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STUDY OF THE APPLICATION OF PLASMA SPRAYED COATINGS ON THE SECTIONS OF THE ASTAZOU III B TURBO - JET ENGINE

Mihailo R. Mrdak
Research and Development Center IMTEL Communications a.d., Belgrade
e-mail: miki@insimtel.com,
ORCID iD: http://orcid.org/0000-0003-3983-1605

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Summary:

The plasma spray process is used extensively in the aerospace industry for manufacturing key components exposed to excessively high temperatures, aggressive chemical environments, wear, abrasion, erosion and cavitation. The process covers a large field of parameters so that almost every layer can be combined with any other as well as with the base material. Coatings can be deposited uniformly; therefore, they allow worn components to be brought to final dimensions in the process of aircraft repair. This research shows an effective procedure of the application of plasma spray coatings on the parts of the Astazou III B turbo - jet engine in the process of repair.The engine manufacturer,Turbomeca, has prescribed that powders should be deposited by plasma spray systems under designation Metco 3M and 7M for the prescribed parameters of powder deposition, so that during the application of other plasma spray depositing systems the parameters must be tested and optimized. The aim was to apply the Plasmadyne plasma spray system during the repair process and to optimize the parameters, which will enable producing coatings that fulfill all the criteria prescribed in the engine manufacturer standard. The optimization of the parameters was carried out with a plasma gun MINI - GUN II with a large number of samples. This paper presents the optimal parameters of the deposition on the ASTAZOU III B engine casing, casing frame, duct and oil tank.The assessment of the coating

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mechanical properties was done by the $HV_{0.3}$ microhardness testing method. Tensile bond strength of the coatings was investigated by a tensile test. The microstructures of the coating layers were evaluated on an optical microscope - OM. The analysis of the microstructures and the mechanical characteristics of the coatings was done in accordance with the TURBOMECA standard. The quality of the deposited coatings was confirmed by a 42-hour test of the ASTAZUO III B engine parts on a test stand. The performed tests have confirmed the quality of the coatings thus enabling the application of the plasma spray technology in the process of the ASTAZOU III B engine overhaul.

Key words: *spray coatings, repairs, plasmas, engines, deposits, coating.*

Introduction

The development of jet engines and the demands for increased resistance to oxidation, hot corrosion and sulphuring of engine parts influenced the development of the thermal spray process and nickel-based powders. For the protection of parts of jet engines, NiAl, NiCr, NiCrAl, NiCrAlY, CoCrAlY, NiCoCrAlY, etc. plasma spray coatings are commonly used today. The most effective protection of substrates from oxidation at temperatures above 800°C is provided by coatings which form oxides of the α-Al_2O_3 and Cr_2O_3 type. In most cases, coatings forming a continuous layer of α-Al_2O_3 are applied since this type of oxide is superior and more reliable as compared to other types of oxides (Mrdak, 2012, pp.182-201). At the beginning of the oxidation, NiO, α-Al_2O_3 and Cr_2O_3 oxide types are rapidly formed as well as spinel phases. The relative ratio of these phases is determined by the initial composition of the alloy. As oxidation continues, the diffusion processes are beginning to show their effects. The nature of these effects depends on the content of the chemical elements in the coating and the diffusion parameters. When the coating has a low content of chromium and aluminum, protective continuous α-Al_2O_3 and Cr_2O_3 oxide layers cannot be formed on the coating surface; instead, undesirable continuous NiO oxide layers are formed. The mechanism of the NiO oxide growth causes the formation of micro pores in the oxide / alloy interlayer. Micro pores grow and merge into large macro pores. The mechanism of the NiO oxide growth creates significant stress which eventually leads to cracks in the oxide layer. The coefficient of the thermal expansion of NiO oxide and that of metal vary considerably. NiO oxide is subjected to tensile stresses as a metal base, so that the elastic deformation of the metal substrate causes breakage and peeling of the oxide layer on the coating surface (Mrdak, 2012, pp.182-201). In order to build up continuous α-

Al_2O_3 and Cr_2O_3 oxide layers on the coating surface, a minimum of 20%Cr and 5%Al should be used for nickel alloys. NiCrAl alloy is added as well as yttrium for better cohesive oxide strength and better adhesive strength of the oxide coating on the substrate. Depending on the alloy type, the content of yttrium in the alloy ranges from 0.1 to 0.5% (Mrdak, 2012, pp.182-201). In exploitation, coatings are often exposed to the influence of impurities in the fuel and air. Depending on gas impurity, coatings can be exposed to a greater or lesser influence of Na, S and V. At high temperatures, diffusion processes occur at the interface between the coating and the gaseous environment, accelerating deposit corrosion. As far as air impurities are concerned, salt sucked by a turbojet engine is in the first place. Salt has the greatest impact on the corrosion of the parts of the turbojet engine that runs on distilled fuel without vanadium content. Salt sucked into the engine reacts with sulfur in the fuel to form sodium sulfate. In gas turbines that operate in the medium where chlorine is present, sodium chloride can also occur. This concerns air vehicles with a gas turbine developing a temperature at the turbine exit of about 750 °C, stationed on aircraft carriers or in coastal areas. Vanadium can also occur as impurity originating from fuel combustion. During fuel combustion, ash with a low melting point is created and deposited on the gas turbine components. Sulfur in fuel reacts with chromium from the alloy, thus forming chromium sulfate which precipitates on grain boundaries. During oxidation, chromium bonds with oxygen, simultaneously releasing sulfur that diffuses into the depth of the surface layer. In this way, new sulfides are formed beneath chromium oxide. Sulphur never goes into the atmosphere, but still diffuses through the surface layer, causing hot corrosion (Mrdak, 2012, pp.182-201). The experience of Turbomeca company which, in the production of the Astazou III B engine, applies plasma spray coatings resistant to oxidation and hot corrosion, as well as coatings for the repair of parts made of Al alloys, enabled the usage of plasma spray technology in the process of engine overhaul. The engine manufacturer prescribes that powder is to be deposited by plasma spray systems labeled Metco 3M and 7M for the prescribed parameters of powder deposition; therefore, the parameters must be optimized when applying other plasma spray depositing systems in order to meet all the criteria set by the Turbomeca standard. For saving and repairing engine parts from oxidation and hot corrosion, the manufacturer of the Astazou III B engine uses Ni/5Al, NiCr/6Al and Ni22Cr10Al1Y powders, and, for recovery of dimensions and repair of parts from aluminum alloys, it uses Al12Si powder. Composite Ni/5Al powder, due to its exothermic reaction during deposition, provides good bonding of the coating to the substrate. The products of this reaction are intermetallic compounds $NiAl_3$, Ni_2Al_3 and NiAl which add to the strength of the coating. These are thick coatings with metallurgical bond at the interface with the base material. The coating consists of lamellae of a solid solution of aluminum in nickel α-Ni (Al), and inter-lamellar oxides NiO and γ-Al_2O_3 uniformly distributed over the boundaries of solid solution lamellae (Knotek, et al., 1980, pp.282-286), (Mrdak, 2015, pp.32-55), (Mrdak, 2013, pp.7-22), (Svantesson, Wigren, 1992, pp.65-69). Coatings are resistant to oxidation, gas corrosion, wear, abrasion and erosion at temperatures up to 980°C. Bond strength with the substrate remains adequate to 700°C (Griffiths, et al., 1980). Coatings deposited in accordance with the Turbomeca standard have values of microhardness of min.140$HV_{0.3}$ and bond tensile strength of min.35MPa. NiCrAl types of coatings in a deposited state consist of a solid solution of chromium and aluminum in nickel γ-Ni (Cr,Al). NiO, α-Al_2O_3, Cr_2O_3, and CrO_3 oxide types are present in layers as well as $Ni(Cr,Al_2)O_4$ spinel phases (Badrour, et al., 1986, p.1217), (Brossard, et al., 2009, pp.1-9), (Mrdak, 2010, pp.5-16), (Mrdak, 2012, pp.182-201), (Mrdak, 2013, pp.7-22), (Tran, et al., 2008, p.701). Tensile bond strength of the coating stays adequate to the operating temperature of 980°C (Mrdak, 2012, pp.182-201). Coatings deposited by the Turbomeca standard have values of microhardness of min.170$HV_{0.3}$ and tensile bond strength of min.35MPa. NiCrAlY alloy is used to protect parts from hot corrosion and high temperature oxidation up to 1100°C (Material Product Data Sheet, 2013, Nickel Chromium Aluminum Yttrium (NiCrAlY) Thermal Spray Powders Amdry 963, DSMTS-0102.1, Sulzer Metco). Addition of yttrium is essential because it significantly increases the adhesion of Al_2O_3 and Cr_2O_3 oxides that are formed in the coating with the coating base, thus preventing cracking and separation of the protective surface oxide layer at thermal fatigue (Mrdak, 2012, pp.182-201). The structure of the inner layers of the coating consists of a solid solution of chromium and aluminum in nickel γ-Ni(Cr,Al) and the intermetallic compound γ'-Ni_3Al. NiO, α-Al_2O_3, Cr_2O_3 and $NiCr_2O_3$ oxides are also present in the structure (Badrour, et al., 1986, p.1217), (Leea, 2005, pp.239-242). Coatings deposited by the Turbomeca standard have microhardness values of min. 200$HV_{0.3}$ and tensile bond strength of min. 35 MPa. Al12Si coating is of a general purpose and is applied for the protection of new aviation parts and in the repair process to restore dimensions of aluminum and magnesium alloy parts changed due to wear (Material Product Data Sheet, 2011, Aluminum 12% Silicon Thermal Spray Powders Metco 52C-NS, DSMTS – 0045.2,Sulzer Metco), (Pramila Bai, Biswas, 1987, p.61). In the deposited state, the coating microstructure consists of two phases: α-Al solid solution and α-Al + Si eutectic mixture. Fine eutectic grains of α-Al + Si are uniformly formed on the boundaries of the α-Al solid solution (Laha et al. 2005, pp.5429-5438). Coatings deposited by the Turbomeca standard have microhardness values of min.70$HV_{0.3}$ and tensile bond strength of min. 25 MPa. For all coatings, the allowed share of micro pores in the microstructure is max.8% and that of unfused particles is up to 15% of a particle size below 60µm (Turbojet engine-standard practices Manuel, Turbomeca).

The aim of the research was to apply the plasma spray system of the Plasmadyne company in repair of the Astazou III B engine and to optimize the powder deposition parameters, in order to produce coatings that will fulfill all the criteria prescribed in the standard of the engine manufacturer. The optimization of the parameters for a MINI - GUN II plasma gun was performed on fixed samples in a special tool. A large number of samples was made to obtain the microstructures and mechanical properties of coatings that will fulfill all the criteria prescribed by the Turbomeca standard. This paper presents the optimum parameters with which coatings are deposited on turbine casing, casing frame, duct and oil tank as well as the mechanical and structural characteristics of the coatings tested on the Astazou III B turbojet engine on the test stand. The performed tests have confirmed the quality of the coatings thus allowing the application of plasma spray technology in the Astazou III B engine overhaul.

Materials and experimental details

For testing and applying coatings on the parts of the Astazou III B turbo-jet engine, four types of Sulzer Metco powders were used: Metco 450NS, Metco 443NS, Amdry 963 and Metco 52C-NS. Metco 450NS powder (Ni/5Al) based on Ni is intended to protect the turbine casing from the influence of high temperature, hot corrosion and erosion. The powder Ni/5Al particles coated with the Ni content of 95.5% and the Al content of 4.5% had a distribution of the granulate of 45-88 µm (Metco 450NS Nickel/Aluminum Composite Powder, 2000, Technical Bulletin 10-136, Sulzer Metco). For the protection of the turbine casing frame from the impact of sand at lower temperatures, Metco 443NS powder (Ni19Cr/6Al) containing 19% Cr and 6% Al was applied. The powder had a grain range of 45-120 µm (Metco 443NS Nickel-Chromium/Aluminum Composite Powder, 2000, Technical Bulletin 10-130, Sulzer Metco). To produce a coating resistant to high temperature oxidation and hot corrosion up to 1200 °C, applied to the duct, Ni22Cr10Al1Y powder alloy with a range of granulation of powder particles of 53-106 µm was used (Material Product Data Sheet, 2013, Nickel Chromium Aluminum Yttrium (NiCrAlY) Thermal Spray Powders

Amdry 963, DSMTS-0102.1, Sulzer Metco). To restore the size of the opening in the Astazou III B engine oil tank, Metco 52C-NS powder was applied, which is aluminum alloy with 12% Si. The granulation of the powder particles was from 45-90 μm (Material Product Data Sheet, 2011, Aluminum 12% Silicon Thermal Spray Powders Metco 52C-NS, DSMTS – 0045.2,Sulzer Metco).

The investigation of the structural and mechanical characteristics of the coatings was done in accordance with the Turbomeca standard (Turbojet engine-standard practices manuel, TURBOMECA). The substrate material of the samples where Ni5Al, Ni19Cr6Al and Ni22Cr10Al1Y coating layers were deposited was stainless steel X15Cr13 (EN 1.4024) in the thermally unprocessed condition. The substrates of the samples where Al12Si coatings were deposited were made of AMS4117 aluminum alloy (AlMg1 EN5005). For microhardness testing and evaluation of the microstructure of the deposited state, 70x20x1.5 mm samples were made. The bases for examining tensile bond strength were Ø25x50mm. The investigation of the microhardness of coatings was done using the $HV_{0.3}$ method. In order to assess the homogeneity of the coating layers, the microhardness measurement was carried out in a direction along the lamellae. Five readings of microhardness values were performed, in the middle and at the ends of the samples, out of which the two extreme values were rejected. The minimum and maximum values of the three remaining values are presented. Tensile bond strength was examined using the tensile test. The tests were performed at room temperature at a tensile speed of 10 mm / min on the hydraulic equipment. Every part of the Astazou III B engine was tested by five specimens. The engine parts samples were rotated at the same rotational speed to ensure the same conditions of coating deposition. The obtained results were averaged and the paper presents the average tensile bond strength values.

The microstructure of the deposited coating layers was examined on an optical microscope - OM. The analysis of the micro pores share in the coating was performed by treating 5 photos at 200X magnification. Through tracing paper, micro pores were labeled and shaded, with a total area of micropores calculated for the total surface of micrographs. The paper presents the mean values of the micropores share in the coatings. Table 1 shows the parts of the Astazou III B turbojet engine, the types of materials used for its parts and the operating conditions for the oparating parts on which coatings were deposited. All Astazou III B engine parts are made of special purpose aircraft materials. The oil tank is made of AG5 - EN AW-5083 aluminum alloy, the casing frame and the turbine casing of 15CDV6 - EN 1.7734 stainless steel, and the duct of AFNOR Z3NCT25 - ASTM A638 nickel alloy.

Table 1 – Parts of the ASTAZOU III B turbo-jet engine
Таблица 1 – Детали турбореактивного двигателя ASTAZOU III B
Tabela 1 – Delovi turbo-mlaznog motora ASTAZOU III B

No.	Part name	Material	Operating conditions
1.	Turbine casing	15CDV6	Temperature t=500-700°C erosion and hot corrosion
2.	Casing frame	15CDV6	Air =200°C, sand particles
3.	Duct	Z3NCT25	High temperature t_{max} =1200°C, hot corrosion
4.	Oil tank	AG5	Synthetic oil t =80-120°C, wear

Turbomeca, engine manufacturer, prescribed that on the Astazou III B engine parts powders are to be deposited with Metco 3M and 7M equipment for the prescribed parameters of powder deposition and the standards on the quality of deposited coatings. Powder deposition parameters were optimised for an atmospheric plasma spray system of the Plasmadayne company that uses a specially designed plasma spray gun MINI - GUN II with the dimensions of Ø25 X 600 mm. A large number of samples were used and the paper shows the optimal parameters with which coatings were deposited on the Astazou III B turbojet engine parts tested on the test stand.

Powder was deposited on the samples and the parts under the same conditions in specially designed and manufactured tools. Coatings were deposited on the preheated rough samples and engine parts at a temperature of 90-120 °C. The MINI - GUN II plasma gun consisted of: anode A 2084-F45, cathode K 1083-129 and gas injector GI 2084 B – 103. The coating deposition was performed with the power supply of 40KW. All coatings were deposited with a plasma gas mixture of Ar-He. The layer thickness of NiAl, NiCrAl and NiCrAlY coatings with a single plasma gun pass was 25µm. The thickness of the Al12Si alloy layer with a single pass of the plasma gun was 30 um.

Figure 1 shows the APS - atmospheric plasma spray system of the Plasmadyne company used to produce coatings. The figure shows the process of powder deposition with a MINI GUN II plasma gun on the Astazou III B turbine engine in a cabin protecting from ionic radiation and noise. The deposition process is performed with a RISE robot.

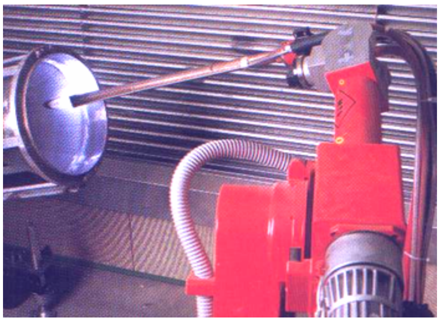

Figure 1 – Deposition of powder on the turbine casing of the ASTAZOU III B turbo-jet engine
Рис. 1 – Нанесение порошка на корпус турбореактивного двигателя Нанесение порошка на корпусе турбины в В турбореактивных Astazou III
Slika 1 – Depozicija praha na kućištu turbine turbomlaznog motora ASTAZOU III B

Table 2 shows the plasma spray parameters for depositing powders with a MINI - GUN II plasma gun. The thickness of the deposited Ni5Al coating on the turbine casing and the Ni19Cr6Al coating on the casing frame was from 0.55 to 0.6 mm. The coating thickness was increased by 0.3 mm for extra machining. The Ni22Cr10Al1Y coating thickness on the edges of the duct ranged from 1.2 - 1.5 mm. It was increased by 0.3 mm for coating machining. At the opening of the oil tank, the Al12Si coating was deposited with a thickness from 0.54 to 0.6 mm with additional thickness for machining.

The investigation of the effect of the deposited coatings on the parts of the ASTAZUO III B turbojet engine was done at the test stand with the engine operation time of 42 hours. The wear of the coatings was determined on the basis of the change in the dimensions of machined surfaces after testing the engine parts. The change in dimensions was measured on a coordinate measuring machine MAUSER ML 28 at eight measuring points around the perimeter of cylindrical parts. This paper presents the mean values of coating wear in mm, compared with the values of allowed tolerances of machined parts.

Table 2 – Plasma spray parameters
Таблица 2 – Параметры плазменнного напылителя
Tabela 2 – Plazma sprej parametri

Parameters	Ni5Al	Ni19Cr6Al	Ni22Cr10Al1Y	Al12Si
Electric Current, (A)	800	800	750	800
Arc voltage, (V)	38	37	40	36
Primary plasma gas, Ar (l/min)	75	75	50	75
Secondary plasma gas, He (l/min)	12	17	37	12

Parameters	Ni5Al	Ni19Cr6Al	Ni22Cr10Al1Y	Al12Si
Carrier gas powder, Ar (l/min)	7	12	10	7
Rotation of the disc for powder, (o/min)	3.2	2.5	2.5	2.3
Distance of plasma guns, (mm)	60	60	65	60
Circumferential speed of the parts, (mm/s)	500	500	500	340
Plasma gun speed, (mm/s)	3	3	3	3

Results and discussion

Figure 2 shows the turbine casing of the Astazou III B turbojet engine and the microstructure of the deposited Ni5Al coating. Red lines on the casing mark the inner surface protected by the plasma spray Ni5Al coating from hot corrosion and erosion caused by particles carried by gas. The microstructure of the Ni5Al coating is lamellar. The light blue lamellae of the coating consist of the α solid solution of aluminum in nickel α-Ni (Al). At the inter-lamellar boundaries of the α solid solution, there are evenly distributed nickel oxide NiO and aluminum γ-Al_2O_3 marked with red arrows (Knotek, et al.,1980, pp.282-286), (Mrdak, 2013, pp.7-22), (Svantesson, Wigren, 1992, pp.65-69). Between the lamellae boundaries of the solid solution and oxide lamellae, there are irregularly shaped dark blue inter-lamellar pores. There are also spherical precipitates of a size of 18 to 25μm, which are always smaller than the granulation of deposited powders. The precipitates did not affect the mechanical properties of the coating. The layers of the deposited Ni5Al coating had the microhardness values of 155 - 179$HV_{0.3}$. The mean value of the tensile bond strength of the coating was 72MPa. The mechanism of destruction was that of adhesion on the substrate / coating boundary. The values of the microhardness and tensile bond strength of Ni5Al coating are above the minimum values prescribed by the Turbomeca standard (min.140 $HV_{0.3}$ and min.35 MPa) (Turbojet engine-standard practices manuel, TURBOMECA). The analysis of photomicrographs of Ni5Al coatings showed that the proportion of pores was 2.5%. The content of pores was significantly lower than the value set by the engine manufacturer Turbomeca (max.8%pores). In the microstructure, there were no unfused powder particles of 45-60 μm, whose presence is allowed in a content of up to 15% by the Turbomeca standard (Turbojet engine-standard practices manuel, TURBOMECA).

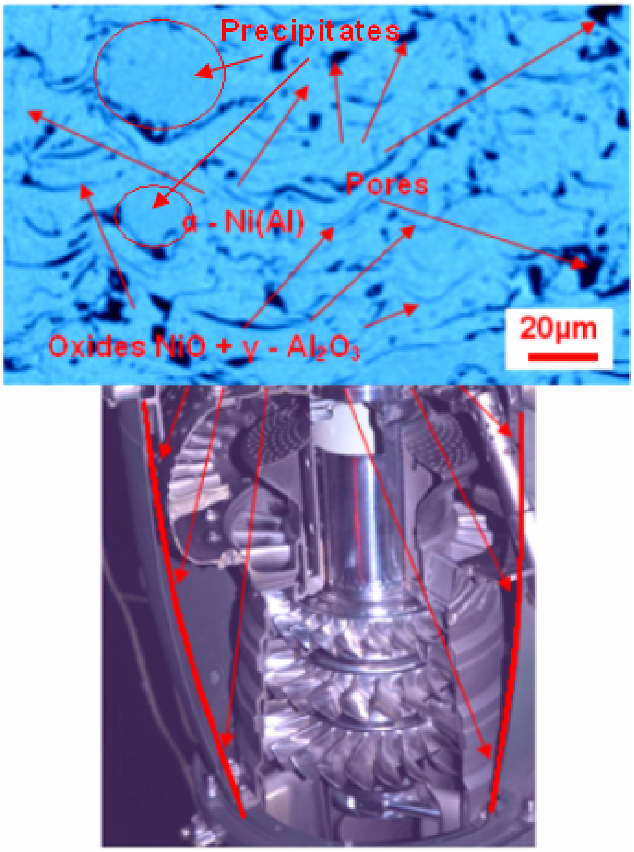

Figure 2 – Turbine casing of the ASTAZOU III B turbojet engine and the microstructure of the Ni5Al coating
Рис. 2 – Корпус турбины турбореактивного двигателя ASTAZOU III B и микроструктура покрытия Ni5Al
Slika 2 – Kućište turbine turbomlaznog motora ASTAZOU III B i mikrostruktura prevlake Ni5Al

Figure 3 shows the casing frame of the Astazou III B engine and the microstructure of the deposited Ni19Cr6Al coating. The inner surface of the casing frame marked with red lines has the deposited Ni19Cr6Al coating which protects the surface from abrasion of sand particles up to 200°C. Coating layers are deposited uniformly on the inner surface, with the coating mechanical properties and its microstructure showing the quality better than that prescribed by the Turbomeca standard. The values of microhardness and tensile bond strength in the Turbomeca standard are min.170$HV_{0.3}$ and 35MPa (Turbojet engine - standard practices manuel, TURBOMECA).

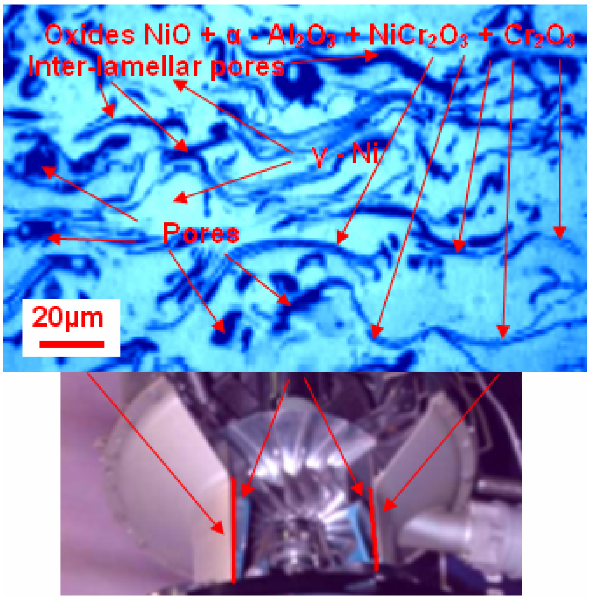

Figure 3 – Casing frame of the ASTAZOU III B turbojet engine and the microstructure of the Ni19Cr6Al coating
Рис. 3 – Входная кромка корпуса турбореактивного двигателя ASTAZOU III B и микроструктура покрытия Ni19Cr6Al
Slika 3 – Međukućište turbomlaznog motora ASTAZOU III B i mikrostruktura prevlake Ni19Cr6Al

The microhardness values of the coating were in the range of 278-315 $HV_{0.3}$. The distribution of microhardness was directly related to the distribution of oxides and pores in the coating layers. The mean value of tensile bond strength of the coating was 52MPa. The character of destruction was adhesion. The structure of the coating layers is lamellar. The coating base consists of light blue lamellae of the solid solution of chromium and aluminum in nickel γ-Ni. At solid solution lamellae boundaries, there are the lamellae of oxides NiO, α-Al_2O_3, $NiCr_2O_3$ and a small amount of Cr_2O_3 marked with red arrows (Brossard, et al., 2009, pp.1-9), (Mrdak, 2012, pp.5-16), (Mrdak, 2012, pp.182-201). Between the boundaries of solid solution lamellae and oxide lamellae there are inter lamellar pores in dark blue. The analysis of photomicrographs showed that the Ni19Cr6Al coating layers had a share of micro pores of 3.5%. The analysis of the coating microstructure showed that the coating microstructure did not contain unfused powder particles whose presence is permitted by the Turbomeca standard in the amount up to 15% and of size under 60 μm (Turbojet engine-standard practices manuel, TURBOMECA). Figure 4 shows the duct of the Astazou III B turbojet engine and the microstructure of the deposited Ni22Cr10Al1Y coating.

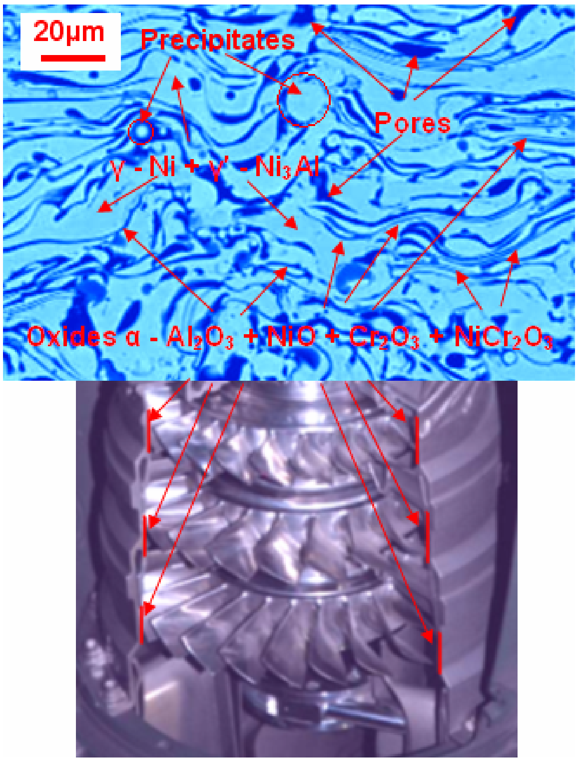

Figure 4 – Duct of the ASTAZOU III B turbojet engine and the microstructure of the Ni22Cr10Al1Y coating
Рис. 4 – Промежуточный контур турбореактивного двигателя ASTAZOU III B и микроструктура покрытия Ni22Cr10Al1Y
Slika 4 – Sprovodni aparat turbomlaznog motora ASTAZOU III B i mikrostruktura prevlake Ni22Cr10Al1Y

The red lines mark the surfaces of the duct ridges where Ni22Cr10Al1Y coating layers were deposited, protecting the surface from high temperature oxidation and hot corrosion up to 1200°C. The microstructure of the deposited Ni22Cr10Al1Y coating is lamellar. The coating base consists of light blue lamellae of the γ-Ni and γ'-Ni_3Al solid solution. The internal structure of the coating is a heterogeneous mixture of the metal basis (γ-Ni + γ'-Ni_3Al) with precipitates, micropores and NiO, α-Al_2O_3, Cr_2O_3 and $NiCr_2O_3$ oxides (Badrour, et al., 1986, p.1217) (Leea, 2005, pp.239-242). At the interlamelar boundaries of the γ-Ni solid solution, there are oxides distributed, in darker shades of blue than the coating base. Dark blue, irregularly shaped pores are present between the boundaries of solid solution lamellae and oxide lamellae. Fine spherical precipitates of the size of 5 to 10µm are present in the microstructure. The microhardness values of the deposited layers were in a range of 297 - 328HV$_{0.3}$. The mean value of the coating tensile bond strength was 49MPa. The mechanism of destruction was adhesion on the substrate / coating boundary. The values of microhardness and tensile bond strength of the Ni22Cr10Al1Y coating are above the minimum value prescribed by the Turbomeca standard (min.200 HV$_{0.3}$ and Min.35 MPa) (Turbojet engine-standard practices manuel, TURBOMECA). The analysis of the micrographs of the Ni22Cr10Al1Y coating showed that the pore share was about 3%. The content of micro pores was lower than the value set by the engine manufacturer Turbomeca (max.8% pores). Unfused powder particles up to 60μm, whose presence is allowed in the content up to 15% by the Turbomeca standard (Turbojet engine-standard practices manuel, TURBOMECA), were not found in the microstructure. Figure 5 shows the oil tank of the Astazou III B turbojet engine and the microstructure of the deposited Al12Si coating. The hole in the oil tank is marked with a red circle, the inner surface of which is protected by the plasma sprayed Al12Si coating against the effects of synthetic oils and wear.

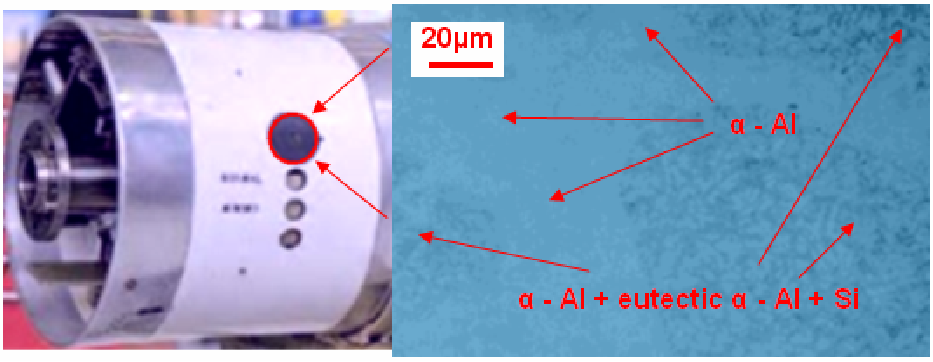

Figure 5 – Oil tank of the ASTAZOU III B turbojet engine and the microstructure of the Al12Si coating
Рис. 5 – Масляный резервуар турбореактивного двигателя ASTAZOU III B и микроструктура покрытия Al12Si
Slika 5 – Rezervoar za ulje turbomlaznog motora ASTAZOU III B i mikrostruktura prevlake Al12Si

The microstructure of the Al12Si coating consists of two phases, the α-Al solid solution and the α-Al + Si eutectic mixture. At the boundaries of the α-Al solid solution, dendritic solidification resulted in α-Al + Si eutectic grains (Laha et al. 2005, pp.5429-5438), (Pramila Bai, Biswas, 1987, p.61). The content of pores in the coating was negligible, which is why the coating microhardness value was at the upper limit of 130 HV$_{0.3}$. The mean value of tensile bond strength of 27MPa was in accordance with the coating microstructure. The mechanism of destruction was adhesion at the substrate / coating boundary. The values of microhardness and tensile bond strength of the Ni12Si coating are above the minimum value prescribed by the Turbomeca standard (min.70$HV_{0.3}$ and min.25 MPa) (Turbojet engine-standard practices Manuel, Turbomeca). In the microstructure there are no unfused powder particles, although the Turbomeca standard allows their presence up to 15%, with a size below 60µm (Turbojet engine-standard practices Manuel, Turbomeca).

After the tests at the test station, the wear of the coatings was significantly lower than the allowable tolerance for engine parts. The Ni5Al coating wear on the turbine casing of 0.002 mm is significantly lower than the allowable tolerance of 0.3 mm. The Ni19Cr6Al coating wear on the casing frame was 0.0025 mm, while the allowed dimension tolerance for the casing frame is 0.3 mm. The Ni22Cr10Al1Y coating wear on the duct ridges was 0.001 mm, while the tolerance for the Ni22Cr10Al1Y coating on the duct ridges is 0.05 mm. At the opening of the oil tank, there were no changes in the size of the Al12Si coating, which is understandable because the coating is subjected to wear during opening and closing of the the tank when changing oil. The wear of the coatings on all tested parts was low. Based on the test results, plasma spray coatings have been successfully applied in the process of the general repair of the Astazou III B turbojet engine.

Conclusion

The research into the characteristics of coatings deposited on the Astazou III B turbojet engine parts by the atmospheric plasma spray system of the Plasmadyne company, with a MINI GUN II plasma gun, showed that they fully meet the criteria established by the engine manufacturer Turbomeca for coatings deposited by the Metco 3M and 7M plasma spray systems. The analysis of the structural and mechanical characteristics of the coatings in the laboratory and the testing of the components within the Astazou III B engine on the test station for a period of 42 hours showed that:

The deposited coating layers had good microhardness, tensile bond strength and microstructure values that meet the criteria prescribed by the Turbomeca standard. All coatings had the microhardness and tensile bond strength values above those prescribed by the Turbomeca standard. The microstructure of the deposited coatings does not show the presence of unfused powder particles up to 60 µm, which is allowed by the Turbomeca standard up to 15%.

During coating testing on the engine parts at the test station, all coatings showed good adhesion and cohesive strength of layers. After dismantling the engine, delamination of coatings, coating peeling through layers and separation of layers from the surface of the engine parts were not found. On the surface of the coatings there are no networks of micro cracks. The coating surfaces on the casing, the casing frame and the oil tank opening showed no traces of burrs. On the duct ridges there are no traces from blade galling.

The average value of wear of the Ni5Al coating on the turbine casing was 0.002 mm. On the casing frame, the average value of wear of the Ni19Cr6Al coating was 0.0025 mm. On the duct ridges, the average value of wear of the Ni22Cr10Al1Y coating was 0.001 mm. At the opening of the oil tank, there were no changes in the size of the Al12Si coating. For the Astazou III B engine parts, coating wear was much lower than the allowable tolerances for machining.

The wear of the coatings on all tested parts was low. Based on the test results, plasma spray coatings have been successfully applied in the process of the general repair of the Astazou III B turbojet engine.

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ИССЛЕДОВАНИЕ ПО ПРИМЕНЕНИЮ ПЛАЗМЕННОГО НАПЫЛЕНИЯ ПОКРЫТИЯ ДЕТАЛЕЙ ТУРБОРЕАКТИВНОГО ДВИГАТЕЛЯ ASTAZOU III B

Михаило Р. Мрдак
Центр исследований и разработок АО „ИМТЕЛ Коммуникации“, г.Белград, Республика Сербия

ОБЛАСТЬ: химические технологии
ВИД СТАТЬИ: оригинальная научная статья
ЯЗЫК СТАТЬИ: английский

Резюме:

Плазменное напыление широко применяется в области авиационной промышленности и производстве ключевых деталей, подверженных воздействию высоких температур, химически агрессивных средств, износу, повреждениям, эрозии и кавитации.

Процесс плазменного напыления включает широкое поле параметров, таким образом его возможно применять к каждому слою, в том числе и защитному слою покрытия. В процессе ремонта самолета плазменное покрытие наносится равномерно, тем самым выравнивая части поврежденных покрытий до необходимой толщины.

В данном исследовании представлен эффективный метод применения плазменного напыления покрытий частей турбореактивных двигателей ASTAZOU III B в процессе ремонта.

Производитель двигателей TURBOMECA рекомендует для покрытия своей продукции порошковые плазменные напылители системы Metco 3M или 7M, предписывая параметры нанесения покрытия, таким образом при применении иных плазменных напылительных систем необходимо провести тестирования и испытания.

Цель данной работы состоит в разработке и производстве плазменного напылителя от компании Plasmadyne, которое будет соответствовать всем стандартам и удовлетворять требования производителя двигателей, с целью его применения в ремонте двигателей.

Проведена оптимизация параметров для плазменных пистолетов MINI – GUN II, в процессе которой было тестировано большое количество образцов. В работе представлены соответствующие параметры нанесения покрытия на корпус, входную кромку корпуса, промежуточный контур и масляный резервоар турбореактивного двигателя ASTAZOU III B. Тестирование механических характеристик покрытия проводилось испытанием микротвердости покрытия, методом $HV_{0.3}$.

Прочность соединения покрытия тестирована по методу испытаний на сдвиг при растяжении. Микроструктура слоев покрытия наблюдалась под оптическим микроскопом − ОМ. Анализ микроструктуры и механических характеристик покрытия был проведен в соответствии со стандартами и рекомендациями TURBOMECA.

Качество нанесенного покрытия подтверждено 42-х часовым испытанием частей двигателя ASTAZUO III B, проведенного в испытательной станции. Выполненные испытания подтвердили качество покрытия, таким образом доказано, что технологию плазменного напыление покрытий можно применять в процессе ремонта двигателей ASTAZOU III B.

Ключевые слова: *плазменное покрытие; ремонт; плазменное напыление; двигатели; депозиты; покрытие.*

STUDIJA PRIMENE PLAZMA NAPRSKANIH PREVLAKA NA SEKCIJAMA TURBOMLAZNOG MOTORA „ASTAZOU III B”

Mihailo R. Mrdak
Istraživački i razvojni centar IMTEL Komunikacije a.d., Beograd

OBLAST: hemijske tehnologije
VRSTA ČLANKA: originalni naučni članak
JEZIK ČLANKA: engleski

Sažetak:

Plazma-sprej proces intenzivno koriste avio-industrije u proizvodnji ključnih komponenti prekomerno izloženih visokim temperaturama, hemijski agresivnim sredinama, habanju, abraziji, eroziji i kavitaciji. Proces

pokriva veliko polje parametara, tako da se može kombinovati skoro svaki sloj sa svakim i sa osnovnim materijalom. Prevlake mogu da se deponuju ravnomerno i stoga omogućavaju da se pohabane komponente dovedu na konačne dimenzije u procesu remonta vazduhoplova. U ovom istraživanju prikazan je efikasan postupak primene plazma-sprej prevlaka na delovima turbomlaznog motora ASTAZOU III B u procesu remonta. Proizvođač motora TURBOMECA predvideo je da se prahovi deponuju plazma-sprej sistemima sa oznakom Metco 3M ili 7M za koje je propisao parametre depozicije prahova, tako da se kod primene drugih plazma-sprej sistema parametri deponovanja moraju ispitati i optimizirati. Cilj rada bio je da se u remontu motora primeni plazma-sprej sistem firme Plasmadyne i izvrši optimizacija parametara, koja će omogućiti da se proizvedu prevlake koje će ispuniti sve kriterijume propisane standardom proizvođača motora. Izvršena je optimizacija parametara za plazma pištolj MINI – GUN II, pri čemu je urađen veliki broj uzoraka. U radu su prikazani optimalni parametri depozicije sa kojima su deponovane prevlake na kućištu, međukućištu, sprovodnom aparatu i rezervoaru za ulje motora ASTAZOU III B. Procena mehaničkih karakteristika prevlaka urađena je ispitivanjem mikrotvrdoće prevlaka metodom $HV_{0.3}$. Zatezne čvrstoće spoja prevlaka ispitane su metodom kidanja na zatezanje. Mikrostrukture slojeva prevlaka procenjene su na optičkom mikroskopu – OM. Analiza mikrostruktura i mehaničkih karakteristika prevlaka urađena je u skladu sa standardom TURBOMECA. Kvalitet deponovanih prevlaka potvrđen je 42-časovnim ispitivanjem delova u sklopu motora ASTAZUO III B na ispitnoj stanici. Izvršena ispitivanja potvrdila su kvalitet prevlaka i na taj način omogućila primenu plazma-sprej tehnologije u proces remonta motora ASTAZOU III B.

Uvod

Razvoj turbomlaznih motora i zahtevi za povećanu otpotnost na oksidaciju, vrelu koroziju i sulfidizaciju delova motora uticali su na razvoj termo-sprej procesa i prahova na bazi nikla. Danas se za zaštitu delova turbomlaznih motora najčešće primenjuju plazma-sprej prevlake NiAl, NiCr, NiCrAl, NiCrAlY, CoCrAlY, NiCoCrAlY i dr. Najefikasniju zaštitu substratima od oksidacije na temperaturama iznad 800°C pružaju prevlake koje formiraju okside tipa α-Al_2O_3 i Cr_2O_3. U većini slučajeva, primenjuju se prevlake koje formiraju kontinualni sloj α-Al_2O_3, jer je ovaj tip oksida superiorniji i pouzdaniji u odnosu na druge tipove oksida (Mrdak, 2012, pp.182-201). Kada je u prevlaci nizak sadržaj hroma i aluminijuma, na površini prevlake ne mogu se formirati zaštitni kontinualni slojevi oksida tipa α-Al_2O_3 i Cr_2O_3, već se formiraju nepoželjni slojevi kontinualnih oksida NiO. Mehanizam rasta oksida NiO uzrokuje nastanak mikropora u međusloju oksid/legura. Mikropore rastu i spajaju se u velike makropore. Mehanizam rasta oksida NiO stvara velika naprezanja, koja na kraju postaju dovoljno velika da prave prskotine u oksidnom sloju. Da bi se nagradili kontinualni slojevi oksida α-Al_2O_3 i Cr_2O_3 na površini prevlake, za legure nikla potrebno je naj-

mnje 20%Cr i 5%Al. Legurama NiCrAl dodaje se i itrijum radi bolje kohezione čvrstoće oksida i adhezione čvrstoće prevlake sa supstratom. Zavisno od tipa legure, sadržaj itrijuma se kreće od 0,1 do 0,5% (Mrdak, 2012, pp.182-201). Iskustvo firme Turbomeka koja u proizvodnji motora ASTAZOU III B primenjuje plazma-sprej prevlake otporne na oksidaciju i vrelu koroziju, kao i prevlake za opravku delova od legure Al, omogućilo je da se pristupi primeni plazma-sprej tehnologije u postupku remonta motora. Proizvođač motora predvideo je da se prahovi deponuju plazma-sprej sistemima sa oznakom Metco 3M ili 7M za koje je propisao parametre depozicije prahova, tako da se kod primene drugih plazma-sprej sistema parametri deponovanja moraju optimizirati, da bi prevlake ispunile sve kriterijume koje propisuje standard Turbomeca. Za spasavanje i opravku delova motora od oksidacije i vrele korozije proizvođač motora ASTAZOU III B koristi prahove Ni/5Al, NiCr/6Al i Ni22Cr10Al1Y, a za obnavljanje dimenzija i opravku delova od legure aluminijuma koristi prah Al12Si. Kompozitni prah Ni/5Al zbog egzotermne reakcije u procesu depozicije omogućava dobro vezivanje prevlake za supstrat. Produkti te reakcije su međumetalna jedinjenja $NiAl_3$, Ni_2Al_3 i NiAl koja dodatno uvećavaju čvrstoću prevlake. To su guste prevlake sa metalurškom vezom na interfejsu sa osnovnim materijalom. Prevlaka se sastoji od lamela čvrstog rastvora aluminijuma u niklu α-Ni(Al) i međulamelarnih oksida NiO i γ-Al_2O_3 ravnomerno raspoređenih po granicama lamela čvrstog rastvora (Knotek, et al.,1980, pp.282-286), (Mrdak, 2015, pp.32-25), (Mrdak, 2013, pp.7-22), (Svantesson, Wigren, 1992, pp.65-69). Prevlake su otporne na oksidaciju, gasnu koroziju, habanje, abraziju i eroziju na temperaturama do 980°C. Čvrstoća spoja sa supstratom ostaje adekvatna do 700°C (Griffiths, H., et al., 1980). Deponovane prevlake po standardu Turbomeca imaju vrednosti mikrotvrdoće min. 140$HV_{0.3}$ i zatezne čvrstoće spoja min. 35MPa. Prevlake tipa NiCrAl u deponovanom stanju se sastoje od čvrstog rastvora hroma i aluminijuma u niklu γ-Ni(Cr,Al). U slojevima su prisutni oksidi tipa NiO, α-Al_2O_3, Cr_2O_3, CrO_3 i spinel faze $Ni(Cr,Al_2)O_4$ (Badrour, et al., 1986, p.1217), (Brossard, et al., 2009, pp.1-9), (Mrdak, 2010, pp.5-16), (Mrdak, 2012, pp.182-201), (Mrdak, 2013, pp.7-22), (Tran, et al., 2008, p.701). Zatezna čvrstoća spoja prevlake ostaje adekvatna do radnih temperatura od 980°C (Mrdak, 2012, pp.182-201). Deponovane prevlake po standardu Turbomeca imaju vrednosti mikrotvrdoće min. 170$HV_{0.3}$ i zatezne čvrstoće spoja min. 35MPa. Legura NiCrAlY se koristi za zaštitu delova od tople korozije i visokotemperaturne oksidacije do 1100°C (Material Product Data Sheet, 2013, Nickel Chromium Aluminum Yttrium (NiCrAlY) Thermal Spray Powders Amdry 963, DSMTS-0102.1, Sulzer Metco). Dodatak itrijuma ima suštinski značaj, jer bitno povećava adheziju oksida Al_2O_3 i Cr_2O_3 koji se formiraju u prevlaci sa osnovom prevlake i tako sprečava pucanje i odvajanje zaštitnog površinskog oksidnog sloja pri dejstvu toplotnog zamora (Mrdak, 2012, pp.182-201). Struktura unutrašnjih slojeva prevlaka sastoji se od čvrstog rastvora hroma i aluminijuma u niklu *γ-Ni(Cr,Al) i međumetalnog jedinjenja γ'-Ni_3Al. U strukturi su prisutni i oksidi NiO, α-Al_2O_3, Cr_2O_3 i $NiCr_2O_3$ (Badrour, et al., 1986, p.1217), (Leea, 2005, pp.239-242). Deponovane prevlake po standardu Turbomeca imaju vrednosti mikrotvrdoće min. 200$HV_{0.3}$ i zatezne čvrstoće spoja min. 35 MPa. Prevlaka Al12Si je opšte namene i primenjuje se za zaštitu novih vazduhoplovnih delova i u procesu remonta za obnavljanje dimenzija delovima od legura aluminijuma i magnezijuma uzrokovanih habanjem (Material Product Data Sheet, 2011, Aluminum 12% Silicon Thermal Spray Powders Metco 52C-NS, DSMTS – 0045.2,Sulzer Metco), (Pramila Bai, Biswas, 1987, p.61). U deponovanom stanju mikrostruktura prevlake sastoji se od dve faze α-Al čvrstog rastvora i α-Al + Si eutektikuma. Po granicama α-Al čvrstog rastvora ravnomerno se formiraju fina eutektička zrna α-Al + Si (Laha, et al., 2005, pp.5429–5438). Deponovane prevlake po standardu Turbomeca imaju vrednosti mikrotvrdoće min. 70$HV_{0.3}$ i zatezne čvrstoće spoja min. 25 MPa. Za sve prevlake, u mikrostrukturi dozvoljen je udeo mikropora maks. 8% i nestopljenih čestica do 15% veličine ispod 60μm (Turbojet engine-standard practices manuel, TURBOMECA).*

Cilj rada bio je da se u remontu motora ASTAZOU III B primeni plazma- sprej sistem firme Plasmadyne i izvrši optimizacija parametara depozicije praha, koja će omogućiti da se proizvedu prevlake koje će ispuniti sve kriterijume propisane standardom proizvođača motora. Izvršena je optimizacija parametara za plazma pištolj MINI-GUN II na fiksnim uzorcima u posebnom alatu. Urađen je veliki broj uzoraka da bi se dobile mikrostrukture i mehaničke osobine prevlaka koje će ispuniti sve kriterijume propisane standardom proizvođača motora Turbomeca. U radu su prikazani optimalni parametri sa kojima su deponovane prevlake na kućištu turbine, međukućištu, sprovodnom aparatu i rezervoaru za ulje i mehaničko-strukturne karakteristike prevlaka, koje su ispitane u sklopu turbomlaznog motora ASTAZOU III B na ispitnoj stanici. Izvršena ispitivanja potvrdila su kvalitet prevlaka i na taj način omogućila primenu plazma-sprej tehnologije u procesu remonta motora ASTAZOU III B.

Materijali i eksperimentalni detalji

Za ispitivanje i primenu prevlaka na delovima turbomlaznog motora ASTAZOU III B upotrebljena su četiri tipa praha firme Sulzer Metco sa oznakama: Metco 450NS, Metco 443NS, Amdry 963 i Metco 52C-NS. Prah Metco 450NS (Ni/5Al) na bazi Ni namenjen je za zaštitu kućišta turbine od uticaja visoke temperature, tople korozije i erozije. Čestice obloženog praha Ni/5Al sa sadržajem 95,5% Ni i 4,5%Al imale su raspodelu granulata od 45 do 88 μm. Za zaštitu međukućišta turbine od uticaja peska na nižim temperaturama primenjen je prah Metco 443NS(Ni19Cr/6Al) koji sadrži 19%Cr i 6%Al. Prah je imao raspon granulacije od 45 do 120 μm. Za izradu prevlake otporne na visokotemperaturnu oksidaciju i vrelu koroziju do 1200°C, koja se primenila na sprovodnom aparatu, koristio se prah legure Ni22Cr10Al1Y sa rasponom granulacije čestica praha od 53 do 106 μm. Za obnavljanje dimenzija otvora na rezervoaru za ulje motora ASTAZOU III B primenjen je prah Metco 52C-NS, koji je legura aluminijuma sa 12%Si. Raspon granulacije čestica praha koji se koristio bio je od 45 od 90 μm. Ispitivanje strukturnih i mehaničkih karakteristika prevlaka rađeno je prema standardu TURBOMECA (Turbojet engine-standard practices manuel, TURBOMECA). Materijal substrata uzoraka na kojem su deponovani slojevi prevlaka Ni5Al, Ni19Cr6Al i Ni22Cr10Al1Y bio je od nerđajućeg čelika X15Cr13 (EN 1.4024) u termički neobrađenom stanju. Osnove uzoraka na kojima su deponovane prevlake Al12Si napravljene su od legure aluminijuma AMS4117 (AlMg1 EN5005). Za ispitivanje mikrotvrdoće i za procenu mikrostrukture u deponovanom stanju napravljeni su uzorci dimenzija 70x20x1,5 mm. Osnove za ispitivanje zatezne čvrstoće spoja bili su dimenzija Ø25x50 mm. Ispitivanje mikrotvrdoće prevlaka rađeno je metodom $HV_{0.3}$. Da bi se procenila homogenost slojeva prevlaka, merenje mikrotvrdoće izvršeno je u pravcu duž lamela. Obavljeno je pet očitavanja vrednosti mikrotvrdoće slojeva u sredini i na krajevima uzoraka, od kojih su odbačene dve krajnje vrednosti. Od tri preostale vrednosti prikazane su minimalne i maksimalne vrednosti. Ispitivanje zatezne čvrstoće spoja rađeno je metodom ispitivanja na zatezanje. Testovi su rađeni na sobnoj temperaturi na hidrauličnoj opremi sa brzinom zatezanja od 10 mm/min. Uz svaki deo motora ASTAZOU III B rađeno je po pet epruveta. Uzorci su sa delovima motora zajedno rotirani istom obimnom brzinom kako bi bili isti uslovi deponovanja prevlaka. Dobijeni rezultati su usrednjeni i u radu su prikazane srednje vrednosti zatezne čvrstoće spoja. Mikrostruktura slojeva deponovanih prevlaka ispitana je na optičkom mikroskopu – OM. Analiza udela mikropora u prevlaci urađena je obradom 5 fotografija na uveličanju 200X. Preko paus-papira mikropore su označene i osenčene, čija se ukupna površina računala na ukupnu površinu mikrofotografije. U radu su prikazane srednje vrednosti udela mikropora u prevlakama. Svi delovi motora ASTAZOU III B napravljeni su od namenskih vazduhoplovnih materijala. Rezervoar za ulje izrađen je od legure aluminijum AG5-EN AW-5083, međukućište i kućište turbine od nerđajućeg čelika 15CDV6-1.7734 EN, a sprovodni aparat od legure nikla AFNOR Z3NCT25 - ASTM A638. Proizvođač motora TURBOMECA predvideo je da se na delovima motora ASTAZOU III B deponuju prahovi sa opremom Metco 3M ili 7M za koje je propisao parametre depozicije prahova i standarde o prihvatljivosti kvaliteta deponovanih prevlaka. Za atmosferski plazma-sprej sistem firme Plasmadayne koji koristi specijalno projektovani plazma-sprej pištolj MINI-GUN II dimenzija Ø25 X 600 mm, izvršena je optimizacija parametara depozicije praha. Urađen je veliki broj ispitnih uzoraka, a u radu su prikazani optimalni parametri sa kojima su deponovane prevlake na delovima koji su ispitani u sklopu turbomlaznog motora ASTAZOU III B na ispitnoj stanici. U posebno projektovanim i napravljenim alatima, pod istim uslovima urađena je depozicija praha na uzorcima i delovima. Prevlake su deponovane na ohrapavljene i predgrejane uzorke i delove motora na temperaturi od 90 do 120°C.

Plazma pištolj MINI- GUN II sastojao se od : anode A 2084 – F45, katode K 1083A – 129 i gas injektora GI 2084 B – 103. Depozicija svih prevlaka urađena je sa snagom napajanja od 40 KW. Sve prevlake su deponovane sa mešavinom plazma gasovima Ar-He. Debljine slojeva NiAl, NiCrAl i NiCrAlY prevlaka sa jednim prolazom plazma pištolja bila je 25 µm, a debljina sloja Al12Si legure sa jednim prolazom plazma pištolja 30 µm. Ispitivanje efekta deponovanih prevlaka na delovim turbomlaznog motora ASTAZUO III B rađeno je na ispitnoj stanici sa vremenom rada motora od 42 časa. Pohabanost prevlaka određena je na osnovu promene dimenzija mašinski obrađenih površina posle ispitivanja delova u sklopu motora. Merenje promena dimenzija rađeno je na koordinatnoj mernoj mašini MAUSER ML 28 na osam mernih mesta po obodu cilindričnih delova. U radu je prikazana srednja vrednost pohabanosti prevlaka, izražena u mm, koja je upoređena sa vrednostima dozvoljenih tolerancija mašinski obrađenih delova.

Rezultati i diskusija

Na kućištu je crvenim linijama označena unutrašnja površina koja je zaštićena plazma-sprej prevlakom Ni5Al od tople korozije i erozije čestica koje gas nosi sa sobom. Mikrostruktura prevlake Ni5Al je lamelarna. Svetloplave lamele prevlake sastoje se od α čvrstog rastvora aluminijuma u niklu α-Ni(Al). Na među-granicama lamela α čvrstog rastvora ravnomerno su distribuirani oksidi nikla NiO i aluminijuma γ-Al_2O_3,, označeni crvenim strelicama. Između granica lamela čvrstog rastvora i oksidnih lamela prisutne su međulamelarne pore nepravilnog oblika tamnoplave boje. U mikrostrukturi su prisutni precipitati sfernog oblika, veličine od 18 do 25 µm, koji su uvek manji od granulacije praha koji se deponuje. Prisutni precipitati nisu uticali na mehaničke karakteristike prevlake. Slojevi deponovane prevlake Ni5Al imali su vrednosti mikrotvrdoće od 155 do 179 $HV_{0.3}$. Srednja vrednost zatezne čvrstoće spoja prevlake bila je 72 MPa. Vrednosti mikrotvrdoće i zatezne čvrstoće spoja Ni5Al prevlake iznad su minimalnih vrednosti koje propisuje standard TURBOMECA (min.140 $HV_{0.3}$ i min. 35 MPa) (Turbojet engine-standard practices manuel, TURBOMECA). Analiza mikrofotografija Ni5Al prevlake pokazala je da je udeo mikropora bio 2,5%. Sadržaj mikropora bio je znatno manji od vrednosti koje propisuje proizvođač motora TURBOMECA (max. 8% pora). U mikrostrukturi nisu uočene nestopljene čestice praha od 45 do 60 µm čije je prisustvo dozvoljeno u sadržaju do 15% po standardu TURBOMECA (Turbojet engine-standard practices manuel, TURBOMECA).

Na međukućištu je unutrašnja površina označena crvenim linijama na kojoj je deponovana prevlaka Ni19Cr6Al koja štiti površinu od abrazije čestica peska do 200°C. Slojevi prevlake deponovani su ravnomerno na unutrašnjoj površini sa mehaničkim karakteristikama i mikrostrukturom prevlake, koji po kvalitetu pokazuju bolje karakteristike od karakteristika propisanih standardom TURBOMECA. Vrednosti mikrotvrdoće i zatezne čvrstoće spoja po standard TURBOMECA su min.

170HV$_{0.3}$ i 35 MPa (Turbojet engine - standard practices manuel, TURBOMECA). Vrednosti mikrotvrdoće prevlake bile su raspona od 278 do 315 HV$_{0.3}$. Raspodela mikrotvrdoće bila je u direktnoj vezi sa raspodelom oksida i mikropora u slojevima prevlake. Srednja vrednost zatezne čvrstoće spoja prevlake bila je 52 MPa. Osnova prevlake sastoji se od svetloplavih lamela čvrstog rastvora hroma i aluminijuma u niklu γ-Ni. Po granicama lamela čvrstog rastvora prisutne su lamele oksida NiO, α-Al_2O_3, $NiCr_2O_3$, Cr_2O_3 i u manjoj količini CrO_3, označene crvenim strelicama (Brossard, et al., 2009, pp.1-9), (Mrdak, 2012, pp.5-16), (Mrdak, 2012, pp.182-201). Između granica lamela čvrstog rastvora i oksidnih lamela prisutne su i međulamelarne pore zagasito plave boje. Analiza mikrofotografija je pokazala da je u slojevima prevlake Ni19Cr6Al udeo mikropora bio 3,5%.

Crvenim linijama obeležene su površine venaca sprovodnog aparata na kojima su deponovani slojevi prevlake Ni22Cr10Al1Y, koji štite površine od visokotemperaturne oksidacije i vrele korozije do 1200°C. Mikrostruktura deponovane prevlake Ni22Cr10Al1Y je lamelarna. Osnova prevlake sastoji se od svetloplavih lamela čvrstog rastvora γ-Ni i γ'-Ni_3Al. Unutrašnja struktura prevlake je heterogena mešavina osnove metala (γ-Ni + γ'-Ni_3Al) sa precipitatima, mikroporama i oksidima NiO, α- Al_2O_3, Cr_2O_3 i $NiCr_2O_3$ (Badrour, et al., 1986, p.1217) (Leea, 2005, pp.239-242). Vrednosti mikrotvrdoće deponovanih slojeva bile su u rasponu od 297 do 328HV$_{0.3}$. Srednja vrednost zatezne čvrstoće spoja prevlake bila je 49 MPa. Vrednosti mikrotvrdoće i zatezne čvrstoće spoja prevlake Ni22Cr10Al1Y iznad su minimalnih vrednosti koje propisuje standard TURBOMECA (min. 200 HV$_{0.3}$ i min. 35 MPa) (Turbojet engine-standard practices manuel, TURBOMECA).

Otvor na rezervoaru za ulje označen je crvenim krugom, čija je unutrašnja površina zaštićena plazma-sprej prevlakom Al12Si od uticaja sintetičkog ulja i habanja. Mikrostruktura Al12Si prevlake sastoji se od dve faze, α-Al čvrstog rasatvora i α-Al + Si eutektikuma. Po granicama α-Al čvrstog rastvora dendritskim očvršćivanjem formirala su se eutektička zrna α-Al + Si (Laha, et al., 2005, pp.5429–5438) (Pramila Bai, Biswas, 1987, p.61). Sadržaj mikropora u prevlaci bio je neznatan, zbog čega je prevlaka imala vrednost mikrotvrdoće na gornjoj granici od 130 HV$_{0.3}$. Srednja vrednost zatezne čvrstoće spoja prevlake od 27MPa bila je u saglasnosti sa mikrostrukturom prevlake. Vrednosti mikrotvrdoće i zatezne čvrstoće spoja prevlake Ni12Si iznad su minimalnih vrednosti koje propisuje standard TURBOMECA (min. 70HV$_{0.3}$ i min. 25 MPa) (Turbojet engine-standard practices manuel, TURBOMECA).

Pohabanost prevlaka posle ispitivanja delova na ispitnoj stanici bila je znatno manja u odnosu na dozvoljene tolerancije za delove motora. Pohabanost Ni5Al prevlake na kućištu turbine od 0,002 mm znatno je manja od vrednosti dozvoljene tolerancije od 0,3 mm. Pohabanost Ni19Cr6Al prevlake na međukućištu bila je 0,0025 mm. Dozvoljena tolerancija dimenzija na međukućištu je 0,3 mm. Pohabanost

Ni22Cr10Al1Y prevlake na vencima sprovodnog aparata bila je 0,001 mm. Tolerancija za prevlaku Ni22Cr10Al1Y na vencima sprovodnog aparata je 0,05 mm. Na otvoru rezervoara za ulje nije došlo do promena dimenzija prevlake Al12Si, što je razumljivo, jer se prevlaka haba kod naizmeničnog otvaranja i zatvaranja rezervoara pri zameni ulja. Potrošnja prevlaka na svim delovima bila je mala. Na osnovu dobijenih rezultata ispitivanja, plazma-sprej prevlake su uspešno primenjene u postupku opšte opravke turbomlaznog motora ASTAZOU III B.

Zaključak

Istraživanja karakteristika prevlaka deponovanih na delovima turbomlaznog motora ASTAZOU III B atmosferskim plazma-sprej sistemom firme Plasmadyne, koji koristi plazma pištolj MINI-GUN II, pokazala su da u potpunosti zadovoljavaju kriterijume koje je propisao proizvođač motora TURBOMECA za prevlake deponovane plazma-sprej sistemima Metco 3M i 7M. Analizom strukturnih i mehaničkih karakteristika prevlaka u laboratorijskim uslovima i ispitivanjima delova u sklopu motora ASTAZOU III B na ispitnoj stanici u trajanju od 42 časa ustanovljeno je da su slojevi prevlaka u deponovanom stanju imali dobre mikrotvrdoće, zatezne čvrstoće spoja i mikrostrukture koje zadovoljavaju kriterijume propisane standardom TURBOMECA. Sve prevlake imale su vrednosti mikrotvrdoće i zatezne čvrstoće spoja iznad vrednosti koje propisuje standard TURBOMECA. U mikrostrukturi deponovanih prevlaka nisu prisutne nestopljene čestice praha do 60 μm, čije je prisustvo dozvoljeno u sadržaju do 15% po standardu TURBOMECA.

U toku ispitivanja prevlaka u sklopu motora na ispitnoj stanici sve prevlake su imale dobru adhezionu i kohezionu čvrstoću slojeva. Posle rasklapanja motora na njegovim delovima nije uočeno raslojavanje prevlaka, ljuštenje prevlaka kroz slojeve i odvajanje slojeva prevlaka sa površina delova. Na površinama prevlaka nisu prisutne mreže mikroprskotina. Površine prevlaka na kućištu, međukućištu i otvoru rezervoara za ulje bile su bez tragova riseva. Na vencima sprovodnog aparata nisu prisutni tragovi i brazde od struganja lopatica.

Prosečna vrednost pohabanosti prevlake Ni5Al na kućištu turbine bila je 0,002 mm. Na međukućištu prosečna vrednost pohabanosti prevlake Ni19Cr6Al bila je 0,0025 mm. Na vencima sprovodnog aparata prosečna vrednost pohabanosti prevlake Ni22Cr10Al1Y bila je 0,001 mm. Na otvoru rezervoara za ulje nije došlo do promena dimenzija prevlake Al12Si. Na delovima motora ASTAZOU III B pohabanost prevlaka bila je mnogo manja od dozvoljenih tolerancija za mašinsku obradu delova.

Potrošnja prevlaka na svim delovima bila je mala. Na osnovu dobijenih rezultata ispitivanja, plazma-sprej prevlake uspešno su primenjene u postupku opšte opravke turbomlaznog motora ASTAZOU III B.

Ključne reči: *sprej prevlaka, popravka, plazma, motori, depoziti, prevlaka.*

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