Reducing the number of craters on quartz glass surface suffering high-velocity impacts of microparticles by application of SiAlN and TaN protective films

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Abstract. On the quartz glass specimens, visually transparent single-layer SiAlN and two-layer SiAlN/TaN films were applied to compare their protective properties against shock impact of high-velocity (5–8 km/s) iron microparticles. The tests performed using a two-stage light-gas gun have shown that the most effective coatings are two-layer films. The structure, optical and mechanical properties of the films were determined.

One of the negative factors of cosmos affecting space vehicles and stations is their bombardment by high-velocity meteoroids of natural origin and micro-shards of space debris that are the product of anthropogenic pollution of space. The probability of collision with large parts is small; however, the shock impacts of microparticles are continuously suffered by the spacecraft. High velocities of their relative motion cause local damage to surfaces and certain parts of the vehicles [1–3].

To protect them, various types of shields are used. However, they cannot be used for optical elements: windows, solar panels, lenses, etc. The impact of a high-velocity microparticle, regardless of its origin, causes mechanical and plasma processes forming a crater on the surface, generating a shock wave and giving birth to microcrack nuclei [4]. This deteriorates the optical and mechanical characteristics of the window glass and electrical parameters of solar panels [5, 6].

One of the ways to solve this problem is to apply high-hardness refractory coatings that are transparent in the visual range of the electromagnetic spectrum, having high coefficient of elastic recovery and low thermal coefficient of linear expansion [7, 8]. This is testified by the results of [9] where it was shown that the application of a visually transparent nanocrystalline SiAlN-based coating with a thickness of 7 μm allows appreciably reducing the surface density of small craters forming after such shock impacts on a quartz glass. It is interesting to study the application of the second layer based on the refractory nitride of a heavy metal and its effect on the shock resistance of the glass. Such nitrides possess high density and melting temperature and should have higher shock wave dissipation capability.

This work is aimed at studying the alteration of quartz glass resistance to the shock-impacts of high-velocity (5–8 km/s) iron microparticles after magnetron deposition of two-layer transparent films based on SiAlN and TaN and their comparison with single-layer SiAlN coatings.
The studies included two types of specimens prepared from KV-grade quartz plates: I – with one-layer SiAlN-based film with a thickness of ~0.6 μm and II – with two-layer film, which first layer is the same as the previous one, while the second one is formed from tantalum nitride (TaN) with a thickness of ~0.3 μm. The method of magnetron film deposition, techniques and devices of structure-and-phase composition and optical-and-mechanical properties of films, as well as the method and mode of specimen testing for resistance against high-velocity (5–8 km/s) microparticles using the two-stage light-gas gun were the same as we described earlier in [9, 10].

The methods of XRD analysis and transmission electron microscopy allowed establishing that the layers of SiAlN form in an amorphous state (figure 1a), while the layers of TaN have columnar structure (figure 1b), and the height of the columns is close to the thickness of the layer (~0.3 μm), while the average width of the column cross-section reaches ~40 nm. Within the wavelength of visible light, the quartz glass with films I and II have an average light transmission coefficient of ~0.82 and 0.79, correspondingly, while that of the glass without the films is ~0.88 (figure 2a).

![Figure 1. Light-field TEM images of the cross-section of (a) SiAlN single-layer film and SiAlN-based layer in the two-layer film, and (b) TaN-based film in the two-layer film. In the top-left corner of the images, there are electronograms obtained from corresponding regions of the two-layer coating layers.](image)

After bombarding the glass specimens by spherical iron microparticles moving with a velocity of 5–8 km/s, their surface becomes covered with craters represented by dents surrounded by a net of microcracks. Figure 2 depicts the surface of the glass specimens obtained by scanning electron microscopy with evident craters including local zones of microcracks forming after the bombardment. It was established that on the glass specimens with two-layer film II and single-layer film I, the surface density of craters \( \rho_I \) and \( \rho_{II} \) under the same experimental conditions is substantially lower than that on the uncovered specimens \( \rho_0 \). The counting of the crater number formed after single bombardment on the total area of the specimens demonstrated that after the application of the single-layer SiAlN film, the relative reduction of the surface density of craters equals \( \rho_0/\rho_I \approx 1.34 \), while after the application of the two-layer SiAlN/TaN films, it increases up to \( \rho_0/\rho_{II} \approx 1.67 \).

For the quartz glass specimens with SiAlN-based single-layer film SiAlN and two-layer SiAlN/TaN film, load curves (\( P-h \)) were plotted using a NHT-S-AX-000X Nano Hardness Tester at the indenter load of 10 mN. They were used to determine the microhardness \( H_m \), modulus of inelastic buckling \( E^* \) and coefficient of elastic recovery \( K_e \) of the films. These data are presented in table 1. Obviously, for the specimens with the two-layer film, the values of \( H_m \) and \( K_e \) are \( \approx 1.3 \) times higher than those for the single-layer film I.
Figure 2. Optical light transmission spectra $T(\lambda)$ of (a) quartz-glass specimens: (1) without coating, (2) and (3) with films I and II, correspondingly. Surface images with local damage (craters) formed after the impact of the high-velocity iron particle flux on (b) uncoated specimens, (c) specimens with film I and (d) specimens with film II.

As for the modulus of inelastic buckling $E^*$, its value is $\approx 1.2$ times higher for film II compared to film I. More effective protective properties of two-layer films II is evidently due to higher mechanical properties compared to film I.

Table 1. Average values of the coefficient of elastic recovery $K_e$, modulus of inelastic buckling $E^*$ and microhardness $H_m$ for films I and II.

| Film type | $K_e$  | $E^*$ [GPa] | $H_m$ [GPa] |
|-----------|--------|-------------|-------------|
| I         | 0.55±0.06 | 194.1±13.5 | 23.6±1.5    |
| II        | 0.71±0.08 | 230.7±19.0 | 30.1±1.9    |

Besides, work [11] studied the effect of the "highly-porous copper–duraluminium" shield construction on the destruction of a steel spherical striker moving with a velocity of 3-5 km/s. It was shown that the two-layer construction more effectively destroys the striker as compared to the single-layer shield from duraluminium. In addition, the maximum depth of shard penetration into the marker plate placed behind the shield and the number of large craters on it decreased. These experimental data, as well as
the results of the numerical study from [12] of the shock impact of hyper-velocity strikers with two-layer barriers qualitatively agree with our experimental data on more effective protection from the shocks of high-velocity microparticles by two-layer films as compared to single-layer ones.

The research has established the following. In single- and two-layer films based on SiAlN (I) and SiAlN/TaN (II) deposited by magnetron sputtering, SiAlN layers are in an amorphous state, while TaN has columnar nanocrystalline structure. Within the wavelength of visible light, the quartz glass specimens with films I and II have an average light transmission coefficient of ~0.82 and 0.79, correspondingly, while that of the glass without the films is ~0.88 (figure 2a). After bombarding of the glass specimens by spherical iron microparticles moving with a velocity of 5–8 km/s, their surface becomes covered with craters represented by dents surrounded by a net of microcracks. On the glass specimens with the two-layer film II and single-layer film I, the surface density of craters $\rho_I$ and $\rho_{II}$ under the same experimental conditions is substantially lower than that on the uncovered specimens ($\rho_0$). After the application of the single-layer SiAlN film, the relative reduction of the surface density of craters equals $\rho_0/\rho_I \approx 1.34$, while after the application of the two-layer SiAlN/TaN films, it increases up to $\rho_0/\rho_{II} \approx 1.67$. On the specimens with two-layer film, the microhardness and coefficient of elastic recovery of film II is $\approx 1.3$ times higher vs. film I, while the modulus of inelastic buckling is $\approx 1.2$ time higher, respectively. More effective protective properties of two-layer films II is evidently conditioned by their higher mechanical properties as compared to single-layer films I.

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