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The PS-PVD method - formation of columnar TBCs on CMSX-4 superalloy

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ABSTRACT

Purpose: The new plasma spraying method.
Design/methodology/approach: The single crystal CMSX-4 nickel alloy was used as base material. The diffusion aluminide layer was deposited during the CVD process and was used as bond-coat. The zirconium oxide stabilized by yttrium oxide was utilized as the deposition material.
Findings: It was proved, that there is a possibility of obtaining the ceramic layer using the PS-PVD process.
Research limitations/implications: The thickness analysis and the chemical composition analysis by light and scanning electron microscopy were performed.
Practical implications: This process can be used in aerospace industry to form oxidation resistant coatings.
Originality/value: In article Plasma Spraying Physical Vapour Deposition Process was described.
Keywords: Metallic alloys; Ceramic and glass; Corrosion; Technological design; Thin and Thick Coatings; Surface treatment

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1. Introduction

Application of thermal barrier coatings (TBC) is a basic way to protect the blades surface in the first stage of high pressure turbine in the aircraft engines against the influence of aggressive environment of oxidizing gases at the temperatures up to 1450°C. Continuous growth of operating temperature and more demanding requirements in terms of reduction of the pollutants emission, determine the intensive development of high temperature resistant coatings. It is focused on new methods and materials for the TBC coatings. Thermal barrier coatings, made from at least two layers, are used currently in industrial practice. The outer ceramic layer has a function of thermal insulation and protects the coated element against the effects of high temperatures. The inner layer is a metallic bond-coat. It protects the element from the influence of corrosive factors (oxidation, hot corrosion) and compensates the differences in physical characteristics of the base material and the ceramic outer layer made of yttria-stabilized zirconium oxide. Currently there are two basic methods developed in aviation technology for obtaining the thermal barrier coatings (TBC) accredited by global manufacturers of aircraft engines (Pratt and Whitney, General Electric, Rolls-Royce). The coating process is performed during the plasma spraying process under atmospheric pressure (APS) in order to protect the inner surface of the combustion chamber. This method is used for obtaining both, the metallic interlayer (multicomponent MeCrAlY alloy) and a outer ceramic layer (yttrium oxide Y_2O_3 stabilized zirconium oxide ZrO_2). Standard thermal barrier coatings are characterized by a bond-coat thickness of approx. 100 µm and by outside (ceramic) layer thickness of 250-500 µm. In APS plasma spraying method, coatings are deposited also on the stationary blade segments inside the directing elements of a high pressure turbine. Two methods of obtaining thermal barrier coatings are used for deposition on surface of the turbine blades portion, especially those of the first stage. The metallic bond-coat is usually formed in a process of diffusion aluminizing, or by physical vapour deposition method (PVD). The aluminide bondcoats consist of phase β-NiAl and are characterized by thickness 30 to 60 μm. They are deposited by using the following methods: Pack Cementation, Out of Pack or Chemical Vapor Deposition. The second method of obtaining the bond-coats, allows forming a layer, made of multicomponent MeCrAlY alloy. It is based on a process of arc evaporation (Arc-PVD) or physical vapour deposition with a use of electron beam (EB-PVD). The outer ceramic layer is obtained during the EB-PVD process. They have different structure, morphology and microstructure components forming a layer during plasma spraying process. They are also characterized by a smaller thickness (100 to 200 μm) and roughness [1,2].

Higher requirements of aircraft engine manufacturers intensify research on alternative methods of producing the ceramic layers of thermal barrier coating (TBC). Currently there is a research conducted on introducing the new production methods. The first of them the use the chemical vapour deposition (CVD) [3]. The CVD process is assisted by using a microwave frequency plasma and using metaloorganic precursors (high temperature process). There is also a research conducted on the CVD process, assisted by laser beam [4]. Thermal conductivity and structure of these coatings are similar to the layers obtained by EB-PVD method. The second, alternative method is physical vapour deposition phase with vaporization conducted with a use of plasma gun (PS-PVD).

In currently used methods of plasma spraying (APS and LPPS), the layers are formed by melting or partially melting powder particles in a plasma jet and impingement on the base material surface. In the processes of physical vapour deposition with evaporation by using electron beam (EB-PVD), the coating material condensates on the substrate surface and creates a layer. The quality of this method is a possibility of obtaining the coatings with crystalline structure. An example is the outer layer of ceramic thermal barrier coating with columnar structure, deposited on the blades of the first stage turbine of the aircraft engine. This technology is characterized by a high cost of the equipment and slow layer growth. Furthermore, there are some difficulties in coatings formation on the elements with complex shapes, such as vanes elements of the aircraft engine.

The PS-PVD technology is an hybrid method and it is a combination of plasma spray (lower cost) with the evaporation of the material forming the layer.. It is one of the most promising methods for implementation in the industrial practice. The foundation of PS-PVD method is to conduct conventional plasma spraying process in the conditions of reduced pressure (LPPS). The conventional LPPS process takes place at a pressure of 50 to 200 mbar and allows to obtain coatings with thickness from 20 μm to 1 μm. The reduction of pressure leads to an increase of the plasma jet length, from 50 mm to approx. 500 mm. The thinnest layers are achieved by using of the Thin Film technology which ensures obtaining the uniform, dense and oxide-free coating. The pressure in the working chamber during the PS-PVD method is much lower and ranges from 0.5 to 2 mbar. It makes further increase of size of the formed plasma jet possible, to the value of 1700 mm (between the base material and plasma gun) and diameter between 200 and 400 mm. The suitably modified 03CP high-energy gun made by Sulzer Metco company allows the plasma gas flow to increase to 200 NLPM and for the current - up to 3000A. The increased energy of the plasma plume (temperature up to 10 000 K, speed to 2000 m/s) and the low pressure in the PS-PVD process, causes the evaporation of the powder introduced into the plasma jet. It changed the course and intensity of physical phenomena occurring in the plasma jet due to evaporation. Thus, layers can also be manufactured on the base material surfaces located close to the plasma jet. The powder that forms a layer of material base surface is administered by a combination of 2 or 4 nozzles connected with the feeders to the plasma jet, in the front part of the gun. Increased number of feeders allows to create multicomponent coatings or gradient [5, 7-9].

The parameters of the plasma jet characteristics under reduced pressure and induced changes in the intensity of the particular phenomena, enable the development of technologies, that lead to improvement of the efficiency as well as the properties of manufactured metallic and ceramic layers. The study of microstructure of MeCrAlY metallic layers showed no trace of oxides, without any additional heat treatment [7].

There is no literature data on the formation of thermal barrier coatings by PS-PVD method. Only a few publications with the results of theoretical approach and the experimental data of manufacturer. Recent studies indicates that the powders with smaller granularity, enabling the evaporation of the material in plasma jet are necessary for the formation process of ceramic layers with a columnar structure. ZrO_2 powder used for plasma gun during APS and LPPS plasma spraying has a granularity higher than 60 μm and lower than 25 μm in case of the PS-PVD process. The publications show that the condition of formation of the ceramic layer with a columnar structure is low powder feeding rate, composition of properly selected plasma gases and greater distance between the plasma gun and the coated element. It was shown, that there is a possibility of coating formation on the complex-shaped elements, such as segments stators in the aircraft engine turbine. The results of the first technological tests conducted by the manufacturer shows, that the coating growth speed is high and is about 100 μm/min [6, 7-10].

2. Experimental

The Research and Development Laboratory for Aerospace Materials at Rzeszow University of Technology is equipped with the LPPS-Thin Film device (Sulzer Metco company). The device design is similar to the first prototype located in the Sulzer company. As distinct from the devices located in NASA and Institute for Material Research our system has vertically oriented vacuum chamber and is equipped with additional loading chamber. The device has a possibility of shifting the plasma gun, which is mounted in the chamber, and the sting with attached samples or blades. The described earlier 03CP plasma gun can be supplied with current intensity up to 3000A and was used during the conducted research.

The first trials were carried out for the current intensity of 2000A and mixture of plasma gases consisting of argon and helium with 1:2 ratio. The spray distance was of approx.

1500 mm. During the plasma spraying process, the samples were moved with a use of sting according to the earlier prepared program. The pressure value under 1 mbar was maintained in the vacuum chamber. The Metco 6700 ceramic powder (zirconium oxide stabilized by yttrium oxide) was used as deposition material.

a) b) c) d)

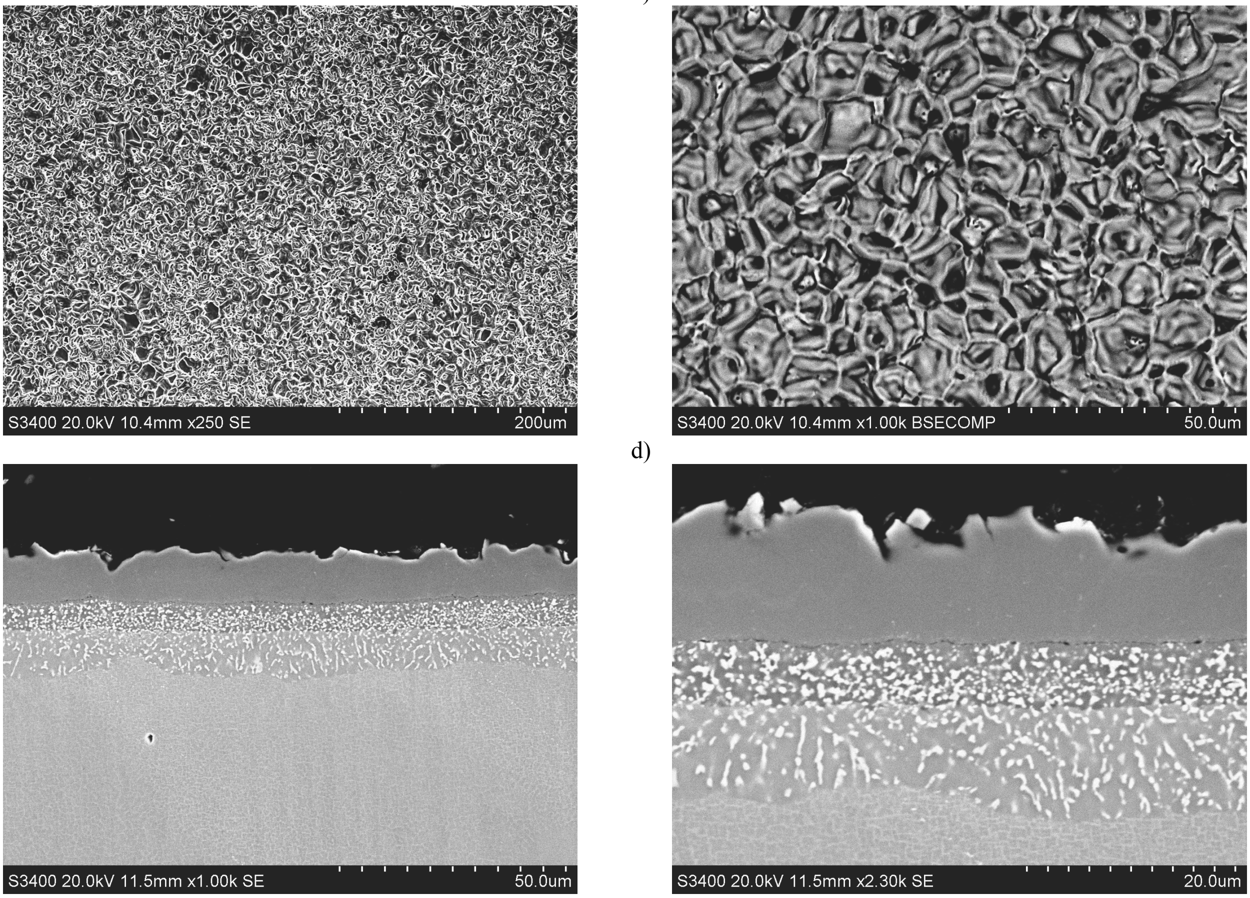

Fig. 1. The surface morphology and microstructure of aluminide coating obtained by CVD method on CMSX-4 superalloy

a) b)

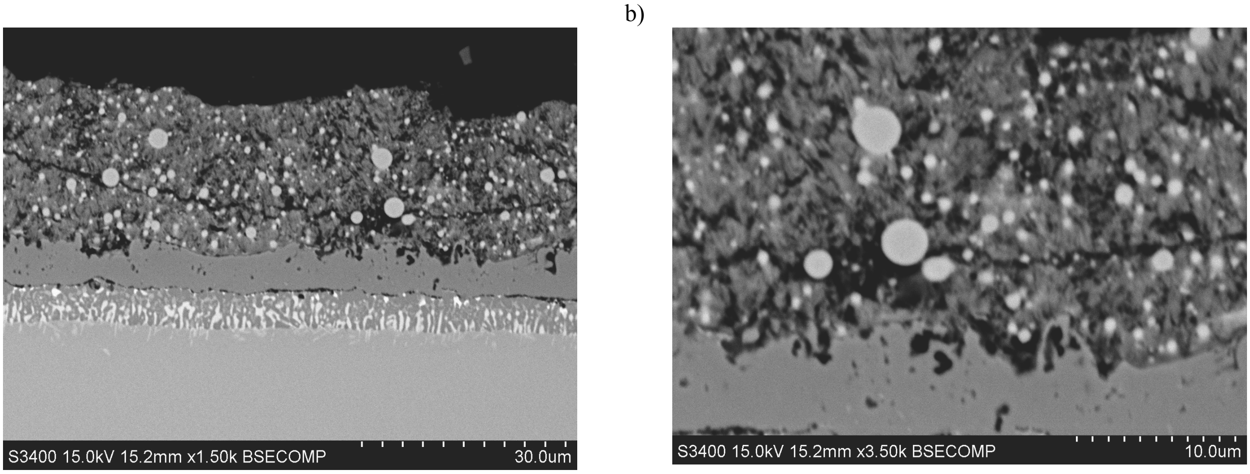

Fig. 2. The microstructure of TBC coating deposited in first test (a) and the details of ceramic layer structure (b)

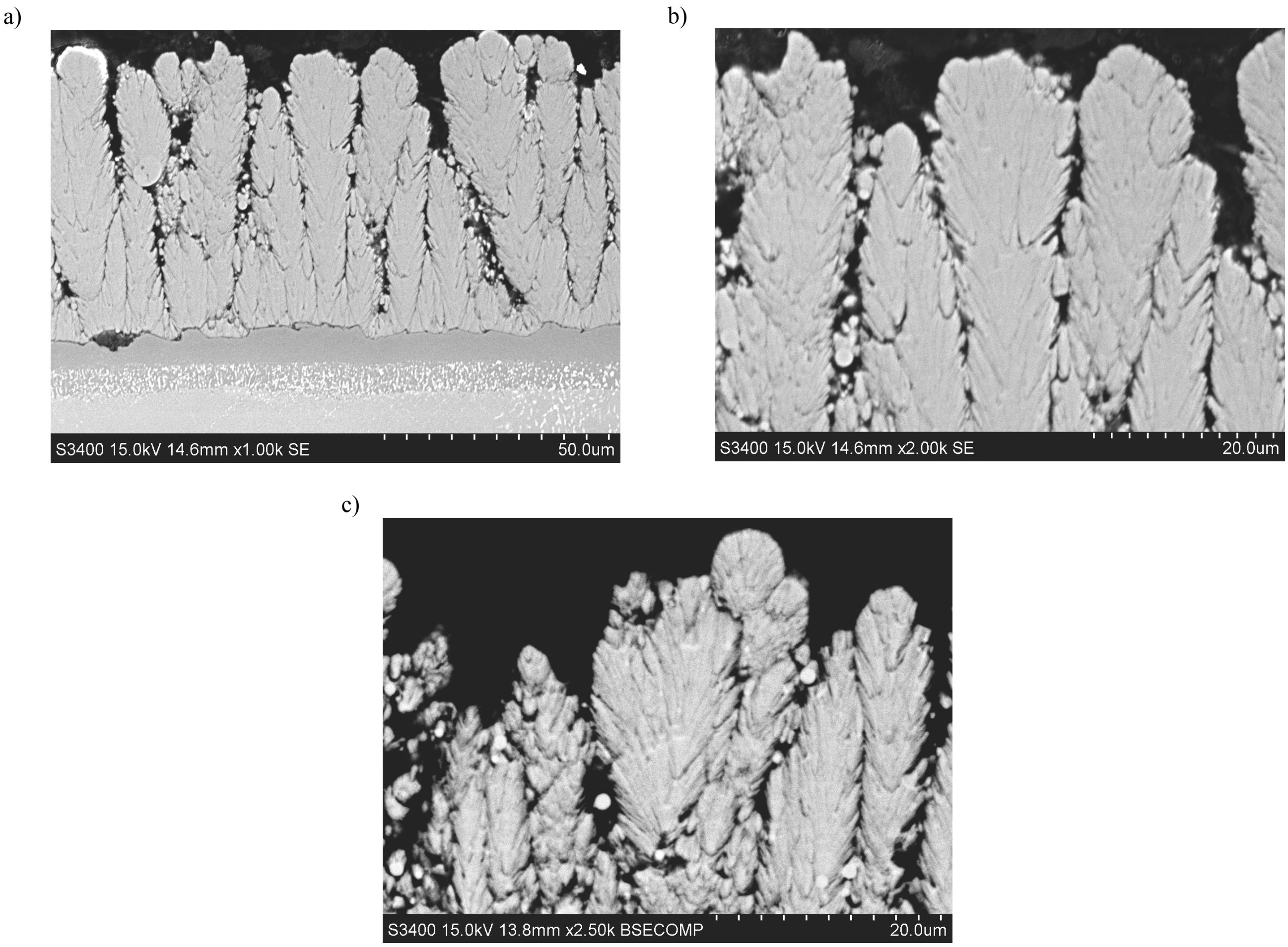

Fig. 3. The microstructure of TBC coating deposited in second test (a) and the details of ceramic layer structure (b, c)

The single crystal CMSX-4 nickel alloy was selected as the base material. The diffusion aluminide layer formed during the low activity aluminizing process was used as bond-coat. The bond-coat was created with a use of BPX-Pro 325S device (Ion Bond company). The HCl flow of 1.4 NLPM and the hydrogen flow of 10.5 NLPM were applied. The aluminizing process was conducted in the temperature of 1000°C for four hours. The thickness of the obtained aluminide coating didn't exceed 20 µm. The bond-coat microstructure is presented on Fig. 1.

3. Results and discussion

During the first technological trials the samples with diameter of 6 mm are attached on the nickel wires with thickness of 1 mm. The samples were moved away from the middle of the plasma plume by 150 mm in order to prevent the sample from falling off. After the process the samples were fully covered with the ceramic layer. The analysis using the Hitachi S-3400 scanning electron microscope was performed in order to assess the coating morphology.

The conducted research proved that it possible to obtain the ceramic layer with small thickness (approx. 30-40 µm). The obtained coating didn't have the proper columnar structure. The more accurate observations revealed a presence of non-stoichiometric zirconium oxide which was evaporated and the presence of many spheroidal particles which most melted without being vaporized (Fig. 2b). The obtained results determined the introduction of the samples into the centre of plasma plume. It was put into effect during the second trial. In order to protect against the fusion of the wires used for fasten the samples, the coating time was shortened by a half compared to the standard conditions. The macroscopic observations showed total coverage of the sample surface with the deposited coating. The ceramic layer was characterized by good adhesion. No falling off or spalling of the was observed. The microstructure analysis showed the columnar structure of the obtained ceramic layer (Fig. 3a). The coating thickness was of about 50 µm. The separate columns had a width of 10 µm. The morphology of the columnar crystals proved that the growth proceeds at an angle of approx. 70^{o} to the substrate surface. Moreover, one has observed in the vicinity of the base material many crystals, with stopped growth by the adjoined particles (Fig. 3 b,c). No side branching were observed in their structure. It is beneficial as far as the expected properties of the TBC coating are concerned. The total thickness of the TBC coating didn't exceed 70 μm.

4. Summary

The PS-PVD technology is a major breakthrough in the development of plasma-spraying processes. It introduces plasma-spraying technologies into the applications where PS-PVD processes used to dominate. The outline presented in this article proves that the literature concerning this technology is still scarce. This fact determines the directions for further investigations into the influence of deposition parameters on the morphology of TBC's.

The results of the initial trials indicated that the PS-PVD process is a promising method of depositing a TBC ceramic layer. The columnar layer deposition was proven to be achievable, although it is normally characteristic of EB-PVD-deposited ceramic coatings. Significant differences in the morphology of columnar crystals were detected, which were observed to be wider and more irregular. The impact of such morphology on the properties of the deposited layer is still to be determined, especially its adhesiveness, oxidation, hot corrosion and erosion resistance. What is more, it is crucial that the proper selection is made of the bond coat between the diffusion aluminide coatings (including the platinum and palladium modified bond coats) and MeCrAlY coatings. As well as this, further research is required into the influence of deposition conditions on the morphology and thickness of the obtained coating. In order to determine this, the next stage of technological trials will be introduced to provide a full description of the phenomena occurring during the deposition process.

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