Obtaining multilayer coatings by the detonation spraying method

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This work were studied the effect of technological parameters of detonation spraying on the phase composition and tribological characteristics on the bases of NiCr and Al2O3 coatings. As well as there was obtained and investigated multilayer coating on the bases of NiCr/NiCr- Al2O3 / Al2O3 . It was determined that during detonation spraying the phase composition of Al2O3 coatings strongly depends on the degree of filling the borehole with a gas mixture. The α - Al2O3-phase content in the coatings increases when the degree of filling is 63% and 54%. Only one CrNi3 phase is observed on the diffractograms and only increase of reflex intensity (020) at barrel filling by 58% is observed by sputtering on the bases of NiCr coatings in different degrees of barrel filling. The results of the coating nanohardness study showed that the hardness of the Al2O3 coating increases depending on the content of α - Al2O3 in it. Al2O3 coating has the maximum nanohardness values and is 16.42 GPa at the borehole is filled to 63%. The nanohardness of NiCr coating has the maximum values at barrel filling by 58% and consisting of 8.02 GPa.

Keywords: detonation spraying, multilayer coating, NiCr, Al2O3, phase, hardness.

Introduction

One of the most serious problems in modern technology is the necessity to ensure conformity between the properties of materials used in various branches of production and the increasingly harsh conditions of their operation. Usually the weakest link of assemblies and parts is their surface, which is exposed to multifactor loads. It is possible to improve the properties of used materials by hardening them with coatings.
Recently, there has been a great deal of interest in high-speed coating technologies that are characterized by high productivity, versatility, ease of automation, and virtually unlimited sizes of surfaces to be coated. High-speed spraying processes can significantly expand the capabilities of conventional thermal spraying of coatings used to protect parts from wear, corrosion, etc. Gas-thermal high-speed methods of coating production include methods of detonation, supersonic air-gas plasma spraying (SAGPS) and high volume of flame (HVOF) spraying [1-4]. Among them, detonation spraying is the most promising. Detonation spraying is carried out using a special detonation gun filled with an explosive gas mixture. Powder sprayed material is used to form the coating. The detonation process accelerates the powder particles to high speeds (up to 1000 m/s), melting them and depositing them on the sprayed surface. The advantages of this method are: low porosity of the coating, high bonding strength with the base of the processed part, low thermal impact, which allows avoiding undesirable thermal stresses and warping even of thin-walled parts of complex design [5-7].

It is necessary to increase their performance characteristics, a combination of high values of various properties (bonding strength, wear resistance, corrosion resistance, etc.) to increase the durability of detonation coatings working in severe conditions. One of the most effective ways to solve this problem is to obtain multilayer coatings. The most promising are multilayer coatings having a gradient structure, the characteristic feature of which is a smooth change in the chemical composition, structure and properties (physical, mechanical, etc.) along the thickness of the coating [8, 9]. Also the multilayer structure can be an effective method of increasing the corrosion resistance of coatings. The interfaces between the layers can act as protective barriers in an aggressive environment [10-13].

In this connection, the aim of this work is to study the effect of technological parameters on the properties of NiCr and Al₂O₃ coatings and the production multilayer coatings on the bases of NiCr /NiCr- Al₂O₃ / Al₂O₃ with having a gradient structure.

Materials, equipment and research methods

Powder of NiCr, Al₂O₃ and NiCr- Al₂O₃ (50/50) with a dispersion of 20-45 µm was used as the sputtering material. The coatings were applied to samples made of 12X18H10T steel by detonation spraying on a CCDS2000 (Computer Controlled Detonation Spraying) detonation machine. Figure 1 shows a schematic diagram of the CCDS2000 detonation facility. The coating is applied with a detonation gun, the barrel of which is filled with an explosive gas mixture, a dosed portion of the powder is thrown into the barrel, and an electric spark excites detonation. The detonation products heat the powder particles until they melt and throw them at high velocity onto a part mounted in front of the cannon barrel. On impact, micro-welding occurs and the powder is firmly (on a molecular level) bonded to the surface of the part. After each shot, the barrel is purged with nitrogen to clean the detonation products residue. The required thickness is built
up by a series of successive series of shots, during which the object can be moved using a manipulator [14, 15].

Coatings on the basis of NiCr and Al$_2$O$_3$ were obtained at different values of the barrel filling volume. An acetylene-oxygen mixture was used as a combustible gas, which is the most demanded fuel in detonation spraying of powder materials. As the amount of explosive mixture increases (from 25 to 60% of the barrel volume), the temperature to which the particles are heated during their movement inside the barrel increases. Technological parameters of obtaining NiCr and Al$_2$O$_3$ coatings are shown in Table 1.

Table 1.
Technological parameters for obtaining NiCr-Al$_2$O$_3$ coatings.

| Number of the sample | Powder name | Volume of barrel filling, % | Number of shots |
|----------------------|-------------|-----------------------------|-----------------|
| 1                    | Al$_2$O$_3$ | 45                          | 20              |
| 2                    | Al$_2$O$_3$ | 54                          | 20              |
| 3                    | Al$_2$O$_3$ | 63                          | 20              |
| 4                    | NiCr        | 54                          | 20              |
| 5                    | NiCr        | 58                          | 20              |
| 6                    | NiCr        | 65                          | 20              |

The multilayer coating on the bases of NiCr/NiCr-Al$_2$O$_3$ / Al$_2$O$_3$ was also obtained by successive spraying of three kinds of powder: 1-NiCr, 2-mixture of NiCr powders (50%) and Al$_2$O$_3$ (50%), 3-Al$_2$O$_3$. The sputtering mode of the multilayer coating on the bases of NiCr/NiCr-Al$_2$O$_3$ / Al$_2$O$_3$ is shown in Table 2.

Table 2.
Technological parameters for the multilayer coating on the bases of NiCr/NiCr-Al$_2$O$_3$ / Al$_2$O$_3$.

| Layer | Powder name | Volume of barrel filling, % | Number of shots |
|-------|-------------|-------------------------------|-----------------|
| 1     | NiCr        | 54                           | 20              |
| 2     | NiCr-Al$_2$O$_3$ | 54                          | 20              |
| 3     | Al$_2$O$_3$ | 63                           | 20              |
X-ray phase studies of the samples were performed by X-ray structural analysis on X’PertPRO diffractometer. Diffractograms were taken using CuKα -radiation (λ =2.2897 Å) at 40 kV and a current of 30 mA. The diffractograms were interpreted using HighScore software. Mechanical properties of the obtained coatings (Young’s modulus, nanohardness) were investigated with the help of nanohardness meter NanoScan-4Dcompact. Nanoindentation of the coatings was performed by the Oliver and Farr method using a Berkovich indenter at a load of 100 Mn (ASTM E2546-07). The cross-sectional morphology of the samples was examined by scanning electron microscopy (SEM) using backscattered electrons (BSE) on a JSM-6390LV scanning electron microscope at accelerated stress.

Results and discussion of studies

Figure 2 presents the diffractograms of Al₂O₃ coatings obtained at different degrees of barrel filling volume. The figure shows that the phase composition of Al₂O₃ coatings changes depending on the degree of barrel filling. The intensity of α-Al₂O₃-phase peaks increases at barrel is filled by 63% and 54%, indicating an increase in the concentration of α-Al₂O₃-phase. At filling of the shaft by 45% the coating consists mainly of γ-Al₂O₃-phase. The change in the phase composition of Al₂O₃ coatings is related to the temperature of powder heating in the spraying process. Since, the powder temperature changes depending on the volume of barrel filling.

Figure 2. Diffractograms of Al₂O₃ coatings obtained at barrel filling volume 63% (a), 54% (b), 45% (c).
Diffractograms on the bases of NiCr coatings obtained at different degrees of barrel filling are shown in Figure 3. The figure shows that all coatings consist of CrNi$_3$. At the same time, an increase in the reflex intensity (020) is observed when the barrel is filled to 58%.

The results of research of nanohardness and modulus of elasticity of coating are presented in the Table 3. The results of the coating nanohardness study showed that the hardness of the Al$_2$O$_3$ coating increases as a function of its $\alpha$-Al$_2$O$_3$ content. The Al$_2$O$_3$ coating has a maximum nanohardness value of 16.42 GPa when the borehole is filled with 63%. The increase in hardness of Al$_2$O$_3$ coatings with increasing $\alpha$-Al$_2$O$_3$-phase in it is quite natural. Since, $\alpha$-Al$_2$O$_3$ has a higher hardness and wear resistance than $\gamma$-Al$_2$O$_3$. The nanohardness of the NiCr coating has maximum values when the barrel is filled to 58% and is 8.02 GPa. The small difference in hardness of NiCr coatings is apparently due to the porosity of the coating, which changes depending on the spraying mode. The table also shows the elastic modulus data. The table shows that the modulus of elasticity of all coatings varies with hardness.

On the bases of study of sputtering mode influence on the structure and properties of NiCr and Al$_2$O$_3$ coatings, we obtained multilayer coating on the bases of NiCr/NiCr- Al$_2$O$_3$ / Al$_2$O$_3$. 
Table 3.
Results of nanoindentation of coatings.

| Sample number | Powder name | Nanohardness, GPa | Young’s modulus, GPa |
|---------------|-------------|-------------------|----------------------|
| 1             | Al₂O₃       | 13.54             | 256.13               |
| 2             | Al₂O₃       | 14.73             | 261.31               |
| 3             | Al₂O₃       | 16.42             | 286.12               |
| 4             | NiCr        | 6.92              | 165.32               |
| 5             | NiCr        | 8.02              | 176.23               |
| 6             | NiCr        | 7.63              | 169.12               |

Figure 4 shows the SEM image of the cross section of multilayer coating on the bases of NiCr/NiCr-Al₂O₃/Al₂O₃. The elemental composition of the coatings was determined by using EDS analysis. From the obtained data, it can be seen that the coatings consist of a lower metal layer, an upper ceramic layer and a transitional layer of a mechanical mixture of metal and ceramics. This confirms the EDS analysis. The results of the EDS analysis are shown in Table 4.

Table 4.
The results of EDS analysis.

| Spectrum     | Al, %  | O, %  | Ni, %  | Cr, %  | Fe, % | Total, % |
|--------------|--------|-------|--------|--------|-------|----------|
| Spectrum 1   | 39.78  | 31.36 | 13.88  | 14.98  | 0     | 100      |
| Spectrum 2   | 29.63  | 26.74 | 24.71  | 18.92  | 0     | 100      |
| Spectrum 3   | 19.56  | 17.42 | 39.56  | 23.46  | 0     | 100      |
| Spectrum 4   | 7.53   | 4.66  | 49.68  | 38.13  | 0     | 100      |
| Spectrum 5   | 1.25   | 1.67  | 23.97  | 15.06  | 58.09 | 100      |

Figure 4. SEM cross-sectional image of multilayer coating on the bases of NiCr/NiCr-Al₂O₃/Al₂O₃.
Conclusion

On the bases of experimental obtained data and their analysis, the following conclusions were made: It was determined that the phase composition and properties of detonation coatings strongly depend on the technological parameters of spraying. When spraying powders based on $\text{Al}_2\text{O}_3$, the chemical and phase composition of the obtained coatings strongly depends on the degree of filling of the barrel with a gas mixture, which makes it possible to control the structure and composition of the coatings and, thus, to obtain coatings with specified properties. The method of obtaining multilayer coatings based on NiCr/NiCr$\text{Al}_2\text{O}_3$/$\text{Al}_2\text{O}_3$ which consists of the lower metal layer, the upper ceramic layer and the transition layer of a mechanical mixture of metal and ceramics on a detonation machine was developed. The study of the elemental composition by the SEM method (EDS) showed that multilayer coating on the bases of NiCr/NiCr$\text{Al}_2\text{O}_3$/$\text{Al}_2\text{O}_3$ has a gradient structure, as there is an increase in the concentration of ceramics from the substrate to the coating surface.

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