Ballistic performance of a composite metal foam-ceramic armor system

Matias Garcia-Avilá a, Marc Portanova b, Afsaneh Rabiei a,∗

a Department of Mechanical and Aerospace Engineering, 911 Oval Dr., Engineering Bldg III, Campus Box 7910, Raleigh, NC 27695-7910, USA
b Aviation Applied Technology Directorate (AATD), U.S. Army Research, Development & Engineering Center, Fort Eustis, VA, 23604-5577, USA

Abstract

Composite Metal Foam is a low-weight, high-strength porous material capable of absorbing great amounts of energy under loading. In this report, Composite Metal Foam panels are manufactured using powder metallurgy technique and 2 mm steel hollow spheres in a steel matrix and used in conjunction with a ceramic plate to fabricate a new light-weight composite armor system. This armor system is tested under ballistic loading using 7.62x51 mm M80 and 7.62x63 mm M2 AP projectiles at varying impact velocities for single and multi-impact scenarios. The material behavior, failure mechanism, and ballistic performance of the armor system are studied for optimization.

© 2014 Elsevier Ltd. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/3.0/).

Keywords: Composite metal foam; Powder metallurgy; Ballistic; Energy absorption

1. Introduction

High performance ballistic protection systems are usually composed of different layers of materials with each layer providing a specific role in the attenuation of projectile energy. Typically, a hard material like ceramic or high hard steel is placed on the projectile strike face, and a softer para-aramid or polymer matrix composite is used as a back-plate. The role of the strike face is to decelerate and degrade the projectile by erosion, fracture, and tumble, while the softer back-plate absorbs the residual kinetic energy of the projectile and fragments, bringing it to rest (David (2009)). Ballistic panels composed of ceramic strike face and fiber reinforced back-plates have been widely studied and have proved to perform well in typical ballistic tests (Medvedovski (2010) Part 1, Medvedovski

* Corresponding author. Tel.: +1 919-513-2674; fax: +1 919-515-7968.
E-mail address: arabiei@ncsu.edu

doi:10.1016/j.mspro.2014.07.571
However, the complexity, high cost and high weight of these systems leaves much room for improvement.

Steel-Steel Composite Metal Foams (S-S CMF) have great potential for energy absorption under quasi-static and dynamic loading conditions (Rabiei (2006), Neville (2008), Rabiei (2009), Rabiei (2007), and Rabiei (2013)). Sintering hollow steel spheres in a compacted steel powder matrix gives CMF its low weight and high strength capabilities. Its foam structure, on the other hand, allows CMF to deform at high compressive stress (~136 MPa) to over 50% strains, thus absorbing great amounts of energy.

In this study, composite armor systems made of S-S CMF panels as backing plates in conjunction with strike face ceramic plates are tested under ballistic loading. The US National Institute of Justice (NIJ) ballistic test standard 0101.06 is used as a guideline to evaluate the ballistic performance of such armor system under impact from 7.62x51 mm M80 (Type III) and 7.62x63 mm M2 Armor Piercing (AP) (Type IV) projectiles for single and multi-shot scenarios.

2. Experimental Procedure

2.1. Materials and Processing

Composite Metal Foam (CMF) panels were manufactured using 2 mm diameter steel hollow spheres embedded in a stainless steel powder matrix using powder metallurgy (PM) techniques previously developed (Rabiei (2006), Neville (2008), Rabiei (2009), Rabiei (2007), and Rabiei (2013)). The hollow spheres were fabricated by Hollomet GmbH in Dresden, Germany, while 316L stainless steel powder with a particle size of 44 μm produced by North American Hoganas High Alloys LLC was used as the matrix material.

Boron Carbide (B₄C) ceramic tiles, 30cm x 30cm with different thicknesses were fabricated for use in the ballistic evaluation. The ceramic tiles were bonded to the CMF back-plate panels to create individual armor targets. All targets had a total thickness of less than 25 mm.

For ballistic testing, the armor system was placed against Roma Plastilina No. 1 clay. The ceramic - CMF armor system setup is shown in Figure 1A.

---

Figure 1. A) Composite armor system showing individual layers of ceramic and CMF placed against clay for ballistic testing and B) image of the ammunition used for Type III (M80) and IV (M2 AP) ballistic testing.

Figure 2. Ballistic test setup showing gun barrel, bullet velocity chronograph, and target location.
2.2. Ballistic Testing Procedure

Ballistic testing of the composite armor system was performed using the setup described in US government’s National Institute of Justice (NIJ) 0101.06 standard (U.S. Department of Justice (2008)) for both Type III and IV armor systems using 7.62x51 mm M80 and 7.62x63 mm M2 AP projectiles respectively (ammunition shown in Figure 1B). A “Mann” type gun, mounted on a two axis adjustable rig was used to aim and fire the projectiles. Velocity chronograph, situated between the gun and the target, was used to calculate the speed of the bullet to ensure projectiles impacted the armor system at the precise speeds specified by the standard. Two high speed digital cameras were aimed at the armor system’s front and back surfaces. The front high speed camera was used to observe projectile impact and its interaction with the ceramic strike face, while a second camera was used to obtain residual exit velocities at the rear of the sample, in the case of complete penetration of the bullet through the armor target. Figure 2 shows the notional setup for ballistic testing experiments.

3. Results and Discussion

3.1. Structural Properties

Digital images of the mesostructure of Steel-steel composite foam made with 2 mm hollow spheres are shown in Figure 3A-C. As can be observed in this figure, composite metal foam shows an even distribution of porosity throughout the entire surface of the panel with the powder matrix infiltrated between the spheres, bonding into a solid bulk material. Figure 3B shows the surface of CMF as processed, where the individual spheres can be seen arranged between the sintered metal-powder. Figure 3C shows a detail image of the cut section of the metal foam after Electrical Discharge Machining (EDM). This even distribution of same size porosities gives CMF its high strength and exceptional energy absorption capability.

3.2. Ballistic Performance

Images of the strike and rear face of the composite armor system after ballistic testing are shown in Figure 4A-B respectively for a Type III impact. The composite armor system formed by the combination of ceramic strike plate and S-S CMF backing plate showed superior ballistic performance against the Type III threat, completely stopping the projectile (Fig. 4A) in both single and multi-shot impacts at specification relevant impact velocities. Similarly, the armor system was able to completely degrade the hardened steel core of the Type IV armor piercing ammunition at velocities in excess of the NIJ Type IV standard. In Figure 4B, the composite metal foam shows compression at the center of the impact area, where the individual spheres are flattened. Some cracking is formed radially outward from the center of the impact area, at the bottom of the sample.

Typical deformation mechanism of an armor system is shown in Figure 5. Upon impact, the hard ceramic face plate shatters while deforming and eroding the tip of the projectile (Smith (1994)). The resulting damage pattern in the ceramic is conical in shape and serves to spread out the impact area so the kinetic energy of the bullet can be absorbed by the ductile backing plate over a larger area than the initial strike zone (Smith (1994)).

As penetration takes place, compressive waves reach the interface between the ceramic and the composite metal foam layer. Due to the mechanical impedance mismatch between the ceramic and the foam, residual tensile waves are formed and reflected back towards the impact point, forming the characteristic radial cracks on the ceramic material and an outward conical perforation on its cross section. The residual compressive waves, as well as the kinetic energy of the bullet, are absorbed by the CMF layer through the deformation of the foam, which then leaves an in-print signature on the ballistic clay (Figure 5). Volumes of material loss for ceramic in compression and tension ($V_{\text{ceramic}}^c$ and $V_{\text{ceramic}}^t$ respectively) and deformed volumes of CMF ($V_{\text{CMF}}$) and bullet ($V_{\text{bullet}}^c$), along with the perforation diameter, back face signature (BFS), and depth of penetration (DOP) into the clay were then measured after each test for energy absorption evaluation.
In order to quantify the ballistic performance of CMF within the armor system, and to determine the influence of impact velocity on the energy absorption capability of the CMF, an energy-based approach was utilized and compared to the energy absorption of CMF under quasi-static loading (Rabiei (2013)).

In ballistic impacts, most of the kinetic energy of the bullet is transformed into brittle fracture of the ceramic under compression and tension, plastic deformation of the projectile and backing plate, and heat. For this study, and since the local temperature at the point of impact could not be measured, the heat generation is considered negligible for energy calculations. The kinetic energy of the bullet ($E_{KE}$) must then be transferred to the armor system as the energy required for plastic deformation of the bullet ($E_{bullet}$), energy absorbed by the ceramic ($E_{ceramic}$) and CMF (ECMF), and residual energy from clay deformation or debris ejected from the target in the event of complete penetration ($E_{res}$) as below:

$$E_{KE} = E_{bullet} + E_{ceramic} + E_{CMF} + E_{res}$$  \hspace{1cm} (1)

Similar studies on energy absorption of armor systems have been reported in the literature (Naik (2012)). The energy per unit volume of material for the projectile, ceramic, and clay can be calculated from their respective stress-strain curves by calculating the area under the curve. By multiplying this energy values by the volume of the material undergoing plastic deformation, the total energy absorbed per each component in composite armor system (bullet, ceramic, CMF) and residual energies (clay, etc.) can be approximated.
Table 1. Energy absorbed by each armor component at given bullet speeds

| Type | Impact Velocity (m/s) | Bullet Energy (J) | E_{CMF} (J) | E_{ceramic} (J) | E_{res} (J) | E_{bullet} (J) | Dynamic/Quasistatic Energy Absorption Ratio |
|------|-----------------------|-------------------|-------------|---------------|-------------|---------------|---------------------------------------------|
| IV   | 869.0                 | 4077.8            | 2812.7      | 35.3          | 0.2         | 1229.6        | 3.1                                         |
|      | 861.7                 | 4009.5            | 2717.8      | 61.8          | 0.3         |               | 2.5                                         |
| III  | 853.1                 | 3511.9            | 2935.2      | 110.9         | 1.8         |               | 2.9                                         |
|      | 861.1                 | 3577.5            | 2932.8      | 179.1         | 1.6         |               | 2.9                                         |
|      | 852.5                 | 3506.9            | 2865.5      | 176.0         | 1.5         |               | 2.9                                         |
|      | 549.6                 | 1457.2            | 957.6       | 35.4          | 0.4         | 464.0         | 1.9                                         |
|      | 534.6                 | 1379.1            | 888.8       | 26.1          | 0.3         |               | 1.8                                         |
|      | 571.5                 | 1575.9            | 1083.7      | 28.1          | 0.2         |               | 2.5                                         |
|      | 578.8                 | 1616.5            | 1120.0      | 32.4          | 0.3         |               | 2.1                                         |

For the bullet material properties, a dynamic yield strength of 80 MPa for a lead-antimony alloy core and 200 MPa for the brass jacket (Type III bullet) (Peroni (2012)), with the strain hardening from the literature (Peroni (2012)) were considered. 2.0 GPa compressive and tensile yield strength for a hardened steel projectile (Type IV) (Johnson (1983)) were also considered. For the Type III threat, a maximum deformation under compression for lead-antimony is taken as 50%, after that, the entire bullet is eroded under tensile stresses since no residue of lead projectile was found embedded in the ceramic/CMF (only some brass residue was found). For the Type IV threat, the hardened steel penetrator exhibited complete erosion. Consequently, a failure strain of 50% was considered for energy calculations with the total volume compressed (V^C_{bullet}) of 70%, with complete failure under tension after that, since other than the jacket fragments, no visible particles of hardened steel were found after the tests.

For the ceramic material, compressive and tensile maximum strengths were considered, along with the corresponding compressive and tensile volumes of material failed after tests, as shown in Figure 5, in order to calculate the energy absorbed by the ceramic (E_{ceramic}).

Residual energy (E_{res}) was calculated from BFS and DOP measurements on clay, and residual velocities of particles obtained from high speed video.

The energy absorbed by the composite foam (E_{CMF}) can then be estimated from equation (1) and divided by the volume of CMF undergoing plastic deformation (V_{CMF}). In order to understand the effect of loading rate on the foam, the dynamic energy absorbed by the CMF panel for each ballistic test was divided by its quasi-static energy absorption (53 MJ/m^3 on average) and plotted against bullet speed in Figure 6 for both Type III and IV tests. All of these energy results are shown in Table 1.

The results shown in Figure 6 suggest an increase in energy absorption of the CMF material with increasing impact speed, which agrees with previous test results generated at lower impact speeds up to 30 m/s (Rabiei (2013)). This increase in strength and energy absorption capability of the composite foam can be related to the inertia of the spheres and the air trapped inside the spheres and porosities which further resist deformation at higher loading rates.

![Figure 6. Ratio of dynamic energy absorbed per unit volume of CMF in ballistic tests normalized by the energy/volume from quasistatic compression tests for different impact velocities](image-url)
It is notable that multiple energy absorption numbers on the chart that are related to the same speed are for samples with various thicknesses of ceramic face-plates. Nevertheless, an increase in the energy absorption per unit volume of the composite foams by a factor of 3, for impact speeds up to 870 m/s is observed.

4. Summary

In order to create a high performance ballistic armor system, a ceramic face-plate with high hardness was bonded to a steel-steel composite metal foam processed by powder metallurgy using 2 mm sphere. The armor system was tested under ballistic loading against the 7.62x51 mm M80 and 7.62x63 mm M2 AP projectiles (Type III and IV respectively) according to US NIJ 0101.06 standard. The results of the ballistic tests were successful at demonstrating the ability of this unique material to absorb ballistic impact energy. The armor system successfully stopped Type III threats, with the ceramic layer blunting and eroding the projectile, and the CMF layer absorbing over three quarters of initial kinetic energy of the projectile through plastic deformation. The armor system was also capable of defeating Type IV threats by completely eroding and fracturing the hardened steel core of the projectile. In this study, steel-steel composite metal foam showed high performance for high speed/high energy absorption applications, with over 3-times increase in energy absorption of the material at impact speeds up to 870 m/s.

5. Acknowledgements

The authors would like to acknowledge North Carolina State University’s Chancellor Innovation Fund (CIF) for its financial support that made this project possible. Special thanks to Dr. Rob Bryant and his team at the Advanced Materials and Processing Branch at NASA Langley Research Center, for granting access to their material processing facilities.

References

Colombo, P., Zordan F., Medvedovski E., 2006. Ceramic-Polymer Composites for Ballistic Protection. Advances in Applied Ceramics 105, 2, 78-83.
David, N.V., Gao X.-L., Zheng J.Q., 2009. Ballistic Resistant Body Armor: Contemporary and Prospective Materials and Related Protection Mechanisms. Applied Mechanics Reviews 62, 5.
Johnson, G.R., Cook, W.H., 1983. A Constitutive Model and Data for Metals Subjected to Large Strains, High Strain Rates and High Temperatures. 7th Int. Symp. Ballist. 21, 541.
Medvedovski, E., 2010. Ballistic Performance of Armour Ceramics: Influence of Design and Structure. Part 1. Ceramics International 36, 2103-2115.
Medvedovski, E., 2010. Ballistic Performance of Armour Ceramics: Influence of Design and Structure. Part 2. Ceramics International 36, 2117-2127.
Naik, N.K., Kumar, S., Ratnaveer, D., Joshi, M., Akella, K., 2012. An Energy-based Model for Ballistic Impact Analysis of Ceramic-composite Armors. Int. J. of Damage Mechanics 0, 0, 1-43.
Neville, B.P., Rabiei A., 2008. Composite Metal Foams Processed through Powder Metallurgy. Mater. Des. 29, 388-396.
Peroni, L., Scapin, M., Fichera, C., Manes, A. Giglio, M., 2012. Mechanical Properties at High-Strain of Lead Core and Brass Jacket of a Nato 7.62 mm Ball Bullet. EPJ Web of Conferences 26,01060.
Rabiei A., Garcia-Avila M., 2013. Effect of Various Parameters on Properties of Composite Steel Foams under Variety of Loading Rates. Mater. Sci. Eng. A 564, 539-547.
Rabiei A., Neville B., Reese N., Vendra L., 2007. New Composite Metal Foams Under Compressive Cyclic Loadings. Mater. Sci. Forum 1868, 539-543.
Rabiei A., Vendra L.J., 2009. A Comparison of Composite Metal Foam’s Properties and Other Comparable Metal Foams. Mater. Lett. 63, 533-536.
Rabiei A., Vendra L., Reese N., Young N., Neville B.P., 2006. Processing and Characterization of a New Composite Metal Foam. Mater. Trans. 47, 2148.
Smith, P., Hetherington, J., 1994. Ballistic Loading of Structures. Butterworth-Heinemann, Oxford, U.K.
U.S. Department of Justice, 2008. Ballistic Resistance of Body Armor NIJ Standard 0101.06. NIJ.