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COMPARATIVE PARAMETRIC NUMERICAL SIMULATIONS OF MATERIALS USED AS LINERS IN THE EXPLOSIVELY FORMED PROJECTILES (EFPs)

*G. HUSSAIN and K. SANAULLAH

School of Chemical & Materials Engineering (SCME), NUST, Islamabad, Pakistan

A conventional shaped charge comprises a conical metal liner projecting a hyper velocity jet of metal that is able to penetrate to great depths into steel armour. However, misalignment problems exist in tandem with jet break up and spewing particles that greatly diminish its penetration power. An EFP, on the other hand, has a liner in the shape of a geometrical recess. The force of the blast molds the liner into a number of configurations, depending on the geometry and the explosive detonation characteristics. This paper presents comparative parametric numerical simulations of materials used as liners in the explosively formed projectiles EFPs. Numerical simulations are carried out using AUTODYN 2D hydrocode to study effects of liner's materials on the shape, velocity, traveled distance, time, pressure, internal energy, temperature, yield stress, divergence or stability, density, compression, and length to diameter (L/D) ratio of EFPs. These parameters are estimated at the instants of maximum as well as at stable velocities. The parametric study reveals that aluminum has maximum velocity in shortest time among the liner materials. From this reason, it was concluded effective standoff was greater for aluminum than more denser metals. Maximum velocity and traveled distance of Tantalum EFP is found to be minimum which may be due to low thermal softening exponent and larger hardening exponent. The simulated yield stress and pressure developed in the Fe EFP reaches at maximum. The L/D ratio for Copper is found to be maximum which supports maximum penetration. From the stability point of view, 1006 MS is found to be the most reliable liner material due to minimum divergence. Generally all liner materials have similar effects of all parameters like pressure, internal energy, temperature, yield stress, divergence or stability, density, compression at the instants of maximum as well as at stable velocities except L/D ratio of EFPs. At the instant of maximum velocity, L/D ratio of Ta and AL EFPs have minimum and maximum L/D ratio respectively whereas Fe and Cu EFPs have minimum and maximum L/D ratio respectively. The velocity attenuation laws for liner materials from maximum to stable velocities are determined and plotted. The EFPs observed at maximum velocities are profilic except tantalum which shows a straight profile one due to higher density. The velocity attenuation laws show material for which maximum and stabilized velocity come earlier than other materials whereas tantalum is the liner's material for which maximum and stabilized velocity take more time than other materials due to lower and higher densities respectively.

Keywords: Explosively formed projectiles (EFPs), Hyper velocity jet

1. Introduction

Explosively Formed Projectiles (EFPs) are used in a number of modern ammunition systems and are fired at a considerable distances from their targets (the standoff is typically ~1000 charge caliber). A relatively high impact velocity at minimum possible angle of attack, the geometry and its aerodynamic stability are the criterions for achieving maximum penetration. Some characteristics and associated applications of EFPs are as under:

- Potential anti- armour warheads.
- Use as single warhead or as submunition.
- Ability to attack targets at much greater standoff distances vis-a-vis conventional shaped charges.
- Fragment of L/D ratio of about 3 are possible to give penetration of one cone diameter at 1000 cone diameters standoff.
- The effect is similar to shaped charge, a shallow concave dish is used instead of the cone.
- As the cone angle increases, the jet length decreases. Liner collapse does not happen as such and there is no separation of jet and slug.
- The liner simply folds into a fragment moving off with high velocity.
- The liner not being surrounded completely by explosive is not fragmented but is expelled by the high pressure gases in one piece and is deformed.

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* Corresponding author : sangra-2000@yahoo.com

- As the apex angle increases so does the tendency to form a high velocity slug.

High pressure and high temperature processes results in the formation of EFPs. There are two methods to analyze the formation process of EFPs which are pseudo-stationary uncompressed ideal fluid model and numerical simulation method [1]. The formation process of EFPs can be analyzed well by the above two methods. The actions of the charge and its cover are complex because of a lot of influencing factors. In this paper, a series of simulated programs are designed to study the material's behaviors at instant of maximum velocity. Two-dimensional hydrocode AUTODYN-2D TM was applied for the numerical simulation. All the calculations were made in the axisymmetric geometry. Though this hydrocode is a fully coupled (multi-processor type) computer program, only the multiple material Eulerian processor was utilized at all the times in this study.

An explosively formed projectile (EFP) liner undergoes extreme, yet controlled, plastic deformation without breaking. This makes designing an optimal EFP a very complicated task. The EFP formation process involves essentially super plastic strains up to 300%, at strain rates of the order of 10^4 s^{-1}, with a resulting adiabatic temperature rise of up to 1000 K or more [2]. Such super plastic-like behavior cannot be explained by conventional theories that only use dislocation generation and arrangements to accommodate strain. The dynamic interactions between the explosive products, base plate, confinement and liner present a challenging problem [2]. Although the initial shockwave- liner interaction may be considered to be approximately planar, there are several basic parameters in the warhead configuration that affect the projectile shape and performance. These can broadly be classified as geometrical factors and material factors. Liner contours, physical dimensions of the explosive charge, charge length, length-to-diameter ratio of the explosive charge (*L/D)*, confinement configurations (asymmetric or symmetric, thicker or thinner), and explosive initiation technique are some of the geometrical factors of interest. Axial thickness, the presence of taper (or lack thereof), and angle of the liner have been observed to affect the shape of the EFP. The material factors include the structure and properties of the liner, casing and explosive, and the processing conditions during the manufacturing of the liner blanks. The properties of the liner that are important in the context of the dynamic EFP formation process and its eventual effectiveness as a penetrator are high density, high ductility, high strength and a high enough melting temperature to prevent melting in the liner due to adiabatic heating. Ta, Cu, Fe, MS and Ta-W alloys show a good combination of these properties and are preferred materials. The casing is typically made of steel because of its low cost, high strength, and density. However, other materials can be used, as long as the mass is sufficient to provide the necessary confinement. The explosive properties of importance are the explosive density, detonation velocity and the explosive energy [3].

2. Simulation and Numerical Modeling

Modern researchers are adopting computer simulations using hydrocodes due to high cost as well as explosive nature of experiments which are difficult to conduct in the laboratory and the rapid advancements in computer technologies. For the purpose of investigating the Munroe effect numerically, some hydrocodes have been utilized by applying several numerical models. In the case of 'self-forging-fragment' analysis, liner angle is fairly greater than the shaped charge. The liner material is not subjected to much serious deformations so Euler hydrocode scheme is more suited for such application [4].

To simulate the entire process of the projectile when it flies a long distance up to target, it requires lengthy computer time and resources. It is fairly operable to simulate just a passage of flying process. Here we aim to simulate a flight distance where EFPs are to be investigated at its maximum and stable velocity. Also velocity attenuation laws for different materials hold during the flight of EFPs but here we are only concerned with simulation that deals with parameters at maximum and stable velocities. Crucial parameters like Pressure, internal energy, temperature, yield stress, total energy, kinetic velocity, density, divergence, compression, momentum and L/D ratio of the EFPs are investigated. Different explosive materials were analyzed and considered. It is well known that explosive performance for an application of this type increases with increasing density. A high-density HMX-type explosive is selected because it lies in high density category (about 1.89 g/cm^3).

2.1. *Initiation method & EOS*

Once the liner material and the explosive were selected, modeling is conducted with the AUTODYN 2D code to study different parameters at the instant when EFPs attain their maximum velocities. Geometrical trough shaped liners and explosive configuration with L/D ratio of 1.17 are used with constraint of constant liner wall thickness in each case. Eulerian technique is used in the simulation to deal with the coupling problem of the fluid and the solid. Different liner materials are modeled in an Euler grid with a linear equation of state whereas explosive is modeled in the same grid using the JWL equation of state. The diameter of the modeling configuration is 36mm with confinement of mild steel included as shown in Figure 1. The point initiation method is used in the simulation. Johnson-Cook Model is used as a strength model in the simulation, it expresses flow stresses in terms of equivalent plastic strain, plastic strain rate and homologous temperature. The yield stress δ is given by equation given below.

$$\delta = [A + (B\varepsilon^{p})\ n]\ [1 + C\ \ln\varepsilon^{*}]\ [1 - T^{*}n] \qquad (1)$$

The expression in the first bracket gives the stress as a function of strain; expressions in second and third brackets represent the effect of strain rate and temperature respectively. Where ε ε^{p} is the effective plastic strain and nondimensional ε* strain rate.

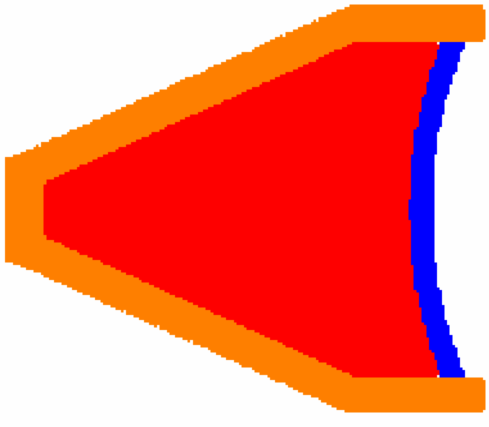


Figure 1. Geometric shape of warhead.

A is yield stress constant, B is strain hardening coefficient, n is strain hardening exponent, C is strain rate dependence coefficient and m is temperature dependence exponent. T* is homologous temperature and is given as:

$$T^{*} = (T - T_{ref}) / (T_{melt} - T_{ref}) \qquad (2)$$

Heat is generated in an element by plastic work and the resulting rise in temperature is computed using specific heat for the material. We applied the JWL equation of state (E.O.S.) to HMX proposed by E. L. Lee [1], and the equation of the state is expressed as,

$$p = A_{jwl}\left(1 - \frac{\omega\eta}{R_1}\right)\exp\left(-\frac{R_1}{\eta}\right) + B_{jwl}\left(1 - \frac{\omega\eta}{R_2}\right)\exp\left(-\frac{R_2}{\eta}\right) + \omega\eta p_{ref}\rho \qquad (3)$$

where p is the pressure, η is ρ/ρref, ρ is the current density, ρ_{ref} is the reference density, e is the specific internal energy, A_{jwl}, B_{jwl}, R_1, R_2, and ω are the material properties of the chemical high explosive given in Table 1 [5].

Table 1. Properties of HMX.

Variables	Properties	Units
Pref	1.89	Kg / cm3
Ajwl	9.4334e-1	Tpa
Bjwl	8.8053e-3	Tpa
Rl	4.700e+0	-
R2	9.00e-1	-
ω	3.5e-1	-
E	1.02e-2	Kj / mm3
Vdet	9.1	m/ms

The input material parameters for Tantalum, Armco Iron and OFHC Copper are given in the Table 2 [6] and for mild steel and Aluminum in Table 3 [6].

Table 2. Input material parameters for tantalum, armco iron and ofhc copper.

Parameters	Tantalum	Armco Iron	Copper
Equation of state	Linear	Linear	Linear
Reference density g/cm^3	16.69	7.89	8.96
Bulk modulus kpa	1.5e+8	1.64e+8	1.29+8
Ref. temperature K	300	300	300
Specific heat j/kg K	1.35e+2	4.52e+2	3.83e+2
Strength model	Johnson Cook	Johnson Cook	Johnson Cook
Shear modulus kpa	6.9e+7	8.0e+7	4.6e+7
Yield tress kpa	8.0e+5	1.0e+6	1.0e+5
Hardening constt. Kpa	5.5e+5	3.8e+5	2.92e+5
Hardening exponent	4.0e-1	3.1e-1	3.1e-1
Strain rate constt.	5.75e-2	6.0e-2	2.5e-2
Thermal softening exponent	4.4e-1	5.5e-1	1.09e+0
Melting temperature k	3293	1812	1356
Failure model	None	None	None
Erosion model	Ints. Geometric strain	Ints. Geometric strain	Ints. Geometric strain
Erosion strain	2.5	2.5	2.5

The reference temperature for all liner's materials is selected as 300K [6]. The input yield stress values were increased from the material library values included in the software to account for the initial shock-induced hardening of the liners prior to the in-flight deformation.

3. Results and Discussion

Numerical simulation was carried out using AUTODYN 2D code to study different parameters of materials used as liners in the configuration of the tapered explosive HMX with casing material 4340 steel. The parameters studied and determined are maximum velocities during the flight of EFPs, times at maximum velocities, and the distances traveled at the same instants. The pressures, internal energies, temperatures, yield stresses generated in the EFPs during their flight are also predicted at the instants when EFPs have gained maximum velocities. The densities that are varied during EFP's flight and consequently the change in compressions are calculated accordingly.

Table 3. Input material parameters for mild steel and aluminum

Parameters	Mild Steel	Aluminum
Equation of state	Linear	Linear
Reference density g/cm^3	7.89	2.70
Bulk modulus kpa	1.8e+8	5.833e+7
Ref. temperature K	300	300
Specific heat j/kg K	4.52e+2	9.1e+2
Strength model	Johnson cook	Johnson cook
Shear modulus kpa	8.18e+7	2.692e+7
Yield tress kpa	3.5e+5	1.67e+5
Hardening constant Kpa	2.75e+5	5.96e+2
Hardening exponent	3.6e-1	5.51e-1
Strain rate constant.	2.2e-2	1.0e-3
Thermal softening exponent	1.0	8.59e-1
Melting temperature k	1811	893
Failure model	None	None
Erosion model	Ints. Geometric strain	Ints. Geometric strain
Erosion strain	2.5	2.5

Another parameter of interest is the L/D ratio of the EFPs at the time of maximum velocities. Divergences resulting from the path of flight of EFPs with changes in the parameters are also predicted. Any of these parameters at maximum velocity of EFPs for any liner material has never been studied before, thus reporting impact of these parameters on EFPs performance is the pinnacle of this paper. The variations in velocities during the path from initial to maximum velocities

Table 4. Output parameters for mild steel, copper, tantalum, aluminum and armco iron at maximum velocities.

Parameters	Mild Steel	Copper	Armco Iron	Tantalum	Aluminum
Velocity (m/s)	2200	2050	2160	1310	3640
Time (µsec)	12.05	10.77	10.75	12.15	10.02
Distance travel led (mm)	17.18	11.78	12.78	8.58	19.48
Density (g/cm^3)	7.931	9.045	7.96	16.83	2.824
Temperature (K)	433	405	488	568	462
Divergence	-1.625E-2 to 1.62e-3	-9.032e-3 to 8.45e-2	-9.127e-3 to 1.523e-2	-1.787e-2 to 1.456e-3	-6.839e-2 to 3.412e-3
Max. Yield stress (TPa)	6.311e-4	3.85e-4	1.46e-3	1.257e-3	3.608e-4
Maximum Compression	4.495e-3	9.447e-4	8.908e-3	8.199e-3	1.407e-2
Internal energy (kj/g)	0.219	0.172	0.227	0.09212	0.897
Pressure (TPa)	8.091e-4	1.219e-3	1.46e-3	1.23e-3	8.206e-4
L/D	0.165	0.1103	0.128	0.092	0.1761

till the attainment of stable velocities are plotted against time. The variations of velocity profiles for the Fe, Ta, Al, and Cu liner materials of EFP has never been studied but an odd investigation on the velocity profile for MS liner material of EFPs has been published in earlier decade. Also stable velocities of the EFPs for Fe, Ta, Al, MS and Cu liner materials during its path towards the target are calculated and all the above said parameters are investigated at the stable velocities. Even at stable velocity which is very important parameter regarding standoff distance of EFP and perforation performance into targets, only parameters like pressure and yield stress are scrutinized. But in this paper we attempt to investigate not only pressure and yield stress but the parameters like density change, compression, temperature, internal energy, divergence or stability and L/D ratio of the EFPs.

3.1. Output parameters of EFPs at maximum velocity

The output parameters of EFPs for Mild Steel, Copper, Armco Iron, Tantalum and Aluminum at their maximum velocities as a result of simulation are tabulated in the Table 4. When we examined the values of the parameters against individual liner material, explicit differences are observed in the values of these parameters. The maximum velocity in case of liner material Aluminum was achieved in the least time due to its softness and low density. Due to low melting point of Aluminum and inter atomic structure, its internal energy and divergence amplitude was simulated to be maximum out of all liner materials. At the point of maximum velocity, Aluminum was the liner material whose compression was found maximum, it might be due to its softness or some other reason, and it is worth needs to be investigated properly. The velocity and traveled distance of Tantalum EFP was found to be minimum which might be due to low thermal softening exponent, high density and larger hardening exponent. The density change and temperature rise were found out to be maximum in case of tantalum at this velocity.

The yield stress and pressure developed in the Armco Iron EFP is simulated maximum. The shapes of the explosively formed projectiles for mild steel, copper, tantalum, aluminum and armco iron at their maximum velocities are given in the Figure 2. We got the profilic behavior of projectiles

Table 5. Output parameters for mild steel, copper, tantalum, aluminum and armco iron at stable velocities.

Parameters	Mild Steel	Copper	Armco Iron	Tantalum	Aluminum
+Velocity (m/s)	1870	1700	1820	1080	3190
Time (μsec)	55.43	60.44	50.82	62.24	36.11
Distance travelled (mm)	190.88	188.88	188.88	164.88	137.88
Density (g/cm^3)	7.9	8.963	7.891	1.669	2.785
Temperature (K)	448	449	503	619	477
Divergence	0.0 to 5.63e-4	-1.58e-3 to 9.89e-4	-2.035e-3 to 0.0	-3.55e-3 to 0.0	-3.52e-3 to 5.67e-3
Max. Yield stress (TPa)	5.14e-4	3.3e-4	8.58e-4	7.62e-4	3.647e-4
Maximum Compression	5.007e-4	3.164e-4	1.66e-4	5.58e-7	1.588e-6
Internal energy (kj/g)	0.199	0.169	0.209	0.0946	0.810
Pressure (TPa)	9.012e-5	4.08e-5	2.7e-5	0.0	0.0
L/D	0.51	0.856	0.47	0.46	0.58

for low density materials and straighter ones for high density materials. Also velocity gradients within the EFPs show its intensity in the central region and reducing its value towards its edges.

3.2. Output parameters of EFPs at stable velocity

The output parameters of EFPs for Mild Steel, Copper, Armco Iron, Tantalum and Aluminum at their stable velocities as a result of simulation are tabulated in the Table 5.

The explicit differences exist among the output parameters of EFPs calculated for maximum and stable velocities for same set of liner's materials. The maximum velocity of Aluminum was greatest among the liner materials. This is one of the reasons why effective standoff is greater for aluminum than more dense metals [3]. The L/D ratio for Copper at stable velocity is found to be maximum which supports maximum penetration. Copper is thus preferred for achieving maximum possible penetration as shown in Figure 2. Where as EFPs of armco iron was found to have larger diameter than other projectiles which indicate its application where wide target hole is required. For the stability point of view, 1006 MS is found to be the most reliable liner's material due to minimum divergence at stable velocity. Also compression and pressure generated with 1006 MS were found to be maximum. The maximum temperature was generated in case of tantalum. The EFPs fragments and its velocities gradient within itself at their stable velocities are shown in the Figure 2. The velocity variations within the EFPs fragments show that intensity of velocity is maximum at the central region and reducing its value towards its edges. The EFPs fragments at their stable velocities are shown in the Figure 3.

3.3. Velocity attenuation laws

Velocity attenuation law for each liner material is different from others due to different material parameters. How a velocity for particular liner material rises to the maximum value and then attenuates to a stable value is shown in Figure 4. The liner materials used for velocity attenuation are as Mild Steel, Copper, Armco Iron, Tantalum and Aluminum. Figure 4 represents prolific behavior of Mild Steel, Copper, Armco Iron, Tantalum and Aluminum from maximum to stabilized velocity.

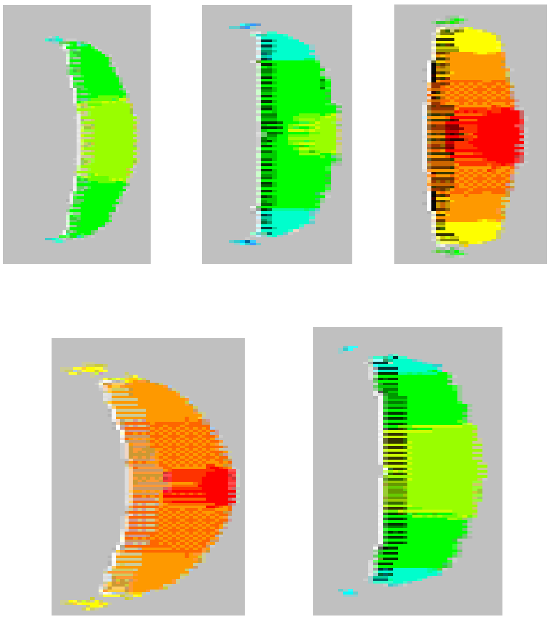


Figure 2. EFPs for mild steel, copper, tantalum, aluminum and armco Iron at maximum velocity/

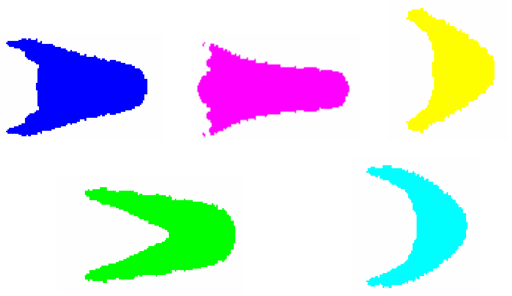


Figure 3: EFPs for mild steel, copper, tantalum, aluminum and armco Iron at stable velocity.

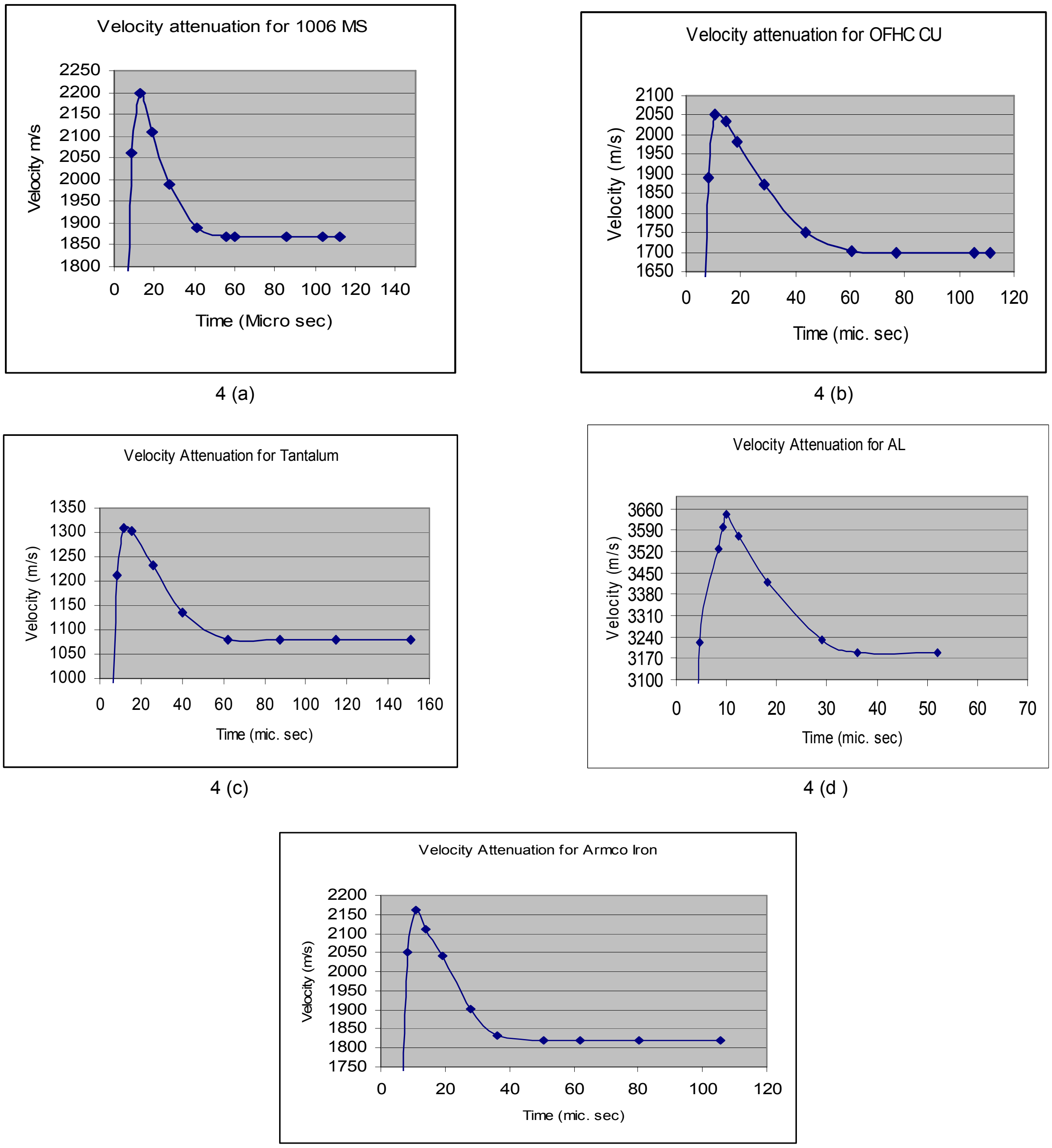
Each liner material has different maximum and stabilized velocities, and also has different times at which maximum and stabilized velocities achieved. Figure 4 (a) represents the velocity attenuation law for Mild Steel in which maximum and stabilized velocity are 2200 m/s and 1870 m/s after 12.05µs and 55.43µs respectively. Figure 4 (b) represents the velocity attenuation law for Copper in which maximum and stabilized velocities are 2051 m/s and 1700 m/s after 10.77µs and 60.49µs respectively. Figure 4 (c) represents the velocity attenuation law for Aluminum in which maximum and stabilized velocities are 3440 m/s and 3020 m/s after 7.436µs and 33.66µs respectively. Figure 4 (d) represents the velocity attenuation law for Tantalum in which maximum and stabilized velocities are 1310 m/s and 1080 m/s after 12.15µs and 62.24µs respectively. Figure 4 (e) represents the velocity attenuation law for Armco Iron in which maximum and stabilized velocities are 2161 m/s and 1820 m/s after 10.75µs and 50.82µs respectively.

These velocity attenuation laws show that Tantalum is the liner material with lowest maximum and stabilized velocities whereas Aluminum is the liner material with highest maximum and stabilized velocities. Also Aluminum is the liner material for which maximum and stabilized velocity come earlier than other materials whereas tantalum is the liner’ s material for which aximum and stabilized velocity take more time than other materials.

4. Conclusions

The output parameters of EFPs for Mild Steel, Copper, Armco Iron, Tantalum and Aluminum at their maximum and stable velocities were found out by simulation using Autodyn 2D hydrocode. The output parameters like traveled distance, time, pressure, internal energy, temperature, yield stress, divergence or stability, density, compression, and Length/Diameter (L/D) ratio of the EFPs at maximum and stable velocities were investigated. When we examined the values of the parameters against individual liner material, explicit differences were observed in the values of these parameters.

The maximum velocity of Aluminum was greatest among the liner materials. The maximum velocity in case of liner material Aluminum was achieved in the least time due to its softness and low density. Due to low melting point of Aluminum and inter atomic structure, its internal energy and divergence amplitude was simulated to be maximum out of all liner materials. At the point of maximum velocity, Aluminum was the liner material whose compression was found maximum. Also velocity and traveled distance of Tantalum EFP were found out to be minimum which might be due to low thermal softening exponent, high density or larger hardening exponent. The density change and temperature rise were found maximum in case of tantalum. The yield stress and pressure developed in the Armco Iron EFP were simulated maximum. The L/D ratio for Copper at stable velocity was found to be maximum which supports maximum



4 (a)

4 (b)

4 (c)

4 (d)

4 (e)

Figure 4. Velocity attenuation laws for mild steel, copper, aluminum, tantalum and armco iron.€.

penetration and thus Copper is preferred for achieving maximum possible penetration. For the stability point of view, 1006 MS was found to be the most reliable liner's material due to minimum divergence at stable velocity and even at maximum velocity. The compression and pressure generated with 1006 MS were found maximum. The temperature generated in case of tantalum was maximum. Velocity attenuation law for each liner material is different from others due to different material parameters. The velocity attenuation laws show that Tantalum is the liner material with lowest maximum and stabilized velocities whereas Aluminum is the liner material with highest maximum and stabilized velocities. Also Aluminum is the liner material for which maximum and stabilized velocity come earlier than other materials whereas tantalum is the liner' s material for which maximum and stabilized velocity take more time than other materials due to lower and higher densities respectively.

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References

[1] W.C. Davis, High Explosive Interaction of Chemistry and Mechanics, Los Alamos Science (2003).

[2] K. Weimann and A. Blache Explosively formed projectile with tantalum penetrator and steel stabilization base 18th international symposium on ballistics San Antonio. 15-19 November (1999).

[3] K. Weimann, Producing Explosively Formed Projectiles, US Patent 535,949 from 1998.

[4] John W. Hermann, Jr. Mechanical Engineer Ammunition Development and Engineering Directorate Us Army, New Jersey 07801 USA. (1987).

[5] F.Rondot, C. Berner. ISL, Performance of aerodynamically optimized EFP simulants., French –Germen Research Institute of Saint-Louis, France.

[6] S.Pappu, L. E. Murr, Hydrocode and micro-structural analysis of explosively formed penetrators University of Texas at El Paso USA, Kluwer Academic Publishers (2002).