ON SEMI-ACTIVE SHIELDING PROTECTION OF SPACECRAFT FROM METEOROIDS AND ORBITAL DEBRIS

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ABSTRACT

For increase of fragmentation and kinetic energy of tangential scattering of fragments (in the system of the mass centre of a cloud of fragments) it is proposed to use in structure of protection chemically active materials.

There is a possibility to use the reaction directly between components of protection shield and orbital medium particles. For this purpose it is supported to use a mesh shield which elements are able to penetrate into indenter deeply. Then, the reaction surface area is increased considerably and the reaction will occur not only in a thin layer near the contact surface but in the tracks generated in the particle just behind the penetrative elements of a shield (in the vapor phase). Most of materials of orbital debris are characterized by a high reaction heat with halogens, oxygen and sulfur. The analysis performed on the current stage allows us to come to conclusion that the most promising materials are polyfluoro-olefins, for example, polytetrafluorethylene $[-C_2F_4-]_n$ (PTFE, fluorocarbon polymer F4). This material is quite enough stable under orbital conditions and, at the same time, it provides with a large energy effect in the reactions with orbital medium particles.

The submitted results of experiments testify to non-thermal character of reaction initiation in conditions of joint plastic deformation PTFE and aluminum at impact.

E. Christiansen (JSC of NASA) made contribution to the semi-active shielding idea too.

1. INTRODUCTION

Use of mesh shields in protect constructions of the orbital modules gives possibility for the increasing of the protection quality. Namely there is a possibility to use the chemical reactions between the protection shield components and particles of the orbital medium in order to enhance the fragmentation effectiveness.

The heterogeneity of the reaction is the main obstacle on the way to an effective realization of such scheme. The reaction rate is proportional to the square of the contact surface of the reacting phases at least at the original stage of the collision between the projectile and bumper. Conditions of the collision makes governing influence on the completeness of the reaction behavior (conversion level) and impact conditions have favourable effect. Owing to this reason using of active (with respect to the projectile material) chemical agents in the continuous shields scarcely makes sense.

During the interaction with the continuous shield the square of the reaction surface is of order the square of the projectile cross section and it increases mainly due to its impact fragmentation. In this case on the time intervals (this is time of several sonic wave run on the characteristic projectile size in order) of interest the conversion level is negligibly small. Moreover it seems that the geometry of interaction between a compact projectile and continuous shields does not allow the reaction to make any significant influence on the transversal spread characteristics.

During the interaction with a mesh shield which elements can deeply penetrate into the projectile the picture is changed drastically. First, the square of a reaction surface essentially increases, second, reaction will proceed not only in a thin layer at a contact surface, but also in the tracks formed in the projectile behind penetrating elements of the shield (in a steam phase).

At last, increase of pressure on an internal surface of tracks due to chemical interaction of projectile materials and the shield should promote increase transversal components of the fragments momentum. The qualitative picture of penetration an element of the shield into a compact projectile is given in Fig. 1.

2. CHEMICAL-MECHANICAL EFFECTS

It is well-known, that the basic fraction of the orbital debris is made with particles of the aluminum alloys alloyed by magnesium, by silicon and other additives. Alloys of the titan, heat resisting alloys and nonmetallic materials are to a lesser degree given. The majority of these materials is characterized by high heat of reaction with halogens, oxygen and sulfur.

Apparently for the semi-active protection the most available materials are polyfluorole: polytetrafluoroethylene $[-C_2F_4-]_n$ (PTFE, fluoroplast F4) and polytetrafluorochlorineethylene $[-C_2F_3Cl-]_n$ (PTFCE, fluoroplast F3). The specified substances are

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stable enough in orbital conditions and, at the same time, provide the large energetic effect in reactions with particles of the orbital environment.

Results of an estimation of the maximal heat of reactions of interest between teflons and components of orbital debris are presented in Tab. 1.

Table 1. Heat effects for the reactions between teflons and orbital medium components particles

No.	Equation of reaction	Heat effect in calculation on a mass unit of an oxidizer, kJ/kg
1	$4\,Al + 3\,C_2F_4 \rightarrow 4\,AlF_3 + 6\,C$	12410
2	$Ti + C_2F_4 \rightarrow TiF_4 + 2\,C$	8560
3	$Si + C_2F_4 \rightarrow SiF_4 + 2\,C$	8630
4	$2\,Mg + C_2F_4 \rightarrow 2\,MgF_2 + 2\,C$	14360
5	$4\,B + 3\,C_2F_4 \rightarrow 4\,BF_3 + 6\,C$	8200
6	$4\,Al + 3\,C_2F_3Cl \rightarrow 3\,AlF_3 + AlCl_3 + 6\,C$	9850
7	$4\,Ti + 4\,C_2F_3Cl \rightarrow 3\,TiF_4 + TiCl_4 + 8\,C$	7300
8	$4\,Si + 4\,C_2F_3Cl \rightarrow 3\,SiF_4 + Si\,Cl_4 + 8\,C$	6440
9	$4\,Mg + 2\,C_2F_3Cl \rightarrow 3\,MgF_2 + MgCl_2 + 4\,C$	11960
10	$4\,B + 3\,C_2F_3Cl \rightarrow 3\,BF_3 + BCl_3 + 6\,C$	6030

As one can see from presented data the heat effects are highly significant (for comparison – the heat effect of the explosive conversion reaction for trotyl is about 4000 kJ/kg).

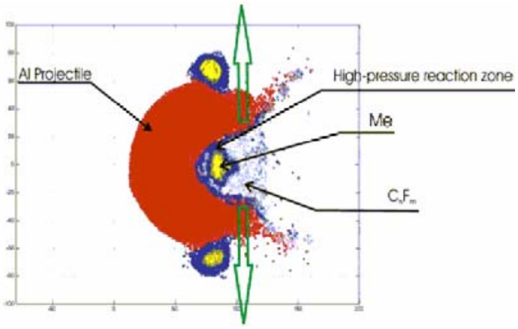

Figure 1. The schematic image of the protection shieldelement penetration into a destroyed particle (Me = Zr,Fe, Cu; C_nF_m – the volatile fluocarbon radicals; the straight arrows show action of additional pressure).

From the practical point of view the most important question concerns on significance of the kinetic restrictions. The chemical contribution to energy of a cloud of fragments will be effective only in that case when characteristic time of reaction is comparable with time of spread of a sonic wave for distance of the several projectile sizes. Therefore the problem consists in maintenance of the enough reaction rate due to a rational choice of design parameter of the shield.

Consider the most investigated system “PTFE - Al”. Before proceeding to the analysis of kinetic laws of interaction in this system, we shall present results of an estimation of initial parameters of impact PTFE with aluminum. At projectile velocity from 3 up to 7 km/s pressure at the front a shock wave will make, accordingly, from 7.7 up to 26 GPa. For comparison, at impact of aluminum on aluminum pressure at the front exceeds 25 GPa already at velocity of 3 km/s.

Pressure decrease at the front a shock wave is the positive factor in the certain attitude. The point is that at destruction on the multi-spall mechanism pressure decrease at the front a shock wave corresponds to the decrease of thermal energy and increase in kinetic energy of fragments of destruction in frame of the center of mass. The last improves fragments scattering and, hence, efficiency of protection.

On the other hand, thermal decomposition PTFE at shock - wave loading begins at pressure about 21 GPa (the corresponding temperature makes about 2000 K). Therefore at impact velocity up to 6 km/s thermal decomposition in PTFE volume does not occur. However in contact to aluminium reaction begins at considerably lower temperatures about 1000 K (energy of activation of the PTFE thermodestruction process makes 118 kcal / mol whereas energy of activation of reaction with aluminium does not exceed 55 kcal / mol). Moreover, there are direct experimental evidences of nonthermal character of activation of chemical interaction PTFE with aluminum under impact conditions (the brief review of studies in this area is given in (*L.P. Orlenko, 2002, Physics of explosion*). In experiments with semi-infinite bumpers from aluminum alloys it has been established, that the ratio of projectile kinetic energy to volume of a cavity takes an abnormally low value (about 0.895 kJ/sm^3) at small impact velocities ~ 900 - 1000 m/s. Thus the analysis of a chemical compound of products of interaction has shown presence of soot and fluoride of aluminum. Results of the experiments testify on initiation of reaction between PTFE and aluminum under conditions of mutual plastic deformation during the impact. Energy released during the interaction (at least, its significant part) is consumed on formation of a cavity, this is a reason of abnormally low value of its specific formation work.

The analysis of the available data allows us to formulate the following physical script of shock interaction of small compact PTFE samples with rather large samples from aluminum alloys. PTFE samples penetrate into aluminum as triggered projectiles owing to low density and sonic speed ($\rho \approx 2.2$ g/sm^3, $c \approx 1.34$ km/s), and also low thermo-mechanical properties (temperature of a softening is about 260^{o}C). Chemical reaction of PTFE with aluminum begins in a thin layer in a vicinity of a contact surface and is accompanied by formation of a large amount of volatile fluocarbon radicals with small molecular weights. The latter entails additional increase of pressure on walls of a formed cavity and accelerates its growth. Formation of fluorides, promoting evaporation of aluminum from a massive phase, rise in temperature due to heat released in reaction and intensive plastic deformation lead to increase the aluminum mass transfer in PTFE and also to increasing in rate of process. It seems rather probable, that at high impact velocities reaction rate is limited by diffusive transfer valence nonsaturated fluorides of aluminum (AlF, AlF_2) in PTFE.

The given qualitative script is identical to cases of rather low velocity penetration of PTFE projectiles into aluminium bumpers and high-velocity interaction of particles of the space environment with mesh shields containing PTFE. The effective contribution of reaction PTFE with aluminum during a fragmentation of particles of the near earth environment is possible, if considerable conversion level is reached during the order of several micro seconds.

For use of mechanical-chemical effects it is necessary to reveal conditions under which it is necessary to expect effective course of reactions and phase transformations. Since the direct estimation of the conversion level of mechanical-chemical transformations into ballistic experiments is rather difficult, for experimental studies the technique based on the well-known method of welding by explosion has been developed. The scheme of shock loading is presented in Fig.2.

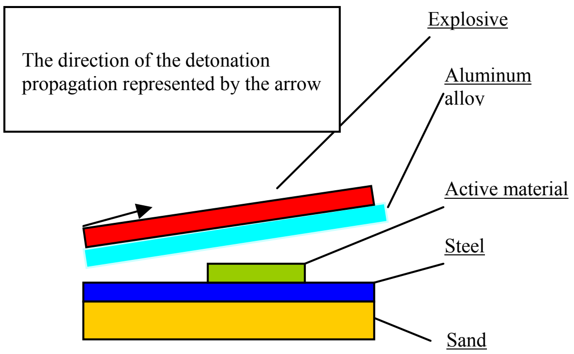

Figure 2. The shock loading scheme

In experiments the velocity of a throwing of plates from aluminium alloys D16 and AMr-6 varied within the range from 150 up to 450 m/s, the angle of incline, γ, changed within the range 6 … 15^0. The thin layer of an active material is teflon, sulfur or polythene (δ = 100…300 microns) was placed in the center of a steel plate. Thickness of this layer was chosen from the condition when the full material ejection in a cumulative jet due to plates impact is absent.

Used impact regimes provided the reliable welding of steel and aluminum plates on edges of assembly so the products of interaction, including gasphase, appeared to be encapsulated in the central part. Appearance of a sample after impact and a section on the median plane in the direction of the detonation spread are presented in Fig. 3.

For an estimation of volume and structure of gasphase products the plant providing opening of the central part of samples with measurement of pressure and by-way of gas in a hermetic capacity. After opening the samples were cut on some fragments part of which was used for manufacturing microsections at angles of 11^0 and 90^0 to the free surface. Analytical investigations were carried out by methods of optical and electronic microscopy, local X-ray spectrum analysis and smallangle x-ray dispersion.

In all experiences formation of a characteristic swelling of an aluminum plate (Figs. 3, 4), close to the form to a spherical segment was observed. The height of a swelling and volume of a cavity essentially depend on the throwing velocity of a plate and also on the kind of an active material. At close velocities of a throwing the greatest sizes of a cavity were observed for teflon films. At use of sulfur and polyethylene the volume of the cavity was essentially (2.5-4 times) less.

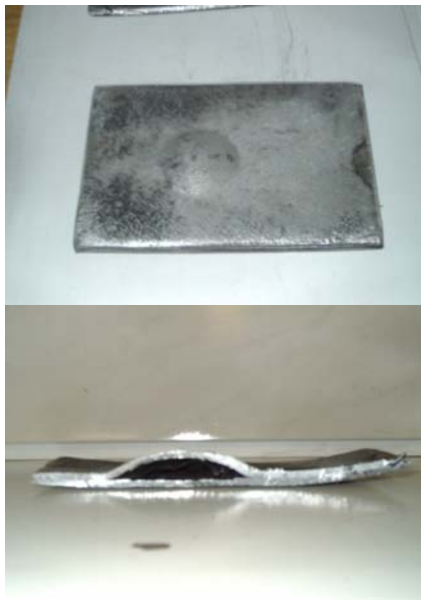

Figure 3. Appearance of assembly after impact and section of assembly on a median plane (polythene – over, teflon – below; v = 300 m/s, $\gamma \approx 7^0$)

During interaction of aluminum with teflon inside a cavity (on the surface of aluminum and a teflon film) the friable soot layer forms. This layer contains, mainly, carbon, aluminum and fluorine. The electron microscopic photo of the surface of aluminum (after removal weakly connected to a surface large soot particles by a brush) and elementary structure of two fragments of the surface are done. The surface of the teflon film and elementary structure of its two fragments were investigated also. For comparison, it can be see, that the soot thin coating on this surface is almost absent. Absence of significant soot formation is typical and for interaction of aluminum with polythene. In this case one can observe only small uniform blackening of the polyethylene film surface. Detailed analytical investigations of the shock interaction of aluminum with sulfur were not carried out (such investigations need special isolation of samples from the atmospheric moisture). Nevertheless, formation of a significant amount of sulfide of aluminum is found in a cavity.

Electron microscopic investigation of microsections shown that the aluminum plate surface after impact interaction with teflon gets roughness with the characteristic sizes 30-70 μm on depth and gets extents (the initial surface contained roughnesses of micron scale).

The electron microscopic image transversal microsection and distribution of elements towards the normal to the surface is given in Fig. 4. On the basis of the experimental studies carried out within the framework of the present project and the performed theoretical estimations it is possible to come to the following conclusions. First of all, application of chemically active substances with respect to particles of orbital dust in the mesh protection shields basically allows to provide a significant additional energy release, promoting a fragmentation and improvement of scattering of fragments. Even at rather low velocities of impact (however at the large shear deformations) high enough velocity and completeness of reaction may be provided. As it follows from the given experimental data, this caused by mutual dispertion of materials on the contact surface that, in its turn, leads to to the sharp increase in the reaction surface and as a consequence, to the increase in completeness of reaction.

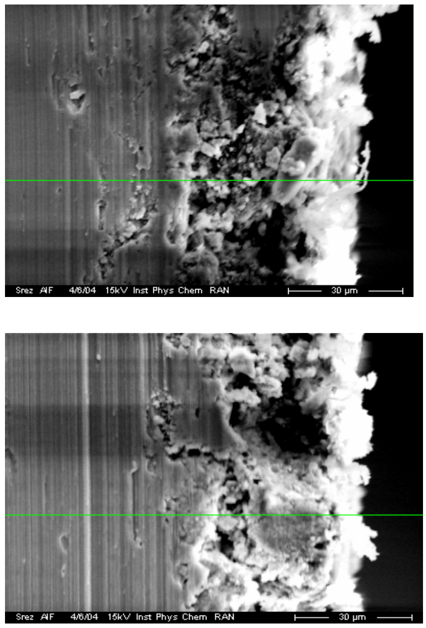

Figure 4. Electron microscopic image of the transversal microsection surface
(over: $v \approx 300$ m/s, $\gamma \approx 7^0$; below: $v \approx 450$ m/s, $\gamma \approx 11^0$)

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