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DEVELOPMENT OF THE GAS GUN DRIVEN EXPANDING CYLINDER TECHNIQUE

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Abstract. Using a gas gun to create rapid expansion in metal cylinders to investigate fracture and fragmentation has been commonplace for the last several decades. Results from such experiments alongside data from explosive and electromagnetic expansion techniques have produced several models for fragment size and mass distributions. We present a new geometry for expansion that can be applied to cylinders at elevated & reduced temperatures whilst keeping the drive mechanism constant, enabling us in the future to experiment over a range of sample temperatures at a fixed strain rate and loading path. This new geometry has been investigated through a series of gas gun experiments employing X-ray radiography and AUTODYN simulations to reveal the deformation and failure behaviour within the cylinder.

Keywords: Fracture, Fragmentation, Expanding Cylinders, Flash X-Ray Radiography, 6061-T6 Aluminium
PACS: 46.50.+a, 62.20.mm

INTRODUCTION

Dynamic fragmentation is a complex late-stage phenomenon in shock experiments. Expanding cylinders have long been an interesting focus of fracture and fragmentation studies, with obvious military applications. Cylindrical ‘ring bombs’ were the inspiration for the first fragment distribution model: Mott’s Theory of Fragmentation [1]. This has been adjusted and improved [2, 3] to resolve issues such as the need to fit a distribution of failure strain into the model and assuming instantaneous fracture. In essence these models use the concept of a release wave propagating from a fracture point, arresting and stopping any further fracture in the section it traverses. The speed of the wave introduces a timescale and hence a limit on the number of fragments a ring or cylinder can fail into, along with the strain rate and distribution of flaws in the material.

Although these models can be adjusted to very accurately predict fragment mass, size, time of fracture etc. there is no way to predict the failure method; post-experiment observations are employed to de-

cide which model to use. Several failure methods have been observed in expanding cylinders: shear banding, void coalescence [4], brittle fracture and sheet or diffuse necking [5]. Being able to isolate a particular failure mode and analyse it over a range of strain rates and materials would enable us to develop physically-based failure models and enhance our means of predicting late-stage fragmentation.

GAS GUN DRIVEN EXPANSION

Using a gas gun to expand cylinders was developed in the late 1970s at AWE by Winter and Prestidge [6]. A metal cylinder is mounted concentric to the gun barrel, and filled halfway by a rubber / polymer. Another polymer (typically nylon or polycarbonate) sabot is then fired into the cylinder. The sabot impacts the rubber infill, where depending on the sabot and insert material one or both of them will deform, forcing the cylinder to expand. Typical radial strain rates are on the order of 10^4 s^{-1} .

Although this technique is well tried and tested there are several issues. The rubber infill can start to deteriorate and break up, possibly leading to anisotropic expansion. As we plan to run this experiment at high & low temperatures ($200 < T < 1000 \text{ K}$), the rubber will become brittle when cooled or simply melt out when heated. There has been some work into using soft metals for the insert, but this does not produce expansion as symmetrical as using polymers [7].

REVISED GEOMETRY

Our proposed solution described here uses a shaped metal insert and a polycarbonate flyer. Our aims are twofold; one to transfer as much of the axial motion in the flyer into radial and two to ensure a single material is driving the expansion. Using an ogival insert means that the sabot will impact on axis first. The resulting shockwave is launched into the sabot on axis and then starts to deflect to arrive normal to the cylinder wall. This should provide a wide region of expansion and be stable at any temperature as the sabot will be at ambient temperature, avoiding changing its material properties.

The final design is shown in figures 1 & 2. The sabot end has been radiused to exaggerate the effect of the centre of the sabot striking first. A spigotted sabot is used to reduce the cylinder's size to 30 mm ID from the gun's full 50.8 mm to enable imaging the whole experiment on the X-ray cassettes.

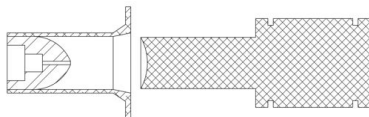


FIGURE 1. Detail of cylinder (left) with ogive insert and radiused sabot

EXPERIMENTAL METHOD

A helium single stage gas gun was used. The sabot is 50.8 mm in diameter for the main body, with a spigot 65 mm long and 29 mm in diameter. The spigot is finished with a 30 mm radius concave end. Machine

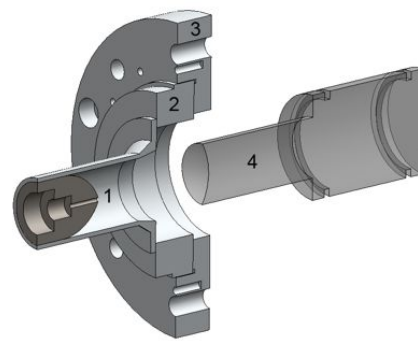


FIGURE 2. Experiment Configuration. 1: Cylinder with Insert, 2: Target Ring, 3: Mounting Ring, 4: Sabot

grade polycarbonate was used¹. The cylinder was machined from solid rod stock 6061-T6 aluminium in as received condition. A section was taken from the end of one of the cylinders revealing that the grain structure was equiaxed in the plane through the cylinder axis. The inner diameter is 30 mm, with a 2 mm wall thickness and 60 mm long along the main section. A larger flange is left on the mounting end to fix the cylinder to the gun barrel. The ogive insert is made from 4340 (EN24T) steel and has been bored out at the back to reduce weight; deflection of the cylinder due to the weight at the end was $\ll 1 \mu\text{m}$. The ogive has a 22.5 mm radius offset by 7.5 mm from the center-axis. It is designed to be a light push-fit into the cylinder with a bead of epoxy on the rear surface. Bonding the ogive in completely would mean the cylinder cannot separate resulting in a trapped jet of polycarbonate causing premature failure. There is a 2 mm hole drilled through the insert to aid alignment to the barrel and possibly fit a Het-V probe to measure sabot velocity.

The X-Ray system consists of 4 300 kV X-Ray heads mounted externally around the target tank separated by 45° on a plane normal to the barrel axis, focused roughly 90 mm from the barrel end. Each head can be fired independently enabling either a sequence of images at different times or multiple heads at once to build up a 3D image. Inside the tank is a cage designed to hold the X-Ray cassettes which are $18 \times 24 \text{ cm}$. These are shown in figure 3, highlighted

¹ Quadrant Engineering Plastic Products, PC1000

A→D. Using cassettes fitted with 400G screens and HDC-G film the heads were operated at 20-30 kV to provide good definition of the sabot and cylinder walls.

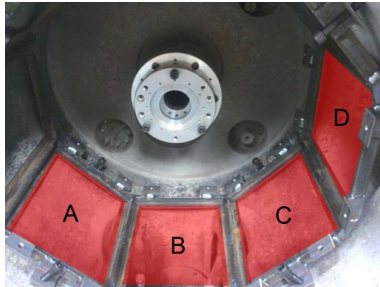


FIGURE 3. Location of the X-Ray cassettes in the gun target tank. Each cassette is 18×24 cm.

RESULTS

A series of 5 cylinders were tested. Sabot velocity was held around 900 ms^{-1} based on the results of the simulations discussed later. By offsetting the timings of the X-Ray heads for each shot we could build up a timeline of the cylinder expansion. A selection of the images are shown in figure 4. The sabot is coming in from right to left. At $5 \mu\text{s}$ after the sabot impacts the ogive, it is clear that the spigot has started to flow and has just made contact with the inner wall of the cylinder. From this instant on the cylinder plastically deforms. The expansion appears to be very symmetric about the axis - these images are taken at different angles showing symmetry is consistent around the cylinder. At $16 \mu\text{s}$ after impact, voids start to form between the polycarbonate and the cylinder, in agreement with the models. We can also see that the peak of the bulge is only slightly moving along the cylinder axis. At some point between $16 \mu\text{s}$ and $30 \mu\text{s}$ fracture has occurred. At $30 \mu\text{s}$ the void opening behind the flowing polycarbonate is becoming much more pronounced, suggesting the cylinder has been “kicked” into expansion rather than continuously pushed. In the final image at $41 \mu\text{s}$ there are clear lateral cracks opening up along the length of the cylinder. The ogive has started to move out of the rear of the cylinder, showing that the bonding method used is sufficient to keep it in place long enough to initiate expansion. Maximum radial strain rate was measured as $\dot{\epsilon}_r = (2.2 \pm 0.2) \times 10^4 \text{ s}^{-1}$.

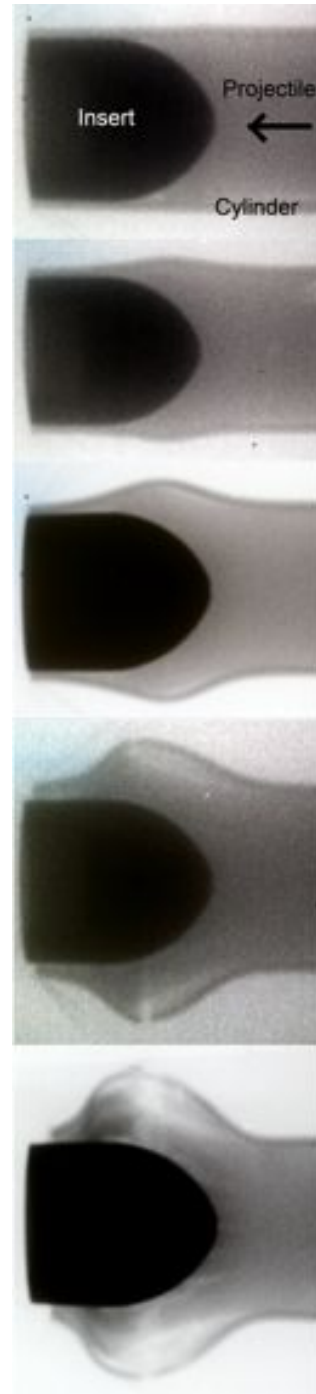


FIGURE 4. X-Ray images, 900 ms^{-1} Sabot. From top, time after sabot impact: $5 \mu\text{s}$, $10 \mu\text{s}$, $16 \mu\text{s}$, $30 \mu\text{s}$, $41 \mu\text{s}$.

MODELLING

Several geometries were modelled using Ansys AUTODYN v13. Ideas tested included conical and hemispherical inserts, with ogival ones giving the most consistent expansion. A Lagrangian mesh 3D quarter-symmetry model was used with the built in shock EOS for the 6061-T6 and polycarbonate with Steinberg-Guinan and Piecewise Johnson-Cook strength models respectively. CTH simulations were also run by the Material Modelling group at AWE. For a 900 ms^{-1} impact, the peak pressure in the cylinder wall was around 0.3 GPa with a maximum strain rate of $2.4 \times 10^4\text{ s}^{-1}$. The top image in figure 5 shows how the compression wave moves from on axis radially outwards to approach normal to the cylinder. The bottom image compares experiment and model at $30\mu\text{s}$. A void has started to form between the sabot and cylinder just behind (to the right-of) the peak of the bulge. This feature is also evident in the X-ray. Changing the strength of the polycarbonate altered (or removed) the appearance of the voids. It is also clear that the cylinder is starting to separate from the insert, avoiding jetting of the polycarbonate. The point of failure around the cylinder is also seen in the model. Overall there was a very strong correlation between the experimental and simulation data.

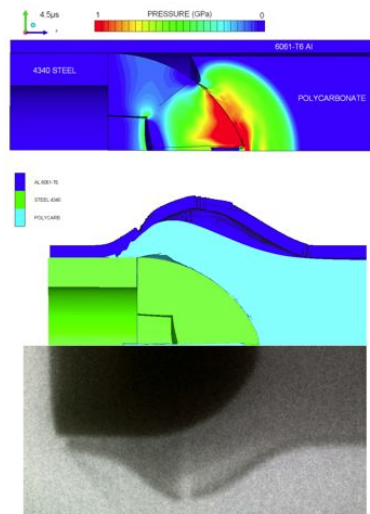


FIGURE 5. AUTODYN Simulation. Top: Pressure contours at $5\mu\text{s}$ after impact. Bottom: Comparison at $30\mu\text{s}$ after impact, showing voiding.

CONCLUSIONS

A new geometry for gas gun driven expansion of metal cylinders designed for use over a range of temperatures has been developed, modelled and tested using flash X-ray radiography, with good agreement between the models and tests. An ogival insert and concave sabot were used to expand 6061-T6 aluminium cylinders at radial strain rates of around $2 \times 10^4\text{ s}^{-1}$. Images of the expanding cylinder were taken over a range of times from initial impact up until post fracture.

Expansion was shown to be consistent with the classic polymer right cylinder geometry and provide axially symmetric expansion over a fairly wide region of the cylinder. The region of maximum deformation was shown to remain fairly static over the length of the cylinder. This constrains the deformation to 2D making analysis of stress and strain states easier and provides an excellent base for creating fragmentation at a range of temperatures. Future work will be to design a heating system and scale the experiment for the 100 mm gun at Imperial using VISAR, high-speed imaging and fragment recovery.

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