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INSTRUMENTED SMALL SCALE ROD PENETRATION STUDIES: THE EFFECT OF PITCH

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Scaled reverse ballistic experiments were performed at an impact velocity of 700 m s^{-1}. The targets were tungsten alloy rods and the projectiles either 3 or 6 mm thick RHA plates. The plate was inclined at 30° to the direction of travel and the interaction was recorded using high-speed photography, strain gauges and VISAR velocimetry. The pitch of the rod was varied in steps of 3° over a total range of 15°. A marked change in the penetration process was found with pitch angle and the results from the diagnostics are interpreted with respect to the observed penetration mechanisms.

INTRODUCTION

Many long rod penetrator systems are based around tungsten alloy rods. In this study tungsten alloy rods were impacted by RHA plates in the, so-called, reverse ballistic impact geometry. This approach allows information to be gathered from instrumented rods which can be used to validate models used in ballistics codes [1–5]. One advantage of such studies is that many instrumental techniques can be applied to the system that may be difficult or even impossible to use at full scale. Previous work from the Cavendish, using a 50 mm bore single stage light gas gun [6], has concentrated on rod / plate interaction at fixed angles of 45° or 60°[7]. This paper extends this research and describes the use of various high-speed diagnostic techniques [8,9] for rod / plate impacts with particular emphasis on the effects of pitch.

The experimental arrangement and the definitions of positive and negative pitch are

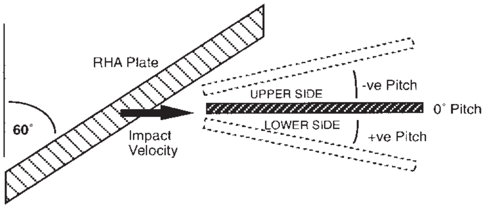

Figure 1. The experimental layout.

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EXPERIMENTAL

The tungsten rods used were 6.0 mm in diameter and 90.0 mm long. Each rod had two constantan (EA-06-031CF-120, Micromeasurements, Basingstoke, UK) foil strain gauges mounted approximately one rod diameter from the impact face. They have a 30 µm polyimide backing for the sensor elements which are arranged in a rectangle, 1.5 x 1.0 mm; strain was measured along the 1.0 mm axis. The gauge factor is 2.01 with a linear range up to 3%. The gauges were powered by a constant current supply which was adjusted to give minimum ringing for a response time of ≈10 ns. As the gauge sensor length is 1 mm, the mechanical response time is ≈4 µs as the sound speed in tungsten is ≈3.8–4.0 mm µs^{-1}. Compression reduces the gauge resistance and gives a – ve signal while tension tends to increase the resistance and results in a +ve signal.

The motion of the tail of each rod was recorded using a Velocity Interferometer System for Any Reflector (VISAR) [10,11]. Laser light is reflected from the surface of interest and the reflected light is fed into the interferometer system. The light used comes from a 1W continuous Ar-ion laser (515 nm). Upon entering the interferometer, the light is split into two beams, one of which travels along a predominantly air-filled path, the other is fed through a glass cylinder which acts as an etalon. The function of the etalon relies on the higher refractive index of glass over air, which causes the light to travel more slowly in the glass than in the air. So the light which emerges from the etalon is delayed in time relative to that which has travelled through air. The light beams are then recombined. If the light was reflected from an accelerating surface a Doppler shift and constructive or destructive interference occurs from which the velocity of the reflecting surface can be determined. The time resolution of this system is 10 ns.

The fibre optic was held in a holder ≈10 mm from the rod tail. When the tail of the rod starts to move, it gets closer to the fibre optic. The signal becomes severely degraded when this distance has closed to less than 4 mm. In all experiments the velocity was measured *normal* to the rod's rear surface as the use of the holder ensured this orientation.

High-speed photographic sequences were taken of the impact events using an Ultranac FS501 image converter camera in conjunction with a Bowen flash. This flash source takes ≈100 µs to reach peak intensity after triggering and maintains a fairly constant light level for ≈500 µs. In these experiments, the illumination was diffuse and the images were backlit. The diffuser consisted of 5 sheets of tracing paper. The camera is capable of operating at framing rates of up to 20 x 10^{6} frames per second and provides 24 frames. In this experiment images were recorded onto Kodak 667 film.

The rods were mounted in a frame made from steel sections welded to a 6.3 mm thick steel base so forming an upright in each corner. The uprights were made of square section pieces with horizontal rods mounted at the upper and lower end. This frame was fixed to the base of the impact chamber of the single-stage light gas gun. This gun has a 50 mm bore, 5 m long barrel and can launch a 500 g projectile at 1000 m s^{-1}.

Rods were suspended between the uprights using thin copper wire. Four wires were used so by attaching the wires to the horizontal rods fine adjustments to the rod alignment can be made. The rod was first aligned to the centre of the barrel at a 0° pitch by mounting a mirror on the front of the rod and reflecting a laser beam projected down the centre line of the barrel. The wires were then adjusted to give the rod the required pitch. The pitch was varied over the experimental series in 3° steps from +6° to –9°. The laser spot was maintained in the middle of the mirror throughout this alignment process. When the correct pitch was attained, the mirror was removed.

With the rod aligned at the required pitch, the gas gun chamber was sealed, the sabot placed in the breech and the interior of the gun evacuated to 1 mbar pressure. The sabot was as shown in figure 2. The upper edge of the plate had been ground to give a flat surface so that upon leaving the barrel this would short a series of velocity pins. The pin output was used to trigger a delay generator connected to the diagnostics. It should be noted that upon impact the sabot is still half to two thirds within the barrel. This allows precision alignment on impact to < 1 mrad, which would not be achieved if the sabot was in free flight.

For the majority of experiments 6 mm RHA plates were used. However, one test was performed with a 3 mm plate at 0° pitch.

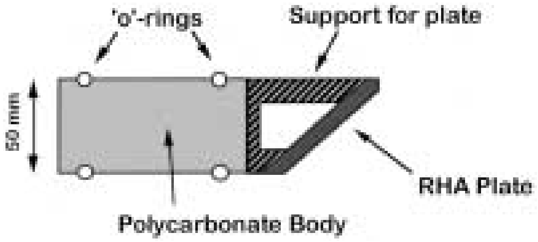

Figure 2. Detail of projectile.

RESULTS

(i) Strain Gauges

For a tungsten rod at 0° against a 3 mm RHA plate the upper gauge showed a small tensile stress and the lower gauge a larger compressive stress. The gauges were only 7 mm from the tip thus indicating that the rod experienced little resistance from the plate and pushed though with little bending. The upper gauge does not go into compression until 8 μs after impact by which time the penetrated plate has moved very near the gauge position. With a 6 mm RHA plate, the gauges showed no tensile phase for the upper gauge: it stayed close to zero strain while the lower gauge went into compression. The rod was compressed and bent in this impact and overall it was much more deformed going through the 6 mm thick plate. It must be remembered that although the maximum strains recorded on the lower gauge are very similar for the 3 mm and the 6 mm plate impacts, it is the comparison between the upper and lower gauges that defines the bending of the rod.

In Figure 4 the traces when the pitch was varied in 3° steps are presented. In these traces a very obvious trend is found which indicates the differing nature of the mechanisms involved.

At high negative pitches, the lower gauges show a rapid rise to high levels of strain while the upper gauges show a slow rise to much smaller compressive strains. At positive pitches, it is the upper gauge trace which rises slowly, while the lower gauge rises rapidly.

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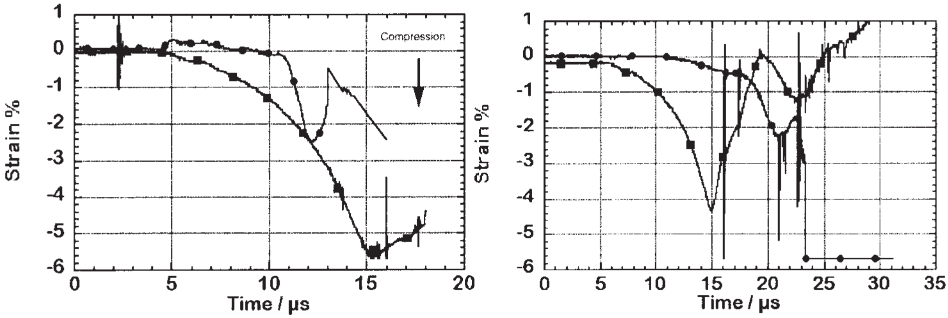
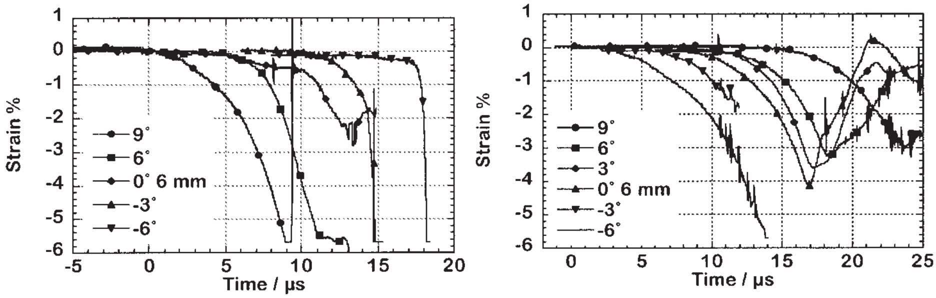
This implies that at negative pitches the rod tends to bend away from the target whereas at high pitches the rod tends to bend towards the target.

Two features which need much closer examination are the general humped nature of the lower traces, where the strain rises then falls close to zero. The traces from the upper gauges show a plateau, especially at 0° and +6°. These would seem to relate to some flexing during the penetration.



(A) (B)

Figure 3 – Strain gauge trace struck by (A) 3 mm thick RHA plate and (B) 6 mm thick RHA plate



(A) (B)

Figure 4. Comparison of strain outputs from gauges on (A) upper side and (B) lower side of Tungsten rod during impact.

Overall a negative pitch tends to favour a sliding action followed by burrowing through the plate, while positive pitches tend to favour an immediate digging action into the surface. This penetration mechanism is what could be expected given the initial angle of contact between rod and plate as emphasised in Figure 5. However, the extent of the bend could not be intuitively predicted and the strain gauges give a valuable quantitative measure. It is this kind of information which is directly relevant to the modelling of this event.

This difference in mechanisms can be checked in several ways: comparison with photographs and by examining the scoring along the face of the plates. These aspects are dealt with later.

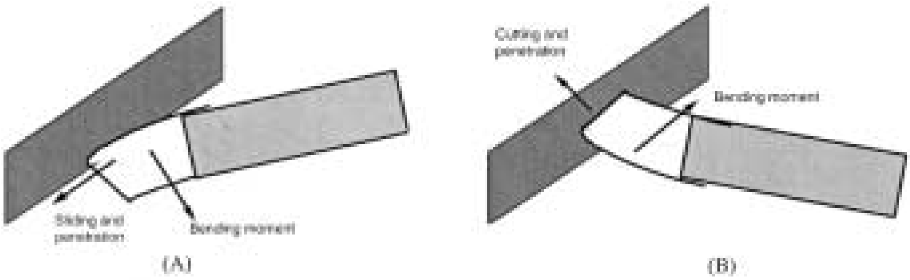


Figure 5. Comparison of mechanisms for (A) positive and (B) negative pitches.

(ii) VISAR

The VISAR traces for the tungsten rods are all very similar showing a rounded, convex form indicating a relatively slow acceleration over ≈20 μs to 35–45 m s^{-1}. There is a break in the acceleration slope approximately 20 μs after the tail of the rod starts accelerating; this could be due to the effect of the rod tip striking the sabot carrying the plate. Pitch again seems to have only a slight effect on the tail velocity of the rod; the rod at –9° pitch having a slightly faster acceleration. This basic similarity, unlike the results of the strain traces, was probably due to the rod fragmenting, which while still having some penetrative effect probably did not transmit the stress pulse as effectively as an intact, though flexing rod. Examples of the VISAR traces are shown in Figure 6.

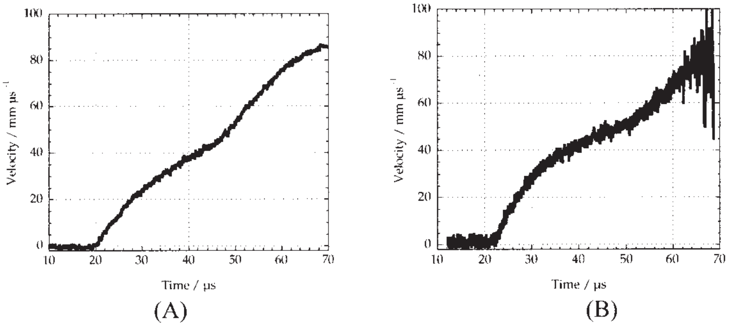


Figure 6. Velocity histories of the rod tail with pitch (A) +6° and (B) –9°.

(iii) High-Speed Photography

Due to the fragmentation of the tungsten rods, significant debris was generated at the impact point. The basic process for negative pitches was: initial contact with some bending, followed by some skidding along the impact face, bulging of the rear of the plate along the skid path and finally the pushing through of the rod. This process tended, however, to be obscured by a dense debris cloud. The positively pitched rods contact the surface, the rear of the plate starts to bulge over a very small region, and the rod pushes through. The bulging of the rear of the plate occurs above the initial centre line of the rod indicating that the rod had bent into the plate surface as seen in Figure 7.

Supporting evidence for these processes were found by comparing the hole shape and the length of any grooves around the hole cut into the surface on the impact surface: negative pitches had long grooves while positive pitches showed short steep ruts leading to the hole.

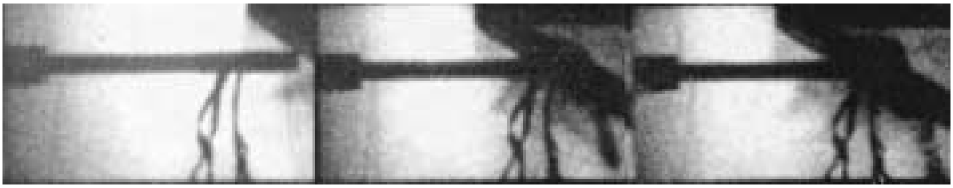


Figure 7. Three frames from a high-speed sequence. Rod pitch +3° pitch.

CONCLUSIONS

Ballistics represents a field in which data interpretation is difficult given the three dimensional nature of the problem and the mix of fracture and large plasticity effects generally seen. Progress will only be achieved by a combination of careful and extensive use of experimental diagnostics and computer modelling. Use of the reverse ballistic geometry aids the acquisition of gauge data.

Tungsten rods show a varied gauge response indicating a change in perforation mechanism with pitch. Rod flexing is away from the plate for negative pitches but into the plate for positive pitches. At negative pitches the rod tip skids, bends and shears before penetration. At positive pitches the rod seems to cut more quickly into the plate as evidenced by the strain gauge records, post impact examination of the plates and the high-speed photographic sequences.

Some evidence of rod straightening is seen at late times in traces with 0° to +6° pitch. These corresponded to small perforation holes in the plates, a good indication that the rod was going straight and so did not cut a large hole in the RHA plate.

It is interesting that pitch had no great effect on the tail velocity, probably due to the rod fragmenting.

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