

ENERGY CONSUMPTION AND NOISE GENERATION
IN THE IMPACT CUTTING OF POLYMERS

by

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ABSTRACT

Although a considerable amount of research has been undertaken on the size reduction of mineral materials, very little fundamental work has been reported on the treatment of more ductile materials, such as polymers. The distinction is important because ductile materials are normally comminuted more by cutting than by crushing or grinding.

The process of size reduction of polymeric material is known as the granulation process, and the machinery used is called the granulator. The machine is basically simple with very little research work having been done so far into its operation characteristics.

To obtain a higher performance from such a machine, the effects of varying several operating and geometric parameters have been studied experimentally in terms of their influence on energy absorbed in cutting polymers and the associated noise levels. To carry out such an investigation, specific designs for high speed testing machines were produced and patented.

Test results provided an insight into and understanding of the cutting mechanisms of polymeric materials in a granulator at speeds of cutting up to 40 metres/second,

besides determining the optimum operating conditions of the machinery for lower power consumption and lesser noise levels.

ORGANISATIONAL SUMMARY OF THE THESIS

This thesis is divided into 11 chapters, followed by machine drawings and publications. In Chapter 1 the commercial importance of granulation of polymeric materials is discussed. Types, design and operation of granulators, and kinematics of the cutting process are presented. Problems facing granulator manufacturers are presented and discussed. Finally, an experimental procedure to be described in the subsequent chapters is designed to provide data which will contribute to the establishment of optimum operating conditions for the machinery.

Chapter 2 of the thesis summarises briefly a review of the most relevant literature concerned with the cutting of polymer materials.

In Chapter 3 the need is discussed for a suitable high speed simulator to be specifically designed for a full investigation of the cutting process in polymer granulators. To satisfy this need a fully controlled high speed testing machine was developed. Designs to modify the testing machine to be used for conventional impact and tensile testing are also given.

In Chapter 4 traditional methods for velocity measurements are discussed and design details of instrumentation to control the operation of the testing machine and provide test data are presented.

Chapters 5,6,7 and 8 contain the experimental work. Chapter 5 deals with the experimental investigation of the effect of various cutting parameters on the energy required to cut at room temperatures. Tests were carried out on seven different polymers. It is found that all the polymers show a strong speed dependence and the nature of dependency falls into two types. Conditions for minimum cutting energies have been determined. Chapter 6 deals with the experimental examination of the effect of varying the test temperature over a wide range ($-45 - 100^{\circ}\text{C}$) on cutting energy. Test results showed that thermal effects are important in the cutting process. Chapter 7 deals with the measurements of noise levels generated in cutting at room temperature. It was found that conditions for low noise levels are also those for low cutting energy. Chapter 8 deals with the micrographic study of cut surfaces. This study was carried out using a scanning electron microscope. Micrographs of cut surfaces are presented and results are discussed.

Chapter 9 deals with the attempt to explain firstly that the cutting mechanism at impact speed is not shear but a fracture process, i.e. a notching process followed by a splitting action leading to crack propagation. Secondly, that thermal effects play a major role in the cutting process and the form of the curves obtained (energy versus blade speed) is due to these effects.

General conclusion and recommendations for running the polymer granulator are given in Chapter 10.

Chapter 11 contains information and details of the testing machine design calculations.

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10. Sensors Guide Pins
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11. Speed Sensors Supporter
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13. Enclosure Base

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1. Noise Generation in Polymer Granulators,
D.P. Isherwood, H.R. Younan and R.C. de Wardt,
P.R.I. Health and Safety Conf. York, April 1984.
2. Impact Cutting Energies of Polymers, D.P. Isherwood
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3. Some Studies on Polymer Granulators, D.P. Isherwood,
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J. Polymer Testing.

NOTATION

A	: cross sectional area of the rotating arm
B	: specimen thickness
C	: clearance between blades
D	: drag coefficient
E	: modulus of elasticity
F	: output frequency of control and revolution counter sensor
F_r	: output frequency of the comparator oscillator
$\bar{F}$	: total drag force
G	: modulus of shear
H	: strain energy
J	: Joule
K	: vane length
l	: length of the arm spindle
L	: length of specimen to be cut
$\bar{L}$	: length of the rotating arm
P	: power to overcome drag force
r	: radius of the arm spindle
r_1	: radius of rotating blade tip (sharpness)
r_2	: radius of fixed blade tip (sharpness)
R	: radius of the cutting circle = total length of the rotating arm
S	: maximum strain energy of shear
t	: chord length of the arm

T_1	: measured time before impact
T_2	: measured time after impact
U	: energy absorbed in cutting
$\bar{U}$	: relative air velocity
V	: blade speed
V_1	: blade speed prior to impact
V_2	: blade speed after impact
w	: rotational speed
W	: specimen width

Greek Symbols

α	: rotating blade angle of attack
β	: bed blade cutting angle
γ	: rotating arm angle of attack
δ	: total elongation of the rotating arm
θ	: rotating blade cutting angle
μ	: micron
ν	: Poison's ratio
ρ	: density of steel
$\bar{\rho}$	: density of air
$\sigma_{\max}$	: maximum yield stress
$\bar{\sigma}_{\max}$	: maximum tensile stress
$\tau_{\max}$	: maximum shear stress

ABBREVIATIONS

ABS	:	acrylonitrile-butadiene-styrene
HDPE	:	high density polyethylene
HIPS	:	high impact polystyrene
M HZ	:	megahertz
LDPE	:	low density polyethylene
PC	:	polycarbonate
PMMA	:	poly(methyl methacrylate)
PP	:	polypropylene
PS	:	polystyrene
PTFE	:	polytetrafluoroethylene
PVC	:	polyvinyl chloride
r.p.m	:	revolution per minute
SEM	:	scanning electron microscope
UP	:	unsaturated polyester

CHAPTER 1

INTRODUCTION

1.1 POLYMERIC MATERIALS

Synthetic large molecules are made by joining together thousands of small molecular units known as monomers. The process of joining the monomers together is called polymerization. The polymer is the pure material which results from the process of polymerization. The term 'plastic' is applied when additives such as stabilizers, lubricants, pigments etc... are added to enhance the properties of the material. Synthetic polymers derive mainly from crude oil after its cracking into naphtha (1).

Various processing methods adopted for the conversion of polymeric raw material into finished articles, have been developed to exploit the ability of the material to flow under the influence of heat and pressure. The most common methods are: injection moulding, extrusion, blow moulding, calendering, film blowing and compression moulding.

Industry adopted the name 'plastics' in the late 1920s, when the formability of these compositions, while in their plastic state, was thought to be their most important feature (2).

The decade 1930-40 saw the initial industrial development of today's major polymers (3): Polystyrene, Polyvinylchloride, Polyolefins, Polymethylmethacrylate and Nylon. A tremendous boost was given to the industry by the Second World War, with its heavy drain on conventional materials together with many new technological problems which had to be solved by the use of plastics. The industry has continued to expand in both the range and the volume of plastics produced throughout the world. Table 1.1 shows the production and consumption of some important polymers in western Europe, Japan and the United States during 1983-4 (4), while Fig. 1.1 shows prices per tonne for major polymers (5).

In many applications, plastics are replacing metals and other more conventional materials, while in others, they are leading to new products based on their special properties. Fig. 1.2 shows the anticipated usage of plastics in cars produced by Ford during the 1980s and early 90s (6). Ford also claims that the Sierra (1985) has already achieved a total plastic usage of 100 Kg, which is equivalent to more than 10% of the total vehicle weight.

1.2 SIZE REDUCTION OF POLYMER PROCESSED SCRAP

In the plastics industry, the price of the raw material is a major factor in the cost of the final product, and reuse of any recoverable materials such as reject products

		W Europe	Japan	U.S.A
LDPE	production	4413	1085	3647
	apparent consumption	3851	1562	3309
HDPE	production	1877	688	2581
	apparent consumption	1632	-	2061
PP	production	1999	1062	2011
	apparent consumption	1631	969	1663
PS	production	1377	1311	2051
	apparent consumption	1201	1166	1993
PVC	production	3725	1420	2752
	apparent consumption	3481	1437	2652

Table 1.1: Production and Consumption of Some Important Polymers in Western Europe, Japan and the United States, during 1983-84.
(Figures in Thousands of Tonnes).

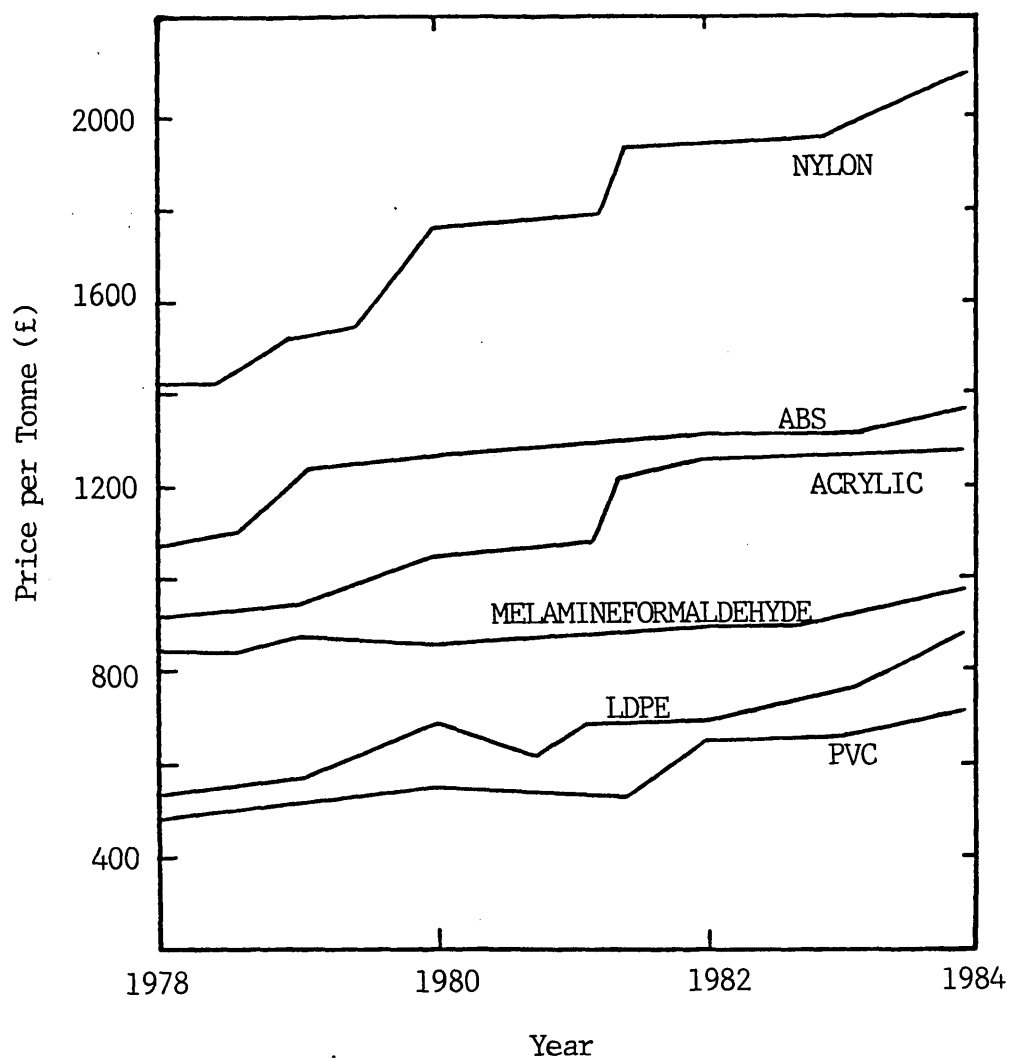


Fig. 1.1: Prices per Tonne for Some Important Polymers.

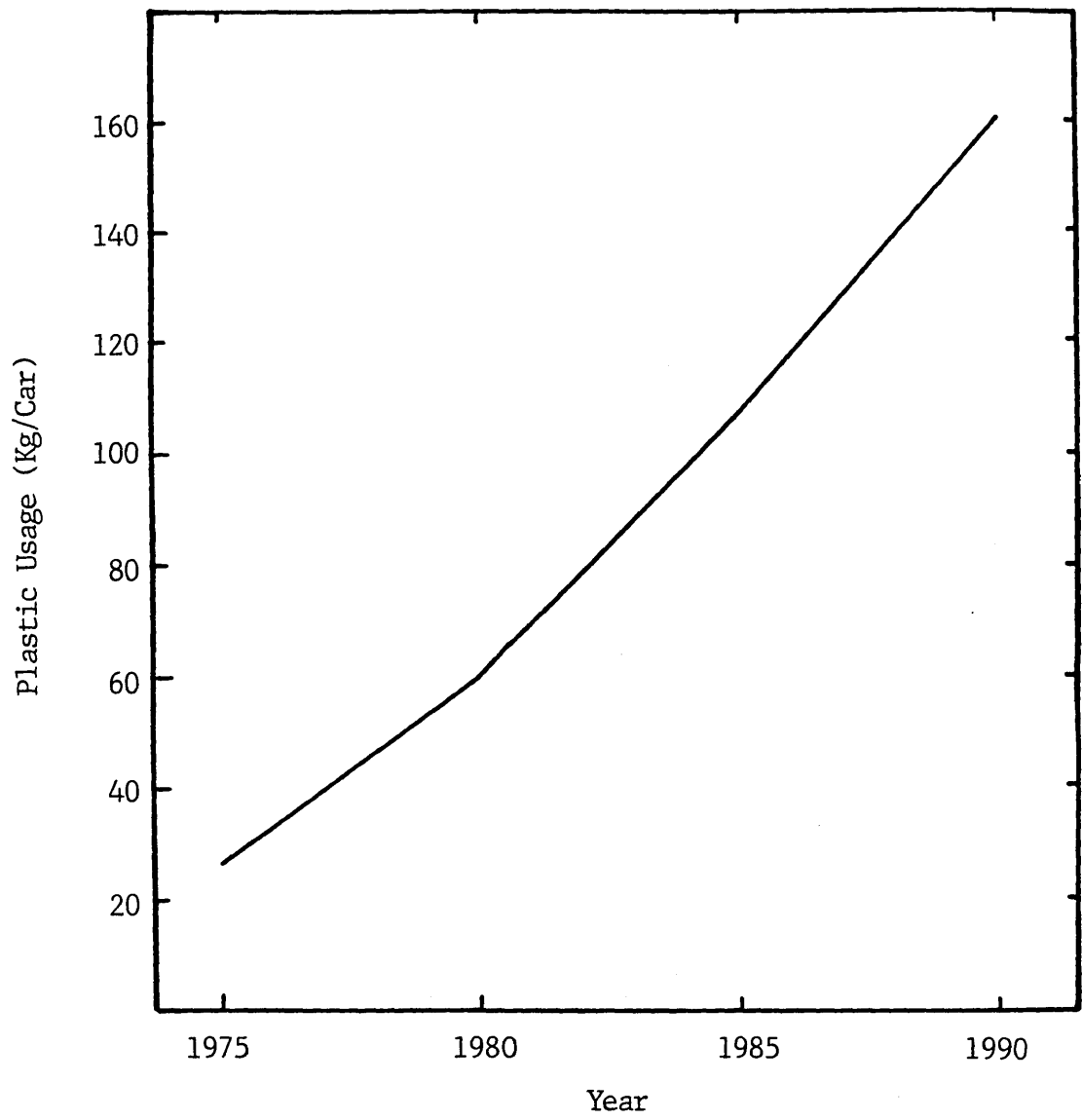


Fig. 1.2: Anticipated Usage of Plastics in Ford Cars.

is an economic necessity. The polymer granulator is designed basically for the recovery of waste materials, which are produced in large quantities in most polymer processing operations. The machine is used to reduce the size of the scrap by cutting rather than crushing or grinding, to small granules which can then be reprocessed. It is therefore one of the most common machines found in the polymer processing industry.

1.2.1 The Importance of Granulation of Polymeric Materials

Granulation of polymeric materials is of considerable commercial importance. In most polymer manufacturing processes, the average scrap production from general processing is 10-15% of total production. To consider particular cases: in injection moulding of small detailed components, such as seals, gears, washers etc... the scrap produced can be as high as 70% of the polymer used, and in the extrusion of large bore piping, the scrap from the rejected and the initial and final sections of the run can be 40-50%. With the cost of polymer raw materials ranging from £600/Tonne for Polypropylene to £1300/Tonne for acrylic powder (Fig. 1.1), it is worthwhile to evaluate carefully the costs of granulating the scrap into a suitable form for recycling. The costs to be considered are:

- the cost of collecting the scrap material without contamination.

- the cost of granulating the scrap material to appropriate size.
- the cost of handling the granulated material in the plant.
- the cost of storing the granulated material.

The cost of collecting scrap material is negligible. Good housekeeping in a plant demands that flash, sprues, runners, defective components etc... be collected and disposed of in some way, the cost of this collection is already built into the operation. However, the cost of granulating the material is a most important consideration: it demands labour time, capital investment and the cost of running the machinery. The granulator requires a minimum of attention on the operator's part, it is a relatively low grade job and could be charged into the operation at approximately £3.00 per hour. A typical granulator of type (28B) produced by Daniels Engineering Ltd., would cost around £15,000, its power consumption is in the range of 112 KW. hour and the power to run the machine comes to approximately £5 per hour. Assuming that the machinery depreciated over a 2 year period, for a machine operating on a single shift basis (approximately 1300 hours per year), it would cost £5.77 per hour for depreciation cost of the equipment. The granulated material must also be removed to a storage area and stored. The cost of handling the material will run at about £3.00 per hour and storage cost usually is negligible.

Based on the above analysis, it would cost approximately £15 per hour to run this machine, including labour cost, machine depreciation cost, and operating cost (excluding any overhead cost or factory burdens). Assuming the average output rate of the granulator of granulated materials suitable to be recycled is 100 Kg per hour, with the average cost of polymer material at £700 per Tonne, the granulator would salvage £70 worth of material per hour, at the same time it is necessary to invest £18 per hour, which gives a net return of around £52 per hour. On a single shift basis the average savings would be £67,000 per year for every machine used. The machine will pay for itself in pure profit in less than four months.

Even when other costs such as cleaning and maintenance of the machine are taken into account, a potential saving of £50,000 a year can be made through the reclamation of scrap from a single granulator. With the increasing cost of raw materials and the increasing cost of labour, the process of granulating the scrap of polymeric materials becomes of considerable economic value. Such savings will in turn help to keep the prices of polymer products at relatively inexpensive levels so that they remain competitive with those of alternative materials.

1.2.2 Polymer Granulator

The process of granulation implies the size reduction of pieces of polymeric material to a specified size. This process is carried out in a granulator.

Fig. 1.3 shows a typical granulator construction. The machine consists of the following main sections:

- feed system
- cutting chamber
- discharge system
- base
- drive components.

The hopper is the inlet feed system to the granulator's cutting chamber. The hopper could be fed mechanically or manually with the material. The hopper consists of the hopper body, flaps or curtains and feed tray. The idea behind providing the unit with flaps or curtains is to prevent the flyback material (which is the material that is thrown from the cutting chamber to the hopper) from leaving the granulator. The hopper can be modified to include tray magnets to prevent metals from reaching into the cutting chamber, or inspection doors to provide access to the unit for cleaning and freeing jammed material (Fig. 1.6).

The cutting chamber consists of the main frame, rotor and bearings. The rotor is equipped with fly

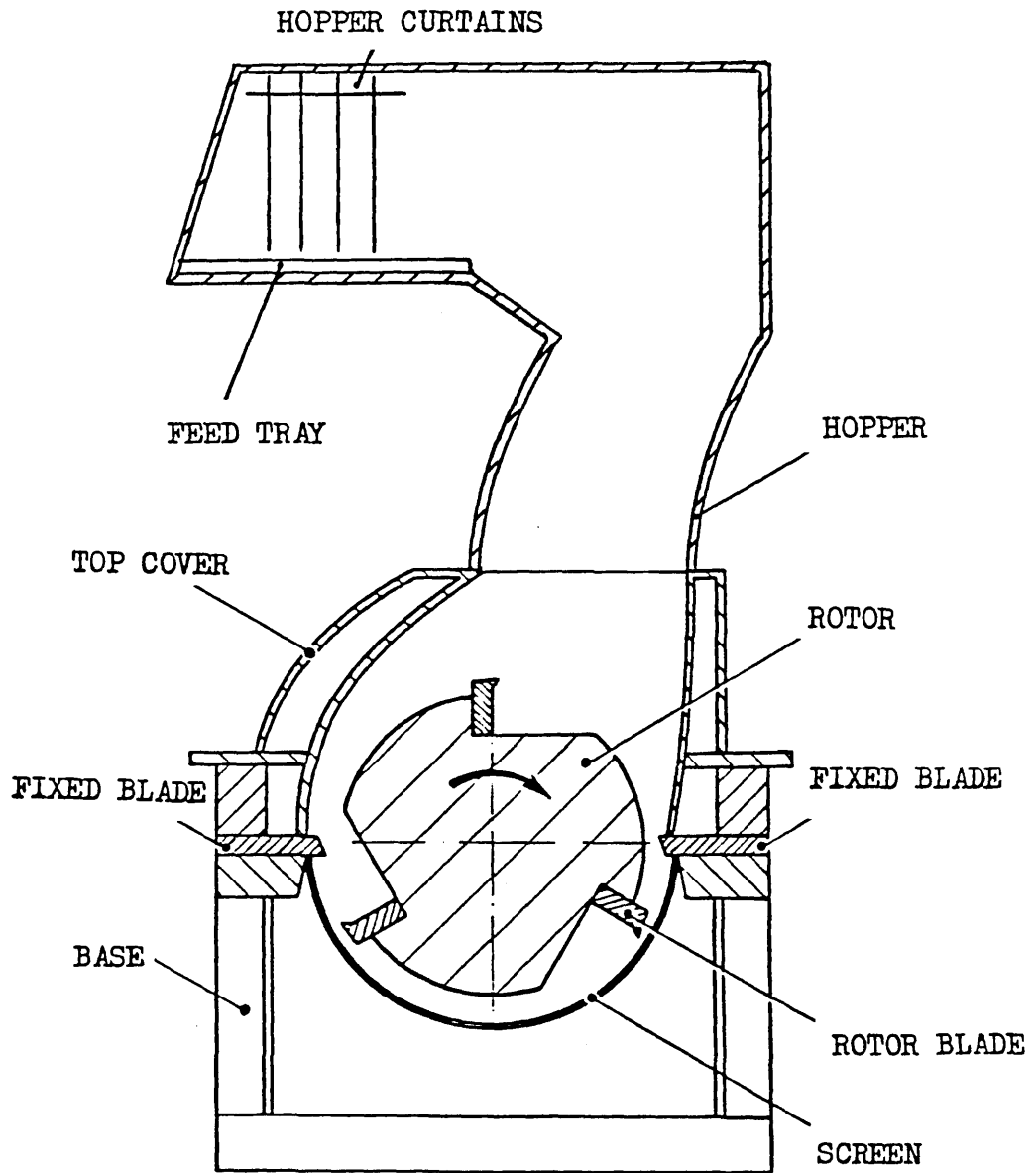


Fig. 1.3: Typical Granulator Construction.

blades and is the part of the granulator which actually does the work. The number of rotor blades can be 2,3,5 or 7, and only one blade is allowed to cut at a time. Rotors are designed to provide a specific cutting mode. Cutting mode is described as the manner in which the rotor blade passes the fixed blade. One of the more recently adopted ideas in rotor blade setting is that of having blades tilted along their length, such that the cutting action is more of a slicing action. There are two types of rotors, open and closed: a closed rotor is machined from a solid billet, while an open rotor (has a large free space available between the blade tip and centre shaft) consists of a rotor shaft with webs welded in place perpendicular to the centre line of the rotor. The closed rotor is used to granulate large thick sections of materials, while the open rotor is used in less vigorous applications.

The cutting chamber contains fixed blades (usually two blades at approximately 180 degrees to each other), whose positions could be adjusted to alter the clearance with the rotor blades. Fig. 1.4 shows the components of a typical cutting chamber.

A sizing screen is mounted to the lower side of the cutting chamber which represents the discharge system.

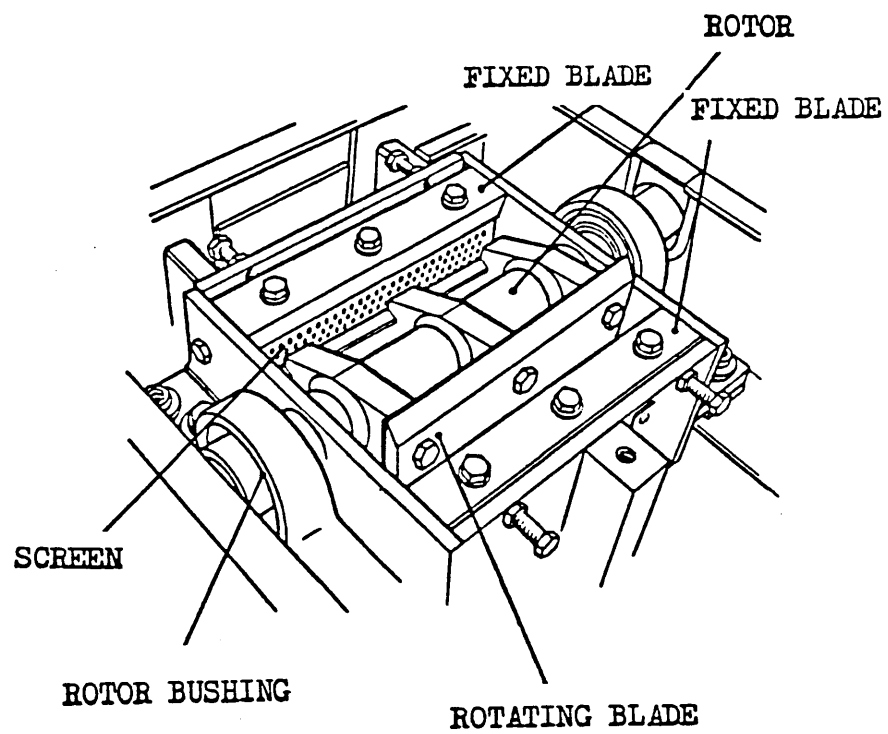


Fig. 1.4: Components of a Typical Cutting Chamber.

The cutting chamber and machine drive components are mounted on the base along with a material collection bin or a transition chute. A transition chute can be baffled to direct particles into a drum or equipped with various tubes for connection to a pneumatic system for the removal of materials.

The drive components are the motor, motor shaft and bushing, motor base, rotor fly wheel and bushing, drive belts, guard and motor controls.

1.2.3 Operation of the Granulator

The apparent method of operation of the granulator may be outlined as follows: the cutting chamber receives the feed material through the hopper, some of the material pieces would be initially dragged by the rotating blades towards the stationary blades, and others would fall between the rotating blade's gap (this depends on the size of the material pieces, number of rotating blades and the speed of rotation), where they would be pushed by the rotating parts towards the stationary blades, or would fall down to the chamber lower surface. If the sizes of the material particles are greater than the screen size and greater than the clearance between the rotating blades and the screen, these particles would be dragged again towards the bed blades.

From the above description it can be seen that:

- particles could be dragged by the rotating blades towards the stationary blades.
- particles could be positioned momentarily or trapped on the fixed blades by the random motion and action inside the chamber, as shown in Fig. 1.5.

The cutting and striking actions take place in both cases. The small particles so produced either become carried round with the rotating blades, or drop under gravity through the gap between the rotor body and stationary blades. If these particles are still too large to pass through the screen, they must be swept round to be further reduced in size. For a particular particle, the granulation process is complete when the particle arrives at the screen plate small enough to pass through.

1.2.4 Types of Granulators

There are many different types of granulators. Granulators can be divided into the following categories:

- light duty machines which have a power rating of up to 30 KW. These machines recover general scrap with 6 mm wall thickness. They are usually hand fed and emptied.

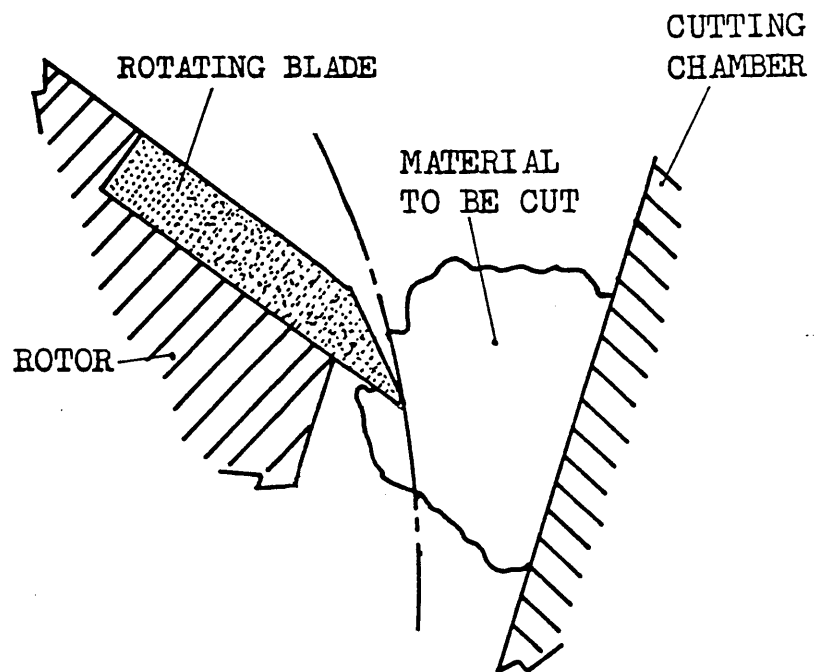


Fig. 1.5: Cutting Action inside the Cutting Chamber.

- medium duty machines usually have larger hoppers, larger screen areas and larger cutting circles with a power rating of up to 100 KW. This type of machine can handle material up to 12 mm wall thickness.
- heavy duty machines which have a power rating of up to 400 KW. They are used to handle large pieces of material and for tough applications. Because of their tremendous noise generation, these machines are installed in separate soundproof rooms.

Fig. 1.6 shows a typical heavy duty granulator.

Medium and heavy duty granulators are usually mechanically loaded and unloaded as shown schematically in Fig. 1.7 where an automatic dumping system loads the reject pieces onto a conveyor system which in turn loads the granulator. After granulation, the material is pneumatically conveyed to a silo for future use. The operator's only responsibilities are loading racks of reject pieces into the system and taking away the empties.

There are granulators specially designed to suit specific applications. For example, Henshe-Kessel (W. Germany) produces a granulator provided with heating facilities for application of plastic film scrap. In operation, film scrap is fed into the granulator chamber, the temperature of the cutting chamber is then increased

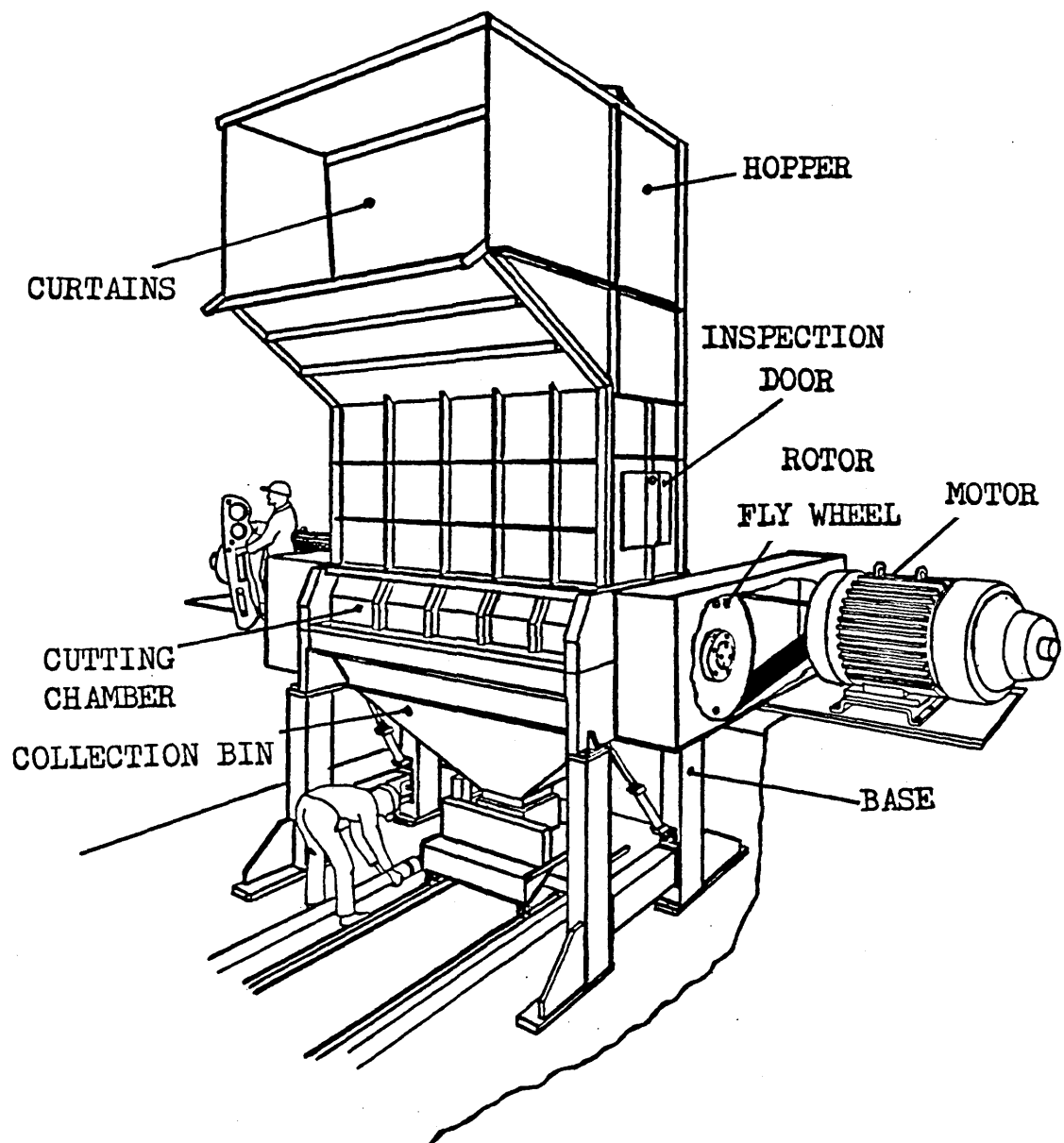


Fig. 1.6: Typical Heavy Duty Granulator.

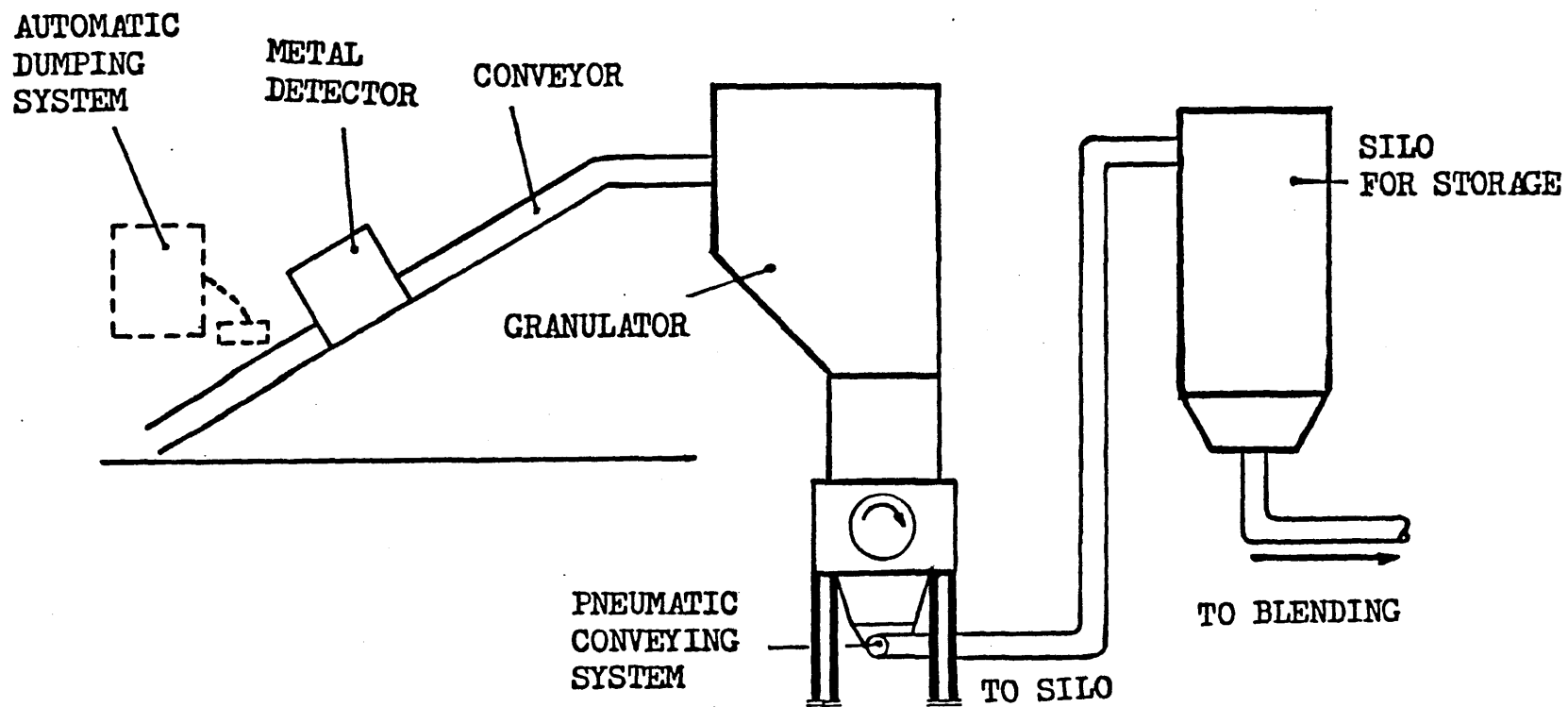


Fig. 1.7: A Schematic Diagram of an Automatic System to Load and Unload Heavy and Medium Duty Granulators.

while the cutting knives are rotated at a speed of 20m/sec. As soon as the softening temperature of the plastic is reached, compressed air is blown into the cutting chamber which has the result of removing the film chips from the cutting chamber walls and also prevents the agglomerates sticking. Krauss-Maffei (W. Germany) produces another type of granulator for application on low bulk scrap materials. The cutting blades are fitted in the base of the cutting chamber. These blades are rotated at a very high speed. The cutting action at a high cutting speed causes the material temperature to rise and in turn to form agglomerates or small lumps. As soon as some limiting temperature is used, water is injected into the cutting chamber to cool the surface of the lumps to prevent them from sticking together. The high temperature of the cutting chamber walls and the material converts this water into steam and this is exhausted into the atmosphere, so that the material is delivered dry.

A technique for granulating at low temperature has been introduced by Foremost (U.S.A.) for materials whose viscosities are highly sensitive to temperature like Nylon and Saturated Polyester. The granulator cutting chamber is provided with a cooling system, so that feed stock can be embrittled before or during the size reduction process.

1.3 KINEMATICS OF THE CUTTING PROCESS, GEOMETRICAL ARRANGEMENTS OF THE BLADES AND CONFIGURATION OF THE BLADE

The concept of cutting is the separation of a part of the material with the aid of a suitable tool. From the macroscopic point of view, the separation zone in the material must coincide geometrically with the cutting edge of the tool. There can be two possible types of cut, either a straight, normal cut or a guillotine type of cut. In the former, the blade edge moves normal to the direction of cutting and the separation zone progresses linearly through the material, while in the latter, the blade edge moves on an inclined angle to the direction of cutting.

The granulator's rotating blade can be mounted to give either a straight type of cut or a guillotine type of cut. In the former the blade is set parallel to the axis of the rotor, while in the latter the blade is set at an angle. Also, the rotating blade could be mounted either tangentially or radially as shown in Fig. 1.8. The steep cutting edge of the blade may be arranged to be on the lower side of the blade as in Fig. 1.9 or on the upper side of the blade as in Fig. 1.10.

When the blade is mounted radially, Fig. 1.8, it gives a chord length equal to the diameter of the cutting circle. Chord length is the chord that is formed by

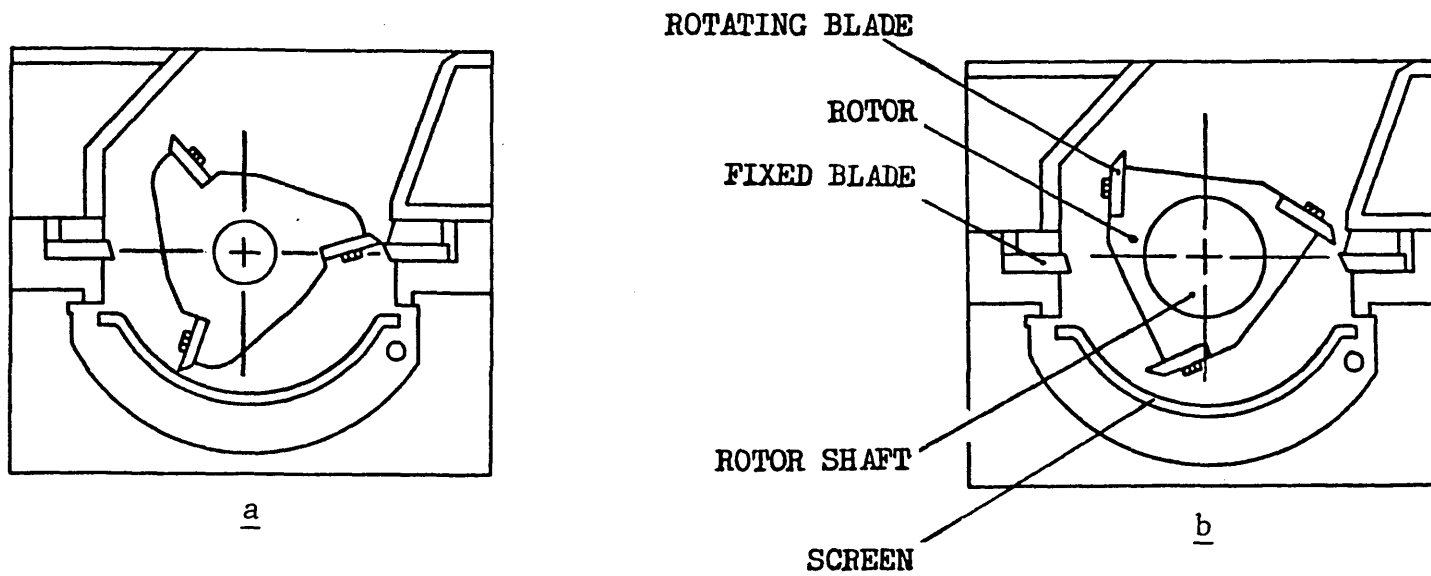


Fig. 1.8: a Rotor with Blades Mounted Radially.
b Rotor with Blades Mounted Tangentially.

- α - Angle of Attack
- β - Bed Blade Angle
- θ - Rotor Blade Angle
- C - Clearance
- R - Radius of Cutting Circle
- L - Broken Part

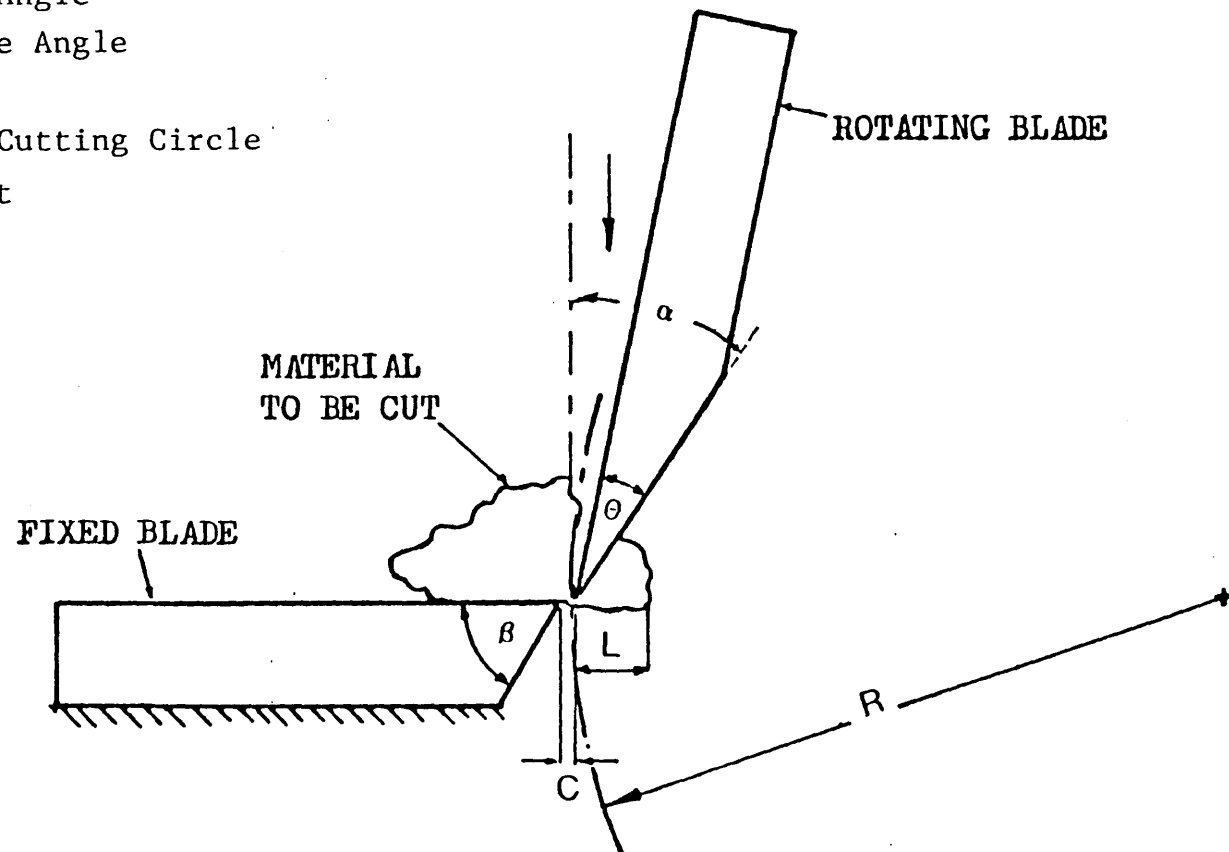


Fig. 1.9: Typical Mounting of a Rotor Blade with the Steep Edge on the Lower Side of the Blade.

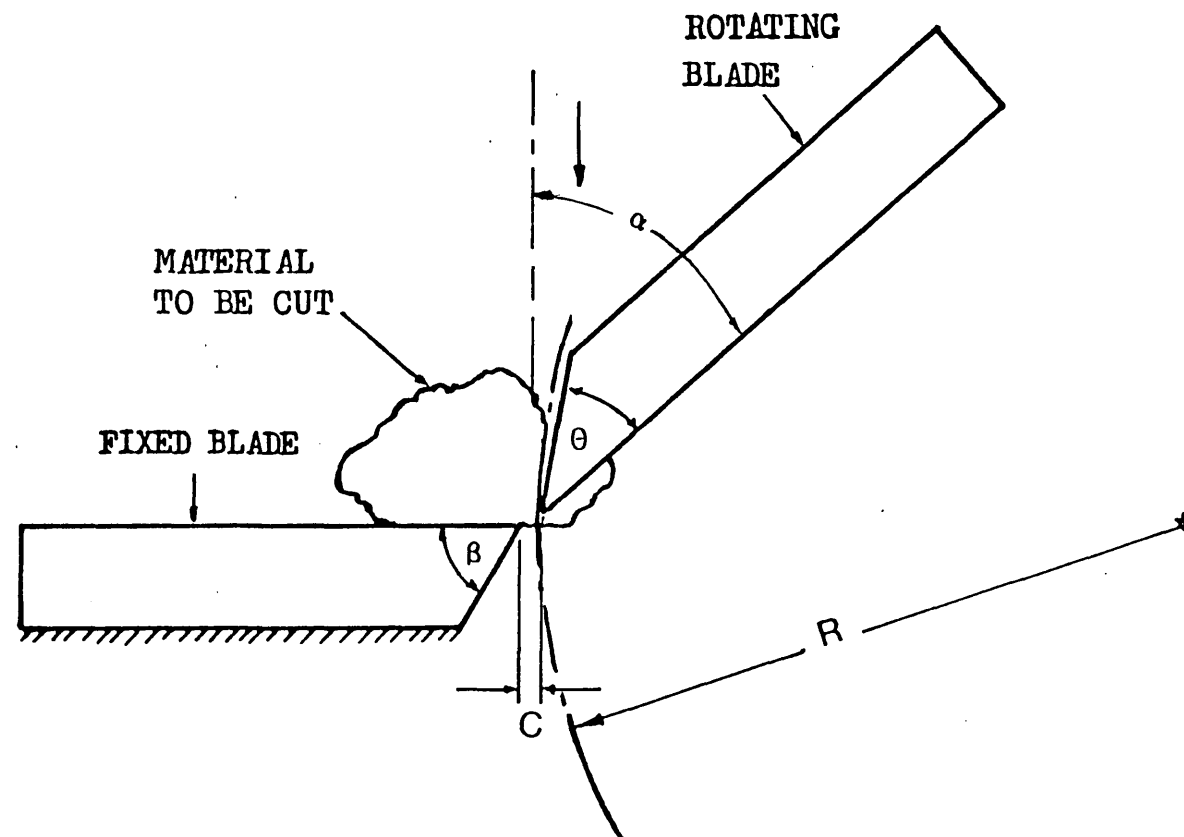


Fig. 1.10: Typical Mounting of a Rotor Blade with the Steep Edge on the Upper Side of the Blade.

extending the rotor knife seat in both directions until it becomes a chord of whatever cutting circle is being used.

In the tangential mounting arrangements, Fig. 1.8, the shortest chord length occurs when the rotor blade is perpendicular as it passes the fixed blade. This case would be defined as the rotor blade having an angle of attack equal to the blade cutting angle, and in the radial case, the rotor blade angle of attack is equal to 90° .

Blade configuration may be defined by the radius of the blade tip (sharpness) and the blade cutting angle. Fig. 1.9 and Fig. 1.10 illustrate the geometrical arrangements of the blades and the blade configuration.

1.4 THE PROCESS OF CUTTING IN THE GRANULATOR CHAMBER AS COMPARED TO OTHER METHODS OF MACHINING AND CUTTING

The process of cutting in the granulator chamber is different from that which takes place in other machining and cutting operations such as turning, shaping, milling and sawing. In the granulator chamber, cutting is done by impact, and the material is completely unsupported during the process of cutting.

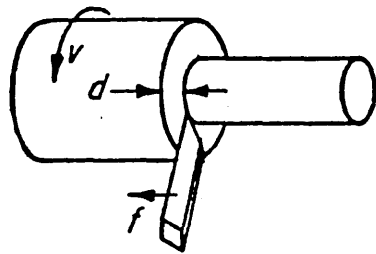
In the other machining and cutting operations, the support is an integral part of the operation and the work

piece is firmly held against the advancing edge of the cutting tool (7). Fig. 1.11 shows a schematic view of some common machining operations (turning, shaping and milling). The principal parameters in cutting are the cutting speed v , the depth of cut d and the feed f .

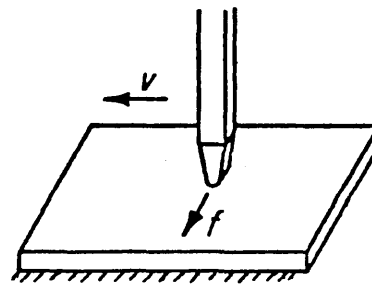
1.5 OBJECTIVES

Although the polymer granulator is one of the most commonly found items of equipment in the polymer processing industry, it has received the least technical attention in the literature. The granulator design appears to have evolved through random considerations and experience in the absence of any fundamental study of its cutting mechanisms. Consequently, the machine performs poorly in operation and also generates a great deal of noise even if no cutting is taking place.

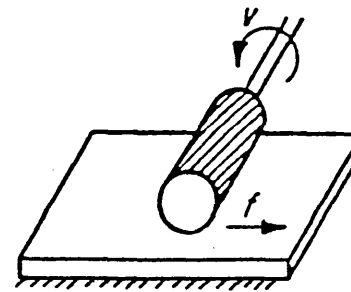
Due to the present rules restricting excessive noise levels and also since the underlying reason for polymer waste reclamation is economy, it is important that both the noise generated by the granulator, and the energy required in cutting polymers be minimised. The granulator cutting chamber is the noise generator and the place where cutting begins. It is necessary to focus on the various parameters of the cutting chamber in order to achieve the optimum operating conditions of the machinery for minimum power consumption and lowest noise levels.



Turning



Shaping



Slab Milling

Fig. 1.11: Schematic Diagram of Some Common Machining Operations.

These parameters are:

- rotor speed.
- blade configuration (sharpness, cutting angle of the blade).
- angle of attack of fly blades
- clearance between stationary and fly blades.
- type of cut (straigh, guillotine, steep edge of the blade, upside down).
- temperature.
- type of polymer.

A major problem that faces granulator manufacturers is the design of the blades and the determination of their optimum setting to give the best performance. An assessment of the cutting efficiency of a given blade configuration and set of operating conditions can be obtained by measuring the energy expended and noise generated in cutting. It is difficult however, to evaluate cutting phenomena by tests on overall machine behaviour because of the complexities introduced by other variables (8,9). In addition, it is difficult and expensive to attain the steady state conditions necessary to make sensible comparisons between tests.

As most granulators operate at speeds between 10-30 m/sec, study of the effects of various cutting parameters on the energy required to cut polymers and on the associated noise levels, had to be carried out on a suitable high speed

simulator. It was necessary, therefore, to design and build a high speed cutting test machine, which encompassed all of the above cutting parameters.

It was hoped that this study would help to identify the mechanisms which control granulator behaviour in order to improve the machinery operating performance and to provide greater insight into the cutting of polymers generally.

CHAPTER 2

CUTTING OF PLASTICS: LITERATURE SURVEY

2.1 INTRODUCTION

A computer search of literature concerned with the cutting of plastics revealed that there was no published work on the impact type of cutting which occurs during the granulation process. However, a number of articles concerned with the cutting and turning operations can be traced back as far as 1946. Most of this work consisted of claims and counter claims regarding the suitability of certain tool materials for the machining of plastics: one group supported the use of low carbon steel tools, another group supported the use of carbide tipped tools and another, diamond-coated tools, (10), (11), (30), (32), (33), (37), (46), (47), (49), (57), (60) and (71).

The work of A.J.T. Eyles (12) appears to be the first of its kind on the subject. He suggested that laminated plastics material can be drilled, counter sunk and tapped by the operations which are employed in the machining of metals, but some modifications are sometimes necessary. He said that the construction of the laminates should be kept in mind and to prevent chipping when a cut runs off, blanks should be backed up with rigid material so that the tool cuts through the backing plate. Others (13 - 34) have made recommendations with regards to turning, milling, drilling and grinding, they also produced some data.

Of these, H.P. Walker (18) was the most specific. He suggested that plastic composites should be machined using carbide tipped tools or high speed steel tools depending on the workpiece quantity. Because of the poor thermal conducting characteristic of plastic materials he suggested the use of coolants which may be a jet of compressed air or a stream of water. He further highlighted the fact that the machining of plastics could be a hazardous process due to dust generation.

R.A. Wason (34), (35) and (36) investigated the various cutting and turning operations for plastics. He indicated that tool sharpness was a major factor in successful machining. Wason suggested zero or marginally negative rake angle for cutting tools and use of air blast as a cooling agent for best results.

H.J. Kipnes (39) performed some work on the machining of one type of plastic, PTFE. He found that high speed cutting tools, with sharp cutting edges, gave the best results. He commented on the fact that because of PTFE's very low thermal conductivity and high heat resistance, it tends to shorten tool life by actually burning tool edges.

A number of other reports (40 - 69) have appeared during the period 1958-62, but they were quite similar to the above-mentioned articles.

Between 1961 and 1981, A. Kobayashi and K. Saito (72, 73, 74, 75 and 76) published a series of papers dealing with the cutting mechanism for plastics. A more quantitative appraisal (77, 78) consisting of a seven-part article on the subject, was published by A. Kobayashi in 1964 and brought out in book form in 1967. It would appear that most of the published data on the machining of plastics is associated with the work of Kobayashi and Saito, and some of their publications appear to be relevant to the present study. Therefore, a concise review of their investigations will be given here.

2.2 A REVIEW OF THE WORK OF KOBAYASHI AND SAITO

Kobayashi and Saito were the first to state that the theory of metal cutting can be applied to explain the mechanism of cutting for some polymers under certain cutting conditions.

The theory of metal cutting is based on the assumption that the metal is an ideal plastic body and will yield under the maximum shearing stress or will be sheared in the shearing zone around the tool cutting edge.

They adopted the method of orthogonal cutting using a single edge tool (Fig. 2.1) to facilitate their observation and analysis of the deformation and fracture phenomena of the polymers during cutting.

F_1 = Frictional Force on Rake Surface
 F_2 = Normal Force on Rake Surface
 R_1 = Resultant Force on Rake Surface
 R = Reaction of R_1 on Material
 α = Rake Angle

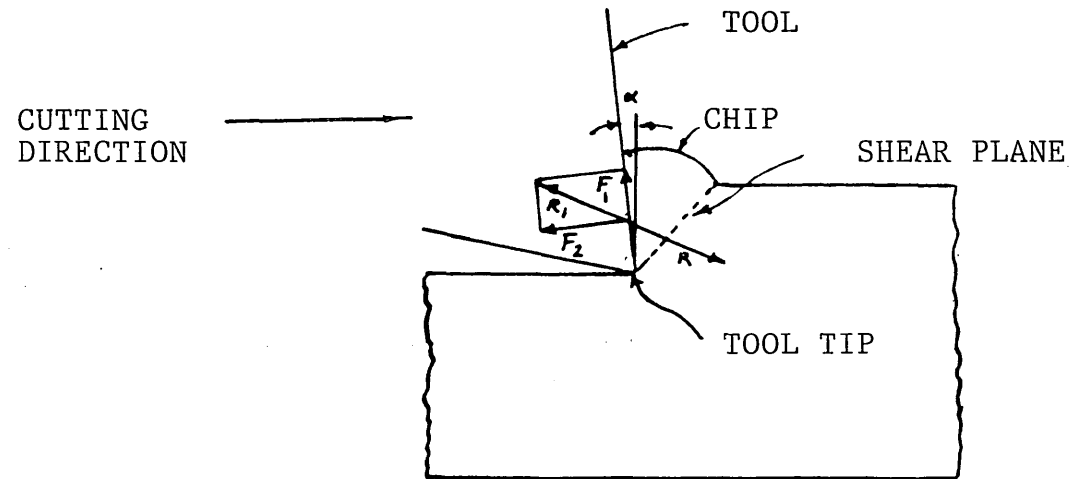


Fig. 2.1: Diagram for Orthogonal Cutting (Forces and Geometry of Cutting).

With reference to Fig. 2.1, when a cutting tool advances into the work material along a given axis, a cutting force R_1 , which is the resultant of the normal force f_1 and the tangential or frictional force f_2 , acts on the tool at the rake surface. The reaction of R_1 on the work material is R , and it is the reaction which deforms and fractures the work material.

Kobayashi and Saito stated that the types of chips obtained with a given kind of polymer vary with the specific conditions of that fracture and these include the depth and speed of cutting as well as the geometries of the tool and work material.

They classified the types of chips obtained into two main categories: continuous and discontinuous. From their observation of microphotographs of the surface of the chip and also of cine-films during cutting, and measurements of cutting forces, the types of chips were further classified into; cleavage type, flow type, shear type, shear with crack type, tear type and crack type.

For example, in slow speed cutting (0.02 m/min) of PTFE and a rather large depth of cut (0.5 mm) with a tool having a 20° positive rake angle, they found that chips are produced smoothly and continuously. The mechanism of chip

formation was described as follows: the work material experiences a tensile strain perpendicular to the cutting direction and a compressive strain parallel to it. The chips are formed by the tensile stress accompanied by the cleavage action of the tool's edge. This chip formation has been called the continuous flow type.

In cutting of PMMA under moderate speed (0.2 m/min) and a small depth of cut (0.25 mm) with a tool having a 10° negative rake angle, they indicated that a shear plane is generated upwards from the edge of the cutting tool and the chip is produced by shearing action along this plane. This chip is continuous because of small shear intervals as shown in Fig. 2.2. Thus, this chip formation has been called the continuous shear type.

The discontinuous type of chips were divided into four types. For example, in cutting of PMMA with a tool having a 10° negative rake angle at a cutting speed of 0.8 m/min and depth of cut 0.5 mm, they observed that the chip is produced by shearing action along a shear plane, shear intervals are rather large and discontinuous chips are produced. They indicated that such chips occur when the shear strain, at the shear plane, becomes larger than the limiting fracture strain. This type of chip formation has been called the discontinuous shear type.

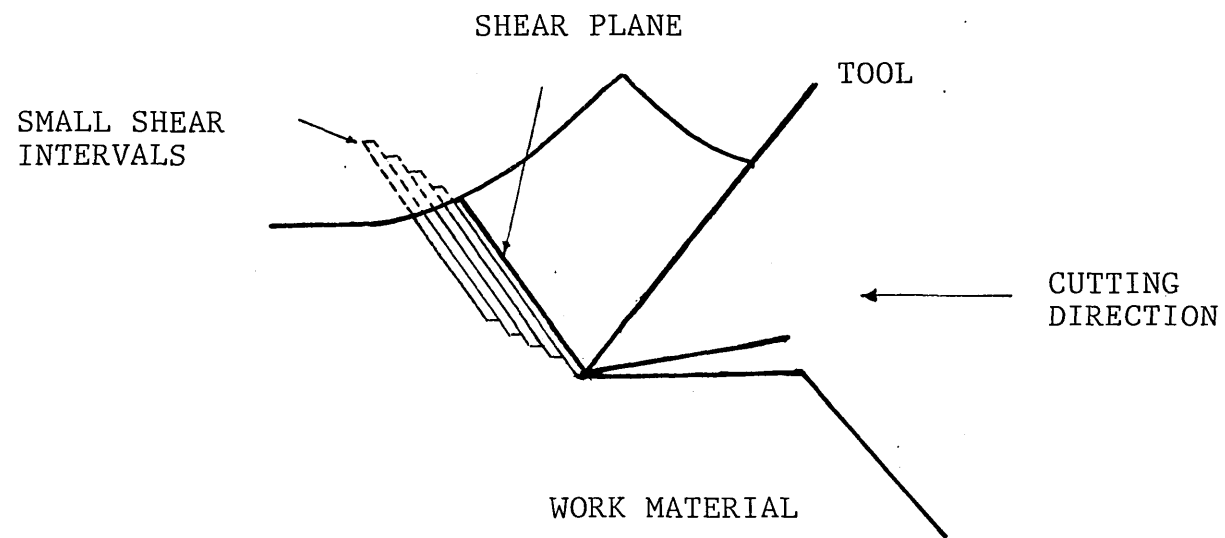


Fig. 2.2: Schematic Diagram of Shear Intervals in Continuous Shear Type Chip.

In cutting of PS with a tool having a 30° negative rake angle, a cutting speed of 0.2 m/min and a depth of cut of 0.25 mm, they found that chips are produced by the complex stress resulting from the action of a large compressive stress operating in combination with a shear stress. The type of chip formation has been called shear with compressive stress, so-called tear type chip.

The type of chips observed in cutting of PMMA with a tool having a 20° positive rake angle at a cutting speed of 0.2 m/min and a depth of cut 0.25 mm, has been called the shear with crack type chip. They indicated that in addition to the separation of the work material along the usual shear plane, occasionally a crack occurs at a downward angle from the cutting edge.

The discontinuous crack type chip was observed in cutting of PMMA with a tool having a large positive rake angle 40° and a depth of cut 0.25 mm at a speed of 0.2 m/min. Kobayashi and Saito indicated that: when the tool advances into the work material, the zone adjacent to the tool's edge deforms plastically. The crack initiates in tension by the wedge action of the tool before the plastically deformed zone can expand. The crack propagates in a periodic succession by the bending moment acting on the chip. Fig. 2.3 shows a schematic diagram of propagation process of crack in crack type chip formation.

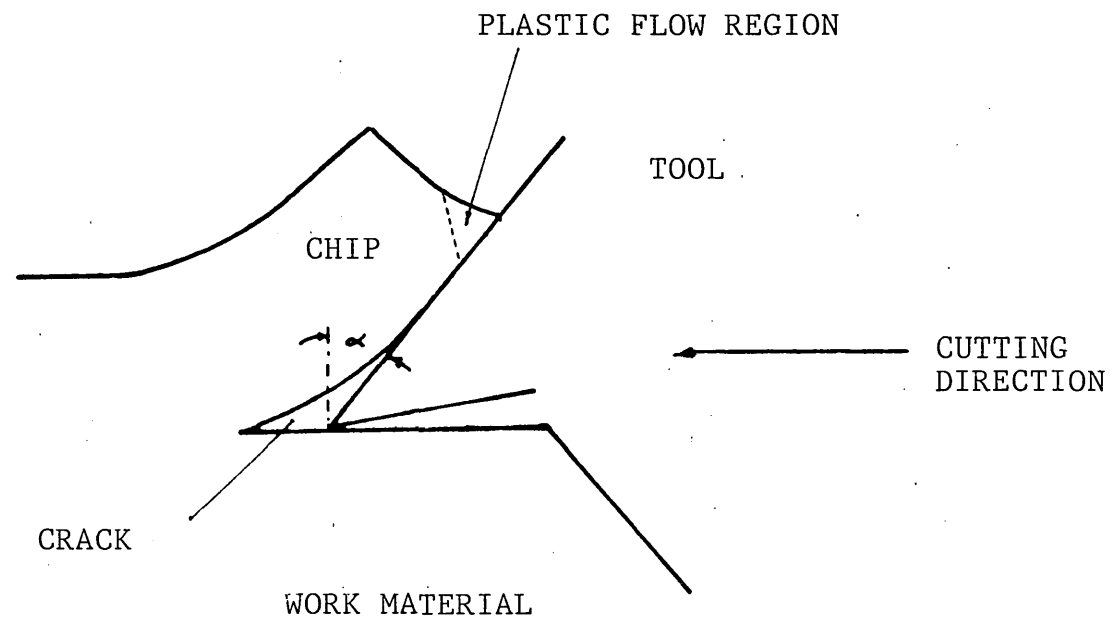


Fig. 2.3: A Schematic Diagram of Propagation Process of Crack in Crack Type Chip Formation

α = Rake Angle

In short, Kobayashi and Saito classified the chips as follows:

- continuous flow chips, resulting from high elastic deformation.
- continuous shear chips, due to shearing action on a slippage plane.
- discontinuous simple shear chips, produced as a result of plastic fracture as a consequence of a simple shear stress.
- discontinuous complex shear chips, due to complex stress.
- discontinuous crack chips, due to tensile shear stresses and brittle fracture.

The continuous flow type chip is observed at low cutting speeds and is associated with materials which exhibit high elasticity (PTFE and PE), with the work material near the tool cutting edge undergoing a tensile strain perpendicular to the cutting direction, and a compressive strain acting along it.

The discontinuous complex type chip results from complex stress, i.e. a larger compressive stress combined with the shear stress when cutting with a negative rake tool.

The discontinuous crack type chip is produced when cutting materials which exhibit brittleness such as PMMA, the chip being produced by cracking. The crack is initiated and propagated when the stress is less than the elastic limit stress and the strain exceeds the limiting fracture strain.

The mechanism of chip formation can be explained by the stress-strain diagrams shown in Fig. 2.4. In curve 1 of Fig. 2.4, from 0 to A is an elastic region and fracture occurs at A. This curve shows brittle fracture. If the chip will be produced by a crack, that is the discontinuous crack type chip.

In curve 2, region AB shows plastic deformation. If the strain of the material during cutting goes over A, it enters into the plastic region, the work material begins to flow plastically and flow type or shear type chip is produced.

Curve 3 shows the elastic deformation with large elastic-like rubber. When the elastic strain of the work material in the region of cutting deformation is large,

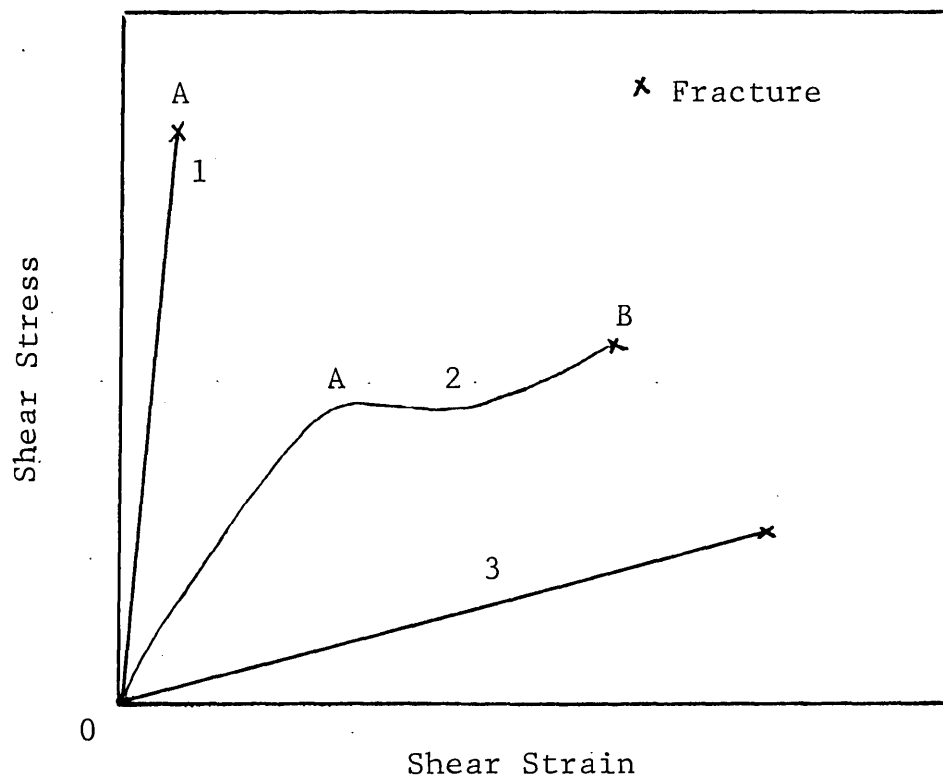


Fig. 2.4: Schematic Diagram of Stress-Strain Curves to Fracture.

the chip becomes continuous. This type of chip formation is the continuous cleavage type.

They stated that in shear cutting there is for every plastic, a particular value of rake angle at which the thrust force ($F_1 \cos \alpha$ - see Fig. 2.1) is zero, this angle is called the "critical rake". They regarded the critical rake as the optimum rake angle, maintaining that the resultant cutting force would then coincide with the direction of cutting and hence, the cutting force would be minimized. In case of crack propagation cutting, they indicated that a large rake angle is required to minimize the cutting force during crack propagation.

Kobayashi and Saito (73, 74) claimed that in the cutting of some plastics (UP, PC) the cutting force is very much dependent on the cutting speed, in such a way that the force increases with speed and shows a maximum value at a particular speed. As the cutting speed increases over that particular value the force decreases quickly with increasing speed and eventually achieves a fairly constant value. The relation between cutting force and cutting speed in UP and PC is shown in Fig. 2.5. They also pointed out that the increase in cutting force with increased speed was due to ductile fracture, and the decrease in the cutting force at high cutting speed was due to brittle fracture.

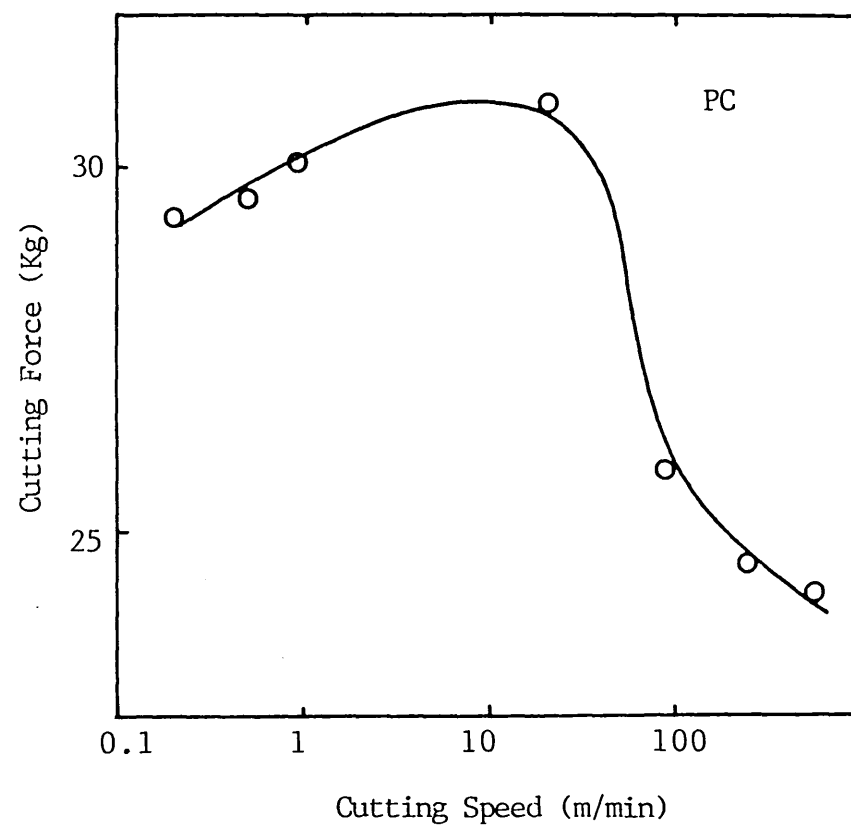
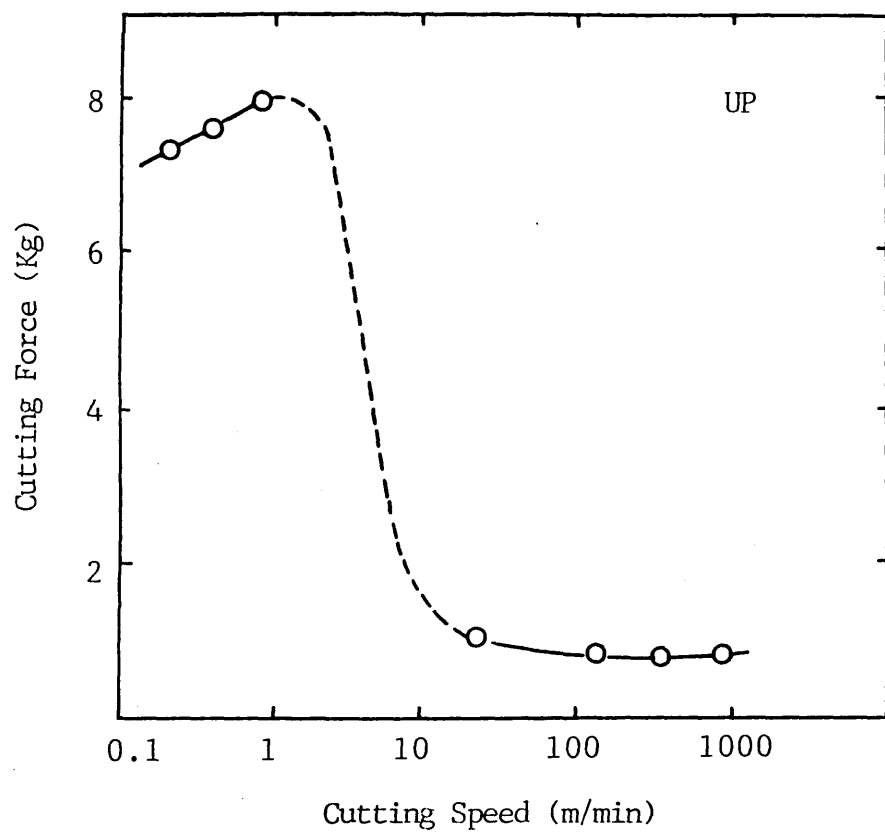


Fig. 2.1: The Effect of Cutting Speed on Cutting Force with UP and PC

The dependency of the cutting force on speed was attributed to viscoelastic effects. Saito used a simple viscoelastic three-element model to predict their results and a good agreement was achieved.

2.3 DISCUSSION OF THE WORK OF KOBAYASHI AND SAITO

The work of Kobayashi and Saito appears to be the most comprehensive available on the subject of plastics machining. Their objective was to characterize the fracture phenomenon in the cutting of plastics in terms of cutting conditions. The cutting conditions include the depth and speed of cutting, the geometries of the tool and work material, the types of chips formed as well as the mechanisms of failure and properties of work material.

However, data have not been supplied to support some of the conclusions drawn, e.g. thermal effects have been mentioned as one of the inherent side-effects associated with the cutting of plastics, but the speed levels at which heat effects become significant have not been investigated. An evaluation of the magnitude of these side-effects on the machined part have not been established.

Secondly, the theory of a single shear plane as applied to metal cutting under an orthogonal cutting arrangement, has been mentioned as a possible theory for the cutting of

plastics, but no experimental work has been undertaken to confirm or disprove this concept.

Thirdly, "critical rake" has been introduced but its significance in the machining process has neither been developed nor established experimentally.

Fourthly, Kobayashi and Saito indicated that the modes of fracture were ductile for low speed and brittle for high speed cutting of UP and PC (as a result of crack propagation). They did not verify howeverk these statements by actual microscopic investigation of the cut surfaces.

Although the work of Kobayashi and Saito is the most comprehensive on the subject of plastics machining, it appears that it is not applicable to the process of cutting which takes place in the granulator chamber, cutting is discontinuous because of relatively small pieces to be cut and is done in impact at high cutting speeds (≈ 20 m/sec). Also, the material to be cut is completely unsupported during the process of cutting. In the other machining operations (such as turning, shaping and milling), the cutting is continuous and speeds of cutting (≈ 2 m/min) are lower than those used in impact cutting. In addition, the work material is firmly held against the advancing edge of the cutting tool and the support is an integral part of the continuous cutting process.

In view of the above, it was found necessary to carry out a study on the impact cutting of polymers in order to identify the mechanisms which control granulator behaviour, with the long term objective of improving machinery operating performance.

CHAPTER 3

DESIGN AND CONSTRUCTION OF A HIGH SPEED CUTTING MACHINE

3.1 INTRODUCTION

An important parameter which must be included in any series of cutting tests is blade speed. In granulators this can be up to 40 m/sec. with a common average of about 10 m/sec. In addition, all blade variables, as shown in Figs. 1.9 and 1.10, are considered along with the facility to deliver a slanting (guillotine) cut which is claimed by some granulator manufacturers to give quieter and more economical cutting.

An obvious way to measure cutting energies is to modify a conventional impact tester by replacing the striker with a cutting assembly and the specimen support system with a fixed blade.

In most of the known impact testers, the striker is either propelled at the specimen by means of a gas gun, dropped from a height, or carried on the end of a pendulum. These instruments have the advantage that the kinetic energy can easily be imparted to the striker before it hits the specimen, the striker may therefore retain a considerable amount of energy even after impact, and the magnitude of the energy levels before and after impact will be such that the difference between them can be measured

easily and with accuracy at low speeds.

The gas type instruments are unsuitable for modification. This is because these machines require a certain amount of play in their guide system to prevent jamming. This is unacceptable in cutting tests because of the need to hold close tolerances on clearances between the fixed and moving blades.

The falling weight tester is a simple machine and in many ways similar to the gas gun type. The striker is dropped freely from a height. The velocity of the striker is a function of the square root of the height and to obtain high velocities a great height is needed.

The pendulum impact tester is also a simple machine. The striker is carried on the end of a pendulum arm and makes impact with the specimen as the arm reaches the bottom of the swing. In comparison with the previous machines, repeatability of speeds in successive tests is easier to achieve because the motion of the pendulum is less subject to vibrations than the moving weight machines. To give the striker high velocities comparable to those that can be given by a gas gun, however, the pendulum arm must be long and consequently heavy. Such machines tend to be very large.

It was therefore necessary to design and build an accurate compact high speed testing machine to simulate the cutting conditions in the granulator chamber. For the sake of simulation, a specimen could either be held loosely against a fixed blade where it could be struck and broken by a blade fixed to a rotating arm or a specimen could be held freely to a blade fixed to a rotating arm and consequently struck and broken against a fixed blade.

3.2 DESIGN OF HIGH SPEED TESTING MACHINE

3.2.1 General Approach

As far as the operation of a machine was concerned, it was considered essential that it should require the minimum of setting up prior to testing. Also it should allow free access to the working area (i.e. the operator should be able to position and remove the specimen with ease) together with an unobstructed view during testing. It was also considered desirable that the operation of the testing machine should be on an automatic basis. Consistent high accuracy was also considered to be the foundation for the design of the testing machine.

3.2.2 Development of High Speed Test Machine

At this stage it was decided to develop a machine which is essentially a compact driven (through a motor) version of a pendulum machine modified for cutting. With such a machine, a close tolerance on clearances between the fixed and moving blades can be achieved together with minimum levels of vibrations, when machine is in operation. Several possibilities were contemplated before a firm design was decided upon. The first idea was to drive the arm by means of a gas gun, as shown in Fig. 3.1. In this design, the testing machine would consist mainly of the following parts:

- a gas gun.
- an arm pivoted near one end where a block with a tapered hole would be attached.

When a cone shaped slug is fired from the gas gun towards the block tapered hole it would become embedded in the block and give the arm a rapid acceleration which would then cut a specimen.

The second idea was to drive the arm by a variable high speed electric motor as shown in Fig. 3.2. In this design, the rig would consist of the following main parts:

- a magnetic clutch (1) fitted to a horizontal shaft (2).
- a long arm (3) joined vertically to the magnetic clutch while a short arm (4) with a wheel is fixed to the other shaft end.

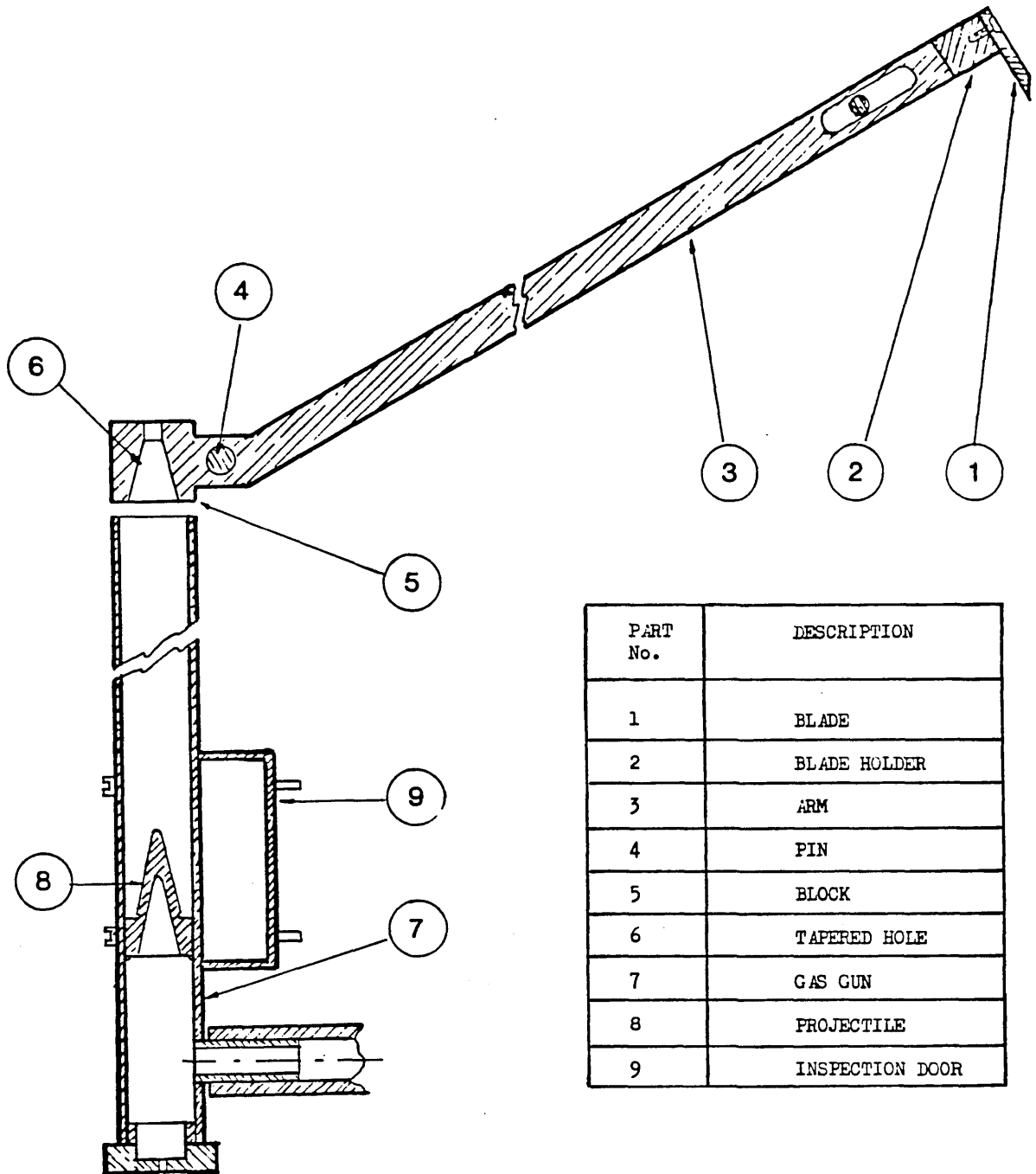
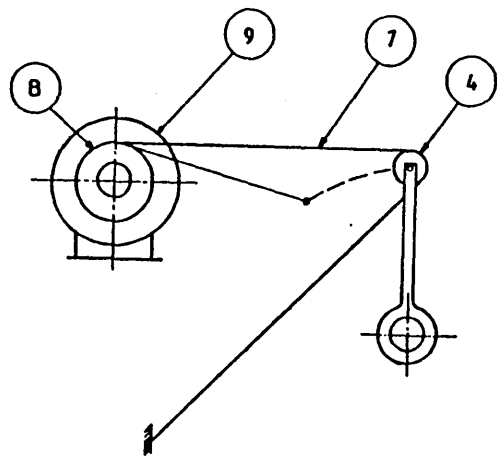


Fig. 3.1: First Design for High Speed Cutting Test Machine.



PART No.	DESCRIPTION
1	BLADE
2	ADJUSTABLE BLADE HOLDER
3	ARM
4	WHEEL
5	SHORT ARM
6	MAGNETIC CLUTCH
7	WIRE
8	PULLEY
9	MOTOR
10	ROLLER BEARINGS

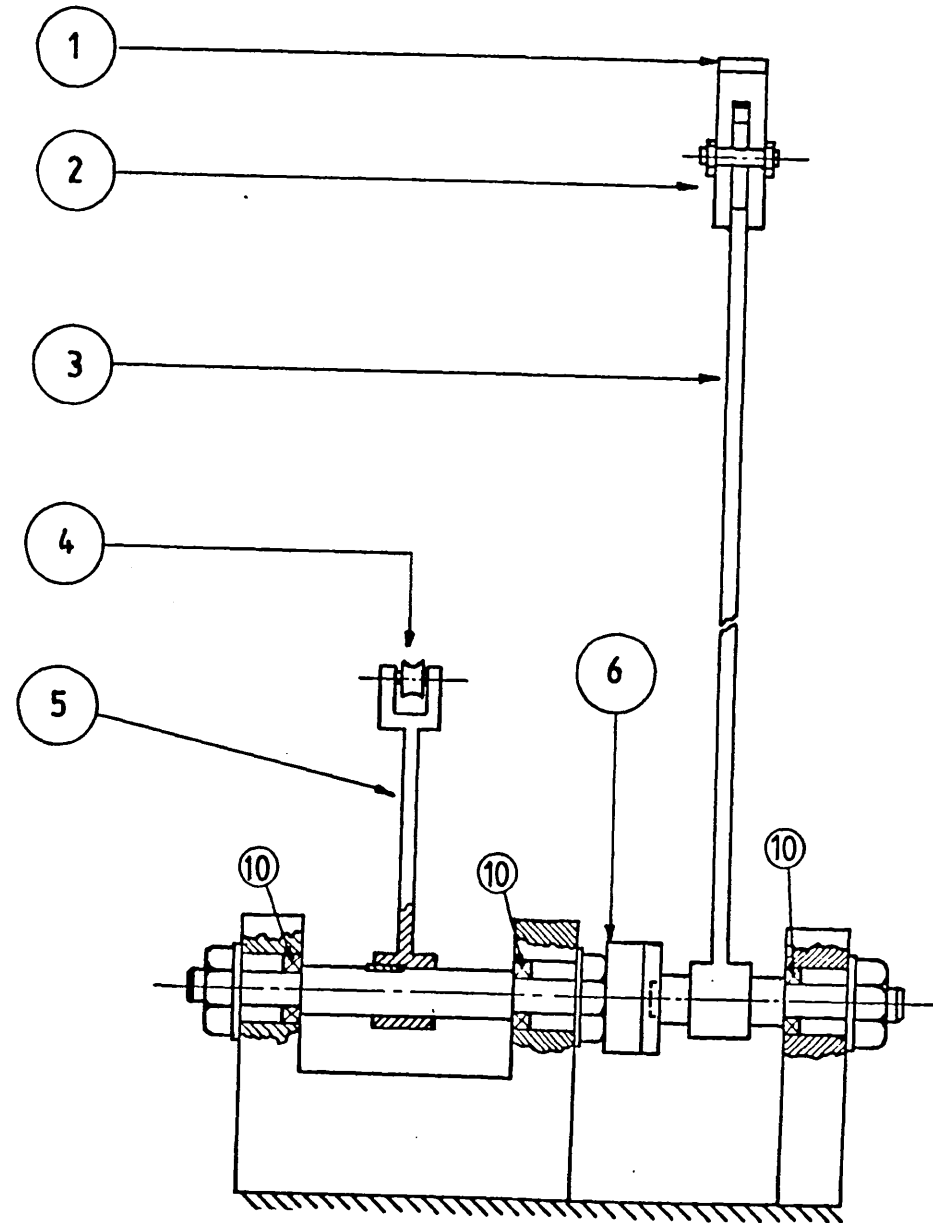
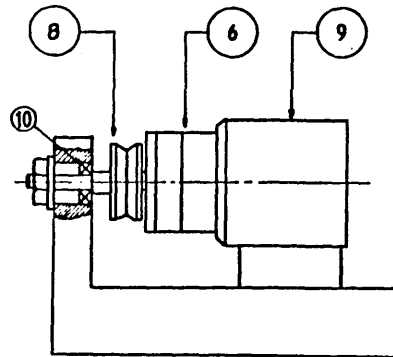


Fig. 3.2: Second Design for High Speed Cutting Test Machine.

- a high speed motor with a pulley attached to it by means of another magnetic clutch.
- a wire would be connected to the pulley at one end and passed around the wheel of the short arm, the other end being fixed to a frame.

In operation, when the motor reaches the required speed, the pulley would be connected to the motor, which would tension the wire and consequently cause a rapid acceleration to the short arm and the long arm. At a specific position in the cutting circle, the long arm would be disconnected from the other parts to rotate freely ready to cut a specimen.

In the above designs, the change in energy of the arm can be related simply to the cutting energy as in conventional impact testing. However, the first design was considered to be unsuitable because the testing machine in operation, appeared to be very noisy and this would have been a difficult problem in proposed measurements of noise levels generated in cutting polymers. A practical problem which arose with the second design was that even with a light arm assembly, it was not easy to generate the high speed required in a single revolution with available commercial compact clutches because of slip caused by the high torque required to accelerate the arm from rest. Therefore, a system was devised so that the specimen was held out of the plane of the moving blade

arc, whilst the arm accelerated up to the desired speed over several revolutions. When the desired speed was attained, the arm was allowed to rotate freely, the specimen being introduced into the path of the blade for cutting to take place.

Energy lost during the impact period would be determined by calculation of the energy of the rotating arm just before and after the contact between the rotating blade and the specimen. This can be derived from the velocity information before and after the event and the knowledge of the mass moment of inertia of the rotating arm.

Energy lost during the impact period due to windage and friction between the mechanical parts would be evaluated in the same way while the machine is running without a specimen in position.

Operation of the machine would be controlled and measurement of changing velocity of the rotating blade could be obtained by application of optical methods.

The latter two designs were patented under the numbers (8224929) and (8224980). Also the final design is under production by Hounsfield Tester Ltd.

3.2.2.1 Description and Operation of the Testing Machine

The testing machine is shown in Fig. 3.3. The basic principle of the design is that a motor drives a rotating arm via an electromagnetic clutch. The speed at which the test is to be conducted is preset and the arm accelerates until this speed is attained. At this point, with the rotating blade having just passed the fixed blade, a photoelectric sensor is operated which causes the clutch to be disconnected and a solenoid attached to the specimen table, is energized. This brings the specimen into the path of the rotating blade, which is now moving freely. The speed of the rotating arm immediately before and after the cut, is measured by two photoelectric sensors. With these measurements, it is possible to calculate the energy loss of the rotating system. Correction for the kinetic energy imparted to the broken part of the specimen could be made and the cutting energy determined. Details of the parts of the testing machine are shown in Fig. 3.6.

3.3 CONSTRUCTION OF THE RIG

The first design presented earlier was used to build the testing machine. Design calculations are given in Section 11.1.

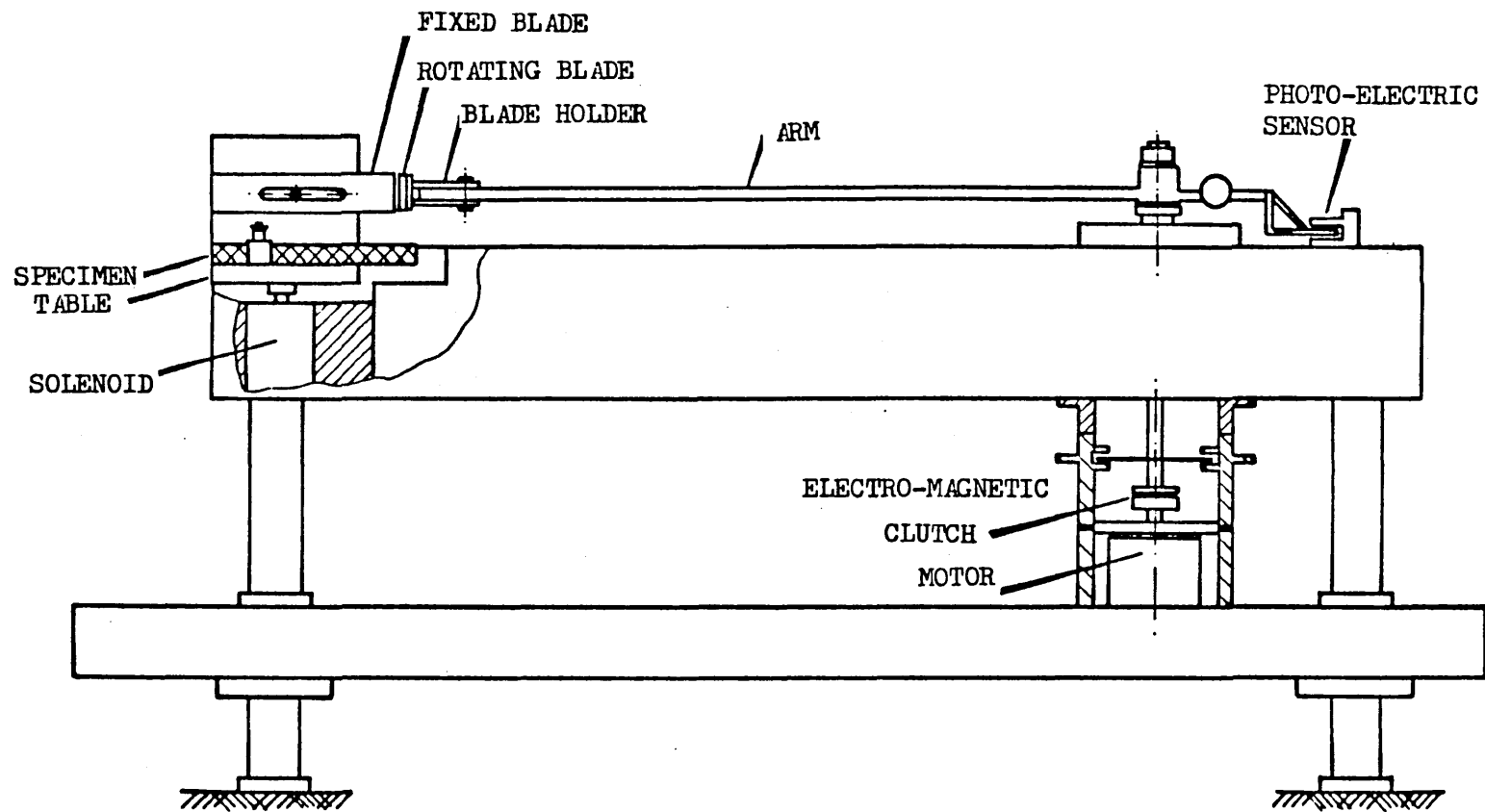


Fig. 3.3: Final Design for High Speed Cutting Test Machine.

3.3.1 The Rotating Arm (Drawings Nos. 1 and 2)

The material used in manufacturing the arm was steel (EN-30B). This steel has high tensile and proof strength in the order of 2200 N/mm^2 (80). This offered a light arm with a small cross section but high strength. Consequently, the inertia of the arm and the aerodynamic effects were minimized.

To reduce the effects of the aerodynamic forces on the arm (81,82), the geometry of the cross section of the arm was chosen as an aerofoil with the following specifications (see also Section 11.1.2.2):

- leading edge diameter	=	3.17 mm
- trailing edge thickness	=	2.5 mm
- chord length	=	6.35 mm
- span	=	280 mm
- angle of attack	=	0
- aspect ratio = span/chord length	=	44

One end of the arm was flattened and slotted so that a blade holder could be mounted. The other end of the arm was prepared to carry an adjustable counter balance and also to carry a vane.

3.3.2 The Arm Spindle (Drawing No. 1)

The arm spindle was made from steel (EN-30B). Its function was to connect the electromagnetic clutch armature spindle to the arm and to provide a tight locking to the arm. The spindle end was machined to give a cone-shaped end. To minimize frictional effects due to rotation, two precision low friction ball races were used. The bearings were manufactured by SKF Ltd.

3.3.3 Arm Spindle Bearings Housing (Drawing No. 3.1)

The housing was made from steel (EN-24) to accommodate the arm spindle bearings. Four holes were drilled in the upper side of the housing for attachment to the machine base.

3.3.4 The Electromagnetic Clutch

The electromagnetic clutch was manufactured by Simplatroll. Ltd. Its function was to carry out repeated connection and disconnection of the arm spindle from the drive. Specifications and permissible tolerances for the electromagnetic clutch are given in Section 11.3 (Electromagnetic clutch survey).

3.3.5 Electromagnetic Clutch Spindles (Drawing
No. 4)

Two spindles were made from EN-30B steel. The function of the first spindle was to carry the electromagnetic clutch armature and that of the second spindle, to carry the rotor of the clutch. To provide the necessary alignment between the spindles and to minimize frictional effects, two ball races were used on the first spindle and one on the second. The bearings were of the same type used previously with the arm spindle and were manufactured by SKF Ltd.

3.3.6 Electromagnetic Clutch Housing

(Drawings Nos. 4.1, 4.2, 4.3, 4.4, 4.5 and 4.6)

To meet the electromagnetic clutch assembly requirements and to obtain a precision location and alignment for the different parts of the electromagnetic clutch, a special arrangement was used. The arrangement also ensured that the machine motor and arm spindles were concentric. It consisted of (Fig. 3.4) drums A, B and C and discs D and E, all made from aluminium. The upper end of drum A was machined to provide an accurate location in a hole in the machine base. Three holes were drilled in the upper surface of the drum for fixing the electromagnetic clutch housing to the machine base. Two holes were drilled radially in the side of the drum to provide access to a flexible coupling (1)

used to connect the arm spindle (2) to the electromagnetic clutch spindle (3). Similarly, in drum B , two holes were drilled to give access to the optical disc (4) and to the electromagnetic clutch armature (5). Drum B had two slots to accommodate the housing for the photoelectric sensors (6). Drum C was machined to accommodate the electromagnetic clutch stator (7). Two holes were drilled in the side of drum C to give access to a flexible coupling (9), used to connect the machine motor shaft (10) to the electromagnetic clutch rotor spindle (11). Disc D was machined to locate in drums A and B and to house the electromagnetic clutch armature spindle bearing (12). Similarly, disc E was machined to locate in drum C . Holes were drilled to attach the motor and three dowels F , in disc E respectively. The dowels F were made from silver steel. Their function was to attach the whole electromagnetic clutch housing and motor mounting to the lower side of the machine base (13).

3.3.7 Flexible Couplings

The flexible couplings were manufactured by Hunt Power Drives Ltd. Their function was to connect the arm spindle to the clutch and to connect the motor shaft to the clutch as shown in Fig. 3.4.

3.3.8 The Motor

A 24 V, 1 KW DC motor manufactured by Normand Electrical Co. Ltd., was used.

3.3.9 The Cutting Blades (Drawings Nos. 5, 5.1 and 5.2)

The blades were made of high speed steel. The fixed blade was slotted to allow positioning to give the required blade clearance. All blades were sharpened to the required values and then hardened.

3.3.10 The Rotating Blade Holders (Drawing No. 6)

These were made of dural aluminium. The holders were machined to give the required blade attack angles and to give a guillotine type of cut. To minimize the effects of aerodynamic forces, the holder cross section was also machined to be an aerofoil.

3.3.11 The Vane (Drawing No. 1)

The vane was made from Titanium in order to give the vane a high stiffness and rigidity. As the vane was a part of the optical speed sensing arrangement, it was painted black to prevent any light reflection.

3.3.12 The Counter Balance Weight (Drawing No. 1)

In order to balance the rotating arm with the other parts attached to it, an adjustable counter balancing weight having an aerodynamic shape, was mounted to the rear end of the arm. The counter balance weight was made from brass.

3.3.13 The Specimen Support Table (Drawing No. 7)

This was made from aluminium and fitted with two precision linear bearings. Its function was to support the specimen loosely using an adjustable rear pivot support.

3.3.14 Table Guide Pins (Drawing No. 8)

The table guide pins were made from silver steel. Their function was to guide the specimen support table during movement.

3.3.15 Table Travel Stops and Bed Knife Supporter

(Drawings Nos. 7 and 8)

Two shoulders were made from steel EN 24. Their purpose was to allow correct positioning of the specimen table and to provide a solid mounting for the fixed blade.

3.3.16 The Solenoid and its Frame (Drawing No. 9)

Its purpose was to drive the specimen table to the cutting position. It was carefully selected for this use, i.e. to permit a large distance of travel with fast action. The solenoid was supplied by RS Components Ltd. The specifications of the solenoid are:

- coil voltage	24 V
- force at 6 mm stroke	0.35 Kg
- maximum stroke	18 mm

A frame for the solenoid was made of sheet steel 1 mm thick and used to fix the solenoid to its position in the machine base.

3.3.17 Optical Disc

The optical disc was manufactured by Hohnier Automation Ltd. It was a part of the optical speed sensing arrangement. To mount the disc in its position, two aluminium discs were made (Drawing No. 4.6). These, and the optical disc are shown in Fig. 3.4.

3.3.18 The Machine Base (Drawings Nos. 3.1 and 3.2)

The base was made of mild steel plate. It was machined on one side to accommodate the solenoid and to

carry the specimen table and stops. On the other side, it was prepared to carry the photoelectric sensors platform. The upper surface of the base was machined to accommodate the arm spindle bearings housing and a spirit level, also the lower surface of the base was machined for legs fixation.

3.3.19 The Base Legs (Drawing No. 3.1)

Made from silver steel, they were machined to attach the machine base to the enclosure base.

3.3.20 The Photoelectric Sensor Housings

(Drawings Nos. 10 and 10.1)

These were made from aluminium, their function was to accommodate the photoelectric sensors and to provide the necessary fine adjustment to locate the sensors precisely with respect to the optical disc and the vane. As shown in Fig. 3.5, an adjustable pin was machined, so that it could be located in a threaded hole in the sensor carrier housing. The other end of the pin was machined to lock the sensor holder by means of a spring washer. The sensor holder was machined to accommodate the photoelectric sensor and its connections and also the guide pins. The sensor carrier housing was machined to locate guide pins and grip screws. Two slots were also machined and holes drilled. In operation, after attaching

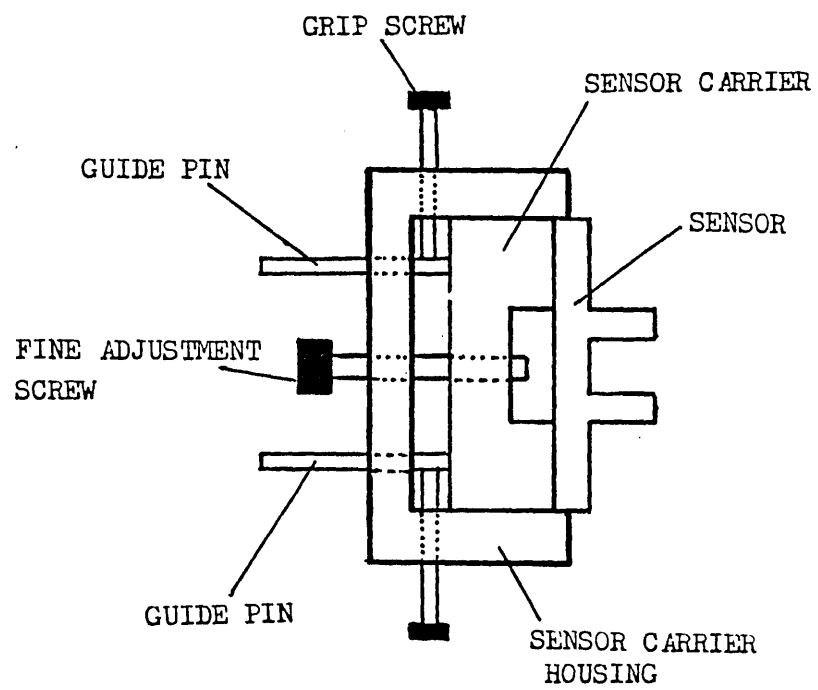


Fig. 3.5: Photoelectric Sensor Housing.

the sensor housing in its position on the clutch housing and turning the adjustable pin clockwise or anti-clockwise, the sensor holder would slide forward or backward. The function of the grip screws was to fix the photoelectric sensor holder at the required position.

3.3.21 Photoelectric Sensors Platform (Drawing No. 11)

This was made from three blocks of aluminium; its function was to carry the vane and photoelectric sensor holders. The first block was machined to carry the photoelectric sensor holders: the second and third were used for attachment to the machine base.

3.3.22 The Enclosure (Drawings Nos. 12 and 13)

The machine was housed in a safety enclosure. Box cross sections of aluminium were welded together to form a base support. Four adjustable steel legs with dampers were attached to the lower surface of the box section and a base sheet of aluminium (5 mm) was fixed to the upper surface. The base was then provided with four sides made of sheets of aluminium 5 mm thick. Finally, the enclosure was provided with a hinged lid of sheet polycarbonate, 3 mm thick and two locks.

3.4 MACHINE ASSEMBLY

The construction of the machine from drawings required precise inspection, fitting and setting-up procedures to ensure accuracy. Parts were inspected in the meteorology laboratory of the Mechanical Engineering Department of Imperial College according to the dimensional requirements shown on the drawings. The areas of close tolerance being: diametral clearance on the arm spindle, clutch spindles, the specimen table guide pins, bearing housings, clutch housing drums and discs, the tip radius of the cutting blade and the parallel tolerance on the table guide pins and also the height tolerance of the clutch housing dowels.

Having achieved satisfactory results from the inspection procedures, the machine assembly was carried out as follows: after lubrication of the arm spindle bearings with light oil (Shell Tellus 15) the housing and bearings were fixed in position. The solenoid frame was located and fixed to the machine base then the solenoid itself was attached to its frame. The specimen table guide pins were fitted tightly to their positions then the table was placed in its location. The table stops were bolted into the machine base. The clutch was assembled accurately and housed in the arrangement shown in Fig. 3.4, the motor was also mounted in position. The arrangement was then positioned and bolted to the main

machine base. The base legs were fixed to their positions and the machine was placed in its enclosure.

The following parts were attached to the arm: the vane, blade holder, blade and counter balance. After balancing, the arm was connected to the arm spindle; the bed knife was located in its position; the photoelectric sensor platform was attached to the machine base; and finally, the photoelectric sensors were mounted on their holders and fixed in position.

Fig. 3.6 shows details of the final design of the testing machine. The assembled machine is shown in Fig. 3.7.

3.5 DETERMINATION OF THE MASS MOMENT OF INERTIA OF THE ROTATING SYSTEM

The mass moment of inertia of the rotating system of the testing machine was determined by experiment and also by calculation. Values obtained showed good agreement. Experimental details and theoretical calculations for determining the mass moment of inertia are given in Section 11.2.

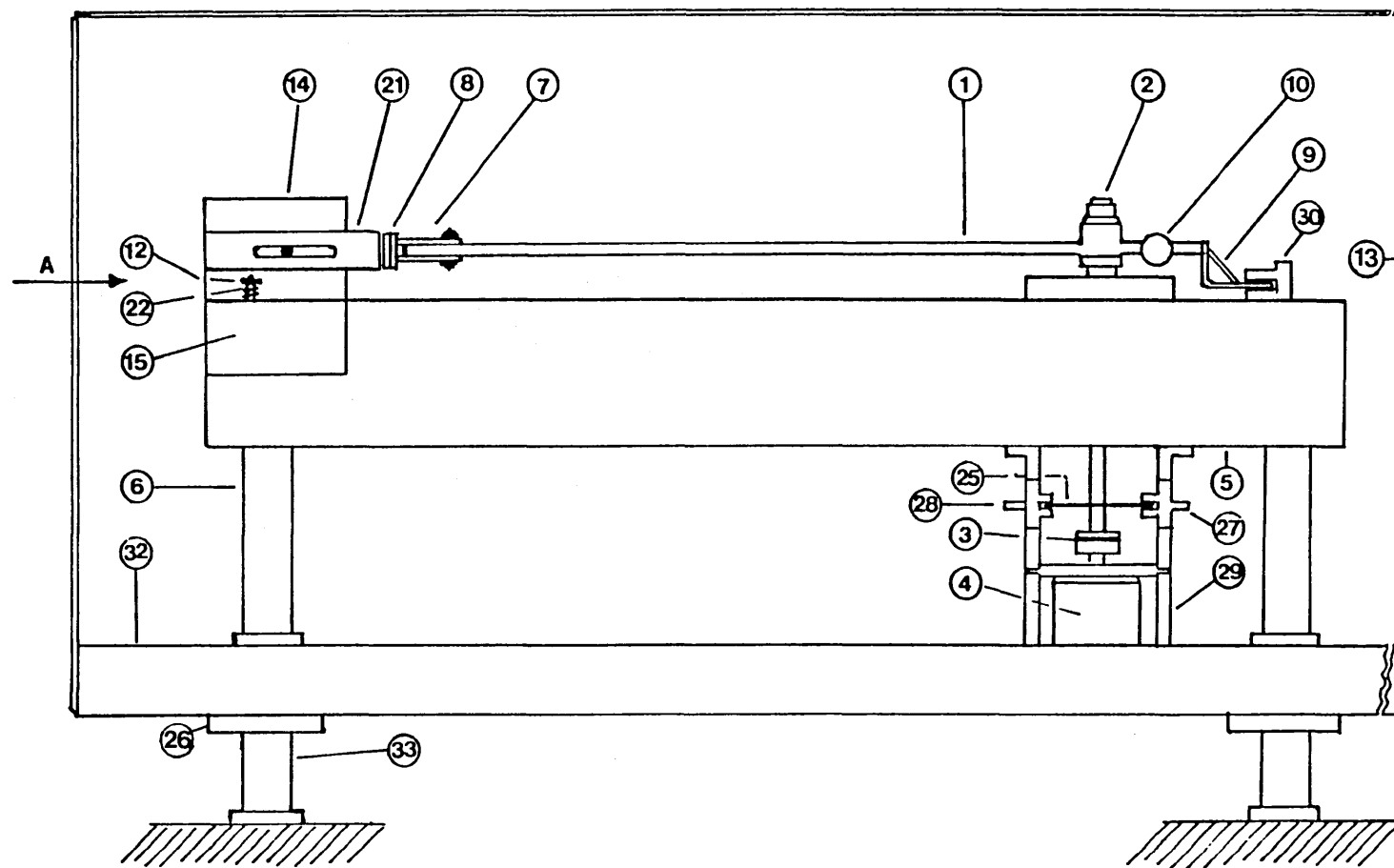


Fig. 3.6: Design Details of the High Speed Cutting Test Machine
(Elevation View),

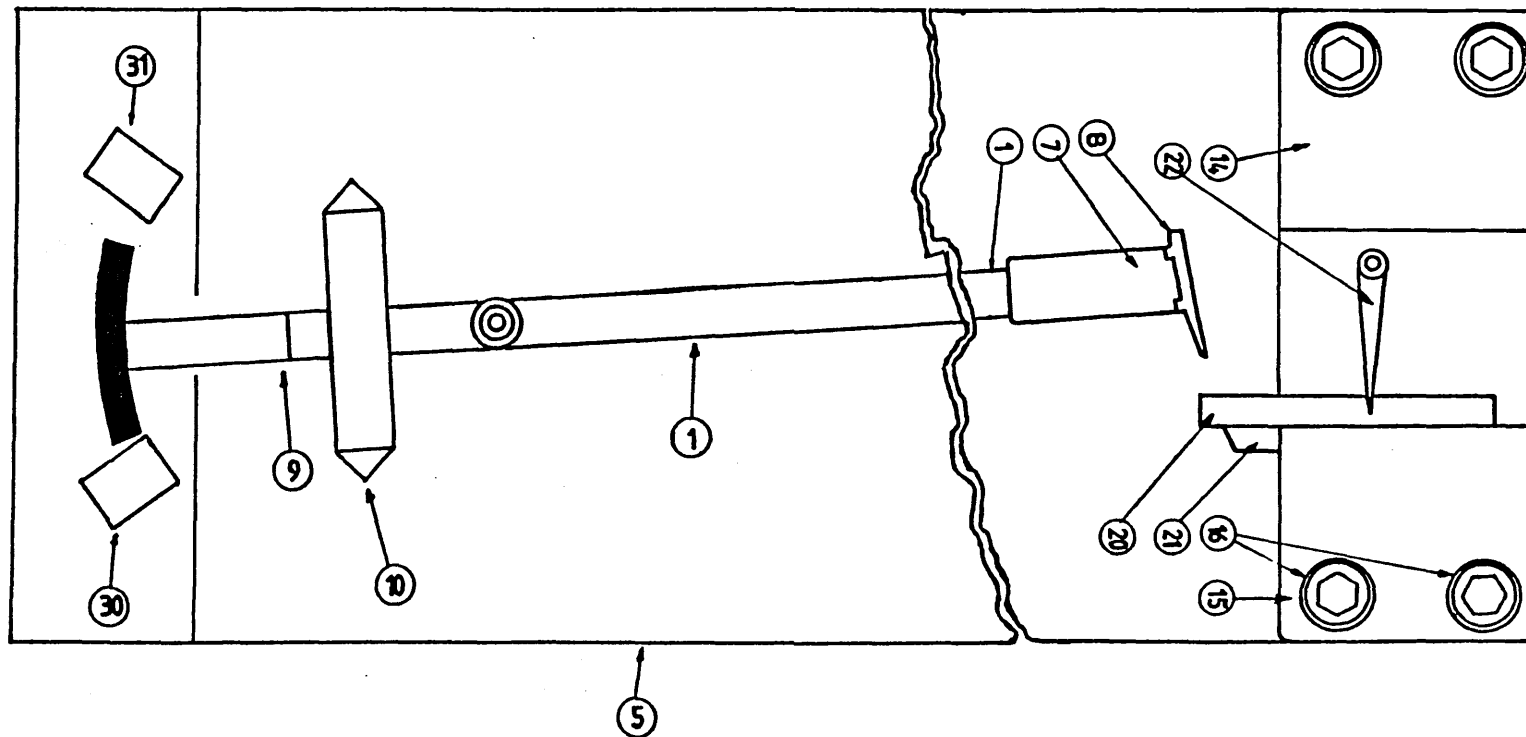


Fig. 3.6.1: Design Details of the High Speed Cutting Test Machine (Plan View).

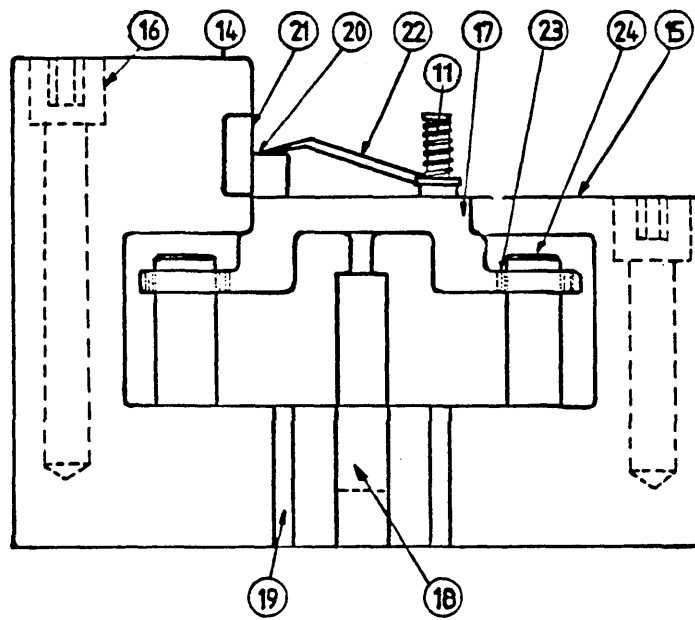


Fig. 3.6.2: Design Details of the High Speed Cutting Test Machine (Side View 'A').

PART NO.	DESCRIPTION	NO. OF
1	ARM	1
2	ARM SPINDLE	1
3	ELECTROMAGNETIC CLUTCH	1
4	DC MOTOR	1
5	MACHINE BASE	1
6	MACHINE BASE LEG	4
7	BLADE HOLDER	-
8	BLADE	-
9	VANE	1
10	COUNTER BALANCE	1
11	SPRING	1
12	NUT	1
13	ENCLOSURE	1
14	BED BLADE HOLDER	1
15	TABLE TRAVEL STOP	1
16	BOLT	4
17	SPECIMEN TABLE	1
18	SOLENOID	1
19	SOLENOID FRAME	1
20	(SPECIMEN)	-

Fig. 3.6 (Continued):

21	BED BLADE	-
22	SPECIMEN SUPPORTER	1
23	SLIDE BEARING	2
24	GUIDE PIN	2
25	OPTICAL DISC	1
26	SHOCK ABSORBER	4
27	PHOTOELECTRIC SENSOR (POSITIONING)	1
28	PHOTOELECTRIC SENSOR (REV. COUNTER)	1
29	ELECTROMAGNETIC CLUTCH HOUSING	1
30	PHOTOELECTRIC SENSOR	1
31	PHOTOELECTRIC SENSOR	1
32	ENCLOSURE BASE	1
33	ENCLOSURE LEG	4

Fig. 3.6 (Continued):

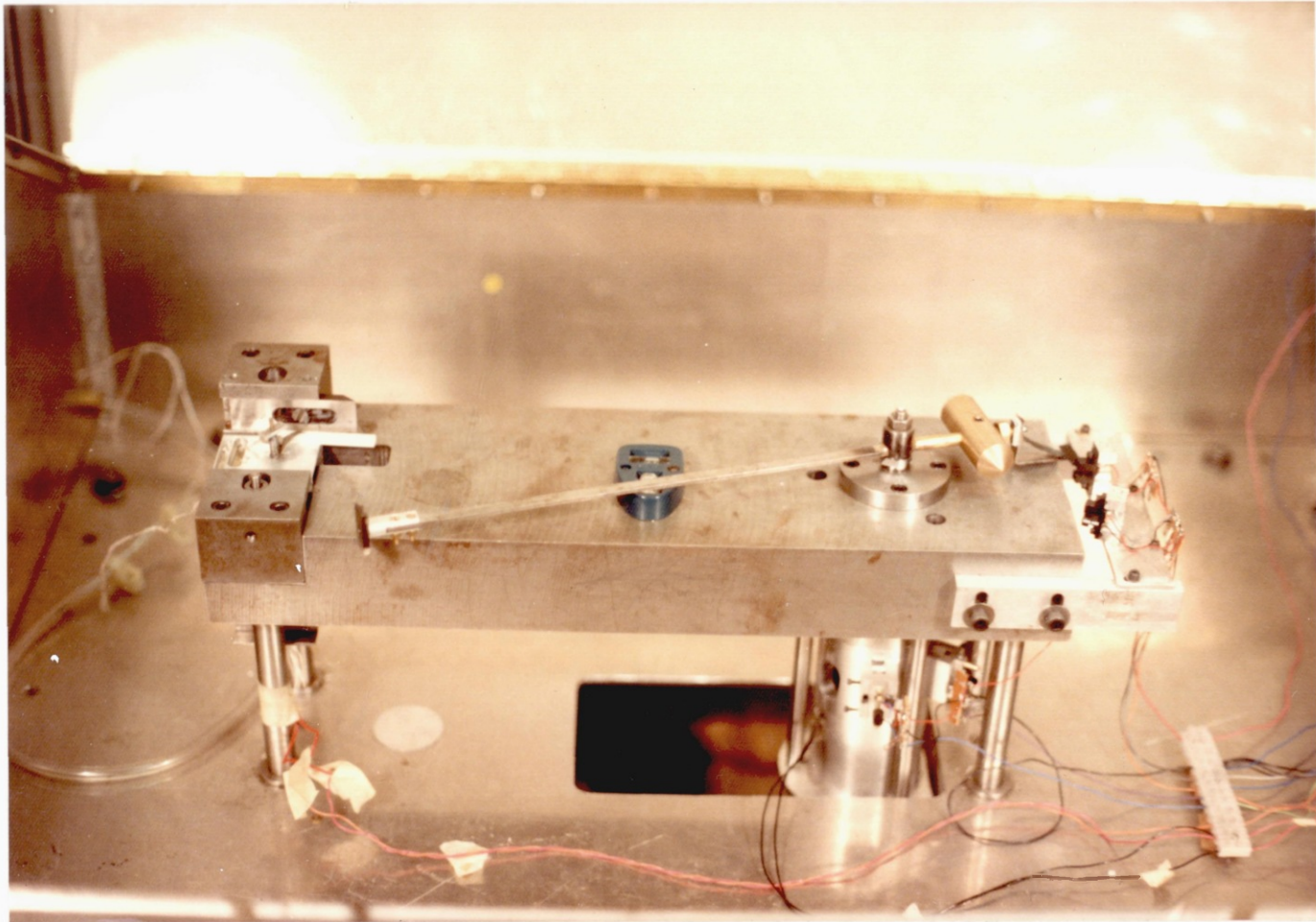


Fig. 3.7: High Speed Cutting Machine.

CHAPTER 4

INSTRUMENTATION FOR CONTROLLING THE OPERATION OF THE TESTING MACHINE AND DATA ENERGY MEASUREMENT

SUMMARY

For high speed tests, it is necessary to employ an efficient high resolution precision instrument to control the operation of the testing machine and to obtain the required data from the test. Therefore an instrument was designed and built for controlling the operation of the testing machine to measure the angular velocity of the rotating arm and the change in the arm rotating speed due to impact. The design uses optocouplers to sense pulse rates proportional to velocities and an associated analogue digital system to convert the pulses for measurement and display of time intervals.

4.1 INTRODUCTION

Traditional methods for velocity measurements in the application of impact tests such as accelerometers and resistance slide wires, cannot easily be adapted for use with the testing machine, since they require mechanical linkage to the rotating arm of the testing machine.

Possible alternative methods involve the use of optical techniques where the detailed measurement of the change in velocity of a freely rotating arm during the impact period can be made. The most common optical techniques are:

- collimated light beam and photocell (photoelectric sensor)
- Laser-Doppler velocimetry.

Optical methods have general advantages in all high speed testing in that there are no inertia problems involved. Neither the moving parts of the testing machine nor the specimen, are directly in contact with any mechanical parts or electrical leads, and can be observed from a remote location. The first technique would generally require a light source, a lens system and a photocell, if the speed of a body can be made to control the amount of light from the source reaching the photocell detector, an electrical signal can be obtained proportional to the speed. Details of the second technique (Laser-Doppler velocimetry) have been given by Durst et al (83) and by Vlachos (84). A diagram of the optical arrangement of the Laser-Doppler velocimeter is shown in Fig. 4.1. In the diagram, a prism divides a single laser beam into two parallel beams of equal intensity. A lense L_1 focuses the laser beam on to an intersection region through which the surface of a

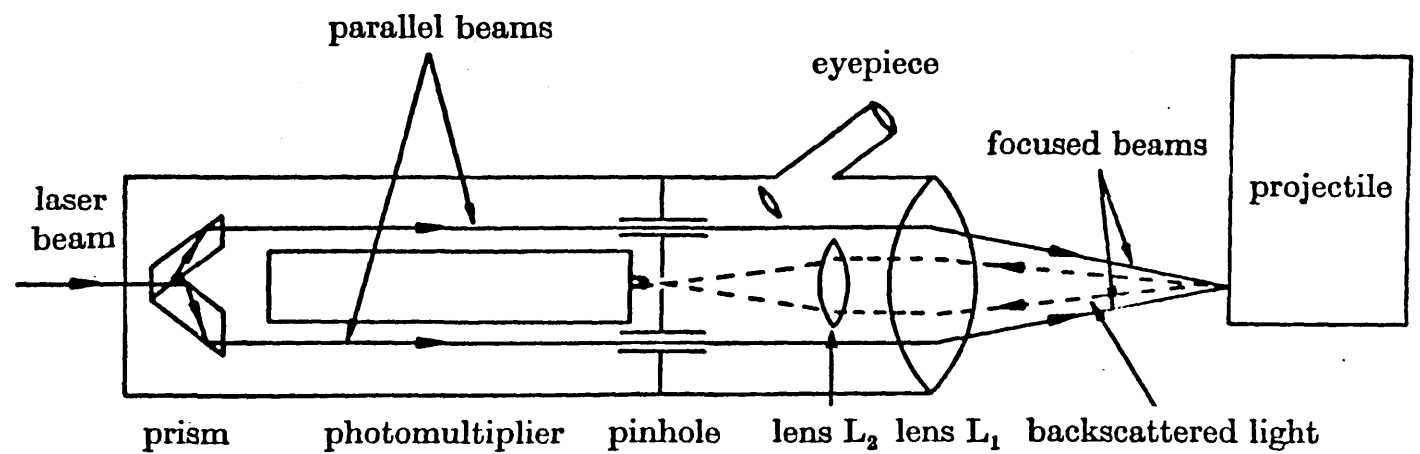


Fig. 4.1: Optical Arrangement of the Laser-Doppler Velocimeter.

projectile passes. Back-scattered light from the surface of the moving projectile in the measuring volume is focused by a second lens L_2 through an adjustable pinhole, and collected by a photomultiplier. The frequency of the two incident light beams is Doppler-shifted by the moving projectile, and the difference in the two resulting frequencies is observed by the photomultiplier. This frequency difference is a function of the projectile velocity where it can be calculated. This method has been shown by Hodgkinson et al (85) to be successful for velocity measurements up to 2.5 m/sec in drop weight impact tests. However, a disadvantage of this technique is that at high test speeds, velocity measurements would be greatly affected by any vibration of the striker and this possibly would present serious problems of accuracy and repeatability. This technique, in addition to its intrinsic cost requires expensive instruments to store and process its output.

The first technique was chosen for the velocity measurements of the testing machine because of its simplicity and also its low cost, which would give the testing machine further attraction commercially, especially to the various tester manufacturers who showed their interest towards the testing machine in its early stages of design.

4.2 THE MEASUREMENT SYSTEM

A schematic diagram of the optical mechanical system is shown in Fig. 4.2. The system consists of the following:

- segmented disc (optical disc).
- photo electric sensors (which include both a light source and emitter).
- vane.

The angular velocity of the striker is found by counting the number of pulses that are produced from photo electric sensor 2. These pulses are generated as a result of the segmented disc passing under the light source of sensor 2.

Sensor 1 is used to detect the position of a reference segment on the optical disc to allow the clutch to be disengaged and the solenoid to be energized.

The speeds of the striker prior to and after impact are obtained by measuring the period of time that sensors (3) and (4) respectively are obscured by the vane mounted on the rear end of the arm. The speed prior to and after impact are related by:

$$V_1 = \frac{K}{T_1} \quad (1)$$

$$V_2 = \frac{K}{T_2} \quad (2)$$

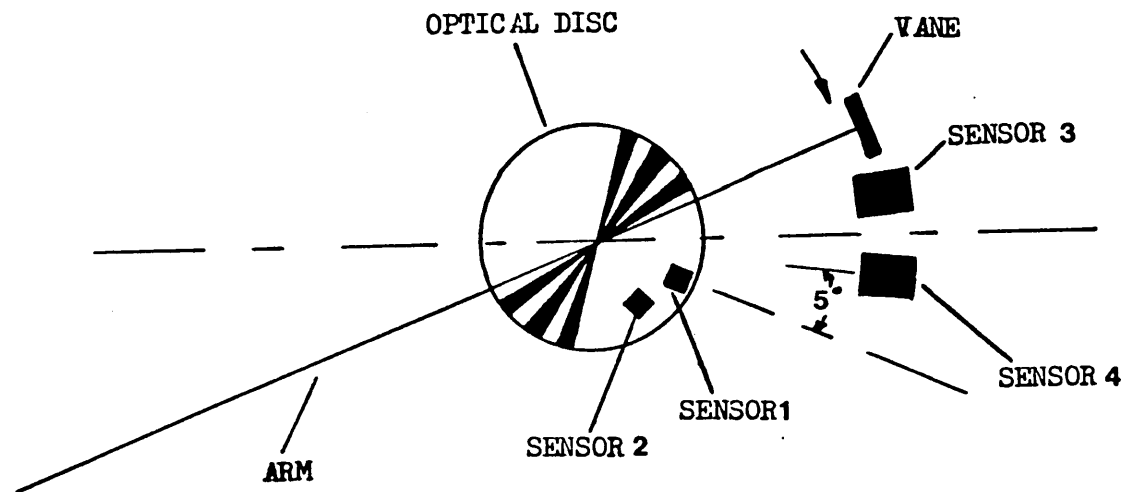


Fig. 4.2: Schematic Diagram of the Optical System (Plan View).

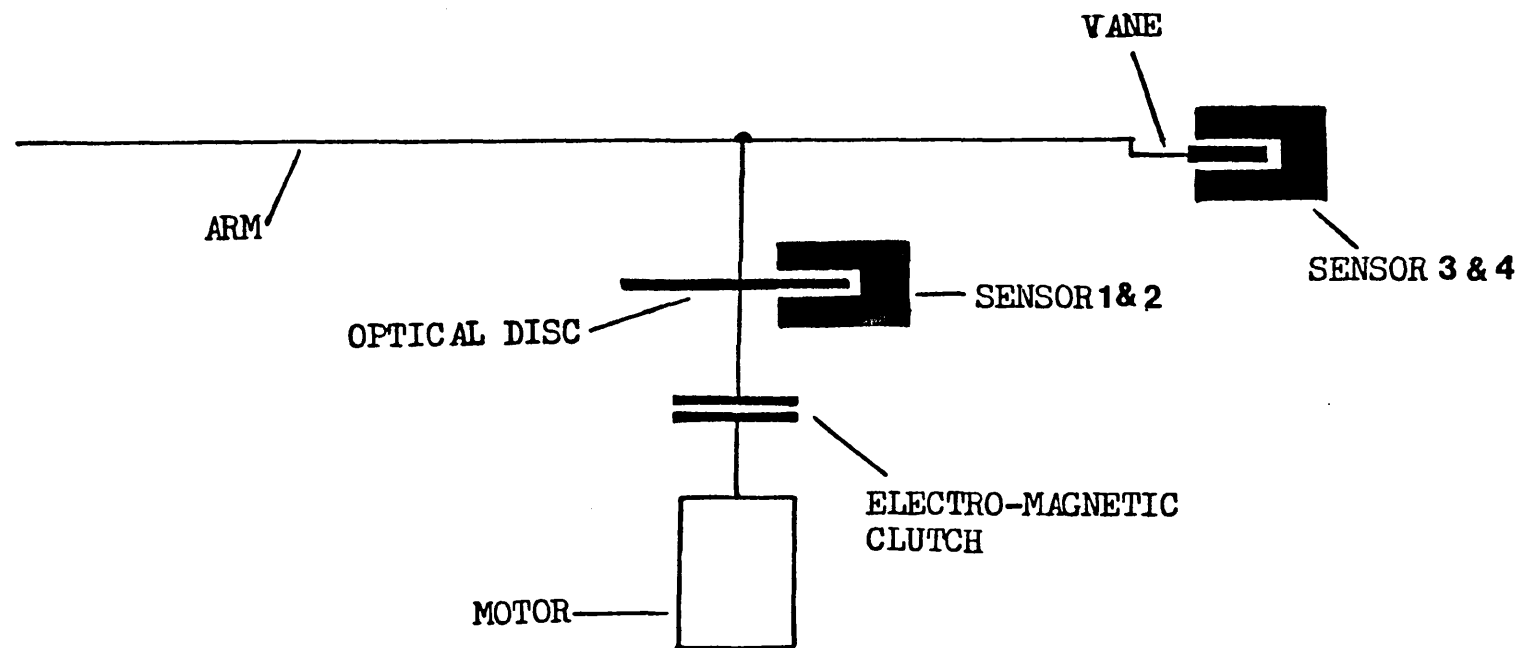


Fig. 4.2.1: Schematic Diagram of the Optical System (Side View).

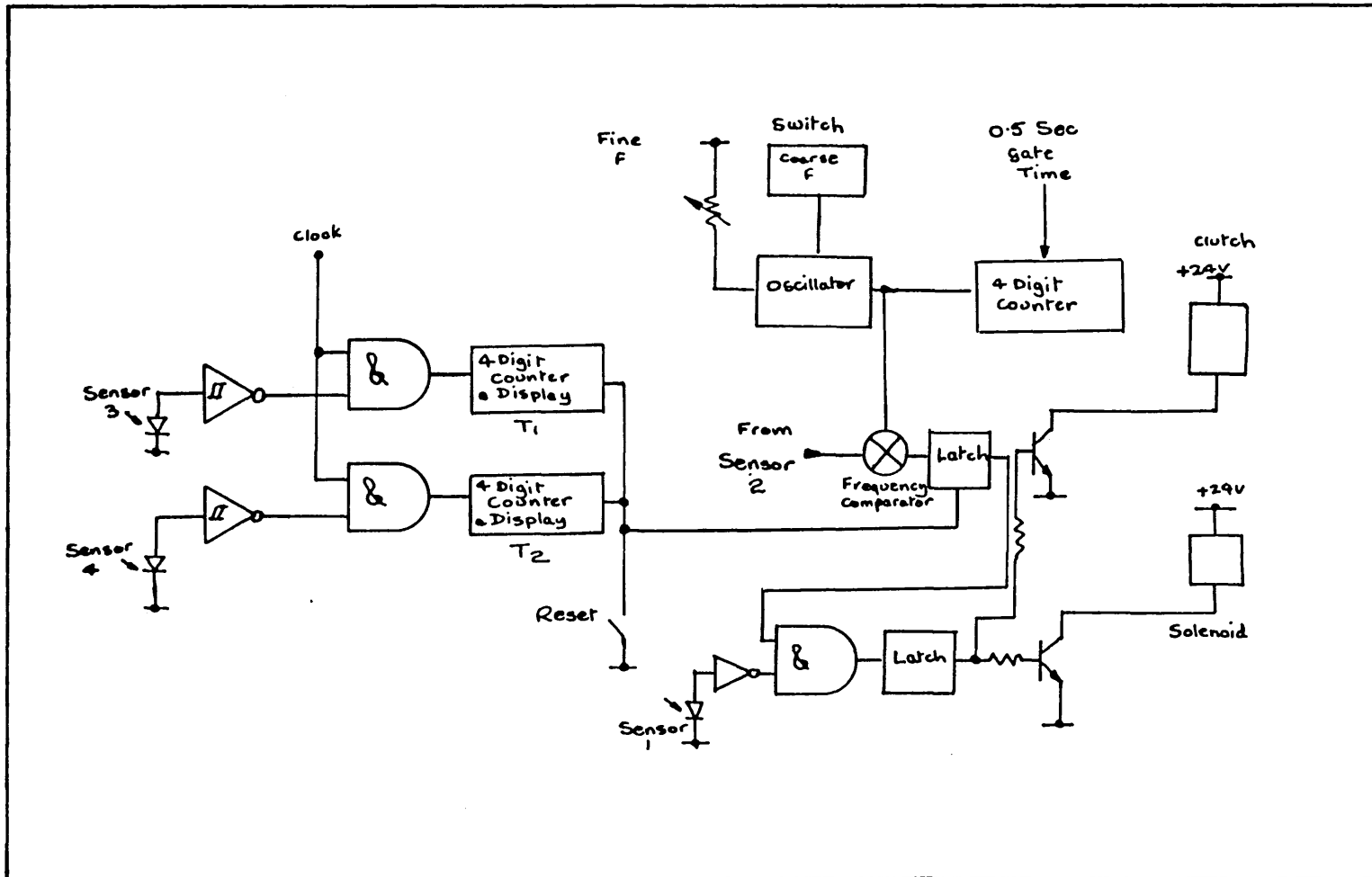


Fig. 4.3: Block Diagram of the Velocity Measurement System.

where K is a constant depending on the length of the vane. T_1 and T_2 are the measured times.

Design details are given in Section 11.4.

4.3 OPERATION OF THE MEASURING SYSTEM

The complete circuit diagram is shown in Figs. 4.4 and 4.5. This circuit can be divided into two separate functions as follows:

4.3.1 Control Unit and Revolution Counter

The output of photoelectric sensor (2) is of square wave form with a frequency (F) equal to the motor speed multiplied by the number of segments on the optical disc. This frequency is compared in a phase/frequency comparator Ic_1 with a reference frequency (Fr) of a preset oscillator consisting of Ic_5 . (Ic_5 is a free-running pulse generator having frequency-determining components (C,R). Course selection is made by switching the capacitor valve. Fine frequency-control is obtained with a variable resistor.)

Assuming the reset button has been pressed to set the initial conditions, when (F) just exceeds (Fr), the output of the comparator falls resetting latch Ic_{3a}

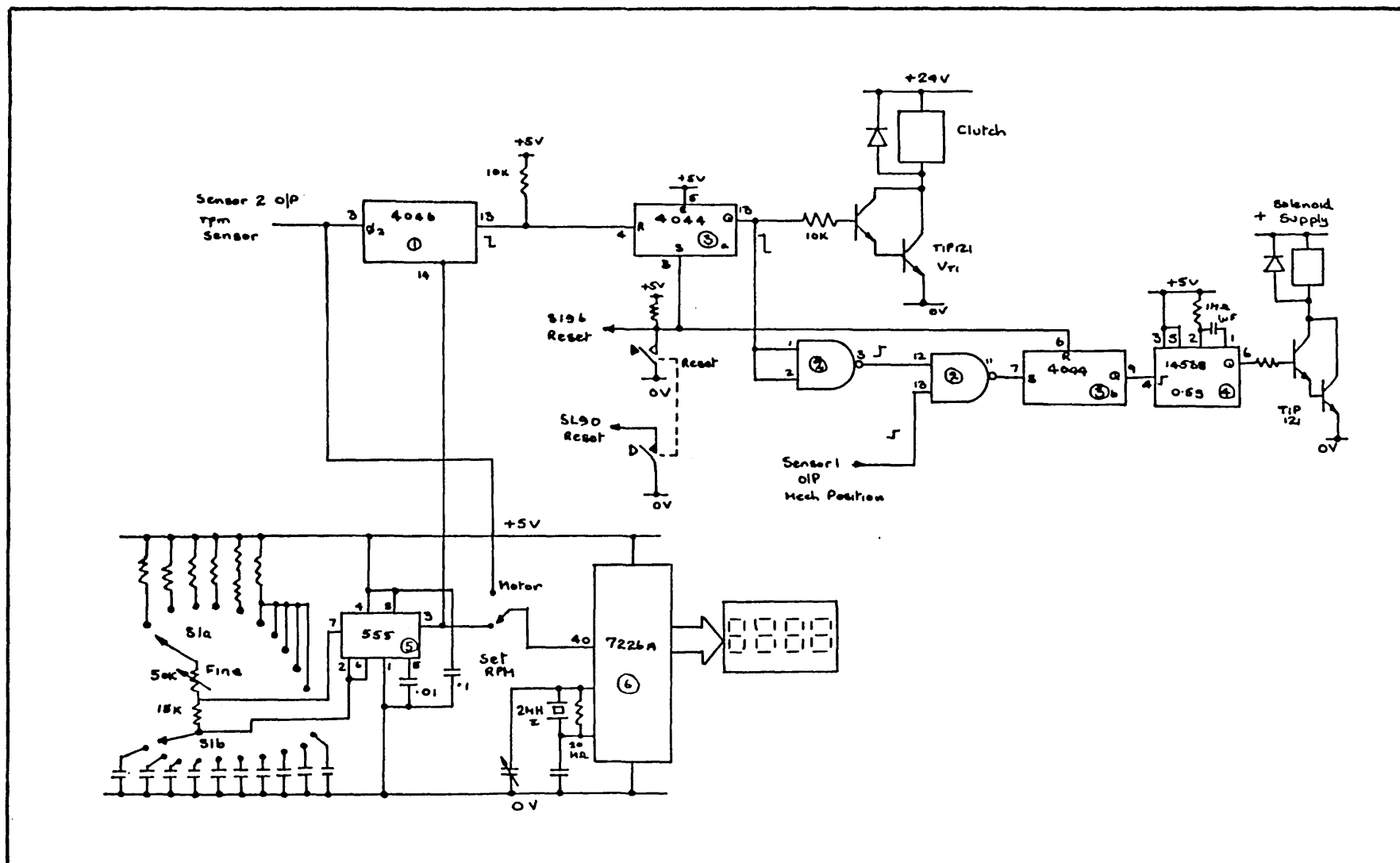


Fig. 4.4: Revolution Counter Measurement and Control Systems Circuit Diagram.

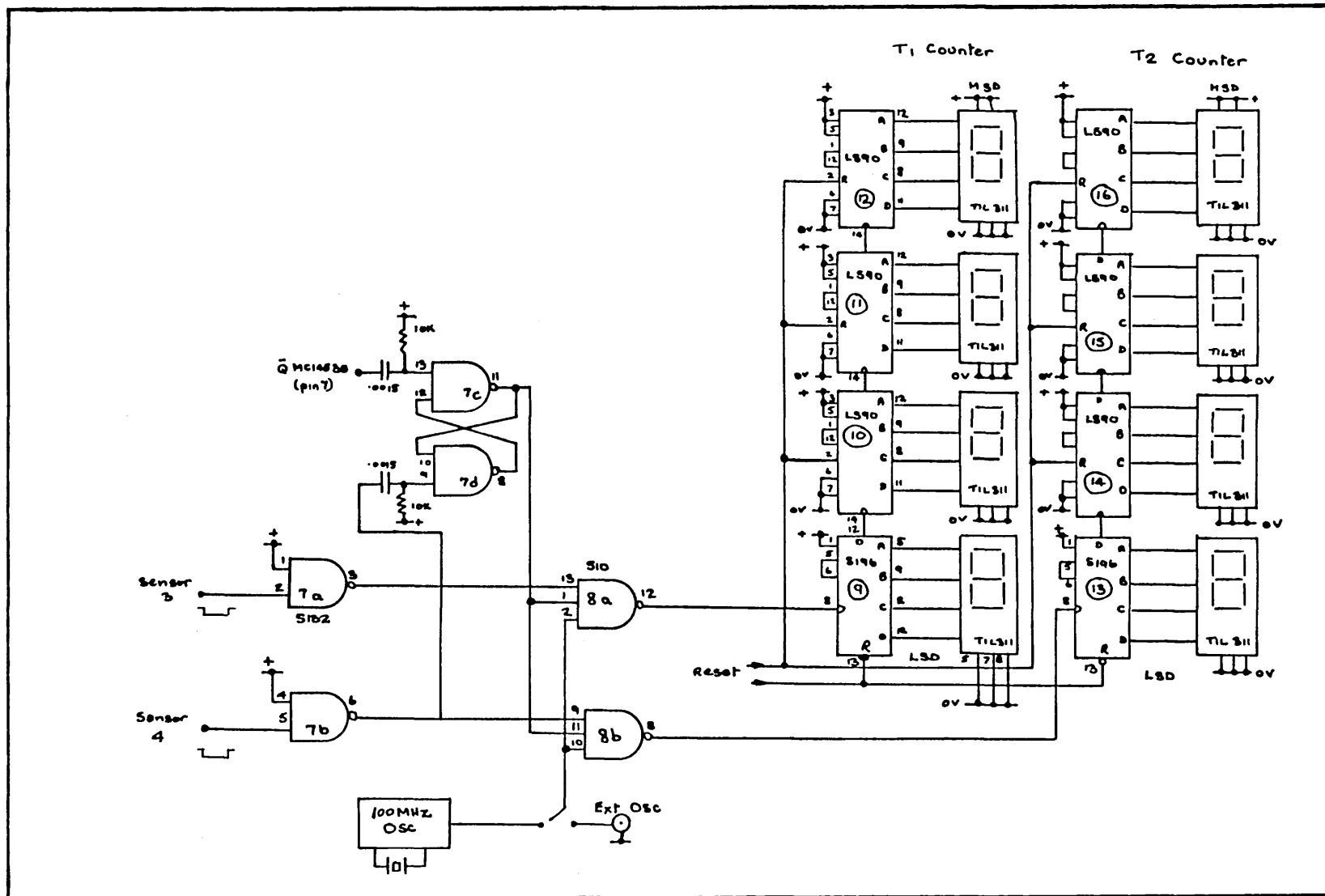


Fig. 4.5: Vane Measurement System Circuit Diagram.

(a set/reset latch). The output of Ic_{3a} goes low and is inverted by NAND gate Ic_{2a} whose output then goes high to energize NAND gate 2b. This NAND gate is primed ready to receive the input from the mechanical position sensor (1), as soon as the output from sensor (1) goes high. The output of the NAND gate 2b goes low, which sets latch Ic_{3c} , causing the clutch to be deactivated and latch Ic_{3b} to be set. The output of this latch also energizes the monostable Ic_4 , to give a pulse output of approximately 1.7 sec driving V_{T2} into conduction and energizing the solenoid.

The output of Ic_5 can be continuously monitored by counter Ic_5 which is a counter and display unit. This is controlled by a crystal having a resonant frequency of 2 MHZ, giving a gate time of 0.5 sec, so that for a disc having 120 segments, the speed is displayed directly in r.p.m. on a 4-digit LED display. The motor speed can be monitored by switching the counter to the output of sensor (2). Fig. 4.6 shows control and revolution counter sensors.

4.3.2 Vane Time Measurements

Ic_{7a} and Ic_{7b} are dual input NAND Schmidt triggers, used as inverters and a high speed device to sharpen up the pulse edges. The latches Ic_{7c} and Ic_{7d} are primed by the Q output of the monostable Ic_4 so that

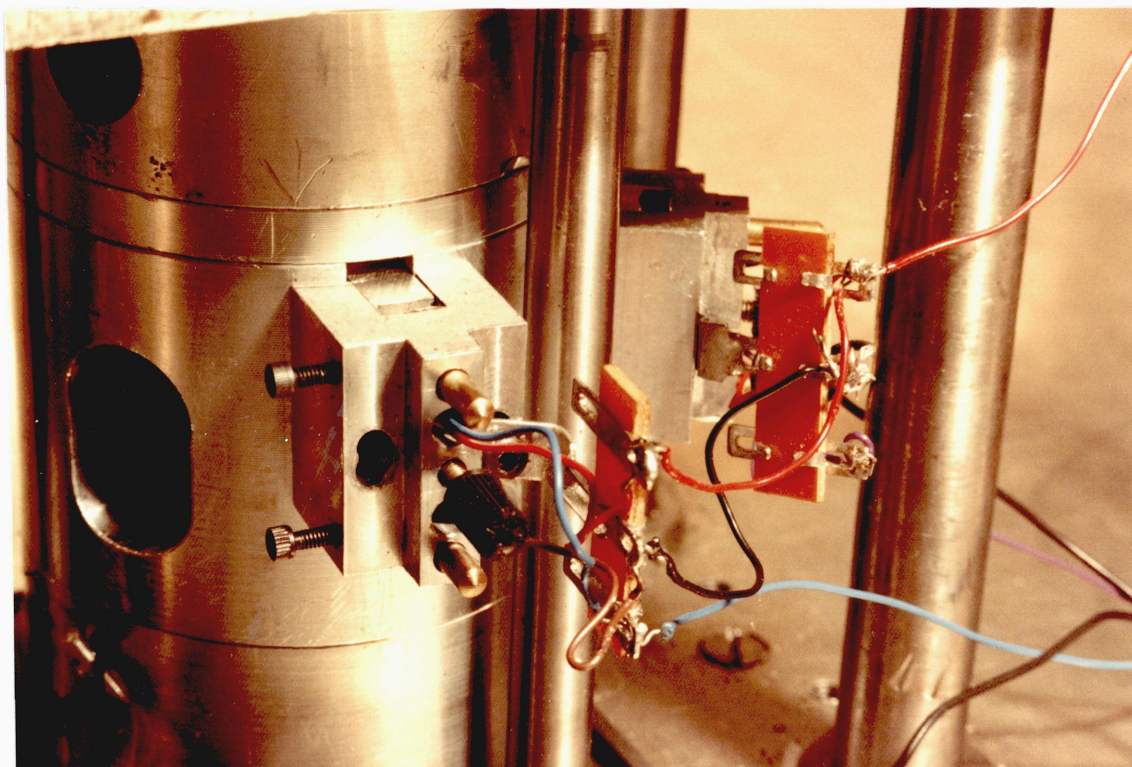


Fig. 4.6: Control and Counter Revolution Sensors.

when the vane comes around in the next revolution, they allow a train of pulses to be passed through NAND gates Ic_{8a} and Ic_{8b} the number of pulses passed is a direct measure of the obscuration time of sensors Nos. 3 and 4. The pulses are derived from 100 MHz stable crystal oscillator giving a time measurement in increments of 10 n seconds. The times before and after impact are measured on counters T_1 and T_2 . Counters T_1 and T_2 consist of decade counters $Ic_9 - Ic_{12}$ and $Ic_{13} - Ic_{16}$ respectively. The times are displayed on a separate 4-digit display and are a function of the arm speed. Speed measurements sensors and the complete measuring system are shown in Figs. 4.7 and 4.8.

4.4 ERROR ANALYSIS

The average repeatability of the measurement system was found to be of the order of 0.1% (Table 4.1)

4.4.1 Factors Affecting the Accuracy of the Angular Velocity Measurements

4.4.1.1 Electronic Component Factors

There are a number of possible sources of error in the measurement of motor speed, these include the stability of the oscillator and the frequency-determining components (C and R), the wave form of the input frequency, the reference frequency and the gating circuit. The oscillator

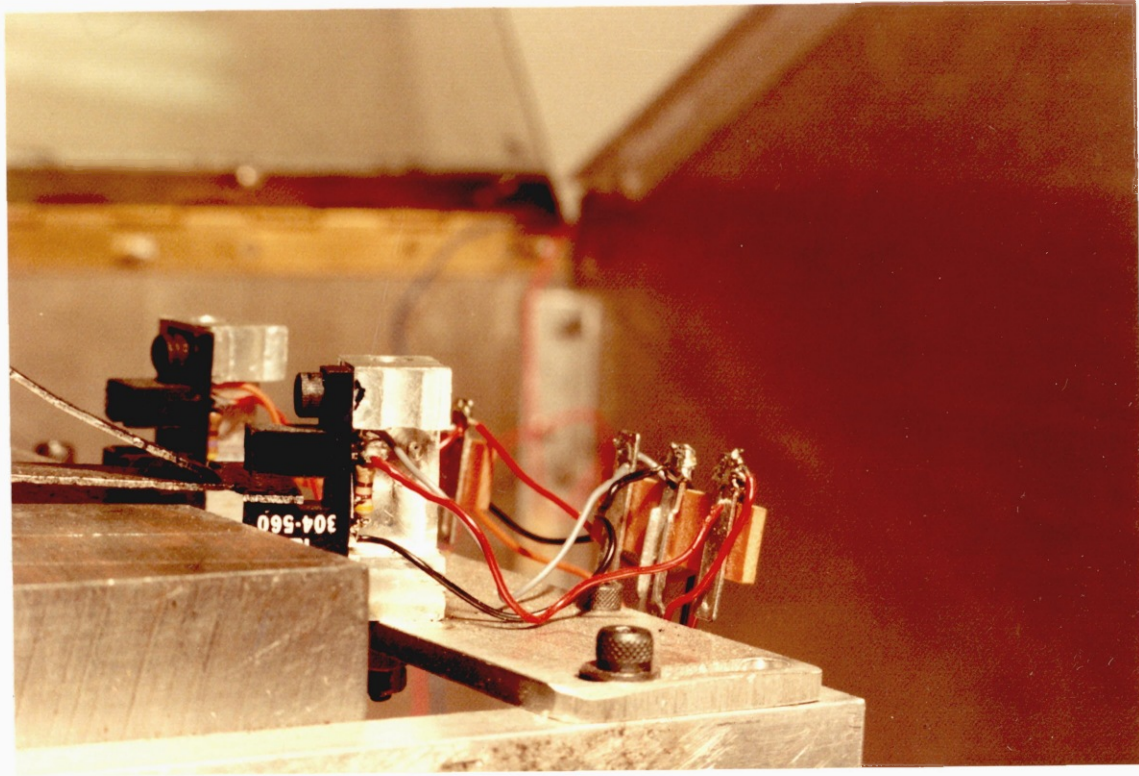


Fig. 4.7: Speed Measurements Sensors.

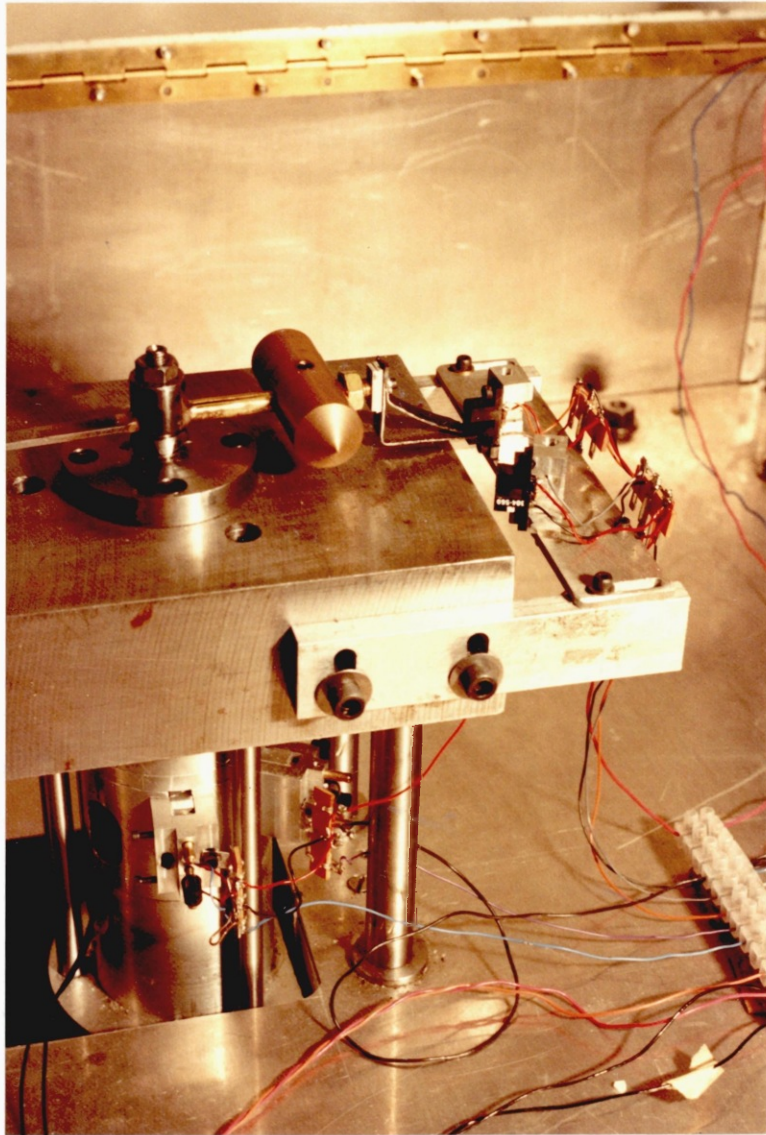


Fig. 4.8: The Machine Control and Measurements System.

and (C and R) must be stable and reliable in operation, similarly, both input frequency (F) and reference frequency (Fr) must be noise-free and stable, i.e. free from internal, external interference and jitter, otherwise a random variation in the comparison between (F) and (Fr) would occur and the direct result would be inaccurate measurement of motor speed and variation in the switch off speed. For the gating circuit the ideal performance is achieved when the gate opens and closes with zero delay time with respect to the gating wave form. This may result in a counter reading not exactly proportional to gate times.

4.4.1.2 Mechanical Factors

On the mechanical side, factors which have an effect on the stability of the input frequency (F) include the following:

- the optical disc (the manufacturer of this particular disc claimed an error of 0.05% in dividing the disc into segments).
- variation of the instantaneous speed of the electric motor driving the optical disc.

- the error in setting the disc from its true centre in the absolute horizontal plane with respect to the photoelectric sensor.

4.4.2 Factors Affecting the Accuracy of Vane-Speed Measurements

The major factors affecting the accuracy of vane-speed measurements are:

- the electromagnetic clutch (the manufacturer of the clutch claimed that the time require for the clutch to disengage is 5 milliseconds $\pm$ 1%)
- the vibration of the mechanical system: the infra red source and detector have rise and fall times of 1 μ sec and 20 nano sec respectively, the incremental time scale derived from 100 MHZ clock allows measurement discrimination to be taken to 0.01 microsec, and since this time is so short, the vibration of the mechanical parts may have an effect on the times displayed.

4.5 CALIBRATION OF THE SYSTEM

As mentioned earlier, sources of measurement inaccuracy could be electronical or mechanical. To assess the

contribution of each part, it was decided to calibrate the electronic side.

To examine the stability of the reference frequency oscillator, a frequency synthesizer (Type: Philips-PM-5134) was used as a pulse generator. Its frequency was fed directly to the comparator and used as (FR). A series of tests for time measurements at different speeds were conducted, it was noticed that there was no improvement in the repeatability of the measurements. This test showed the reliability of the pulse generator of the system.

To examine the stability of the frequency-determining components, the following tests were carried out: the input frequency (F) from the optical transducer was eliminated from the comparator, the frequency synthesizer was substituted for the optical transducer output and set for an output of 2000 pulses (equivalent to a speed of 1000 r.p.m.). This frequency was compared to the number of pulses equivalent to a setting speed of 1000 r.p.m.

The accuracy of the variable-frequency oscillator and its frequency-determining components, was found to be of the order of 0.01%. A series of similar tests at different setting speeds was carried out which gave the same level of accuracy. The previous test gave a measure of the stability of the reference frequency source.

An oscilloscope (Type: Medelec-SM19.74.1) was used to examine the input frequency wave form. The test showed that there was jitter present with maximum peak to peak value of 6 microseconds. .

The calibration tests gave the conclusion that the main source of error in the system is related to the input frequency which is a direct result of the normal Engineering tolerance.

4.6 CONCLUSION

The system met the following requirements for a high-speed cutting-testing machine:

- repeatability of speeds within 0.1% (Table 4.1)
- range of operating speeds could be as high as 100 m/sec
- besides its low cost (£200) and its compact size, the system is flexible for additional processing for its output data and for further modifications.

4.7 SUGGESTIONS FOR FURTHER MODIFICATIONS

To improve the accuracy of the system beyond 0.1% the following steps may be carried out:

- dynamic filtering of the input frequency

READING NO.	MEASURED SPEED (m/sec)
1	30.01
2	30.009
3	30.007
4	30.003
5	30.007
6	30.009
7	30.006
8	30.007

Table 4.1: Arm speed Measurements at
Preset Speed of 30 m/sec.

- a drive motor maintaining its speed at a predetermined value,
- an optical disc with a higher number of segments and using photoelectric sensors with greater resolving power,
- eliminating the residual magnetism from the clutch after being switched off.

CHAPTER 5

ENERGY MEASUREMENTS IN CUTTING OF POLYMERS

AT ROOM TEMPERATURE

5.1 INTRODUCTION

The parameters under investigation are listed in Section 1.5. The work programme involved examining the influence of each parameter on energy absorbed in cutting. Results of tests where changing the parameter did not show any marked effect, have only been described briefly, whilst all other test results are given.

In comparing the test results, energy absorbed in cutting is evaluated in terms of energy absorbed per unit area of the surface created as a result of cutting.

5.2 EXPERIMENTAL PROGRAMME

5.2.1 Materials

Since the cutting mechanism and fracture behaviour of different polymers is likely to vary in the granulator, it was thought appropriate to investigate the cutting of several materials in this programme. Since polymeric materials have a variety of mechanical properties, all of the experiments were carried out on seven different

types of polymers. Sheets of different materials were obtained from a variety of resin manufacturers, it was noted that several processing methods were involved:

- LDPE BP Rigidex HO-60-45P injection moulded
- PP (Homo polymer) ICI compression moulded
- PC Bayer Makrolon extruded
- ABS Monsanto LUSTRAN ABS 244 injection moulded
- PVC Modified BP Breon PVC injection moulded
- HIPS BP (CP40) injection moulded
- PMMA ICI compression moulded

5.2.2 Testing Conditions

The specimens used throughout the investigation were cut from sheets using a circular saw. (Although milling produces superior specimen surface finish, the circular saw was preferred because of the large number of specimens required). Specimen dimensions are shown in Table 5.1. Most specimens were of cross section 3 mm by 3 mm although other specimens were used up to 6 mm by 3 mm to assess any size effect. All specimens were of length 50 mm. Specimen dimensions were measured carefully by a micrometer.

All the materials were stored and tested in an air conditioned laboratory maintained at a temperature of $20^{\circ}\text{C} \pm 1^{\circ}\text{C}$ and a relative humidity of $50\% \pm 1\%$.

Material	Specimen Dimensions (mm)	
	Width (W)	Thickness (B)
LDPE	3	3
PP	3	3
PC	1.5	3
ABS	2.5	3
PVC	3	3
HIPS	3	3
PMMA	3	3

Table 5.1: Specimen Dimensions of the Various Materials Tested.

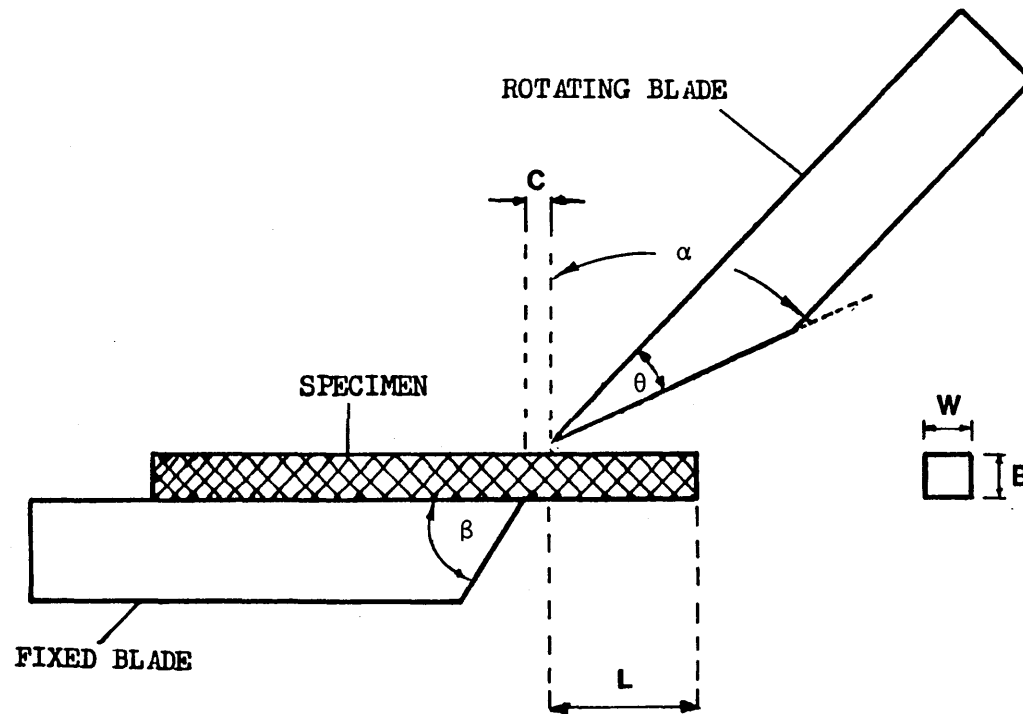


Fig. 5.1: Parameters of Cutting Under Investigation.

- specimen thickness (B) the dimension normal to
the cutting edge of the
rotating blade

Some tests were also performed with a slanted blade to impart a guillotine type of cut and others with the rotating blade upside down.

5.2.3 Experimental Methods

The tests were performed at room temperature using the machine which has been described in Chapter 3.

The method involved in operating the testing machine is explained in Section 3.2.2.1.

The gap between the fixed blade and the rotating blade was measured using a feeler gauge. The correct setting was achieved by adjusting the fixed blade forward and backward.

The length of specimen to be cut was measured carefully, and marked, before the specimen was placed in its position on the testing machine table.

The radii of the tips of the blades were carefully checked under a microscope and regular inspections

were made during testing periods, so that the blade could be replaced if wear was evident.

The other cutting parameters were varied by either changing the blades or the rotating blade holder.

Energy absorbed in cutting was determined by the subtraction of energy loss in windage and bearing friction from the total energy loss during the impact period. Total energy loss during the impact period was considered to be the sum of the energy required to cut, the energy loss in windage and bearing friction and the kinetic energy of the cut part of the specimen. This total loss of energy was determined by the calculation of the energy of the rotating system of the testing machine just before and after the impact period. This was derived from the velocity information immediately before and after the contact between the rotating blade and the specimen and the knowledge of the mass moment of inertia of the rotating system. Energy loss in windage and bearing friction was determined in the same way, while the testing machine was running without a specimen in position.

Fig. 5.2 shows details of the apparatus used to carry out this study and Fig. 5.2.1 shows a specimen in position ready to be cut.

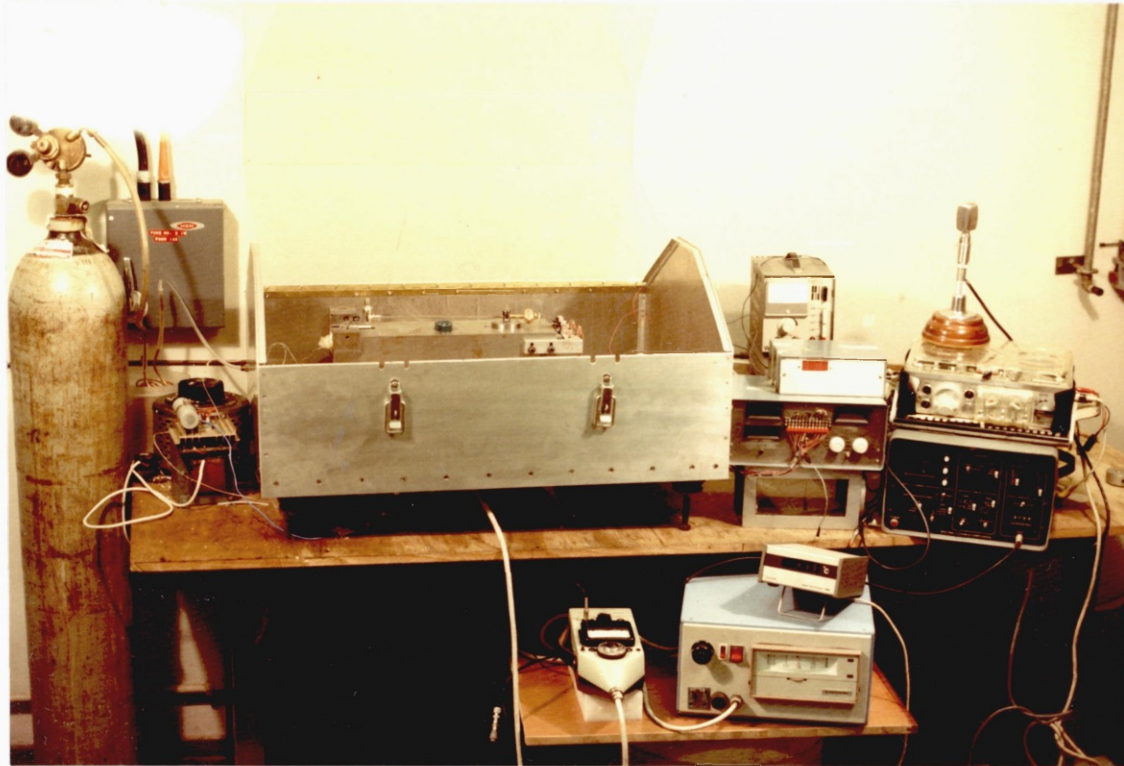


Fig. 5.2: Test Apparatus

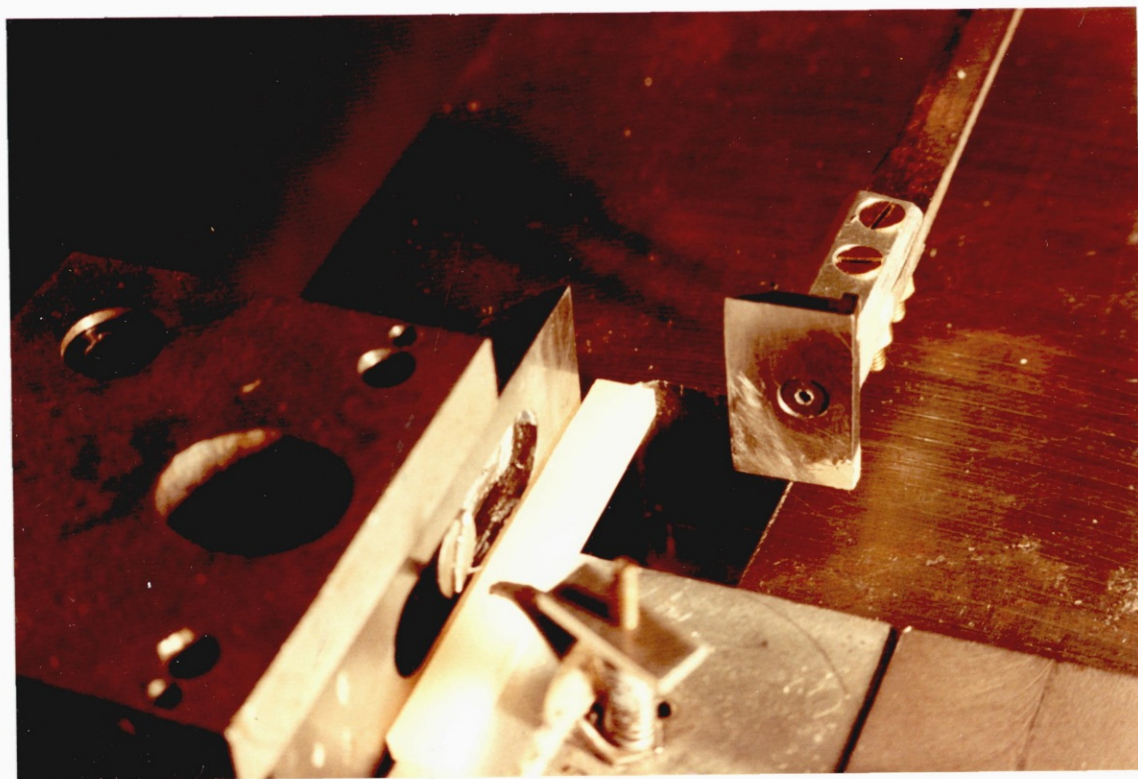


Fig. 5.2.1: A Specimen in Position Ready to be Cut.

5.2.4 Results

The most striking effect was that of cutting speed. This is shown in Fig. 5.3-5.9 for conditions which became those for the standard test: rotating blade tip radius 120 microns, and its cutting angle 20 degrees, fixed blade tip radius 120 microns and its cutting angle 45 degrees, angle of attack 25 degrees, clearance 0.1 mm and cut length 2 mm. It can be seen that there is a dramatic increase in cutting energy sometimes by a factor of five, as the speed is increased from 7 to 30 m/sec (Fig. 5.4). The materials shown in Figs. 5.3-5.6 differ from those in Figs. 5.7-5.9 in that the former demonstrate a clear peak in the curves whereas the latter appear to tend to an upper bound, although it is possible that a peak may be reached at very high speeds.

Figs. 5.3-5.9 also show the effect of cut length for all the materials tested. From the test results it can be seen that the cutting energy is dependent on the length of specimen to be cut. However, for materials such as LDPE, PP, PC and ABS (Figs. 5.3-5.6), the dependency of the cutting energy on length of specimen to be cut is clearer in the test speed range where the maximum cutting energy occurred. Above this range, there is less dependency between the cutting energy and the length of specimen to be cut. A cutting energy independent of cut length can be obtained by extrapolating the curves (Fig. 5.49a) to zero cut length.

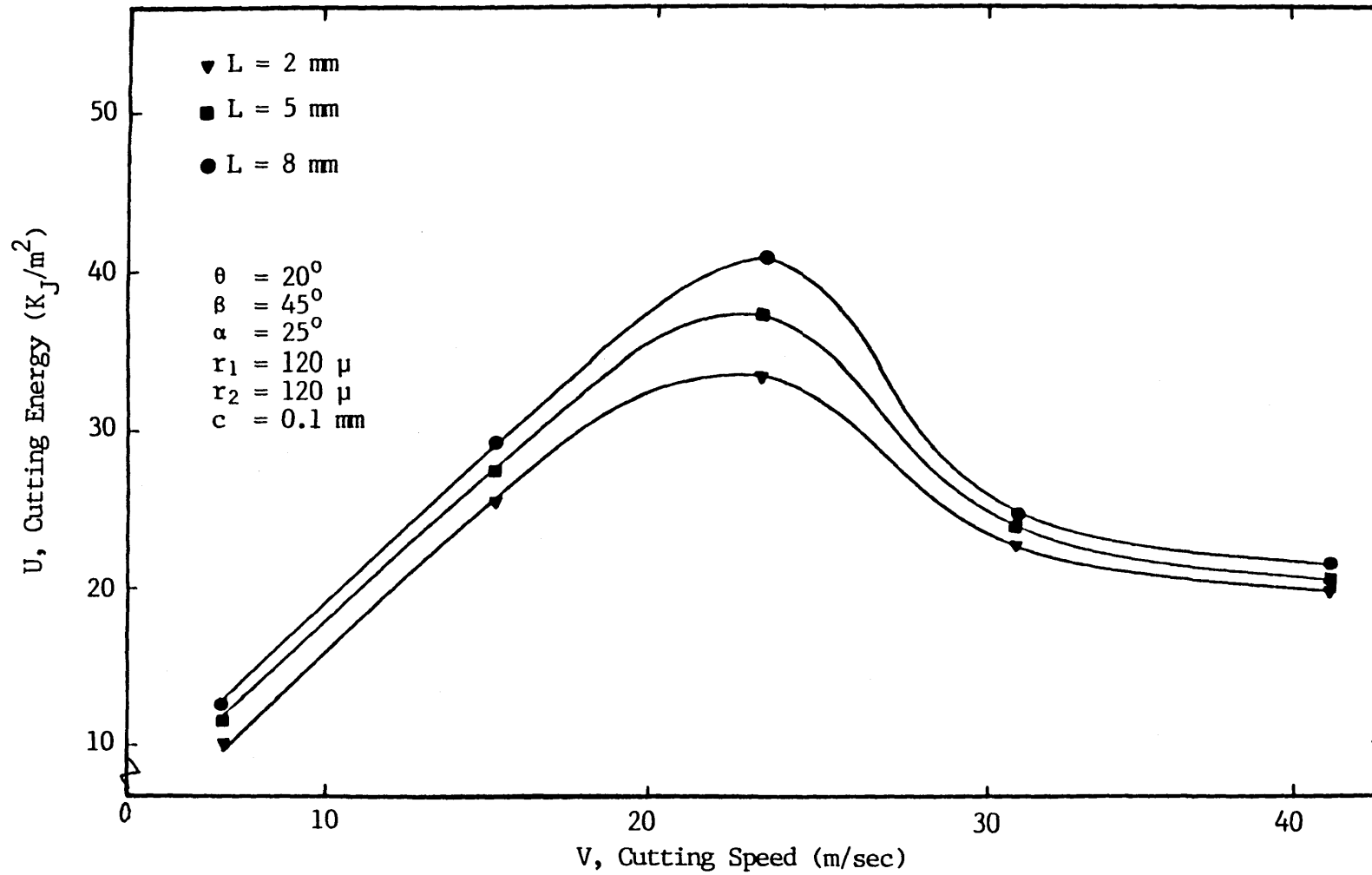


Fig. 5.3: LDPE - Cutting Energy Versus Cutting Speed for Several Specimen Lengths to be Cut.

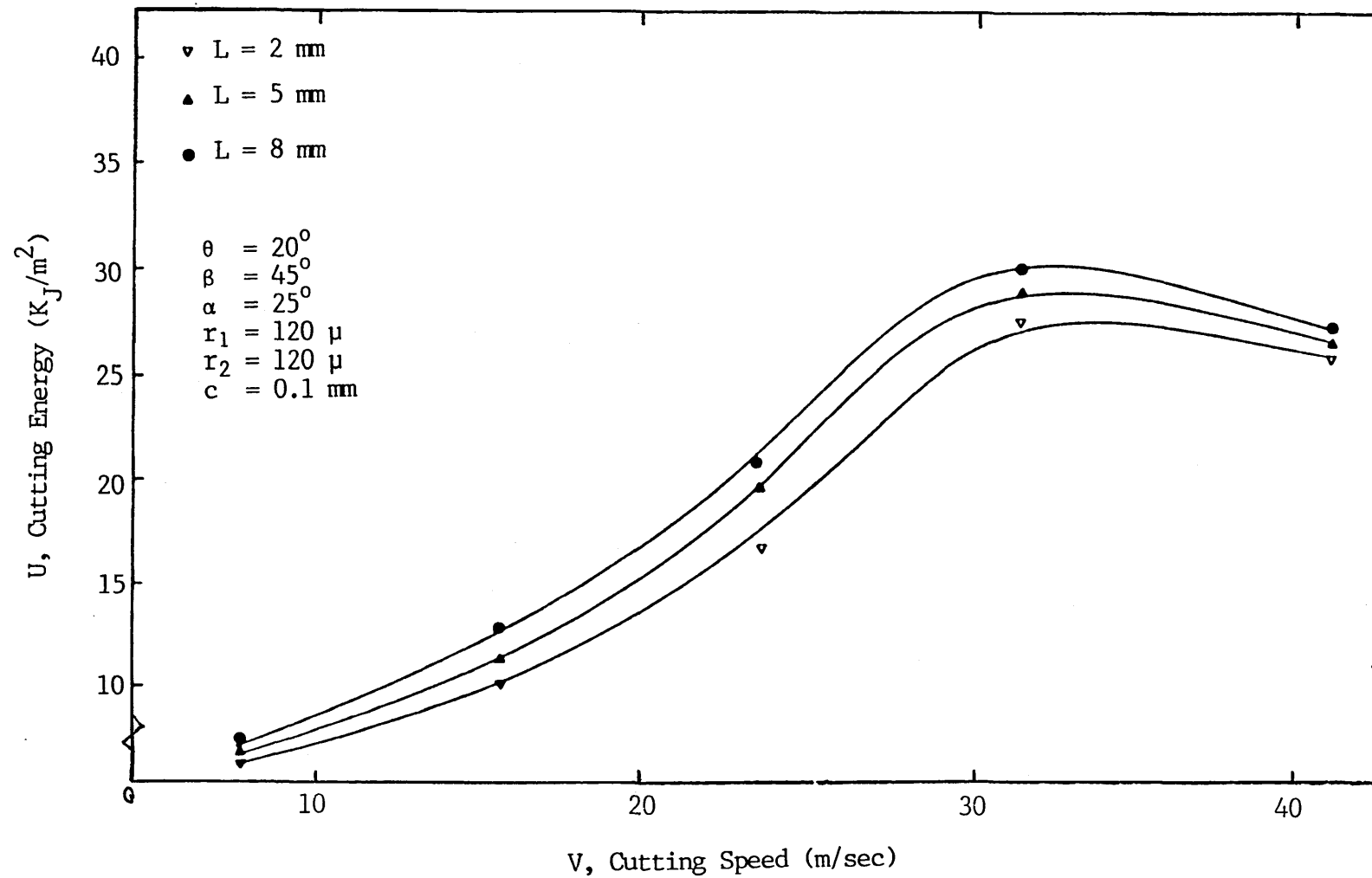


Fig. 5.4: PP - Cutting Energy Versus Cutting Speeds for Several Specimen Lengths to be Cut.

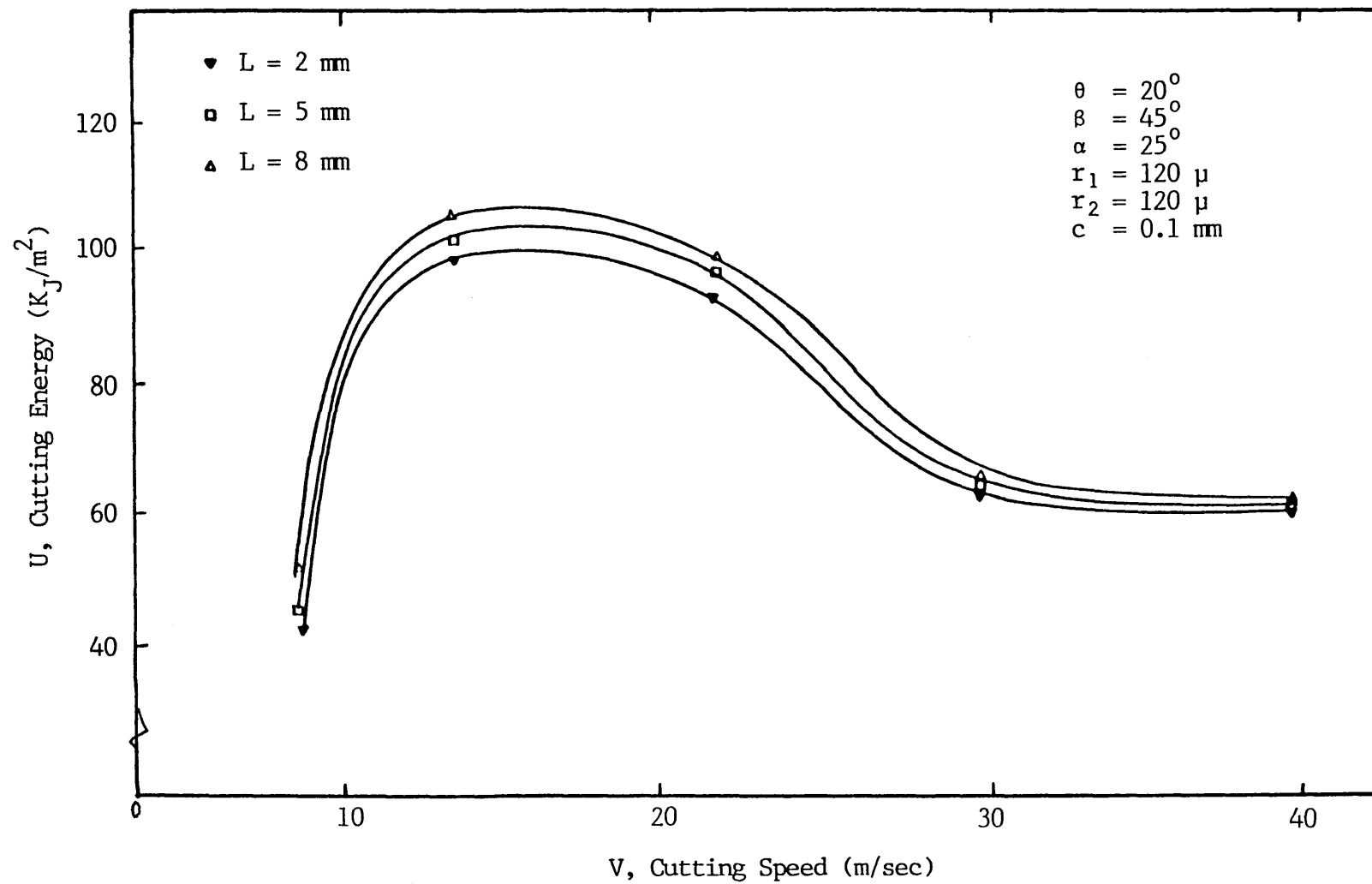


Fig. 5.5: PC - Cutting Energy Versus Cutting Speeds for Several Specimen Lengths to be Cut.

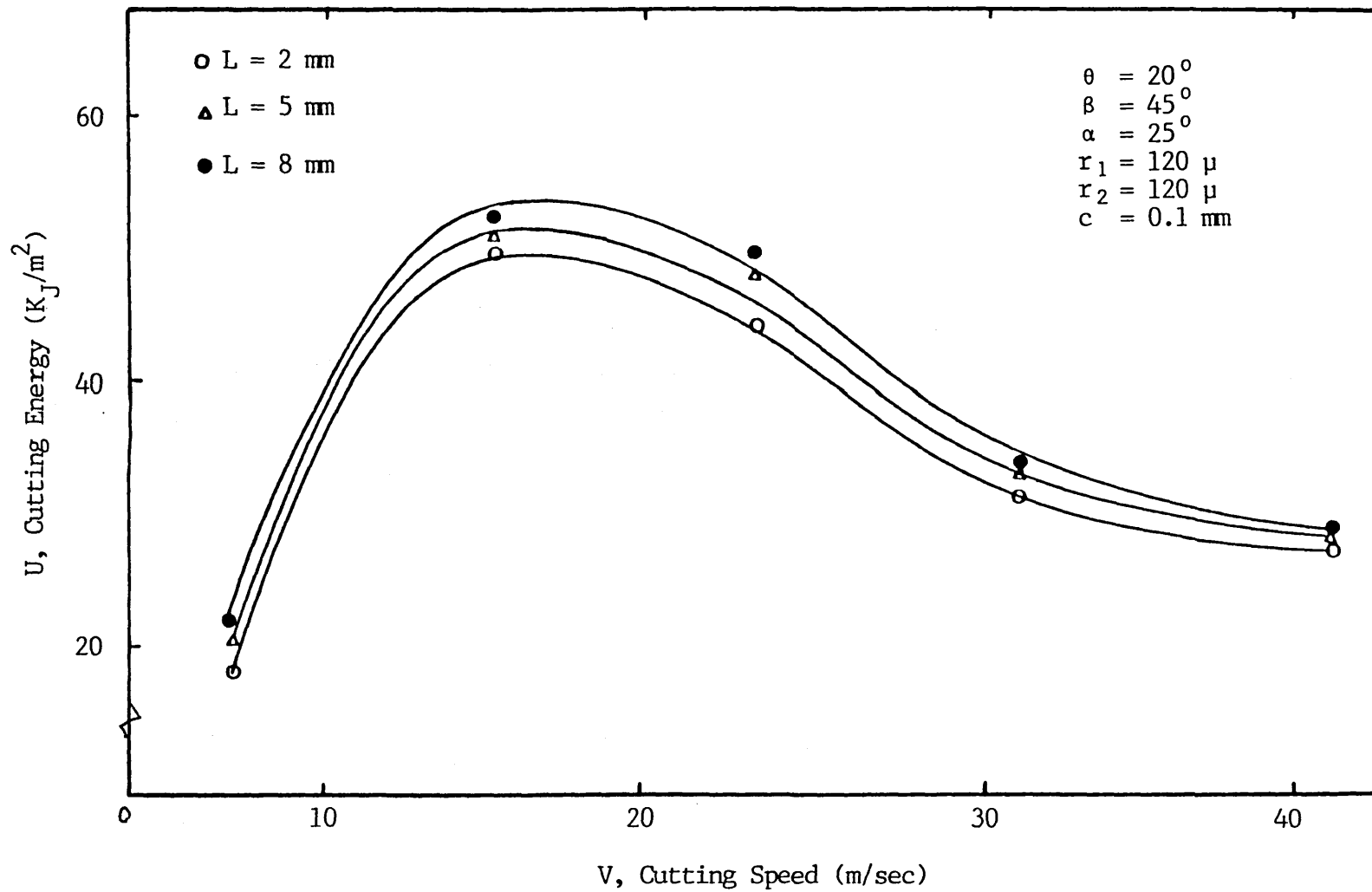


Fig. 5.6: ABS - Cutting Energy Versus Cutting Speeds for Several Specimen Lengths to be Cut.

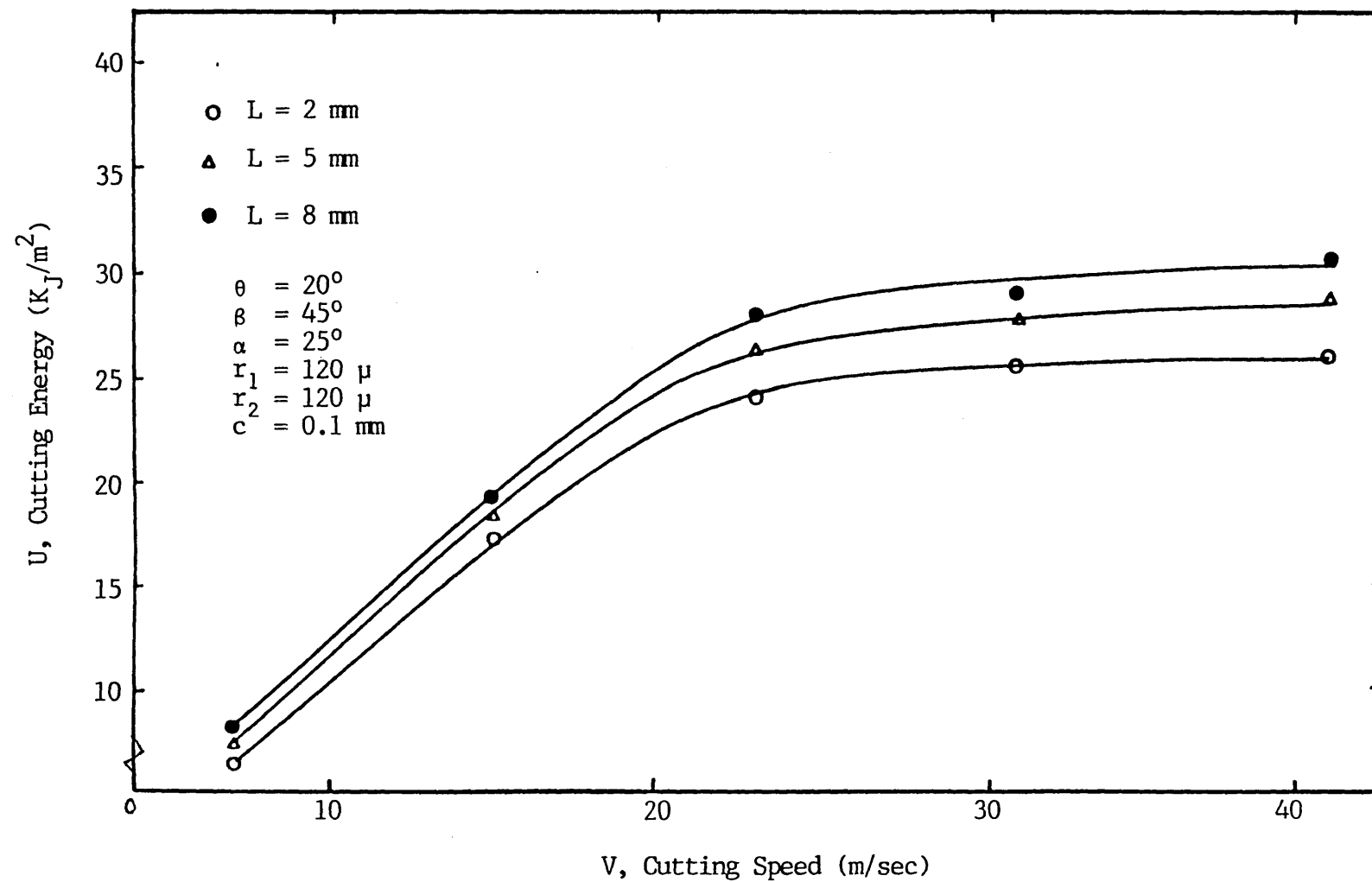


Fig. 5.7: PVC - Cutting Energy Versus Cutting Speeds for Several Specimen Lengths to be Cut.

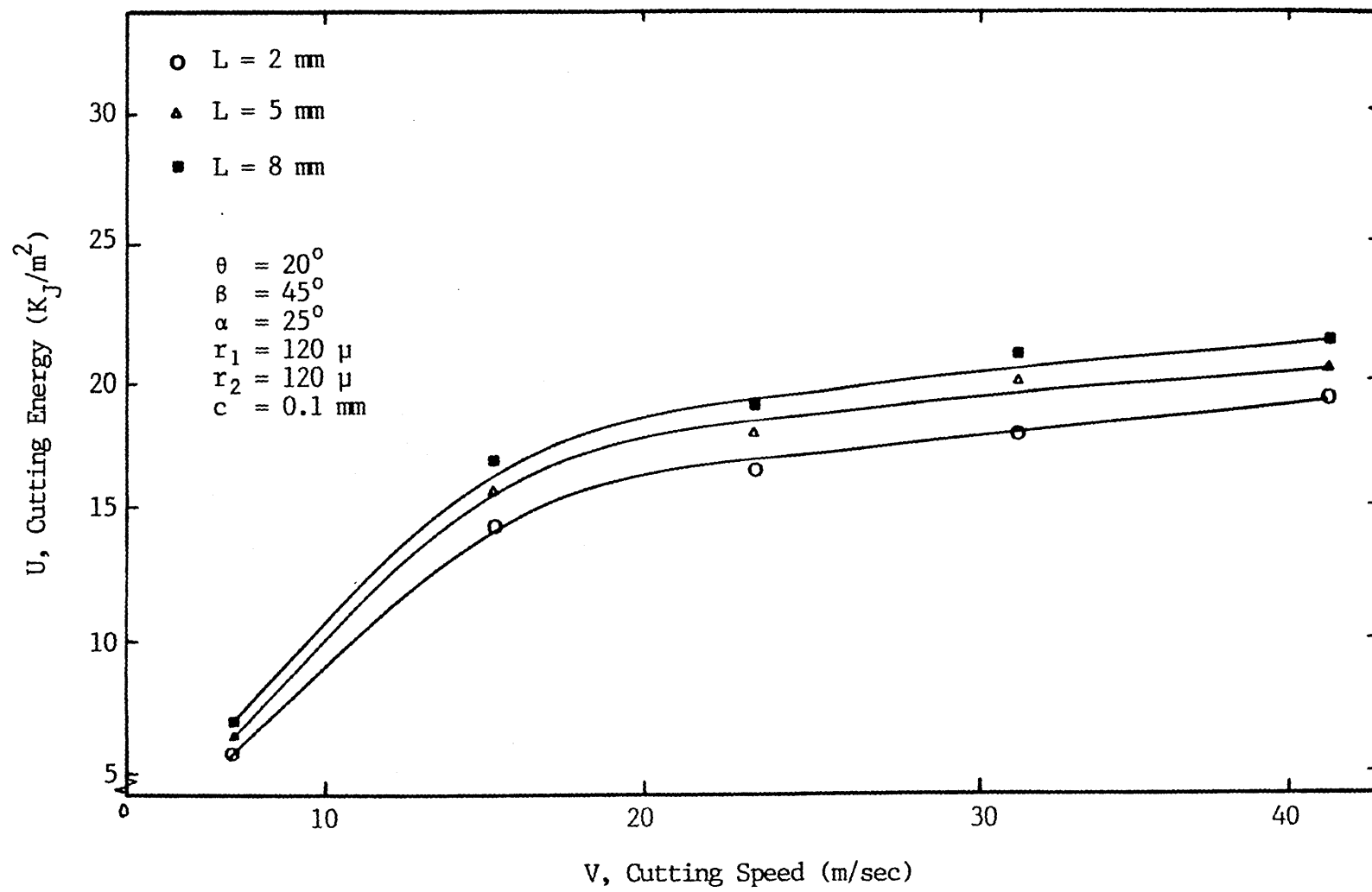


Fig. 5.8: HIPS - Cutting Energy Versus Cutting Speeds for Several Specimen Lengths to be Cut.

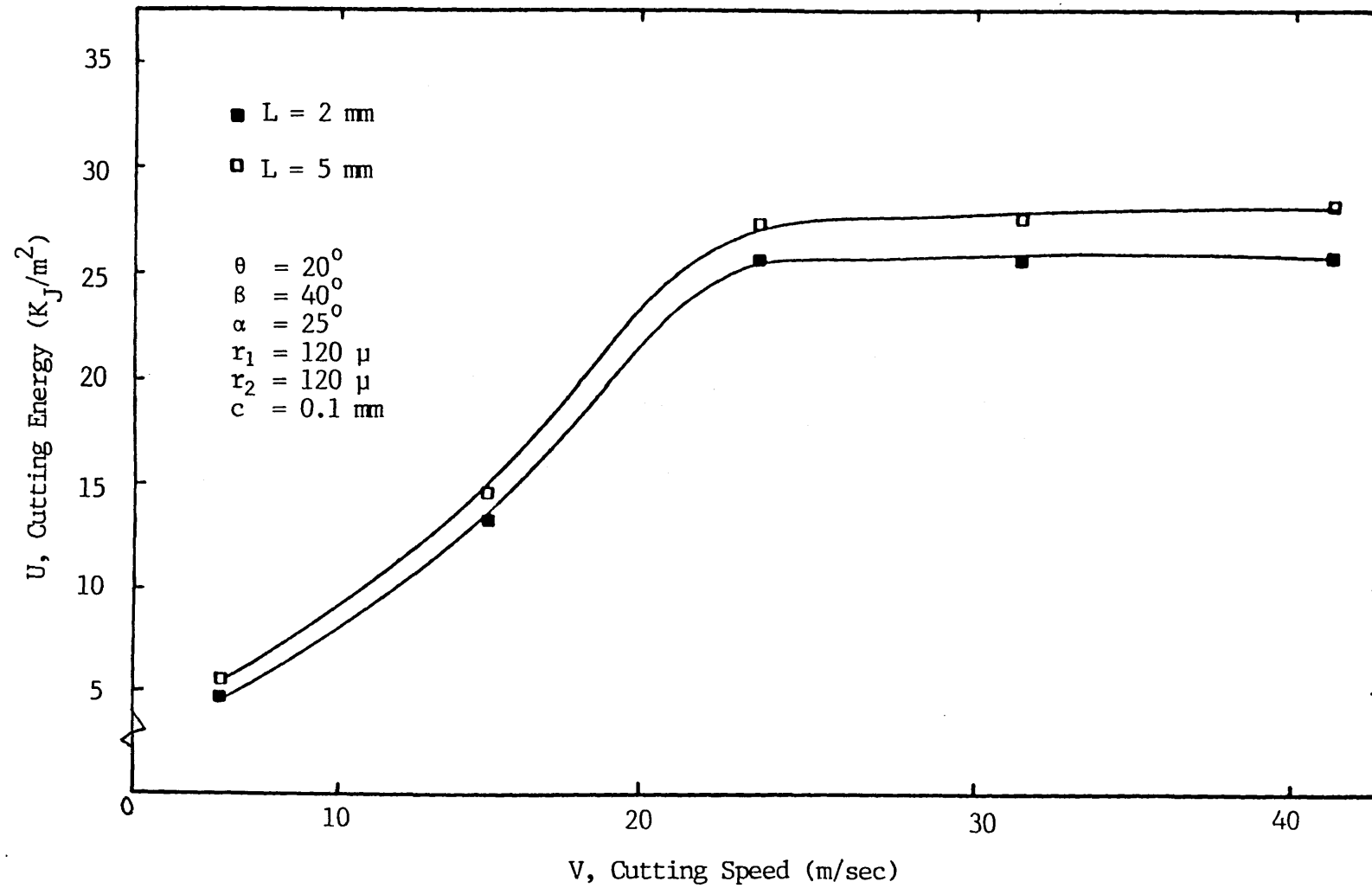


Fig. 5.9: PMMA - Cutting Energy Versus Cutting Speeds for Two Specimen Lengths to be Cut.

This exercise has been carried out and it was found that kinetic energy imparted to the cut part of the specimen was negligible and results are therefore given for tests with minimum cut lengths. The small increase in the cutting energy with the increase in the length of specimen to be cut, is to be expected, since additional work must be done in deformation and also in imparting kinetic energy to the cut portion and this will increase as the size of the cut portion increases.

The clearance effect on cutting energy is not strong as shown in Figs. 5.10-5.16, for materials such as LDPE, PP, PC, PVC, ABS and HIPS (Figs. 5.10-5.15). The lowest cutting energy occurs at the lowest clearance between the rotating blade and the fixed blade and an increase in clearance gives a slight increase in the energy required to cut. There is, however, less clearance effect at high cutting speeds than at low. PMMA shows no clearance effect at all (Fig. 5.16). It was also found that changing fixed blade geometry and sharpness had no effect on cutting energies.

Figs. 5.17-5.23 demonstrate the strong effect of sharpness of rotating blade on cutting energy. For all materials tested it can be seen that the ratio of cutting energies per unit area for the bluntest blade to that of the sharpest is not less than 3:2. Figs. 5.17 and 5.23 show the effect of sharpness for LDPE and PMMA

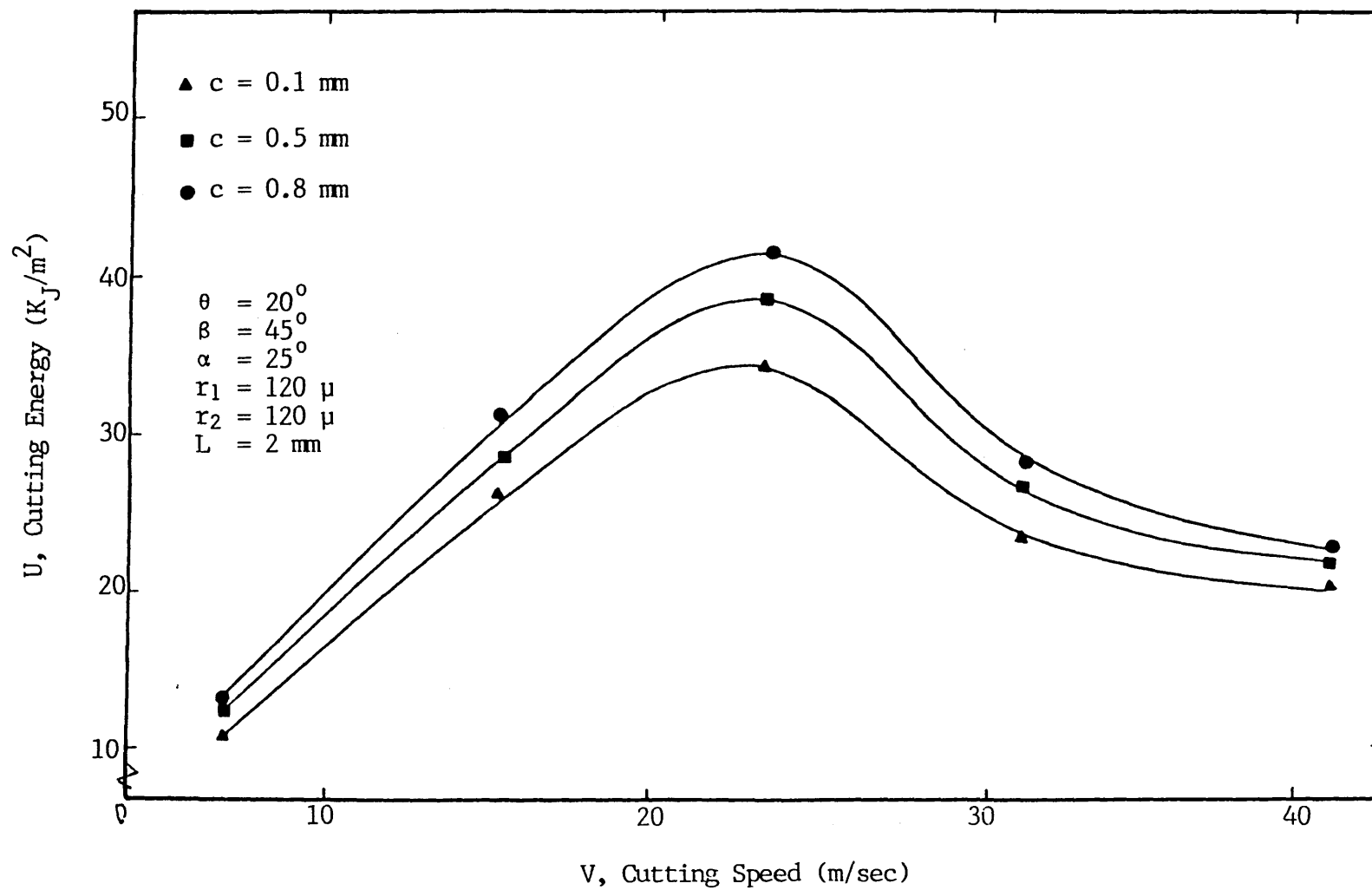


Fig. 5.10: LDPE - Cutting Energy Versus Cutting Speeds for Several Blade Clearances.

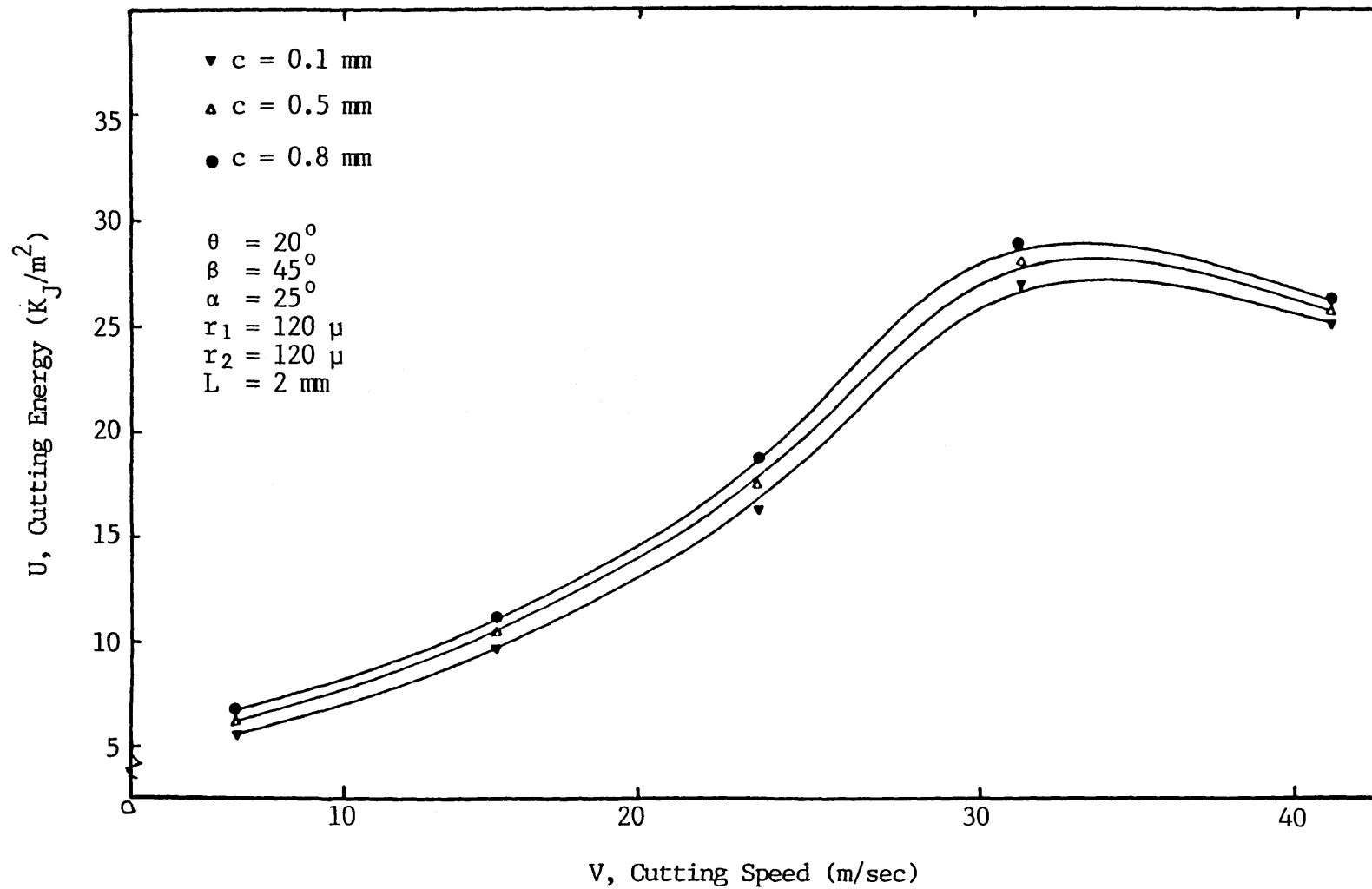


Fig. 5.11: PP - Cutting Energy Versus Cutting Speeds for Several Blade Clearances.

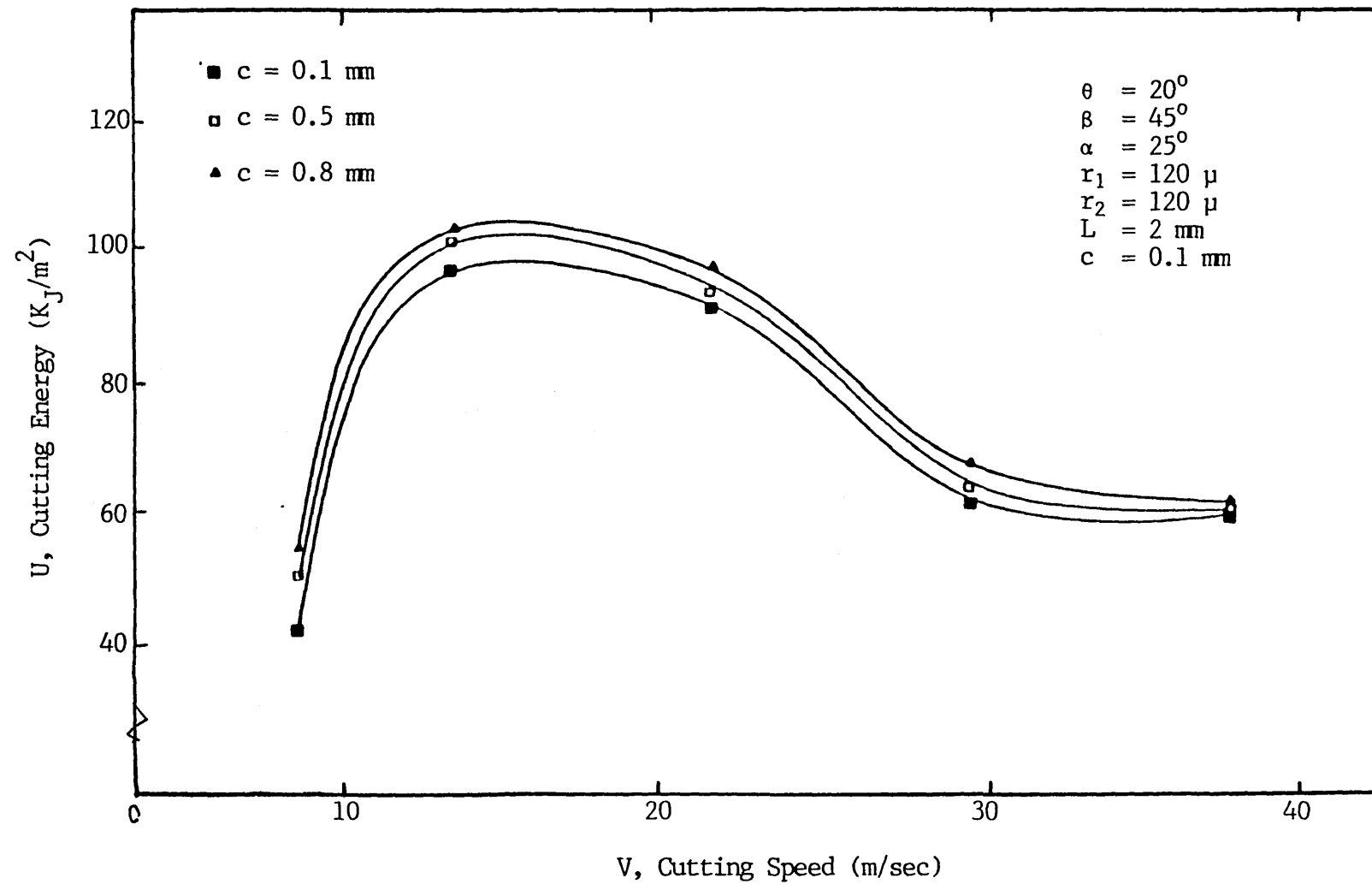


Fig. 5.12: PC - Cutting Energy Versus Cutting Speeds for Several Blade Clearances.

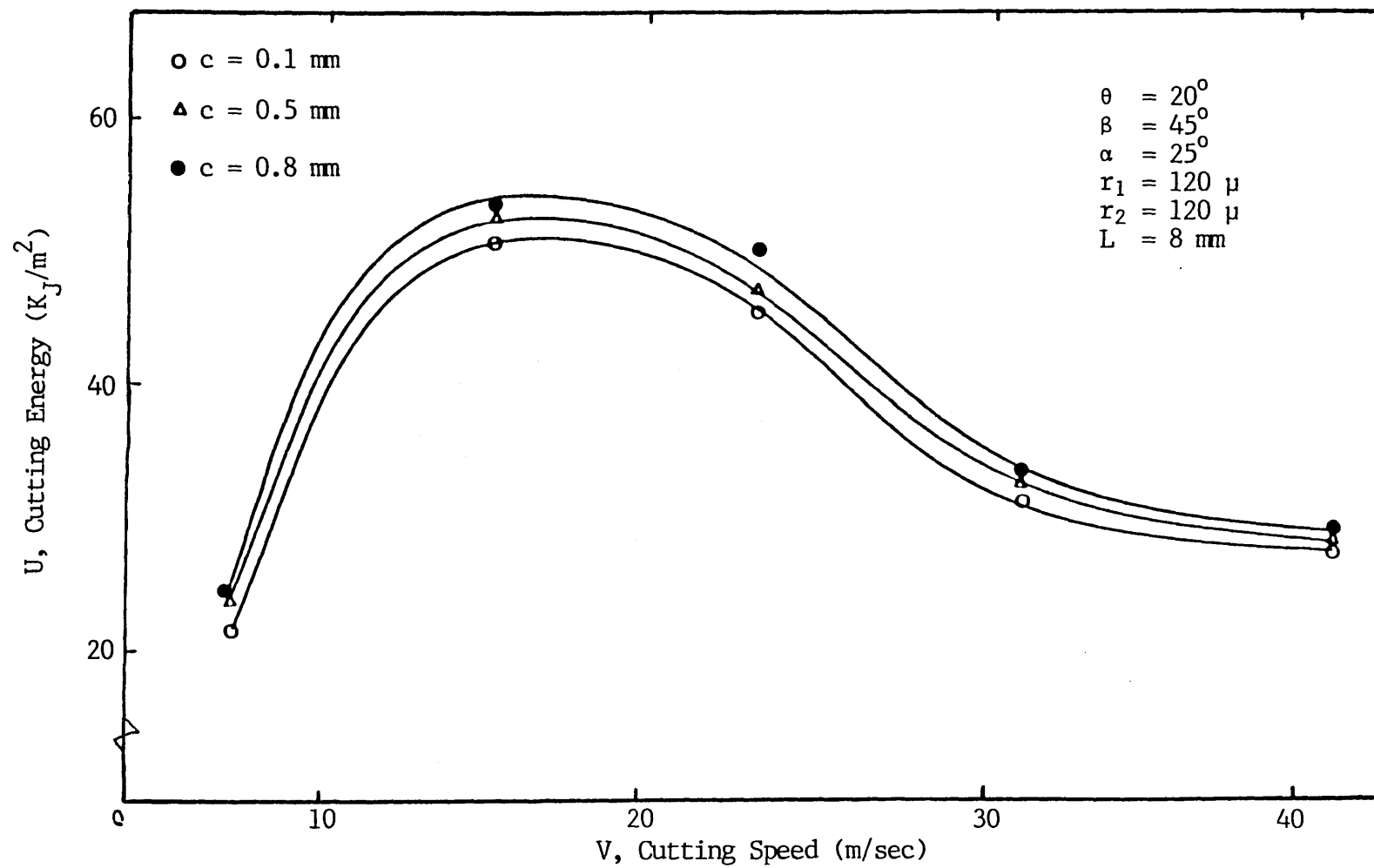


Fig. 5.13: ABS - Cutting Energy Versus Cutting Speeds for Several Blade Clearances.

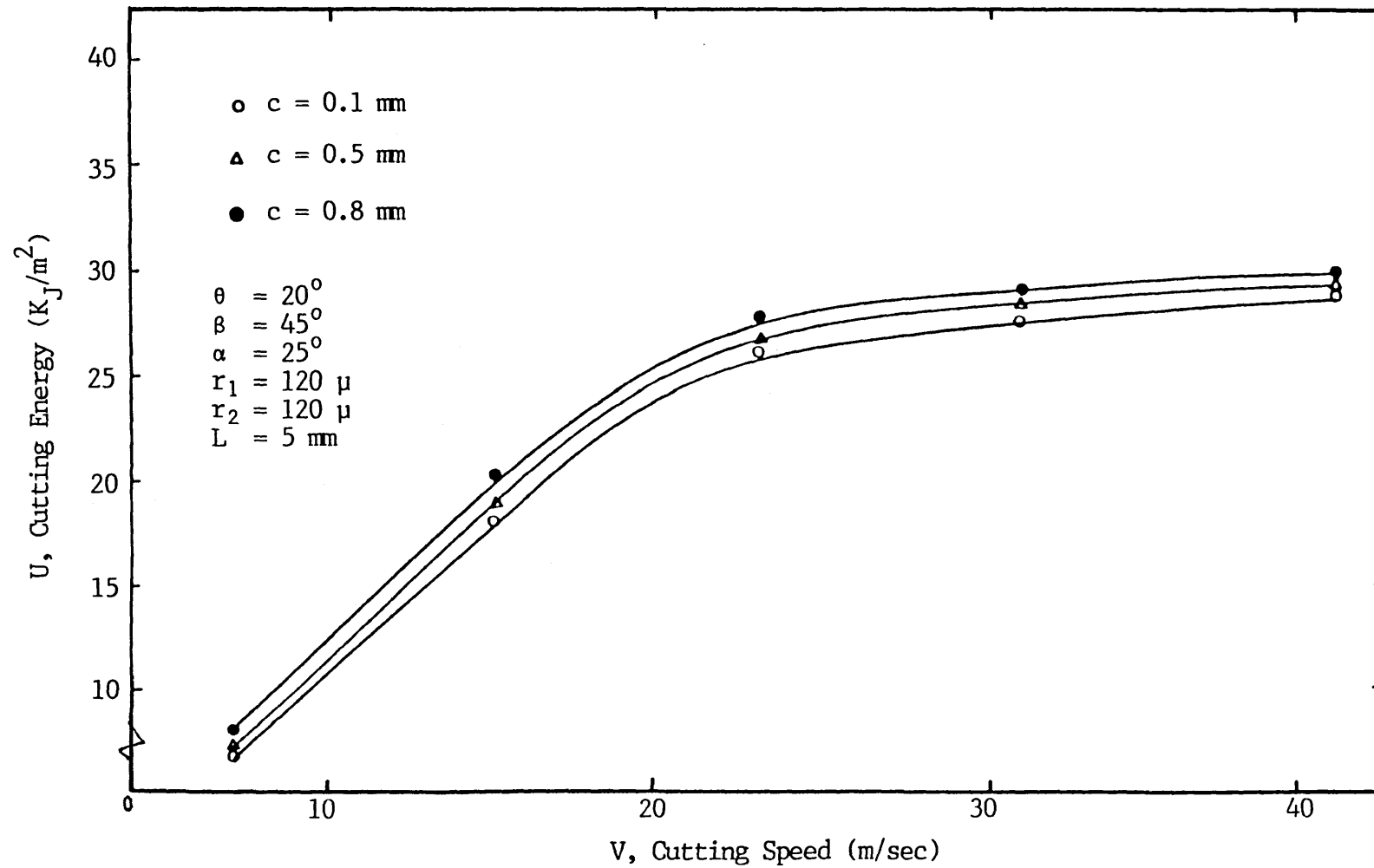


Fig. 5.14: PVC - Cutting Energy Versus Cutting Speeds for Several Blade Clearances.

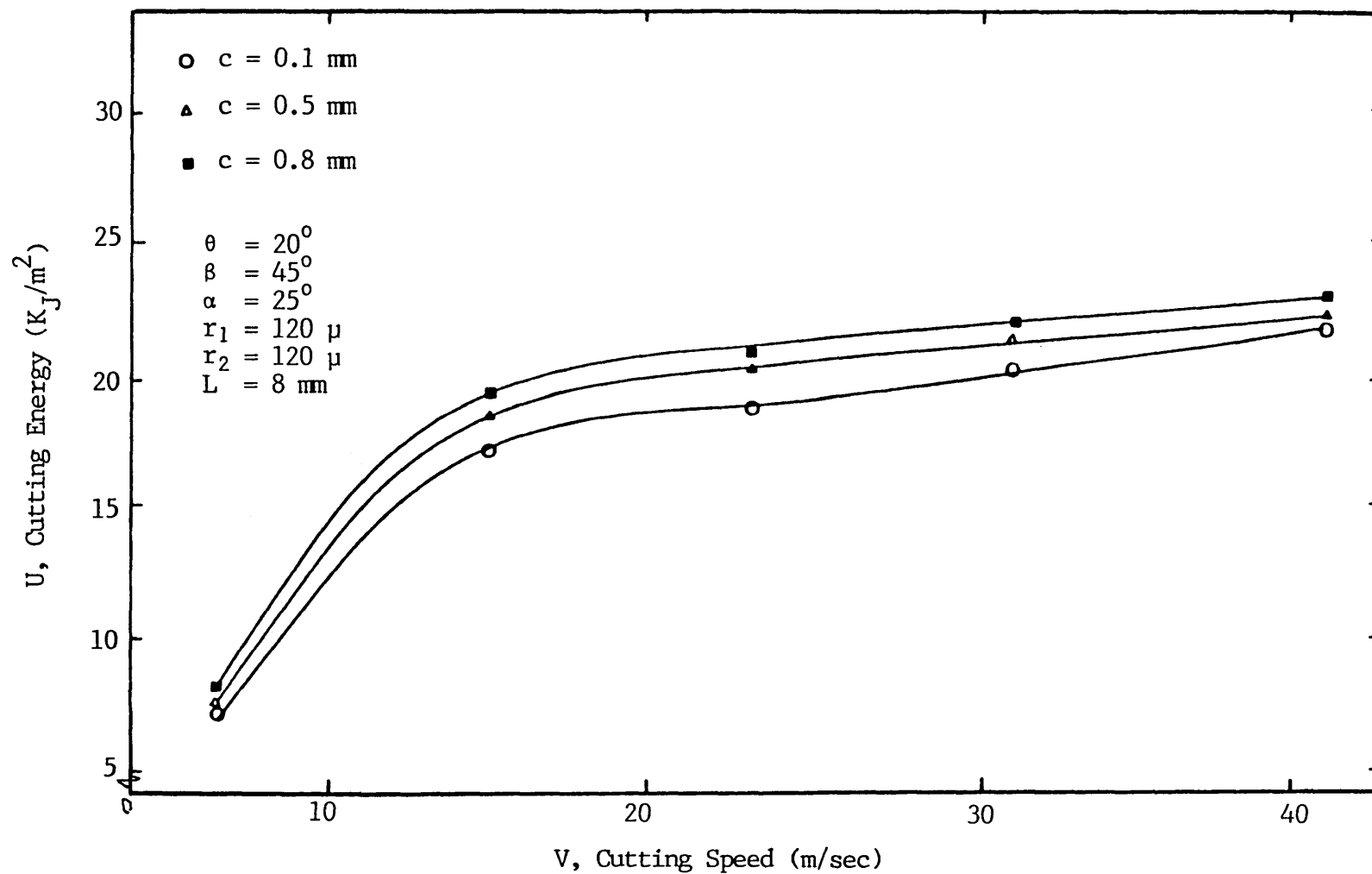


Fig. 5.15: HIPS - Cutting Energy Versus Cutting Speeds for Several Blade Clearances.

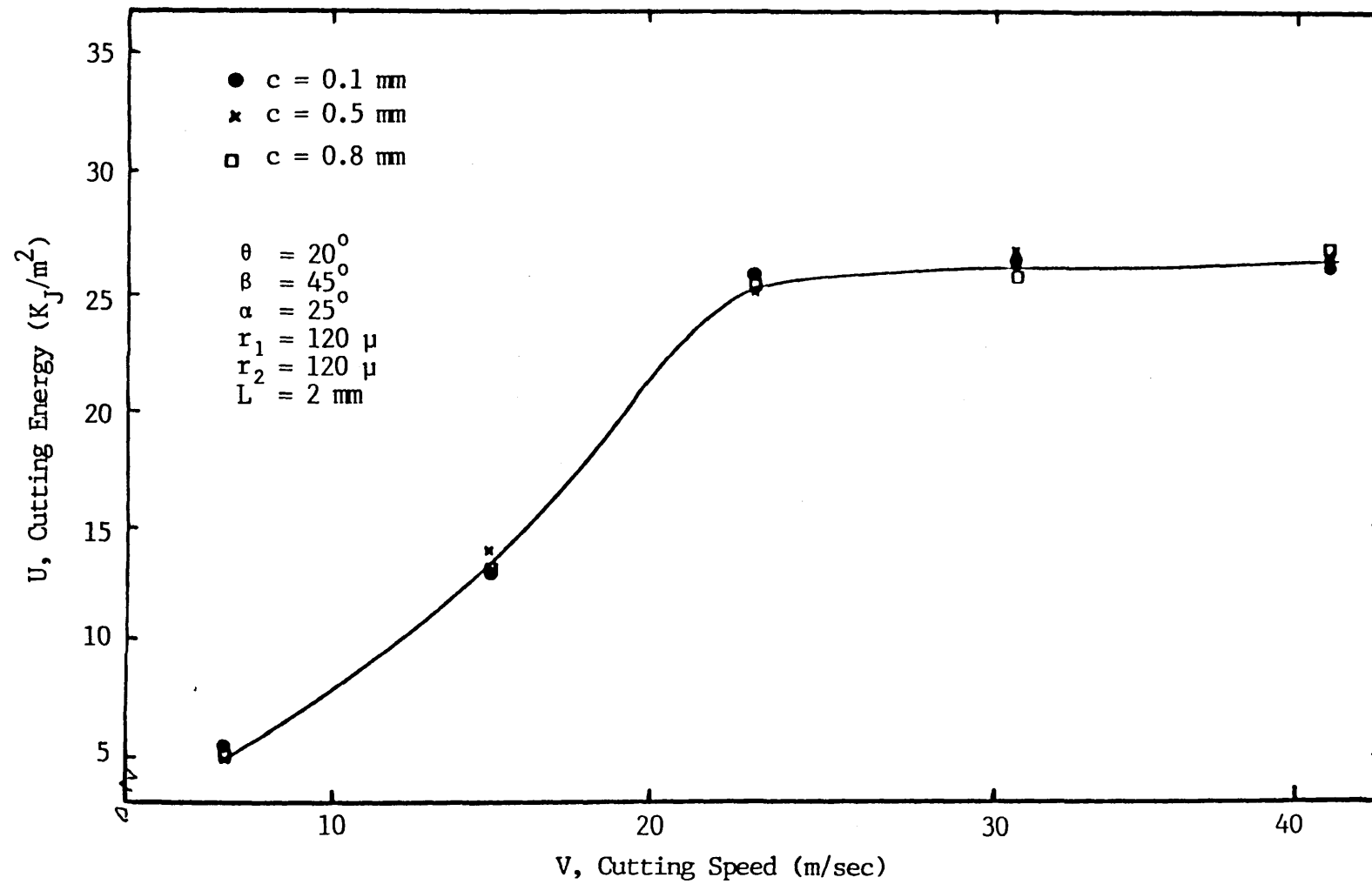


Fig. 5.16: PMMA - Cutting Energy Versus Cutting Speeds for Several Blade Clearances.

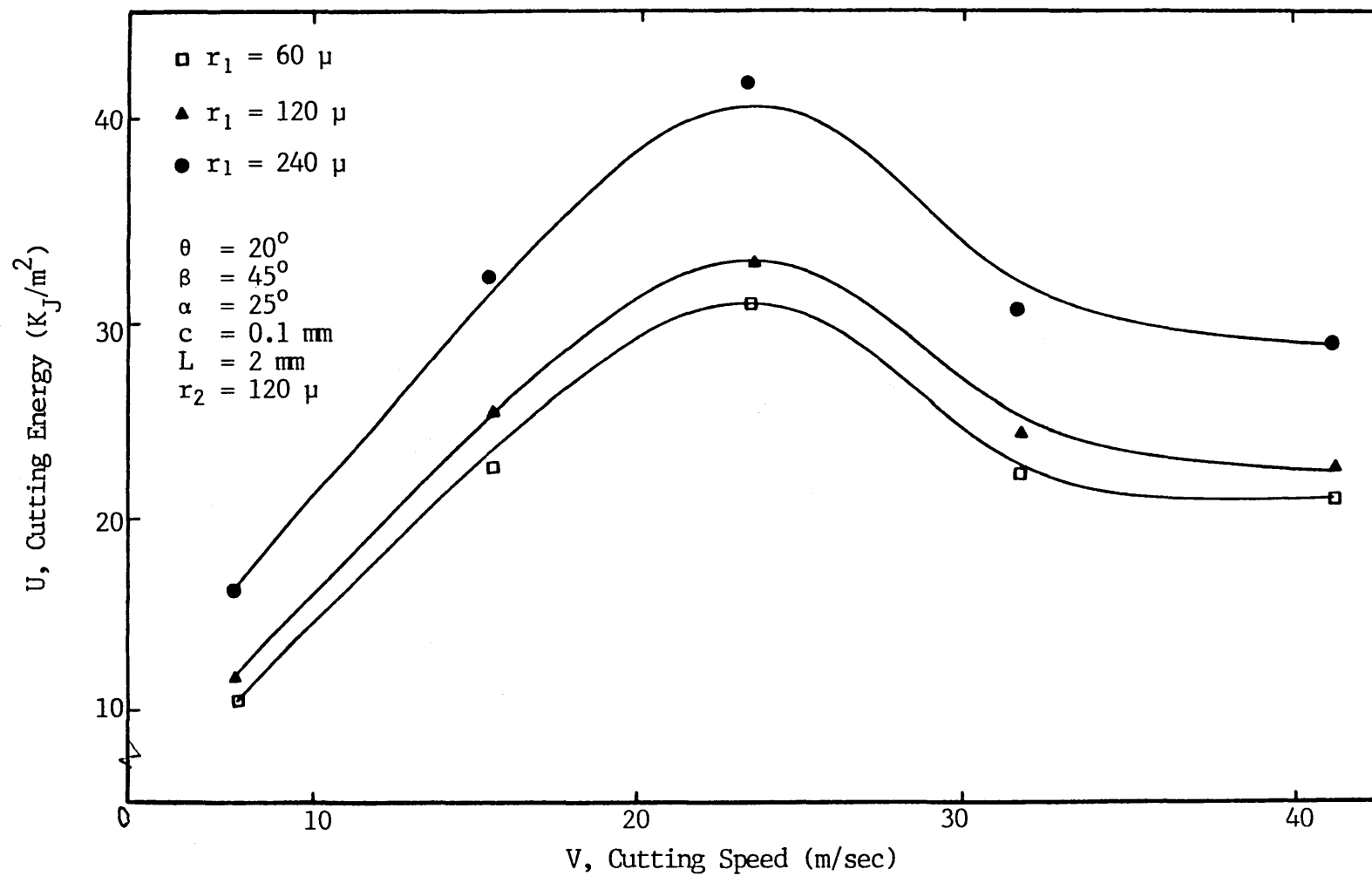


Fig. 5.17: LDPE - Cutting Energy Versus Cutting Speeds for Several Degrees of Rotating Blade Sharpness.

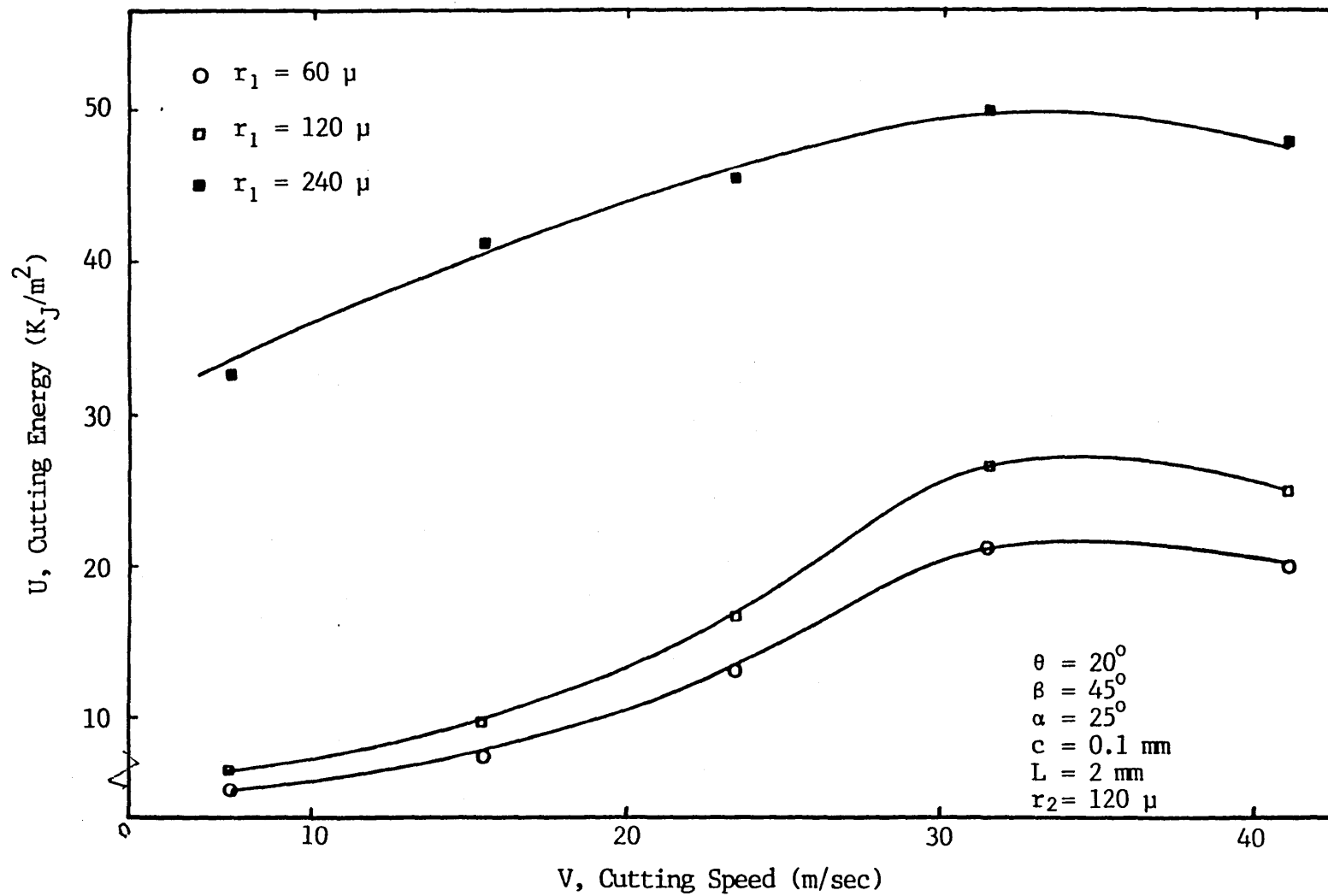


Fig. 5.18: PP - Cutting Energy Versus Cutting Speeds for Several Degrees of Rotating Blade Sharpness.

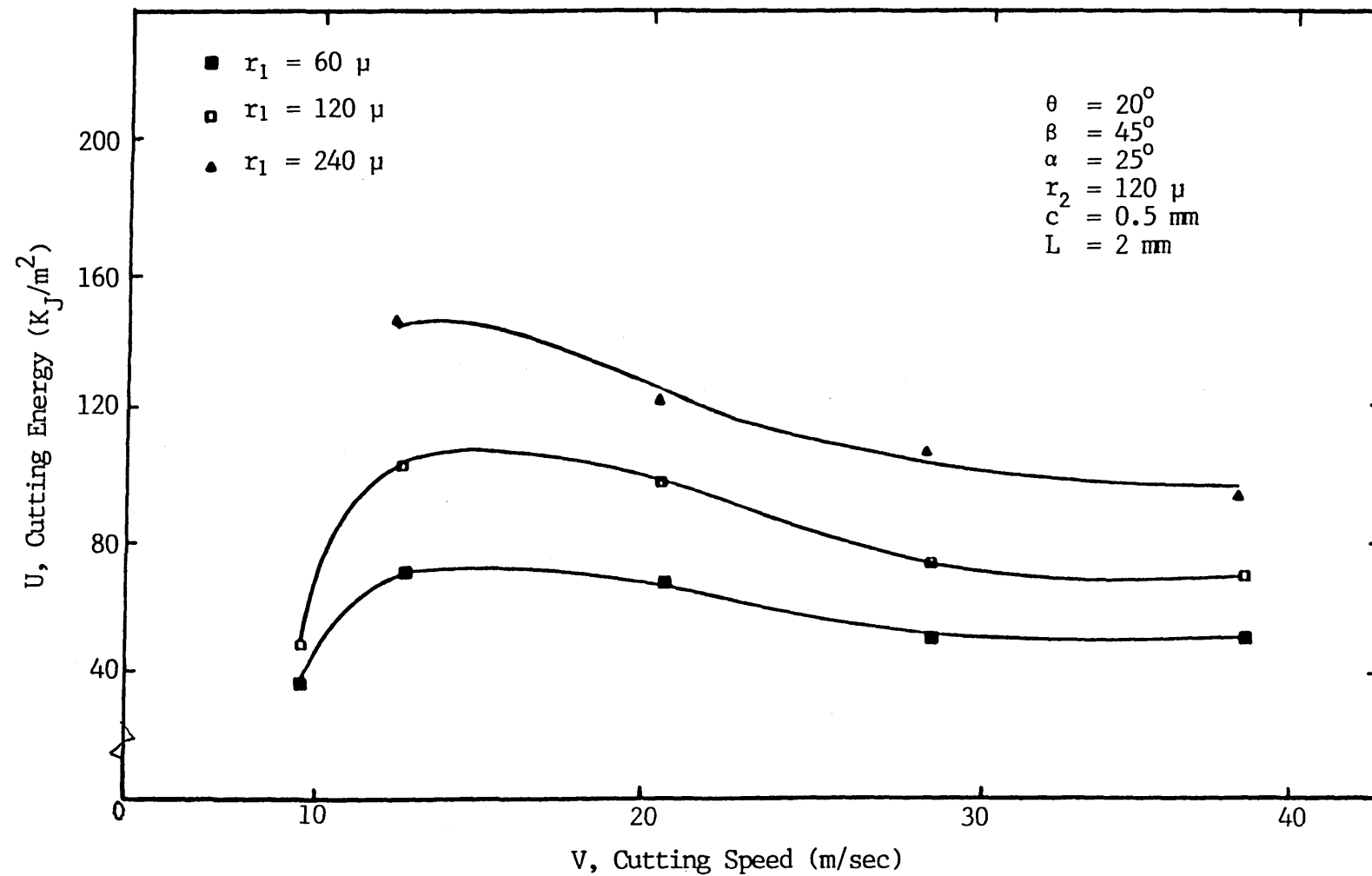


Fig. 5.19: PC - Cutting Energy Versus Cutting Speeds for Several Degrees of Rotating Blade Sharpness.

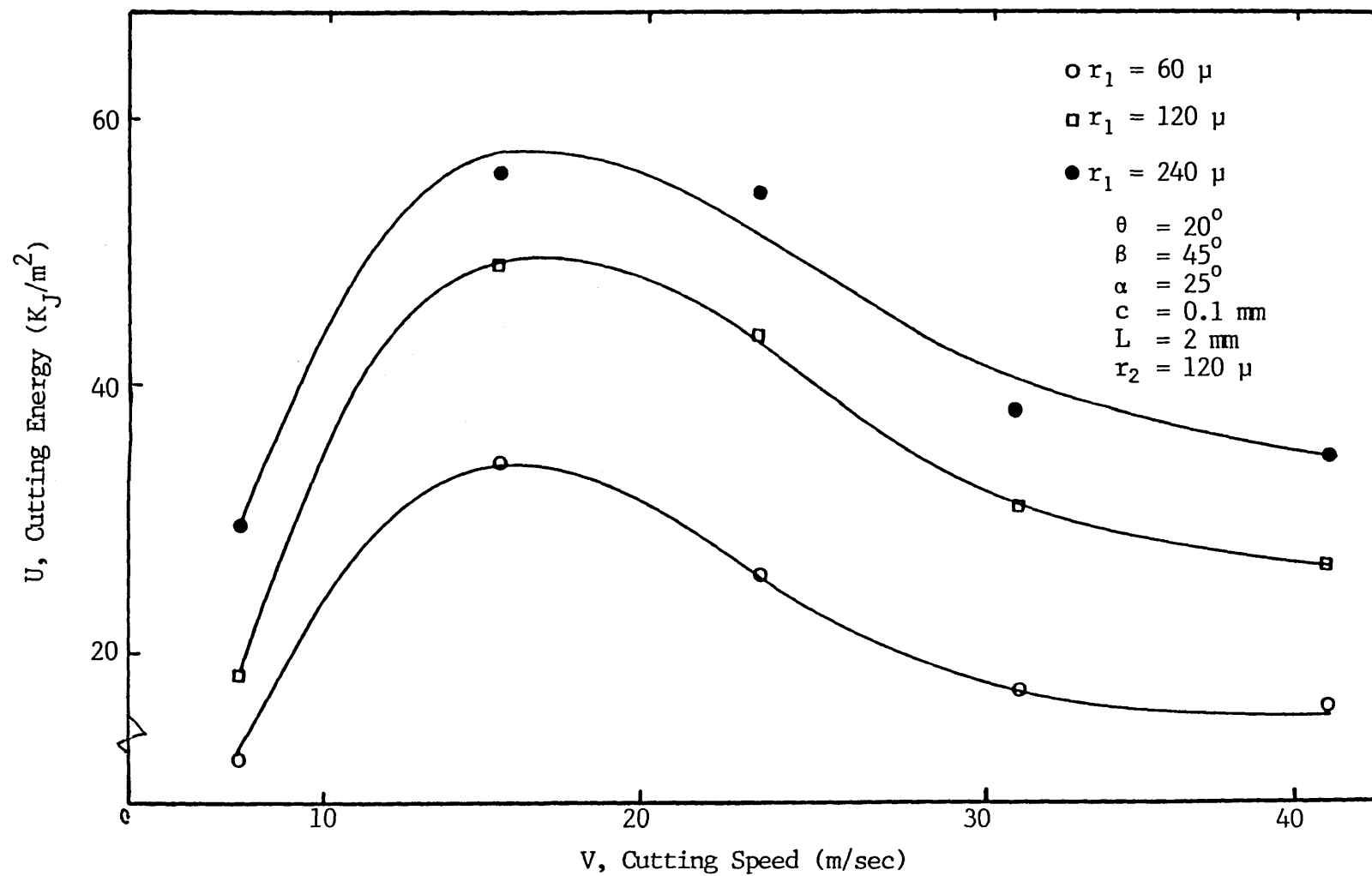


Fig. 5.20: ABS - Cutting Energy Versus Cutting Speeds for Several Degrees of Rotating Blade Sharpness.

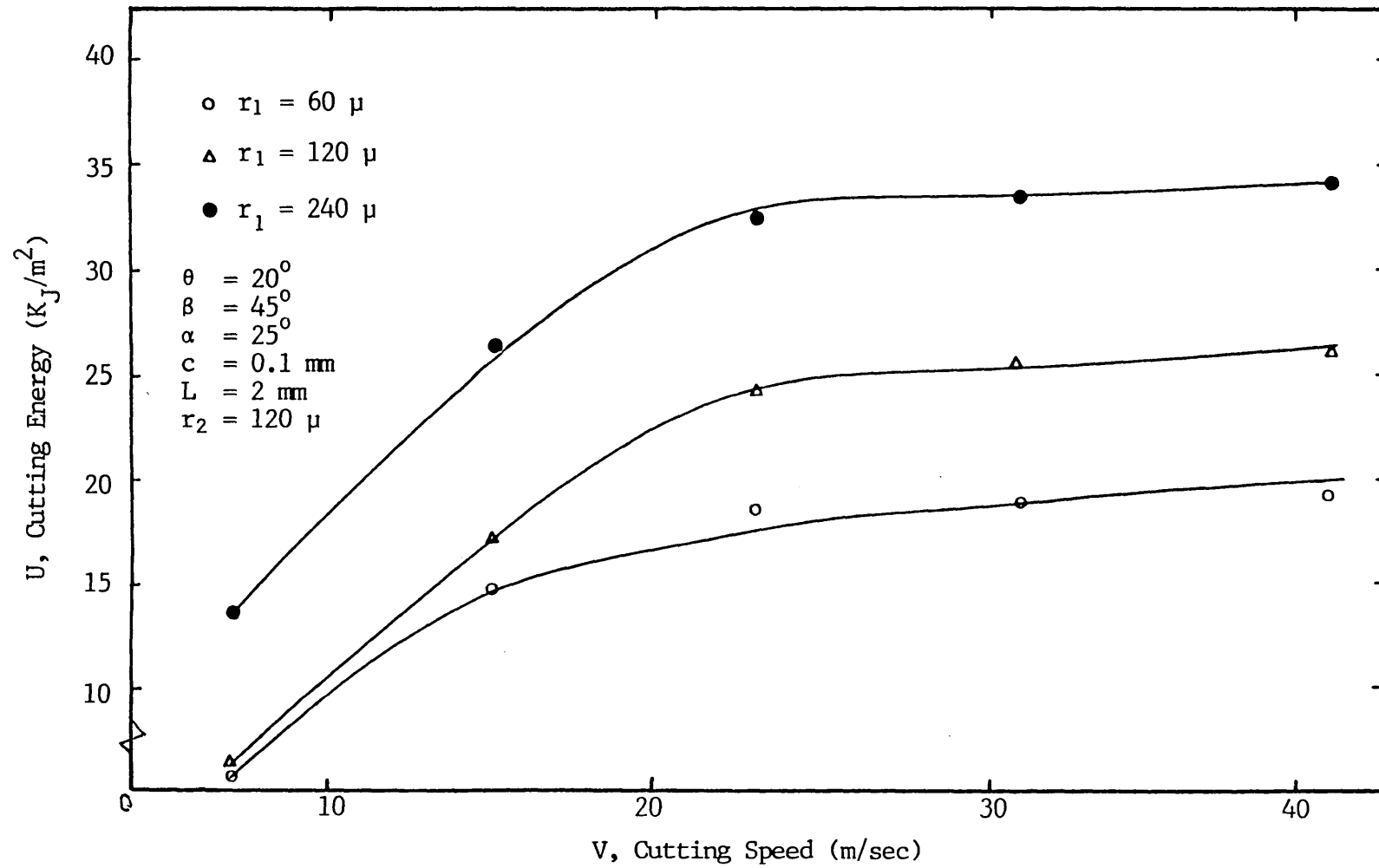


Fig. 5.21: PVC - Cutting Energy Versus Cutting Speeds for Several Degrees of Rotating Blade Sharpness.

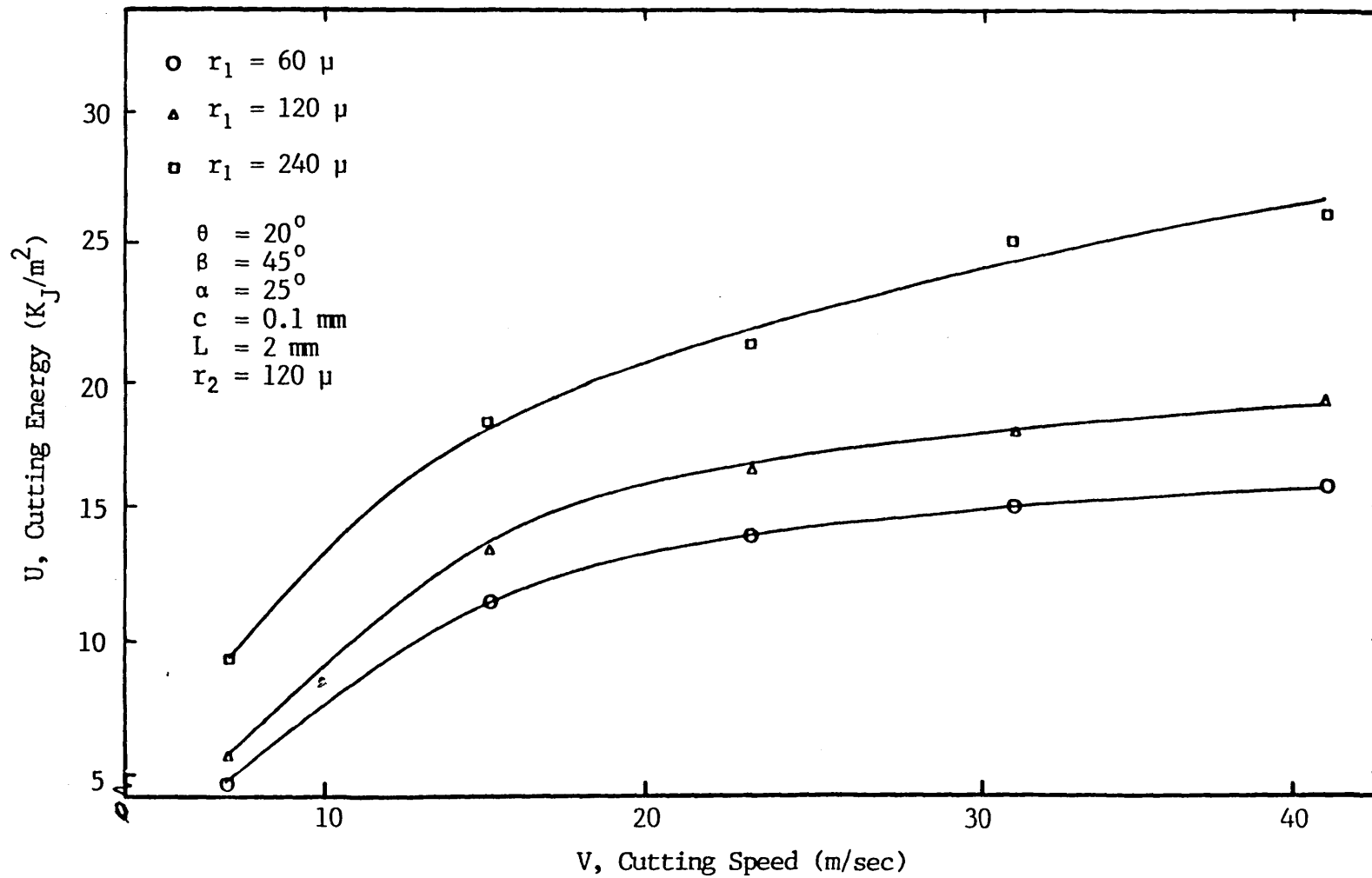


Fig. 5.22: HIPS - Cutting Energy Versus Cutting Speeds for Several Degrees of Rotating Blade Sharpness.

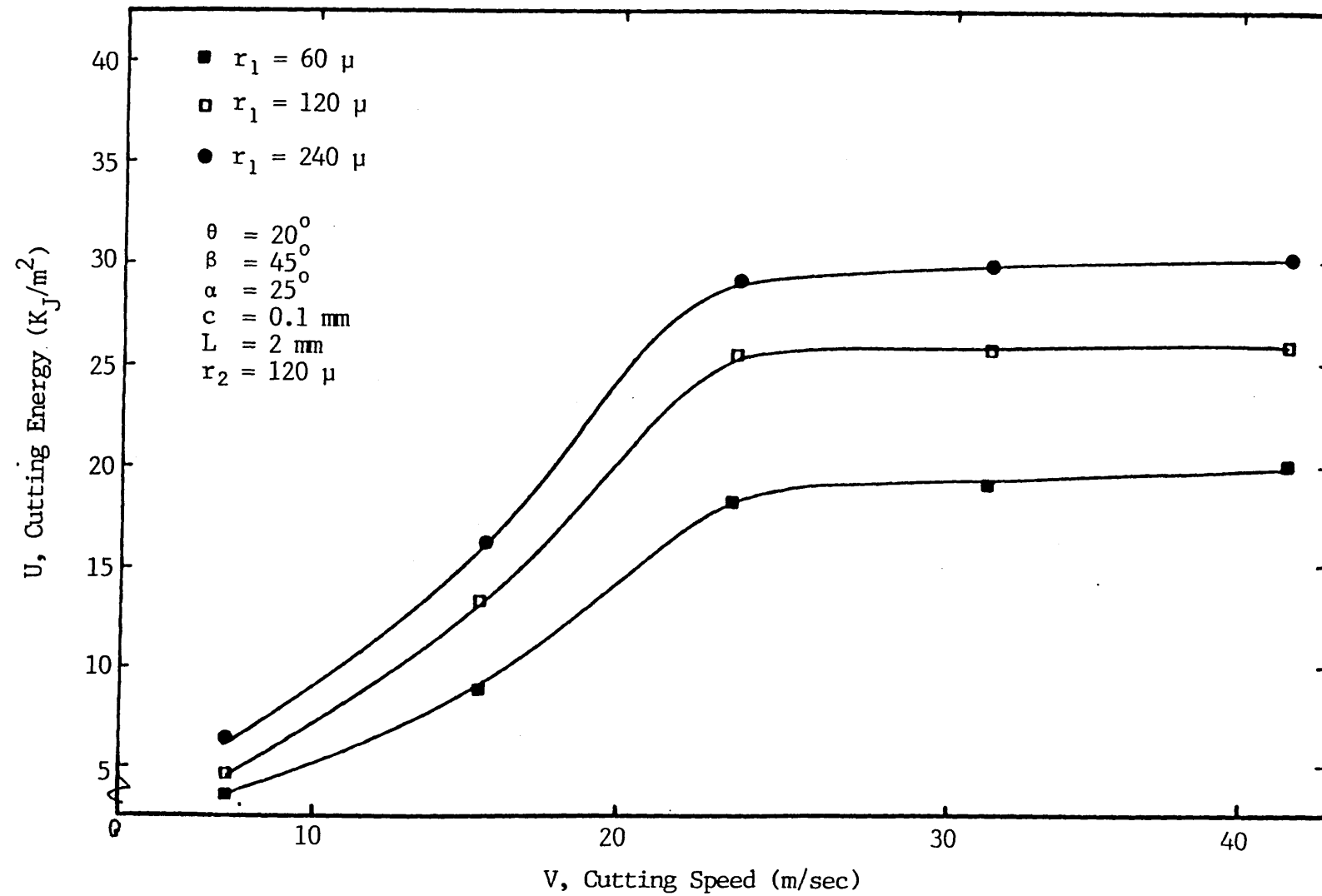


Fig. 5.23: PMMA - Cutting Energy Versus Cutting Speeds for Several Degrees of Rotating Blade Sharpness.

which represent extremes of behaviour of the test conducted with the blade of intermediate sharpness. For LDPE the intermediate test runs close to the sharp test, whereas for PMMA it runs closer to the blunt test. In the other tests, the intermediate bluntness curve runs approximately mid-way between the other two tests (except for PP, Fig. 5.18, which is similar to the behaviour of LDPE).

Fig. 5.24-5.30 show the effect of rotating blade angle of attack. It appears that the effect is strong and the lowest cutting energy is obtained when the rotor blade has the smallest angle of attack. This was the case for all the materials tested. Since a rotating blade with a large angle of attack is likely to cause more deformation to the part of the specimen to be cut and therefore perform more work, it would be expected for cutting energies to increase when the angle of attack is increased.

Fig. 5.31-5.37 show the effect of changing the cutting angle of the rotating blade on the cutting energies for all the materials tested. Whilst it appears that the effect is strong, it should be noted that the angle of attack is also changed in these tests. For example, Fig. 5.25 is considered which shows the effect of changing the angle of attack of the rotating blade

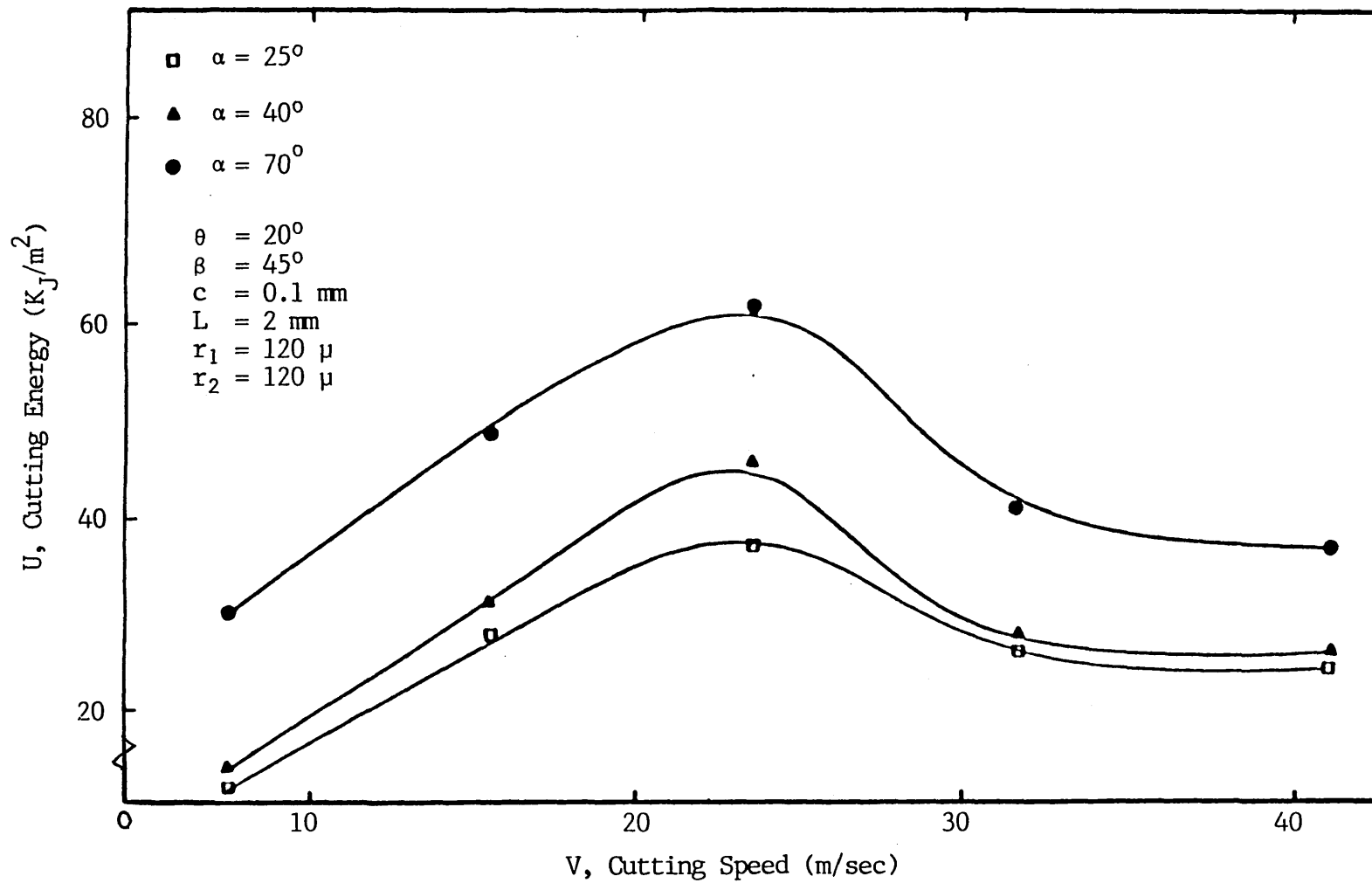


Fig. 5.24: LDPE - Cutting Energy Versus Cutting Speeds for Different Angles of Attack (Rotating Blade).

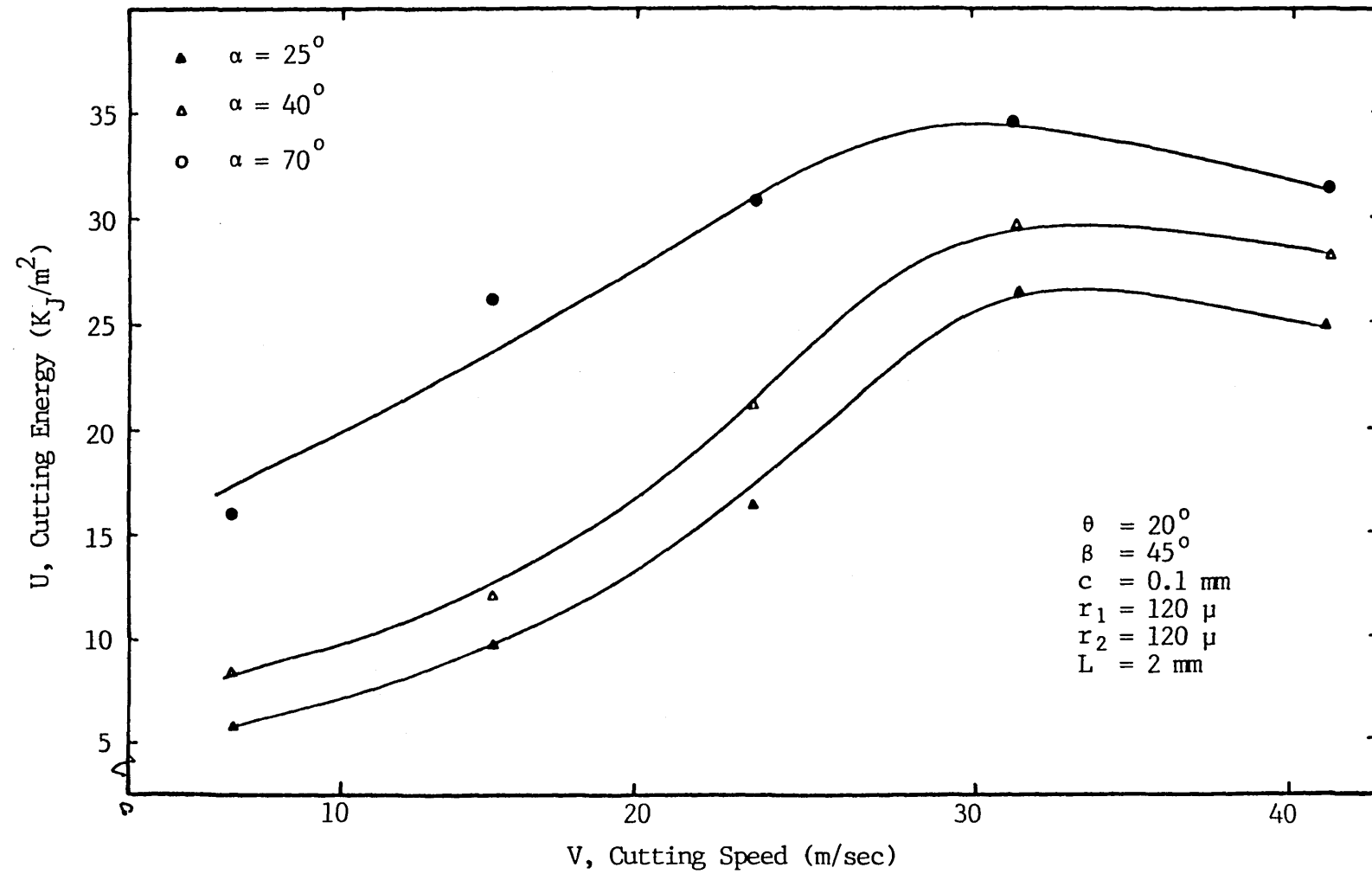


Fig. 5.25: PP - Cutting Energy Versus Cutting Speeds for Different Angles of Attack (Rotating Blade).

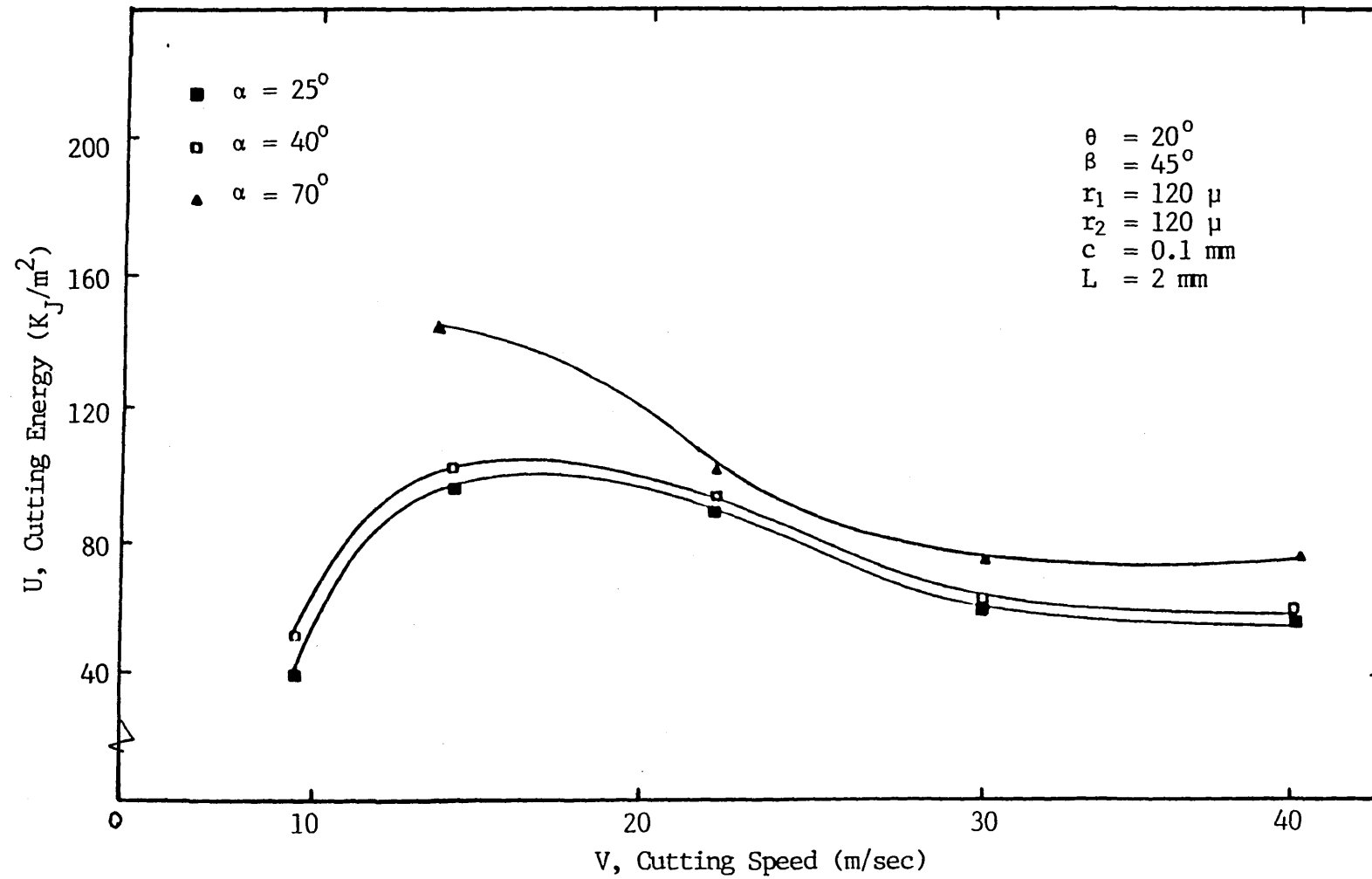


Fig. 5.26: PC - Cutting Energy Versus Cutting Speeds for Different Angles of Attack (Rotating Blade).

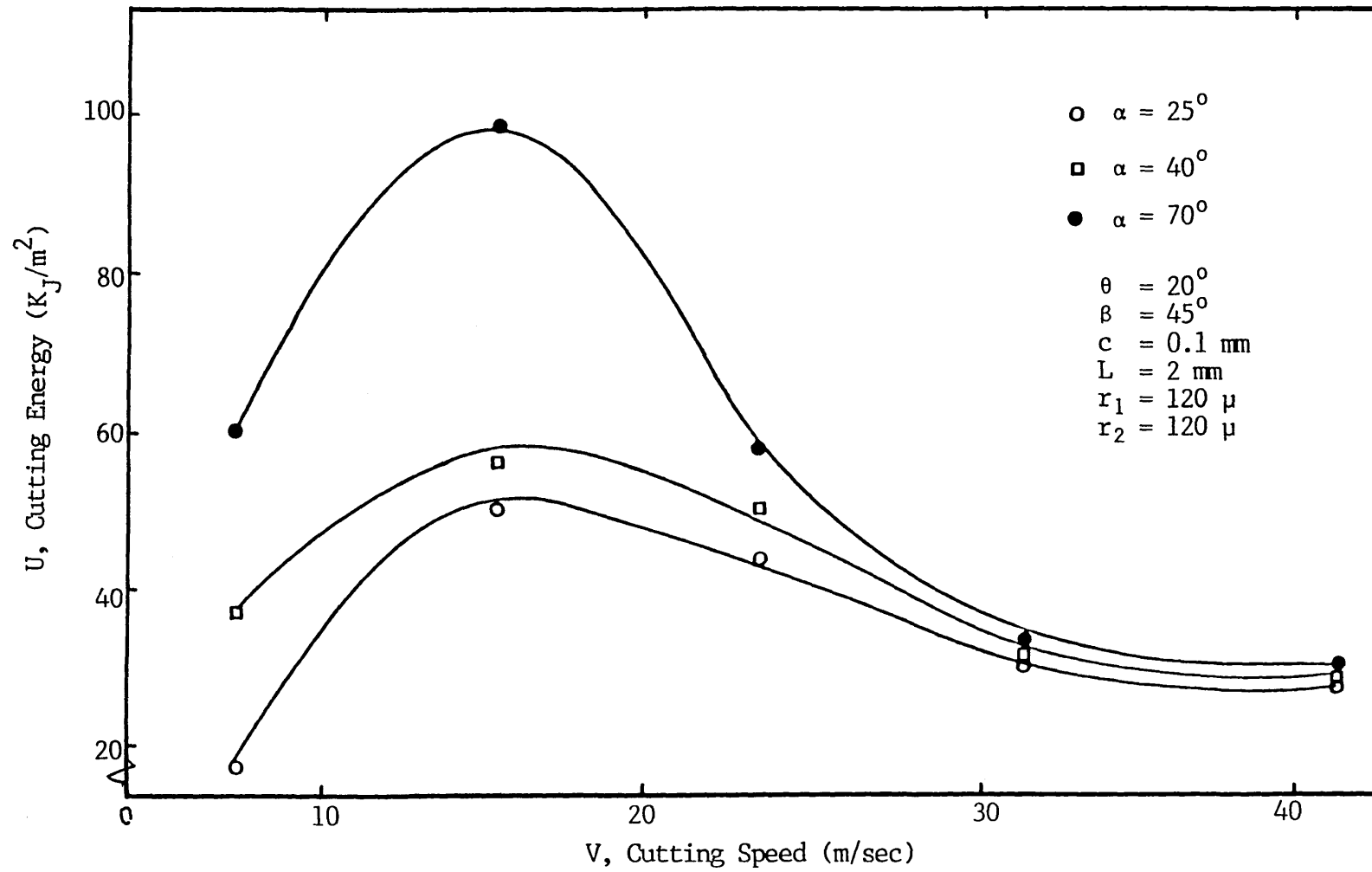


Fig. 5.27: ABS - Cutting Energy Versus Cutting Speeds for Different Angles of Attack (Rotating Blade).

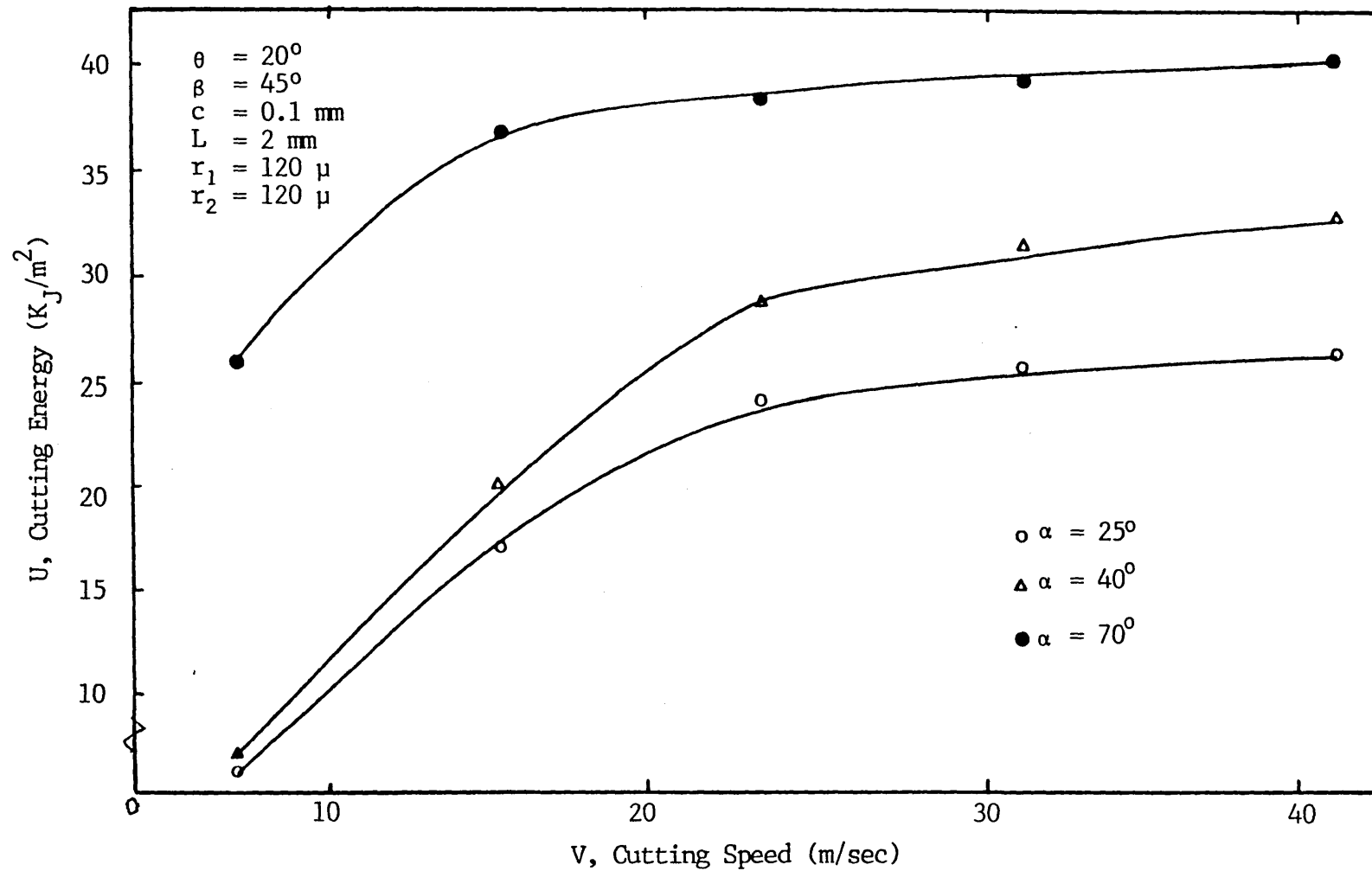


Fig. 5.28: PVC - Cutting Energy Versus Cutting Speeds for Different Angles of Attack (Rotating Blade).

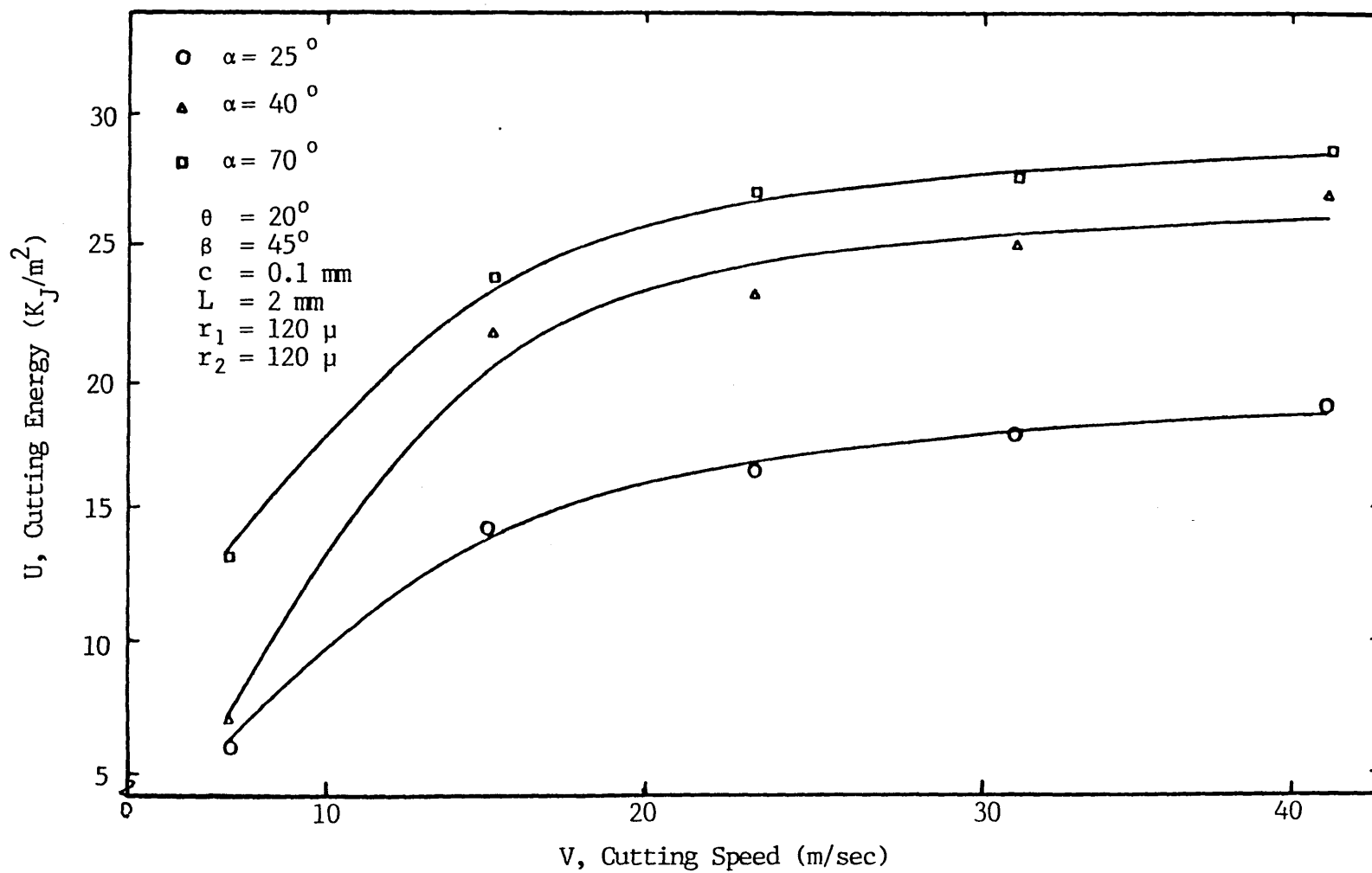


Fig. 5.29: HIPS - Cutting Energy Versus Cutting Speeds for Different Angles of Attack (Rotating Blade).

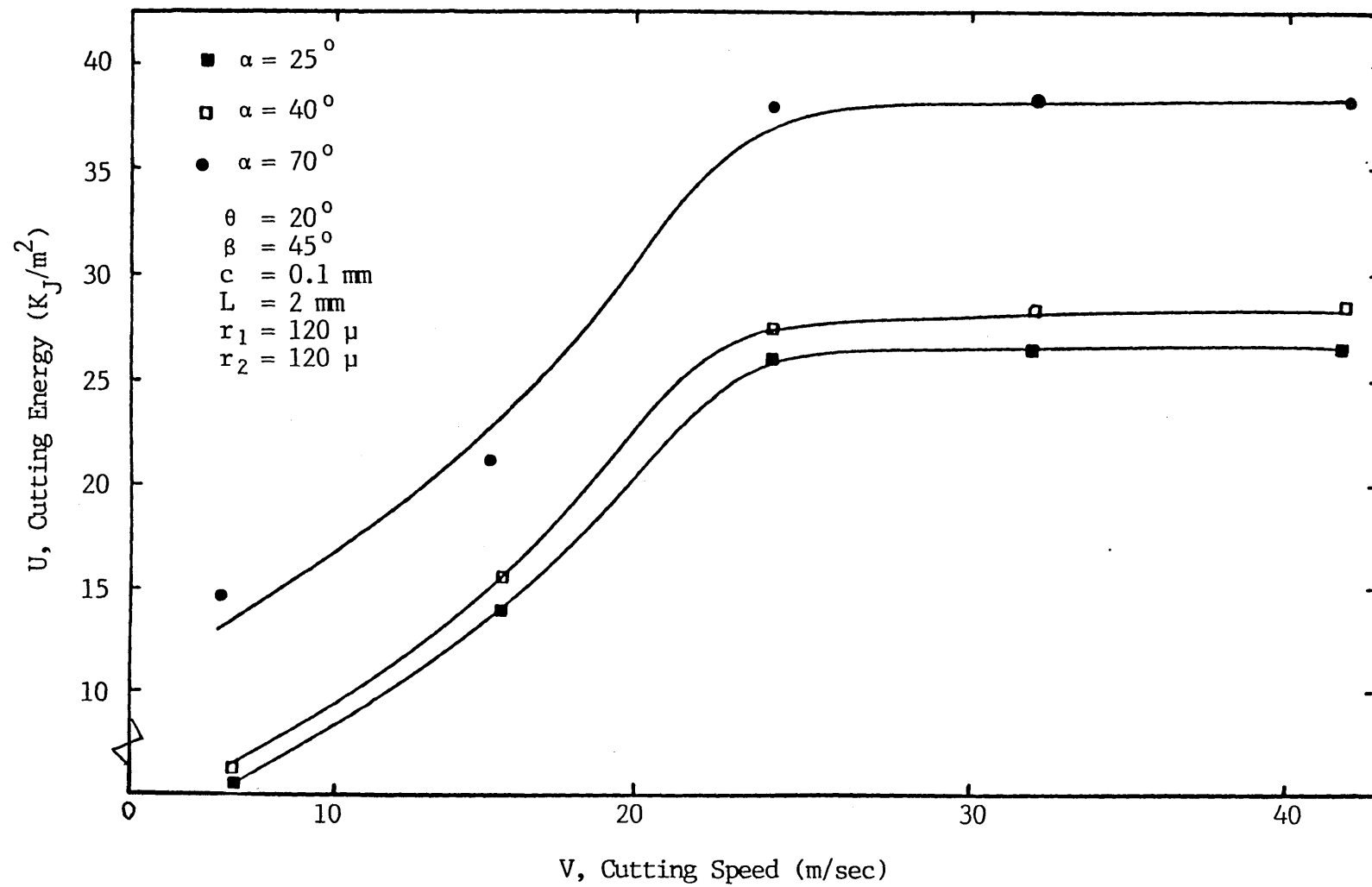


Fig. 5.30: PMMA - Cutting Energy Versus Cutting Speeds for Different Angles of Attack (Rotating Blade).

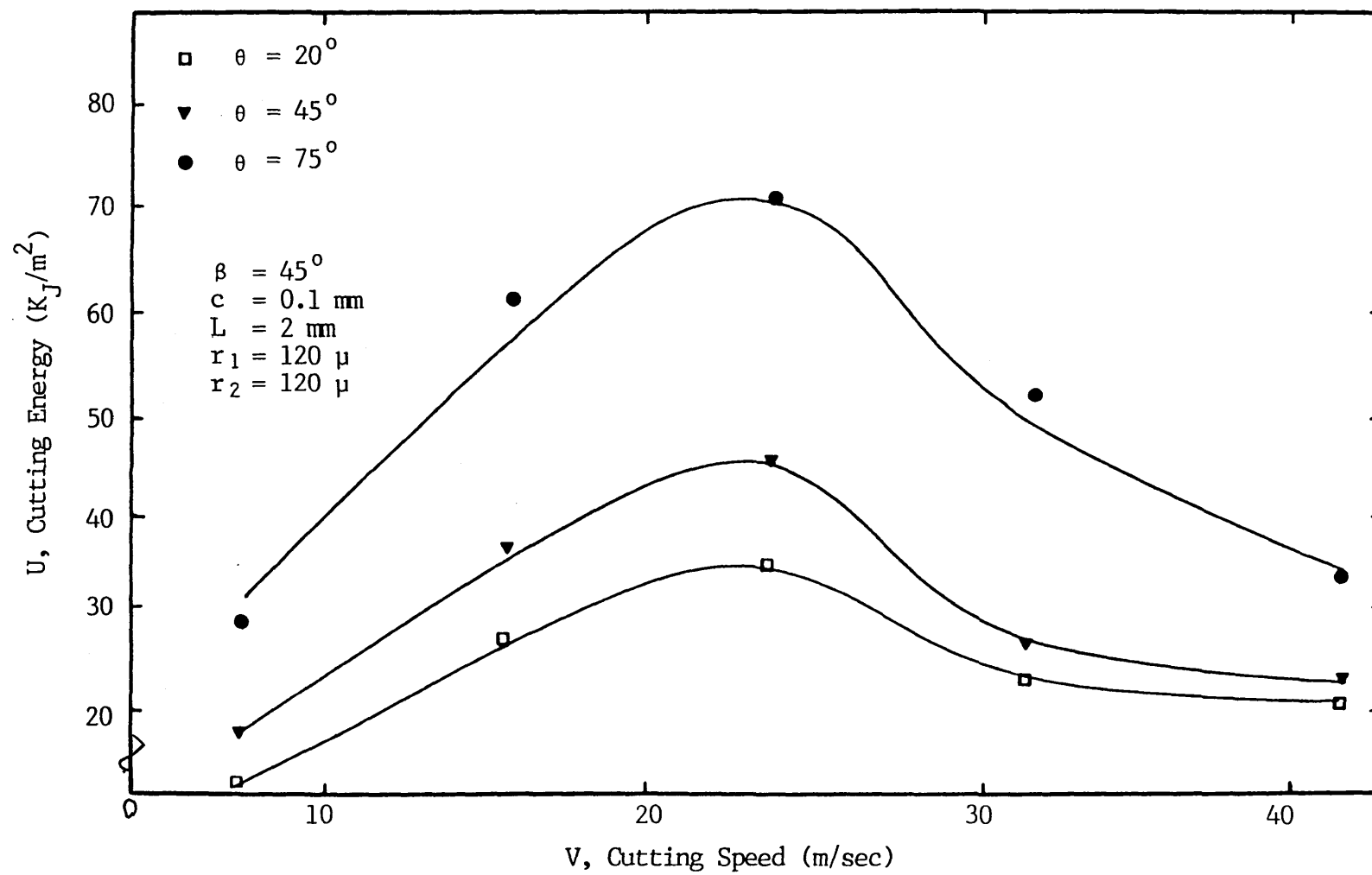


Fig. 5.31: LDPE - Cutting Energy Versus Cutting Speeds for Different Rotating Blade Cutting Angles.

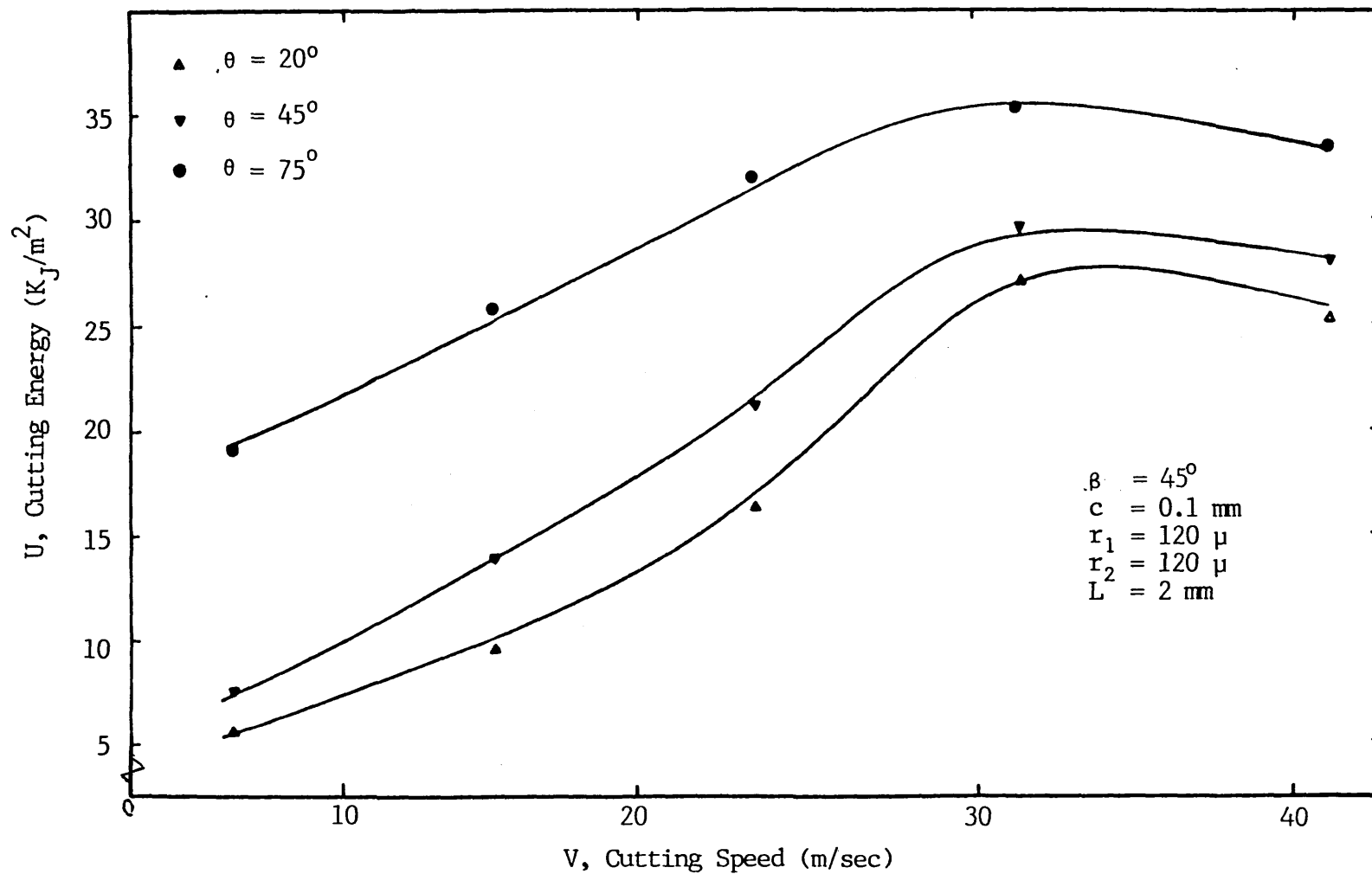


Fig. 5.32: PP - Cutting Energy Versus Cutting Speeds for Different Rotating Blade Cutting Angles.

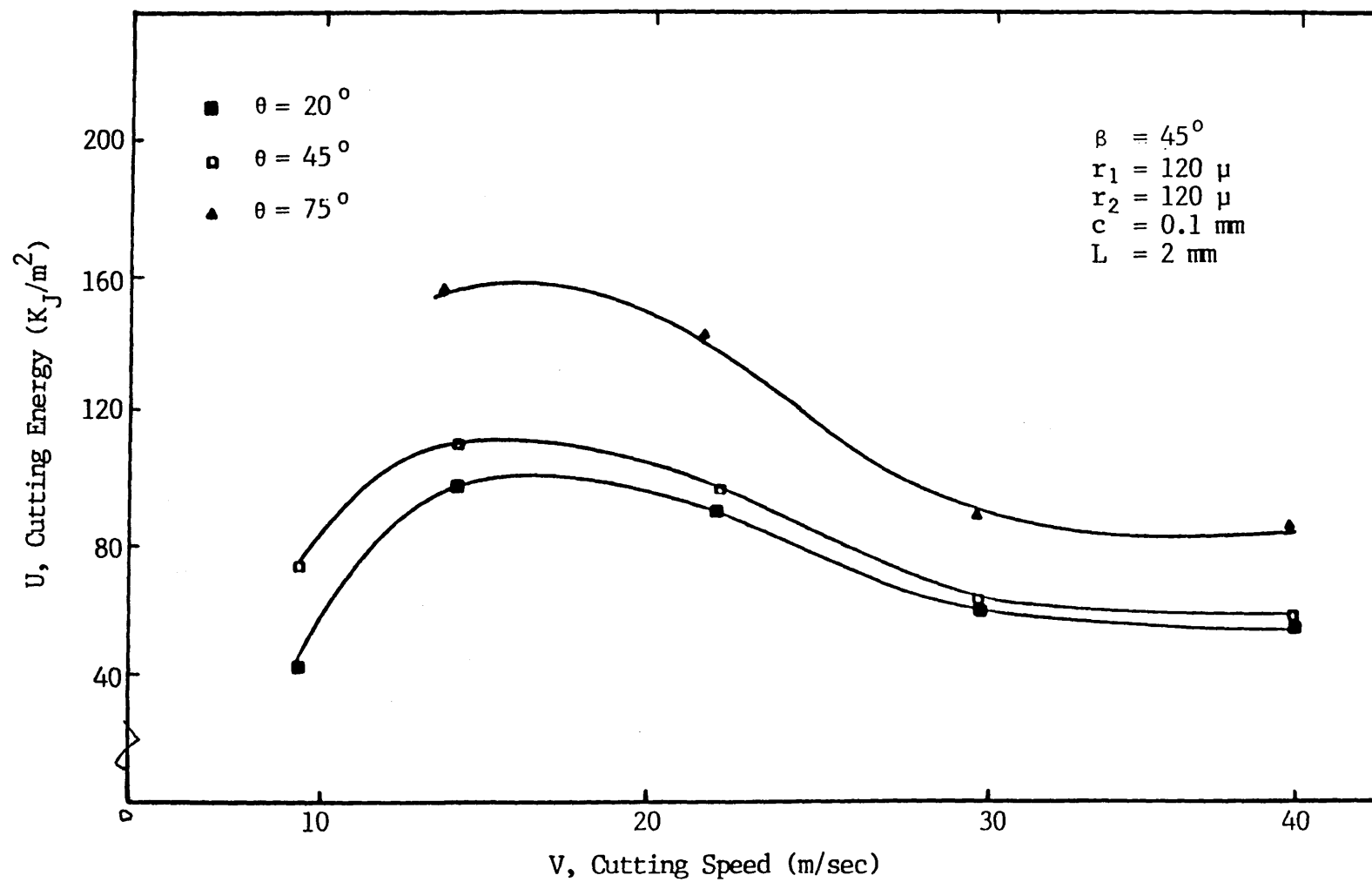


Fig. 5.33: PC - Cutting Energy Versus Cutting Speeds for Different Rotating Blade Cutting Angles.

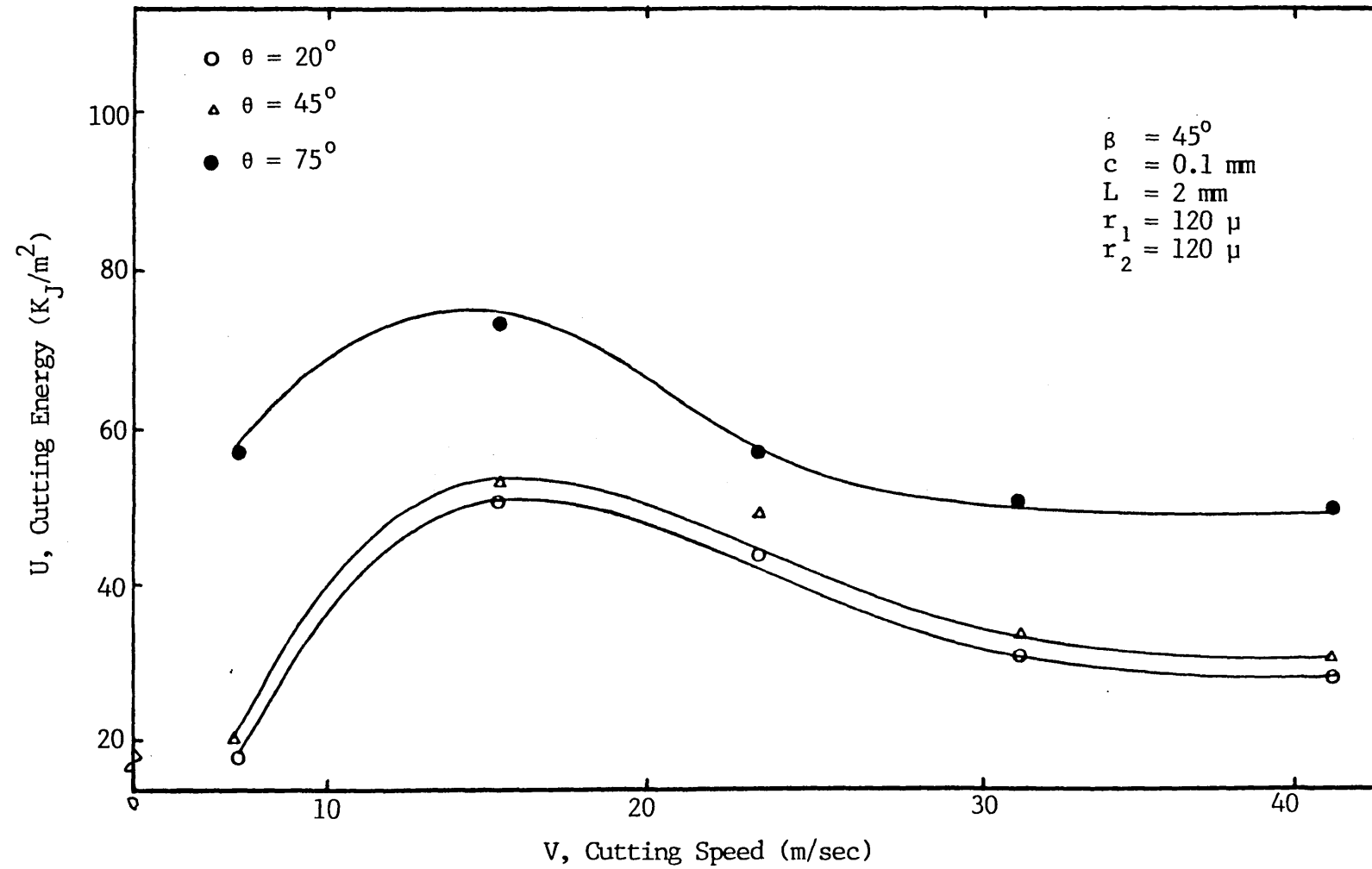


Fig. 5.34: ABS - Cutting Energy Versus Cutting Speeds for Different Rotating Blade Cutting Angles.

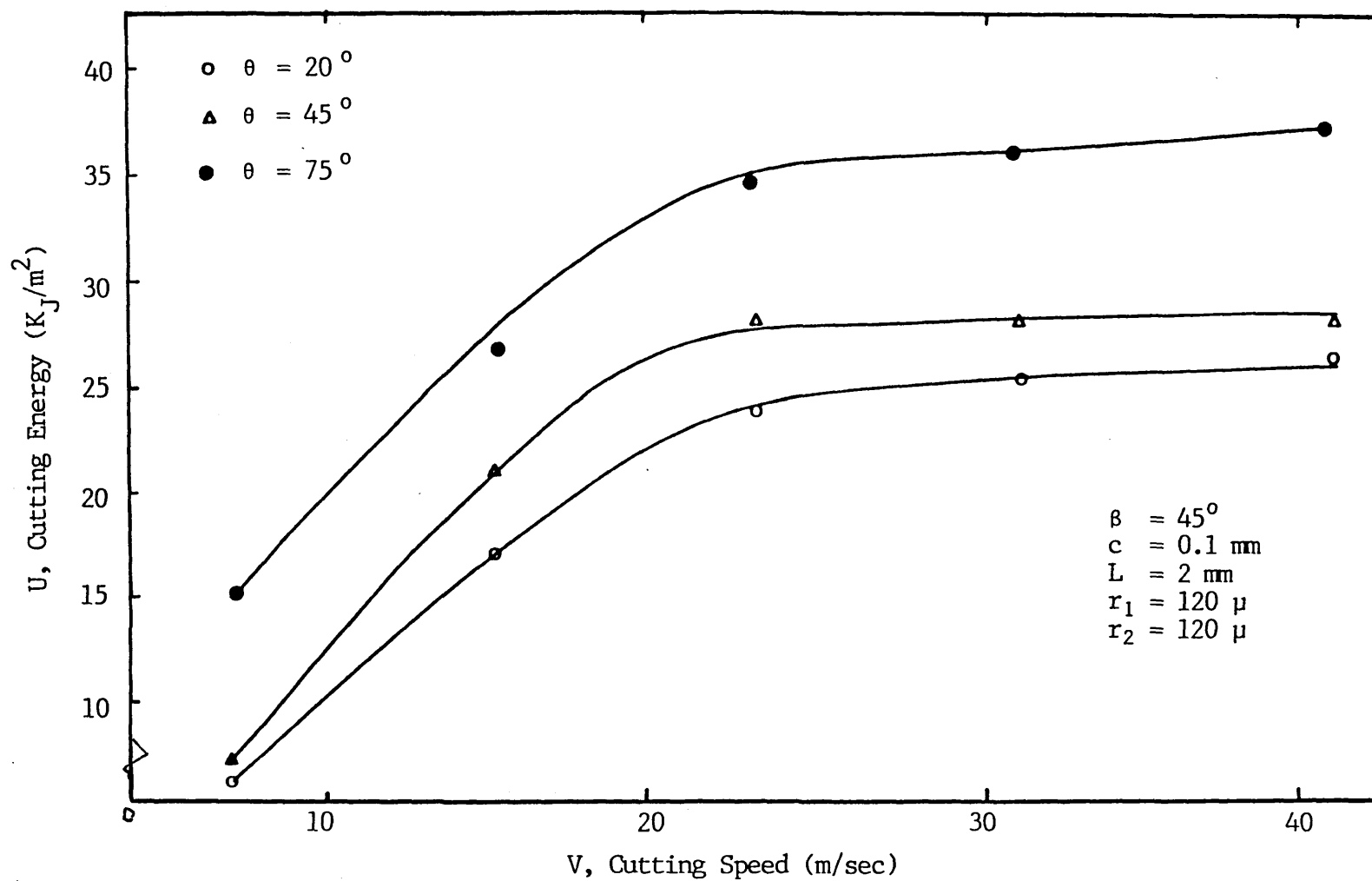


Fig. 5.35: PVC - Cutting Energy Versus Cutting Speeds for Different Rotating Blade Cutting Angles.

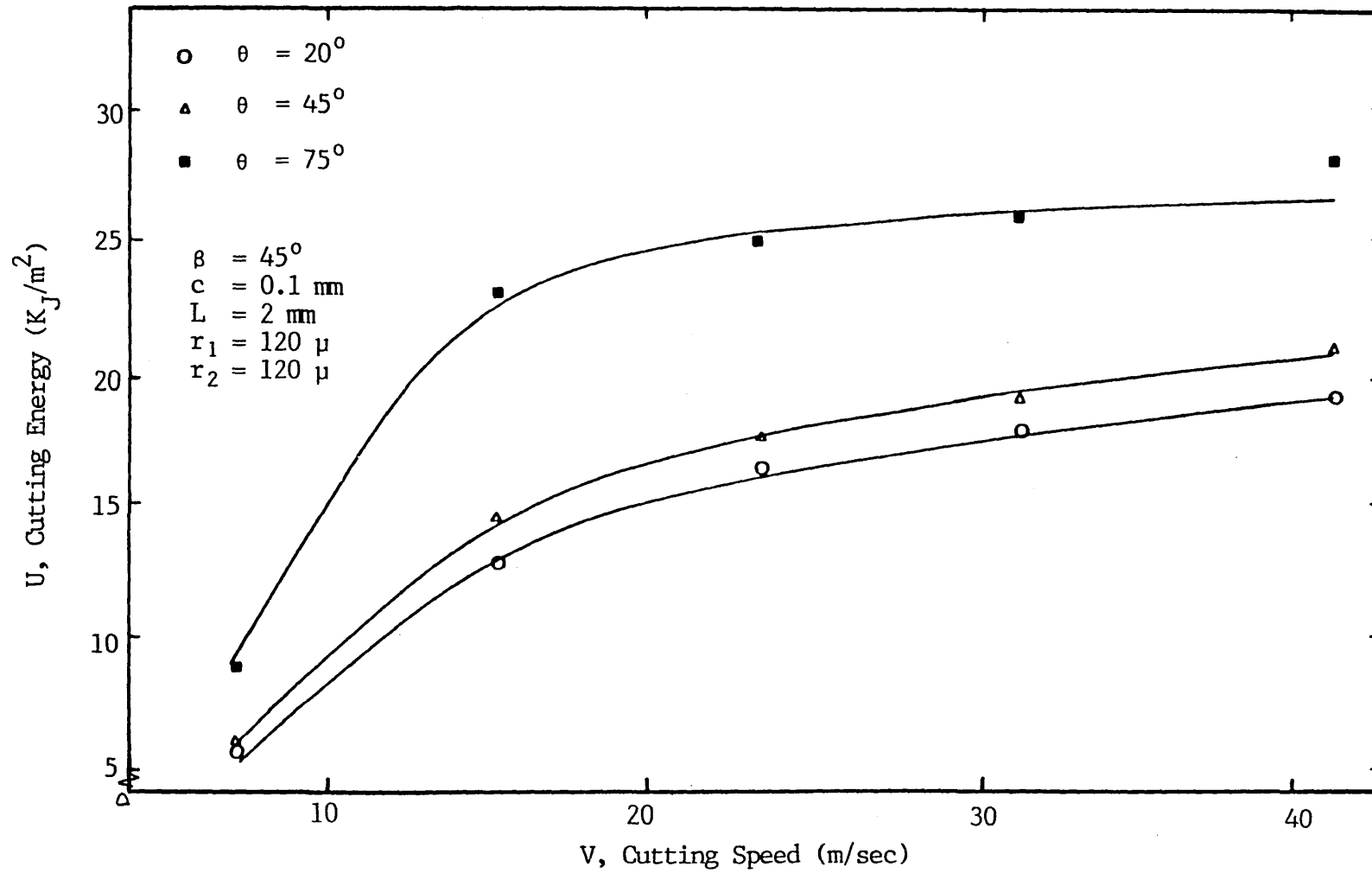


Fig. 5.36: HIPS - Cutting Energy Versus Cutting Speeds for Different Rotating Blade Cutting Angles.

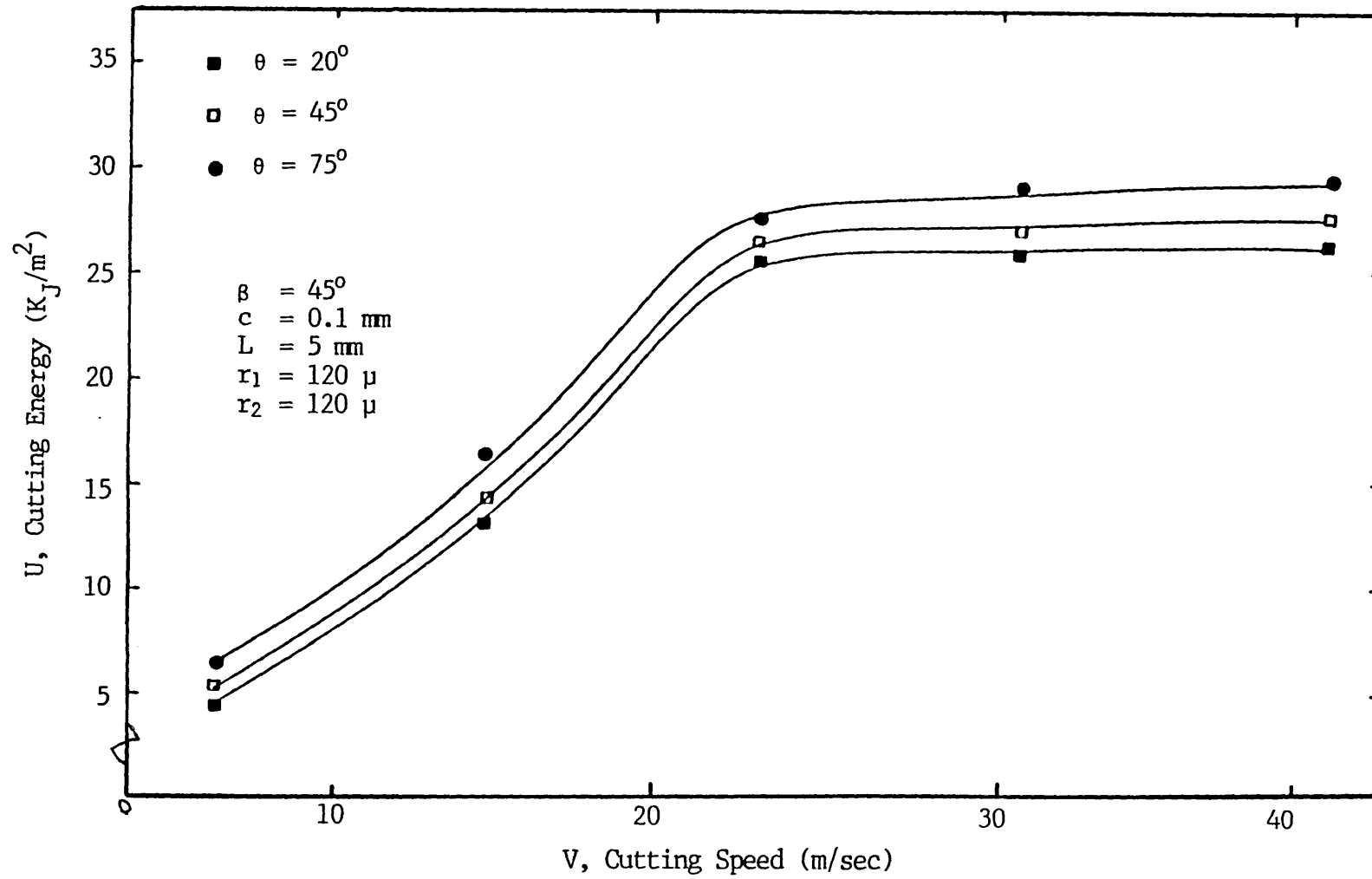


Fig. 5.37: PMMA - Cutting Energy Versus Cutting Speeds for Different Rotating Blade Cutting Angles.

on cutting energy of PP (blade cutting angle is constant), and compared with Fig. 5.32 which shows the effect of changing the rotating blade cutting angle on cutting energy of the same material, it can be seen that the curves of both figures rank the cutting energies in order of angle of attack irrespective of blade cutting angle. This is further illustrated in Fig. 5.38 for PC where the curves for varying blade cutting and attack angles are plotted together, where it can be seen that ranking by rotating blade angle of attack is again found. (There are no results at low speeds for higher blade angles and angles of attack, as cutting was ineffective). The suggestion is that the angle of attack is important in cutting and the blade cutting angle is of little consequence (provided that the angle of attack is unaffected), but not all the materials demonstrate this effect so clearly as shown, for example, in Figs. 5.30 and 5.37 for PMMA.

The effect of turning the rotating blade upside down so that the steep edge of the blade is uppermost is shown in Figs. 5.39-5.45, from which it can be seen that the cutting energies with this type of cut are greater than those for the standard tests with a straight cut. This was expected since mounting the rotating blade upside down requires a larger angle of attack which causes this increase of the cutting energy. Also Figs. 5.39-5.45 show the effect of the guillotine type of cut. It is clear that the cutting energies for

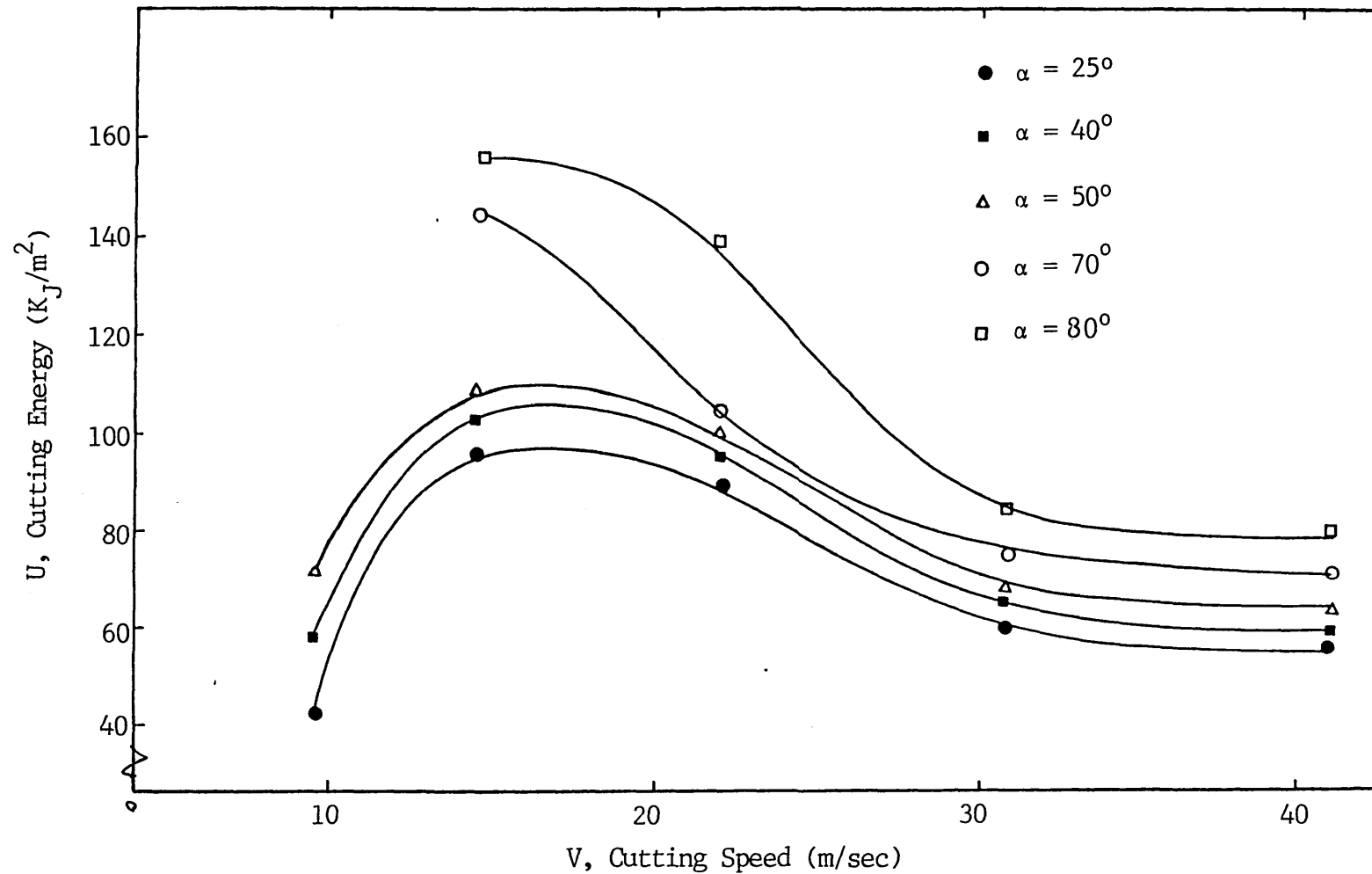


Fig. 5.38: PC - Cutting Energy Versus Cutting Speed for Several Rotating Blade Angles of Attack and Cutting Angles.

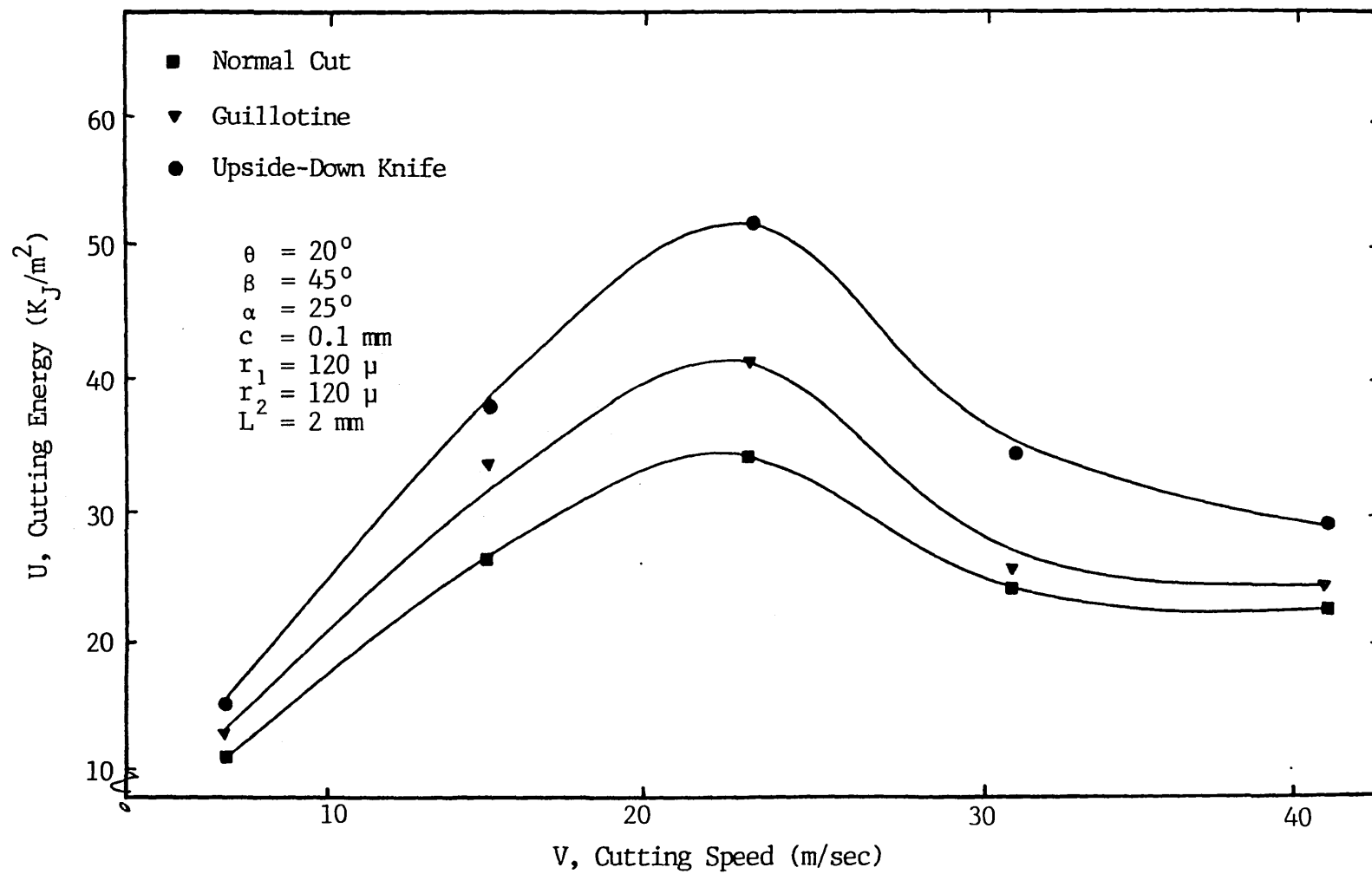


Fig. 5.39: LDPE - Cutting Energy Versus Cutting Speeds for Three Cutting Modes.

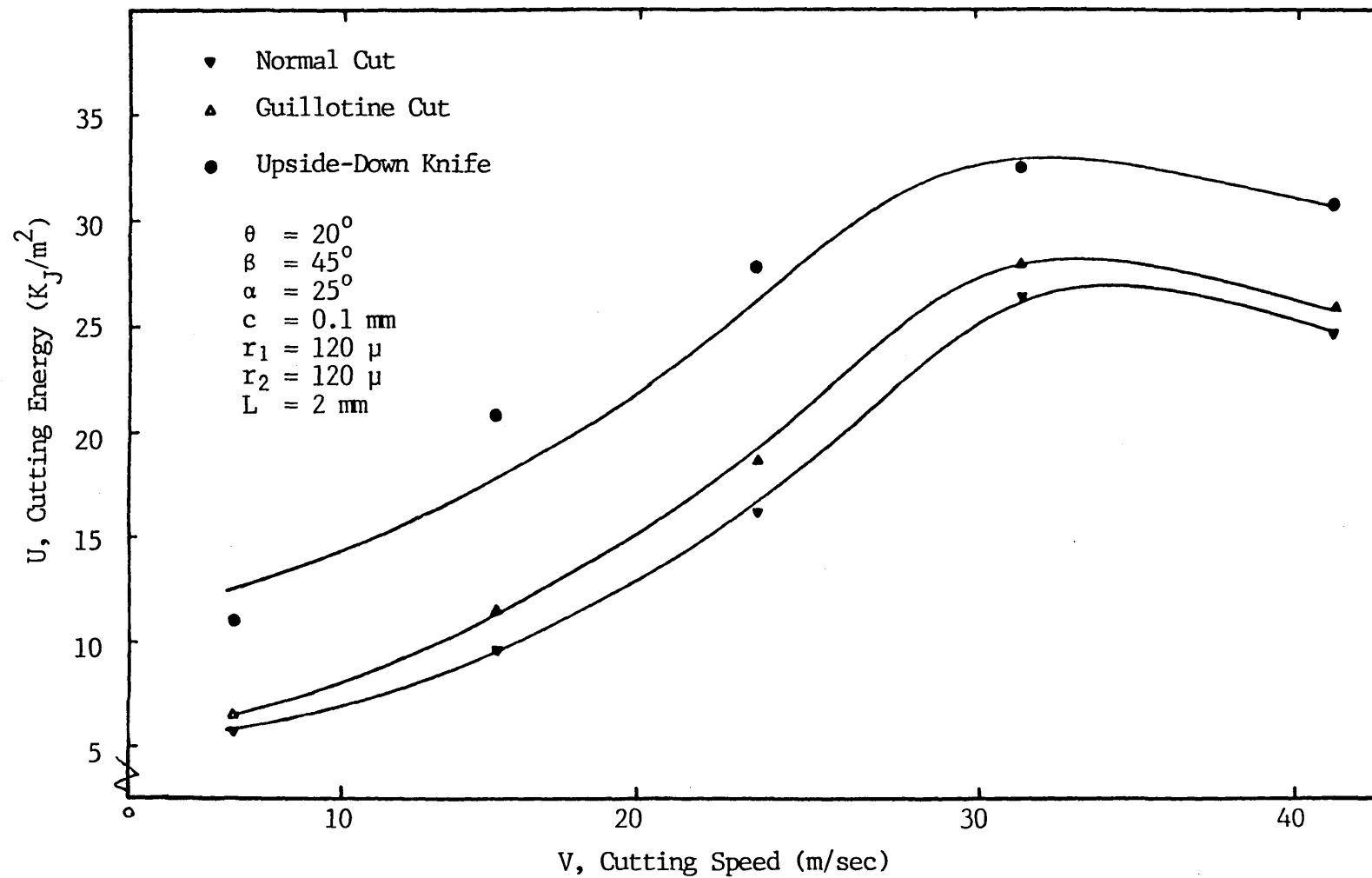


Fig. 5.40: PP - Cutting Energy Versus Cutting Speeds for Three Cutting Modes.

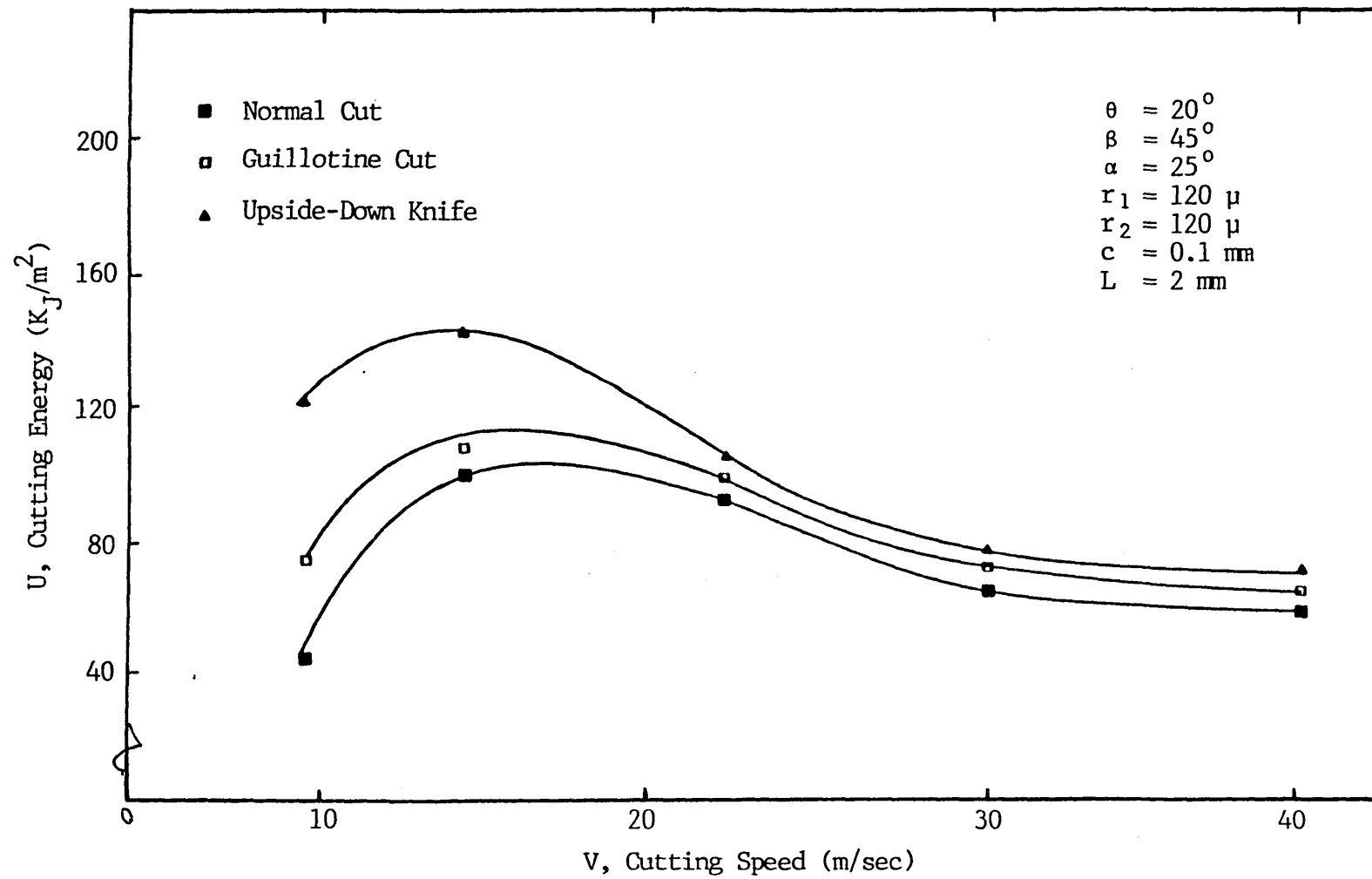


Fig. 5.41: PC - Cutting Energy Versus Cutting Speeds for Three Cutting Modes.

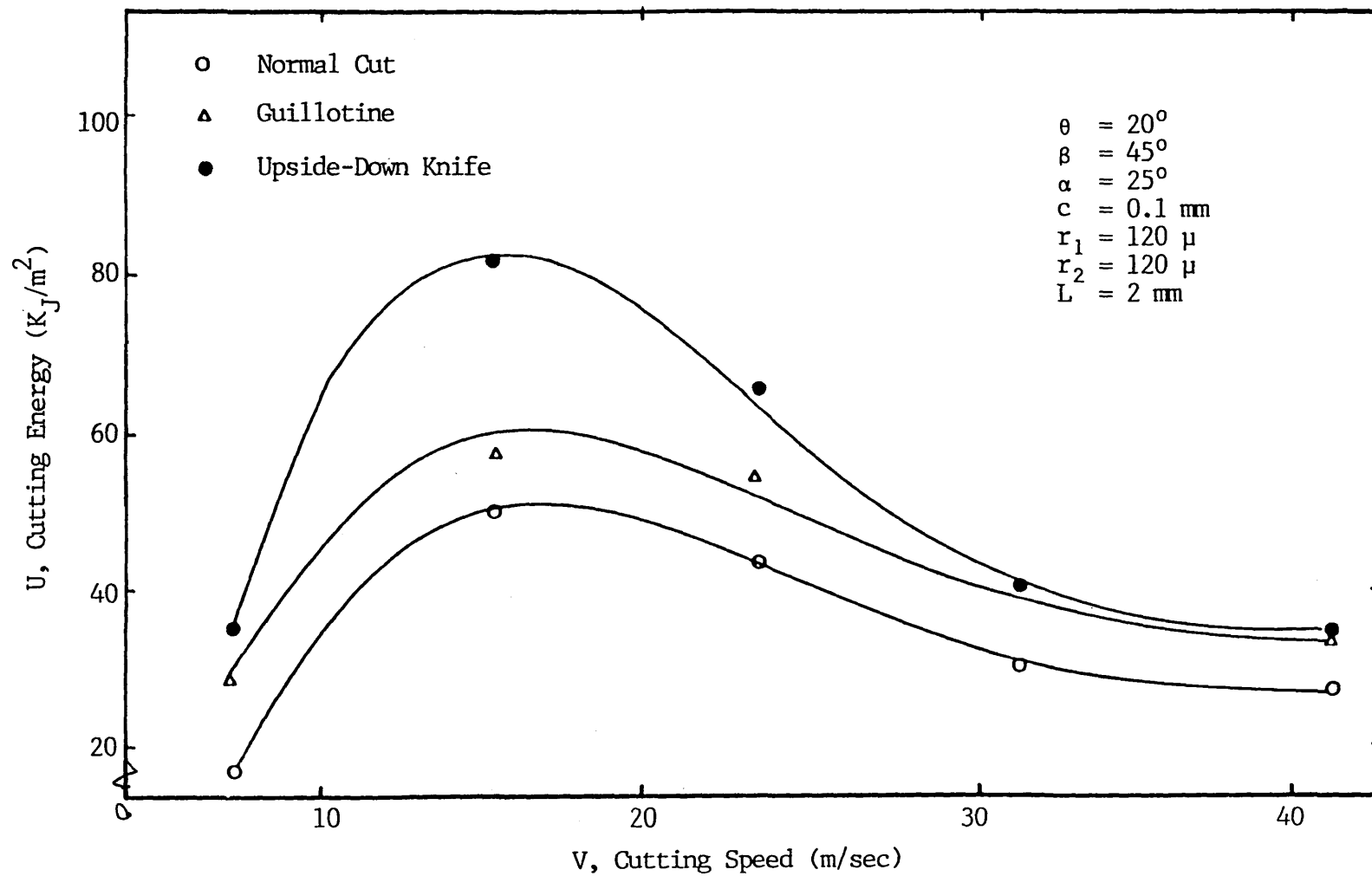


Fig. 5.42: ABS - Cutting Energy Versus Cutting Speeds for Three Cutting Modes.

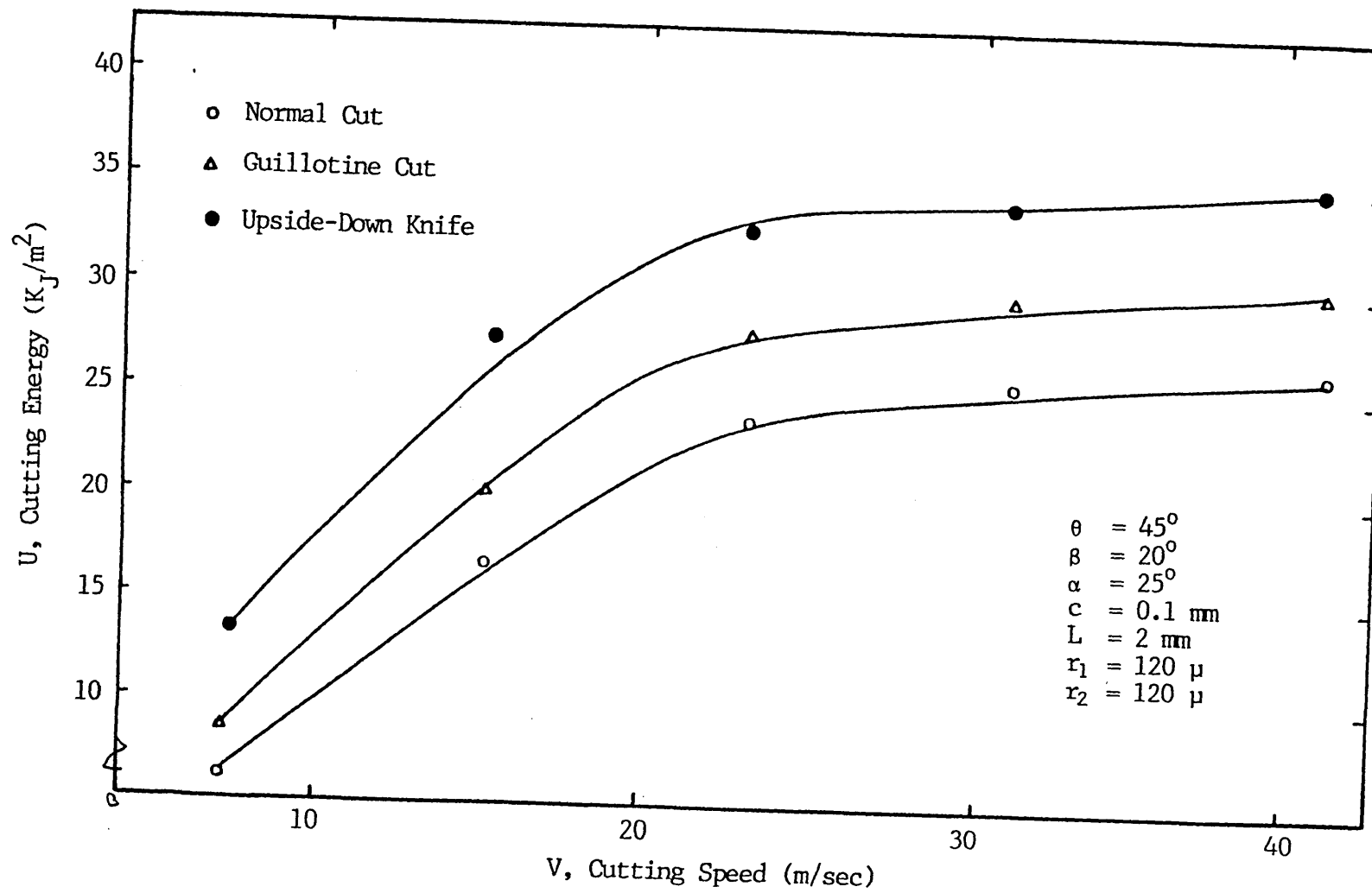


Fig. 5.43: PVC - Cutting Energy Versus Cutting Speeds for Three Cutting Modes.

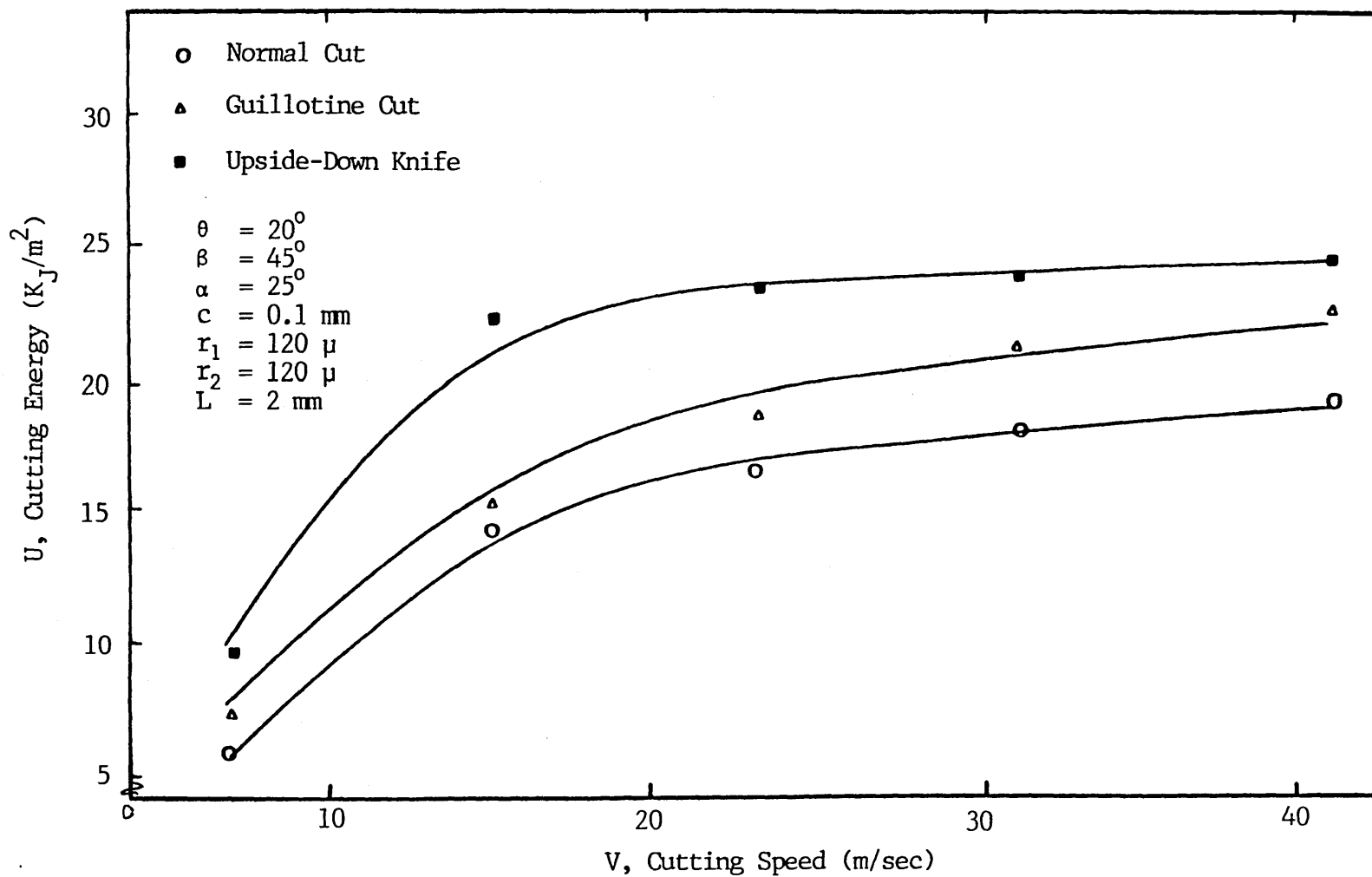


Fig. 5.44: HIPS - Cutting Energy Versus Cutting Speeds for Three Cutting Modes.

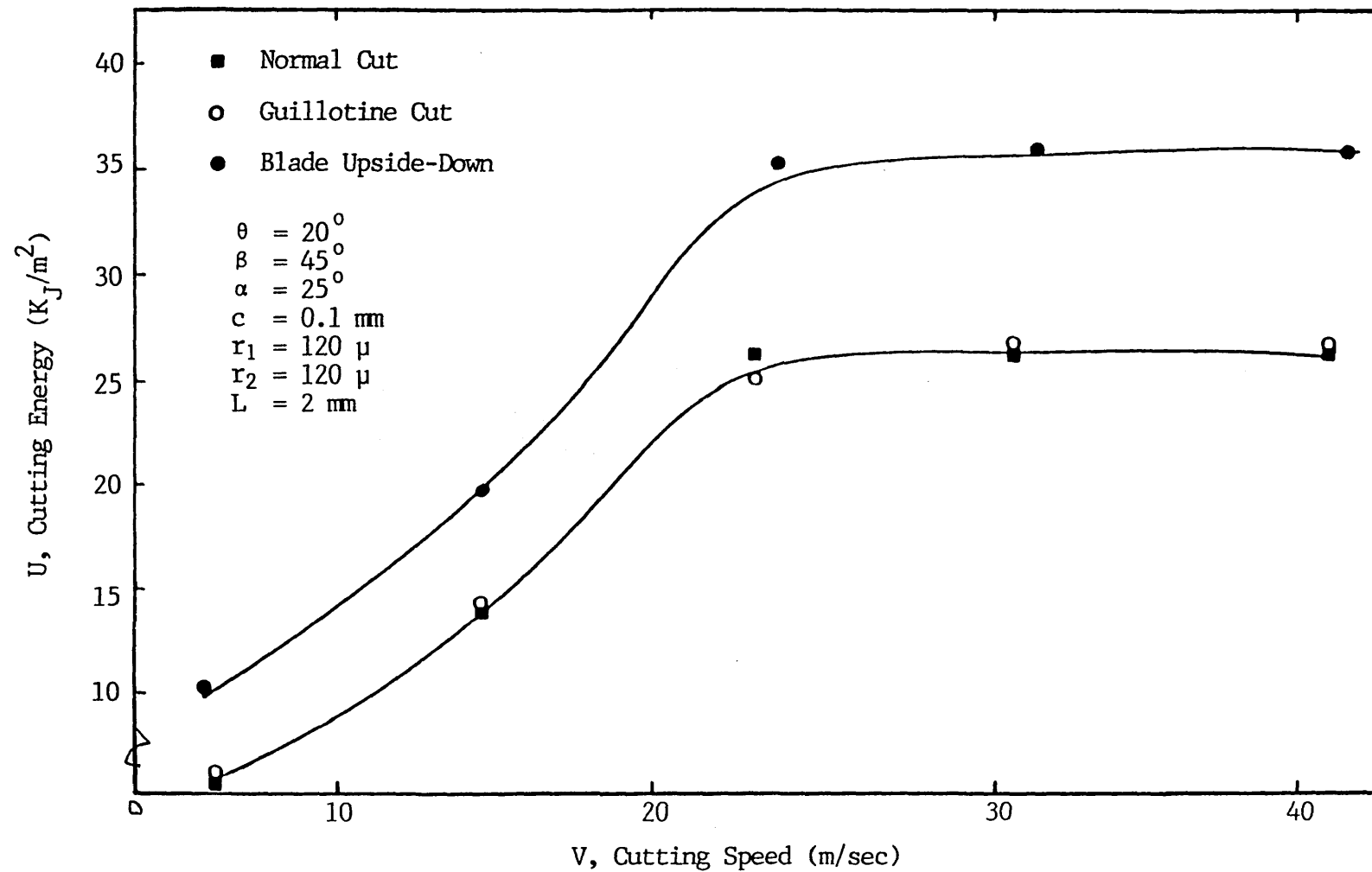


Fig. 5.45: PMMA - Cutting Energy Versus Cutting Speeds for Three Cutting Modes.

all materials except PMMA are greater than those for the standard tests with a straight cut. For PMMA the cutting energy is the same.

No significant widths effects were found. There was a slight variation between widths for some polymers, but there was no clear pattern to these and it was assumed that the discrepancies were attributable to slight inconsistencies of material properties between different sheets of the same material.

Similarly, there was little evidence of a thickness effect except for PMMA for which the energy per unit cut area decreased with increasing specimen thickness. This suggests that the more brittle PMMA demonstrates a more localised, initiation effect than the other, more ductile materials. This behaviour is also found in some impact tests.

5.2.5 Discussion

Of all the varied parameters in these tests, the speed of rotation of the knife was found to have the most effect on the absorbed energies, particularly in the speed range 7-25 m/sec. However, the polymers tested behaved in two different ways, some polymers demonstrated a clear peak in their cutting energies whereas others

appeared to require energies which increase steadily toward an upper bound as the cutting speed increases. For example, the cutting energy for materials such as LDPE, PP, PC and ABS (Figs. 5.3-5.6) shows a significant increase with increase in knife speed and shows a maximum value at a particular speed of cutting for each material, referred to as the 'critical speed'. As the cutting speed is increased above that critical value, the energy required to cut decreases rapidly to a fairly constant value.

On the other hand, the cutting energy for PVC, HIPS and PMMA, (Figs. 5.7-5.9) increases sharply with increased knife speed up to 25 m/sec. Above that speed, there is a more gradual increase in the absorbed energy.

Fig. 5.46 is a plot of cutting energy versus cutting speed for all materials tested. From this figure it can be seen that materials such as PC, ABS, LDPE and PP reach the peak of their cutting energy at different cutting speeds (and therefore have different critical speeds), and the materials which require the higher levels of energy to cut, reach their peaks earlier than those which require lower levels. For example, the peak cutting energy for PC is $98 \text{ K}_J/\text{m}^2$, for ABS is $49 \text{ K}_J/\text{m}^2$, for LDPE is $33 \text{ K}_J/\text{m}^2$ and for PP is $28 \text{ K}_J/\text{m}^2$ (ignoring the kinetic energy imparted to the cut part of the specimen which is considered to be negligible) while the critical

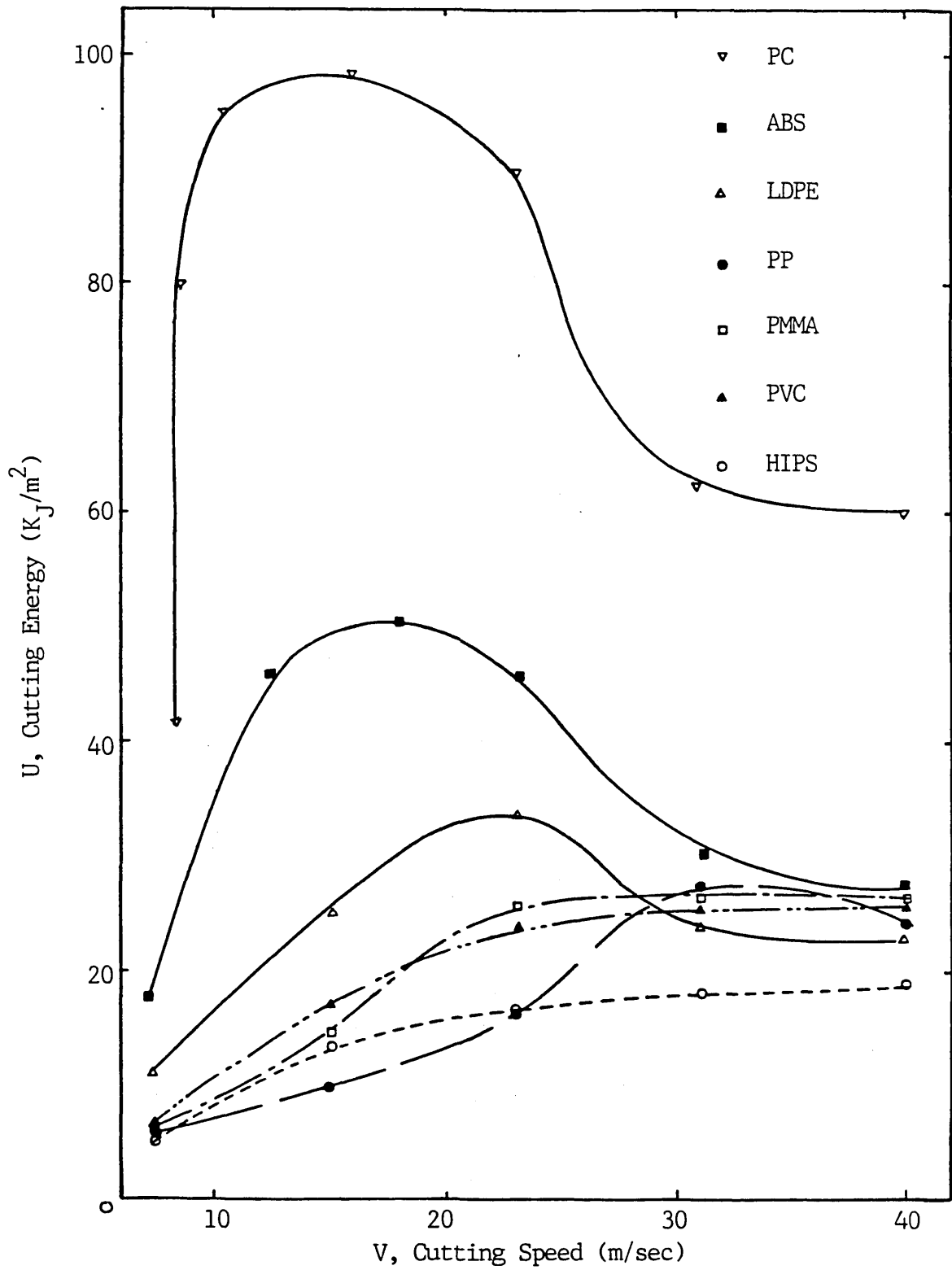


Fig. 5.46: Cutting Energy Versus Cutting Speed for all the Materials Tested.

cutting speed for PC is 15 m/sec, for ABS 18 m/sec, for LDPE is 24 m/sec and for PP is 34 m/sec approximately.

The other materials (PMMA, PVC and HIPS) whose cutting energies do not show a peak (Fig. 5.46) in the test speed range, show different rates of increase in their cutting energy above a cutting speed of 25 m/sec. For example, PMMA which of the three has the highest cutting energy at 25 m/sec, shows the least increase at higher speeds; whereas HIPS with the least cutting energy at 25 m/sec, increases the most rapidly above 25 m/sec; and PVC is the median material for both conditions.

The absence of an actual peak on the cutting energy/blade speed curve for PMMA, PVC and HIPS (Fig. 5.46), in the speed range investigated here, does not preclude the possibility of a peak occurring at some higher speed for these materials. Whilst there is no hard evidence to suggest that this is the case (for conclusive proof blade speeds well in excess of 40 m/sec would be required, for which the present rig was not designed) there is equally no good reason to suppose that these materials should behave differently. In Fig. 5.46 at higher blade speeds for these three materials, between 25 and 40 m/sec, there is in each case evidence of a levelling off in cutting energy with increased blade speed. It is suggested therefore that at some higher speed a peak may be reached

for each of these materials, in this order, PMMA followed by PVC and then HIPS.

Kobayashi and Saito (73 and 74) examined the effect of cutting speed on force in the machining of UP and PC in the low speed range. The relation between the cutting force and speed in the machining of UP and PC is shown in Fig. 2.1. It can be seen that the force increases slightly with increasing speed, and shows a maximum value in the range 0.1-1 m/min for UP and 0.1-30 m/min for PC. As the cutting speed continues to increase, the force decreases slowly in the range 1-1000 m/min for up and 30-500 m/min for PC. However, the results of the present study show that the increase in cutting energy with increased speed, is more dramatic and occurs more quickly than suggested by the force measurements of Kobayashi and Saito. For materials whose cutting energy did not peak in the range of speeds investigated, (PVC, HIPS and PMMA) the recorded energy is increased by approximately a factor of five, as the cutting speed increases from 7 to 25 m/sec as shown in Fig. 5.46.

For the other materials which demonstrate a clear peak, the cutting energy is increased by approximately a factor of three for materials such as PC, ABS and LDPE and by a factor of approximately five for PP in the speed ranges 7-15 m/sec, 7-18 m/sec, 7-24 m/sec and 7-32 m/sec

respectively, as shown in Fig. 5.46.

It can also be seen that the cutting energy for materials such as PC, ABS and LDPE decreases to approximately half the peak value when the speed is increased further, but for PP the fall in energy is quite small in the speed range beyond the peak energy. In the present study the fall in cutting energy took place in a very short time in less than two decades of cutting speed, while in Kobayashi and Saito's tests the drop occurred over a longer period.

In short, from a comparison between Kobayashi and Saito's work and the present study, it can be seen that they conducted their tests at lower cutting speeds than those used in the present study and the rise and fall in the cutting force which they observed, occurred at much lower speeds and over wider speed ranges than any of the peaks observed in the present work. In addition, the increase in cutting force which they noted, was far less dramatic than has been found here.

Strong rate effects have been observed in notched impact testing by Williams et al (86 and 87) and they also reported evidence of upper bounds (86), although it is not clear if these are peaks or not. The rate sensitivity reported in impact is not as strong

as found in the cutting work reported here, however. In tests on PTFE, HDPE and PMMA (87), they found that the fracture toughness was proportional to the square root of the strain rate, whereas in the tests reported here the dependence over the speed range 7-20 m/sec is essentially linear as shown in Fig. 5.47. The reasons advanced by Williams et al for the energy increase is that of crack tip blunting induced by high local heating. If thermal blunting is a contributing factor to high energy requirements then it must be in addition to the blunting effect of the blade tip rather than one which supercedes it since sharp blades give much lower cutting energies than blunter ones throughout the full speed range tested. Whatever the cause of the blunting near to the blade tip, its effect is strong and gives clear evidence of the desirability of sharp blades in any cutting operation. It appears that for the ductile LDPE and Polypropylene, a modest reduction in sharpness ($r_1 = 120 \mu$), but still maintaining a sharp cutter, is acceptable, but further reductions in sharpness ($r_2 = 240 \mu$) give much higher energies. Whereas brittle PMMA shows a different effect, a very sharp blade ($r_1 = 60 \mu$) gives considerable advantage over the blade of intermediate sharpness ($r_1 = 120 \mu$) but additional bluntness ($r_1 = 240 \mu$) has less effect.

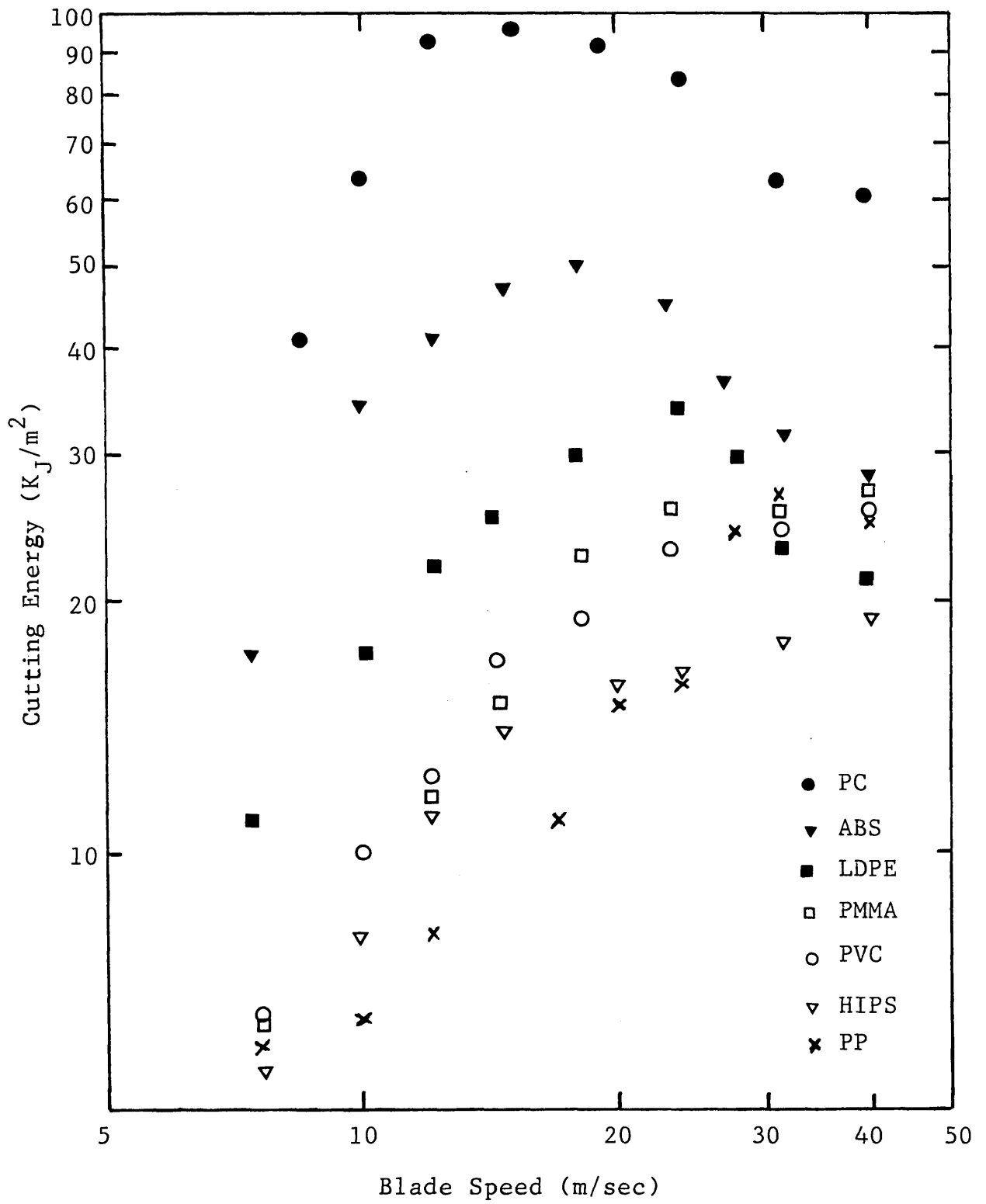


Fig. 5.47: Cutting Energy versus Blade Speed

Clearance (Figs. 5.10-5.15) is not a significant factor in these high speed cutting tests and for brittle PMMA changing clearance does not change cutting energies at all (Fig. 5.16). At very high cutting speeds, even for ductile materials, the clearance effect is negligible (Figs. 5.10-5.13) and removal of the fixed blade altogether has no effect. The implication of this is that the cutting action at these speeds and on these specimen sizes is not a simple shearing mechanism but is rather one of notching followed by a wedging action which ultimately leads to an unstable crack propagating through the specimen as shown in Fig. 5.48.

The results indicate that blade cutting angle, by itself, is not significant in controlling cutting energies and that rotating blade angle of attack is the significant factor. This is not surprising as the specimen is only affected by the cutting face which deforms the cut piece, the trailing face does not touch the material during the cut (as shown schematically in Fig. 5.48). Since a blade with a large angle of attack causes more deformation and therefore performs more work, it is to be expected that the cutting energies will increase with increasing angle of attack. Similarly, an increase in the length of material to be removed will cause an increase in energy requirement because of the additional work of deformation and of kinetic energy imparted to the cut portion of the specimen.

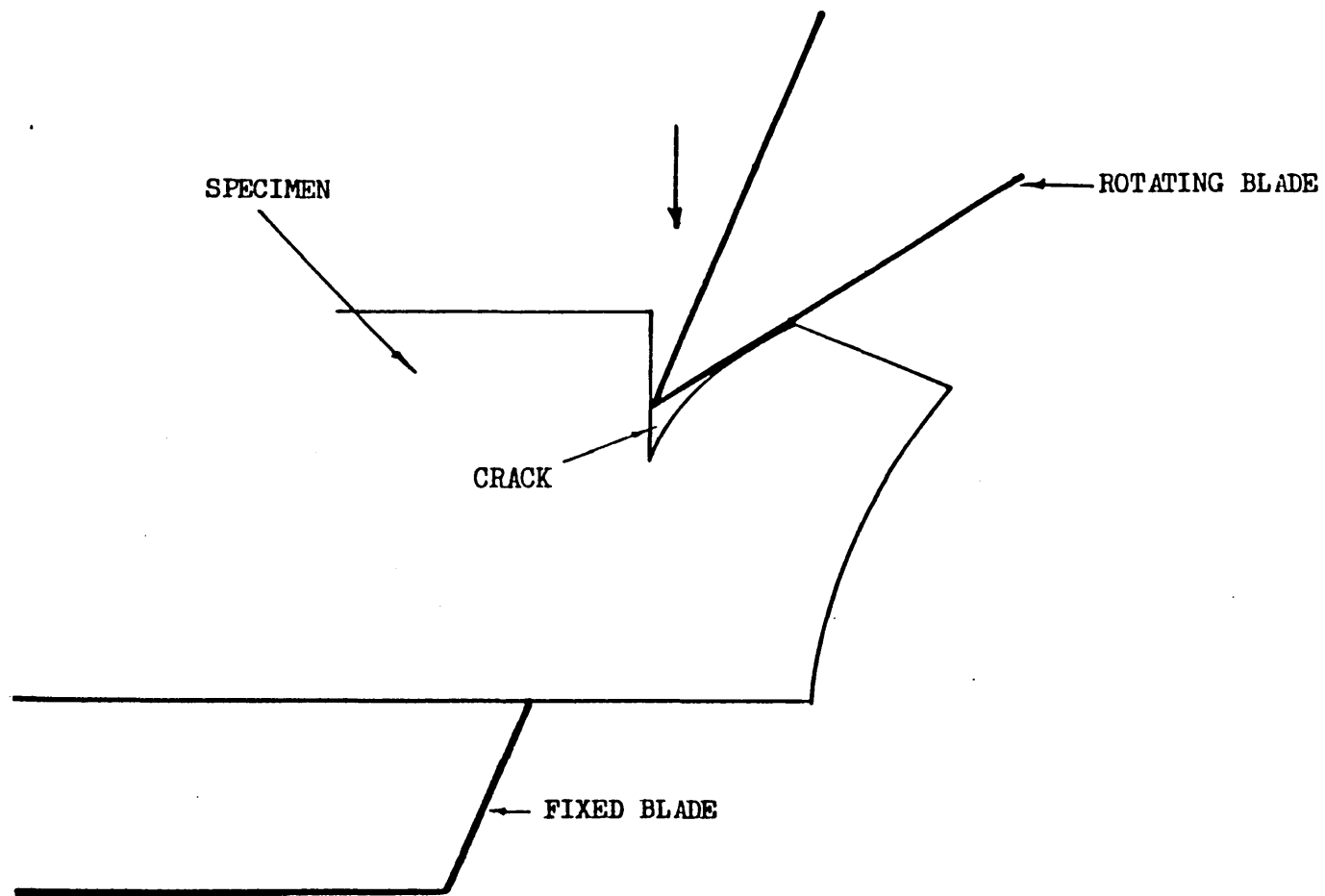


Fig. 5.48: Schematic Diagram of the Process of Cutting.

Figs. 5.49a,b,c and d are four plots of cutting energy versus several values of length to be cut, clearances, blade sharpness, and angles of attack at a cutting speed of 30m/sec for a ductile material (PP) and a brittle material (HIPS). From Figs. a and b it can be seen that the effects of length to be cut and clearance are small. For example, the cutting energy is increased by 7 per cent for PP and 10 per cent for HIPS as the length to be cut is increased from 2 to 8 mm also the cutting energy is increased by 6 per cent for PP and 9 per cent for HIPS as the clearance is increased from 0.1 to 0.8mm.

On the other hand, the effects of sharpness and angle of attack (Figs. 5.49c and d) appear to be strong. For example, the cutting energy is increased by 40 per cent for PP and 60 per cent for HIPS as the sharpness is increased from 240 to 60 microns, also the cutting energy is increased by 20 per cent for PP and 30 per cent for HIPS as the angle of attack is increased from 25 to 70 degrees.

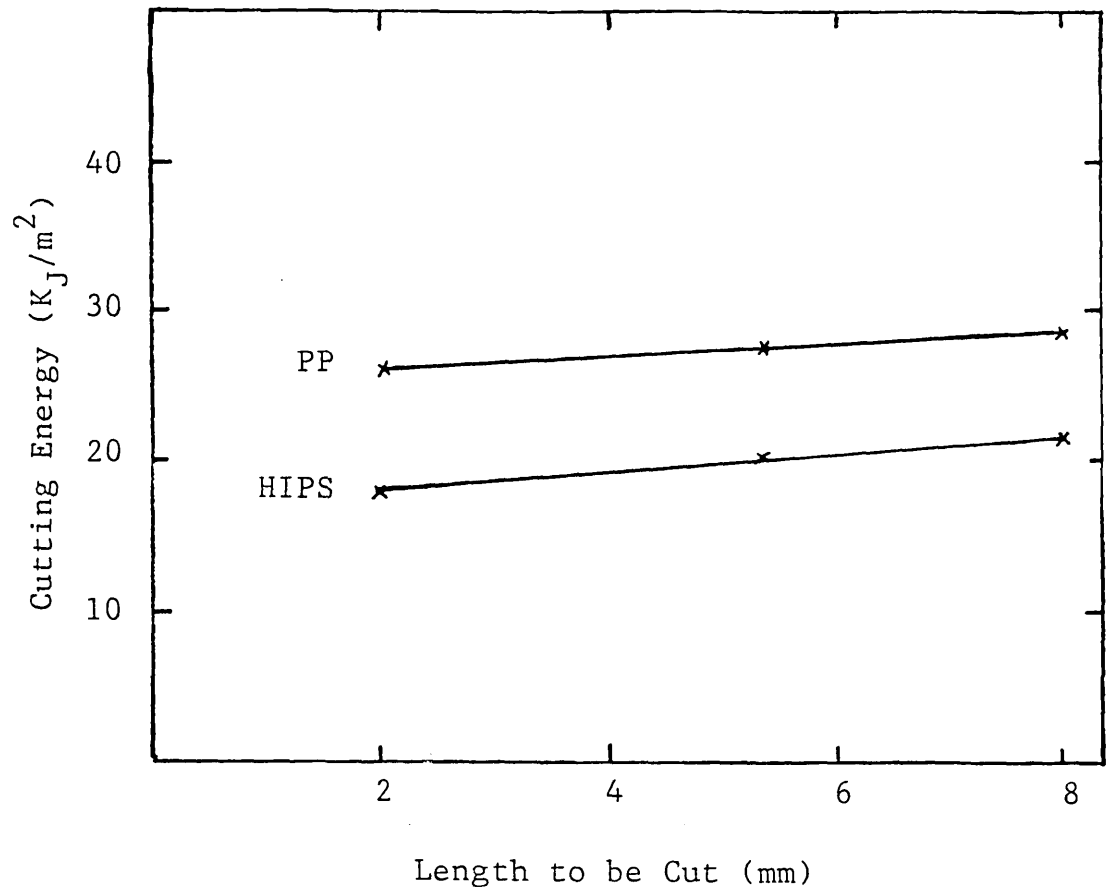


Fig. 5.46.a: Cutting Energy versus Several Lengths to be Cut for PP and HIPS at Blade Speed of 30m/sec.

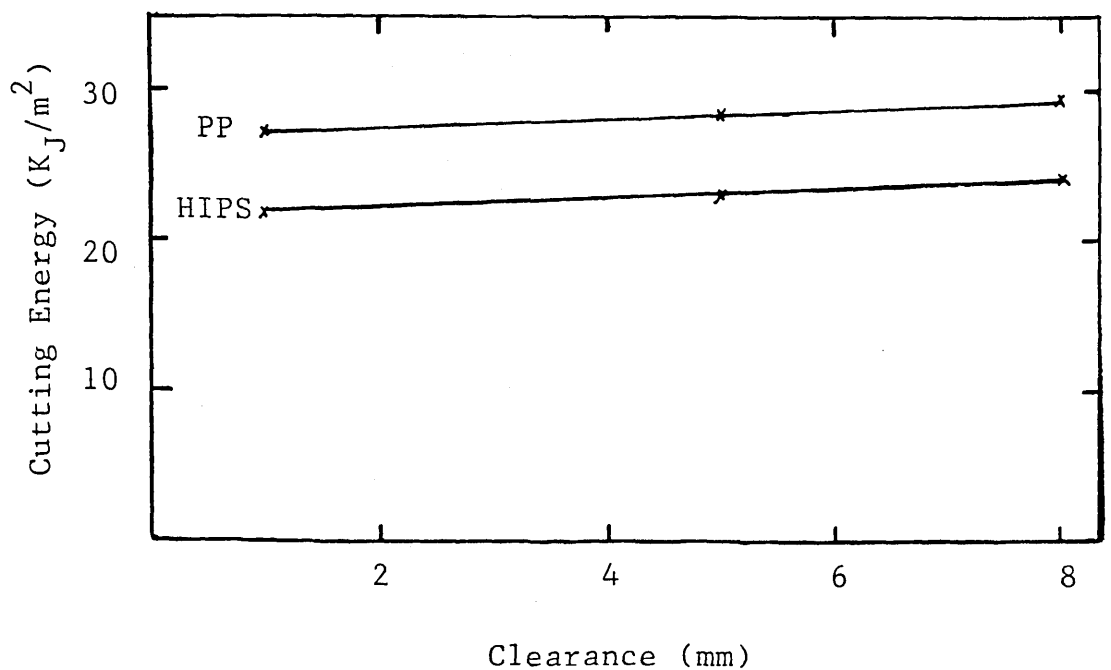


Fig. 5.46.b: Cutting Energy versus Several Blade Clearances for PP and HIPS at Cutting Speed of 30m/sec.

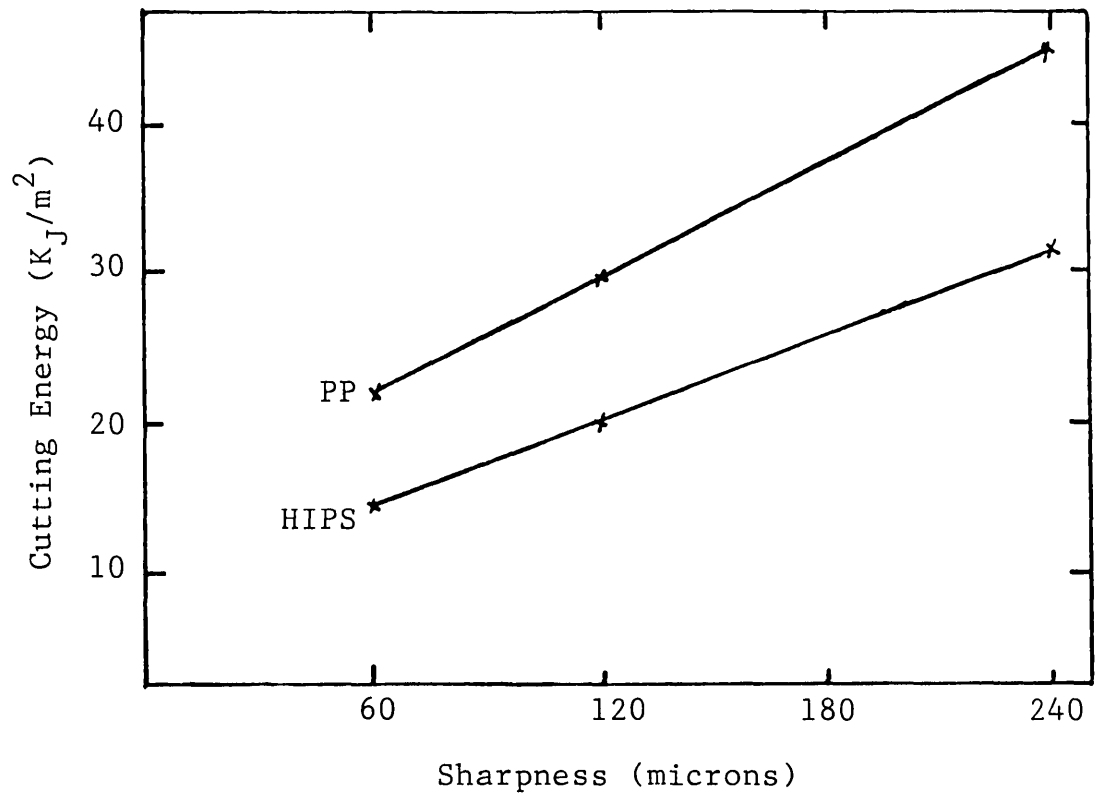


Fig. 5.46.c: Cutting Energy versus Several Degrees of Blade Sharpness for PP and HIPS at Blade Speed of 30m/sec.

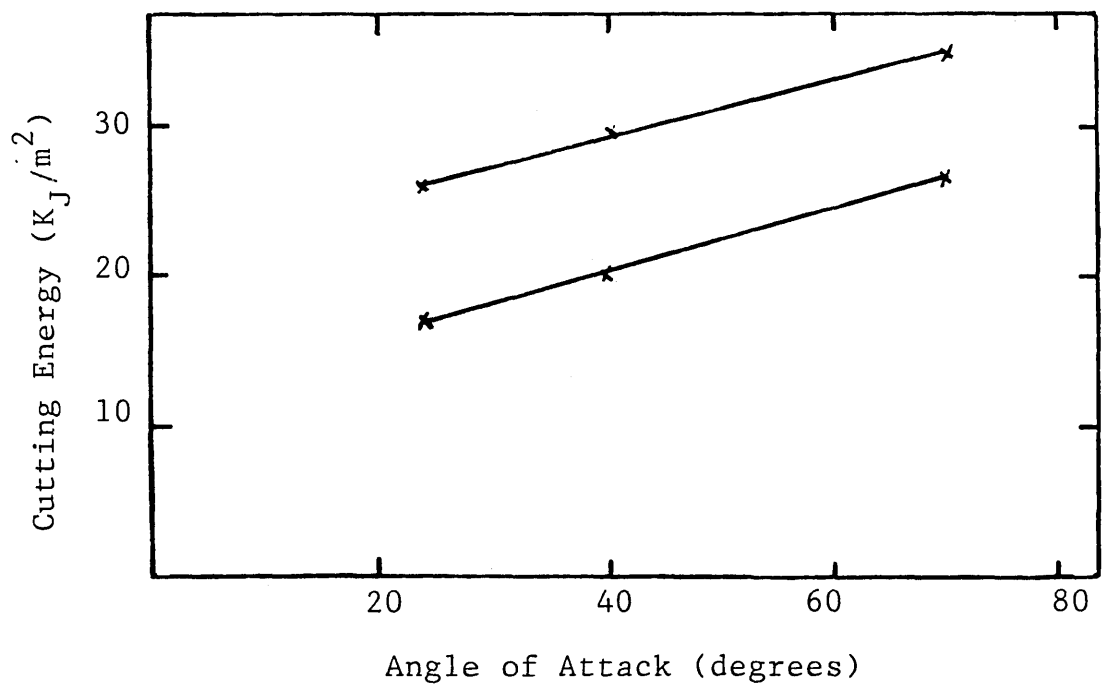


Fig. 5.46.d: Cutting Energy versus Several Angles of Attack for PP and HIPS at Blade Speed of 30m/sec.

The use of a guillotine action increases energy requirements for all polymers (Figs. 5.39-5.45). This finding is inconsistent with some granulator manufacturers' claims of lower energy levels using slanted cuts. This may be because the effect of a guillotine cut is to spread the rotor loading over a finite time interval so that the drive mechanism is not subjected to shock loading. Certainly other manufacturers claim power advantages by using a series of staggered blades instead of a single, long blade, whilst still maintaining straight cuts. It is suggested that the reason for the higher energy levels using guillotine cuts in the tests reported here is that a greater amount of notched area is necessary before a crack can be forced to run through the specimen.

A clear fact to emerge from the experiments is that, whatever the polymer, the conditions required for minimum cutting energy are the same, these are:

- low blade speed
- minimum clearance, but of no significance for brittle materials or for very high speed cutting,
- maximum blade sharpness to give highly localised stress intensities,
- minimum rotating blade angle of attack to reduce redundant deformation of the cut piece

- a straight cut should be used, but there may be an advantage in using staggered blades in practical situations to avoid high shock loads.

There is no evidence that the fixed blade condition has any effect on high speed cutting energies; also it was possible to cut materials (HIPS, PVC and PMMH) at high speeds without a fixed blade and the cutting energies were the same as those obtained with a fixed blade present. The fixed blade merely acts as a supporting anvil allowing the moving blade to control the cutting process.

5.2.6 CONCLUSION

The energy required to cut small scale polymer specimens when subject to high speed single cuts, is strongly dependent on cutting blade speed, particularly in the range of 7-25 m/sec. This effect is similar to, but greater than, that reported in the varied rate notched impact testing of polymers. Some polymers (PVC, HIPS and PMMA) showed energies which increased continuously throughout the speed range tested, whereas others (LDPE, PP, PC and ABS) showed a clear maximum. It appears that cutting under the test situation is not a shear process but is more akin to crack propagation following notching. The fact that fixed blade conditions are unimportant and that

at high speeds it can be removed without effect, coupled with the observed clearance effect, tend to confirm this view. Minimum energies are obtained for minimum bluntness, angle of attack, clearance and speed for all materials but there are different types of dependence on these variables particularly between materials showing extremes of ductility.

The precise mechanism which governs the rate effect is not clear, but in view of the similarity with notched impact behaviour, it is believed that strong local thermal conditions play a major role. To support this view it was decided to combine the cutting experiments with a microscopic study of the cut surfaces, which is given in Chapter 8.

CHAPTER 6

THE EFFECT OF TEMPERATURE ON ENERGY ABSORBED IN CUTTING OF POLYMERS

6.1 INTRODUCTION

Properties of polymeric materials are highly dependent on temperature. There exists a 'ductile-brittle transition temperature': below this temperature, the material exhibits brittle characteristics and above this temperature, the material exhibits ductile characteristics. It was therefore found necessary to examine the effect of temperature on the energy required to cut polymers.

6.2 EXPERIMENTAL PROGRAMME

6.2.1 Test Equipment and Testing Conditions

Variation of test temperature was achieved by cooling or heating the test specimen while it was placed in the testing machine table. Temperature below ambient was obtained by using the cooling system shown in Fig. 6.1. In the system, nitrogen is fed via a reduction valve into a spiral copper tubing placed in a flask containing liquid nitrogen. A rubber tube is connected to the spiral. The other end of the rubber tube is prepared to allow jets of the cold gas to be directed on to the test specimen and a dummy specimen. To ensure that test, and dummy specimens have the same

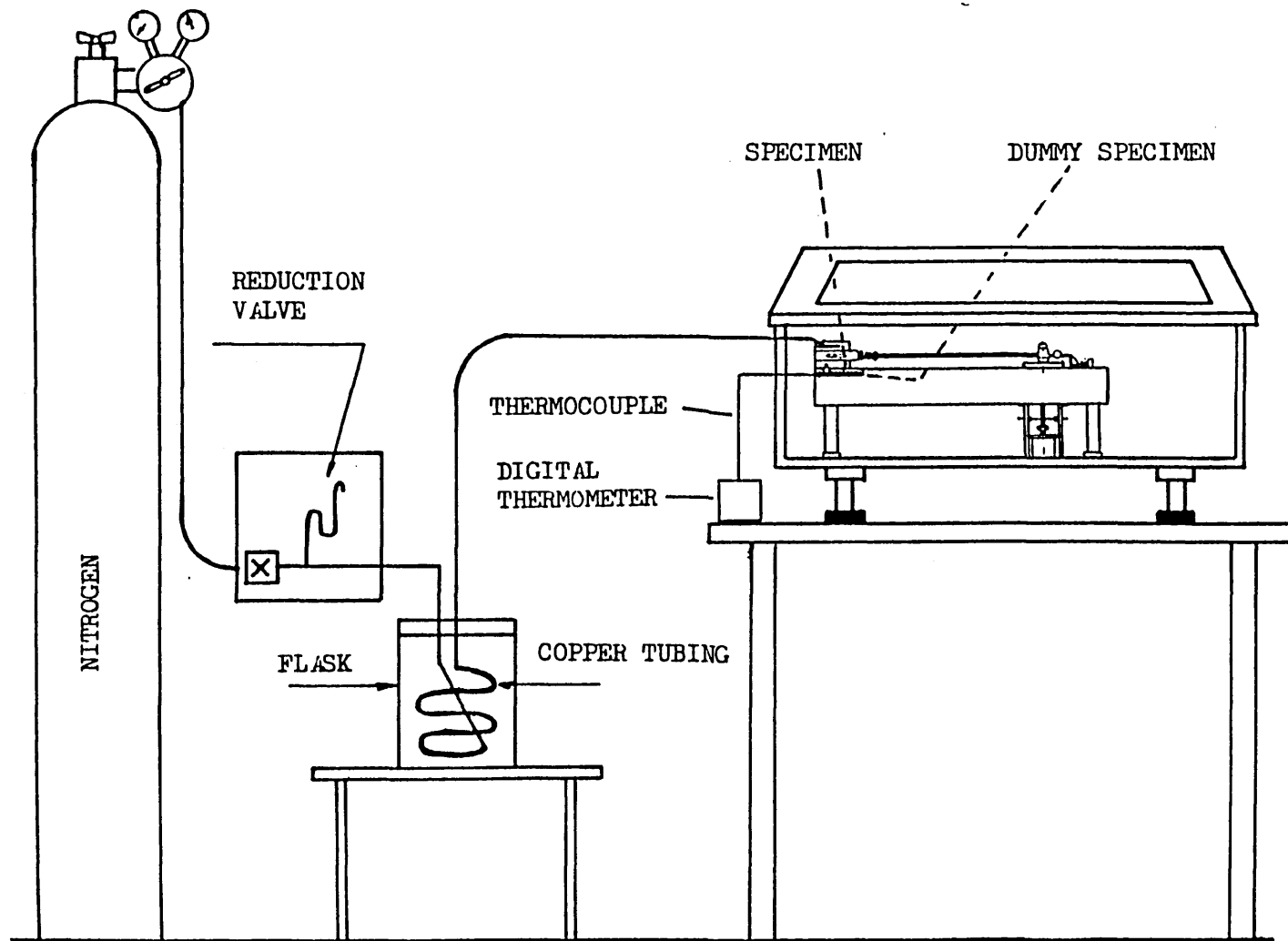


Fig. 6.1: Schematic Diagram of Test Apparatus.

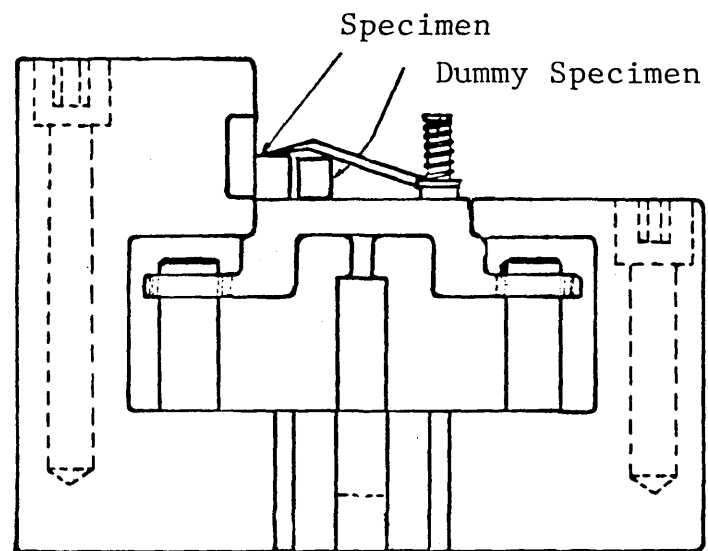


Fig. 6.1a: The position of the Dummy Specimen in relation to the Test specimen (Side View).

temperature, the dummy specimen was placed in a permanent position very close to the test specimen (Fig. 6.1a).

The temperature of the test was registered using a thermocouple connected from one end to the interior of the dummy specimen and from the other end to a digital thermometer. The required temperature was obtained by controlling the flow rate of nitrogen gas passing through the spiral.

Temperatures above ambient were achieved by the use of a hot air blower controlled by a 'Eurotherm' control unit. The hot air was blown and directed on to the specimen and the dummy specimen. The function of the 'Eurotherm' control unit was to monitor the difference between the preset temperature and that currently measured through the dummy specimen. The 'Eurotherm' control unit was accurate to within ± 1 °C.

The experiments were carried out on the same polymers given in Section 5.2.1 and specimen dimensions are given in Table 5.1. Ranges of test temperatures for each material tested are shown in Table 6.1. These materials were tested over the speed range 7 to 40 m/sec.

Material	Range of Test Temperature (°C)
LDPE	-45 to +65
PC	-45 to +120
ABS	-45 to +80
PP	-45 to +65
PVC	-45 to +65
PMMA	-45 to +100
HIPS	-45 to +100

Table 6.1: Range of Test Temperature for the Various Materials Tested.

6.2.2 Results and Discussion

Test results are shown in Figs. 6.2-6.8, from which it can be seen that the test temperature has a strong effect on the energy required to cut and the combined effects of temperature and rate are complex. The temperatures and blade speeds at which minimum and maximum energies were obtained are given in Table 6.2.

However, for materials which showed a peak in their cutting energies such as LDPE, PC and ABS (Figs. 6.2-6.4), an increase in the temperature causes a decrease in their cutting energies and at lower temperatures (above -45°C), there is a rise in their energies. At a temperature of -45°C , there is a sharp drop in the absorbed energies of LDPE (Fig. 6.2) and PC (Fig. 6.3) and there is a rise in the cutting energy of ABS (Fig. 6.3).

For the other materials (PP, PVC, PMMA and HIPS Figs. 6.5-6.8), the dependency of cutting energy on test temperature is such that an increase in the test temperature causes an increase in the absorbed energy, and the lower the test temperature, the lower the energy required to cut. The lowest levels of cutting energy occur at the lowest test temperature of -45°C .

Also, for materials which showed a peak in their cutting energies (LDPE, PC, ABS and PP Figs. 6.2-6.5),

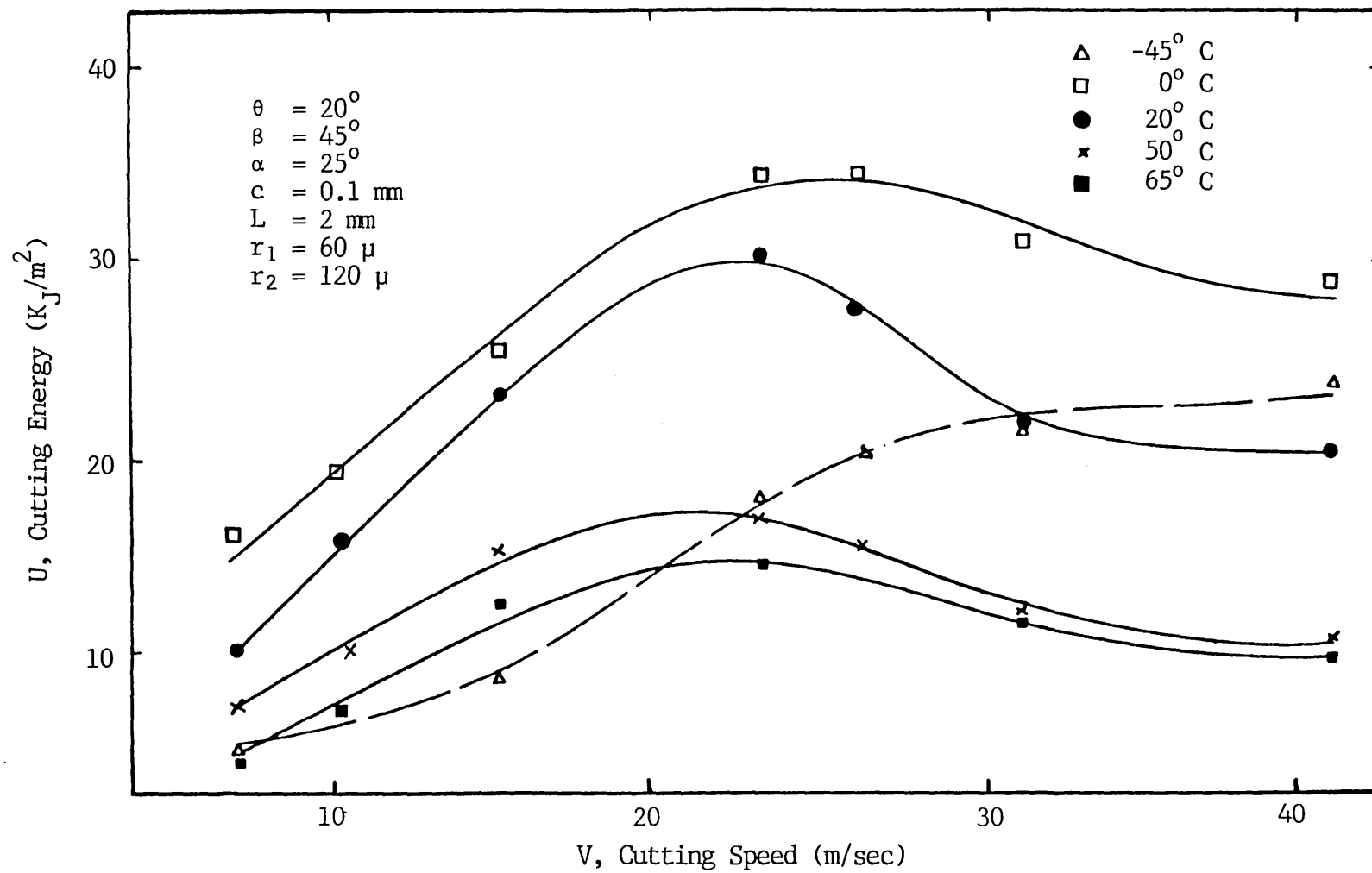


Fig. 6.2: LDPE - Cutting Energy Versus Cutting Speeds at Different Temperatures.

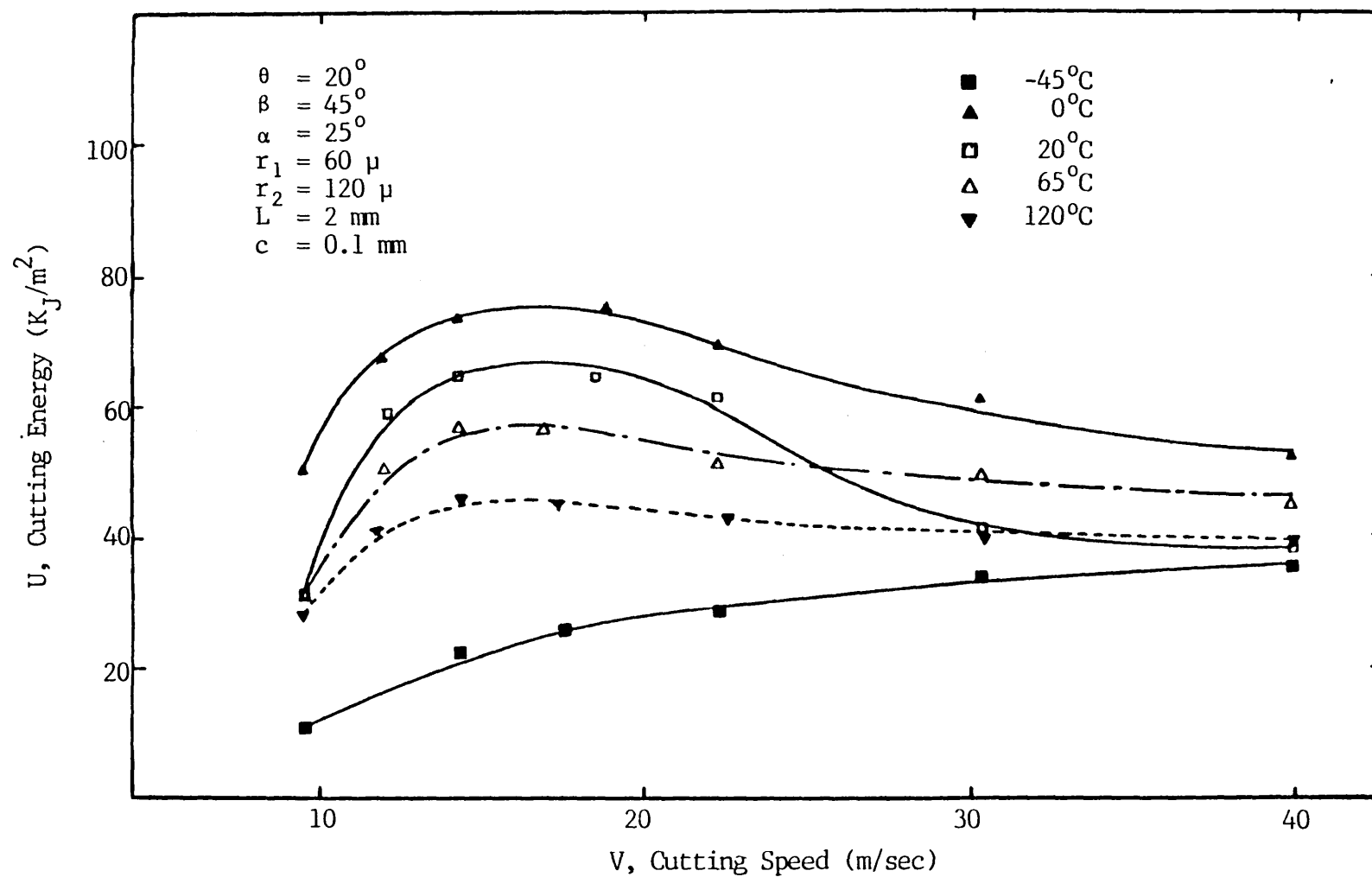


Fig. 6.3: PC - Cutting Energy Versus Cutting Speeds at Different Temperatures.

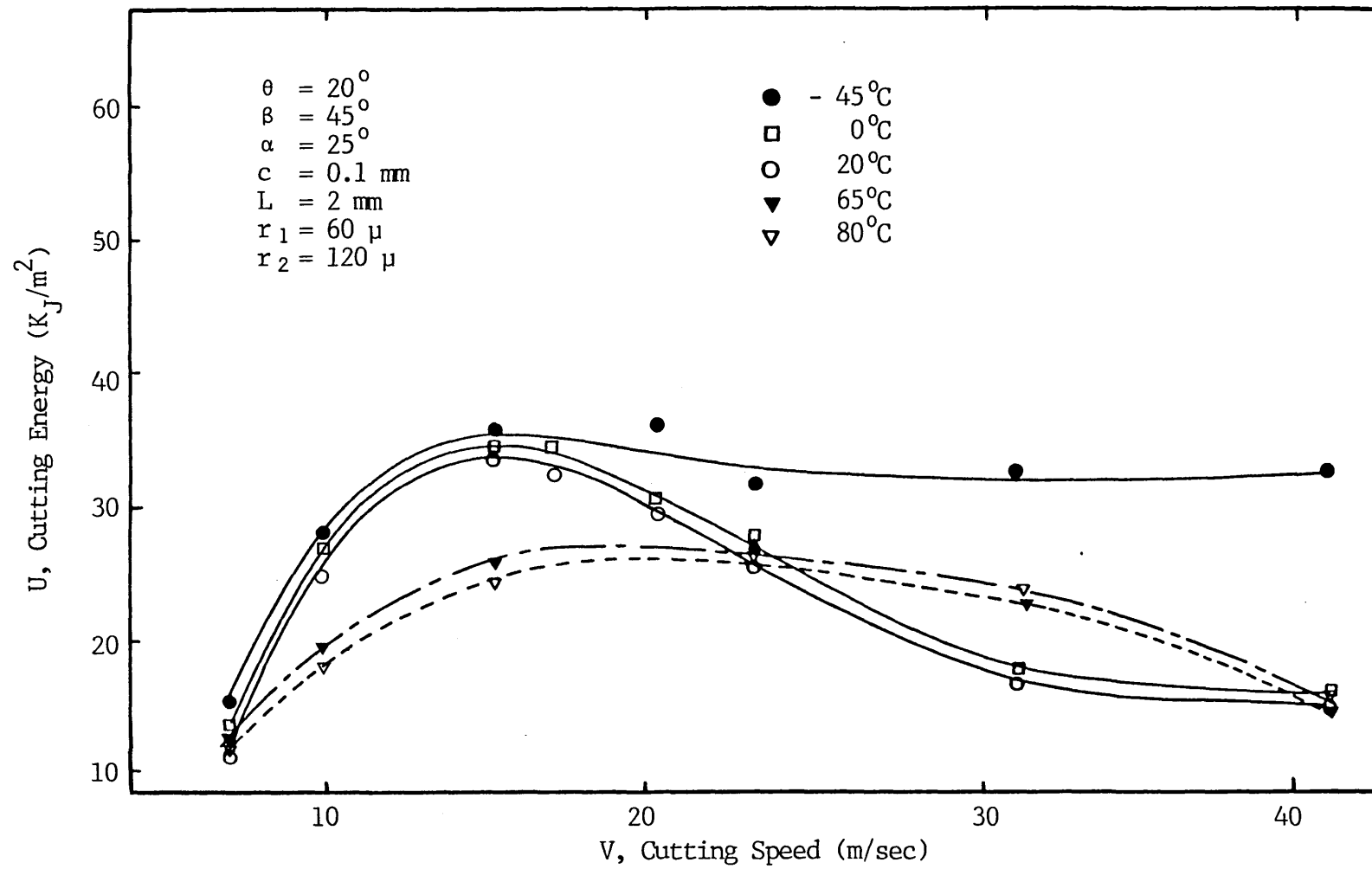


Fig. 6.4: ABS - Cutting Energy Versus Cutting Speeds for Different Temperatures.

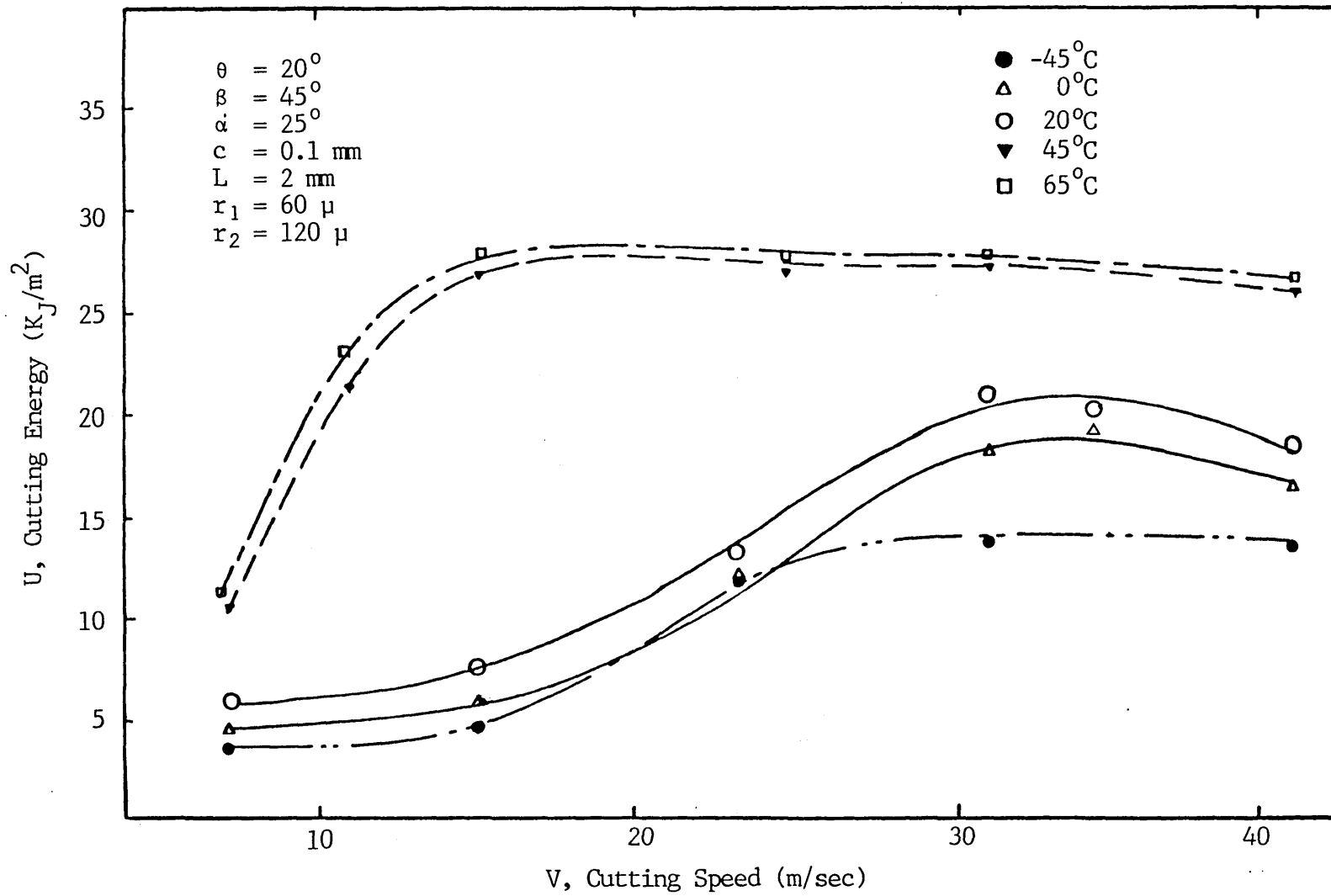


Fig. 6.5: PP - Cutting Energy Versus Cutting Speeds at Different Temperatures.

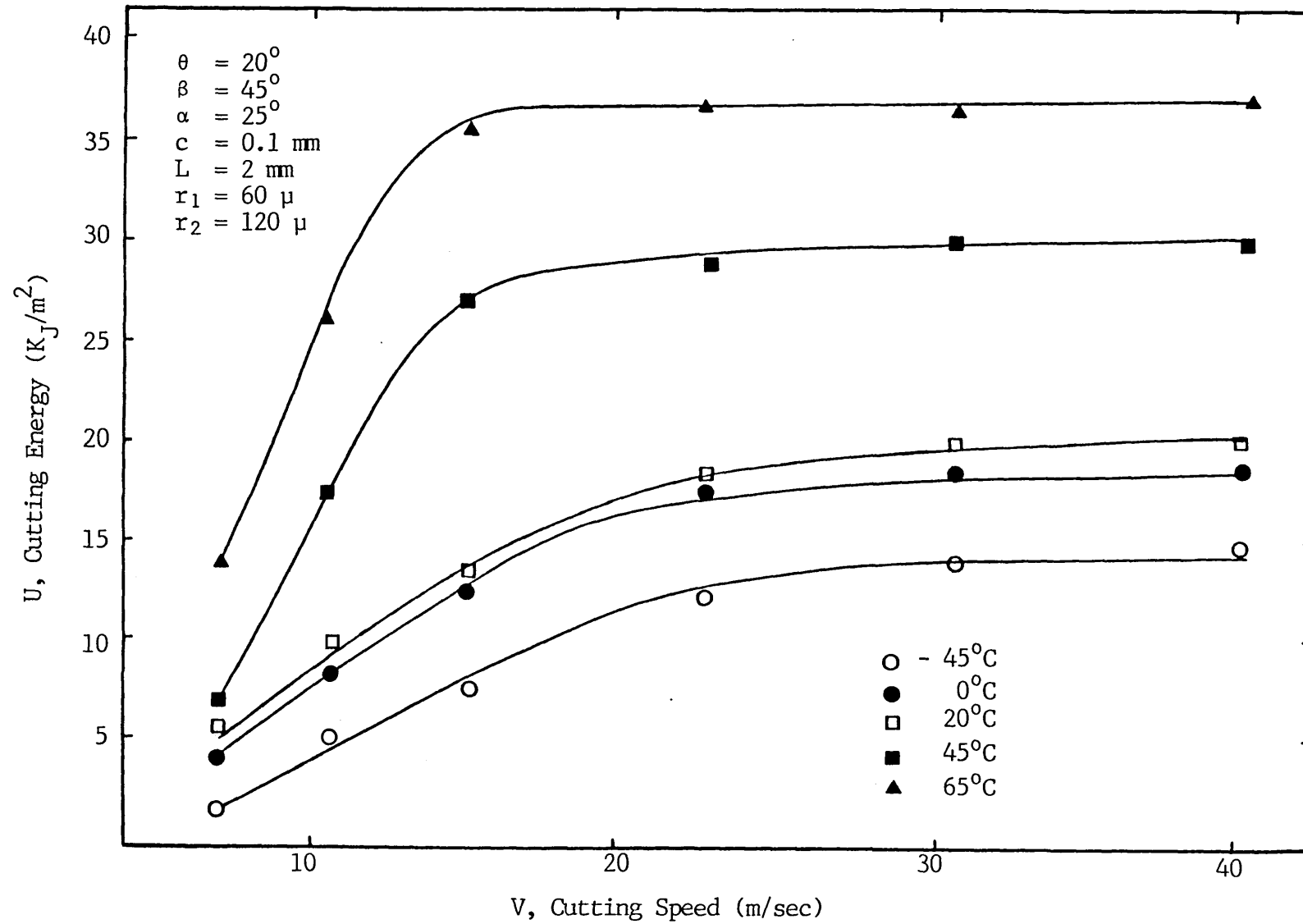


Fig. 6.6: PVC - Cutting Energy Versus Cutting Speeds at Different Temperatures.

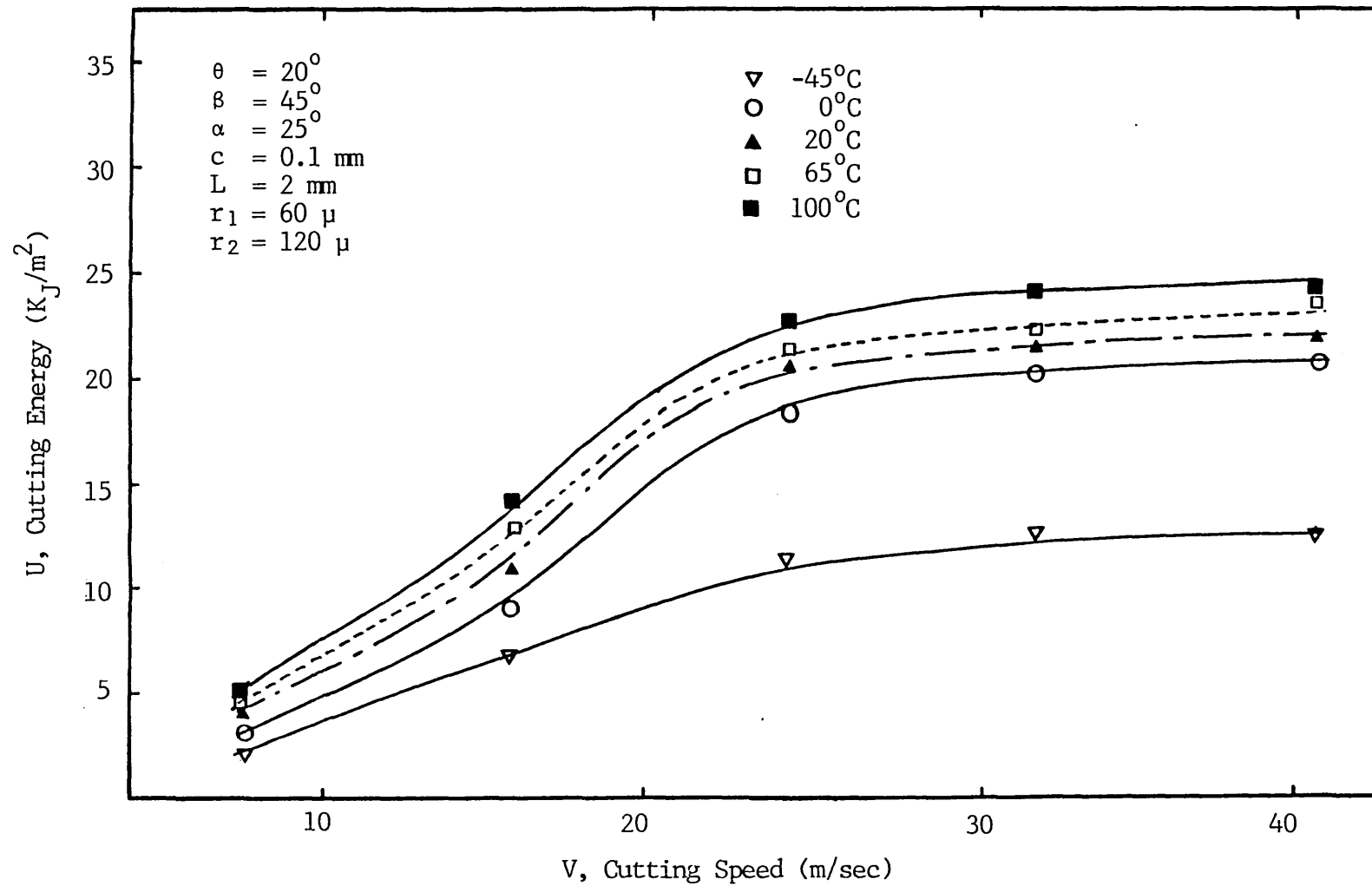


Fig. 6.7: PMMA - Cutting Energy Versus Cutting Speeds at Different Temperatures.

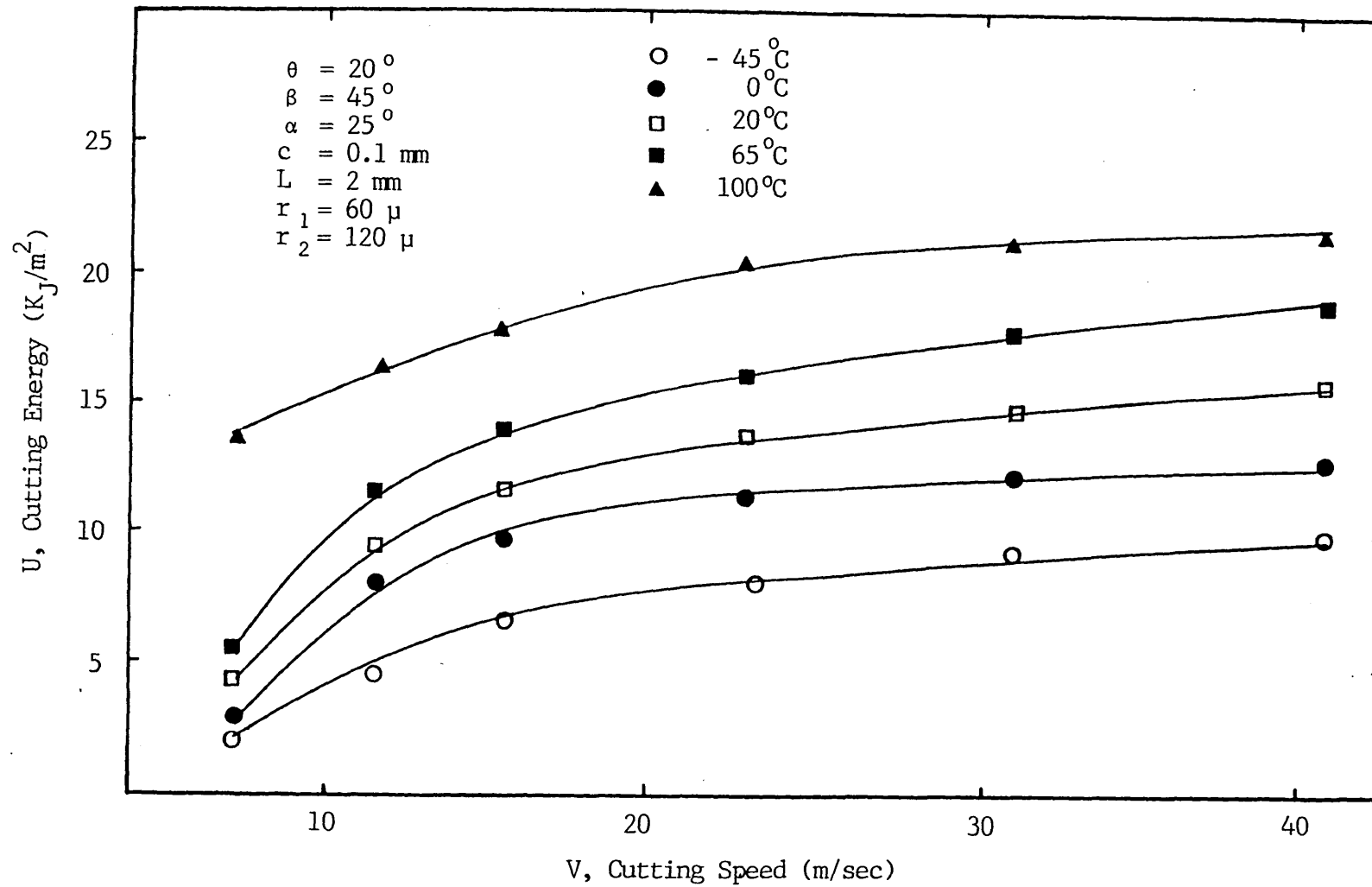


Fig. 6.8: HIPS - Cutting Energy Versus Cutting Speeds at Different Temperatures.

	Material						
	LDPE	PC	ABS	PP	PVC	PMMA	HIPS
Minimum Energy (K_J/m^2)	4	18	12	4	3	2.5	2
Test Temperature ($^{\circ}C$)	-45	-45	80	-45	-45	-45	-45
Blade Speed (m/sec)	7	10	7	7	7	7	7
Maximum Energy (K_J/m^2)	35	80	36	28	37	25	23
Test Temperature ($^{\circ}C$)	0	0	-45	65	65	100	100
Blade Speed (m/sec)	28	19	20	18	40	40	40

Table 6.2: The Temperatures and Blade Speeds for Minimum and Maximum Cutting Energies.

it appears that at low test temperatures there is an increase in the speed at which the peak energy occurred. (The values of these speeds are given in Table 6.3).

For example, at a test temperature of -45°C , the highest cutting energy for LDPE, PC and PP appear to occur at a cutting speed of 40 m/sec, and for ABS at 22 m/sec. However, this is in contrast to energy measurements at room temperature which showed that the maximum values of observed energy for the above four materials occurred at speeds of 24 m/sec, 15 m/sec, 34 m/sec and 18 m/sec respectively.

6.2.3 Conclusion

The conclusion that can be reached from the test results is that thermal effects are important in the cutting process. A reduction in temperature did not necessarily give rise to a reduction in cutting energy, and for ABS the cutting energy increased as temperature decreased. Although the combined effects of temperature and rate appeared complex, one feature clearly emerged and this was that a reduction in temperature caused an increase in the speed at which the maximum in the energy versus speed curve occurred.

	Test Temperature		
	+20 °C	0 °C	-45 °C
Material	V (m/sec)	V (m/sec)	V (m/sec)
LDPE	24	26	40
PC	15	18	40
ABS	18	19	22
PP	34	35	40

V = Blade Speed

Table 6.3: Blade Speeds at which Peak Energy Occurred at Low Test Temperatures.

In addition, for most of the materials, the lowest level of cutting energy occurred at the lowest test temperature (-45°C) at a cutting speed of 7 m/sec. The difference between energy levels at room temperature and those at lower temperature at the same cutting speed of 7 m/sec is about 30%. Such a small saving of absorbed energy cannot justify the expense required to use a cooling plant with the granulator for the purpose of cooling the granulated materials.

Finally, an attempt to correlate the dependence of cutting energy upon rate and temperature using W.L.F equation was found to be unsuccessful. (The W.L.F equation is given by (93):

$$\text{Log } t = -A(T - T_g)/B + T - T_g \quad 6.1$$

where t is the shift factor, A and B are constants, T and T_g are the test and glass transition temperature respectively. Equation 6.1 signifies that a shift in the test time scale, will produce the same change in material mechanical properties as will a related change in temperature given by equation 6.1.) This firstly because the shift factor (and the material fracture properties) can not be determined due to the fact that it is not known what the local temperature is at the blade tip, even at the lowest cutting speed. Secondly, the combined rate and temperature observed in the present study was complex. Finally, the applicability of the W.L.F equation to the properties of non rubbery polymers is very limited (93).

CHAPTER 7

NOISE MEASUREMENTS IN CUTTING OF POLYMERS

7.1 INTRODUCTION

Noise generation is a major problem in polymer granulation. The difficulties associated with high noise levels are serious and noise considerations are of prime importance in the selection of a suitable granulator. The usual solution to reduce noise levels is the extensive use of sound insulation. With sound insulation there is additional time for clean out and maintenance as well as heat retention, making scrap recovery one of the most expensive operations in the moulding room. The experimental work to be described in this section however, is concerned with noise levels which can be reduced at source by the choice of appropriate operating settings, blade orientation and blade configuration.

In addition, it was thought useful to follow the experimental work with a study on the design of the granulator in order to identify any other possible sources of noise generation and to make suggestion for their elimination.

7.2 EXPERIMENTAL PROGRAMME

7.2.1 Test Equipment and Testing Conditions

The noise produced during cutting has been measured with the aid of the following equipment:

A - an impulse sound level meter with built-in amplifier and a linear frequency response peak detection circuit, Type 2209.

B - a precision microphone, Type 4145.

C - an extension cable with microphone connectors in both ends, length 3 mm, diameter 6 mm, Type A0 0027.

D - a tape recorder, Type TR 16.

The first three items being manufactured by Bruel and Kjaer, item D was a Philips product.

Tests for noise measurements were performed at room temperature (20° C). The programme of work involved examining the effects of cutting speed, the clearance between the rotating blade and the fixed blade, type of cut, mounting the blade upside down (Fig. 1.10), the angle of attack and sharpness of the rotating blade, on the noise made during cutting. Seven different polymers were tested over the speed range 7 to 35 m/sec. These polymers are given in

Section 5.2.1.

7.2.2 Experimental Methods

In order to conduct the noise measurements, the microphone was mounted horizontally in the plane of rotation towards the test specimen at a distance of 15 cm. The microphone was connected to the sound level meter. The sound level meter was then connected to the tape recorder, so that the tape recorder was used as a signal storage for the sound level meter. In order to obtain precise values of the sound level meter readings (in a digital form), the tape recorder output was connected to the spectrum analyser, so that when the record was played back, the stored signals were fed to the spectrum analyser, and the required noise values were obtained. Fig. 7.1 shows a schematic diagram of the test equipment.

7.2.3 Results and Discussion

The first set of tests to be carried out examined the effect of clearance between the rotating blade and the fixed blade. In contrast to the energy measurements which showed an increase of energy required to cut with increasing clearance, no significant change in noise level was found for changes in clearance for the specimens tested (Fig. 7.01).

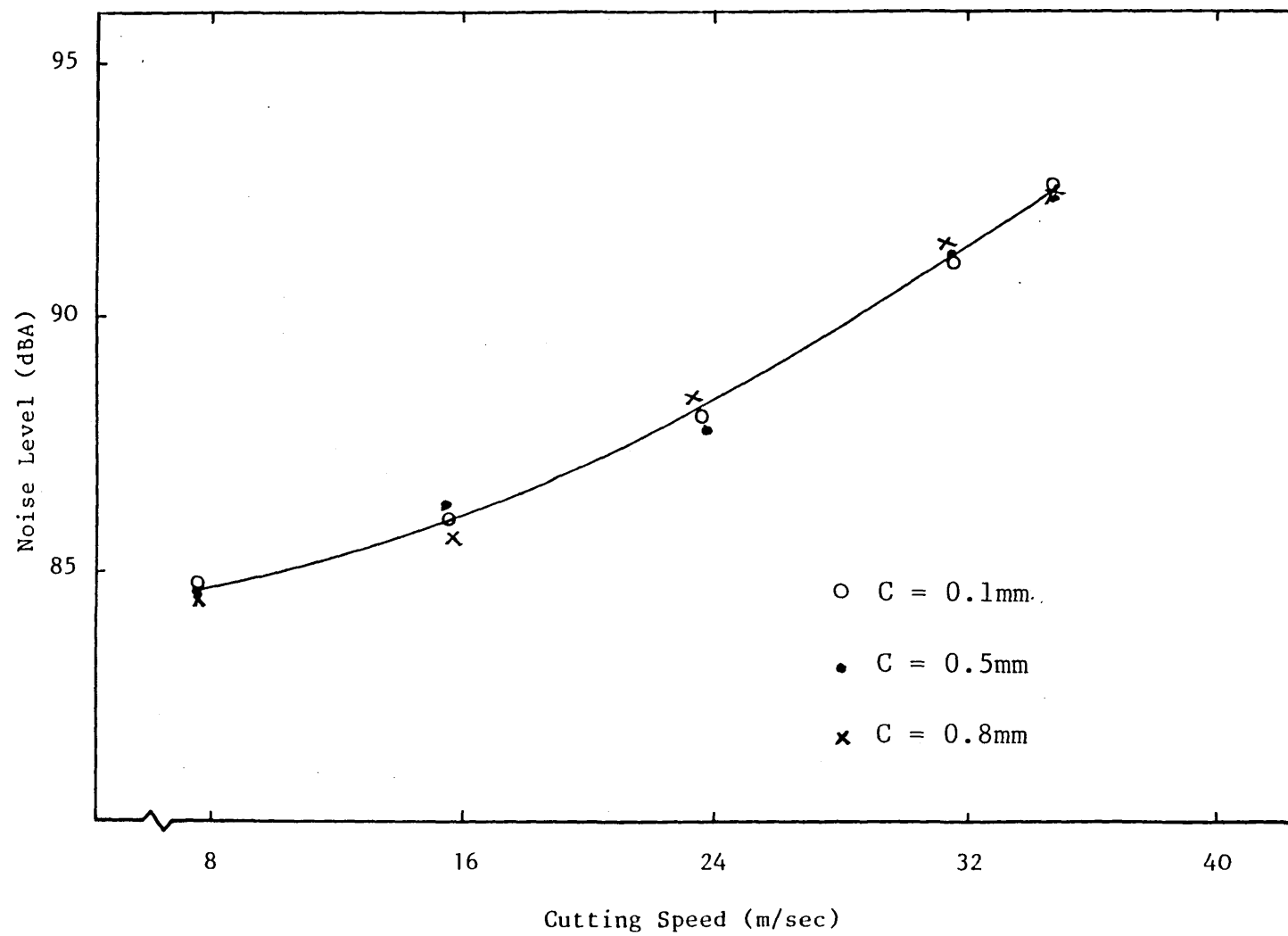


Fig. 7.01: HIPS - Noise Level Versus Cutting Speed.

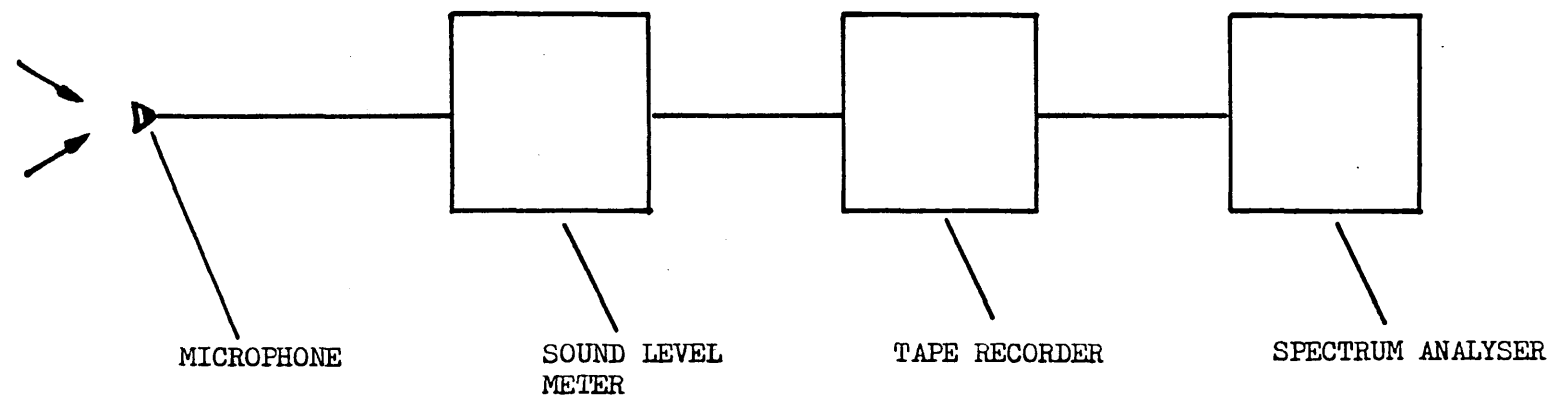


Fig. 7.1: Schematic Diagram of Noise Measurements Equipment.

The second series of tests was to examine the effects of guillotine cut and also of turning the blade upside down. It was found that there was no noticeable change in noise levels in either case, throughout the speed range tested (Fig. 7.02).

Further tests examined the effects of cutting speed, blade sharpness and angle of attack of the rotating blade. Test results are shown in Figs. 7.2 - 7.8. From the figures it can be seen that there is a remarkable increase in noise levels with speed increase, even when no cutting takes place. For example, in cutting of LDPE (Fig. 7.2), noise level is increased from 85 to 95 dBA as the speed is increased from 8 to 31 m/sec. When there is no cutting taking place, the noise level is also increased from 83 to 92 dBA as the speed is increased from 8 to 31m/sec.

There is also a clear relationship between the sharpness of the rotating blade and noise level, i.e. the sharper the blade, the lower the noise level. For example, in cutting of PP at a speed of 8m/sec (Fig. 7.3), noise level is increased from 87 to 90 dBA as the sharpness of the blade is increased from 240 to 60 microns.

In addition, from Figs. 7.2 - 7.8 it can be seen that there is also a strong effect of the angle of attack of the rotating blade, such that an increase in the angle of attack causes an increase in noise level. For example, in

cutting of PMMA at a speed of 8m/sec (Fig. 7.8), noise level is increased from 83 to 88 dBA as the angle of attack is increased from 25 to 70 degrees.

7.2.4 Conclusion

The conclusion that can be reached from the test results is, that noise levels increase significantly with rotational speed. A reduction of noise levels does not appear to be achieved by increasing or reducing the gap between the rotating blade and fixed blade, or by adopting a guillotine type of cut or by mounting the rotating blade upside down (Fig. 1.10).

Low noise levels can be achieved by increasing the sharpness of the rotating blade, decreasing the angle of attack of the rotating blade and by reducing the cutting speed.

Also, after examining the whole design of the granulator (Fig. 1.3), the following modifications were thought to be necessary in order to reduce noise levels during the cutting process. Firstly, minimising the amount of material thrown from the cutting chamber against the hopper walls by providing the hopper with flaps made of rubber. The flaps will also help to absorb noise radiation. Secondly, lining the internal surfaces of the hopper, and the chamber with resistant material (rubber), to absorb any sort of impact of material against these surfaces and to prevent noise radiation. Finally, stiffening the screen and providing it

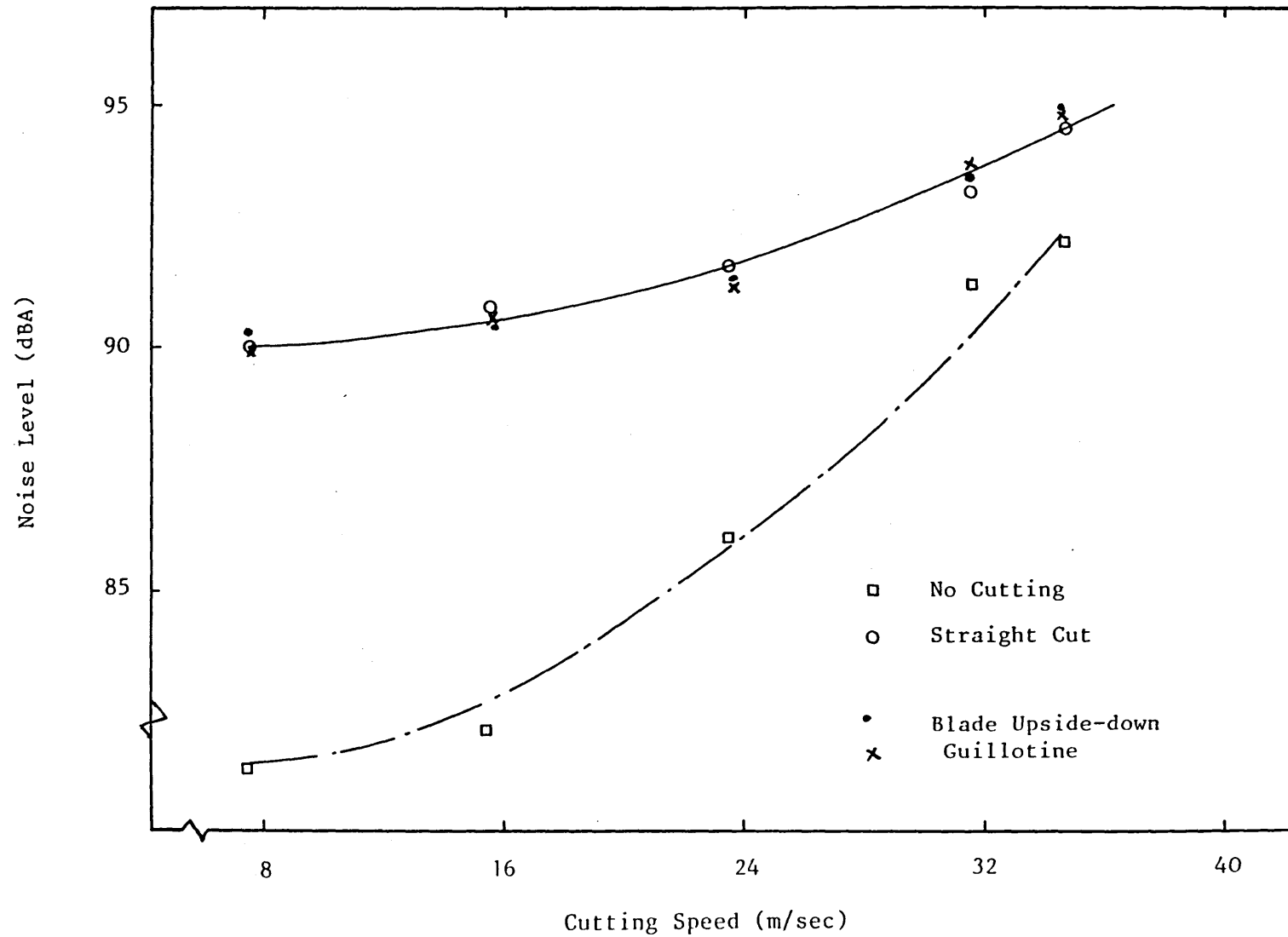


Fig. 7.02: ABS - Noise Level Versus Cutting Speed.

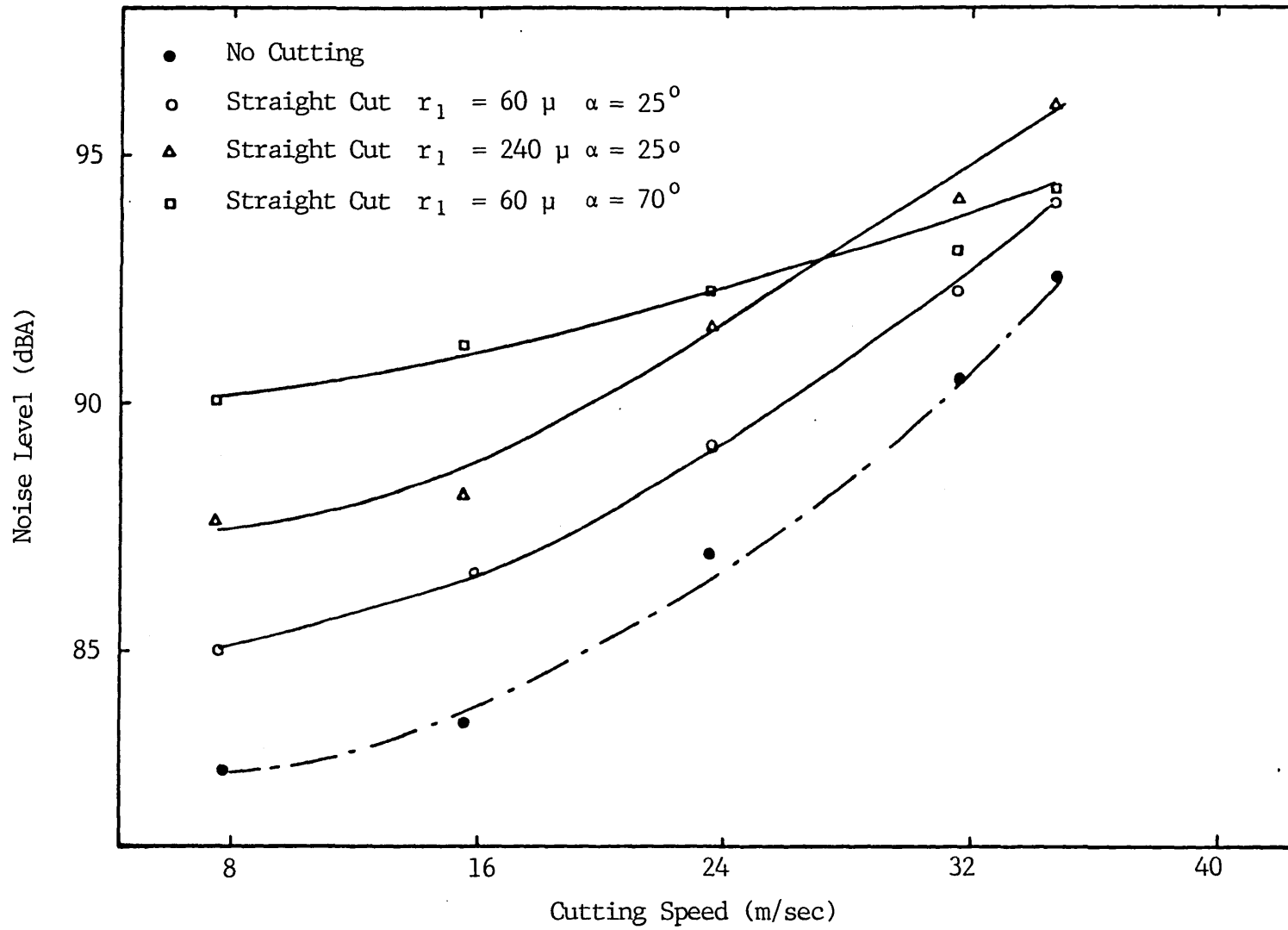


Fig. 7.2 : LDPE - Noise Level Versus Cutting Speed.

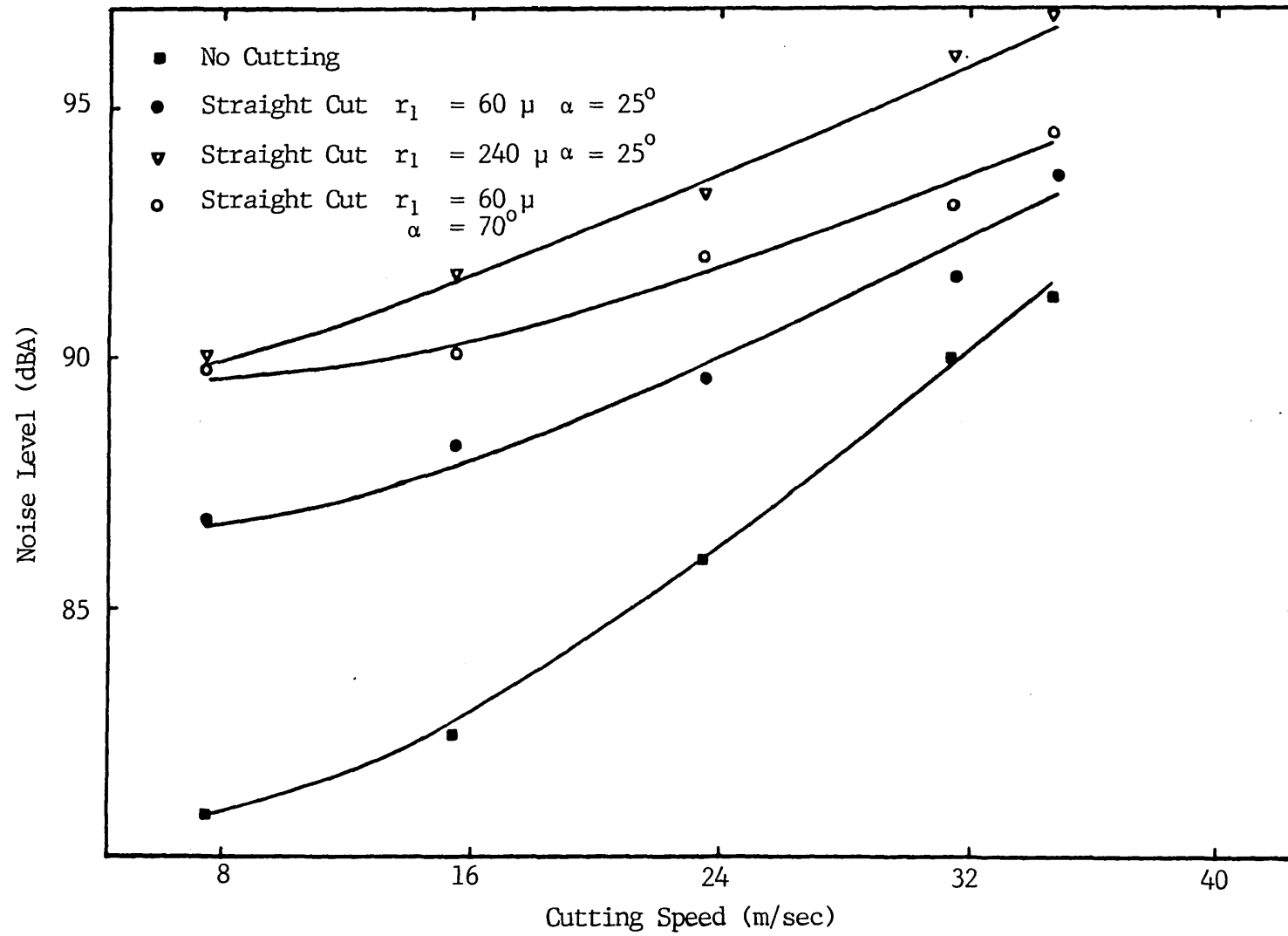


Fig. 7.3 : PP - Noise Level Versus Speed.

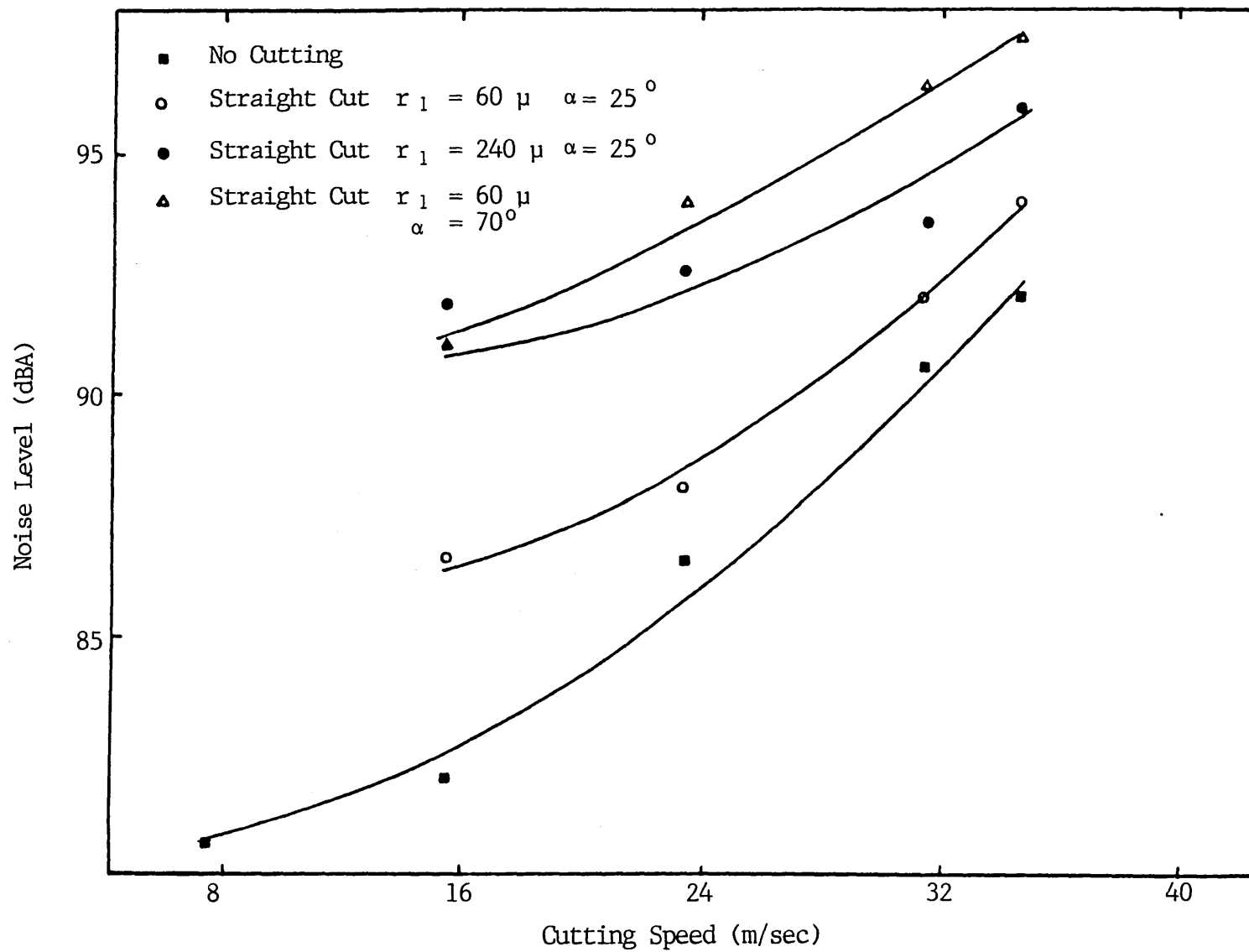


Fig. 7.4 : PC - Noise Level Versus Cutting Speed.

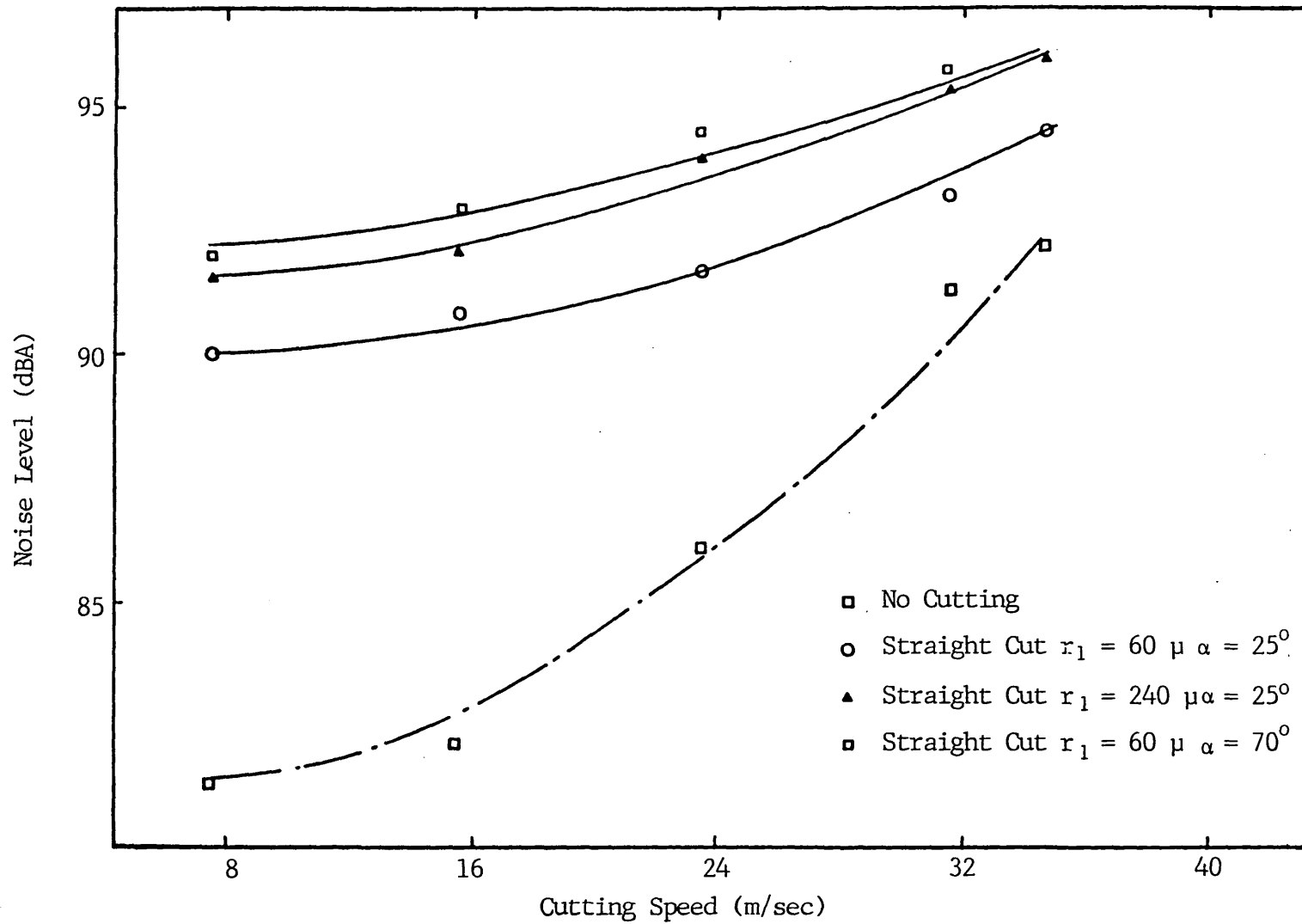


Fig. 7.5: ABS - Noise Level Versus Cutting Speed.

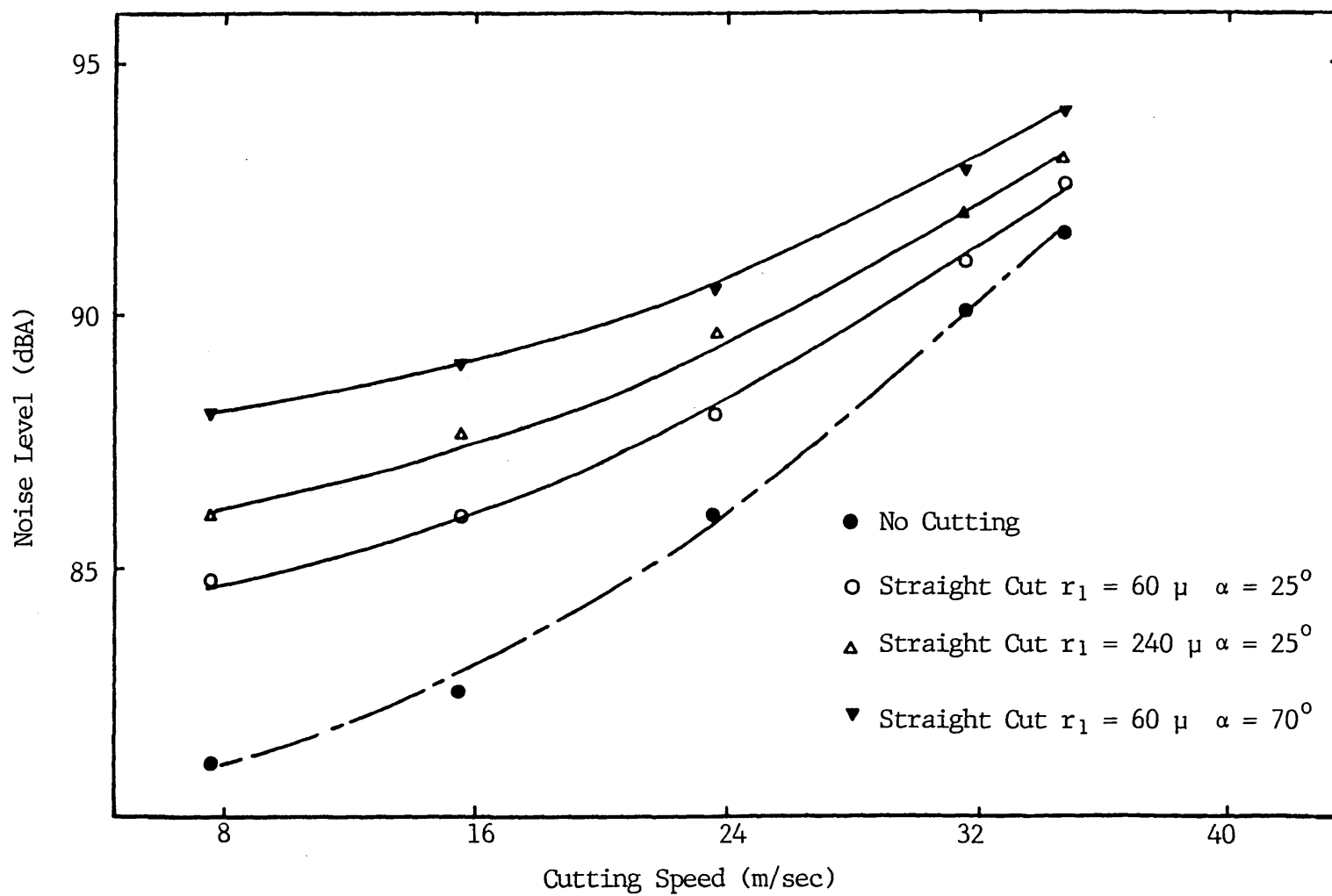


Fig. 7.6: HIPS - Noise Level Versus Cutting Speed.

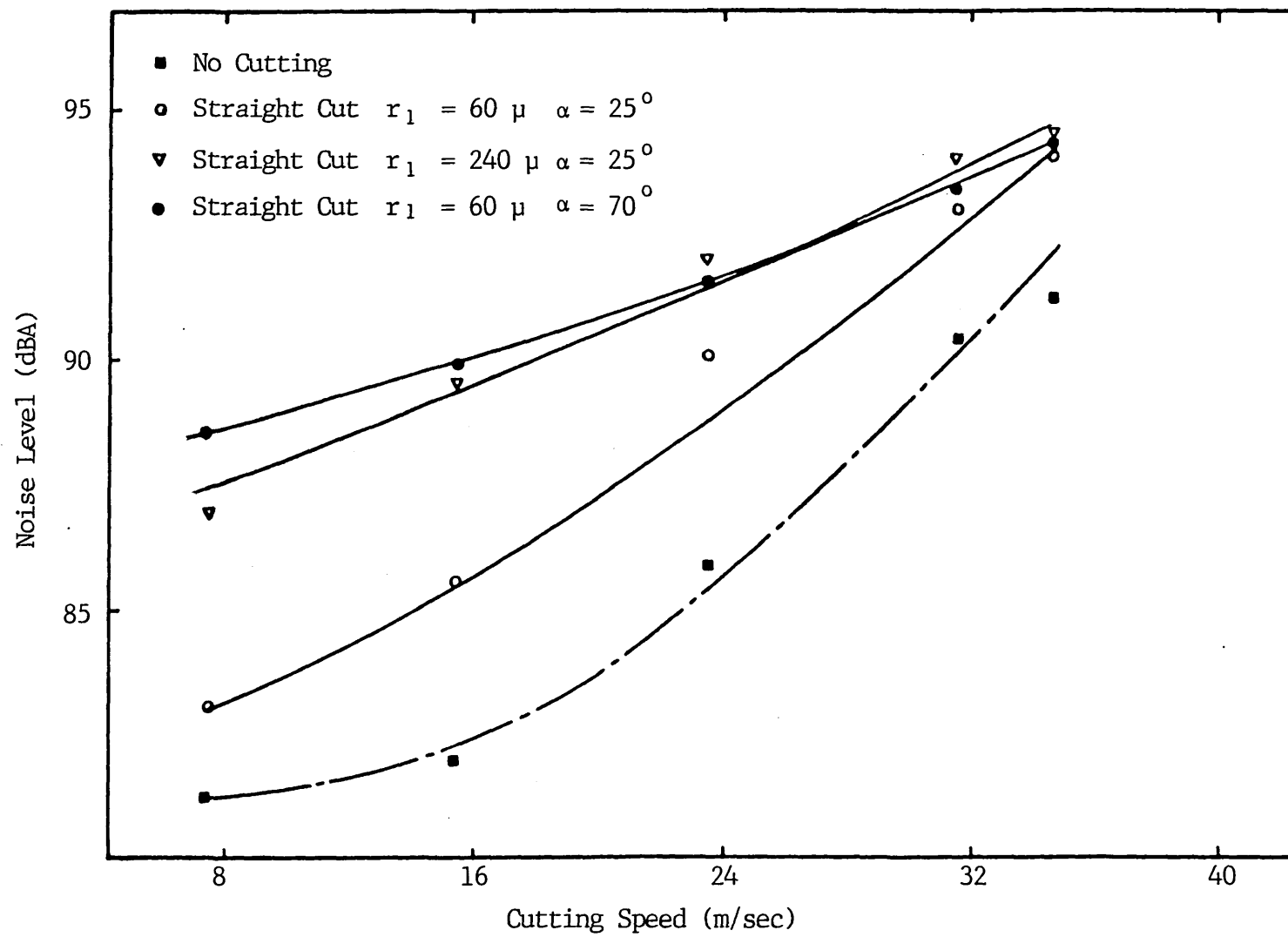


Fig. 7.7 : PVC - Noise Level Versus Cutting Speed.

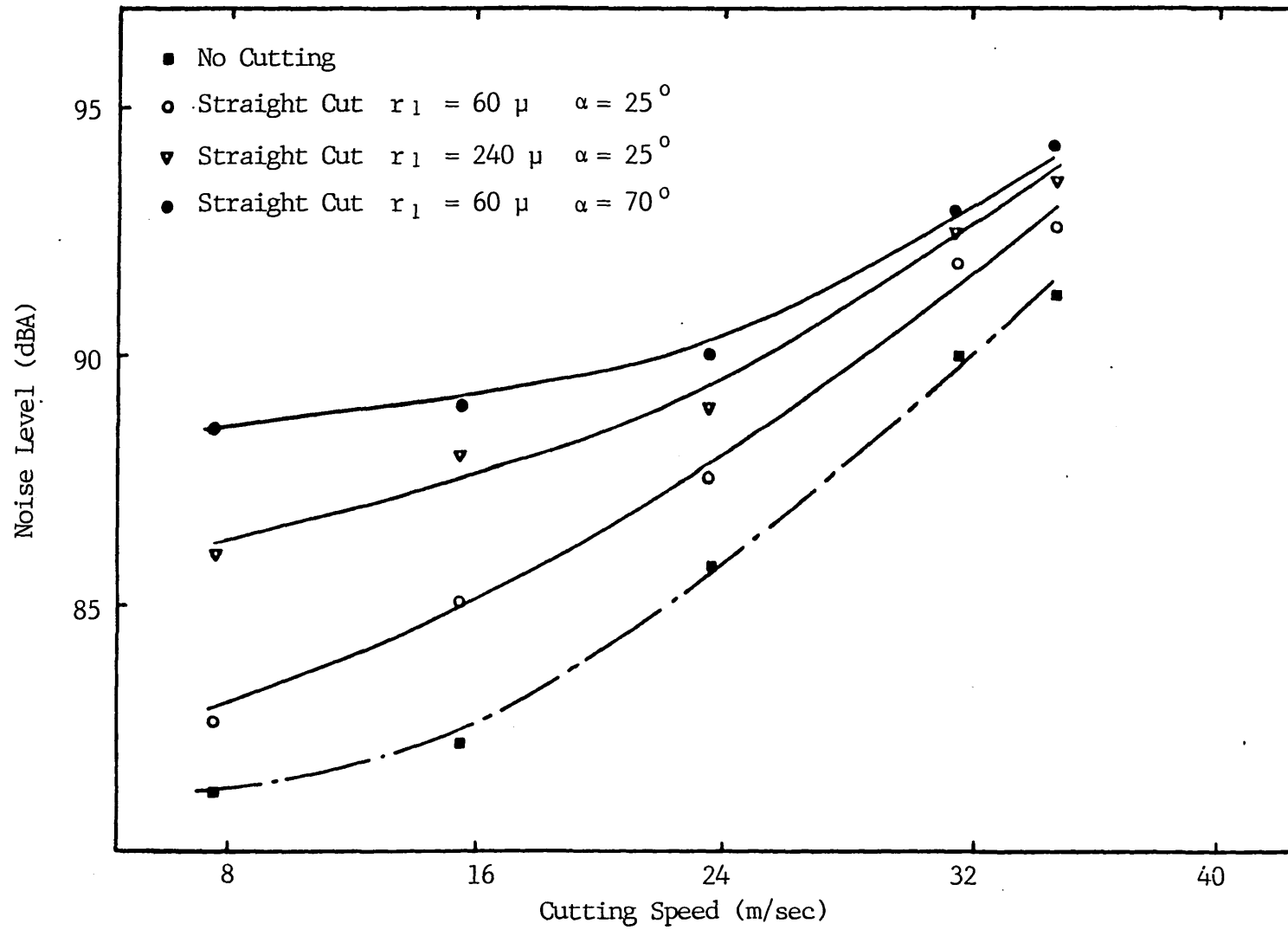


Fig. 7.8 : PMMA - Noise Level Versus Cutting Speed.

with external damping and good fixation with the machine frame to reduce vibrations and noise emission, resulting from the severe impact of the material against the screen surface.

The above modifications were carried out experimentally on a granulator machine (type 28.A produced by Daniels Engineering Ltd). Test results showed that there was a reduction in noise levels by approximately 3 dBA.

CHAPTER 8

EXPERIMENTAL: MICROGRAPHIC STUDY OF THE CUT SURFACES

8.1 INTRODUCTION

In order to attempt to identify and explain the mechanism of impact cutting in polymers, it was found useful to combine the test results with a micrographic study of the cut surfaces. With this study, it was hoped that reasons for the strong dependency of cutting energy on knife speed might be revealed. A number of micrographs are presented in this chapter which support the idea of impact notching and adiabatic phenomena at the crack tip leading to substantial energy absorption during cut growth.

8.2 APPARATUS

A JEOL JSM-T200 scanning electron microscope was used for examination of the cut surfaces. An Edwards S 150A sputter coater was used for coating the specimen with gold, to restrict surface charging of the polymer.

8.3 SPECIMEN PREPARATION

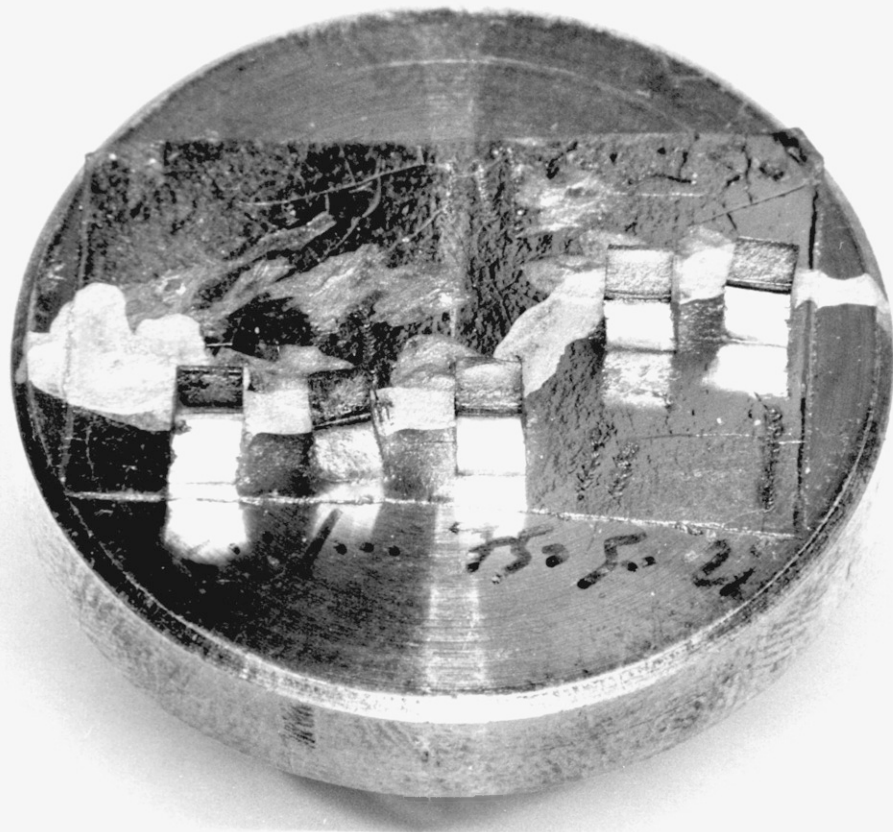
The surface of the specimen to be examined was cut out from the test piece to a suitable dimension (4 mm)

for mounting on the SEM specimen holder. The specimen was cleaned with distilled water in an ultrasonic bath, then allowed to dry at ambient temperature for at least 25 minutes. Four or five specimens were usually secured to an aluminium stub using double-sided adhesive tape. The specimens (and the stub) were subsequently coated using gold in the Edwards S 150A sputter coater, at a deposition rate of about 150 Å per minute. Care was taken to avoid local heating. After sputtering, a small amount of conducting paint was applied between the specimen and the stub to ensure good conduction. This was necessary and sufficient to prevent charging when the specimen was examined in the scanning electron microscope. A photograph of prepared specimens ready for examination is shown in Fig. 8.1. The holder of the specimen stub is shown in Fig. 8.2.

8.4 CUT SURFACE EXAMINATION

This was carried out with the JEOL-JSM T200 scanning electron microscope using secondary electron imaging. An accelerating voltage of 10 KV or 15 KV and a working distance of 20 mm was used.

Most of the examinations were performed at an accelerating voltage of 15 KV, the higher accelerating voltage giving better resolution and sharper pictures.



10 mm

Fig. 8.1: Typical Specimens on Aluminium Stub
Ready for Examination on the SEM.

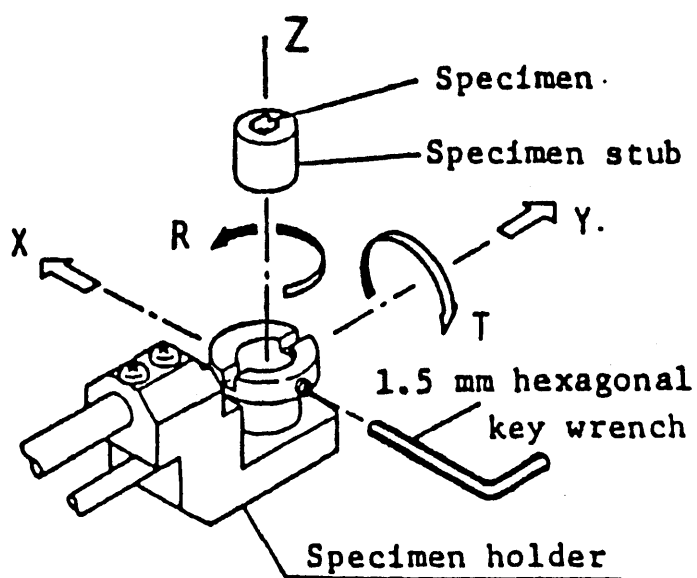


Fig. 8.2: SEM Specimen Holder Showing Various Degrees of Movement.

However, care had to be exercised to avoid electron beam damage of the coated surface of the specimen, especially at high magnification > 3500 . This was done by reducing the spot size (beam intensity) whenever necessary.

8.5 RESULTS AND DISCUSSION

All of the cut surfaces of whatever material showed three distinct zones. These regions could be identified clearly but their relative size depended upon the material and blade speed. This is indicated on the schematic diagram of Fig. 8.3 (the relative length of each zone being approximately as indicated). Fig. 8.4 shows two micrographs of typical cut surfaces for a brittle material (HIPS) and a ductile material (LDPE); both produced at room temperature at a cutting speed of 7 m/sec. From the micrographs, it can be seen that zones A and B are similar for either brittle or tough materials, however, compared to zones A and B, zone C showed dissimilar surface features.

Each zone will be dealt with separately. Explanations for the observable features will be concise since highly-detailed micrographic study of cut surfaces is not the primary objective of this work.

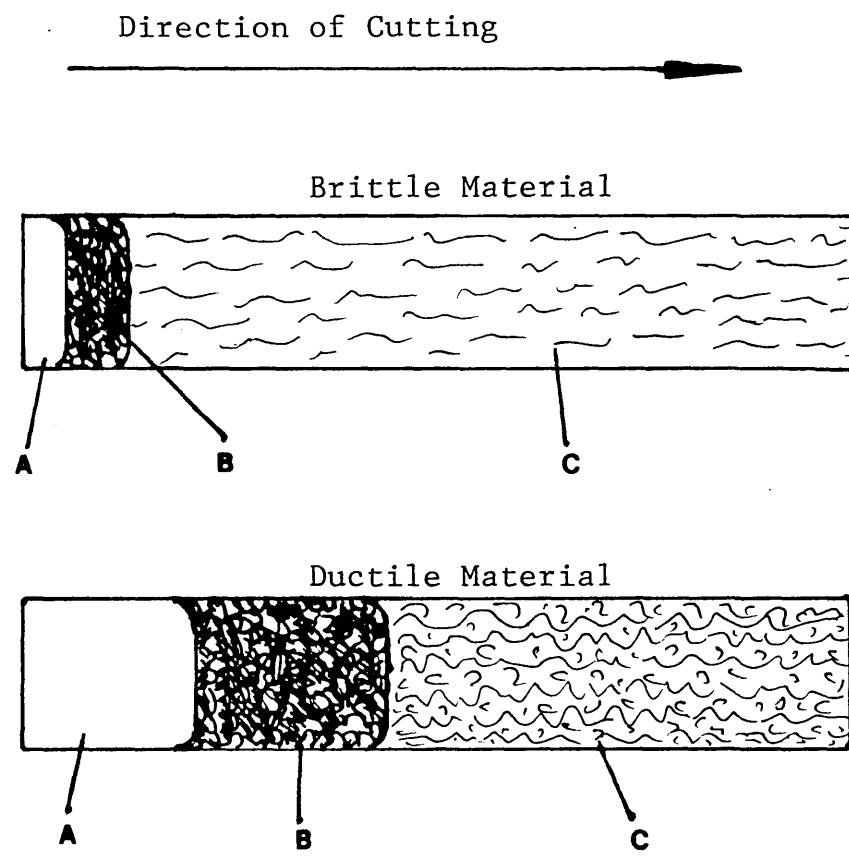
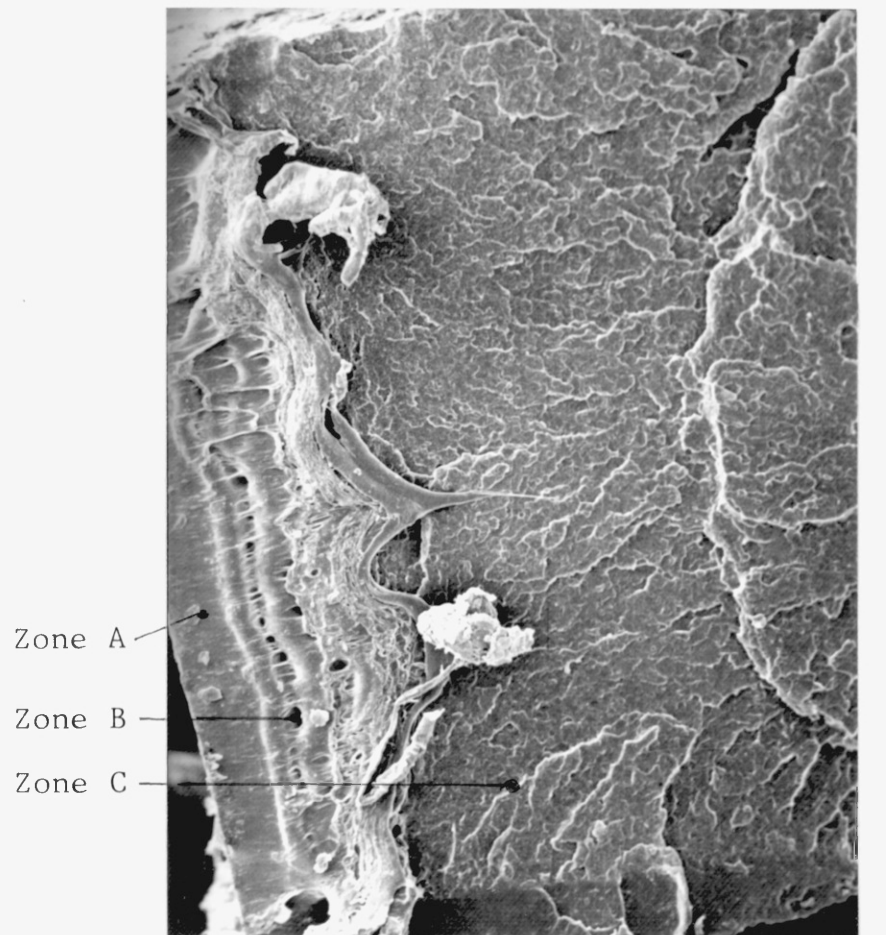


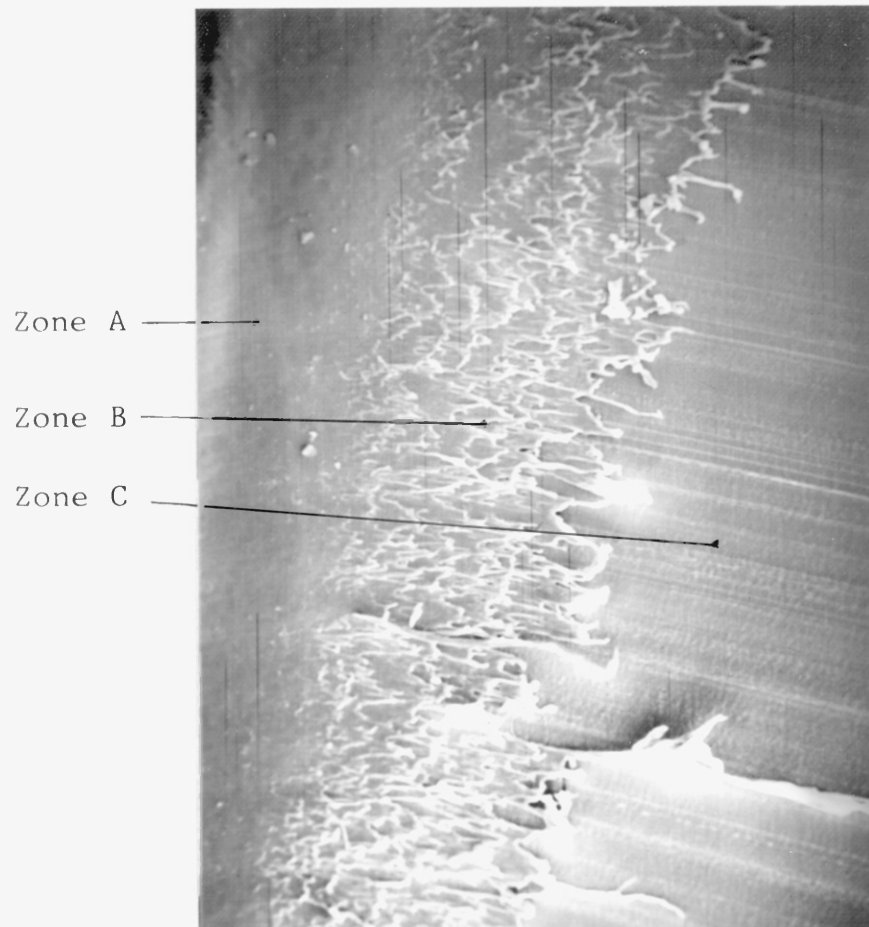
Fig. 8.3: Schematic View of Cut Surface Features.

Direction of Cutting →



a

0.1 mm



b

0.5 mm

Fig. 8.4: Scanning Electron Micrographs of Cut Surfaces of: a LDPE, b HIPS.
Direction of Cutting from Left to Right.

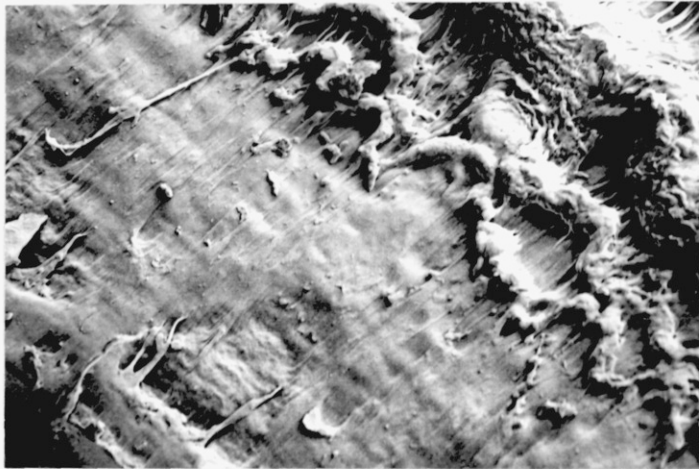
8.5.1 Zone A

From the scanning electron micrographs of Fig. 8.4, it can be seen that zone A which occurs at the edge where the knife enters the specimen, is relatively smooth. This zone could be attributed to the extent to which the blade enters the test piece before a crack runs ahead of the blade. Measurements of the length of zone A at high magnification, reveal that, semibrittle and brittle materials (PVC, HIPS and PMMA) have much smaller zone lengths than those for tough materials (LDPE, PP, PC and ABS). Surprisingly the length of zone A appears to be approximately constant for a given material whatever the blade speed. Fig. 8.5 shows high magnification micrographs taken from cut surfaces of PP produced at cutting speeds of 7 m/sec and 41 m/sec. The micrographs show that the length of zone A at the above cutting speeds is approximately constant. (200 μ). The above relationship between zone A length and cutting speed for every material tested is shown in Fig. 8.6. From the graph it can be observed that the smallest and biggest zone lengths exist for PMMA and LDPE.

8.5.2 Zone B

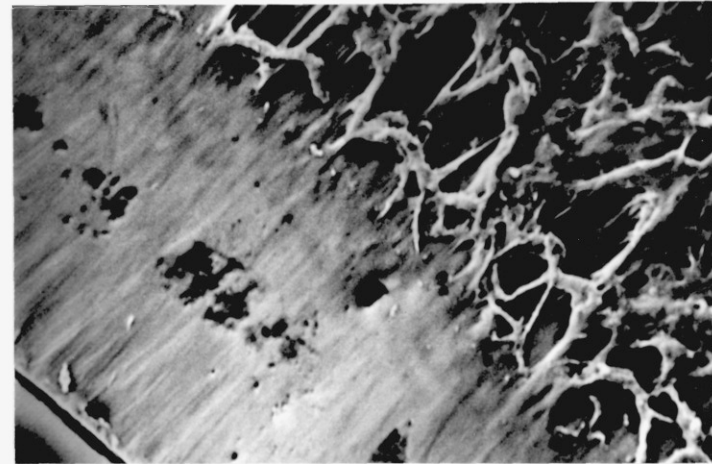
Figs. 8.7-8.13 show a series of low and high magnification micrographs taken from cut surfaces of PMMA, HIPS, PVC, LDPE, PP, PC and ABS. Each micrograph is directly

Direction of Cutting



a

0.1 mm



b

0.1 mm

Fig. 8.5: Scanning Electron Micrographs of Cut Surfaces of PP (Zone A) Produced at Cutting Speeds of a 7 m/sec and b 41 m/sec.

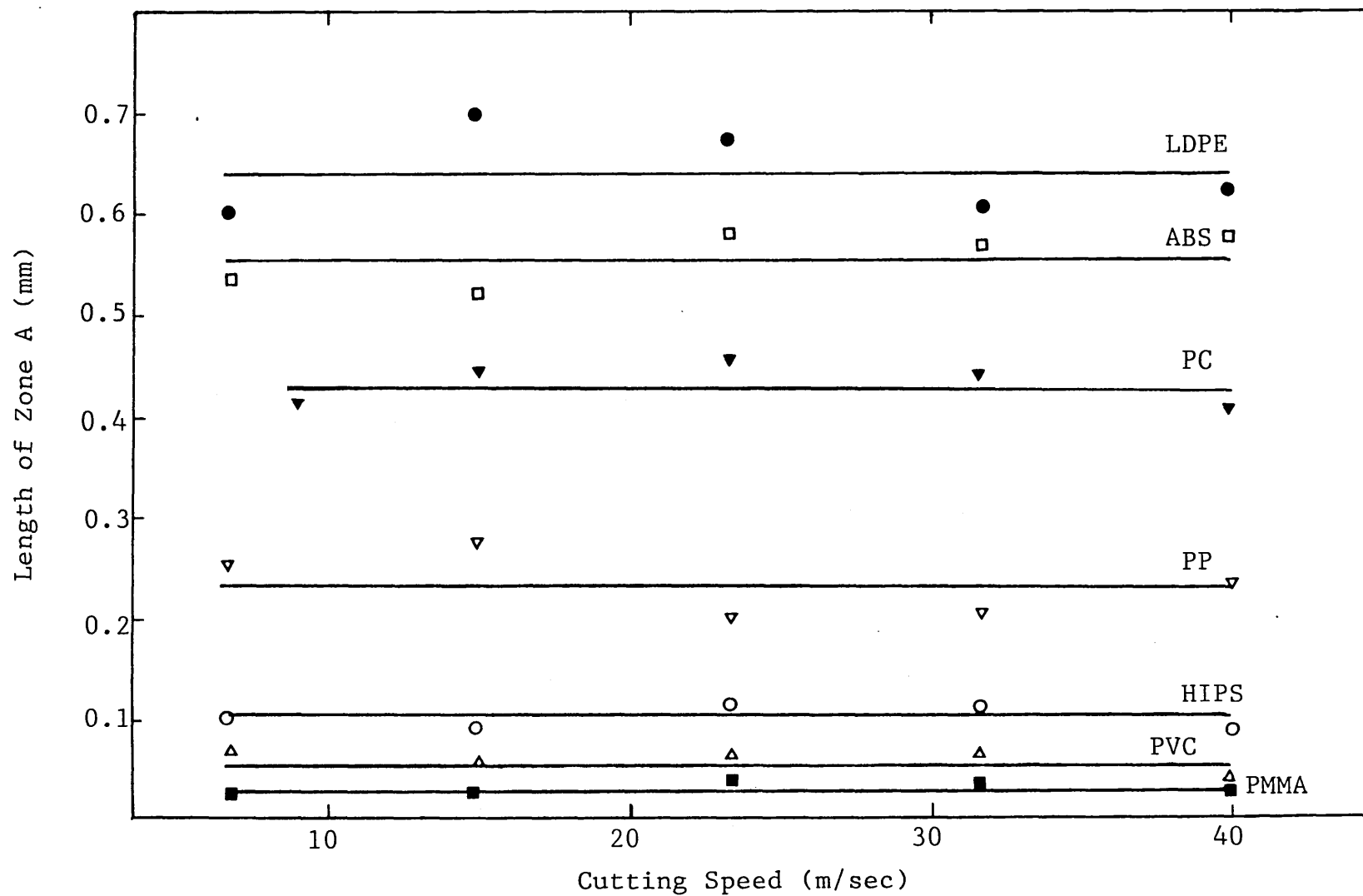


Fig. 8.6: The Relationship between Length of Zone A and Cutting Speed.

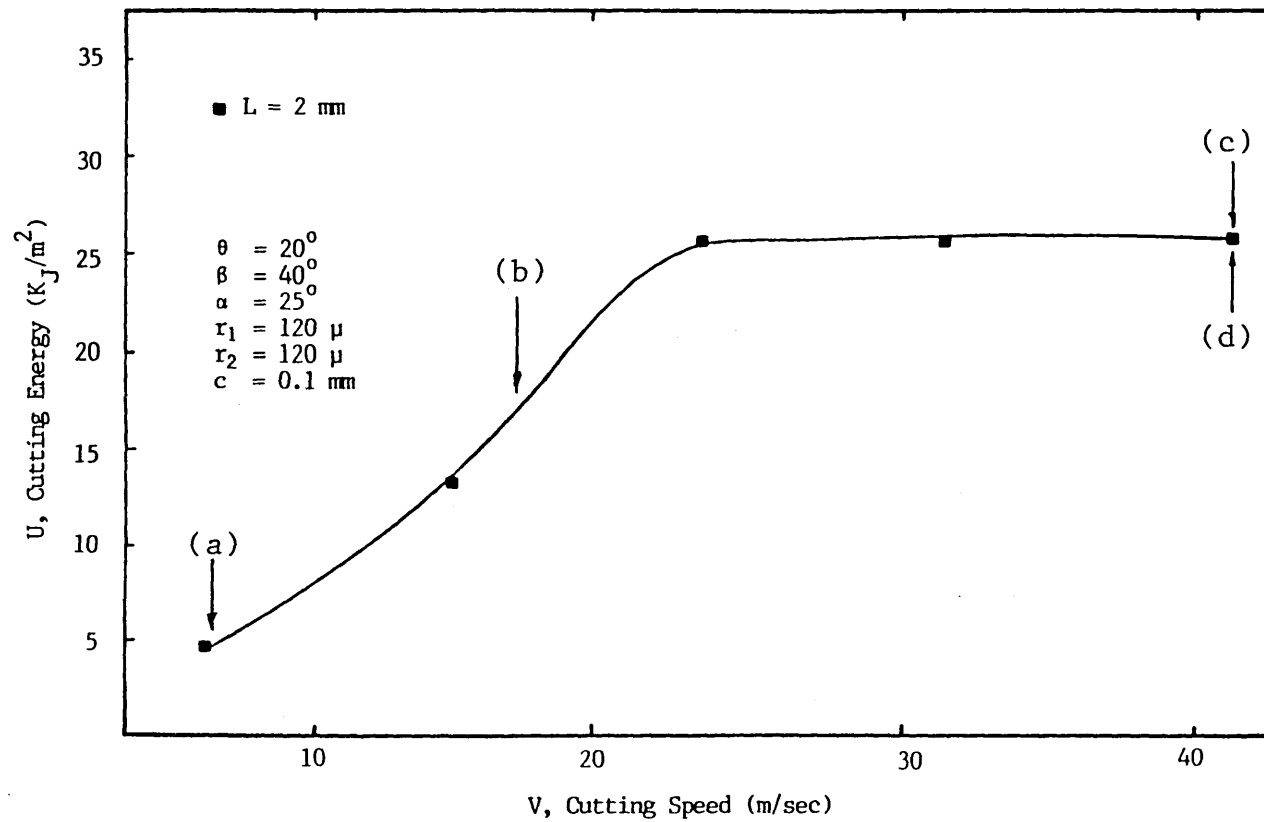
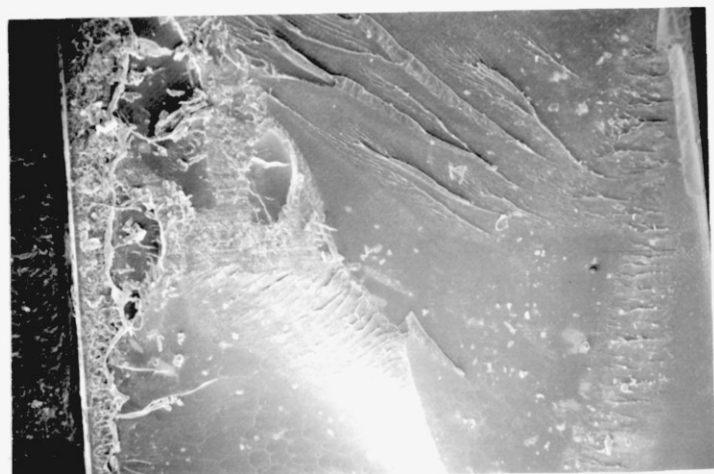


Fig. 8.7: Scanning Electron Micrographs of Cut Surfaces of PMMA,
 Taken at Positions Shown on the U-V Curve.
 Direction of Cutting from Left to Right.

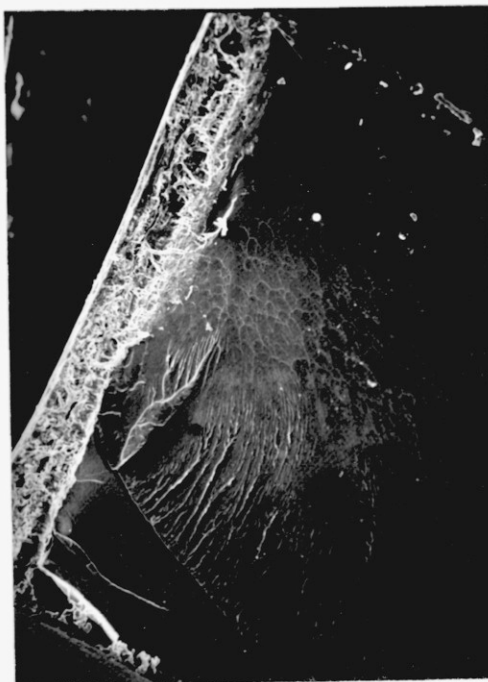
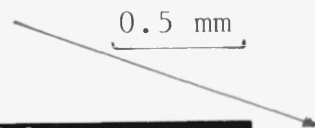
Direction of Cutting



0.5 mm

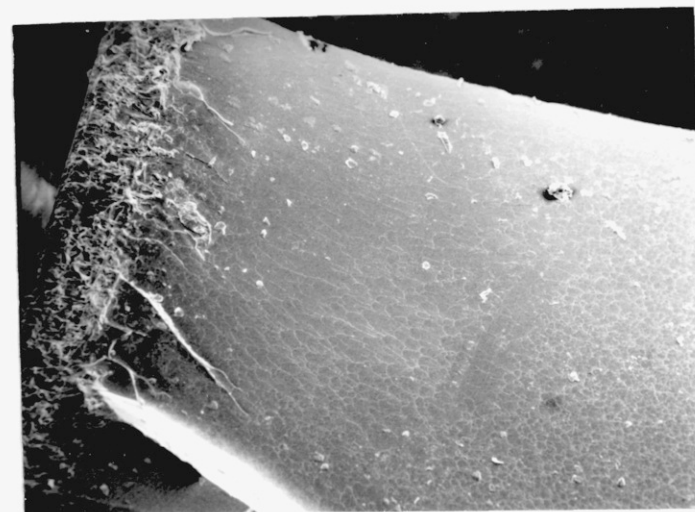


(a)



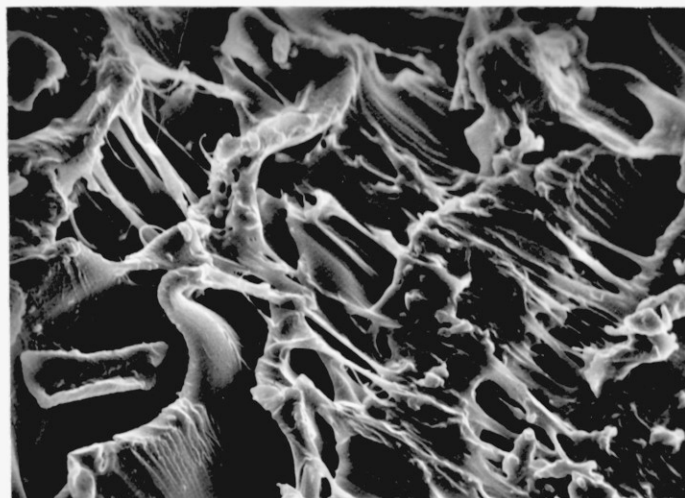
(b)

0.5 mm



(c)

Fig. 8.7 (Continued):



(d) $10\ \mu$

Fig. 8.7 (Continued): (Surface Appearance at Zone B).

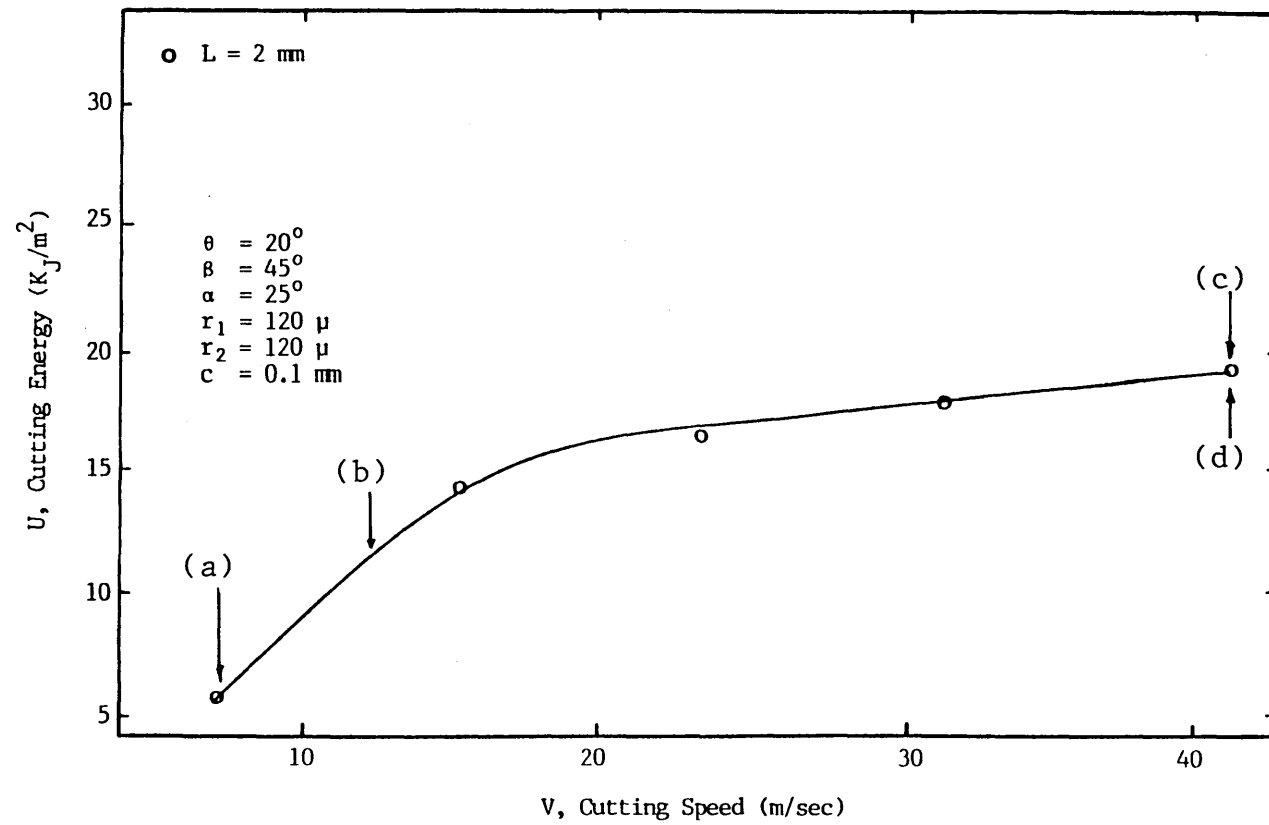


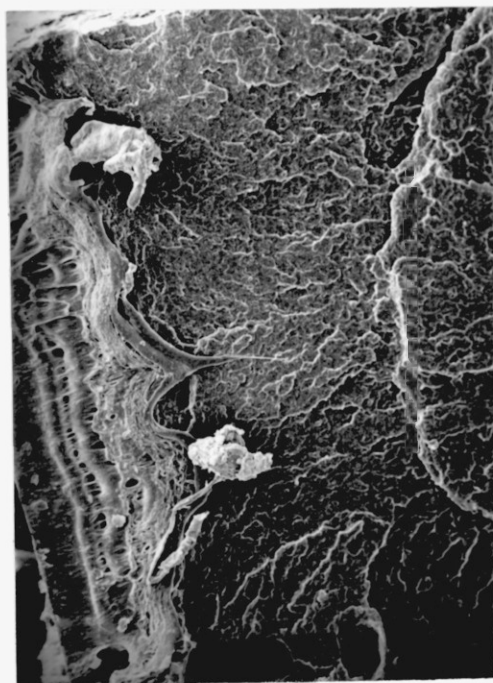
Fig. 8.8: Scanning Electron Micrographs of Cut Surfaces of HIPS, Taken at Positions Shown on the U-V Curve. Direction of Cutting from Left to Right.

Direction of Cutting —————→

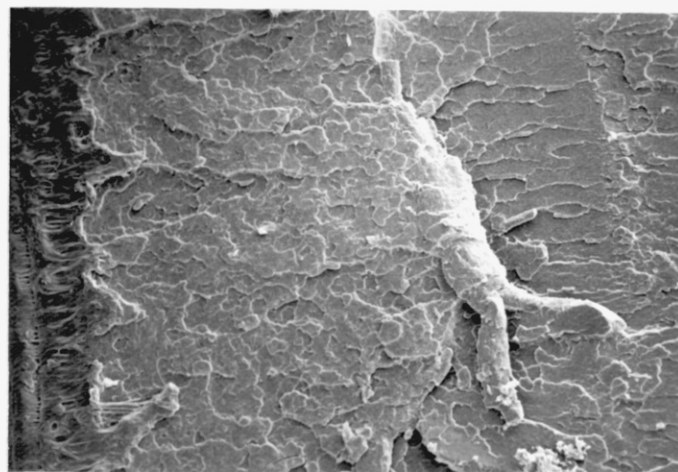
0.5 mm

0.5 mm

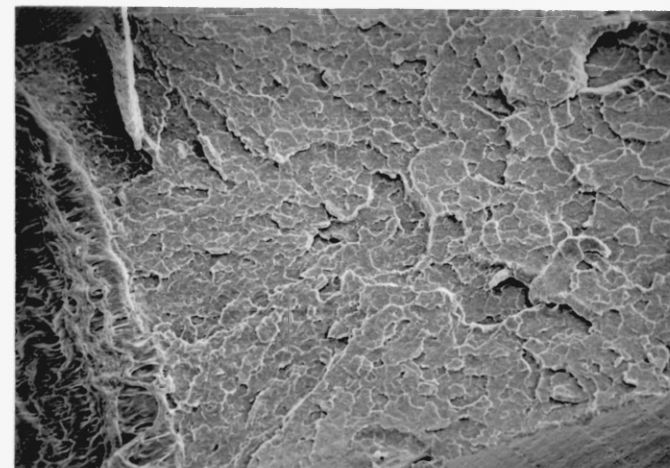
0.5 mm



(a)



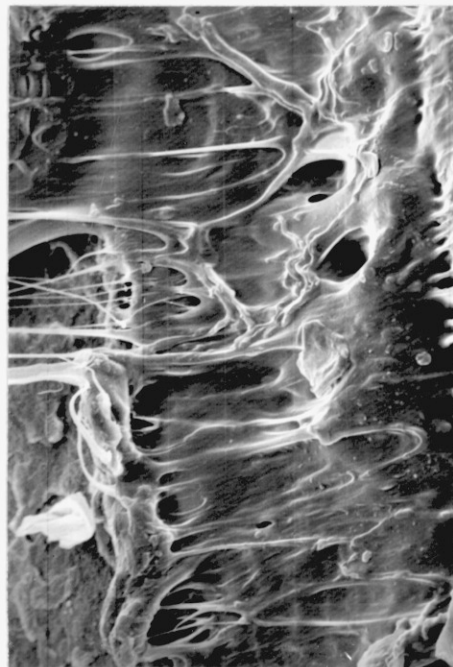
(b)



(c)

Fig. 8.8 (Continued):

0.1 mm



(d)

Fig. 8.8 (Continued): (Surface Appearance at Zone B).

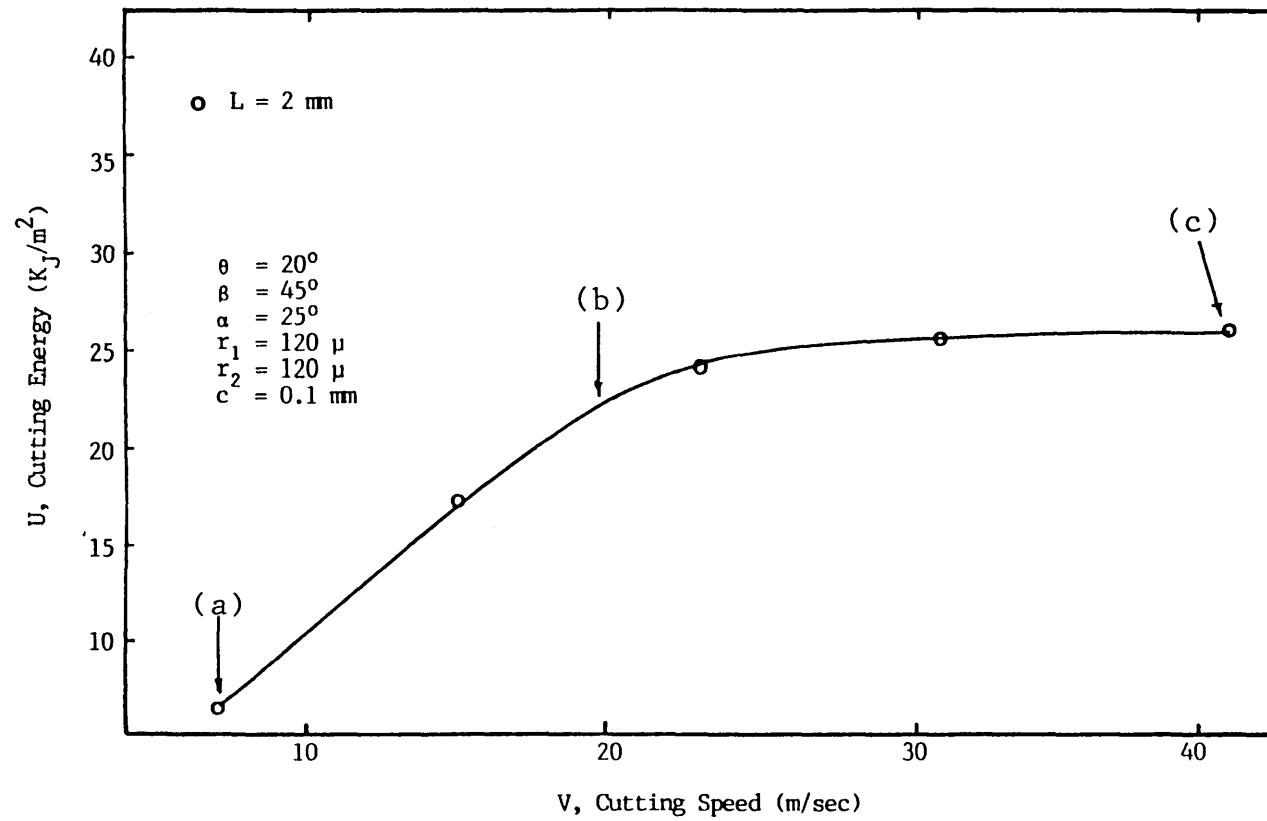
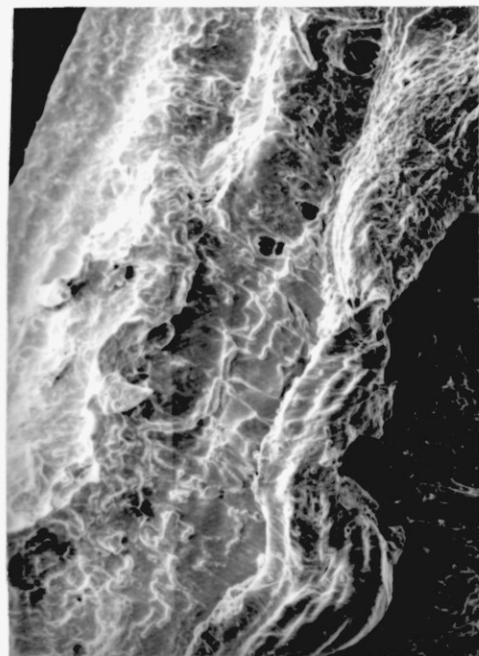


Fig. 8.9: Scanning Electron Micrographs of Cut Surfaces of PVC,
 Taken at Positions Shown on the U-V Curve.
 Direction of Cutting from Left to Right.

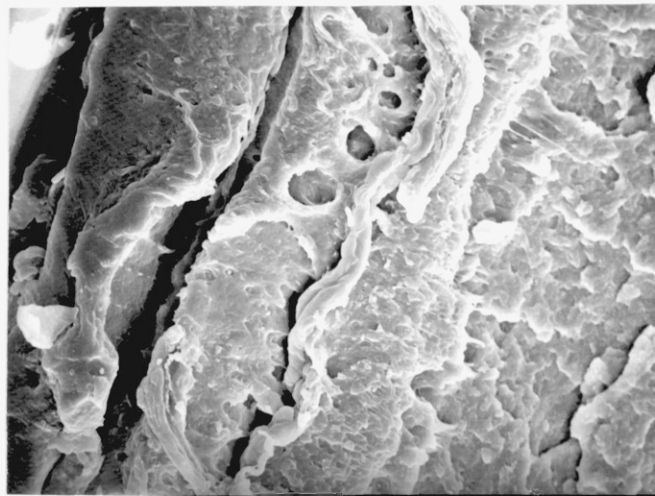
Direction of Cutting —————→

0.1 mm



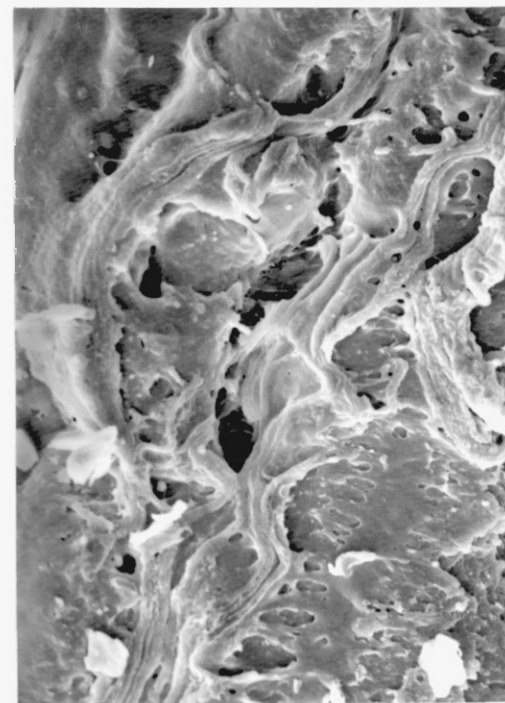
(a)

0.1 mm



(b)

0.1 mm



(c)

Fig. 8.9 (Continued):

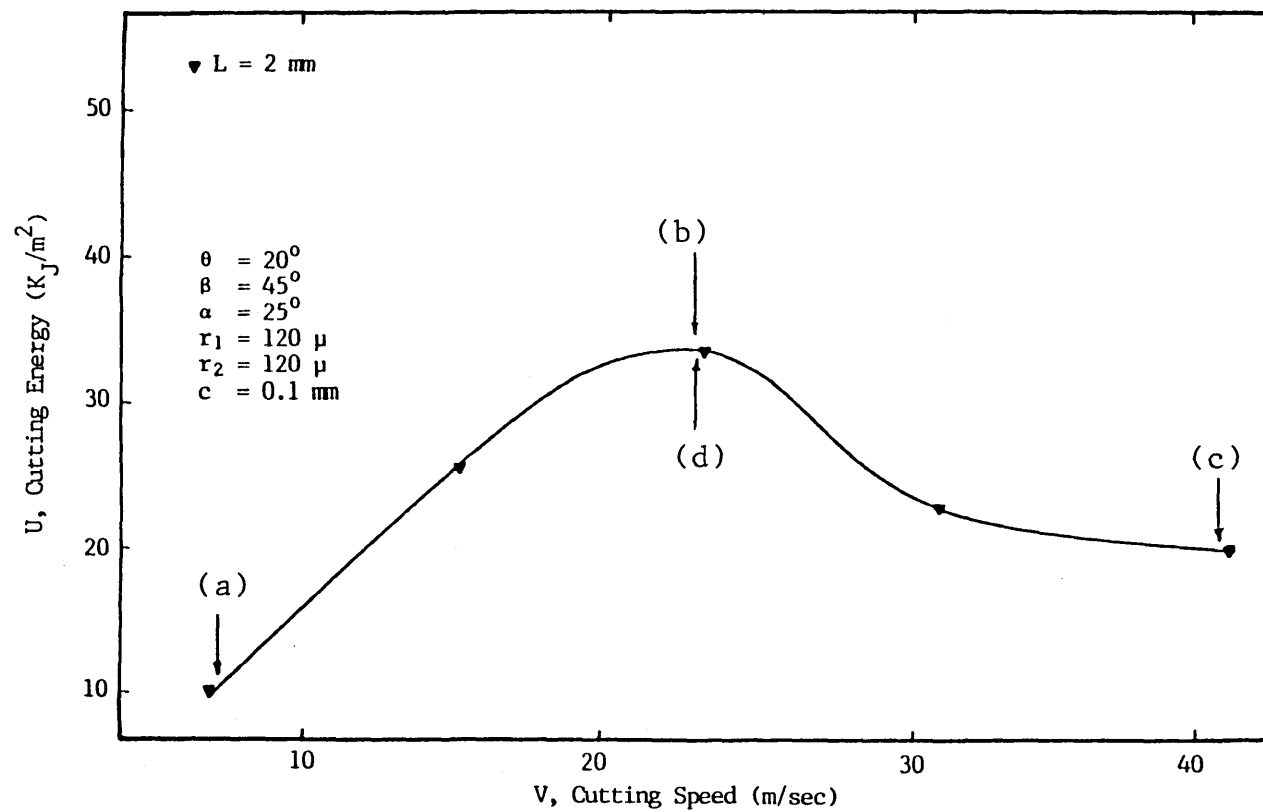


Fig. 8.10: Scanning Electron Micrographs of Cut Surfaces of LDPE, Taken at Positions Shown on the U-V Curve. Direction of Cutting from Left to Right.

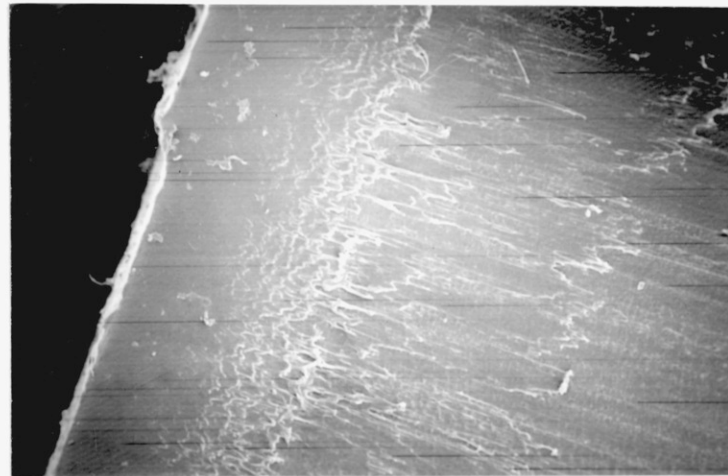
Direction of Cutting →

0.5 mm



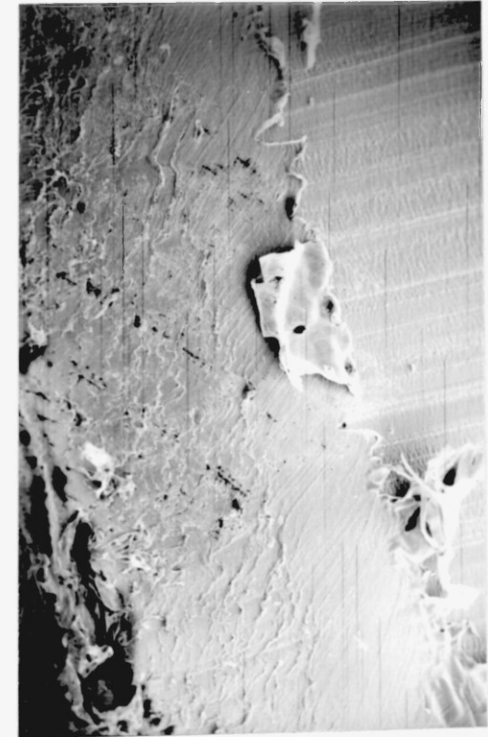
(a)

0.5 mm



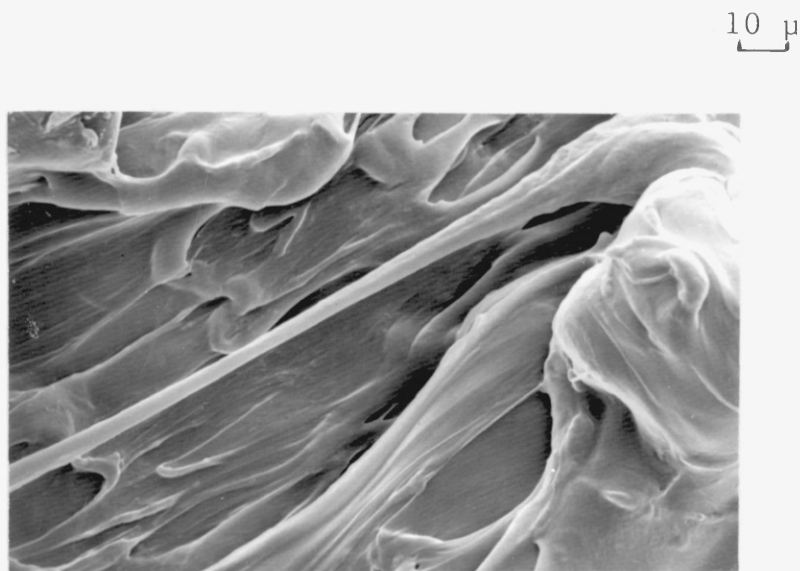
(b)

0.5 mm



(c)

Fig. 8.10 (Continued):



(d)

Fig. 8.10 (Continued): (Surface Appearance at Zone B).

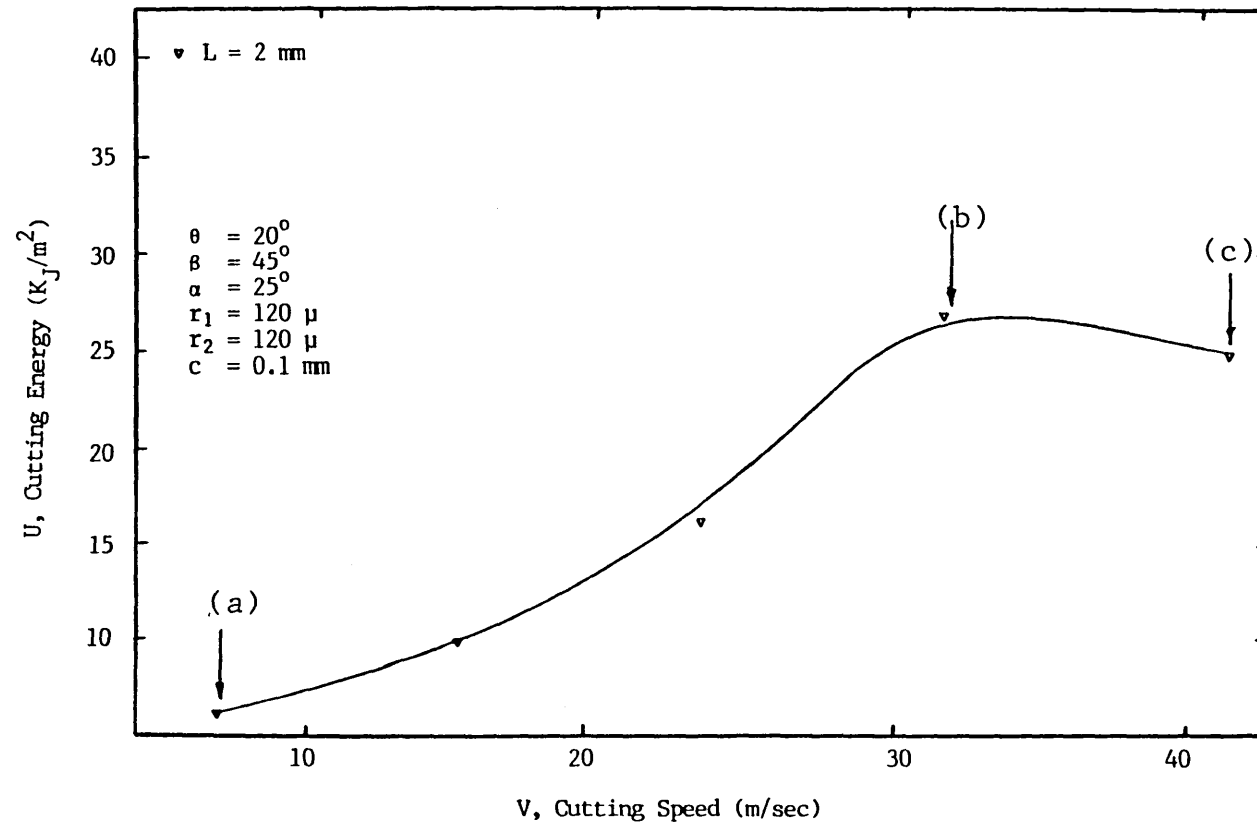
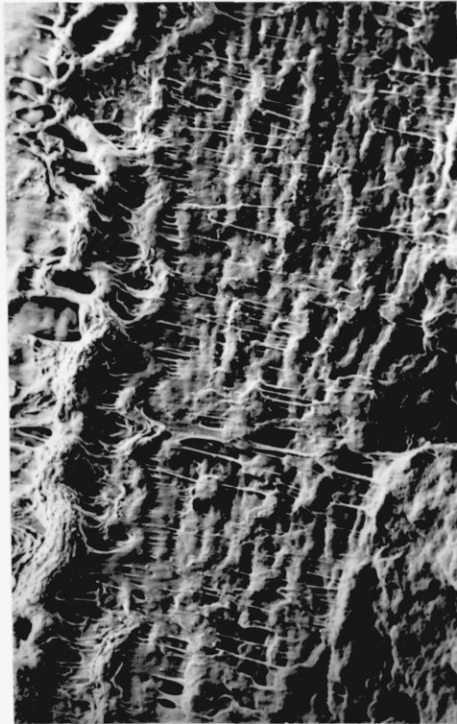


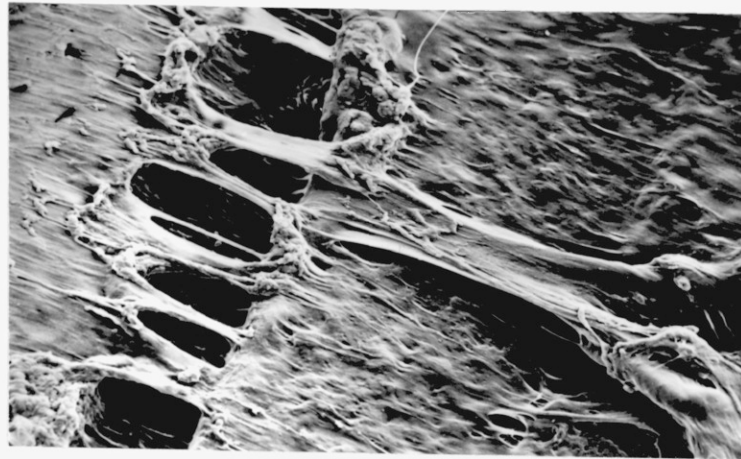
Fig. 8.11: Scanning Electron Micrographs of Cut Surfaces of PP,
 Taken at Positions Shown on the U-V Curve.
 Direction of Cutting from Left to Right.

Direction of Cutting —————→

0.1 mm

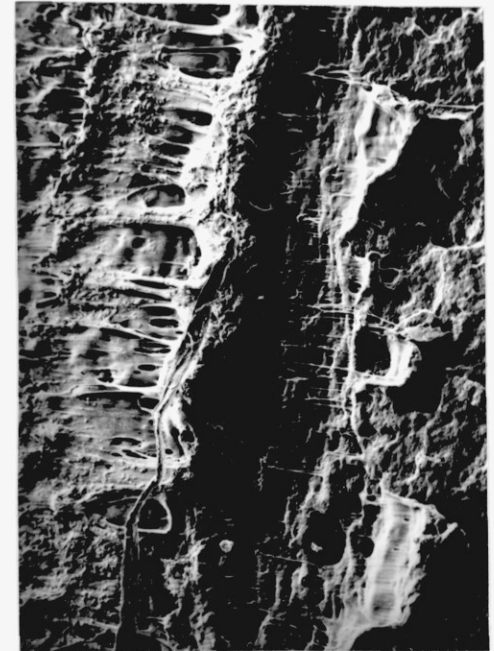


(a)



(b)

0.1 mm



(c)

Fig. 8.11 (Continued):

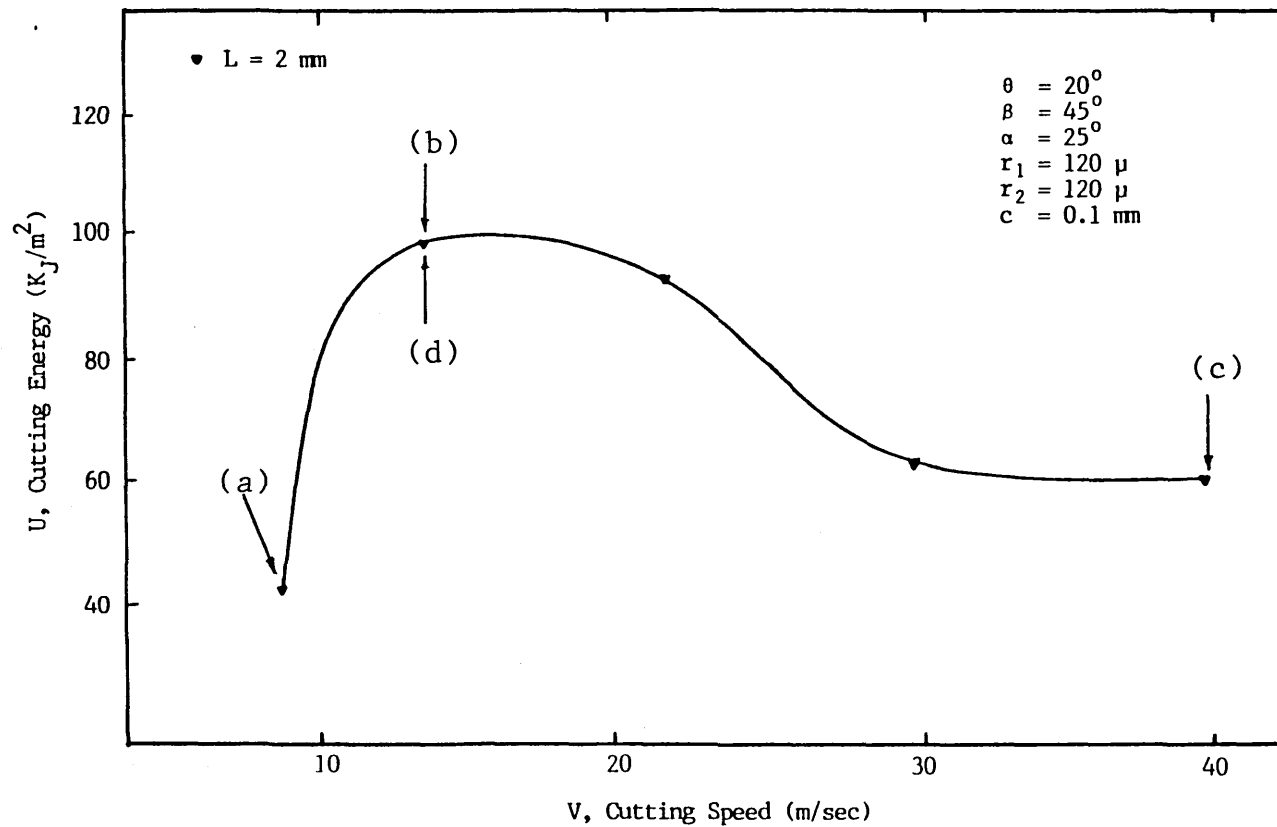
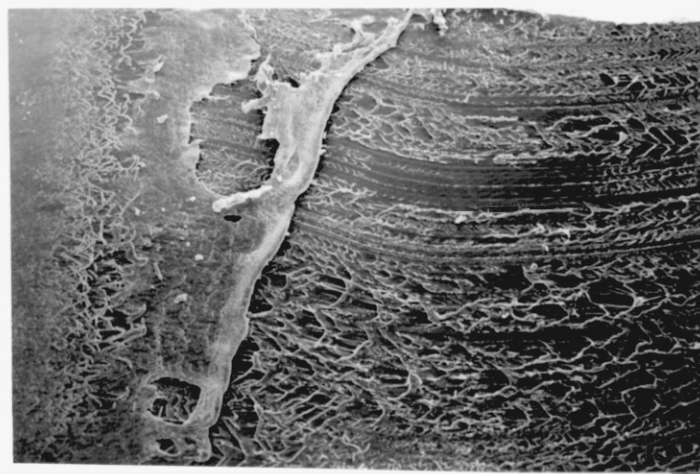


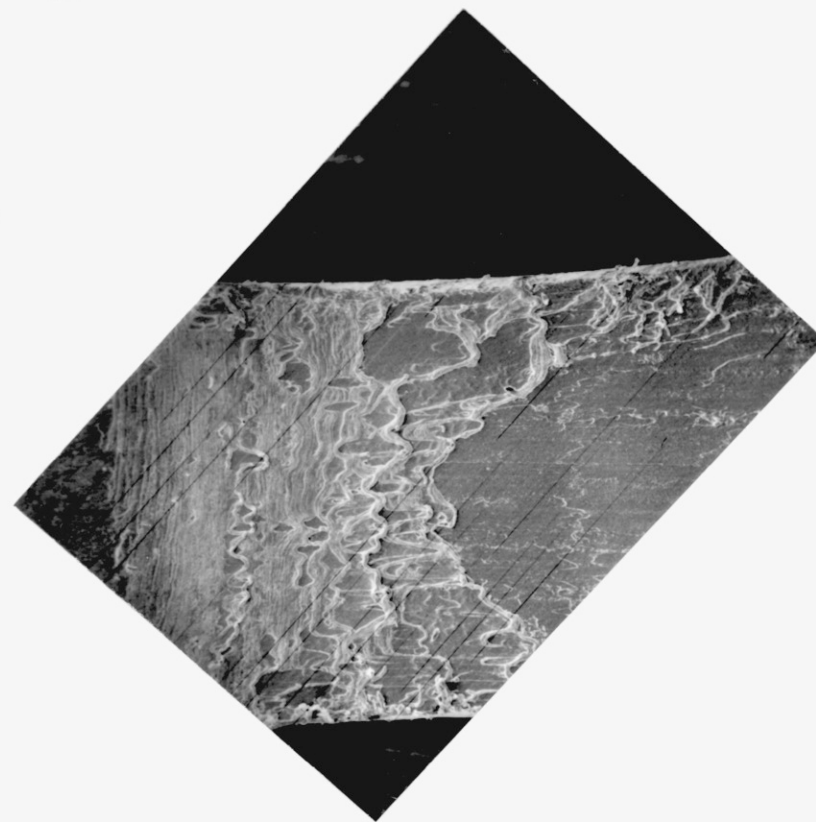
Fig. 8.12: Scanning Electron Micrographs of Cut Surfaces of PC,
 Taken at Positions Shown on the U-V Curve.
 Direction of Cutting from Left to Right.

Direction of Cutting →

0.5 mm



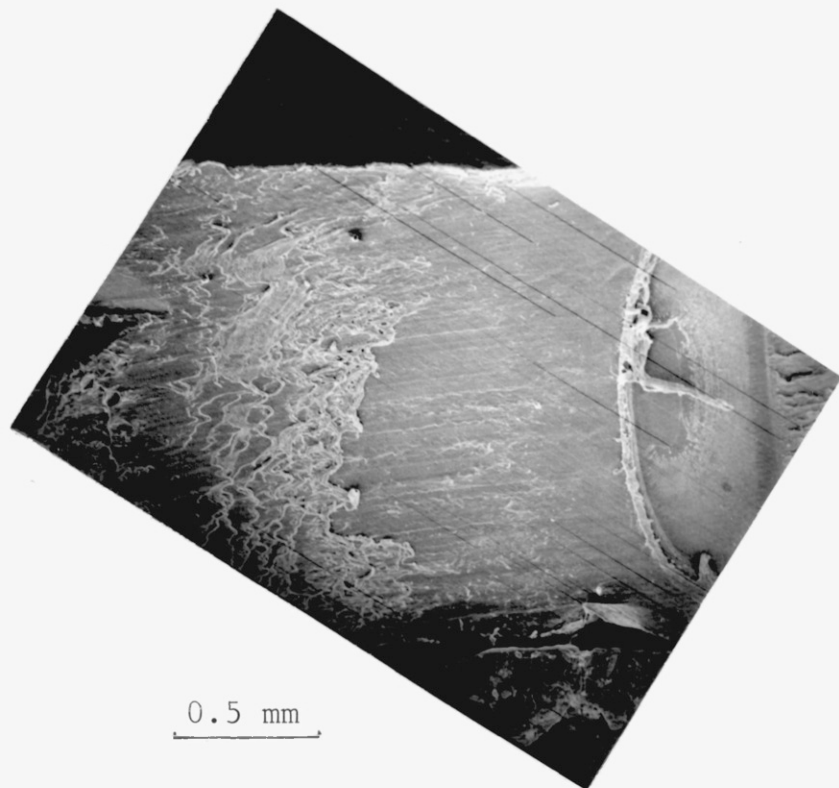
(a)



(b)

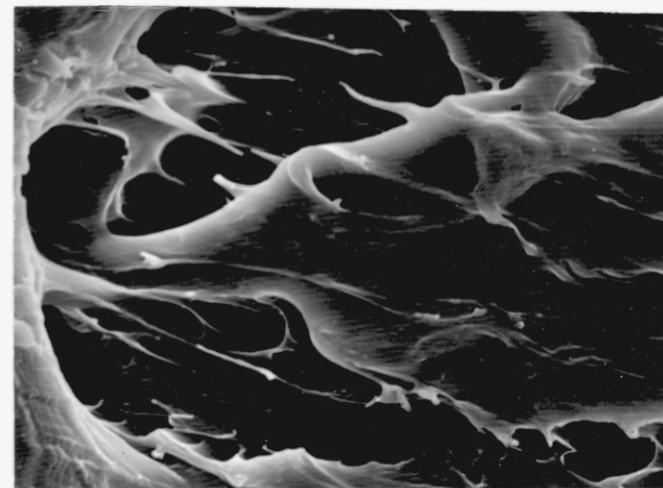
Fig. 8.12 (Continued):

Direction of Cutting —————→



(c)

10 μ



(d)

Fig. 8.12 (Continued):

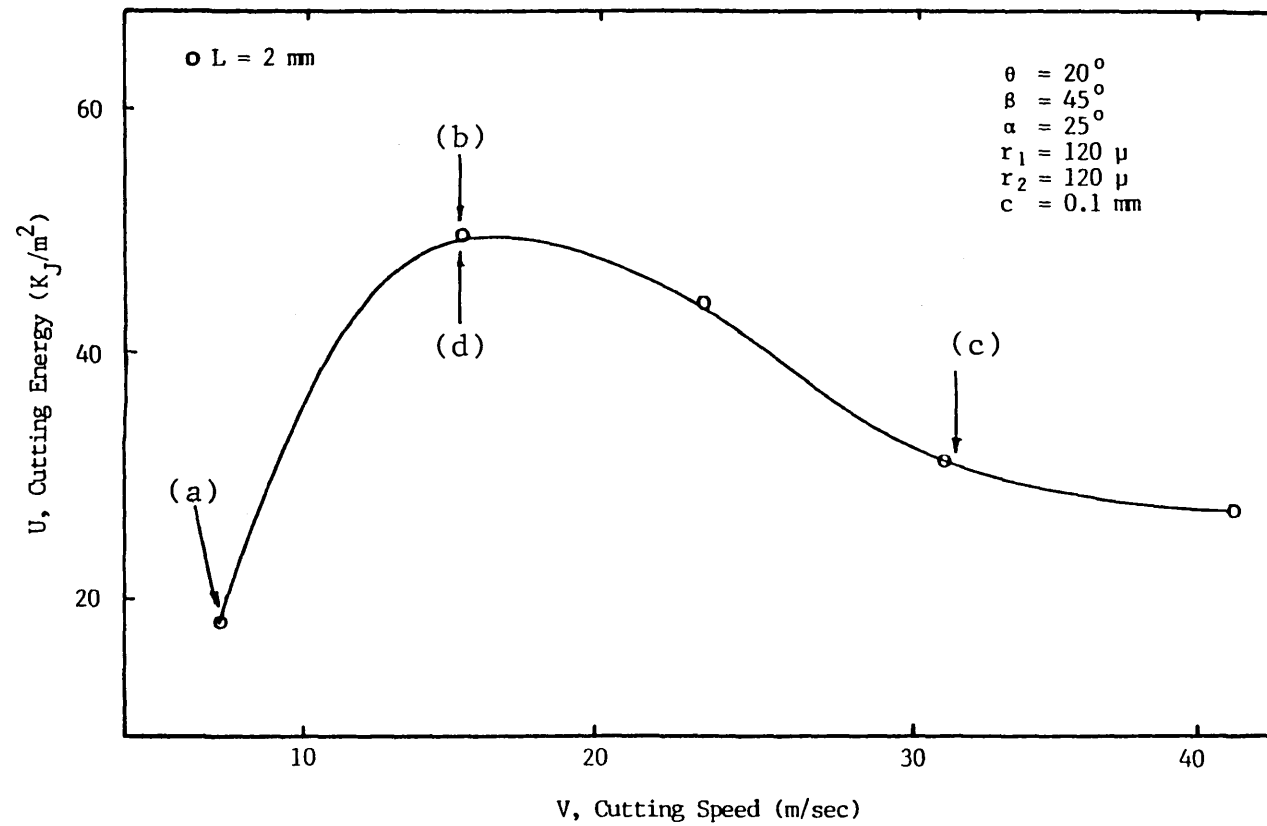
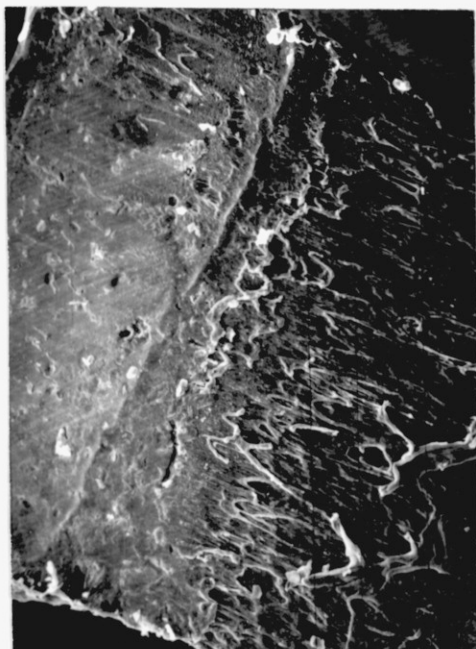


Fig. 8.13: Scanning Electron Micrographs of Cut Surfaces of ABS, Taken at Positions Shown on the U-V Curve. Direction of Cutting from Left to Right.

Direction of Cutting

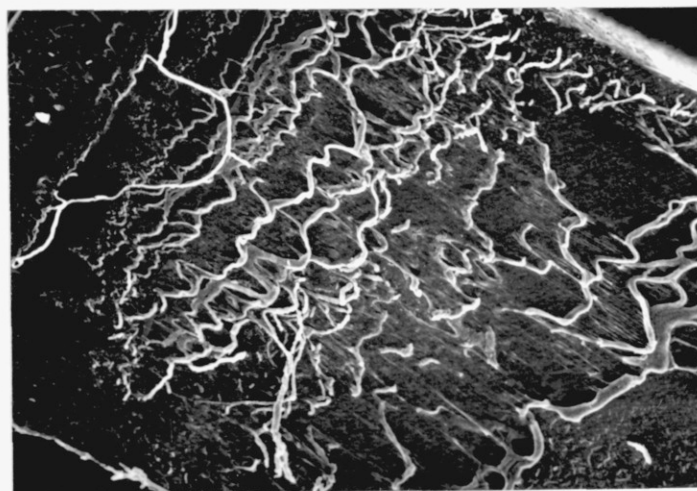


0.5 mm



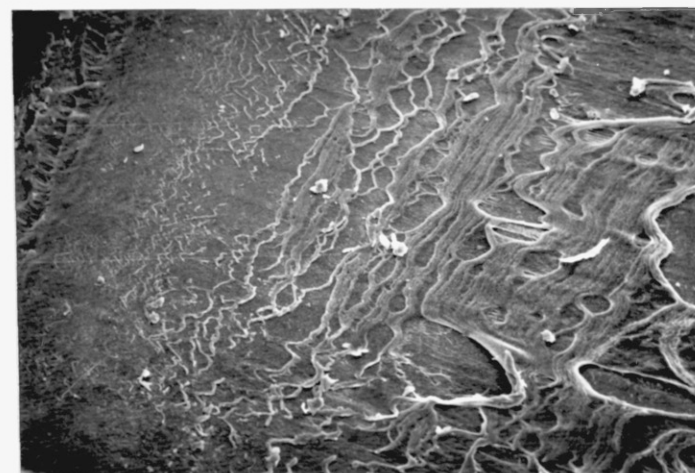
(a)

0.5 mm



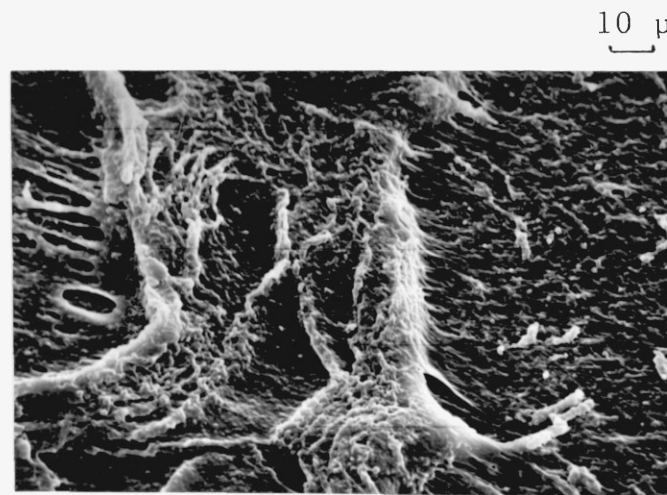
(b)

0.5 mm



(c)

Fig. 8.13 (Continued):



(d)

Fig. 8.13 (Continued): (Surface Appearance at Zone B).

related to its position on the 'cutting energy - cutting speed' curve. From the micrographs it can be seen that the surface at zone B differs according to cutting speed. At low speeds, the surface appears to be soft and stretched (like the consistency of a soft material being pulled apart), whilst at higher speeds, a smooth, smeared film is evident on both the cut surface and also on the blade surface. This is interpreted as being due to the effects of localised heating. It is suggested that with relatively diffused heating the material will be softened over a relatively large volume, (but still small in relation to specimen size) and this leads to the stretched 'toffee-like' consistency. With highly localized heating however, the material will be very soft in a thin band only leading to the smear effect. It will, therefore be postulated that the thermal interpretation provides basis for explanation of the various rate effects, which have been observed.

Fig. 9.5 shows a plot of cutting energy against the length of zone B. It can be seen that there is a reasonable proportionality which exists for all material tested. This leads to the idea that the cutting energy is dissipated in zone B, and it is argued that this dissipation takes the form of heat. This is consistent with the heating interpretation previously discussed. This heating phenomenon,

will be referred to later in a possible explanation of the observed cutting behaviour.

Referring to Fig. 9.5, it can be seen that low cutting energy materials have small zones, which are characteristic of more brittle materials (PMMA, HIPS and PVC), whilst tougher materials (PC, ABS, PP and LDPE) have much larger zones. Giving the interpretation of zone B, previously described, this is not surprising, but confirms the importance of this zone as a parameter in cutting.

8.6.3 Zone C

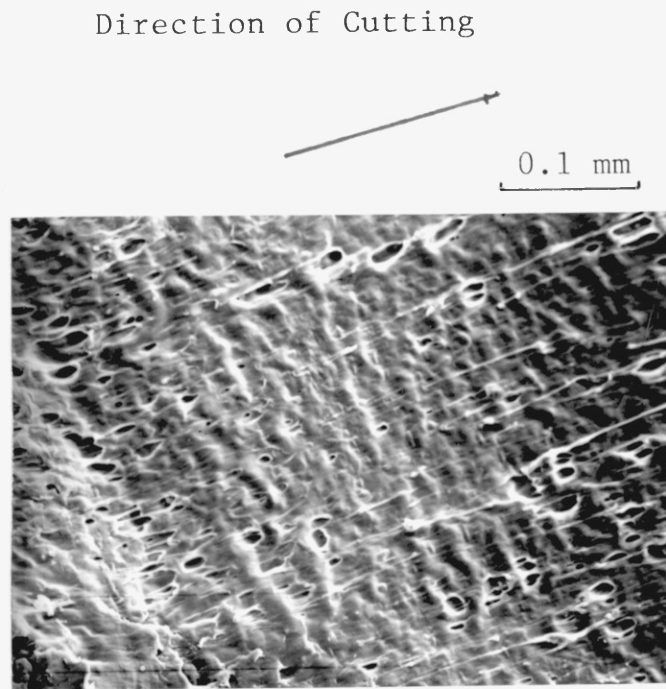
Surface features of zone C differed greatly from those of zone A and B. These features are basically the normal features to be observed in fracture surfaces produced, in either ductile or brittle failure.

For tough materials such as LDPE, ABS, PC and PP, irregular features with ductility or drawing are always observed in zone C of cut surfaces. Fig. 8.14 shows two micrographs (high magnification) of zone C, taken from cut surfaces of LDPE. These cut surfaces were produced at cutting speeds of 7 m/sec and 40 m/sec at room temperature.

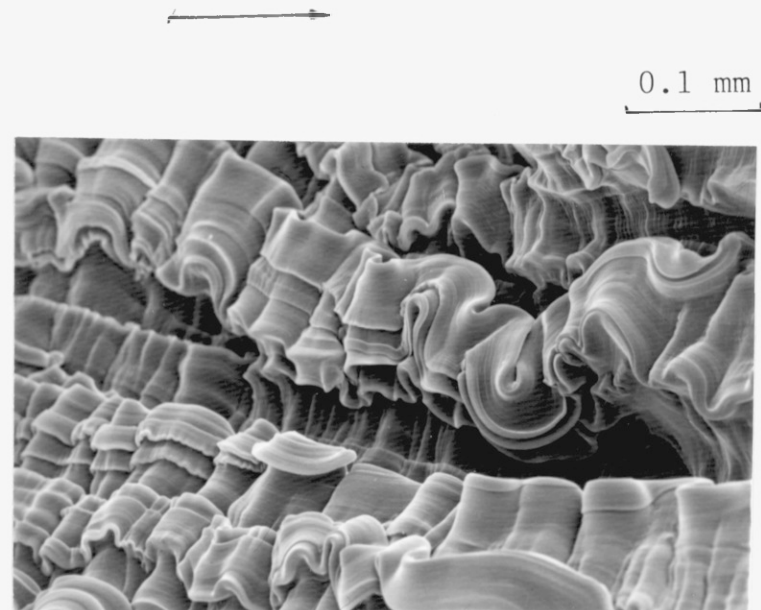
The first micrograph reveals that the cut surface is covered with unstraightened twisted strings. It is not known exactly what failure mechanism is causing this surface feature. However, the mechanism of failure may be attributed to the growth and coalescence of voids which is accompanied by the drawing of the material between them (88).

The second micrograph in Fig. 8.14 shows the presence of a heated surface. This feature could be attributed to considerable local heating.

Fig. 8.15 shows a micrograph (high magnification) of zone C taken from a cut surface of PP. The cut surface was produced at a cutting speed of 7 m/sec. The surface is rough unfibrillated with conical features. Such spherulitic features (89 and 90) were attributed to the failure of an amorphous region either between parallel lamellae within individual spherulites, (interlamellar failure)



(a)



(b)

Fig. 8.14: LDPE - Difference in Surface Appearance at Zone C of Cut Surfaces that have been Produced at Blade Speeds of (a) 7 m/sec and (b) 40 m/sec.

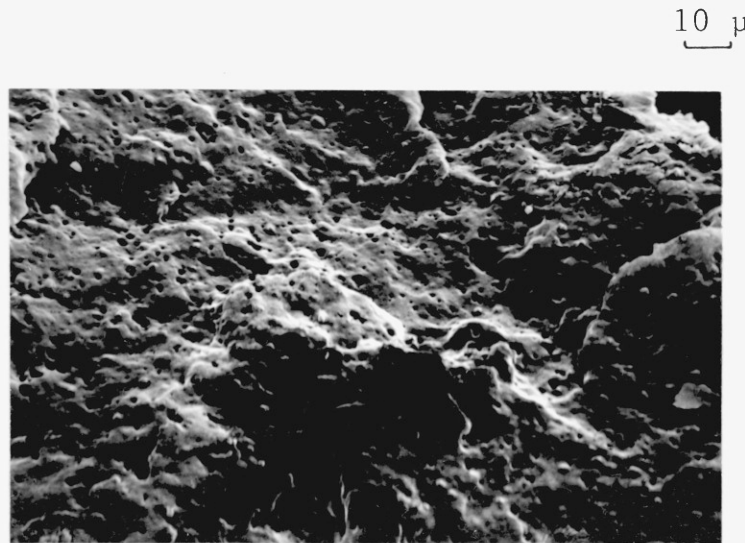


Fig. 8.15: PP - Surface Appearance at Zone C of Cut Surface Produced at Blade Speed of 7 m/sec.

or between adjacent spherulite boundaries, (interspherulitic failure) (90 and 91).

Figs. 8.7, 8.8 and 8.9 show a series of micrographs taken from cut surfaces of PMMA, HIPS and PVC, from which it can be observed that surfaces at zone C appear to be smooth or slightly rough and for PMMA, patterned with hyperbolic and line markings.

Fig. 8.16 shows a micrograph (high magnification) of zone C of PMMA. It can be seen here that the hyperbolic markings have distinct foci. It has long been recognised (93) that this represents the site of a secondary fracture initiated ahead of a main crack front, most probably caused by void growth near the crack tip. The hyperbolic shape results from the intersection of the main crack front with the circular front produced by the expanding void in a plane parallel to the main fracture. If the plane is sufficiently close to that of the latter, the two may become joined by a small step in the surface. The density of these markings (Fig. 8.7 C) have been shown by Cotterell (94) to be a direct function of crack speed, the density increasing for increasing crack speeds. This is presumably a consequence of the higher stress intensity of the crack tip at higher crack speeds causing more voids to expand in an unstable manner. The line markings (Fig. 8.7a) (river type) are thought to be caused by crack propagation on slightly different levels



Fig. 8.16: Markings on Cut Surface of PMMA (Zone C).

all the way across the section thickness which results in a multiplanar fracture (93).

Another interesting feature can be observed in the cut surfaces of PVC (Fig. 8.17) and PMMA (Fig. 8.7b) of what appears to be a series of arrest lines. They are indicative of stick-slip crack propagation. It is suggested by Andrews (93) that as the crack grows in size, it tends to accelerate because more and more energy is available for its propagation. The acceleration of the fracture gives rise to instability, the most common example of which is crack forking. Once a fork has developed, the branches require twice the energy previously available if they are to continue unhindered and one branch is often 'arrested' and the other continues. Also stick slip phenomenon has been attributed to crack tip blunting effects (95).

It is of interest at this point to consider that some features are observable macroscopically in zone C of the cut surfaces of PMMA. The existence of two distinct features in zone C of cut surfaces of PMMA produced at low and high cutting speeds, can be observed: the first is the appearance of smooth regions (mirror type reflecting the light) and the second, the disappearance of the mirror regions and the surface becoming misty (Fig. 8.7b).

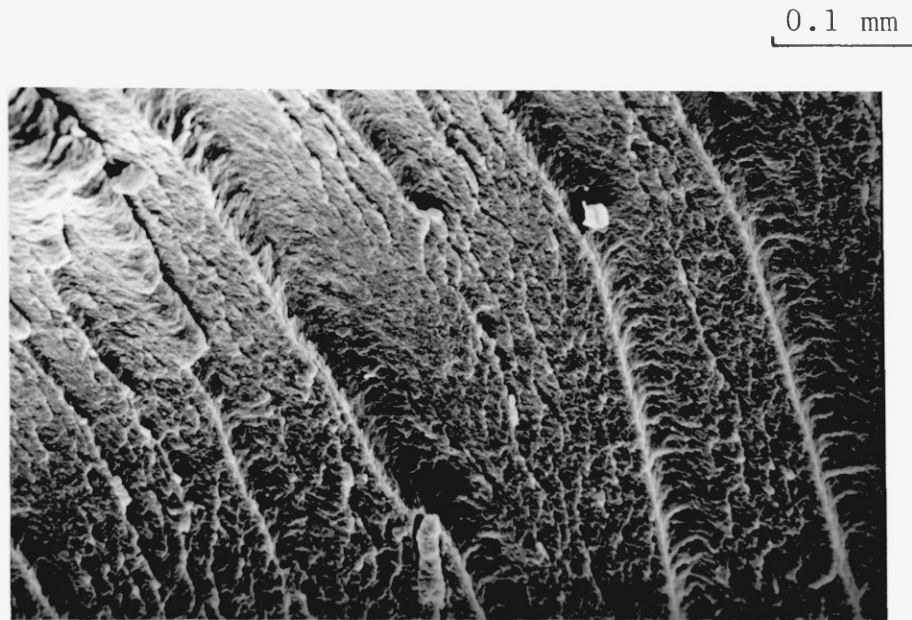


Fig. 8.17: Arrest Lines on Cut Surface of PVC (Zone C).

It is suggested by Andrews (93) that the smooth surfaces are caused by the void coalescence on a micro scale. The fracture front propagates at one plane through the material leaving a featureless surface in its wake. The misty surfaces have been attributed to the existence of heterogeneity in the material and its interaction with the fracture process.

To support the idea that the cutting mechanism of polymers in granulators is not a shear process but crack propagation following notching, it can be seen from a slow speed test in Fig. 8.18 that there is a crack ahead of the blade tip possibly caused by the wedging action. This micrograph was taken of a specimen (LDPE) with the blade wedged on it having been subjected to a cutting speed of 0.75 m/sec, which did not have sufficient inertia to effect a complete cut.

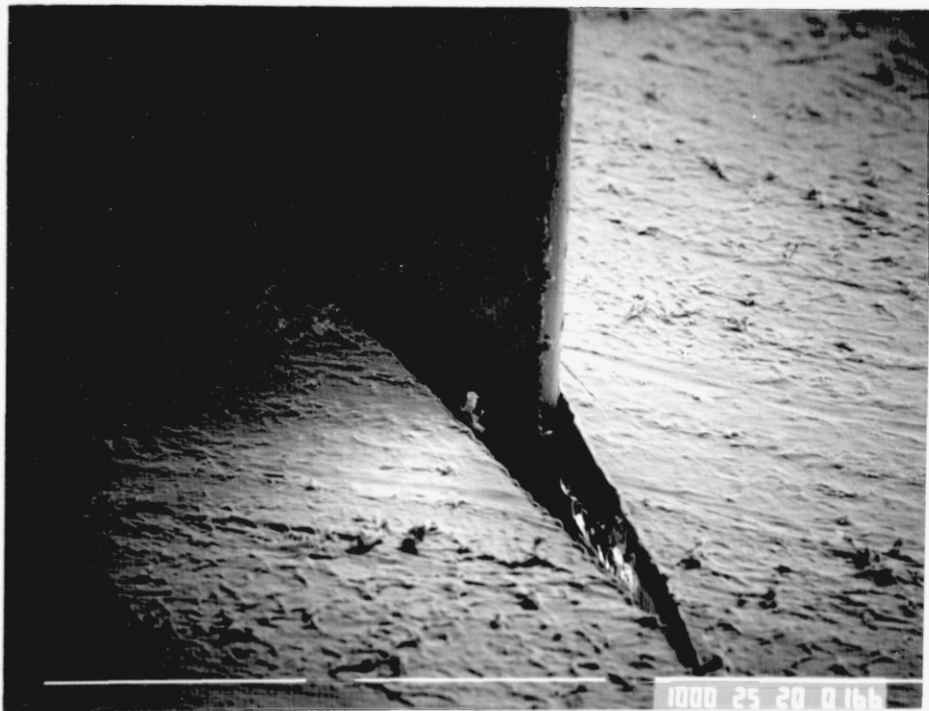


Fig. 8.18: ESM Picture Showing Crack Running Ahead of the Blade Edge.

CHAPTER 9

GENERAL DISCUSSION

The results presented here lead to the important conclusion that the mechanism of cutting under test conditions cannot be classified as a shear process, but more resembles a fracture process. Results from the micrographic study of the cut surfaces (the existence of a smooth featureless surface - zone A - which occurs at the edge where the blade enters the specimen before a crack runs ahead of the blade - also the arrest lines on the cut surfaces - zone C - Figs. 8.7.6 and 8.17) are indicative of stick-slip crack propagation which has been observed elsewhere in epoxy resins and is related to a crack tip blunting mechanism (93,95). Such findings tend to confirm the above conclusion as do the following facts: that fixed blade conditions are unimportant (Section 5.2-4) and at high cutting speeds it can be removed without effect; the observed rotating blade sharpness was found to be significant (Figs. 5.17-5.23); but clearance effects were minor (Figs. 5.10-5.23).

It is suggested that the cutting process takes place in two stages. The first is the indentation by the blade edge of the material and setting up of a plastic zone (or a craze) ahead of the blade. At some stage, fracture by crack propagation due to the wedging action of the advancing blade

takes place, thus the second stage is propagation of a crack unstably by the tensile stress that results from the bending moment applied to the part of the material to be cut.

Fig. 9.1 is a diagram of the cutting process.

The chip that is separated from the material (as a result of the blade wedging action) has a length l and can be treated as a cantilever beam fixed at one end. The force f causes a bending moment which tends to split the material. If it is assumed that there is a plastic zone of length a tending to oppose the fracture process, therefore the diagram in Fig. 9.1 may be simulated by the superimposition of the two systems shown in Fig. 9.2.

In the first, the cantilever is subjected to a concentrated load $\bar{f}$ at its free end. In the second, the cantilever is subjected to a uniformly distributed load σ_y (yield stress) along the length a . Therefore the deflection of the chip v (Fig. 9.1) can be written as:

$$v = v_1 - v_2 - \bar{\theta} (l-a) \quad (1)$$

where v_1 is the deflection of the cantilever shown in Fig. 9.2.a, the sum of v_2 and $\bar{\theta} (l-a)$ is the total deflection of the cantilever shown in Fig. 9.2.b. Now we consider the value v_1 , from the elastic beam theory, the moment at Z is given as:

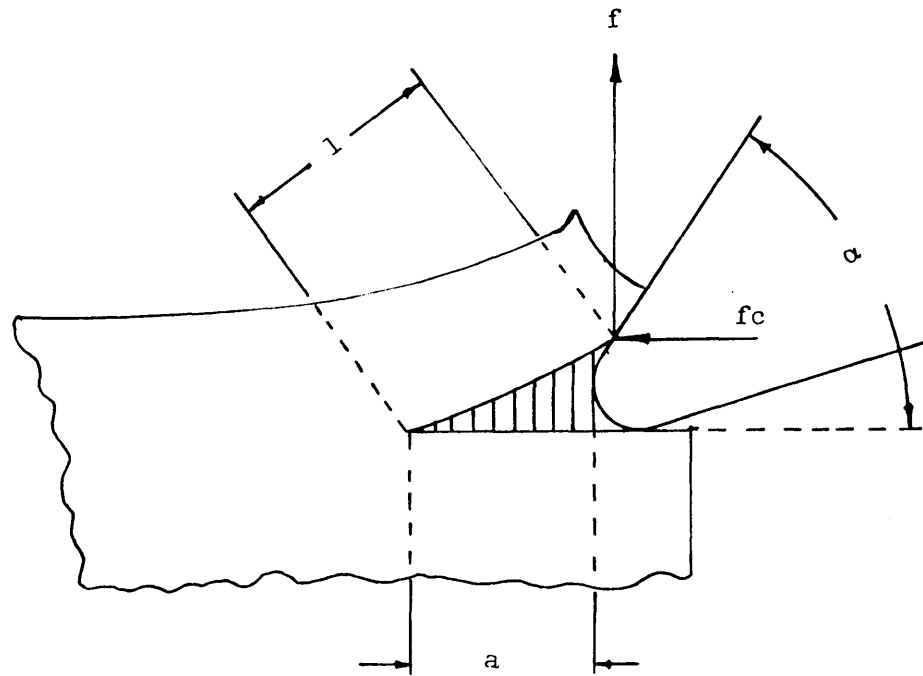


Fig. 9.1: Schematic Diagram of the Cutting Process

f_c : cutting force, f : normal force = $f_c \sin \alpha \cos \alpha$

α : angle of attack, l = cantilever length, a : plastic zone length

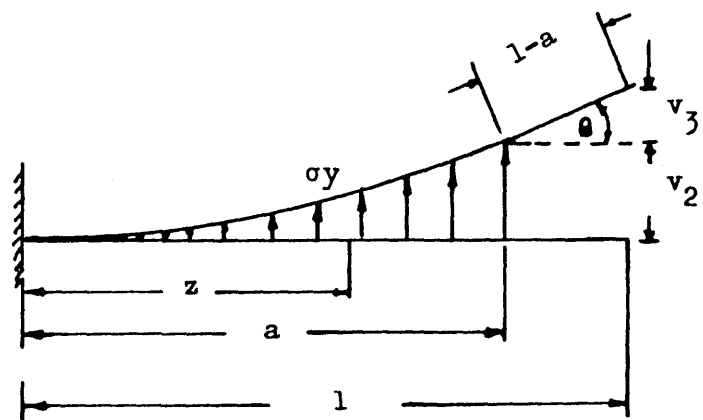
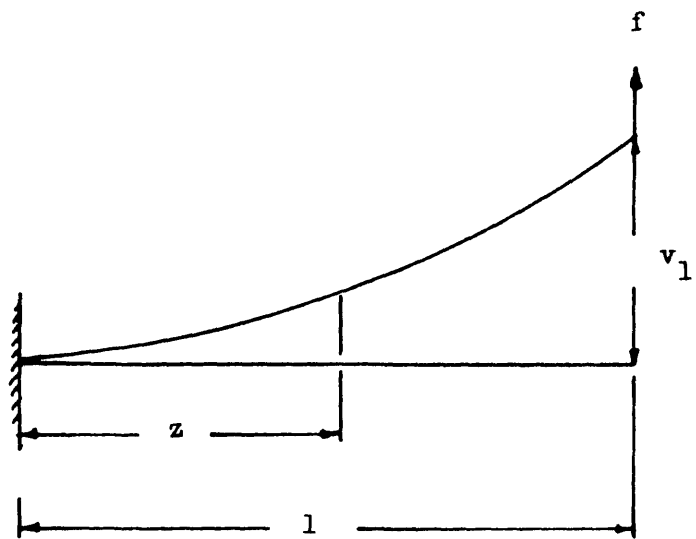


Fig. 9.2: The Cutting Process Two Part System.

$$M = EI \, d^2 v_1 / dz^2 = f(1-Z) \quad (2)$$

where E = Young's modulus

I = second moment of area

and the deflection v_1 at $Z = 1$ is obtained as in equation 3,

$$v_1 = fl^3 / 3EI \quad (3)$$

similarly, if we consider the value v_2 (Fig. 9.2.b), the moment M at Z ($0 < Z \leq a$) is obtained (from beam theory (96)), as in equation 4,

$$M = EI \, d^2 v_2 / dz^2 = \sigma_y (a-Z)^2 / 2 \quad (4)$$

Then the deflection v_2 can be obtained as in equation 5,

$$v_2 = \sigma_y^2 a^4 / 8EI \quad (5)$$

Also the value of $\bar{\theta}$ is given by the value dv_2 / dZ (integrating equation 4) when $Z = a$, i.e.

$$\bar{\theta} = (dv_2 / dZ)_a = \sigma_y a^3 / 6EI$$

and,

$$v_3 = \sigma_y a^3 (1-a) / 6EI \quad (6)$$

From equations 3, 5 and 6, we obtain the deflection of the chip v as in equation 7,

$$v = (8fl^3 + \sigma_y a^4 - 4\sigma_y a^3 l)/24 EI \quad (7)$$

Now fracture will occur when the deflection v reaches a maximum value $\bar{v}$ when $f = \sigma_y a$ and $l = a$, i.e.

$$\bar{v} = 5\sigma_y a^4/24 EI \quad (8)$$

Also, force f and energy to initiate fracture $\bar{E}$ are obtained as in equations 9 and 10,

$$f = (24\bar{v} EI/5 \sigma_y)^{1/4} \sigma_y \quad (9)$$

$$\bar{E} = \bar{v}f = (24I/5 e_y)^{1/4} \sigma_y \bar{v}^{5/4} \quad (10)$$

where e_y is the yield strain. Furthermore, the maximum deflection $\bar{v}$ can be expressed in terms of fracture strain e and a gauge length d (d is the gauge length on which the strain is based. This gauge length represents the blade tip diameter), i.e.

$$\bar{v} = ed \quad (11)$$

Therefore equation 10 can be written as:

$$\bar{E} = c \sigma_y e^{5/4} \quad (12)$$

where $c = (4.8 I/e_y)^{1/4} d^{5/4}$ and is a constant for a given polymer and test conditions (e_y is independent of test rate and temperature (97)). Equation 12 predicts, at least qualitatively the appropriate behaviour of a given specimen and material but the effects of sharpness d appear to be overestimated. Cutting energy will increase by decreasing blade sharpness (see Figs. 5.17 - 5.23) but not in a consistent manner for different materials. Also, energy will increase by increasing the angle of attack due to the large amount of plastic deformation required to bend the part of the material that has been cut (Figs. 5.24 - 5.30). In addition, equation 12 shows that cutting energy is temperature dependent due to the fact that the yield stress and fracture strain are also temperature dependent.

Fig. 9.3 is a plot of yield stress and fracture strain values versus temperature for PVC (98). From the figure, it can be seen that at high temperatures there is rapid fall in the yield stress values, but the rise in fracture strain has less effect on the results from equation 12, i.e. at high temperatures the yield stress will be the dominant factor in determining cutting energy levels (equation 12).

Fig. 9.4 is a plot of $\sigma_y e^{5/4}$ versus temperature. From the figure it appears that there is an increase in $\sigma_y e^{5/4}$ values by approximately a factor of five as

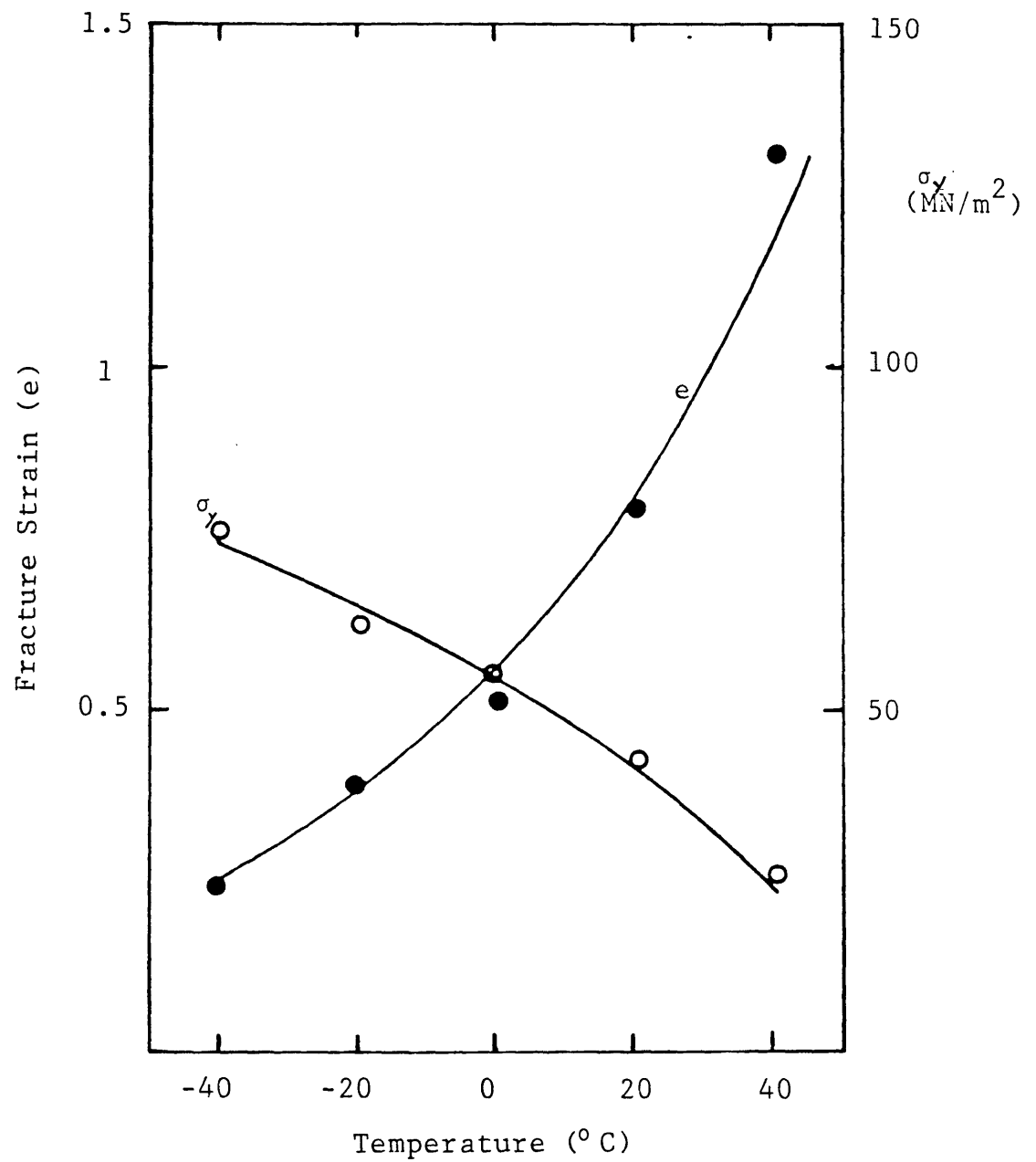


Fig. 9.3: The Effect of Temperature on the Tensile Properties of PVC (Reference 98).

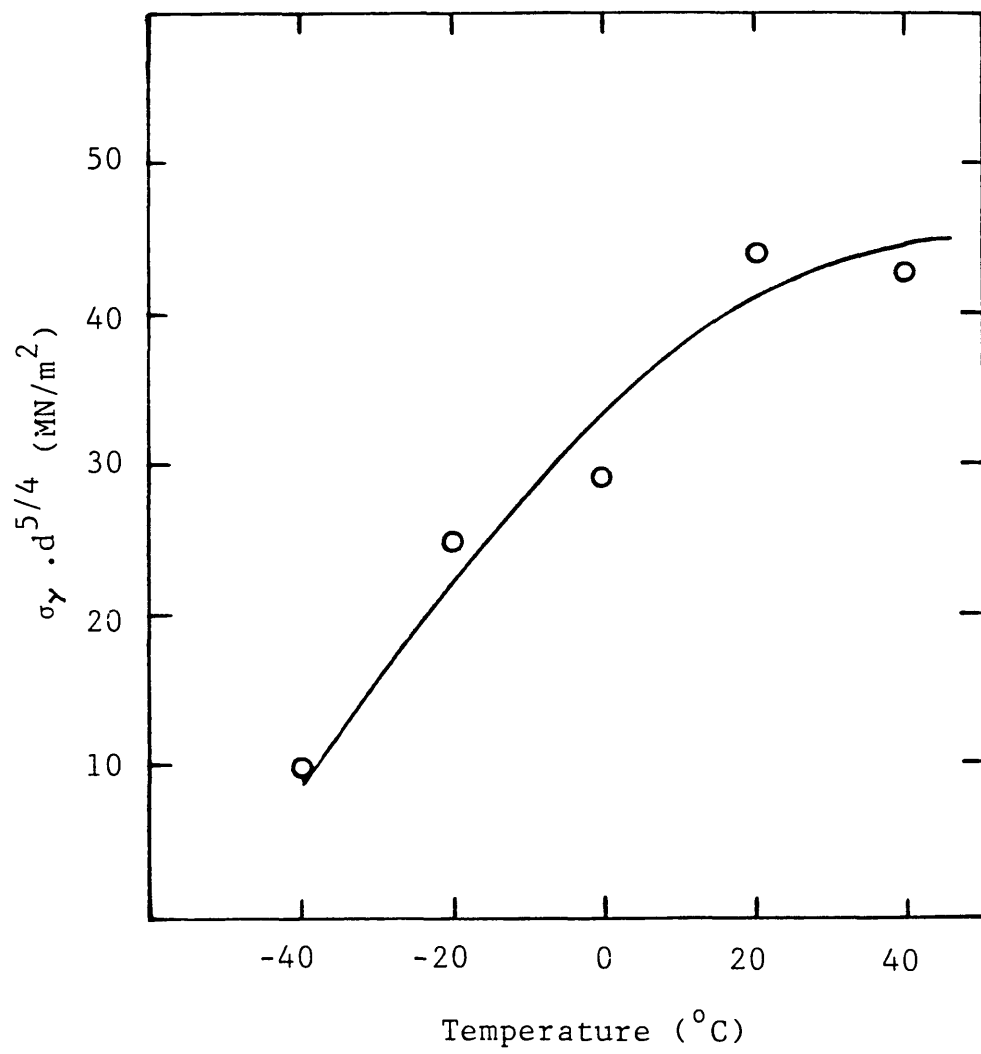


Fig. 9.4: $\sigma_\gamma \cdot e^{5/4}$ Versus Temperature for PVC.

the temperature is increased from -45 to 40°C. This dramatic increase in the $\sigma_y e^{5/4}$ value is similar to the sharp rise in the cutting energy levels for PVC in the present study as the blade speed is increased from 7 to 40 m/sec (Fig. 5.46). Also, it is suggested that at temperatures higher than 40°C (Fig. 9.4) the curve would level off and eventually fall forming a peak.

Therefore this simple model based on changes of fracture properties due to temperature does predict the appropriate trend which was observed in practice, and it is therefore suggested that the idea that local thermal effects control cutting behaviour, first suggested on the basis of the micrographs (Section 8) is confirmed.

Williams et al (86, 87) in crack propagation studies, explain increased toughness with rate in terms of notch tip blunting induced by adiabatic heating at the crack tip. The width of the zone affected, b , is given by:

$$b = G_c / a c_p (T_s - T_o) \quad (13)$$

where G_c is the fracture toughness for sharp crack, T_s and T_o are the softening and test temperature respectively, a is the density and c_p the specific heat.

The adiabatic toughness is given by:

$$\begin{aligned} G_B &= U G_c / a c_p (T_s - T_o) \\ &= G_c (T/T_s - T_o) \end{aligned}$$

The parameter $U/a c_p$ represents the effective temperature rise (T) due to the extra energy U absorbed in zone b.

The time, t , for diffusion through a distance Y is given by:

$$t = Y^2/X \quad (X \text{ thermal diffusivity})$$

Then a minimum loading time to limit the heat generated within zone b, is given by:

$$t_{\min} = G_c^2 / a c_p K (T_s - T_o)^2 \quad (14)$$

where K is the material thermal conductivity.

This time is that at which the adiabatic zone at T_s is established and a rapid transition to a higher value of G_c occurs. At longer loading times than t_{min} , the heat generated in the zone at the crack tip may be dissipated isothermally, causing no dramatic rise in temperature and no consequent increase in G_c .

This work reported here is relevant to that of Williams et al (86,87). However, in the present work if it is assumed that all the cutting energy is converted into heat within the region around the cutting blade tip, the local temperature can be elevated to a point close to the softening temperature (depending on the test speed). This idea is supported by two observations, firstly the detection of what appear to be heated zones on the cut surfaces. The appearance of these zones suggests that the polymer has been subjected to intense local heating. For a given polymer, the cutting energy shows reasonable proportionality with the length of the heated zone (Section 8.5.2) as shown in Fig. 9.5. Secondly, for each polymer tested loading times are smaller than t_{min} calculated from equation 14. Table 9.1 shows the above data for tests with blade tip radius 120 μ and peak cutting speed.

It is of interest to mention that, measured values of lengths of heated zone for most of the material tested, show reasonable agreement with values of zone widths

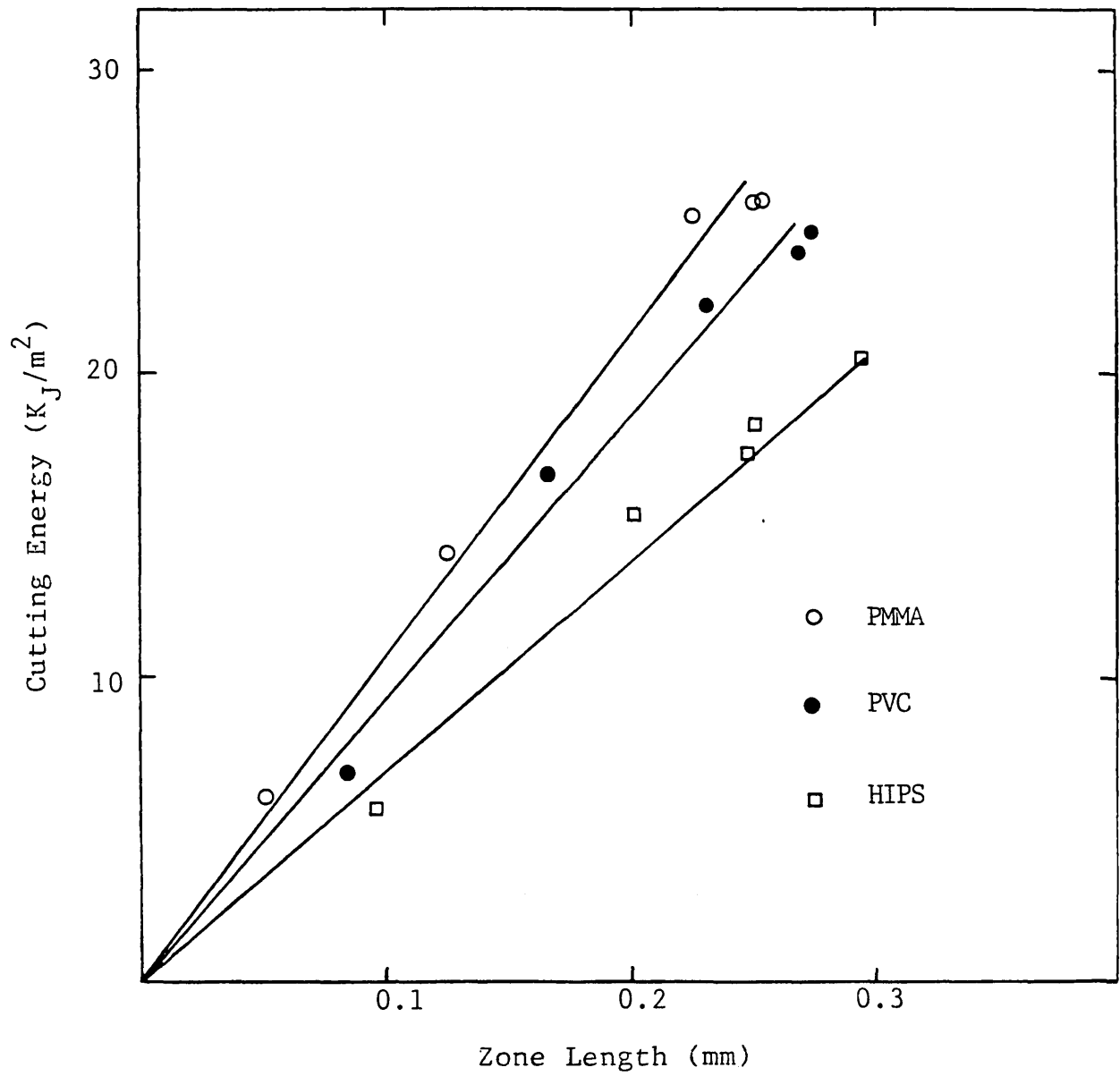


Fig. 9.5: Cutting Energy Versus Heated Zone Lengths for Each Polymer Tested.

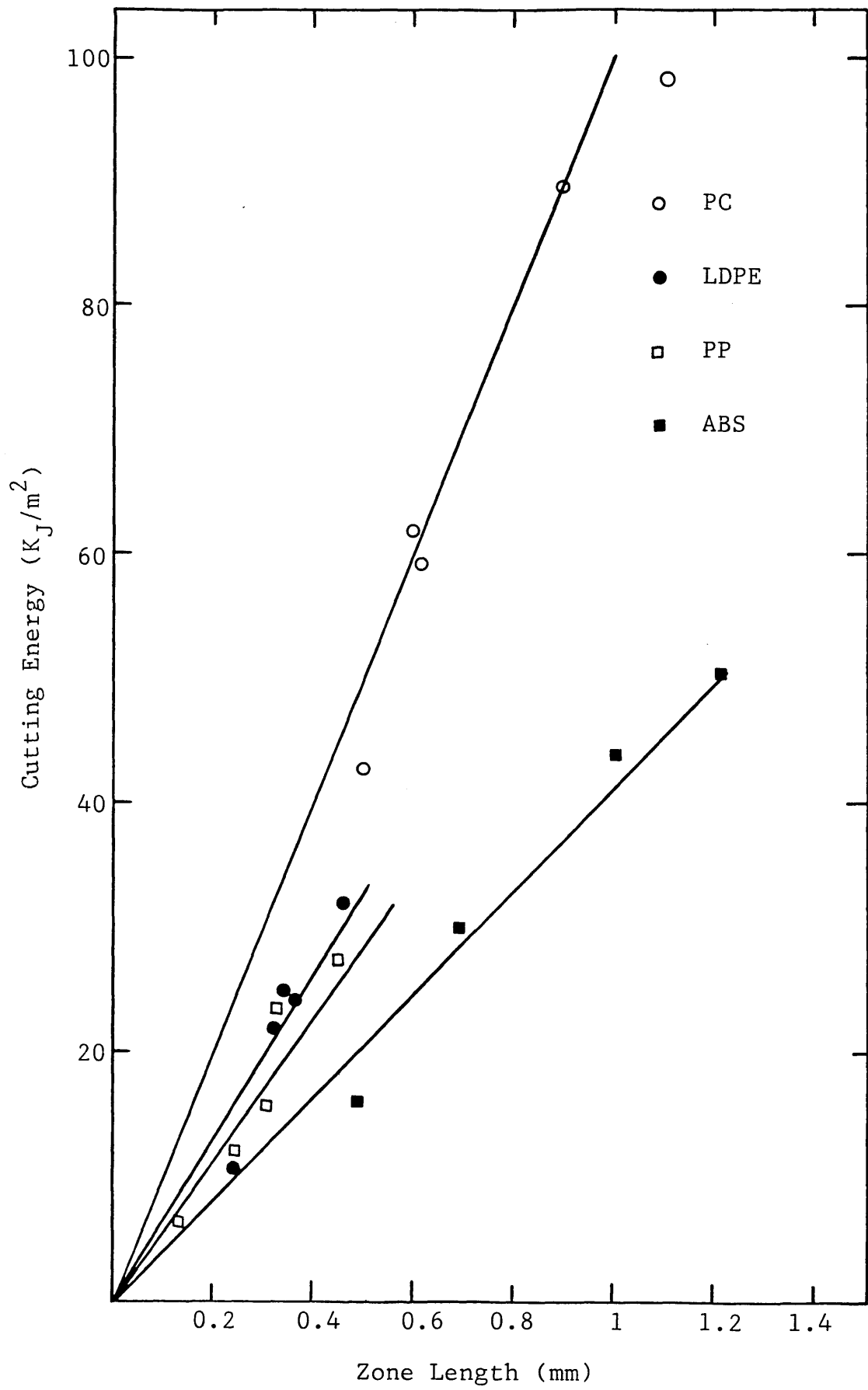


Fig. 9.5 (Continued):

Material	Observed Loading Time (ms)	$t_{\min}$ (ms) from Equation 9.2
PMMA	0.0006	27
HIPS	0.002	24
PVC	0.0012	66
PC	0.01	130
ABS	0.011	1769
PP	0.05	30
LDPE	0.013	36

Table 9.1: Observed Loading Time and $t_{\min}$
for Tests with Blade Tip Radius
120 μ and Peak Cutting Speed.

Observed Loading Time =
Zone A Length / Blade Speed
(Section 8.5.1)

predicted from equation 13, however, there is no physical reason for that.

Williams et al (87) reported that the fracture toughness was proportional to the square root of the strain rate, whereas in the present study, the dependence of cutting energy on the speed is linear (Fig. 5.47). It is suggested that the moderate increase in toughness observed by Williams et al represents a medium degree of blunt crack situation. The dramatic increase in energies observed in the present study can therefore occur as a result of higher levels of temperature rise. This argument is strengthened by the fact that loading times in the present work, are much smaller than those reported by Williams et al (87) as shown in Table 9.2.

Some polymers (LDPE, PP, PC and ABS) showed a clear peak in their cutting energies while others (PVC, HIPS and PMMA) showed continuous increase throughout the speed range (Fig. 5.46). Using equation 12 an explanation for the above phenomenon may be outlined as follows: the polymers (LDPE, PP, PC and ABS) which showed peaks in the cutting speed curve require higher levels of energy than the others, therefore higher energy would be generated and dissipated adiabatically causing a local temperature rise and thermal softening. This will lead to a decrease in the value of the yield stress and an increase in the

Material	Loading Time (ms)	
	Present Work	Williams et al
PMMA	0.004	0.2
HIPS	0.016	-
PVC	0.008	-
ABS	0.062	-
PC	0.057	-
PP	0.028	-
LDPE	0.078	-
HDPE	-	0.5
PTFE	-	0.4

Table 9.2: Comparison between Loading Times Observed by Williams et al and Those in the Present Study at a Cutting Speed of 7 m/sec.

fracture strain value and a consequent increase in the energy required to cut (equation 12). A dramatic rise in temperature occurs as the speed is increased causing the energy to be elevated to a maximum. By further increase in the speed, a state could be reached in which the region around the blade tip has become soft and molten, this would result in rapid fall in the yield stress (for a given polymer the yield stress can approach zero at the softening temperature) also, a fast drop in the cutting energy at that particular speed. When further softening is no longer possible and the region around the blade tip has the consistency of a very soft material, there is no further drop in the cutting energy when the speed is increased.

Therefore, it is suggested that the polymer which requires the highest level of energy to cut will demonstrate a peak earlier than the others. This is because the material will be subjected to a maximum level of intense heating which will lead to an earlier local softening. For example, the peak cutting energy for PC is $98 \text{ K}_J/\text{m}^2$, for ABS is $49 \text{ K}_J/\text{m}^2$, for LDPE is $33 \text{ K}_J/\text{m}^2$ and for PP is $28 \text{ K}_J/\text{m}^2$ while the peak speed for PC is 15 m/sec, for ABS is 18 m/sec, for LDPE is 24 m/sec and for PP is 34 m/sec approximately (Fig 5.46).

The other materials (PVC, HIPS and PMMA) whose cutting energies did not drop with further increases in the speed, required low levels of energies (Fig 5.46), therefore low

levels of heat would be generated and dissipated adiabatically causing no dramatic drop in the yield stress value. However, it is suggested that if the cutting speeds were to be increased (i.e. very short loading times) beyond the range tested, it is possible that those materials might be subjected to sharp local temperature rise which would result in a fast drop in the yield stress value leading eventually to a fall in their cutting energies. This view is supported by the fact that at higher blade speeds for those materials, between 25 and 40 m/sec, there is in each case evidence of a levelling off in cutting energy with increased speed (Fig. 5.46).

The effect of test temperature on cutting energy was interesting and confirms the conclusion that thermal effects are significant in the cutting process. It is important to mention that the increase in test temperature gave a reduction in the cutting energies for the materials (LDPE, PC and ABS) which showed peaks in their energies (Fig 5.46) and caused a rise in the energies of the other materials (PVC, HIPS and PMMA) whose energies showed a continuous increase with speed. This is shown in Fig. 9.6 which is a plot of cutting energy versus test temperature for all the materials tested. It appears from Fig. 9.6 that

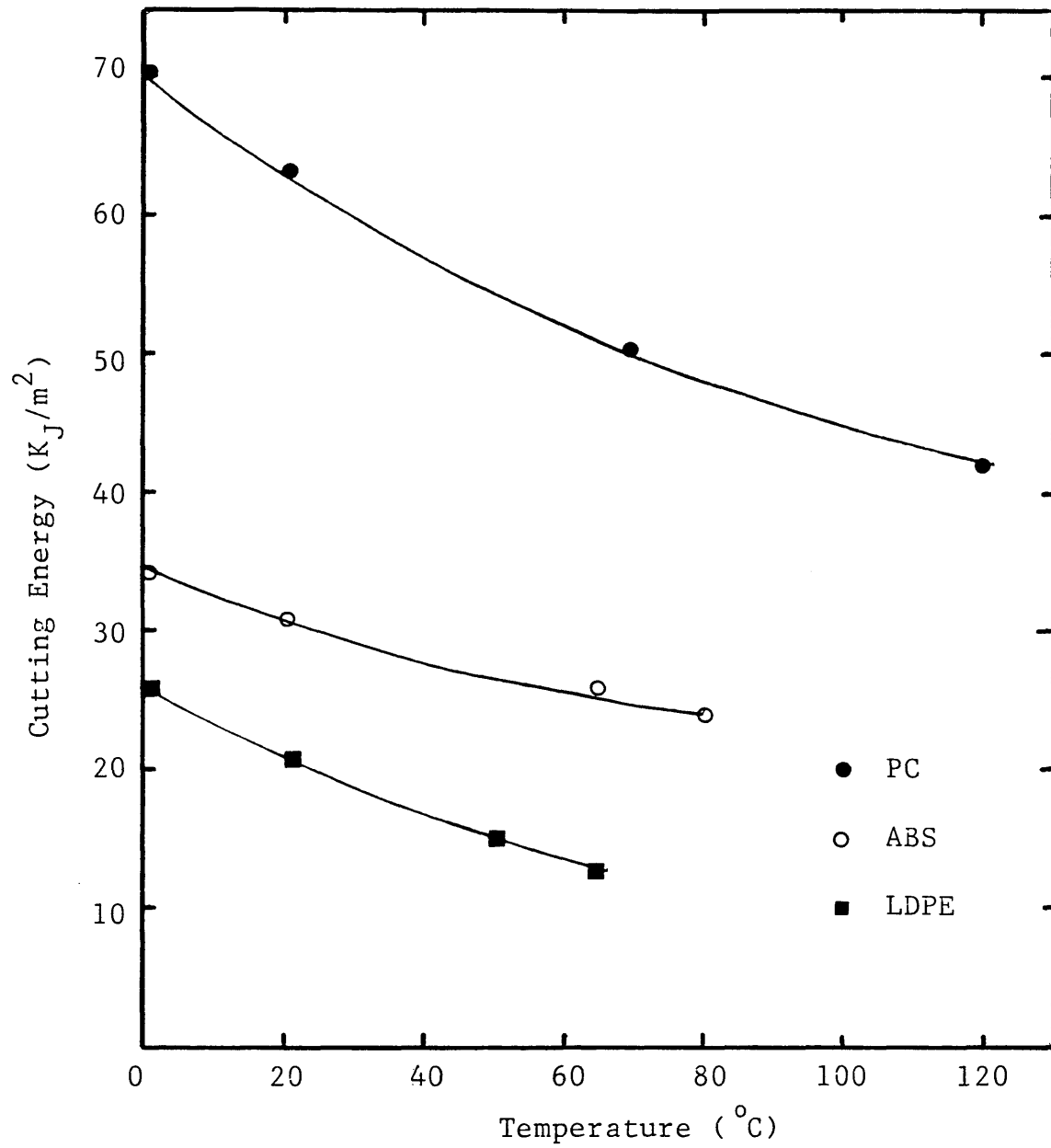


Fig. 9.6: Cutting Energy versus Temperature for Tests with Rotating Blade Tip Radius $60\text{ }\mu$ and 15 m/sec Cutting Speed.

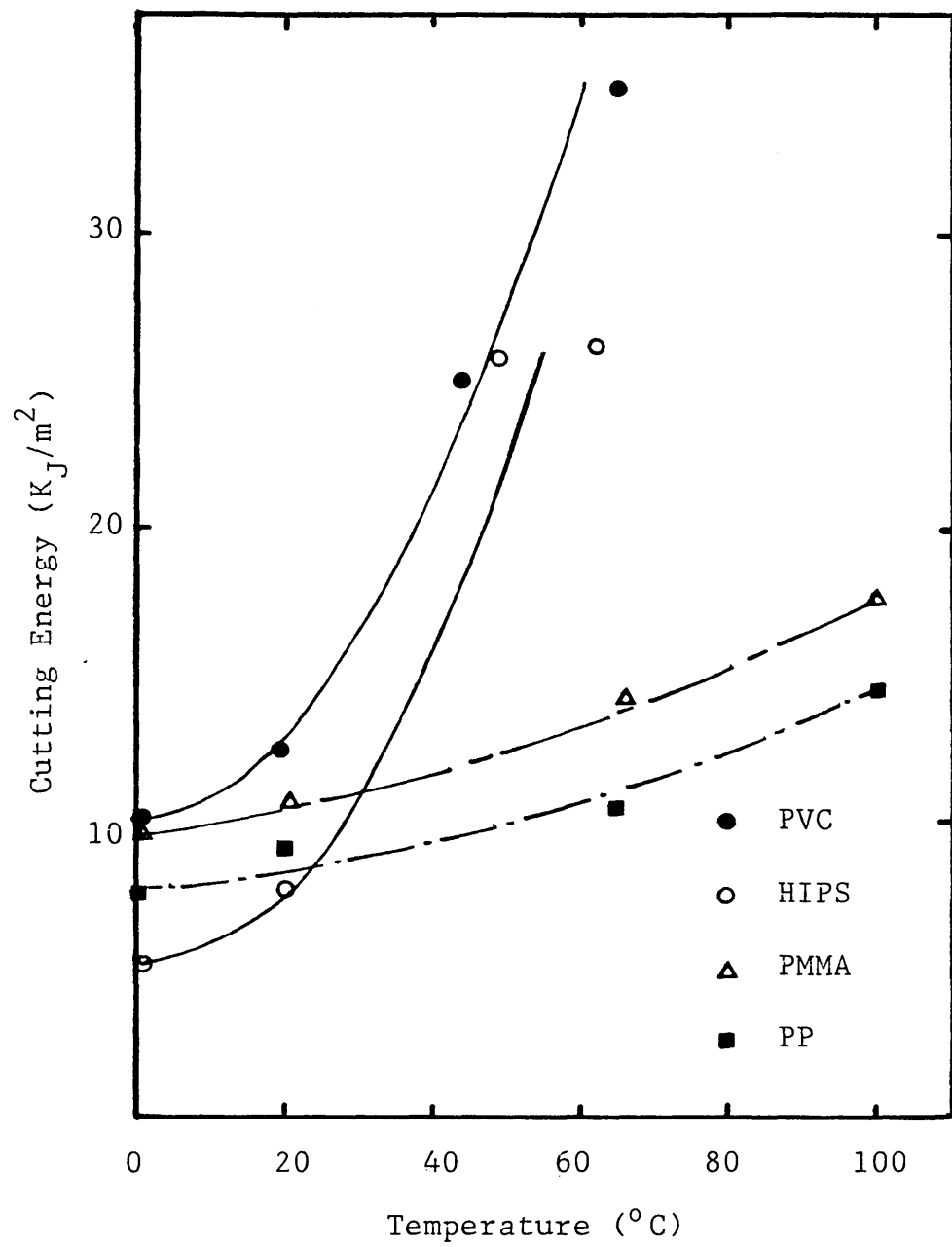


Fig. 9.6 (Continued):

although PP showed a peak in its cutting energy at room temperature (Fig. 5.4), there is a rise in that energy with an increase in test temperature (Fig. 6.5). However, for PP and the other materials whose cutting energies did not show peaks there is a possibility of reduction in the energy if the temperature is increased beyond the test range.

It should be emphasised that this curve (Fig. 9.6) is not directly applicable to the results on the effect of speed as it is not known what the local temperature is at the blade tip, even at the lowest cutting speeds.

The depth to which the blade indents the specimen was found to be independent of cutting speed for a given polymer (Section 8.5.1 - Figs. 8.5 and 8.6). This may be explained in terms of crack opening displacement (COD) fracture mechanics analysis. If it is assumed that at a certain stage during the cutting process a crack runs unstably ahead of the blade, and the strain energy release rate exceeds a critical value (usually denoted by G_c) and that the energy release rate is of the usual form, then

$$G_c = \pi \sigma_c^2 a/E$$

where, σ_c = a critical stress on the crack plane

a = critical crack length at instability

E = Young's modulus

In the case where the driving force is the blade, then

$$\sigma_c \propto \Delta E$$

where, Δ = a displacement associated with the blade geometry. Also, G_c can be written as:

$$G_c = \sigma_y \delta$$

where, σ_y = yield stress

δ = COD

then the crack will run for:

$$a = \bar{c} \delta (\sigma_y/E) / \Delta^2 = c \delta e_y / \Delta^2$$

where, $\bar{c}$ = a constant also e_y is independent of rate and temperature (97). It is assumed that the crack runs at a given speed due to the elastic energy in the system, i.e. the crack speed is constant irrespective of cutting speed. Therefore, the appropriate COD is the running crack COD which is constant and this leads to the result of a constant critical crack length for a given specimen and material. Consequently, the depth for which the blade indents the specimen before the crack runs is independent of blade speed.

The effect of friction between the blade edge and the polymer on energy required to cut was examined by lubricating the blade edge with an anti-friction oil (Moly-Slip). Test results showed that there was no change in cutting energy when the lubricated blade was used throughout the speed range tested. It is therefore suggested that frictional effects at high cutting speed are unimportant due to the fact that loading times are very short (Table 9.1).

CHAPTER 10

CONCLUSIONS AND RECOMMENDATIONS

A number of conclusions can be drawn from this study. Firstly, the conditions for low cutting energy are the same as for low noise emission for all materials. These conditions are: low blade speed, minimum clearance, maximum blade sharpness, and minimum rotating blade angle of attack. This is in contrast to findings by Kobayashi and Saito (73) in machining of plastics. Kobayashi and Saito observed that low cutting forces are obtained under different blade conditions for the various materials tested.

Secondly, the process of cutting at high blade speed is not a shear process, but it represents a fracture process (i.e. notching followed by a wedging action which leads to an unstable crack propagating through the specimen - Section 9 - Fig. 9.1). The above views are confirmed by the following observations: that fixed blade conditions are unimportant (Section 5.2.4) and at high cutting speed, the fixed blade can be removed without effect. Also, clearance effects were minor (Figs. 5.10 - 5.23), implying that shear is not an important mechanism. On the other hand, the observed rotating blade sharpness was found to be significant,

which is to be expected in fracture type situation (Figs. 5.10 - 5.23).

Thirdly, blade speed (test rate), plays a dominant role in cutting of polymers. The energy required to cut is strongly dependent on blade speed. Some polymers tested (PMMA, HIPS and PVC) showed a continuous increase in absorbed energy (Fig. 5.46) throughout the speed range, whereas others (LDPE, PP, ABS and PC) showed a clear peak (Fig. 5.46).

The explanation for the strong dependence of energies on speed for the materials which showed a clear peak (PC, ABS, PP and LDPE) can be outlined as follows: at low speed the energy dissipated in the plastic zone (ahead of the blade tip) is retained locally, and gives a moderate rise in temperature. This, in turn, results in a small drop in the yield stress, and a higher increase in the fracture strain (Section 9 - Fig. 9.3) and a consequent increase in the absorbed energy (Section 9 - Equation 12). A dramatic rise in temperature occurs as the speed is increased, (due to shorter loading times and higher levels

of energy dissipation) causing the energy to be elevated to a maximum. By further increase in the speed of the blade, a state could be reached in which the plastic zone around the blade tip has become soft and molten, this would result in a rapid fall in the yield stress (Section 9 - Fig. 9.3) also a fast drop in the cutting energy at that particular speed. The polymer which requires the highest level of energy to cut, will demonstrate a peak earlier than the others (Fig. 5.46), due to the sharp rise in temperature which in turn will effect the material fracture properties (yield stress and fracture strain - Section 9).

The other materials (PVC, HIPS and PMMA) whose cutting energies did not drop with further increases in the blade speed, required low levels of energies (Fig. 5.46), therefore low levels of heat would be generated, and dissipated adiabatically causing no dramatic drop in the yield stress value. The absence of actual peak on the cutting energy for those materials (Fig. 5.46) does not preclude the possibility of a peak occurring at some higher speed beyond the range tested (i.e. shorter loading times). This view is supported by the fact that at higher blade speed for those materials, between 25 and 40 m/sec there is in each case evidence of levelling off in cutting energy, with increased speed as shown in Fig. 5.46.

The elevated toughness observed in varied rate impact testing (86 and 87) has been demonstrated to be due to thermal effects (adiabatic local heating). In view of the similarity with notched impact behaviour, it is believed that the same mechanism (adiabatic local heating) is operating here as well, giving the sharp rise (and drop) in cutting energies.

This view is supported by two observations: firstly the detection of what appear to be heated zones (Section 8.5.2) on the cut surfaces. At low blade speed, the surfaces appear to be soft and stretched (like the consistency of a soft material being pulled apart), whilst at higher speeds, a smooth, smeared film is evident on both, the cut surface and also on the blade surface. The appearance of those heated surfaces and the existence of a thin film of the molten material on the blade surface, suggests that the polymer has been subjected to intense local heating. Secondly, the cutting energy showed reasonable proportionality with the length of the heated zone (Fig. 9.5).

In varied rate impact testing (86, 87) a critical loading time has been calculated below which the zone at the crack tip is regarded as being adiabatic, the material in this region reaching a softening temperature and a rapid transition to higher value of fracture toughness occurs. In the present study, measured loading times (Table 9.1) were found to be

much smaller than the critical loading times (Equation 9.14). This fact, tends to confirm the view that adiabatic local heating mechanism is the mechanism which governs the cutting process.

Therefore, in view of the above observations and evidence, it is believed that the most likely explanation for the absorbed energy being strongly dependent on speed, is concerned with thermal effects.

The effect of test temperature on cutting energy was interesting and confirms the conclusion that thermal effects are significant in the cutting process.

It is of interest to mention that the increase in test temperature gave a reduction in the cutting energies for the materials (LDPE, PC and ABS) which showed peaks in their energies (Fig. 5.46) and caused a rise in the energies of the other materials (PVC, HIPS and PMMA) whose energies showed a continuous increase with speed (Section 6 - Fig. 9.6).

Finally, from the results of the experimental programme undertaken, it is felt that the cutting mechanism for polymers in the granulators is better understood. Also, for a quieter granulator which is economical to run and inexpensive to buy, the following recommendations are reached:

- low cutting speed.
- the blades must be very sharp and frequent sharpening is essential.
- rotating blade angle of attack must be kept to a minimum.
- minimizing the amount of material thrown from the granulator chamber against the hopper walls, by providing the hopper with flaps made of rubber (Section 7.2.4).
- lining the internal surfaces of the hopper and the chamber with resistant material i.e. rubber to absorb any sort of impact of material against these surfaces.
- stiffening the screen and providing it with external damping and good fixation, with the machine frame to reduce vibrations and noise emission.

CHAPTER 11

APPENDICES

11.1 CALCULATIONS

11.1.1 Design of the Rotating System

11.1.1.1 Cross Sectional area of the arm

Fracture energies of tough polymers such as ABS could reach a level of 25 KJ/m^2 (99). For a specimen with a cross sectional area equal to 30 mm^2 , the energy absorbed in fracture would be 0.75 J. For the purposes of design, the maximum impact energy supportable by the arm would be taken as this energy of fracture multiplied by a factor of ten (i.e. 7.5 J). Therefore to obtain a sufficiently stiff arm, the maximum impact energy must be equal to the maximum strain energy of the arm. (P. 222 Elements of Strength of Materials, S. Timoshenko, 1977 (100)).

The strain energy (H) of a cantilever beam subjected to an impact energy load is given (100) as:

$$H = \frac{1}{9} (A \cdot \bar{L}) \frac{\sigma_{\max}^2}{2E}$$

where

A = cross sectional area of the cantilever beam

$\bar{L}$ = length of the cantilever beam

$\sigma_{\max}$ = maximum yield stress

E = modulus of elasticity

For steel (30B)

$$E = 186 \times 10^9 \text{ N/m}^2$$

$$\sigma_{\text{max}} = 2200 \times 10^6 \text{ N/m}^2$$

So that with an arm length of 0.3 m and impact energy of 7.5 J, the cross sectional area was calculated to be $17 \times 10^{-6} \text{ m}^2$. The actual cross sectional area of the arm was chosen to be $25 \times 10^{-6} \text{ m}^2$.

11.1.1.2 Total Elongation of the Arm and the Corresponding Maximum Tensile Stress due to the Centrifugal Tension

To calculate the total elongation of the arm it was assumed that the arm is a homogeneous slender prismatic bar (the blade holder and the blade itself were considered as a part of the arm). Total elongation is given (p. 11, Strength of Materials, R. Stephens, 1970 (101))

as:

$$\delta = \frac{\rho \omega^2 \bar{L}^3}{3E}$$

and the maximum tensile stress as:

$$\bar{\sigma} = \frac{\rho w^2 \bar{L}^3}{2}$$

where

$\bar{\sigma}$ = density of the material of the arm

w = angular velocity

$\bar{L}$ = length of the arm

E = modulus of elasticity

taking

$$\rho = 8.05 \times 10^3 \text{ Kg/m}^2$$

$$w = 2500 \text{ r.p.m.}$$

$$\bar{L} = 0.3 \text{ m}$$

$$\text{and } E = 186 \times 10^9 \text{ N/m}^2$$

Total elongation was calculated to be $0.003 \times 10^{-3} \text{ m}$ and the corresponding maximum tensile stress acting on the arm was calculated as $144 \times 10^5 \text{ N/m}^2$. These figures were considered to be acceptable.

11.1.1.3 Design of the Arm Spindle

It was considered that the arm spindle would be subjected to a torsional impact load of 7.5 J which must not exceed the maximum strain energy of shear (S) in the arm spindle. The maximum strain energy of shear is given (p. 83, Elements of Strength of Materials, S. Timoshenko, 1977 (100)) as:

$$S = \frac{1}{2} (\pi r^2 l) \frac{\tau_{\max}^2}{2G}$$

where

r = radius of the spindle

l = length of the spindle

$\tau_{\max}$ = maximum shear stress = $\frac{1}{2} \bar{\sigma}_{\max}$

$\bar{\sigma}_{\max}$ = maximum tensile stress

G = shear modulus = $\frac{E}{2(1 + \nu)}$

(Mechanical Metallurgy, p. 51, G. Dieter (102))

E = modulus of elasticity

ν = Poisson's ratio

taking

l = 0.2 m

$\sigma_{\max} = 2.2 \times 10^9 \text{ N/m}^2$

$E = 186 \times 10^9 \text{ N/m}^2$

and $\nu = 0.33$

the radius was calculated to be 1.6×10^{-3} m. The radius of the spindle was chosen to be 3.2×10^{-3} m, to include a safety factor of 2 over and above the impact energy assumptions.

11.1.2 Aerodynamics of the Rotating System

11.1.2.1 Introduction

To reduce the effects of aerodynamic forces on the rotating system, it was necessary to design the different parts of the rotating system to have aerodynamic shapes. (Drawings Nos. 1 and 2). Such a design would minimize the power required to drive the rotating system and also result in a smoother and quieter operation.

The rotating system consists of the following components, as shown schematically in Fig. 11.1.

- a arm and blade holder
- b rotating blade
- c counter balance weight carrier
- d counter balance weight
- d vane

The cross sectional geometry of the blade holder and the arm were designed to be aerofoils with the specifications shown in Table 11.1. The counter weight balance was machined to have an aerodynamic shape and was made in cylindrical form, as shown in Drawing No. 1.

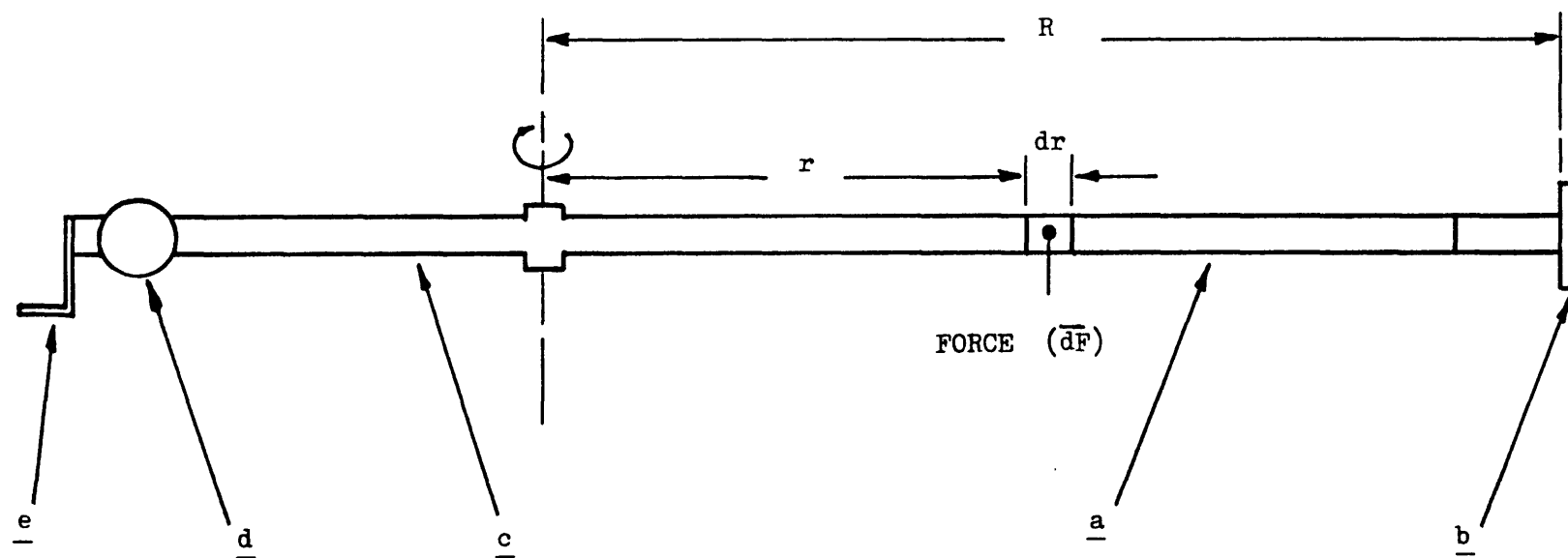


Fig. 11.1: Schematic Diagram of the Rotating Arm.

Leading Edge Diameter (mm)	3.17
Trailing Edge Thickness (mm)	2.5
Chord Length (mm)	6.35
Span (mm)	280
Angle of Attack (degrees)	0
Aspect Ratio (Span/Chord Length)	44

Table 11.1: Specifications of Cross Sectional Geometry of the Blade Holder and the Arm.

11.1.2.2 Estimation of Aerodynamic Drag
Force and the Power Required to
Overcome this Force

The total drag force of the rotating system was calculated by summing the drag forces of the component parts. Drag force is given (p. 49, Fundamentals of Aircraft Flight, F. Teichmann (82)) as:

$$\bar{F} = D A \left(\frac{1}{2} \rho \bar{U}^2 \right)$$

where

D = drag coefficient

A = projected plane area of the wing (chord x span)

ρ = air density

$\bar{U}$ = relative air velocity

For component a (Fig. 11.1), by taking a small element dr at a distance r from the axis of rotation, the drag force acting on this element would be:

$$d\bar{F} = D (t dr) \left(\frac{1}{2} \rho w^2 r^2 \right)$$

The power (dp) required to overcome this force would be:

$$dP = d\bar{F} w r$$

and the total drag force ($\bar{F}$) acting on component a is obtained by integration such that ,

$$\overline{F} = \int_{r=0}^{r=R} dF = D \ t \ \rho \ w^2 \ R^3/6$$

so that the total power (P) required to overcome this force would be:

$$P = \int_{r=0}^{r=R} \overline{dF} \ w \ r = D \ t \ \rho \ w^2 \ \frac{R^4}{8}$$

where

D = drag coefficient of component a

t = chord length

$\overline{\rho}$ = density of air

w = rotational speed

R = span of component a

By taking D = 0.12 (p. 89, Airplane Aerodynamics,
D. Domasch, 1957 (103))

t = 0.008 m,

$\overline{\rho}$ = 1.22 Kg/m³

w = 200 rad/sec

R = 0.3 m

the drag force of element a was calculated to be
0.16 Newtons and the power required to overcome this
force was calculated to be 7 Watts.

The drag forces of the other components of the rotating system were calculated in a similar way by using the appropriate drag coefficients. The total drag force of the rotating system and the power required to overcome it were calculated to be 0.4 Newtons and 19 Watts respectively. This power was taken into consideration when the testing machine motor was selected. Fig. 11.2 shows the different components of the forces acting on the arm.

11.2 DETERMINATION OF THE MASS MOMENT OF INERTIA OF THE ROTATING SYSTEM

Moment of inertia of a body can be determined either by calculation or by experiment. Since the moment of inertia of the rotating system of the testing machine was an important factor in the accurate measurements of the kinetic energy of this rotating system, it was found necessary to determine the moment of inertia of the rotating system by both methods. The first method involved calculations based on the mass and the dimension of each component of the rotating system. The mass moment of inertia was calculated to be $13.5 \times 10^{-4} \text{ Kg.m}^2$. To determine the mass moment of inertia by experiment, the counter balance weight of the rotating system was placed in different positions on either side of the position where the rotating system was balanced. For every position,

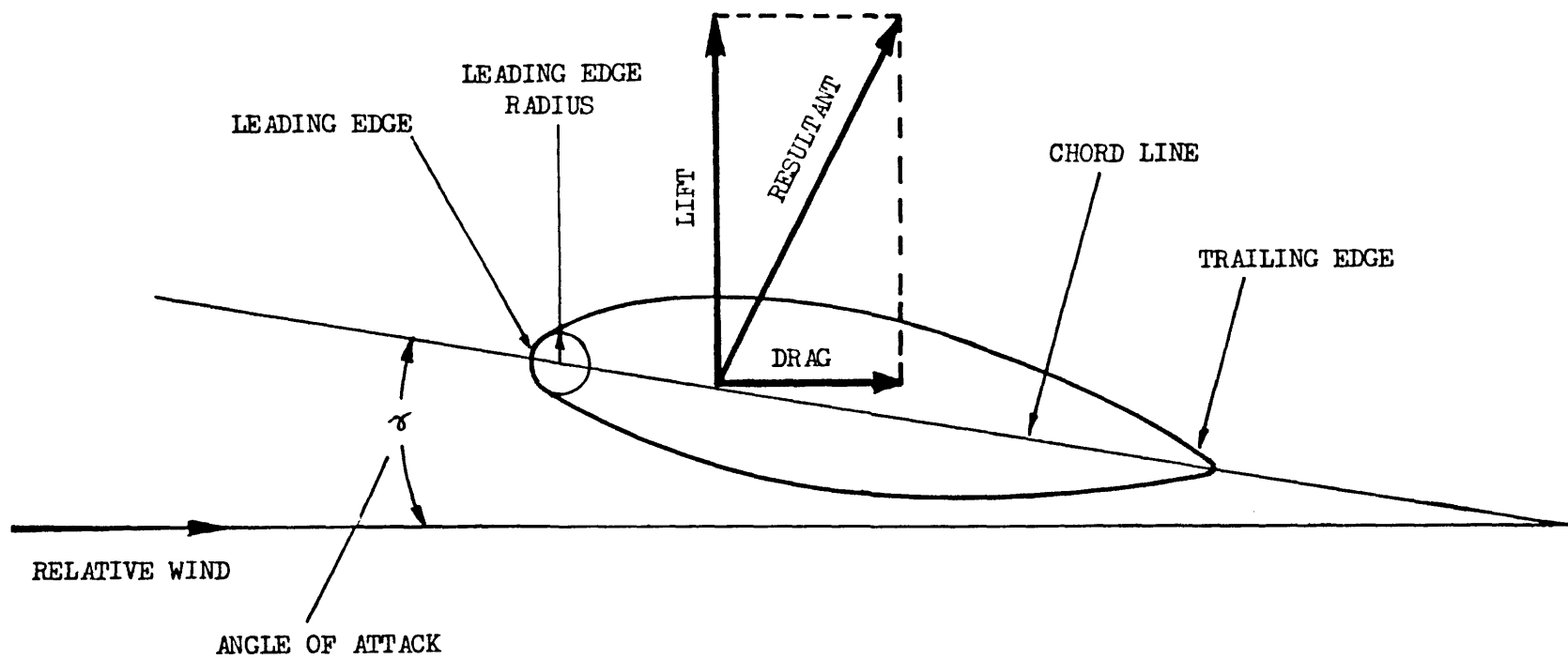


Fig. 11.2: Aerodynamic Forces Acting on the Rotating Arm.

the rotating system was allowed to oscillate as a compound pendulum where the moment of inertia at each position was measured. From these measurements it was possible to determine the moment of inertia of the rotating system at the correct position of the counter balance weight. The moment of inertia was found to be $14.6 \times 10^{-4} \text{ Kg.m}^2$. It was decided to take the mass moment of inertia as an average value of $14 \times 10^{-4} \text{ Kg.m}^2$.

11.3 ELECTROMAGNETIC CLUTCH SURVEY

The electromagnetic clutch was used for repeated connection and disconnection of the arm spindle from the driving power. An ideal clutch should offer the following advantages:

- complete elimination of backlash between its parts.
- no residual torque when mounted vertically (zero drag torque).
- precise and rapid engaging.
- faster release times.
- operation is smooth, quiet and stable.
- no wear.
- compactness.

Different types of electromagnetic clutches are available commercially. After careful considerations, it was decided to use an electromagnetic clutch produced by

Simplatroll Ltd. Specifications and assembly permissible tolerances are shown in Table 11.2. The Simplatroll clutch is shown in Fig. 11.3. It consists of a stator, which carries a coil, a rotor with its friction material and armature with a prestressed spring. The stator has to be concentric with the shaft and to be secured to the machine frame. The rotor transmits its torque to the shaft with a parallel key and keyway. The armature has to be fixed to the drive. In operation, when the voltage supply is switched on, the armature is attracted to the rotor with its friction material and thus transmits the torque. When the voltage is switched off, the prestressed spring pulls the armature back into its original position and the clutch is open.

11.4 DESIGN OF THE TESTING MACHINE CONTROL SYSTEM

11.4.1 Locating the Positioning Sensor

The positioning sensor was placed at 5° from sensor No. 3, as shown in Fig. 4.3. This angular distance allows the system to discriminate between the outputs of the two sensors, this also allowed approximately 15 milliseconds minimum time (the time for approximately one revolution at 4000 r.p.m.) to ensure that the electromagnetic clutch was completely disengaged and the solenoid energized to project the specimen into the path of the arm at the right time before the impact took place.

Torque (N.m)	0.6
Maximum Speed (r.p.m.)	10000
Voltage (Volt)	24
Input Power (Watt)	6
Weight (gm)	97
Inertia of the Armature (Kg.m^2)	1.3×10^{-7}
Gap between Rotor and Armature (mm)	0.15
Permissible Parallel Shaft Misalignment (mm)	0.06
Armature Face Must Run True	

Table 11.2: Specifications of the Electromagnetic Clutch.

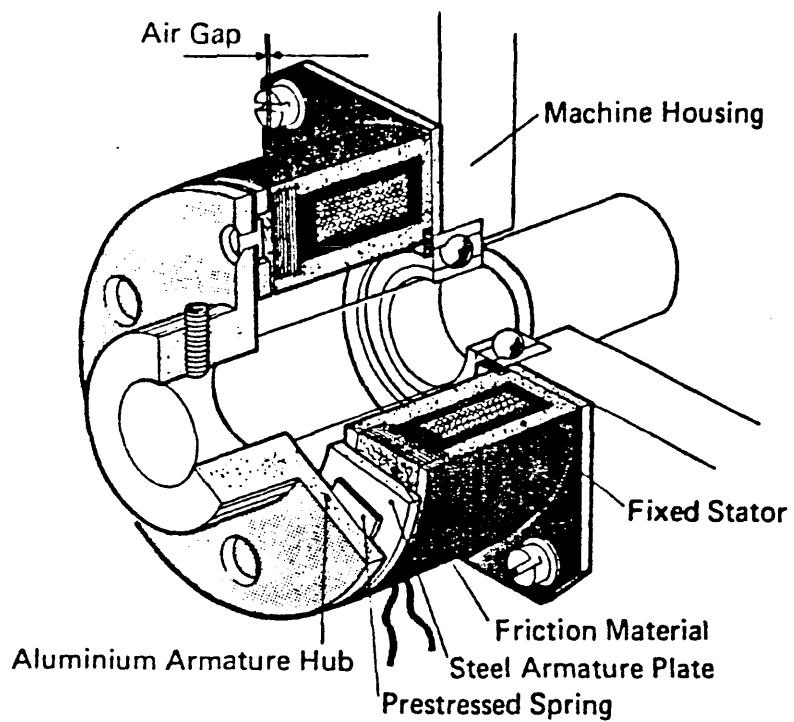


Fig. 11.3: Various Parts of the Electromagnetic Clutch.

The time required to position a specimen into the path of the arm was found to be 28 milliseconds and was measured as follows: a micro switch was supported at a position relevant to the striker level, the micro switch connected to a counter, the signal used to energize the solenoid was used to operate the counter, and when the table carried by the solenoid reached its final position, it switched off the micro switch, consequently setting off the counter, while the time was displayed.

A similar arrangement was carried out to check the time of disengagement of the electromagnetic clutch. This time was found to be 10 milliseconds.

11.4.2 Selection of the Signal Generator

The output of photoelectric sensor No. 2 (the r.p.m. sensor - Fig. 4.3) is a square wave with a frequency equal to the number of segments on the optical disc multiplied by the disc's rotational speed.

Suppose the disc has (M) segments and rotates at (w) r.p.m. thus the number of pulses generated per second F :

$$F = M.w/60$$

Hence for a range of speeds from 100 to 4000 r.p.m. and for a disc having 120 segments:

$$F_{\min} = 120 \times 100/60 = 200 \text{ P/s}$$

$$F_{\max} = 120 \times 4000/60 = 8000 \text{ P/s}$$

The signal generator was chosen to cover this range.

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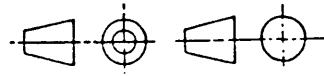
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MACHINE DRAWINGS

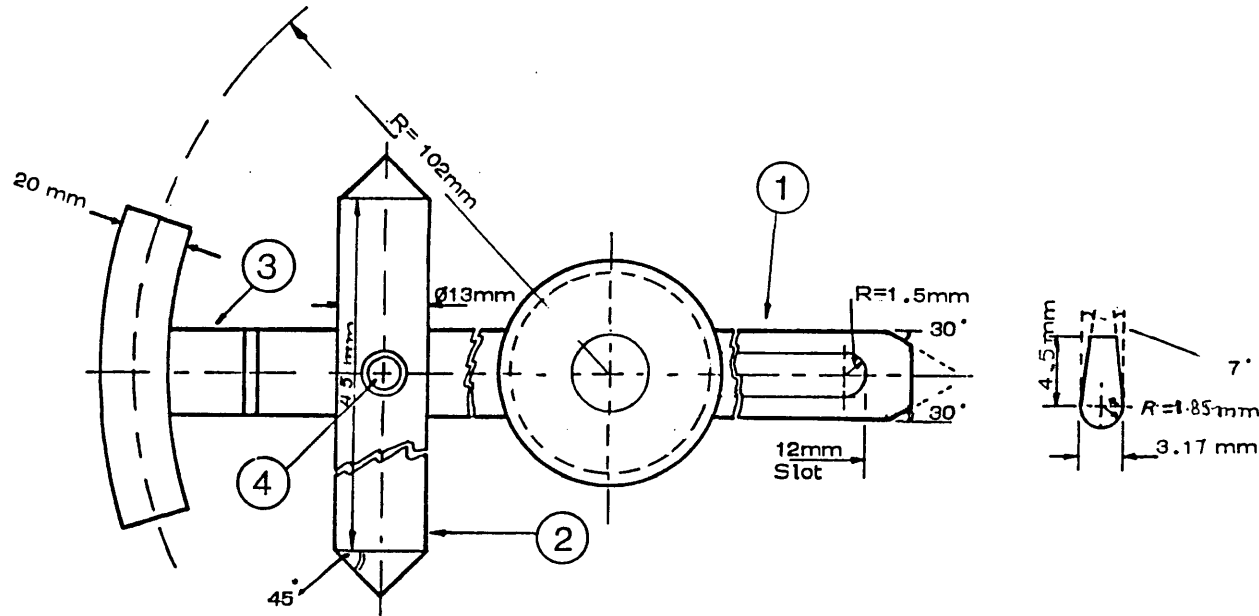
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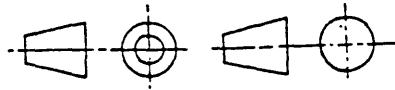
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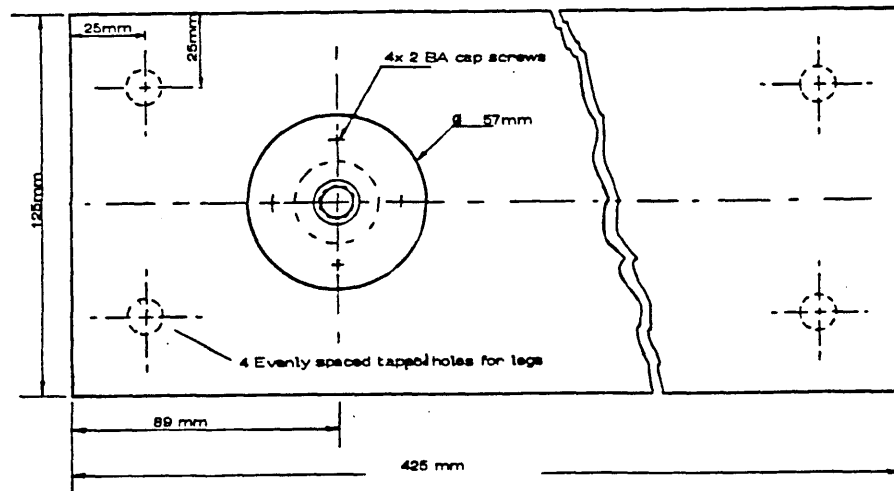
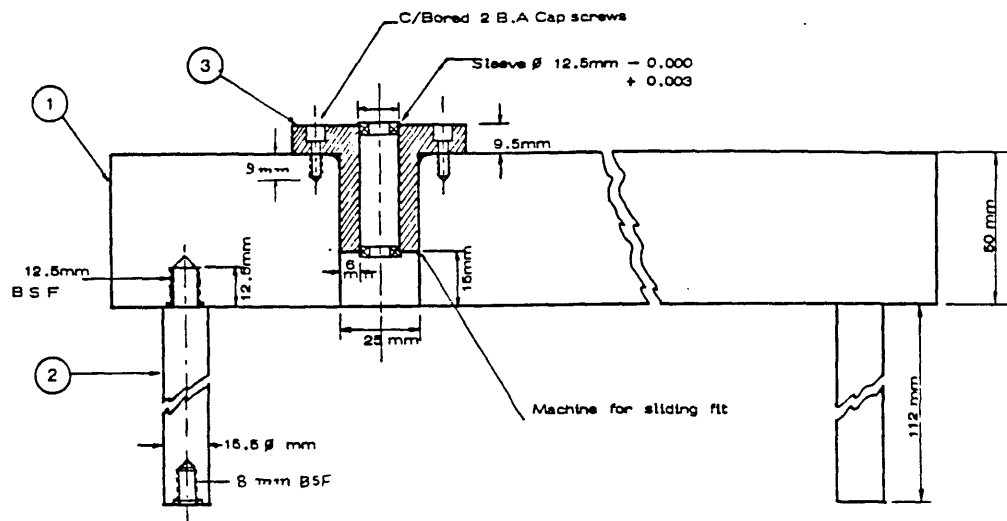
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4	1	GRIP SCREEN	S.EN24	

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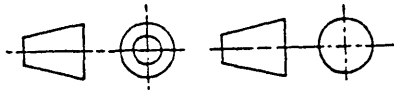


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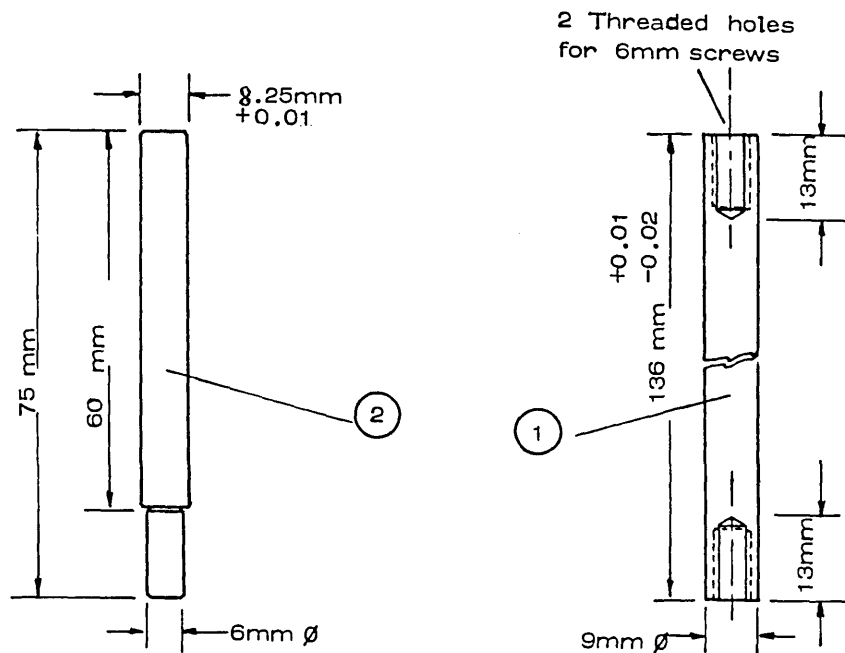


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3	1	BEARINGS HOUSING	S.EN24	

Mechanical Engineering Dept. Imperial College, London SW7 2BX	DRAWN	H-Y. GUNMAN	SCALE	F/S	TITLE	H-S-T n/c	CLASS	DRAWING NUMBER
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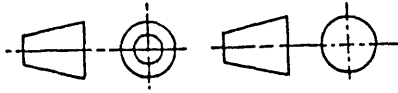
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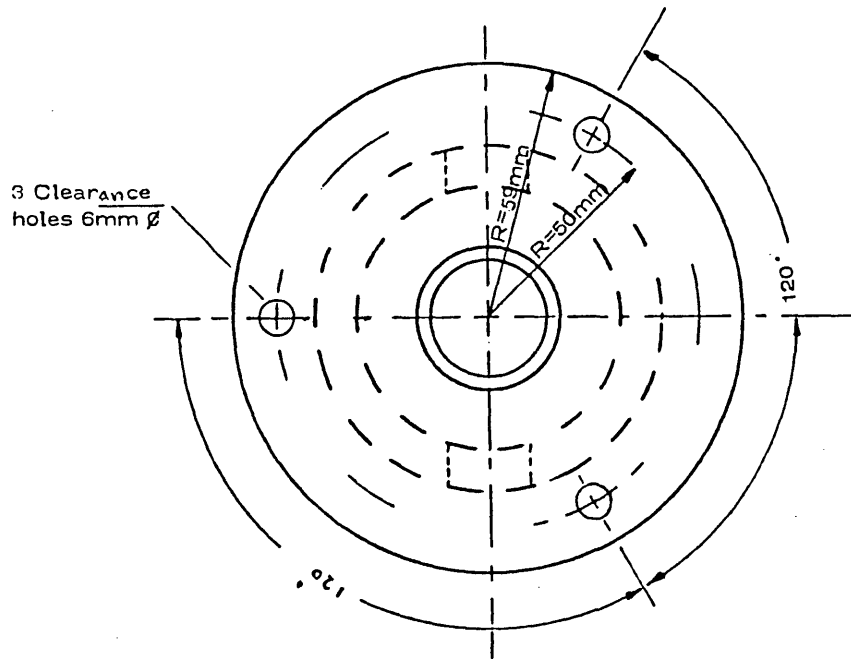
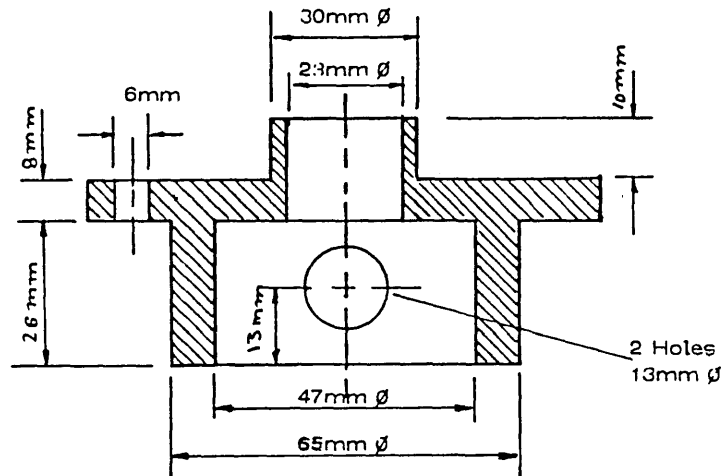
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 Mat. SEN.30B
 No of parts 1

Part No. 1 Dowel
 Mat. Silver Steel
 No of parts 3

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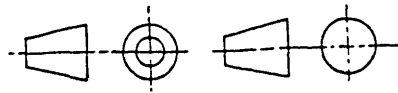


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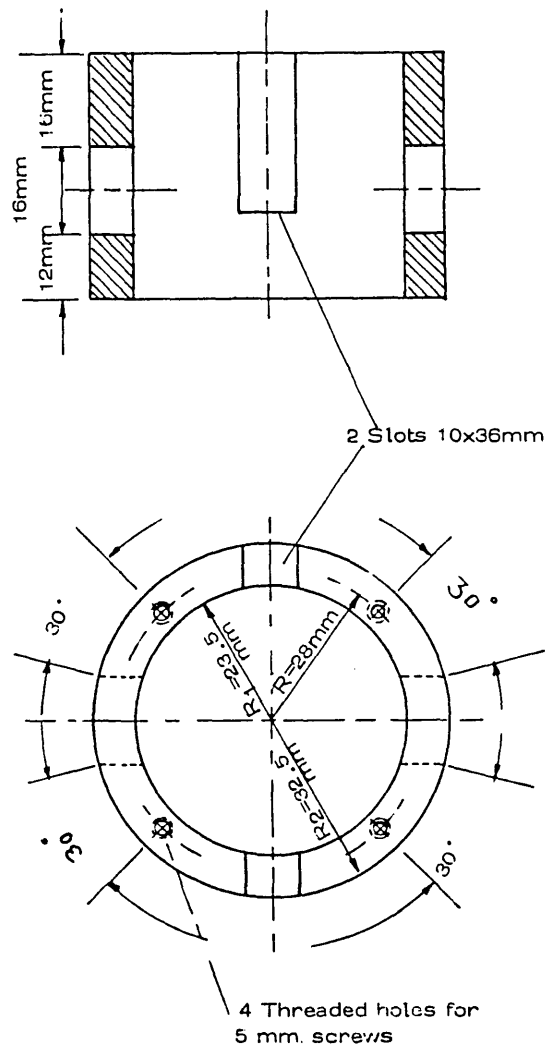


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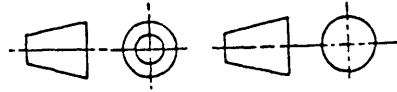


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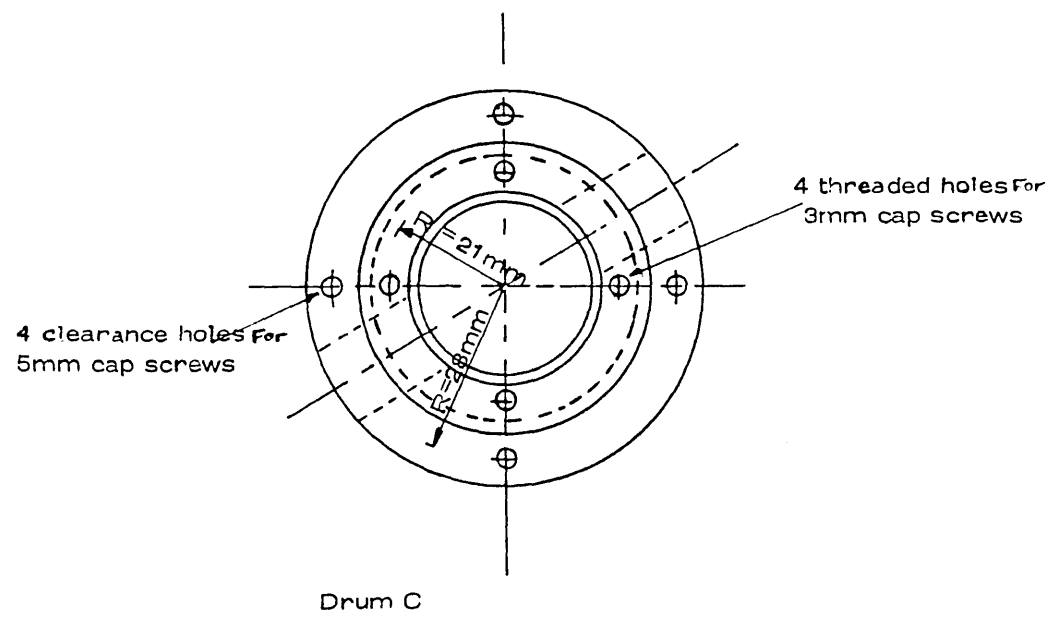
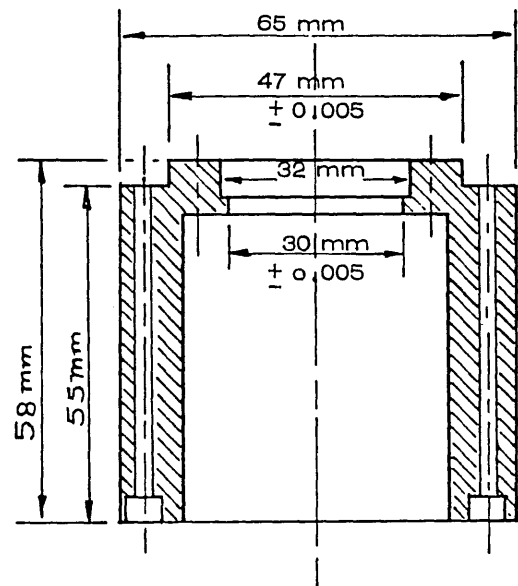


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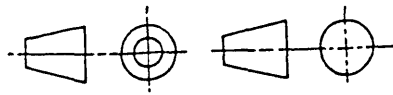
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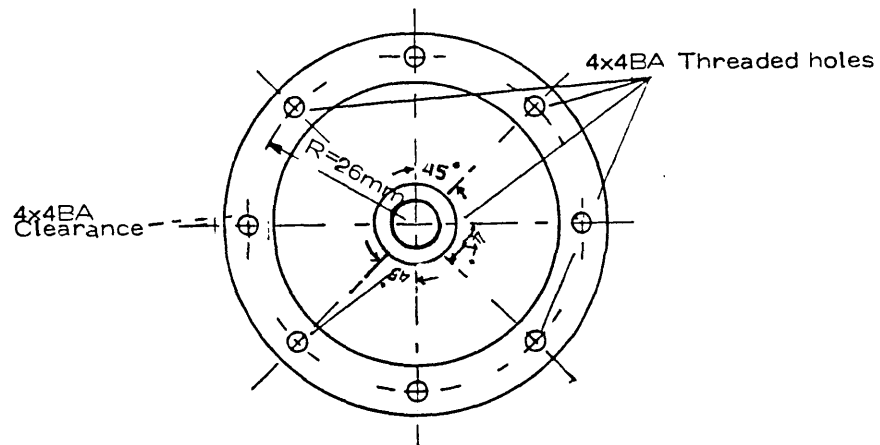
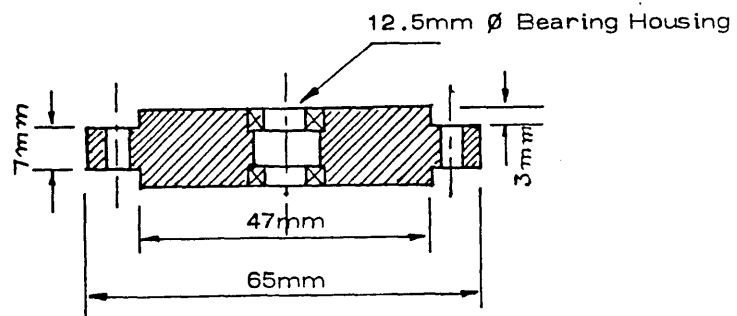
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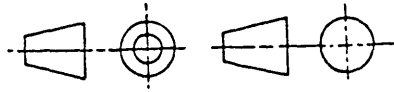


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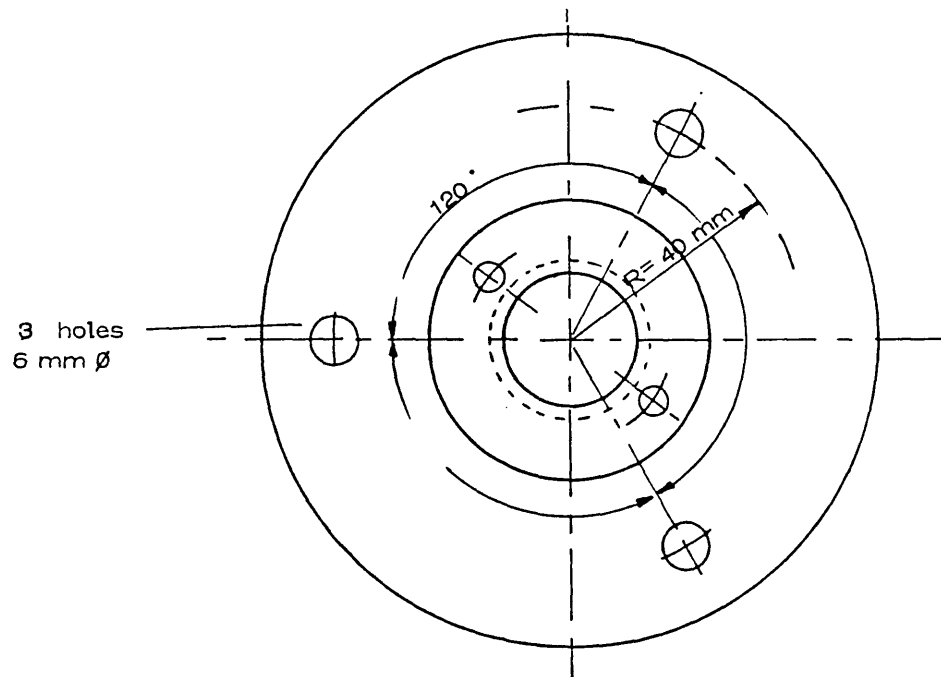
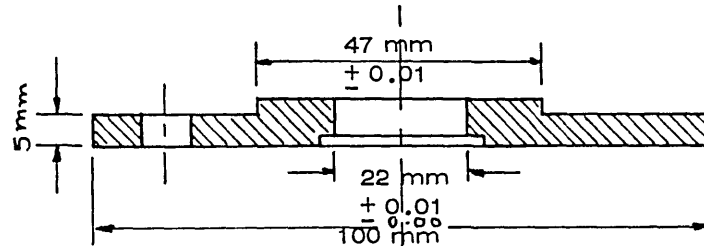


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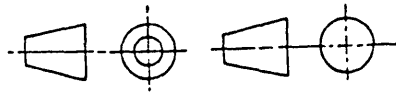


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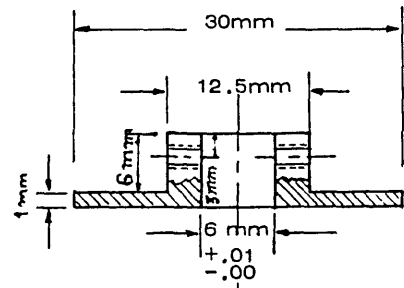


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Mechanical Engineering Dept.				DRAWN		H. YOUNG		SCALE		F/S		TITLE		H-S-T Mic		CLASS		DRAWING NUMBER	
Imperial College,				APPROVED				DATE		2.8/7/82		AMMDS				GROUP		NAME	
London SW7 2BX				CHECKED												A		E.M.H.	

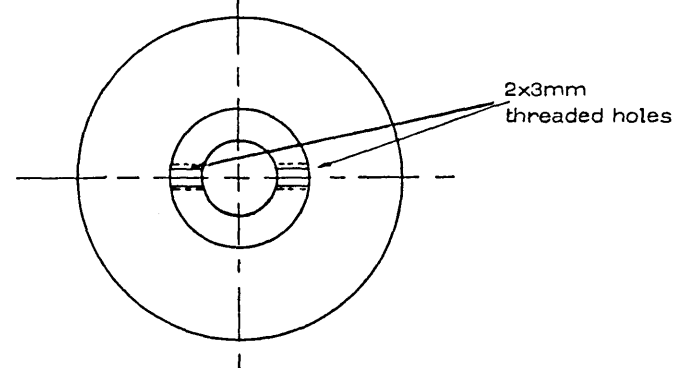


LIMITS ON DIMENSIONS		
DEC	±	0.10"
FRACT	±	$\frac{1}{32}$
DEC MM	±	0.25 MM
UNIT MM	±	1 MM
UNLESS SPECIFIED		

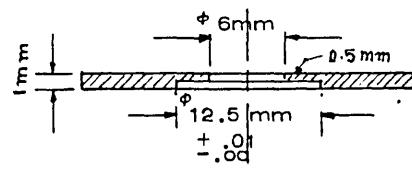


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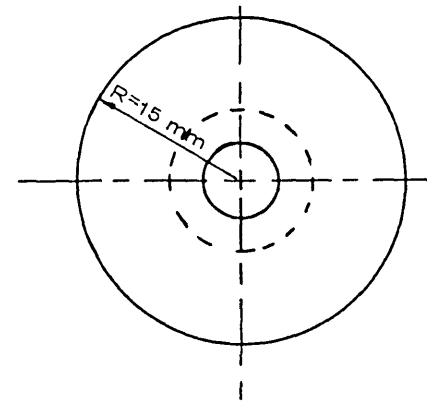
Mat. Al.



- 1 Upper part of holder
- 2 Lower part of holder

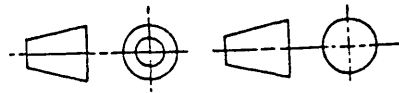


2

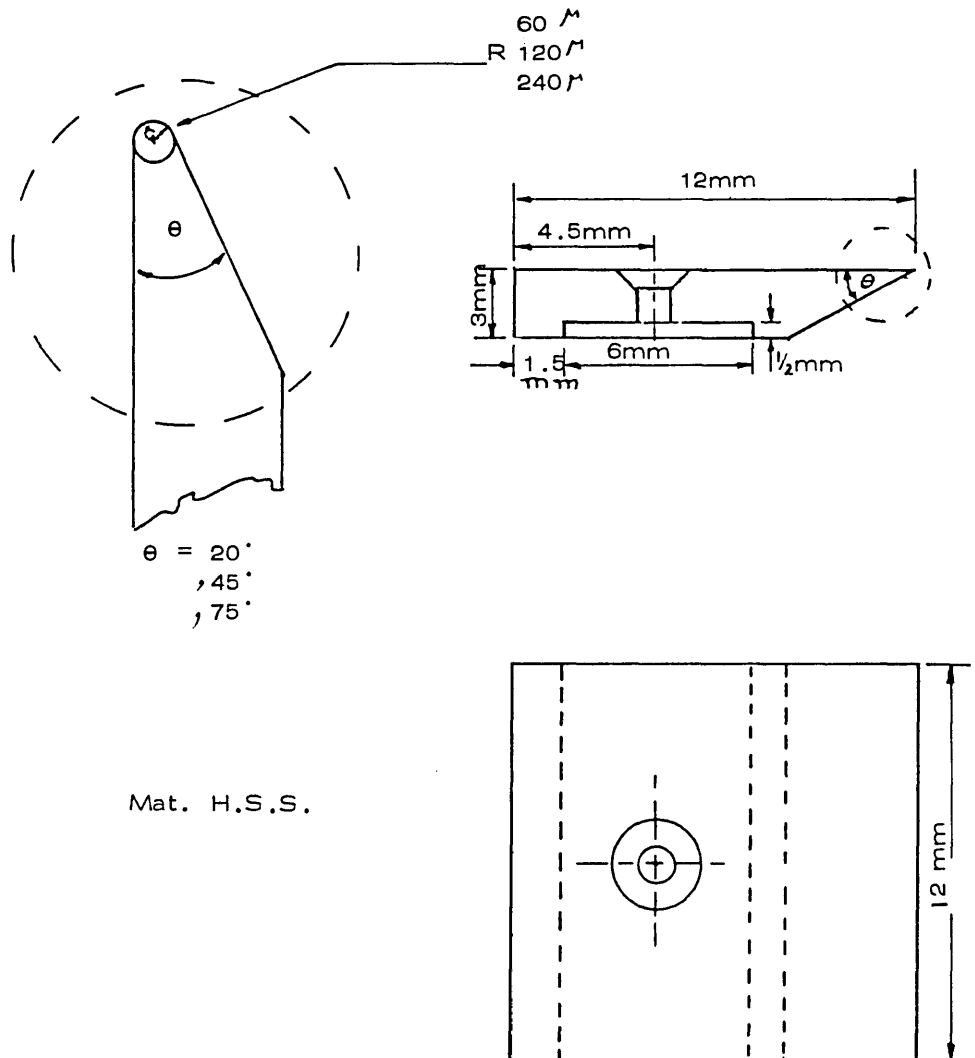


OPTICAL DISC SUPPORTER

Mechanical Engineering Dept. Imperial College, London SW7 2BX	DRAWN	HYMAN	SCALE	TITLE	H-S.T Mic	CLASS	DRAWING NUMBER
	APPROVED		2 F/S				M14 0013
	TRACED		DATE	AMMDTS		GROUP	NAME
	CHECKED		5/8/82			A	EMH



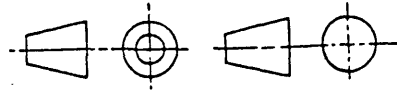
LIMITS ON DIMENSIONS		
DEC	±	0.10"
FRACT	±	$\frac{1}{32}$ "
DEC MM	±	0.25 MM
UNIT MM	±	1 MM
UNLESS SPECIFIED		



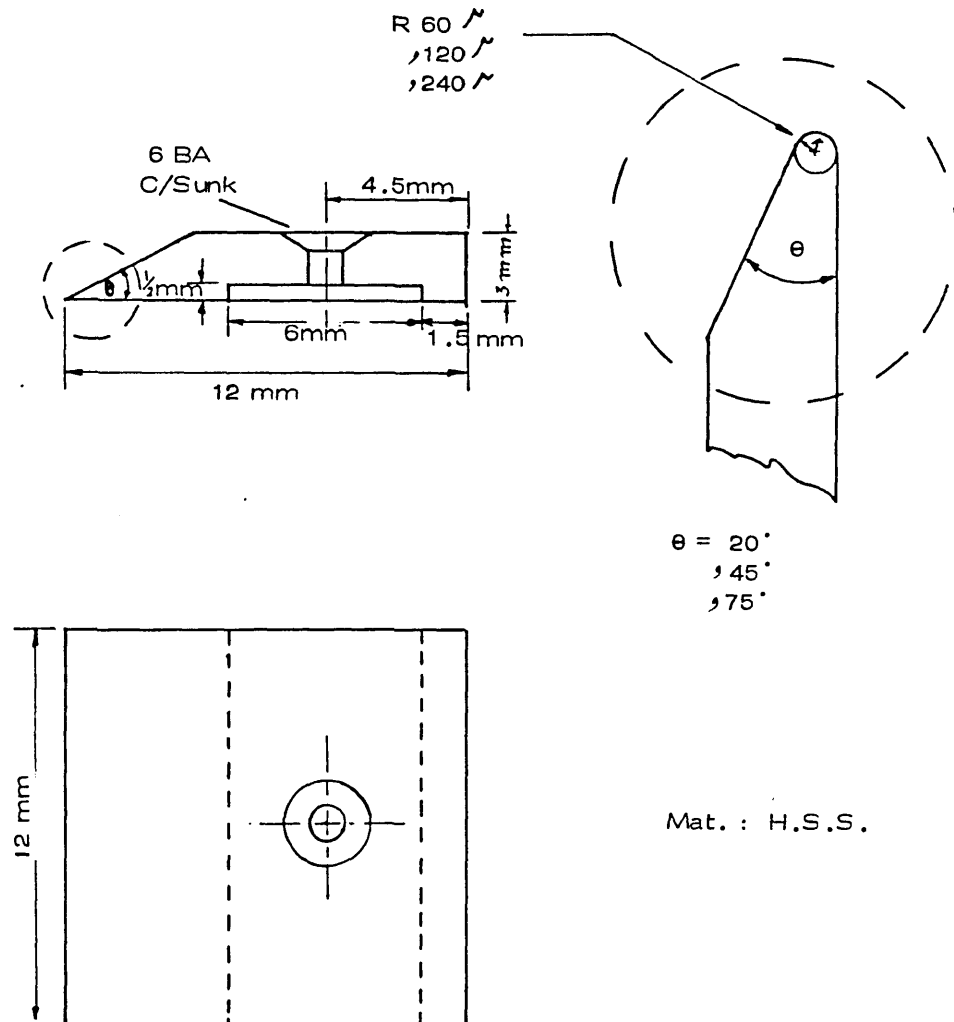
Mat. H.S.S.

Rotating Blade 1

Mechanical Engineering Dept. Imperial College, London SW7 2BX	DRAWN	H. YOUNG	SCALE	TITLE	H.S.T. M/C	CLASS	DRAWING NUMBER
	APPROVED		SE/S				601
	TRACED		DATE	AMMDS		GROUP	NAME
	CHECKED		28/1/82			B	BLADES

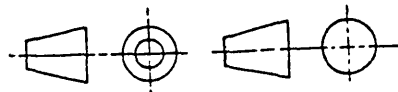


LIMITS ON DIMENSIONS	
~~D/C~~	~~0.00"~~
~~FRACT~~	~~$\frac{1}{32}$"~~
DEC MM	0.25 MM
UNIT MM	1 MM
UNLESS SPECIFIED	

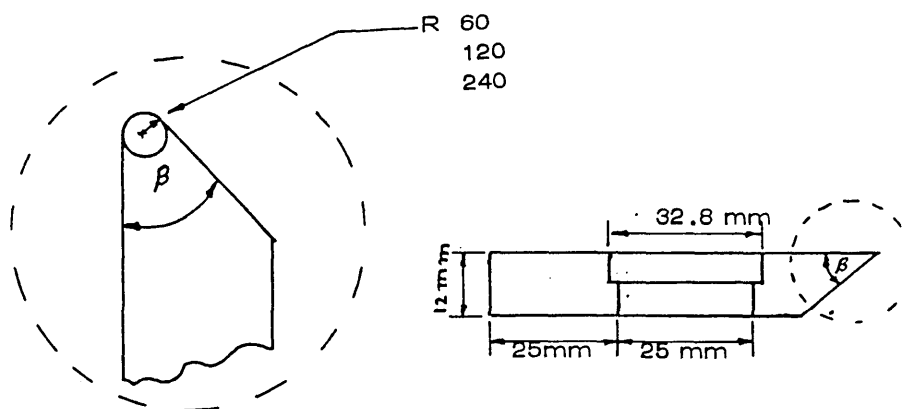


Rotating Blade 2

		6		ROTATING BLADE		H.S.S.	
				DESCRIPTION		MATERIAL	
						REMARKS	
Mechanical Engineering Dept.		DRAWN	H. Young	SCALE	TITLE	CLASS	DRAWING NUMBER
Imperial College,		APPROVED		S.F/S	H.S.T.M/C		Boil
London SW7 2BX		TRACED		DATE	AMMDIS	GROUP	NAME
		CHECKED		3/7/82		IS	BLADE 5

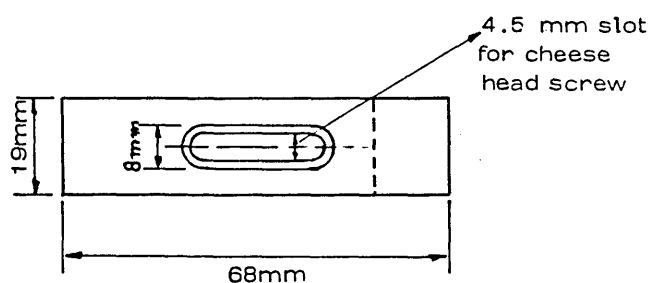


LIMITS ON DIMENSIONS	
~~D/C~~	~~0.00"~~
~~FRACT~~	~~$\frac{1}{32}$"~~
DEC MM	0.25 MM
UNIT MM	1 MM
UNLESS SPECIFIED	

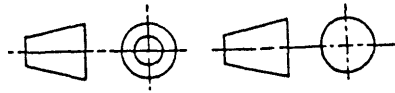


$\beta = 45^\circ$
 $, 70^\circ$

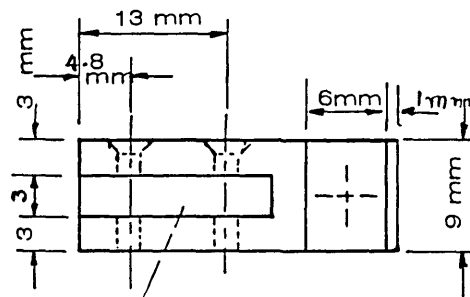
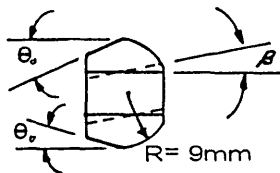
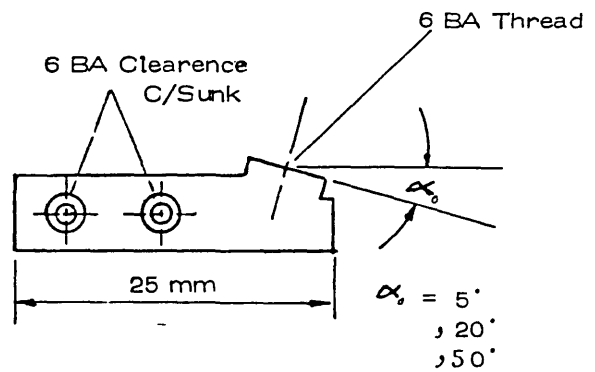
Mat. H.S.S.



					6		FIXED OLAGE		H.S.S			
					PART No		DESCRIPTION		MATERIAL		REMARKS	
Mechanical Engineering Dept.					DRAWN		H. J. T.M.L.C.		CLASS		DRAWING NUMBER	
					APPROVED		SCALE				8 012	
Imperial College,					TRACED		DATE		GROUP		NAME	
London SW7 2BX					CHECKED		5/7/82		D		BLADES	
					AMMDS							



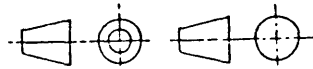
LIMITS ON DIMENSIONS	
DEC	$\pm 0.10"$
FRACT	$\pm \frac{1}{32}$
DEC MM	$\pm 0.25 \text{ mm}$
UNIT MM	$\pm 1 \text{ mm}$
UNLESS SPECIFIED	



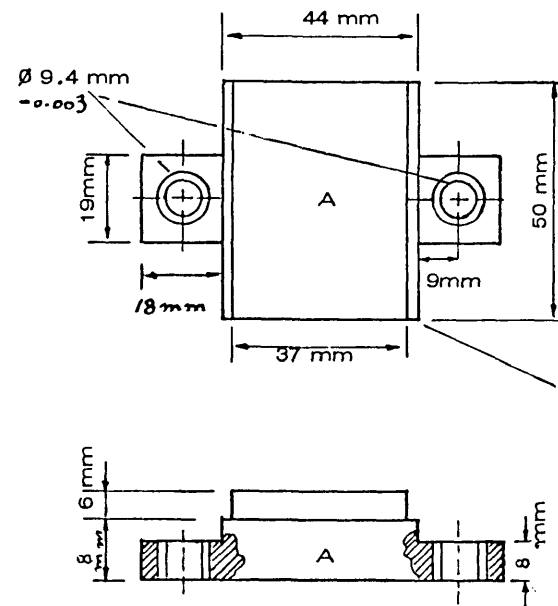
Mat. D.A1

Blade Holder

Mechanical Engineering Dept. Imperial College, London SW7 2BX	DRAWN	H. YOUNG	SCALE	2 F/5	TITLE	H.S.T.M/C	CLASS	DRAWING NUMBER
	APPROVED							BH1
	TRACED						GROUP	NAME
	CHECKED			12/6/82	AMMDIS		H	HOLDERS



LIMITS ON DIMENSIONS	
DEC	± 0.10"
FRACT	± 1/32
DEC MM	± 0.25 MM
UNIT MM	± 1 MM
UNLESS SPECIFIED	



5 Specimen table Mat. D Al

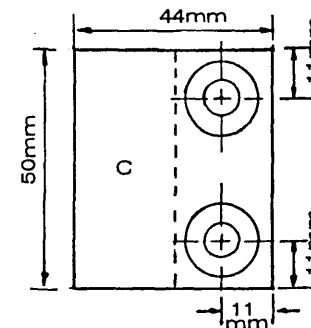
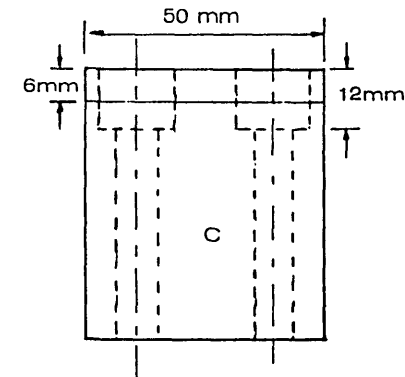
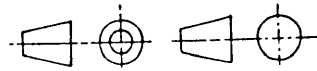


Table travel stop Mat. Mild steel

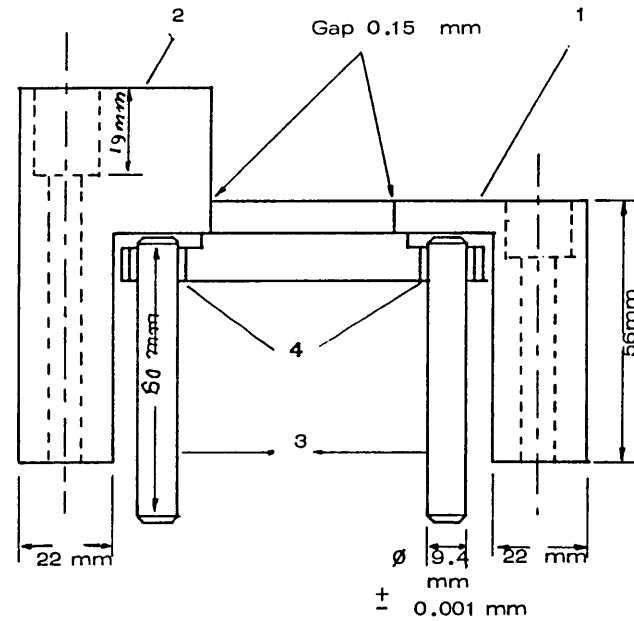
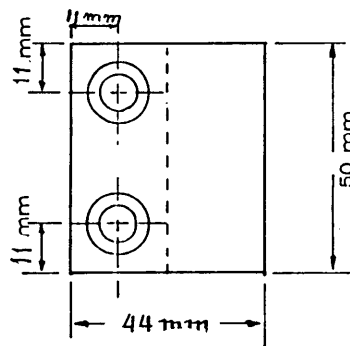
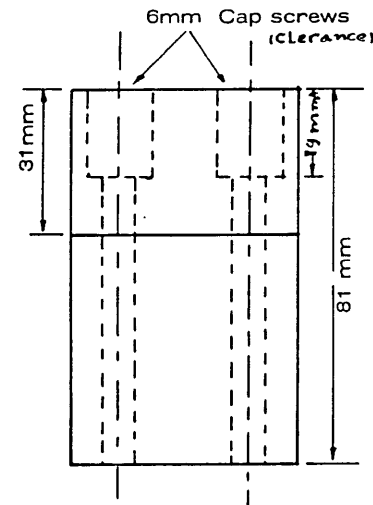
1	5	SPECIMEN TABLE	D-HL.	
PART	No	DESCRIPTION	MATERIAL	REMARKS

Mechanical Engineering Dept.	DRAWN	H-YOUNG	SCALE	TITLE	H-S.T MIC	CLASS	DRAWING NUMBER
Imperial College.	APPROVED		4/11/85				T 5-015
London SW7 2BX	TRACED		DATE	AMMDIS		GROUP	NAME
	CHECKED		3/8/86			M	MIC

DEF 111706-2



LIMITS ON DIMENSIONS	
DEC	± 0.10"
FRACT	± 1/32
DEC MM	± 0.25 MM
UNIT MM	± 1 MM
UNLESS SPECIFIED	

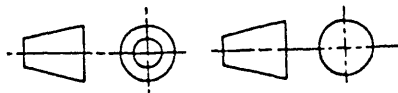


- 1 & 2 Table travel stops Mat. M/Steel
 3 Pins Mat. S/Steel
 4 Sliding bearings

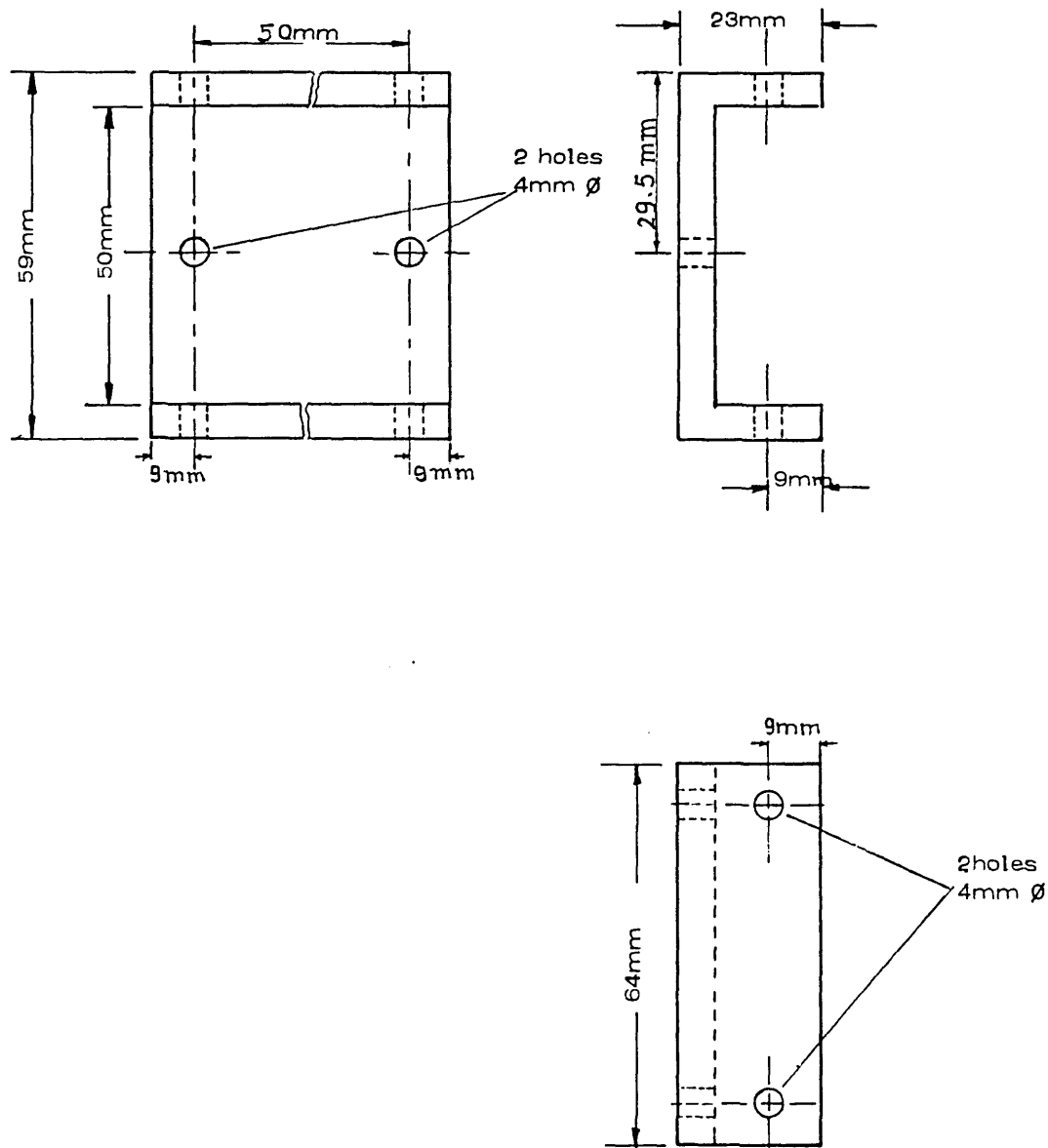
2	3	GUIDE PINS	S.S.T	
1, 1	1/2	TABLE TRAVEL STOP & BLADE HOLDER	M. ST.	
PART No	QTY	DESCRIPTION	MATERIAL	REMARKS

Mechanical Engineering Dept.	DRAWN	H. J. VAN NUN	SCALE	TITLE	H.S.T.M.C	CLASS	DRAWING NUMBER
Imperial College,	APPROVED		1/5				TJ 016
London SW7 2BX	TRACED		DATE	AMMOTS		GROUP	NAME
	CHECKED		16/8/81			M	MIC

REV 111704 B

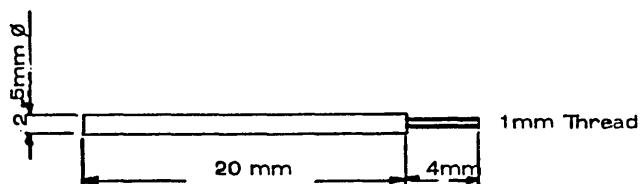
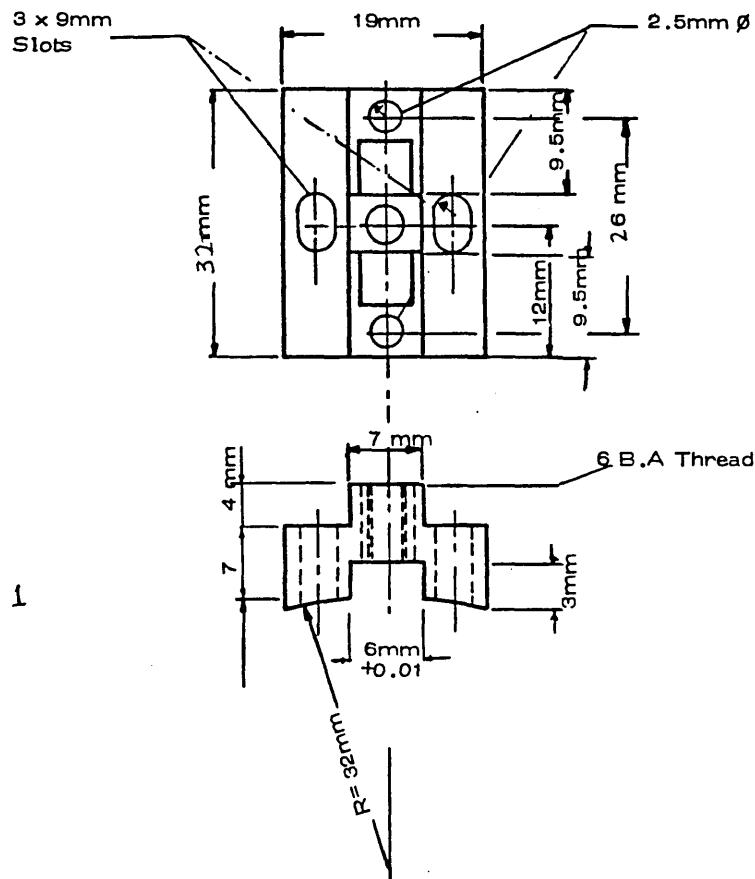
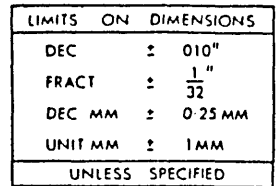


LIMITS ON DIMENSIONS		
DEC	±	0.10"
FRACT	±	$\frac{1}{32}$ "
DEC MM	±	0.25 MM
UNIT MM	±	1 MM
UNLESS SPECIFIED		

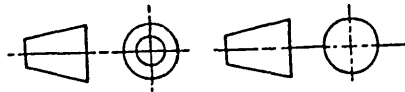


1. SOLENOID HOLDER

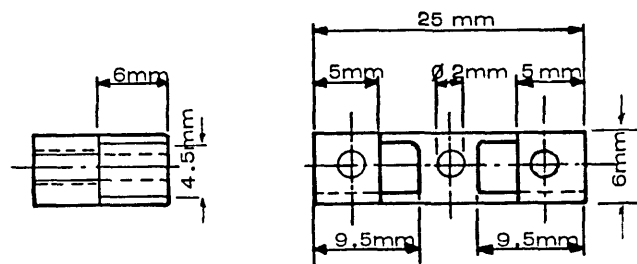
					1		2		SOLENOID HOLDER		H.S.T			
					PART NO.		NO. OF		DESCRIPTION		MATERIAL		REMARKS	
Mechanical Engineering Dept.					DRAWN		H.T. 10/11/82		SCALE		TITLE		H.S.T M/C	
Imperial College,					APPROVED				F/S				DRAWING NUMBER	
London SW7 2BX					TRACED				DATE		AMMDIS		GROUP	
					CHECKED				29/1/82				NAME	



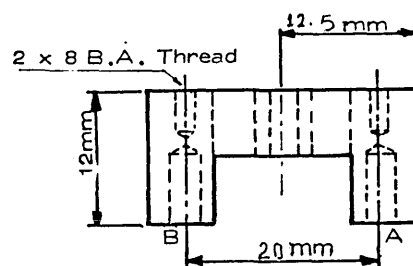
				2	2	GUIDE PINS	BRASS	
				1	2	PHOTO. S. HOUSING	D.A.L.	
				PRI No	NO OF	DESCRIPTION	MATERIAL	REMARKS
Mechanical Engineering Dept.				DRAWN	H. YOUNG	SCALE	TITLE	
Imperial College,				APPROVED		2 1/2"	E.M. HOUSING	
London SW7 2BX				TRACED		DATE	CLASS	
				CHECKED		16/9/58	DRAWING NUMBER	
							S - 01	
							GROUP	
							NAME	
							CLUTCH & SENSORS HOUSING	



LIMITS ON DIMENSIONS		
DEC	±	0.10"
FRACT	±	$\frac{1}{32}$ "
DEC MM	±	0.25 MM
UNIT MM	±	1 MM
UNLESS SPECIFIED		

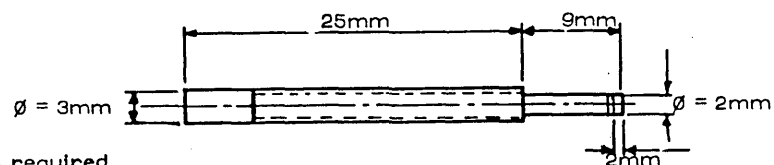


2 Pieces required
Mat. D. Al.



A&B
2 x 6 B.A.
Threaded screws

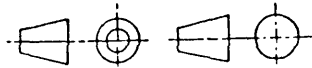
1



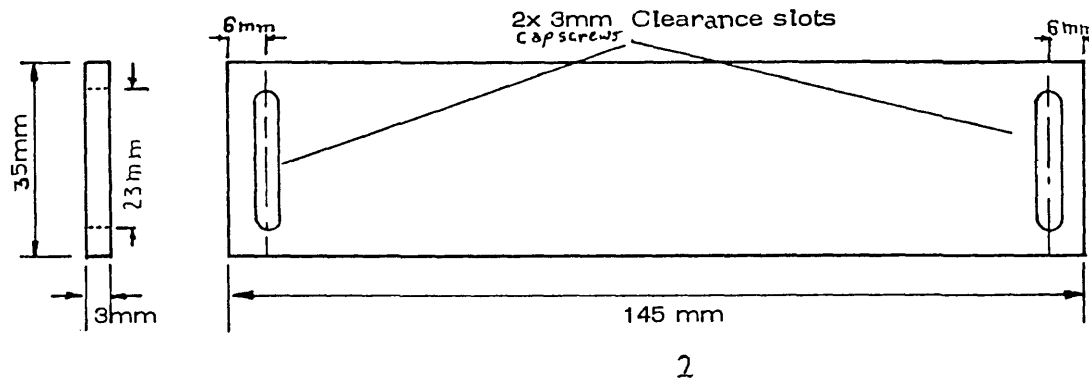
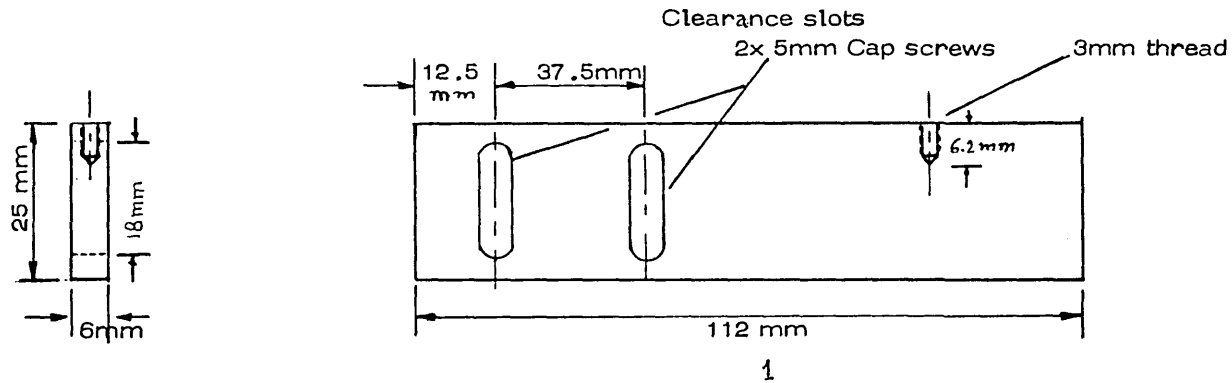
2 Pieces required
Mat. Brass

2

Mechanical Engineering Dept. Imperial College, London SW7 2BX	DRAWN	H. YOUNG	SCALE	2 F/S	TITLE	E.M. HOUSINGS	CLASS	DRAWING NUMBER
	APPROVED			DATE	AMMDIS		GROUP	NAME
	TRACED			12/9/87				CLUTCH & SENSOR HOUSE
	CHECKED							



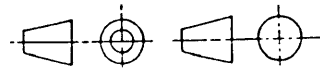
LIMITS ON DIMENSIONS	
DEC	± 0.10"
FRACT	± 1/32
DEC MM	± 0.25 MM
UNIT MM	± 1 MM
UNLESS SPECIFIED	



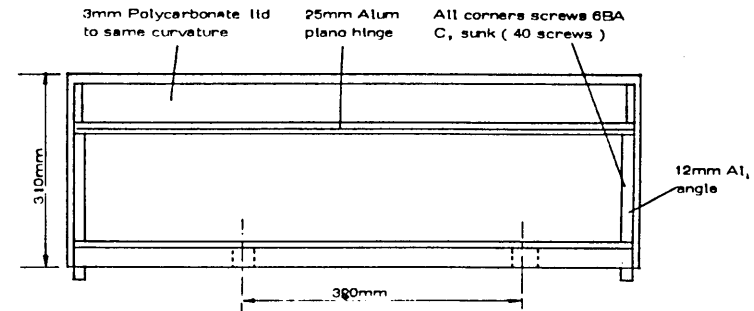
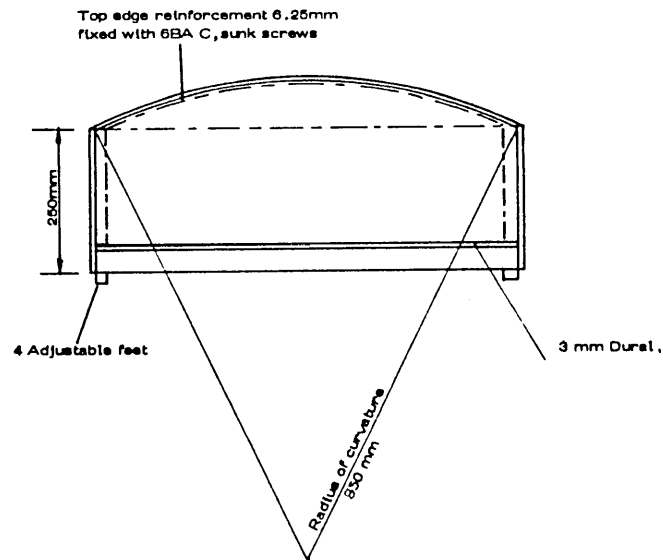
2	1	SUPPORTER	D.H.L.	
1	2	SENSOR HOUSING CARRIER	D.H.L.	
PART No	REV	DESCRIPTION	MATERIAL	REMARKS

Mechanical Engineering Dept.	DRAWN	H. TOWNAN	SCALE		TITLE	H.S.T MIC	CLASS	DRAWING NUMBER
Imperial College,	APPROVED		F/S					SC 03
London SW7 2BX	TRACED		DATE		AMMDS		GROUP	NAME
	CHECKED		13/10/88				S	CARRIER

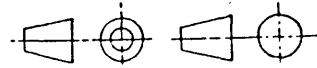
REV 1117000 2



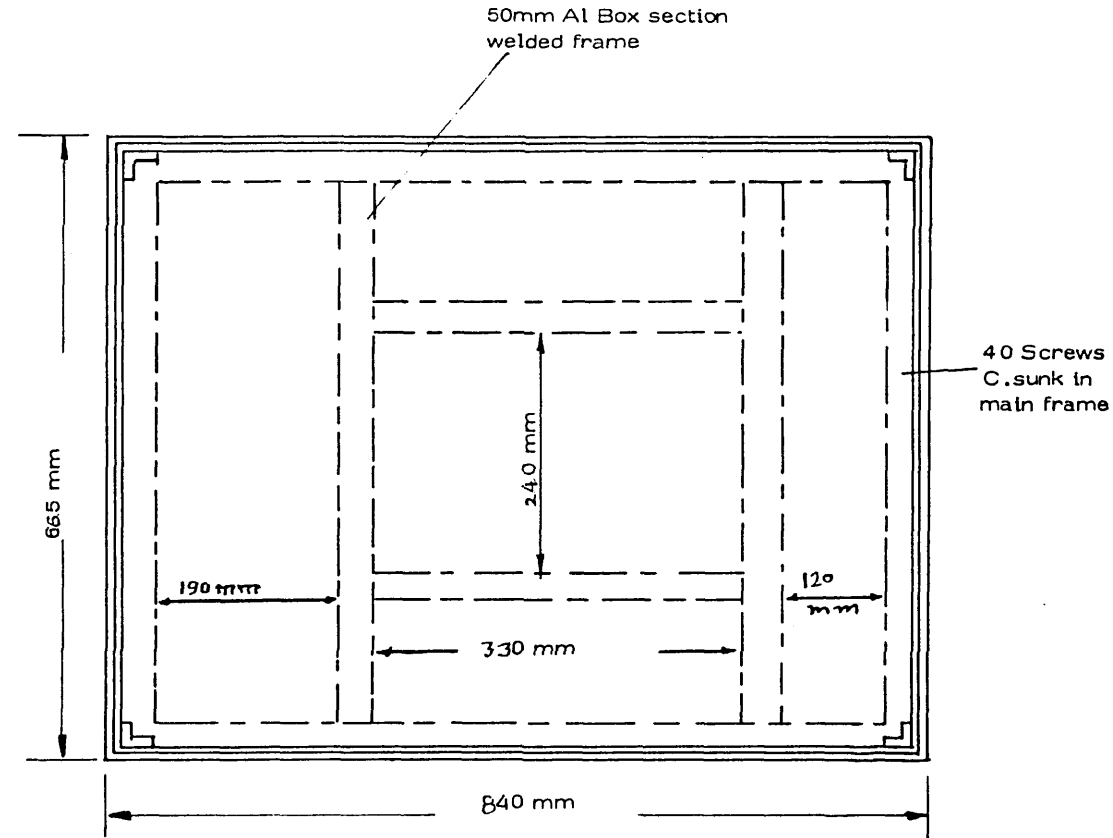
LIMITS	ON	DIMENSIONS
DEC	±	0.10"
FRACT	±	$\frac{1}{32}$ "
DEC MM	±	0.25 MM
UNIT MM	±	1 MM
UNLESS SPECIFIED		



							1		ENCLOSURE			
					PART No		No OF		DESCRIPTION		MATERIAL	
Mechanical Engineering Dept.					DRAWN		H. Young		SCALE		TITLE	
Imperial College,					APPROVED				1/4 P/S		H.S. T.M.C.	
London SW7 2BX					TRACED				DATE		AMMOTS	
					CHECKED						CLASS	
											DRAWING NUMBER	
											C-04	
											GROUP	
											NAME	
											C	
											m CAB	



LIMITS ON DIMENSIONS	
DSC	$\pm 0.10^\circ$
FRACT	$\pm \frac{1}{32}$
DEC MM	$\pm 0.25 \text{ mm}$
UNIT MM	$\pm 1 \text{ mm}$
UNLESS SPECIFIED	



1		ENCLOSURE BASE		
PART No	No	DESCRIPTION	MATERIAL	REMARKS
		CLASS	DRAWING NUMBER	
		GROUP	NAME	
		C	M.C.I.B.	

Mechanical Engineering Dept.	DRAWN	H. YOUNG	SCALE	TITLE
Imperial College,	APPROVED		1/10 F/S	
London SW7 2BX	TRACED		DATE	AMMDS
	CHECKED		15/8/82	

NOISE GENERATION IN POLYMER GRANULATORS

D.P. Isherwood, H.R. Younan and R.C. de Wardt

SUMMARY

Investigations on noise generation in polymer granulators show that the noise produced is speed dependent to a greater extent than output rate. Therefore it is recommended that low speed operation should be carefully examined. Some observations are also made on the effect of blade configuration on noise emission.

(P.R.I. Health and Safety Conf. York, April 1984)

IMPACT CUTTING ENERGIES OF POLYMERS

D.P. Isherwood and H.R. Younan (Department of Mechanical Engineering, Imperial College of Science and Technology, London)

SUMMARY

Some experiments on a specially developed machine to measure the energy required to cut polymers at impact speeds are reported. The conditions for minimum cutting energy are reported and the results are discussed.

(4th Review Meeting - Programme and Papers - S.E.R.C., P.E.D., April 1984)

SOME STUDIES ON POLYMER GRANULATORS

D.P. Isherwood, R.C. de Wardt and H.R. Younan

SUMMARY

The operating mechanisms of polymer granulators are examined and it is concluded that the overall behaviour should be considered to be a combination of input, output and cutting effects. Output rate versus speed curves are explained in terms of feedstock form and cutting requirements. Some observations of screen hole design and blade arrangements are also made. Conditions for the lowest cutting energy and the effect of speed on cutting energy are reported.

(Proc. Conf. Polymer Processing Machinery, P.R.I. Bradford, July 1985)

AN IMPACT CUTTING TEST FOR POLYMERS

D.P. Isherwood and H.R. Younan, (Department of Mechanical Engineering, Imperial College of Science and Technology, London S.W.7)

SUMMARY

A machine has been designed and built to determine the energy required to cut polymer specimens by a single blade travelling at speeds of up to 45 metres per second. A full range of blade settings has been tested for seven different polymers and the conditions for minimum cutting energy have been determined. It is found that all the polymers show a very strong speed dependence and that the nature of the dependence falls into two types. The cutting process at impact speeds does not appear to be controlled by a shear mechanism but rather to be a notching process followed by a splitting action leading to crack propagation.

(Accepted for publication in J. Polymer Testing)