ORIGINALNI NAUČNI ČLANCI
ORIGINAL SCIENTIFIC PAPERS

STRUCTURE AND PROPERTIES OF PLASMA SPRAYED APS-NI20AL COATINGS

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Summary:

The aim of this study is to obtain, by optimizing the deposit parameters, optimal structural and mechanical properties of Ni20Al layers to be applied on a radar station part. The powder was deposited by the process of atmospheric plasma spraying (APS), with a plasma spray (PS) distance of 80, 90 and 100 mm. The coating with the best characteristics was deposited on the hardener of the GTD 2PV8 turbo gas engine for a radar station, in order to reduce the effect of oxidation and vibration on the wear at 450 - 500°C. The quality of Ni20Al coating layers was assessed on the basis of their microstructure, microhardness and tensile strength. The best structure and mechanical properties were found in the layers deposited with a distance of plasma spray of 80 mm. The surfaces morphology of the deposited coatings and the fracture morphology of the best layers were examined with the SEM (scanning electron microscope). The microstructure of the deposited layers of coatings was examined by light microscopy. The microstructural analysis of the deposited layers was performed according to the Pratt-Whitney standard. The evaluation of the mechanical properties of the layers was done by examining microhardness with the $HV_{0,3}$ method and tensile testing was used for the bond strength. Studies have shown that the plasma spray distance significantly affects the mechanical properties and the microstructure of coatings. The effect of Ni20Al coating application has been tested on a hardener of the GTD 2PV8 turbo gas engine on a radar station.

Key words: *structural properties, radar, property, plasma, microstructures, layers, deposits, coatings.*

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Introduction

The composite Ni20Al nickel - aluminide powder was developed for aviation industry. Its important characteristic is a good deposition by plasma spray at the atmospheric pressure APS. NiAl is an important intermetallic material used in aviation industry and other industries. This material has good resistance to oxidation, corrosion and erosion. The material can be produced as an alloy or as clad powder. In the second case, clad powder produces intermetallic compounds using various sources of heat such as plasma (Moshksar, Mirzaee, 2004), (Hashemi, et al., 2009), (Sampath, et al., 1990), (Kumar, Selvarajan, 2006). The most important feature of nickel - aluminide is high strength and toughness with excellent resistance to high temperatures. These characteristics were the basis for the development and a wider application of NiAl-based coatings. Plasma spray technology is used widely in the production of intermetallic surface layers. NiAl coatings deposited by plasma spray have found wide application in the protection of areas exposed to elevated and high temperatures (Liu, White, 1985, pp.365-371), (Cahn, 1991, pp.18-25), (Chen, et al., 1993, pp.357–363), (Liu, Sikka, 1986, pp.13-16). In particular, these coatings have a potential demand in aviation industry and other industries of high-performance (Chen, et al., 1993, pp.357-363), (Liu, Sikka, 1986, pp.13-16). Nickel – aluminide plasma spray coatings are used as bonding coatings, where their function is to minimize thermo - mechanical stresses at the substrate/coating interface, as well as to increase coating adhesion (Hiemann, 1986). The coefficient of thermal expansion of these alloys is intermediate between the thermal expansion coefficients of ceramics and metals, and therefore can reduce stress at the interface. Moreover, the exothermic reaction between Ni and Al leads to better coating adhesion. In addition, it is mainly used as a bonding layer for ceramic materials (Lee, et al., 1996, pp.3003-3009). Nickel-based coatings are used when there is a need for good wear resistance combined with oxidation or hot corrosion resistance (Rosso, Bennani, 1998, pp.524-530). The Ni20Al coating is typically used as a bonding layer to improve adhesion of the subsequently deposited top layer, as a middle layer for mitigating non-complance materials with different coefficients of thermal expansion, as a bonding layer resistant to oxidation for operating temperatures up to 650°C, as well as for the protection and revitalization of parts damaged by wear, oxidation and vibration. To obtain a functional layer, it is necessary to choose carefully a combination of plasma spraying parameters. For the control of plasma spray processes, the correlations between the parameters must be known well, as well as the individual effects of the parameters on the coating characteristics. One of important atmospheric plasma spray parameters is the distance of plasma spraying, which significantly affects the oxidation of melted particles during deposition on the surface as well as the pore size and the content. The oxide content increases with the distance increasing between the substrate and the plasma gun. In addition, with the increasing plasma spray distance, the content of pores increases, which significantly affects the mechanical properties of coatings (McPherson, Cheang, 1989). During the plasma spray process, nickel and aluminum react chemically above 660°C and form nickel - aluminide with an exothermic reaction which further transmits heat to the melted particles and to the surface. The products of this reaction are formed intermetallic compounds Ni_3Al, Ni_2Al_3 and NiAl which additionally increase the strength and the adhesion of coatings. These intermetallic compounds show superior properties at elevated temperatures. The key feature of the powder is to form coatings which are self - bonding for a wide range of metal substrates. Self-bonding materials require minimal surface preparation for good adhesion of the coating, which is suitable for thin substrates. Coatings deposited with optimal parameters are dense with a metallurgic bond at the interface with the base material. The properties of plasma deposited coatings are influenced by the microstructure of the layers. The microstructure and the phases that are formed when NiAl is the deposited depend of raw materials, technological processes and parameters used. NiAl is available as alloyed and as powder clad. For this work, the clad of Ni20Al powder was of interest. The clad of NiAl powder consists of the core of Ni and the outer shell of Al (Deevi, et al., 1997, pp.335-344). Aluminum is a chemical element that protects the coating of Ni from oxidation by forming Al_2O_3 oxide and an intermetallic compound γ'-Ni_3Al in the basic alloy α-Ni. At the atmospheric pressure, the Ni20Al powder deposited by the plasma spraying process produces a lamellar coating which consists of the α-Ni solid solution which includes γ'-Ni_3Al phases and the NiAl phase in traces (Knotek, Lugscheider, 1976, pp.244-251), (Knotek, et al., 1980, pp.282-286). In accordance with the dual diagram of Ni-Al, the γ'-Ni_3Al phase is built with the aluminum content of 12.5-14 wt.% Al, while the NiAl phase is built with the aluminum content of over 17 wt.%Al (ASM Handbook, 1992). The NiO oxides and γ-Al_2O_3 and pores are between the base lamellas at the interfaces.

This paper presents the results of experimental investigations of the influence of the plasma spray distance (PS) on the microstructure and the mechanical properties of the Ni20Al coating layers. The main objective was to attest the quality of coating and to apply it on the hardener of the GTD 2PV8 turbo gas engine on the radar station. Three groups of samples were made with three different plasma spraying distances: 80, 90 and 100 mm. The microstructure and the mechanical properties of coating layers were analyzed and studied in order to select the best coating quality. The coating with the best properties was tested on the hardener of the GTD 2PV8 turbo gas engine on the radar station at a time period of over 100 hours.

Materials and experimental details

The substrate material on which the coating layers were deposited was X15Cr13 stainless steel (EN 1.4024) in the thermally unprocessed state. For the production of coatings, the powder of the 'Sulzer Metco' company labeled Metco 404NS was used. The Ni20Al powder is composite powder with 80 wt.% Ni and 20 wt.% Al with a grain powder in a particle size range from 53µm to 90µm. The powder is well deposited and bonded for the Ni and Fe-based basis. The SG -100 plasma gun of the atmospheric plasma spray system (APS) by 'Plasmadyne' was used for powder deposition. The SG-100 plasma spray gun consisted of the cathode type K 1083-129, the anode type A 2084-145 and the gas injector type GI 2083-130. The Argon gas was used in the combination with the Helium and the power of supply of 40 KW. The plasma spray distance was the main parameter for the powder deposition. In this experiment, three different plasma spray distances (80mm, 90mm and 100mm) were used. An optimal distance of the plasma gun from the substrate allows the coating layers to have the smallest content of non-melted particles, oxides and pores. The pores, as volume errors, together with non-melted particles and oxides in the layers, significantly influence the strength of the coating and the protective effect of the coating in exploitation. The detailed values of plasma spray parameters have been shown in Table 1.

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

Deposition parameters	Values
Plasma current, I (A)	800
Plasma Voltage, U (V)	38
Primary plasma gas flow rate Ar (l/min)	47
Secondary plasma gas flow rate He (l/min)	31
Carrier gas flow rate (l/min)	6
Powder feed rate (g/min)	50
Stand-off distance (mm)	80/90/100

The substrate surfaces were roughened with the white electrical corundum Al_2O_3 with particles sizes of 0.7 - 1.5mm before depositing the powder. The coatings were deposited with a thickness of 0.15 mm. The coating layers with the best structural and mechanical properties are deposited on the hardener of the GTD 2PV8 turbo gas engine.

The testing of the structural and mechanical properties of the coatings was done in accordance with the 'Pratt & Whitney' standard (Turbojet Engine, 2002, Pratt & Whitney).

The samples with the dimensions 70 × 20 × 1.5 mm were used for the microhardness measurement and for the microstructure analysis. The microhardness of coatings was measured along the coating layers with the Vickers method ($HV_{0.3}$) with a load of 300 g. The measurement was done in the middle and at the ends of the samples. The presented results of microhardness were the averaged values.

The bond strength testing was done with the tensile testing method. The paired samples of dimensions Ø25 × 50 mm, one of which was with the deposited coating, were used for measuring the strength of the bond between the coating and the substrate. The testings were performed at room temperature at a speed of 1 mm/min. Five samples were done for each plasma spraying distance, and the measured values were averaged.

The microstructural analysis of the coating layers was done on the light microscope. The surface morphology of deposited coatings and the fracture morphology of the best layers were examined with the SEM.

Results and discussion

The measured values of the microhardness and the bond strength of deposited Ni20Al coatings depending on the plasma spray (PS) distance are shown in Figs. 1 and 2. The values of the microhardness of the coating layers are directly related to the plasma spraying distance. The plasma spray distance significantly affects the microhardness values and the bond strength of the deposited layers. The layers of Ni20Al coating, deposited with the smallest distance of 80 mm have a microhardness value of $220HV_{0.3}$ that is within the limits prescribed by the powder manufacturer (190 - $230HV_{0.3}$) (Material Product Data Sheet, 2011).

These layers have shown the best microstructure with a denser packing of the melted particles and with the lowest proportion of the interlamellar oxides and pores. The highest value of the microhardness of $273HV_{0.3}$ was found in the layers with the highest proportion of oxides that were deposited with a plasma spray distance of 100 mm. A higher microhardness value than $243HV_{0.3}$ was also found in the layers deposited with a plasma spray at a distance of 90 mm. The layers of coatings deposited at a larger distance had the microhardness values above the prescribed values. The values of the microhardness coatings were in accordance with the proportion of the oxide in the deposited layers. Larger distances of the plasma spray affected a higher degree of the oxidation of melted powder particles, followed up by a larger propotion of inter-lamellar oxides. These were confirmed by the metallographic examination of the coating layers.

Tensile bond strength is directly related to the plasma spray distance and to the proportion of inter-lamellar oxides and pores in the microstructure of Ni20Al coatings. The measurements of the values of the tensile bond strength showed that, for all three plasma spray distances, the obtained values were higher than 20.7MPa, which is prescribed by the powder manufacturer (Material Product Data Sheet, 2011).

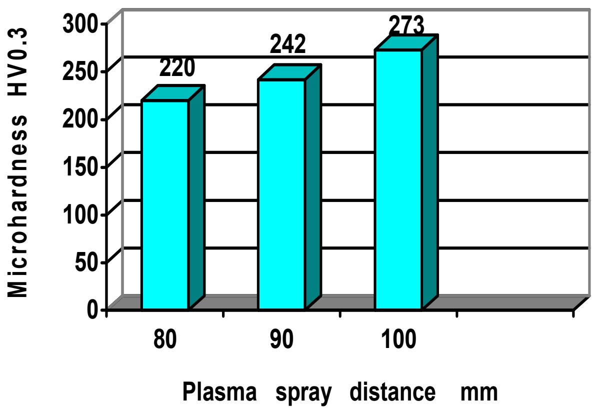

Figure 1 – Microhardness of Ni20Al layers
Slika 1 – Mikrotvrdoća Ni20Al slojeva

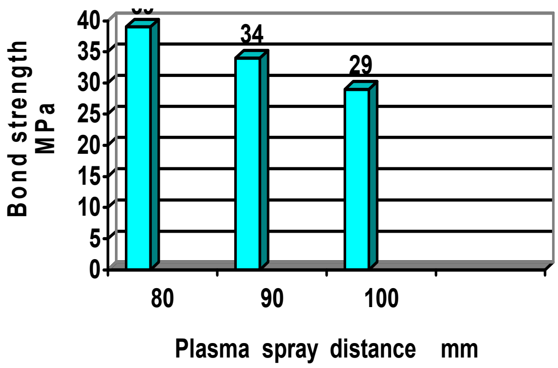

Figure 2 – Bond strength of Ni20Al layers
Slika 2 – Čvrstoća spoja Ni20Al slojeva

All deposited coatings had good values of the tensile bond strength resulting from the exothermic reaction of Al and Ni that occurs during the deposition of powder (McPherson, Cheang, 1989), (Deevi, et al., 1997, pp. 335-344), (Material Product Data Sheet, 2011). The exothermic reaction enabled obtaining a good adhesion strength with the substrate as well as obtaining a good inter-lamellar cohesive strength. The highest value of the bond strength of 39MPa was found in the layers deposited by plasma spraying with the smallest distance. These layers had the lowest proportion of oxides NiO and Y - Al_2O_3 and pores (Knotek, Lugscheider, 1976, pp. 244-251), (Knotek, et al., 1980, pp. 282-286).

The tensile bond strength testing showed that, for all deposited coatings, the mechanism of destruction occured at the interface between the substrate and the coating. This indicates a good melting of powder particles and their bonding to the substrate for all three plasma spray distances. Since the proportion of oxide, unmelted particles and pores is directly related to the microhardness values and the coating bond strength, the measured values for the deposited coating with the lowest plasma spray distance indicate that their proportion is the smallest in this coating. Also, these values are verified by the analysis of the coating microstructure on the light microscope.

Figs. 3 and 4 show the microstructures of the layers deposited by plasma spray (PS) at a distance of 80mm, which had the best microstructure and mechanical properties. The qalitative analysis of the deposited Ni20Al layers (Fig. 3) showed that, at the substrate/coating interface, there was an insignificant proportion of particles of the Al_2O_3 electric corundum due to roughening.

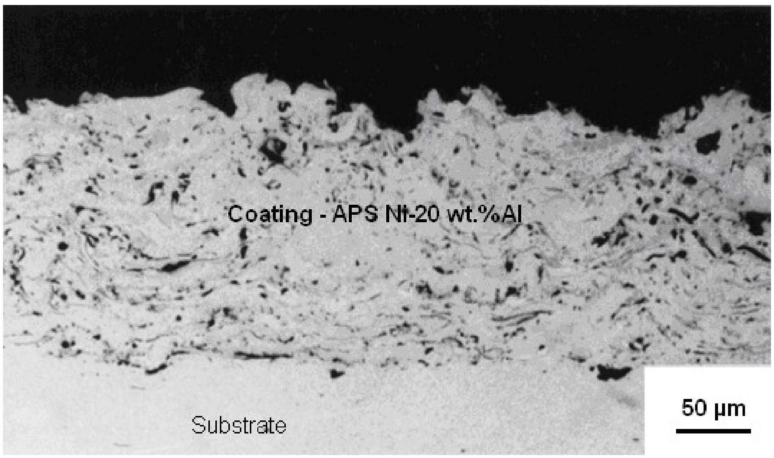

Figure 3 – NI20Al coating microstructure deposited with a (PS) distance of 80 mm
Slika 3 – Mikrostruktura NI20Al prevlake sa (PS) odstojanjem 80 mm

Along the substrate/coating interface, there are no microcracks and macrocracks. The coating/substrate bond is uniform without the separation of the coating layers from the substrate. The structure of the coating is lamellar. The coating layers were continuously deposited without the presence of microcracks and macrocracks. There were no unmelted powder particles present in the layers. The coating substrate consists of a solid solution of α – Ni, which is light gray, and an intermetallic phase of γ'-Ni_3Al and NiAl (Fig. 4). In the lamellar base of the solid solution and intermetallic phases, the thin inter-lamellar oxide NiO and Y - Al_2O_3 films are clearly observed, derived from the oxidation of Ni and Al in the process of cooling and solidification of melted powder particles (Knotek, Lugscheider, 1976, pp.244-251), (Knotek, et al., 1980, pp. 282-286).

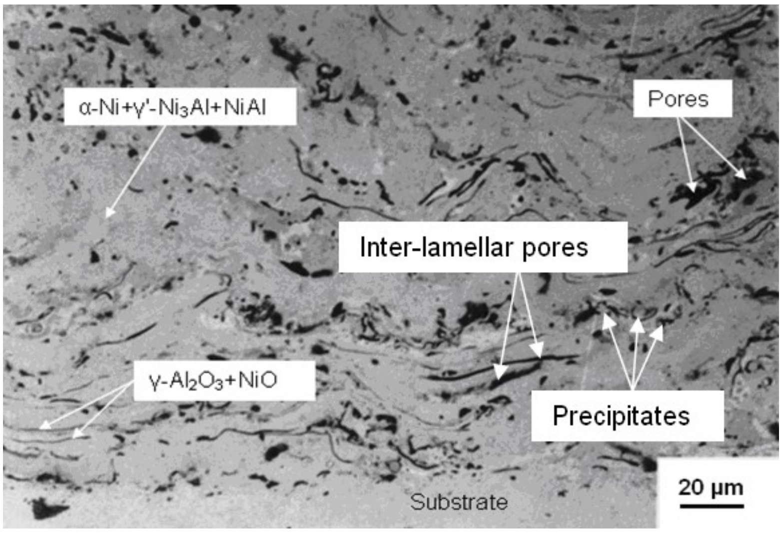

Figure 4 – NI20Al coating microstructure deposited with a (PS) distance of 80 mm
Slika 4 – Mikrostruktura NI20Al prevlake sa (PS) odstojanjem 80 mm

Dark inter-lamellar and spherical pores are clearly seen through the substrate layers. Due to a lower plasma spray distance, melted particles are more shortly retained in the plasma jet so rough oxides are not seen in the coating layers . Also, the coating layers do not show unmelted particles, microcracks and macrocracks. Precipitates of a spherical shape can be seen in a smaller proportion in the coating layers. The precipitates are a result of the impact of melted powder particles with the substrate and with the previously deposited layer. After the impact with the substrate, the melted particles chip at the ends, solidify and remain in the coating as residue.

Fig. 5 shows a scanning electron microphotography (SEM) of the surface of the Ni20Al coating deposited with the plasma spray at a distance of 80mm. The microphotography shows that the melted powder particles are uniformly distributed.

Unmelted particles are not present in the microstructure on the coating surface. Precipitates of a spherical shape can be seen in a small proportion. Along the boundaries of deposited particles,inter-lamellar pores and pores of irregular shape are observed. The microstructure of the Ni20Al coating surface is typical for atmospheric plasma spray (APS) coatings.

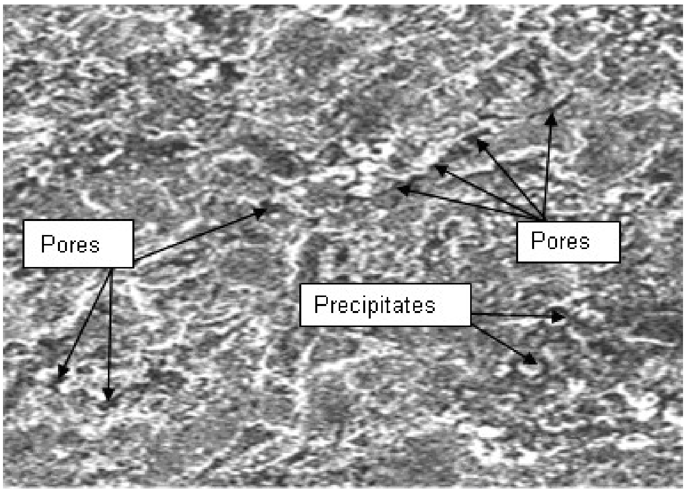

Figure 5 – SEM surface morphology of the Ni20Al coating deposited with a (PS) distance of 80 mm
Slika 5 – (SEM) Morfologija površine Ni20Al prevlake deponovane sa (PS) odstojanjem 80 mm

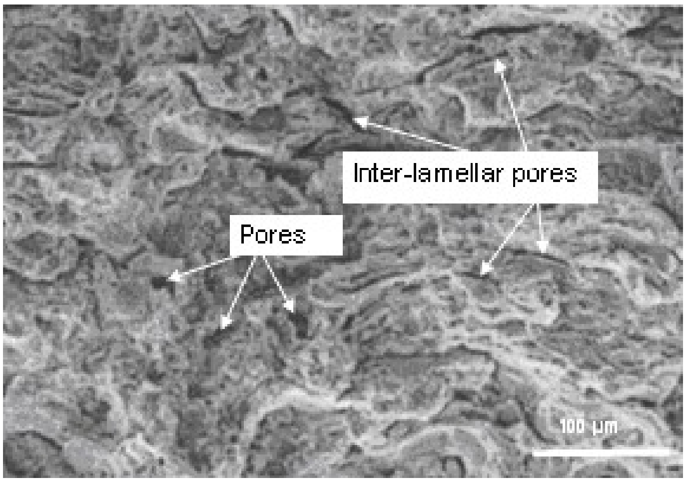

Figure 6 – SEM fracture morphologies of the Ni-20Al coating deposited with a (PS) distance of 80 mm.
Slika 6 – (SEM) Morfologije loma Ni-20Al prevlake deponovane sa (PS) odstojanjem 80 mm

Fig. 6 shows a microphotography of the fracture of the Ni20Al coating layers deposited with plasma spray at a distance of 80mm. The fracture morphology of the NiAl coating is seen at the fracture. The coating fracture is ductile. The microphotography clearly shows inter-lamellar pores and pores of irregular shapes present throughout the whole cross section of the coating; they did not affect the cohesion and adhesion strength significantly. Microcracks and macrocracks cannot be seen through the coating layers.

Conclusion

Ni20Al coatings were deposited by the procedure of atmospheric plasma spraying with three different plasma spraying (PS) distances of 80, 90 and 100 mm. The mechanical and microstructural characteristics of the deposited layer were researched and analyzed with the light microscope and the scanning electron microscope (SEM), which led to the following conclusions.

The coating microhardness, tensile bond strength and microstructure were in accordance with the terms of the plasma spray powder deposition. The quality of the coatings was directly dependent on the plasma spray distance.

The values of the coating microhardness increased with the increase of the plasma spraying distance due to the oxidation of melted particles and the formation of NiO and Y - Al_2O_3 oxides. The coating layers deposited with the highest plasma spraying distance of 100 mm had the highest microhardness values These layers had the highest proportion of oxides. The layers deposited with the plasma spray distance of 80 mm had the microhardness values within the prescribed limits by the powder manufacturer. These layers had the lowest proportion of oxides.

The values of the tensile bond strength of the coatings for all three plasma spray distances were higher than the minimum value prescribed by the powder manufacturer. The highest value of the tensile bond strength is shown in the layers with the lowest plasma spray distance and with the smallest proportion of oxides in the microstructure. The fracture occured along the coating/substrate interface in all investigated coatings. The values of the microhardness and the tensile bond strength were in correlation with their microstructures.

The structure of the layers of the deposited coatings is lamellar. The substrate consists of the solid solution of α - Ni and the intermetallic phases γ'-Ni_3Al and NiAl. In the lamellar base of the solid solution there are thin inter-lamellar NiO and Y - Al_2O_3 oxide films, derived from the oxidation of Ni and Al in the process of cooling and solidification of the melted powder particles. Inter-lamellar pores and spherical pores are present in the coating layers. Rough oxides, unmelted particles, microcracks and macrocracks are not present In the coating layers while precipitates of a spherical shape are seen in a smaller proportion.

The obtained results have shown that the plasma spray distance significantly affects the structure and the mechanical properties of the coating layers. The testings of the coatings have confirmed that the best layers were deposited with a plasma spray distance of 80 mm.

The Ni20Al coatings, deposited with a plasma spray distance of 80 mm that showed the best microstructure and mechanical properties were deposited on the hardener of the GTD 2PV8 turbo gas engine on a radar station.

The application of the coating have significantly improved the efficiency of the hardener and the operational reliability. The effects of oxidation, vibration and wear have been significantly reduced on the part in the temperature range of 450 - 500°C. The effect of the Ni20Al coating has been tested and confirmed on the hardener of the GTD 2PV8 turbo gas engine on the radar station over a period of 100 hours in the "Moma Stanojlović" Aeronautical Plant - Batajnica.

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STRUKTURA I SVOJSTVA NIKAL-ALUMINID PREVLAKE DOBIJENE PLAZMA RASPRŠIVANJEM PRI ATMOSFERSKOM PRITISKU

OBLAST: hemijske tehnologije
VRSTA ČLANKA: originalni naučni članak

Sažetak:

Cilj ovog istraživanja je da se optimizacijom parametara deponovanja dobiju optimalne strukturne i mehaničke karakteristike Ni20Al slojeva, koji će se primeniti na delu za radarsku stanicu. Prah je deponovan atmosferskim plazma sprej (APS) postupkom sa plazma sprej (PS) odstojanjem 80, 90 i 100 mm. Prevlaka sa najboljim karakteristikama deponovana je na utvrđivaču turbo- gasnog motora GTD 2PV8 za radarsku stanicu, da bi se smanjio uticaj oksidacije i vibracija na habanje na 450–500°C. Procene Ni20Al slojeva prevlake urađene su na osnovu njihovih mikrostruktura, mikrotvrdoća i zatezne čvrstoće. Najbolju strukturu i mehaničke karakteristike pokazali su slojevi deponovani sa plazma sprej odstojanjem od 80 mm. Morfologija površine deponovane prevlake i morfologija loma najboljih slojeva ispitana je na SEM-u (skening elektronskom mikroskopu). Mikrostruktura slojeva deponovanih prevlaka ispitana je na svetlosnom mikroskopu. Mikrostrukturna analiza deponovanih slojevima urađena je u skladu sa standardom Pratt-Whitney. Procena mehaničkih karakteristika slojeva urađena je ispitivanjem mikrotvrdoće metodom $HV_{0.3}$ i čvrstoće spoja ispitivanjem na zatezanje. Istraživanja su pokazala da plazma sprej odstojanje bitno utiče na mehaničke osobine i mikrostrukture prevlaka. Efekat primene Ni20Al prevlake ispitan je na utvrđivaču turbogasnog motora GTD 2PV8 na radarskoj stanici.

Uvod

Kompozitni nikal-aluminid prah Ni20Al razvijen je za potrebe vazduhoplovne industrije. Važna karakteristika je dobro deponovanje praha plazma sprejom na atmosferskom pritisku (APS). Ovaj materijal ima dobru otpornost na oksidaciju, koroziju i eroziju. Materijal se može proizvoditi kao legura ili kao kompozitni prah. Najvažnija karakteristika nikal-aluminida je velika čvrstoća i žilavost sa odličnom otpornošću na visoke temperature. NiAl prevlake deponovane plazma sprejom našle su široku primenu za zaštitu delova koji su izloženi povišenim i visokim temperaturama (Liu, White, 1985, pp.365-371), (Cahn, 1991, pp.18-25), (Chen, et al., 1993, pp.357-363), (Liu, Sikka, 1986, pp.13-16). Konkretno, ove prevlake imaju potencijalnu tražnju u avio-industriji i drugim industrijskim granama visokih performansi (Chen, et al., 1993, pp.357-363), (Liu, Sikka, 1986, pp.13-16). Ni20Al prevlaka tipično se koristi kao vezni sloj da poboljša adheziju naknadno deponovanog gornjeg sloja, kao srednji sloj za ublažavanje neusklađenosti materijala sa različitim koeficijentima termičkog širenja, kao oksidaciono otporan vezni sloj za radne temperature do 650°C, za zaštitu i revitalizaciju delova uzrokovanih habanjem, oksidacijom i vibracijama. Da bi se dobio funkcionalni sloj neophodno je pažljivo odabrati kombinaciju plazma sprej parametara. Jedan od bitnih atmosferski plazma sprej parametara je plazma sprej odstojanje koje znatno utiče na oksidaciju istopljenih čestica u toku deponovanja na podlogu i na veličinu i sadržaj pora. Prevlake deponovane sa optimalnim parametrima su guste sa metalurškom vezom na interfejsu sa osnovnim materijalom. Prah Ni20Al deponovan plazma sprej postupkom na atmosferskom pritisku proizvodi lamelarne prevlake, koje se sastoje od čvrstog rastvora α-Ni u kojem se nalaze faze γ'-Ni_3Al i u tragovima faza NiAl (Knotek, Lugscheider, 1976, pp.244-251), (Knotek, et al., 1980, pp. 282-286). Po dvojnom dijagramu Ni-Al, faza γ'-Ni_3Al se gradi sa sadržajem aluminijuma od 12,5-14 tež.%Al, a faza NiAl sa sadržajem aluminijuma preko 17 tež.%Al (ASM Handbook, 1992). Između lamela osnove na međugranicama se nalaze oksidi NiO i γ -Al_2O_3 i pore.

U ovom radu prikazani su rezultati eksperimentalnih istraživanja uticaja plazma sprej odstojanja (PS) na mikrostrukturu i mehanička svojstva slojeva prevlake Ni20Al. Glavni cilj je bio da se prevlaka primeni na utvrđivaču turbo- gasnog motora GTD 2PV8 na radarskoj stanici. Urađene su tri grupe uzoraka sa tri različita plazma sprej odstojanja 80, 95 i 100 mm. Analizirane su i proučavane mikrostrukture i mehaničke karakteristike prevlaka da bi se odabrala prevlaka najboljeg kvaliteta. Prevlaka sa najboljim karakteristikama testirana je na utvrđivaču turbogasnog motora GTD 2PV8 na radarskoj stanici u periodu od 100 sati.

Materijali i eksperimentalni detalji

Materijal substrata na kojem su deponovani slojevi prevlake bio je od nerđajućeg čelika X15Cr13 (EN 1.4024) u termički neobrađenom stanju. Za proizvodnju prevlaka koristio se prah firme „Sulzer Metco” *sa oznakom Metco 404NS. Prah Ni20Al je kompozitni obloženi prah sa 80 tež.%Ni i 20 tež.%Al sa rasponom granulacije čestica praha od 53 μm do 90 μm. Za depoziciju praha korišćen je plazma pištolj SG -100 atmosferski plazma sprej sistema (APS) firme „Plasmadyne". Plazma sprej pištolj SG -100 sastojao se od katode tipa K 1083 -129 A , anode tipa A 2084-145 i gas injektora tipa GI 2083-130. Kao gas korišćen je argon u kombinaciji sa helijumom i snaga napajanja od 40 KW. Plazma sprej odstojanje bio je osnovni parametar za deponovanje praha. U eksperimentu su korišćena tri različita plazma sprej odstojanja 80 mm, 90 mm i 100 mm. Pre deponovanja praha površine substrata su se hrapavile belim plemenitim elektrokorundom Al_2O_3 sa česticama veličine od 0,7 do 1,5 mm. Prevlake su deponovane sa debljinom do 0,15 mm. Ispitivanje strukturnih i mehaničkih karakteristika prevlaka rađeno je prema standardu Pratt & Whitney (Turbojet Engine, 2002, Pratt & Whitney). Za merenje mikrotvrdoće i analizu mikrostrukture uzorci su bili dimenzija 70×20×1,5 mm. Mikrotvrdoća prevlaka rađena je duž slojeva prevlaka metodom Vickers ($HV_{0.3}$) sa opterećenjem od 300 g. Ispitivanje čvrstoće spoja rađeno je metodom ispitivanja na zatezanje. Za merenje čvrstoće spoja između prevlake i substrata korišćeni su upareni uzorci dimenzija Ø25×50 mm od kojih je jedan bio sa deponovanom prevlakom. Ispitivanja su izvršena na sobnoj temperaturi pri brzini od 1 mm/min. Mikrostrukturna analiza slojeva prevlaka urađena je na svetlosnom mikroskopu. Morfologija površine deponovane prevlake i morfologija loma najboljih slojeva ispitana je na SEM-u (skening elektronskom mikroskopu).*

Rezultati i diskusija

Vrednosti mikrotvrdoće slojeva prevlaka u direktnoj su vezi sa plazma sprej odstojanjem. Plazma sprej odstojanja bitno utiču na vrednosti mikrotvrdoće i čvrstoće spoja deponovanih slojeva. Slojevi Ni20Al prevlake deponovane sa najmanjim odstojanjem od 80 mm imaju vrednost mikrotvrdoće od $220HV_{0.3}$ koja je u granicama koju propisuje proizvođač praha ($190–230HV_{0.3}$) (Material Product Data Sheet, 2011). Najveću vrednost mikrotvrdoće od 273 $HV_{0.3}$ imali su slojevi sa najvećim udelom oksida koji su deponovani sa plazma sprej odstojanjem od 100 mm. Slojevi prevlaka deponovanih sa većim odstojanjem imali su vrednosti mikrotvrdoće iznad propisanih vrednosti. Vrednosti mikrotvrdoća prevlaka bile su u skladu sa udelima oksida u deponovanim slojevima. Merenjem vrednosti zatezne čvrstoće spoja ustanovljeno je da su se za sva tri plazma sprej odstojanja dobile vrednosti više od 20.7MPa, koju propisuje proizvođač praha (Material Product Data Sheet, 2011). Sve deponovane prevlake imale su dobre vrednosti zatezne čvrstoće spoja koje proizilaze iz egzotermne reakcije Al i Ni koja se dešava za vreme depozicije praha (McPherson, Cheang, 1989), (Deevi, et al., 1997, pp.335-344), (Material Product Data Sheet, 2011). Najveću vrednost čvrstoće spoja od 39MPa pokazali su slojevi koji su deponovani sa najmanjim plazma sprej odstojanjem. Ti slojevi imali su najmanji udeo oksida NiO i Y- Al_2O_3 i pora. Na slikama 3 i 4. su prikazane mikrostrukture slojeva deponovanih sa plazma sprej odstojanjem 80 mm, koji su imali najbolju mikrostrukturu i mehaničke karakteristike. Struktura prevlake je lamelarna. Slojevi prevlake deponovani su kontinualno bez prisustva mikropukotina i makropukotina. U slojevima nisu prisutne neistopljene čestice praha. Osnova prevlake sastoji se od čvrstog rastvora α - Ni svetlosive boje i intermetalnih faza γ'-Ni_3Al i NiAl (Sl.4). U lamelarnoj osnovi čvrstog rastvora i intermetalnih faza jasno se uočavaju tanki međulamelarni oksidni filmovi NiO i Y-Al_2O_3 koji potiču od oksidacije Ni i Al u procesu hlađenja i očvršćavanja istopljenih čestica praha (Knotek, Lugscheider, 1976, pp.244-251), (Knotek, et al., 1980, pp. 282-286). Kroz slojeve osnove jasno se uočavaju tamne inter-lamelarne i sferne pore. U slojevima prevlake se u manjem udelu uočavaju precipitati sfernog oblika. Precipitati su posledica sudara istopljenih čestica praha sa substratom i prethodno deponovanim slojem. Na slici 5. prikazana je (SEM) skening elektronska mikrofotografija površine Ni20Al prevlake deponovane sa plazma sprej odstojanjem 80 mm. Na mikrofotografiji se vidi da su istopljene čestice praha pravilno razlivene. U mikrostrukturi na površini prevlake nisu prisutne neistopljene čestice. U manjem udelu uočavaju se precipitati sfernog oblika. Duž granica deponovanih čestica uočavaju se međulamelarne pore i pore nepravilnog oblika. Mikrostruktura površine Ni20Al prevlake tipična je za (APS) atmosferski plazma sprej prevlake. Na slici 6. prikazana je mikrofotografija loma slojeva Ni20Al prevlake deponovane sa plazma sprej odstojanjem od 80 mm. Na prelomu se vidi morfologija loma NiAl prevlake. Prelom prevlake je žilav. Na mikrofotografiji se jasno vide interlamelarne pore i pore nepravilnog oblika koje su prisutne po celom preseku prevlake koje nisu bitno uticale na kohezionu i adhezionu čvrstoću.

Zaključak

Atmosferski plazma sprej postupkom su deponovane Ni20Al prevlake sa tri različita (PS) plazma sprej odstojanja 80, 90 i 100 mm. U ovom radu, istraživane su i analizirane mehaničke i mikrostrukturne karakteristike deponovanih slojeva na svetlosnom mikroskopu i (SEM) skening elektronskom mikroskopu, na osnovu čega se došlo do sledećih zaključaka.

Mikrotvrdoća, zatezna čvrstoća spoja i mikrostrukture prevlaka su bile u skladu sa uslovima plazma sprej deponovanja praha. Vrednosti mikrotvrdoće prevlaka se povećavaju sa povećanjem plazma sprej odstojanja zbog oksidacije istopljenih čestica. Slojevi prevlake deponovane sa najvećim plazma sprej odstojanjem 100 mm su imali najveće vrednosti mikrotvrdoće. Slojevi deponovani sa plazma sprej odstojanjem 80 mm su imali vrednosti mikrotvrdoće u granicama koje je propisao proizvođač praha. Ti slojevi imali su najmanji udeo oksida NiO i Y- Al_2O_3 .

Najveću vrednost zatezne čvrstoće spoja su pokazali slojevi sa najmanjim plazma sprej odstojanjem koji su u mikrostrukturi imali naj-

manji udeo oksida. Za sve ispitivane prevlake lom je išao na interfejsu između prevlake i substrata.

Struktura slojeva deponovanih prevlaka je lamelarna. Metalografska analiza prevlaka na svetlosnom mikroskopu je pokazala da se osnova prevlake sastoji od čvrstog rastvora α - Ni i intermetalnih faza γ'-Ni_3Al i NiAl. U lamelarnoj osnovi čvrstog rastvora su prisutni tanki međulamelarni oksidni filmovi NiO i Y- Al_2O_3 koji potiču od oksidacije Ni i Al u procesu hlađenja i očvršćavanja istopljenih čestica praha. U slojevima prevlaka su prisutne interlamelarne i sferne pore. U slojevima prevlaka nisu prisutni grubi oksidi, neistopljene čestice, mikropukotine i makropukotine. Dobijeni rezultati su pokazali da plazma sprej odstojanje bitno utiče na strukturu i mehaničke karakteristike slojeva prevlaka.

Primenom Ni20Al prevlake deponovane sa plazma sprej odstojanjem od 80 mm koja je pokazala najbolju mikrostrukturu i mehaničke karakteristike, deponovana je na utvrđivaču turbomlaznog motora 2PV8 za radarsku stanicu. Primenom prevlake znatno se poboljšala efikasnost utvrđivaču turbomlaznog motora i pouzdanost rada. Na delu je znatno smanjen uticaj oksidacije i vibracija na habanje u rasponu temperature od 450 do 500°C. Efekat primene Ni20Al prevlake ispitan je i potvrđen na utvrđivaču turbogasnog motora GTD 2PV8 na radarskoj stanici u Vazduhoplovnom zavodu „Moma Stanojlović" – Batajnica u periodu od 100 sati.

Ključne reči*: strukturne osobine, radar, osobina, plazma, mikrostrukture, slojevi, depoziti, prevlake.*

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