Numerical simulation of metal-intermetallic laminate composites failure under dynamic loading

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Abstract

The processes of multilayer composites failure under dynamic loading were investigated. Fracture model of brittle materials subjected to high velocity impact was used. Deformation and fracture of Al_3Ti - Ti metal-intermetallic laminate composite materials under dynamic loading was numerically simulated using the finite element method.

Keywords: **MIL composites, dynamic loading, failure**

Introduction

Progress in the creation of new technological innovations mainly depends on the development and improvement of technologies for obtaining materials with required properties, so the creation of materials with desired structural and functional properties is currently an area of increased attention in materials science and technology. A new promising class of structural materials includes metal-intermetallic laminate composite materials (MILCM) which are represented by a multilayer composition with alternating metal and intermetallic layers [1]-[7]. These composite materials are attractive for use in aerospace engineering and many other areas, and methods for obtaining of MILCM allow us to use new technologies expanding the functionality of laminate composites and the area of application.

In this work the processes of high-velocity interaction of a projectile with a multilayer MILCM target were numerically investigated in axisymmetric geometry using the finite element method. The set of equations for describing unsteady adiabatic motion of an elasto-plastic medium, including nucleation and accumulation of microdamages and temperature effects, consists of the equations of continuity, motion, and energy [7]-[9]. To simulate numerically the failure of the material under high velocity impact, we applied the active-type kinetic model determining the growth of microdamages, which continuously changes the properties of the material and induce the relaxation of stresses. The strength characteristics of the medium (shear modulus and dynamic yield strength) depended on temperature and the current level of damage taking into account probabilistic approach to numerical simulation of fracture [10]-[12]. The critical specific energy of shear deformations was used as a criterion for the erosion failure of the material that occurred in the region of intense interaction and deformation of contacting bodies. To simulate the brittle-like failure of the intermetallic material under high velocity impact, we modified the kinetic model of failure and included the possibility of failure above Hugoniot elastic limit (HEL) in the shock wave and the sharp drop in the strength characteristics for the failure of material.

Formulation of the Problem

In the computations we used the target consisting from 17 composite intermetallic Al_3Ti - titanium alloy Ti-6-4 layers. Total thickness of the target was 19.89 mm. The thicknesses of intermetallic layer and the layer of titanium alloy were varied. The penetrator used was a tungsten heavy alloy rod with an initial diameter of 6.15 mm and length of 23 mm [1]. Initial impact velocity was of 900 m/s.

To simulate numerically the processes of high velocity shock loading, we use the model of an elastic-plastic damaged medium characterized by the presence of microcavities (pores, cracks). In the model the total volume of the medium W comprises the undamaged part of the medium of density ρ_c which occupies volume W_c, and microcavities of zero density which occupy volume W_f. The average density of the damaged medium is connected with the above-introduced parameters by the relationship $\rho = \rho_c(W_c/W)$. The degree of damage of the medium is characterized by the specific volume of microcavities $V_f = W_c/(W_*\rho)$.

A mathematical model used in the numerical code for solving high velocity impact problems is based upon a set of differential equations of continuum mechanics. The system of equations governing the nonstationary, adiabatic (for both elastic and plastic deformation) motion of a compressible medium with allowance for the evolution of microdamages comprises the continuity equation, the equation of motion, the energy equation [8] [9].

To simulate numerically the failure of the material at high velocity impact, we applied the active-type kinetic model determining the growth of microdamages, which continuously change the properties of the material and induce the relaxation of stresses:

$$\frac{dV_f}{dt} = \begin{cases} 0, \text{ if } |P_c| \le P^* \text{ or if } (P_c > P^* \text{ and } V_f = 0), \\ -\operatorname{sign}(P_c) K_f (|P_c| - P^*)(V_2 + V_f), \text{ if } P_c < -P^* \text{ or if } (P_c > P^* \text{ and } V_f > 0) \end{cases} \tag{1}$$

Here $P^* = P_k V_1/(V_f + V_1)$, and V_1, V_2, P_k, and K_f are material constants determined experimentally. The form of condition (1) was chosen according to the experimental data. We assume that there are the fracture areas of identical initial sizes in the material with the effective specific volume V_1. Cracks or pores are formed and grow in these fracture areas when the tensile pressure exceeds a certain critical value P^* that decreases during the growth of microdamages. The constants in (1) were chosen by comparing the results of computations and experiments concerning the recording of a free surface velocity when a specimen was loaded by planar impulses of compression. The same set of constants is used to calculate both build-up and collapse of cracks and pores (depending on the sign of P_c).

The material model includes the equation of state of the Mie-Grüneisen type that represents pressure as a function of specific volume and specific internal energy, the deviatoric elastic constitutive relationships, the von Mises yield criterion taking into account temperature effects. The strength characteristics of the medium (shear modulus and dynamic yield strength) depend on temperature and the current level of damages.

$$G = G_0 K_T \left(1 + \frac{cP}{(1+\mu)^{1/3}}\right) \frac{V_3}{(V_f + V_3)}$$

$$\sigma = \begin{cases} \sigma_0 K_T \left(1 + \frac{cP}{(1+\mu)^{1/3}}\right)\left(1 - \frac{V_f}{V_4}\right), \text{ if } V_f \le V_4 \\ 0, \text{ if } V_f > V_4 \end{cases} \tag{2}$$

$$K_T = \begin{cases} 1, & \text{if } T_0 \le T \le T_1 \\ \frac{T_m - T}{T_m - T_1}, & \text{if } T_1 < T < T_m \\ 0, & \text{if } T \ge T_m \end{cases}$$

Here T_m is the melting point of the substance, and c, V_3, V_4, and T_1 are the constants.

To simulate the brittle-like failure of the intermetallic material under high velocity impact, we developed the model for the possibility of failure above HEL in the shock wave and the sharp drop in the strength characteristics for the failure of materials [13]:

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

$$P_f = \begin{cases} 1, & \text{if } \sigma_{sh} < \sigma_{HEL} \\ P_f^k, & \text{if } \sigma_{sh} \ge \sigma_{HEL} \end{cases},$$

where σ_{sh} is the stress in the shock wave ($\sigma_{sh} < 0$ for compression), P_f^k, V_f^k, σ_f, σ_{HEL} are the constants.

The critical specific energy of shear deformations is used as a criterion of the erosion failure of the material that occurs in the region of intense interaction and deformation of contacting bodies. The current value of the specific energy of shear deformations is defined from the relationship

$$\rho \frac{dE_{sh}}{dt} = S_{ij}\varepsilon_{ij}$$

The critical value of the specific energy of shear deformations depends on the conditions of interactions and is a function of the initial impact velocity

$$E_{sh}^c = a_{sh} + b_{sh}\upsilon_0$$

where a_{sh} and b_{sh} are the constants. When $E_{sh} > E_{sh}^c$ in the computational cell near the contact boundaries, the cell is assumed to be damaged and the parameters in neighboring cells are corrected with regard for the principles of conservation laws.

Results and Discussion

We consider the interaction of a projectile with a finite thickness target. The problem is formulated using the Cartesian coordinate system with initial (at t = 0) and boundary conditions. The initial conditions are characterized by the absence of internal stresses, and the projectile moves toward the target with a velocity υ_0. There are no external loads on free surfaces of the interacting bodies, while the conditions of sliding are implemented on the contact surfaces between the projectile and the target. The finite-element relations used to solve the formulated problem are given in [14] [15].

Fig. 1 shows the computer images with a section of the projectile and composite target at the time of 60 μs. The thickness of intermetallic Al_3Ti layer in this case was of 0.94 mm, the thickness of the layer of Ti-6Al-4V titanium alloy was of 0.23 mm. The computations demonstrate the fact that the MIL composite target withstands the impact loading.

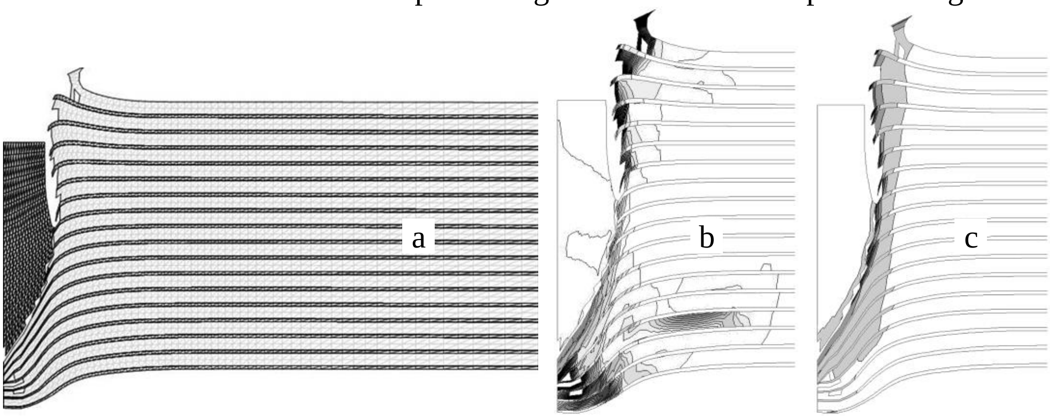

Figure 1: Computer images with a radial section of the projectile/target assembly (a), specific volume of microdamages (b) and specific shear deformation energy (c) at 60 μs

The distribution of the damage and the deformation patterns are illustrated in Figs. 1b and 1c which show the section contours of the projectile and composite target, the contours and fields of the specific volume of microdamages (Fig. 1b) and the specific shear deformation energy (Fig. 1c). The low level of microdamages in the layers of titanium alloy shows the brittle damage stops distribution in the intermetallic layers.

Table 1: Results of simulations for target layers of different thicknesses

	Al_3Ti [mm]	Ti-6-4 [mm]	Areal density [g/cm^2]	Depth of penetration [mm]		Average velocity [m/s]	
				40 μs	60 μs	40 μs	60 μs
1	0.94	0.23	7.02	17.00	18.49	150	30
2	1.17	-	6.54	21.12	25.41	350	150
3	-	1.17	8.97	18.73	20.90	200	50
4	0.47	0.70	7.99	22.95	28.71	430	250
5	0.23	0.94	8.49	24.15	-	470	-
6	0.70	0.47	7.52	21.86	26.44	410	220
7	1.04	0.13	6.81	22.85	-	440	-

The Table 1 represents the results of simulations for target layers of different thicknesses. The results show that the depth of penetration depends on the thicknesses of intermetallic and titanium alloy layers. The MIL composite target withstands the impact loading for the 0.94 mm Al_3Ti / 0.23 mm Ti-6-4 (the ratio is about 4/1). In this case the intermetallic layer provides the failure of the projectile and the metal layer stops the distribution of damage. In the other cases the perforation of the MIL composite target takes place. There is the same result for the uniform target made of either Al_3Ti (line 2 in the Table 1) or Ti-6-4 (3).

Conclusions

The results obtained demonstrate that destruction of the intermetallic layer is brittle compared to plastic failure of the metal layer. The computations have shown that the optimal composite target has a higher ballistic resistance in comparison with a uniform target either Al_3Ti or Ti-6-4. The optimum construction of the MIL composite should include a metal layer of sufficient thickness, which would stop the distribution of brittle damage. The results show that the depth of penetration depends on the thicknesses of intermetallic and titanium alloy layers. The composite target withstands the impact loading for the ratio about 4/1 (Al_3Ti / Ti-6-4).

Acknowledgments

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