Grinding specifics of plasma coatings melted with high-frequency currents

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Abstract. This paper presents the research into the finishing treatment of plasma sprayed nickel coatings hardened by high-energy heating with high-frequency currents. We analyzed the coatings surface topography images and profilograms of the after grinding. The coatings were melted at various specific power values and samples traverse speeds relative to the inductor. We also described the different types of surface structural modifications that are formed depending on the melting mode parameters. The research revealed that high-temperature treatment within the efficient range of technological modes results in forming a dense homogeneous structure in the coating with minimal number of pores. The polished surface of such molten coatings has a regular microrelief and a low level of roughness ($Ra = 0.305 \, \mu m$). These properties are achieved owing to a significant increase in the structure qualitative properties during the melting process.

1. Introduction

The manufacturing process of applying wear-resistant plasma coatings on the machine parts surface requires finishing machining to ensure the appropriate dimensional accuracy and surface roughness [1-7]. Most often, abrasive grinding is used as a finishing treatment.

The recent improvements in the quality of plasma coatings are due to the combined technologies which involve melting the sprayed layer by a highly concentrated energy source. The high-energy heating with high-frequency currents has been shown to possess a clear advantage at re-processing conductive plasma coatings after the technology options analysis of the main concentrated energy sources (electric arc, electron beam, laser, plasma, and induction) processing methods which can be used for repeated high-energy impact on the structure of plasma coatings [8]. A characteristic feature of this process is that the heating source is volumetric and energy is released at a certain depth of the surface layer, whose value depends on the thermal properties and electrical resistivity of the coating material, as well as on the frequency of the current. In addition, a significant advantage of this method is the technology option to control the depth of induction heating penetration correlating it with the thickness of the applied coating [9].

The research [10, 11] demonstrates that the qualitative properties of the wear-resistant plasma coatings structure increase after heating by high-frequency currents: the number of pores and unmolten powder particles is reduced. Additionally, there is an increase in adhesive strength and wear resistance, which will undoubtedly determine the nature of the finishing machining.
Such defects as pores have significant influence on the micro-relief formation of plasma coatings surface during grinding [12]. When abrasive grains of the grinding wheel penetrate into the coating, the pores become stress concentrators and promote the microcracks development. Notably, in addition to the pores, the surface roughness depends on the quality of the structure. Taking into account the fact that this combined technology significantly affects the sprayed layer properties, the finishing treatment has its own peculiarities whose identification requires research.

The purpose of this work is to study the surface roughness of plasma sprayed coatings made of nickel powder accounting for the specific features of the molten structure after the finishing abrasive grinding.

2. Materials and methods
The studies of surface roughness after finishing machining were carried out on the example of wear-resistant coatings made of self-fluxing nickel powder of the PG-12N-01 brand (fractional particle size is 50 ... 100 μm).

Spraying was performed on samples made of steel 20 with a 40 kW PUN-8 plasma torch. Plasma spraying modes and coating layer thickness were adopted based on previous studies [13, 14].

Coating melting was carried out on an induction unit equipped with the VCHG 6-60/0.44 model generator with an operating current frequency of 440 kHz. Heating was carried out continuously in a sequential manner by the loop inductor equipped with N87 magnet core. Studies on the melting of plasma sprayed nickel coatings were conducted in the specific power range between $3.0 \times 10^8$ W/m$^2$ and $3.2 \times 10^8$ W/m$^2$ with a relative traverse speed between 40 mm/s and 100 mm/s [15, 16]. The depth of energy release ranged between 0.6 and 0.8 mm.

Mechanical finishing was carried out on a 3G71 flat-grinding machine. The workpieces were fixed on the machine table using a magnetic plate. Grinding was performed with a 300 mm diameter abrasive wheel of green silicon carbide with grains grit number 80 (F24). The wheel was of medium hardness (L) with an open structure (8) on a bakelite bond (B). The operating parameters selection was based on the experience of finishing treatment of wear-resistant plasma coatings [12, 17].

The spindle speed was 2250 min$^{-1}$ (at a cutting speed of 35 m/s). The transverse feed corresponded to 0.3 mm for the double stroke of the table. Taking into account the length of the workpiece and the over travel, the working stroke was equal to 100 mm, and the speed of moving the table in the longitudinal direction was within 11 ... 14 m/min, which corresponded to the frequency of 55...70 double moves per minute. The cutting depth was 0.02 mm, the allowance to be removed was within 0.12 to 0.15 mm, with the thickness of the sprayed coating between 0.65 and 0.70 mm. A water-based solution of NaNO3 (2%) with a flow rate of 2.4 l/min was used as a cooling lubricant. Grinding was performed in several passes and was completed with a sparking-out process.

The topography study and the measurement of the coatings surface roughness after the finishing machining was carried by Zygo New View 7300 research complex.

3. Results and discussion
Figure 1 shows an image of a typical unmolten surface of a plasma sprayed nickel coating obtained using a Carl Zeiss Axio Observer Alm scanning microscope.

The surface of the sprayed coating (Figure 1) has a rough structure with unevenly melted powder particles and pores.

Figure 2 shows an image of the typical topography of the coating surface and the corresponding profilogram after grinding. A characteristic feature of these coatings is an open porosity. The surface profilogram clearly shows a “dip” caused by porosity. On the whole, the processed coatings surface has an irregular microrelief. Undoubtedly, the surface roughness value reflects the number and size of pores. In this case, the surface roughness is $R_a = 0.884$ μm. In addition to the pores, the roughness depends on such indicators of the structure quality as how melted the powder particles are.
High-energy heating by high-frequency currents forms a dense and uniform structure, with pores and unmolten particles almost completely disappearing, as it is shown in Figure 3.

Figure 3. Image of a typical melted surface of the plasma sprayed nickel coating

However, various modifications of the structure can be formed depending on the level of temperature exposure during the melting process. This parameter will undoubtedly affect the surface roughness after finishing treatment.
The minimum values of the specific power (between $3.0 \times 10^8$ and $3.1 \times 10^8$ W/m$^2$) and the maximum values of the sample traverse speed relative to the inductor (80 to 100 mm/s) result in incomplete melting of the coating whose structure practically does not differ from the initial state. Such coatings' surface after finishing treatment is identical to the polished surface of the unmolten coating.

On the contrary, a structure with an excessive degree of thermal influence is formed at high power (between $3.1 \times 10^8$ and $3.2 \times 10^8$ W/m$^2$) and low sample traverse rates (40 to 60 mm/s). Figure 4 shows the results of the surface study of this structure version after finishing grinding in topography and a profilogram.

![Surface of the coating with excessive melting after grinding: a - topography; b - profilogram](image)

The defective surface after finishing treatment in figure 4 (a) is due to significant overheating during melting, which causes thermal micro-cracks, areas of the material bubbling, burnout of elements and changes in the coating chemical composition. Therefore, the polished surface has a high roughness, with the value of $Ra = 1.439 \, \mu m$.

Given the experience and mathematical simulation techniques of heating by high frequency currents [9, 18], we defined the most efficient modes of subsequent induction high-energy impact: power density range between $3.1 \cdot 10^8$ W/m$^2$ and $3.2 \cdot 10^8$ W/m$^2$ at a relative traverse speed between 70 mm/s and 75 mm/s.

A uniformly molten structure with stable quality characteristics is formed when processing coatings in the set operating modes. According to [8, 10, 11], the metallographic analysis of cross-sections at the transition boundary between the coating and the substrate shows a uniform character, there are practically no discontinuity defects, which is clearly reflected in the adhesive strength increase.

Figure 5 shows the corresponding profilogram and topography of the molten coating surface after grinding.

The surface of the melted nickel coating after grinding in this case has a low roughness $Ra = 0.305 \, \mu m$, which corresponds to the level of finishing treatment.

The polished surface of the coating has a regular character. There is no open porosity, which significantly affects the microrelief. The increase in the qualitative characteristics of the coating structure caused by the high-frequency currents melting has a significant impact on the final surface roughness.
4. Conclusion
Studies on the final machining of unmolten plasma sprayed nickel coatings showed that the roughness value after grinding is significantly affected by the number and size of pores, as well as by the presence of unmolten particles.

High-temperature heating of plasma sprayed nickel coatings structure by high-frequency currents within the efficient technological mode allows eliminating these shortcomings and forming a dense structure practically without pores and unmolten particles.

A surface with a regular microrelief and low roughness $Ra = 0.305 \mu m$ is formed after finishing processing of such molten coatings.

However, it is necessary to take into account that the formation of a structure with insufficient or excessive temperature exposure should be avoided during plasma coatings melting. Overheating is especially undesirable, since it leads to changes in the chemical and phase composition, the appearance of thermal cracks in the coatings and to a rough surface formation after finishing grinding.

5. Acknowledgments
This work was financially supported within the framework of the NSTU Research and Development Thematic Plan (project No. TP-PTM-1_20 project).

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