Computational Study of a Functionally Graded Ceramic-Metallic Armor

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Functionally graded materials (FGM) are material candidates for niche Army applications such as armor. Development of an FGM with a tailored ceramic-to-metal through-thickness gradient is one approach where an improved mass and space armor material for ballistic protection can conceivably be provided. This work investigates the ballistic efficiency of a postulated FGM ceramic-metallic armor system composed of aluminum nitride (AlN) and aluminum. The study had two primary objectives: 1) development of a method to model an FGM, and 2) examination of the computationally derived ballistic performance of the FGM armor system.

The FGM was modeled as a series of discrete (bonded) layers, with adjusted material parameters such as density and strength, to approximate a gradient structure. The Johnson-Holmquist-Beissel ceramic model was used for the AlN and the Johnson-Cook metal model was used for the aluminum, and the computations were performed using the EPIC code. For a discrete six layer system with appropriately adjusted material parameters, results showed an increase of approximately 15% in the ballistic performance of the simulated FGM when compared to an equivalent target composed of AlN and aluminum. This paper will present the results of the computations of this implementation, and discuss the limitations of the computational approach.

INTRODUCTION

Development of lightweight, high performance armor for ballistic protection is a critical need for ground platforms. Appearance of increasingly lethal ballistic threats (e.g. 12.7 mm armor piercing (AP) versus 7.62 mm ball projectiles) have resulted in the necessity for more robust (and generally heavier) armor solutions to provide the required survivability against such escalating threats. Functionally graded materials

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(FGM) have been proposed as potential candidates for these niche Army applications. Development of an FGM with a tailored ceramic-to-metal through-thickness gradient is one approach where an improved mass and space armor material for ballistic protection can conceivably be provided [1]. FGMs offer several advantages for use in ballistic protection designs as the ceramic/metal composite can support a large structural load; there is an absence of abrupt impedance changes and no discrete material interfaces; and the metallic back is usable for mechanical attachment. A build-test-rebuild development approach for such materials is highly time and cost inefficient, and would likely lead to very limited use of the FGM even is successful due to the extended time for fielding. A better approach is to make use of high performance modeling (with hydrocodes like EPIC) to derive desired through-thickness gradients in material strength for optimal performance of the FGM as armor, and then to computationally evaluate that notional construct's ballistic performance. The subsequent implementation of a proposed design is then passed to appropriate parties for fabrication. Prior work [2, 3] has looked primarily at TiB-Ti FGM systems; however, the current EPIC library of materials limited the choice of potential FGM armors that could be examined, but the basic approach would still be valid as new materials are added. For this reason, a postulated system of aluminum nitride (AlN) and aluminum (Al) was chosen. Although we attempted to consider a realistic material system, the ability to make a specific design was not considered.

MODELING APPROACH

The FGM was modeled as a series of discrete (bonded) layers, with adjusted material parameters such as density and strength, to approximate a gradient structure [4]. The modeling approach used to model a graded armor system incorporates the use of three models. The JHB model [5] is used for the brittle materials and the Johnson-Cook (JC) strength and fracture models [6, 7] are used for the metals. The JC strength model is reduced to a simple two constant model and is expressed as

$$\sigma = C1 + C4P \tag{1}$$

where C1 is the initial strength and C4 is the pressure term. The original JC strength model did not include a pressure dependency, but was added later to expand its capability [8].

The most difficult aspect of modeling a FGM is how to account for the changing material behavior going from the top layer, to the bottom layer. The design goal of a FGM is to produce a target that has a gradual change in material behavior, typically going from a strong, brittle response on the top, to a soft, ductile response on the bottom. This gradual change in material response, through the thickness of the target, is thought to improve the ballistic response over a simple two material target. The modeling approach used herein models the FGM as a number of discrete, bonded layers, each having its own material response. The JHB model is used to represent the more brittle layers and the JC models are used to represent the more ductile layers.

For this work, two targets are investigated, a two-layer target and a six-layer target as presented in Figure 1. The two-layer (referred to as standard) target is a traditional configuration consisting of a hard, brittle top layer (aluminum nitride) backed by a soft, ductile rear layer (aluminum). The JHB model is used for the aluminum nitride (AlN) and the Johnson-Cook models are used for the aluminum (Al). The constants are listed in Table I where the AlN is described by layer 1 and the Al is described by layer 6. The six-layer (gradient) target is an attempt at modeling a FGM target by gradually changing the material properties for each layer. The JHB model is used to describe the top three layers (layers 1-3) and the JC models are used for the bottom three layers (layers 4-6). The general idea is to modify the properties of each layer such that they transition from the top layer (AlN) to the bottom layer (Al) in a systematic manner. For example, the density of AlN is $\rho = 3.336$ g/cm^3 and the density of Al is $\rho = 2.768$ g/ cm^3. A reasonable transition in density, from layer 1 to 6, would be $\rho = 3.336$ g/cm^3, $\rho = 3.134$ g/cm^3 , $\rho = 3.043$ g/cm^3 $\rho = 2.951$ g/cm^3 $\rho = 2.860$ g/cm^3 and $\rho = 2.768$ g/cm^3 respectively (this also ensures that the mass of the two layer target is equal to the six layer target). Similarly, the strength and fracture characteristics were transitioned from a strong and brittle behavior for layer 1 to a weak and ductile behavior for layer 6. A schematic of the strength and ductility (strain to failure) used for each of the six layers is presented in Figure 2 and the model constants are provided in Table I. It should be noted that the responses (for each of the 6 layers) presented in Figure 2 are subjective and different responses could have been chosen. Using different responses will produce different computed results.

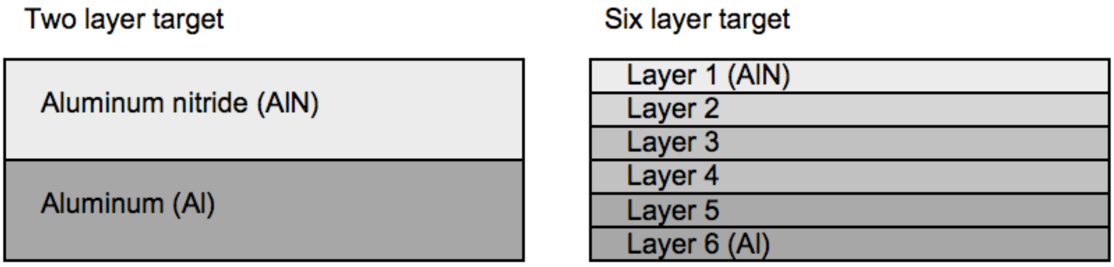

Figure 1. Initial geometry for the two (standard) and six (gradient) layered target.

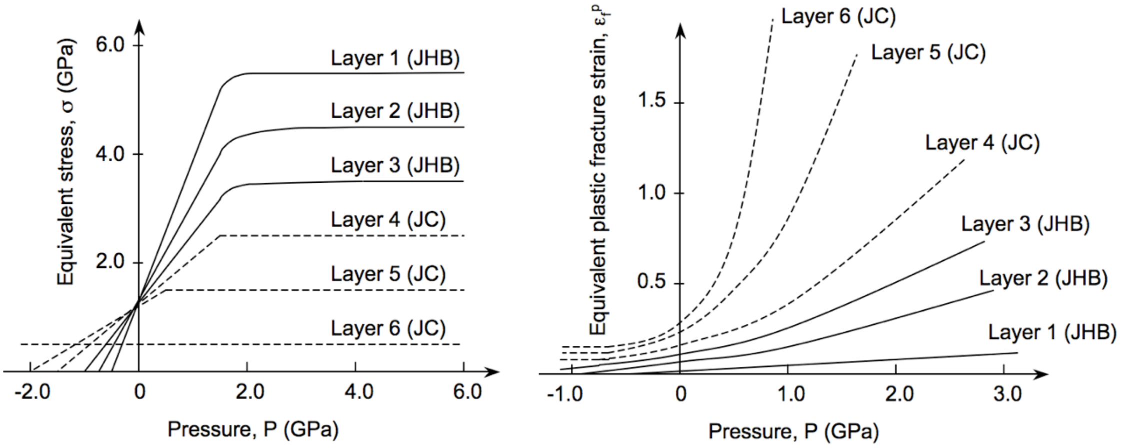

Figure 2. A schematic of the strengths (shown on the left) and fracture responses (shown on the right) for each of the six layers in the target.

	Layer 1	**Layer 2**	**Layer 3**	**Layer 4**	**Layer 5**	**Layer 6**
Density, ρ (Kg/m^3)	**3226**	**3134**	**3043**	**2951**	**2860**	**2768**
Shear Modulus, G (GPa)	**127**	**107**	**87**	**66**	**46**	**26**
Tensile Strength, T (GPa)	**0.50**	**0.75**	**1.00**			
Intact Strength, σ_i (GPa)	**4.31**	**3.50**	**2.80**			
Maximum Strength, s_{max} (GPa)	**5.50**	**4.50**	**3.50**	**2.50**	**1.50**	**0**
Maximum Failed Strength, s_{max}^* (GPa)	**0.20**	**0.16**	**0.12**			
Bulk Modulus, K1 (GPa)	**201**	**176**	**151**	**127**	**102**	**77**
Pressure Constant, K2 (GPa)	**260**	**234**	**207**	**181**	**154**	**128**
Pressure Constant, K3 (GPa)	**0**	**25**	**50**	**75**	**100**	**125**
Damage Constant, D1	**0.16**	**0.56**	**0.63**			
Damage Exponent, N	**1.00**	**1.26**	**1.47**			
Specific Heat, c (J/kg-^{o}C)	**735**	**763**	**791**	**820**	**848**	**876**
Yield Stress, C1 (GPa)				**1.25**	**1.0**	**0.5**
Pressure Coefficient, C4				**0.83**	**0.5**	**0**
MaximumStrength, s_{max} (GPa)				**2.5**	**1.5**	**0**
Fracture Constant, D1				**0**	**0**	**0.14**
Fracture Constant, D2				**0.16**	**0.22**	**0.14**
Fracture Constant, D3				**-2.1**	**-2.0**	**-1.5**

Table I. Material model constants used for the two and six layer targets.

COMPUTED RESULTS

Computations were done to determine a ballistic limit for both targets when impacted by a bullet-like projectile composed of S-7 hard tool steel with a length and diameter, respectively, of 75 and 15 mm for an L/D ratio of 5. Ballistic limit results obtained showed the standard target was perforated at 848 m/s and the gradient modified target at 1004 m/s, indicating a performance improvement of approximately 15% (Figure 3).

The damage plot results for the FGM with a projectile velocity of 1000 m/sec are shown in Figure 4. The standard target has been perforated while only moderately eroding the projectile; the gradient target has completely stopped it. In the standard target the AlN layer has completed failed at 50 μsec and there is failed material appearing at the back side of the target already, while in the gradient target it appears that only the first layer has completely failed and the second layer is almost totally failed. There is no failure at the back side, and it appears that the projectile may be dwelling on the target. By 100 μsec the Al back side of the standard target has failed and the projectile has perforated the target. In the gradient target at the same time, fully

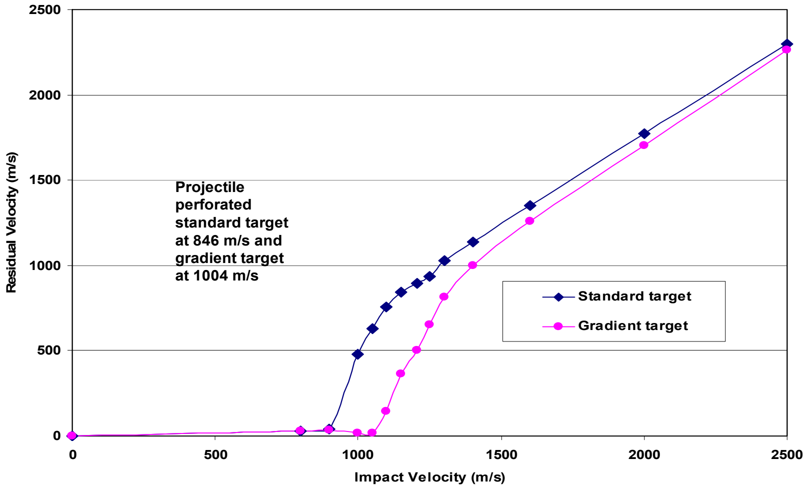

Figure 3. Computed ballistic limit of the 2 layer and six layer targets.

damaged (failed) material has appeared under the projectile to the 5th layer. At 150 µsec the projectile has passed through the two layer target, while stopped in the gradient. The bottom layer in the gradient target has damage, but is not failed. A "modified" conoidal damage region has formed underneath the impact point. Unlike the normal conoid which expands to the outer surface in a typical ceramic target, this region appears to expand and then shrink as the bottom layers become less cermet and more metallic. Figure 5 is a kinetic energy plot of the two targets versus time. At ~50 µsec, where the plots for the two targets begin to diverge, (as noted above) the standard target has failed completely in the ceramic layer and has an initiation of failed material at the rear surface.

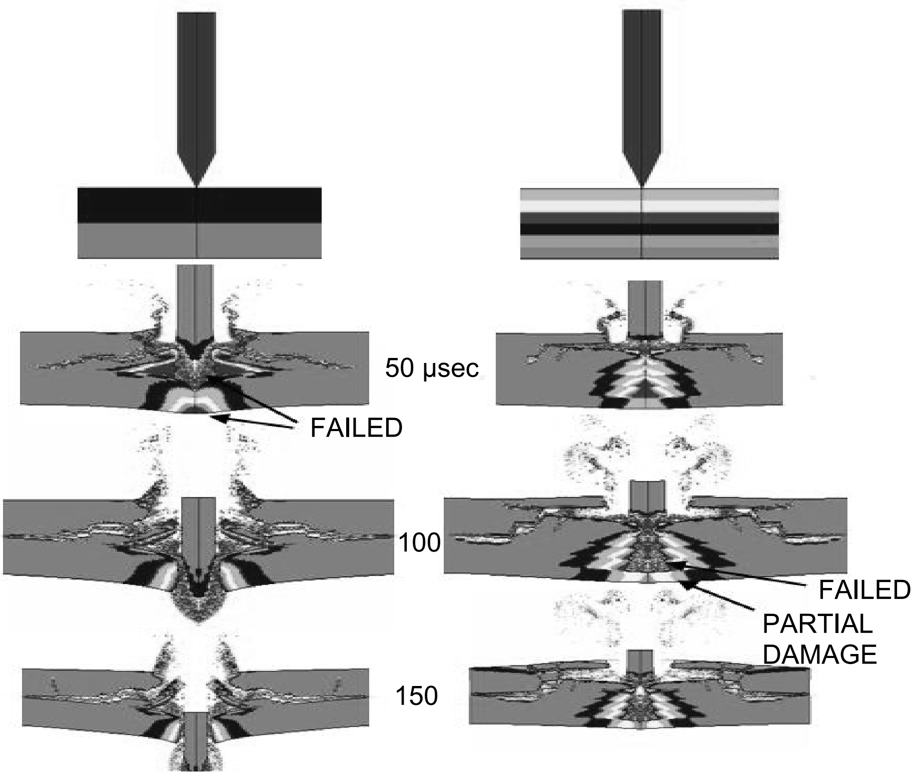

Figure 4. Damage plots of the for the standard (left) and gradient (right) layer targets at 1000 m/s

FAILED

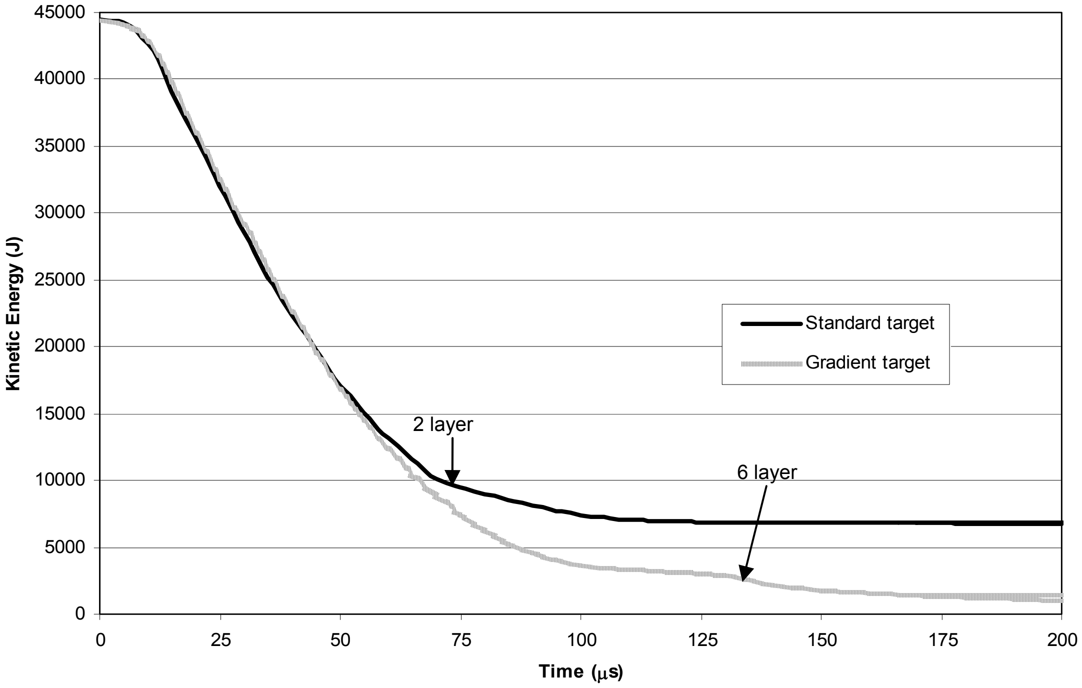

Figure 5. Kinetic energy at a projectile velocity of 1000 m/s.

SUMMARY AND CONCLUSIONS

A notional FGM of aluminum nitride and aluminum was modeled as a series of discrete (bonded) layers, with adjusted material parameters to approximate a gradient structure. The Johnson-Holmquist-Beissel ceramic model was used for the AlN and the Johnson-Cook metal model was used for the aluminum, and the computations were performed using the EPIC code. For a discrete six layer system with appropriately adjusted material parameters, results showed a increase of approximately 15% in the ballistic performance of the simulated FGM when compared to an equivalent target composed of AlN and aluminum.

The results show that additional study of such FGM armors is warranted, and could provide valuable information in guiding the development of such armors by eliminating the need to pursue designs which do not provide required improvements in ballistic performance. As with any computational studies, the need to produce hardware for experimental testing and validation is not eliminated, but made more efficient.

Additional work needs to be done to populate the material database in order to enable other FGM combinations to be examined and evaluated. Coordination with material processing experts is essential to assure that only physically realizable systems are scrutinized.

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