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THE INFLUENCE OF INTERLAYER THICKNESS ON TEMPERATURE DISTRIBUTION AND STRESS IN THERMAL BARRIER COATINGS

Key words: TBC, temperature distribution, thermal stress, FEM.

Abstract: The article presents the results of numerical calculations of temperature distribution and thermal stress in a thermal barrier coating (TBC) applied by thermal spraying on the element of nickel superalloy. The assumed point of reference was a set of conventional TBCs made of the 8YSZ powder with the insulating layer thickness ranging between 150 µm and 300 µm. A numerical analysis was conducted to examine thermal barrier coatings where the outer ceramic layer was made of powders of a new type with the generalised formula being RE2Zr2O7, where RE = Gd, La, Sm, and Nd. For all cases, it was assumed that the primer would be the NiCoCrAlY type coating obtained by plasma spraying similarly to the outer insulating layer. The primer depth ranged from 150 µm to 300 µm. The assumed substrate material was the In 625 type nickel superalloy.

Wpływ grubości międzywarstwy na rozkład temperatury i naprężeń w powłokowych barierach cieplnych

Słowa kluczowe: powłokowe bariery cieplne, rozkład temperatury, naprężenie cieplne, MES.

Streszczenie: W opracowaniu przedstawiono wyniki obliczeń numerycznych rozkładu temperatury i naprężeń cieplnych w powłokowej barierze cieplnej (TBC) naniesionej na elemencie z nadstopu niklu metodą natrysku cieplnego. Jako punkt odniesienia przyjęto konwencjonalne powłoki TBC otrzymane z proszku 8YSZ o grubości warstwy izolacyjnej na poziomie wynoszącym od 150 µm do 300µm. Analizie numerycznej poddano powłoki TBC, w których zewnętrzną warstwę ceramiczną otrzymano z proszków nowego typu o ogólnym wzorze RE2Zr2O7, gdzie RE=Gd, La, Sm i Nd. We wszystkich przypadkach przyjęto, że warstwa podkładowa to powłoka typu NiCoCrAlY otrzymana metodą natrysku plazmowego, podobnie jak zewnętrzna warstwa izolacyjna. Grubość warstwy podkładowej wynosi od 150 µm do 300 µm. Jako materiał podłoża przyjęto nadstop niklu typu In 625.

Introduction

A thermal field, which appears in a solid body subject to deformation, is a cause of both tough and transitional states of strain and stress that arise in that body. Thermal stresses are formed through the changes in the value and temperature distribution. These stresses have a significant impact on the process, mechanical strength, and the durability of structural components and systems [1]. As an effect of thermal stresses, which attend the manufacturing processes and exploitation of elements consisting of parts characterised by different mechanical and thermal properties, one needs to consider the possibility of internal stresses emerging in the element after its temperature has equalised. This issue is important for numerous reasons, including those related to interfaces between ceramic and metallic materials [2-4]. Internal stresses combined with stresses triggered by thermal or mechanical loads may lead to the destruction of an element. Obtaining effective solutions to many complex problems has been made possible thanks to the development of numerical methods of the finite element method (FEM). From the technical prospect, an important example of the deployment of the above method may be the determination of non-stationary thermal fields and fields of thermal stresses in heat generating turbines or elements of reaction engines.

To assess the reliability and durability of thermal barrier coatings (TBC), one must first analyse thermal insulation as well as issues of the mechanical strength of TBCs. An important role in the study of above-named problems is played by the finite element method (FEM), which is used for calculations related to thermal insulation, as well as issues of the durability of the TBC layer.

The finite element method is also used to resolve internal stresses generated in the process of plasma spraying or caused by the disagreement of thermal expansion coefficient values between the coating and the substrate. The finite element methods are being applied to assign changes in the temperature gradient values under real exploitation conditions. A solution to these problems is based on thermo-mechanical calculations.

When it is necessary to increase the efficiency of turbines designed for aircraft engines as well as stationary gas turbines, one must seek solutions which may enable the operating temperature of critical parts of engines made of nickel superalloys to be reduced in operation [5, 6]. Increased efficiency is mainly obtained by raising gas temperature at the turbine outlet. One of the solutions used to increase turbine efficiency is plasma spraying of thermal barrier coatings. They consist of protective layers that increase the service life of elements of the engine's hottest section. They are characterised by low thermal conductivity, which enables the reduction of the substrate material temperature by ca. 200°C.

In the aircraft industry thermal barrier coatings are used, because this barrier has an advanced protective system. They are built of four layers. The first layer of the system in question is a bond coat (BC), also referred to as the primer. In many aspects, it constitutes the most critical element of the coating system, being decisive in the system's durability. It is characterised by high content of aluminium, which, while diffusing into the surface, forms a compact oxide layer (α- Al_2O_3) under conditions of oxidation. Owing to this property, it secures the surface against further oxidation. Another task of the bond coat is to increase corrosion resistance in an environment containing sulphur compounds. It must also be characterised by low propensity for the formation of brittle transient phases as well as resistance to mutual diffusion between the bond coat's alloy components and the substrate material [5, 6]. On the surface of the primer, there is a layer formed by the aforementioned thermally grown oxides (TGO), whose main component is α- Al_2O_3 oxide. It is formed through oxidation of the bond coating surface. The sealing atmosphere is composed of process gases that penetrate the area of contact between the bond coat and the ceramic layer through fractures formed in the outer ceramic coat and a mesh of pores. The main factors directly affecting the properties of the TGO zone include its adherence to the primer and the bond coat's chemical composition, which conditions the type of oxides to be formed. In the course of prolonged operation of the layer, some unfavourable and more complex oxides are formed, such as $NiAl_2O_3$ or NiO. An increase in the thickness of the TGO layer is unfavourable and contributes to the propagation of micro-fractures in the TBC [6, 7].

The last element of the thermal barrier coating is a ceramic insulating layer. The material typically used to build this layer is zirconium oxide stabilised with yttrium oxide at the weight ratio of ca. 7–8% Y_2O_3, designated as 8YSZ. The foregoing stems from its superior insulating properties. 8YSZ is known for its very low thermal conductivity coefficient, which equals 2.3 W/mK, and some other of its advantages are the low thermal expansion coefficient (11x10^{-6} °C^{-1}) and low density of ca. 6.04 g/cm^3. What also proves to be a very important property of the 8YSZ oxide is the melting point which comes to ca. 2,700°C, owing to which it is possible to use it in hot sections of aircraft engines [5, 7–11].

1. Research methodology

This article presents a numerical analysis of heat flux in model thermal barrier coatings executed by the application of the finite element method (FEM). The Algor program was used for computer simulation. A specific geometry was developed for the models used to perform numerical analysis by the finite element method. An aspect of axial and symmetric nature was examined, and a model of axial symmetry subject to axial and symmetric thermal loads was analysed. Having studied the problem in question in the symmetry domain, one could obtain computational results for the phenomena occurring over the entire volume of the model. By that means, a three-dimensional problem was brought down to a two-dimensional problem. Models are basically assumed to be made of the substrate material, i.e. the layer of the In 625 nickel superalloy, the A365-2 type primer (NiCoCrAlY), and the ceramic layer (8YSZ). Every model differs from one another in terms of the thickness of the primer and the ceramic layer. The bond coat thickness in individual models is, respectively, 0.075 mm, 0.1 mm, 0.125 mm (…) up to 0.3 mm, whereas the ceramic layer thickness is 0.15 mm, 0.2 mm, 0.25 mm, 0.3 mm, 0.4 mm, and 0.5 mm.

The research comprised an analysis of elastic strains. Its initial stage was a numerical analysis of the thermal field. Boundary conditions of the first kind were defined. Temperature load was assumed according to the model's surfaces. Temperature of 1,200°C was applied on the surface of the 8YSZ ceramic layer, whereas the temperature assumed for the outer surface of the nickel superalloy layer was 800°C (Fig. 1).

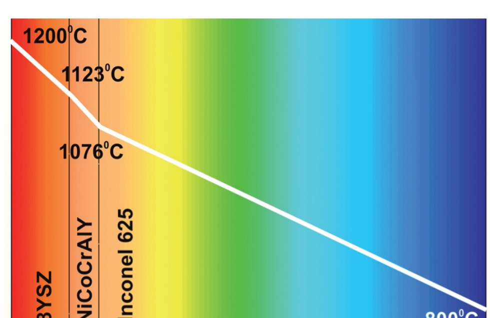

Fig. 1. Thermal load in the model

The next stage of the study was the determination of the distribution of thermal stresses in the models developed. Specific constrains were set against the freedom of the models. It was assumed that cross sections of the models were not moving in the direction of the z-axis. Since the axial-symmetric thermal field was known in the analysed models, it was possible to establish the state of stress that occurred in them.

The study analysed the distribution of temperature and thermal stress in two areas of the developed models. The zones of temperature and stress distribution studied are illustrated in Figure 2. It is the area of interface between the ceramic material and the bond coat (I) as well as between the bond coat and the metallic substrate (II). What is typically analysed is the distributions in the area of the insulating ceramic layer; however, the author's previous research implies a considerable impact of the bond coat type and thickness on the insulation [8–11]. For all of the cases analysed, graphs were developed showing the change in temperature and stress, depending on the variable thickness of the individual layers.

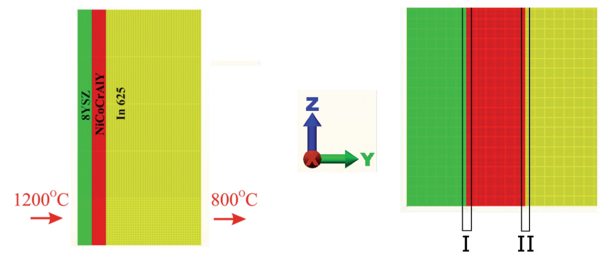

Fig. 2. Areas that examined the distributions of temperature and stress: I- 8YSZ-NiCoCrAlY interface, II-NiCoCrAlY-In625 interface

2. Results of numerical calculations

The numerical simulations enabled the determination of the distribution of temperature and thermal stress for different layer thicknesses and insulating undercoat. Figure 3 shows the insulating properties of the 8YSZ ceramic layer. The foregoing diagrams imply that the thickness of the ceramic layer is critical to the temperature values on the bond coat surface. The thermal barrier based on zirconium oxide stabilised with yttrium oxide (8YSZ) causes a temperature drop across the insulating layer thickness, which is about 117°C for a 0.075 mm thick bond coat and for insulating ceramic layers with the thickness of 0.15 and 0.50 mm. When translated into the temperature of the substrate made of the In 625 alloy, the foregoing implies that it will drop by 80°C up to 105°C for the 8YSZ-based coating.

Having analysed the temperature changes occurring on the surface of the bond coat and of the substrate material as a function of the bond coat thickness, one could find that an increase in the thickness of the NiCoCrAlY primer causes the temperature on the bond coat surface to rise. As for the 8YSZ ceramic coating, a temperature increase of 25°C was observed on the bond coat thickness increase by 0.025 mm (from 0.075 to 0.3 mm) irrespective of the ceramic layer thickness. Simultaneously, we found a temperature drop in the In 625 substrate ranging from 11 up to 37°C for an increasing primer thickness and on the ceramic layer thickness ranging from 0.075 to 0.500 mm (Fig. 4). The above results indicate the important role of the bond coat material as well as the impact of its thickness on the temperature distribution on the substrate material surface and on the bond coat surface. The foregoing is particularly important if one accounts for how extensively the primer surface develops, being a result of the manner in which it is settled and, at the same time, constituting one of the requirements ensuring appropriate adherence of the ceramic layer.

Figure 5 shows the hoop stress distribution for a model constructed of a 300 μm thick ceramic barrier coating and a bond coat with the thickness of 200 μm deposited on an element made of nickel superalloy. When analysing the influence of the interlayer thickness of the stress distribution in the numerical models, it was found that, with the increasing thickness of NiCoCrAlY, the stress on its surface was increased to a small extent. Values of hoop stress on the 8YSZ-NiCoCrAlY area are around ca. 20 MPa, and on the NiCoCrAlY-In625 surface, they are approximately ca. (-150) MPa. In spite of the varying bond coat thickness, stresses do not change

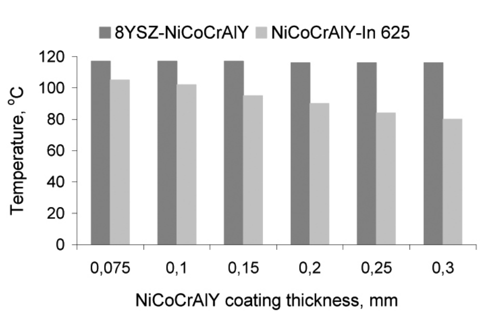

Fig. 3. Changing the temperature on the bond coat surface (I) and substrate surface (II) for different NiCoCrAlY thicknesses

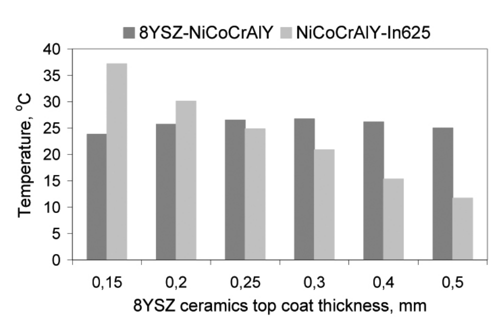

Fig. 4. Changing the temperature on the bond coat surface (I) and substrate surface (II) for different 8YSZ ceramics top coat thicknesses

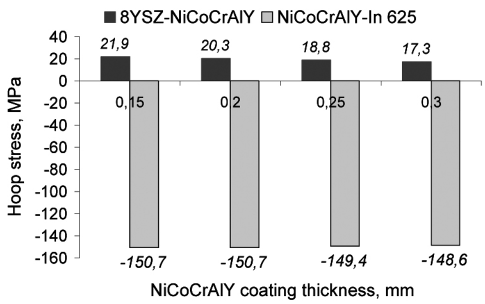

Fig. 5. Graph of hoop stress distribution in the model coated with a 300 µm thick 8YSZ layer on the NiCoCrAlY bond coat and on the In 625 substrate material for different bond coat thicknesses

significantly in the models analysed. A preliminary conclusion thus formulated that the stress distribution in thermal barrier coatings will primarily depend on material properties of the bond coat.

The studies performed are essentially of a preliminary nature. Application of the finite element method to simulate the behaviour of elements operating at high temperatures is currently a typical solution developed and used in many commercially available programs. The fact of having received results comparable to those provided in the literature has confirmed the high convergence of the studies that has allowed for the preliminary numerical model prepared to be considered applicable. In the subsequent stage of research, the results obtained so far by the numerical method will be verified experimentally.

Conclusions

Based on the analysis performed and the results acquired, the following conclusions have been drawn:

1. Thermal loads that affect a ceramic layer protecting elements made of nickel superalloy produce high stresses in the NiCoCrAlY bond coat.
2. The thickness of the insulating ceramic layer exerts a major influence on temperature distribution in the thermal barrier coating cross section.
3. The temperature gradient in the bond coat zone is favourable to the occurrence of high values of stress, thus contributing to the reduction of the service life of the thermal barrier coating.
4. The increasing thickness of the NiCoCrAlY primer causes the temperature on its surface to rise.
5. As the bond coat thickness increases, temperature on the nickel superalloy surface drops and, at the same time, the temperature rises on the bond coat surface.
6. Consequently, while choosing the bond coat thickness, one must not only account for the substrate temperature, but also for the temperature on the bond coat surface, which affects the kinetics of oxidation.
7. The thickness of the ceramic layer and of the bond coat has not been found to exert a significant impact on the stress distribution change in the models analysed.

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