Gas-dynamic spraying, as a method of the component recovery in the power engineering industry

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Abstract. The purpose of the study is to decide on the possible protective coating formation of "Ni-Al" system by applying the method of cold gas-dynamic powder spraying with "Dimet-403" unit. The phase composition, microstructure and mechanical characteristics of the coating after spraying and subsequent heat treatment have been investigated. The developed coating can be used for protection against high-temperature gas-phase corrosion of internal surfaces of working blades of gas turbine engines during their manufacture or repair.

1. Introduction

The method of cold spray, which is based on dispersion of powder mixtures by compressed air, is used for the deposition of metal coatings on the working surface of machine elements [1]. Deposition of coatings is carried out with the unit "Dimet-403" (figure 1) in which mixture of hot air and powder forms the high-speed stream at the exit of supersonic nozzle. The method is based on the effect of forming a metal layer at the time of spraying at supersonic speed (2-3 sound speed) [1]. The temperature of the carried metal particles is significantly lower than the fusing temperature. At the same time, heating up of particles is carried out due to the conversion of kinetic energy into thermal energy at impact with the supporting plate immediately upon coating formation. The method of cold gas-dynamic powder spraying is characterized by the absence of noticeable thermal effect on the material of supporting plate, the possibility of controlling composition and thickness of coatings, economy and simplicity of coating application. Clean metal and ceramic surfaces of details usually do not demand any special preparation.

However, to clean surface, to remove mechanical impurities, oxides and to increase adhesion strength of a coating (due to creation of roughness) it is desirable to carry out preliminary grit blasting during the coating application on steel, nickel and titanic alloys. The method of gas-dynamic spraying allows carrying out the preliminary abrading of the product's surface with the unit "Dimet-403". It is also possible to use composite reinforced powder mixtures having in their composition malleable metal particles and particles of solid component (corundum), thus combining the spraying process with abrasive surface preparation in one technological cycle.

To resolve the important problem of modern engine-building, it was decided to develop a coating to protect the internal surfaces of the rotor blades of GTE turbines having a complex configuration because of the high-temperature gas corrosion. For this purpose, the slurry production method has been used for the coatings manufacture of new blades since the 1970s. Nevertheless, in contexts where
resources of spare parts used in the repair of GTE are stretched, the issue of the development of repair technologies is still acute. The task of service life extension of the turbine blade is solved today by applying heat-resistant coatings on their working surface [2-4]. For this purpose, various technologies of electron-beam deposition and plasma spraying are used [5]. However, all known methods allow obtaining coatings only on external surfaces of the details of the GTE hot path. That is why it was tried to renovate the protective coating on the internal surfaces of the high-pressure turbine rotor blade using gas-dynamic powder spraying.

![Figure 1. "Dimet-403" cold gas-dynamic powder spraying unit.](image)

2. Methods of research

Objects of study:

1. N3-00-02 grade powder mixture with 57% of nickel and 43% of aluminium oxide;
2. The powder mixture of A-20-01 grade with 57% of aluminium and 43% of aluminium oxide;
3. Ni-Al system coating made up of powder mixtures N3-00-02 and A-20-01 by the method of gas-dynamic spraying using Dimet-403 unit and post-heat treatment at 750 °C for 4 hours. Derivatographic studies of the powder mixtures have been conducted on the derivatograph NETZSCH STA 449F1 in the argon environment.

The phase constitution of coatings was investigated by the method of X-ray diffraction analysis with a diffractometer "Drone-3M" (Cu-Kα-radiation, the symmetric shooting according to Bragg-Brentano).

Metallographic examination was conducted with a scanning electron microscope "VEGA//TESCAN" and with an optical microscope «Neofot-32». The quantitative metallographic analysis was using the «Good phase» computer program.

Microhardness and the adhesion strength of the coatings were measured at cross shif with a microhardness tester PMT-3 at the load of 1 H and 2 H on the indenter in accordance with the State Standard 9450-76.

3. Research results

Nickel-based powders (the powder mixture of N3-00-02) and aluminium-based powders (the powder mixture of A-20-01) whose dispersion is about 20 µm have been selected as input materials for forming the protective coating. The phase composition of powder mixtures is a combination of two phases: metal (nickel or aluminium) and aluminium oxide (corundum). The corundum particles in the initial powders are designed for the bombardment of a workpiece surface to clean it and to form an abrupt relief pattern so it becomes possible to improve the adhesion of the coating to the basic layer.

The derivatogramms of these powder mixtures are shown in figures 2 and 3. The high-temperature behaviour of the powder mixture N3-00-02 shows the curve in figure 2. In the 500-800 °C temperature range, smooth growth of the differential scanning curve is observed due to nickel oxidation followed
by the forming of NiO oxide. It is known that the temperature range of 500-1000 °C is characterized by an excessive growth of the oxide film due to the high diffusion rate of Ni ions on the limits of NiO grains [6].

On the differential scanning curve of the aluminium-based powder mixture (the powder mixture of A-20-01) shown in figure 3, there is a clear minimum at a temperature of about 660 °C which corresponds to the melting temperature of Al. To form a protective coating with intermetallic composition, a diagram of phase states of the Ni-Al system was taken as the basis [7]. According to this chart, a ratio of about 50/50 of weight parts of nickel and aluminium and temperature of heating in the range of 600 to 800 °C are necessary to receive an intermetallic β-NiAl phase in a nickel matrix.

That is why the powder mix of N3-00-02 and A-20-01 in the proportion of 50/50 weight parts was prepared for coating application.

Figure 2. Derivatogram of powder mixture N3-00-02.

Figure 3. Derivatogram of power mixture A-20-01.

It was found by X-ray diffraction analysis that the phase composition of the powder mixture was a combination of three phases: nickel, aluminium and corundum.
The derivatogram of this powder mixture is shown in figure 4. On the differential scanning curve at a temperature about 650 °C there is a clear maximum corresponding to the formation of the intermetallic compound NiAl (β-phase).

![Derivatogram](image)

**Figure 4.** Derivatogram of powder mix of the Ni-Al system (50/50 weight parts).

The X-ray diffractional analysis method established that the phase composition of the coating is composed of the powder mixture after being sprayed and heat-treated at a temperature of about 750 °C within 4 hours. Nickel with face-centred cubic lattice (F.C.C lattice - Ni) is the main phase. There are also an intermetallic phase β-NiAl and aluminium oxide α-Al₂O₃ (corundum) in the coating, which was also at the composition of initial powder mix. Displacement towards larger angles of reflection on Ni diffractograms compared to the reference standard [8] reveals the existence of compressive stresses in the material, that have a positive effect on its adhesive strength. The adhesion strength tests of the coating carried out by the method of microindentation showed satisfying adhesion strength to the base layer. Along the lines of separation between coating and base, there are no subcutaneous defects, cracks and shape deformation of the imprint from the indenter (figure 5).

![Photomicrograph](image)

**Figure 5.** Photomicrograph of the nanoindentation process along the lines of separation between coating and base(400)
Figure 6 shows the microstructure of the cross-section of the Ni-Al coating after gas-dynamic spraying. Thickness of the coating is about 400 µm. No through porosity is observed. The line of separation between coating and base is clear, without any defects as shearing distortions, discontinuity flaws, subcutaneous defects. Light base is a nickel phase and black inclusions are corundum grains. At high-speed gas-dynamic powder spraying, most of the solid corundum particles having high kinetic energy face an elastic collision with the surface, but some fraction of the particles fall on the base layer. That is why inclusions of Al₂O₃ can be found not only in the coating but also in the line of separation between coating and base and even in the near-surface layer of the process material. Figure 7 shows the distribution of elemental composition in the cross-section of the coating. The light background corresponds to Ni reflections, and a synchronous surge of aluminium and oxygen reflections is observed in zones of black inclusions, which indicates a corundum compound.

The average microhardness of the coating is 250 kg/mm².

Figure 6. Electronic micrograph of "Ni-Al" coating cross-section after gas-dynamic spraying.

Figure 7. Distribution of elemental composition in the cross-section area of "Ni-Al" coating after gas-dynamic spraying.
Figure 8 shows the microstructure of the cross-section of the Ni-Al coating after the post-heat treatment at 750 °C within 4 hours. Coating thickness is about 300 µm. No through porosity is observed in the coating. The line of separation between coating and base is clear, without any defects as shearing distortions, discontinuity flaws, subcutaneous defects. Three phases - light, grey and black - can be distinguished in the micrograph of the coating cross-section.

The analysis of the distribution of elemental composition (figure 9) showed that the light basis represents a phase of nickel, grey inclusions are grains of intermetallic phase (β-фазы (NiAl), black inclusions are grains of corundum (Al₂O₃)).

Figure 8. Electronic micrograph of the cross-section area of "Ni-Al" protective coating after gas-dynamic spraying and subsequent thermal treatment at 750 °C for 4 hours (x500).

Figure 9. Distribution of elemental composition in the cross-section of "Ni-Al" coating after the gas-dynamic spraying and subsequent thermal treatment.
The percentage of β-phase makes approximately 30%, and corundum is about 10%, the rest is nickel. Thus, the heat treatment triggers the formation of an intermetallic phase (β-фаза) and, as a result, the microhardness of the coating increases to 415 kg/mm². Diffusion and condensation protective coatings with phase composition based on Ni-solid solution were developed in the 1990s [6] and were designed to increase the heat resistance of the surface of heat resistant nickel alloys. An important property of heat resistant coatings is their resistibility to thermal stress cracking. The thermal stability of the coating can be improved by increasing the plastic phase (γ-фаза) (Ni-solid solution) in its structure. High-plasticity condensation coatings have the structure (γ+β) in which the quantity of β-phase is less than 50% of the volume of a covering [6].

The method of jet spraying on the finished product has been also examined. The inner cavity of the GTE rotor blade (made of nickel alloy In 738) of the high-pressure turbine (HPT) of the gas-compressor unit GTK-10I was coated. The segments of the gasketed working ring of the gas turbine plant SGT-400 were also coated.

A full cycle was carried out on the blades, the complete repair cycle was carried out: sandblasting and mechanical operation, reduction thermal treatment and application of the thermal protective coating of zirconium dioxide. The application was done by the method of high-energy plasma spraying on the outer working surface of the blade on heat-resistant intermetallic sublayer [9] (figure 10). The advantage of the gas-dynamic powder method is the possibility of coating application without removing the old coating that remains after operational activity from the inner cavities of the blades, which is almost impossible to do.

![Figure 10. High-pressure turbine rotor blade of gas turbine engine MS 3142 of gas-compressor unit GTK-10I after recovery works (a) with an internal cavity (b).](image-url)

It should be noted that the method of gas-dynamic powder spraying proposed in this study does not cause heating of the main material of the detail, and the post-heat treatment mode of the coating used in this study can be combined with the reductive heat treatment mode (e.g., tempering) used for heat resistant nickel alloys.
4. Conclusion
The protective coating of the Ni-Al system on the basis of nickel with about 30% of an intermetallic β-NiAl -phase, with the microhardness of 415 kg/mm² and satisfactory adhesive strength was developed using the method of gas-dynamic powder spraying. These coatings can be used as part of the recovery technology for the protection against high-temperature gas corrosion of internal cavities of GTE working blades. The method of gas-dynamic powder spraying can be used both for new blades and as part of the recovery technologies for the service life extension.

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