

INFLUENCE OF A POWDER FEED RATE ON THE PROPERTIES OF THE PLASMA SPRAYED CHROMIUM CARBIDE- 25% NICKEL CHROMIUM COATING

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Summary:

The plasma spray process is a leading technology of powder depositing in the production of coatings widely used in the aerospace industry for the protection of new parts and for the repair of worn ones. Cermet $75Cr_3C_2 - 25Ni(Cr)$ coatings based on Cr_3C_2 carbides are widely used to protect parts as they retain high values of hardness, strength and resistance to wear up to a temperature of $850^\circ C$. This paper discusses the influence of the parameters of the plasma spray deposition of $75Cr_3C_2 - 25Ni(Cr)$ powder on the structure and mechanical properties of the coating. The powder is deposited using plasma spraying at atmospheric pressure (APS). The plasma gas is He, which is an inert gas and does not react with the powder; it produces dense plasma with lower heat content and less incorporated ambient air in the plasma jet thus reducing temperature decomposition and decarburization of Cr_3C_2 carbide. In this study, three groups of coatings were deposited with three different powder feed rates of: 30, 45 and 60 g/min. The coating with the best properties was deposited on the inlet flange parts of the turbo - jet engine TV2-117A to reduce the influence of vibrations and wear. The structures and the mechanical properties of $75Cr_3C_2 - 25Ni(Cr)$ coatings are analyzed in accordance with the Pratt & Whitney standard. Studies have shown that powder feed rates have an important influence on the mechanical properties and structures of $75Cr_3C_2 - 25Ni(Cr)$ coatings.

Key word: *property; powders; plasmas; feed rate; coatings; chromium.*

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Introduction

Thermal spray coatings belong to a developing field of surface engineering. These high-quality functional coatings are applied to new parts in basic industry and for the renovation of parts, mainly because of their excellent characteristics, characterized by high resistance to wear, erosion, abrasion, corrosion resistance and resistance to high temperatures (Berget, et al., 2007, pp.7619-7625), (Jankura, Bačová, 2009, pp.359-366), (Mann, Arya, 2003, pp.652-667), (Monticelli, et al., 2004, pp.1225-1237), (Wheeler, Wood, 2005, pp.526-536). Coatings must provide effective protection against wear and oxidation as well as have high thermal conductivity in order to secure proper and efficient functioning of parts in service (Bala, et al., 2007, pp.201-218). The primary aim of coatings is to be stable in operation and provide good protection (Fernandez, et al., 2005, pp.1-7). Cermets are a combination of hard ceramic phases embedded in tough metal matrices. Typical coating systems are WC-Co, NiCr-Cr₃C₂ and Fe-CrAlY-Cr₃C₂. In the thermal spray technology, Cr₃C₂-NiCr cermet coatings have been used extensively to mitigate erosion and abrasive wear at high temperatures up to 850°C. (Matthews, et al., 2007, pp.59-64), (Tillmann, et al., 2010, pp.392-408). Cr₃C₂-NiCr coatings, when compared to other cermet coatings, offer better resistance to corrosion and oxidation; they also have a high melting point and high hardness, strength and wear resistance up to 850°C. In addition to these functions, the coefficient of thermal expansion of the Cr₃C₂ carbide ($10.3 \times 10^{-6} \text{C}^{-1}$) is almost the same as the coefficient of the thermal expansion of iron ($11.4 \times 10^{-6} \text{C}^{-1}$) and nickel ($12.8 \times 10^{-6} \text{C}^{-1}$), which are the basis of most high-temperature alloys. This reduces thermal expansion stresses during thermal cycles (Kamal, et al., 2008, pp.358-372). Thermally sprayed cermet coatings are considered to be an important option for the replacement of electro deposited chromium on many components in industries (Guilemany, et al., 2002, pp.107-113). The application of cermet coatings results in a better service life of machinery components. Coatings based on chromium carbide are often used in gas turbines, vapour turbines, and aviation engines to improve slip resistance as well as abrasive and erosive wear (Hillery, 1986, pp.2684-2688). Parts on which this coating is applied are: hydraulic cylinders and piston rods, valve stems, turbine components, ship engine valve spindles, pump housings and others. (Material Product Data Sheet, 2012, Woka 7203 Chromium Carbide - 25% Nickel Chromium Powders, DSMTS-0031.1, Sulzer Metco).

The 75Cr₃C₂-25Ni(Cr) powder contains 75% of hard chromium carbide resistant to abrasion and 25% of nickel-chromium alloy (80%/20%) as a carbide binder resistant to corrosion and oxidation. The powder grain size is from 11 to 45 µm. (Material Product Data Sheet, 2012, Woka 7203 Chromium Carbide - 25% Nickel Chromium Powders, DSMTS-

0031.1, Sulzer Metco). The high energy level of the plasma causes the decomposition of the initial Cr_3C_2 carbide, so that other types of carbides are present in the coating. The Cr-C system is formed by three types of crystal structures such as Cr_{23}C_6 , Cr_7C_3 and Cr_3C_2 (Kajihara, Hillert, 1990, pp.2777-2787). At $1534 \pm 10^\circ\text{C}$, the first eutectic reaction $\text{L} = (\text{Cr}) + \text{Cr}_{23}\text{C}_6$ occurs and the solubility of C in the Cr-C solid solution is increased to 0.07 wt% C. The first peritectic reaction $\text{L} + \text{Cr}_7\text{C}_3 = \text{Cr}_{23}\text{C}_6$ occurs at $1576 \pm 10^\circ\text{C}$. Moreover, at $1727 \pm 7^\circ\text{C}$, there is another eutectic reaction $\text{L} = \text{Cr}_7\text{C}_3 + \text{Cr}_3\text{C}_2$ and the melting temperature of the Cr_7C_3 carbide is $1756 \pm 10^\circ\text{C}$. Another peritectic reaction occurs at $1811 \pm 10^\circ\text{C}$ when Cr_3C_2 carbide is formed by the reaction of $\text{L} + \text{C} = \text{Cr}_3\text{C}_2$ (ASM HANDBOOK VOLUME 3. Alloy Phase Diagrams, ASM International, Printed in the United States of America). In a series of carbides (Cr_{23}C_6 , Cr_7C_3 and Cr_3C_2), Cr_3C_2 carbide has the best mechanical properties and a coating with a higher content of this carbide is more resistant to wear. The microstructure of the coating is important as well as the chemical composition of the coating material. In cermet coatings with different thermal spray processes considerable variations are observed in the composition and the microstructure due to the exposure of powder to high temperatures and to different gas rates in the process (Matthews, et al., 2007, pp.59–64). Besides carbide and the metal phase, thermally sprayed coatings consist of oxide and pores located at the lamella boundaries originating from the spraying process conditions (Kamal, et al., 2009, pp.1004-1013). Therefore, coatings should be carefully sprayed and the spraying parameters should be carefully chosen prior to deposition. For example, $75\text{Cr}_3\text{C}_2$ - 25NiCr coatings deposited by the HVOF process are dense and in their microstructure there is less porosity due to high rates and relatively low temperature. The microhardness of $75\text{Cr}_3\text{C}_2$ - 25NiCr sprayed coatings produced by different systems were tested in previous studies. Virojanupatump published the influence of the $75\text{Cr}_3\text{C}_2$ - $25\text{Ni}(\text{Cr})$ powder processing technology on the characteristics of coatings deposited by the HVOF spray system (Wirojanupatump, et al., 2001, pp.829-837). The coating of sintered and crushed powder shows the highest value of microhardness - $910\text{HV}_{0.3}$, the microhardness of the coating deposited from a mixture of powders is $650\text{HV}_{0.3}$, and the value of the microhardness of the coating deposited by composite powder is $820\text{HV}_{0.3}$. He and Manish found that in the coating sprayed by agglomerated $75\text{Cr}_3\text{C}_2$ - $25\text{Ni}(\text{Cr})$ powder there was present only the Cr_3C_2 carbide phase (He, et al., 2000, pp.555-564), (Manish, et al., 2006, pp.29-38). In the microstructure of the coatings deposited by agglomerated and sintered $75\text{Cr}_3\text{C}_2$ - $25\text{Ni}(\text{Cr})$ powder, Matthews also found significant amounts of the Cr_3C_2 phase (Matthews, et al., 2009, pp.1086-1093), (Matthews, et al., 2009, pp.1094-1100). The concentration of Cr_7C_3 carbide was too low. Similar work was

done by Suegama, who used the XRD analysis for the agglomerated $75\text{Cr}_3\text{C}_2 - 25\text{Ni}(\text{Cr})$ powder and for the coating sprayed with the HVOF system and found that the powder consists of Cr_3C_2 carbide, Cr_7C_3 and a basis based on Ni (Suegama, et al., 2006, pp.434–445). In the $75\text{Cr}_3\text{C}_2 - 25\text{Ni}(\text{Cr})$ coatings, deposited by plasma spraying, there are present the particles of carbide types Cr_3C_2 , Cr_7C_3 and Cr_{23}C_6 . The phenomenon of a significant degradation of Cr_3C_2 carbide particles has been published in the literature (Ji, et al., 2006, p.6749) (Picas, et al., 2003, pp.1095). Cr_7C_3 and Cr_{23}C_6 carbides are formed by the decomposition of the primary Cr_3C_2 carbide. Due to the decomposition of the Cr_3C_2 carbide, in accordance with the Pratt & Whitney standard, an acceptable value of the microhardness of the $75\text{Cr}_3\text{C}_2 - 25\text{Ni}(\text{Cr})$ coating is in the range of 450-850HV_{0.3} (Turbojet Engine - Standard Practices Manual (PN 582 005), 2002, Pratt & Whitney, East Hartford, USA). Verdon C. et al. found that higher values of hardness of Cr_3C_2 -NiCr coatings can be obtained because of high density and cohesive strength as result of high influence of high-speed of particles during deposit (Verdon et al., 1998, pp.11-14). Non uniform values of hardness along coatings have been reported by many authors. This variation in hardness values is attributed to microstructural changes along the coating cross-section. These changes may be microstructural because of the presence of porosity and oxides of Ni(Cr) alloy, such as: NiO, NiCr_2O_4 , Cr_2O_3 and CrO_3 , unmelted and semi-melted particles in the coating structure (Brossard, et al., 2010, pp.1608-1615), (Matthews, et al., 2007, pp.59-64), (Mrdak, 2011, pp.9-14). Thermal spraycoatings show a typical lamellar structure with carbides in the structure and with clear boundaries of lamellas, due to precipitation and re-hardening of melted powder droplets. Lamellas are oriented parallelly to the substrate surface. Also, in the microstructure of coatings, unmelted particles can be found as well as semi-melted powder particles and the presence of fine particles - precipitates formed after the breaking of some powder particles during collision with the substrate. During spraying, oxides can be formed, because of oxidation during the flight of melted drops to the substrate on which they are deposited (Mrdak, 2010, pp.5-16), (Mrdak, 2011, pp.9-14), (Mrdak, 2012, pp.182-201), (Mrdak, 2013, pp.68-88). In the microstructure of $75\text{Cr}_3\text{C}_2 - 25\text{Ni}(\text{Cr})$ coatings, there are three different zones. The dark zone indicates the presence of primary Cr and C, revealing the Cr_3C_2 phase. The second zone is gray, which indicates the presence of Cr_7C_3 and Cr_{23}C_6 carbides. In addition to Cr and C, this area contains Ni. The third zone is white and consists primarily of the NiCr phase (Sukhpal, et al., 2012, pp.569-586).

This paper presents the results of the experimental investigation of the impact of the powder feed rate g / min on the mechanical properties and the microstructure of cermet $75\text{Cr}_3\text{C}_2 - 25\text{Ni}(\text{Cr})$ coatings. The main

goal was to apply the cermet $75\text{Cr}_3\text{C}_2 - 25\text{Ni}(\text{Cr})$ coating deposited by the APS - atmospheric plasma spraying process on the inlet flange of the turbo-jet engine TV2 117A. Three groups of samples are made with the values of the powder feed rate of: 30, 45 and 60 g/min. The microstructure and the mechanical properties of the coatings were analyzed in order to select a coating with the best properties. The coating with the best mechanical and structural properties was tested and homologated on the part of inlet flange of the turbo - jet engine TV2-117A at the testing station for a period of 45 hours in VZ "Moma Stanojlovic" - Batajnica.

Materials and experimental details

For the production of coatings the powder of the Sulzer Metco company marked Woka 7203 was used (Material Product Data Sheet, 2012, Woka 7203 Chromium Carbide - 25% Nickel Chromium Powders, DSMTS-0031.1, Sulzer Metco). The Woka powder contains 75% of hard Cr_3C_2 chromium carbides and 25% of a nickel-chromium alloy (80% / 20%). The $75\text{Cr}_3\text{C}_2 - 25\text{Ni}(\text{Cr})$ powder particles were spheroidized by agglomeration and sintering with a range of the powder particle grain size from 11 to 45 μm . Due to the content of 25Ni(Cr) alloy, the powder deposits well and bonds to the base based on Fe and Ni. Fig. 1 shows a scanning electron micrograph (SEM) of the morphology of powder particles. Spherical grains of powder Cr_3C_2 (brown) and the particles of the 25Ni(Cr) alloy (white) can be seen.

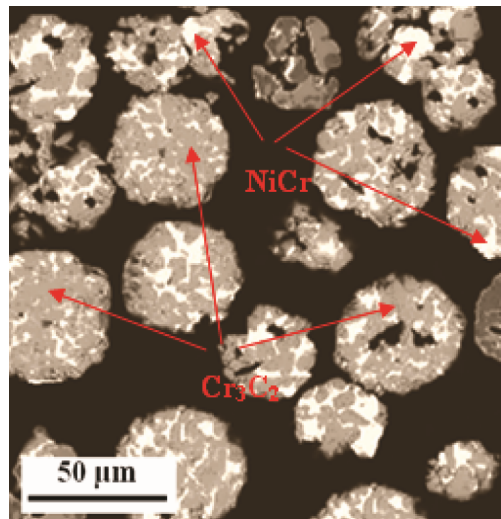


Figure 1 – (SEM) Scanning electron micrograph of $75\text{Cr}_3\text{C}_2 - 25\text{Ni}(\text{Cr})$ powder particles
Slika 1 – (SEM) Skening elektronska mikrografija čestica praha $75\text{Cr}_3\text{C}_2 - 25\text{Ni}(\text{Cr})$

The substrate material on which the coatings for testing microhardness are deposited and which is used for the evaluation of the microstructure in the deposited state is made of steel Č.4171 (X15Cr13 EN10027), thermally unprocessed, with the dimensions of 70x20x1.5mm. (Turbojet Engine – Standard Practices Manual (PN 582005), 2002, Pratt & Whitney, East Hartford, USA). The bases for testing the bond strength are also made of steel Č.4171(X15Cr13EN10027), thermally unprocessed, with the dimensions of Ø25x50 mm (Turbojet Engine – Standard Practices Manual (PN 582005), 2002, Pratt & Whitney, East Hartford, USA).

The examination of the microhardness of coating layers was done by the method HV_{0.3}. The measurement was done in the direction along the lamellae, in the middle and at the ends of the sample. There were five readings in three places and the minimum and maximum values are presented in the paper..

Tests for tensile bond strength were done at room temperature on hydraulic equipment with a speed of 10 mm / min for all tests. For each group of samples there were three specimens and the average values are given in the paper.. Mechanical and microstructural characterizations of the coatings were done according to the Pratt & Whitney standard (Turbojet Engine – Standard Practices Manual (PN 582005), 2002, Pratt & Whitney, East Hartford, USA).

The microstructural analysis of the coatings was done on a light microscope. The morphology of the powder particles was done on the SEM (Scanning Electron Microscope).

For powder deposition, the atmospheric plasma gun SG -100 of the plasma spray system (APS) Plasmadyne was used. The plasma spray gun SG -100 consisted of a cathode type K 1083 -129 A , an anode type A 2084 -145 and a gas injector type GI 2083 -130. As a gas, argon was used in a combination with helium and with a power supply of 40 kW. Before depositing, the substrates were not preheated and the substrate surfaces were roughened with white electro-corundum with a granulation from 0.7 to 1.5 mm. The aim of increasing the roughness of the substrate surface is removing the thin oxide layer in order to make the surface more reactive using molten powder and in order to get a better bond between the coating and the substrate. In selecting the powder deposition parameters, the powder feed rate (g/min.) was taken as the main parameter. The powder feed rate is one of important parameters that influence the stress state of the coating which is directly related to the cohesion strength, microhardness and adhesion of the coating. The share of unmelted particles, oxides and pores in the coating can be significantly controlled by controlling the powder feed rate. The powder feed rate must be optimal to enable complete melting of the powder par-

ticles and to reduce the minimum percentage of unmelted particles, oxides and pores in the coating layer. In this study there were three groups of samples. In the first group of samples, the powder feed rate was 30 g/min. With a carrier gas flow rate of 5 l/min, in the second group of samples, this rate was 45 g/min. with a carrier gas flow rate of 6 l/min, and in the third group of samples, the rate was 60 g/min. with a carrier gas flow rate of 7 l/min. Other parameters of the powder deposition had the following values: plasma current of 700 A, arc voltage - 36 V, the primary gas (Ar) - 47 l/min, the flow of secondary gas (He) - 12 l/min, and plasma arc distance - 100 mm from the substrates. The coatings were formed with a thickness of 0.2 mm. The detailed values of the plasma spray deposition parameters are shown in Table 1.

Table 1 – Plasma spray parameters
Tabela 1 – Plazma sprej parametri

Deposition parameters	Values		
Plasma current, I (A)	700	700	700
Plasma Voltage, U (V)	36	36	36
Primary plasma gas flow rate, Ar (l/min)	47	47	47
Secondary plasma gas flow rate, He (l/min)	12	12	12
Carrier gas flow rate, Ar (l/min)	5	6	7
Powder feed rate (g/min)	30	45	60
Stand-off distance (mm)	100	100	100

Results and discussion

The values of the microhardness and bond strength of the deposited $75\text{Cr}_3\text{C}_2 - 25\text{Ni}(\text{Cr})$, coatings depending on the powder feed rate, are shown in Figs. 2 and 3. The values of the microhardness of the coating layers are directly related to the powder feed rate. The powder feed rate significantly affects the values of the microhardness of the deposited layers, which must be optimal in order to ensure complete melting of powder particles and reduction of unmelted particles, pores and oxides in the coating layers to a minimum. Non-uniform values of microhardness attributed to microstructural changes along the coating cross-section are measured in the coating layers. Microstructural changes were caused by the presence of porosity, unmelted particles, Ni(Cr) alloy oxide and decomposed carbides in the structure of the coatings, which was confirmed by metallographic examinations of coating layers. The $75\text{Cr}_3\text{C}_2 - 25\text{Ni}(\text{Cr})$ coating layers deposited with the lowest powder feed rate of 30g/min have a microhardness value of 515-798HV_{0.3}.

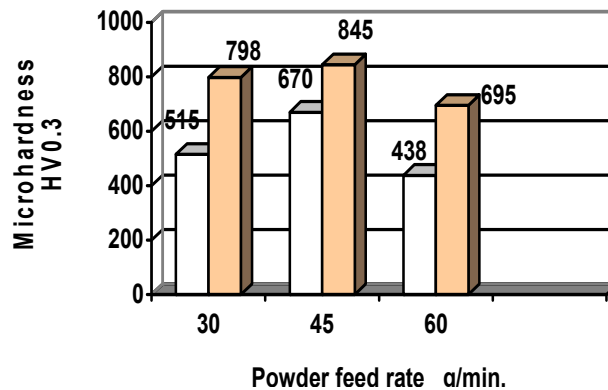


Figure 2 – Microhardness of 75Cr3C2 - 25Ni(Cr) layers
Slika 2 – Mikrotvrdoća 75Cr3C2 - 25Ni(Cr) slojeva

With a lower powder feed rate than the optimum one, primary Cr_3C_2 carbide powder has enough time to degrade in plasma with pores which reduce the microhardness of the coating. The layers deposited with a powder feed rate of 45g/min have the microhardness values of 670-845 $\text{HV}_{0.3}$, which is consistent with the values (450–850 $\text{HV}_{0.3}$) prescribed by the Pratt & Whitney standard (Turbojet Engine – Standard Practices Manual (PN 582005), 2002, Pratt & Whitney, East Hartford, USA). These layers showed the densest and the best microstructure, which was also confirmed by metallographic examinations of the coatings. The coating layers deposited with the highest powder feed rate of 60g/min had the lowest values of microhardness of 438-695 $\text{HV}_{0.3}$. With a powder feed rate higher than the optimum rate, all powder particles do not have enough time to be completely melted, which leads to the increase of the proportion of unmelted particles and coarse pores in the coating layers. Unmelted particles together with pores decrease the coating microhardness.

Tensile bond strength is, as well as microhardness, directly related to the powder feed rate, presence of pores, unmelted particles and inter lamellar oxides. The measurements of the tensile bond strength showed that the powder feed rates of 30 and 45g/min give values of more than 35 MPa, which is prescribed by the Pratt & Whitney standard (Turbojet Engine – Standard Practices Manual (PN 582005), 2002, Pratt & Whitney, East Hartford, USA). The highest value of tensile strength of 47MPa was found in the layers deposited with the powder feed rate of 45 g / min. These layers in the microstructure did not have coarse pores, unmelted particles or semi-molten particles. Since the presence of pores, unmelted particles and oxides is directly related to the values of the bond strength of coatings, the measured values of the coating deposited with the powder feed rate of 45g/min. indicate that their share is the lowest in this coating. These values were also confirmed by the analysis of the microstructure of the coatings under a light microscope.

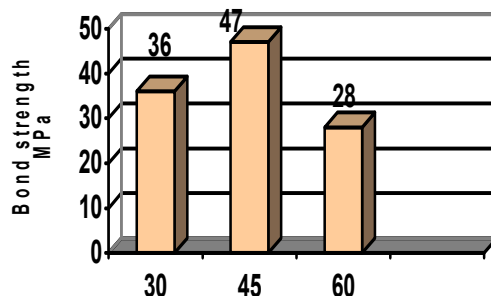


Figure 3 – Bond strength of 75Cr3C2 - 25Ni(Cr) layers
Slika 3 – Čvrstoća spoja 75Cr3C2 - 25Ni(Cr) slojeva

Figs. 4 and 5 show the microstructures of the layers deposited with the powder feed rate of 30 g / min. The qualitative analysis of the deposited 75Cr₃C₂-25Ni(Cr) layers showed that the substrate / coating interface has a negligible share of corundum Al₂O₃ particles due to roughening.

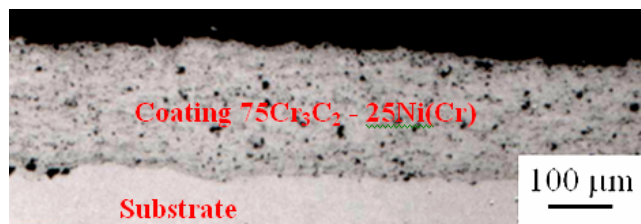


Figure 4 – 75Cr3C2 - 25Ni(Cr) coating microstructure deposited with the powder feed rate of 30 g/min
Slika 4 – Mikrostruktura 75Cr3C2 - 25Ni(Cr) prevlake deponovane sa brzinom dovoda praha 30 g/min

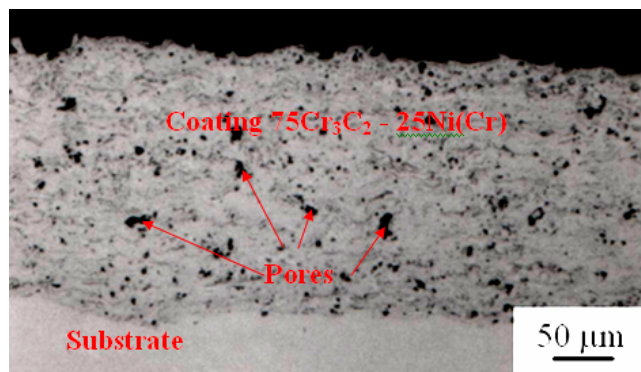


Figure 5 – 75Cr3C2 - 25Ni(Cr) coating microstructure deposited with the powder feed rate of 30 g/min
Slika 5 – Mikrostruktura 75Cr3C2 - 25Ni(Cr) prevlake deponovane sa brzinom dovoda praha 30 g/min

Along the substrate/coating interface, micro-cracks and macro-cracks are not present. The coating/substrate bond is uniform, without the separation of coating layers from the substrate. The coating structure is lamellar (Fig.5). The coating layers were deposited continuously without the presence of micro-cracks and macro cracks. Unmelted powder particles are not present in the layers. Through the coating layers, we can clearly see dark micro pores of irregular spherical shapes, which affected the coating to have a lower microhardness value of 850 HV0.3 prescribed by the Pratt & Whitney Pratt & Whitney standard (Turbojet Engine – Standard Practices Manual (PN 582005), 2002, Pratt & Whitney, East Hartford, USA).

Figs. 6 and 7 show the microstructures of the $75\text{Cr}_3\text{C}_2$ -25Ni(Cr) coating layers deposited with the highest powder feed rate of 60g/min., which had the worst microstructure and mechanical properties.

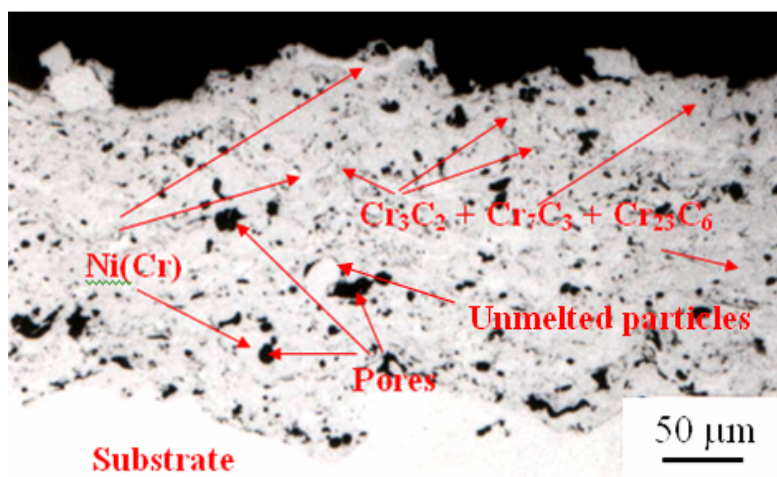


Figure 6 – $75\text{Cr}_3\text{C}_2$ - 25Ni(Cr) coating microstructure deposited with the powder feed rate of 60 g/min

Slika 6 – Mikrostruktura $75\text{Cr}_3\text{C}_2$ - 25Ni(Cr) prevlake deponovane sa brzinom dovoda praha 60 g/min

Because of a high powder feed rate, all particles do not have enough time to melt completely in the plasma jet, due to which unmelted particles and coarse pores (black) are present in the coating layers (Fig. 6., and 7). The coatings show a lamellar structure with limited inter-lamellar bonding. Therefore, micro pores are present as volumetric errors with large concentrations of stress which can cause the appearance of micro-cracks and accelerated wear during exploitation. Limited bonding of lamellae in the deposit decreases microhardness and fracture toughness. Through the coating layers, there can be clearly seen thin interlamellar films of gray

oxides: NiO, NiCr₂O₄, Cr₂O₃ and CrO₃ (Fig.7) originating from the oxidation of Ni and Cr in the process of the melting of Ni (Cr) particles in plasma (Brossard, et al., 2010, pp.1608-1615), (Mrdak, 2011, pp.9 - 14). In the coating there are dispersed Cr₃C₂ carbides in dark gray, located in the light gray area of Cr₂₃C₆ and Cr₇C₃ carbides formed in plasma by the temperature decomposition of the primary Cr₃C₂carbide (Fig.7). Throughout the carbide layers, there are also present bright white lamellae of the Ni(Cr)alloy (Sukhpal, et al., 2012, pp.569-586).

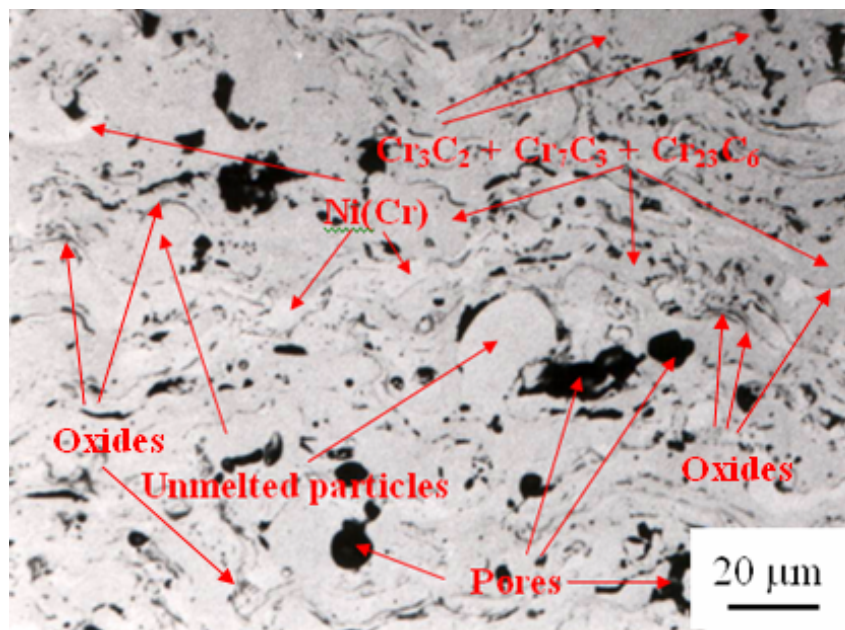


Figure 7 – 75Cr₃C₂ - 25Ni(Cr) coating microstructure deposited with the powder feed rate of 60 g/min
 Slika 7 – Mikrostruktura 75Cr₃C₂ - 25Ni(Cr) prevlake deponovane sa brzinom dovoda praha 60 g/min

Fig. 8 shows the layers of the 75Cr₃C₂-25Ni(Cr) coating deposited with the powder feed rate of 45g/min., which had the best microstructure and mechanical properties. The coating shows a lamellar structure with good inter-lamellar bonding. Good inter-lamellar bonding of the lamellae in the deposit increases the value of microhardness and fracture toughness, as confirmed by the mechanical testing of coatings. Micro cracks and macro cracks are not present in zhe inner lazers of the coating. In the coating layers there are no unmelted particles and coarse pores, which points to good melting of particles and good diffusion of particles during the coating process on the metal substrate. The microstructure of the coating is layered

with longitudinal lamellar Cr_{23}C_6 and Cr_7C_3 carbides (light gray) containing dispersed Cr_3C_2 carbides (dark gray). In the coating layers there are present fine black micropores and thin oxide layers of NiO , NiCr_2O_4 and Cr_2O_3 (light gray). The oxide layers are the result of incorporating air into the plasma jet and the oxidation of $\text{Ni}(\text{Cr})$ alloys during the deposition, i.e. they are an inevitable consequence of the application of the plasma spray process in atmospheric conditions. In the light gray zone of the Cr_{23}C_6 and Cr_7C_3 carbides, white light lamellae of $\text{Ni}(\text{Cr})$ alloy are clearly visible.

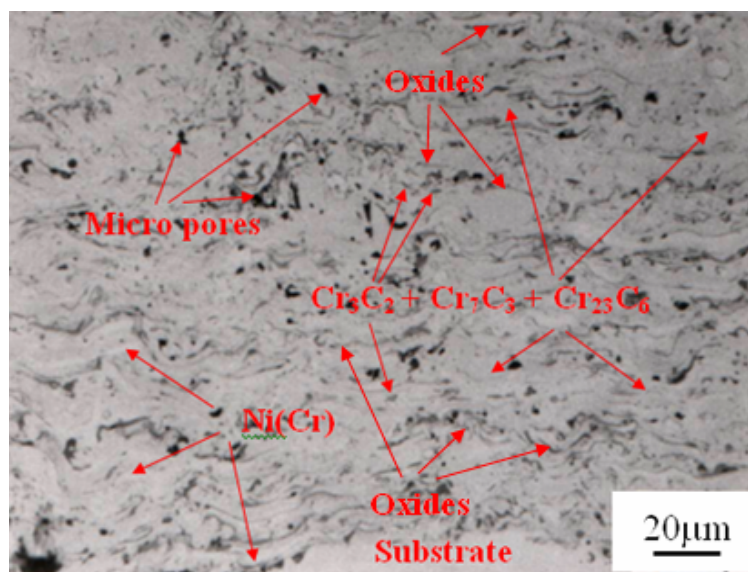


Figure 8 – $75\text{Cr}_3\text{C}_2 - 25\text{Ni}(\text{Cr})$ coating microstructure deposited with the powder feed rate of 45 g/min

Slika 8 – Mikrostruktura $75\text{Cr}_3\text{C}_2 - 25\text{Ni}(\text{Cr})$ prevlake deponovane sa brzinom dovoda praha 45 g/min

Conclusion

$75\text{Cr}_3\text{C}_2-25\text{Ni}(\text{Cr})$ coatings were deposited by the atmospheric plasma spraying (APS) process with three powder feed rates of 30, 45 and 60g/min. This paper analyzes the mechanical properties and the microstructures of the deposited layers by light microscopy. The morphology of the powder particles was examined on a Scanning Electron Microscope (SEM). The analysis led to the following conclusions.

The morphologies of the agglomerated powder particles of $75\text{Cr}_3\text{C}_2-25\text{Ni}(\text{Cr})$ are spherical in shape, consisting of sintered Cr_3C_2 carbides and particles of $25\text{Ni}(\text{Cr})$ alloy.

The values of the microhardness and the bond strength of the deposited layers were directly related to the powder feed rate (g/min). The layers deposited with the powder feed rate of 45g/min. had the highest values of microhardness (670-845HV_{0.3}) and the tensile bond strength of 47MPa, which are within the limits of 450–850 HV_{0.3} and min.35MPa prescribed by the Pratt & Whitney standard. The microhardness and tensile bond strength values were correlated with their microstructures.

The structure of the deposited 75Cr₃C₂-25Ni(Cr) coatings is lamellar. Micro pores (black) were present in all coatings. The layers deposited with the powder feed rate of 45g/min did not have coarse micro pores in the microstructure. These layers had the best microstructure. These layers did not show the presence of unmelted powder particles, precipitates, and inter-lamellar pores. The microstructure of the coating is layered with longitudinal lamellar carbides. Light gray fields are Cr₂₃C₆ and Cr₇C₃ carbides created by the decomposition of the primary Cr₃C₂ carbide. In the light gray fields of the Cr₂₃C₆ and Cr₇C₃ carbides, there is a dispersed phase of the primary non-decomposed Cr₃C₂ carbide (dark gray). In the light gray zone of the Cr₂₃C₆ and Cr₇C₃ carbides, there are light white lamellae of the Ni(Cr) alloy. In the coating layers, there are also present thin NiO, NiCr₂O₄ and Cr₂O₃ oxide layers (light gray). The oxide layers are the result of incorporating air into the plasma jet and the oxidation of Ni(Cr) alloys during the powder deposition.

The coating deposited with the powder feed rate of 45g/min., which showed the best mechanical properties and the microstructure, has been tested and homologated on the inlet flange parts of the turbo jet engine TV2-117A at the test station for 45 hours in VZ "Moma Stanojlovic", – Batajnica.

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UTICAJ BRZINE DOVODA PRAHA NA SVOJSTVA PLAZMA
NAPRSKANE HROMKARBID 25% NIKAL HROM PREVLAKE

OBLAST: hemijske tehnologije
VRSTA ČLANKA: originalni naučni članak

Sažetak:

Plazma-sprej postupak je vodeća tehnologija deponovanja praha u cilju izrade prevlaka koje imaju široku primenu u avio-industriji za zaštitu novih i opravku pohabanih delova. Kermet prevlake $75Cr_3C_2 - 25Ni(Cr)$ na bazi Cr_3C_2 karbida imaju veliku primenu za zaštitu delova, jer zadržavaju visoke vrednosti tvrdoće, čvrstoće i otpornosti na habanje do temperature od $850^\circ C$. Ovaj rad razmatra uticaj parametara plazma-sprej depozicije praha $75Cr_3C_2 - 25Ni(Cr)$ na strukturu i mehaničke karakteristike prevlake. Prah je deponovan plazma-sprej postupkom na atmosferskom pritisku (APS). Pri izboru parametara kao plazma gas koristio se helijum, koji je inertan i ne reaguje sa prahom, proizvodi gušću plazmu sa manjim toplotnim sadržajem i manje inkorporira okolni vazduh u mlaz plazme, što smanjuje temperaturno razlaganje i dekarburizaciju karbida Cr_3C_2 . U istraživanju su deponovane tri grupe prevlaka sa tri različite brzine dovoda praha od 30, 45 i 60 g/min. Prevlaka sa najboljim karakteristikama deponovana je na ulaznoj pri rubnici dela turbo-mlaznog motora TV2-117A da bi se smanjio uticaj vibracija i habanja. Analizirane su strukture i mehaničke karakteristike $75Cr_3C_2 - 25Ni(Cr)$ prevlaka u skladu sa standardom Pratt & Whitney. Istraživanja su pokazala da brzine dovoda praha bitno utiču na mehaničke osobine i strukture $75Cr_3C_2 - 25Ni(Cr)$ prevlaka.

Uvod

Termo-sprej prevlake pripadaju razvoju oblasti inženjerstva površina. Ove visokokvalitetne funkcionalne prevlake primenjuju se na novim delovima u baznoj industriji, kao i za renoviranje delova, uglavnom zbog svojih odličnih karakteristika, koje odlikuje visoka otpornost na habanje, eroziju, abraziju, otpornost na koroziju i otpornost prema visokim temperaturama (Berget, et al., 2007, pp.7619-7625), (Jankura, Bačová, 2009, pp.359-366), (Mann, Arya, 2003, pp.652-667), (Monticelli, et al., 2004, pp.1225-1237), (Wheeler, Wood, 2005, pp.526-536). Kermet prevlake su kombinacija keramičkih tvrdih faza ugrađenih u žilavoj metalnoj osnovi. Cr_3C_2-NiCr kermet prevlake se intenzivno koriste za ublažavanje abrazionog i erozionog habanja na visokim temperaturama do $850^\circ C$ (Matthews, et al., 2007, pp. 59–64), (Tillmann, et al., 2010, pp. 392–408). Prevlake Cr_3C_2-NiCr u odnosu na druge kermet prevlake nude veću otpornost na koroziju i oksidaciju, takođe ima visoku tačku topljenja i održavanje visoke tvrdoće, čvrstoće i otpornosti na habanje do $850^\circ C$. Primenom kermet prevlaka dobio se bolji radni vek komponenti mašina. Prevlake na bazi hrom karbida često se koriste na gasnim turbinama,

parnim turbinama i vazduhoplovnim motorima da poboljšaju otpornost na klizanje, abraziono i eroziono habanje (Hillery, 1986, pp.2684-2688). Delovi na kojima se primenjuje ova prevlaka su : hidraulički cilindri i klipnjače, pločice ventila, turbinske komponente, sita i čunjevi, vretena i ventili brodskih motora, kućišta pumpi i dr. (Material Product Data Sheet, 2012, Woka 7203 Chromium Carbide – 25% Nickel Chromium Powders, DSMTS-0031.1, Sulzer Metco). U kermet prevlakama sa različitim termo-sprej procesima uočene su značajne varijacije u sastavu i mikrostrukтури usled izlaganja praha visokim temperaturama i različitim brzinama gasa u procesu (Matthews, et al., 2007, pp.59–64). U prevlakama $75Cr_3C_2$ - 25Ni(Cr) deponovanim plazma-sprej postupkom prisutne su čestice karbida tipa Cr_3C_2 , $Cr_{23}C_6$ i Cr_7C_3 . Fenomen značajne razgradnje čestica karbida Cr_3C_2 publikovan je u literaturi (Ji, et al., 2006, p.6749), (Picas, et al., 2003, pp.1095). Karbidi Cr_7C_3 i $Cr_{23}C_6$ formiraju se razgradnjom osnovnog karbida Cr_3C_2 . Zbog razgradnje karbida Cr_3C_2 , po standardu Pratt & Whitney prihvatljiva vrednost mikrotvrdoće prevlake $75Cr_3C_2$ - 25Ni(Cr) je raspona 450–850 $HV_{0.3}$ (Turbojet Engine – Standard Practices Manual (PN 582005), 2002, Pratt & Whitney, East Hartford, USA). Neuniformne vrednosti tvrdoće duž prevlaka prijavili su mnogi autori. Ova varijacija u vrednosti tvrdoće pripisuje se mikrostrukturnim promenama duž poprečnog preseka prevlaka. Ove promene mogu biti mikrostrukturne zbog prisustva poroznosti, oksida legure Ni(Cr) kao što su: NiO, $NiCr_2O_4$, Cr_2O_3 i CrO_3 , neistopljenih i poluistopljenih čestica u strukturi prevlaka (Brossard, et al., 2010, pp.1608-1615), (Matthews, et al., 2007, pp. 59–64), (Mrdak, 2011, pp. 9-14).

U ovom radu predstavljeni su rezultati eksperimentalnih istraživanja uticaja brzine dovoda praha (g/min) na mehanička svojstva i mikrostrukturu kermet prevlake $75Cr_3C_2$ - 25Ni(Cr). Glavni cilj bio je da se na ulaznoj prirubnici dela turbomlaznog motora TV2-117A primeni kermet prevlaka $75Cr_3C_2$ - 25Ni(Cr) deponovana APS – atmosferskim plazma-sprej postupkom. Urađene su tri grupe uzoraka sa vrednostima brzine dovoda praha od 30, 45 i 60 g/min. Analizirane su mehaničke karakteristike i mikrostrukture prevlaka da bi se odabrala prevlaka najboljih karakteristika. Prevlaka sa najboljim mehaničkim i strukturnim karakteristikama je testirana i homologovana na ulaznoj prirubnici dela turbomlaznog motora TV2-117A motora na ispitnoj stanici u trajanju od 45 časova u VZ "Moma Stanojlović" – Batajnica.

Materijali i eksperimentalni detalji

Za proizvodnju prevlaka koristio se prah firme Sulzer Metco s oznakom Woka 7203 (Material Product Data Sheet, 2012, Woka 7203 Chromium Carbide - 25% Nickel Chromium Powders, DSMTS-0031.1, Sulzer Metco). Prah Woka sadrži 75% tvrdog hrom karbida Cr_3C_2 i 25% legure niki-hrom (80%/20%). Čestice praha $75Cr_3C_2$ - 25Ni(Cr) su sferoidizirane aglomeracijom i sinterovanjem sa rasponom granulacije čestica praha od 11 do 45 μm .

Materijal substrata na kojem su deponovane prevlake za ispitivanje mikrotvrdoće i za procenu mikrostrukture u deponovanom stanju izrađen je od čelika Č.4171 (X15Cr13 EN10027) u termički neobrađenom stanju dimenzija 70x20x1,5mm (Turbojet Engine – Standard Practices Manual (PN 582005), 2002, Pratt & Whitney, East Hartford, USA). Osnove za ispitivanje čvrstoće spoja takođe su izrađene od čelika Č.4171(X15Cr13EN10027) u termički neobrađenom stanju dimenzija Ø25x50 mm (Turbojet Engine – Standard Practices Manual (PN 582005), 2002, Pratt & Whitney, East Hartford, USA).

Ispitivanje mikrotvrdoće slojeva prevlaka rađeno je metodom $HV_{0.3}$. Merenje je urađeno u pravcu duž lamela, u sredini i na krajevima uzorka. Urađeno je pet očitavanja na tri mesta, a u radu su prikazane minimalne i maksimalne vrednosti.

Ispitivanja zatezne čvrstoće spoja vršena su na sobnoj temperaturi na hidrauličnoj opremi brzinom od 10 mm/min, za sva ispitivanja. Za svaku grupu uzoraka urađene su tri epruvete, a u radu su prikazane srednje vrednosti. Mehaničke i mikrostrukturne karakterizacije dobijenih prevlaka urađene su prema standardu Pratt & Whitney (Turbojet Engine – Standard Practices Manual (PN 582005), 2002, Pratt & Whitney, East Hartford, USA).

Mikrostrukturna analiza prevlaka urađena je na svetlosnom mikroskopu, a morfologija čestica praha na SEM-u (skening elektronskom mikroskopu).

Za depoziciju praha korišćen je plazma-pištolj SG -100 atmosferski plazma-sprej sistema (APS) firme Plasmadyne. Kao gas korišćen je argon u kombinaciji sa helijumom i snaga napajanja od 40 kW. Pri izboru parametara depozicije praha kao osnovni parameter uzeta je brzina dovoda praha (g/min). U ovom istraživanju urađene su tri grupe uzoraka. Kod prve grupe uzoraka brzina dovoda praha bila je 30 g/min sa protokom nosećeg gasa od 5 l/min, kod druge grupe uzoraka ova brzina bila je 45 g/min sa protokom nosećeg gasa od 6 l/min, a kod treće grupe uzoraka 60 g/min sa protokom nosećeg gasa od 7 l/min. Ostali parametri deponovanja praha imali su sledeće vrednosti: plazma-struja 700 A, napon luka 36 V, protok primarnog gasa (Ar) 47 l/min, protok sekundarnog gasa (He) 12 l/min, i odstojanje mlaza plazme 100 mm od supstrata. Prevlake su formirane sa debljinama do 0,2 mm.

Rezultati i diskusija

Brzina dovoda praha bitno utiče na vrednosti mikrotvrdoće deponovanih slojeva, koja mora da bude optimalna da bi se obezbedilo potpuno topljenje čestica praha i na minimum smanjio procenat neistopljenih čestica, pora i oksida u slojevima prevlaka. Mikrostrukturne promene uzrokovane su prisustvom poroznosti, neistopljenih čestice, oksida legure Ni(Cr) i razgrađenih karbida u strukturi prevlaka, što su potvrdila metalografska ispitivanja slojeva prevlaka. Slojevi deponovani brzinom dovoda praha od 45g/min imaju vrednosti mikrotvrdoće od

670-845HV_{0,3} koje su u skladu sa vrednostima (450–850 HV_{0,3}) koje propisuje standard Pratt & Whitney (Turbojet Engine – Standard Practices Manual (PN 582005), 2002, Pratt & Whitney, East Hartford, USA). Ti slojevi su pokazali najgušću i najbolju mikrostrukturu, što su potvrdila metalografska ispitivanja prevlaka.

Zatezna čvrstoća spoja je, kao i mikrotvrdoća, u direktnoj vezi sa brzinom dovoda praha, prisustva pora, neistopljenih čestica i međulamelarnih oksida. Najveću vrednost zatezne čvrstoće spoja od 47MPa pokazali su slojevi, koji su deponovani sa brzinom dovoda praha od 45 g/min. Ti slojevi u mikrostrukturi nisu imali grube pore, neistopljene čestice i poluistopljene čestice. Pošto je prisustvo pora, neistopljenih čestica i oksida u direktnoj vezi sa vrednostima čvrstoće spoja prevlaka, to izmerene vrednosti za prevlaku deponovanu sa brzinom dovoda praha od 45g/min ukazuje na to da je njihov udeo najmanji u ovoj prevlaci.

Kvalitativna analiza deponovanih 75Cr₃C₂-25Ni(Cr) slojeva pokazala je da je na interfejsu supstrat/prevlaka zanamarnjiv udeo čestica korunda Al₂O₃ od hrapavljenja. Duž interfejsa između substrata i prevlake nisu prisutne mikropukotine i makropukotine. Veza prevlake sa substratom je uniformna bez odvajanja slojeva prevlake sa substrata. Slojevi prevlake su deponovani kontinualno bez prisustva mikropukotina i makropukotina. Prevlaka deponovana sa brzinom dovoda praha 45g/min, koja ima najbolje mehaničke karakteristike pokazuje lamelarnu strukturu sa dobrim interlamelarnim vezivanjem. Dobro međulamelarno vezivanje lamela u depozitu povećava vrednosti mikrotvrdoće i žilavost loma, što su potvrdila mehanička ispitivanja prevlaka. Unutrašnji slojevi prevlake su bez prisutnih mikroprskotina i makroprskotina. U slojevima prevlake ne uočavaju se neistopljene čestice i grube pore, što govori o dobroj istopljenosti čestica i dobrom razlivanju čestica tokom procesa nanošenja na metalnu osnovu. Mikrostruktura prevlake je slojevit sa podužnim lamelama karbida Cr₂₃C₆ i Cr₇C₃ svetlosive boje u kojima se nalaze dispergovani karbidi Cr₃C₂ tamnosive boje. U slojevima prevlake prisutne su fine mikropore crne boje, kao i tanki slojevi oksida NiO, NiCr₂O₄ i Cr₂O₃ svetlosive boje. Oksidni slojevi su posledica inkorporiranja vazduha u mlaz plazme i oksidacije legure Ni(Cr) tokom depozicije, tj. neizbežna su posledica primenom plazma-sprej postupka u atmosferskim uslovima. U svetlosivoj zoni karbida Cr₂₃C₆ i Cr₇C₃ jasno se vide svetlo-bele lamele legure Ni(Cr).

Zaključak

Atmosferskim plazma-sprej postupkom (APS) deponovane su prevlake 75Cr₃C₂-25Ni(Cr) sa tri brzine dovoda praha 30, 45 i 60g/min. U radu su analizirane mehaničke karakteristike deponovanih slojeva i mikrostrukture na svetlosnom mikroskopu. Morfologija čestica praha ispitana je na (SEM) skenirajućem elektronskom mikroskopu. Na osnovu izvršenih analiza došlo se do određenih zaključaka.

Morfologije aglomerisanih čestica praha $75Cr_3C_2 - 25Ni(Cr)$ su sfernog oblika koje se sastoje od sinterovanih čestica karbida Cr_3C_2 i čestica legure $25Ni(Cr)$.

Vrednosti mikrotvrdoće i čvrstoće spoja deponovanih slojeva bili su u direktnoj vezi sa brzinama dovoda praha (g/min). Slojevi deponovani sa brzinom dovoda praha 45g/min imali su najveće vrednosti mikrotvrdoće 670-845HV_{0,3} i zatezne čvrstoće spoja 47MPa, koje su u granicama od 450 do 850 HV_{0,3} i min 35MPa koje su propisane standardom Pratt & Whitney. Vrednosti mikrotvrdoće i zatezne čvrstoće spoja bile su u korelaciji sa njihovim mikrostrukturama.

Struktura deponovanih prevlake $75Cr_3C_2 - 25Ni(Cr)$ je lamelarna. U svim prevlakama su prisutne mikropore crne boje. Slojevi deponovani sa brzinom dovoda praha 45 g/min nisu imali grube mikropore u mikrostrukтури. Ti slojevi imali su najbolju mikrostrukтуру. U njima nisu prisutne neistopljene čestice praha, precipitati i interlamelarne pore. Mikrostrukтура prevlake je slojevita sa podužnim lamelama karbida. Svetlosiva polja su karbidi tipa $Cr_{23}C_6$ i Cr_7C_3 nastali razgradnjom primarnog karbida Cr_3C_2 . U svetlosivim poljima karbida $Cr_{23}C_6$ i Cr_7C_3 prisutna je dispergovana faza primarnog nerazgrađenog karbida Cr_3C_2 tamnosive boje. U svetlosivoj zoni karbida $Cr_{23}C_6$ i Cr_7C_3 prisutne su svetlobele lamele legure $Ni(Cr)$. U slojevima prevlake prisutni su i tanki slojevi oksida NiO , $NiCr_2O_4$ i Cr_2O_3 svetlosive boje. Oksidni slojevi su posledica inkorporiranja vazduha u mlaz plazme i oksidacije legure $Ni(Cr)$ tokom depozicije praha.

Prevlaka deponovana sa brzinom dovoda praha 45 g/min, koja je pokazala najbolje mikrostrukture i mehanička svojstva testirana je i homologovana na ulaznoj prirubnici dela turbomlaznog motora TV2-117A na ispitnoj stanici u trajanju od 45 časova u VZ "Moma Stanojlović" – Batajnica.

Ključne reči: osobine, prah, plazma, brzina dovoda, prevlaka, hrom.

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