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SHAPED CHARGE WARHEADS CONTAINING LOW MELT ENERGY METAL LINERS

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In this paper we present data on shaped charge warheads containing low melt energy metal liners. The metals chosen for the study included, silver, titanium, and zirconium, depleted uranium (DU) and of course copper. We observed that zirconium had the highest cumulative jet length followed by silver, titanium, DU and finally copper. We also observed that zirconium had the longest break-up time followed by silver, DU, titanium and finally copper. DU had the lowest plastic particle velocity followed by silver, zirconium, copper and then titanium, the latter being similar to copper. The highest and most desirable material ductility factor of the metals tested was achieved by zirconium followed by silver, titanium and then DU. Compared with copper, all the metals tested had longer break-up times, better (lower) plastic particle velocities (with the exception of titanium) and better (higher) material ductility factors.

INTRODUCTION

It is well known that traditional metallic shaped charge jets break up into discrete particles after a few charge diameters of motion and that the inherent off-axis velocity components of these particles causes a significant decrease in penetration performance the greater the distance travelled. Copper is the traditional shaped charge liner material but it has long been recognised that other metals, and perhaps other materials, having lower melt energies may well have increased long stand-off potential because of the enhanced thermal softening that will occur. Thermal softening of the jet material leads to increased material ductility and hence a greater cumulative jet length and an assumed greater penetration performance. Examples of metals with low melt energies include titanium, zirconium, silver and depleted uranium (DU) and all these were included in the study. In view of the different densities of the metals studied, constant mass liners were used so that the cumulative mass-velocity plots would be similar, if not the same. The aim of the work was to identify if any commercially pure metal liners could provide improved jet break-up times and improved jet material ductility when compared with copper.

MATERIAL MODELS

Several material models have been developed for metallic materials [1–4]. Most of these material algorithms are based on semi-empirical fits to material test data and have a basis in dislocation mechanics. In general these models express the deviatoric flow stress (σ) as a function of strain (ε), strain rate ($\dot{\varepsilon}$), temperature (T) and grain size (d), i.e.

$$\sigma = f\left(\varepsilon, \dot{\varepsilon}, T, d\right) \tag{1}$$

The exact functional form of this relationship depends on the model chosen and many functional forms exist.

A highly regarded model amongst the shaped charge community is the Zerilli-Armstrong model [5–7]. This material model has different functional forms for different crystal structures and it also has been extended to allow for other effects such as phonon drag and the variation of the shear modulus with temperature. For face centred cubic metals:

$$\sigma = C_1 \varepsilon^{n} \exp\left[-C_2 T + C_3 T \ln \dot{\varepsilon}\right] + C_4 + C_5 d^{-\frac{1}{2}} \tag{2}$$

for body centered cubic and hexagonal close packed metals:

$$\sigma = C_1 \exp\left[-C_2 T + C_3 T \ln \dot{\varepsilon}\right] + C_4 + C_5 d^{-\frac{1}{2}} + C_6 \varepsilon^{n} \tag{3}$$

The Zerilli-Armstrong data for a range of metals available in the open literature is shown in Table 1 for the general form

$$\sigma = C_1 \varepsilon^{n} \exp[-C_2 T + C_3 T \ln(d\varepsilon/dt)] + C_4 + C_5 d^{-1/2} + C_6 \varepsilon^{m}$$

Other forms of the material algorithm have been developed to allow for path dependency [8], and they can also be used in the analysis of jet break-up. The material algorithms for titanium and zirconium have been published [9]. It was apparent from the magnitude of their constants, in particular the strain hardening constant, and by preliminary analysis that jets derived from these metals had potential to provide improved performance at increased moderate stand-off distances when compared with copper.

Table 1. Zerilli-Armstrong material algorithm constants

Metal	C_1 (MPa)	C_2 (K^{-1})	C_3 (K^{-1})	C_4 (MPa)	C_5 (MPa mm	C_6 (MPa)	n	m
Cu	890	0.0028	0.000115	46.5	5	0	0.5	0
Ta	1125	0.00535	0.000327	0	19	310	0	0.44
	1750	0.00975	0.000675	0	19	650	0	0.650
W	16500	0.591	0.000279	0	25.6	860	0	0.443
	24900	0.666	0.000307	20	25.6	860	0	0.443
	41000	0.061	0.000307	20	25.6	860	0	0.443
Mo	937	0.0036	0.000107	0	22.65	647	0	0.401
Zr	600	0.0024	0.000132	21	7.9	76	0	0.51
Ti	1100	0.00226	0.00017	54	14.86	300	0	0.5
Fe	1033	0.00698	0.000415	0	22.0	266	0	0.289

The relevance of material models to this study is that the jet break-up and elongation process is directly related to the flow stress, σ. Knowing how this parameter varies as function of strain, strain rate, temperature, and grain size is therefore essential for the accorate prediction of jet break-up characteristics using analytical modelling or hydrocodes.

Several important concepts will now be defined in relation to the use of these material models. The plastic wave velocity is the velocity at which plastic stress waves may propagate through metals and may be defined by:

$$V_{PL} = \left(\frac{1}{\rho_o} \frac{d\sigma}{d\varepsilon} \right)^{1/2} \tag{4}$$

The plastic particle velocity ΔV_{PL} is the maximum particle velocity difference which can be observed in a stretching jet which undergoes particulation and is given by:

$$\Delta V_{PL} = \int_o^{\varepsilon_N} V_{PL}\, d\varepsilon \tag{5}$$

where ε_N is the strain at necking corresponding to the value derived from the tensile instability condition, which is determined by the form of the material algorithm according to Goldthorpe [10].

Another important parameter is the concept of plastic work. This is the amount of energy which the material acquires due to plastic deformation and is given by:

$$E = \int_o^{\varepsilon_1} \sigma\, d\varepsilon \tag{6}$$

Since the processes occurring in shaped charges are essentially adiabatic, i.e. there is insufficient time for energy losses to occur by heat transfer, large temperature rises may occur due to severe plastic work. Hence:

$$T - T_0 = \frac{E}{C_p} \tag{7}$$

JET BREAK-UP

A number of analytical jet break-up models have been proposed and reviewed [11]. They are all essentially similar and allow for strain rate effects as well as incorporating a plastic particle velocity term. A model developed within DERA [12,13] gives an analytical expression for the break-up time:

$$t_b = \frac{\pi r_0}{\Delta V_{PL}} - \frac{1}{\dot{\varepsilon}_0} \tag{8}$$

Here r_0 and $\dot{\varepsilon}_0$ are the radius of the jet and strain rate at the point of jet formation.

It can be observed that the break-up time and hence the cumulative jet length is an inverse function of ΔV_{PL}.

The relevance of this to the present study is that the break-up time is affected by changes in the plastic particle velocity which arise from modifications in the temperature, grain size and strain rate effects. These in turn are related to the charge design, the liner material and the liner material processing routes. A deeper understanding of the jet break-up process will allow the shaped charge designer to be in a better position to design charges for long stand-off applications.

Metals with low melt energies

The melt energy of a particular material may be defined as the total energy required to take a material from absolute zero, through any phase changes to its melting point and to produce melting. In mathematical terms the melt energy may be expressed by:

$$\Delta H_m = \int_0^{Tm} C_p\, dT + \sum_{i=1}^{n} L_t + L_f \tag{9}$$

where L_t is the latent heat of phase change (there may be more than one) and L_f is the latent heat of fusion.

For solid state transitions, that is from one crystal type to another, the specific heat may change value in a dramatic way and hence additional expressions are required:

$$\Delta H_m = \int_0^{Tm} C_p\, dT + \sum_{i=1}^{n} L_t + L_f + \int_0^{T1} C_p(1)\, dT + \sum_{i=1}^{n} L_{t(1)} + L_{f(1)} + \int_0^{T2} C_p(2) dT + \sum_{i=1}^{n} L_{t(2)} + L_{f(2)} + \int_0^{Tn} C_p(3) dT + \sum_{i=1}^{n} L_{t(n)} + L_{f(n)} \tag{10}$$

Thermal properties of materials are a matter of record.

It is also important that the specific heat is generally a function of temperature:

$$C_p = a + bT + cT^2 \tag{11}$$

and may be represented by an appropriate polynomial. The specific heat is also a more complex function of hydrodynamic pressure and this fact needs to be allowed for if we are to have a very accurate description of the material behavior in a hydrocode simulation. Candidate materials that appear attractive in terms of melt energies are titanium, zirconium, silver, gold and uranium. Table 2 shows the melt energies for a range of candidate shaped charge liner materials. It can be seen that there are several liner materials that have melt energy values considerably lower than that of copper. The value of the strain hardening constant and exponent in the material algorithm are also related, to the total melt energy [14 and 15].

Table 2. Melt energies for various metals

Metal	ΔH_m (kJ kg^{-1})	ΔH_m (Jm^{-3})	ΔH_m (kJ mol^{-1})
Cu	727.137	6.515×10^9	46.209
DU	215.503	4.105×10^9	51.289
W	681.866	1.316×10^{10}	125.361
Ta	631.688	1.0486×10^{10}	114.304
Mo	1015.440	1.0378×10^{10}	97.421
Al	1228.240	3.316×10^9	33.138
Fe	1074.841	8.462×10^9	60.029
Au	237.450	4.5828×10^9	46.771
Ag	395.719	4.155×10^9	42.686
Zr	808.181	5.245×10^9	73.722
Ti	1376.064	6.1923×10^9	65.913
Pb	118.711	1.3474×10^9	14.453
Zn	376.768	2.7115×10^9	24.829
Pt	373.012	7.982×10^9	72.771

MATERIAL DUCTILITY

A concept of material ductility applied by Baker [16] has been used in order to quantify the quality of various jets produced from the chosen design. This concept is based on the analysis of the break-up of jets by the use of instability equations and can be readily derived from equations published by Chou [17]. The resultant formula describes a relation between break-up time and material ductility factor Q.

$$t_{b\,(final)} = Q(dm/dV.1/\pi)^{1/3} \tag{12}$$

This equation can be used to analyse a range of jets provided that the full jet kinematics are known. The larger the value of Q, then the more dynamically ductile the material being studied. It is important to note that different warhead designs will have different sets of Q values. In other words, any designs of warhead which give rise to substantially different mass-velocity profiles will have different Q values.

FIRING TRIALS AND ANALYSIS OF JET CHARACTERISTICS

The warhead design used for the metal liners was based on a constant mass depleted uranium hemispherical design, initiated by means of a plane wave generator and loaded with LX 14 explosive. One principle advantage of this hemispherical design is that it can produce inherently straight jets that contain about 80% of the liner mass. The magnitudes of the jet lateral velocity vectors for these types of design, witch can be as low as 20 ms^{-1} are significantly lower than those produced by conventional conical liner shapes, typi-

cally 80 ms^{-1}. The use of constant mass designs implied that the cumulative mass-velocity plots should be similar for all of the materials another feature that makes a comparison between the different materials easier. The lower density materials will also produce fatter jets at earlier times and for similar values of ΔV_{PL}, the break-up times will be longer as shown by equation 8.

Firings were carried out at stand-off distances in the range 40 to 100 CD and residual jet penetration measured into rolled homogeneous armour. Flash radiography was used to capture the jets at 2 X-ray times in the region of 1000 microseconds and about 50 microseconds apart. The jet kinematics were quantified by the analysis of the X-ray data using the DERA jet regression routine JETREG, which is incorporated in the DERA analytical suite of programmes known as JET [18].

The extended jet characteristics are presented in Table 3. It should be pointed out that the masses of the jets as calculated using JETREG, were based on the assumption that the jet particles were ellipsoids.

Table 3. Extended jet characteristics

Metal	No. particles	Jet length (mm)	V tip (kms^{-1})	Vtail (kms^{-1})	Break-up time $t_{b\ final}$ (μs)	Plastic particle velocity (ms^{-1})	Material ductility factor (Q)
Ag	55	1456.0	6.48	3.01	419.6	64.26	181.9
Ag	62	1563.5	6.66	2.99	426.0	60.16	233.22
Zr	54	2058.9	6.75	3.34	603.8	64.34	246.1
Zr	48	2049.4	6.7	3.18	582.2	74.9	217.0
Ti	33	1327.4	6.34	2.99	396.2	104.69	175.7
Ti	33	1229.9	6.46	2.58	317.0	121.25	135.1
DU	84	1700.0	6.4	3.3	548.4	37.35	217.67
DU	87	1686.4	6.61	3.59	558.4	35.12	226.60
Cu	38	1130.5	5.90	2.56	338.5	90.25	161.53

The analysis of the data from the firing of the rather novel liner metals DU, silver, zirconium and titanium, in a hemispherical warhead design indicates that all of these materials are capable of producing ductile jets. From Table 3 it can be seen that the plastic particle velocity values for the silver and zirconium jets are low and this indicates that these metals are more ductile than copper. This fact is also reflected in the values of the material ductility parameter, Q, which is larger than that of copper. Of some significance is the fact that the metal processing route for the silver liners was close to being ideal in as much that the final equi-axed average grain diameter was in the order of 15 microns.

Work carried out by one of the authors almost 20 years ago and published later, recognised that isotropy and average grain diameter of a metallic liners is of considerable importance [19]. The commercially pure titanium liners used in this study had an average grain diameter of about 120 microns and the commercially pure zirconium had an average grain diameter of 80 microns. These grain sizes were an order of magnitude larger than we would have liked however, it is nevertheless the case that the quality of the jets produced from the liners was high in terms of their break-up behaviour and their material ductility. As far as we are aware this-degree of material ductility has not previously been reported for metal lined shaped charges.

The results of the firings from the designs containing depleted uranium (DU) liners are similar to those obtained from previous firings. Depleted uranium exhibits the lowest experimentally determined plastic particle velocity value (30 ms^{-1}) for any metallic liner material fired so far. Together with its high density (19050 kg m^{-3}) this value of plastic particle velocity makes DU very attractive as a shaped charge liner material from a performance perspective although clearly its toxicological implications need to be considered. Whilst the cumulative length of the zirconium jet was longer than that of DU, the effective length based on the square root density law is greater for DU than for the other metallic liner materials so far tested.

It should be noted that the highest energy available explosive composition was used to drive these designs because an increase in the adiabatic shock heating leads to a higher jet temperature leading to more ductile jets with high cumulative jet lengths.

CONCLUSIONS

Silver, zirconium, titanium and DU when tested in a constant liner mass hemispherical design all produced ductile jets with longer break-up times than copper. This enhanced material ductility is due to the intrinsic material properties of these metals and can be quantified by the use of an appropriate material algorithm in relation to the analysis of tensile instabilities. This implies that compared with copper, there is potential for these materials to provide better optimum penetration performance at greater stand-off distances.

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