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Low cycle fatigue performance of Ni-based superalloy coated with complex thermal barrier coating

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ABSTRACT

Thermal barrier coatings (TBCs) are widely applied to protect high-temperature components against high temperatures in harsh environments. Nineteen cylindrical specimens of Inconel 713LC were manufactured using the investment castings technique, and 10 specimens were subsequently coated with a novel complex thermal barrier coating (TBC) system. The TBC system comprises a metallic CoNiCrAlY bond coat (BC) and a complex ceramic top coat (TC). The TC is a mixture of a near eutectic nanocrystalline ceramic made of zirconia (ZrO_2), alumina (Al_2O_3), silica (SiO_2) and conventional yttria stabilized zirconia (YSZ) ceramic in the ratio of 50/50 in wt%. Low cycle fatigue (LCF) tests were carried out in a symmetrical push-pull cycle under strain control at 900 °C. Cyclic hardening/softening curves, cyclic stress-strain curves and fatigue life curves of the TBC-coated and uncoated material were assessed. Fatigue life curves in total strain representation showed transient behaviour. Fracture surfaces and polished sections parallel to the loading axis of the TBC-coated and uncoated specimens prior and after cyclic loading were observed by means of scanning electron microscopy (SEM) to study the degradation mechanisms during high-temperature LCF. TBC delamination was observed at the TC/BC interface, and rafting of precipitates occurred after high-temperature exposure. The microstructural investigations further the discussion of the differences in the stress-strain response and the fatigue life of the TBC-coated and uncoated superalloy.

1. Introduction

The importance of surface protection against the harsh environments of inlet gases at high temperatures in propulsion units and power generators increases rapidly with industrial demands on the higher efficiency of these devices. The surface of substrate material can be modified in several different ways. Diffusion coatings based on simple and modified aluminides are widely used, and they represent a thoroughly investigated type of coating with excellent corrosion and oxidation resistance [1–8]. However, inlet temperatures in gas turbines often reach up to 1500 °C (1200 °C in contact with component surfaces), and these coatings cannot provide the temperature protection that is needed in particular high-temperature applications. Thermal barrier coating (TBC) systems combine corrosion and oxidation resistance with effective thermal insulation, which is created by the low thermal conductivity of TBCs [9–13]. TBCs are successfully utilized together with an advanced inner cooling system inside the substrate material. A typical example of the substrate material is Ni-based superalloy Inconel 713LC, which was developed six decades ago but is still widely used due to its low price and favourable properties, such as high creep resistance, long high-temperature fatigue life and hot corrosion and oxidation resistance. On the substrate, a metallic CoNiCrAlY bond-coat (BC) layer is deposited to compensate for the significant differences in physical properties of the substrate material and insulating upper layer. Finally, a ceramic insulating top-coat (TC) [9] is mostly based on yttria-stabilized zirconia (YSZ) and its variations. However, the fatigue properties of Ni-based superalloys coated with conventional YSZ TBC coatings have been rarely investigated [14–17]. Low cycle fatigue (LCF) tests performed on uncoated Inconel 713LC and coated with conventional YSZ showed an insignificant effect of the coating on the fatigue life in the Coffin-Manson representation and a decrease of fatigue life in the Basquin representation [14]. The study of Kuba et al. [15] reported a beneficial effect of TBC coating on the fatigue life of Inconel 738LC. On the other hand, Ray et al. [16] showed a detrimental impact of a TBC system on the C263 superalloy in the high-stress amplitude domain and a positive effect for low strain amplitudes. YSZ coatings, however,

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suffer from environmental damage caused by volcanic ash, desert sand and dust, known as calcium-magnesium-aluminium-silicate (CMAS) attack. Therefore, new types of oxide-ceramic TBCs with near eutectic composition have become a subject of interest [18–21]. Fatigue data are, however, very rare. Obrtlík et al. [22] reported the fatigue behaviour of Inconel 713LC coated with $ZrO_2 + SiO_2 + Al_2O_3$ eutectic TCs. The obtained results showed higher fatigue life in high strain amplitudes and a negligible effect of TBC in lower strain amplitudes, compared to the uncoated Inconel 713LC, even though the TC exhibits a number of crack-like defects after heat treatment. The combination of YSZ with eutectic $ZrO_2 + SiO_2 + Al_2O_3$ provided the newly formed TBC with sufficient cohesiveness and resistance to premature cracking during high-temperature mechanical loading [23,24].

Data presented in this paper are part of a more complex research programme aiming at the development of modern and advanced TBC systems for aerospace and industrial applications. The fatigue behaviour of the substrate material Inconel 713LC, as well as Inconel 713LC coated with different types of TBC coatings, has been investigated [14,22,25–29]. High-temperature LCF performance of Ni-based superalloy Inconel 713LC coated with a complex TBC system were investigated in the symmetrical push-pull cycle at a temperature of 900 °C. The degradation mechanisms were studied in detail by means of scanning electron microscopy (SEM).

2. Materials and Methods

2.1. Inconel 713LC

Ni-based superalloy Inconel 713LC was provided by PBS Velká Bíteš, a.s. in the form of button-ended rods made by investment casting which were subsequently machined to final specimen shape with the gauge length roughness R_a of 0.4 μm. The chemical composition in wt% was as follows: 11.98Cr, 4.1Mo, 0.06C, 6.04Al, 0.59Ti, 1.82Nb, 0.05Ta, 0.06Zr, 0.008B, bal. Ni. The substrate material consisted of a coarse dendritic structure with an average grain size of 0.66 mm, measured by the linear intersection method. Casting defects and shrinkage pores were randomly distributed both between and inside the dendritic grains. Microstructure comprises face-centred cubic (fcc) γ matrix channels and coherent fcc γ' precipitates. The typical morphology of γ' strengthening precipitates distributed in the γ matrix is shown in Fig. 1a.

2.2. Surface Treatment

Prior to deposition of the TBC coating, 10 cylindrical specimens were grit blasted by angular brown alumina (Al_2O_3) particles with an F14 particle size. The pressure of blasting air was 5 atm., and the blasting distance was 100 mm with an angle of 90°. Samples were subsequently cleaned in an ultrasonic bath for 10 min to reduce the amount of remnant grit particles and dried with compressed air. Alumina particle remnants can be a source of fatigue crack initiation; however, they do not affect fatigue life in the LCF region at elevated temperatures [26]. The increased roughness (Ra = 10.4 μm) of grit blasted surfaces provides better adhesion of TBC coating to the substrate. Fig. 1b represents the back-scattered electron (BSE) image of the TBC coating of the as-sprayed specimen. The TBC includes CoNiCrAlY BC deposited via air plasma spraying (APS) by an F4MB-XL gun (Sulzer Metco). A plasma torch operated at 600 A (150 kW power) with the flow of 65 slpm of argon and 14 slpm of hydrogen. Spraying distance was 140 mm. Two passes of the plasma gun were utilized to reduce internal stresses within the BC. A commercially available powder (H.C.Starck Amperit 415) with an average powder particle size of 45 ± 22 μm was used for BC deposition. Subsequently, a powder mixture was formed of conventional agglomerated and sintered YSZ (8% wt. Y_2O_3, H.C.Starck Amperit 827) powder with a particle size of 45 ± 10 μm, and a eutectic ceramic powder called Eucor composed of zirconia (ZrO_2), alumina (Al_2O_3) and silica (SiO_2) with a particle size of 40–63 μm. The ratio of the YSZ/EUCOR powder mixture was 50/50 wt %. The powder mixture was plasma sprayed as the insulating TC by a hybrid water stabilized plasma torch (WSP-H 500). The WSP-H torch operated in air at 500 A (150 kW power) with 15 slpm of Argon. The powder mixture was injected into the plasma jet at 70 mm distance from the torch nozzle (feeding distance) at a rate of 75 g/min. The spraying distance was maintained at 300 mm. The rotation of samples during grit blasting and spraying was ensured by a turning machine with the speed of 2000 RPM. The deposition process details and the ternary equilibrium phase diagram of the ZrO_2-Al_2O_3-SiO_2 can be found elsewhere [20,30]. The final surface of the TBC-coated specimens is very rough as can be seen in Fig. 1c.

2.3. Characterization Methods

Qualitative X-ray diffraction phase analysis of the TC after the spraying was performed using Empyrean from PANalytical. The dominant tetragonal zirconia phase was apparent from measured spectra. Peaks of monoclinic zirconia and alumina were also detected as minor phases (not shown here). The average thickness and average porosity measurements of the TBC were accomplished on metallographic sections of the unloaded specimen and three selected specimens after LCF tests using the StreamMotion image analysis system. The Vickers hardness of the TBC coating and substrate material was measured on polished sections using a screw-driven testing machine (ZWICK Z2.5) equipped with a micro-hardness head (ZHU0.2) and with optics using a load of 0.2 kgf (1.96 N). The microstructural investigations were accomplished by means of the scanning electron microscope (SEM; TESCAN Lyra3 XMU) equipped with an energy dispersive X-ray (EDX) spectroscopy analyser.

2.4. Low Cycle Fatigue Tests Specification

For the purpose of the LCF tests, 9 uncoated specimens in as-cast condition and 10 specimens coated with YSZ/Eucor TC + CoNiCrAlY BC were cyclically loaded on the MTS 810 servo-hydraulic testing machine under total strain control conditions at 900 °C in an ambient laboratory atmosphere. We used fully reversed triangular waveform ($R_\varepsilon = -1$) with the constant strain rate of $2 \times 10^{-3}\,s^{-1}$. The total strain was controlled with a sensitive MTS extensometer (632.53F-14) with a 12 mm long base. The extensometer was equipped with 11.7 cm long ceramic tips, and it was placed outside the furnace and cooled by compressed air. Heating was provided by a three-zone resistance furnace. The temperature was controlled by three independent thermoregulators and monitored by three thermocouples attached to the upper end of the gauge length and to both specimen ends. The temperature gradient within the gauge length of a specimen was ± 1.5 °C. The gauge length and diameter of cylindrical specimens were 15 and 6 mm, respectively. The diameter of the TBC-coated specimens ranges from 6.71 to 6.87 mm. Plastic strain amplitude ε_{ap} and stress amplitude σ_a were evaluated from recorded hysteresis loops. The number of cycles to failure was assessed as a number of elapsed cycles when the criterion defined by Eq. (1) was reached or at the time of fracture before the criterion was met. The equation is as follows:

$$\frac{\sigma_m}{\sigma_a} = -0.3, \tag{1}$$

where σ_m stands for mean stress. The value −0.3 relates circa to a surface crack through half of the circumference of a specimen. The details of the high-temperature LCF testing and test evaluation of the TBC-coated materials can be found elsewhere [22].