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THE DESIGN AND PERFORMANCE OF ANNULAR EFP'S

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A charge resulting in an Explosively-Forged Projectile in the shape of a short thin-walled pipe was designed using a finite difference code. The liner (OFHC copper) was in the form of a contoured washer with variation in thickness. The outer rim was designed to have a forward inclination and to be significantly thinner than the inner rim, with the result that the outer rim folded forward and downward ahead of the inner rim. The charges were manufactured, and tests proved that their performance was satisfactory, with little reduction in penetration up to 90 calibers stand-off. The final shape of the EFP approximated that of an annulus with the diameter of the inner rim of the liner. Its length was about a 1/3rd of its diameter.

INTRODUCTION

Some warheads are not sufficiently robust to withstand the shock of an encounter with a thin outer wall of a target, and would benefit if a large enough hole had been punched out of the wall by a precursor charge prior to impact by the main warhead. Ways to achieve this were investigated in a technology exercise by designing and testing a sub-scaled cutting charge that produces a copper projectile in the form of an annulus. A similar charge has been described by [1], where its use as a safe demolition charge was studied.

The work by [1] was repeated as a first step. In this, the finite difference code Autodyn™ was used to design a charge that would result in the deformation of a copper liner to a cup shape with the rim of the liner folding in behind the central portion. The evolution of the liner is depicted in Fig 1. Charges were manufactured to this design and tested. The scaled results were on par with those obtained by [1]. A flash X-ray image of the deformed liner at a late stage is included in Fig 1. As can be gauged from the figure, this charge will have a satisfactory performance over only a small standoff range (in this case in the region of 8 cm) due to the divergence of the nose of the cup and the convergence of the rear towards the axis.

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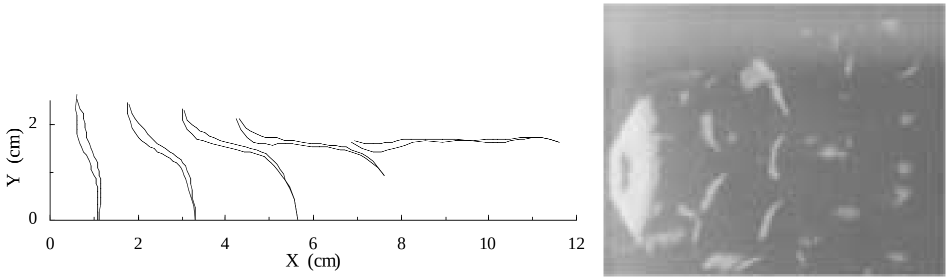

Figure 1: The liner profile at 10, 20, 30, 40 and 60 μs (the lowest two rows of cells having been removed at about 35 μs), and an FX image at 125 μs.

This divergence is of little consequence for use in ordnance disposal, but is decidedly undesirable against targets with random orientations. The effect of the sensitivity to stand-off is amply illustrated by the adjacent photograph, where an inclined (60°) steel plate was perforated at the design standoff, but with failure to perforate the upper part of the target due to the increased standoff.

As an exercise to achieve a performance that would be less dependent on standoff, Autodyn™ was used in the design of a charge that would result in an annular EFP. The charge had an annular explosive and a liner with a hemispherical section, as in Fig. 2, with the X-axis an axis of revolution. The simulations revealed that the initial acceleration of the liner is symmetric, with implosion asymmetries only starting to develop once the detonation products have reached the axis. Thereafter, the increased pressures near the axis cause the inner part of the liner to have a larger acceleration.

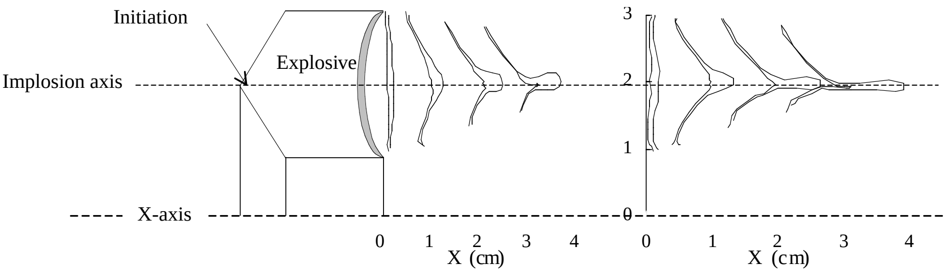

Figure 2: The liner profiles at 6, 10, 15 and 20 μs for symmetric (left) and asymmetric (right) liners.

At later times an additional asymmetry is seen to develop, in that the lower half becomes thinner while the top half apparently retains it thickness near the collapse region. The lower tail reduces in thickness as it moves towards the slug, since it is expanding away from the axis. It merges with the slug ahead of the upper tail. This is caused by the larger initial acceleration of the lower tail due to its smaller mass and the high on-axis detonation product pressure. This asymmetry causes the front end of the slug to have an upward velocity component.

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At later times, the implosion is somewhat more symmetrical, but, since the mass of material imploding from above is so much larger than that from below, the rear of the slug has a downward velocity component. This will cause the slug to rotate to such an extent that the tails will be shorn off at later times, with the slug then tending to behave like a smoke ring. The effects of this asymmetry can be significantly decreased by introducing an asymmetry in the thickness profile of the liner, the inner section being thicker than the outer section, as also employed by [2] for a straightsided annular liner configuration where jetting was required. It is then also easier to attain a large length for the body of the slug, as is observable in Fig. 2.

THE PRESENT APPROACH

The secondary symmetry associated with the implosion axis in Fig. 2 is only necessary if one wants to achieve jetting. It can be dispensed with for annular EFP's, easing the task of the designer. The only inherent asymmetry then resides in the detonation products, where the pressure remains appreciably higher near the axis. The section of the liner nearest the axis will thus be influenced by the detonation products for a longer time.

The main problem with the cookie cutter design [1] is that the liner's central half is incapable of 'freezing' at any diameter, since the outward-directed velocity component causes a thinning of the section as it expands (Fig. 1). One can now take the approach to dispense with that part of the charge that forms the expanding nose of the projectile.

A good approach would be to have a forward-folding liner, the liner being thin near the outer edge to implode at a higher speed, and followed at progressively lower speeds and angles by liner elements at smaller radii, until one would have quite a thick liner at the inner edge making up the rear the ring. For such a projectile, the elements from the liner outer edge have to be faster and more downward-directed than sections closer to the axis. This was achieved by curving the liner forward and introducing a progressive thinning towards the rim. Attempts to achieve a design using a curved liner with a constant horizontal thickness to ease manufacture were not successful. The projectile evolution of Fig. 3 was the result of a large number of runs with different liner configurations, aimed at achieving a projectile with a diameter of about 25 mm and a reasonable length and wall thickness. The simulation predicted that the projectile would freeze at about 80 μs, with a speed of 1,55 km/s and a length of 15 mm.

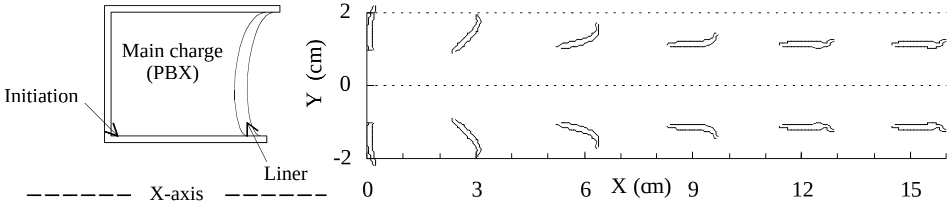

Figure 3: Projectile shape at 0, 20, 40, 60, 80 and 100 μs after initiation. A section view of the charge as simulated is also sketched, the dashed line again being an axis of revolution.

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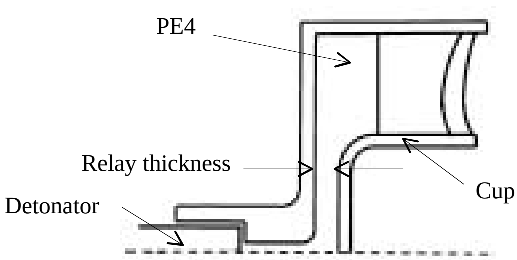
THE RESULTS

The design for manufacture had to contend with the need for the relay of detonation to the lower edge of the main charge, which was machined from PBX bar stock. To this end, the configuration of Fig. 4 was used. A plastic explosive (PE4) was used as a relay charge within a steel housing with a diameter of 45 mm. A steel cup was inserted into the annulus to effect good contact between the PE4 and the main charge and to enforce axial symmetry. It was hoped that a relay thickness in the region of 1 mm would suffice. However, it was found that this thickness had to be increased to nearly 3 mm to ensure reliable corner turning in the PE4 on the axis. This increased thickness had an effect on the ultimate EFP shape – in Fig. 4 the radiographs of two EFP's taken at 100 µs after initiation are compared. The relay web thickness of the charge on the left was at the minimum 3 mm, achieved by forcing the cup in to a greater depth, while in the other radiograph the web thickness was 5 mm. With a thinner relay the manufactured item (and the observed EFP shape) is much closer to the required annular shape (Fig 3), since the inner rim of the liner will be relatively slower than the outer rim.



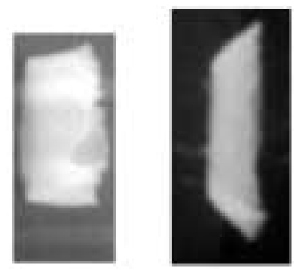


Figure 4: Design, and radiographs at 100 µs 3 mm relay 5 mm relay.

Penetration as a Function of Stand-off Distance

A number of charges were fired at thick mild steel targets at a range of stand-offs up to 4 m (90 calibers) from the charges. The hole profiles at stand-offs between 2 and 20 calibers were generally symmetrical and similar to the profile of Fig. 5(a), with maximum depths ranging between 11 and 14 mm, and some evidence of tumbling at the larger stand-offs. Of the four charges fired at a stand-off of 90 calibers, one of the impacts showed evidence of large tumble, in one the EFP had clearly suffered break-up into two fragments, while the remaining two had good integral in-line impacts. The hole profile of Fig. 5(a) depicts the best of these, the other one being quite similar.

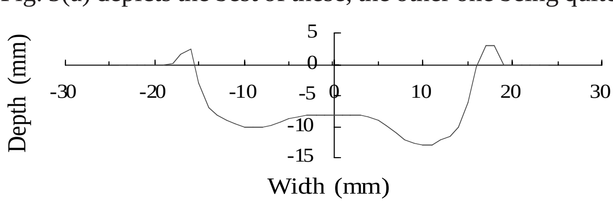
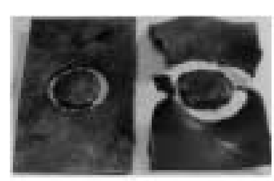


Figure 5(a): Hole profile at 90 calibers



5(b): Example of plugging

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It is gratifying to note the good penetration potential at such a large stand-off. The charge could also punch out plugs from two 3,2 mm mild steel plates inclined at 60° to the charge axis at a stand-off of 5 calibers, as can be seen in Fig. 5(b). The tumble observable at large stand-offs could have been caused by non-precision of assembly and/or aerodynamic forces.

The charge does not perform well against multiple spaced plates – the EFP shatters upon impact with the first plate.

The Evolution of the Projectile

The projectile evolution was determined with flash X-rays. Fig. 6 is a collage of the predictions and the FX results for three shots where the timing made direct comparison with the predictions possible. Radiographs at other times are also shown.

The agreement between predicted and measured shape is quite good, except for a flaring out of the forward portion. This flaring may at least partially be ascribed to the relatively large relay thickness (Fig. 4). Freezing apparently took place between 60 and 100 µs, in line with the prediction. The length of the ring is satisfactory, and there are indications from the serrated front edge of the ring and from FX photographs taken soon after initiation that the outer rim of the liner had spalled off early on. Such spalling could be reduced significantly by using heavier confinement, but heavier confinement would have made the observation of the evolution of the projectile more difficult. The measured projectile velocities were all within 200 m/s from the predicted value, with a measuring error of perhaps 100 m/s.

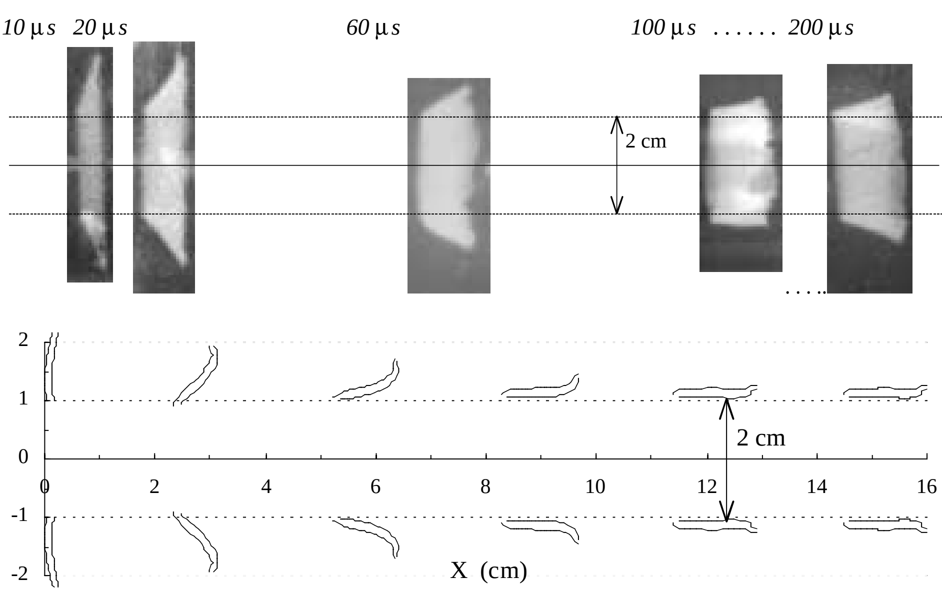

Figure 6: Collage of predictions at 0, 20, 40, 60, 80 and 100 µs after initiation, and results at the indicated times.

Since the amount of deformation experienced by the liner is actually quite small in comparison with that of a normal EFP, one could get by with an unsophisticated strength model for the liner. An ordinary von Mises model was used.

In the present design the aim was to achieve an annulus with the diameter of the inner edge of the liner. An annular EFP with a diameter equal to the diameter of the outer edge of the liner would not result in a stable EFP, as a result of the radially-outward velocity component. The performance of such a charge will again be quite stand-off dependent.

REFERENCES

1. M. C. Chick et al., "Development of a Cookie-Cutter Explosively Formed Projectile", *17th International Symposium on Ballistics,* Midrand, South Africa, p. 2–167 1998
2. D. J. Leidel, "A Design Study of an Annular Jet Charge for Explosive Cutting", *Thesis, Drexel University,* 1978