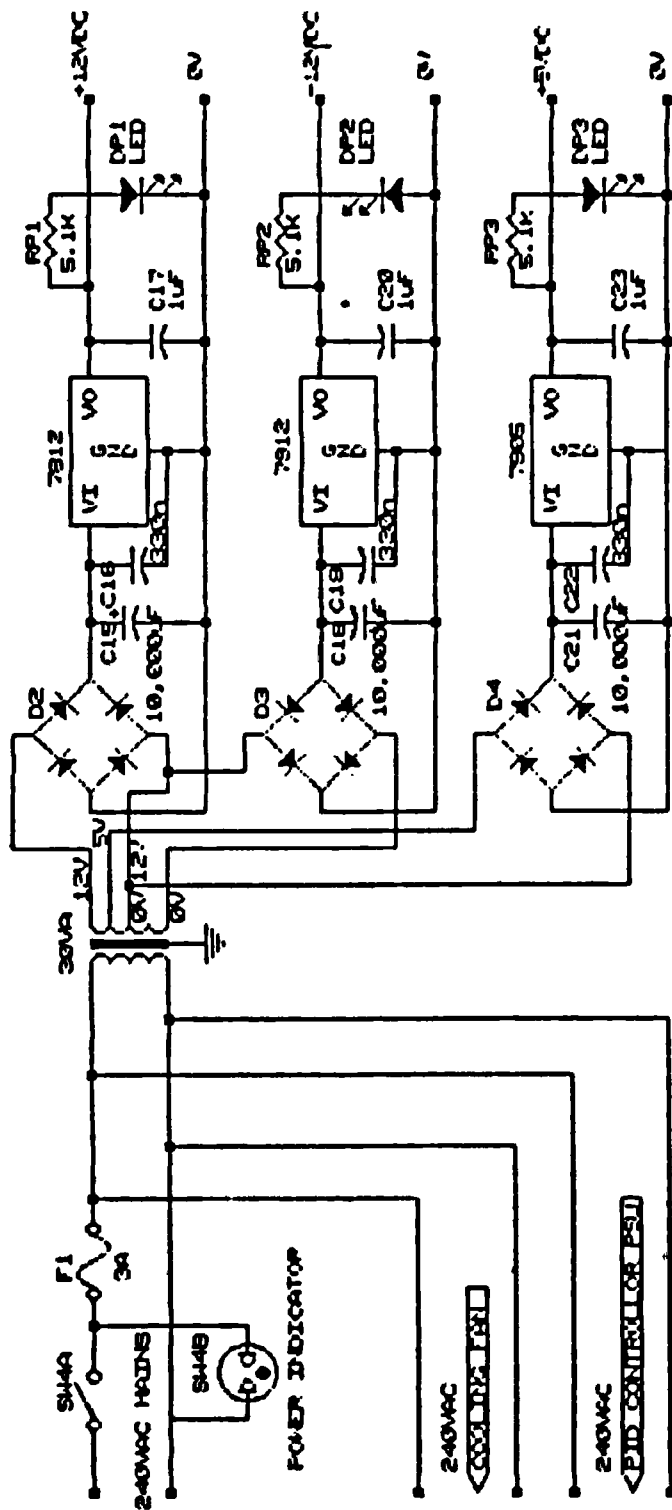
iii). Single point evaluation was used for optimum control gain search, while the Golden Section method requires two points at the same time to decide the next move.

iv). In the Golden Section method the search zone reduces at the fixed rate of 0.382, while for the optimum control gain search method the un-certainty zone reduces by either 0.382 or 0.618 depending on the system performance. Therefore the optimum control gain search is generally faster than the Golden Section method.

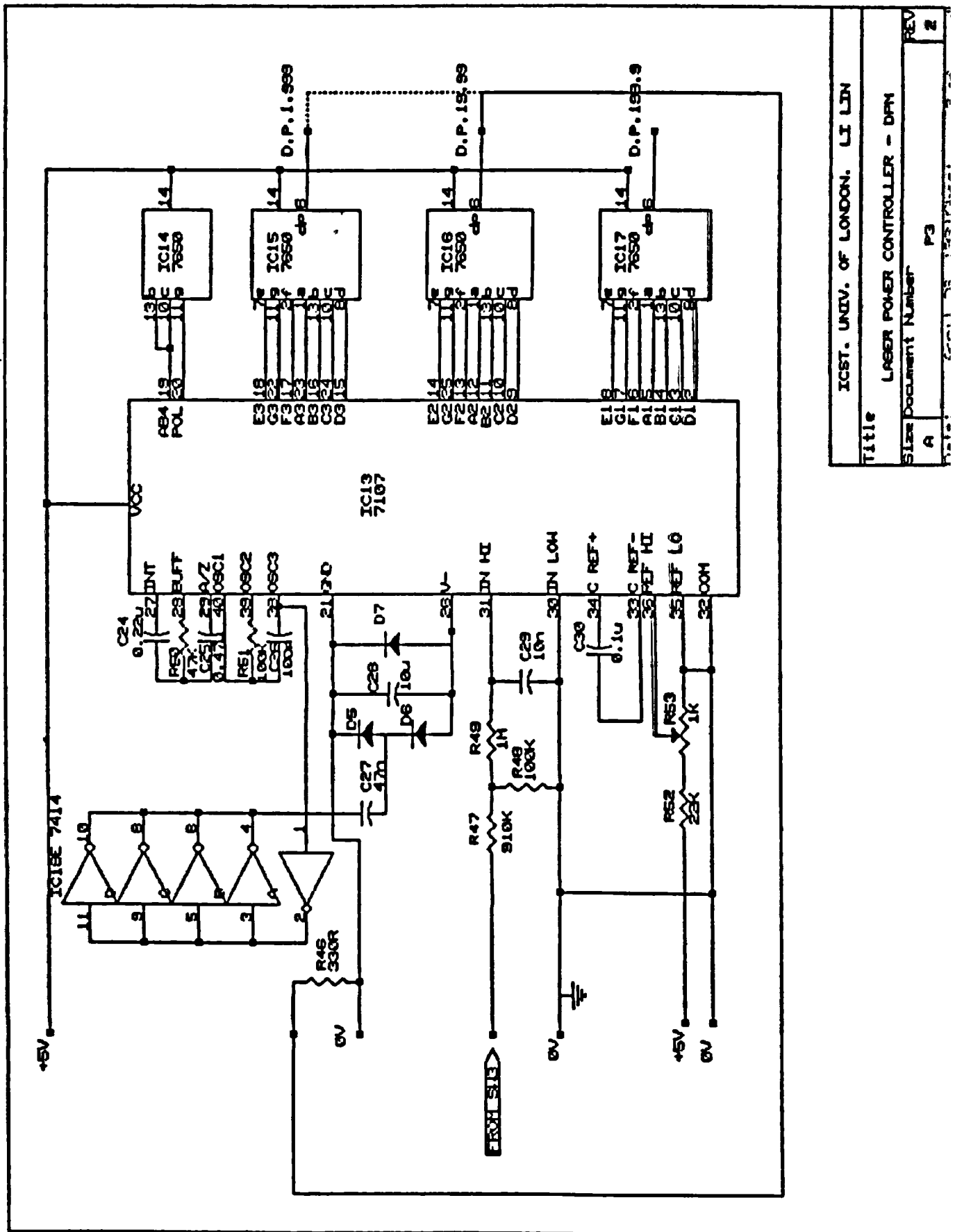
v). The optimum control gain search is dynamic and flexible, which tracks the moving optimum point, while the Golden Section method is static, which can only find the fixed optimum point.

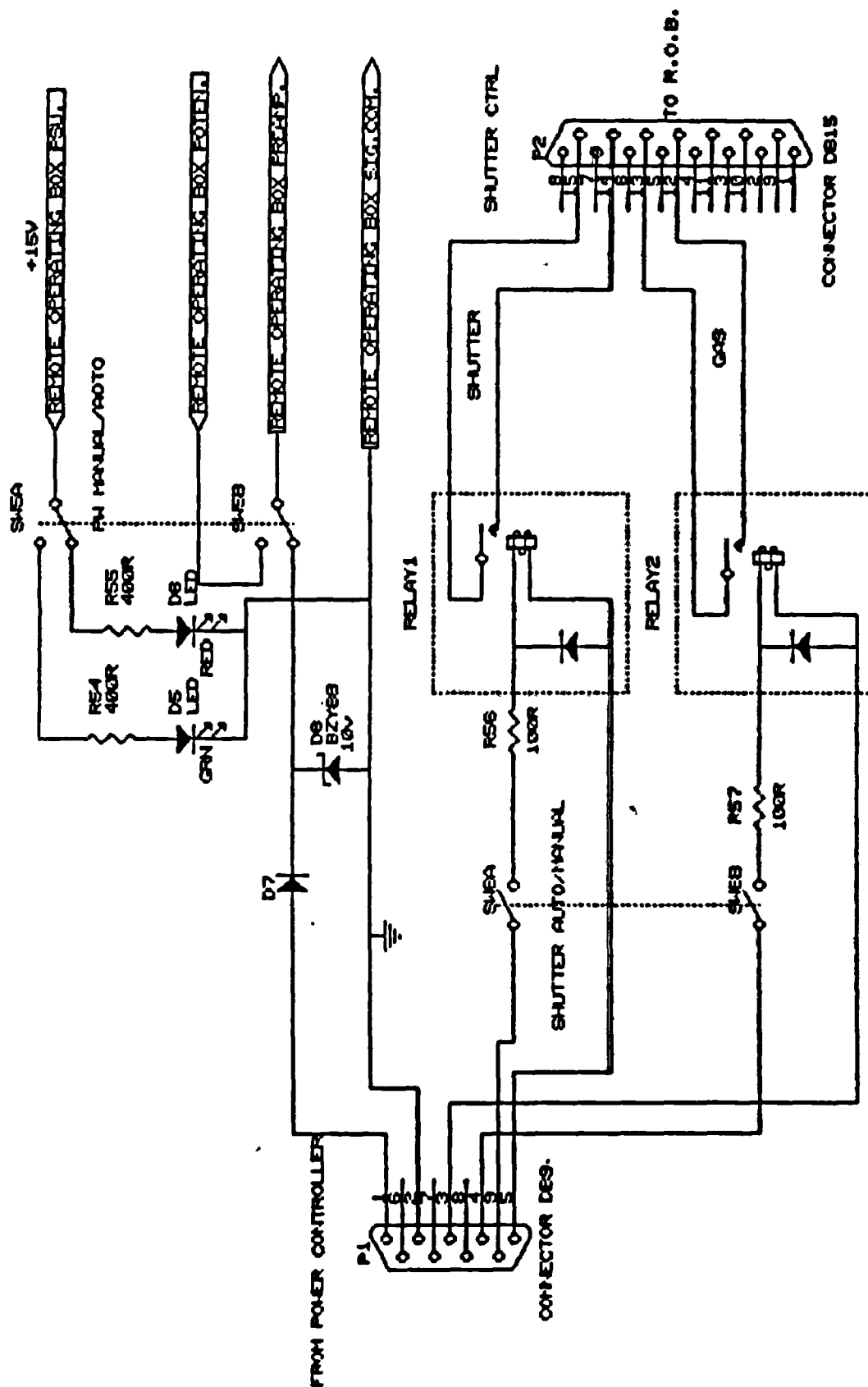
APPENDIX F

LASER POWER CONTROL CIRCUIT DIAGRAMS



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