Dynamic Fracture and Fragmentation: Studies in Ti-6Al-4V

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Declaration of Originality

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Abstract

This study concentrates on the development of experimental techniques that are of benefit to research into high strain rate fracture and fragmentation. Two main areas are pursued, namely the effect of the stress state in the sample and the initial temperature of the sample on the resulting fracture mechanism and fragmentation behaviour when under tensile loading at strain rates of $10^4$ s$^{-1}$. Both areas use expanding rings and cylinders to achieve this. Experiments are designed and fielded on explosively loaded Ti-6Al-4V rings where the aspect ratio (sample wall thickness to height) is adjusted to create stress states ranging from uniaxial stress to plane strain with velocimetry and fragment recovery used to measure the expansion and failure processes. A transition to necking before failure under uniaxial stress was observed, as opposed to ductile tearing under shear loading in plane strain conditions. Intermediate geometries were found to undergo massive internal damage not seen in the other experiments, leading to premature failure and smaller fragments.

Temperature dependence was investigated using a new gas gun driven expanding cylinder technique with Ti-6Al-4V cylinders 150 mm long, 50 mm inner diameter and 4 mm wall thickness reaching temperatures between 150 K and 800 K before expansion. The loading mechanism was found to be highly repeatable and independent of sample temperature, providing a robust platform for generating high strain rate tensile and failure test data at temperatures unobtainable by other means. A full suite of velocimetry, high speed imaging, fragment recovery and microscopy techniques were used to fully characterise the material during and after deformation. At elevated temperatures adiabatic shear banding was found to be an active failure mechanism. The fragmentation toughness parameter $K_f$ was found to be $101 \pm 13$ MPa m$^{1/2}$ under these conditions.
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Introduction

For a full understanding of a material’s behaviour under high strain rate loading the terminal response needs investigation. The knowledge of under what conditions, when and how a material will ultimately fail is necessary whether the desire is to avoid or promote it. Fracture under quasi-static or steady state conditions has been extensively studied. While the seminal work by Griffith [1] on the deviation from a material’s ideal toughness was published almost a century ago, investigation of its dynamic counterpart has been slightly more recent. The exact point at which an event becomes dynamic is blurred between research topics, but for this work the definition by Ravi-Chandar will be used. They state [2] that a problem must be considered a dynamic process if the event of interest is on the same order of time as the propagation of the stress wave through the sample. Hence this definition is dependent on a range of factors such as the size of the sample, how the load is applied and the loading rate.

For an experiment to reach the point of dynamic fracture and fragmentation the sample will have typically experienced a complex loading history. It is important that this is recorded as each state through this history will contribute to the failure mechanisms and processes. Due to this for a true material properties based understanding of the events one must design the experiment such that external influences are minimised and the loading remains as simple or clean as possible.

Fragmentation experiments are intrinsically destructive events, particularly once the sample becomes larger than a few mm in size. Large amounts of space are needed for mitigation, and even then there is a risk of damaging expensive diagnostics. For these reasons there is a strong push to improve the predictive capability of hydrocodes and computer simulations such that they might be used instead of experiments. However, at present, the popular existing models such as those of Mott [3] and Grady [4] on which many of the hydrocodes build on and use for comparison are largely statistical and empirical in nature. Many assumptions are made about the material response and the loading in the sample, these models are discussed at length in
1. INTRODUCTION

The main aims of this study were to develop new methods of studying the deformation, dynamic fracture and resulting fragmentation of materials under high strain rate tensile loading. Experiments and methodologies are detailed that enable controlled loading of rings and cylinders into expansion in a way that minimises the influence of the loading and the time-to-equilibrium that limits other techniques such as the tensile Kolsky bar platform. Explosive and gas gun techniques are used to investigate the effect of the stress state and the initial temperature of the sample respectively at strain rates on the order of $10^4 \text{s}^{-1}$, typical of impact, ballistic and shock events that structural materials are often exposed to where fracture is of concern.

Tests are completed on the titanium alloy Ti-6Al-4V, percentage by weight. This alloy has widespread use in the aerospace and defence industries owing to its high specific strength and resistance to corrosion and as such has a strong research base to start from. However, due to its poor thermal conductivity it is also susceptible to adiabatic shear banding at high strain rates and its hexagonal-close-packed atomic structure introduces a level of anisotropy making it an interesting material to validate experiments designed to produce uniform radial expansion.

This study begins with a review of the popular models for fracture and fragmentation (chapter 2), followed by a discussion of the main research platforms that are used in experimental studies. These drives use explosives, pulsed power discharge and gas gun launchers, each with its own advantages and disadvantages (chapter 3). The first section concludes with chapter 4 where the motivation and aims are set for the experimental work that follows. The experimental section begins by covering the diagnostics used such as laser based velocimetry and high speed imaging in chapter 5. The first experiments are explosively launched rings of Ti-6Al-4V with differing geometries to investigate the effect of stress state on the sample failure mechanism (chapter 6). The other experimental sections deal with the development of a new gas gun target geometry to allow for expanding cylinder experiments at high and low temperatures (chapter 7), a temperature control system that can operate in the vacuum environment of a gas gun target tank (chapter 8) and finally the application of these to large scale tests on Ti-6Al-
1. INTRODUCTION

4V cylinders on the Institute of Shock Physics 100 mm large bore gas gun facility (chapter 9). Final discussion and conclusions are given in chapter 10 with appendices containing technical drawings, raw data and miscellaneous details at the end.

1.1 Collaborations

During the course of this study experimental work was completed through collaboration with other research institutions in the shock field. Through the use of facilities at these groups experimental data was collected that would not have been otherwise possible. The use of flash X-ray radiography with Dr. Paul Hazell at the Dynamic Response Group, Shrivenham Defence Academy (UK) allowed imaging the internal expansion processes of a gas gun driven cylinder and assisted development of the main technique used in this study. Similarly, working with Dr. Sergey Razorenov’s group at the Institute of Problems of Chemical Physics, Chernogolovka (Russia) enabled the use of energetic materials for studying explosively driven fragmentation. These collaborations are made clear in the relevant parts of this thesis.
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1.2 Publications related to this study

- D R Jones, D E Eakins, P J Hazell, D J Chapman, G J Appleby-Thomas
  Development of the gas gun driven expanding cylinder technique

- D R Jones, D E Eakins, A S Savinykh, S V Razorenov
  The effects of axial length on the fracture and fragmentation of expanding rings

- D R Jones, D J Chapman, D E Eakins
  A gas gun based technique for studying the role of temperature in dynamic fracture and fragmentation

- D R Jones, D J Chapman, D E Eakins
  Gas gun driven dynamic fracture and fragmentation of Ti-6Al-4V

- D R Jones, D J Chapman, D E Eakins
  A method for studying the temperature dependence of dynamic fracture and fragmentation
  *Journal of Visualized Experiments*, Reviewed and accepted, in press (2014)
This chapter begins with an overview of the fracture mechanics field, from the quasi-static classical descriptions of fracture through to the processes seen at higher strain rates such as spall and adiabatic shear banding. Once a background of the possible failure mechanisms is established the second part covers existing work on the post-fracture fragmentation behaviour, comparing statistical and energy-balance approaches.

2.1 Quasi-Static Fracture Mechanics

The field of fracture mechanics is extremely important in engineering. Fracture is defined as the separation of a body into two or more pieces in response to an imposed stress \[6\]. At the most simplistic level fracture is avoided by ensuring a material is not subjected to stresses which surpass its yield strength while in use. However, in the mid 20\textsuperscript{th} century catastrophic failures of ships and planes began to occur even though calculations showed the nominal stress in the part was below the yield stress \[7\].

Griffith’s The Phenomena of Rupture and Flow in Solids \[1\] studied the discrepancy between the theoretical and observed tensile strength of glass. Griffith observed a length scale effect, where by placing glass fibres of varying diameter under a tensile stress he found a relationship where the smaller the diameter the larger the breaking tensile stress. The essence of Griffith’s work is that in a given sample there will be microflaws or cracks, which act to concentrate the localised stress in their vicinity \[8\]. Earlier work by Inglis \[9\] had analysed the stress distribution around a crack, although predicting a singularity at the tip of a perfectly sharp crack where the stress would increase to infinity. Griffith built on this work by moving to an energy-balanced approach, postulating that the stability of a crack or flaw is dependent on the relationship between the local stored strain energy and the energy required to create new surface area. Figure 2.1 left, demonstrates the stress intensity around a crack of length \(a\) in
2. FRACTURE AND FRAGMENTATION

the side of a plate under plane stress. A region of height \( \beta a \) either side of the crack has been unloaded with the rest of the material under a stress \( \sigma \).

\[ U^* = \frac{\sigma^2}{2E} \]  
(2.1)

For the crack in figure 2.1 the strain energy released per unit thickness, \( U \), is given by \( U^* \) multiplied by the area either side of the crack:

\[ U = \frac{\sigma^2}{2E} \cdot \pi a^2 \]  
(2.2)

This is shown by the dashed black line in figure 2.1 right. This energy released by the crack is in competition with the energy required to create the new surface area, \( S \), given by:

\[ S = 2\gamma a, \]  
(2.3)

where \( \gamma \) is the surface energy of the material. \( S \) is represented by the dashed red line. The
sum of $U + S$ is the total energy for a given crack length and is plotted as a solid blue line. It is clear that the energy sum has a maxima corresponding to a critical crack length, $a_c$. Once the crack exceeds this length the solution becomes unstable and the crack will rapidly progress through the sample. Equating the derivative of the energy sum to zero as:

$$\frac{d}{da} (U + S) = 2\gamma - \frac{\sigma^2}{E}\pi a = 0,$$

the critical stress $\sigma_c$ for a crack of length $a$ at which this occurs can be calculated. To this point it has been assumed that the material fails in a brittle manner - Griffith based his theory on glass rods. The equations for $\sigma_c$ for brittle failure under plane stress and plane strain are shown in the top row of table 2.1.

<table>
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<tr>
<th>Fracture</th>
<th>Plane Stress</th>
<th>Plane Strain</th>
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<td>Brittle</td>
<td>$\sigma_c = \sqrt{\frac{2E\gamma}{\pi a}}$</td>
<td>$\sigma_c = \sqrt{\frac{2E\gamma}{\pi a(1-\nu^2)}}$</td>
</tr>
<tr>
<td>Ductile</td>
<td>$\sigma_c = \sqrt{\frac{2EG_c}{\pi a}}$</td>
<td>$\sigma_c = \sqrt{\frac{2EG_c}{\pi a(1-\nu^2)}}$</td>
</tr>
</tbody>
</table>

Orowan [11] and Irwin [12] suggested that for cracks in ductile materials the energy balance needed to be adjusted as the majority of the strain energy was released through dissipation in a region of plastic flow around the crack tip. Unstable crack growth now occurs when a critical strain energy release rate is reached, given the parameter $G_c$, and replaces the $\gamma$ in the Griffith equations as per the bottom row of table 2.1.

2.1.1 Stress Intensity Factor $K$ and Fracture Mode

The mode of a crack is dependent on the direction that the stress is applied relative to the crack. The three basic modes are shown in figure 2.2. Mode I cracks appear under tension, where the stress acts normal to the crack direction pulling the material apart as in the analysis
just described. Mode II cracks occur under shear loading, where the stresses are applied in opposite directions along the direction of the crack (in plane shear). Finally, mode III cracks are a result of a tearing shear stress, where the stresses act in opposite directions parallel to the crack plane and normal to the crack direction (out of plane shear).

Figure 2.2: The three crack modes: Left: Mode I, Tensile opening. Centre: Mode II, In plane shear. Right: Mode III, Out of plane shear.

For each mode $i$ there is an associated stress intensity factor, $K_i$. These relate to the critical strain energy through the equations in table 2.2. The value of the stress intensity factor that would result in unstable crack growth is defined as $K_c$ and is defined as the material’s fracture toughness (units of Pa·m$^{1/2}$), quantifying the resistance of a material to failure under quasi-static loading.

Table 2.2: Griffith critical strain energy $G_c$ with critical stress intensity factor $K_{ic}$ (fracture toughness)

<table>
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<th>Mode, $i$</th>
<th>Loading</th>
<th>Griffith critical strain energy, $G_c$</th>
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<td>I</td>
<td>Tensile Opening</td>
<td>$G_c = \frac{K_{ic}^2}{E}$</td>
</tr>
<tr>
<td>II</td>
<td>In Plane Shear</td>
<td>$G_c = \frac{K_{ic}^2}{E}$</td>
</tr>
<tr>
<td>III</td>
<td>Out of Plane Shear</td>
<td>$G_c = \frac{K_{ic}^2}{2\mu}$, $\mu =$ shear modulus</td>
</tr>
</tbody>
</table>
2.2 Dynamic Fracture

The transition from classical fracture mechanics to dynamic fracture occurs when inertial effects in the material become significant \[13\]. These effects can result from a rapidly applied load or from rapid crack propagation releasing a loaded material. In the former case the stress applied to the crack will be highly transient and assuming a quasi-static loading will not be accurate. Likewise for the latter case, if a flaw is introduced to a material under a large load (e.g. notching a loaded tensile test specimen) then as the crack tip propagates through the sample there will be an associated inertia of the material around the fracture. As a rule of thumb, if the loading rate is such that deformation is localised, i.e. the loading time is short compared to the time taken for a wave in the material to cover a representative distance, then the problem must be given a full dynamic analysis \[2\]. The following sections cover the processes behind fracture phenomena particular to dynamic events such as shock or ballistic loading and the experimental evidence for them.

2.2.1 Spall

At a base level, spall fracture is defined as the failure of a material in tension as a result of two interacting decompression waves \[14\]. Consider a sample initially under pressure that is then released at the front and rear surfaces - rarefaction waves will propagate inwards from these free surfaces. These waves serve to relax the stress in the sample to zero, i.e. they move particles in the opposite direction to the direction of the wavefront. Where they meet and cross over a region is formed of intense uniaxial strain and high strain rate, typically \(>10^4 \text{s}^{-1}\) over a time on the order of \(\mu\text{s}\) \[15\]. As the region’s strain and stress state can be accurately diagnosed, spall measurements are a useful technique for examining a material’s dynamic tensile strength.

This situation can occur in a variety of loading scenarios. A narrow ‘triangular’ shock as produced under explosive or pulsed energy beam (laser or particle) loading will reflect from the target rear free surface as a rarefaction - as the loading pulse is very short the release wave from the front surface follows the initial shock closely and hence the rarefactions interact near the rear surface. A common method of generating spall with an impact is shown in figure \[23\].

In this experimental setup a flyer is launched into a target in a plate impact configuration.
Both components are machined from the material of interest. The flyer is half the thickness of the target. This locates the spall plane roughly halfway through the thickness of the target and helps to ensure that the area around the spall plane can be recovered for sectioning and imaging without further damage. The AUTODYN simulation in figure 2.3 used a 5 mm flyer and 10 mm target, with an impact velocity of 500 m s$^{-1}$. No failure model was used.

At impact, a shock wave propagates right into the target and left into the flyer so that the pressure and particle velocity are equal across the interface. At $\sim$1 $\mu$s the shock in the flyer reaches the rear free surface. This then reflects right into the flyer as a rarefaction fan, reducing the pressure to zero. At 2 $\mu$s this rarefaction enters the target from the left, at the same time as the shock in the flyer reaches the flyer free surface and reflects back also as a rarefaction. This is also shown in figure 2.4 as the breakout of the elastic precursor and main shock. The target now contains two converging rarefaction fans which begin to interact near the middle of the target. As they cross each other a region of intense tensile stress is formed, demonstrated by the blue diamond on the $x-t$ plot. As mentioned, this model has no failure model implemented so no spall is observed. The material retains strength and the stress / release waves continue to reverberate through the target.

Figure 2.4 shows the same model now with a failure criterion included. The target material model has been adjusted to include the Grady spall failure model [16]. This defines a stress
value $\sigma_f$ such that if the principal stress in a cell exceeds this value the cell fails, defined as

$$\sigma_f = \sqrt{2\rho_0 c_0^2 \sigma_Y \varepsilon_c}, \quad (2.5)$$

where $\rho_0$ and $c_0$ are the material’s initial density and bulk sound speed respectively, $\sigma_Y$ is the yield stress and $\varepsilon_c$ is a critical strain parameter (0.15 in the 6061-T6 aluminium used here). Aspect ratios of 6-10:1 (diameter:thickness) are used to ensure that there is a large area of uniaxial strain, i.e. unaffected by lateral release waves \cite{17}. The released area is shown in figure 2.4 at the edge of the target.

With the failure model included it is clear that the region in the centre of the target has accumulated damage in the form of voids. The nucleation, growth and coalescence of these voids is the characteristic spall process. Taking the free surface velocity history on the right of figure 2.4 explains this further. The initial rise in velocity corresponds to the breakout of the elastic precursor ($\sim75\ \text{m/s}$) and the plastic shock wave (initially slightly attenuated by the reflecting elastic wave). From 2\ $\mu$s on the rarefactions in the target converge. The reduction in free surface velocity relates to the tensile stress inside the target, effectively pulling the two faces back inwards. However, in this case the tensile stress generated has exceeded the spall strength, meaning the material can no longer support a tensile stress. Rarefactions (now releasing from...
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a tensile state as opposed to compressive) propagate out from the spall plane and exhibit as the increase in free surface velocity seen at 3.6 µs. The difference between the maximum and minimum free surface velocity in this pulse, \( \Delta f_s \), can be used to calculate the spall strength \( \sigma_{sp} \).

From Kanel [18],

\[
\sigma_{sp} = \frac{1}{2} \rho_0 c_0 \Delta f_s,
\]

where \( \rho_0 \) is the initial density and \( c_0 \) is the bulk sound speed. This approach assumes that the material’s non-linear behaviour under compression is negligible and that the sound speed is constant. Further work [19] has concentrated on addressing these issues to enable work at elevated stresses. However, as the tensile conditions responsible for the spall are highly dependent on the loading rate [20] and loading history [21], the spall strength will vary accordingly, meaning care must be taken when comparing results between materials and loading platforms.

2.2.2 Adiabatic Shear Banding

Adiabatic shear bands are localised regions of intense plastic strain along the planes of maximum shear in a specimen, i.e. normally along 45° to the loading direction [22]. The formation process initiates with plastic deformation in a sample, generating heat. With increasing strain rates, the heat generated does not have sufficient time to dissipate into the surrounding material [5]. While a metal will typically strain harden, that is the stress needed to generate further strain increases with accumulated strain, the increase in temperature will cause the plastic region to thermally soften [23]. If the effect of thermal softening dominates over the strain hardening an instability forms in the deforming region, with further plastic work being concentrated into this zone. While the adiabatic prefix is accurate in that there is not time for the heat to dissipate while the instability forms, when the load is removed the heat quickly transfers into the surrounding material. This leaves evidence of adiabatic shear in the form of regions where the grain size is much reduced and the hardness increases consistent with quenching [24]. This localised heating along the planes of maximum shear was first noted by Tresca during research into forging metals [25]. Titanium is particularly susceptible to this deformation mode due to its high strength and low thermal conductivity [26]. This is exaggerated in its high strength alloy derivatives, with shear bands initiating at much lower amounts of strain [27]. Figure 2.5
taken from the work of Molinari et al.\textsuperscript{28}, demonstrates an adiabatic shear band typical of the ones found in Ti-6Al-4V. The band runs from the top left to bottom right, a narrow zone of plastic deformation approximately 10\(\mu\text{m}\) wide.

Figure 2.5: Example of an adiabatic shear band in Ti-6Al-4V from Molinari et al.\textsuperscript{28}. This was produced during machining at a cutting speed of 13 m s\(^{-1}\).

The shear bands serve as initiation sites for void nucleation and growth, with fracture occurring along the shear band as these coalesce\textsuperscript{29}. The importance of failure through adiabatic shear banding and its relation to fragmentation is discussed further in section 2.3.3.

2.3 Fragmentation Statistics

This section covers the main models in use for fragmentation studies in a roughly chronological order of development. These models are largely empirical and statistical in nature, with parameters that need extensive experimental investigation to populate.

2.3.1 The Behaviour of Cased Charges

The importance of dynamic fracture and fragmentation to military applications is clear. A large body of work in the area was produced during the 1940s, with seminal papers published by Taylor and Gurney. It is unsurprising that this work concentrated on more applied problems, specifically the behaviour of cased charges such as explosive bombs and shells. Many of the experiments made use of standard munitions and artillery. For this reason much of the early
work relates the behaviour of the casing cylinder to the ratio of explosive charge mass to the case mass.

Taylor’s vast works [30] discussed the angle that a cylindrical bomb casing will expand at when detonated at one end. This was calculated assuming an adiabatic equation of state for the gaseous explosive products. Early high speed photography data showed that his approximations were close and also that there was a delay between cracks appearing on the surface of the cylinder and explosive products being released from these cracks. Taylor postulated that the intense internal pressure generated by the contained explosives created a region of compression in the cylinder wall into which the cracks generated in the tensile region of the outer wall could not penetrate. However, this assumes that the failure in the outer region is only through mode I (tensile) fracture and neglects failure through shear.

Gurney [31] developed a model for the velocity of the bomb casing and therefore the initial fragment velocity. He assembled data covering a range of munitions tests with devices ranging from 20 g to 1400 kg. With the assumption that the kinetic energy transferred from the explosive products to the casing for each unit mass of the explosive is only dependent on the ratio of the explosive mass to the casing mass he produced formulae for a range of geometries (spherical charges, charges sandwiched between two plates etc.), with the case velocity of a finite length cylinder given by

\[ v_g = \sqrt{2E} \left[ \left( \frac{M}{C} + \frac{1}{2} \right) \left( 1 + \frac{R_c}{L_c} \right) \right]^{-1/2} \] (2.7)

where \( v_g \) is the case velocity, \( \sqrt{2E} \) is the Gurney constant for the explosive used, \( M \) and \( C \) are the case mass and explosive mass and \( R_c \) and \( L_c \) are the explosive charge radius and length [32].

### 2.3.2 Mott’s Statistical Fragmentation Theory

While the previous works concerned the behaviour of the sample up to the point of failure, the key paper by Mott in 1947 [3] made a significant move towards predicting the statistical nature of the fragmentation process. This has become the basis for much of the following work to the present. Mott reduced the expanding cylinder experiment to a two-dimensional problem by considering only a slice of the cylinder, ignoring effects along the length. This is shown in
2. FRACTURE AND FRAGMENTATION

Figure 2.6: Mott release waves in an expanding fracturing ring. **Left**: Uniformly expanding ring showing multiple fractures. **Right**: Detail of red highlight. Mott release waves propagate from the fracture at a to b between which the stress is now zero. The grey region (b to c) is still under a uniform hoop stress.

The ring is uniformly loaded over the inside boundary, driving it into expansion at a velocity $u(t)$. The radius of the ring is given by $r(t)$ and we assume that the wall thickness is negligible compared to the radius. With this constraint the instantaneous strain rate $\dot{\epsilon}(t)$ is given by:

$$\dot{\epsilon}(t) = \frac{u(t)}{r(t)} \quad (2.8)$$

The right of figure 2.6 shows a detail of an area soon after a fracture has occurred. Point a is the location of the new free surface created. Perhaps the most important inference by Mott is that once this fracture at a occurs, a release wave (now known as Mott waves) propagates into the rest of the ring. This wave acts to reduce the stress in the region it traverses to zero, shown as the white area between a and point b which represents the location of the wavefront. Point c is an arbitrary location at some point along the ring that is still straining at a uniform rate, shown as grey in the detail. As a whole Mott’s theory of fragmentation states that the motion of these release waves coupled with a fracture activation rate (with strain) determine the distribution of fragment lengths. Mott’s theory requires several assumptions:

- Even in a homogeneous sample there will be a distribution in the failure strain
- The material has a rigid - perfectly plastic response
- Fracture occurs instantaneously, *i.e.* there is no breakage timescale or cohesive zone
The first point is Mott’s approach to fracture in ductile materials. Whereas in brittle materials the macroscopic strength is dominated by the presence of flaws [1] Mott postulated that in ductile materials this is governed by the distribution in fracture strain at the limit of ductility. This has an associated probability density function $\lambda(\varepsilon)$ where each point in the material can accrue strain until it reaches its local value for failure. Mott uses an exponential form as this ‘gives a rapid increase from negligible to large values as $[\varepsilon, \text{strain}]$ increases’. This produces the function

$$\lambda(\varepsilon) = 1 - \exp\left(-\frac{C}{\gamma}e^{\gamma \varepsilon}\right),$$  \hspace{1cm} (2.9)

where $\lambda(\varepsilon)$ is the probability of failure before a normalised failure strain of $\varepsilon$ is reached and $C$ and $\gamma$ are constants.

Figure 2.7: Left: Mott’s exponential failure probability distribution for $\gamma = 8$, 12 and 16. C is adjusted so that $\lambda = 0.5$ for a strain of 1. Right: Distribution applied to a quarter-ring in AUTODYN with $\gamma = 8$ and 16.

Figure 2.7 (left) shows this equation for various values of $\gamma$, where $C$ is set so that the probability of failure is 0.5 for a normalised failure strain of 1. On the right is an example of this distribution applied to a part in the AUTODYN explicit analysis software, with $\gamma$ values of 8 and 16. It is clear that larger values of $\gamma$ reduce the amount of heterogeneity in a sample.

The other assumptions made by Mott affect the release waves and their propagation. The ring material is considered to have a rigid - perfectly plastic response, that is any fracture will occur while the sample is in a state of plastic deformation. This means that the release waves propagate into a region that is still plastically deforming at a constant flow stress (b to c) making them exhibit diffusive behaviour [23]. The motion of this wavefront with time
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can be calculated and used to infer a maximum fragment length. Following the interpretation of Mott’s paper by Zhang and Ravi-Chandar [34] we initially consider a uniformly expanding ring such that the strain rate is constant around the entire azimuth, defined as $\dot{\varepsilon}_0$. This is demonstrated in figure 2.8.

![Figure 2.8: Mott release waves around a fracture site, adapted from Zhang and Ravi-Chandar [34].](image)

Left: Fracture, released section (white), release wave front (b) and region at constant strain rate (grey). Right: Particle velocity and tensile stress in the sample at a time $t$ after fracture.

At time $t = 0$ a fracture occurs at the point $x = 0$. Mott assumes instantaneous fracture, and at a time $t$ later the release wave has propagated to point b, the location of which is described by $s(t)$. Point c is an arbitrary location in the stressed region moving at a velocity $\dot{\varepsilon}_0s$. As the material is perfectly plastic the tensile stress here is the yield stress, $\sigma_Y$. To ensure continuity between the released and stressed regions at $x = s(t)$ the region ab must be moving at a velocity $\dot{\varepsilon}_0s(t)$. We equate the change in momentum of the region ab to the force applied to it $\sigma_Y$:

$$\rho \dot{\varepsilon}_0 s \frac{ds}{dt} = \sigma_Y,$$

where $\rho$ is the density after release; through integration of this the motion of the Mott release wavefront $s(t)$ is produced

$$s(t) = \left(\frac{2\sigma_Y t}{\rho \dot{\varepsilon}_0}\right)^{1/2}.$$

Here arises the diffusive nature of the Mott wave’s propagation, as with increasing time the size of the unloaded region that must be accelerated to $\dot{\varepsilon}_0s(t)$ increases where the force acting on it remains constant. From this a value for the nominal theoretical fragment length can be deduced, as a release wave propagates a distance $s$ either side of a fracture the length of a
2. FRACTURE AND FRAGMENTATION

released region will correspond to two release waves meeting head-on, i.e. a length of \( \sim 2s \). Remembering Mott’s first postulate that the sample will have a standard deviation in failure strain, \( \Delta \varepsilon \), the time window \( t \) for all the fractures covered by this range to initiate is given by \( t = \Delta \varepsilon / \dot{\varepsilon} \). Hence the fragment length predicted by Mott’s theory, \( l_{\text{MOTT}} \) is:

\[
l_{\text{MOTT}} = 2 \left( \frac{2\sigma_Y t}{\rho \dot{\varepsilon}} \right)^{1/2} = 2 \left( \frac{2\sigma_Y \Delta \varepsilon}{\rho \dot{\varepsilon}^2} \right)^{1/2}
\] (2.12)

Mott’s theory predicts an inversely proportional relationship between the fragment length and the strain rate. At lower strain rates there is ample time for the Mott waves to travel around the sample, releasing the stress and stopping fracture at weaker sites. As the strain rate increases the fragmentation response will become dominated by the distribution chosen for the failure strain (\( \lambda(\varepsilon) \)) as there is less time for the release waves to propagate hence a higher number of weak points will go through to failure.

The motion of the wave is governed by kinematic properties (\( \dot{\varepsilon} \)) and material properties (\( \rho, \Delta \varepsilon \) and \( \sigma_Y \)). This is one of the main critiques of Mott’s theory - the standard deviation in failure strain for a sample is extremely difficult to measure and keep constant between experiments making it a largely empirical fit. Secondly, for early values of time, equation 2.11 tends to an infinite value for the velocity of the release wave. This is due to the assumption that the material has rigid - perfectly plastic behaviour. Mott acknowledged this and pointed to work by Lee [35] who completed a full elastic-plastic material solution finding that the release wave velocity is initially equal to the elastic wave speed but soon tends to the plastic model [36]. Finally, there is no inclusion of the fracture mechanism, which is known to be an important and complex interaction in ductile materials. As mentioned earlier in this chapter, ductile failure is typically proceeded by one or a combination of plastic deformation, necking, void growth and coalescence and adiabatic shear localisation. Kipp and Grady [37] included a cohesive zone in their analysis of Mott’s theory, where the stress drops to zero over a critical timescale as opposed to instantaneously. The works of Grady and his colleagues are discussed in the next section.
2.3.3 Grady’s Energy Based Fragmentation Theory

Whereas Mott assumed that the time and energy dissipation during fracture was not important, these are the base principles of the work of Grady et al. Grady follows a similar analysis to Mott for the motion of the release waves from the fracture site, although now instead of an instantaneous fracture where the stress drops to zero immediately it now tends to zero over some time. The relationship proposed by Kipp and Grady [37] is a linear reduction in the tensile stress from the yield stress to zero over a time and distance for the fracture to fully open. This is shown in figure 2.9.

Figure 2.9: Left: Location of the fracture surface and release wave used by Kipp and Grady [37], adapted from Grady [33]. Right: Tensile stress in the fracture zone, reaching zero at a critical crack displacement $y_c$ at which an energy $\Gamma$ has dissipated.

The left side is similar to the diagram used for Mott’s analysis (figure 2.8) with the observer at a point $x = 0$ where at time $t = 0$ fracture initiates in a sample flowing under a constant tensile stress $\sigma_Y$. The displacement of the fracture surface is given by $y(t)$ and the position of the release wave, the boundary between the rigid and plastic regions, is $x(t)$. However, now the stress in the fracture region drops from $\sigma_Y$ as in the plot on the right of figure 2.9. When the fracture surface has reached a critical crack opening defined as $y_c$, the stress has fully released to zero. The area under this curve (highlighted orange) is equivalent to the energy required by fracture, $\Gamma = \sigma_Y y_c/2$. The change in momentum of the released zone is now the difference in tensile stress between the position of the rigid - plastic boundary $x(t)$, equal to the yield stress $\sigma_Y$, and the end at the fracture surface $y(t)$ such that:

$$\rho \dot{x} \frac{dx}{dt} = \sigma_Y - \sigma(y), \quad (2.13)$$
where the stress at the fracture surface is given by

\[ \sigma(y) = \sigma_Y \left( 1 - \frac{y}{y_c} \right), \quad (2.14) \]

valid for a crack opening displacement \( 0 \leq y \leq y_c \). Combining equations 2.13 and 2.14 produces

\[ \rho \dot{\varepsilon} x \frac{dx}{dt} = \frac{\sigma_Y^2}{2\Gamma} y. \quad (2.15) \]

which is then combined with the equation of motion for the fracture surface

\[ \frac{dy}{dt} = \dot{\varepsilon} x \quad (2.16) \]

to produce the motion of the rigid-plastic boundary during the time which the crack is opening, i.e. while \( y \leq y_c \):

\[ x(t) = \frac{1}{12} \frac{\sigma_Y^2}{\rho \Gamma} t^2. \quad (2.17) \]

It is clear from equation 2.17 that the original problem with Mott’s theory where the release wave initially has infinite velocity is now resolved. Using equations 2.16 and 2.17 we can calculate the position of the fracture surface \( y(t) \) with

\[ y(t) = \frac{1}{36} \frac{\dot{\varepsilon} \sigma_Y^2}{\rho \Gamma} t^3. \quad (2.18) \]

Setting \( y = y_c \) in equation 2.18 along with \( \Gamma = \sigma_Y y_c / 2 \) we can calculate the time at which the fracture process has completed, \( t_c \)

\[ t_c = \left( \frac{72 \rho \Gamma^2}{\sigma_Y^3 \dot{\varepsilon}} \right)^{1/3}. \quad (2.19) \]

Finally, the position of the release wave at this time, \( x_c \), is given by the equation

\[ x_c = \left( \frac{3 \Gamma}{\rho \dot{\varepsilon}^2} \right)^{1/3}. \quad (2.20) \]

After this time there is no longer cohesion in the fracture zone, and the behaviour reverts to
the original rigid - perfectly plastic description of Mott. A plot of the positions of the fracture surface and release wave according to Mott and Grady is shown in figure 2.10.

Figure 2.10: Position of the fracture surface $y(t)$ (black, equation 2.18) and the release wave $x(t)$ (rigid - plastic boundary) according to Mott (blue, equation 2.11) and Grady (red, equation 2.17) for the material Ti-6Al-4V at a strain rate of $10^4 \text{s}^{-1}$.

This example has been calculated for Ti-6Al-4V at a strain rate of $10^4 \text{s}^{-1}$ using the values $\rho = 4430 \text{ kg m}^{-3}$, $\sigma_Y = 1.1 \text{ GPa}$ and $\Gamma = 30 \text{ kJ m}^{-2}$. This produces the values 2.79 $\mu\text{s}$ for the time of fracture completion and 5.86 mm for the position of the release wave at this time. Figure 2.10 demonstrates how the inclusion of a fracture energy initially delays the propagation of the release wave front. After the time $t_c$ the motion changes to follow the initial analysis by Mott, the dotted line has been included to show the shape of equation 2.17.

As the release waves will arrest any further straining and therefore fracture in the regions they travel, it is appropriate to assume that there is a maximum fragment with that can be sustained. For situations where the available energy from loading is such that the fragmentation is governed by fracture initiation and completion there will be a bound on the fragment length of twice the distance covered by the release waves during the fracture time, $x_c$. Hence Grady predicts a nominal fragment length of

$$l_{GRADY} = 2x_c = \left( \frac{24\Gamma}{\rho \sigma_Y^2} \right)^{1/3}. \quad (2.21)$$

Figure 2.11 compares $l_{MOTT}$ and $l_{GRADY}$ for a range of strain rates in Ti-6Al-4V using the
previous values with a failure strain spread $\Delta \varepsilon$ of 0.015. In the strain rate region $10^3 \text{s}^{-1}$ to $10^5 \text{s}^{-1}$ typical of impact and ballistic studies (and therefore the majority of data that these models have been developed with) there is difference little between the two.

Grady’s method removes the distribution in failure strain $\Delta \varepsilon$, but also removes the relationship to the yield stress $\sigma_Y$. The dependence on material properties now arises through the fragmentation energy parameter $\Gamma$. Grady and Hightower state that there are two main failure mechanisms in expanding metal shells, ductile failure and failure along adiabatic shear bands [38]. Proposed relationships for $\Gamma$ based on material properties for these failure modes are set out in table 2.3.

The energy required by ductile fracture is governed by a parameter $K_f$. In this mechanism the fracture occurs through the opening of mode I cracks. Hence $K_f$ is known as the material’s fragmentation toughness, analogous to the quasi-static parameter $K_{Ic}$, the mode I fracture toughness. While the fracture toughness can be used for a rough calculation (within an order of magnitude [38]) of $\Gamma_D$ the fragmentation toughness can be calculated from experimental data. Taking the reciprocal of the predicted average fragment length (equation 2.21) the number of fractures per unit length for the Grady energy approach, $N_G$:

$$N_G = \left( \frac{\rho \dot{\varepsilon}^2}{24\Gamma} \right)^{1/3}.$$  (2.22)
Using the relationship for $\Gamma_D$ from table 2.3 and $E = \rho c_0^2$ where $c_0$ is the elastic wave speed we arrive at

$$K_f = \left( \frac{\rho c_0 \dot{\varepsilon}}{\sqrt{12N^{3/2}}} \right),$$

(2.23)

where $N$ is equal to the total number of cracks in the sample divided by the circumference $N = N_{TOT}/2\pi r$ [40]. Grady predicts a two-thirds power scaling of $N$ with strain rate compared to Mott’s linear scaling (equation 2.12).

The equation for the fragmentation energy follows a similar approach to that of ductile fracture, tracking the location of the boundary between the rigid released region and the rest of the sample flowing plastically. Grady describes a shear band process zone [41] within which the shear stress relaxes from the ambient temperature value to the much lower value in the
adiabatically heated region around the localised band. The energy dissipated in the shearing process is then used in place of the energy required for fracture to give fragment size predictions.

2.3.4 Combining the Statistical and Energy Based Theories

Grady’s most recent efforts on fragmentation theory with Olsen have concentrated on combining the statistical aspects of Mott’s work with the energy-based theories of Grady and colleagues. Using data gathered on expanding uranium - niobium (U-6N) rings they examine which areas each theory excels at and then argue a method of merging them [4]. Quoting Grady and Olsen, ‘Frequency, and in particular, statistical spacing of fractures are consistent with predictions of the Mott theory. The favourable strain rate dependence and the very close agreement between static fracture toughness \( K_{ic} \) and the inferred dynamic toughness \( K_f \) are, on the other hand, well predicted by the energy-based theory.’

They begin by proposing an alternate form of the Mott strain dependent fracture activation function \( \lambda(\varepsilon) \), replacing the exponential form in equation 2.9 with the power law (the hazard function Weibull distribution [3]):

\[
\lambda(\varepsilon) = \frac{n}{\delta} \left( \frac{\varepsilon}{\delta} \right)^{n-1},
\]

where \( n \) and \( \delta \) are constants. This is used in conjunction with Mott’s diffusion-based equation for the motion of the release wave front (equation 2.11) in the form where \( \varepsilon \) is the argument:

\[
s(\varepsilon) = \left( \frac{2\sigma_Y \varepsilon}{\rho \varepsilon^2} \right)^{1/2}.
\]

Equations 2.24 and 2.25 representing the fracture activation and the amount of released (i.e. safe from fracture) material compete to produce the number of fractures per unit length,

\[
N_M = \beta_n \left( \frac{\rho \varepsilon^2}{2\pi \sigma_Y} \frac{n}{\delta} \right)^{n/(2n+1)},
\]

where \( \beta_n \) is a constant approaching unity for reasonably large \( n \) [4]. This will also produce a linear relationship to strain rate, with the standard deviation of the hazard function \( (\delta/n) \) controlling the number of fragments as per Mott’s original effort with an exponential distribution.
Equating the equations for the number of fragments from the energy based (equation 2.22) and statistical (equation 2.26) theories to each other will produce values for the power law constants as:

\[ n = 1, \quad \delta = \beta \frac{12}{\pi} \frac{\Gamma}{\sigma_Y} \cong \frac{5}{\sigma_Y} \]  

(2.27)

Figure 2.12 plots the power law activation rate against the energy based activation rate, using the values \( n = 5, \delta = 0.05, \sigma_Y = 1.1 \text{ GPa} \) and \( \Gamma = 30 \text{ kJ m}^{-2} \).

Figure 2.12: Combining the statistical activation function of Mott (black, dashed) and the energy limited function of Grady (red, dashed).
2. FRACTURE AND FRAGMENTATION
Dynamic Fracture and Fragmentation: Driving Mechanisms

This chapter provides a background into experimental studies of dynamic fracture and fragmentation, beginning with the reasoning behind the use of axially symmetric geometries such as rings, cylinders and spheres by examining the limits of lower strain rate tensile testing apparatus. The key works in driving expansion in a round sample are then described, from the early work with explosives and munitions to the more recent developments working with pulsed power and gas guns. The advantages and disadvantages of each system are presented.

3.1 Tensile Testing at High Strain Rates

This study concerns the dynamic fracture of a material under tension. Conventional tensile testing apparatus such as servohydraulic rams can operate up to strain rates on the order of $10^2 \text{s}^{-1}$. For strain rates in the region of $10^2$ to $8 \times 10^3 \text{s}^{-1}$ the split Hopkinson pressure bar (SHPB) \cite{kolsky} or Kolsky bar\footnote{The SHPB implies compression testing, the use of two bars as developed by Kolsky \cite{kolsky} is more general and covers compression, tension and torsion testing \cite{harding}.} is widely used \cite{harding}. Application of this technique to tensile testing was pioneered by Harding et al in 1960 \cite{harding}. In short, tensile testing with a Kolsky bar involves two bars, an input and an output. The sample of interest is located between these bars, connected to them at each end. A tensile pulse is sent through the input bar, either by impacting the free end in the opposite direction (away from the sample) \cite{kolsky} or storing tension by preloading the bar while clamped and promptly releasing it \cite{harding}. Strain gauges on the input and output bars measure the incident, transmitted and reflected strain pulses (the bars remain elastic throughout). The transmitted pulse can be used to infer the stress history of the sample, with the reflected pulse used to attain the strain rate with time in the sample. This can be used to generate a dynamic stress strain relationship for the sample \cite{harding}. Further diagnostics
such as high speed imaging and digital image correlation can be used to extract more detailed information about the sample’s behaviour [49].

Neglecting the finer points of the Kolsky bar technique, the point of contention for this study is the time taken for the sample to reach an equilibrium state. An inherent problem with the Kolsky bar is that the sample is loaded from one end. This means there is a finite time for the stress waves to propagate though the sample, with Davies and Hunter estimating that at least three reverberations of the loading wave through the sample are needed to reach this state [50], with larger values for a greater impedance mismatch between the sample and the bars [51]. At high strain rates the consequences of this one-ended loading are that the sample must be made smaller to reach equilibrium before significant plastic deformation accumulates. Taking an extreme example of a very long sample, regions closest to the input bar could fracture before the pulse reaches the output bar. Reducing the stress, strain and strain rate of the sample at failure would be impossible using strain gauge measurements. This limiting sample size is typically smaller than the nominal fragment length predicted by the theory (section 2.3). Finally, as discussed earlier, the fragmentation response of a body is dominated by the interplay of Mott release waves from multiple fracture sites. The combination of these issues make the Kolsky tensile bar test unsuitable for studying phenomena such as dynamic fracture and fragmentation at strain rates above $\sim 10^3 \text{s}^{-1}$.

### 3.2 Why Axially Symmetric Geometries?

The strain rates of interest to this study are on the order of $10^4 \text{s}^{-1}$ as this is the regime commonly experienced in situations where fracture and fragmentation are important, such as the design of munitions, mitigation systems, impact and ballistic events. The founding research in the field during the 1940s (discussed in section 2.3) by Gurney [31], Taylor [30] and Mott [3] focused on the behaviour of standard military hardware at the time. The results of these early studies made it apparent that there was a need for studying the dynamic response of materials under well defined conditions as existed for quasi-static conditions. For this a method of driving a large (to support multiple fracture initiation) sample into a uniform high strain rate tensile stress state with a rapid equilibration time is needed.
This can be achieved by expanding axially symmetric geometries, that is the ring, cylinder and sphere. As opposed to the Kolsky tensile test where the sample is loaded at one end the sample is now loaded uniformly over the entire inner surface. Compressive states have been investigated by loading the outer surface as developed by Nesterenko et al.\cite{nesterenko1996} but this technique is not discussed further in this study. An example of the initial geometry, loading surface and resulting ideal tensile stress state for expanding rings, cylinders and spheres is shown in figure 3.1.

![Figure 3.1: Loading faces (red) and the resulting stress state for the three axially symmetric geometries in uniform expansion.](image)

The expansion process begins with a load or drive over the red surface - the contemporary methods to produce this drive are described in section 3.3. Assuming the load takes the form of an impulse (i.e. is applied for a short time) and is even over the entire loading surface, a radial stress wave or shock will be launched into the wall of the sample. This wave propagates through and reaches the outer wall (or free surface), at which point it returns into the wall as a release wave and the whole thickness of the sample is in expansion. The reverberation of waves through the wall soon dissipates - as the sample accrues hoop strain the radial waves will be propagating through plastically flowing material\cite{plasticflow}. At this point the entire azimuth is in a uniform stress - strain - strain rate state determined by the expansion velocity and material properties.

Figure 3.2 demonstrates this process in a simulation of an expanding perfect ring, that is the wall thickness is equal to the height of 3 mm as in figure 3.1 left. The ring has been
3. DRIVING MECHANISMS

loaded with a driver consisting of an explosive charge inside a copper thick walled cylinder, over
which the ring is placed (further detail of this method in section 3.3.1 specifically figure 3.3e).
The two $x - t$ plots provide the radial stress and hoop stress through the ring wall with time.
At approximately 4$\mu$s the shock wave from the copper driver enters the ring, as a strong
compressive pulse in the radial direction. This also creates a compressive hoop stress as the
outer wall of the ring is yet to move. The initial loading wave reflects from the outer wall as a
rarefaction, demonstrated in the velocity plot on the right measuring the motion of the point
marked with a red X.

This loading pulse continues to reverberate in the ring, although it is quickly damped as more
radial strain is accumulated. From around 7$\mu$s on it is clear that the radial stress associated
with the loading has greatly reduced, and the ring is now in a state of uniform tensile hoop
stress as demonstrated in the centre $x - t$ plot and by the reduction in expansion velocity. It
is important to note that this simulation did not include a failure model for the ring, meaning
it retains strength and the velocity returns to and oscillates around zero at late times.
3.3 Existing Drive Mechanisms

There are three main techniques for driving axially symmetric geometries into expansion. This study concentrates on rings and cylinders. In chronological order, the techniques utilise explosives, pulsed power discharge and light gas guns. Each method has its own advantages and disadvantages with respect to attainable strain rates, sample size, possible materials and so on. The subtle idiosyncrasies of each method are also discussed, factors that must be taken into account such as shock loading of the sample, sample heating etc. that could affect the fracture and fragmentation response.

3.3.1 Explosively Driven Methods

The earliest work on expanding rings and cylinders was driven using explosive charges. This concentrated on characterising the effectiveness of munitions and warheads [30, 31]. Explosively driven expansion can either be through direct drive or can use a buffer cylinder. In the former, the sample is filled with an energetic material, typically a secondary ‘military’ polymer bonded explosive such as RDX [54]. Direct drive with initiation at a single end (figure 3.3a) is the most commonly used method found in the literature [55–60] owing to the simplicity of the experimental setup and the ability to compare the results with the well established empirical analyses of Gurney and Taylor. The experiment is readily scaled from a few grams of explosive up to several kg, the charge either being pressed and machined to size or cast directly into the sample cylinder. The initiation point can be changed, either using detonators at the end of the charge or an exploding wire throughout the entire length of the charge, initiating a large area simultaneously. The wire method (figure 3.3c) means that the entire cylinder is driven into expansion at the same time, providing a stress state closer to the ideal plane strain condition than detonation at the end(s). Hiroe et al have investigated these different methods of initiation, including the effects of the wire not being aligned down the centre of the charge [61]. Rings can be directly driven if stacked to contain the explosive, as performed by Goto et al [32]. This work compared a stack of rings (figure 3.3d) with an equivalent length cylinder, examining the results of the different stress state in the sample (the rings tending to uniaxial stress) on the fracture strain, finding that for their materials (AerMet 100 and AISI 1018 steel) the
uniaxial stress state provided a higher failure strain. Another method of driving rings with explosives was developed by Johnson, Stein and Davis [62] where a buffer was used between the explosive and the sample. Here, as per figure 3.3e, the ring is placed over a buffer cylinder of 4340 steel which contains a column of explosive which is detonated at each end simultaneously. The shock wave generated by the explosive propagates through the buffer wall and couples into the sample, launching it into expansion. Careful choice of geometry and materials can enable the ring to be launched into free expansion almost immediately, that is there is only one interaction between the driver and the sample. This technique has since been used for strain rates on the order of $10^3 \text{s}^{-1}$ [63, 64] through to $10^4 \text{s}^{-1}$ [53, 65]. Related to the HE drive technique is the exploding wire method. In this configuration the explosive charge is replaced with a thin conductive wire, through which a large pulse is discharged from a capacitor bank causing the wire to become a rapidly expanding plasma. The resulting radial shock wave can either drive the sample directly [66] or use a buffer as per the explosive method. Al-Maliky and Parry [67] used an exploding wire with various polymer buffers to drive polymer rings at up to $1.6 \times 10^4 \text{s}^{-1}$. The exploding wire method is included here instead of the electromagnetic drive section as the loading pulse is more comparable to that as produced by explosives.

Figure 3.3: Commonly used explosively driven cylinder (a - c) and ring (d, e) configurations (not to scale).

While the explosive drive is versatile in that the strain rate can be readily controlled through
3. DRIVING MECHANISMS

material choice, explosive mass and composition and it can be scaled to extremely large geometries such as full size warheads, there are several limitations. Firstly, they require special facilities such as blast chambers or ranges. The amount of explosive for a medium size cylinder experiment can be on the order of kg, typically out of reach for most academic research institutions. As the experiments are essentially bombs they are intrinsically destructive hence the diagnostics used must either be carefully shielded or disposable. For direct drive experiments as the sample fails the explosive products will be released from the fracture sites, the cloud from which can obscure diagnostics such as high speed cameras and laser based velocimetry leading to a premature loss of data. Gold and Baker have used flash X-ray radiography to image through the debris cloud produced by an exploding warhead [68] although as this images though the entire sample tracking individual crack growth can be difficult. Finally, the explosive can couple strong shocks (Grady [69] calculated between 30 and 60 GPa for one experiment) into the sample, causing internal damage and plastic work or heating before significant expansion has taken place. In many materials of interest to the field such as high strength steels this is sufficient to cause a phase change [70] which if used as a buffer material could mean a complex multi-wave structure is transmitted into the sample, complicating analysis of any free surface velocity measurements. In some cases other forms of damage such as spall have been observed around the ends of explosively driven cylinders, suggesting a non-uniform stress state [71].

3.3.2 Electromagnetically Driven Methods

As an alternative to the explosively driven ring of Johnson et al, Niordson developed a method where magnetic pressure is used to launch the ring [72]. At the centre of the device is the drive coil, a solenoid where the coil is well supported from the inside. The sample ring is then placed over the coil. A large capacitor bank via a high speed switch discharges a rapid current pulse (typically on the order of $10^3$ to $10^4$ A over 10s of μs) through the drive coil. This drive current can be measured with a Rogowski coil for use as an input in simulations. An example of the experimental geometry is shown in figure 3.4. Following Lenz’s law of induction, the drive current induces a current in the opposite direction in the sample. As the two currents

\footnote{An inductive pickup sensor suited to measuring large, rapid current pulses [73].}

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are opposing, the magnetic field around both the drive coil and sample will have the same
direction, causing a large magnetic pressure to act on the outside face of the coil and the inside
face of the ring. Remembering that the drive coil is supported, that is it can not contract, the
pressure acts to drive the ring outwards into expansion. Assuming that the induced current, $I_2$,
is approximately equal to the drive current, $I_1$, the pressure $P$ on the inside face of the sample
ring is given by:

$$P = \frac{\mu I^2}{2w^2},$$

(3.1)

where $I = I_1 = I_2$, $\mu$ is the permeability of the medium between the ring and coil and $w$
is the height of the ring [74]. Using a 12 $\mu$F capacitor bank charged to 20 kV Niordson was
able to drive aluminium and copper rings to radial strain rates around $5 \times 10^3$ s$^{-1}$. Forrestal
and Walling studied the response of 6061-T6 aluminium in the elastic-plastic regime, look-
ning at the Bauschinger effect in rings that have strained plastically but not to failure under
compression [75] and expansion [76].

Wesenberg and Sagartz expanded 6061-T6 aluminium cylinders at strain rates around
$10^4$ s$^{-1}$, finding good agreement between their experimental fragmentation results and Mott’s
statistical theory [74] (section 2.3.2). Similar research has more recently been performed by
Grady and Olsen [4] and Zhang and Ravi-Chandar [77]. From equation 3.1 it is clear that the
driving pressure is proportional to the square of the current. Pulse shaping techniques enable
adjustment of this loading, making the drive relatively ‘gentle’ when compared with the strong
shock characteristic pulse generated by explosive loading. An extensive critique and review of
the electromagnetic ring was completed by Gourdin [78], where some of the limitations were discussed. A major criticism of the technique is the undesired Joule heating of the sample ring, due to the large current induced and the resistance of the material. Whereas Grady and Benson estimated that the temperature increase from this was only around 10 K for a good conductor such as aluminium or copper, Gourdin measured the current in the sample during the expansion and calculated that this estimate is an order of magnitude out, a copper ring increasing by 150 K as a result of the load needed to reach expansion at $10^4 \text{s}^{-1}$. He demonstrated that depending on material and sample size there will be a limiting strain rate at which the sample will melt, $4 \times 10^4 \text{s}^{-1}$ for a 1 mm$^2$ cross section copper ring. A proposed solution was to use a composite sample, where the material of interest is placed over a highly conductive driver ring in which the majority of the current and therefore drive pressure is generated. This was validated with a copper / tantalum configuration, producing faster expansion with much reduced heating when compared to a plain tantalum ring. Electrical noise is also a consideration, with the large rapid fluctuations in electric field generated posing a threat to sensitive diagnostics such as digitisers and strain gauges. Finally, as the sample ring fractures electrical arcs form between the newly created free ends. If a form of high speed imaging is used, as by Zhang and Ravi-Chandar [77] this can provide a temporal history of fracture initiation.

3.3.3 Gas Gun Operation Overview

The last expansion method described uses a gas gun to drive the sample and is the basis for the majority of the experimental work in this study. While the gas gun is a very general term in shock physics, the design and construction is dependent on factors such the velocity range of interest and the projectile size and mass. The work in this study used two gas guns, at the Institute of Shock Physics, Imperial College and the Dynamic Response Group, Cranfield University. These facilities share a common design, both being single-stage double-diaphragm light gas guns as described by Hutchings and Winter [79]. As gas guns are typically used for plate-impact experiments, where two flat samples are brought into contact at high velocity, a brief overview of the operation of this gas gun design is given followed by the adaptations made for application to expanding rings and cylinders in section 3.3.4.
3. DRIVING MECHANISMS

Figure 3.5: Simplified cross section diagram of a single-stage double-diaphragm light gas gun as used in this study.

A simplified diagram of a single-stage double-diaphragm light gas gun is shown in figure 3.5. The single-stage designation means that the stored compressed gas acts directly on the projectile, i.e. there is only one driving stage. The firing process begins with evacuating the barrel, target tank and behind the projectile to a reasonably low vacuum (on the order of $10^{-2}$ Torr). This is important for two reasons, increasing the projectile velocity as there is much reduced air resistance acting on it and it minimises the effects of a bow-shock ahead of the projectile interfering with the target prior to impact. To further increase the available velocity helium (hence light gas gun) is used for the driving gas as it has the fastest sound speed, neglecting hydrogen. Hydrogen is not usually used for single stage guns as the large volumes used would produce an extremely dangerous situation when air is reintroduced to the target tank post-shot, creating a combustible environment that may contain very hot fragments of target or projectile. However, hydrogen is widely used as the second-stage driving gas in two stage guns as the much reduced volume makes venting the equipment safely much easier [80]. The double-diaphragm refers to the firing operation. The diaphragms are shown in figure 3.5 as the green areas between the reservoir and the breech, and the breech and the barrel. These are designed in a way to burst at a specific pressure $P_B$ where

$$P_1 > P_B > P_2,$$

(3.2)

$$P_B > (P_1 - P_2).$$

(3.3)

The chamber between the two diaphragms is now charged to $P_2$, followed by charging the reservoir to $P_1$. The value of $P_1$ is chosen from the desired projectile velocity and mass, with
3. DRIVING MECHANISMS

$P_2$ then chosen to suit the relationships in equations 3.2 and 3.3. The volume of the reservoir is much greater than the volume between the diaphragms. Charging in this order ensures that neither diaphragm experiences a pressure greater than the burst pressure $P_B$. When ready to fire, the chamber between the diaphragms is quickly dumped to atmosphere, meaning the diaphragm holding back the reservoir pressure is now under $P_1$ (remembering $P_1 > P_B$) and ruptures. The helium charge expands as a shock and ruptures the second diaphragm, followed by a shock ringing between the projectile and rear of the reservoir. Hence the projectile is accelerated with a series of shocks down the barrel. The projectile exits the barrel into the target tank, usually passing through some sort of velocity measurement system such as laser light gates. The target is mounted so as to reduce the impact tilt, the deviation in planarity between the projectile and target. The projectile and target are caught in a momentum trap, to slow the resulting mass without damage to the target tank. This can be designed to soft recover the samples without further damage for later analysis.

3.3.4 Winter’s Gas Gun Drive Expanding Cylinder

A projectile and target design for expanding cylinder experiments was first proposed by Winter and Prestidge [81]. The plate target in figure 3.5 is replaced with the target cylinder, mounted coaxially to the barrel. The cylinder is filled some distance along its length with a right cylinder polymer insert, Winter and Prestidge using a silastomer rubber. The projectile is also a right cylinder polymer, originally nylon with an outer diameter just less than the inner diameter of the target cylinder. This is launched down the barrel into the target cylinder. Care must be taken with target fabrication and alignment to ensure that the projectile can freely enter the cylinder without touching the inside wall. Once the projectile impacts the polymer insert both begin to deform, transferring the projectile’s axial momentum into radial motion behaving in a similar manner to a Taylor impact test [82, 83], only now confined by the sample cylinder. As a result the deforming polymers drive a region of the cylinder into expansion from the inside wall. A similar approach has since been used by Thornhill et al [84], where both the projectile and insert were polycarbonate. A simulation of this method used to expand a Ti-6Al-4V cylinder, 26 mm outer diameter and 3 mm wall thickness is shown in figure 3.6.
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Figure 3.6: AUTODYN simulation of a Winter geometry gas gun driven expanding cylinder experiment, 2D axial symmetry. Ti-6Al-4V cylinder, polycarbonate projectile and insert, projectile velocity 900 m s$^{-1}$ projectile velocity. Time given is after impact. Red circle highlights the area covered by the gauges used in figure 3.7.

The expansion profile will depend on the material used for each component, the cylinder wall thickness and the projectile velocity. Winter reports in later work [85] that use of stiffer materials such as aluminium for both the projectile and insert produces unsatisfactory expansion, as the deformation is not uniform around the circumference. With the polymer on polymer method at strain rates on the order of $10^3$ to $10^4$ s$^{-1}$ a Gaussian, bell-shaped profile is common, with the peak of this profile slowly translating along the cylinder due to the momentum of the projectile. The interface between projectile and insert can be seen moving in figure 3.6 with the expansion peak following behind it. This profile creates a range of radial strain rates from a maximum at the expansion peak down to zero at areas yet to be affected. If adequate diagnostics are used to capture the whole cylinder this data can be of great use to material model validation, as to reproduce the profile the model’s strain rate dependent stress-strain data must be accurate. Fracture occurs along the cylinder length, producing long fragments with the width of interest to statistical fragmentation models. These longitudinal cracks typically converge at some point or radial failure occurs at the expansion peak, effectively bifurcating the cylinder.

Figure 3.7 shows the stress in the cylinder wall with time for the model in figure 3.6 with data produced by gauges through the wall thickness located at the impact plane (circled red). The simulation was designed in such a way to enable direct comparison with the explosively
3. DRIVING MECHANISMS

Figure 3.7: Stress states and free surface velocity from a simulation of a gas gun driven expanding Ti-6Al-4V cylinder shown in figure 3.6. Left: Radial stress. Centre: Hoop stress. Right: Free surface velocity measured at the red X. (Compare with figure 3.2, page 48 for an explosively driven example.)

driven ring example in figure 3.2, i.e. the material, sample size and radial strain rate are approximately equal. From the plot of radial stress the initial loading is similar to the explosive method, a radial compressive stress being generated in the wall. However, whereas the wave in the explosive drive then reverberates in the wall the gas gun method supports this load for longer, at a much reduced intensity. Likewise after around 5 µs the wall is expanding under a uniform tensile hoop stress. The difference in loading is best demonstrated in the free surface velocity plot, with a longer rise time to peak expansion velocity with negligible oscillation of the wall, indicative of a more ‘gentle’ loading path using the gas gun drive instead of the explosive drive helping to avoid the associated complications of driving a strong shock wave into the sample.

The polycarbonate method has seen use in characterising a range of materials. Thornhill et al studied the effect of heat treatment on fragmentation in the steel alloy AerMet [84] at strain rates up to $2.5 \times 10^4 \text{s}^{-1}$. Vogler et al [86] have also used polycarbonate with a two-stage gun to give a projectile velocity of 1900 m s$^{-1}$ enabling small but thick walled cylinders to be driven, with velocimetry and high speed imaging being used to calculate the fragmentation toughness $K_f$ (section 2.3.3) for AerMet and a uranium-niobium alloy. The relationship between $K_f$ and density was probed in an extensive study of a range of materials from copper to tantalum-tungsten alloys [87]. Stirk and Winter have continued with the rubber insert working
3. DRIVING MECHANISMS

on stainless steel and copper-beryllium alloys [40, 88]. As an alternative to the plane strain conditions produced by an expanding cylinder, Liang et al. [89] have recently published a technique to drive a single ring into uniaxial stress expansion using a gas gun. The modification involves replacing the target cylinder with a thick, steel cylinder over which the sample ring is placed. This is much the same as the buffered explosive drive method. The radial shock produced by the expansion of the projectile and insert is transmitted through the steel driver and launches the ring into free expansion.

The gas gun method, either with a rubber or polymer insert, provides a useful compromise between the ability to drive large samples gained with explosives with the relative ease of access to equipment found with the electromagnetic drive. The gas gun is commonplace in most research institutions with an interest in dynamic phenomena such as fracture and fragmentation. The geometry is easily scaled, with the strain rate controllable through the projectile velocity. As gas guns are used for many other studies of shock and sub-μs events most are already equipped with laser based velocimetry and high speed imaging. Furthermore, any non-metallic material could be studied, as long as it is capable of supporting the weight of the insert and retains its shape under vacuum. However, the time taken to set up an experiment like this on a gas gun takes much longer than an explosive or electromagnetic one. The alignment of the target cylinder to the barrel needs to be exact to ensure that the expansion will be uniform. It is also relatively energy inefficient, as the longitudinal motion of the projectile must be converted to radial expansion. For large samples (over ∼50 mm or so) the projectile velocity needed to reach strain rates $>10^4 \text{s}^{-1}$ will be above the limit of many single stage gas guns. Where explosive and electromagnetic drives will have an electrical trigger system that can be used to synchronise diagnostics, an exact time of impact for a gas gun drive can be difficult to ascertain. One solution is to place a piezo trigger pin inside the centre of the insert, giving the time at which the projectile contacts the impact face. However, for small samples the diameter of this pin may be too large and begin to distort the expansion. For simulations the time of impact is important, as the behaviour of the driving material needs to be correct before one can examine the cylinder deformation. The time between impact and first motion of the cylinder wall matching the experiment would be a good indicator of the
model’s accuracy. The last disadvantage is that soft recovery of the fragments produced can be difficult. Whereas explosive and electromagnetic drives can have the sample contained in a small box and the majority of debris be collected, the gas blast following the projectile in a gas gun will tend to destroy any forms of confinement around the cylinder. Smaller fragments can become entangled in the momentum trap (typically filled with cotton rags) to a point where recovery is impossible, meaning the percentage of mass recovered in a gas gun experiment is typically lower than with the other drive methods.

### 3.4 Drive Method Summary

Three methods of driving rings and cylinders into expansion have been demonstrated. Even though each method has advantages and disadvantages, displayed in table 3.1, the end results are largely similar. Strain rates on the order of $10^3$ to $10^5$ s$^{-1}$ are within reasonable reach of all drives, the choice inevitably coming down to the experimental facilities available to the investigator. One major difference of the gas gun drive is that some of the material used to drive the expansion is isolated from the sample until the expansion begins. Moving to a design where all the drive comes from the projectile, such that it flows around the insert instead of them both deforming, would enable the temperature of the sample to be adjusted without affecting the expansion drive. This is impossible with the explosive and electromagnetic drive as a temperature increase or decrease will cause problems such as detonation of the explosive or melting of the drive coil. Modification of the gas gun method to facilitate this are discussed in the related experimental parts of this study, chapter 7.
### Table 3.1: Advantages and disadvantages of the three drive methods

<table>
<thead>
<tr>
<th>Drive Method</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Explosive</strong></td>
<td>+ Can be used in a variety of geometries + Can provide the highest strain rates</td>
<td>- Requires special facilities - Explosive products can obscure diagnostics - Intense shock in sample</td>
</tr>
<tr>
<td><strong>Electromagnetic</strong></td>
<td>+ Very little debris produced + Rapid turnaround + Relatively gentle loading + Arcing in the sample provides a record of failure strain with high speed imaging</td>
<td>- Sample must be conductive or use a buffer - Resistive heating of sample limits available strain rates - Can only drive small samples (Wall thickness ~1 mm)</td>
</tr>
<tr>
<td><strong>Polymer Gas Gun</strong></td>
<td>+ Can drive large samples + Sample can be any rigid material + Can drive rings or cylinders + Lowest risk of damage to diagnostics</td>
<td>- Time consuming experimental setup - Complicated timing of diagnostics - Fragment soft recovery difficult</td>
</tr>
</tbody>
</table>
Motivation and Aims

This chapter builds on the theoretical work and the drive methods described earlier to set out the motivation and aims for the experimental work in this study. The areas that would benefit from further investigation were identified as the effects of the stress state and the initial temperature in the sample. Stress state, or the history of the loading in the sample, controls the loading that leads to failure and as such decides the fracture mechanism(s) that can operate. Similarly the initial temperature affects the response and deformation of the sample to loading, and can lead to activation of fracture mechanisms such as adiabatic shear banding as described in section 2.2.2. These two areas are studied with the same material, Ti-6Al-4V (percentage by weight, also referred to as Grade 5 titanium alloy). Ti-6Al-4V is the most widely used titanium alloy, particularly in the aerospace and defence fields due to its high specific strength which is retained to high temperatures and is typically used up to around 600 K [90]. Owing to its popularity Ti-6Al-4V is relatively well characterised in the shock / impact regime, having been studied with Kolsky compression, tension and torsion bars [91], plate impact experiments [17] [92] [93], ballistic impacts [94], Taylor rod tests [95], imploding cylinders [24] and expanding cylinders [87]. There has also been substantial work on developing material models [96] [98] enabling the use of hydrocodes to assist in experimental design. However, Ti-6Al-4V is an anisotropic material owing to its hexagonal-close-packed structure, and is highly sensitive to grain structure and preferential textures depending on the processing to reach the final sample. Finally, it has very poor thermal conduction making it susceptible to failure through adiabatic shear banding at strain rates above $10^2$ s$^{-1}$ [26] due to the inability to dissipate heat generated by plastic deformation. Hence Ti-6Al-4V was chosen as it is of interest to the field, has a strong foundation of research and exhibits interesting fracture behaviour at high strain rates. As an aside, the poor thermal conduction increased the challenge with the work on temperature in the latter part of this study, where if another metal had been studied such as copper or aluminium the thermal equilibrium would have been more
easily attainable and as such provided a good test for the technique. It should be noted that this study primarily concentrates on the methodology side of the experiments, that is the development and validation of the loading techniques and a measure of their applicability. Where results are shown these form relatively small data sets for the highly statistical nature of fragmentation and as such more data would be required to arrive at confident numerical values.

4.1 Motivation

4.1.1 Stress State in the Sample

While the influence of stress state on fracture has been extensively studied under quasi-static loading, high strain rate fracture and fragmentation studies have concentrated on rings and cylinders as covered in section 3.2. In general a ring, i.e. a square cross section, will tend to a steady state of uniaxial stress. In this condition the ring can be considered as a rod that is uniformly straining along the length direction at all points along the length, as in the models used by Mott and Grady et al. This is the same state generated as the typical quasi-static tensile tests performed on servo-hydraulic machines. A uniformly expanding cylinder deforming where the radial strain rate is uniform along the entire length (note that end effects limit the range of this assumption to the central regions) will tend to a state of plane strain, such that there is no strain along the length direction. Each of these conditions has its own governing set of principal stresses.

Studies to present have mostly focused on comparing the results of rings against cylinders. Goto et al [32] performed experiments on directly explosively loaded steel rings and cylinders, both having a wall thickness of 3 mm with the cylinders 20 cm long. Two separate configurations were used, one with velocimetry and one with fragment recovery, meaning no direct measurements of the expansion or strain rate were made on the material that was used for fragment analysis, the authors making the assumption that the technique was repeatable. Zhang and Ravi-Chandar have published a series of extensive papers on aluminium and copper expanding rings and cylinders [77, 99, 100] at high strain rates with cylinder lengths between 1 and 10
times the wall thickness. They observed a change from necking in rings to sheet localisation in cylinders, although as the experiments used an electromagnetic launcher the wall thickness was very thin. Inconsistencies in the magnetic pressure from this drive also created non-uniform expansion, especially for the cylinder cases. Velocity and strain rate measurements were made with the high speed imaging data, leading to large uncertainties and poor temporal resolution.

With the above considered, the aims of the work on stress state (chapter 6) were to develop a drive that could launch rings and cylinders at controlled strain rates regardless of their geometry, while allowing for laser based velocity interferometry and fragment recovery on the same experiment. Explosive drive with a buffer was chosen as it was the available facility at that time. Likewise the sample size was determined by fact that the raw material was provided in tube form. The primary aim was to reach a radial strain rate of $10^4 \text{s}^{-1}$ in a relatively large Ti-6Al-4V sample with a wall thickness of 3 mm and lengths from 1 to 4 times the wall thickness. With the aid of simulation data this would enable investigation of the fracture mechanism and resulting fragmentation for a known stress state, expansion velocity and strain rate.

### 4.1.2 Initial Sample Temperature

The models described in the previous chapters make little allowance for the influence of temperature. Mott (equation 2.12, section 2.3.2) assumed instantaneous fracture and a rigid-perfectly plastic material response. The only temperature dependent parameter is the flow stress of the material. It is well known from quasi-static studies that the sample temperature can have a pronounced effect on the failure, such as the ductile to brittle transition at low temperatures particularly evident in BCC metals [6]. This behaviour has also been observed in high $\beta$ phase content Ti-6Al-4V samples [101]. Moving towards dynamic events it has been shown that the spall strength of a metal drops with increasing temperature [102]. Grady’s models for fragmenting cylinders use his fragmentation energy, described in table 2.3 of section 2.3.3. While this value changes depending on the type of fracture observed (brittle, ductile or though adiabatic shear banding) this is very much a reactive instead of predictive model, i.e. one must know the type of fracture that will occur before one can predict the fragmentation.

With this considered the aim was to be able to study the effect of the initial sample tempera-
4. MOTIVATION AND AIMS

ture on which fracture mechanisms presented and how that affected the resulting fragmentation. A strain rate of \(10^4 \text{s}^{-1}\) was desired as in this regime all three of the fracture types mentioned earlier (brittle, ductile and ASB) are active and this rate is typical of that experienced in ballistic and impact events. Similar to the stress state work it was thought necessary to be able to use velocimetry and fragment recovery on the same experiments, to make the data as useful as possible for future model development. A range of initial temperatures from 100 K to 1000 K was planned to ensure that the typical operating range of most metals would be covered.

The gas gun drive method was chosen as the basis for the work, with many developments made to the original technique of Winter to make the experiment suitable for work at high and low temperatures while being compatible with high speed imaging and velocimetry. Explosives and electromagnetic launchers were not pursued due to the complications that result when they are heated or cooled. Two sets of experiments will be covered, the first where the geometry modifications are tested with flash X-ray radiography and a second where the temperature control system is validated on full-scale Ti-6Al-4V cylinders.
This chapter provides an overview of the diagnostics used in the experimental work of this study. Dynamic fracture and fragmentation experiments are typically on the order of tens to hundreds of µs in duration. This time window contains a wealth of information that needs to be captured accurately for comparison with and validation of material models and simulations. As large scale experiments can be expensive both in cost and time to prepare, simultaneous use of multiple diagnostics is desirable. This becomes especially important where fragmentation is concerned, as the full history of the sample needs to be recorded to ensure that the statistical nature of the fragmentation can be linked to the loading conditions and reveal any experimental issues that could produce anomalous results.

There are several critical measurements during an expanding ring or cylinder experiment. The most important is the expansion velocity, as many subsequent parameters can be extracted from this such as radial displacement, strain and strain rate. These characterise the loading history of the sample. Secondly, the point of failure (strain at first fracture) and the temporal activation of subsequent fracture sites is key to the models of fragmentation set out in section 2.3 requiring a high speed camera or video system. Flash X-ray radiography is often used with explosive trials as it has the ability to penetrate through the detonation products and debris and image the cylinder where optical cameras could not. These diagnostics applied to the experiment are defined as primary or in situ diagnostics. As with any type of measurement, there is always a compromise between the spatial and temporal resolution. Figure 5.1 provides a rough map of the application ranges of the diagnostics described here. The laser based velocimetry methods can provide ns time steps but only for certain points on the sample. As we move to a larger field of view through radiography to framing and high speed cameras it is clear that as more of the sample is observed the time between measurements must increase, hence the importance of using multiple systems to extract as much information as possible is reiterated.
Measurements made outside of the actual experiment are defined as secondary diagnostics. As this study used Ti-6Al-4V, which can have significant microstructure and texture depending on processing, it was important to characterise the starting material. Light microscopy (LM) and electron microscopy (EM), specifically electron backscatter diffraction (EBSD) techniques were used for this. These give an image of the grain structure and orientation in the sample. Recovered fragments were prepared and subjected to LM and EM on arrested fractures and fracture surfaces to ascertain the failure mechanisms that occurred.

5.1 Laser Based Velocimetry

Two forms of laser based velocimetry were used, VISAR (velocity interferometer system for any reflector) and PDV (photon Doppler velocimetry). While the systems are quite different (VISAR being a velocity interferometer and PDV being a displacement interferometer) they are both capable of high temporal resolution measurement of velocities on the order of $10^3 \text{ m s}^{-1}$. The systems are described in order of use in this study.

5.1.1 VISAR: Velocity Interferometer System for Any Reflector

The VISAR was first published by Barker and Hollenbach in 1972. In short, the system is a wide angle Michelson interferometer where the input light has been collected from the target, as shown in figure 5.2. The light from the target is split into two legs at the beam splitter BS. Leg 1 reaches mirror M1 and returns to the beam splitter. Leg 2 passes though an eighth wave...
plate WP and an etalon E on each pass as it reflects back from mirror M2. The refractive index of the etalon means that the apparent position of mirror M2 is actually closer to the beam splitter at position M2’. By configuring the legs such that M1 and M2’ are at the same distance from the beam splitter spatial coherence of the light is not required, hence the input light can be from a diffuse surface such as a shocked target.

![Schematic of a conventional VISAR, from Dolan [105]](image)

The physical difference in leg length introduces a time delay $\tau$ in leg 2 hence an interference fringe pattern is created when the legs are recombined at the beam splitter. As the surface being measured accelerates or decelerates the Doppler shifted light returning will interfere with light from a time $\tau$ earlier, which will have a different shift. This means the interference fringe intensity will vary with time at a rate defined by the surface velocity. The velocity $v$ can be calculated using the VISAR approximation [105],

$$v(t) \approx v_i + \frac{\lambda F(t)}{2\tau(1 + \Delta\nu/\nu_0)} \quad (5.1)$$

where $v_i$ is the initial velocity, $\lambda$ is the laser wavelength, $F(t)$ is the fringe count and $\Delta\nu/\nu_0$ is a refractive index correction used if the surface is backed by a window (zero otherwise). As the output light intensity is sinusoidal, there will be times around the intensity minima and maxima where the variation in intensity is difficult to discern. For this reason a wave plate is placed in the delayed leg before the etalon, delaying the $P$ polarisation component by $90^\circ$ relative to $S$. The output of the interferometer is then sent through a polarising beam splitter with each component recorded by a separate photodetector. This means that when one component is at
an inflexion point the other component can be used to gather the change in fringe intensity more accurately. Also, the direction of acceleration can be extracted from the change in relative phase between the two polarisations. The beam intensity monitor is used to normalise the two signals to eliminate ambiguity in changes of intensity.

The system used in chapter was as per above, with a 514 nm probe laser wavelength $\lambda$ and a velocity per fringe constant VPF or $\lambda/2\tau$ of 305 m s$^{-1}$. The target was not backed with a window material hence no correction was needed. The data was analysed with the standard method as per Dolan where the two detector signals were normalised by the beam intensity monitor then the ellipse formed by plotting $D_1$ against $D_2$ used to examine for missed fringes while $v(t)$ was calculated with equation and the VPF above. The raw data collected by the beam intensity monitor and two detectors is presented in appendix C.

### 5.1.2 PDV: Photon Doppler Velocimetry

The gas gun driven expanding cylinder experiments in chapter used PDV (also known as HetV, heterodyne velocimetry in the UK) to measure the projectile velocity and cylinder expansion velocity. Developed by Strand et al in 2006, the system takes advantage of optical components related to the telecommunications industry, specifically 1550 nm hardware. The system used in this study was assembled by Dr. David Chapman of the Institute of Shock Physics. A schematic of the optical system is shown in figure 5.3. The system was entirely fibre-coupled apart from the small distance between the probe and the target surface. Two configurations were used, referred to as standard and upshifted. At the core of the PDV system is a component called a circulator. Here, this has three ports numbered 1-3. Light that enters port 1 exits from port 2, and likewise from 2 to 3. The efficiency in the opposite direction is extremely low ($<10^{-6}$). This and the coupler are standard telecommunications band hardware.

In the diagram, the probe laser at a frequency $f_1$ (black lines) is sent to port 1 of the circulator, exits port 2 and arrives at the target surface via the probe. Full details of the probes used are given in the relevant experimental sections. The reflected Doppler shifted light ($f_r$, blue lines) is collected by the probe and returns to the circulator where it enters port 2 and exits port 3. The return signal is then mixed with a reference signal $f_2$ at the coupler,
generating a beat frequency $f_b$ (purple lines). The velocity of the target surface is related to the beat frequency through the following relationship:

$$f_b(t) = 2 \left[ \frac{v(t)}{c} \right] f_1,$$  \hspace{1cm} (5.2)

where $v(t)$ is the surface velocity and $c$ is the speed of light. The configuration depends on where the reference light is sourced. For the standard configuration a portion of the probe laser was split off and used for the reference, i.e. $f_1 = f_2$. An IPG Photonics ELR-2-1550-LP-SF was used as the probe laser. In the upshifted configuration a separate laser (NP Photonics ‘Rock’ Fibre Source) with a slightly different frequency was used as the reference, the purpose of this will be explained after the data analysis.

The beat frequency was recorded with a high-bandwidth digitiser (Miteq DR-123G-MV) and oscilloscope, either a Tektronix DPO71604 or a LeCroy Wavemaster 816Zi-A (both rated to 16 GHz). The resulting data was a time-varying frequency which was then processed with a short-time Fourier transform (STFT) producing a power spectrum of frequency with time as per the typical methods \[108\] \[109\]. A Hamming window was used in all analyses. A Gaussian was then fit to each time step of the power spectrum to give the peak frequency and used with equation (5.2) to extract the velocity. The projectile velocity was measured with the standard configuration. Here the velocity was relatively constant over the time measured, usually the last 30\,\mu s or so before impact. Due to this a large number of time points could be included in the STFT window producing an accurate measure of the beat frequency and therefore projectile
velocity. However, from equation 5.2 it is clear that as the velocity tends to zero (or is small, such as in the initial stages of the surface acceleration) the beat frequency will also tend to zero. Hence the STFT window must be made excessively large to contain enough frequency cycles to determine the peak frequency, reducing the temporal resolution.

For these reasons upshifted PDV was developed [110] where the reference laser frequency differs from the input laser frequency. This introduces a non-zero velocity beat frequency that is dependent on the difference between the probe and reference lasers. The system used here had an NP Photonics Rock Source as the reference laser, which is tuneable over a wide range such that the zero-velocity beat frequency could be set as desired, typically at 5 GHz. Now at low velocities there are an adequate number of complete cycles to maintain fine temporal resolution, although there is an offset velocity that needs to be removed after the analysis. An example spectrogram is shown in figure 5.4 using a Hamming window with 20000 points (at 25 ps per point) and a window overlap of 75 percent. The velocity offset is clearly visible until around 3 µs, with this removed the peak velocity at 16 µs is 255 m s\(^{-1}\). Upshifted PDV was used for the cylinder expansion velocity measurements as features on the order of 10 m s\(^{-1}\) were expected in the early time data.

![Example upshifted PDV spectrogram, showing the zero-velocity beat frequency offset at approximately 4.91 GHz.](image)

Figure 5.4: Example upshifted PDV spectrogram, showing the zero-velocity beat frequency offset at approximately 4.91 GHz.
5.2 High Speed Imaging

Where the laser velocimetry systems described earlier excel at fine temporal resolution they can only measure a single point on the surface. This can be extended by using multiple probes but the area in between will still be an extrapolation. For experiments where the deformation can be non-uniform such as along the length of an expanding cylinder it is important to have an imaging system to capture the whole profile. This also assists in interpretation of the velocity data and can explain unexpected results. Imaging is also the most reliable and accurate way of determining the point of failure. This study used three imaging systems, flash X-ray radiography, high speed video and a framing camera.

5.2.1 Flash X-Ray Radiography

Fragmentation experiments often present a challenge to imaging diagnostics in that the sample ring or cylinder can become obscured by the drive material, most evident in explosively driven work. Similarly, with gas gun driven expansion, the drive mechanism needs to be well characterised. As the sample cylinder is typically optically opaque only radiographic techniques can observe the internal behaviour. A flash X-Ray radiography system is one method of achieving this. An X-ray source is placed one side of the sample and produces a pulse of X-rays. Depending on the density and the path length through the sample a certain percentage of the initial beam will be attenuated. The other side of the sample is a detector, which records the high energy X-ray photons as interpretable data.

The flash X-ray system used for some of the work in this study was a Scandiflash Model 300, with four independent X-ray channels. Each channel consisted of a power supply, a Marx generator that supplies up to 300 kV, and the X-ray head. Each head contained a heated cathode and a target anode. The Marx generator was discharged across these, accelerating electrons from the cathode into the anode. A combination of bremsstrahlung and K-shell emission from the target nuclei produced a continuous spectrum of X-ray photon energies with peaks corresponding to the target material’s electronic structure. Hence the target material and accelerating voltage from the Marx generator controlled the distribution in X-ray photon energies produced. On the opposite side of the sample for each head was the film cassette.
These were covered by ballistic polycarbonate plates to protect from fragments and debris. The film cassette contained a scintillator and a piece of film. The scintillator emits light in another regime when struck by high energy photons such as X-rays; ceramic terbium-activated gadolinium-oxysulfide was used which has an emission peak at 545 nm \[ \text{[111]} \]. This green light was then captured with HDC-G (high contrast, green sensitive) film. The exposure was set by the length of the X-ray pulse, 20 ns with this system. The accelerating potential was adjusted to provide the best contrast between the materials of interest. The ability to resolve edges depends on the sample geometry and the spot size of the X-ray head. Imaging a round object such as a cylinder will always give softer or more blurred edges than a square example, as instead of an abrupt change in path length the distance tends to zero gradually towards the edge of the cylinder. A larger spot size also introduces blur as photons from the whole source area can arrive at the same point on the scintillator and the recorded image becomes a convolution of the sample and the spot size. The structure of the scintillator and film also cause an inherent ‘graininess’ in the image. The film was digitised with an Epson Perfection V700 at 6400 dpi and 16 bit depth greyscale with post processing completed in ImageJ. Figure 5.5 (left) shows an example flash radiograph of a 6061-T6 aluminium cylinder, steel insert and polycarbonate projectile taken with the system described here. The X-ray heads were arranged around the gas gun target tank every 45°. They could be triggered independently, allowing for a temporal record of the deformation to be compiled. Alternatively, orthogonal heads could be triggered simultaneously to capture the deformation of a sample from two views at once to examine the axial symmetry of the experiment. Further details on the location of the X-ray system relative to the target are in the relevant experimental chapter [7].

5.2.2 High Speed Video and Framing Cameras

Two high speed imaging systems were used, a high speed video and a framing camera. The former was a Phantom v1610 manufactured by Vision Research. The interframe time is dependent on the resolution chosen. To achieve frame rates over $10^5 \text{s}^{-1}$ the amount of the sensor used must be reduced. For example, to image every 10 µs the resolution was set at $384 \times 288$ pixels. Increasing the speed to one every 5 µs meant reducing this further to $256 \times 160$. Beyond
5. DIAGNOSTICS

this the resolution limits the amount of quantitative data that can be extracted. The camera has a black and white sensor that produces 12 bit depth images. An example image is shown in figure 5.5, centre.

Figure 5.5: Comparison of different high speed imaging diagnostics on similar experiments. Left: Flash X-Ray radiography. Centre: High speed video, Phantom v1610. Right: Framing camera (silhouetted), IVV UHSi 24.

The framing camera was an IVV UHSi 12/24 from Invisible Vision. This is an intensified camera, where the sensor is divided into twelve $1000 \times 1000$ segments. Each of these are read individually, at a rate up to one image every 5 ns ($200 \times 10^6$ s$^{-1}$ frame rate). This sensor then needs $10 \mu$s to clear and the twelve frames can be read again so a maximum of 24 images per experiment can be recorded although the second twelve will show ‘ghosting’ from the previous twelve due to the decay time of the phosphor in the intensifier. Note that the frame rate no longer depends on the sensor resolution meaning high quality images can be taken at any frame rate. However, due to the nature of the sensor the IVV requires much more intense lighting than the Phantom camera. For this reason these cameras were used in slightly different applications. Lighting was provided by two Bowens Gemini 1500 W flash guns which had a rise time (time to peak light output) on the order of 100 $\mu$s. The Phantom camera was placed the same side of the target as the flash guns, front lighting the sample. As this camera is more sensitive it provides more detail on the cylinder surface, making it possible to track fracture initiation and growth. The IVV was placed on the opposite side such that it observed a silhouette of the cylinder, early work showed that it was difficult to provide enough light to this camera to observe surface fracture. However, the sharp edge created with a silhouette was readily seen and produces high resolution images for accurate tracking of the cylinder edges to compare with the PDV velocimetry data. An example of this is shown in figure 5.5, right. Further
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details such as exposure time, focal length and aperture are given in the relevant experimental sections.

5.2.3 Triggering Pins

The above diagnostics needed to be accurately triggered and timed to the experiments. For the explosive work a simple ionising pair of copper strips were attached to one end of the charge which produced a voltage that triggered the oscilloscopes. For the gas gun shots, a make pair was used in conjunction with a conditioning circuit. The projectile was given a conductive ring around the shoulder, which as it exited the barrel made a connection across two bare wires (the details of this pair and their location are given in the experimental chapters). These bare wires connected via BNC cables to the conditioner. The circuit diagram for this is in figure 5.6 with the switch on the right representing the make pair. An external power supply charged the capacitor to a chosen voltage with resistor R1 in series. When the make pins were connected by the projectile the capacitor then discharged in series with R2, the voltage over which is then measured with another cable. This produced a well defined voltage spike that could be used to trigger diagnostics reliably. The polarity of the pulse could be set to rising or falling edge depending on which way the probes around R2 were applied.

![Figure 5.6: Triggering pin circuit diagram.](image)

5.3 Material Characterisation and Analysis

The Ti-6Al-4V was characterised before and after experiments. This was to observe the starting microstructure and texture and then determine which fracture mechanisms had occurred during
failure. For this a mixture of optical and electron microscopy was used, including electron backscatter diffraction. These facilities were kindly provided by the Materials department at Imperial College London with a great deal of assistance from Dr. Terry Jun.

5.3.1 Ti-6Al-4V Sample Preparation

The preparation process for both types of microscopy was very similar. The Ti-6Al-4V was first sectioned with a Struers Accutom-50 with water cooling of the sample to reduce the amount of heating and damage generated by the cutting process. The sections were then mounted in a heated press bakelite mould to enable preparation of the desired surface. Grinding with water lubrication was performed in steps from 240 to 4000 grit for approximately 15 minutes at each stage. Polishing was then performed with a 0.05μm colloidal silica suspension (Struers OP-S) for a further 15 minutes followed by 30 seconds etching with Kroll’s reagent, a mix of 2% HF, 10% HNO₃ and 88% distilled water by volume. To relieve surface stresses induced by the grinding process the polishing and etching process was repeated three times. The final etch was omitted for optical imaging under polarised light and electron backscatter diffraction work.

5.3.2 Light Microscopy

For magnification up to around 50× optical microscopy was performed with an Olympus BX51. This has the option to image with polarised light, which can reveal preferential grain orientation or texture in the material as shown in figure 5.7 left. The bands of light and dark material are regions where the grains are preferentially aligned, this is particularly evident when looking at hexagonal-close-packed materials such as Ti-6Al-4V. To examine the grain structure the samples were etched before imaging, this is shown in figure 5.7 right with the α phase in yellow and β phase in black. Note that the larger area of black in the bottom left of the image is an arrested crack propagating into the material.

5.3.3 Electron Microscopy

The fracture surfaces left at the edges of fragments were observed with a scanning electron microscope, specifically a JEOL JSM-5610LV. The benefit of SEM imaging is that a large
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Figure 5.7: Light microscopy examples, Ti-6Al-4V. Left: 2.5× magnification under polarised light. Right: 50× magnification, etched with Kroll’s reagent under normal illumination.

depth of focus is achieved, allowing for studies of the topography of a surface. The example image in figure 5.8 left shows a fracture surface of a Ti-6Al-4V fragment. The lighter areas in the image correspond to high points, such as the edges of the parabolic dimples left as grains separate under shear loading here (vertical direction). From these images we can get an idea of grain size and loading direction. Some SEM work was also done on the polished and etched samples, as in figure 5.8 right showing the α phase material now as dark areas.

Figure 5.8: Examples of SEM imaging in Ti-6Al-4V. Left: Fracture surface from failure under shear loading. Right: SEM of a polished and etched sample, α phase in black, β phase in white.

5.3.4 Electron Backscatter Diffraction

Finally, quantitative analysis of the grain size, structure and orientation was performed using electron backscatter diffraction. In brief, the sample is placed in the electron beam inside an SEM at an angle of 70° to the beam. A detector is then placed near the sample such that the
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detector is at 90° to the beam. Where the incident electrons satisfy the Bragg conditions in
the sample they backscatter and create diffraction patterns on the detector known as Kikuchi
bands [112]. These can then be indexed to determine the orientation of the lattice in terms of
the Euler angles with respect to a reference lattice orientation at that point. The sample is
translated through the beam to raster an area, creating an orientation map of the surface of
the material. The microscope used was a Zeiss Auriga FIB-SEM in conjunction with a Bruker
e-Flash detector. The indexing was performed in the Bruker eSprit software, then exported
as raw data containing the phase and Euler angles of each x-y point in the map. This was
then post-processed using the open source Matlab toolbox MTEX [113]. An example map of
highly textured Ti-6Al-4V is shown in figure 5.9. MTEX is a powerful suite that can provide
information on the grains’ length, area, perimeter, inverse pole maps and so on. Where used
in the experimental chapters details are given as to how the grains are defined from the raw
angle data.

Figure 5.9: EBSD orientation map of Ti-6Al-4V showing strong texture in a horizontal band. Red
grains correspond to the \{0001\} plane being normal to the observer.
This chapter describes a series of experiments on explosively driven expanding Ti-6Al-4V rings. The aim of these was to examine the effect that stress state has on the dynamic fracture and fragmentation process. The ring length was adjusted to study states from uniaxial stress through to plane strain at radial strain rates of $10^4 \text{s}^{-1}$. Single point VISAR was used to record the expansion velocity with recovered fragments examined with optical and electron microscopy to determine the fracture mechanism. Under a uniaxial stress state the samples were observed to fail through necking, where plane strain produced tensile shear cracking at $45^\circ$ to the radius. An intermediate state showed internal damage and spall around the entire circumference of the ring. This work was performed in collaboration with Dr Sergey Razorenov and the Institute of Problems of Chemical Physics, Russian Academy of Sciences on site at their laboratories in Chernogolovka, Moscow Oblast, Russia.

### 6.1 Experiment Overview

The reasons behind using rings and cylinders for dynamic fracture and fragmentation research were described in section 3.2. These two axially symmetric geometries can be described by an aspect ratio, that is the ratio between the wall thickness and the length of the sample. For example, a perfect ring with a square cross section will have an aspect ratio of 1:1. As the sample becomes longer and tends towards a thin walled cylinder the aspect ratio decreases. When these geometries are launched into expansion they will experience a different stress state. A perfect ring will reach a steady state of uniaxial stress, *i.e.* pure hoop stress. A long thin walled cylinder will approach plane strain conditions, such that there is no strain along the length of the cylinder. If we were to extend this approach to a uniformly expanding thin
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spherical shell each part of the sample would be in equal biaxial tension. These states are demonstrated as a function of the principal stresses $\sigma_1$ and $\sigma_2$ on a two dimensional von Mises yield surface in figure 6.1. On the right of the figure is a cylinder showing the directions the principal stresses act in for all geometries, with $\sigma_1$ being hoop stress, $\sigma_2$ axial stress and $\sigma_3$ (not shown and assumed to be zero in all cases) radial or through thickness stress.

![Diagram of stress states](image)

Figure 6.1: Left: Tensile stress states on the von Mises yield surface for an expanding ring, cylinder and sphere. Adapted from Warnes et al [53]. Right: Principal stresses 1 (hoop) and 2 (axial) on a thin walled cylinder.

The difference between stress states can be quantified with a parameter called the stress triaxiality, $\eta$, a measure of how directional the loading in the sample is. The following equations are used to calculate values for $\eta$:

Hydrostatic pressure, $P$:

$$P = \frac{1}{3} (\sigma_1 + \sigma_2 + \sigma_3),$$  \hspace{1cm} (6.1)

von Mises effective stress, $\sigma_m$:

$$\sigma_m = \sqrt{\frac{(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_1 - \sigma_3)^2}{2}},$$  \hspace{1cm} (6.2)

which combine as follows:

$$\eta = -\frac{P}{\sigma_m},$$  \hspace{1cm} (6.3)

with the minus sign being added to ensure that a tensile state has a positive value for $\eta$. The relationships between the principal stresses assumed for each geometry are shown in table 6.1.

There are several assumptions made, the first being that in all cases the stress in the radial direction, $\sigma_3$, is zero. For this to be accurate the wall thickness of the sample must be much less
than the radius (maximum of ∼1:5). It is also a steady state assumption, meaning that these ideal states will not be reached until the sample is in free expansion and the radial stress or shock wave generated by the loading has dissipated. In the case of the cylinder the relationship between the two principal stresses is set by the Poisson’s ratio of the material and reaches 0.5 after yielding \[53\], hence the value of 0.577 corresponds to the late time plastic deformation from expansion.

<table>
<thead>
<tr>
<th>Geometry</th>
<th>Stress State</th>
<th>Principal Stresses</th>
<th>Stress Triaxiality, (\eta)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ring</td>
<td>Uniaxial Stress</td>
<td>(\sigma_1 \neq 0)</td>
<td>0.333</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\sigma_2 = \sigma_3 = 0)</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\sigma_1 \neq 0)</td>
<td></td>
</tr>
<tr>
<td>Cylinder</td>
<td>Plane Strain</td>
<td>(0 \leq \sigma_2 \leq 0.5\sigma_1)</td>
<td>0.577</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\sigma_3 = 0)</td>
<td></td>
</tr>
<tr>
<td>Sphere</td>
<td>Equal Biaxial Stress</td>
<td>(\sigma_1 = \sigma_2)</td>
<td>0.667</td>
</tr>
<tr>
<td></td>
<td></td>
<td>(\sigma_3 = 0)</td>
<td></td>
</tr>
</tbody>
</table>

The experiments in this section were performed to study the influence of the loading or stress triaxiality on the fracture mechanism and resulting fragmentation of Ti-6Al-4V at strain rates around \(10^4\) s\(^{-1}\). The expansion drive development and manufacture is discussed, followed by a thorough characterisation of the as-received sample material. Results are then presented along with concluding remarks.

### 6.2 Buffered Explosive Drive Mechanism

The drive mechanism was a buffered explosive charge, the type briefly discussed in section 3.3.1 and figure 3.3e. This technique evolved from a design originally prepared by Johnson et al. In this original configuration a solid right cylinder of 4340 steel was used as the buffer, or driver. From one end a blind hole was drilled into this, which received a pressed charge of Composition C-3 explosive. The hole was then capped with a seismographic detonator. The sample ring of interest was pressed onto the outside of the driver until it rested against a shoulder, locating the ring around the location of the explosive charge. The samples were 50.8 mm [2"]
in diameter with a 2.54 mm [0.1"] square cross section (aspect ratio of 1:1). The displacement of the ring from the driver was measured with high speed photography, enabling Johnson et al to calculate stress-strain curves for a range of materials at strain rates up to $0.8 \times 10^4 \text{s}^{-1}$. However, the stress calculations require measuring the deceleration of the ring due to the internal hoop stress. As such Johnson et al had to double differentiate the displacement data from photographs leading to large uncertainties. While analysis methods that avoided this were developed by Perrone [114] they required that the investigator had prior knowledge of the material’s strain rate dependent data, severely limiting the application for new uncharacterised materials. Finally, Hoggatt and Recht [63] made slight adjustments to the driver in that detonation was now initiated at each end. A streak camera produced a continuous record of the ring displacement, and fitting a parabola to the data removed much of the noise introduced during the double differentiation. Again, this limited the effectiveness to materials that exhibited this simple response. The method used in this study is a close relative to the work of Warnes et al [53] where a VISAR system (described in section 5.1.1) was used to directly measure the expansion velocity of the sample. This enabled them to acquire more accurate data on aluminium and copper at rates around $5 \times 10^3 \text{s}^{-1}$. However, in this work, the concern was not to accurately measure the stress in the sample (as the calculations only remain trivial for a perfect ring) but to use the velocity data to produce a record of the strain rate in the sample.

Two experimental configurations were tested, using AISI 4340 steel and M1 copper (Russian designation equivalent to US C11000 or BS C106) for the driver. Both were right cylinders, 60 mm long with an outer diameter of 43 mm. This is shown in figure 6.2. The only dimension to differ between the drivers was the diameter of the explosive charge. RDX was used in all experiments, pressed to a density of 1.6 g cm$^{-3}$ in a hydraulic press under confined uniaxial compression with a force of 20 kN. For the steel driver the RDX had a diameter of 20 mm, compared with the smaller charge in the copper driver of 10 mm diameter. Detonation was initiated simultaneously at each end of the charge by low-jitter detonators located in recesses in the charge. The rings were manufactured from Ti-6Al-4V cylinders originally supplied by AWE (full characterisation of this material is discussed in section 6.4). The inner and outer
diameters of the different rings were kept constant at 43 mm and 49 mm respectively, meaning all samples had a wall thickness of 3 mm. To control the stress state the length of the sample was varied, producing perfect rings (3 mm long, 1:1 aspect ratio), wide rings (6 mm long, 1:2 aspect ratio) and short cylinders (12 mm long, 1:4 aspect ratio). This covers a range from uniaxial stress (perfect rings) to approaching plane strain (cylinders). These were a close sliding fit over the driver and located at the driver midpoint by a small shoulder machined on the outer driver surface, not shown in figure 6.2.

![Cross sections and dimensions of the drivers and RDX charges for the steel (left) and copper (right) drivers, showing the locations at each end of the explosive charge for the detonators and example Ti-6Al-4V rings. All dimensions in mm. Right shows steel driver assembly with the orientation of the VISAR beam.](image)

For the 3 mm geometry, three rings were placed on one driver. This was to increase the amount of fragments produced and hence aid recovery. The rings were designated left, centre and right where the centre ring was at the driver midpoint and the other two were each side in contact. The driver and ring assemblies were mounted with the long axis horizontal in a wooden frame that supported the driver at each free end. This was designed to not interfere with the expansion process and allow release of the detonation products and gases without obscuring the VISAR beam. The VISAR entered the explosive chamber as a collimated beam, roughly 10 mm in diameter. As this reached the bench where the experiment was located it passed though a turning mirror and a lens to bring the beam to a focused spot in the middle of the sample ring’s width. The outer surface of the rings was very lightly abraded which provided a diffuse finish to aid the amount of light returned to the VISAR.

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6. EXPLOSIVELY DRIVEN RINGS: STRESS STATE EFFECTS

6.3 Expansion Drive Simulations

To assist in designing the drivers the commercial explicit dynamics software Ansys AUTODYN v13 was used [115]. AUTODYN is a hydrocode developed to simulate explosive, blast, ballistic and impact events. For all simulations in this study each part is modelled as a Lagrangian mesh, a ‘solid’ formed of an assembly of nodes. This can deform and flow in the simulation space which is effectively an empty perfect vacuum. Each node of the mesh is a finite element with an associated mass, volume and energy (kinetic and thermal). The hydrocode then solves the conservation of mass, momentum and energy equations for each timestep at each node given a set of initial and boundary conditions. In addition to the conservation equations the state variables (pressure, density, temperature etc.) are calculated in accordance to the material’s equation of state (EoS) and strength models. The total stress tensor can be split into its hydrostatic components (responsible for volumetric changes) and the deviatoric components (describing changes in shape). The equation of state is a set of values or functions that govern the former dependencies between pressure, volume and energy while the strength model defines the resulting strain, strain rate and yield surface with the applied deviatoric stresses [116]. For a given material the choice of EoS and strength model will depend on the conditions expected in the simulation with each one covering different areas of phase, stress, strain and strain-rate space. The models in this section used four materials, Ti-6Al-4V, 4340 steel, M1 copper and RDX. The metals Ti-6Al-4V, steel and copper all used a Mie-Grüneisen EoS based on data from the shock Hugoniot, specifically the assumed linear relationship between the shock velocity $U_s$ and the particle velocity $u_p$ as:

$$U_s = C_0 + s u_p, \quad (6.4)$$

where $C_0$ is the shock speed at an infinitesimally small particle velocity, i.e. the ambient pressure bulk sound speed:

$$C_0 = \sqrt{K_s/\rho_0}, \quad (6.5)$$

where $K_s$ is the isentropic bulk modulus and $\rho_0$ is the initial density [117, chapter 4]. These are used with the Rankine-Hugoniot jump conditions. For a shock wave propagating through a material (at an initial state designated with a subscript 0) at a velocity $U_s$ with respect to the
observer the conservation of mass, momentum and energy across the shock front are expressed as:

\[
\rho = \rho_0 \frac{(U_s - u_p)(U_s - u_p)}{(U_s - u_p)^2}, \quad (6.6)
\]

\[
\sigma_H - \sigma_0 = \rho_0(u_p - u_p)(U_s - u_p), \quad (6.7)
\]

\[
E_H - E_0 = (\sigma_H + \sigma_0)(1/\rho_0 - 1/\rho) = 1/2(u_p - u_p)^2, \quad (6.8)
\]

where \( \sigma \) is the stress in the direction of shock propagation and \( E \) is the energy. The stress and energy states reached on the Hugoniot behind the shock are given by \( \sigma_H \) and \( E_H \) respectively.

Combining equations 6.4, 6.5 and 6.6 gives \( \sigma_H \) as:

\[
\sigma_H = \frac{\rho_0 C_0^2 \mu}{(1 - s\mu)^2}, \quad (6.9)
\]

where \( \mu \) is the volumetric strain, \((1 - V/V_0)\). The Mie-Grüneisen EoS surface is then calculated from these reference Hugoniot states through the relation:

\[
P(V, E) = \sigma_H + \Gamma \frac{V}{(E - E_H)} \quad (6.10)
\]

where \( \Gamma \) is the Grüneisen parameter, defined as \( \Gamma(V) = V(\delta P/\delta E)_V \). The RDX was modelled with a Jones-Wilkins-Lee (JWL) EoS [118]. This is commonly used for explosives in hydrocodes and is both applicable for the solid unreacted material and the detonation products. It is a largely empirical model based on adiabatic expansion of the detonation products [119], populated by experimental results. Parameters for the four materials’ equations of state are shown in table 6.2.

The response of the meshed parts to deviatoric stresses is controlled by the strength model. As with EoS choice, there are a wide range of strength models depending on the material properties and the simulation parameters. The two strength models used for the metals in the simulation are popular in the impact/ballistic community, namely the Steinberg-Guinan and Johnson-Cook models. The Ti-6Al-4V and copper used the Steinberg-Guinan strength model, developed by Steinberg, Cochran and Guinan [121]. They noted that while the yield stress
6. EXPLOSIVELY DRIVEN RINGS: STRESS STATE EFFECTS

Table 6.2: Simulation Equation of State parameters

<table>
<thead>
<tr>
<th>Material [Reference]</th>
<th>(\rho_0) (kg m(^{-3}))</th>
<th>(C_0) (mm (\mu)s(^{-1}))</th>
<th>(s)</th>
<th>(\Gamma)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6Al-4V [97]</td>
<td>4419</td>
<td>5.13</td>
<td>1.028</td>
<td>1.23</td>
</tr>
<tr>
<td>M1 Copper [97]</td>
<td>8930</td>
<td>3.94</td>
<td>1.489</td>
<td>2.02</td>
</tr>
<tr>
<td>4340 Steel [70]</td>
<td>7830</td>
<td>4.67</td>
<td>1.440</td>
<td>1.50</td>
</tr>
</tbody>
</table>

RDX Jones-Wilkins-Lee EoS \[120\]

<table>
<thead>
<tr>
<th>(\rho_0) (kg m(^{-3}))</th>
<th>(v_D) (m s(^{-1}))</th>
<th>(P_C,J) (GPa)</th>
<th>(A) (GPa)</th>
<th>(B) (GPa)</th>
<th>(R_1)</th>
<th>(R_2)</th>
<th>(\omega)</th>
<th>(\varepsilon_0) (GPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.601</td>
<td>8193</td>
<td>27.99</td>
<td>609.77</td>
<td>12.95</td>
<td>4.50</td>
<td>1.40</td>
<td>0.25</td>
<td>9.00</td>
</tr>
</tbody>
</table>

(von Mises flow stress) increases with plastic strain, both the yield stress and shear modulus also increase with pressure and decrease with temperature. They also suggest that strain rate strengthening is limited above a certain rate, based on free-surface velocity measurements from shock experiment data at the time. An explanation of this is given that the thermal softening outdoes any rate dependent hardening at very high rates. The governing equations for yield stress \(Y\) and shear modulus \(G\) take the following, very similar forms:

\[
G = G_0 \left[ 1 + \left( \frac{G'_P}{G_0} \right) \frac{P}{\eta^{1/3}} + \left( \frac{G'_T}{G_0} \right) (T - 300) \right], \tag{6.11}
\]

\[
Y = Y_0 [1 + \beta (\varepsilon + \varepsilon_0)]^n \times \left[ 1 + \left( \frac{Y'_P}{Y_0} \right) \frac{P}{\eta^{1/3}} + \left( \frac{G'_T}{G_0} \right) (T - 300) \right], \tag{6.12}
\]

where \(\eta\) is compression \((V/V_0)\), \(\beta\) and \(n\) are work hardening coefficients and \(\varepsilon\) is equivalent plastic strain. Primes indicate derivatives with respect to the subscript, and the subscript 0 to the initial state where \(T = 300\) K, \(P = 0\) and \(\varepsilon = 0\).

The Johnson-Cook model \[122\] was used for the steel. This provides a single equation for the yield stress which can be broken down into three terms. The Johnson-Cook equation is as follows:

\[
Y = [A + B\varepsilon^n][1 + C \ln \dot{\varepsilon}^*][1 - T^{-\eta}] , \tag{6.13}
\]
The first bracket accounts for work hardening where \(A\) is the initial yield stress, \(\varepsilon\) is the effective plastic strain and \(B\) and \(n\) are constants. This is valid for standard experimental conditions where the sample is at room temperature and deforming at the reference strain rate \(\dot{\varepsilon}_0\). The relation takes the familiar power-law hardening as in the Steinberg-Guinan yield stress (equation 6.12). The second bracket considers strain rate dependence where \(C\) is a constant and \(\dot{\varepsilon}^*\) is the normalised strain rate, \(\dot{\varepsilon}/\dot{\varepsilon}_0\). Hence as the strain rate increases above the reference rate the yield stress slowly increases due to the logarithmic dependency. The final bracket introduces thermal softening through the homologous temperature, \(T_H\), the ratio of the sample temperature to the melt temperature \(T/T_{melt}\). The yield stress drops to zero as the sample approaches the melt temperature. The Johnson-Cook model is readily populated through tensile, torsion and Taylor (rod on anvil) impact testing [123]. The values used for the strength models are given in table 6.3.

<table>
<thead>
<tr>
<th>Material</th>
<th>(G_0) (GPa)</th>
<th>(Y) (GPa)</th>
<th>(Y_{max}) (GPa)</th>
<th>(\beta)</th>
<th>(n)</th>
<th>(G_P^\prime) (GPa)</th>
<th>(G_T^\prime) (GPa K(^{-1}))</th>
<th>(Y_P^\prime)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6Al-4V</td>
<td>41.9</td>
<td>1.33</td>
<td>2.13</td>
<td>12</td>
<td>0.10</td>
<td>0.4819</td>
<td>-0.02698</td>
<td>0.015300</td>
</tr>
<tr>
<td>M1 Copper</td>
<td>47.7</td>
<td>0.12</td>
<td>0.64</td>
<td>36</td>
<td>0.45</td>
<td>1.3500</td>
<td>-0.1798</td>
<td>0.003396</td>
</tr>
</tbody>
</table>

4340 Johnson-Cook Strength Model [123]

<table>
<thead>
<tr>
<th>(G) (GPa)</th>
<th>(A) (GPa)</th>
<th>(B) (GPa)</th>
<th>(n)</th>
<th>(C)</th>
<th>(T_{melt}) (K)</th>
<th>(m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>81.8</td>
<td>0.792</td>
<td>0.510</td>
<td>0.26</td>
<td>0.014</td>
<td>1793</td>
<td>1.03</td>
</tr>
</tbody>
</table>

The final input for each material is a failure and erosion model. Failure can be implemented through simple models such as those that require a critical principal stress or strain at a node, or more involved approaches such as the Johnson-Cook damage model [123], void nucleation and growth for failure like spall [124] and adiabatic shear banding [125]. Where these are included they are discussed in more detail - note that the majority of simulations, especially concerning design of the experiment, omit a failure model as it is only the expansion launch behaviour that is desired. Erosion is when a node cell is removed due to excessive distortion of...
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the mesh. This can also be activated by the failure model. When AUTODYN removes a cell
the momentum is transferred to the rest of the part, although mass is lost. For this reason the
simulation will fail or produce unreasonable results if excessive erosion occurs.

The behaviour of the shock wave from the RDX in the driver was investigated using two-
dimensional axisymmetric models. These take a slice of the geometry such that only one plane
is modelled with a symmetry constraint normal to the plane. AUTODYN defaults to the $x - y$
plane, where the $x$ axis is aligned with the length of the cylinder. The symmetry constraint
is around the $x$ axis. This is shown in figure 6.3 right. The parts were meshed such that the
cells were square in all areas, with a cell edge length of 100 $\mu$m for the RDX, copper and steel
and 50 $\mu$m for the Ti-6Al-4V. Detonation was initiated along two lines at the ends of the RDX
charge, highlighted red in figure 6.3.

![Figure 6.3: AUTODYN simulation geometry, 12 mm ring, copper driver. Left: Revolved by 360°
image of the two-dimensional model, demonstrating the symmetry around the x-axis. Right: Dimensions
of the model in mm. Detonation lines highlighted red.](image)

Zero time for the simulation data corresponds to when detonation occurred. Data is ex-
tracted from the model either as images in the case of contour plots or through the use of
gauges. Gauges are assigned to cells according to the user. They then track with the cell
through the duration of the experiment and write certain variables to a history file at each
cycle. Gauges can be used to compare directly with experimental data, for example placing
one on the surface of the sample and tracking the velocity to compare with VISAR or PDV
data. When the model is sufficiently validated from these direct comparisons other data can
be extracted, such as the temperature or density at that point. In these simulations arrays of
gauges were used to enable reconstruction of part profiles and $x - t$ plots through post process-
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ing in MATLAB as per appendix B. These arrays were located in a line along the y direction at the driver midpoint (x = 30) and along the inner and outer ring surfaces.

A series of pressure contour plots from the simulation in figure 6.3 are shown in figure 6.4. Note that the images have been cropped horizontally - in the actual model the RDX detonation products expand outwards to each side. The detonation front progressing through the charge is clear. The ratio of the detonation velocity to the elastic wave speed in the copper results in the angled motion of the shock in the copper driver. The angle taken from the images of 31° is in good agreement with the arctangent of this ratio \(4760 \text{ m s}^{-1}/8193 \text{ m s}^{-1}\).
of avoiding this would be to initiate the RDX with a wire discharge along the centre axis. However, this was not available at the time and similar analyses by Lambert et al [60, chapter 1] have shown the gains to be minimal.

As discussed in sections 3.2 and 3.3.1, one issue with explosive loading is the amount of strain and damage created in the sample as part of the launch process prior to significant expansion occurring. This is due to the strong radial shock wave in the driver. As this shock couples into the ring it causes compression and heating. This initial compression can interfere with failure strain estimates. If one takes a recovered fragment and attempts to use the final wall thickness to estimate the failure strain, the thinning due to the loading will artificially increase this value. Goto et al approached this problem by using simulation data to calculate the effective plastic strain from the through thickness strain [32]. The AUTODYN simulations were used to examine this loading strain and at what point the sample enters free expansion, i.e. has separated from the driver. This was done by comparing the through-thickness strain with an $x-t$ diagram and the free-surface velocity. Through thickness strain $\varepsilon_{tt}(t)$ is defined as the strain in the radial direction, such that:

$$\varepsilon_{tt}(t) = \ln \left( \frac{h(t)}{h_0} \right),$$

where $h$ is the wall thickness of the ring. In this convention a compression or thinning of the wall produces a negative strain value. A simulation with a 3 mm ring is shown in figure 6.5. On the left is a plot of the ring inner (blue) and outer (red) wall radii with time, against the through thickness strain accumulated (black). The radial stress data from the same simulation is then presented in an $x-t$ diagram on the right with the same timescale. The shock wave is seen propagating through the driver towards the ring interface at 21.5 mm. The slightly stepped appearance of the shock front in the driver is an artefact of the gauges being spaced every 0.5 mm (reduced to 0.1 mm in the ring). The radial shock wave reaches the driver/ring interface at time $t_1$ ($\sim$6.9 $\mu$s) and couples into the ring. The inner wall of the ring begins to move creating a compressive strain in the wall, shown by the black trace in the left plot. At time $t_2$ the shock reaches the outer (free) surface of the ring and reflects back as a rarefaction wave. This further accelerates the ring outwards, creating a region of tensile stress and reducing
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the amount of through thickness strain. Finally, at time $t_3$, the rarefaction wave reaches the ring/driver interface. Due to the copper’s higher impedance the rarefaction reflects back into the ring as a shock and proceeds into the driver as a rarefaction. The shock once again accelerates the ring outwards, separating it from the copper driver completely. From $t_3$ onwards the ring is in free expansion, and the radial loading shock continues to reverberate in the ring dampening over time. At times later than $t_3$ any through thickness strain (averaging out the small oscillations from the dying radial wave) is a result of thinning as the ring expands. Hence one can extrapolate back and observe that the loading process has created roughly 3 percent through thickness strain. Similar amounts are found for the 6 and 12 mm cases. The time to reach free expansion from when the shock enters the ring for all cases will be on the order of 1 µs given the elastic wave speed ($6.13 \text{ mm} \mu\text{s}^{-1}$) and the 3 mm wall thickness. In experiments where the free surface velocity is measured free expansion will initiate roughly half this time after the first motion is detected.

![Figure 6.5: AUTODYN simulation data, 3 mm ring, copper driver. Left: Plot of the ring inner (blue) and outer (red) wall locations against through thickness strain (black, equation 6.14) with time. Right: $x-t$ diagram of the copper driver and Ti-6Al-4V ring showing radial stress. The ring enters free expansion from $t_3$ onwards.](image)

6.4 Ti-6Al-4V Characterisation

Rings were machined with the same dimensions as the 3 mm samples, then sectioned and prepared as per section 5.3.1. These sections were made so as to show three planes of the
material, normal to the hoop, radial and axial directions. An Olympus BX51 microscope was used with a polarised light source to produce the low magnification images shown in figure 6.6. Each plane of the image covers an area roughly 4.5 mm$^2$. Polarised light microscopy is particularly effective at revealing preferential grain orientations in hexagonal-close-packed materials such as titanium \[127\]. The images show clear band-like zones where there is such grain alignment in the axial-radial and hoop-radial planes. This is consistent with the material being processed through rolling or extrusion along the axial direction.

![Image of orientation of imaging planes and optical microscopy images](image)

Figure 6.6: Ti-6Al-4V characterisation. Left: Orientation of the imaging planes. Right: Optical microscopy images at 2.5x magnification under polarised light of the three planes.

To ascertain the actual crystal orientation in the sample responsible for the difference in reflected polarised light electron backscatter diffraction was used. The microscope was a Zeiss Auriga equipped with a Bruker e$^-$ Flash detector. The sample was tilted to 70° relative to the electron beam and brought into focus at around 500 times magnification. The detector then raster scanned an area of the sample 320 by 240 $\mu$m with a 0.5 $\mu$m step size. This ensured that a representative amount of each plane was sampled for grain size calculation. Figure 6.7 shows two inverse pole figure maps, corresponding to the axial-radial and hoop-radial planes. These images were produced using the MTEX open source EBSD software package \[113\]. Each pixel is assigned a color based on the Euler angle of the crystal at that point. Certain colours correspond to the observer being normal to specific planes, for example if a pixel is red this indicates that the observer is looking normal to the basal plane, \{0 0 0 1\} (along the c axis). Grain boundaries were defined as the point where the misorientation between two neighbouring pixels (or group of
pixels) is greater than a certain angle, in this case set at 5°. Certain areas of the maps, notably the lower part of the left map, had poor band contrast. This is due to the tilt of the sample plane moving the lower part slightly out of focus in the microscope. The band contrast refers to the strength of the Kikuchi bands on the detector, weak contrast making determination of grain orientation difficult. The software has an option to intelligently artificially index pixels using data from their neighbours, and so filling in the empty spaces. While this has little effect on the qualitative effectiveness of the pole figure map, for quantitative analysis such as grain sizing these regions were left as no data and not included. For reasonable accuracy in grain analysis the map should contain at least a thousand grains - even with the poorly resolved areas omitted the maps still contain several thousand grains of α phase titanium. It is evident that the bands of texture observed under polarised light are regions where the $c$ axis of the α titanium crystals are aligned with the hoop direction. The hoop-radial plane image corroborates this as the band shows the prismatic planes \{1 0 \bar{1} 0\} are normal to the surface, hence the $c$ axis would be aligned with the hoop direction.

The EBSD data was also used to provide quantitative data on the grains. The non-indexed grains are typically sub-micron in diameter and present as pixels of missing data. In the MTEX software the grain ‘set’ can be manipulated through applied conditions. As recommended by the operating manual, a condition was set such that grains with less than 5 measurement points over their area (point spacing being 0.5 μm) were omitted from analyses. If these points are contained in a known grain they are filled with the surrounding grain’s properties. Figure 6.8 shows histograms of the grain principal axis data for the planes shown in figure 6.7. This axis is the longest line between two points on a grain. Note that the number of measurements constraint has set a lower bound of around 1.5 μm. The distributions have a similar profile, although the peak is lower for the axial-radial plane at 2.25 μm compared to 3.75 μm.

In addition, the mean principal axis length, area and aspect ratio for the planes were calculated. The aspect ratio is defined as the principal axis length of a grain divided by the maximum width of a line normal to this (grain length to width), with very similar mean values and distributions for the two planes. Errors are calculated from the standard deviation and the number of points (grains) in a set. The average grain principal axis was $(5.07 \pm 0.07)$ μm
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Figure 6.7: Inverse pole figure maps for two planes of the Ti-6Al-4V samples. The colour corresponds to the crystal plane normal to the observer as defined in the legend.

in the axial-radial plane and $(6.51 \pm 0.11) \mu m$ in the hoop-radial plane, both having a mean aspect ratio around 1.6. These values are typical of a fully equiaxed Ti-6Al-4V grain structure as produced by annealing and slow cooling in air \[128\]. In summary, the material was found to be predominantly primary $\alpha$ phase titanium grains on the order of $5 \mu m$ long in a fully equiaxed structure with bands of preferential texture where the $c$ axis is aligned with the hoop direction.

6.5 Experimental Results and Discussion

A series of four experiments were performed, the first using the steel driver and following using the copper driver. The experiments are presented here first in order of driver material, then ring geometry. In all experiments the VISAR data was reduced as per the conventional methods \[105\] to provide the expansion velocity with time. The raw VISAR data is presented in appendix \[C.1\] for completeness. The velocity data was integrated to give the radial displacement. With these
values and the initial outer radius of the ring, the following equations were used to give radial strain $\varepsilon_r(t)$ and radial strain rate $\dot{\varepsilon}_r(t)$ with time:

$$\varepsilon_r(t) = \frac{r(t)}{r_0} - 1,$$

$$\dot{\varepsilon}_r(t) = \frac{\dot{r}(t)}{r(t)},$$

where $r(t)$ is the ring outer radius, $r_0$ is the initial radius (24.5 mm) and $\dot{r}(t)$ is the radial expansion velocity. Recovered fragments were cleaned in an ultrasonic bath, then prepared for microscopy as detailed in section 5.3.1.

### 6.5.1 Steel Driver, 12 mm Ring

The steel driver was used to expand a 12 mm wide ring. The ring, driver and assembly are shown in figure 6.9. The RDX charge consisted of several pellets pressed into contact inside the driver. The aspect ratio of this ring (1:4) tends to a plane strain stress state under uniform expansion. The expansion velocity data is shown in figure 6.10, experimental data in black and the AUTODYN simulation data in red. The experimental data has been smoothed with a Fourier low-pass filter [129] to reduce high frequency noise on the trace towards the end of the record, the unprocessed data is shown in appendix C.2.

It is clear that the ring experienced several loading steps before reaching the peak expansion velocity of 604 m s$^{-1}$. From the early-time detail (figure 6.10 right) there were three main steps, 

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Figure 6.8: Histograms of the grain principal axis (longest line possible in each grain) and grain aspect ratio (principal axis to width) for the two planes shown in figure 6.7.
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Figure 6.9: 12 mm ring, steel driver. Left: 12 mm ring. Centre: 4340 steel driver with ring installed. Location shoulder is visible on the right. Right: Driver ring assembly and an RDX pellet, 20 mm diameter (RDX powder visible in the rear).

Figure 6.10: 12 mm ring, steel driver. Left: Expansion velocity, experimental data (black) against simulation data (red). Right: Detail of 0.2 to 2.2 µs showing the multi-step loading of the ring.

each having a ‘precursor’ approximately one-third the magnitude of the step. The periodicity of the steps is too short to be a simple reverberation of the loading wave through the thickness of the ring. The simulations predicted a small leading wave between 0.6 µs and 0.75 µs. Analysis of the model showed this was due to the edges of the ring being loaded first, as discussed around figure 6.4. This structure approximates the first velocity step in the experimental data in timing and magnitude. However, the cause of the other two steps requires further investigation. A possible cause could be a phase change in the driver which would present as a multi-wave structure at the shock front that propagates into the ring. The α – ε phase transition in 4340 steel is 13 GPa [70] on the Hugoniot. The Chapman-Jouget pressure of RDX at 1.6 g cm$^{-3}$ is 28.3 GPa [130] which couples into the steel well in excess of the phase transition
pressure. Secondly, recovered driver fragments showed severe failure along planes at 45° to the radius, possibly indicative of the driver prematurely failing under compression in the radial direction due to the high pressure generated by the RDX inside. The AUTODYN model cannot reproduce phase transitions, likewise no failure was considered as the steel and copper drivers were not given a failure or fracture model. Hence if either of these events was the cause of the multi-wave structure the simulations would not generate the profile observed.

The simulation predicted a higher peak velocity of 733 m s\(^{-1}\). Multiple gauges were placed along the outer surface of the ring and it was found that moving away from the exact ring midpoint would give a velocity profile closer to that observed by the VISAR, suggesting that the experiment was slightly misaligned. The experimental data suffers from noise around 3 µs making comparison with the oscillation in the simulation difficult, although the general deceleration profile is in agreement. The simulation shows that from this time on the velocity at all points on the outer surface of the ring collapses onto a single curve as expected from a uniform plane strain expansion. The radial strain and radial strain rate calculated from the velocity data are plotted in figure 6.11. Peak radial strain rate corresponds to the time of peak velocity with a value of 2.48 × 10\(^4\) s\(^{-1}\). Once the ring enters free expansion the strain rate relaxes and slowly drops from 1.9 × 10\(^4\) s\(^{-1}\) to 1.5 × 10\(^4\) s\(^{-1}\) over the rest of the measurement, hence the approximately linear relationship between strain and time. For this period the average strain rate is 1.66 × 10\(^4\) s\(^{-1}\).

![Figure 6.11: 12 mm ring, steel driver. Radial strain rate (black) and radial strain (blue) with time.](image)

The recovered material accounted for 61 percent of the original ring mass over nine frag-
ments. These are shown in figure 6.12. The average fragment mass, length and width were 1.57 g, 13.2 mm and 11.6 mm respectively. Fragments had a slightly barrelled cross section, such that the midpoint of the ring had expanded more than the edges. The minimum reduction in width is evidence for a plane strain stress state dominating the expansion.

![Figure 6.12: 12 mm ring, steel driver. Recovered fragments, ring inner face facing up.](image)

Failure was almost exclusively at 45° to the radial direction. SEM imaging of the fracture surfaces at the end of fragments showed parabolic dimples associated with ductile tearing under mode II (shear) loading. This type of fracture surface has been observed in Ti-6Al-4V where adiabatic shear banding has occurred by Liao and Duffy [26], however the authors noted that they also observed the same dimples in samples that had failed at very low strain rates ($0.5 \times 10^{-3} \text{s}^{-1}$). To fully determine the fracture mechanism occurring samples with arrested cracks were observed. Arrested cracks were found to always initiate on the outer surface of the ring, at the midpoint across the width. In some cases these had propagated through the entire fragment thickness but not the width. A selection of these arrested and through thickness cracks were sectioned, polished and etched with optical microscopy showing no sign of plastic deformation as associated with adiabatic shear banding either ahead or around the crack. Arrested cracks were found to have blunt tips. Some arrested cracks were found to have further cracks branching off from the main crack, as shown in figure 6.13.

The steel driver introduced several complications and uncertainties to the experiment. The possibility of a multi-wave loading, either due to a phase change or premature failure makes characterising the loading history of the ring difficult. The fragments in figure 6.12 show a darkened line along the length that would appear to be caused by the explosive products from the RDX, meaning driver failure must occur early in the expansion process. The large amount of RDX needed for a $10^4 \text{s}^{-1}$ strain rate hindered recovery as the fragments as well as the mounting
hardware were launched over a large area in the blast chamber, some becoming embedded in the walls. For these reasons, following experiments used the copper driver.

Figure 6.13: 12 mm ring, steel driver. Left: Optical microscopy of an arrested crack with another crack branching off. Right: SEM image of a fracture surface showing more branching cracks penetrating into the surface.

### 6.5.2 Copper Driver, 12 mm Ring

The copper driver used a much smaller amount of RDX, the charge diameter being 10 mm verses 20 mm with the hole through the driver being reduced to match. Pure copper has greater ductility than the steel, no phase changes in this region and a very low Hugoniot elastic limit [131]. The simulations predicted similar values to the steel for peak expansion velocity although lower late time velocity consistent with a shorter loading as a result of less explosive charge. It was thought a combination of the reduced explosive mass and simpler response of the copper driver would remove the issues with the steel driver. The expansion velocity data for the copper driver experiments are shown in figure 6.14.

Figure 6.14: Expansion velocity histories for the experiments that used the copper driver, showing experimental data (black) against simulation data (red).
Evident in all three traces is a precursor wave with a free surface velocity around $110\,\text{m s}^{-1}$. This is the Hugoniot elastic limit in the Ti-6Al-4V although attenuated by release waves as a result of being loaded from the ring edges first. This is not present in the simulation data, studies by the author on other geometries such as plate impact in AUTODYN have shown that a mesh resolution of at least $10\,\mu\text{m}$ or finer is needed to reveal elastic precursor features. This precursor is detailed in the left of figure 6.15.

The data for the 12 mm ring is on the left of figure 6.14. As with the steel driver, there is again a stepped loading pulse. It is believed that this is due to misalignment of the VISAR focal point, as with the previous experiment moving to a gauge away from the ring centre reproduces the experimental data. The recovered fragments showed no signs of explosive products on the inner face meaning the driver retains structural integrity well into the ring expansion process. The peak radial strain rate as measured was $2.15 \times 10^4\,\text{s}^{-1}$ (from a peak velocity of $529\,\text{m s}^{-1}$). Using the simulation velocity data at the centre of the ring this raises to $2.54 \times 10^4\,\text{s}^{-1}$ although except for the intensity of the initial rise the whole ring width tends to the same velocity. The measured strain rates are plotted in figure 6.15 right. The late time strain rate is lower than found with the steel driver but follows a similar pattern, slowly decreasing from $1.7 \times 10^4\,\text{s}^{-1}$ to $1.2 \times 10^4\,\text{s}^{-1}$ over the recorded data. The data shows that the strain rates generated in the sample are largely independent of the ring size, all samples tending to a similar value.

![Figure 6.15: Expanding rings, copper driver. Left: Detail of the elastic precursor. Right: Radial strain rate with time.](image)

Fragment recovery was much improved over the steel driver with 98 percent of the original ring found. This enabled the fracture surfaces to be paired and the entire ring reconstructed.
The fragments are shown (inner face up) in figure 6.16. Fragment lengths covered a range of 11 mm to 37 mm and had an average length of 22.5 mm. The fragments had a very similar appearance to the steel driven 12 mm ring with minimal reduction in width and a slightly barrelled cross section. There were striations across the width on both the inner and outer faces, evidence of slip planes inside the ring presenting at the surface and acting as seeding sites for fractures.

Arrested fractures were again observed to originate on the outer surface at the midpoint of the ring width. A sectioned example is shown in figure 6.17. The crack takes a convoluted path through the fragment, abruptly changing direction several times and splitting into two cracks at 90° to each other at the tip. The centre shows a high magnification image of one of these tips, the microstructure showing no sign of deformation preceding the crack. Finally, the right image shows the characteristic parabolic dimples seen on the fracture surfaces indicating ductile failure through in-plane shear loading (mode II fracture).

### 6.5.3 Copper Driver, 6 mm Ring

The 6 mm ring reached a peak expansion velocity of 515 m s$^{-1}$. The free-surface velocity profile shows a much more direct path to this peak value, suggesting the VISAR was more accurately aligned to the centre point of the ring width. This produced a peak radial strain rate of 2.09 $\times$ 10$^4$ s$^{-1}$, with the later-time average strain rate similar to the other experiments (figure 6.15). Both simulation and experiment show a very large pull-back or deceleration after the peak velocity is reached. Analysis of the simulations showed this pull-back corresponds to
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Figure 6.17: 12 mm ring, copper driver. *Left*: Optical micrograph, 2.5x mag. showing arrested crack propagating in from outer ring surface. *Centre*: 50x mag. detail of the circled crack tip. *Right*: SEM image of a fracture surface showing parabolic dimples.

the release waves from the ring edges colliding and creating a region of tension in the sample. From the original ring mass 79 percent was recovered, the fragments are shown in figure 6.18

Figure 6.18: 6 mm ring, copper driver. Recovered fragments, ring inner face facing up.

Upon examination of the recovered material it was apparent that there was a unique form of damage. In addition to the typical radial failure seen at the ends of the fragments there were also ‘bands’ of damage around the entire circumference of the sample, these are shown as the vertical cracks in figure 6.18. These cracks initiated on the inner face and were found to penetrate through around three-quarters into the ring thickness, although in some cases through the entire wall meaning the inner shoulders of the ring were lost (for examples see fragments 2, 3, 7-9 starting from the left in figure 6.18). Fragment number 5 was sectioned across the width and prepared for optical microscopy as earlier. The resulting images are shown in figure 6.19

The internal cracks have two regions, near the inner surface the fracture path is linear at 45° to the vertical (radial direction). This is consistent with ductile or tensile tearing and extends for around 0.75 mm in from the inner ring face. Past this point the fracture mechanism converts to void nucleation, growth and coalescence as seen during spall fracture. From the detail of the
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circled area (figure 6.19, centre) these spall planes are shown to form in the vertical direction, then link to each other at 45°. This void nucleation and growth is consistent with the sample being under large tensile forces such as from release waves interacting with each other. This pattern of growth and coalescence has been seen in Ti-6Al-4V under plate impact loading [17]. SEM imaging of a fracture surface from this internal damage as in figure 6.19 right, showed regions of round dimples consistent with tensile failure and sheets of shear fracture through which the tensile failure planes had been linked together. This type of fracture resulting from release waves propagating in from the edges has been seen in flash radiography studies on the Phermex facility [132, shots 1515 and 1627]. These experiments launched steel plates into square and rectangular cross section iron bars, with the radiography showing fracture propagating inwards from the lower edges, opposite to the fracture seen in the Ti-6Al-4V here. This is due to their experiments loading from the centre of the sample first where here the edges were loaded first.

Figure 6.19: 6 mm ring, copper driver. Left: Optical micrograph, 2.5x mag. showing internal damage propagating from inner face. Centre: 50x mag. detail of the circled spall region. Right: SEM image of a circumferential fracture surface showing areas of round dimples connected by smooth shear planes.

Without further study it can not be determined from these results whether the linear fracture at the inner face or the tensile spall damage towards the inside of the ring occurs first. However, the large pull-back in velocity thought to be from release waves interacting from the models would place this internal damage before the traditional radial fracture that produces the individual fragments. The lack of reverberation in the experimental data after the pull-back agrees with this - the creation of internal voids obstructs the passage of the radial loading wave. As there was no failure model used in the simulation the pull-back is larger, and the
reverberation occurs as normal. The total recovered mass was 79 percent of the original, with the average fragment length just 13.94 mm. This is much shorter than the other copper driver experiments, in contrast to the predictions made by fragmentation models that similar strain rates will produce similar length fragments (section 2.3). An explanation for this would be the circumferential damage occurs early in the expansion process and provides initiation sites for premature radial fracture. The ends of the fragments are more complex and jagged than the 12 mm cases due to multiple fractures intersecting.

6.5.4 Copper Driver, 3 mm Rings

The velocity history for the centre of the three 3 mm rings is shown in figure 6.14, right. This shows that the 3 mm ring reached the highest expansion velocity and therefore radial strain rate, at $662 \, \text{m s}^{-1}$ and $2.70 \times 10^4 \, \text{s}^{-1}$ respectively. The late-time strain rate is very close to the values of the 12 mm ring. The initial loading wave breakout and following reverberation is very clear suggesting the VISAR was well centred on the sample. The left and right rings will have experienced a marginally lower expansion velocity and strain rate as the converging shock waves in the driver concentrate the loading at the midpoint. The simulation and experimental data are in close agreement, particularly in the late-time deceleration, indicating that the strength model for the Ti-6Al-4V is most accurately calibrated for a uniaxial stress state. The recovered fragments from the three rings are shown in figure 6.20. The rings could be identified by marks left from the explosive products from the ends of the driver on the exposed ring sides.

The 3 mm uniaxial stress case produced fragments with no arrested fractures, unlike all the other experiments. Instead fragments were found to have undergone necking before failure with most fragments having arrested necks. The necks were measured to have thinned by around 15 to 20 percent from the original wall thickness, although areas that had not necked only exhibited minimal thinning suggesting that the majority of the hoop strain is accommodated by material from these localised regions as seen in other works on expanding perfect rings [133]. A typical fragment is shown on the left of figure 6.21 with the width of necked and un-necked regions marked. The average fragment lengths were longer for the left (25.46 mm) and right (27.32 mm) rings than the centre (20.57 mm), consistent with strain rate dependent model
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Figure 6.20: 3 mm ring, copper driver. Recovered fragments. Centre ring was at the midpoint of the driver and recorded by the VISAR system.

theories. Analysis of the fragment ends showed a mixture of failure at 45° to the radius and the more typical of uniaxial tensile tests cup-and-cone failure (a mixture of tensile mode I failure towards the centre of the sample and mode II in plane shear at the edges). An SEM image of one such region is shown in figure 6.21, right, where there is a transition from round to parabolic dimples, evidence of mode I and II failure.

Figure 6.21: 3 mm rings, copper driver. Left: A typical fragment, showing the width of necked and un-necked regions. Right: SEM image of a cup-and-cone type fracture surface showing a mixture of mode I (round dimples, left side) and mode II (parabolic, right side) failure.
6.6 Conclusions

A series of expanding Ti-6Al-4V ring experiments were performed using a buffered explosive charge as the driver. This material was characterised with polarised light microscopy and electron backscatter diffraction, revealing a primary $\alpha$ titanium equiaxed microstructure with bands of preferential texture where the crystal $c$ axis lies in the hoop direction (normal to both the radius and axial directions). The rings had a constant wall thickness of 3 mm and the ring length was adjusted to cover 3 mm long (perfect ring, aspect ratio 1:1), 6 mm long (wide ring, aspect ratio 1:2) and 12 mm long (short cylinder, aspect ratio 1:4). Under uniform expansion these geometries tended to stress states from uniaxial stress to plane strain respectively. Two driver configurations were used, both being a right cylinder 60 mm long and 43 mm outer diameter. One driver was machined from 4340 steel and the other from M1 copper (C11000 equivalent). A column of RDX pressed to a density of $1.6 \text{ g cm}^{-3}$ was placed inside the driver and ran the full length. In the steel driver the charge was 20 mm diameter and reduced to 10 mm for the copper. In both cases the charge was simultaneously initiated from each end with low-jitter detonators. The ring expansion velocity was recorded with a single point VISAR laser interferometer system and the data used to calculate radial displacement and strain rate. Recovered fragments were subjected to optical and electron microscopy techniques to ascertain the fracture mechanisms responsible for the ring fragmentation. A summary of the velocity, strain rate and recovered fragment data is shown in table 6.4. Peak expansion velocities were between 515 and 662 m s$^{-1}$, producing maximum strain rates on the order of $2 \times 10^4$ s$^{-1}$. Average strain rates (the rate governing the deceleration of the sample once in free expansion) were very similar between experiments at around $1.5 \times 10^4$ s$^{-1}$ over the remainder of the recorded data.

The steel driver was only used briefly due to uncertainties in the loading produced in the ring, where there are several steps before peak velocity is reached. There was also explosive residue on the inside of recovered fragments indicating the driver fails early in the expansion process. The simulations used predict the pressure generated by the RDX in the steel is over the 13 GPa $\alpha - \varepsilon$ phase transition but can not actually model this phase change. Likewise, no attempt to simulate failure of the steel driver was made. Other researchers have made
Table 6.4: Summary of explosively driven ring results

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Peak Velocity (m s(^{-1}))</th>
<th>Peak Strain Rate (\times 10^4) s(^{-1})</th>
<th>Recovered (#)</th>
<th>Recovered (%)</th>
<th>Mean Length (mm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12 mm Ring Steel Driver</td>
<td>612</td>
<td>2.48</td>
<td>9</td>
<td>60.9</td>
<td>13.19</td>
</tr>
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<td>2.15</td>
<td>8</td>
<td>98.0</td>
<td>22.52</td>
</tr>
<tr>
<td>6 mm Ring Copper Driver</td>
<td>515</td>
<td>2.09</td>
<td>12</td>
<td>79.2</td>
<td>13.94</td>
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<td>2.70</td>
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<td></td>
</tr>
</tbody>
</table>

use of 4340 steel as the explosive buffer, although with much smaller amounts of explosive and smaller samples [53, 62]. Future work with this driver at this size would require a more thorough experimental characterisation. Without a sample installed high speed imaging would be used to examine failure, while a form of multiple point velocimetry (VISAR or PDV) would be used to measure the free-surface velocity of the driver along the length. The latter would demonstrate the wave that is coupled into the sample.

Experiments with the copper driver showed that the three ring geometries had markedly different failure modes and resulting fragmentation properties. The 12 mm short cylinder sample failed through ductile cracking due to mode II in-plane shear loading, as commonly found in other plane strain studies. Moving to the other end of the scale with the 3 mm rings a state of uniaxial stress dominated. This created necking before failure, where most of the strain allowing for radial expansion was localised to these short regions. Where a neck had gone through to complete failure a mixture of ductile mode I and mode II failure was observed as typical of the cup-and-cone fracture surface left by low strain rate uniaxial tensile tests. The 6 mm ‘wide ring’ geometry produced the most atypical results. In addition to the radial fracture seen in the other experiments there were also two bands of circumferential damage around the entire inner face of the ring fragments. Figure 6.22 shows fragments from the copper driver experiments next to each other, with this circumferential damage clearly visible.
Analysis of the 6 mm fragments showed this internal damage to be consistent with spall, formed by coalescing voids. A large pull-back in the velocity trace and tracking the release waves in the simulation show that the spall occurs early in the expansion, and then acts to weaken and prematurely seed the radial fracture in the ring. This leads to the average fragment length of the 6 mm sample being much shorter than the other experiments even though the strain rate is consistent between all studies and the more complex jagged fragment ends. No adiabatic shear banding was observed in any of the experiments, despite it being common in studies of Ti-6Al-4V at these strain rates \cite{24,134}.

The overall profiles of the velocity traces produced by the simulations were in close agreement with experimental data in all cases, especially the late-time deceleration data. The uniaxial stress state produced the most similar results, suggesting that the values for the Steinberg-Guinan strength model of the Ti-6Al-4V were most applicable under this loading. If one was to begin improving the models a reasonable starting point would be to omit the ring entirely and characterise the driver first, as if this behaviour is not accurately predicted then adjustment of the ring models to compensate will produce erroneous values.

These experiments have documented a method for investigation of the effects of the stress state (triaxiality) experienced by the sample on the dynamic fracture and fragmentation behaviour at high strain rates. Future work would primarily focus on improving the velocimetry, moving to a robust multi-point system with better optics that would alleviate the problems with the misalignment both initially and due to ring movement. Having multiple points on each sample would give a measure of the expansion symmetry and decrease the chance of the
measurement point being over a fracture site. With these issues solved a high speed imaging system would provide quantitative numbers for fracture strain and temporal activation, data necessary for the introduction of failure models into the simulations. The experimental setup here is readily applied to other sample materials, with different strain rate regimes available through choice of explosive, explosive mass and driver material.
Gas Gun Driven Cylinders I: 
Ogive Geometry Development

This chapter describes a new gas gun driven expansion geometry with a view to making experiments with the cylinder at reduced or elevated temperatures possible. This was facilitated by changing the insert in the cylinder from a polymer right cylinder to a steel ogive shaped part. It will be shown that this transferred the deformation responsible for driving the cylinder into expansion wholly to the projectile. As the projectile is separate from the target cylinder until impact it will not be affected by the temperature of the cylinder and ogive insert. Simulations used to develop the geometry are presented first, followed by a series of validation experiments on 6061-T6 aluminium cylinders using flash X-ray radiography to image the deformation and flow of the projectile inside the cylinder. The experimental work was completed in collaboration with Dr Paul Hazell and the Dynamic Response Group at Cranfield University, Shrivenham, UK and was published in the Journal of Applied Physics [135].

7.1 Overview & Motivation

The gas gun driven expanding cylinder was originally developed by Winter and Prestidge [81] as a way of studying dynamic fracture and fragmentation without the use of explosives. In brief this technique, described in detail in section 3.3.4, has a target cylinder mounted concentrically to a gas gun. This is filled some distance along the length by a polymer insert and a matching right cylinder polymer projectile is launched into the target cylinder. The resulting impact behaves in a similar manner to a rod-on-rod Taylor test, although as it is surrounded by the target cylinder the polymers drive this into expansion from the inside face. To date the polymer inserts have either been silastomer rubbers [40] [81] [85] or polycarbonate [81] [86] [87]. The typical Gaussian shaped expansion created by these methods is useful for material model validation.
as a range of strain rates are covered. Figure 7.1 shows a series of high speed images from an expanding copper cylinder experiment performed by the author where both the projectile and insert were polycarbonate. The temporal activation of fracture can be measured, as well as crack propagation along the cylinder. These data feed into the fragmentation models and allow calculation of the material’s fragmentation toughness.

Figure 7.1: Three images of an expanding copper cylinder using a polycarbonate projectile and insert, approximately 55 µs between frames. Projectile enters from the left.

Where the previous chapter described experiments to examine the effect of stress state on dynamic fracture and fragmentation, another region where models are lacking is the effect of temperature. The experiments detailed here work towards a robust experimental platform where the temperature can be controlled while keeping other parameters such as loading and strain rate constant. Through adjustment of the initial cylinder temperature one can examine where different fracture mechanisms become important, such as a transition from ductile tearing to adiabatic shear banding. The experimental aims that this new platform had to meet were as follows:

- Uniform radial expansion at strain rates on the order of $10^4 \text{ s}^{-1}$
- Ability to apply multiple diagnostics simultaneously (velocimetry, high speed imaging and fragment recovery)
- Control of cylinder temperature from 100 K to 1000 K
- Repeatable loading independent of cylinder temperature
- Minimise effects of loading on the cylinder
The strain rate criterion was to allow comparison with other work by the author on Ti-6Al-4V and in general this strain rate is commonly studied for dynamic fracture due to it being comparable with impact and ballistic events. This was the desired strain rate at the peak of the expansion profile - areas either side of this will have lower values and tend to zero. As these type of experiments are costly to prepare and perform, it is important that as much data as possible can be extracted from each one. Hence the second requirement was that velocimetry and high speed imaging could be employed at the same time giving crucial strain rate and strain at failure information. This meant that the use of a jacket type system for heating or cooling would be complicated by having to remove it before the shot, in vacuum and quickly enough to avoid the cylinder returning to ambient temperature. The diagnostics also needed to be operable without being affected by the temperature of the cylinder. The temperature bounds covered a realistic range thought possible with standard laboratory equipment. The cryogenic available, liquid nitrogen (LN$_2$) set a possible lower limit of 77 K, hence 100 K was a reasonable aim given the thermal conduction between the target and the gas gun. Similarly, 1000 K was considered readily available through methods such as resistive heaters or halogen lamps [136], and well in excess of temperatures that would be expected in real world use.

The loading that drives the expansion needed to be unaffected by the temperature to ensure that the other experiment parameters such as strain rate and expansion profile remained constant. This is a key point and required moving away from the ‘classic’ method where both the projectile and insert deform. If the insert remains constant in shape and the deformation constrained to just the projectile this will provide repeatable loading as the projectile is unaffected by the state of the target cylinder. Finally, the loading mechanism should have as little influence as possible on the cylinder. This can be from the initial loading wave, as with explosive loading where a strong shock introduces through thickness strain and damage to the sample or heating when electromagnetic drive is used. With the Winter gas gun method one possible issue with the loading is the fact that two separate parts drive the expansion. Even when the projectile and insert are the same material there is still an interface between the two pushing against the internal cylinder wall. Looking at the right image in figure 7.1 there is a very clear failure around the circumference of the cylinder. This is often seen with this
expansion mechanism \[86\] and could be a result of jetting at the interface between the two polymers.

The new experiment geometry discussed in this chapter (along with the temperature control systems discussed in the next one) fulfilled all the initial requirements. The following sections cover the simulations used to assist in developing the geometry, followed by the planning and fielding of a set of validation experiments on a smaller scale gas gun using 6061-T6 aluminium cylinders and flash X-ray radiography. The results are presented and compared with simulations, with conclusions made and leading into the next chapter on some initial results on heated and cooled Ti-6Al-4V cylinders using the large bore gas gun at the Institute of Shock Physics.

### 7.2 Geometry Development

With the constraint that the driving mechanism is wholly transferred to the projectile, the challenge was to convert as much of the projectile’s longitudinal momentum into radial motion. It was decided to use 4340 steel for the insert as it is a very well characterised material that retains its strength over the temperature range of interest. To create radial motion the point of impact between the projectile and insert needs to be on the centre axis so that the resulting shock wave moves outwards into the projectile. Using a pointed insert (elongated along the centre axis) means that as the projectile continues to move towards the insert there is a time-delay between contact at the centre and contact at the edges. Hence the shock wave generated at the centre is continuously supported by the further contact at each timestep. This can be enhanced by having a projectile with a concave leading face. Care must be taken with the design to try and reduce the motion of the expansion region along the cylinder as this can cause fracture around the circumference direction before the natural radial fragmentation has occurred.

#### 7.2.1 AUTODYN Insert Geometry Simulations

Three insert geometries were examined first, having a conical, round and ogival (nosecone like) profile. Simulations performed in AUTODYN used the methods described in section \[6.3\]. Initial
simple simulations were 2D axisymmetric, with a Lagrangian mesh on the order of 500 µm. Cylinders were 6061-T6 aluminium, 70 mm long, 30 mm inside diameter with a 2 mm wall thickness. The projectile was polycarbonate, with a length of 70 mm and an outside diameter of 29 mm. The leading face was angled at 20° to the radius, such that the rotated profile had a concave conical shape. This was given an initial velocity condition of 1000 m s⁻¹, travelling from right to left in all figures. The insert was 4340 steel in all cases. The angled insert had a convex conical profile with a 45° angled tip. The rounded insert had a hemispherical leading face with a 15 mm radius. The final shape tested was an ogive, specifically a tangent ogive. This is a nosecone-style shape that is formed by taking a section of a circle such that the base of the shape lies on the radius and the outer edge is tangential to the original curve, effectively making a hemisphere where one axis is elongated. These geometries are shown at the top of figure 7.2.

Figure 7.2: The three geometries initially tested in AUTODYN simulations. Top row: Geometry and material location. Lower rows: Pressure contour plots of the projectile.

The equation of state and strength model data are given in appendix D. The lower images in figure 7.2 show the pressure in the projectile to demonstrate the behaviour and general direction of the shock wave generated by the impact. Note that the times of the contour plots are not the same for each row - the images were chosen at times where the shock position or cylinder...
deformation were similar. The first row of contour plots shows the initial growth of the shock in the projectile from the axis out towards the cylinder. The second row then shows the ‘width’ of this wave that reached the outer surface of the projectile and the start of radial deformation. Subsequent rows then demonstrate how the projectile for each insert case began to expand the cylinder. It is clear that the angled insert does not covert enough of the longitudinal motion into radial, with the sloped profile creating a polycarbonate jet that eventually punctures the cylinder. Moving to the round insert the expansion was more uniform but still far from the ideal Gaussian profile with a smaller jet still forming. The final ogive case provides the most uniform expansion along the length of the cylinder. Gauges placed along the outer face of the cylinder were used to track the expansion velocity as a function of time and position along the cylinder, with time-distance contour maps produced and displayed in figure 7.3. Note that the extreme jetting in the angled example led to degenerate cells (cells that have overly distended) causing the simulation to finish earlier than the other examples at around 18 µs.

Figure 7.3: Cylinder expansion velocity maps as a function of position along the cylinder and time for the three insert geometries in figure 7.2.

The angled insert map shows that there was quite a narrow region of the wall driven into expansion at a high velocity around 0.6 mm µs⁻¹ (600 m s⁻¹). If one compares this to the round insert it is clear that the expansion was over a wider region and at a lower intensity for the round case although there was a secondary loading from 15 µs as the weaker jet mentioned earlier forms. The ogival insert had the widest, most uniform expansion region and there was no jetting seen in the late-time data although the velocity reached was the lowest of the three tested. With these initial simulations completed it was decided to concentrate on the ogival
insert geometry, the final adjustment being to alter the shape of the projectile from a conical to a rounded concave face. This further delayed the contact between the rest of the projectile and the insert and provided a wider region of expansion. The final geometry is shown in figure 7.4.

\[ r_{og} = 1.5r_b, \]
\[ r_p = 2r_b. \] (7.1)

This was found to be the best compromise between efficiency (the strain rate generated for a given projectile velocity) while retaining a clean Gaussian expansion profile. For example, the simulations above have a cylinder inner diameter of 30 mm, setting the ogive and projectile radii as 22.5 mm and 30 mm respectively.
For a given projectile velocity, cylinder wall thickness and material the ogive based drive produces a lower strain rate than the classic Winter polymer on polymer method. However, the less intense radial shock wave generated in the cylinder wall with the ogive drive creates more of a sustained push than an impulsive load. The expansion velocity needed to generate a certain strain rate is shown in the plot on the left of figure 7.5. This was calculated using equation 2.8 assuming a 5 percent level of strain has been reached. The red line corresponds to the regime of interest to this study, $1 \times 10^4$ s$^{-1}$. The plot on the right of figure 7.5 shows the results of a series of simulations in AUTODYN on cylinders of 6061-T6 (red) and Ti-6Al-4V (blue) with a 30 mm inner diameter using the ogive geometry in figure 7.4 examining the peak strain rate generated against the projectile velocity. Peak strain rate was calculated using gauges along the length of the cylinder and corresponds to the expansion at the middle of the Gaussian expansion profile. There is a clear linear relationship over this area of strain rate space for the two materials. The values for Ti-6Al-4V are lower due to the material’s superior strength and higher density compared to the 6061-T6.

Figure 7.5: Left: Cylinder wall expansion velocity needed for a given strain rate as a function of the initial outer wall diameter according to equation 2.8 assuming 5 percent radial strain. Right: AUTODYN ogive drive simulation data, 30 mm inner diameter cylinder with a 2 mm wall thickness for 6061-T6 and Ti-6Al-4V cylinders showing peak radial strain rate against projectile velocity. Adapted from Jones et al [135].

While these simulations suggested that the ogive geometry was capable of producing the desired strain rates given the projectile velocities available, there was a feature concerning the behaviour of the polycarbonate that required further investigation. The AUTODYN simulations predicted that as the expansion process continues, the wall of the cylinder separates from
the flowing polycarbonate behind the peak of the expansion region. These voids are shown in figure 7.6, becoming pronounced from around 20 \(\mu s\) after impact. Simulations run in CTH\(^1\) by colleagues did not predict these, this was believed to be due to a different polycarbonate strength model being used. As this behaviour governs when the cylinder enters free expansion experimental investigation was required. The ogive was not bonded into the cylinder for the models. If a friction or bonding constraint was used then the cylinder could not ‘peel away’ from the insert, the flowing polycarbonate became trapped and formed a jet at the join.

Figure 7.6: Images taken from a 2D (revolved into 3D in post processing) simulation of a 6061-T6 cylinder, 30 mm inner diameter, 2 mm wall thickness with a 900 m s\(^{-1}\) projectile velocity. Time is given relative to the point of impact. By 24 \(\mu s\) there are voids appearing as the cylinder wall separates from the flowing polycarbonate.

7.3 Validation Experiments

These preliminary experiments were performed to characterise the behaviour of the ogive insert and the polycarbonate projectile. This is important as these control how the target cylinder deforms. If simulations are to be used to try and accurately model the failure of the cylinder it is crucial that the model accurately reproduces the loading that the cylinder undergoes, as shown by the stress state dependence in chapter 6. There were two areas of interest, the interaction between the ogive and the projectile and the interaction between the projectile and the inner cylinder wall. The former was mainly concerned with how much the insert deforms during the experiment. Simulations predicted only minimal damage during the expansion. If this was found to be the case then the insert could be used to house temperature control apparatus. This could be measured by analysis of the recovered ogive after an experiment. The latter

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\(^1\)A hydrocode developed by Sandia National Laboratories, www.sandia.gov/CTH/
7. GAS GUN DRIVEN CYLINDERS I: OGIVE METHOD

problem, specifically whether the voiding predicted by the simulations in figure 7.6 presented more of a challenge. As the cylinder was optically opaque, imaging of the interface between the projectile and the inner wall was complicated. Conventional high speed imaging systems could have been used if the cylinder was replaced with a clear alternative such as a plastic although this would not have the same response as the metal targets. Flash X-ray radiography was chosen as a suitable method of imaging through the cylinder.

7.3.1 Flash X-ray Radiography Configuration

The gas gun target tank was equipped with a Scandiflash Model 300 flash X-Ray radiography system. This system is typical of those used for studies of impact, ballistic, detonics and explosives [138]. The setup consisted of four X-ray heads mounted around the target tank, normal to the barrel axis. These were arranged in 45° steps from the vertical. Each head had an independent power supply in the form of a Marx bank capable of delivering an accelerating potential between 20 kV and 300 kV. These were triggered from a central control box, which takes an input signal from the gas gun (such as the projectile breaking a light gate) and then passes each head a trigger signal after a pre-determined time delay. The arrangement of the heads is shown in figure 7.7, left.

![Flash X-ray radiography equipment schematic](image)

**Figure 7.7:** Flash X-ray radiography equipment schematic. *Left:* Arrangement of heads around and cassettes inside the target tank, looking down the gun barrel. *Right:* Location of the four film cassettes in the mounting frame. The two machined rings in the centre are where the target was mounted.

Each head had a corresponding film cassette mounted inside the target tank, the other side
of the barrel axis. The film cassette contains a scintillator and a sheet of film as per section 5.2.1. These were held in a steel frame with a polycarbonate sheet covering each cassette to protect it from debris and the gas blast after the projectile leaves the barrel. The cassette locations relative to the heads are shown in figure 7.7. The centre of the image projected onto each cassette was around 90 mm from the end of the barrel. The heads could be triggered independently or simultaneously. Triggering separately with a time delay between each flash allowed a temporal history of the expansion to be recorded, although each image is at a different angle relative to the cylinder axis. As heads 1 & 3 and 2 & 4 are orthogonal to each other if these were triggered simultaneously the images can be used to measure the symmetry of the expansion.

7.3.2 Experimental Geometry

Detailed technical drawings of the cylinder, insert and projectile are given in appendix A.2. The geometry used was very similar to the simulations in figure 7.6. Cylinders were machined from solid rod stock 6061-T6 aluminium with the cylinder axis aligned along the rod stock. A section of a surplus cylinder was polished and etched to reveal an equiaxed grain structure. The cylinders were 60 mm long, 30 mm long with a wall thickness of 2 mm. These were machined with a larger flange left on one end to enable bonding to a target ring which would then mount into the alignment plates of the gas gun target tank. The cylinders were machined from 6061-T6 aluminium as these shots were more concerned with testing the geometry, Ti-6Al-4V is much more expensive and difficult to machine in comparison. The inserts were machined from 4340 steel, with a base radius of 15 mm and an ogive radius of 22.5 mm. A 2 mm hole was drilled through the full length of the insert along the centre axis to enable alignment of the cylinder and insert assembly to the gas gun barrel optically. The rear of the ogive was also machined out to reduce weight. As the assembly was supported by the opposite end this weight reduction has a significant effect due to the large moment. The void left by this was also considered as a place to house temperature control systems and needed testing. The gas gun used was a single stage double diaphragm design with a 50.8 mm bore. The projectile was launched by a sabot, machined as one piece from PC1000 polycarbonate. The projectile length was 65 mm, chosen to provide enough time for expansion before the rest of the sabot impacted the cylinder. The
ogive was a very light press fit into the rear of the cylinder, with a small bead of epoxy used around the very rear of the cylinder to insert interface. There is no need for these two parts to be mechanically joined, this was only to make assembly and mounting of the cylinder and insert easier. As mentioned in the simulation section, the cylinder needs to be able to separate away from the insert as it expands to avoid causing a polycarbonate jet in the corners where the ogive face meets the inner cylinder wall. The leading edge of the sabot had a thin aluminium ring installed. Two pairs of wires were mounted 15 mm apart and connected through a power source to an oscilloscope. The bare ends of these pairs were mounted such that as the sabot left the barrel the aluminium ring made contact between each pair, the output from which was used to trigger the X-ray heads and provide a time-of-flight measurement to give the projectile velocity. A diagram of the setup is shown in figure 7.8.

Figure 7.8: Components for the ogive geometry validation shots. Top: Cross section in the axial radial plane, showing the machined recess and 2 mm hole through the ogive. Bottom: Images of the prepared components.

### 7.4 Experimental Results

Based on the simulation data and the plot in figure 7.5, right, the desired projectile velocity was 900 m s\(^{-1}\) to ensure that a strain rate of at least 10\(^4\) s\(^{-1}\) was generated. A series of five
shots were fired with one misfiring at a projectile velocity of only $158 \text{ m s}^{-1}$. The rest of the series had an average projectile velocity of $(915 \pm 45) \text{ m s}^{-1}$ with the uncertainty produced by the accuracy in measuring the distance between the velocity pins. The velocity was the same for each experiment to keep the expansion process constant between shots, enabling X-rays from each one to be compiled into a temporal history of the deformation. The velocities for the five shots are plotted in figure 7.9.

![Figure 7.9: Projectile velocities for the five shots. Shot #4 was not included in the calculation of the average velocity.](image)

Test images were taken with the insert and cylinder target in place with a dummy projectile resting inside the cylinder. It was found that the best contrast between the components was produced with the X-ray heads firing under a 20 kV to 30 kV accelerating potential. After each experiment the film sheets were extracted from the cassettes and developed. These fixed films were then transmission scanned (back-lit) using an Epson Perfection V700 as 16 bit-depth greyscale images. The developed film was clear in regions that had not been exposed to X-rays and progressively darker with increasing exposure. Post processing was completed in ImageJ where each image was cropped, inverted such that darker areas represent less X-ray exposure and the range adjusted to provide the best contrast. In some cases false colour look-up tables were applied to enhance the visibility of certain features. The X-ray flash delays were increased with each shot to build up the deformation profile over the first 45 µs from impact shown in figure 7.10.

The first three frames were processed to produce the outlines of the three components, which have been filled according to material to help demonstrate the location of each part. The
Figure 7.10: Ogive geometry validation experiments. Compilation of X-ray images forming a timeline of the expansion process. Left: Inverted scans of the X-ray film. Right, top: Regions extracted in ImageJ, showing the projectile, insert and cylinder. Bottom: False colour images to emphasise voiding.
projectile enters each frame from the left. At 9µs after impact the polycarbonate has started to flow around the ogive insert, although there is not yet contact along the entire rounded face of the ogive. The next frame at 14µs clearly shows the cylinder beginning to expand around the projectile. By 20µs this expansion has become more pronounced and voids are starting to form between the projectile and cylinder behind the peak of the expansion. This is due to the longitudinal momentum of the projectile, a result of the projectile moving faster through the cylinder than the expansion velocity of the wall. This region where voids are present is now in free expansion and rapidly approaches a purely tensile state as the radial loading wave dies out. The later two images at 34µs and 45µs are shown against false-colour images to further emphasise the voiding. The ogive can be seen to begin ejecting from the rear of the cylinder stopping any possibility of jetting caused by trapped polycarbonate between the ogive and inner cylinder wall. At 34µs there is a clear fracture in the cylinder wall in the lower half of the image. The orientation of this suggests that it is in the circumferential direction, possibly a result of converging longitudinal fractures. Note that this is not seen in the image at 45µs as the images are taken at different orientations relative to the cylinder axis. In the final image there are very weak signs of longitudinal fracture presenting as lighter bands along the length of the cylinder, this is more evident in figure 7.11 in the blued image. The ogive was recovered after each experiment and examined for damage. The tip of the ogive had slightly blunted and in all cases the length had only reduced much less than 1 mm in agreement with simulation predictions of minimal deformation.

Over the whole deformation sequence the expansion maintains an axisymmetric profile, initially with a Gaussian shape but skewing to the right as the projectile continues to move through the frame and fracture weakens the cylinder. The peak of the expansion region translates approximately 8 mm along the length of the cylinder over the 45µs record. Two images taken at orthogonal angles have been placed together in figure 7.11. These were taken at the same time after impact and show the extent to which the expansion is equal around the entire azimuth of the cylinder.
7. GAS GUN DRIVEN CYLINDERS I: OGIVE METHOD

7.4.1 Comparison with Simulations

Figure 7.12 shows X-ray images at 20 µs and 34 µs against images taken from the simulation described in 7.2.1. Overall the simulation and experiment show very close agreement. The voiding between the projectile and wall was seen as predicted as was the general shape of the expansion region. At 34 µs the simulation shows extensive thinning of the cylinder wall. In the X-ray image the wall has also thinned and gone through to failure, the model was not able to predict failure as no model was included.

ImageJ was used to measure the radius of the cylinder at the expansion peak and an undeformed region from the digitised X-rays. Using the baseline from the undeformed region the radius of the expansion peak was calculated and plotted against simulation data in figure 7.13 top. The errors rise from uncertainty in locating the edge of the cylinder and from the distance
Figure 7.13: Ogive geometry validation, comparison of experimental (black dots) and simulation (red lines) data. *Top:* Radius of the peak of the expansion region with time. *Centre:* Average interframe velocity of the expansion peak from X-rays against gauge data from simulation. *Bottom:* Average interframe radial strain rate at the expansion peak.
between the two velocity pins for the time value. There is close agreement between the two data sets until approximately 20 µs after which the curves deviate and the simulation predicts a slower increase in radius. This is matched by the velocity plot in the centre of the figure. Here, the displacement of the peak between each frame was divided by the interframe time to give an average interframe velocity and plotted against radial velocity data from AUTODYN. At the point where the data diverge the cylinder has accrued on the order of 30 percent radial strain. Other work on expansion of the similar alloy 6061-0 aluminium tubes (electromagnetically launched) has shown that this is around the onset of failure and localisation [139]. As there was no failure model implemented in the simulation the model will retain strength and therefore decelerate the cylinder where the experiment has begun to fail. Finally, the lower plot shows the average interframe radial strain rate, the quotient of the interframe velocity and radius. The peak radial strain rate value of \((2.07 \pm 0.27) \times 10^4 \text{s}^{-1}\) is closely matched by the model.

### 7.5 Conclusions

The aim of this experimental work was to produce a platform for loading cylinders into expansion using a gas gun in such a way that the temperature of the cylinder can be controlled without affecting the loading mechanism. For this to be possible required departing from the classical Winter method where the insert is required to deform. The challenge in this is that the longitudinal momentum of the projectile must be efficiently transformed into radial motion without causing localised regions of flow that will jet through the cylinder wall. It was decided to experiment with using a steel insert, shaped to create a time-dependent contact interface that would generate a supported radial shock in the projectile. The projectile would remain as a polymer, specifically polycarbonate.

Several insert geometries were modelled using AUTODYN, including conical, hemispherical and ogival shapes. In these early models with an angled leading face on the projectile the ogive insert showed the most promising expansion, reaching the strain rate requirement of \(10^4 \text{s}^{-1}\) while achieving the wide, Gaussian shaped expansion region of the Winter method. This was further refined by changing the leading face of the projectile to a concave radiused profile. With these components, the geometry can be scaled to suit the gas gun or cylinder size, the
key dimensions being a simple ratio of the cylinder inner diameter as per equation 7.1.

The ogive geometry was validated with experiments on 6061-T6 aluminium cylinders using flash X-ray radiography to probe the behaviour of the interfaces between the projectile and cylinder and the expansion profile. The experimental data was found to be in close agreement with the predictions from the AUTODYN model, the model capturing the behaviour of the projectile and the voiding created between it and the cylinder inner wall. Quantitative data such as the radius, radial velocity and radial strain rate were also within acceptable errors. The deviation between simulation and experimental data in the later times could be used as an indicator of the time where failure and fracture initiate in the experiments.

This work provided a strong starting point to continue with the other experimental aims, introducing a form of temperature control. The ogive insert was observed to perform well even when largely hollowed out without significant damage. Hence the ogive can be used to house heating or cooling equipment with the benefit that this will not obscure diagnostics such as high speed imaging or laser based velocimetry. The next chapter details the development and testing of temperature control systems and presents initial results on Ti-6Al-4V cylinders.
7. GAS GUN DRIVEN CYLINDERS I: OGIVE METHOD
This chapter covers the methods used later for heating and cooling the sample in a gas gun driven expanding cylinder experiment. Some areas of shock physics research such as spall strength and Hugoniot elastic measurements enjoy well-established and tested techniques for controlling sample temperature. These are discussed along with the difficulties in applying them to an expanding cylinder configuration. The solution for both heating and cooling was found by using the ogival insert to house temperature control apparatus. Heating was performed with a resistive load and high current power supply, with cooling using liquid nitrogen. In both cases the system was remotely operable and the temperature logged at multiple points over the sample. Initial results achieved a range from around 150 K to 800 K in a 50 mm inner diameter by 150 mm long Ti-6Al-4V cylinder.

8.1 Existing Methods for High Strain Rate Work

Measurements of the dynamic response of materials at temperature generally fall into two areas. The first primarily covers the initial deformation and behaviour of the sample, for example the onset of yield and the magnitude of the elastic precursor (Hugoniot elastic limit). One of the earliest studies of the former was performed by Gust using the reverse Taylor impact test (anvil-on-rod) [136]. In this, a gas gun was used to launch a ‘rigid’ plate impactor, the anvil, at a target rod. The target rod was heated to a maximum of 1235 K using either a furnace arrangement or high intensity halogen lamps focused on the sample with parabolic reflectors. Another area that has been extensively studied is the effect of temperature on the spall strength. A well-established method for measuring both the elastic limit and spall strength is the one first proposed by Kanel et al where an explosive lens is used to propel a flyer into a disc-like target [140]. In this and successive works [102, 141] the sample is heated with a resistive load heater, typically a coil of NiChrome wire in close proximity to the sample. This heating
8. TEMPERATURE CONTROL SYSTEMS

Technique has also seen use on gas gun plate impact studies [142] and Kolsky bar studies where the heater surrounds the cylindrical sample [143]. Induction heating systems where a drive coil induces large high frequency currents in the sample have also seen some use [144, 145]. The sample size is quite small in all these works. Gust’s rods were on the order of 30 mm long by 6 mm diameter, with the round plate impact studies typically up to several mm thick.

While radiative heat transfer works for heating, cooling requires thermal contact between the temperature apparatus and the sample. For systems where the experiment does not need to be performed in vacuo such as Kolsky bar work a coolant such as liquid nitrogen (LN$_2$) can just be flowed around the sample [146]. At increasing strain rates such as gas gun work the experiment is typically in an evacuated tank to avoid launching a small shock into the target from the compressed air ahead of the projectile. Under these conditions direct contact between the cryogenic and sample is not possible. Espinosa and Arrieta have performed work on flyer plate impacts by mounting the target plate in an aluminium ring. This ring had internal channels through which the LN$_2$ was flowed. With this arrangement care must be taken to ensure that movement or binding as a result of different thermal expansion rates of the sample and mounting is minimised or can be adjusted for - Espinosa used a laser and mirror system to monitor the sample tilt. At the extreme end of the scale very low temperatures have been achieved (below 30 K) on the Z machine$^1$ in liquid deuterium samples using liquid helium as a coolant [147, 148].

8.1.1 Difficulties in Application to Expanding Cylinders

Reiterating the aims of section 7.1, the desired temperature range for the Ti-6Al-4V cylinder work was 100 K to 1000 K. The design required that the cylinder temperature would have no effect on the expansion drive and not inhibit the use of diagnostics such as laser velocimetry and high speed imaging. This is further complicated by the size of the cylinders (150 mm long by 50 mm inner diameter, more details in the following chapter) and that the Ti-6Al-4V has a very poor thermal conductivity at 6.7 W m$^{-1}$ K$^{-1}$, almost two orders of magnitude less than copper. Mounting the target also becomes an issue, as with the weight of the ogive there must be a

$^{1}$http://www.sandia.gov/z-machine/, a pulsed power facility.
secure bond between the cylinder and the mounting ring in the gas gun tank. This mounting
ring is designed to allow for alignment of the cylinder both concentrically and parallel to the
barrel axis and is a large, steel body and hence acts as a thermal sink with respect to the
cylinder. It will be shown in the following sections that these obstacles can be avoided through
the new ogive based geometry in chapter 7. Heating methods are shown first.

8.2 Heating

8.2.1 Initial Designs and Testing

Under the constraint that the cylinder must be available to optical diagnostics the heating
mechanism must be removable prior to the actual shot firing. Initial designs worked from
the paper by Gust mentioned earlier, with a clamshell jacket that surrounded the cylinder
containing several high power halogen infra-red lamps\(^2\). This would then be servo actuated in
a way to open away from the cylinder in a pincer movement enabling it to then drop down
away from the experiment. A rendering of this is shown in figure 8.1.

![Clamshell heating jacket rendering](image)

Figure 8.1: Clamshell heating jacket rendering. This would be mounted with the hinge underneath
the cylinder, allowing it to open up and drop away from the sample once the desired
temperature is reached. The red tubes represent halogen infra-red lamps.

The lamps would be surrounded by a highly reflective jacket to reflect as much radiation
in towards the cylinder as possible. This in turn would be surrounded by an insulator such
as fibreglass matting to avoid heating nearby sensitive components such as PDV probes. The
advantage of this design is that the heating is evenly distributed along the cylinder length.
The use of a reflector and equally spaced lamps would have created a fairly uniform azimuthal

\(^2\)Philips 14103Z/98, 2000 W, 235 V
heating. However, it was not known how the lamps would perform in a vacuum. There were also concerns about the amount of electrical power needed with each lamp running at 235 VAC and 9 A, drawing over 16 kW at full load. Therefore while this design would have produced rapid, even heating the issues with removing the heater and possible electrical hazards in case of a failure meant another option had to be pursued.

One conclusion of chapter 7 was that the ogive still produced very uniform and controllable expansion even when the rear (that is the part that contacts the inner cylinder wall) has been largely hollowed out. This was seen as a possible location for temperature control apparatus. Although the heating would then be from one end instead of along the whole length, if the unheated end of the cylinder was adequately isolated from the mounting hardware then eventually the system would reach an acceptable thermal equilibrium. Initial tests were completed with a 4340 steel insert (the ogival profile omitted for ease of machining) that contained five cartridge heaters in the rear. The insert had an outer diameter of 42 mm to fit into a sample Ti-6Al-4V cylinder (the same stock as used for the explosively driven rings in chapter 6). The cartridge heaters were manufactured by Türk+Hillinger GmbH, model number 120004. Each heater contained a NiChrome coil in a stainless steel casing. The coil was electrically insulated from the casing by magnesium oxide (MgO). The casing had an outer diameter of 6.5 mm and a length of 40 mm and the heaters had a power rating of 200 W at 230 VAC. Five holes were drilled and reamed as specified by the manufacturer in the rear of the insert at a 13 mm radius from the centre with a 72° spacing. The heaters, insert and cylinder are shown in figure 8.2.

![Figure 8.2: Experimental setup for initial testing of a heating insert containing 5 cartridge heaters. Left: Heaters and insert. Right: Insert installed in the test Ti-6Al-4V cylinder.](image)

Power was supplied by an autotransformer, allowing the voltage to be adjusted from 0 V to 240 VAC. The heaters were connected in parallel. The cylinder and heating insert assembly
was mounted vertically with the insert at the top on a bed of sand for thermal and electrical isolation in case of a fault. For these tests no temperature measurements were made, the aim was to validate that the cartridge heaters could be used in this configuration. The voltage was increased in steps of 20 V and held for 5 minutes at each stage. The cartridge heaters would fail in a repeatable manner at around 200 VAC. Once this was reached the casing would rupture, the manufacturers’ data sheet stating that the MgO is gas-tight sealed into the stainless steel sheath. In some cases this was followed by the heater and power cable igniting. A similar issue has been observed by Davis and Foiles where cartridge heaters were used for preheating a sample prior to isentropic compression [149]. It is believed that the difference in thermal expansion, however minimal, between the cartridge and the insert causes areas of poor thermal contact on the heater sheath. This leads to localised heating and thermal runaway, resulting in complete degradation of the NiChrome wire and MgO insulator. Analysis of the steel insert through colouring due to oxide formation and the resulting thin film interference suggests that a temperature on the order of 600 K was reached at the external surface of the insert [150]. For this reason, and the remaining uncertainty regarding how these sealed heaters would perform under vacuum, the final design moved away from commercial solutions.

8.2.2 Resistive Load Heating System

The final solution was to take parts from both the radiative lamp based system and the conduction based cartridge system. The benefit of the radiative solution is that there does not need to be thermal contact between the heat source and the cylinder (or insert). The advantage of the cartridge system where the heat source is inside the cylinder does not need removing prior to the shot. A combination of these produced the resistive load design shown here, where in short a NiChrome coil is placed inside the hollow of the insert. This is subjected to a high current so that Joule heating causes it to increase in temperature until it glows, radiating heat towards the inner wall of the insert. This in turn heats up and transmits the heat into and along the sample cylinder.

Joule or Ohmic heating is proportional to $I^2R$, where $I$ and $R$ are the current in and resistance of the work piece respectively. The cartridge heaters mentioned earlier use very thin
NiChrome wire, to increase $R$ enabling them to be run from standard mains supply. However, this also makes them susceptible to weak or hot spots as found. Hence the heating coil settled on made use of much thicker wire, 14 standard wire gauge (SWG) or 2.03 mm diameter with a composition of 80 percent nickel and 20 percent chromium by weight. This has a melting point of approximately 1700 K. To reach the same level of heating a dedicated power supply was used, a BK Precision 1900, capable of driving 60 A at 16 VDC into a sample. The wire was formed into a helical coil and supported inside the rear of the ogive on a Macor spindle. Macor is a high temperature machinable glass ceramic that could resist the temperatures generated by the NiChrome coil while providing electrical isolation. Figure 8.3 shows a cross section of the cylinder, insert, coil and spindle at the top. Below this are images of an ogive and heating coil used for testing.

![Figure 8.3: Heating system resistive coil and insert design. Top: Cross section rendering of the coil (yellow), macor spindle (white) and the ogive inside the cylinder. An M6 bolt secures the spindle in place. Bottom: A coil, spindle and insert used for testing as shown on the right. Note this test was not performed under vacuum hence the oxidisation on the metal components.](image)

The cylinder here and in the following chapter is Ti-6Al-4V with an inner diameter of 50 mm. The ogive dimensions are set as per equation 7.1. The recess in the rear of the ogive is 40 mm
diameter by 35 mm deep. The shaft of the macor spindle is 35 mm long with an outer diameter of 25 mm. Coiling the NiChrome wire tight around the spindle therefore leaves around 3 mm between the coil and the inner wall of the insert recess. The spindle is held inside the ogive with an M6 bolt. A belleville washer was placed between the insert and the bolt head to maintain tension in case of movement due to thermal expansion.

The power supply and control system was built in house by the author. The system needed to be firstly safe, that is the electrical system can be physically disconnected from the target and gas gun in the event of a fault. The power delivered to the coil needed to be easily controlled and logged remotely, along with the temperature along the cylinder. This data needed to be saved for analysis of the thermal profiling the sample experienced prior to expansion. The system used National Instruments LabVIEW software and hardware, specifically a NI-DAQ USB-6009 acquisition board. This hardware can log and drive multiple analogue and digital inputs and outputs simultaneously. The LabVIEW software environment was used to develop a ‘virtual instrument’ (VI) that could write to and read from the NI-DAQ and other hardware, saving the data at a timestep specified by the user. From the VI the user could input the desired current to pass to the coil and record the temperature at up to 8 points as well as the voltage and current in the coil. A schematic of the circuit used for controlling the power supply is shown in figure 8.4 above a screen shot of the VI. Starting at the left, the blue coloured box represents the NI-DAQ. This connected via USB to a computer. The three connections at the top are a reference ground and two analogue outputs (AO 0 and AO 1) capable of 0 to 5 V. These were connected to a port on the rear of the high current power supply, shown in green. Through the software the user specified a desired current and voltage limit for the supply, which was then converted to a voltage and sent to pins 2 and 3 on the power supply. The outputs of the supply, V+ and V-, were passed through the relay control box in orange. This housed a potential divider, consisting of resistors R1 and R2 and a fast acting fuse. The values of the resistors were chosen such that the measured voltage would be approximately 10 percent of the actual, bringing the maximum 16 V output of the supply below the 5 V limit of the analogue inputs of the NI-DAQ while ensuring that the current remained at a very low level. Pins AI 0+ and AI 0- on the NI-DAQ measured this reduced voltage, and the software was calibrated such
Figure 8.4: Heating system control.  
Top: Schematic of the heating control and supply hardware.  
Bottom: Screenshot of the LabVIEW VI. Thermocouple logging is on the left, with control over the power supply on the right.
that this value is used to provide the voltage in the coil. To provide isolation of the supply from the gas gun in the event of a failure a normally open mechanical relay was used, shown at the lower left of the orange box. This relay could switch up to 100 A but required 12 V to energise, more than the 5 V output of the NI-DAQ. To solve this the NI-DAQ digital output PO.0 was used to operate a solid state control relay, which in turn switched an external 12 V supply to the mechanical relay. This power supply was connected to the mains supply in the control room. This provided another level of safety, if there was a fault with the control software the 12 V supply could be switched off and the 100 A relay would revert to open without the user having to enter the gun room. It was decided to not include proportional-integral-derivative (PID) control due to the complexity of the system (multiple materials and interfaces) and that the experimental run was short at four shots, hence the time developing and calibrating such a system would outweigh any benefits brought by it. Multi-strand copper cable with a 16 mm$^2$ cross sectional area was used to carry the high current, with electrically isolated vacuum tight fittings fitted to a port on the gas gun. The temperature was logged with a Pico Technology TC-08 USB thermocouple logger. This unit can record up to eight thermocouples in addition to the onboard cold-junction temperature. This was integrated into the VI for the power supply as shown on the left of figure 8.4, bottom. Each thermocouple can be individually activated and calibrated for the junction type. At the bottom of the VI window are two file paths; for each time step the VI writes the data for the selected thermocouples and the current, voltage and relay state data to two text files. The append to file option was used to prevent loss of the thermal history of the sample in case of a software error. The time interval between recorded points was 1000 ms for all experiments.

The temperature was measured at several points along the cylinder length. For the heated experiments J-type thermocouples were used, a combination of iron and constantan. These are accurate over a range of approximately 300 K to 1050 K. The thermocouples were bonded to the outer surface of the cylinder. Two high temperature adhesives were used, both manufactured by Holt Lloyd, Gun Gum and Fire Gum. These are intended for use in the repair of metals subjected to high temperatures, such as the exhaust manifold of an internal combustion engine. Both consist mainly of sodium silicate and magnesium silicate and a binding agent. They are
applied as a paste and then cured through heating, the moisture boiling off and the silicate compounds left bond together. The thermocouples were held in place with electrical tape then a small amount of the Gun Gum placed over the thermocouple bead. This was then cured in an oven between 400 K and 450 K for around one hour. The Fire Gum had a higher moisture content and when cured was quite porous. For this reason the Fire Gum was used as a secondary adhesive, to keep leads etc. in place. It was not used to bond the thermocouples on as the porosity could lead to improper temperature measurement. Figure 8.5 shows a typical cure cycle, testing the Gun Gum (red) and Fire Gum (black). The higher moisture content of the Fire Gum presented as a small plateau near the boiling point due to the latent heat of the water.

![Figure 8.5: Curing the high temperature adhesive used to affix the thermocouples to the cylinder. Left: Ti-6Al-4V cylinder as used in chapter 9 in the oven. Right: Typical curing cycle for the high temperature adhesives, Gun Gum (red) and Fire Gum (black) manufactured by Holt Lloyd.](image)

The rest of the experimental design such as thermally isolating as much as possible the cylinder from the mounting ring is discussed in the next chapter (chapter 9). The heating system was found to be able to heat the cylinder to a maximum of approximately 850 K at the rear end (by the insert). Using the full power of the supply, 62 A, caused the M6 bolt holding the macor spindle and coil in place to deform and melt, shorting the resistive coil against the inner wall of the ogive insert. This could have been remedied by using a material with a higher melting point. However, as there were a limited number of Ti-6Al-4V cylinders available it was not until the last shot of the experimental run that full power was tested. The temperature
measured along the cylinder for all four experiments at the time of impact is shown in figure 8.6. Shots C (red) and D (orange) were heated with a constant current of around 40 A and 55 A respectively, with shot D being taken to full power once the peak temperature had plateaued at around 850 K and then failing as mentioned. In both cases it took approximately one hour for the temperature to cease rising at the insert end. A reasonable error value of 5 percent has been added owing to the calibration of the logging hardware and the quality of contact between the thermocouple and the cylinder.

![Temperature at points along the cylinder for the four experiments in chapter 9 at the time of impact, joined with a spline fit. The cylinders were 150 mm long, with zero corresponding to the end that the projectile enters. The tip of the ogive is at approximately 75 mm and the insert contacts the inner cylinder wall between 110 mm and 150 mm.](image)

It is clear that this heating method introduced a thermal gradient along the length of the cylinder (as does the cooling discussed later). It will be shown that the peak of the expansion region is found to be around 95 mm along the cylinder, with the full extent of the Gaussian profile extending from 70 mm to 120 mm. Over this region the delta in surface temperature is approximately 160 K. Note that this is for Ti-6Al-4V, a notoriously poor thermal conductor. For experiments on other metals such as steel or copper it would be expected that this thermal gradient would be much reduced. Improving the isolation between the cylinder and mounting hardware would improve this, suggestions are discussed in the relevant experimental chapter.
8.3 Cooling

Liquid nitrogen was used as the cryogenic agent for the cooling work. In contrast to the work of Espinosa and Arrieta described earlier where cooling is facilitated by passing the liquid through the mounting ring and allowing the target to conduct heat away, for the expanding cylinder experiments the ogive was used again. It will be shown that the mounting hardware also contacts the laser velocimetry probes for ease of maintaining alignment. Attempting to cool these components would require more LN$_2$ and could possible cause issues by changing the optical properties of the probes.

The ogive was identical to the heated version, the rear being machined out with a tapped hole in the centre. This void was sealed with a 6061-T6 aluminium cap that threaded onto a piece of M6 studding bonded into the tapped hole in the ogive. The interface between the cap and the ogive was sealed with a PTFE O-ring, 40 mm inner diameter by 2.5 mm thick. PTFE was used as rubber o-rings become brittle at cryogenic temperatures and could fail if there was movement from thermal contraction. The cap had two SwageLok fittings installed to connect to 3/8” copper tubing. This is shown in figure 8.7.

![Figure 8.7: Cooling system ogive modification. Top: Exploded and labelled diagram of the components. Bottom, left: Aluminium cap with O-ring and pipe fittings installed. Right: Cap installed on ogive insert.](image)

The LN$_2$ supply was a pressurised 3 bar 120l dewar. The output of this passed through a

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$^3$Polytetrafluoroethylene, Teflon®
needle valve to set the flow rate and a solenoid gate valve to seal the flow off from the experiment. The latter was a gate valve manufactured by Asco, part number SCE222E002LT and was rated for cryogenic use. The output of the solenoid valve was fed through a feedthrough on the gas gun target tank. This feedthrough consisted of a SwageLok bulkhead connector thermally isolated from the steel tank with a PEEK\textsuperscript{4} polymer plate. Inside the tank 3/8” outer diameter copper tube linked the other side of the feedthrough to the ogive insert, then from the insert to another feedthrough at the top of the tank. By bringing the LN\textsubscript{2} in at a low level and venting from the top this design minimised back pressure as the cryogenic boils off inside the tubing and ogive. The vented products were allowed to escape straight into the laboratory atmosphere as the air management system of the gas gun laboratory could process the amount of gaseous nitrogen produced without the oxygen percentage diminishing to an unsafe level. A schematic of the system is shown in figure 8.8.

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{fig88.png}
\caption{Schematic of the cryogenic cooling system.}
\end{figure}

The temperature of the cylinder was measured with three type K (chromel - alumel) thermocouples, using the same VI and hardware as the heating experiments for logging. These were bonded to the cylinder using ÅngstromBond 9266, a two part epoxy that remains slightly flexible when set. This was to ensure that as the cylinder contracts from cooling the thermocouples remain affixed.

Once the gas gun target tank was evacuated (typically around 300 mTorr) the solenoid valve was opened from the control room. Then the needle valve was slowly opened until there was a steady flow of LN\textsubscript{2} through the system, this was observed from the thermocouple data and the visible condensed water around the exhaust vent. The rest of the experiment was

\textsuperscript{4}Polyether ether ketone, a thermoplastic thermal insulator suitable for vacuum use.
then conducted from the control room. The dewar contained enough LN$_2$ to flow for around 45 minutes. The blue points in figure 8.6 show the temperature distribution along the cylinder. Over the expansion region (95 mm to 120 mm) the temperature varies from 180 K to 140 K with the end nearest the insert reaching a minimum of 120 K. Extrapolating the temperature data suggested that with a larger dewar it would be possible to reach around 120 K over the entire expansion region. There were minor issues with ice formation on the cylinder, possibly due to moisture from the plywood shields used to protect the inside of the has gun target tank from fragments. This could be solved by holding the chamber at vacuum for longer prior to cooling or by installing a moisture trap (cold finger), i.e. a large surface area such as a sphere that is filled with LN$_2$ prior to the supply to the ogive. This would draw the moisture to the trap and condense it before it could accumulate on the target cylinder.

8.4 Conclusions

The initial aims were a method of controlling the temperature of the cylinder, in particular the expansion region, to a steady state temperature between 100 K and 1000 K while keeping the target available to diagnostics such as laser velocimetry and high speed imaging. This was attempted through use of the ogive insert at the rear of the cylinder as developed in chapter 7. It is important to note that these temperature control systems were developed and tested during the shot sequence in chapter 9, and therefore the modifications suggested as a result of this chapter’s findings were not able to be implemented. Future experiments would incorporate these changes.

For heating, a resistive load consisting of a NiChrome coil over a ceramic spindle was mounted in the rear of the ogive. This was then supplied with a high current, up to 62 A, with a system that enabled remote control and logging of the power delivered and the temperature along the cylinder. A maximum temperature of (850 ± 43) K was reached at the rear end of a 150 mm long Ti-6Al-4V cylinder. The corresponding maximum average temperature over the length of the expansion region was (700 ± 50) K with a range of (160 ± 11) K. This range decreased with the maximum temperature. The thermal gradient is a result of losses to the mounting hardware (the details of which are discussed in chapter 9) and the poor thermal
conductivity of Ti-6Al-4V. Without changes to the experimental design other metals such as copper or steel would have a much reduced gradient.

Cooling was performed by sealing the recess at the rear of the ogive insert with an aluminium cap, then passing LN$_2$ through this chamber from a pressurised dewar. Control over the cooling rate was facilitated through a needle valve to regulate the flow rate and a solenoid valve activated from the control room to stop or start the flow. At a reasonable flow rate the dewar remained pressurised enough to flow continuously for 45 minutes, over which time a minimum temperature of $(120 \pm 6)$ K at the end of the cylinder closest to the insert. The average temperature over the expansion region was $(160 \pm 11)$ K with a range of $(40 \pm 3)$ K. Analysis of the cooling rates and the points at which they would equilibrate suggested that with a larger reserve of LN$_2$ it would be possible to reach an average of $120$ K over the expansion region.

From these experiments it is clear that only some of the initial aims were met. In both cases the method of temperature control is almost completely non-invasive, the only change that could possibly hinder the application of imaging or laser velocimetry diagnostics is the bonding of the thermocouples to the cylinder, although these are applied in a line leaving one side of the cylinder clear for imaging. The lower end of the desired thermal range was almost reached, producing an average over the area of interest of $(160 \pm 11)$ K compared to the intended 100 K. However, the maximum average temperature reached in the expansion region was only $(700 \pm 50)$ K, quite short of the original goal of 1000 K. The peak at the rear of the cylinder was $(850 \pm 43)$ K. This required almost maximum current from the power supply, and softened the bolt holding the resistive coil in place to the extent that the coil shifted and shorted out against the inside of the ogive. This could be solved through the use of a different material for the bolt and a more capable power supply. The following chapter describes the design and results of the expanding cylinder experiments that this temperature control system was tested on.
8. TEMPERATURE CONTROL SYSTEMS
Gas Gun Driven Cylinders II: Studies at Temperature

This chapter details a set of experiments where the heating and cooling methods described in the previous chapter were tested on expanding Ti-6Al-4V cylinders. The cylinders were 150 mm long with a 50 mm inner diameter and a 4 mm wall thickness. These shots were performed on the 100 mm bore large format gas gun at the Institute of Shock Physics. The full thermal history of each cylinder was recorded, that is any heating needed during preparation and the temperature record up to the point of impact. The expansion process was diagnosed with multiple channels of upshifted PDV along the length of the cylinder and high speed imaging. Recovered fragments were measured, weighed and probed with optical and electron microscopy techniques to ascertain the fracture mechanisms. Firstly some simulations are presented where the ogive based geometry of chapter 7 was scaled to suit the larger gas gun and the cylinder material changed to Ti-6Al-4V. These simulations were used to assist in designing the experiment. The application of the cooling and heating methods already discussed is summarised along with details of the diagnostics and their timing and synchronisation. The as received Ti-6Al-4V was fully characterised to determine the elastic constants and the microstructure. Finally, the initial results of this method to study temperature dependent fracture and fragmentation are presented and followed with conclusions and suggestions for improvement. The work at room and low temperature was presented at the Shock Compression of Condensed Matter group meeting in Seattle, 2013 [151].

9.1 Overview & Motivation

The initial purpose of this experimental run was to validate that the temperature control methods developed would work in situ, that is in the gas gun target tank environment, without
affecting the expansion drive and without impeding the diagnostics. The systems needed to perform safely, predictably and reliably. With these conditions met this would open the technique for application to other materials and strain rates. Ti-6Al-4V was chosen owing to the variety of ways it can fail through, some shown in chapter 6. One failure mode not observed in the explosively driven rings work but commonly found by others is adiabatic shear banding. The experiments here would provide information on how the initial temperature affects the initiation of adiabatic localisation and shear, for strain rates on the same order as the explosively driven ring work.

The 100 mm gas gun allows for the use of multiple diagnostic systems simultaneously. Introducing another variable in the form of temperature into the already complex behaviour of fragmentation meant that for the data to be as useful as possible for simulation and material model development the maximum amount of data needed to be extracted from each shot. Hence the temperature (up to the point of impact) and the expansion velocity were measured at multiple points along the length of the cylinder. Upshifted PDV and custom order optical probes typically allowed around 100 \( \mu s \) of velocity history to be extracted. The projectile velocity was also measured with PDV. Multiple high speed imaging systems were used on each shot, usually having one examining fracture initiation and growth and the other silhouetted to provide a profile of the expansion region. Having these diagnostics synchronised and their timings recorded by a central system (the Acqiris, discussed later) meant that the PDV and imaging data could be cross referenced and validated against each other such that strain with time (resolution limited by the camera inter-frame time) could be extracted for any point along the cylinder and compared with the arrival of fractures. Combined with the fragment recovery and processing these shots were extremely well diagnosed and present a large amount of novel data available for simulation comparison and development.

In summary, the motivation of these shots was to deploy the temperature control systems on a set of preliminary experiments with a suite of diagnostics to capture information on the thermal history of the cylinder up to impact, the projectile velocity, the expansion velocity at multiple points, the expansion profile, strain to failure and the fragmentation statistics and fracture mechanism. This data is then used to evaluate the ogive method at temperature and
9. GAS GUN DRIVEN CYLINDERS II: TEMPERATURE

the quality of expansion drive and initial results on Ti-6Al-4V are given.

9.2 Scaling simulations

Simulations were performed in AUTODYN to examine how the geometry developed with the 30 mm 6061-T6 aluminium cylinders in chapter 7 would scale with size to a larger gas gun and behave with a Ti-6Al-4V cylinder. The simulation techniques were covered in section 6.3. The polycarbonate projectile and 4340 steel insert used the same EoS and strength data as the simulations in chapter 7. The Ti-6Al-4V used the same EoS and strength data as the explosively driven rings, albeit with some values such as density and sound speed changed to reflect the measured values that are described in the material characterisation section of this chapter (section 9.4). Simulations used a Lagrangian mesh for all components with a cell size around 200 µm for the cylinder. A quarter-symmetry three dimensional environment was used. Note that as with all simulations in this study, no attempt was made to predict or retroactively match the fracture and fragmentation. The simulations were purely used as a tool to assist in designing and prototyping the experimental approaches. An image of the model is shown in figure 9.1. This image has been mirrored in the vertical direction - when running only one quarter of the experiment was modelled. No mounting hardware was included.

The cylinder, ogive and projectile dimensions are described in full in section 9.3.1. In brief, the cylinder was 150 mm long with an inner diameter and wall thickness of 50 mm and 4 mm respectively. The projectile and ogive were scaled according to equation 7.1. Gauges were placed along the outer surface of the cylinder in a line spaced every 2 mm to record the
Figure 9.2: AUTODYN simulation data, Ti-6Al-4V cylinder, 150 mm long, 50 mm inner diameter, 4 mm wall thickness, 1000 m s\(^{-1}\) projectile velocity. The initial geometry and several timesteps are shown below displacement, velocity and strain rate maps with the same length scale to demonstrate the expansion relative to the position of the ogive.
cylinder’s radial displacement and expansion velocity, generating the maps shown at the top of figure 9.2. Shown below the maps is a sequence of images showing the deformation of the projectile and cylinder around the ogive. The scale of these images matches the scale of the maps, allowing one to directly observe the map of radius, velocity or strain rate with respect to the location of the ogive in the cylinder.

For direct comparison between the gauge data and the PDV data from the experiment as will be shown later some further work on the simulation data was necessary. A PDV probe will only register motion normal to the probe beam. Hence the equivalent data from the gauges was the pure radial component of the velocity, easily extracted from the software. However, the gauges tracked with the Lagrangian node they are initially assigned to. If there was longitudinal motion along the cylinder the gauge moved away from the point that was being measured by the PDV and comparison was no longer valid. Taking the position with time from the gauges showed that around the expansion region a node can move in the longitudinal direction by several mm. To solve this problem some post-processing of the simulation data was performed in Matlab. A three-dimensional surface was created, with position along the cylinder as the \( x \) axis, time after impact along the \( y \) axis and the parameter of interest (radius, radial velocity or radial strain rate) as the \( z \) component. A uniform grid of 1000 \( \times \) 1000 cells was produced from taking the limits of the \( x \) and \( y \) axes. The Matlab function \texttt{griddata} then fits by linear interpolation the 3D surface values to the uniform grid. If one then wants to compare a PDV probe, for example at 75 mm along the cylinder, a lookup function finds the \( x \) column of the uniform grid that is closest to the PDV location (and reports the difference). The data in this column remains fixed to one point along the cylinder length. The 1000 \( \times \) 1000 grid was arbitrary, a finer resolution could be used if desired.

The simulation data presented here is for a projectile velocity of 1000 m s\(^{-1}\), this was found to create a radial strain rate of around 1 \( \times \) 10\(^4\) s\(^{-1}\) at the peak of the expansion region. From both the map of the outer radius and the images taken from the simulation it is clear that the expansion region began with a Gaussian profile and remained this way until considerable radial strain had accumulated. The voiding behind the expansion peak seen in the 6061-T6 aluminium work was still evident but far less pronounced, due to the higher density and strength of the
Ti-6Al-4V meaning expansion was more difficult to drive. There was a re-load in velocity and strain rate from around 40 $\mu$s onwards, and from 70 $\mu$s after impact the profile began to skew towards the rear of the cylinder, both owing to the longitudinal momentum of the projectile. The peak of the expansion region initiates at approximately 80 mm along the length and translates some 40 mm over the entire 95 $\mu$s window. Similar work on Ti-6Al-4V by Thornhill et al [87] with a wall thickness of 4.8 mm at a radial strain rate of $2 \times 10^4$ s$^{-1}$ found the Ti-6Al-4V to fail at around 15 percent radial strain. The simulations here suggested that this geometry and projectile velocity would create a uniform and even expansion up to and beyond this point at the desired strain rate of $1 \times 10^4$ s$^{-1}$. Analysis of the radial velocity with position and time revealed waves propagating along the outer cylinder surface away from the expansion region. Taking the slope of the wave ‘line’ in the map showed a wave speed on the order of 2500 m s$^{-1}$ to 3000 m s$^{-1}$, in agreement with the Rayleigh wave speed for Ti-6Al-4V of 2900 m s$^{-1}$ calculated from the material’s Poisson’s ratio and the shear wave speed [152]. It is seen that once these waves reach the end they reflect and the cylinder ‘shrinks’ in length slightly as material flows to accommodate the large radial strain in the expansion region. This would later be seen experimentally, through evidence of slipping between the entry end of the Ti-6Al-4V cylinder and the grub screws locating it in the mounting ring. The large void at the rear of the ogive (discussed in section 9.3.1) created no observable difference in the expansion process when compared with a solid insert.

9.3 Experimental Configuration

The large scale of the 100 mm gas gun and hence the increased cylinder size necessitated a different approach rather than simply scaling up the whole of the aluminium cylinder experiments in chapter 7. For example, the original method of mounting the cylinder via a larger flange at one end would require a lengthy machining process and a large amount of waste material when scaled to the 50 mm Ti-6Al-4V shots. The weight of the ogive, exacerbated by its position at the rear of the cylinder, would be too great for bonding the cylinder to the mounting ring. The addition of PDV required more mounting hardware that would maintain alignment to the cylinder during alignment of the cylinder to the gun. Finally, to make the temperature control
as efficient as possible the alignment system had to be thermally resistive.

### 9.3.1 Cylinder, Projectile and Mounting Hardware

Detailed drawings of the experimental configuration are shown in appendix A.3. The final cylinder dimensions were 150 mm long with a 50 mm inner diameter and a 4 mm wall thickness machined from solid as received rod stock Ti-6Al-4V. This material is characterised in section 9.4. The ogives were manufactured from 4340 steel as with the aluminium cylinders, with the base and ogive radii 25 mm and 37.5 mm respectively according to equation 7.1. The projectiles were made from PC1000 polycarbonate. These had a length of 150 mm by an outer diameter of 48 mm and a concave leading face with a 50 mm radius. The rear of the projectiles had a male M30 by 50 mm thread to fasten them into a corresponding female thread on the front of the sabot. The sabots were also polycarbonate, with an overall length of around 150 mm. These sabots are the standard design used for plate impact on the large bore gas gun, with sealing O-rings near the front and rear edges. The sabot length was chosen to ensure that the centre of mass of the complete projectile remained between these two supporting O-rings to minimise tilt of the projectile. The total mass of the projectile and sabot was around 1.6 kg in all cases. Finally, the leading edge of the sabot had an aluminium ring bonded on to provide a conductive surface for triggering make pins and also provide a reflective surface for a PDV probe to measure the projectile velocity. The cylinder, ogive, projectile and assembled projectile and sabot are shown in figure 9.3.

![Figure 9.3: Ti-6Al-4V expanding cylinder, basic parts. Left: Cylinder, insert and projectile. The black marked area was to test the surface finish for the PDV diagnostics. Right: Assembled projectile and sabot with O-rings and aluminium trigger ring.](image)
The ogive was a very light press fit into the rear of the cylinder. It was located by placing the ogive point-up on a granite flat, then sliding the cylinder down rear-first over it. The ogive was then secured in place with three M3 grub screws, the holes for which are visible in the cylinder in figure 9.3. These screws were to enable moving the cylinder without dislodging the ogive, but only provide a very small amount of force such that the ogive can eject from the cylinder during the shot and avoid creating polycarbonate jets. The outer surface of the cylinders were lightly polished to a just diffuse finish on a lathe after machining. It was found that without this the grooves left by the turning acted as a diffraction grating when illuminated by the PDV, making probe alignment difficult.

The gas gun target mounting system is configured for plate impact studies. A typical plate target locates into a ring that is offset from the end of the barrel. This ring is made concentric with a barrel plug and then normal to the end of the barrel with a depth micrometer to minimise tilt between the flyer plate and target. Concentricity is critical to an expanding cylinder shot as the projectile must enter the cylinder cleanly without contact with the inner wall. Hence the mounting system for these shots needed to be able to address the concentricity and coaxiality of the cylinder to the barrel simultaneously, while minimising thermal conductivity between the cylinder and mounting ring. The cylinder was mounted in a ‘top-hat’ sleeve which extended for 30 mm along the length of the cylinder from the end of entry. This sleeve was then bolted to a ring which mated into the existing plate impact adjustment ring. The holes in the sleeve for these three bolts were oversized to allow movement in the $x - y$ plane relative to the barrel. In this designation, $x$ represents horizontal movement, $y$ represents vertical and $z$ is along the barrel axis, so that these holes give concentricity adjustment. The sleeve was spaced off from the ring with Macor spacers and belleville washers. Combining this with three M5 set screws to act as a kinematic mount gave rotational adjustment around the $x$ and $y$ axes independently, allowing for the cylinder to be made coaxial to the barrel. A polycarbonate barrel plug was used to align the cylinder to the barrel. This was fed into the barrel so that a length protruded with a 48.9 mm outer diameter, i.e. just less than the inner diameter of the cylinder. The cylinder alignment was adjusted until the plug could be moved in and out of the cylinder with as little resistance as possible. The mounting sleeve and ring are shown in figure 9.4 with another image
in figure 9.5, top.

Figure 9.4: Mounting system for the large format gas gun at the Institute of Shock Physics. Left: Solidworks model of the cylinder and mounting system. Right: The cylinder and mounting system attached to the gas gun mounting ring. Just visible in the end of the barrel and between the ring and sleeve is the polycarbonate alignment plug.

This mounting system was found to hold the cylinder securely in place while providing easy adjustment and quick alignment to the barrel plug. Once alignment was made the barrel plug was withdrawn from the breech end of the barrel with a length of rope. To test the resilience of the system to vacuum cycling and slip over time, the target tank was brought down to vacuum and then allowed to slowly relax to atmospheric pressure overnight. The following day the alignment plug was pushed down the barrel and went into the cylinder without problem, suggesting that there had been no movement. Note that this cycle was much longer than envisaged during experiment preparation, in practice the alignment plug was left in the cylinder until all other work in the target tank had been completed. The last step before loading the projectile and sealing the breech end was to remove the plug.

9.3.2 Diagnostics: PDV

The PDV system used is described in detail in section 5.1.2. This section covers the application of this system, specifically the optical probes used and their deployment on the experiment. In total five channels were used on each experiment, one ‘regular’ (self-referencing) channel for the projectile velocity and four upshifted channels to measure the expansion velocity of
the cylinder. The projectile channel used a small diameter 1.6 mm collimating probe (working distance 70 mm) bonded into a length of 14 gauge hypodermic needle tubing that was fed through a hole in the mounting sleeve. The probe was aimed at the aluminium ring on the shoulder of the sabot. By mounting it in the tube the probe could be offset from the rear of the sleeve such that the probe would be impacted by the sabot at approximately the same time the projectile impacted the ogive. This gave a true velocity at impact and an estimate of the time of impact from the PDV data, with loss of signal as the sabot impacted the probe. The working distance of the probe and the reflectivity of the aluminium ring enabled the velocity to be recorded for around 50 µs prior to impact for the 1000 m s\(^{-1}\) projectile velocity.

The expansion velocity was measured at four points along the length of the cylinder. The simulations presented earlier were used to decide the location of these, placing them so they were equally spaced with two probes roughly either side of the expansion peak. Note that the absolute position of the probe relative to the cylinder was not critical, however it was important to measure as accurately as possible where each probe was focused along the cylinder to enable comparison between experiments and with simulation data. As the experiments would be performed with the cylinder at temperature it was necessary to space the probes away so that they were not affected by the temperature. Each probe consisted of an aluminium tube with a lens bonded in at one end and the fibre bonded in the other to give the desired working distance. The probes were ordered from Laser 2000 and had a part number LPF-04-1550-9/125-S-21.5-100-4.5AS-60-3A-3-3. They had a 3 m long single mode fibre pigtail, with a 9 µm core. The probe body outer diameter was 8 mm with an aspheric lens at the end giving a working distance of 100 mm. With 1550 nm light the Gaussian spot profile produced at the working distance was typically 120 µm diameter at 50 percent of the peak intensity and 220 µm diameter at 13.5 percent. As the cylinder expands the surface will tilt relative to the optical path from the probe, hence a large lens was needed to ensure that light was still captured when significant radial strain and therefore tilt had accumulated. The slightly diffuse finish of the cylinder also assisted in this. For alignment of the probes a simple optical circuit was used. A low power 1550 nm laser was connected to the first port of a circulator. The second port was connected to the PDV probe and the third directly to a power meter. By measuring
the amount of light sent to the probe after the circulator beforehand and comparing with the measured reflected power a percentage could be calculated for the return signal. This provided a qualitative measure of how even the surface finish of the cylinder was and whether the probes were performing as expected (some had very low return signal and were discarded). A well aligned probe and a good surface finish delivered approximately 20 percent of the incident light back to the detector.

The probes were bonded into modified kinematic mounts, Thorlabs model KMSS/M. These are designed to take a mirror on the front via an M4 screw hole, this was drilled out to accommodate the 8 mm probe. The four channels needed to be at different lengths along the cylinder. Due to the offset added by mounting the probes in the kinematics it was decided to stagger them, such that they are not actually along a straight line on the cylinder. The four were set on an under hanging arm below the cylinder connected to the sleeve. As they were staggered, a mount was made each side to ensure that the probes were still normal to the cylinder surface. This is shown in figure 9.5 bottom. This configuration separates the probes by 15 mm along the cylinder in two pairs, with each pair looking at a slightly different area around the circumference. The arm was machined to hold the probe at 105 mm from the cylinder surface. This increases the efficiency of the probe, if one assumes a Gaussian distribution of efficiency against working distance, centred at 100 mm, then by mounting the probe slightly further away as the surface moves towards the probe the efficiency will increase then decrease, as opposed to just decreasing if it was mounted at the working distance. With this design the probes are mounted to the same base as the cylinder, the sleeve. Hence the cylinder can be aligned to the gas gun barrel without affecting the alignment of the probes relative to the cylinder, greatly reducing the time spent preparing the target and allowing the majority of PDV setup to be done with low power (Class I) lasers. When the cylinder has been aligned to the barrel the final alignment of the probes with the Class IV lasers could be completed within 30 minutes. As with the cylinder mounting hardware, once aligned the whole chamber was evacuated overnight. The following day the probes were still aligned and gave strong return signals. The positions of the focal spots along the cylinder were measured using a ruler and a laser viewing card to make the 1550 nm light visible. The position was recorded and then
Figure 9.5: Ti-6Al-4V expanding cylinder experiments, mounting hardware and PDV arrangement. 
*Top:* The components used to mount the cylinder. Starting from the left, the 160 mm gas gun target ring. Centre, mounting sleeve. Right, PDV arm and angled mounts. Bottom, macor spacers and belleville washer stacks to provide tilt adjustment. *Bottom, left:* PDV arm with kinematics and probes installed. *Right:* Detail of the kinematic mounts showing the angle needed to keep the probe beam normal to the cylinder.
a photo taken of each spot location for a more accurate measurement though processing with ImageJ. The position of each spot was typically within 2 mm of the ‘ideal’ location, predicted from the CAD drawings. Tolerances in the modification of the kinematic mounts and the pointing error of the probe multiplied by the large working distance are responsible for this variation. For all shots both the projectile velocity PDV and the upshifted expansion velocity PDV had approximately 5 mW power sent to each probe and 1 mW to each channel as the reference.

9.3.3 Diagnostics: High Speed Imaging

Again, as per the PDV, this section details how the imaging was arranged for this set of experiments, with full details on the camera hardware given in section 5.2.2. The imaging path was identical for all four shots, although the first shot used a slightly different camera arrangement. Observing the cylinder from the rear (i.e. looking down the gun barrel) and considering a clock face, the cameras observed the cylinder from the 3 o’clock and 9 o’clock positions. Lighting was provided by two Bowens Gemini Pro 1500 W flash guns from the 12 o’clock and 3 o’clock positions, meaning one camera was front lit and one was silhouetted. For the first shot the silhouetted camera was replaced by a high speed video camera, and used a low magnification lens to capture the whole experiment from the projectile leaving the barrel through to expansion and fragmentation. This was to ‘de-risk’ the first experiment and provide information on what had occurred in the event that the shot did not perform as planned. Figure 9.6 shows the arrangement of the cameras and lighting with the PDV beams added.

The flash guns had a rise time of ∼100 µs. The flash guns as with all the diagnostics were triggered by a make pair system as the sabot left the barrel (triggering and timing are discussed in detail in the next section). As a result of this rise time and the triggering caused by the sabot instead of the projectile there needed to be a large stand-off between the end of the barrel and the cylinder, around 250 mm. Adding the distance from the cylinder entry to the ogive and subtracting the length of the projectile meant there was at least 150 µs before impact for all shots, allowing several frames to be lit and captured before impact. However, by spacing the cylinder back it was no longer in line with the viewing ports of the gas gun target tank. Optical
breadboards were installed each side with 250 mm square mirrors used to form a periscope to relay the cylinder image through the ports (figure 9.7, left). On the outside of the target tank, each camera had another smaller mirror mounted on an adjustable base to turn the image path through 45° once more. This moved the cameras out of a direct line with the ports, allowing for illumination and imaging though the same port as with camera and flash gun 1 while ensuring that if there was a failure of the window the camera would not be damaged. The external mirror was shielded from flash gun 1 with cardboard and black-out tape to avoid reflections directly into the camera, as shown in figure 9.7 centre and right. While this improved the quality of the front-lit images the silhouetted ones had a small region where this mirror blocks some of the back lighting.

For all shots except the first camera 1 (front-lit) was a Phantom v1610 high speed video camera, manufactured by Vision Research. This was paired with a Zeiss Planar T* 85 mm f/1.4 ZF lens. Camera 2 (silhouetted) was the Invisible Vision IVV UHSi 12/24 using a Nikon
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Figure 9.7: Camera and lighting for the Ti-6Al-4V expanding cylinder experiments. Left: Breadboard and mirrors forming periscope inside the gas gun target tank with the port visible. Centre: The same port from the outside, showing the final turning mirror on a kinematic mount and the flash hood. Right: The flash gun, mirror (shielded from reflecting the flash directly into the camera with cardboard) and Phantom v1610 high speed video camera.

80-200 mm f/2.8 AF-D lens. For the first shot the IVV was used as camera 1 and a Phantom v7.3 for camera 2. Typical frame rates for the v1610 and IVV were around 5 µs to 10 µs between frames with a sub-µs exposure. The v7.3 was used to get a view of the whole experiment, due to the operation of these Phantom cameras this slowed the frame rate to ∼40 µs inter-frame time to give a large enough field of view.

9.3.4 Diagnostics: Triggering, Timing and Synchronisation

The effectiveness of using multiple diagnostics simultaneously is maximised if the timing between each system is known, allowing for comparison of the laser velocimetry data with the high speed imaging to give an accurate measure of strain to failure. For simplicity and reliability a single trigger was used to initialise all diagnostics. Coupled with the recording duration of the oscilloscopes and cameras used this system allowed for a up to a 10 percent error in projectile velocity with minimal loss of data; although in practice the projectile velocity varied from the desired 1000 m s\(^{-1}\) by less than 1 percent. The trigger system consisted of a single ‘make’ pair, two exposed wires in the path of the sabot. These were made from RG-405 rigid coaxial microwave cable with the outer copper jacket stripped. The pins then connected to the conditioning circuit described in section 5.2.3 which produced a rapid falling edge signal from 0 V to −4 V when the exposed ends were shorted together. A pin pair is shown installed on the end of the barrel in figure 9.8, left, using the cylinder alignment plug to ensure that the pins
will contact the conductive ring on the sabot. The right of figure 9.8 shows the rear of the gas
gun target ring, with the cylinder just visible through the centre and the white macor spacer
also seen. The velocity block in the centre of the image was a secondary or backup projectile
velocity measurement. This was a set of three make pairs identical to the trigger pair arranged
in a perspex block with a 10 mm spacing between each pair. They were staggered such that
as the first pair is bent by the sabot they do not contact the second, and so on. This system
was installed in case the heat melted the projectile velocity probe as it was mounted from the
cylinder sleeve. It was found that the projectile velocity PDV was reliable at all temperatures
tested. In contrast, the velocity pins suffered from electrical noise and in some cases was far
out of agreement with the PDV data. From analysis of the time of first movement in the high
speed imaging compared to the time of the sabot leaving the barrel it could be shown that the
PDV data was correct in this case. One reason for the velocity pins failing is a gas blast ahead
of the projectile moving the pins. This could have led to contact between different pairs and
caused the anomalous data.

Timing of the diagnostics was facilitated by two delay generators, a Stanford Research Sys-
tems DG535 and a Quantum Composers 9500+. Both manufacturers quote a jitter between
channels of under 100 ps. The barrel trigger fed into the input trigger port of the DG535, set
to trigger under a falling edge at a level of −1.5 V. Once the DG535 was triggered it then im-
mmediately sent an output pulse to trigger the 9500+ delay generator through its EXT/GATE
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In turn the 9500+ was configured to then send a signal after a 5 ns delay to trigger the Acqiris. The Acqiris is a high speed digitiser, manufactured by Aglient Technology, model number U1056B. This was used with a pre-trigger to record all the timing information such as trigger signals, camera monitor (frame rate) signals and the velocity pin block for a 500 µs window, starting 50 µs before the barrel pin trigger was shorted. Chaining the delay generators like this will introduce a time delay from jitter and signal propagation through cables, a conservative estimate for this would be on the order of 100 ns from the barrel trigger activating to the Acqiris being triggered. A block diagram of the signal routes and diagnostic hardware is shown in figure 9.9 top. The arrows denote the direction of the signal, and where a signal splits such as the line from the DG535 to the v1610 this means the line was terminated at the Acqiris with a T-connector over the diagnostic. This was done for the barrel trigger and both cameras. This technique allows for accurate timing of the images produced by the Phantom, as the time of the first frame denoted frame 0 in the software can be extracted as the next clock cycle after the trigger pulse has been received. Looking at the timing data in figure 9.9 bottom, one can see the monitor of the v1610 clock signal as the solid dark blue line (in this case running at approximately 250000 frames a second or 5 µs interframe) and the trigger signal sent to it at 0 µs as the dashed dark blue line. The next clock cycle occurs at around 4.75 µs - this is the time of frame 0 and the other timings can then be extracted from the software relative to this. It is important to note that without a record of both the trigger and the monitor an accurate measure of the absolute frame times can not be gained from the Phantom control software as the wait for the next clock cycle is not accounted for.

Outputs A and B of the DG535 were used to trigger the cameras with positive TTL pulses. For both cameras the DG535 delay was set to 5 ns and the camera software was used to control the frame timings. The Phantom cameras when armed are continuously recording. When they receive a trigger signal the camera will save a certain amount of frames before and after the trigger, much the same as the pre-trigger function on an oscilloscope. The software was configured such that an equal amount of frames were before and after the trigger, covering a range on the order of one second, much longer than the experiment. The IVV can only record events after it has been triggered. Due to the operation of the camera and its sensor, the
Figure 9.9: Ti-6Al-4V expanding cylinder diagnostic setup. *Top:* Block diagram of the diagnostic equipment showing the links, arrows denote the signal direction. The Acqiris (yellow) was used to synchronise different diagnostics and allowed for direct comparison between velocimetry and high speed imaging. *Bottom:* Typical timing data recorded by the Acqiris.
image quality can be enhanced by using the software to define the delay as then the camera has a ‘buffer’ once triggered where it can prepare and clean the CCD ready for the exposures, reducing noise. If one was to set the software such that the first exposure is taken immediately and use the DG535 to introduce the delay the camera does not have time to complete this. The IVV does have an option for intelligent triggering, that is it can reconfigure the frame timings on the fly depending on the projectile velocity, using two triggers a known distance apart such as the velocity block. The repeatability of the projectile velocity with the 100 mm gun meant that this was not needed, but it could be of use for situations such as capturing a fragment in free flight where the velocity would not be known before the experiment. The C⊔D port of the DG535 was used to trigger the flash guns. This was configured to become low between the delay times of C and D, set to 5 ns and 1 s respectively. The cable was T-connected over the 12 o’clock flash and terminated in the 3 o’clock one. The Bowens units have a self powered trigger, this setup ensured that the flashes were triggered at 5 ns with the pulse one second long to ensure that that they release the full charge of the flash.

The green blocks in figure 9.9 top relate to the PDV systems and their digitisers. These were connected with high bandwidth SMA cables to the oscilloscopes. For the expansion velocity measurements a recording window of 500 µs was used at a sample rate of 40 GHz or 25 ps per point with a 20 percent pre-trigger. The projectile velocity used a 400 µs window and sampled at 25 GHz or 40 ps per point with a 50 percent pre-trigger. The 9500+ was used to trigger both oscilloscopes, sending trigger pulses at a delay such that zero time on the oscilloscopes would be approximately the point at which the projectile impacted the ogive. When triggered, the oscilloscopes then send a signal from their external out ports to the Acqiris, in figure 9.9 one can see the purple and magenta lines representing these signals.

9.3.5 Fragment Recovery and Mitigation

The gas gun is usually equipped for plate impact experiments, where the projectile and impacted target continue through the target tank door and into the expansion tank and momentum trap. Very little debris is produced laterally and what is is caught by a debris shield extending from

\[1\text{SubMiniature version A, a high bandwidth connection and cable.}\]
the door to just behind the target. In contrast, an expanding cylinder experiment launches the majority of the cylinder mass outwards in the radial direction. As the fragments were analysed post mortem it was important that as little further damage was inflicted on them as possible. Similarly, it was necessary to avoid launching hot fragments at velocities on the order of 100 m s$^{-1}$ directly at the target tank wall.

A framework was designed to hold six panels of mitigation material around the target, with a large seventh panel clamped to the base of the target mounting frame. This covered most of the azimuth around the cylinder, with remaining areas such as the supporting pieces covered with 5 mm thick steel plate. A picture of this frame is shown in figure 9.10 left. Each panel was held in its own angle-iron frame, allowing for easy replacement in case of damage. These were slotted at the ends to allow adjustment inside the tank, and anchored via 40 mm steel box-section supports to the tank interior. M8 studding was then used to ‘pin’ the frame in place against the inner wall of the tank. For this work 25 mm thick plywood was used. A similar arrangement was used to protect the door of the tank, with a 40 mm steel box-section octagon holding seven plywood panels as in figure 9.10. The lower panel was omitted as the larger panel at the base in the tank covers this region. This system was used for shots at the maximum working pressure of the gas gun (690 bar) without any sign of deformation or damage.

It should be noted that with plywood this is not so much a soft recovery system. For a true soft capture some sort of graded density material should be used such that the fragments are gently decelerated. For example, this could be a low density foam, backed by a high density foam and then a soft plastic or wax. Time and financial constraints limited these experiments to plywood, although many fragments were extracted from these panels with little signs of further damage. The time taken to evacuate the tank to a reasonable level of vacuum (250 mTorr or so) increased greatly, taking over one hour compared to around 15 minutes without the plywood. This was due to the moisture in the wooden panels.

### 9.4 Ti-6Al-4V Initial Characterisation

The Ti-6Al-4V was supplied by Smiths Metal Centres Limited, London, UK as a 1630 mm long solid round bar peeled and polished to a 65 mm diameter to the AMS 4967 specification, that is
a microstructure consisting of equiaxed or elogated primary $\alpha$ phase titanium in a transformed $\beta$ matrix. First, discs were taken from the bar with wire-cut electrical discharge machining (EDM). These had a thickness of 3 mm, 5 mm, 10 mm and 15 mm. They were then lapped such that each end was flat to within a few light bands when viewed under an optical flat and sodium light source. These discs were then used to calculate the density, longitudinal and shear wave speeds and elastic moduli of the Ti-6Al-4V. They were then sectioned for optical and electron microscopy (EBSD) to probe the microstructure.

### 9.4.1 Density Measurements

The thickness of each disc was measured at five points, the centre and at 12, 3, 6 and 9 o’clock. The diameter was then measured across 12-6 o’clock and 9-3 o’clock. The average of each was used to calculate the volume of each disc, which was then plotted against the mass as in figure 9.11 left. A linear fit was applied to these points resulting in a Pearson’s $r$ correlation coefficient of 1. The slope of this line gave the density of the as received material, $\rho_0 = (4428 \pm 1) \text{kg m}^{-3}$ in SI units.
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9.4.2 Wave Speed Measurements and Elastic Moduli

Longitudinal and shear wave speeds were measured with ultrasound using an Olympus 5058PR pulser and a Tektronix DPO2024 oscilloscope sampling at 1 GHz. Both wave speeds were measured in the pulse-echo configuration (a single sided measurement with only one transducer) with a pulse voltage of 400 V at a 1 kHz repetition rate. Longitudinal measurements were made with the Olympus A1095-RM 5 MHz transducer with a thin layer of vacuum grease to ensure coupling to the sample. Shear measurements used the Olympus V155-RM 5 MHz transducer coupled through a thin layer of a mixture of treacle and light oil. Measurements were made on the four different thickness samples at the centre and 15 mm in from the edge. No discernible difference could be found between the two locations for the longitudinal data and a very small variation was found in the shear data. At least ten reverberations of the pulse were recorded for all cases. An auto-correlation function (ACF) was then applied to the signal in the OriginPro 9 software package and a mean time of flight extracted. Figure 9.11, right, plots the distance travelled (twice the sample thickness) against the ACF time, with the slopes of the linear fits to the data giving the wave speeds. The correlation coefficient for both fits was greater than 0.999. The longitudinal and shear wave speeds were used to calculate the bulk sound speed. From the measured wave speeds and density the elastic moduli, Lame’s first parameter and Poisson’s ratio were calculated for the material and were found to be in agreement with the
values in the literature [153]. The measured and calculated parameters are set out in table 9.1. It is important to reiterate that the wave velocities were measured along the extrusion direction of the as received rod. As seen with the material used for the explosively driven rings there can be extensive preferential texture evident in Ti-6Al-4V. For this reason one of the discs was then sectioned into cubes such that the different axes (radial, axial and hoop direction) of the rod stock could be investigated with EBSD techniques to determine grain structure and alignment. The methods used were the same as described in sections 5.3.4 and 6.4.

Table 9.1: Density, wave speeds and elastic moduli for the Ti-6Al-4V

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Unit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Initial Density</td>
<td>$\rho_0$</td>
<td>4428 ± 1</td>
<td>kg m$^{-3}$</td>
</tr>
<tr>
<td>Longitudinal Wave Speed</td>
<td>$C_L$</td>
<td>6184 ± 3</td>
<td>m s$^{-1}$</td>
</tr>
<tr>
<td>Shear Wave Speed</td>
<td>$C_S$</td>
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<td>m s$^{-1}$</td>
</tr>
<tr>
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<td>m s$^{-1}$</td>
</tr>
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<td>169.5 ± 0.2</td>
<td>GPa</td>
</tr>
<tr>
<td>Shear Modulus</td>
<td>$G$</td>
<td>43.5 ± 0.8</td>
<td>GPa</td>
</tr>
<tr>
<td>Bulk Modulus</td>
<td>$K$</td>
<td>111.4 ± 0.3</td>
<td>GPa</td>
</tr>
<tr>
<td>Elastic Modulus</td>
<td>$E$</td>
<td>115.6 ± 1.8</td>
<td>GPa</td>
</tr>
<tr>
<td>Lame’s First Parameter</td>
<td>$\lambda$</td>
<td>82.4 ± 1.6</td>
<td>GPa</td>
</tr>
<tr>
<td>Poisson’s Ratio</td>
<td>$\nu$</td>
<td>0.327 ± 0.004</td>
<td>-</td>
</tr>
</tbody>
</table>

9.4.3 Electron Backscatter Diffraction Analysis

EBSD analysis was performed using a Zeiss Auriga SEM in the materials department of Imperial College London. Five samples were EDM machined from the lapped 10 mm thick disc. These five samples had markings on the edges so that their orientation with respect to the as received material could be determined. Three of the samples were taken from the same radius on the disc as the cylinders used in the experiment (inner radius of 25 mm) such that the area investigated
would be truly representative of the sample material. These three samples were observing the hoop-radial, hoop-axial and axial-radial planes. The remaining two samples were taken from the centre of the disc, looking at the hoop-radial and hoop-axial planes. The values and distributions for the average grain principal axis, aspect ratio and area are shown in table 9.2 and figure 9.12. All EBSD measurements taken had at least 2400 grains visible, in most cases this was closer to 10000.

Table 9.2: EBSD Grain Statistics for the as received Ti-6Al-4V at a radius of 25 mm

<table>
<thead>
<tr>
<th>Imaging Plane</th>
<th>Average Grain Principal Axis (µm)</th>
<th>Average Grain Aspect Ratio</th>
<th>Average Grain Area (µm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hoop - Radial</td>
<td>4.13 ± 0.05</td>
<td>1.483 ± 0.007</td>
<td>8.31 ± 0.21</td>
</tr>
<tr>
<td>Hoop - Axial</td>
<td>5.68 ± 0.03</td>
<td>1.503 ± 0.003</td>
<td>15.02 ± 0.15</td>
</tr>
<tr>
<td>Axial - Radial</td>
<td>7.64 ± 0.05</td>
<td>1.653 ± 0.006</td>
<td>25.26 ± 0.38</td>
</tr>
</tbody>
</table>

Figure 9.12: EBSD Analysis of the Ti-6Al-4V. Histograms showing grain parameter as a function of the map area. *Left*: Grain principal axis. *Right*: Grain aspect ratio. Mean values in table 9.2.

From the average data one can see that the grains were largest in the axial-radial plane, both in principal axis and area. However, they were also more lenticular, increasing in aspect ratio (so that the length to width difference increased). This is consistent with the grains elongating in the axial direction as the raw material was extruded. In contrast to the Ti-6Al-4V used for the explosively driven rings, no preferential texture was observed in any of the five samples imaged. The material was supplied as peeled and polished, *i.e.* a layer of material
has been machined off after the extrusion or forging process, with the samples being taken a further 12 mm from the outside edge. Work studying the effect of hot extrusion of Ti-6Al-4V by Kimura et al. [154] found that most of the strain accumulated by the billet’s microstructure was confined to a layer near the surface. This region where large amounts of deformation that may have led to preferential texture could have been removed as part of the peeling process or might not have reached the depth where the samples originated from. It is not known what processing the explosive rings material had undergone, if any. Optical microscopy in conjunction with the EBSD grain analysis above found the Ti-6Al-4V to meet the specification it was supplied as, a mostly equiaxed or elongated $\alpha$ phase in a $\beta$ matrix, with an average grain principal length on the order of 4 mm to 8 mm.

9.5 Evaluation of the Experiments

A series of four shots was fired in total, each one having a different initial temperature. One was cooled, one was at ambient temperature and the remaining two were both heated. As discussed in section 9.1, this experimental run had two main areas of interest. First was to evaluate how the experiment and diagnostics performed over the temperature range, and second was to examine the initial results produced on the Ti-6Al-4V characterised earlier. This section deals with the experiment’s performance.

9.5.1 Projectile Velocity Measurement and Repeatability

From the simulation work earlier a projectile velocity of $1000 \text{ m s}^{-1}$ was chosen to produce the desired peak radial strain rate of $10^4 \text{ s}^{-1}$. All experiments had a combination of projectile velocity diagnostics in the form of a single PDV channel and a velocity block of three staggered make pairs. It was originally thought that the high temperatures expected could conduct through the mounting hardware and adversely affect the velocity PDV, hence the inclusion of the velocity block as a secondary measurement. However, in all cases the PDV channel was fielded successfully while the velocity block proved to be unreliable and produced anomalous results. Accuracy was limited due to the difficulty in measuring the distance between make...
pairs - the length of exposed wire required to reach the trigger ring on the projectile meant the wires were susceptible to bending. Moving to a stiffer material such as pencil leads or hypodermic tubing was also problematic; it is believed that the larger cross section of these meant that the air-shock ahead of the projectile displaced them out of the way of the trigger ring. This air-shock was a result of the poor target tank vacuum caused by the amount of plywood used for fragment capture and mitigation. The PDV probe was normal to this blast, hence presented a very small surface area. This still produced uncertainties in the impact velocity due to slight movement of the probe. Analysis of the variation in measured velocity over the 30 µs or so of velocity history prior to impact enabled an error estimation of $5 \text{ m s}^{-1}$, or 0.5 percent for this projectile velocity. The data for the four shots is shown in figure 9.13 with the average impact velocity calculated as $(999.8 \pm 1.2) \text{ m s}^{-1}$.

![Image](image_url)

Figure 9.13: Impact velocity for the four Ti-6Al-4V expanding cylinder shots measured with PDV.

### 9.5.2 Cylinder Mounting, Temperature and PDV Measurements

The performance of the temperature system with regards to how well it could control the cylinder temperature was covered in section 8.4. The mounting system was found to perform well over the entire range of cylinder temperatures reached, facilitating quick and simple alignment of the cylinder to the barrel and remaining aligned over long times. Analysis of the expansion velocity and high speed imaging data suggests that there was no contact between the projectile and the inner cylinder wall prior to the impact with the ogive and such it can be assumed that both the concentricity and coaxiality conditions were met. Similarly, the PDV
mounting system was resistant to movement during the evacuation and thermal cycling of the
target tank and cylinder. One modification was made for the highest temperature shot, after
observing the temperature of the PDV mounting arm rising during the first heating shot. The
arm was drilled through along the length and a hose barb fitting installed at each end. An
ethylene glycol and water solution was then flowed through the arm using a commercial laser
head chiller unit (ThermoTek T255) circulating the solution at 275 K. This ensured the probes
remained at room temperature and stopped any damage as a result of heating. In other work
on the dynamic response of Ti-6Al-4V at elevated temperatures by Arrieta and Espinosa [145]
problems were observed with the formation of an oxide layer on the sample surface reducing
the reflected signal for their laser velocimetry, going so far as to coat the surface with a thin
layer of platinum. The experiments here had no such issues, the PDV signal remaining fairly
constant over the heating cycle. Arrieta and Espinosa do not specify the laser they used, only
that it involved an air-delay leg interferometer hence one assumes it followed the standard
VISAR system and used green (532 nm) light (beams are also visible in images in the paper).
This wavelength is shorter than the PDV system used (1550 nm), hence the PDV would need
a thicker oxide layer before any anti-reflective behaviour was observed.

For all shots typically around 100 µs was recorded on each channel, or around 60 percent
maximum radial strain. The combination of the upshifted PDV system and the relatively slow
(compared to something like a plate impact breakout) accelerations enabled a large amount of
frequency cycles to be contained in each slice analysed with the Fourier methods. A standard
analysis would involve a window containing $10^4$ points which at the 25 ps per point rate of the
oscilloscope combined with a 75 percent window overlap produced one data point every 62.5 ns,
sufficiently fine resolution for the work here. This made the measurements particularly robust
to signal drop-out and noise.

9.5.3 Imaging Quality and Timing

The optimum imaging setup was found when the high speed video camera (Phantom v1610)
was front-lit and the framing camera (IVV) was silhouetted. The first experiment at room
temperature where the IVV was front-lit produced quite dark images, while high in resolution
it was difficult to ascertain the initiation and propagation of fractures along the surface. This was due to the relative inefficiency of the intensifier and CCD, requiring much more light than the Phantom cameras. The IVV was most useful in a silhouette configuration as the images could be used to generate accurate line-outs of the cylinder profile. However, the turning mirror for the front-lit camera placed in the path of the flash gun used to silhouette meant that only one edge of the cylinder could be resolved. This could have been improved by using a smaller turning mirror, such that the shadow cast by it would be hidden behind the cylinder profile when viewed by the IVV. For the cooled shot the v1610 used a resolution of $388 \times 288$ pixels, with an exposure of $1.71 \mu$s giving an interframe time of $10 \mu$s. This produced very clear, well lit images with the fractures and surrounding features easily observed. However, the interframe time was deemed to be too long. The process from zero fracture to all visible fractures occurring was on the order of $30 \mu$s so only a few frames covered this window of interest. The final two shots on heated cylinders reduced the resolution to $256 \times 160$ pixels with a $0.45 \mu$s exposure allowing the interframe time to be reduced to $4.76 \mu$s, over double the earlier frame rate. At this resolution fractures presented as bright lines along the cylinder, due to reflection of the flash from the newly created surfaces in the fracture acting as a diffuse reflector. This made them readily observable, and allowed for capturing the temporal fracture observation over at least 6 or so frames. Further reduction in resolution in pursuit of higher frame rates would have either excessively limited the area of the cylinder imaged or made determination of fracture time impossible.

### 9.6 Initial Results

Presented in figure 9.14 is a legend to the results here. The top plot shows the location of the four expansion velocity PDV channels (A-D) along the cylinder and in respect to the ogive insert. The colours chosen for the four probes will remain in use throughout this section. One can see that within errors the location of the probes for each shot is consistent enough to allow for direct comparison of the PDV data between shots. The lower plot is the thermal data for each shot at the time of impact. The points relate to the location of the thermocouples and the dashed line is a spline-fit between these. Again, a cross section of the cylinder and ogive
has been added for clarity. The velocimetry and high speed imaging data is presented first in section 9.6.1 followed by the analysis on recovered fragments in section 9.6.2.

Figure 9.14: References for the location of the PDV probes (top) and the thermal profile of the cylinder (bottom) for each of the four shots. A cross section of the cylinder has been included to allow observation with respect to the ogive location. Projectile would approach from the left.

A summary of the four shots fired is shown in table 9.3. For each shot the projectile velocity is given, followed by the cylinder surface temperature at 80 mm and 120 mm along from the entry end. This distance approximately covers the full extent of the Gaussian expansion region. The peak radial strain rate is the largest value measured by the PDV probes by taking the quotient of the velocity and radius for each time point. Note that as the probes were spaced off from the centre of the expansion region the actual peak radial strain rate here would have been slightly larger, but due to the limits in the framing rate of the cameras the PDV produced a much more reliable value. The final column is the radial strain at the point of failure. This
accuracy of this value is predominantly controlled by the frame rate of the camera used. For example, in frame \( m \) there is no visible fracture, but in the next frame, \( n \), fracture has occurred. Hence it can be considered that the failure strain value lies between the strain at the expansion peak in frames \( m \) and \( n \), defined as \( \varepsilon_m \) and \( \varepsilon_n \) respectively. The failure strain \( \varepsilon_f \) and its associated error \( \sigma_{\varepsilon_f} \) were then calculated using:

\[
\varepsilon_f = \frac{\varepsilon_n + \varepsilon_m}{2} \quad (9.1)
\]

\[
\sigma_{\varepsilon_f} = \frac{\varepsilon_n - \varepsilon_m}{2} \quad (9.2)
\]

From this it is clear that a faster frame rate (\( i.e. \) less time between \( m \) and \( n \)) for a given strain rate will produce a more representative value for the failure strain.

Table 9.3: Summary of the four shots fired

<table>
<thead>
<tr>
<th>Shot</th>
<th>Projectile Velocity (m s(^{-1}))</th>
<th>Temperature at 80 mm (K)</th>
<th>Temperature at 120 mm (K)</th>
<th>Peak Radial Strain Rate (10(^4) s(^{-1}))</th>
<th>Failure Strain, ( \varepsilon_f ) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (Ambient)</td>
<td>997 ± 5</td>
<td>290 ± 15</td>
<td>290 ± 15</td>
<td>0.98 ± 0.01</td>
<td>18.2 ± 3.1</td>
</tr>
<tr>
<td>2 (Cooled)</td>
<td>1001 ± 5</td>
<td>175 ± 9</td>
<td>141 ± 7</td>
<td>1.03 ± 0.01</td>
<td>7.4 ± 5.2</td>
</tr>
<tr>
<td>3 (Heated)</td>
<td>999 ± 5</td>
<td>552 ± 28</td>
<td>665 ± 33</td>
<td>1.05 ± 0.01</td>
<td>12.5 ± 3.4</td>
</tr>
<tr>
<td>4 (Heated)</td>
<td>1002 ± 5</td>
<td>657 ± 33</td>
<td>790 ± 40</td>
<td>1.04 ± 0.01</td>
<td>24.1 ± 2.4</td>
</tr>
</tbody>
</table>

9.6.1 Velocimetry and High Speed Imaging Data

The expansion drive was found to be remarkably constant over the range of cylinder temperatures tested. This section begins with a description of the data from the first shot, performed at ambient temperature. The expansion velocity PDV data is presented with a description of the various features, and compared with simulation data. The velocimetry data from the other
three shots is then introduced to demonstrate the repeatability of the ogive loading technique. Figure 9.15 left, shows the data for the ambient temperature shot (number 1). The data here has been smoothed using the same Fourier based low-pass filter analysis as the VISAR traces in section 6.5.1 [129]. The raw (as produced by the PDV analysis in section 5.1.2) data is shown in the early time detail on the right of the figure as solid lines, compared with the AUTODYN data as dashed lines.

The first radial motion was detected by C as a small amplitude wave, approximately 10 m s$^{-1}$ for 5 $\mu$s. This matches closely both in magnitude and timing with the Rayleigh or surface waves seen propagating along the cylinder in the simulations (particularly in figure 9.2). During this interaction probe B registers a large acceleration up to a velocity of 255 m s$^{-1}$ over 12.8 $\mu$s. This corresponds to the main loading as a result of the flowing polycarbonate projectile impacting the inner surface of the cylinder. This is soon followed by a large acceleration at probe C as there is further contract between the projectile and inner cylinder wall, reaching 301 m s$^{-1}$ which corresponds to the peak radial strain rate measured by the PDV of $0.98 \times 10^4$ s$^{-1}$. Probes A and D at the ends of the expansion region also observe a small amplitude distortion before the expansion proper. As point A is ‘upstream’ of the expansion peak, that is closer to the cylinder entry, it observes relatively little expansion as the momentum of the projectile pushes the deformation region along the cylinder. Indeed, the model predicted that this point will eventually contract as opposed to expand as material flows from this location to allow for the
straining in the expansion region. The early time data (to around 25 µs) is in close agreement with the simulation data. This is again due to the simulation having no failure model. Analysis of the strain and high speed imaging data showed that this is around the limit of the cylinder and fractures soon appear on the outer surface. However, the use of the models as a tool to assist in designing the experiments with respect to geometry and strain rate with projectile velocity has been validated both here and with the earlier work on 6061-T6 aluminium. The initiation of failure leads to a re-load in the expansion velocity as the flowing projectile is still acting against the failing cylinder which rapidly loses strength. The images from the IVV for this time period are shown at the bottom of figure 9.16 against plots of the strain as calculated from the PDV data and line-outs taken from the IVV frames 6 to 12 (5 µs to 35 µs).

Figure 9.16: Ti-6Al-4V cylinder, shot 1, ambient temperature. Top, left: Radial strain calculated from the PDV data against the time of the IVV frames. Right: Line-outs taken from the IVV frames shown against a cross section of the cylinder and ogive. Bottom: Four frames 5 µs apart from the IVV camera, showing strain localisation, crack initiation and full fracture. Projectile travels from left to right.

At frame 9 there are faint lines appearing on the surface of the cylinder, indicative of
localised strain in the wall below. By frame 10 at 25 µs these lines have gone through to surface cracks, appearing much brighter as the new free surface acts as a diffuse reflector to the flash gun. Finally, at frame 11 (30 µs) these cracks have now fully penetrated the cylinder wall, evident through the ejecta as polycarbonate or hot gases can now escape. From the definition earlier we can then say that the failure strain, $\varepsilon_f$, of the cylinder has been reached by frame 10 with the value and error also affected by the strain in frame 9. Using equations 9.1 and 9.2 the failure strain $\varepsilon_f$ for the cylinder at ambient temperature was found to be 18.2 ± 3.1 percent.

This was the general pattern observed in all the expanding cylinder shots. The cylinder is first driven outwards rapidly by the polycarbonate, seen in the PDV as a rapid acceleration on probes B and C, followed by a deceleration as the hoop stress in the cylinder wall acts against the drive. Once a certain amount of radial strain has accrued the hoop strain in the cylinder begins to localise and eventually causes fracture. At this point the cylinder loses strength and the velocity increases again, with probe D measuring a large late time acceleration. By this point the cylinder exhibits extensive failure and the longitudinal momentum of the projectile causes the downstream side of the expansion region to swiftly ‘peel away’ from the ogive. The repeatability of the drive mechanism independent of temperature is demonstrated in the velocity and strain plots in figure 9.17 where the data from probes B and C for all four experiments has been amalgamated.

![Figure 9.17: Expansion velocity data (left) and radial strain data (right) for the four expanding cylinder shots from probes B (solid lines) and C (dashed lines).](image)

In both plots the solid lines are probe B and the dashed lines are probe C. Beginning
with the expansion velocity plot it is seen that the first 15µs to 20µs of expansion is very similar between all four shots, particularly the pattern of the oscillations produced by the reverberating loading wave (in B) and the surface wave along the cylinder (C). The difference in peak expansion velocity before failure between 14µs and 16µs is 25 m s\(^{-1}\), which resulted in a very small range in peak radial strain rate of \(0.98 \times 10^4\) s\(^{-1}\) (shot 1) to \(1.05 \times 10^4\) s\(^{-1}\) (3). The early radial strain was also very uniform across the shot series. The full recorded velocity history for all shots at B and C is shown in figure 9.18 with the line style and colour in the same pattern as before. The velocity history should be considered alongside the radial strain data for all shots in figure 9.19 and the front-lit high speed imaging data in figure 9.20.

![Figure 9.18: Full recorded expansion velocity at probes B (solid) and C (dashed) for the four expanding cylinder experiments.](image)

The ambient temperature shot will be used as the basis for comparisons, remembering that the first failure was observed at 18.2 ± 3.1 percent, or between 20µs and 25µs. This agrees within errors with the value measured by Thornhill et al [87] of 15 percent (their errors were unstated) for expanding Ti-6Al-4V cylinders at room temperature. From the green line in figure 9.19 one can see that the fracture process has completed by 35µs, with 6 visible fractures along the length of the cylinder. Only longitudinal (horizontal in the image) fractures are counted with the visible field covering approximately 50 percent of the cylinder surface.
At this point the fractures that have developed have fully released the interspersed material and no new fractures will occur in the expansion region. The existing longitudinal fractures continue to grow along the cylinder length and converge to create fragments. In addition to this process fracture can also occur in the circumferential direction, for example somewhere along the length of a strip created by longitudinal fracture. These fractures effectively bifurcate the cylinder along the length.

Figure 9.19: Radial strain at probes B (solid lines) and C (short dashed lines) with time for the four shots. The green markers and long dashed lines are the number of longitudinal cracks visible on the front-lit high speed camera images with time. The black dots and numbers represent the times of the frames used in the text and figure 9.20.

Starting with the cooled cylinder, it was found that fracture initiates earlier in the expansion
Figure 9.20: Front-lit high speed imaging of the four shots over a 10 µs to 50 µs window. The top edge of each image corresponds to the time of that frame against the purple 10 µs interval markers. Each frame is numbered on the right to enable matching with the plots in figure 9.19. Shot 1 was captured with the IVV camera, shots 2-4 with the v1610.
process at a failure strain of $7.4 \pm 5.2$ percent. The large error in this measurement is a result of the relatively slow frame rate compared to the other shots. However, this allowed a finer resolution hence the larger and clearer images in figure 9.20. From the velocity data in figure 9.18 one can see that there are two distinguishing features with the cooled cylinder. Firstly, the reload signal at point $C$ ($20 \mu s$) has a higher magnitude and occurs earlier than the ambient temperature signal. This is accompanied a short time later at point $B$ ($24 \mu s$) by a plateau in expansion velocity in contrast to the deceleration measured in the other shots.

This plateau is then seen at point $C$ from $35 \mu s$ onwards. The high speed imaging data showed the fracture process completed earliest and at the lowest radial strain with no further fractures observed after $28 \mu s$. The lack of deceleration suggests that there is very little resistance to further deformation, with the high speed imaging showing that the longitudinal fractures rapidly converge to form fragments in free flight.

Shot 3, heated to 552 K to 665 K over the expansion region, exhibited very similar behaviour to the ambient temperature cylinder. While fracture initiated marginally earlier (although the two failure strain values overlap when the uncertainty is taken into account) with cracks visible by $19 \mu s$ the temporal activation of subsequent fractures followed the same pattern as the ambient cylinder with the fracture process terminating by $34 \mu s$ with 5 cracks visible. The deceleration of the cylinder wall for both probe locations is almost identical to the rates seen with the ambient cylinder. Work by Majorell et al. [155] showed the flow stress of Ti-6Al-4V to steadily decrease with temperature, finding a sudden drop at around 800 K for a strain rate of $10^{-3} \text{s}^{-1}$. However, this transition temperature was found to increase with strain rate, results at $10^2 \text{s}^{-1}$ showing a inverse linear relationship between flow stress and temperature up to 1200 K. Work by Lee and Lin [143] on Kolsky bar compression of Ti-6Al-4V at strain rates up to $5 \times 10^3 \text{s}^{-1}$ found that the flow stress at a true strain of 0.1 dropped by some 15 percent when heated from 300 K to 600 K and deformed at $2 \times 10^3 \text{s}^{-1}$. However, as Ti-6Al-4V is a poor thermal conductor at high strain rates and large strains the amount of thermal softening through adiabatic heating will reduce the offset originally caused by the initial temperature. This could result in the difference in the velocity data between 15 $\mu$s and 30 $\mu$s, where the cylinder has been loaded and then briefly allowed to expand under its own inertia. The higher
flow stress of the cooler ambient cylinder would explain the velocity pull-back observed in shot 1 (also seen in shot 2 with the cooled cylinder until failure initiates around 20 µs) but not in shots 3 and 4 where the cylinder was heated. For shot 3 the late time data (30 µs onwards) again replicates the ambient temperature shot, suggesting that at this lower level of heating the fracture process is unchanged from the ambient to the ~600 K case of shot 3. As the longitudinal fracture activation has finished by 40 µs the deceleration is governed by the residual strength of the cylinder as the longitudinal cracks continue to extend along the length of the cylinder and converge to form fragments. This transition from a single cracked body to multiple fragments would appear to terminate at 80 µs for the ambient temperature shot as the velocity levels off indicative of a fragment in free flight. The data for shot 3 does not reach this time but the preceding behaviour and analysis of recovered fragments (section 9.6.2) would suggest that at this temperature there is little change in the dynamic fracture and fragmentation behaviour when compared to ambient temperature performance.

The final experiment, shot 4, was heated to 657 K and 790 K at the entry and rear ends of the expansion region respectively. The initial deformation and velocity data was in line with the other heated cylinder, however the failure strain was definitely larger than the other experiments at 24.1 ± 2.4 percent leading through to a final number of 8 visible cracks over a 15 µs window. The velocity data for probe B shows the highest expansion velocity for that point of all experiments and a slightly lower deceleration, in line with the reduced flow stress of the Ti-6Al-4V at temperature. The data for probe C has an anomalous dip in the signal between 32 µs and 36 µs. Frames 42 and 43 correspond to this time in figure 9.20 where a crack at the lower edge of the cylinder is shown forming, followed by some ejecta. It is possible that the PDV probe was focused on an area that failed, causing the discontinuity in velocity as the surface followed experienced localisation. The deceleration measured by C was the most intense of all shots, with both B and C levelling out from 60 µs onwards at a constant expansion velocity of approximately 150 m s⁻¹ compared with 200 m s⁻¹ for the ambient cylinder and 380 m s⁻¹ for the cooled cylinder. Shot 4 reaches this constant value some 20 µs earlier than the ambient temperature cylinder. However, in contrast to the cooled cylinder where fracture initiated early resulting in high velocity fragments, the increased failure strain of the heated shot 4 enabled
more of a reduction in the radial velocity before the cylinder fragmented.

The Grady fragmentation toughness, $K_f$, was calculated from the number of cracks visible and the strain rate at failure from equation \[2.23\] The total number of cracks was assumed to be twice the number of visible cracks with an error of $\pm 1$. The values for each shot are plotted in figure [9.21] in red, against the failure strain (black) and failure strain rate (blue).

![Figure 9.21: Fracture and fragmentation properties against the average temperature over the expansion region. Black circles represent the failure strain (strain at first fracture). The right axes plot the failure strain rate (blue upward triangles) and the fragmentation toughness (red downward triangles). Average fragmentation toughness is plotted as a red dashed line. The shot numbers are labelled on the x axis.](image)

There appears to be no correlation between the cylinder initial temperature and the fragmentation toughness. The average fragmentation toughness was found to be $101 \pm 13 \text{ MPa m}^{1/2}$, in close agreement with the value of $107 \text{ MPa m}^{1/2}$ found by Thornhill et al. [87] in Ti-6Al-4V cylinders, even though they used a thicker cylinder wall (4.8 mm compared to the 4 mm here) and a higher strain rate of $1.98 \times 10^4 \text{s}^{-1}$.

### 9.6.2 Fragment Analysis

Fragment recovery was made difficult due to the momentum trap used on the 100 mm gas gun. This system involved a large catch can that was filled with rags. The momentum of the sabot would tend to collect a large amount of the cylinder and carry it through at high
velocity into these rags, with smaller fragments becoming embedded and difficult to identify and remove. Recovered fragments were cleaned with acetone. This was mostly necessary for the heated shots where either polycarbonate from the projectile or material from the rags had melted onto the fragments. By soaking the recovered material in a magnetically stirred acetone bath the polymer residue left dissolved and any small ferrous fragments from other parts of the experiment were easily identified. The fragments were weighed and their principal length (the longest length along any direction of the fragment) and width (longest line perpendicular to the principal length) were measured. From the latter two the aspect ratio (AR, length to width) was calculated. The data for these is presented in table 9.4.

Table 9.4: Summary of the recovered fragments

<table>
<thead>
<tr>
<th>Shot</th>
<th>Number of Fragments</th>
<th>% Original Mass</th>
<th>Average:</th>
<th>Average:</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Mass (g)</td>
<td>Length (mm)</td>
</tr>
<tr>
<td>1</td>
<td>41</td>
<td>63.8%</td>
<td>7.00 ± 1.32</td>
<td>29.1 ± 2.9</td>
</tr>
<tr>
<td>2</td>
<td>63</td>
<td>70.2%</td>
<td>4.99 ± 0.91</td>
<td>27.5 ± 2.0</td>
</tr>
<tr>
<td>3</td>
<td>71</td>
<td>82.4%</td>
<td>5.20 ± 1.38</td>
<td>24.1 ± 2.7</td>
</tr>
<tr>
<td>4</td>
<td>78</td>
<td>76.1%</td>
<td>4.36 ± 0.84</td>
<td>23.2 ± 2.0</td>
</tr>
</tbody>
</table>

It is difficult to draw conclusions on the fragmentation statistics from these experiments. Firstly, the recovery was quite poor for the first experiment, with much fewer fragments recovered, particularly of the smaller fragments. This has skewed the average fragment mass to a number much higher than the other shots. Only shots 3 and 4 recovered what is generally accepted as enough of a representative amount, much of the literature using at least 75 percent for analysis. Secondly, as discussed in section 2.3 fragmentation is an inherently statistical process and it would be hasty to base conclusions on such a limited sample size. However while these data may not be representative of the fragmentation they are indicative of the fracture mechanisms occurring at each temperature. As such the fragment analysis will focus on the
optical and electron microscopy techniques used on the fracture surfaces and arrested cracks. Fragments were prepared for microscopy as per section 5.3.1. Figure 9.22 shows a typical analysis of a fragment, from shot 1 (ambient temperature).

Figure 9.22: Shot 1, ambient temperature cylinder, fragment processing. The red box was sectioned to show an arrested fracture, left and a freshly exposed internal fracture surface, right.

The majority of fragments recovered from all shots had the classic ‘shear lips’ where the edges (along the longitudinal direction) lay at approximately 45° to the radius. This is shown in the full fragment, figure 9.22 top left, and in the sectioned and mounted image (left, second from top). For shot 1 the fracture was found to be a result of ductile tearing under mode II.
(in plane shear) loading, demonstrated by the parabolic dimples seen in the SEM images of the fracture surfaces. These images are very similar to those found by Liao and Duffy in torsion-loaded Ti-6Al-4V [26], with dimples where the material has torn apart linked by smoother areas where fracture surfaces have slid against each other. This pattern was observed regardless of the strain rate (they covered from $0.5 \times 10^{-3} \text{s}^{-1}$ to $1.5 \times 10^{3} \text{s}^{-1}$) or whether adiabatic shear had occurred. The area ahead of and surrounding arrested fractures here did not contain any sign of dynamic transformation or recrystallisation that would indicate adiabatic shear localisation was active. The fracture on the left of figure 9.22 shows a mixed failure mode, though mode II shear at the outer area which transfers to mode I (pure tensile loading) towards the inner face of the fragment. The appearance of the fracture from smooth and straight at $a$ to irregular and coarse at $b$ corroborates with this, although with explosively driven samples this is often seen the other way round with shear failure on the inner surface [3, 38]. However, the loading under direct explosives is orders of magnitude more intense on the cylinder wall and tensile mode I failure can not initiate until the loading wave has dissipated. The location of $b$ in the centre of the fragment could mean that interacting release waves from the neighbouring fracture surfaces created a region of tension through the same process as spall, transforming the mode II fracture to mode I.

The cooled cylinder exhibited much the same fragment characteristics as the first shot. Images taken under optical microscopy of a sectioned fragment are shown in figure 9.23. Again the dominant failure mode was ductile tearing under mode II loading along planes at $45^\circ$ to the radius. The evolution of a fracture is non-trivial, as shown by the convoluted fracture path in the fragment, taking multiple right-angle turns and eventually splitting into a fork at the tip. Fractures were found to originate on both the internal and external surfaces. In a small amount of fragments damage was found to have occurred perpendicular to the radius, that is in a plane parallel to the inner and outer surfaces. On first observation the direction and appearance of the damage appeared consistent with spall. However, work on other HCP materials [140] and Ti-6Al-4V [145] at temperature have shown that the spall strength is inversely proportional to the temperature. A more reasonable proposition would be that the complex paths taken by the radial fractures weakened the sample material such as the fragment ‘strips’ began to
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peel away from the ogive the large bending and tensile stresses caused the fragment to begin to split through the thickness. SEM imaging of these internal damage planes found circular dimples consistent with mode I tensile loading. As with shot 1, no evidence for adiabatic shear banding was found.

Figure 9.23: Shot 2, cooled cylinder. Cross section of fragment showing multiple arrested internal fractures, with detail of the lower right. Arrows indicate increasing levels of magnification. Cylinder outer face is at the top of the image.

There was no discernible difference between the fragments recovered from shot 3 and those from shot 1, with fracture surfaces showing ductile tearing under mode II loading. Figure 9.24 shows some SEM images of a fracture surface, with the same parabolic dimples and sliding sheets seen with the SEM images from shot 1 in figure 9.22. The only unique feature was that there were large areas of oxidisation and discolouration on the fragments as a result of the residual oxygen in the recovery tank, as shortly after impact the projectile and target pair break the seal between the target tank held at a vacuum around 200 mTorr and the recovery tank which was only evacuated to several Torr. Again, fractures were seen to take a complex path through the fragment often making 90° turns in their motion. One fragment was recovered that was almost the entire length of the original 150 mm long cylinder.

Finally, fragments from shot 4 were found to contain evidence of adiabatic shear banding. This is shown in figure 9.25. The fragment pictured at the top left has multiple arrested longitudinal fractures, the cylinder axis is from left to right in the picture. This could be
identified from slight machining marks left by the turning process. A section was made along the red line such that when mounted and polished the face pointed to by the red arrow was visible. The cross section at the top left shows the overall profile of the fragment thickness as well as the location of the more detailed images at the bottom. The 45° ends of the fragment are clearly visible, again seeing multiple intersecting fractures. Point a was observed with optical and electron microscopy techniques, finding the shear band to be on the order of 10µm to 20µm thick. Imaging at higher magnification showed a very fine grain structure in the band consistent with transformed material being rapidly quenched by the surrounding material once the loading ceased. The fracture propagated along this weakened material through the nucleation and coalescence of voids with transformed material visible along the edges of the fracture. Image b shows a shear band imaged under polarised light that has not failed. Both type a and b were commonly found in fragments from shot 4 lying approximately 45° to the radial direction.
Figure 9.25: Shot 4, second heated cylinder. *Top, left:* Recovered fragment, outer face visible, and line of sectioning with the red arrow indicating the viewing orientation. *Right:* Cross section of fragment and location of detailed views a and b. *Bottom:* Shear bands found at a and b, with an SEM detail of the one at a. Image b was taken under polarised light.
9.7 Conclusions

The original aims of this section of work were as follows; validate the heating and cooling systems could be used on a real experiment, ensure that the desired diagnostics could be used without compromise and test the whole system on Ti-6Al-4V cylinders. The performance of the temperature control and measurement systems was covered in section 8.4. Application to a real experiment was in general successful. The process of mounting and aligning the target cylinder in the gas gun was only slightly complicated by adding temperature as a variable in that care had to be taken to ensure the thermocouples were not in the field of view of the camera. Cycling the target though vacuum and cooling or heating had no effect on the alignment of the target. This was confirmed with the alignment plug for the vacuum case, and through the PDV data and the axial symmetry of the expansion for the thermal cases. The thermal isolation between the cylinder and mounting hardware was one area that would benefit from improvement. Future work would use a ceramic shim between the cylinder and the mounting sleeve to help minimise thermal transport between the cylinder and the gas gun. This would also avoid the issues found with the PDV probes beginning to heat which required cooling the mounting arm, although once this modification was made (section 9.5.2) the PDV functioned reliably regardless of the cylinder temperature. In other works problems have been reported when using VISAR on a hot target due to oxide layer formation reducing the returned signal [145]. The typical wavelengths used for these systems (1550 nm and 532 nm for PDV and VISAR) mean that a thicker layer would have to form to reduce the PDV reflectivity, allowing for more time with the target at temperature. The PDV recorded the expansion velocity at four points for a maximum of 110 µs or to a strain around the expansion peak well in excess of 60 percent.

The PDV was complimented with high speed imaging, the optimum setup found to be a front-lit Phantom v1610 high speed camera and a silhouetted IVV framing camera. This meant that the v1610 could give a measure of the failure strain (strain at first fracture) and the IVV could be used to produce line-out data to measure the expansion profile along the cylinder. The accuracy of the failure strain measurements was limited by the frame rate of the v1610, running at a maximum of 210000 frames/second (4.76 µs interframe). The reduction in
resolution required to achieve faster than this made resolving features smaller than a mm or so impossible. At the strain rates in this study \(10^4 \text{s}^{-1}\) this interframe time caused errors on the order of 10 to 20 percent in the failure strain measurement. While the IVV framing camera was capable of mega-pixel images at much higher frame rates the amount of light required by the intensifier meant that it was better suited for silhouette work. As only half the cylinder was imaged this required the assumption that the fracture activation was uniformly distributed around the cylinder. A more robust approach would have been to either use mirrors or multiple cameras to image more of the cylinder although this was prohibitively expensive and optical access to the target through the gas gun tank was limited.

Fragment recovery was quite low, especially with smaller fragments as they were extremely difficult to locate and separate from the rags used in the momentum trap. This was exacerbated by the 100 mm sabot. The large bore of the ISP gas gun meant that the cylinder had to be a smaller diameter than the barrel to reach the required strain rate of \(10^4 \text{s}^{-1}\). Whilst the fracture process had completed, the fragments and remaining undeformed cylinder ends were then impacted and carried through into the momentum trap by the sabot body. If the projectile was the full diameter of the barrel or a sabot stripping device was used then this would not occur, and the fragments would be able to expand outwards with very little longitudinal velocity such that they would not end up in the rags. This would also mean that the ends of the cylinder would remain intact such that the fragments from the expansion region could be easily identified. The low fragment recovery rate here coupled with the damage caused by the sabot made statistical analyses of the fragmentation with temperature difficult, though this was due to the gas gun and not the experimental design. Ideally the experiments would have been performed on a smaller calibre such as a 50 mm gun but only the 100 mm gun was available.

The preliminary results with Ti-6Al-4V cylinders showed the drive mechanism to be highly repeatable independent of the sample temperature, with excellent agreement between the early time PDV data for all four shots. Peak strain rate prior to failure was between \(0.98 \times 10^4 \text{s}^{-1}\) and \(1.05 \times 10^4 \text{s}^{-1}\). The experiment at the highest temperature, an average of \((724 \pm 52) \text{K}\) between 80 mm and 120 mm, was found to have the highest failure strain of \(24.1 \pm 2.4\) percent. The cooled cylinder (average of \((158 \pm 11) \text{K}\)) had the lowest failure strain at \(7.4 \pm 5.2\) percent. The
ambient and \((609 \pm 43)\) K were both around 15 percent within errors. The fracture mechanism was predominantly ductile tearing under mode II or in plane shear loading. Only in shot 4, at the highest temperature reached, were there any signs of adiabatic shear banding occurring. The fragmentation toughness was observed to be independent of temperature over the range studied with an average value of \(101 \pm 13\) MPa m\(^{1/2}\) over the four shots even though the fracture mechanism was markedly different at high temperatures.

The work in this and the two preceding chapters has shown that moving to the ogive based expansion over the classic Winter style uniquely opens the platform to studies of expansion at temperature, areas where explosives and electromagnetic launchers can not access. With slight modifications and improved hardware (faster cameras and a smaller calibre gun capable of \(1\) km s\(^{-1}\)) accurate, highly diagnosed experiments could be completed under repeatable loading independent of temperature.
10
Conclusions

This final chapter refers back to chapter 4 where the general aims and objectives of the study were defined and evaluates their successes and shortcomings. More detailed conclusions for each set of experiments are given at the ends of the relevant chapters.

10.1 Stress State in the Sample

The sample stress state or loading path was identified as one area that was lacking in the research of dynamic fracture and fragmentation. An experimental technique was developed that enabled high strain rate uniform tensile deformation of samples in stress states from uniaxial stress through to plane strain. The sample material was Ti-6Al-4V that was fully characterised with EBSD methods prior to being launched. In short, rings of this material with a constant wall thickness but different height were machined such that their aspect ratio (the ratio of these two dimensions) varied between 1:1, a perfect ring, and 1:4, a short cylinder. These were then placed individually over a driver, either a copper or steel cylinder that contained a charge of RDX explosive. This was detonated simultaneously at each end and the converging shock waves propagated through the driver, launching the rings into uniform expansion at strain rates on the order of $10^4 \text{s}^{-1}$. The expansion velocity was measured with a single point VISAR system and the recovered fragments measured, weighed and subjected to light and electron microscopy to determine the fracture mechanism. It was decided to not persevere with the steel driver as anomalous profiles were seen in the ring velocity that suggested the loading drive was not as desired, that is the ring was being loaded multiple times before reaching free expansion.

Subsequent experiments with the copper driver were performed on rings 3 mm, 6 mm and 12 mm high with a constant 3 mm wall thickness. Peak strain rates were around $2 \times 10^4 \text{s}^{-1}$ with the average over the recorded history around $1.5 \times 10^4 \text{s}^{-1}$. Hence the copper driver was found to be suitable for driving high strain rate uniform expansion in these rings. Issues were
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experienced with alignment of the VISAR beam, specifically being able to ensure that the beam was focused at the midpoint of the ring. This again led to inconsistencies in the velocity history although with careful analysis of simulation data a reasonable estimate of the true behaviour was extrapolated. Future efforts with this system would move away from a free space VISAR to a fibre based system or a multiple channel PDV suite. Probes would be placed at multiple points around the azimuth of the sample. These would be located in a fixture surrounding the sample such that alignment would be consistent and accurate. Using multiple probes would mean that the symmetry of the expansion could be validated as well as possibly observing the effect of release waves propagating from fracture sites. Similarly a high speed imaging system would be of great use as this would enable direct measurement of the strain at failure and temporal activation of fracture around the sample.

The results found that under uniaxial stress failure was preceded by necking, with many arrested necks found in the fragments. Where these necks had gone through to failure SEM imaging of the fracture surfaces found a mixture of tensile fibrous failure in the form of round dimples in the centre of the thickness and mode II shear failure towards the edges (parabolic dimples) much the same as the cup-and-cone features seen in quasi-static and low strain rate tensile testing. The other extreme, the 12 mm rings under plane strain conditions, were found to fail almost exclusively through ductile tearing under mode II in plane shear loading with fracture surfaces presenting at 45° to the radial direction. This was confirmed through observation of parabolic dimples on the fracture surfaces, and light microscopy of arrested fractures found no sign of dynamic transformation or recrystallisation around or ahead of the fracture that would suggest adiabatic shear banding had occurred. Finally, the intermediate 6 mm high rings had a unique form of internal damage in the circumferential direction. This was in the form of planes of tensile damage, void nucleation and growth, in the plane normal to the hoop direction at 45° to the radius. Analysis of the stress wave propagation in the simulations and similar results seen in radiographic imaging of fracture suggest that this damage was caused by the interaction of release waves from the edges of the sample in a manner similar to spall fracture. This would appear to happen early in the expansion process and the internal damage then acted to prematurely seed the traditional radial failure, leading to much smaller fragments than the
10.2 Initial Sample Temperature

Temperature was the other variable chosen for further investigation. Due to limitations of the expansion drive methods as detailed in chapter 3, this meant that a new system had to be developed building upon the gas gun methods of Winter and Prestidge. Two main sets of experiments were performed, the first using flash X-ray radiography to image the internal processes of the new target and projectile geometry to confirm that the drive was suitable for purpose. The second set of experiments then designed, installed and tested on large scale Ti-6Al-4V cylinders a system to heat or cool the cylinder while still being able to use multiple velocimetry probes, high speed imaging and fragment recovery and drive the cylinder at a radial strain rate of $10^4 \text{s}^{-1}$.

10.2.1 Ogive Geometry Development

The classic gas gun drive method of Winter and Prestidge made use of both the projectile and cylinder insert deforming to drive the radial expansion. As such both the insert and projectile were made from a polymer, either a plastic or rubber compound. This is obviously unsuitable for work at temperatures away from room temperature. The aim was to replace the polymer insert with a new, steel insert that was designed to not deform. Through this the deformation and drive mechanism was transferred wholly to the projectile, which is unaffected by the cylinder temperature as there is no contact until the moment of impact. The aims of the geometry development work were to arrive at a suitable shape for the insert and projectile that would create uniform radial expansion at strain rates of $10^4 \text{s}^{-1}$ that remained repeatable at temperatures over a range of 100 K to 1000 K. It was important that the drive be unaffected by the sample temperature to keep experimental conditions constant between shots.

The optimum geometry was found to be a steel ogive or nosecone profile insert. The projectile was made from polycarbonate with a concave radiused leading face so that impact between the projectile and insert occurred on the revolution axis first. The delayed contact between the
rest of the projectile and ogive faces created a supported radial shock wave in the projectile, transferring the longitudinal momentum from its launch into radial motion towards the inner cylinder wall. Expansion was found to be uniform around the azimuth with a Gaussian profile when viewed from the side. These experiments with a 6061-T6 aluminium cylinder reached a maximum strain rate around $2 \times 10^4 \text{s}^{-1}$ for a projectile velocity of 900 m s$^{-1}$. The ogive method was found to require a slightly higher projectile velocity than the Winter method to achieve a given radial strain rate, although the expansion region did not translate as much along the length of the cylinder and only one material now drove the cylinder wall outwards. The radiography and recovered samples showed that the steel ogive underwent very little deformation and the expansion process was unaffected by hollowing out the rear of the insert. This void was then chosen as a place to house temperature control apparatus.

10.2.2 Temperature Control Systems

The ogive was used as the source of either heating or cooling, transferring heat through conduction with the rest of the cylinder. For heating, a resistive load was placed inside the rear of the ogive insert. This was a NiChrome coil wrapped around a ceramic spindle. This was then powered with a high current supply, fully remotely operated via a LabVIEW software interface. Similarly, the temperature was logged at multiple points along the cylinder length which was also recorded by the software. A maximum current of 62 A was delivered to the coil before the mounting bolt holding the spindle in the insert failed and the coil shorted against the insert. With this considered the maximum average temperature generated in the cylinder over the expansion region, between 80 mm and 120 mm from the entry end, was $(724 \pm 52) \text{ K}$ with a temperature difference of 130 K. Cooling was performed by sealing the ogive recess with an aluminium cap, then flowing LN$_2$ from a pressurised dewar and regulator through this void. Again, this system was remotely operated and the temperature along the cylinder logged. The average and difference in temperature over the same region were $(158 \pm 11) \text{ K}$ and 34 K respectively.

In both the heated and cooled configuration there was a thermal gradient created over the expansion region. This was due to poor thermal insulation between the cylinder, mounting
sleeve and gas gun target mounting ring. While ceramic spacers were used between the sleeve and ring, the sleeve itself had quite a large thermal mass and acted as a sink to the cylinder. Future efforts would be greatly improved by isolating the cylinder from the sleeve, such as with a thin layer of ceramic between the two. However, as the laser diagnostics are also mounted to the sleeve and alignment between the cylinder and gas gun barrel is key care would be needed to ensure that the thermal expansion of the cylinder would cause movement with respect to the sleeve. Ti-6Al-4V was a challenging material to test this system on owing to its very poor thermal conductivity. It is thought that with these minor modifications to the way the cylinder is gripped and with a more conductive material thermal equilibrium would be possible.

10.2.3 Expanding Cylinders at Temperature

The temperature control systems were deployed on a set of large scale Ti-6Al-4V expanding cylinders, 150 mm long with a 50 mm inner diameter and 4 mm wall thickness. A projectile velocity of $1000 \text{ m s}^{-1}$ was used to generate peak radial strain rates on the order of $10^4 \text{ s}^{-1}$ in cylinders with the expansion region at a range of temperatures between $(158 \pm 11) \text{ K}$ and $(724 \pm 52) \text{ K}$. The deformation and failure was observed with four channels of upshifted PDV measuring the expansion velocity and two high speed imaging systems. This allowed for measurement of the initial drive, which was found to be remarkably repeatable and independent of the cylinder temperature, meeting the aim of developing a drive system capable of the above. The experiment design was also successful at being able to field multiple diagnostics and fragment recovery on the same shot without temperature adversely affecting the data capture. Although fragment recovery was generally poor owing to the 100 mm sabot transferring a large amount of the fragments into the rags and momentum trap the high speed imaging data allowed for calculation of the fragmentation toughness, of which no discernible relationship with temperature was observed. The average value was found to be $101 \pm 13 \text{ MPa m}^{1/2}$ over the temperature range, in good agreement with published data on the same material.

The cooled cylinder was found to have the lowest failure strain at $7.4 \pm 5.2 \text{ percent}$ with the cylinder at the highest temperature (shot 4) having the largest failure strain of $24.2 \pm 2.4 \text{ percent}$. However, the intermediate shots did not follow a linear relationship between these two
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extremes. Up to shot 3 at a temperature of $(609 \pm 43)\, \text{K}$ the fracture mechanism was found to be ductile tearing under mode II (in plane shear) loading, resulting in fragments having edges at $45^\circ$ to the radius. This was confirmed with SEM and light microscopy of failure surfaces and arrested fractures. Only in the cylinder at $(724 \pm 52)\, \text{K}$ was there evidence of failure occurring along adiabatic shear bands, with the cracks propagating through the nucleation and coalescence of voids in these bands. Again, optical and SEM imaging showed these bands as thin strips of material with a very fine grain structure, indicative of high temperature transformation followed by rapid quenching by the surrounding material. These bands were found at $45^\circ$ to the radial direction.

Overall, this method of studying high strain rate tensile deformation and fracture with a gas gun was a success, providing a platform for generating unique data in the field. No other system at present allows for such a wealth of data to be measured, recording the entire history of the sample from loading, through deformation to fracture and fragmentation while keeping all experimental variables but temperature constant between shots. With some minor modifications to the mounting system to aid reaching thermal equilibrium in the cylinder based on these preliminary experiments this ogive based geometry promises to be a powerful experimental tool for producing temperature dependent data for material model development and validation.
Bibliography


A.1 Ti6Al4V Explosively Driven Rings

Chapter 6

Figure A.1: Part dimensions for the explosively driven Ti6Al4V rings. All dimensions in mm. Top, left: Steel driver (20 mm $\phi$ explosive charge). Right: Copper driver (10 mm $\phi$ explosive charge). Bottom: Dimensions of the Ti6Al4V rings.
A.2 6061-T6 Aluminium Gas Gun Driven Cylinder

Chapter 7

Figure A.2: Part dimensions for the 6061-T6 30mmØ gas gun driven expansion experiments. All dimensions in mm. Top, left: 6061-T6 cylinder. Right: 4340 steel ogive insert. Bottom: Polycarbonate projectile with sabot.
A.3 Ti-6Al-4V Expanding Cylinder at Temperature

Figure A.3: Ti-6Al-4V gas gun driven expanding cylinder. All dimensions in mm. Top: Cylinder, Middle: Ogive insert, Bottom: Projectile.
Figure A.4: Ti-6Al-4V gas gun driven expanding cylinder. All dimensions in mm. Top: Mounting sleeve, Middle: PDV mounting arm, Bottom: PDV probe mount.
Appendix B

MATLAB Files

B.1 xtplot.m

Description: This function reads in gauge data from AUTODYN in csv format and plots as a 2D contour $x-t$ plot. The optional outputs are three matrices, the $ij$ in each one corresponding to a gauge’s location $x_{ij}$ and pressure $P_{ij}$ (or indeed any other variable) at a time $t_{ij}$.

```matlab
function [t, x, P, actualmeantime, xtdiagram, flyer_r, flyer_f, target_imp, target_fs] = xtplot(x_values, P_values, timestep)

% x and P are csv files of the
% gauge's location and pressure
% timestep samples every n us

% Ask which gauges are the sample boundaries
flyer_rear = input('Gauge #, flyer rear:');
flyer_front = input('Flyer front:');
target_impact = input('Target, impact face:');
target_rear = input('Target, free surface:');

% Read data
xStruct = importdata(x_values, ',', 3);
PStruct = importdata(P_values, ',', 3);
% Get just the numerical data
xdata = xStruct.data;
Pdata = PStruct.data;

% Trim the cycle count data
% Del 1st column (cycle no.)
xdata(:,1) = [];
Pdata(:,1) = [];

% Run through and select chosen timesteps
starttime = min(xdata(:, 1));
dftime = max(xdata(:, 1));
timewindow = dftime - starttime;
cyclecount = numel(xdata(:, 1));
avtimestep = timewindow / cyclecount;
step = round(timestep / avtimestep);
actualmeantime = step * avtimestep;

% Select every n rows
xdata = xdata(1:step:end, :);
Pdata = Pdata(1:step:end, :);
```
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36 % Calculate no. of gauges
37 num_col = (size(Pdata, 2) - 1);
38
39 % Create matrices of time, space and pressure
40 % Time - same for every column
41 t = repmat(Pdata(:,1), 1, num_col);
42 % space and pressure have the first column (time) cut off
43 for jj=1:num_col
44     x(:,jj) = xdata(:,(jj+1));
45     P(:,jj) = Pdata(:,(jj+1));
46 end
47
48 % ************* Plotting *************
49 xtdiagram = contourf(x, t, P, 200, 'LineColor', 'none');
50 hold on
51
52 % Add the boundaries
53 flyer_r = plot(x(:, flyer_rear), t(:, flyer_rear));
54 flyer_f = plot(x(:, flyer_front), t(:, flyer_front));
55 target_imp = plot(x(:, target_impact), t(:, target_impact));
56 target_fs = plot(x(:, target_rear), t(:, target_rear));
57 set(flyer_r, 'LineWidth', .5, 'Color', 'black');
58 set(flyer_f, 'LineWidth', .5, 'Color', 'black');
59 set(target_imp, 'LineWidth', .5, 'Color', 'black');
60 set(target_fs, 'LineWidth', .5, 'Color', 'black');
61 hold off
B.2 fit_surface_to_uniform_grid.m

Description: Used for non-uniformly spaced gauge data as output by AUTODYN to track a surface. Data read as per B.1 a grid of 1000 x 1000 cells (lines 67, 68) is created from the limits of the x and t data and a linear fit is used between the original data and the grid, resulting in a uniformly spaced data set allowing slices to be made. Plots a 3D surface of the fitted data with an undersampled grid overlaid for clarity (line 90). The user is asked to input where the slices should be made to compare with experimental data. The function outputs matrices for time, position and value as per B.1 their respective uniformly spaced versions TI, XI, YI, a surface plot theplot with the undersampled wireframe thewire, the four slices pdvA-D as matrices of position, time and y value and their overlaid plots plotA-D. Lines 75-78 can be used to measure the distance between the requested PDV location and the actual provided position.

```matlab
function [tpoints, xpoints, ypoints, TI, XI, YI, theplot, thewire, ... pdvA, pdvB, pdvC, pdvD, plotA, plotB, plotC, plotD, ... actualmeantime] = fit_gauges_to_uniform_grid(x, y, timestep)

% x and y are csv files of the
% gauge's location and parameter
% timestep samples every n us

% Ask where the PDV channels are
pdvA = input('Position of pdvA: ');
pdvB = input('pdvB: ');
pdvC = input('pdvC: ');
pdvD = input('and pdvD: ');

% Undersampling for the wireframe
wireno = input('Plot wireframe every n points, n: ');

% Read data
xStruct = importdata(x, ',', 3);
yStruct = importdata(y, ',', 3);
% Get just the numerical data
xdata = xStruct.data;
ydata = yStruct.data;

% Trim the cycle count data
% Del 1st column (cycle no.)
xdata(:,1) = [];
ydata(:,1) = [];

% Run through and select chosen timesteps
starttime = min(xdata(:, 1));
endtime = max(xdata(:, 1));
timewindow = endtime - starttime;
cyclecount = numel(xdata(:, 1));
```

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35 avtimestep = timewindow / cyclecount;
36 step = round(timestep / avtimestep);
37 actualmeantime = step * avtimestep;
38
39 % Select every n rows
40 xdata = xdata(1:step:end, :);
41 ydata = ydata(1:step:end, :);
42
43 % Calculate no. of gauges
44 num_col = (size(ydata, 2) - 1);
45
46 % Create matrices of time, space and pressure
47 % Time - same for every column
48 tpoints = repmat(ydata(:,1), 1, num_col);
49 % space and pressure have the first column (time) cut off
50 for jj = 1: num_col
51     xpoints(:, jj) = xdata(:, (jj + 1));
52     ypoints(:, jj) = ydata(:, (jj + 1));
53 end
54
55 % Reshape matrices into vectors
56 xvec = reshape(xpoints, 1, []);
57 yvec = reshape(ypoints, 1, []);
58 tvec = reshape(tpoints, 1, []);
59
60 % Find min and max of x and y
61 xvec_min = min(xvec);
62 xvec_max = max(xvec);
63 tvec_min = min(tvec);
64 tvec_max = max(tvec);
65
66 % Create uniform grid with 1000 intervals
67 xi = xvec_min:((xvec_max - xvec_min)/1000):xvec_max;
68 ti = tvec_min:((tvec_max - tvec_min)/1000):tvec_max;
69 [XI, TI] = meshgrid(xi, ti);
70
71 % Fit the ypoints data to the uniform grid
72 YI = griddata(xvec, tvec, yvec, XI, TI);
73
74 % Find the columns that correspond to the PDV probe location
75 [A, A_col] = min(abs((XI(1, :)) - pdvA));
76 [B, B_col] = min(abs((XI(1, :)) - pdvB));
77 [C, C_col] = min(abs((XI(1, :)) - pdvC));
78 [D, D_col] = min(abs((XI(1, :)) - pdvD));
79
80 % ******************************************** Plotting ********************************************
81
82 % Plot the full simulated surface, called theplot
83 theplot = surf(XI, TI, YI);
84 set(theplot, 'EdgeColor', 'none');
85 alpha(0.75);
% Add a wireframe over it, spaced every wireno
thewire = wireframe(XI, TI, YI, wireno);

% Simulated PDV lineouts as matrices
[pdvA] = [XI(:, A_col) TI(:, A_col) YI(:, A_col)];
[pdvB] = [XI(:, B_col) TI(:, B_col) YI(:, B_col)];
[pdvC] = [XI(:, C_col) TI(:, C_col) YI(:, C_col)];
[pdvD] = [XI(:, D_col) TI(:, D_col) YI(:, D_col)];

% Add the simulated PDV lineouts to the surface
plotA = plot3(pdvA(:, 1), pdvA(:, 2), pdvA(:, 3));
plotB = plot3(pdvB(:, 1), pdvB(:, 2), pdvB(:, 3));
plotC = plot3(pdvC(:, 1), pdvC(:, 2), pdvC(:, 3));
plotD = plot3(pdvD(:, 1), pdvD(:, 2), pdvD(:, 3));
set(plotA, 'LineWidth', 4, 'Color', 'black');
set(plotB, 'LineWidth', 4, 'Color', 'black');
set(plotC, 'LineWidth', 4, 'Color', 'black');
set(plotD, 'LineWidth', 4, 'Color', 'black');

hold off
Appendix C

Explosively Driven Rings: Data

C.1 Raw VISAR data

Figure C.1: Raw VISAR data for the four experiments as recorded by the oscilloscope. Black and red lines are the two polarisations and blue is the beam intensity monitor.
C. EXPLOSIVELY DRIVEN RINGS: DATA

C.2 Velocity Data

Figure C.2: Expansion velocity reduced from the VISAR data (no filtering or smoothing applied) for the four experiments.
# Appendix D

## Ogive Geometry Development: Simulation Parameters

### Table D.1: Simulation Equation of State and Strength Parameters

<table>
<thead>
<tr>
<th>Material [Reference]</th>
<th>$\rho_0$ (kg m$^{-3}$)</th>
<th>$C_0$ (mm µs$^{-1}$)</th>
<th>$s$</th>
<th>$\Gamma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>6061-T6 Al [97]</td>
<td>2703</td>
<td>5.24</td>
<td>1.400</td>
<td>1.97</td>
</tr>
<tr>
<td>Ti-6Al-4V [97]</td>
<td>4419</td>
<td>5.13</td>
<td>1.028</td>
<td>1.23</td>
</tr>
<tr>
<td>4340 Steel [70]</td>
<td>7830</td>
<td>4.67</td>
<td>1.440</td>
<td>1.50</td>
</tr>
<tr>
<td>Polycarbonate [156]</td>
<td>1200</td>
<td>1.93</td>
<td>2.650</td>
<td>0.61</td>
</tr>
</tbody>
</table>

### Steinberg-Guinan Strength Model [97]

<table>
<thead>
<tr>
<th>Material</th>
<th>$G_0$ (GPa)</th>
<th>$Y$ (GPa)</th>
<th>$Y_{max}$ (GPa)</th>
<th>$\beta$</th>
<th>$n$</th>
<th>$G_P'$</th>
<th>$G_T'$ (GPa K$^{-1}$)</th>
<th>$Y'_P$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ti-6Al-4V</td>
<td>41.9</td>
<td>1.33</td>
<td>2.13</td>
<td>12</td>
<td>0.10</td>
<td>0.4819</td>
<td>-0.02698</td>
<td>0.015300</td>
</tr>
<tr>
<td>6061-T6 Al</td>
<td>27.59</td>
<td>0.29</td>
<td>0.68</td>
<td>125</td>
<td>0.10</td>
<td>1.8000</td>
<td>-0.01700</td>
<td>0.018908</td>
</tr>
</tbody>
</table>

### 4340 Steel Johnson-Cook Strength Model [123]

<table>
<thead>
<tr>
<th>$G$ (GPa)</th>
<th>$A$ (GPa)</th>
<th>$B$ (GPa)</th>
<th>$n$</th>
<th>$C$</th>
<th>$T_{melt}$ (K)</th>
<th>$m$</th>
</tr>
</thead>
<tbody>
<tr>
<td>81.8</td>
<td>0.792</td>
<td>0.510</td>
<td>0.26</td>
<td>0.014</td>
<td>1793</td>
<td>1.03</td>
</tr>
</tbody>
</table>

### Polycarbonate piecewise Johnson Cook Strength Model [156]

<table>
<thead>
<tr>
<th>$G$ (GPa)</th>
<th>$Y_0$ (GPa)</th>
<th>$Y(\varepsilon = 0.1)$ (GPa)</th>
<th>$Y(\varepsilon = 0.5)$ (GPa)</th>
<th>$Y(\varepsilon = 0.6)$ (GPa)</th>
<th>$Y(\varepsilon = 0.7)$ (GPa)</th>
<th>Strain Rate Constant</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.00</td>
<td>0.081</td>
<td>0.088</td>
<td>0.143</td>
<td>0.168</td>
<td>0.187</td>
<td>0.04</td>
</tr>
</tbody>
</table>