Modification of the composite multi-layer oxide ceramic coating on meteoroid shielding element by compression plasma flow

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Abstract. The aim of this work is investigation of the influence of high-energy plasma impact on composite multi-layer coating (NiAl as a sublayer and Al_2O_3 as a top coat) on meteoroid shielding element. In order to reach this goal qausi-stationary plasma accelerator with impulse gas feeding was used. Experiments were conducted with use of helium and hydrogen gas mixture and nitrogen as plasma forming substance. Plasma accelerator generates plasma jet with electron temperature ≈ 150 kK and electron density $(2.5–4) \times 10^{16}$ cm^{-3}. Visual examination, photography and spectral measurements were made through special vacuum chamber optical windows.

1. Introduction

The efficiency of objects protection from damage caused by high-energy impact shock-resistance is determined by materials used for this protection. With regard to the spacecraft shielding, high-strength materials must meet basic requirements—the minimum density, high viscoplasticity, hardness [1]. These characteristics correspond to ceramic plasma coatings. The aim of this work is investigation of the influence of high-energy plasma impact on composite multi-layer coating (NiAl as a sublayer and Al_2O_3 as a top coat) deposited on meteoroid shielding element (2 mm thick aluminium base), as well as investigation of multi-layer coating properties and ballistic tests on modified meteoroid shielding elements. In order to reach this goal qausi-stationary plasma accelerator with impulse gas feeding was used.

2. Qausi-stationary plasma accelerator design

Qausi-stationary plasma accelerator is a magneto-plasma compressor (MPC) working on the ion current transport base. The plasma acceleration in an axially symmetric system of two electrodes is accompanied by its compression due to the interaction of the longitudinal current component with its own azimuthal magnetic field. As a result, behind the inner electrode cut forms compression plasma flow with parameters significantly higher than in the electrode gap MPC is a system of two coaxial copper electrodes separated by a caprolone insulator [2]. Impulse gas feeding system supplies the accelerator with the plasma forming substance. An outer copper electrode (anode) is sectioned and is a set of cupper rods uniformly distributed circumferentially.


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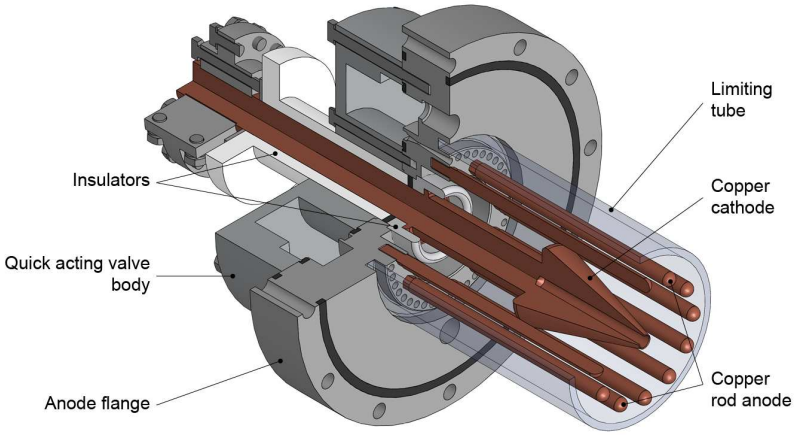


Figure 1. Construction of MPC.

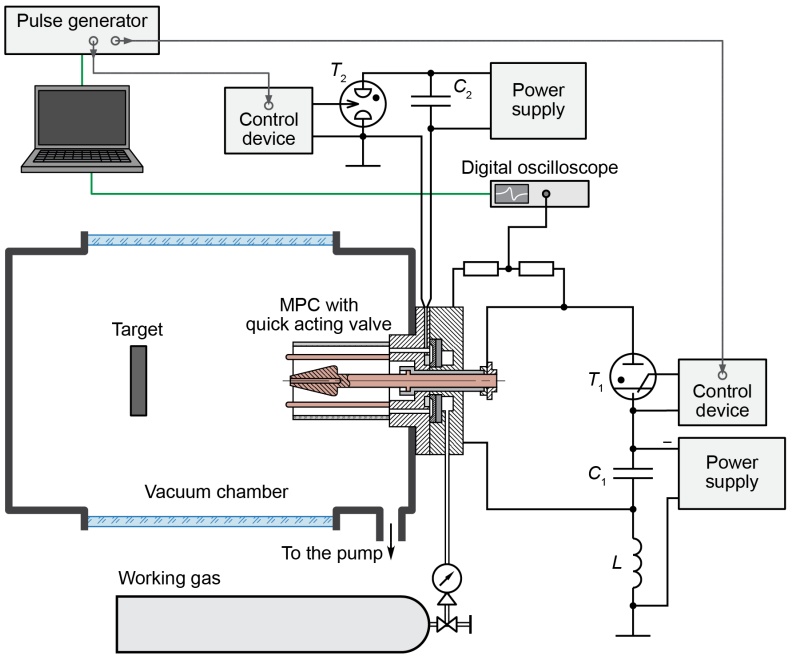


Figure 2. Schema of the experimental facility.

The inner electrode (cathode) has a divertor. The construction of MPC is shown on figure 1 (half-sectional view).

MPCs was placed on the flange of the 250 liters vacuum chamber equipped with special optical windows for visualization, high-speed photography, and spectral studies of plasma. Schema of the experimental facility is shown on figure 2.

MPC starts operating as a result of capacitor bank discharge. This discharge was commutated by a thyratron. High-voltage power supply charges the capacitor bank with a total capacity of 600 μF to initial voltage of 7.3 kV. MPC electrodes were electrically connected to the capacitor battery via a set of 16 high-voltage co-axial cables. The electromagnetic quick acting valve supplies gas feeding. It starts to operate when the capacitor of 240 μF and 4 kV discharge

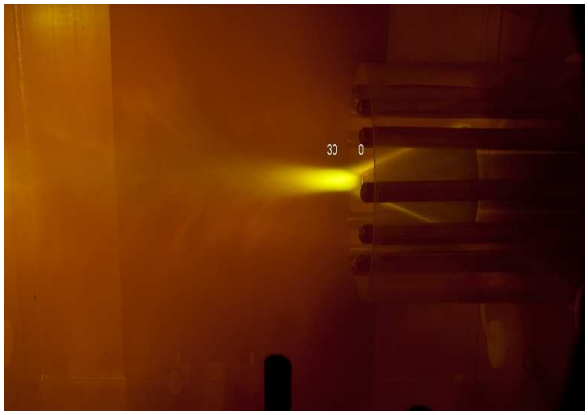


Figure 3. Photography of glowing plasma.

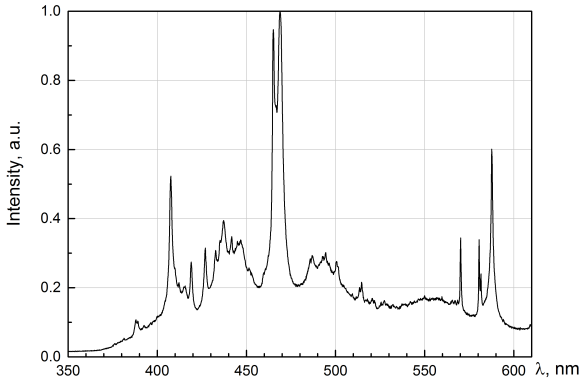


Figure 4. Emission spectrum of the plasma.

through the coil generates magnetic field. This field repulse the metal plate of quick acting valve and gas inflows through the nuzzles into the MPC discharge area. To prevent gas spreading in vacuum chamber we put limiting glass tube around electrodes and nuzzles as shown on figure 1.

3. Diagnostics of plasma flow

Plasma fow parameters were investigated in the open space within the vacuum chamber. Mixture of gases He + H_2 was used in the experiments as the plasma forming substance. The residual air pressure in the vacuum chamber was 2.1 Torr. The integral photography of glowing plasma that reveals the structure of the plasma jet and shown in figure 3. In figure 4 the emission spectrum of the plasma for the time period 20.7–20.9 μs from the beginning of the accelerator operation is shown. The measurements were made by a spectrometer S150A-IV with use of circular diaphragms system for sharply directed diagram of sensitivity. Diaphragms were adjusted to provide emission intensity measurements from area with diameter of 2 mm at a distance of 30 mm from the inner electrode. This region corresponds to a plasma jet compression area.

Temperature and the electron density in the area of compression were calculated on the basis of spectroscopic investigations. The electron temperature T_e in this area was determined by the ratio of the total intensity of the helium line 468.6 nm to the intensity of the spectrum continuum in the vicinity of the line [3], as well as the relative intensity of the line Hγ to a continuum and verified by the dependence of the intensity ratio of singlet and triplet helium lines on the electron temperature [4]. The maximum electron temperature T_e in the compression zone of the plasma flow was about 150 $\pm$ 50 kK. Electron concentration N_e was determined from the Stark broadening of the He1 lines 501.6 nm. Electron concentration was $(2.5–4) \times 10^{16}$ cm^{-3} at the maximum value of the discharge current of 240 kA [4].

4. Electrophysical measurements

The dynamics of voltage on the MPC capacitor bank (figure 5) and the current in the discharge circuit was controlled during the experiment (figure 6). The voltage was measured by means of a high-voltage probe with dividing ratio 1000. The discharge current was measured using inductionless coaxial shunt. The signals from the probe and shunt were sent to the inputs of a digital oscilloscope. Electrical measurements of the discharge parameters of the MPC operating in free plasma outflow mode showed that the discharge is oscillatory. The maximum discharge current was up to 240 kA. Time dependence of the instantaneous discharge power $P(t) = U(t)I(t)$ (figure 7) allows us to conclude that a significant part of the energy (about 86%) stored in the capacitor bank goes into discharge energy during first half period of 28 μs.

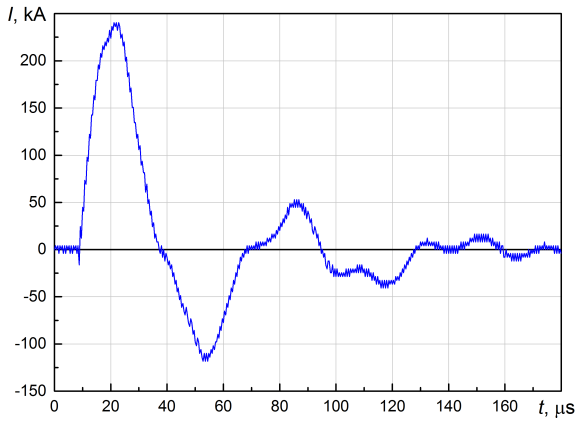


Figure 5. Oscillogram of the current in the discharge circuit.

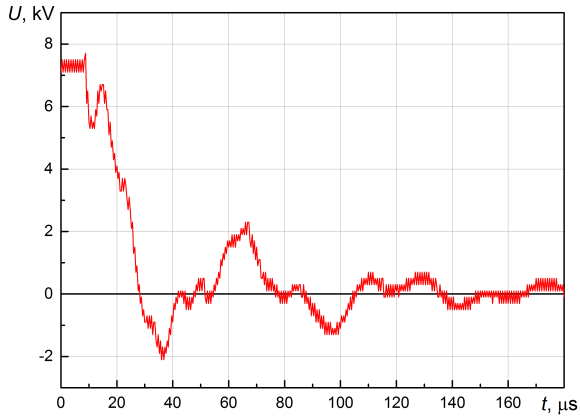


Figure 6. Oscillogram of the voltage on the MPC capacitor bank.

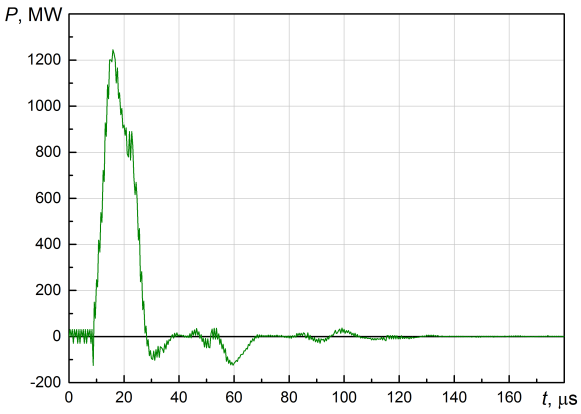


Figure 7. Time dependence of the instantaneous discharge power.

5. Compression plasma flow treatment of model shielding elements with a dual layer composite coating

Compression plasma flow treatment of model shielding elements with a dual layer composite coating surface (viscous metal sub-layer of NiAl and the of hard ceramic oxide Al_2O_3 top layer) was performed firstly in order to cause the surface layer of ceramic oxide unsteady melting and re-crystallization, resulting in formation of hard polycrystalline layer. Secondly, as a result of thermal impact, to improve the viscous adhesion characteristics of the metal and ceramic layers. The plasma forming gas in this experiments was nitrogen. To achieve a surface layer of ceramic oxide melting and re-crystallization of sufficient intensity, as a result of experiments, following parameters were chosen: the residual gas pressure in the vacuum chamber was 0.5 Torr, the thickness of the oxide Al_2O_3 ceramics was 400 μm, the time delay of between the start of the quick acting gas valve and the launch of the MPC was 1200 μs, the capacity of MPC capacitor bank was 600 μF, the voltage on the capacitor bank was 7.3 kV. The optimal distance between the MPC and the target (shielding element in a heat-eliminating holder) was 120 mm in order to achieve a sufficiently high homogeneity of the compression plasma flow impact on the shielding elements surface.The integral photography of plasma jet intaraction with shielding elements in heat-eliminating holder is shown in figure 8.

General view of the shielding elements with composite coatings and micrographs of elements surface before and after the compression plasma flow treatment are shown in figure 9. Composite

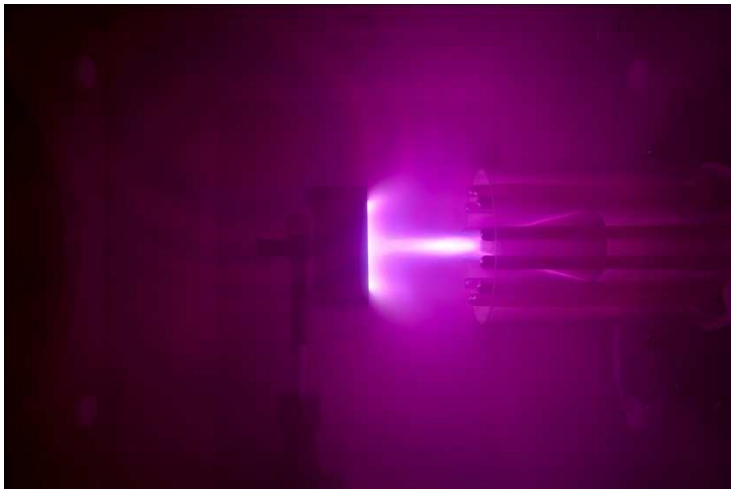


Figure 8. The interaction of compression plasma flow with the surface of the shielding element.

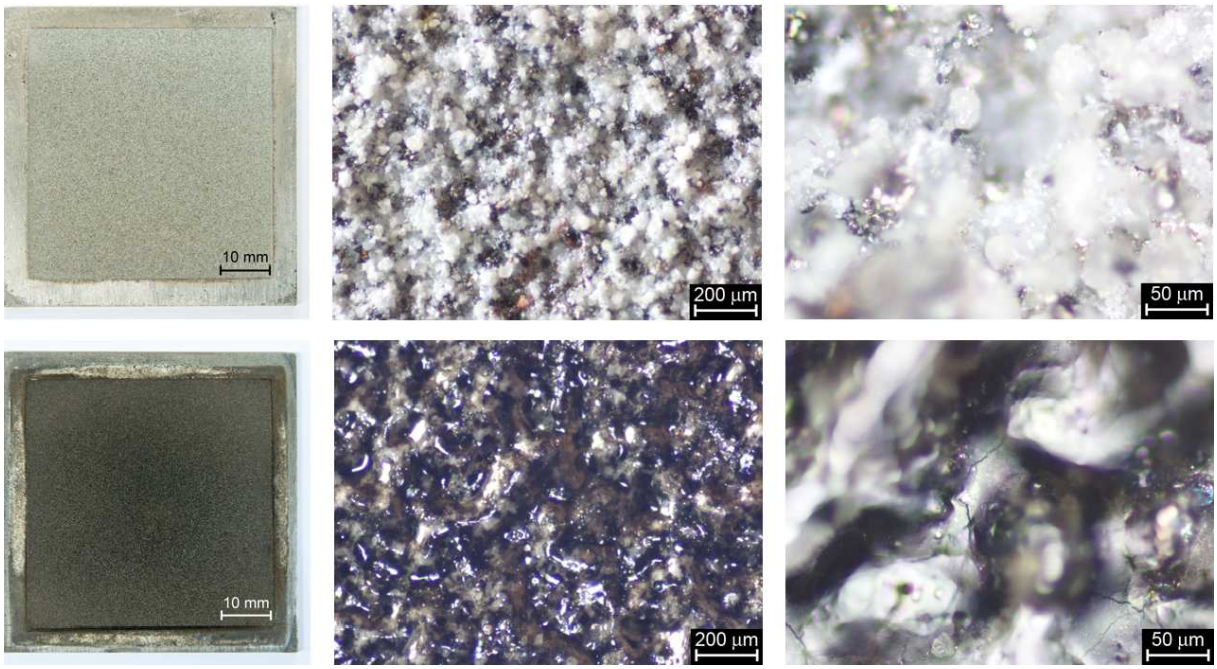


Figure 9. The elements surface image before (top row) and after (bottom row) the compression plasma flow treatment.

coating of hard Al_2O_3 oxide ceramic is a porous structure consisting of fused Al_2O_3 particles with size of 10–15 μm. Metallic inclusions formed as a result of erosion of the plasma torch electrodes are observed in the space between the particles. After surface treatment of composite coatings by compression plasma flow, polycrystalline layer of high strength is produced resulting unsteady melting and re-crystallization. Thus, the areas of the polycrystalline layer, wherein the metal inclusions were found, became painted in different colors depending on the chemical composition of inclusions.

Analysis of the central part of the coating cross section after compression plasma flows treatment was performed using raster electron microscopy. Results showed the formation of the

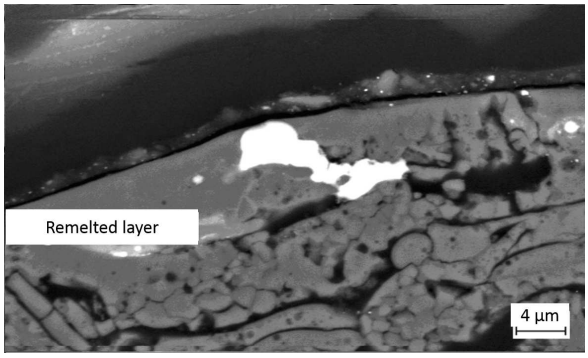


Figure 10. The raster electron microscopy image of coating cross section after compression plasma flows treatment.

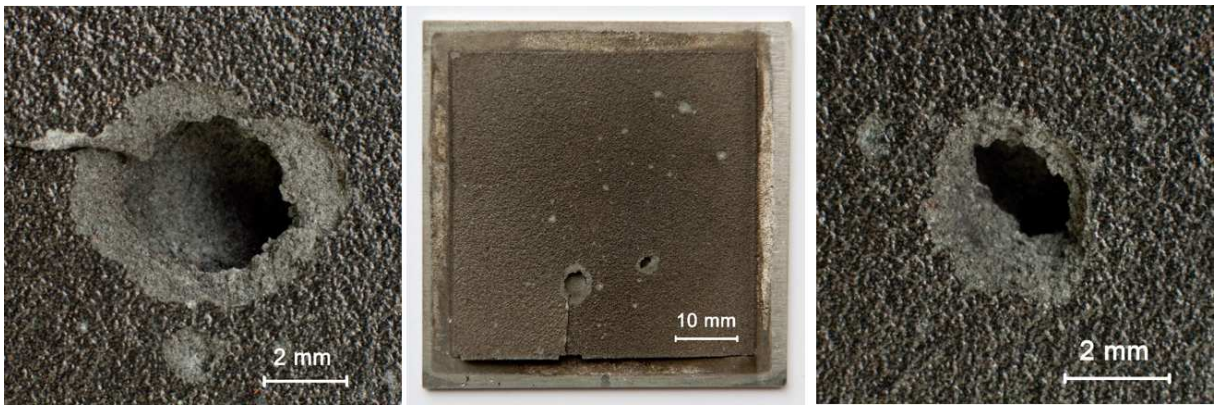


Figure 11. The image of modified shielding element after ballistic test.

re-melted layer with a thickness of about 6–7 μm, in which there are metal particles undissolved in the melt oxide (figure 10).

Ballistic tests of meteoroid shielding element were conducted with use of two-stage light-gas magnetoplasma launcher. Construction and operational principles of this launcher are described in details in [5]. As a result of the projectile (graphite ball with a diameter of 2.5 mm and speed of 4.8 km/s) impact, crater (d≈4 mm) appeared and part the composite coating peeled off in the vicinity of the crater, but meteoroid shielding element remained unpierced (figure 11).

6. Conclusions

Plasma jet was generated by quasi-stationary plasma accelerator. In the jet plasma, the electron temperature was 150 ± 50 kK and electron density was (2.5–4)×10^{16} cm^{-3}. This plasma impacts the surface layer of oxide ceramics and causes an unsteady melting and re-crystallization of this layer and improving the characteristics of the viscous coupling of NiAl metal layer and a layer of a solid oxide ceramics Al_2O_3. The result of compression plasma flow impact is the formation of the re-melted oxide layer of 6–7 μm thickness. Ballistic tests of meteoroid shielding element with use of projectile (graphite ball with a diameter of 2.5 mm and speed of 4.8 km/s) caused coating peeling off in the vicinity of the crater 4 mm in diameter, but meteoroid shielding element remained non-pierced.

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