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ANALYTICAL CODE AND HYDROCODE MODELLING AND EXPERIMENTAL CHARACTERISATION OF SHAPED CHARGES CONTAINING CONICAL MOLYBDENUM LINERS

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A molybdenum lined shaped charge design was modelled using, both analytical code, JETFORM, and a hydrocode, GRIM. Molybdenum conical liners were manufactured using six different processing routes. These liners were then incorporated into shaped charges, which were fired and the jets were captured using single orthogonal flash X-radiography. The jet characteristics that were exhibited from each processing route were compared with each other in regard to cumulative mass and cumulative length. The cumulative mass, as a function of jet velocity was compared to the predictions of both JETFORM and GRIM. The behaviour of the jets at early times (50 µs) was compared to the predictions of GRIM and the velocity of a small incoherent portion of the jet was compared to the predictions of the coherency algorithm, which is incorporated within JETFORM. Other jet characteristics, including jet dynamic ductility and temperature were uncovered from the analysis and are discussed later in more detail.

1. INTRODUCTION

Molybdenum was first investigated as a shaped charge liner material because of its relatively high bulk sound speed (5055.5 ms^{-1}) at ambient pressure, and its moderately high density (10220.0 kgm^{-3}). More recent studies [1–4] have indicated that molybdenum can produce highly ductile jets provided that the material is in the appropriate thermo-mechanical condition and preferably has a fine grain size (3–5 microns). The high bulk sound speed is important in relation to the high coherent jet tip speed, which may be obtained from molybdenum liners in the appropriate designs. At room temperature molybdenum is a brittle material which may undergo a ductile to brittle transition at ~200 K depending on the previous deformation history and the purity of the material. One of the main objectives of this current research exercise was to optimise the processing route for molybdenum liners in order to increase the dynamic ductility and consequently enhance armour penetration potential.

2. MATERIAL PROCESSING ROUTES

Since molybdenum is a refractory material, having a melting point of 2893 K, many of the preferred processing routes are based upon the consolidation of metal powder rather than re-melting the material and processing cast material. The use of processing routes based upon those of powder metallurgy means that depending on the starting size of the powder, then there is some control over the final grain size of the consolidated material. Initially six different processing routes were investigated. These were: pressing and sintering using a 2 micron molybdenum powder, pressing, sintering, forging and stress relieving, pressing, sintering, forging and recrystallisation, extrusion of a pressed and sintered billet, stress relief at 1100°C for two hours for an extruded billet, and recrystallisation at 900°C for one hour for an extruded billet. In all cases, except for the material that was heated at 1100°C for two hours, and the pressed and sintered material, the final grain size was 3–5 microns. In the other two cases, the final grain size was 20 microns.

3. HARDWARE

A partially optimised 75 mm calibre conical charge design was used as a test vehicle for this exercise. A 30 degree conical liner was fitted to an aluminium case by means of a retaining ring and the explosive filling material was vacuum cast EDC1s, an octol type formulation. A peripheral initiation system, based upon a steel barrier was used together with an explosive train, which was initiated by a RP80 high voltage detonator.

4. EXPERIMENTAL

Single orthogonal flash X-radiography was carried out at times ranging from 40 micro-seconds up-to 220 micro-seconds using a 450 keV X-ray source in our own firing facility. Both extended jet and early time jet data was obtained from this process.

5. ANALYTICAL MODELLING

The initial design was modelled using the DERA JET suite. This included, JETFORM and JETBRK, in order to produce a robust design which had a tip speed near the coherency limit for molybdenum and had a significant cumulative jet length based upon known break-up criteria for molybdenum jets. In order to quantify the full motion history of the experimental jets, the program JETREG was used to process the measurements of the jet particles. These jet particles were treated as ellipsoids, since this more closely represents the actual shape and is also likely to produce a more reliable estimate of the jet mass.

6. HYDROCODE MODELLING

A two dimensional, axi-symmetric hydrocode, known as GRIM was used to simulate the shape charge liner collapse and jet formation at early times (<100 μs). A Zerilli-Armstrong constitutive model for molybdenum, having the correct grain size was used in the simulation. The Mie-Gruneisen thermodynamic equation of state for molybdenum was also used in the simulation. The predicted cumulative mass versus jet velocity data was to be compared with both the experimental data and that which was obtained from the JETFORM simulation.

7. JET BREAK-UP ANALYSIS

Using the methods of [5] and appropriate Zerilli-Armstrong material models, it was possible to calculate the values of the plastic particle velocities (ΔV_{pl}) for different processing routes, since the constants in the material model will vary, and also for different grain sizes. This exercise will help to give some insight into which parameters are important with regard to the determination of jet break-up behaviour. The dynamic ductility factor, Q, is determined from the following equation:

$$T_{bf} = L_j/(V_{tip} - V_{tail}) = Q(1/\pi.dm/dV)^{1/3}$$

8. RESULTS

A plot of the cumulative jet length as a function of jet velocity for each of the material processing routes, is shown at Figure l. The cumulative mass, as a function of jet velocity for each of the material processing routes and for both the JETFORM and GRIM simulations, is shown in Figure 2. A picture of a flash X-radiograph of the jet at 50.7 μs for recrystallised molybdenum is shown in Figure 3.

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Table l. Molybdenum jet characteristics

Material type	Grain Size (microns)	Cumulative jet length (mm)	Break-up time (micro-seconds)	Plastic particle velocity (ms^{-1})	Dynamic Ductility Factor (Q)	Particle aspect ratio
(A) pressed, sintered, forged (recryst.)	5.0	1366.05	133.4	103.29	98.35	6.27
(B) pressed, sintered, forged stress relieved	5.0	1282.88	117.48	128.46	88.45	7.17
(C) extruded billet	5.0	1180.02	122.54	95.28	109.46	6.5
(D) extruded billet stress relieved	20.0	1073.10	96.33	129.43	81.29	6.23
Copper charge	10-15	967.82	120.08	91.13	81.15	8.135

Portions of the extended jets, which were produced from material having different processing routes, for times of the order of 200 µs, are shown in figures 4–9. Various jet break-up characteristics are shown in table 1 and jet coherency and velocity data is shown in table 2. In table 3 the variation of the predicted plastic particle velocity with the material processing route, is given.

Table 2. Jet Coherency and velocity data

Parameter Material	V_{tip} (ms^{-1}) experiment	V_{tip} (ms^{-1}) model	$V_{coherent}$ (ms^{-1}) experiment	$V_{coherent}$ (ms^{-1}) model
(A)	11,090.0	11,661.0	12,110.0	11,661.0
(B)	11,290.0	11,661.0	N/A	N/A
(C)	11,240.0	11,661.0	N/A	N/A
(D)	11,570.0	11,661.0	N/A	N/A

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Table 3. Calculated plastic particle velocity data

Parameter Material	Grain size (microns)	Jet Temp. (K)	Strain rate (s^{-1})	Necking strain	ΔV_{pl} (ms^{-1})
(1)	5.0	2000	7.59E4	0.14145	59.95
(2)	5.0	2000	7.59E4	0.30646	83.06
(3)	5.0	2000	7.59E4	0.17428	73.26
(4)	5.0	2000	7.59E4	0.12856	55.98
(5)	5.0	2000	7.59E4	0.18341	66.40

(1) Arc cast, 88% reduction on swaging, recrystallised.
(2) Extruded billet, stress relieved.
(3) HERF, 20% cold work.
(4) HERF, 20% cold work, recrystallised.
(5) Extruded, recrystallised at 1100°C.

9. DISCUSSION

This study into the utilisation of molybdenum as a shaped charge liner material has uncovered a number of interesting features. Significant differences (100 s mm) in cumulative jet length can be obtained by the use of different material processing routes. Whilst grain size is important, the magnitudes of the strain hardening constant and the strain hardening exponent, as determined from a material algorithm, such as that proposed by Zerilli and Armstrong, also have a significant bearing on the values of the plastic particle velocity and hence the break-up parameters. The apparent inconsistency between the magnitudes of the empirical plastic particle velocity values and those predicted from the material models is due to the difficulty in determining the actual number of wavelets in the jet. In some cases particles may contain two or more wavelets since it is not easy to determine where the necking point is. For example, the calculated necking strain for material (4) was 0.12865, which corresponds to a value of 0.938, for the ratio of the necked radius to the unperturbed radius. In a real jet, having a radius of 1.5 mm, the necked radius value would be 1.4 mm and this would be difficult to observe unless one used image enhancement techniques. If one was able to count the number of jet wavelets accurately then the magnitudes of the empirical plastic particle velocity and that calculated from the model would be similar. This can also be confirmed when one carries out simulations using the program JETBRK. If the correct value of the plastic particle velocity is used then the predicted cumulative jet length closely matches that of the experiment. Whereas if there are inconsistencies in the value of the empirical plastic particle velocity and that predicted from a material algorithm, then there will be a miss-match between the empirical cumulative jet length and that which is predicted from the simulation.

The dynamic ductility of some of these molybdenum jets is comparable or better than that exhibited by jets that were produced from fine grain size copper liners (table 1). Further material processing refinements can be carried out on molybdenum since there is plenty of scope for this in the field of powder metallurgy.

Other features of note are, the prediction of the coherency limit on the jet tip speed was close to that of the experimentally determined value and again this gives us added confidence in the functioning of the coherency algorithm [6] within JETFORM. The cumulative mass-jet velocity plots for both GRIM and JETFORM agree closely with the experimental data. This is another area where both models are working well.

In conclusion it is readily apparent that molybdenum has a high potential as a shaped charge liner material due to its intrinsic high dynamic ductility and that further research should be directed to improve the material processing routes and to carry out further design iterations using optimisation techniques.

11. ACKNOWLEDGEMENTS

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10. REFERENCES

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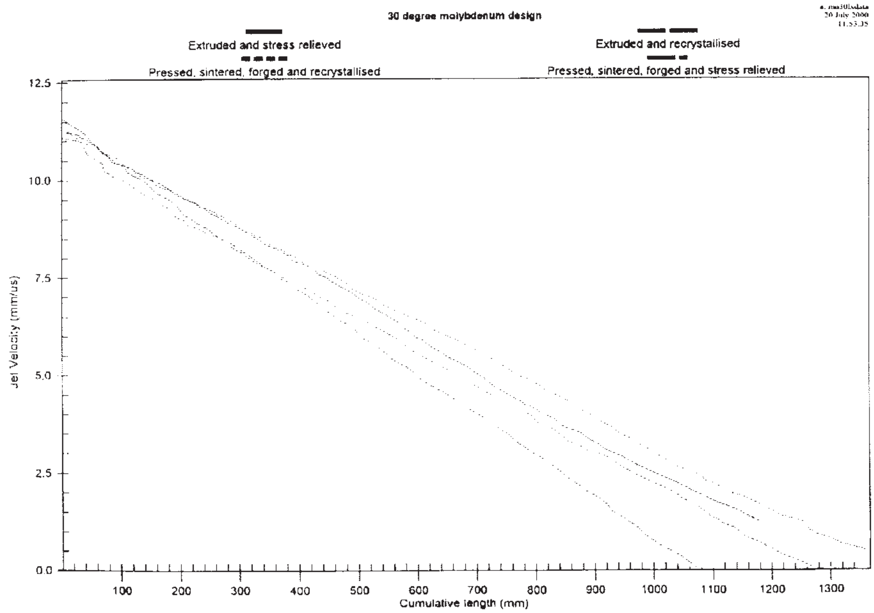
Figure 1.



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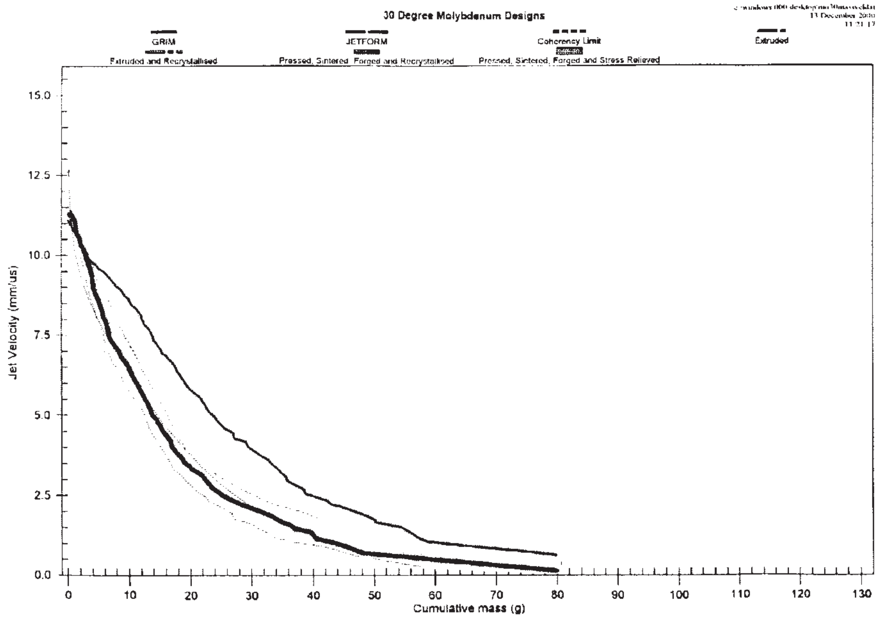

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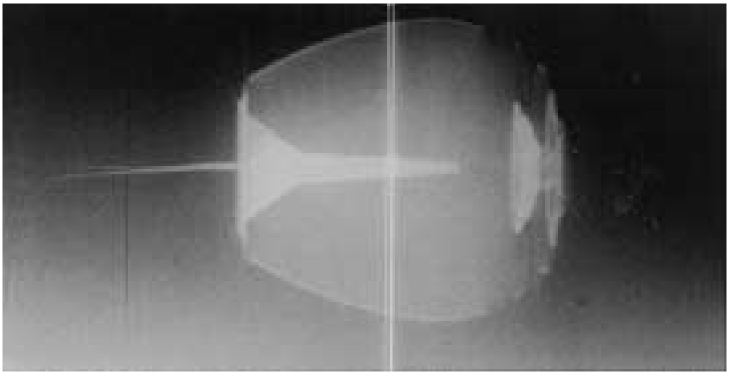
Figure 3.



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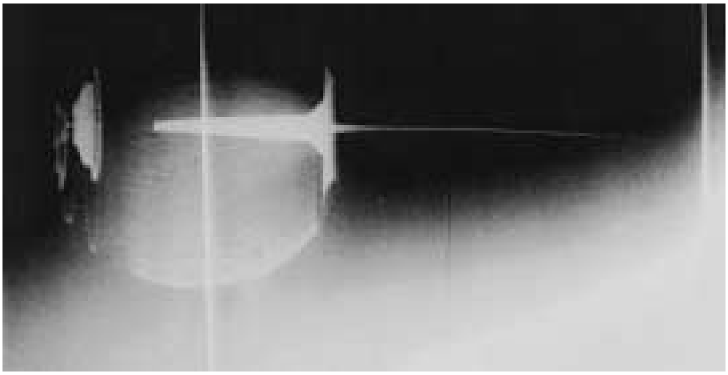

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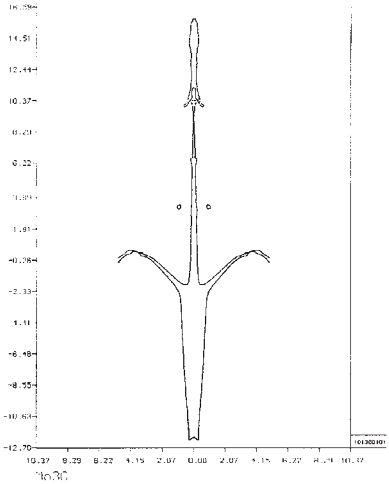

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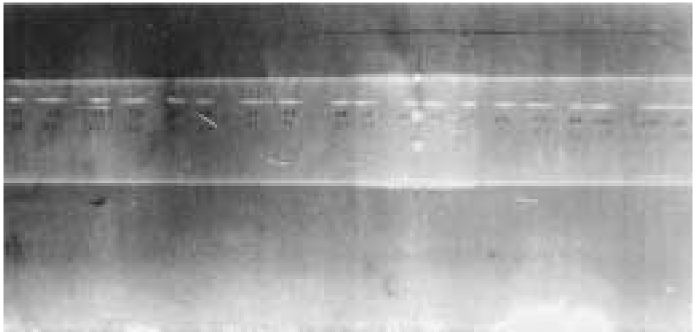

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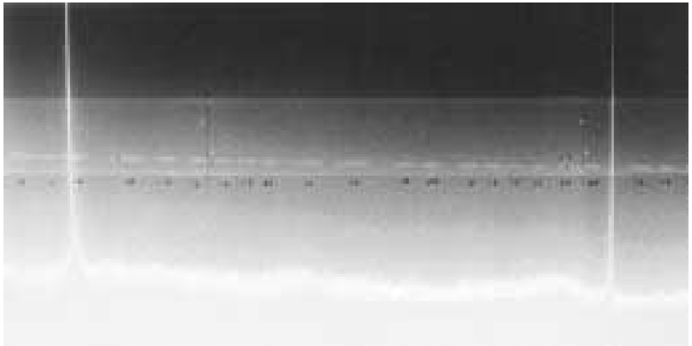

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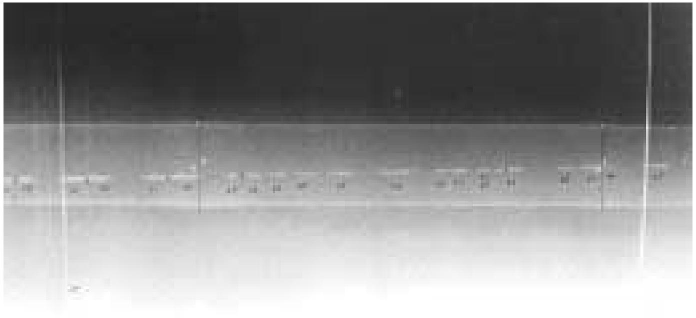

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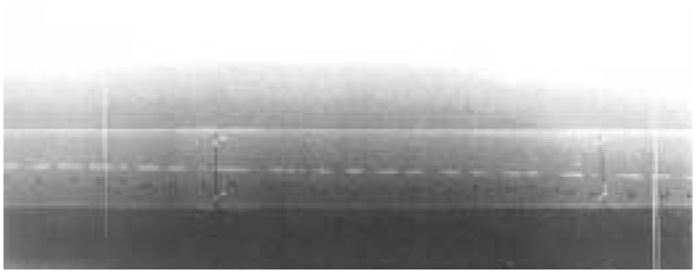

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