A Study on Propagation Characteristic of One-dimensional Stress Wave in Functionally Graded Armor Composites

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Abstract. The development of Functionally Graded Materials (FGM) for energy-absorbing applications requires understanding of stress wave propagation in these structures in order to optimize their resistance to failure. One-dimensional stress wave in FGM composites under elastic and plastic wave loading have been investigated. The stress distributions through the thickness and stress status have been analyzed and some comparisons have been done with the materials of sharp interfaces (two-layered material). The results demonstrate that the gradient structure design greatly decreases the severity of the stress concentrations at the interfaces and there are no clear differences in stress distribution in FGM composites under elastic and plastic wave loading.

1. Introduction
Early composite targets were made by simply bonding a ceramic tile to a metal backing plate. The underlying idea is to use the hard ceramic layer to defeat and erode the projectile, and to use the backing plate to absorb the impact energy and increase the fracture resistance of the target. The full potential of ceramic hard facing layers has not been achieved because the interface between ceramic and metal has an unfavorable impedance mismatch that may even induce tensile failure. At present, functionally graded materials (FGM) was introduced to armor structure design. The advantage of using FGM is their superior resistance to interfacial failure. Analytical and computational studies of the evolution of stresses and displacements in FGM show that the utilization and optimization of structures and geometry of a graded interface between two dissimilar layers can reduce stresses significantly. The emergence of functionally graded materials (FGM) provides a possible avenue for solving this problem since an FGM layer between the ceramic and metal can make the impedance change continuous rather than abrupt. FGM materials could, therefore, reduce the intensity of reflected

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stress waves, so the tensile stresses might be reduced or even removed entirely.

Some simplified analytical models [1-3] and numerical simulations [4] have been developed and used for the analysis and optimization of materials consisting of layers of different materials. But there is as yet no consistent method available to evaluate and compare composites with different layering configurations and varying layer properties. It is difficult to use case-by-case simulations to gain a systematic understanding of the ballistic response of composite structures. Without such a systematic understanding, development and optimization of composite structures often becomes a trial-and-error process. In this paper, we want to investigate one-dimensional stress wave in FGM composites under elastic and plastic wave loading and analyze the stress distribution through the thickness.

So this paper tries to demonstrate and understand the propagation characteristics of elastic and plastic stress wave in FGM. The numerical simulation has been implemented in accordance with standard split Hopkinson pressure bar (SHPB). The striker bar impact the incident bar at velocities of 15 and 25 m/s, respectively, which lead to the elastic and plastic stress wave in the specimen. A notional FGM of aluminum nitride (AlN) and aluminum (Al) was modeled as a series of discrete (bonded) layers, with adjusted material parameters to approximate a gradient structure. Some comparisons have been done with the materials of sharp interfaces (bi-layered specimens).

2. Modeling approach

2.1 Computed models

![Image](image.png)

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

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 specimen 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. For this work, two specimens are investigated, a two-layered specimen and a six-layer specimen with a linear function as shown in figure 1. The two-layer specimen is a traditional configuration consisting of a hard, brittle top layer (aluminum nitride) backed by a soft, ductile layer (aluminum). The six-layer specimen is treated as a system of discrete layers, which transit from the top layer (AlN) to the bottom layer (Al) in a systematic manner. The JH-2 model is used to describe the top three layers (layers 1-3) and the JC model is used for the bottom three layers (layers 4-6). The distribution characteristics of ceramic volume fraction for the six layer specimen are shown in figure 2.

In the numerical model, the interfaces between all layers are regarded as perfect interfaces, in which shear slip is ignored. The height and diameter of all specimens are 2cm and 6mm, respectively.

2.2 Material parameters

The modeling approach used to model a graded material incorporates the use of two models. The JH-2
[5] model is used for the rock-like materials. The Johnson-cook(JC) [6] strength and fracture models are used for the metal. The JH-2 model is used to represent the more brittle layers. The JC models are used to represent the more ductile layers. In our work, the JH-2 model is used to describe the left three layers (layers 1-3), and the JC models are used for the right three layers (layers 4-6). The general idea is to modify the properties of each layer such that they transit from the top layer (AlN) to the bottom layer (Al) in a systematic manner. The constants are listed in table 1 where the AlN is described by layer 1 and the Al is described by layer 6. The six-layer (gradient) specimen is an attempt at modeling a FGM specimen by gradually changing the material properties for each layer. Similarly, the strength and fracture characteristics could also be transited from a strong and brittle behavior for layer 1 to a weak and ductile behavior for layer 6.

![Figure 2. Distribution characteristics of ceramic volume fraction for the six-layer specimen](image)

Table 2. Material model constants used for the two and six layer specimens

| Constant               | Layer1  | Layer2  | Layer3  | Layer4  | Layer5  | Layer6  |
|------------------------|---------|---------|---------|---------|---------|---------|
| Density (Kg/m³)        | 3226    | 3134    | 3043    | 2951    | 2860    | 2768    |
| Bulk Modulus (GPa)     | 201     | 176     | 151     | 127     | 102     | 77      |
| Shear Modulus (GPa)    | 127     | 107     | 87      | 66      | 46      | 26      |
| K2 (GPa)               | 260     | 234     | 207     | 181     | 154     | 128     |
| K3 (GPa)               | 0       | 25      | 50      | 75      | 100     | 125     |
| HEL(GPa)               | 6.41608 | 5.33188 | 4.3959  |         |         |         |
| p HEL                  | 3.54462 | 2.99539 | 2.52756 |         |         |         |
| Equivalent Stress (GPa)| 4.3072  | 3.50475 | 2.8025  |         |         |         |
| Tensile Strength (GPa), T | 0.50    | 0.75    | 1.00    |         |         |         |
| Strength Constant (GPa), A | 0.96246 | 0.93725 | 0.90785 |         |         |         |
| Fractured Constant B (GPa)| 0.20    | 0.16    | 0.12    |         |         |         |
| Fractured Exponent M   | 0.21    | 0.21    | 0.21    |         |         |         |
| D1                     | 0.16    | 0.56    | 0.63    |         |         |         |
| D2                     | 1.00    | 1.26    | 1.47    |         |         |         |
| Specific Heat (J/Kg °C) | 735     | 763     | 791     | 820     | 848     | 876     |

3. Computed result and discussion

3.1. Propagation characteristic of elastic stress wave
Computations were done to determine the propagation characteristic of elastic stress wave, while the striker bar impact at the velocity of 15m/s. Figure 4 shows the pressure-time histories from the bi-layered specimen. Numerical sample points in the specimen are shown in figure 3. Because the bi-layered (ceramic/metal) specimen has a sharp interface which is more likely to lead to tensile stresses, it is necessary to observe the load characteristic of the bi-layered specimen at first. From figure 4, some phenomenon can be observed: (1) the pressures value of all numerical sample-points are still equal to zero after unloading finish, which indicates that materials do not exhibit yield behavior; (2) The lowest pressure is still greater than zero, which indicates that there is no negative pressure zone when the stress waves go through the specimens.

Figure 3. Numerical sample-point in the specimen

Figure 4. The pressure-time histories for all numerical sample points of bi-layered specimen.

Figure 5 shows the effective stress distribution through the thickness of bi-layered and FGM specimens. Stress concentration is found at the ceramic/aluminum interface in the bi-layered specimen and the maximum stress value locates at the ceramic layer near interface. In FGM specimen, there is no obvious stress concentration, and the maximum stress value locates at the middle of the metal-like components. The results reveal that the gradient structure design greatly decreases the severity of the stress gradient at the interfaces during the elastic deformation.

Figure 5. The effective stress distribution through the thickness (Time=250μs)

3.2 Propagation characteristic of plastic stress wave

Computations were done to determine propagation characteristic of plastic stress wave, while the striker bar impact at the velocity of 25m/s. Figure 6 shows the pressure-time histories from the bi-
layered and FGM specimens. Numerical sample-points in the specimen are the same to that of the figure 3. We can find both bi-layered and FGM specimens have experienced plastic deformation (some pressure values still retain negative after the stress waves go through the specimens). During the stress wave loading, a negative pressure zone at the interface between ceramic and metal have appeared in the bi-layered specimen, while the FGM specimen still retains compressive status.

**Figure 6.** The pressure-time histories for all numerical sample points of bi-layered and FGM specimen.

Figure 7 shows comparisons of the effective stress distribution through the thickness at 250μs (at the higher striker bar velocities). When compared with the low striker bar velocities, no obvious difference of distribution characteristics can be found except higher stress values. The region of high stress concentration still appears at the ceramic layer near ceramic/aluminum interface in the bi-layered specimen. In FGM specimen, the high stress still located at the middle of the metal-like components but the stress gradient become severe.

The literature [7] also compared the elastic and plastic deformation of FGM. The results show plastic deformation of the materials can significantly affect their response to wave propagation. In particular, a major effect of plastic deformation is to lead to a more homogeneous stress distribution within the components. In our work, the similar mechanical phenomenon has not been found.

4. Summary

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
ceramic model was used for the AlN, and the Johnson-Cook metal model was used for the aluminum, with the computations performed using the LS-DYNA code. We have investigated the propagation characteristic of one-dimensional stress wave with the low and high striker bar velocities.

Comparing with bi-layered specimens, we obtain the following conclusions.

1. The bi-layered specimen has obvious stress concentrations at the ceramic layer near the interface between the ceramic and metal (whether elastic or plastic wave). The gradient structure design greatly decreases the severity of the stress concentration at the interface.

2. There is no negative pressure zone in both bi-layered and FGM specimens under the elastic loading. But under the plastic loading, the bi-layered specimen has a negative pressure zone at the interface between ceramic and metal.

3. Compared with the low striker bar velocities, there is no obvious distinction in the distribution characteristics in the higher striker bar velocity, except higher stress values.

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