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Calculation and Experimental Study on High-speed Impact of Heat-resistant Coating Materials with a Meteoric Particle

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Abstract. The given article presents the conducted calculation and experimental study on destruction of heat-resistant coating material of an aircraft in the process of high-speed interaction of the steel spherical projectile. The projectile is imitating a meteoric particle. The study was conducted in the wide range of velocities. The mathematical behavioral model of heat-resistant coating under high-speed impact was developed. The interaction of ameteoric particle with an element of the protective structure has especially individual character and depends on impact velocity and angle, materials of the interacting solids.

INTRODUCTION

As a rule, modern protective structures of space aircraft have a layer ofheat-resistant coating (HRC) materials [1-3]. Composite materials based on polymeric fibers with the use of epoxideas a binding substance are widely used as elements of structures bearing high power and thermal loadings. The analysis and numerical modeling of processes of powerful pulse energy release, in the particular case – high-speed impact, in such composite materials require knowledge of their thermophysical properties in a wide range of states arising ininteraction. However, the available experimental data on composite polymeric materials are insufficient.

The development scientific fundamentals of predicting consequences of high-speed impact for degree of deterioration of heat-resistant properties of a HRC in the impact zone is currently important. Rational design and placing demand on strength properties of materials are being based on physical and numerical modeling of processes of high-speed interaction. In this connection, the development of mathematical models and numerical techniques allowing describing deformation and destruction processes of multilayered shell structures in materials in the wide range changing parameters of dynamic load take on a bigger role for space research.

The research objectof this work is the stress-strain state and destruction of HRC materialin the process of high-speed interaction of the steel spherical projectile imitating a meteoric particle. The purpose of the work is development of models, techniques and calculationprogramsof interaction of meteoric particles with HRC materials.

MATHEMATICAL MODEL

Specific volume of the porous medium υ is given as a sum of matrix specific volume υ_m and pore specific volume υ_p . Porosity of material is characterized by the relative void volume $\xi = \upsilon/\upsilon_p$ or the parameter $\alpha = \upsilon/\upsilon_m$ called porosity, which are connected by the dependence $\alpha = 1/(1-\xi)$. The system of equations describing the motion of porous elasto-plastic medium is of the form:

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$$\frac{d}{dt}\int_V \rho dV = 0, \frac{d}{dt}\int_V \rho \mathbf{u} dV = \int_S \mathbf{n}\cdot\boldsymbol{\sigma} dS, \frac{d}{dt}\int_V \rho E dV = \int_S \mathbf{n}\cdot\boldsymbol{\sigma}\cdot\mathbf{u} dS,$$
$$\mathbf{e} = \frac{\mathbf{s}^{CR}}{2\mu} + \lambda\mathbf{s}, \mathbf{s}:\mathbf{s} = \frac{2}{3}\sigma_T^2 \tag{1}$$

where t – the time; V – the integration volume; S – the surface of integration volume; $\mathbf{n}$ –the outer normal unit vector; ρ – the density; $\boldsymbol{\sigma} = -p\mathbf{g} + \mathbf{s}$ $\boldsymbol{\sigma} = -p\mathbf{g} + \mathbf{s}$ – the stress tensor; $\mathbf{s}$ – its deviator; p – the pressure; $\mathbf{g}$ – the metric tensor; $\mathbf{u}$ – the velocity vector; $E = \varepsilon + \mathbf{u}\cdot\mathbf{u}/2$ – the total specific energy; ε – the internal specific energy; $\mathbf{e} = \mathbf{d} - (\mathbf{d}:\mathbf{g})\mathbf{g}/3$ – the strain velocity deviator; $\mathbf{d} = (\nabla\mathbf{u} + \nabla\mathbf{u}^T)/2$ – the strain velocity tensor; $\mathbf{s}^{CR} = \mathbf{s} + \nabla\mathbf{u}\cdot\mathbf{s} + \mathbf{s}\cdot\nabla\mathbf{u}^T$ – the Kotter-Rivlinco rotational derivative; $\mu = \mu_{m0}(1-\xi)\left[1 - (6\rho_{m0}c_{m0}^2 + 12\mu_{m0})\xi/(9\rho_{m0}c_{m0}^2 + 8\mu_{m0})\right]$, $\sigma_T = \sigma_S/\alpha$, – the effective shear modulus and yield stress respectively; $\rho_{m0}, c_{m0}, \mu_{m0}$ – the initial density, volume sound velocity and shear modulus of matrix material; σ_S - the dynamic yield stress of matrix material. The parameter λ is eliminated by the Mises plasticity condition.

The system of equations **Ошибка! Закладка не определена.**is ended by the equation of state and relations describing the growth kinetics and pore flowing.

If the linear dependence of shock wave velocity *D*on mass velocity *u* for the matrix material $D = c_{m0} + qu$ is known, the equation of state of the porous material is of the form

$$p = \frac{\rho_{m0}}{\alpha}\left[\gamma_{m0}\varepsilon + \frac{c_{m0}^2\left(1 - \frac{\gamma_{m0}\eta}{2}\right)\eta}{(1-q\eta)^2}\right] \tag{2}$$

where $\eta = 1 - \rho_{m0}\frac{\upsilon}{\alpha}$, γ_{m0} – the Grüneisen coefficient of the matrix material.

Compaction of an initially porous material when compressing is described by the equation:

$$\frac{\rho_{m0}c_{m0}^2\left(1 - \frac{\gamma_{m0}}{2}\eta\right)\eta}{(1-S_{m0}\eta)^2} + \rho_{m0}\gamma_{m0}\varepsilon - \frac{2}{3}\sigma_s \ln\left(\frac{\alpha}{\alpha-1}\right) = 0 \tag{3}$$

The kinetics equation of pore compaction is used for determining the parameter α under the condition $p - \frac{2}{3}\frac{\sigma_s}{\alpha}\ln\left(\frac{\alpha}{\alpha-1}\right) > 0$, otherwise $\frac{d\alpha}{dt} = 0$. The growth of pores in the plastically deformed material when stretching is described by the equation:

$$\frac{\rho_{m0}c_{m0}^2\left(1 - \frac{\gamma_{m0}}{2}\eta\right)\eta}{(1-S_{m0}\eta)^2} + \rho_{m0}\gamma_{m0}\varepsilon + a_s \ln\left(\frac{\alpha}{\alpha-1}\right) = 0 \tag{4}$$

The kinetics equation of pore growth describes the evolution of the parameter α α in the range $1 < \alpha_{00} < \alpha \le \alpha_*$. It is used at

$$\alpha p + a_s \ln\left(\frac{\alpha}{\alpha-1}\right) < 0.$$

Otherwise $\frac{d\alpha}{dt}=0$. The equation includes three easily determined parameters: $a_S, \alpha_{00}, \alpha_*$. $a_S=\frac{2}{3}\sigma_s$. α_{00} - there is dual porosity in the material, α_* – the critical value of porosity when destruction of the material occurs.

The parameters of equations of state c_{m0} and q q of composite materials, which are multicomponent homogeneous mix, are determined in terms of shock adiabatic curves of mix components $D_i=c_{0i}+q_i u$ by graphic method using ratios in the front of the shock wave:

$$D=\upsilon_{m0}\sqrt{\frac{p_m}{\upsilon_{m0}-\upsilon_m(p_m)}},\ u=\sqrt{p_m(\upsilon_{m0}-\upsilon_m(p_m))},$$

where $\upsilon_{m0}=\frac{1}{\rho_{m0}}=\sum_{i=1}^{n}m_i\upsilon_{m0i}$ $\upsilon_{m0i}=\frac{1}{\rho_{m0i}}$ $m_i=\nu_i\frac{\rho_{m0i}}{\rho_{m0}}$ .The initial density, volume and mass concentration of the i mix component are designated by ρ_{m0}, ν_i, m_i respectively.

Invariables (υ_m, p_m), the shock adiabatic curve of the matrix material of a composite has the form:

$$\upsilon_m(p_m)=\sum_{i=1}^{n}\left\{\upsilon_{m0i}-\frac{1}{p_m}\left[\frac{c_{0i}}{q_i}\sqrt{\frac{p_m q_i}{p_{m0i}c_{0i}^2}+\frac{1}{4}-\frac{1}{2}}\right]^2\right\}m_i \quad (5)$$

The shear modulus of the matrix material and yield stress are determined by shear moduli and yield stresses of components: $\mu_{m0}^{-1}=\sum_{i=1}^{n}\nu_i\mu_{m0i}^{-1};\sigma_s=\sum_{i=1}^{n}m_i\sigma_{si}$.

To calculate the dynamic destruction of fragile composite materials of complex structure, it is reasonable to apply phenomenological approach [4] in which strength criteria are expressed through invariant connections between critical values of loading macro characteristics – stresses and deformations. In this case, in the process of dynamic loading before performance of criterion of durability, material is described as linearly elastic body. As a strength condition, the criterion offered in [5] is used:

$$3J_2=[AI_1+B]\left\{1-(1-C)\left[1-\frac{J_3}{2}\left(\frac{J_2}{3}\right)^{-\frac{3}{2}}\right]\right\} \quad (6)$$

where I_1, J_2, J_3 – the first invariant of stress tensor, the second and third invariants of stress deviator respectively; $A=R_c-R_p$ $B=R_cR_p$ $C=\frac{3T_c^2}{R_cR_p}$ R_c R_p T_c – ultimate strengths under uniaxial compression, stretching and pure shear respectively.

The surface (6) for isotropic materials has to correspond to the convexity condition (according to the Drucker-Hill's postulates) which sets the following limits on the calculated parameters $0.530\le\frac{T_c}{\sqrt{R_cR_p}}\le 0.577$ .Numerical values A, B, C are determined by the ultimate strengths of a composite in the process of stretching, compression and pure shear obtained under dynamic loading.

After completion of the strength criterion it is considered that material is damaged by cracks. Fragmentation of the damaged by cracks material which was affected by the stretching stresses occurs when the relative void volume reaches critical value $\xi_*=\frac{\alpha_*-1}{\alpha_*}$,where α_* – the critical value of porosity when destruction of the material occurs.

If the material damaged by cracks is affected by the compressive stress, the fragmentation criterion is the limiting value of intensity of plastic deformations $e_u^* = \frac{\sqrt{2}}{3}\sqrt{3T_2 - T_1^2}$ where T_1 and T_2 - the first and second invariants of strain tensor.

The destroyed material is modeled by the granulated medium with standing the compressive loadings but not withstanding the stretching stresses. The numerical realization of mathematical model is carried out by the software package in full spatial design.

CALCULATION AND EXPERIMENTAL DATA

To identify the main processes affecting the behavior of HRC material under high-speed impact experimental studies using 23 mm caliber smooth-bore ballistic setup were done. A steel spherical element was placed in the guiding device which separated after the exit from the bore on the tracer streak. This made it possible to fix the interaction of the projectile and the barrier without hindrance. For photo and video recording of the main stages of projectile flights and their interaction with targets on the tracer streak, two high-speed “Fantom” cameras having 110 thousand fps shooting speed were used.

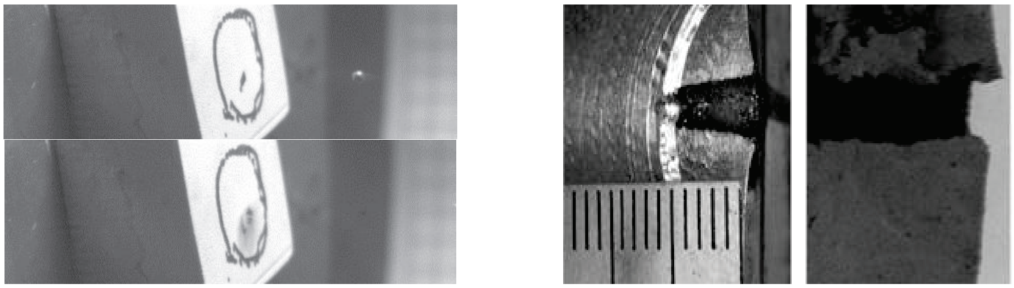
In the present work, the hurled assembly consisting of the guiding device with dividing polyethylene petals, the textolite pallet and the projectile in the form of a steel spherical element was used. Figure 1 shows parts of the hurled assembly (*a*) with the steel spherical element, *(b)*assembly in which the spherical element is not deformed when speeding-up in the bore.

After carrying out some proving experiments it was noticed that petals come after the projectile on the barrier, thereby distorting the result of experiment. For separation of parts of the guiding device from the spherical element, cutoff plates were installed on the tracer streak.

(a) (b)

FIGURE 1. Kit of parts of hurled assembly with the use of polyethylene and textolite (a) and complete assembly with a spherical element of 23 mm caliber (b)

The diameter of steel spherical elements d = 3 mm. The range of velocities of hurled assemblies made 2.5 … 2.6 km/s. The research on impact of a steel spherical element against compound barriers was conducted: a front layer is the HRC material under study (the analog of material [1]); a back layer is the barrier – "witness". Round disks made of dural alloy with the diameter of 160 mm and thickness of 70 mm was used as a barrier - "witness". As a result of impact with the steel spherical element, in the barrier - "witness" a crater of various depth h and diameter D formed depending on properties of the studied material sample and impact velocity.



(a) (b)

FIGURE 2. Impact of the spherical element against the compound barrier and the result of interaction

Figure 2a illustrates the results of video recording and photos of the compound target after interaction with the steel spherical element. So, Figure 2b shows that the spherical projectile stopped in the barrier - "witness". The experiment showed that under impact of the steel spherical projectile with the diameter of 3.17 mm at the speed of 2563 m/s against the compound target, HRC sample of 34 mm thick was punched on the barrier - "witness", in which the crater of 4.9 mm deep and 3.5 mm in diameter was formed.

From the results of experiments it is possible to draw a conclusion that the materials under study have some protective properties against high-speed impact. The obtained data may be used for verification of mathematical behavior model of HRC under interaction with a meteoric particle.

The HRC material is a multicomponent high-porous composite on inorganic ceramic basis with resin binders and silicon organic raw rubber. It has the average initial density ρ_0 = 0.65g/cm^3 and relative void volume 66% what corresponds to the initial value of porosity α_0 = 2.9677.

The parameters of the equations of state and mathematical model of composite materials studied in this work are given in Table 1.

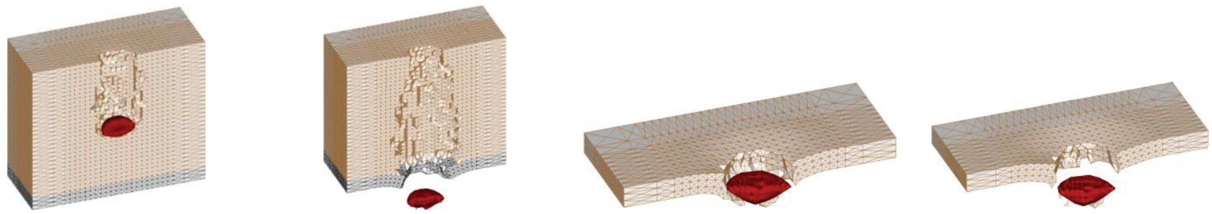
TABLE 1. The parameters of the equations of state and mathematical model

Material	ρ_{m0}, g/cm^3	c_{m0}, km/s	q	γ_0	ρ_{m0}, g/cm^3	μ_{m0}, GPa	σ_{ms}, GPa	R_c	R_p	T_c	a_s, GPa	α_{00}	ζ_*	e_u^*
HRC	1.9255	2.0	1.76	1.41	1.9255	3.64	0.01357	0.0156	0.0105	0.073	0.009	1.01	0.6774	0.3
Steel	7.85	4.56	1.50	2.26	7.85	82.0	1.00	-	-	-	0.17	1.0006	0.3	1.5
D16T	2.63	5.386	1.39	2.13	2.63	27.7	0.18	-	-	-	0.27	1.0002	0.3	1.0
Carbonfibre	1.46	2.9	1.22	0.26 0.48	1.46	6.67	1.5754	1.22	1.66	0.7877	1.0508	1.004	0.05	0.4

Testing of the calculation technique under conditions of the described above test gave divergence with the experiment on the depth of formed in a barrier - "witness" crater by 4.1%.

Let us consider the impact of the spherical steel projectile with the diameter of d_0 = 2 mm again stan aircraft component. As a rule, an aircraft component contains four layers: the first layer –10 mm thick HRC, the second – 1 mm thick carbon fibre, the third – 20 mm thick aluminum honeycombs, the fourth – 1 mm thick carbon fibre.

In case when the diameter of aluminum honeycombs exceeds the diameter of a meteoric particle under normal impact there can be a situation when a projectile flies through the honeycombs. This option is considered in Fig. 3. The projectile at first interacts with a layered barrier (HRC + carbon fibre), then with the second layer of carbon fibre.



2 μs 4.5 μs 5 μs 6.5 μs

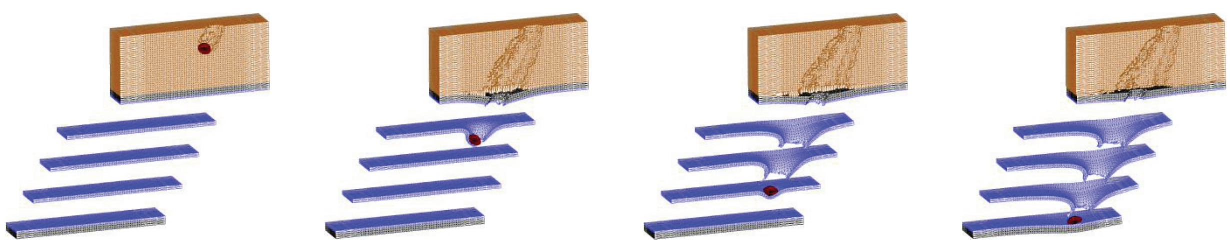
FIGURE 3. Chronogram of interaction of a steel spherical element of 2 mm in diameter with layer – separated (HRC + carbon fibre + carbon fibre) component at V_0 = 5000 m/s

As seen from the figure, a steel particle punches the first layer of carbon fibre at 4.5 μs, thus its velocity makes 2454 m/s. Then it punches the second layer of carbon fibre, residual velocity is 1849 m/s.

The most probable case of shock interaction of a meteoric particle with the aerodynamic screen is the impact at an angle which differs from a normal angle. In this case, after punching HRC layer and the first layer of carbon fibre the particle interacts with thin aluminum barriers. Let us consider the configuration of five separated barriers: the first barrier consists of 10 mm thick HRC layer, 1 mm thick carbon fibre layer and 0.33 mm thick aluminum layer; the second, third and fourth barriers are made of 0.66 mm thick aluminum; the fifth barrier is1 mm thick carbon fibre.

Let us consider the impact of the spherical steel element of 2 mm in diameter when interacting with the given separated configuration at an angle 60° at different velocities. Figure 4shows the results of interaction at velocityV_0 = 3000 m/s.

When moving in HRC layer, the steel particle is slightly deformed. The bore in HRC practically follows the particle size in diameter. At 8 μs the punching of carbon fibre layer occurs, and the particle interacts with thin aluminum barriers. By 40 μs it reaches the second layer of carbon fibre and at 51 μsit stops without having punched it. During interaction the steel ball "reduced" if its initial weight was 0.031 g, after interaction it made 0.029 g. During all process in the interaction zone of HRC and the first layer of carbon fibre due to shock-wave processes loosening of HRC and its peeling from carbon fibre occur. As a result, the destruction zone of HRC increases.



2 μs 13 μs 26 μs 51 μs

FIGURE 4. Chronogram of interaction of a steel spherical element of 2 mm in diameter with layer separated (HRC + carbon fibre + aluminum honeycombs + carbon fibre) configuration at an angle 60° at V_0 = 3000 m/s

Figure 5 presents the results of interaction of a steel spherical element of 2 mm in diameter with the separated configuration at an angle 60°atV_0 = 9000 m/s. In this case, the steel particle fractured at 5 μs when colliding with the second aluminum barrier.

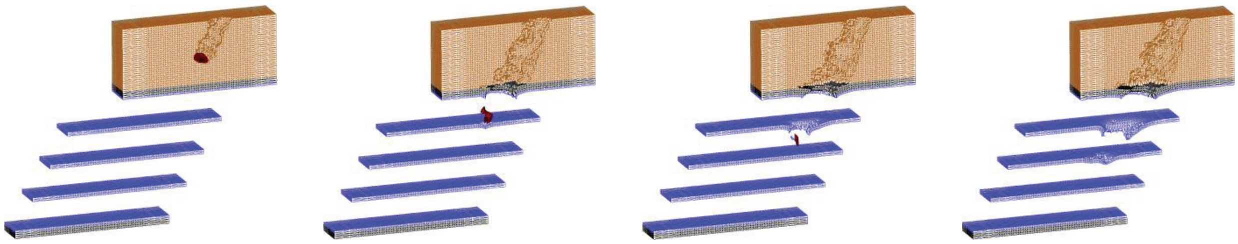

1 μs 3 μs 4 μs 5 μs

FIGURE 5. Chronogram of interaction of a steel spherical element of 2 mm in diameter with layer separated (HRC + carbon fibre + aluminum honeycombs + carbon fibre) configuration at an angle 60°at V_0 = 9000 m/s

CONCLUSIONS

The experimental methods were developed to apply for research of high-speed impact of spherical particles against multilayered barriers using 23 mm caliber ballistic setup.

The mathematical behavior model of HRC material in the conditions of high-speed interaction with a meteoric particle was developed.

The computation algorithm was offered to study the interaction of a high-speed meteoric particle with the protective design of an aircraft in full spatial design.

Under the impact velocity of about 2.5 km/s a steel meteoric particle passing through HRC layer is slightly deformed, leaving behind a bore whose diameter is close to the diameter of a spherical element.

With increase in velocity to 9 km/s, the steel meteoric particle makes the extending bore in HRC, but generally does not punch the protective configuration(HRC + carbon fibre + aluminum barriers + carbon fibre) when meeting at a normal and at an angle (45°, 60°).

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