The influence of ALN-Al gradient material gradient index on ballistic performance

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Abstract: Ballistic performance of the gradient material is superior to laminated material, and gradient materials have different gradient types. Using ls-dyna to simulate the ballistic performance of ALN–Al gradient target plates which contain three gradient index (b = 1, b = 0.5, b = 2). Through Hopkinson bar numerical simulation to the target plate materials, we obtained the reflection stress wave and transmission stress wave state of gradient material to get the best gradient index. The internal stress state of gradient material is simulated by amplification processing of the target plate model. When the gradient index b is equal to 1, the gradient target plate is best of all.

1. Introduction
In the double composite armor system, due to the differences of elastic modulus, hardness, density between ceramic panel and toughness panel, it result in layer acoustic impedance mismatching and stress concentration. Under the impact of projectile, the reflection tensile wave cause ceramic panel serious damage, which greatly limits the target plate ballistic performance. In the 1990 s, American scientists put forward a new gradient armor concept, and it gradually becomes the development trend of armor materials. The content of gradient armor varied with the thickness (step change) in the middle of the transition layer, not only reserved the ceramic material resistance to penetration of the superior performance, but also having good toughness metal materials, that can improve the composite target plate ability to resistance to penetration[1]. The study of gradient material impact behavior, there are two ways to describe gradient material constitutive. One way is that determining to use JH2 or JC constitutive equation by the volume fraction of ceramic. We choose using JH2 constitutive when volume fraction of ceramic is higher than fifty percent, otherwise using JC constitutive. Like Douglas W. Templeton, he uses interpolation to describe the middle intermediate layers material properties, and results shows an increase of approximately 15% in the ballistic performance of the simulated FGM when compared to double laminated armor [2]. Another way is using a new constitutive to describe gradient material. Like Y. Li and K. T. Ramesh, they put forward an equation to describe the stress-strain relationship of mixed material, and get several gradient structure stress states [3][4]. But they have no further analysis to get the optimization of gradient type. And theoretically for
gradient materials are also deduced. Hugh A. Bruck use one-dimensional model to get a time delay phenomenon, which despond on the composition gradient and the difference in base material properties. This is presented by time-history profiles of reflected stress waves[5]. Therefore, this paper not only studies AlN-Al gradient armor gradient index for the influence on ballistic performance, but also to get the optimization of gradient index by the time-history profiles of reflected stress waves.

2. Numerical simulation of ballistic performance to gradient armor

2.1 Numerical simulation model

The whole model take 1/4 modeling, and the radius of projectile is 0.5 cm, length is 5 cm. The total thickness of target plates is 3 cm, and we choose six layers to ensure the accuracy and calculated amount about gradient material. Each layer thickness is 0.5 cm, and radius is 10 cm, and the nodes are tied between layer and layer.

2.2. Material parameters

| Density (g/cm³) | Elastic modulus (GPa) | Poisson ratio | Yield stress (GPa) | Tangent modulus (GPa) | Beta |
|----------------|-----------------------|--------------|-------------------|-----------------------|------|
| 7.65           | 200                   | 0.29         | 1.6               | 80                    | 1.0  |

Considered three target plates gradient model and the variation about ceramic volume fraction of ALN with the thickness are shown as follows equation 1:

\[ f(z) = \left( \frac{z}{h} \right)^b \] (1)

- \( b \) — interpolation index;
- \( h \) — target plate thickness;
- \( z \) — along the thickness direction coordinate values;

We take \( b \) is 2, 1, and 0.5, as shown in figure 2:

Figure 2 ALN volume fraction varied with the thickness of the target

Target plate material parameters (b=1) is shown in figure 3[3]: The Constitutive model of layer 1 is the AlN JH2 material model, layer 6 is Al JC material model, and the middle layer material parameters are obtained by the equation 1. When \( b = 1 \), layer 1, 2, 3 is JH2 material model, and layer 4, 5, 6 is JC material model; When \( b = 0.5 \), layer 1, 2, 3, 4 is JH2 material model, and layer 5, 6 is JC material model; when \( B = 2 \), layer 1, 2 is JH2 material model, and layer 3,4,5,6 is JC material model.
The top three layer material model parameters of double laminated are pure ceramics, and the others are pure metal aluminum.

| Layer 1 | Layer 2 | Layer 3 | Layer 4 | Layer 5 | Layer 6 |
|---------|---------|---------|---------|---------|---------|
| Density, $\rho$ (Kg/m$^3$) | 3226 | 3134 | 3043 | 2951 | 2860 | 2768 |
| Shear Modulus, G (GPa) | 127 | 107 | 87 | 66 | 46 | 20 |
| Tensile Strength, $T$ (GPa) | 0.50 | 0.75 | 1.00 | | | |
| Intact Strength, $c$ (GPa) | 4.31 | 3.50 | 2.80 | | | |
| Maximum Strength, $s_{\text{max}}$ (GPa) | 5.50 | 4.50 | 3.50 | 2.50 | 1.59 | 0 |
| Maximum Failed Strength, $s_{\text{max}}$ (GPa) | 0.20 | 0.16 | 0.12 | | | |
| Bulk Modulus, $K_1$ (GPa) | 201 | 176 | 151 | 127 | 102 | 77 |
| Pressure Constant, $K_2$ (GPa) | 260 | 234 | 207 | 181 | 154 | 128 |
| Pressure Constant, $K_3$ (GPa) | 0 | 25 | 50 | 75 | 100 | 128 |
| Damage Constant, $D_1$ | 0.16 | 0.56 | 0.63 | | | |
| Damage Exponent, $N$ | 1.00 | 1.26 | 1.47 | | | |
| Specific Heat, $c$ (J/kg°C) | 735 | 763 | 791 | 820 | 848 | 876 |
| Yield Stress, $C_1$ (GPa) | 1.25 | 1.00 | 0.50 | | | |
| Pressure Coefficient, $C_4$ | 0.63 | 0.50 | 0.00 | | | |
| Maximum Strength, $s_{\text{max}}$ (GPa) | 2.50 | 1.50 | 0.50 | | | |
| Fracture Constant, $D_1$ | 0 | 0 | 0.14 | | | |
| Fracture Constant, $D_2$ | 0.16 | 0.22 | 0.14 | | | |
| Fracture Constant, $D_3$ | -2.1 | -2.0 | -1.5 | | | |

**Figure 3** target plate material parameters (b=1)

### 2.3 Ballistic Performances Results

From Figure 4, we can get the residual velocity of the projectile, the kinetic energy of the projectile, and penetration depth of the target plates about four kinds of target. And it can be seen that the ballistic performances of target (the gradient index $b = 1$) is best, and the double laminate composite is worst.

#### 3. Numerical Simulation of Hopkinson Bar

According to the theory about one dimensional stress wave, the peak value of target plate material
reflection wave is smaller, then the ballistic performance of target plate is better [6].

![Figure 5 Hopkinson bar model](image1)

The whole model contains impact bar, incident bar, target plate material, transmission bar, and the impact bar impact incident bar as 32 m/s speed. The modeling data of each part are shown as table 2:

| part                | radius(mm) | length(mm) | material mode              |
|---------------------|------------|------------|----------------------------|
| impact bar          | 5          | 200        | elastic steel model        |
| incident bar        | 6.5        | 1000       | elastic steel model        |
| target plate material | 5        | 30         | JC,JH2 interpolation       |
| transmission bar    | 6.5        | 500        | elastic steel model        |

The peak values of reflection and transmission stress wave about four kinds of target plates are shown as table 3:

| target plate | Incident wave (GPa) | reflection wave (GPa) | transmission wave (GPa) |
|--------------|---------------------|-----------------------|------------------------|
| laminated    | 0.610               | 0.395                 | 0.505                  |
| b=1          | 0.610               | 0.370                 | 0.512                  |
| b=0.5        | 0.610               | 0.353                 | 0.514                  |
| b=2          | 0.610               | 0.384                 | 0.510                  |

It can be seen from table 3: the reflection wave peak value of double laminated target plate is higher than that of gradient target. And the reflection wave peak value of gradient index b = 0.5 is minimum, But according to figure 4, ballistic performance of target (b=1) is better than that of target (b = 0.5), and this will be explained in section 4.

4. Stress wave in the target plate material internal propagation

Due to the low thickness of the target plate material (only 3 cm) and the velocity of stress wave (5000m/s), it is difficult to extract the internal stress wave propagation curve from Hopkinson bar simulation or experiments. By using numerical simulation technology, it is easy to obtain the internal stress wave propagation curve by the thickness of model expanded 100 times (3m). Initial loading conditions for the gradient material is applying a 2 us pressure wave on the pure ceramic surface, which is as shown in figure 6. And the reflection wave peak value about four kinds of target plates are shown in table 4.

![Figure 6 numerical simulation model and loading initial condition](image2)
|      | b=1  | laminated | b=0.5 | b=2   |
|------|------|-----------|-------|-------|
| layer1 | 0.00252 | 0.00107  | 0.00243 | 0.00205 |
| layer2 | 0.00246 | 0.00110  | 0.00244 | 0.00252 |
| layer3 | 0.00280 | 0.00180  | 0.00288 | 0.00264 |
| layer4 | 0.00260 | 0.00112  | 0.00288 | 0.00242 |
| layer5 | 0.00225 | 0.00101  | 0.00245 | 0.00205 |
| layer6 | 0.00191 | 0.00113  | 0.00170 | 0.00213 |

From Table 4 we can see that, in the target plate internal stress state, the reflection wave peak value of double laminated is minimum. But the tensile strength of pure ceramic is less than that of gradient material ceramic phase. When the peak values of reflection stress wave are at the same level, the third ceramic layer of double laminated is failure first of all, and the failure spreads to the whole ceramic plate quickly. But gradient armor ceramic phase layer have just partial failure. Though the comparison the gradient material ceramic phase of b = 1 with b = 0.5, it can be seen that the reflection wave peak values are the same in layer 3 and layer 4 (ceramic phase) when the gradient index b = 0.5. And when b = 1, the reflection wave peak value of layer 3 ceramic phase is less than that of b = 0.5 slightly, but the tensile strength is a little stronger because of the gradient index interpolation. Therefore, the ballistic performance of gradient index b = 1 is better than that of b = 0.5.

5. Conclusions

Through the numerical simulation of AlN-Al gradient material by LS-dyna, the conclusions are as follows:

1. We use interpolation to describe the intermediate layers material properties and get ballistic performance of four kinds of target, and b=1 is the best gradient index can be seen from figure 4;
2. Through the Hopkinson bar numerical simulation, double laminated target plate reflection wave peak value is higher than gradient, gradient index b = 0.5 minimum value of the reflection wave;
3. By expanding the model of target 100 times, the internal stress wave propagation of target can be obtained. And it has proved that b=1 is better than b=0.5 by the reflection wave peak value about layer 3 and layer 4.

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