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Effect of support material creep on the delamination failure of air plasma sprayed thermal barrier coatings

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ABSTRACT

The effect of support material creep on failure of ceramic thermal barrier coating (TBC) was studied. A simplified cylindrical model TBC-system was used: Instead of Ni-superalloy and bond coat (BC) the substrates consisted of a Fe–Cr–Al–Y-alloy with BC-like chemical composition, namely Fecralloy with low creep strength and oxide dispersoid strengthened PM2000 Fe–Cr–Al–Y samples. After sandblasting the substrates surface, yttria stabilized zirconia thermal barrier coatings were applied by air plasma spraying. Slices were extracted from the cylindrical specimens and the lateral slice-surfaces were polished. Then they were thermally cycled to assess the effect of support material creep on delamination induced TBC failure. The damage evolution was examined at the lateral slice cross-sectional surface after different numbers of thermal cycles. The study shows a significant delay and deceleration of delamination crack growth for the low creep strength Fecralloy, in contrast to observations made for the high creep strength substrate material. The experimental results indicate that stresses which promote delamination failure are partially relaxed by creep deformation in the near interface regions, which appear to be more pronounced for support materials with low creep strength.

1. Introduction

Ni-superalloy components in the first stages of gas turbines are typically protected by thermal barrier coating (TBC) systems, which usually consist of a partially Y_2O_3 stabilized ZrO_2 top-coat (P-YSZ) – the actual TBC – and a Ni(Co)–Cr–Al–Y bond coat (BC) on an appropriate substrate material, i.e. cast Ni-base superalloy [1].

The aim of TBC is to increase application temperature and lifetime by reduction of the thermal load of the underlying components. The TBC is typically produced by air plasma spraying (APS) or electron beam physical vapor deposition (EB-PVD). The BC provides adhesion of the TBC to the substrate. In case of APS–TBCs, the BC surface is roughened by sandblasting to improve mechanical adhesion of the TBC [1]. Furthermore, the BC protects the Ni-alloy substrate from oxidation by forming a dense alumina scale (thermally grown oxide, TGO) at high temperatures and accommodates, up to a certain extent, strain mismatches between TBC and substrate by plastic deformation. The BC is usually produced by vacuum plasma spraying (VPS). During high temperature operation, thermal mismatch as well as lateral growth strain and thickening of the TGO (the principles of lateral Al_2O_3-scale growth are described in [2]) result in stresses, which can lead to initiation and growth of delamination cracks and finally to spallation failure of the TBC [1].

Rösler et al. [3] and Bednarz [4] carried out finite element method (FEM) based simulations of a TBC-system with periodic 2-D TBC–BC interface roughness and variable creep strength of the layers. They showed that a low creep-strength BC can significantly reduce the stresses in the system and therefore delay crack formation and extend lifetime. Hence, a quantitative discussion of stresses and the effect of creep of the different layers onto the stress level can be found in [3,4] and the current work focused on the experimental verification of the theoretical predictions described in these works [3,4].

The current work presents therefore an experimental study of this creep related effect on TBC damage during thermal cycling of cylindrical samples. To exclude the influence of interdiffusion between superalloy and BC on the damage, a simplified model system without Ni-superalloy substrate was studied. Instead of superalloy and the VPS-BC, bulk specimens completely made of conventional produced material (not plasma-sprayed) with similar composition as a usual BC were used. Instead of Ni(Co)–Cr–Al–Y, as available materials with sufficiently different creep strengths two Fe–Cr–Al–Y alloys were used to model BCs with different creep strengths (creep properties reported in [5]): 1.) a conventionally casted low creep strength Fecralloy and 2.) a powder-metallurgically produced oxide dispersoid strengthened PM2000. For example under a tensile stress of 100 MPa at 900 °C (reported in [5]), Fecralloy has a secondary creep rate of approximately $9 \cdot 10^{-2}$–$1 \cdot 10^{1}\ s^{-1}$ (estimated by linear regression), whereas PM2000 has a largely different secondary creep rate of approximately $3 \cdot 10^{-4}\ s^{-1}$.

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That implies that Fecralloy has at least a ~300 times higher secondary creep rate than PM2000 under these stress/temperature conditions.

2. Experimental

To vary the creep strength, conventional Fecralloy Eisen-Chrom™ with relatively low creep strength and oxide dispersoid strengthened (ODS) PM2000 were used. Fecralloy was delivered by GoodFellow as rod (diameter = 10 mm) with 4.84 wt.% Al, 21.8 wt.% Cr and <0.005 wt.% Y. PM2000 was fabricated by Plansee as rod (diameter = 50 mm) with 5.2 wt.% Al, 20.0 wt.% Cr and 0.39 wt.% Y as Y_2O_3-dispersoids.

Cylindrical samples of both substrate variants were produced with a length of 30 mm and a diameter of 9 mm. The surfaces were roughened by sandblasting (grain size of 60–120 μm) at Technische Universität Braunschweig, IfW, which resulted in a roughness depth R_z of 7.7 μm. Then a ~300 μm thick 8% partially yttria-stabilized zirconia air plasma-sprayed thermal barrier coating was deposited at Technische Universität Braunschweig, IfW.

Slices were extracted from the cylindrical samples of both substrate variants (Fig. 1a and b). The dashed contour line on the cylindrical sample in Fig. 1a) indicates the extracted slice. In the following, the free lateral cross section surface of the slice in Fig. 1b) is called "lateral slice-surface". The lateral slice-surfaces at both slices were grinded and polished to enable the microscopic examination. The viewing direction of the microscopy is illustrated in Fig. 1b) by a 3-dimensionally drawn arrow and the examined region is marked by a perspectival tilted rectangle.

The specimens were thermally cycled up to a maximum cycle number of 1161 cycles by moving them automatically into and out of a tube furnace [6]. The minimum and maximum temperatures were 60 °C and 1050 °C, respectively. The dwell time at maximum temperature was 2 h and the heating and cooling time 13.3 min. Damage was observed at the lateral slice-surface by light microscopy after certain cycle numbers up to a cycle number of 631 cycles.

3. Results

Figs. 2 and 3 show micrographs of the lateral surface of the slices extracted from the cylindrical samples before thermal cycling and after certain cycle numbers. Each image presents the same position on the sample. The following phenomena become obvious from these images.

Before thermal cycling (cycle 0) no damage is visible, except of the usual small intersplat cracks in the TBC. After 1 cycle segmentation cracks have formed along the entire sample circumference in the TBC for both substrate variants. These cracks are less pronounced for the high creep strength PM2000 than for the low creep strength Fecralloy substrate. With further cycling the number of segmentation cracks increases, while their separation decreases. In case of the low creep strength Fecralloy substrate, 90 segmentation cracks with a median separation (including all segmentation cracks) of ~300 μm were observed after 1161 cycles. In case of PM2000 substrate, after 802 cycles 37 segmentation cracks with a median separation (including all segmentation cracks) of ~760 μm were observed.

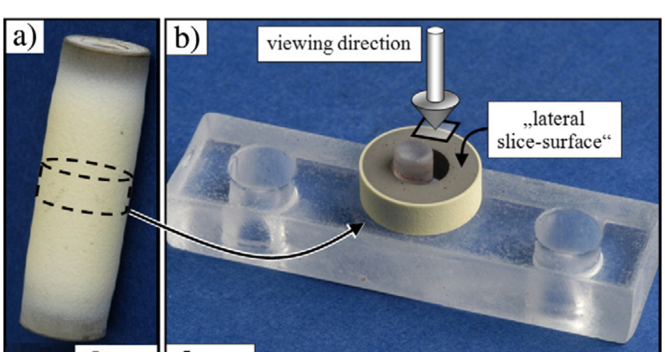

Fig. 1. a) Coated cylindrical sample, the extracted slice is indicated, b) the extracted specimen slice placed on the sample holder.

For the Fecralloy substrate, the width of approximately every second to third of the segmentation cracks of the TBC increased continuously and in most cases almost linearly with increasing cycle number (Fig. 4). The width of the other segmentation cracks remained almost constant. The widening rates were between 0.003 and 0.065 μm/cycle, with a median of 0.034 μm/cycle. After 631 cycles the measured width values were ~8 to 47 μm, with a median of 21 μm. In contrast, no widening of the segmentation cracks in the TBC on the PM2000 substrate occurred.

After 71 cycles significant plastic deformation of the Fecralloy substrate became visible at the tip of the segmentation cracks (darker area underneath the segmentation crack in Fig. 2 at cycle 71, marked by an arrow). In contrast, no such deformation features were found in the PM2000 substrate close to the segmentation cracks. After 166 cycles the segmentation cracks in the TBC on Fecralloy substrates penetrated the substrate, branched and led to local oxidation that progressed with every further cycle.

The TBC and the region close to the TBC/substrate interface at both sample variants are obviously elevated with respect to the central part of the slice surface (substrate material loss due to oxide scale spallation was not observed). This was observable because of the polishing of the lateral slice-surface prior to the microscopy investigation step of specimens after certain cycle numbers (for the Fecralloy-substrate sample after ≥118 cycles; for the PM2000-substrate sample after ≥1 cycle except after 31 cycles). That was carried out to remove the oxide scale which formed on the lateral slice-surface on the substrate (dark area underneath the TBC in Figs. 2 and 3), in order to make the TGO scale in the TBC–substrate interface visible and to improve the contrast between the substrate and delamination cracks. In doing so often only the TGO and a very limited amount of substrate material close to the interface were removed by polishing both substrate variants (visible as a bright white strip at the interface, marked in Fig. 2 at cycle 118 and in Fig. 3 at cycle 1 by arrows). This indicates that this region obviously is elevated with respect to the central part of the lateral slice surface (material loss due to oxide scale spallation was not observed). For the P2000-substrate sample this was only the case after 1, 120, 420 and 628 cycles (see Fig. 3). In the other cases (after 70, 151, 221 and 292 cycles) the whole oxide scale was reached by polishing, indicating a significant lower elevation of the near-interface region at the P2000-substrate. The different height-levels of the substrates at both substrate variants could be confirmed at cross-sections of the sample shown in Figs. 5 and 6. These figures indicate expansion of the TBC and the substrate in the near interface regions in axial direction of the sample. Note that the height-level difference between substrate surface and center is much less pronounced for the high creep strength PM2000 substrate (Fig. 6).

Moreover, there are larger zones visible at the lateral-slice surface of the low creep strength Fecralloy-substrate sample underneath nearly all segmentation cracks after ≥118 cycles (marked at cycle 118 by an arrow, i.e. at those locations where plastic deformation took place after ≥71 cycles), where the oxide scale was also removed by polishing and therefore is obviously elevated, too. Such zones were not found in PM2000 substrate samples.

The cross-section of the Fecralloy substrate sample additionally revealed that the TBC is bended towards the substrate (Fig. 5a), indicating expansion of the TBC and/or the TGO in the axial direction of the sample. This curvature effect was not found for PM2000 substrate samples.

The TBC was adherent on the Fecralloy substrate in most regions even after 631 cycles, except near segmentation cracks, where delamination cracks with a length of around 100 μm were observed after