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Studying the Structure and Adhesion Strength of Thermal Barrier Coating

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Abstract. The structure and adhesive strength of thermal barrier coatings produced by successive deposition of layers is studied. The coating is applied in three layers: i) a diffusion aluminosilicide coating that provides protection against high temperature oxidation and corrosion, with a thickness of 50 µm; ii) a metal sublayer providing a smooth transition from a metal coating to a ceramic one, with a thickness of 100 to 120 µm; iii) a ceramic layer decreasing the temperature of the blades during operation, with a thickness of 70 to 100 µm. The total coating thickness ranges from 0.17 to 0.27 mm. It is shown that the second and third layers deposited by plasma spraying are quite dense, the porosity being less than 5 vol%. During tensile tests carried out on an Instron testing machine, the failure of glued samples was always detected in the adhesive joint. The adhesive strength of the applied epoxy-based adhesive was 12 MPa; it can be stated that the adhesive strength of the coating is higher than 12 MPa.

INTRODUCTION

Thermal barrier coatings are designed to reduce the surface temperature of parts, e.g. gas turbine engine blades, during operation. Typically, such coatings consist of zirconia ZrO_2 stabilized with Y_2O_3 [1]. The introduction of the Y_2O_3 additive can prevent polymorphic transformations and preserve the cubic or tetragonal phase at room and even lower temperatures [2–4]. The content of yttrium oxide 6–8 wt% corresponds to higher thermal stability of plasma-sprayed coatings. The disadvantage of these coatings is low adhesive strength. There are a number of technological solutions to improve the adhesion of the coating to the metal base. The widespread application of intermediate metal layers of the composition Ni-Cr-Al-Y between the sample (or part) and the outer ceramic layer to increase its adhesion and reduce the differences in the thermal expansion coefficients between the ceramic and the base [5]. The analysis of the damageability of such coatings showed that it was necessary to solve not only issues related to the protective characteristics of the coating or its constituent layers, but also problems arising from the need to match the layers in a multilayer thermal barrier coating (MTBC) in terms of thermal expansion coefficient, diffusion interaction, and other physical and mechanical characteristics [6, 7]. Otherwise, the service life of an MTBC will be limited by mechanical violations of the integrity of the multilayer composition, which will not allow full use of the protective properties incorporated in the design and composition of the coating. The purpose of the work was to study the structure and adhesive strength of a multilayer thermal barrier coating with a ceramic outer layer of the composition ZrO_2-7 wt% Y_2O_3.

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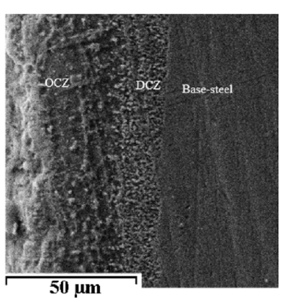
MATERIALS AND RESEARCH METHODS

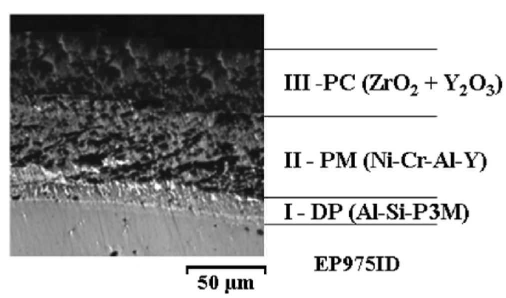
Coatings were applied onto the EP975 ID (ZhS6UD-ID) heat-resistant nickel alloy, used for the manufacture of disks and vanes of gas turbine engines. The chemical composition of the alloy is (wt%): 0.1 – 0.16 C, 7.5 – 9 Cr, 14.1 – 0.17 Co, 9.5 – 11.0 W, 4.5 – 5.1 Al, 2.0 – 2.7 Ti, 1.0 – 2.0 Nb, up to 1 Fe, 0.8 – 1.5 Mo, up to 0.03 Ce, up to 0.4 Si, up to 0.01 S, up to 0.015 P, with Ni as the base. Multilayer coatings were obtained by sequentially applying three layers. The first to apply was an Al-Si-RZM thermal diffusion layer of in sealed containers with a fusible seal. A powder mixture of the following composition was used: 98 wt% powder of 49 Fe-28 Al-17 Si-6 RZM alloy and 2 wt% AlF_3 activator. Thermodiffusion saturation was carried out at a temperature of 950 °C for 6 h. Before applying the second layer, the surface of the samples was prepared in order to clean it from oxide films and give it the necessary roughness. For abrasive-jet processing of the samples, a regime was chosen that made it possible to maintain a diffusion alumosiliconized layer with a thickness of at least 50 µm. The surface was treated by blowing with fused white electro corundum, with a particle size of 315 to 500 µm. After abrasive blasting, the samples and the blades were blown with dry compressed air to remove dispersed abrasive particles. Then, a Ni-Cr-Al-Y metal sublayer was deposited by plasma spraying. The third layer was a direct thermal barrier coating of the composition ZrO_2 – 7 wt% Y_2O_3. After each stage of the deposition of layers, the following studies were performed: metallographic analysis with a Neophot-21 microscope, X-ray microanalysis with a Tescan Vega II XMU scanning electron microscope using the INCA Energy 450 energy dispersive microanalysis system with an ADD detector with the INCA software; the surface roughness of the samples was determined with a 3D surface analyzer using a Wyko NT-1100 optical interferometer profilometer with the Veeco software package. The microhardness value of each layer was determined on a transverse section of the sample after applying the entire multilayer composition using a Leica VMHT Auto hardness tester. The adhesive strength of the coatings was assessed by the results of stretching, at a speed of 1 mm/min, of the adhesive joint of the coated plate and the counter sample on an Instron 8801 hydraulic testing machine.

RESEARCH RESULTS AND DISCUSSION

To increase the heat resistance of thermal barrier coatings, prior to the plasma spraying of the sublayer and the ceramic layer, thermal diffusion alumosiliconizing of the surface of the nickel alloy samples was carried out. In this case, a coating was formed consisting of NiAl aluminides with a microhardness of 900 HV 0.05, a thickness of 70 to 80 µm, and a surface roughness Ra = 9 µm. After diffusion alumosiliconizing, the chemical and phase composition of the surface layer of the nickel alloy changed, and the aluminosilicide coating formed inland from the surface of the samples, without leading to an increase in their size (Fig. 1a). The properties and composition of the diffusion aluminosilicide coating are presented in detail in [7]. After abrasive blasting, the surface roughness of the samples decreased to Ra = 3 µm (Fig. 2a). The second metal sublayer (in wt%) of Ni-22Cr-10Al-1Y was applied onto the thus prepared surface by plasma spraying, with a thickness of 100 µm. The microhardness of this sublayer was about 600 HV 0.05. This sublayer consists of NiAl aluminides and a Ni-based solid solution. The metal sublayer is quite dense, its porosity being less than 5 vol% (Fig. 1b). The surface roughness increased slightly and amounted to Ra = 6 µm (Fig. 2b). The pattern of the distribution of the chemical elements in such a layer was reported in [7].



(a)



(b)

FIGURE 1. The coating microstructure: a – a secondary electrons image of the first diffusion layer (OCZ is the outer coating zone of NiAl; DCZ is the diffusion coating zone with silicides of chromium, tungsten, titanium, and molybdenum), b – a metallographic image of the MTBC (PC is plasma ceramic layer providing protection against high temperatures; PM is plasma metal sublayer; DP is heat-resistant diffusion coating)

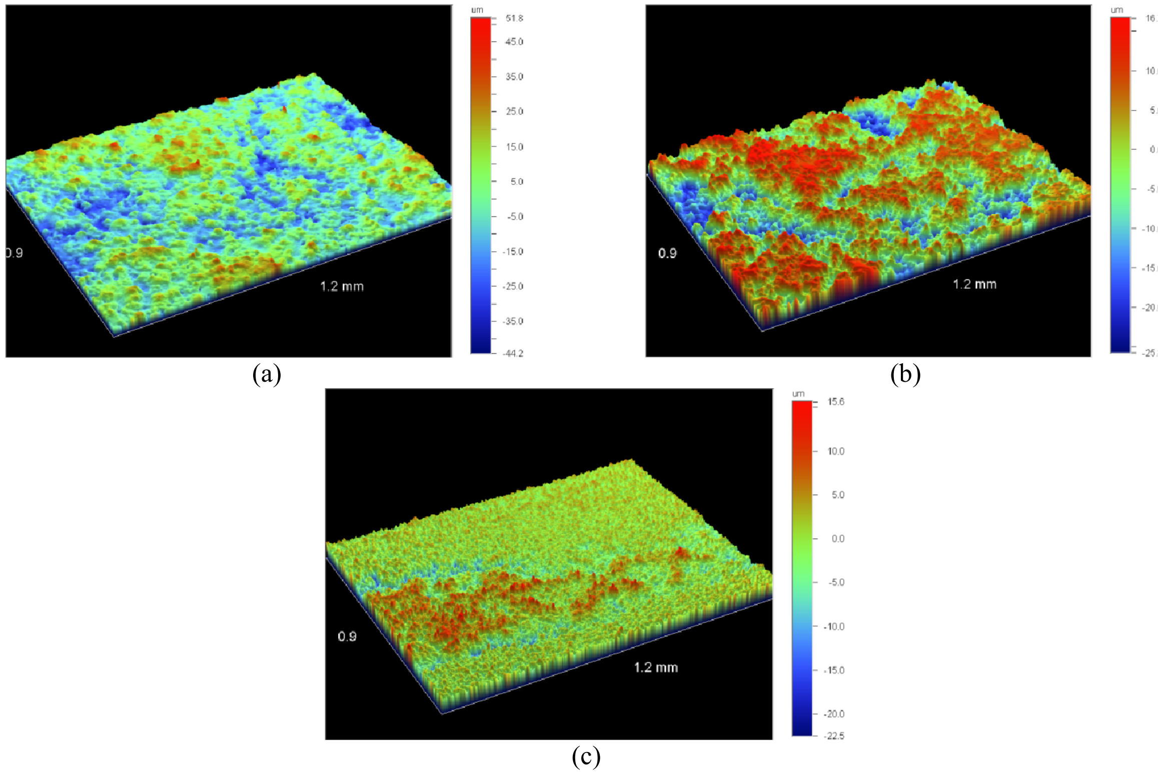


FIGURE 2. Surface profile and roughness of the sample: a – after alumosiliconizing and subsequent surface abrasive-jet machining; b – after alumosiliconizing, surface abrasive-jet machining, and subsequent application of a plasma sublayer; c – after alumosiliconizing, surface abrasive-jet machining, and subsequent application of a plasma sublayer and ceramics

The outer ceramic layer, which decreases the surface temperature of heat-resistant nickel alloys, consists of zirconium dioxide ZrO_2 stabilized with 7 wt% Y_2O_3. The distribution of the elements in the MTBC is shown in Fig. 3. The total thickness of the multilayer composition on the surface of the samples averaged 0.22 mm.

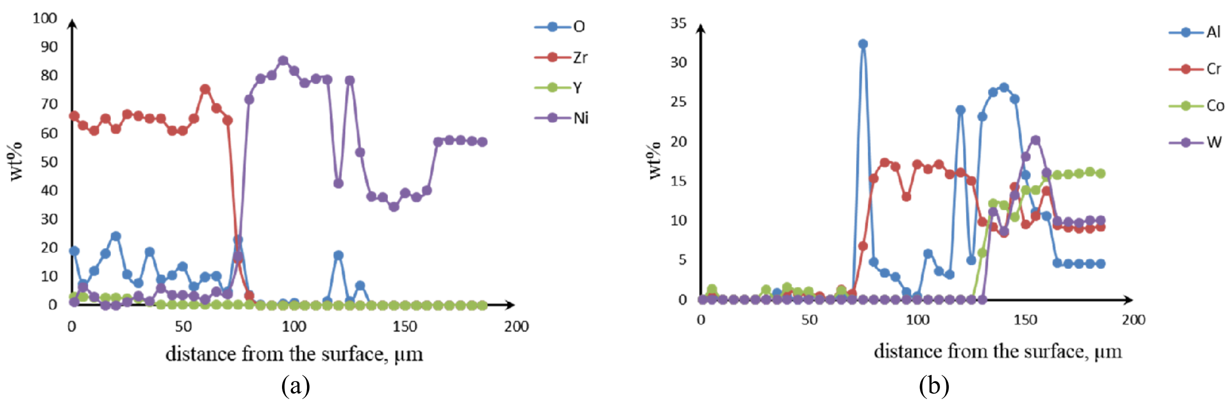


FIGURE 3. Distribution of the chemical elements over the MTBC thickness: a – the elements constituting the ceramic layer of the metal base; b – the metal constituents of the coating and the nickel alloy

During the tensile tests of the counter sample and the adhesive joint between a flat sample with a ZrO_2–7% Y_2O coating applied directly onto the samples of the heat-resistant nickel alloy, the joint failed along the ceramic layer within the first seconds of testing. There was no cleavage or delamination of the layers in the coating (Fig. 4). Previously, the adhesive strength of the adhesive joint was determined, and it amounted to 12 MPa; therefore, it can be stated that the adhesive strength of the MTBC under study significantly exceeds 12 MPa. This value is quite sufficient to maintain the integrity of the composition on the surface of the blades of gas turbine engines, experiencing mainly minor tensile stresses.

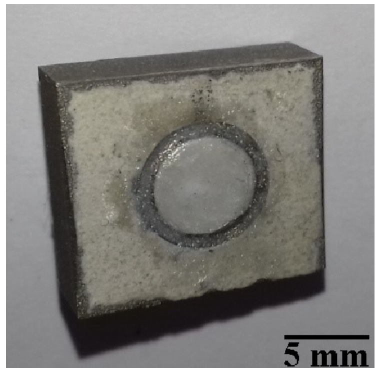


FIGURE 4. The appearance of the sample with MTBC after adhesion strength tests, with the adhesive layer on the sample surface

CONCLUSION

The research results have shown that the MTBC coating consists of three layers of different chemical composition, strongly bonded to each other. The total coating thickness is on average 0.22 mm, while the thickness of the samples increases by 0.17 mm, which is important for gas turbine engine blades in terms of preserving the hydrodynamics of the engine. The second metal sublayer Ni-Cr-Al-Y and the third thermal barrier layer ZrO_2 – 7 wt% Y_2O, deposited by plasma spraying, are fairly dense, their porosity being less than 5 vol%. In the course of tensile testing, the destruction of the adhesive assemblies of the MTBC-coated samples with the counter samples is always observed only in the adhesive joint. Since the adhesive strength of the applied epoxy-based adhesive was previously determined to be 12 MPa, it can be stated that the adhesive strength of MTBC is higher than 12 MPa, which is quite sufficient to maintain the integrity of the composition during the operation of gas turbine engine blades.

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