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Fracture of metal-intermetallic laminate target under high-velocity impact

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Abstract. Deformation and fracture of laminates under high-velocity impact were numerically investigated. Targets consisting of alternating layers of intermetallide (Al_3Ti) and titanium alloy (Ti-6Al-4V) were used as laminate composites. A high-strength steel core was used as a projectile. Impact velocities were varied in the range of 2000-5000 m/s. Fracture of intermetallic layers is described by the brittle fracture model, and fracture of titanium alloy layers is described by the active-type kinetic model. The erosion fracture model is used to simulate the fracture of the material under intensive deformation. The modified finite element method (without a global stiffness matrix) was used for numerical computations. It is revealed the increasing role of shock wave processes in the fracture of targets with increasing an impact velocity. The metal-intermetallic laminate target delaminates due to the fracture of intermetallic layers in shock waves and the formation of main cracks in these layers.

1. Introduction

Metal-intermetallic laminates (MIL) are currently considered to be promising structural materials. Due to the peculiarities of the structure, MILs have high specific strength characteristics and ballistic resistance [1 - 4]. MILs are called biosimilar materials and composed of alternating intermetallic and metal or alloy layers.

The creation of such materials by scientists was driven by the study of structures of natural biological systems, for example, the shell structure of the marine mollusk Haliotis rufescens (abalone) is hard brittle layers of $CaCO_3$ bonded with a plastic boundary organic phase. For Ti-Al_3Ti composites, titanium trialuminide (Al_3Ti) which has high hardness and compression strength at relatively low density imitates the role of $CaCO_3$ plates, and plastic and crack-resistant titanium alloy (Ti-6Al-4V) layers required to stop cracking and dissipate the energy of impact using plastic deformation, acts as a boundary binding phase.

Dynamic loading of MILs has been little studied so far. At present, a small number of both experimental and theoretical works are devoted to this problem. In experimental studies it is difficult to record the dynamics of the high-velocity process. Analysis of the samples saved after loading does not provide a reliable evaluation of fracture mechanisms. Numerical simulation, within the framework of the numerical codes used, allows the dynamics of deformation and fracture of loaded bodies to be investigated.

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At present, increased attention is paid to numerical methods applied for studying the mechanical behavior of technical systems. Very often, commercial softwares, such as MatLab, ALGOR, Solid Works (Cosmos Works), and ANSYS are used for analysis [5 - 7]. The most popular numerical method used to solve problems of deformation and fracture of materials and structural elements is the finite element method (FEM) which is the basis for the above-mentioned softwares. At the same time, the development of research softwares based on FEM remains relevant [8 - 11].

In this work, the loading of the Ti-Al_3Ti multilayer target at initial impact velocities of 2000, 3000 and 5000 m/s is numerically simulated and studied. In experiments such velocities can be reached using light-gas guns [12]. The purpose of the work is to evaluate the effect of the initial velocity of the projectile on the fracture of the target, its strength characteristics and the degree of fracture after interaction. Research software based on FEM is used for numerical simulation of dynamic processes.

2. Research methods

In the work the damaged medium model characterized by the presence of microdamages in the material is used. The specific volume of microdamages V_f is used as a parameter of material damage:

$$V_f = \frac{W_f}{\rho_c W_c}, \tag{1}$$

where W_f is the volume occupied by microdamages, ρ_c is the density of undamaged material, W_c is the volume occupied by the undamaged medium.

The system of governing equations comprises the equations of continuity, motion, and energy which are obtained from the laws of conservation of mass, momentum, and energy. The equation of state is constructed according to the Mi-Grüneisen equation that assumes the presence of "cold" and "thermal" parts. The equation of state determines the pressure in an undamaged substance in the entire range of loading conditions as a function of specific volume and specific internal energy. The coefficients of the equation of state are determined by the Hugoniot adiabat constants. To connect the components of the stress deviator with those of the strain rate tensor, the constitutive relations containing the Yaumann derivative are used. The von Mises yield condition is used to describe plastic flow. In the computations, the effect of temperature and material damage on the shear modulus and dynamic yield strength is considered.

A kinetic fracture model that simulates the metal tension fracture is used for titanium alloy layers. For intermetallic layers, a brittle fracture model is used [13]. In contrast to the kinetic fracture model, in which the fracture of elements is caused by only tensile stress, the brittle failure model includes both tensile and compressive stress components. Consequently, dynamic yield strength σ in the brittle fracture model depends on both compressive (2) and tensile (3) stress components:

$$\sigma = \begin{cases} \sigma_0, & \text{if } \sigma_z \ge P_f \\ K_f \sigma_0, & \text{if } \sigma_z < P_f \end{cases}, \tag{2}$$

where σ_z is the stress component in shock wave ($\sigma_z < 0$ under compression), P_f is material constant ($P_f < 0$), and coefficient K_f can be varied from 0 to 1.

$$\sigma = \begin{cases} \sigma_0 \left(1 - \frac{V_f}{V_4}\right), & \text{if } V_f < V_f^k \\ \sigma_f, & \text{if } V_f^k \le V_f < V_4 \\ 0, & \text{if } V_f \ge V_4 \end{cases}, \tag{3}$$

where V_4, V_f^k, σ_f are constants [13, 14].

Kinetic and brittle fracture models are used during the propagation of shock waves (areas of compression) and unloading waves (areas of tension). For intensive interaction and deformation of contacting bodies, an erosion fracture model is used. Here, the fracture criterion is the critical value of the specific energy of shear deformations E_{sh}. The current value of this energy is determined by the formula:

$$\rho \frac{dE_{sh}}{dt} = S_{ij}\varepsilon_{ij}, \quad (4)$$

where S_{ij} are the components of the stress tensor deviator, ε_{ij} are the components of the strain rate tensor.

The critical value of the specific energy of shear deformations is chosen depending on the interaction conditions:

$$E_{sh}^{c} = a_{sh} + b_{sh}\upsilon_0, \quad (5)$$

where υ_0 is the initial impact velocity, a_{sh} and b_{sh} are constants.

When the condition $E_{sh} > E_{sh}^{c}$ is met in the computation cell, this cell is considered to be fractured according to the erosion fracture model and is removed from further computations, and the parameters of neighboring cells are corrected according to conservation laws, that is, the mass of fractured material is subtracted from the mass of computational nodes.

The axisymmetric high-velocity interaction of a high-strength steel ogival-headed projectile with a multi-layer laminate target is considered. To solve this problem, the finite element method is used.

3. Computational results and discussion

The interaction of a Ti – Al_3Ti multilayer target consisting of six composite layers with a total thickness of ≈ 7 mm and an average density of 3513.32 kg/m^3 with a high-strength steel projectile was numerically simulated. The thickness ratio of intermetallic layers to the titanium alloy in the composite layer is ≈ 4/1. The diameter of the projectile is 4.2 mm, and the length is 14.5 mm. The initial velocity of the projectile was varied. The computations were performed for velocities of 2000, 3000 and 5000 m/s. The mesh of the target was nonuniform and, since the geometry was axisymmetric, the nonuniform mesh was implemented along the target radius, and the size of the elements increased with distance from the interaction area.

The critical value of the specific energy of shear deformations (5) depends on the interaction conditions and is given by the function of the initial impact velocity; therefore, its value for each material was varied for different initial velocities of the projectile. The critical values of the specific energy of shear deformations for three materials used in the computations are presented in Table 1.

Table 1. Critical values of the specific energy of shear deformations E_{sh}^{c}

	E_{sh}^{c}, J/kg		
υ_0, m/s	High-strength steel (a_{sh} = 3330 J/kg; b_{sh} = 0.33)	Al_3Ti (a_{sh} = 1000 J/kg; b_{sh} = 0.5)	Ti-6Al-4V (a_{sh} = 3170 J/kg; b_{sh} = 0.167)
2000	3960	2000	3500
3000	4290	2500	3670
5000	4950	3500	4000

With an initial projectile velocity of 2000 m/s, by the time 5.5 μs (Figure 1a), a macrocrack is formed in the second composite layer inside the intermetallide. The macrocrack starts growing in the rear surface of the target and at the time of 10.5 μs the main macrocrack is formed in this layer (Figure 1b).

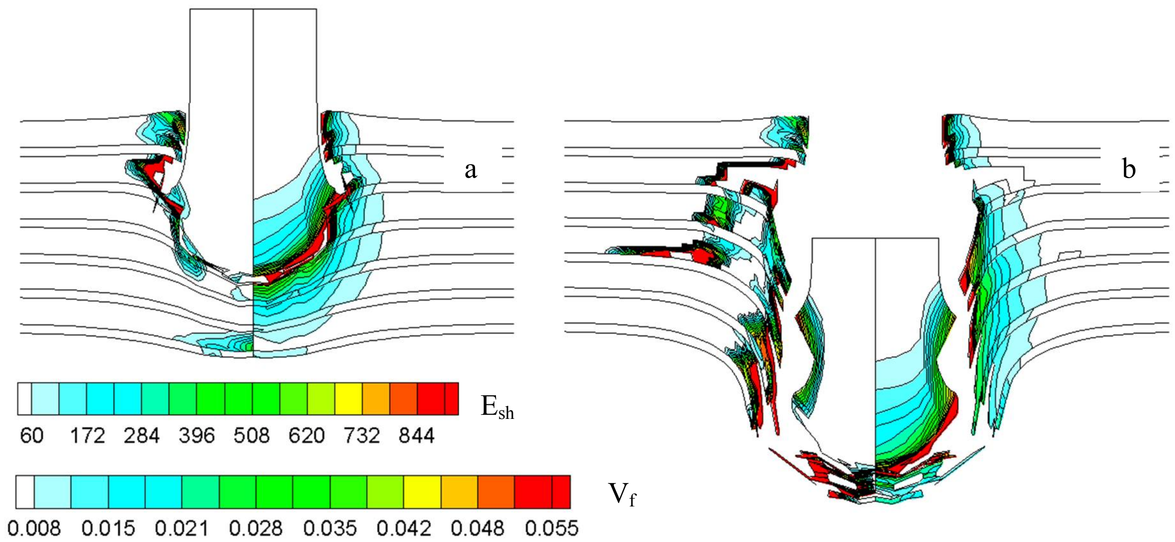

Figure 1. Fields of specific volume of microdamages (cm^3/g) (left) and specific energy of shear deformations (kJ/kg) (right) at an initial impact velocity of 2000 m/s: (a) at the time of 5.5 μs; (b) at the time of 10.5 μs.

Figure 1b shows the degree of the target fracture and the growth of macrocracks in the intermetallic layers. More intensive crack growth is prevented by the titanium alloy layers. After completion of the interaction between the target and the projectile, delamination of the target takes place. At 2000 m/s, the cone-shaped fracture will take place in the cross-section of the target, which is typical for brittle fracture.

With an increase in the initial velocity of the projectile, the role of shock wave processes propagating in the target increases, and delamination of the target subjected to unloading waves takes place (Figure 2). It is worth noting that with an increase in the initial impact velocity, the delamination degree of the target increases. In this case, delamination of the multilayer metal-intermetallic composite occurs due to the formation of macrocracks in intermetallic layers.

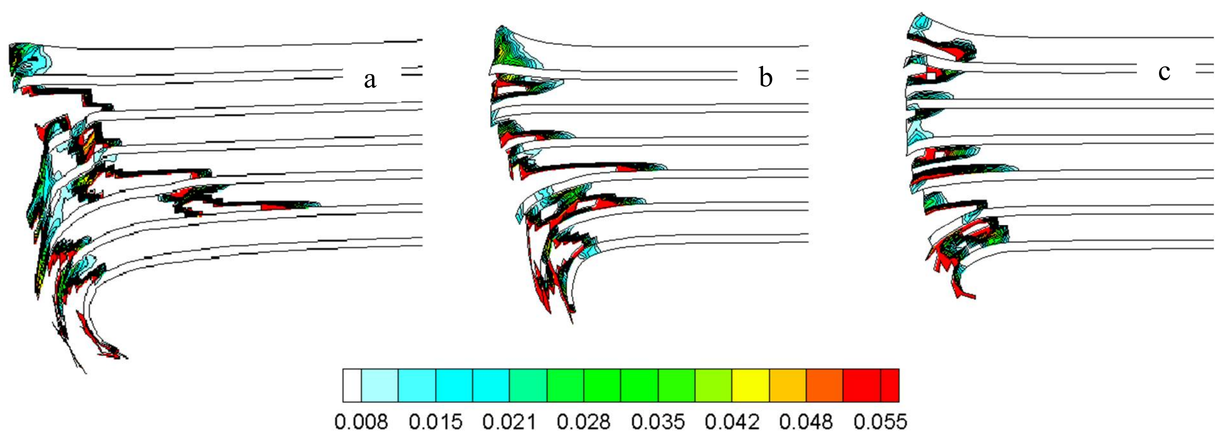

Figure 2. Fields of specific volume of microdamages (cm^3/g) in targets interacting with projectiles at different initial velocities: (a) 2000 m/s; (b) 3000 m/s; (c) 5000 m/s; t = 20 μs.

At relatively low impact velocities (700 - 1100 m/s [15]), the role of shock wave processes is much lower and, therefore, tensile loads that occur during the penetration of the projectile rather than the unloading wave contribute much more to the fracture of the target. But at the same time, the large specific volume of microdamages is observed in intermetallic layers, and titanium layers, as with higher impact velocities, prevent the spread of main cracks [15].

The decrease in the velocity of the projectile after interacting with the target (after-penetration velocity) depends on the initial velocity of the projectile (Figure 3). With an initial impact velocity of 2000 m/s the after-penetration velocity of the projectile decreases by 35% and by approximately 17.5% at 3000 m/s, and with an initial impact velocity of 5000 m/s the after-penetration velocity decreases by 6.3%.

During the interaction with the target, the projectile is fractured and its length decreases. Figure 4 shows the different length of the projectile for different initial impact velocities, but after interacting with the target, the length of the projectile L_{proj} changes by about one magnitude in all three cases, the difference in length by 10 μs is 0.69 mm - 3.44%. The length of the projectile after interaction with the target in the considered range of impact velocities decreases by about 2 times.

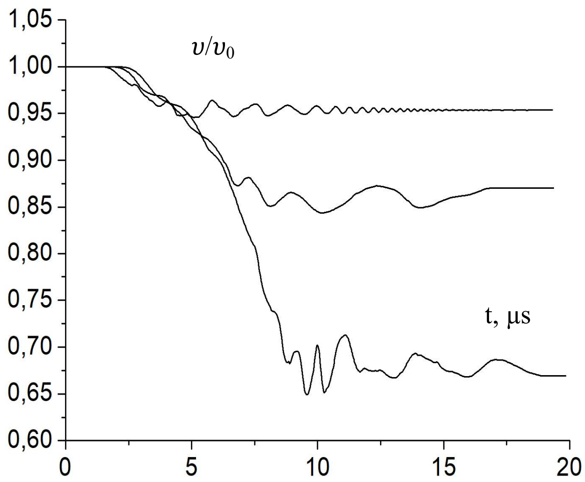

Figure 3. Dimensionless quantity υ/υ_0 describing the ratio of the velocity of the rear part of the projectile to its initial velocity versus the interaction time for different initial impact velocities: (1) 2000 m/s, (2) 3000 m/s, (3) 5000 m/s.

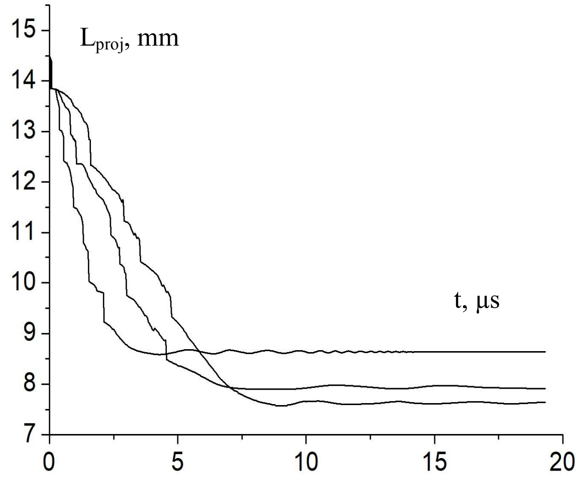

Figure 4. Length of the projectile as a function of time for different initial impact velocities: (1) 2000 m/s, (2) 3000 m/s, (3) 5000 m/s.

4. Conclusion

Deformation and fracture of metal-intermetallic laminate composites Ti-Al_3Ti under high-velocity impact were numerically investigated using the modified finite element method. Fracture of intermetallic layers was described by the brittle fracture model, and fracture of titanium alloy layers was described by the active-type kinetic model. The erosion fracture model was used to simulate the fracture of the material under intensive deformation.

Numerical simulation of deformation and fracture of the laminates shows that with an increase in the initial impact velocity in the velocity range of 2000–5000 m/s, the role of shock-wave processes in the fracture of a target increases. In contrast to lower impact velocities, at which the deformation factor acting in the penetration area of the projectile, contributes more to the fracture of a multilayer target, the fracture of intermetallic layers in the shock wave is observed at higher impact velocities.

The delamination of the multilayer metal-intermetallic target takes place due to the fracture of intermetallic layers in shock waves and the formation of main cracks in these layers.

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