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Citation: *J. Appl. Phys.* **114**, 173508 (2013); doi: 10.1063/1.4828867

View online: <http://dx.doi.org/10.1063/1.4828867>

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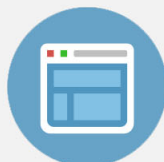
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A gas gun based technique for studying the role of temperature in dynamic fracture and fragmentation

D. R. Jones, D. J. Chapman, and D. E. Eakins^{a)}

Institute of Shock Physics, Imperial College London, London SW7 2BW, United Kingdom

(Received 15 August 2013; accepted 18 October 2013; published online 5 November 2013)

Presented in this work is a new experimental technique to facilitate studies of materials under uniform radial expansion at rates of strain typically seen in ballistic and impact studies (10^3 to 10^5 s^{-1}) at temperatures around 100–1000 K. Previous work places a right-cylinder polymer insert in a sample cylinder, into which a matching polymer projectile is launched using a gas gun. The impact and resulting deformation of the polymers imparts radial momentum to the cylinder. This work replaces the polymer insert with a steel ogive. A polycarbonate projectile deforms around the insert and drives radial expansion. The uniform radial expansion created has a less complex interface than previous work as only one material is driving the cylinder wall. As deformation of the insert is no longer necessary, the opportunity to heat or cool the cylinder prior to expansion is now available for studies into the effect of temperature on fracture and fragmentation behavior. This paper describes the design of this new impact configuration alongside how strain rate and expansion profile can be controlled. Validation experiment results with 6061-T6 aluminum and Ti-6Al-4V cylinders using a variety of diagnostics are compared with numerical modelling, where the benefits of this technique in assisting development of material strength and failure models are discussed with methods to control the sample temperature. [<http://dx.doi.org/10.1063/1.4828867>]

I. INTRODUCTION

The fracture and fragmentation of a body is a frequent terminal response in scenarios involving dynamic loading under high strain rate and pressure conditions. The ability to accurately predict this failure behavior is important for two reasons; on the one hand, a robust understanding of the failure processes involved could help to avoid fracture for example as desired in engineering and aerospace industries. Second, this understanding can be used to control the manner in which materials fail exercising control over fragmentation statistics such as size, mass, and velocity.

In dynamic loading, the resulting high strain rates in the sample mean inertia can no longer be neglected and as such quasi-static analysis is no longer applicable.¹ The strain rate at which this occurs depends on the particular scenario. The scale and geometry of traditional dynamic tensile loading apparatus typically produce a single failure site which is useful for understanding incipient failure processes. However, the study of whole body failure and the communication between fracture sites is more effectively studied through uniformly loading an axially symmetric sample such as a ring or cylinder. For example, dynamically loading the inner wall of a cylinder introduces a radially propagating wave through the wall and drives expansion of the cylinder. Once the cylinder separates from the driver, this wave will dissipate and the stress state in the sample will be dominated by a circumferential hoop stress which is uniform over the entire azimuth. During expansion, multiple fracture sites initiate around the cylinder with the number and size of resulting fragments controlled by their release interactions.

Cylinder expansion experiments traditionally employ velocimetry and high speed imaging to measure strain to failure and transient deformation and fragmentation. These data provide a good base for modelling the experiment to examine different strength and failure models. Additionally, fragment recovery and subsequent metallography allow determination of the fracture mechanism. The experimental technique described here facilitates simultaneous deployment of all the above diagnostics whilst being scalable over a range of sample sizes and strain rates. Importantly, this new technique provides the ability to adjust the initial temperature of the sample cylinder which will broaden the data available for material model development. This area of temperature dependent data is unique to this gas gun technique as the loading mechanism is unaffected by the sample temperature.

Introducing a method of controlling the initial temperature of an expanding cylinder will provide the means to investigate the thermal dependence of various relaxation and failure processes during dynamic loading. Titanium, for example, is susceptible to adiabatic shear localization during dynamic loading.² Heating of the sample could reduce this localization behavior as the entire cylinder will already be thermally softened. Cooling could enhance the effect as any small amount of heat generated by slip will create a region much weaker than the surrounding material. Twinning has also been observed as a deformation mechanism in pure titanium at extremely low temperatures.³ Investigating the role of temperature will assist in linking fragmentation statistics to the fracture mechanisms involved.

This paper details the development of this new technique briefly introduced previously⁴ and describes validation experiments on 6061-T6 aluminum and Ti-6Al-4V.

^{a)}d.eakins@imperial.ac.uk

II. DRIVING CYLINDERS INTO EXPANSION

Fracture and fragmentation studies on axially symmetric geometries have been commonplace since the mid-20th century with several seminal papers being published. Taylor⁵ studied the behavior of explosive filled cylinders relating the detonation velocity to the expansion velocity and discussed the radial strain at failure. Gurney⁶ linked the ratio of the masses of the bomb casing and the explosive content to the velocity of the fragments produced. Mott⁷ introduced the idea for a fracture distribution governed by release waves. So called Mott release waves emanate from a fracture site arresting further strain and fracture in the material they traverse, where the speed of these waves sets a limit on the number of fragments. Geometries tested have included spheres,⁸ hemispheres,⁹ cylinders,^{10–12} rings,^{13,14} and explosive shells.¹⁵

The largest volume of work published on expanding cylinders has focused on explosively loaded samples.^{16–20} The material of interest is either packed with an explosive charge or can be placed on a “driver cylinder” containing the charge designed to transfer radial momentum to the sample ring or cylinder around it.²¹ This can introduce a strong shock wave into the cylinder and affect material properties. From Grady²² the peak pressures coupled into the metal can be on the order of 30–60 GPa, sufficient to produce a phase change in steel which is commonly used either for study or as a driver. Ideally, the sample will be loaded once to enable hoop stress to dominate as early as possible. Even if a driver is used, a phase change will introduce a multiple wave structure into the sample. Another issue with explosive experiments is the production of a large amount of debris which can obscure camera and laser based diagnostics and requiring explosive handling facilities.

For these reasons, alternative methods to drive expansion have been explored. Two electromagnetic drive based mechanisms have been developed. Ensminger and Fyfe replaced the explosive charge with a thin wire which explodes when subjected to a large current pulse.²³ The resulting rapidly expanding plasma drives the ring outwards. Niordson’s method utilises the Lorentz force²⁴ where the sample cylinder is placed over a wire solenoid through which a current pulse is sent. The opposite induced current in the sample creates a large magnetic pressure between the two. However, extending this technique to larger samples requires more current (magnetic pressure is proportional to the current squared). With higher currents Joule (resistive) heating thermally softens or even melts the sample putting a practical limit on the range of this technique.²⁵ Typical samples have a sub-mm wall thickness which can require ~ 10 kA to drive at strain rates of 10^4 s⁻¹.²⁶ The fracture behavior of thin-walled cylinders is not necessarily comparable with thick-walled (where wall thickness is not negligible compared to the cylinder radius) samples. The wall thickness affects the stress state in the wall with shear failure much more prevalent in thick-walled samples²⁷ compared to void coalescence and necking in thin-walled counterparts.²⁸

Winter and Prestidge²⁹ were the first to use a light gas gun to create expansion in cylinders. This involved half

filling the target cylinder along the length with a rubber silastomer material. This is then aligned concentrically with the barrel and a nylon projectile is launched into the cylinder. As the projectile impacts the rubber insert both materials deform and expand radially, driving the walls of the cylinder outward. Similar work using polycarbonate as both the insert and the projectile has been completed by Vogler *et al.*³⁰ This technique is easily scaled to suit the gun bore and the apparatus needed is well within the reach of a university or research group. Strain rate can be controlled through the size of the sample or the amount of energy delivered through projectile velocity. The expansion velocity needed as cylinder diameter varies to achieve radial strain rates of 10^3 to 10^5 s⁻¹ is shown in Figure 1. These data were calculated using (Ref. 21)

$$\dot{\epsilon}_r = \frac{\dot{r}(t)}{r(t)}, \quad (1)$$

where $\dot{\epsilon}_r$ is the instantaneous radial strain rate and $r(t)$ is the cylinder outer radius at time t . It is clear from this and Figure 1 that a larger cylinder requires a higher expansion velocity for a given strain rate. For the work described herein, a radial strain rate of 10^4 s⁻¹ was targeted to enable direct comparison of resulting data to similar rate work found in ballistic and impact studies. At this dynamic rate, adiabatic shear band and strain localization can contribute to the fracture behavior alongside ductile and brittle failure.

The Winter and Prestidge method has been used to study a range of metals^{30–32} at ambient temperatures. However, extension to higher or lower temperatures requires addressing several limitations of this technique. The use of multiple driving components leads to a discontinuity between the two which can cause jetting or a stress localization affecting the natural fracture behavior. At higher impact velocities the polymer insert can deteriorate and expand out through the cracks in the cylinder, obscuring diagnostics. Investigation

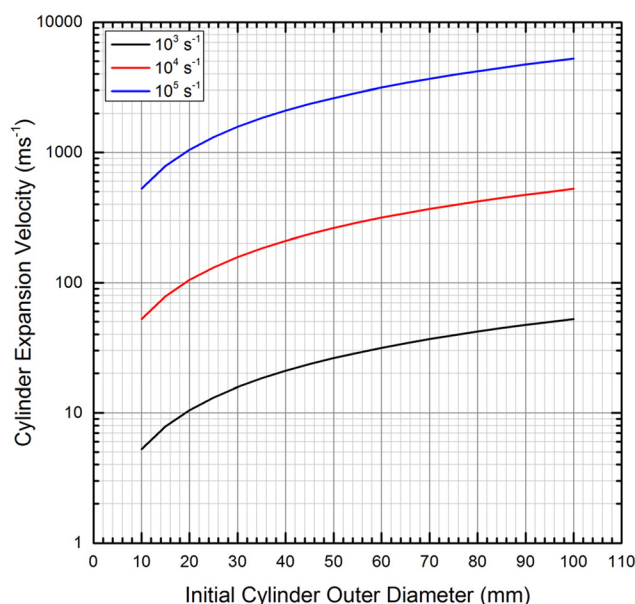


FIG. 1. Radial velocity needed to obtain radial strain rates for a range of initial cylinder outer diameters at 5% radial strain, calculated from Hoggatt and Recht.²¹

into using soft metals such as aluminum for both insert and projectile found the expansion profile to be asymmetric, producing unsatisfactory results³³ due to the non-uniform loading.

Presented here is a new gas gun driven expansion mechanism that offers exploration of material behavior under conditions that are inaccessible with conventional drives, either with the Winter and Prestidge method or explosive/electromagnetic drive. The aims of the new experimental geometry were as follows:

- Uniform radial expansion at a strain rate of $\sim 10^4 \text{ s}^{-1}$.
- Field multiple velocimetry and high speed imaging diagnostics simultaneously.
- Reduce effects of the drive mechanism on the material properties.
- Control of sample temperature without affecting the driving process.

To address the need to perform experiments at high temperatures, the polymeric insert has been replaced with a material that does not undergo appreciable softening within the regime of interest ($100 \leq T \leq 1000 \text{ K}$). Additionally, using a material with a good thermal conductivity provides flexibility to use the insert to introduce temperature control of the sample. Using a high strength material able to maintain shape under impact at these temperatures transfers the drive wholly to the projectile. In order to achieve the desired strain rates, as much radial momentum as possible needs to be imparted by the projectile to the cylinder. This requires moving away from the conventional style flat-ended insert and projectile. By employing an unmatched shaped pair to create a radially dependent impact time, the resulting shock front is redirected towards the inner cylinder wall. With this geometry, there is now only one material driving the cylinder wall reducing the chance of an instability such as in the case where two polymers are flowing as in the conventional technique.

This method becomes unique in that the part which drives expansion (now the projectile) is isolated from the sample until the experiment begins. With all other methods the driver material, be it explosives, an electromagnetic coil or the polymers as used currently in gas gun driven expansion, must also be heated to the desired sample temperature. A series of simulations were used to examine the performance of different shaped inserts and projectiles.

III. NUMERICAL MODELLING

Simulations were performed in the commercial explicit analysis software Ansys AUTODYN v13 (Ref. 34) on cylinders of 6061-T6 aluminium and Ti-6Al-4V. The features of interest were the radial strain rate generated and the expansion profile along the cylinder for a given geometry and projectile velocity. A 3D quarter symmetry Lagrangian mesh was used with a mesh convergence study showing a cell size of $200 \mu\text{m}$ to be adequate for these observations. Where possible the mesh was configured as such to produce a uniform cube cell structure. As these initial simulations presented here were not concerned with late-time phenomena such as localization and fracture, failure models were not used. A shock ($U_s - u_p$) equation of state was used along with the Steinberg-Guinan strength model,³⁵ the parameters of which are listed in Table I. Equations (2) and (3) refer to the yield stress and shear modulus for this strength model, respectively

$$Y = Y_0 [1 + \beta(\varepsilon + \varepsilon_i)]^n \times \left[1 + \left(\frac{Y'_P}{Y_0} \right) \frac{P}{\eta^{1/3}} + \left(\frac{G'_T}{G_0} \right) (T - 300) \right], \quad (2)$$

where Y is the yield stress, β is the hardening constant, ε is the effective plastic strain ($i = \text{initial}$), n is the hardening exponent, P is pressure, η is the change in specific volume (compression), G is the shear modulus, and T is temperature. Primes refer to the derivative with respect to the subscript and the subscript 0 to the reference state where $T = 300 \text{ K}$, $P = 0$, $\varepsilon = 0$

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

To reduce computational time, not all of the experimental setup was recreated in the model; any hardware for mounting the cylinder or the diagnostics and the main sabot body used to launch the projectile were omitted. To validate this, a direct comparison with these parts included was run with no resolvable effect on the simulation outcome.

A. Geometry refinement

Conical and hemispherical steel inserts with respectively shaped polycarbonate projectiles were evaluated at impact

TABLE I. Cylinder material equation of state and strength model parameters.

Shock equation of state parameters: $U_s = C_0 + su_p$								
Material	Initial density, ρ_0 (kg m ⁻³)		Bulk Sound Speed, C_0 (mm μ s ⁻¹)		s		Grüneisen Γ	
Al 6061-T6 (Ref. 36)	2703		5.24		1.400		1.97	
Ti-6Al-4V (Ref. 36)	4419		5.13		1.028		1.23	
Steinberg-Guinan strength model parameters								
Material	Shear modulus, G_0 (GPa)	Yield stress, Y (GPa)	Max yield Stress (GPa)	Hardening Constant, β	Hardening Exponent, n	G'_p	G'_T (GPa K ⁻¹)	Y'_p
Al 6061-T6 (Ref. 36)	27.6	0.29	0.68	125	0.1	1.8000	−0.01700	0.018909
Ti-6Al-4V (Ref. 36)	41.9	1.33	2.13	12	0.1	0.4819	−0.02698	0.015300

velocities around $700\text{--}1000\text{ m s}^{-1}$. While changing the insert shape eliminated the discontinuity between the materials driving the expansion and the resulting premature failure of the cylinder, the expansion profile was found to be unsatisfactory. Insufficient momentum was transferred radially, meaning the deformation region of interest would quickly transfer along the cylinder length. Instead of this region being in the state of uniform tensile hoop stress desired there was a dominating longitudinal stress. Results were improved by increasing the radius on the face of the projectile and elongating the insert. The optimized geometry to generate radial strain rates on the order of 10^4 s^{-1} was found to be a tangent ogive insert, shown in Figure 2. This is paired to a projectile with a concave impact face of constant radius. By increasing the length of the insert towards an ogive shape, the impact occurs on axis and further contact between the projectile and insert is delayed. The initial shock wave produced at impact is continuously supported and diverted towards the inner cylinder wall as the projectile moves further into the sample. There are three dimensions that can be used to scale this design to any diameter: the ogive and base radii of the insert and the radius of the concave face of the projectile (r_{ogive} , r_{base} , and r_{proj} , respectively, in Figure 2). The optimum dimensions were found to be when the base:ogive radii are 1:1.5 and base:projectile radii are 1:2.

B. Expansion simulations

Simulations were run using 6061-T6 aluminum and Ti-6Al-4V cylinders, 30 mm inner diameter and 2 mm wall thickness. Figure 3 shows the geometry of the model with the material locations followed by a series of pressure contour plots. For these images, the projectile velocity was 900 m s^{-1} . Time after impact is defined as the time after the initial impact between the concave face of the projectile and the tip of the ogive. The first contour plot at $1\text{ }\mu\text{s}$ demonstrates this is along the axis of symmetry. As the projectile progresses, there is further collision between the radiused faces of the projectile and ogive. This delayed

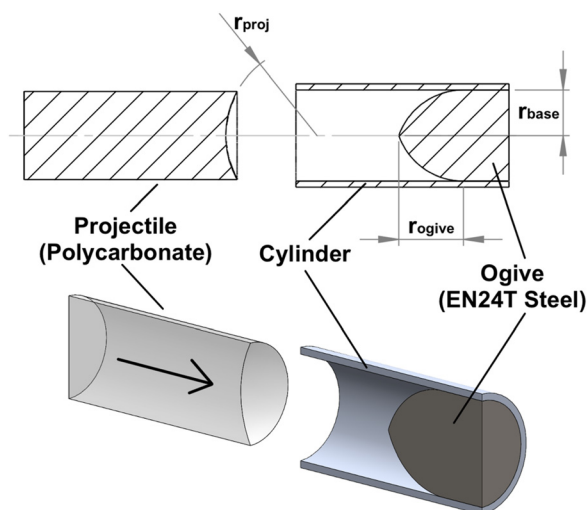


FIG. 2. Cross section of the ogive based expansion geometry. Projectile travels left to right.

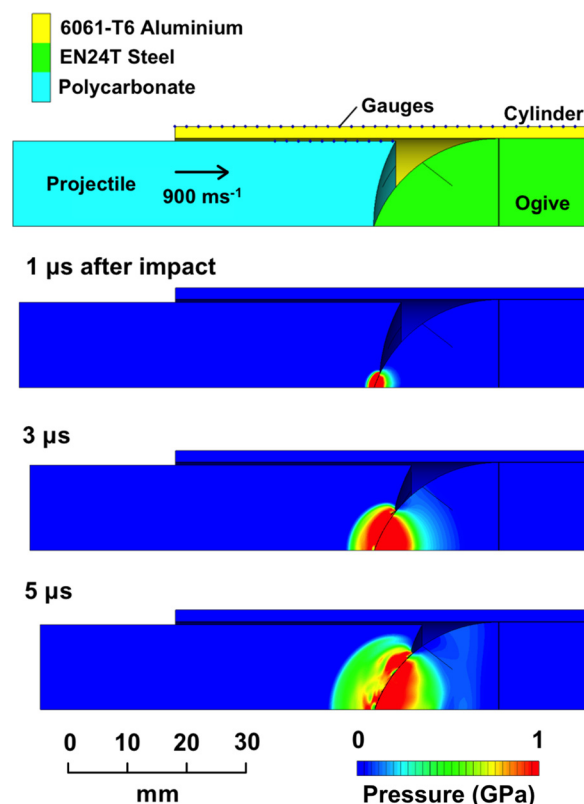


FIG. 3. 6061-T6 aluminum model, 30 mm inner diameter cylinder. Top: Material and gauge locations (dark blue diamonds). Bottom: Generation of radial shock wave in projectile.

contact continuously supports the initial radial stress wave generated at impact, broadening the wave along the cylinder. Later in time, the wave is approaching normal to the cylinder wall and when the wave reaches the outer surface of the projectile covers a length of around 10 mm. This wide region made possible by the use of the two unmatched radii on the projectile and ogive provides a large area of uniform expansion.

To measure the expansion velocity gauges (points that move with the node they are assigned to) were placed along the length of the outer surface of the cylinder on a 2 mm spacing, shown as blue diamonds in Figure 3. Gauges were also placed on the outer surface of the projectile to track movement and the time of impact on the inner cylinder wall. A series of simulations were run where the initial projectile velocity ranged between $400\text{ and }1200\text{ m s}^{-1}$ for cylinders of 6061-T6 aluminum and Ti-6Al-4V. From these gauge data, a plot of peak radial strain rate with projectile velocity was generated and shown in Figure 4.

A clear linear relationship is observed between the projectile velocity and the predicted peak radial strain rate generated in the expansion region. For the aluminum, a doubling of impact velocity almost exactly doubles the resulting strain rate. At a given projectile velocity, the predicted strain rate is lower in the Ti-6Al-4V than the 6061-T6 aluminum due to the titanium exhibiting higher strength. These simulations provided indication of what projectile velocities to use and assisted in timing diagnostics when experiments were performed.

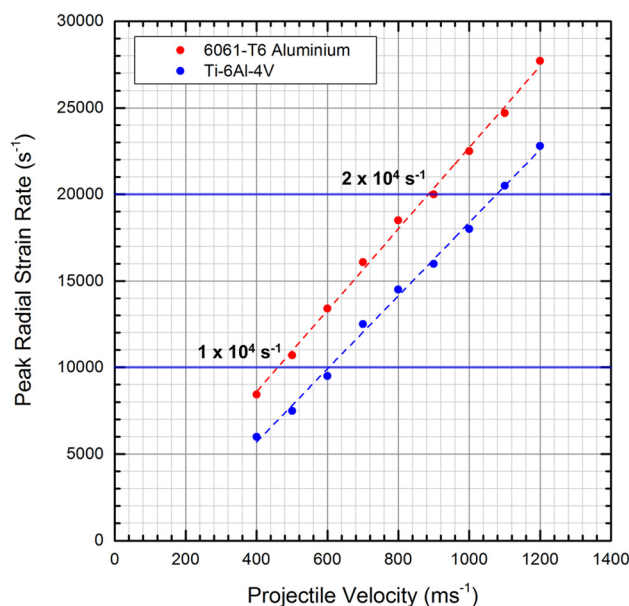


FIG. 4. Results from simulations of a 30 mm inner diameter, 2 mm wall cylinder in 6061-T6 aluminum and Ti-6Al-4V showing the effect of projectile velocity on the peak radial strain rate produced in the cylinder. Strain rates of 1×10^4 and $2 \times 10^4 \text{ s}^{-1}$ are highlighted.

IV. EXPERIMENTAL VALIDATION

Experiments were performed using this geometry on two materials: 6061-T6 aluminum and Ti-6Al-4V. Sections IV A–IV C discuss the planning and execution of these experiments; the primary aims being to determine the behavior of the polycarbonate, steel ogive, and cylinder material to validate simulation data for use in future experimental design. Laser based velocimetry alongside high-speed imaging (both optical and flash X-Ray radiography) was used to capture key data such as expansion velocity, strain rate, strain at fracture, and the expansion profile. Due to the differences in the mounting systems and scale of the gas guns used, issues such as aligning the cylinder to the gun barrel and diagnostic location are discussed in their respective sections. All times stated in the experimental results are taken as time after impact on the axis defined as the point where the concave face of the projectile reaches the tip of the ogive.

For all experiments, the projectile was made of PC1000 polycarbonate and the ogive insert was machined from EN24T (4340) steel (Fig. 5). The dimensions for the components followed the optimum ratio found in the modelling results. The diameter of the projectile shaft was slightly undersized compared with the cylinder inner diameter by 1 mm. This ensured that any small concentric misalignment did not result in the projectile impacting the cylinder end which would cause serious damage to the barrel and target tank and that the projectile was deforming plastically when it reached the inner wall of the cylinder.

The ogive only needs to be securely located in the cylinder for the purposes of target setup and alignment. During the impact, there is no mechanical reason for the ogive to be held by the cylinder. If the cylinder is bonded to the ogive simulations predicted that a trapped jet of polycarbonate

would puncture the cylinder at this join, prematurely ending the uniform expansion. For this reason, the ogive is a close sliding fit in the cylinder and either very lightly bonded with a bead of epoxy on the join at the rear or gripped with a trio of small grub screws, enabling the cylinder to “peel away” from the ogive as it expands. Modifications to the basic ogive insert were to hollow the rear cylindrical part, reducing the mass. This assisted alignment by reducing the moment of the ogive on the length of the cylinder as well as providing space for temperature control systems. Finally, a small hole (2 mm) drilled fully through the insert along the axis was found to have negligible influence on the expansion behavior. This hole can be used for concentric alignment of the cylinder to the barrel while also providing means of mounting a probe for measurement of projectile velocity or time of impact.

A. 6061-T6 aluminum—flash X-ray radiography

A series of experiments were completed using cylinders machined from solid rod stock 6061-T6 aluminum. These had an inner diameter of 30 mm and a wall thickness of 2 mm, with an ogive and projectile radii of 22.5 mm and 30 mm, respectively. A sample was taken from the aluminum and etched to reveal an equiaxed grain structure in the plane parallel to the cylinder diameter. Work was completed using the 50.8 mm bore helium single-stage light gas gun at the Dynamic Response Group, Cranfield University. This facility has the capability to employ flash X-ray radiography enabling observation of the interaction between the projectile and the cylinder. The 65 mm long projectile was mounted concentrically on the front of a 50.8 mm diameter sabot. A metal ring was machined onto the leading edge of this main sabot for triggering of the X-ray heads and projectile velocity measurement with pairs of make pins. The cylinder had a flange at one end which was bonded onto the target mounting system on the end of the gun barrel (Figure 6, center).



FIG. 5. Left to right: Ogive, projectile, and Ti-6Al-4V cylinder as used in Sec. IV B. Threaded section at the top of the projectile is used to attach it to the sabot.

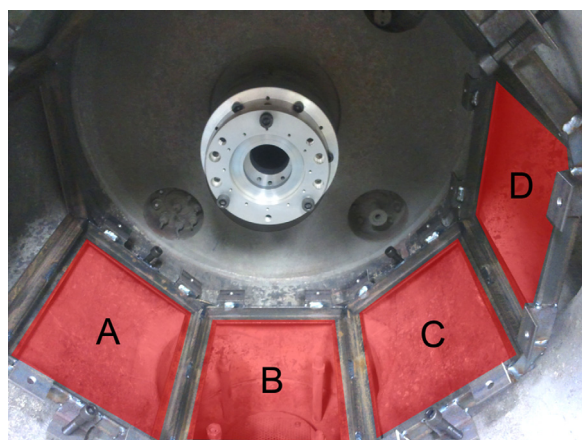


FIG. 6. Target mounting ring (center) and location of the four X-ray cassettes (A-D) in the Cranfield light gas gun target tank. Cassettes are 18×24 cm.

The gas gun target chamber has four 300 kV X-ray heads mounted externally at 45° to each other, with the corresponding film cassettes labelled A-D in Figure 6. The accelerating potential was adjusted to enhance contrast between the cylinder wall, projectile, and ogive. Optimum contrast with 400G screens and HDC-G film was between 20 and 30 kV. The heads were individually triggered to obtain a temporal history. In one experiment, pairs of orthogonal heads were triggered simultaneously to verify uniform expansion symmetry.

1. 6061-T6 aluminum—experimental results

A series of five identical cylinders were impacted with an average projectile velocity of $(915 \pm 45) \text{ m s}^{-1}$. This value was chosen to ensure that a radial strain rate of at least 10^4 s^{-1} was achieved based on simulation results in Sec. III B. Figure 7 shows a time sequence of the expansion process over a total of $45 \mu\text{s}$ with a selection of the radiographs collected from these experiments. The projectile enters the frame from the left with the ogive at right clearly visible for reference. The timings for the images were chosen to correspond with development of interesting features in the simulations. At $9 \mu\text{s}$, the polycarbonate projectile has started to deform around the insert; however, there is not yet contact along the full length of the ogive face. The projectile has expanded to meet and initiate radial movement of the wall. At $14 \mu\text{s}$, expansion is clearly evident. The next image at $20 \mu\text{s}$ demonstrates that the polycarbonate is flowing further around the insert and voiding (highlighted red) between the projectile and cylinder is occurring. The region of the cylinder where this void appears is now in free expansion and rapidly approaches a purely tensile stress state, the cylinder having been “kicked” into expansion. By $34 \mu\text{s}$, these voids are much more pronounced and there is evidence of fracture in the lower part of the frame. The ogive has started to eject from the rear of the cylinder. The separation of the cylinder from the ogive ensures that there is no jetting caused by trapping the polycarbonate and the fit is sufficient to locate the ogive long enough to initiate expansion. At $45 \mu\text{s}$, considerable radial strain has accumulated and cracks along the

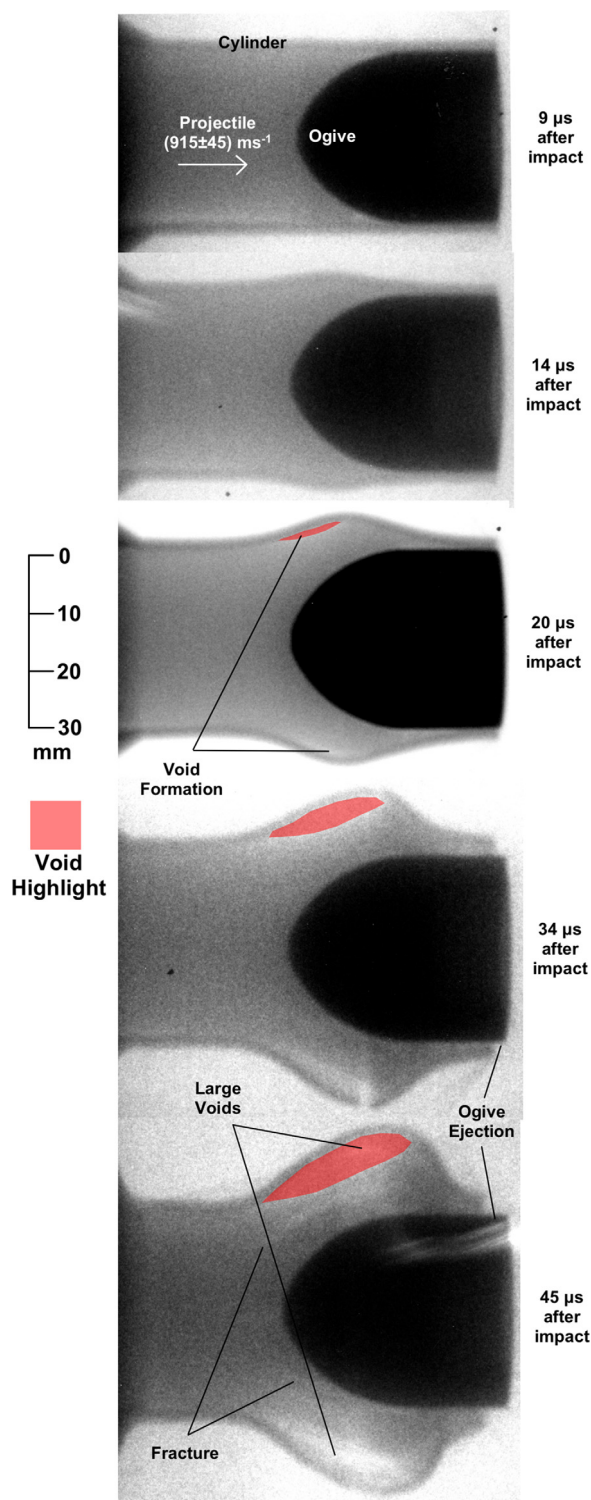


FIG. 7. X-ray radiographs, 6061-T6 cylinder. The upper void formations are highlighted red for clarity.

length of the cylinder become visible. Over the whole sequence, it is evident that the expansion is highly symmetric about the axis (this sequence is composed of radiographs obtained from multiple orientations around the cylinder). The peak of the expansion is translating along the axis slightly (~ 8 mm over the entire sequence shown) due to the momentum in the polycarbonate and the weakening of the cylinder as fracture occurs longitudinally. From simulation

and experimental data, it is seen that this voiding and translation behavior is dependant on the strength of the polycarbonate and the cylinder material—the Ti-6Al-4V cylinder in Sec. IV B retained the “bell curve” expansion shape until considerable fracture had occurred. For all experiments, the ogive was recovered intact with the tip being slightly deformed (length was reduced by <1 mm).

The radius of the expansion region peak has been extracted from the X-ray images, shown in Figure 8. The peak was measured and compared with an undeformed region to determine deformed diameter. Errors are a result of needing several pixels for edge detection after digitization of the X-ray films and jitter in the timing of the X-ray heads. The plot compares the X-ray data with the peak radius taken from the AUTODYN simulation in Sec. III B. From $25 \mu\text{s}$ onwards, the experimental and simulation curves diverge. This is due to no failure model being implemented and the simulation cylinder retaining strength causing deceleration of the expansion region, whereas the experimental data show that fracture has occurred between by $34 \mu\text{s}$. The maximum average radial strain rate was measured as $\dot{\epsilon}_r = (2.2 \pm 0.2) \times 10^4 \text{ s}^{-1}$ using the average radial velocity and average radius between X-ray frames, showing strong agreement with the rate predicted in Figure 4.

B. Ti-6Al-4V—high-speed imaging and velocimetry

Experiments were also performed on cylinders of Ti-6Al-4V (% by weight). Cylinders were machined from solid rod stock with the cylinder axis along the extrusion direction. Samples of the same raw stock have been retained for further characterisation work such as microstructure analysis, Taylor tests, and plate impact experiments. Inner diameter was 50 mm with a 4 mm wall, $\sim 70\%$ larger than the 6061-T6 cylinders. The aim was to validate this experiment for larger cylinder diameters with future plans to investigate

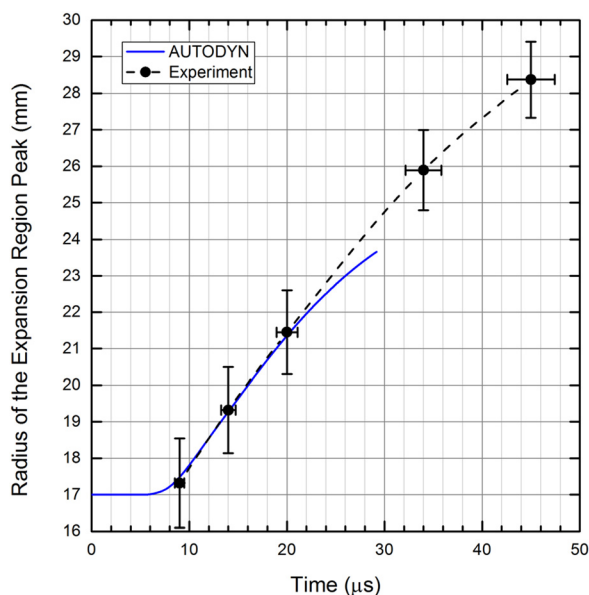


FIG. 8. Radius of the peak of the expansion region extracted from the X-ray radiographs (points) compared with results from AUTODYN simulations (line) for the 6061-T6 experiments.

the fracture and fragmentation behavior of this material at high and low temperatures. These experiments were performed on the 100 mm bore helium driven single-stage gas gun at the Institute of Shock Physics, Imperial College (ISP). The large diameter (2 m) target tank of this gun enabled simultaneous use of two high-speed imaging systems and multiple Photon Doppler Velocimetry (PDV) channels, both standard³⁷ and frequency-shifted.³⁸ A 5 m long catch can enables soft recovery of the cylinder fragments. The larger sample size and the higher strength of the titanium necessitated more energy being delivered to the target to attain a strain rate of 10^4 s^{-1} to compare with the 6061-T6 aluminum work. The same geometric ratios described in Sec. III A were used with a projectile velocity of 1000 m s^{-1} .

For accurate expansion velocity measurement, a frequency shifted PDV system was used. This is an interferometer based optical technique where a 1550 nm laser is coupled into a fiber and delivered via a probe to the measurement surface. The Doppler-shifted reflected light is collected back into the probe and interfered with a reference laser of a slightly different frequency. The lasers used were an IPG Photonics ELR-2-1550-LP-SF and an NP Photonics Rock Source yielding a zero velocity beat frequency of $\sim 4.9 \text{ GHz}$ which increased with surface motion towards the probe. The resulting time-varying beat frequency was measured using a Miteq DR-125G-MV 13 GHz photodetector and 16 GHz Tektronix 71604 oscilloscope sampling at 50 GS s^{-1} . A sliding short time Fourier transform was applied to the raw signal according to the method described by Dolan³⁹ using a 100 ns window with 75% overlap and a Hamming filter to reduce the velocity history.

An aluminum ring was bonded to the leading edge of the main sabot to provide a reflective surface to measure projectile velocity with a PDV probe. The velocity probe can be seen in Figure 9 as the white fiber at the top of part 2. The ring also provided an electrical short for triggering all diagnostics and another measurement of velocity with three pairs of make pins. Radial expansion velocity was measured with four channels of frequency-shifted PDV. A modular mounting system has been designed to place the probes in two configurations with minimal obscuring of the high-speed cameras' field of view. The probes can be deployed along the length of the cylinder as in this experiment (Figure 9, part 3) where the data can be used to calibrate high-speed imaging data to provide the expansion velocity at any point along the cylinder. The probes could also be mounted in a “halo” configuration around the cylinder at a chosen length along the sample to check the axial symmetry of the expansion. As the cylinder expands, the surface will move away from normal to the probe. Once the surface has rotated sufficiently that the reflected beam no longer returns into the probe, the velocity signal will be lost. This effect is amplified by wanting a long record of radial velocity, up to failure strain which is usually $>10\%$. For a cylinder of this size, measurement to fracture over a large axial length can be on the order of $100 \mu\text{s}$. The deflection away from normal increases with distance between the probe and the sample.

As this experiment will be run with the cylinder at temperatures approaching 1000 K, the PDV probes and fibers

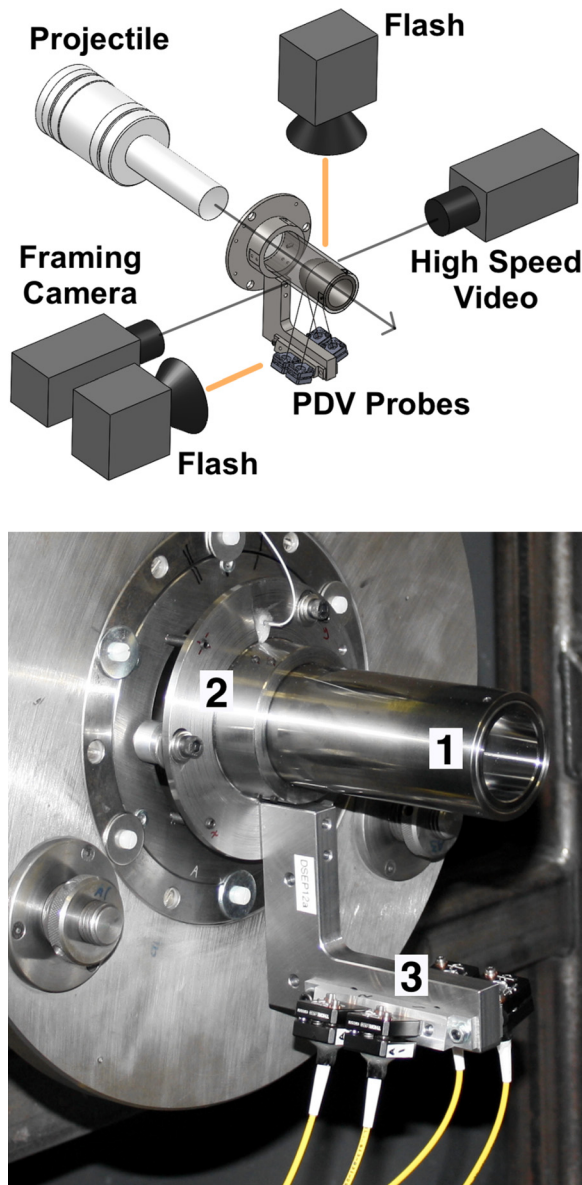


FIG. 9. Ti-6Al-4V expanding cylinder experiment. Top: Diagnostic configuration. Bottom: Target mounted in the ISP 100 mm gun tank. (1) Cylinder and ogive. (2) Alignment and mounting sleeve. (3) PDV probes and kinematic mounts. Gun barrel is to the left of the image.

must be well away from the cylinder to avoid damage from the high temperature. To avoid this deflection problem probes were ordered from OZ optics using a 7.2 mm diameter lens, producing a $200\text{ }\mu\text{m}$ spot with a 100 mm focal length. To maximize the working distance, the probes were placed 105 mm from the outer cylinder wall. The cylinder (Figure 9, part 1) was mounted in a sleeve (2) which in turn attached to the mounting ring on the gun. The probes were bonded into kinematic mounts placed on a large L bracket (3) fitted to the sleeve. This means that the main probe alignment could be completed before the experiment with low power lasers. Once mounted in the gun, only a fine final adjustment was necessary. The kinematic mounts were staggered to enable closer spacing of the probes along the length. The mounts were angled at 15° to ensure that the beam was normal to the cylinder surface. The surface was lightly polished while still on the lathe to assist in as much laser light

returning to the probe as possible; the power delivered to each probe was 5 mW. Alignment of the cylinder to the gun barrel was via the mounting sleeve (part 2, Figure 9). Three M6 bolts held the sleeve to the gun through oversized holes providing concentric adjustment. Belleville washers are used on these bolts to allow slight tilting of the sleeve controlled by three grub screws replicating a kinematic mount to ensure that the cylinder and barrel axes were aligned. A barrel plug with a spigot matching the cylinder inner diameter was used as a reference for alignment.

The imaging diagnostics (Figure 9, top) consisted of a Phantom v7.3 high-speed camera and an Invisible Vision UHSi-24 framing camera. Two Bowens Gemini flash units were used for lighting. The gun has three ports at the 3, 9, and 12 o'clock position. One flash unit (1000 W) was placed on the top port. Through one side port was the framing camera and other flash (1500 W) to track the strain at which localization and failure occur in the cylinder. The Phantom was placed at the other side port to take a silhouette of the cylinder enabling calculation of strain and strain rate along the whole cylinder in addition to checking the symmetry in one plane.

1. Ti-6Al-4V experimental results

Figure 10 shows the PDV data for a Ti-6Al-4V cylinder experiment with a projectile velocity of 996 m s^{-1} . The axial location of each of the four PDV probes is shown with a cross section of the cylinder for comparison of probe location with the ogive insert. Experimental data are shown by a solid line, where the dashed lines are radial velocity for the same point taken from an AUTODYN simulation. The simulation used the material properties in Sec. III. A $200\text{ }\mu\text{m}$ mesh was used and no material failure model was included.

The agreement between experiment and simulation for probes B and C is good with the model capturing some of the more subtle features such as oscillation of the radial stress wave in the cylinder wall between 26 and $30\text{ }\mu\text{s}$. While the overall profile of the velocity trace for probes A and D matches the experiment, the timing of events disagrees by around $1\text{ }\mu\text{s}$. However, as these probes are either side of the initial region of interest they are less important to strain rate prediction. The overall shape of the expansion closely matches the high-speed imaging data. From $35\text{ }\mu\text{s}$ onwards, the simulation and experimental data for probes B and C begin to diverge. The simulation predicts a stronger deceleration in the radial velocity. From analysis of the high-speed imaging data, it is known that this is around the time when strain localization begins to appear on the outer surface of the cylinder suggesting failure initiation. As there is no failure model implemented, the model is retaining strength resulting in this larger deceleration of the cylinder wall.

The PDV data were used to calculate radial strain rate by integrating the velocity data to give radius as a function of time and using Eq. (1). The peak radial strain rate before fracture was measured at $0.98 \times 10^4\text{ s}^{-1}$ by probe C at $34\text{ }\mu\text{s}$.

Figure 11 shows images from the framing camera at 45 and $55\text{ }\mu\text{s}$ after impact. The expansion has a clearly symmetric bell curve shape around the peak radial strain. At $45\text{ }\mu\text{s}$

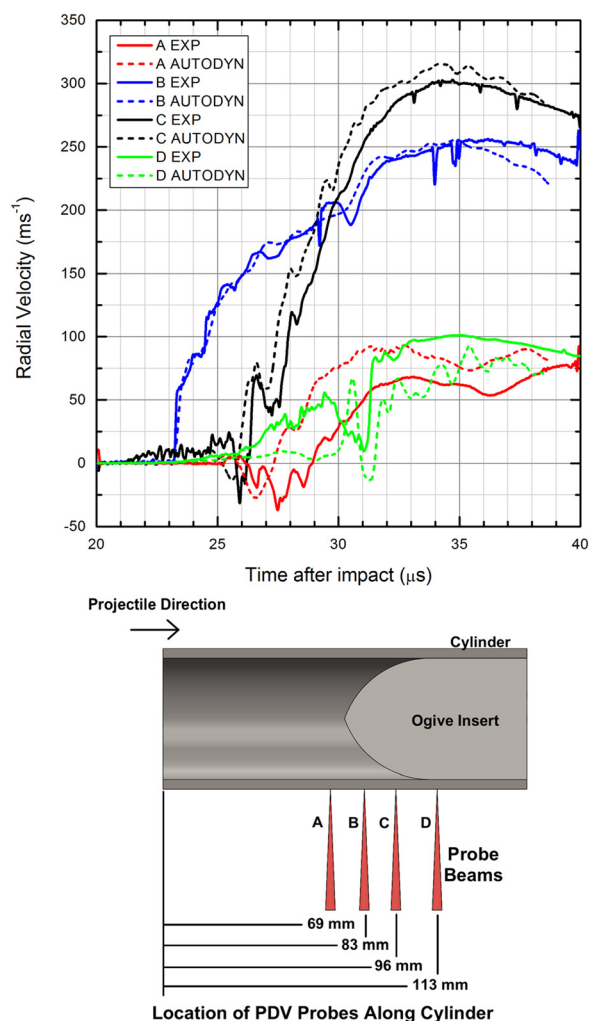


FIG. 10. Radial velocity data for an expanding Ti-6Al-4V cylinder, projectile velocity 996 m s^{-1} . Solid lines are experimental data, dotted are simulation. Bottom: Probe location along the length of the cylinder.

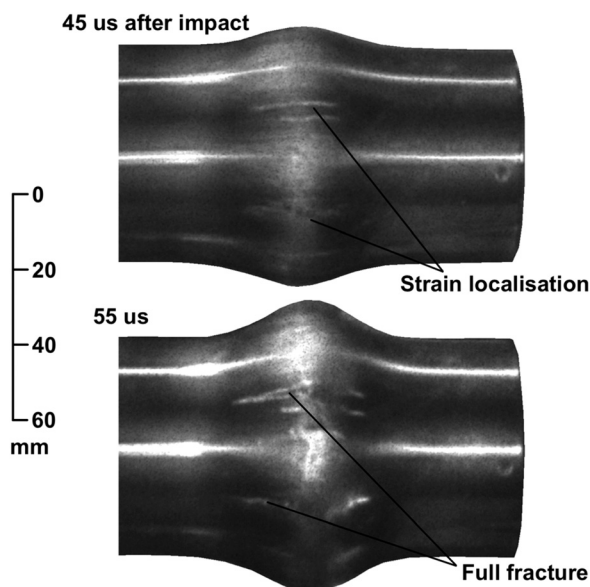


FIG. 11. Images taken at $45 \mu\text{s}$ and $55 \mu\text{s}$ after impact at 996 m s^{-1} (left to right direction) for a Ti-6Al-4V cylinder. Strain localization is evident on the cylinder surface at $45 \mu\text{s}$ which has developed into full fracture by $55 \mu\text{s}$.

there is evidence of strain localization on the outer surface of the cylinder, which proceeds though to full fracture by $55 \mu\text{s}$. Once the cylinder has weakened through failure in this region the longitudinal (along the length) cracks converge until the cylinder has failed around the circumference, separating it into two lengths. The strips of material left by this longitudinal fracture then peel away from the cylinder axis. Probe D demonstrates that after failure the material downstream of the bifurcation point is then further accelerated by the flowing polycarbonate at a velocity in excess of the original expansion velocity (470 m s^{-1} compared to $\sim 300 \text{ m s}^{-1}$). Sixty-three percent of the original mass of the cylinder was recovered. A plot of the fragment mass distribution is shown in Figure 12. The average fragment had a mass of 7.12 g and a length/width factor of 1.80 . The distribution shows several large fragments (the largest being 9% of the original mass) with the main contribution to the total coming from fragments weighing 7 to 15 g (1.6%–3.3%). Fragments exhibited sharp lips at 45° to the radius, indicative of ductile failure along the planes of maximum shear as the authors have seen in the same material under explosive loading.⁴⁰ The material unaccounted for was lost into the momentum trap system, fragments becoming embedded into the rags used. Future work will use a recently developed capture system that allows for recovery of the fragments around the cylinder, providing insight into the spatial distribution.

Figure 13 shows a composition of the data obtained from a Ti-6Al-4V cylinder experiment. The plot consists of the data from the four probes, showing radial velocity and the time at which 10% and 20% radial strain is reached for each point. Overlaid onto the time vs. position plane are profiles of the cylinder taken from the high speed imaging systems for a qualitative demonstration of the evolution of the expansion process. The tip of the ogive is located 75 mm into the cylinder. It is clear from Figures 10 and 13 that movement of the outer cylinder wall initiates at around 85 mm (closest to probe B). An area between 80 mm and 100 mm along the

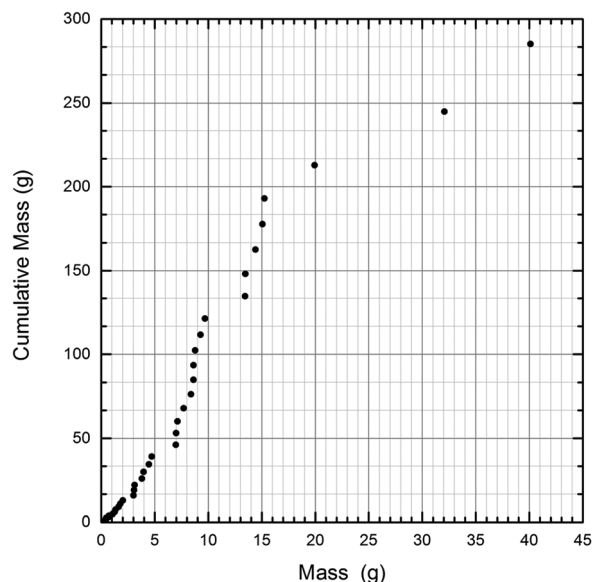


FIG. 12. Fragment distribution for a Ti-6Al-4V cylinder, 996 m s^{-1} projectile velocity; 63% mass recovered.

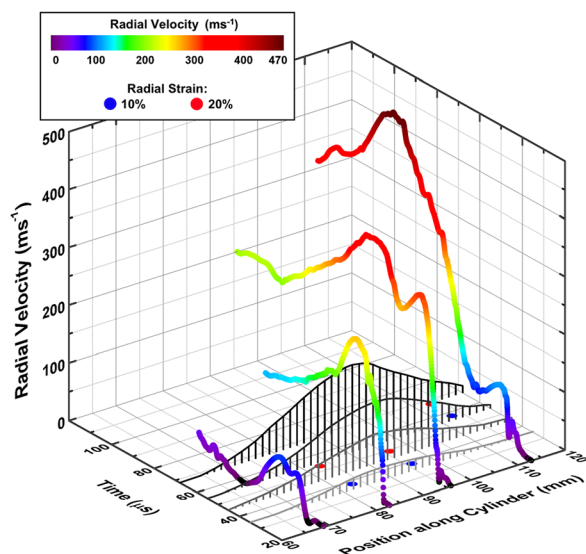


FIG. 13. Velocimetry data of an expanding Ti-6Al-4V cylinder (50 mm inner diameter, 4 mm wall thickness, 996 m s^{-1} projectile) from the 4 PDV probes (A-D) with times for each probe location to reach 10% and 20% radial strain. Four cylinder profiles taken from the framing camera to provide a qualitative demonstration of the expansion shape.

cylinder initially experiences a uniform expansion, reaching 10% and 20% radial strain at very similar times ($38 \mu\text{s}$ and $\sim 50 \mu\text{s}$, respectively). This area accelerates to a radial velocity between 250 m s^{-1} (B) and 300 m s^{-1} (C) in $10 \mu\text{s}$.

C. Summary of experimental results

The new ogive based expansion geometry has been used on two materials, 6061-T6 aluminum and Ti-6Al-4V. Two size cylinders were used (inner diameter of 30 mm and 50 mm in aluminum and titanium, respectively) with the same geometric ratios $r_{\text{base}} : r_{\text{ogive}} : r_{\text{proj}}$ of 1:1.5:2. The use of this geometry has been shown to drive uniform radial expansion with no scaling effects and validated using velocimetry, high speed imaging, and flash X-ray radiography data. Strain rates on the order of 10^4 s^{-1} were attained in both series of experiments. The expansion profile was favorable in both materials to create a state where hoop stress dominates once the initial radial wave from the projectile impacting the inner cylinder wall has damped out.

The geometry lends itself to employment of several diagnostics simultaneously enabling a large amount of data to be collected per shot. The PDV setup can be installed outside of the target tank, with only a final adjustment needed once the cylinder is aligned to the barrel. The desired strain rate can be achieved through a combination of selecting cylinder diameter or projectile velocity depending on the application. The problems identified with the classical right-cylinder polymer insert have been overcome and the new geometry opens doors to experimentation at states other than room temperature.

V. TEMPERATURE CONTROL

As mentioned from the offset, to expand the application of this gas gun based technique the aim is to control the temperature of the sample cylinder prior to impact, both heating

and cooling over a range on the order of $100 < T < 1000 \text{ K}$. Temperature control is an area where the gas gun drive is superior to high explosive or electromagnetic drive. There are obvious issues with explosive degradation or even detonation if one was to heat a filled cylinder, for example, RDX has an autoignition temperature of 470 K .⁴¹ Although feasible on an electromagnetic drive experiment, it would be difficult; no metallic materials can be placed between the drive coil and the sample without disturbing the uniformity of the magnetic drive. Any form of heating coil placed on the outside of the sample will obstruct diagnostics. Gust⁴² performed work on heated (up to 1235 K) samples in a reverse-Taylor impact configuration. For this, three high intensity halogen lamp based parabolic furnaces were arranged around the target; however, the sample size was only 6 mm diameter by 30 mm length. The amount of lighting needed to heat a cylinder on the 100 mm gas gun would severely obscure the PDV and camera diagnostics.

The ogive insert has the advantages of being able to withstand and operate at extremes of temperature while also being hollow at the rear; providing space that can be used for temperature control apparatus. A series of experiments are planned using the same geometry as the Ti-6Al-4V cylinder presented in Sec. IV B. For temperatures up to $\sim 1000 \text{ K}$, a Macor spindle is machined to bolt into the insert. Around this spindle is placed a coil of nichrome wire. A high current power supply (60 A) is used to resistively heat the coil, which transfers heat to the insert and the surrounding cylinder. For work from cryogenic temperatures up to ambient, the insert is sealed with an aluminum cap and PTFE O-ring. This cap has two pipe fittings that are used to flow liquid nitrogen or a cooled gas through the insert thus lowering the temperature in the cylinder. These methods of temperature control both have the advantage that there is nothing surrounding the sample cylinder so no change to the diagnostic placement is needed and there is still the possibility to observe the whole

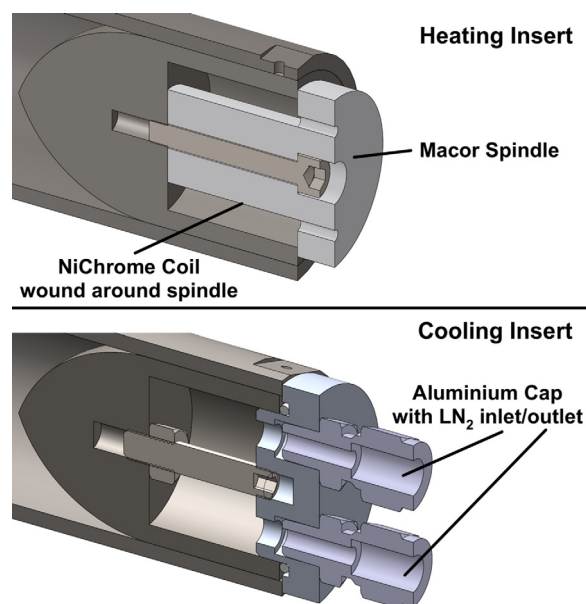


FIG. 14. Adapted ogive insert for temperature control. Top: Heating insert with NiChrome coil. Bottom: Cooling insert with liquid nitrogen feedthroughs.

circumference of the cylinder. Temperature will be recorded using thermocouples placed at each end of the cylinder to track the temperature control profile and ensure a minimized temperature gradient along the cylinder prior to firing. A schematic of the two inserts for temperature control is shown in Figure 14.

VI. CONCLUSIONS

The aim of this work was to develop a technique to drive cylinders into expansion using a gas gun that improves the drive mechanism and facilitates experimentation in regimes other than standard room temperature. The issues identified with the classic right-cylinder polymer insert and projectile technique are that two materials are driving the expansion and that the interface between these materials is in contact with the cylinder inner wall. This can lead to flow instabilities and complicates the modelling process. The main issue for our area of interest is that the experiment only works at room temperature; at elevated temperatures, the polymer insert will melt or become brittle at low temperature.

Our solution was to develop an insert specifically designed to *not* deform, such that the projectile flows and imparts radial momentum to the sample cylinder. A steel tangent-ogive shaped insert is located in the rear of the cylinder into which a polycarbonate projectile with a concave radiused impact face is launched. Ratios for the dimensions of the ogive and projectile have been studied. The geometry here of $r_{base} : r_{ogive} : r_{proj}$ of 1:1.5:2 provides controllable, repeatable, and scalable expansion with the provision for experiments at high and low temperatures. The experimental technique has been validated with 6061-T6 aluminum and Ti-6Al-4V in two cylinder sizes at radial strain rates of 10^4 s^{-1} using single stage light gas gun platforms with no modification to the gun hardware. A large body of data concerning the behavior of the projectile and insert inside the cylinder and the resulting expansion velocity and fragmentation processes has been produced.

Numerical modelling predictions have proved to be a useful tool for prediction of the experiment and material behavior up to the time where failure initiates, results deviating from experimental data from this point on. This experimental technique combined with future work on the effect of temperature on the dynamic fracture and fragmentation behavior is expected to provide a rich supply of data for development and improvement of material understanding and failure models.

ACKNOWLEDGMENTS

The authors gratefully acknowledge continued funding and support for the project from the Atomic Weapons Establishment (AWE) and Imperial College London and would also like to thank the Dynamic Response Group at Cranfield University, Shrivenham for provision of the flash X-ray facilities, Ron Winter and Stewart Stirk of AWE for useful discussions, and the Aeronautics and Physics Mechanical Instrumentation workshops at Imperial College for sample preparation.

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