Failure of the laminate composites under impact loading

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Abstract. The paper represents the results of numerical simulation of fracture of laminate composites under impact loading. The behavior of a composite target that consists of a titanium alloy (Ti-6-4) and a titanium-titanium trialuminide intermetallic (Al₃Ti) layers were studied. A special model is applied to describe the brittle-like fracture of intermetallic. The axisymmetric problem is solved using the finite element method. In the computations, the thickness of the layers was varied. The multilayered composites were compared with monolithic intermetallic and titanium targets.

1. Introduction

At present a metal-intermetallic laminate (MIL) composite is considered to be a new, promising, light and hard material [1-5]. The superior specific properties of these composites make them attractive for aerospace and other applications. Production method for creating MIL composites allows new embedded technologies to be incorporated into the materials, enhancing their functionality and utility [1]. The development of the technologies for the production of such materials, the laboratory test methods and the computational modeling of mechanical behavior under dynamic loading are of interest to modern materials science. There are a few of experimental works in the scientific literature devoted to studying the behavior of laminate composites under dynamic loading [1, 5, 6]. The experimental data show that it is difficult to identify the contribution of different failure mechanisms to the development of damage areas in the composites. Therefore, to analyze the behavior of MIL composites, the use of computational modeling becomes more important, since it allows the high-velocity loading of composite targets to be investigated in a wide range of initial conditions in the framework of a unified mathematical approach [7-15].

In this work the processes of dynamic interaction of a projectile with a titanium-titanium trialuminide composite target were numerically investigated. The axisymmetric geometry and the finite element method were used. The set of equations describes unsteady adiabatic motion of an elastic-plastic medium including temperature effects. It consists of the equations of continuity, motion, and energy [16]. The active-type kinetic model is used to simulate nucleation and evolution of microdamages (pores, cracks). According to the model the microdamages continuously changes the strength properties and induce the stresses relaxation. Shear modulus and dynamic yield point (strength characteristics of the medium) depends on temperature and the damage level [16, 17]. The erosion failure model is used to simulate the fracture of the material in the region of intense deformation. The critical value of the specific energy of shear deformations is used as a criterion for
the model. The kinetic model of brittle-like failure to simulate the failure of the intermetallic material is used. The model includes the possibility of failure in the shock wave above Hugoniot elastic limit [17, 18].

The problem is solved using the finite element method that is modified to analyze the impact of deformable solids [19, 20]. In the computations, the thickness of the intermetallic/metal layers was varied to evaluate the strength characteristics of the composite. An optimum ratio of the composite layer thickness was found for the loading conditions studied. The multilayered composites were compared with monolithic intermetallic and titanium targets.

2. Statement of the problem

We use the model of an elastic-plastic damaged medium in numerical simulations. The model is characterized by the presence of microcavities (pores, cracks). The set of equations describes unsteady adiabatic (for both elastic and plastic deformation) motion of an elastic-plastic medium. It consists of the equations of continuity, motion, and energy [16].

The active-type kinetic model is used to simulate nucleation and evolution of microdamages (pores, cracks). According to the model the microdamages continuously changes the strength properties and induce the stresses relaxation:

\[
\frac{dV_f}{dt} = \begin{cases} 
0 & \text{if } |P_c| \leq P^* \text{ or if } (P_c > P^* \text{ and } V_f = 0), \\
-\text{sign}(P_c)K_f\left(|P_c| - P^*\right)(V_f + V_j), & \text{if } P_c < -P^* \text{ or if } (P_c > P^* \text{ and } V_f > 0)
\end{cases}
\]

Here \(V_f\) – the specific volume of microcavities, \(t\) – time, \(P_c\) – pressure in the undamaged part of the medium, \(P^* = V_P^P/(V_1+V_j)\), and \(K_f, P_k, V_1\), and \(V_2\) are constants.

The equation of state of the Mie-Grüneisen type is used. The EOS represents pressure \(P_c\) as a function of specific volume and specific internal energy. The model includes the deviatoric elastic constitutive relationships, the von Mises yield criterion for plastic deformations and it takes into account temperature effects. Shear modulus \(G\) and dynamic yield point \(\sigma\) depends on temperature and the level of damages:

\[
G = G_0 K_T \left(1+\frac{cP}{(1+\mu)^{1/3}}\right) \frac{V_3}{(V_fV_4)};
\]

\[
\sigma = \begin{cases} 
\sigma_0 K_T \left(1+\frac{cP}{(1+\mu)^{1/3}}\right) \left(1+ \frac{V_f}{V_4}\right), & \text{if } V_j \leq V_4, \\
0, & \text{if } V_f > V_4
\end{cases}
\]

\[
K_T = \begin{cases} 
1, & \text{if } T_0 \leq T \leq T_i \\
\frac{T_m - T}{T_m - T_i}, & \text{if } T_i < T < T_m \\
0, & \text{if } T \geq T_m
\end{cases}
\]

Here \(\mu=V_0/(V-V_j)-1, V\) and \(V_0\) are the current and initial specific volumes, respectively, \(T_0\) and \(T\) are the initial and current temperature, respectively, \(T_m\) is the melting point, and \(T_i, c, V_i,\) and \(V_4\) are the constants.

3. Model of brittle fracture

In this work the dependence of the dynamic yield point for modeling of the brittle material fracture during compression is given by [17]:

\[\]
\[ \sigma = \begin{cases} 
\sigma_0, & \text{if } \sigma_z \geq P_{fr} \\
K_f \sigma_\ell, & \text{if } \sigma_z < P_{fr} 
\end{cases} \]

Here \( \sigma_z \) is the stress component in the shock wave (\( \sigma_z < 0 \) under compression); \( P_{fr} \) is the material constant (\( P_{fr} < 0 \)). The coefficient \( K_f \) can be varied from 0 to 1. When \( K_f = 0 \), the dynamic yield point in the shock wave drops to zero after exceeding the Hugoniot elastic limit, which is typical for completely brittle fracture (for example, boron carbide), when \( K_f = 1 \) the character of deformation is completely plastic, and the dynamic yield point in the shock wave is not changed during compression. The intermediate values \( K_f \) allow the combined plastic deformation and brittle fracture to be described. Under tensile loading, the dependence of the dynamic yield point in the modeling of brittle fracture is given by \( (V_f^k, \sigma_t) \) are the constants):

\[ \sigma = \begin{cases} 
\sigma_0 \left(1 - V_f / V_4 \right), & \text{if } V_f < V_f^k \\
\sigma_f, & \text{if } V_f^k \leq V_f < V_4 \\
0, & \text{if } V_f \geq V_4 
\end{cases} \]

4. Erosion failure model

The erosion failure model is used to simulate the fracture of the material in the region of intense deformation. The critical value of the specific energy of shear deformations is used as a criterion for the model.

The current value of the specific energy of shear deformations \( E_{sh} \) is defined as:

\[ \rho \frac{d E_{sh}}{dt} = S_{ij} \varepsilon_{ij} \]

Here \( \rho \) is the density, \( S_{ij} \) are the components of the stress deviator, \( \varepsilon_{ij} \) are the components of the strain-rate tensor. The critical value of the model depends on the initial impact velocity \( v_0 \):

\[ E_{sh}^c = a_{sh} + b_{sh} v_0 \]

where \( a_{sh} \) and \( b_{sh} \) are the constants. When \( E_{sh} > E_{sh}^c \) in the computational element, the cell is assumed to be damaged.

5. Results and discussion

In the computations we used the composite target consisting from 17 layers. Each composite layer consisted of titanium trialuminide intermetallic layer (Al\(_3\)Ti) and titanium alloy layer (Ti-6Al-4V). Total thickness of the target was 19.89 mm. The thicknesses of intermetallic layer and the layer of titanium alloy were varied. The projectile used was a tungsten heavy alloy rod with initial velocity of 900 m/s. Initial diameter of the projectile was of 6.15 mm and length of 23 mm [1].

Figure 1 shows the computer images of a section of the composite target and projectile at \( t = 0 \). In this case the thickness of Al\(_3\)Ti layer was of 0.94 mm, the thickness of the Ti-6-4 layer was of 0.23 mm. Figures 1b and 1c illustrate the section contours of the target and projectile and the distribution of the damage and the deformation patterns. Figure 1b shows the contours and fields of the specific shear energy and figure 1c shows the contours and fields of the specific volume of microdamages. The low level of microdamages in the titanium alloy layers demonstrates the fact that the metal layers stop the distribution of brittle damage. In this case the MIL composite target withstands the impact.

Figure 2 shows the distribution of the damage patterns in the section of the composite target and projectile at 60 \( \mu \)s for the titanium-titanium trialuminide intermetallide layers of different thicknesses. Levels of \( V_f \) correspond to figure 1c.

These computation variations differ in the layer-thickness ratio of intermetallide and a titanium alloy, while in the computation variation «a» the thickness of the intermetallide layer is higher than
that considered earlier (figure 1, variation «g»), and is lower in the computation variants b-d. The computational results of uniform targets from Ti-6-4 (figure 2e) and Al₃Ti (figure 2f) are given for comparison. All of the above computation variations show worse results compared to the previously considered computation variation «g».

![Figure 1](image)

**Figure 1.** Radial section of the projectile and target (a) at $t=0$, specific shear energy, kJ/kg (b) and specific volume of microdamages, cm$^3$/g (c) at 60 μs.

The same conclusion is confirmed by the computation results given in table 1, where the depth of penetration $L_k$ and average velocities $v_s$ of the projectile are given at time of 40 and 60 μs. It is worth noting that the values obtained for the time of 60 μs are not given for some computation variations, since the result of interaction (perforation) is determined earlier.

| Thickness of layer, mm | Areal density, g/cm$^2$ | $L_k$, mm | $v_s$, m/s |
|------------------------|------------------------|-----------|------------|
|                        |                        | 40 μs     | 60 μs     | 40 μs | 60 μs |
| Al₃Ti | Ti-6-4 | 40 μs | 60 μs | 40 μs | 60 μs |
| a | 1.04 | 0.13 | 6.81 | 22.9 | - | 440 | - |
| b | 0.70 | 0.47 | 7.52 | 21.9 | 26.4 | 410 | 220 |
| c | 0.47 | 0.70 | 7.99 | 23.0 | 28.7 | 430 | 250 |
| d | 0.23 | 0.94 | 8.49 | 24.2 | - | 470 | - |
| e | 0 | 1.17 | 8.97 | 18.7 | 20.9 | 200 | 50 |
| f | 1.17 | 0 | 6.54 | 21.1 | 25.4 | 350 | 150 |
| g | 0.94 | 0.23 | 7.02 | 17.0 | 18.5 | 150 | 30 |

The depth of penetration depends on the thicknesses of titanium alloy and intermetallic layers. The MIL composite target withstands the impact when the ratio is about 4/1 (line g in the table 1). In this case the thickness of the Al₃Ti layer is of 0.94 mm and the one of the Ti-6-4 titanium alloy is of 0.23 mm. The intermetallic layer provides the failure of the projectile and the metal layer stops the distribution of brittle damage in the MIL target. The perforation of the composite target takes place in the cases a-d. There is the same result for the Al₃Ti uniform target (line f in the table 1).

**6. Conclusion**

The results of numerical simulation have shown that a multilayered metal-intermetallic composite has higher strength characteristics compared with a uniform Al₃Ti intermetallic target in the entire studied range of loading and also a uniform Ti-6-4 titanium alloy target with an optimal ratio of
intermetallide/metal layers. The optimum construction of the multilayered titanium-titanium trialuminide intermetallide composite should include a metal layer of sufficient thickness, which would stop the distribution of brittle damage from the intermetallic layer.

Figure 2. Specific volume of microdamages in radial section of the target and projectile at 60 μs. Parameters of a–f are presented in the table 1.

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