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THERMAL BARRIER COATINGS FOR THE COMBUSTION CHAMBER COMPONENTS OF AVIATION ENGINES

Анотація

В процесі експлуатації жарова труба авіаційного газотурбінного двигуна схильна до динамічних, вібраційних навантажень, пульсацій газового потоку, корозійний-ерозійної дії агресивного середовища продуктів згорання палива. От чому термобар'єрні покриття (ТБП) використовуються для захисту подібних деталей, збільшуючи їх ресурс і надійність. В даний час продовжується активна розробка ТБП з метою кращого захисту деталей гарячої частини ГТД для відповідності вимогам до підвищеної паливної ефективності і знижених викидів в навколишнє середовище. Метою даної роботи є дослідження і аналіз працездатності покриття ТЗП-3, нанесеного плазмовим методом, на жаровій трубі двигуна Д-18Т.

Abstract

While operating a flame tube of aviation gas turbine engine is exposed to high-heat-flux stresses, dynamic and vibration loads, gas flow pulsations and corrosion-erosion effect of combustion residues under high temperature conditions. That is why thermal barrier coatings (TBC) are used for the protection of such components, increasing their work life and reliability. Presently TBCs are aggressively designed to protect gas turbine engine hot-section components in order to meet future engine higher fuel efficiency and lower emission goals. The purpose of this work was research and analysis of the work ability of plasma-sprayed coating TZP-3 applied to the flame tube of D-18T engine.

Reliable and steady work of aviation gas turbine engine severely depends on the efficiency of the combustion chamber components.

One of the combustion chamber components in aviation gas turbine engine mostly subjected to heat stresses is a flame tube. While operating it is exposed to high-heat-flux, dynamic and fatigue stresses, gas flow pulsations and to both high temperature erosion and corrosion by harsh environment of combustion gases. Meanwhile the temperature of the component elements rises locally up to the values of temperature 950°C and even higher. Operating conditions analysis of D-18T flame tubes has shown that the constant increasing of the temperature in combustion chamber, high levels of gas-abrasive erosion and requirements for reliable long lifetime operating time (from 5000 up to 20000 hours) are not provided by the protective refractory enamels. So that resulted in need for applying new and more effective techniques of protection like thermal spraying processes.

Nickel based superalloys are currently the material of choice for flame tubes and other combustion chamber components. These alloys have the required combination of strength and heat resistance at high temperatures (>1000°C). Through extensive development the maximum operating temperature of these alloys has continually been enhanced leading to increases in the engine operating temperature. This development has enabled significant advances in material performance but further improvements appear unlikely since they now operate in environments where the temperature approaches 90% of their melting point. As gas inlet temperatures have continued to rise, failure by thermally-induced mechanisms has been avoided by active cooling. The most promising approach is the use of a thermal barrier coating (TBC) system which thermally protects combustion chamber components and allows for their use at higher engine gas temperatures. This significantly reduces the surface temperature of the metal component thus enabling conventional superalloys to continue to be used. This approach then enables either an increase of the engine operating temperature or a decrease of cooling air flow leading to significant improvements in engine performance, for example, in thrust that is of great importance for military applications, or, prolongation of component life at current temperatures that is more considerable for commercial planes. Today, only the latter is utilized, but advances in TBCs and in applying new component designs that meet the requirements for TBCs and their performance, may eventually enable increases in engine operating temperatures. It's of great importance because it has been reported that a 170°C increase in the engine operating temperature improves an engines thrust by 5.0% and efficiency by 1.0%.

Another way is applying Silicium carbide (SiC)-based ceramic matrix composites (CMC) as a material of choice for flame tubes and other combustion chamber components. This type of CMC can withstand exposures to temperatures up to 1650 0C [2,3] and is utilized on Snecma M88 series engines that power the Dassault Rafale, General Electrics engine F414 that powers F-18 Hornet [4] and so on. But this approach requires a development of new multilayered thermal and environment barrier coating systems to protect these CMCs from severe operating conditions. This is an ongoing R&D work of Glenn Research Center, NASA [2].

The earliest TBCs were frit enamels, which were applied to aircraft engine components in the 1950s [1]. The first ceramic TBCs were applied by flame spraying and, subsequently, by plasma spraying. The use of thermal barrier coatings (TBCs) has resulted in a significant improvement in the efficiency of aircraft gas turbines and has the potential to do the same in land-based gas turbines. The use of TBCs can achieve temperature differentials across the coating of as much as 175°C and furthermore depending on the thickness of the coating. Figure 1 shows the improved temperature capability of nickel-base superalloys over the years and the effective improvement associated with the use of TBCs to lower the metal temperature.

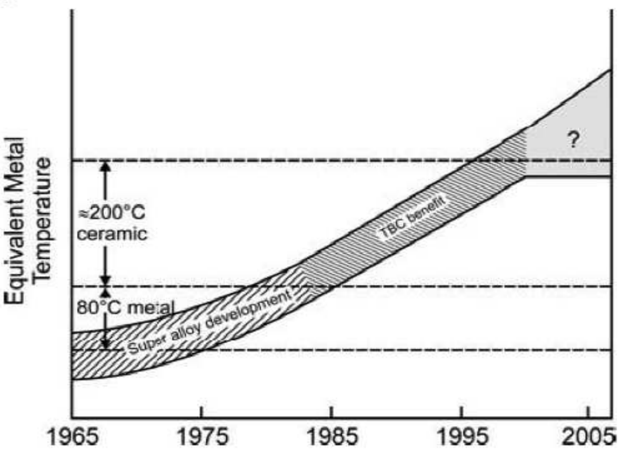

Fig. 1. Schematic diagram showing the increase in metal temperature in gas turbines resulting from superalloy development and the effective increase associated with the introduction of thermal barrier coatings

Presently TBCs are aggressively designed to protect gas turbine engine hot-section components in order to meet future engine higher fuel efficiency and lower emission goals [2].

Currently TBC's are applied using either an electron beam physical vapor deposition (EBPVD) approach or a less expensive air plasma spray method (APS).

Typical TBC systems for foreign aviation gas turbine engines consist of a nickel-base superalloy substrate coated with MCrAlY (M=Ni,Co) or a diffusion aluminide bond coat, for example, platinum aluminide, which forms a heat resistant alumina layer (thermally-grown oxide, TGO) on to which is deposited a yttria-stabilized zirconia (YSZ) layer. Yttria stabilized zirconia has become the preferred TBC layer material for gas turbine engine applications because of its low thermal conductivity, and its relatively high (compared to many other ceramics) thermal expansion coefficient. This reduces the thermal expansion mismatch with the high thermal expansion coefficient metals to which it is applied. It also has good erosion resistance which is important because of the entrainment of high velocity particles in the engine gases.

Our enterprises that produce aviation and industrial gas turbine engines can't afford such expensive materials and techniques nowadays so they are trying to find the way out designing new TBCs based on zirconia stabilized by calcium oxide without any rare-earth metal dopants. TBC system of this type — TZP-3 — was designed jointly by Pridneprovska Academy of Building and Architecture and State Enterprise "Zaporozhye Machine-Building Design Bureau Progress" named after Academician A.G. Ivchenko.

APS coating TZP-3 originally was designed for application on flame tubes of D-18T engine combustion chamber. Now this coating is utilized much more widely, almost for all the engines of "Ivchenko-Progress" design. This TBC is cermet type one and its design can be represented as three sequentially deposited layers. The first one is bond coat, the second is a transition layer and the third one is protective layer. TZP-3 composition was designed so that the coefficient of thermal expansion (CTE) changed smoothly from a super-alloy substrate up to the outer layer [5] as you can see from Fig. 2.

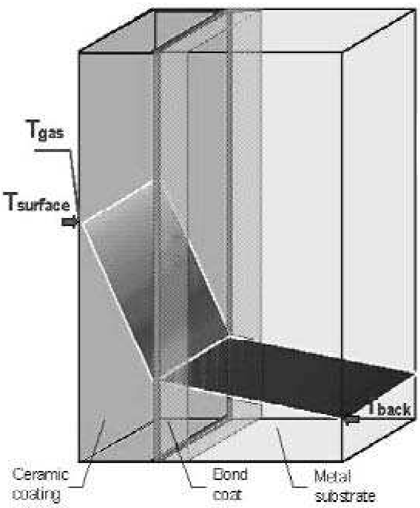

Fig. 2. Thermal conductivity chart of the TBC

Spraying of the flame tube was made at SE ZMDB "Progress" site using the versatile plasma system УПУ-8М. Mixture of the argon and the nitrogen was used as plasma generative gas. Forming of the TBC on the combustion chamber components was carried out by consistent spraying of several layers, which had different functionalities. For the minimization of the thermal stresses in layers of the coating a heating temperature of a component while spraying TBC did not exceed 100°C. That was provided by dry compressed air blowing of the component underside [6, 7]. A general view of a combustion chamber internal casing with air plasma sprayed TZP-3 is represented in Fig. 3.

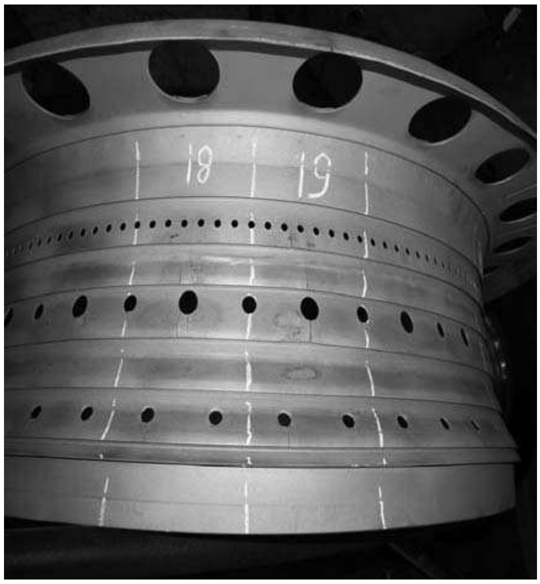

Fig. 3. A combustion chamber internal casing of D-18T engine coated with TZP-3

Within the works done prior to TZP-3 implementation such properties of this plasma sprayed coating were researched and analyzed: adhesive and cohesive strength, durability under thermal cycling, heat resistance and porosity. Adhesive and cohesive strength were determined using a pin method and a gluing technique (according to DSTU 2639-94). Durability under thermal cycling was determined for the samples produced from flame tube material ВЖ-98 using КС-2Г test rig (SE ZMDB "Progress" site). Such operation modes were applied: heating up to temperature 1050±10°C in the gas flow with a speed of ~100 m/s during 35s, then cooling down to 20...30°C by dry compressed air blowing during 40s. The samples sustained 2876 cycles without any inflations and spalling of the coating. These operation modes were set according to requirements for operating conditions of D-18T engine (flight cycles).

Heat resistance of the materials utilized in hot-section area of gas turbine engine is one of the most important properties that influence on their reliability and lifetime. The surface areas of TBC on the flame tubes are extended ones and they can't be precisely calculated. That's why traditional techniques of heat resistance calculation are not working. The method developed is based on calculation of relative weight change of the coated specimen exposed to temperature in open air during definite time interval.

Porosity of TZP-3 was determined using hydrostatic weighing technique (DST 18893-73) and proved out to be of optimal 10% value.

Series of TZP-3 microstructure photographs were made using optical microscope Olympus IX-70 both for as-sprayed coatings and after 9 hours annealing in order to compare these microstructures. You can see them in Fig. 4 and 5. Our associates from Pridneprovska Academy of Building and Architecture carried out more detailed image and X-ray diffraction analysis.

As you can see on Fig. 5, structure of the TBC has become brighter-this is an evidence of nickel's chemical transition to nickel oxide.

Now there are several R&D work under way: one of them is aimed to optimize nickel percentage in present TZP-3 composition to minimize coating inflation risks while local overheating during operation life: another one is aimed to get thermal barrier coating with a long lifetime for operating under 1400 0C for applying it to combustion chamber and other hot-section components. Application of HVOF deposition of the first TBC layer is really the most prospective solution for enhancement of TZP-3 performance capabilities. It will result in its almost 100% density of the bond coat and extremely high adhesive properties-more than 2 or 3 times higher than could be reached by APS technique. This method gives also an opportunity to implement wider range of materials.

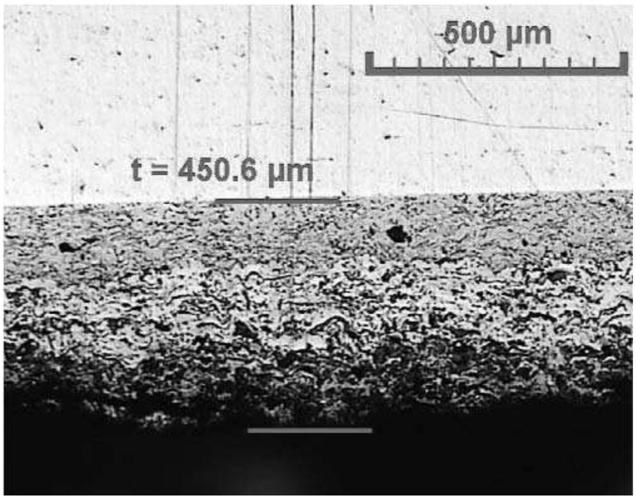

Fig. 4. TZP-3 microstructure photograph of as-sprayed coating

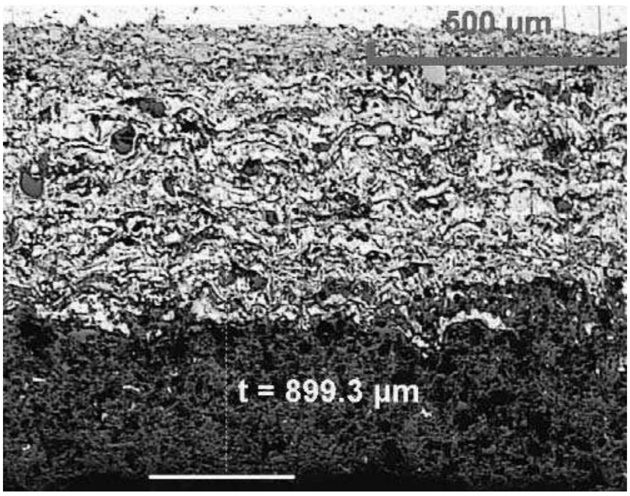

Fig. 5. TZP-3 microstructure photograph of the coating after 9 hours annealing

Summing everything said above, some conclusions can be made.

Conclusions

1. Application of the coatings for the protection of the engineering material operated under high-heat-flux conditions and in an aggressive environment can significantly increase gas temperatures, reduce cooling requirements, and improve engine fuel efficiency, reliability and operating life.

2. Fundamental understanding of sintering and thermal cycling degradation of thermal barrier coating systems under engine high-heat-flux conditions will provide insights into how to further maximize the coating capabilities.

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