Properties of technical aluminum under the effect of dynamic alloying

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Abstract Dynamic alloying in the mode of super-deep penetration (SDP) allows us to evaluate the effects that occur in the materials of the spacecraft when interacting with high-speed streams of cosmic dust. The results of the experiments are presented, confirming that dynamic alloying in the SDP mode creates anisotropy in a solid body and leads to a change in physical properties (electrical resistance, electron work function). The dynamic alloying increased the anisotropy of electrical resistance in technical aluminum 99.7% Al in 2.05 times (105%), led to a decrease of the electrical resistance in the longitudinal direction by 16% and increase in the transverse direction by 41%.

1. Introduction

Failure of control systems during long flights significantly reduces reliability and, accordingly, increases the cost of using satellites and space stations. Therefore, the reasons for such failures are continually being searched. An increase in the flight time of satellites and space stations in near-earth space leads to an increase in the likelihood of collisions with space debris [1,2,3]. Dodging macro-objects (space debris) can be accomplished by maneuvering. The detection of streams of micro-objects (cosmic dust) is currently unrealistic.

For a long time, the collisions of streams of dust particles with metal modules of spacecraft were considered only from the position of erosion of the outer surface. The researchers have now concluded that such collisions lead to the appearance of plasma and damage to electronic control systems [4,5,6]. Loss of tightness by modules is traditionally used as the main criterion for registering shell penetration. As a rule, no depressurization is observed upon collision with dusty objects. Currently, there are research data in the field of dynamic alloying, which shows that the process of penetration of micro-objects occurs by the collapse of the channel-crater. Therefore, there is no depressurization of metal modules [7]. In the case of implementation of dynamic alloying in the super-deep penetration (SDP) mode, the barrier limitation on penetration is $10^2$ - $10^4$ calibers of the striker. Accordingly, the possible penetration depth of dust microparticles can reach tens and hundreds of millimeters [8,9]. The change in mechanical properties under dynamic loading [7,10,11] indirectly points a change in the physical properties of the material, and the peculiarities of the dynamic alloying process in the SDP mode should increase the anisotropy of the material being processed.
Lightweight constructions, metals and their alloys are used as the materials for the shell of aircraft and spacecraft. The necessity for high performance and low-cost materials caused the researchers worldwide to switch the focus from monolithic to composite materials. Also, a significant effort has been made to create numerous combinations of metal matrix composites. Intensive labor is dedicated to creation of the lightweight constructions: reinforced Al composites [12,13], hybrid lightweight composites design [14], production of the special lightweight fillers [15] and applications of it in Al- and Mg-lightweight composites [16]. Among the metal matrix composites, aluminum-based composites are treated as the most promising structural materials due to their high corrosion, wear resistance, specific modulus, and weight for automobile and aerospace applications [12].

Super-deep penetration (SDP) is a complex physical phenomenon, when in a split-second stream of powder particles with a fraction less than 100 microns, accelerated to speeds of 700-3000 ms⁻¹, penetrates the solid metal body at depth in tens, hundreds mm. At the same time, the high and ultra-high pressure (0.2-20 GPa), intensive deformation, local heating, friction is occurred [17]. Dynamic alloying in the SDP mode is characterized by the simultaneous action of various physical factors on the material (high pressure, significant pressure gradients inside a solid metal body, zones of intense tension and compression, temperature, radiation, etc.). Such a complex effect occurs in the time interval of 10⁻⁹-10⁻⁴ s, which significantly changes the conditions of heat and mass transfer. The intensity of loading is so high that destruction or irreversible changes are possible in the body on which it acts. Unlike classical alloying, SDP provides the introduction of alloying elements into an already solid body, and to a greater depth than when using surface hardening and ion implantation methods [7-9].

The SDP process, in a simplified form, is the formation of extended high-pressure zones with different levels of stress state in mutually perpendicular directions. These zones are reinforcing a metal solid. In particular, the SDP process involves the creation of alternating zones of tensile and compressive stresses and, accordingly, extrusion into the channel regions of the interaction products of the introduced and matrix material [7,17].

The anisotropic nature of the flow of energy and mass transfer processes during SDP suggests, due to the freezing of defects during unloading onto a metal matrix at the stage of termination of penetration, a formation of a residual anisotropic structure of the composite material. The processes of multidirectional intense deformation and freezing of defects are most clearly reflected in such physical properties as electrical conductivity and thermal conductivity. Therefore, the verification of the hypothesis, that the anisotropy in the nature of the course of SDP processes should lead to a strong anisotropy of physical properties, should be carried out based on experiments with electrical conductivity in aluminum and the distribution of the electron work function (EWF) over the surface.

The electron work function (EWF) is one of the fundamental characteristics of matter in a condensed state. The EWF value is influenced by such factors as the chemical composition of the surface, crystal lattice defects, adsorption of substances from the surrounding atmosphere, etc. [18]. The high sensitivity of this parameter to the state of the surface determines the interest in using ERW for characterizing the metal surface after various types of processing.

According to the existing theoretical models, local deviations of the surface EWF values are mainly associated with the deformed state of the metal and the adsorption of atoms or molecules on its surface. The effect of the deformed state of the metal on the EWF of the surface is determined by the change in the length and angle of interatomic bonds due to changes in the volume and density of atomic clusters under load [19].

Experimental measurements of the EWF of a metal surface and its changes caused by mechanical stresses have also been published [20-24]. In particular, it has been shown that alternating loading of aluminum and titanium specimens leads to a decrease in the EWF in the stress concentration region. It can be assumed that the observed changes in the EWF are associated with both an increase in the number of dislocations and the formation of new surfaces in the process of sample destruction associated with the development of a crack. Various researchers independently showed that elastic tensile deformations lead to a decrease in the recorded values of the EWF, while elastic compression deformations, on the contrary, to their growth [22]. Changes in the contact potential difference can also be associated with
the transfer of matter to the metal surface. The adsorption of atoms or molecules on the surface is accompanied by charge transfer between the adsorbate and the substrate, which leads to the modification of the surface double layer. The consequence of this is a change in the surface potential nor a corresponding change in the external EWF [23,24]. The treatment of a metal surface by electrochemical or high-energy (in particular, plasma) impact also leads to a change in its contact potential difference [25,26]. In this case, both a change in the EWF of the surface and a change in its electrochemical potential take place.

A significant number of materials show different mechanical behavior under dynamic loads compared to quasi-static. Therefore, a comprehensive study of material dynamic behavior is essential for applications in which dynamic loads are dominant [27,28]. Let’s consider results of such processes using technical aluminum as an example.

2. Experimental Methods

Dynamic processing in SDP mode was carried out in the following conditions [17]: average particles speed 1000 ms\(^{-1}\), exposure time - 400 microseconds, the material of billets: casting technical aluminum A7 (99.7% Al, interstate standard GOST 11069-2001, DIN 3.0275), the material of powder particles (strikers) – SiC powder (60%), 63-70 microns and Pb powder (40%), 10-90 microns.

To measure the electrical resistance plates were cut out of the target material (Ø40 mm, length 150 mm) using electro-spark processing. 4-5 plates were cut from each sample in the transverse and longitudinal directions. Electrical resistance was determined as the average of the measurements. The electrical resistance measured on the treated sample by two-probe method was compared with measurements on the initial material.

Besides, the distribution of the electron work function over the surface of the plates in the longitudinal and transverse directions was studied. The topology of the electron work function of the plate surface was registered by the scanning Kelvin probe method [23,24].

3. Results and Discussion

To determine the anisotropy of electrical resistance measurements was carried out in mutually perpendicular directions: longitudinal and transverse.

Measurement of electrical resistance in the longitudinal direction are shown in Table 1:

| Sample    | Average electrical resistance $\rho_{av}$, $10^{-8}$ Ohm.m |
|-----------|-----------------------------------------------------------|
| Initial   | 5.2792                                                     |
| SDP treated | 4.4192                                                   |
| SDP treated | 4.4118                                                   |

In the treated aluminum $\rho_{av,SDP} = (\rho_{av,SDP1} + \rho_{av,SDP2})/2 = 4.4155\cdot10^{-8}$ Ohm.m

Thus $\rho_{av,SDP}/\rho_{av,Initial}=0.8364$ and therefore, it has been established that electrical resistance in the longitudinal direction after treatment decreased by 16.36%.

Measurement of electrical resistance in the transverse direction are shown in Table 2:

| Sample    | Average electrical resistance $\rho_{av}$, $10^{-8}$ Ohm.m |
|-----------|-----------------------------------------------------------|

Table 2. The electrical resistance of plates of technical aluminum A7, transverse direction
Sample Depth of sample, m Average electrical resistance $\rho_{av}$, $10^{-8}$ Ohm-m

| Sample                        | Depth of sample, m | Average electrical resistance $\rho_{av}$, $10^{-8}$ Ohm-m |
|-------------------------------|-------------------|------------------------------------------------------------|
| 1. Initial                    | -                 | 6.3785                                                     |
| 2. Initial                    | -                 | 6.4756                                                     |
| 1. SDP treated                | 0.043             | 9.3896                                                     |
| 2. SDP treated                | 0.093             | 8.7530                                                     |
| 3. SDP treated                | 0.097             | 8.9770                                                     |
| 4. SDP treated                | 0.136             | 9.2366                                                     |

Therefore, in the initial aluminum A7 $\rho_{av \, \text{initial}} = (\rho_{av2} + \rho_{av3})/2 = 6.4270 \cdot 10^{-8}$ Ohm-m.

In the treated aluminum $\rho_{av \, SDP} = (\rho_{avSDP1} + \rho_{avSDP2} + \rho_{avSDP3} + \rho_{avSDP4})/4 = 9.08905 \cdot 10^{-8}$ Ohm-m.

Then $\rho_{av \, SDP}/\rho_{av \, \text{initial}} = 1.4126$, i.e. the electrical resistance after the treatment in the SDP mode increased by 41.26%.

If we consider the changes in the electrical resistance after processing from the upper part (the surface of the introduction of the SiC (60%) + Pb (40%) stream, then the sample 1 is cut at a depth of 43 mm ($\rho_{avSDP1}=9.3896 \cdot 10^{-8}$ Ohm-m) $\rho_{avSDP1}/\rho_{av\text{initial}} = 1.4610$), sample 2 at a depth of 93 mm ($\rho_{avSDP2}=8.7530 \cdot 10^{-8}$ Ohm-m) ($\rho_{avSDP2}/\rho_{av\text{Initial}}=8.9770 \cdot 10^{-8}$ Ohm-m) ($\rho_{avSDP3}/\rho_{av\text{initial}}=1.3619$), sample 3 at a depth of 97 mm ($\rho_{avSDP3}=8.9770 \cdot 10^{-8}$ Ohm-m) ($\rho_{avSDP4}/\rho_{av\text{Initial}}=1.3960$), and sample 4 at a depth of 136 mm ($\rho_{avSDP4}=9.2366 \cdot 10^{-8}$ Ohm-m) ($\rho_{avSDP4}/\rho_{av\text{Initial}}=1.4370$). Thus, in the transverse direction, the relative electrical resistance in processed technical aluminum changes markedly up to a depth of 136 mm (Figure 1).

The obtained data are summarized in Table 3. A production of an ordinary aluminum billet by casting leads to the anisotropy of electrical resistance in the longitudinal and transverse directions by 21% ($\rho_{l}/\rho_{t}$). Additional high-energy processing of such billet, as expected, increased the anisotropy of electrical resistance up to 2.05 times ($\rho_{SDP1}/\rho_{SDP2}$).

| $\rho_{av \, SDP}/\rho_{av \, \text{Initial}}$ | Depth, mm |
|---------------------------------------------|-----------|
| 1.4126                                      | 1.3208    |
| 1.3610                                      | 1.3604    |
| 1.3960                                      | 1.3809    |
| 1.4370                                      | 1.4308    |

Figure 1. Change in the relative electrical resistance over the depth of the A7 technical aluminum sample

**Table 3.** Electrical resistance of technical aluminum A7 in mutually perpendicular directions, depending on the nature of the processing
The Kelvin probe method measures the contact potential difference arising between the measured surface and the surface of the reference sample. In this case the measured surface and the reference sample form a flat capacitor and do not contact each other. The value of the contact potential difference will be determined by the difference between the EWF of the reference sample and the studied one [20]. Due to its high sensitivity, the method is used in physicochemical studies, in the study of friction processes, as well as in the study of deformation and destruction of metallic solids 23,24]. It should be noted that the EWF [25] is the energy that must be spent to remove an electron from a solid or liquid substance into a vacuum. Hence, it follows that the EWF depends both on the state of the volume of metal and on the state of its surface. This second component depends on the crystallographic orientation of the surface, adsorbed atoms, the presence of defects on the surface, surface microroughness, etc.

Figure 2 shows the topology of EWF of the sample of A7 technical aluminum. The distribution of the EWF over the surface is nonuniform. The upper part of the longitudinal section is the crater zone, the area of impact on the sample of a high-energy stream of powder particles. The upper and the central zone, which are marked in red, correspond to the lowest EWF. With an increase in the distance from the crater, the region of low EWF, on the one hand, is localized in the center, on the other hand, at a depth of about 90 mm, it dissipates with the formation of several regions with a reduced EWF. This distribution of the zone of the low value of the EWF shows the distribution of the impact of the high-energy stream of powder particles over the sample.

The distribution of EWF over the transverse sections of the sample depends on the depth of the section obtained. The transverse sections of the top and bottom of the sample, as expected, demonstrate a greater uniformity of the EWF. At the same time, the section at a depth of 50 mm from the top of the sample demonstrates a pronounced area with a reduced EWF.

This non-uniformity of the distribution of the EWF in the longitudinal and transverse sections of the sample correlates with the recorded change in the electrical resistance in the longitudinal and transverse directions (Table 3).

The observed changes in the EWF along the depth of the sample coincide with the data on the change in hardness along the depth of the sample (Brinell) obtained earlier [29]. It was found out that the effect of processing by dynamic alloying in the SDP mode on the hardness of technical aluminum A7 was significant up to a depth of 100 mm. The study of the change in the EWF, in turn, showed that the zone of low EWF along the depth of the sample also extends to approximately the same depth.

Measurement of EWF with a Kelvin probe method confirms that dynamic alloying in the SDP mode provides alternating loading of samples, material transfer and leads to a creation of many structural defects of various levels, located unevenly throughout the sample volume. An increase in the density of...
defects, in turn, provides anisotropy of the mechanical and physical properties of the material.

Figure 2. The topology of the electron work function of A7 technical aluminum plates after treatment with SDP. A - longitudinal section, B - transverse section, C - transverse section of initial A7 technical aluminum

4. Conclusions
Based on the analysis of literature sources describing the behaviour of a solid metal body exposed to a high-energy stream of powder particles (in the SDP mode) and experimental data, the following main conclusions can be drawn:

Dynamic alloying in the SDP mode leads not only to a change in mechanical properties [22] but also in physical properties (electrical resistance, EWF);

A casting of an aluminum billet leads to the anisotropy of electrical resistance in the transverse and longitudinal directions in 1.21 times (21%). Additional high-energy processing in the SDP mode increased the anisotropy of electrical resistance in 2.05 times (105%).
Dynamic alloying in the SDP mode led to a decrease of the electrical resistance in the longitudinal direction by 16% and to increase in the transverse direction by 41%.

Measurement of EWF by a Kelvin probe confirms that dynamic alloying in the SDP mode provides a creation of many structural defects of various levels, located unevenly throughout the sample volume. An increase in the density of defects, in turn, provides anisotropy of the mechanical and physical properties of the material.

The hypothesis that the anisotropic nature of deformation processes and redistribution of the energy of pressure fields during dynamic treatment in the SDP mode leads to the anisotropy of the structure and physical properties in a metal solid after exposure is confirmed.

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