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Damage evolution of a thermal barrier coating system with 3-dimensional periodic interface roughness: Effects of roughness depth, substrate creep strength and pre-oxidation

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ABSTRACT

Damage evolution during thermocyclic loading of atmospheric plasma sprayed thermal barrier coating (TBC) systems with 3-dimensional (3-D) periodical quadratic, hexagonal and stochastical interface roughness was compared. Furthermore, effects of roughness depth, substrate creep strength and pre-oxidation were investigated. As substrates planar Fecralloy EisenChrom™ was used. The samples with periodical hexagonal roughness showed on average near cubic oxidation kinetics and faster oxidation at the roughness valleys than at the peaks. The coatings on all samples with 3-D quadratic roughness failed immediately after TBC-deposition. For the other profiles excessive segmentation and continuous crumbling of the TBCs occurred. However, the coatings mostly did not spall-off during 836 oxidation cycles. Thermography permitted to detect <1 mm diameter spot-shaped initial delaminations (IDs) that formed during thermal cycling. With progressive cycling their number and area increased until they merge. The positions where IDs formed correlated with locally larger TBC thicknesses associated with the spray path during TBC deposition. Samples with pre-deposited oxide layer showed significant larger delamination areas after thermal cycling. Sample bending towards the TBC and deformation of the substrate below the TBC occurred, indicating stress relaxation. Despite the partially large delaminations, this relaxation led to the prevention of macroscopic TBC detachment and large area spallation till the end of the thermal cycling tests. Cross-sections of the 3-D periodic roughened samples revealed no effect of the roughness depth on the amount of cracking or on damage evolution after certain cycle numbers.

1. Introduction

To protect blades and vanes in the first stages of gas turbines from overheating, they are coated by partially Y_2O_3 stabilized ZrO_2 (P-YSZ) thermal barrier coatings (TBC). The coating is typically applied by air plasma spraying (APS) or electron beam physical vapor deposition (EB-PVD) [1]. An underlying Ni(Co)–Cr–Al–Y interlayer, deposited by vacuum plasma spraying (VPS), protects the base material from hot corrosion by forming a dense Al_2O_3-scale (thermally grown oxide, TGO) at high temperatures [2]. Additionally this interlayer accommodates, up to a certain extent, strain mismatches between TBC and base material by plastic deformation. In case of APS-TBCs the surface of the Ni(Co)–Cr–Al–Y interlayer is roughened by sandblasting to provide a good bonding to the base material [3]. Therefore this interlayer is commonly called bond coat (BC). The base material is usually a Ni-base superalloy to ensure adequate creep resistance under operationally induced loads.

During thermal cycling of the turbine, stresses arise in the layered system due to differences in thermal mismatch. Additional stresses are induced by the lateral growth and thickening of the TGO. These stresses can lead to initiation and growth of delamination cracks typically located in or close to the TBC-BC interface finally resulting in spallation of the TBC that terminates the lifetime of the component [4]. Spallation of TBC leads to overheating of the respective component and can damage other parts of the turbine. To prevent this, components have to be removed and repaired before failure. Therefore TBC-lifetime prediction is an important aspect in current research efforts on TBC systems.

It has been verified in previous, mostly experimentally based investigations that stresses [5–7] as well as crack formation and lifetime [6, 8–16] of a TBC strongly depend on the interfacial roughness and TGO thickness. Furthermore, the effect of interface roughness on the stress state was studied numerically by finite element method (FEM) simulations [8,17–26]. For model development a periodic TBC-substrate interface roughness was assumed in these studies to reduce calculation complexity. Hence, for validation of these modeling results a comparison to experimental studies on real systems with similar periodic roughness is needed. To permit more accurate lifetime estimations, it would be an advantage to decrease lifetime scatter that might be related to local roughness undulations, where a periodically roughened real interface appears to be a promising approach.

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Initial experimental studies with 2-D periodically roughened cylindrical samples with different roughness depth [27] were not successful and led to very low lifetimes. Therefore, the current work aims at a clarification of the interface roughness effect and pre-oxidation for 3-D periodic interface roughness profiles. Additionally, comparative tests were made with stochastic (sand-blasted) interface roughness. To exclude the effect of interdiffusion and thermal mismatch between BC and Ni-base material, the coating was directly deposited on bulk material with similar chemical composition as used for BCs. However, planar samples were used for simplification. Nevertheless, the results are complementary to the mentioned thermal cycling tests with cylindrical 2-D periodic and also with stochastic (sand blasted) roughened samples with the same substrate material and different roughness depth, which were already presented in an earlier work [27].

2. Experimental

The initial aim of the study was to investigate the effect of interface roughness depth and additionally of the creep strength of the BC on the damage behavior of a ZrO_2-TBC. To exclude the influence of the Ni-base superalloy on the thermal mismatch stresses and the effect of interdiffusion between the superalloy and the BC on the damage behavior, the superalloy was absent and a BC-like material was used as substrate for the TBC instead. Due to the fact that VPS-Ni/CoCrAlY-BCs are not producible with sufficient low creep strength, conventionally casted and rolled Fecralloy Eisen-Chrom™ was used as a model alloy for the VPS-BC, since it is available with relative low creep strength [28] and has similar chemical composition compared with usual Ni/CoCrAlY-BCs. Fecralloy was delivered by GoodFellow as rod (diameter 16 mm) with 4.84 wt.% Al, 21.8 wt.% Cr and $<$0.005 wt.% Y. Disk-shaped flat samples were extracted from this rod with a diameter of 16 mm and a thickness of 2 mm.

Periodic, 3-dimensional (3-D) surface structures with quadratic and hexagonal shape were applied directly into the substrate surface by laser ablation at Fraunhofer Institute for Laser Technology, Aachen (ILT). The wavelength was 40 μm and the roughness depth was either 10 or 20 μm. After structuring, some of the specimens were pre-oxidized at 1050 °C for 220 h resulting in an oxide thickness of 2.0 μm. Additional samples were produced with stochastic roughness by sandblasting (sand grain size of 60–120 μm) at Technische Universität Braunschweig (IfW), resulting in an average roughness depth of $R_z =$ 7.7 μm, without pre-oxidation. Finally a ~150 μm thick 8% P-YSZ APS TBC was deposited at Sulzer LTD Switzerland. From each variant 6 specimens were produced. The different roughness profiles prior to deposition of the Al_2O_3-layer and the TBC are exemplified in Figs. 1 and 2. A coated specimen is illustrated in Fig. 3.

For samples with 3-D periodic hexagonal roughness, the Al_2O_3-scale thickness d after oxidation at 1050 °C was measured at cross-sections as a function of exposure time t. The data were fitted via the commonly used relationship $d = kt^{1/n}$ where k and n are the fitting parameters [29].

The specimens were thermally cycled by moving them automatically into and out of a tube furnace [27]. The minimum and maximum temperatures were 60 °C and 1050 °C, respectively. The dwell time at maximum temperature was 2 h and heating and cooling times were 13.3 min each.

Damage was observed by infrared pulse thermography [27] and by SEM at cross-sections in the early stages of the thermal cycling test after 100–300 cycles and after advanced damage after 836 cycles (the maximal tested cycling number, when the test was aborted, because of extensive crumbling of the TBC). In the thermographic images green and green-yellow areas typically represent adherent TBC. Yellow and red areas indicate delaminated TBC, where red areas indicate more extensive delamination crack opening than yellow zones. The spatial resolution of the used IR pulse thermography is 0.5 mm.

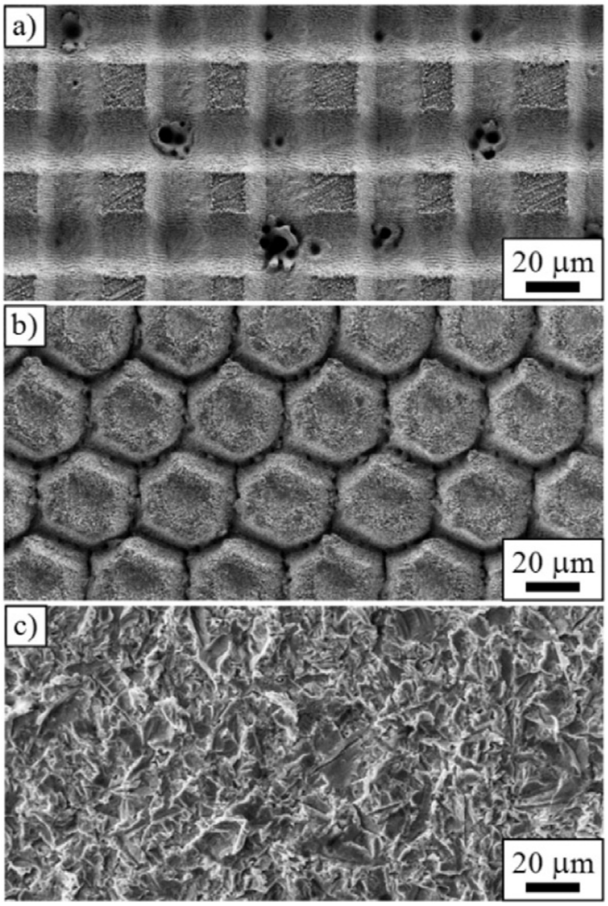

Fig. 1. SEM-image of the sample surface after inducing the roughness: a) 3-D periodic quadratic (laser-ablated), the black marks are related to manufacturing errors (molten metal), b) 3-D periodic hexagonal (laser-ablated), c) 3-D stochastic (sand-blasted).

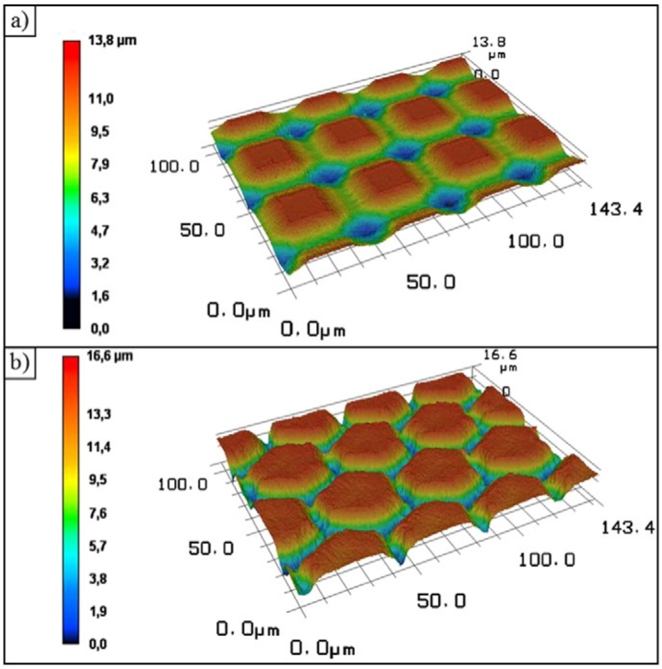

Fig. 2. Confocal-laser-scanning-microscope image of a sample surface after inducing the roughness: a) 3-D periodic quadratic (laser-ablated), b) 3-D periodic hexagonal (laser-ablated).

The amount of delamination cracking was assessed by measuring the respective gap area at TBC cross-sections in the early stages of the thermal cycling test after 100–300 cycles with the phase measuring