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Determining a critical strain for APS thermal barrier coatings under service relevant loading conditions

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ABSTRACT

Despite the huge progress made in recent years in analysing the degradation behavior and the reliability of thermal barrier coating systems, there is still some deficit in the capability to predict damage evolution in terms of crack initiation and crack growth, which ultimately leads to macroscopic delamination and spallation of the coating system. In order to obtain this prediction capability, a fundamental understanding of the damage evolution processes under isothermal, thermo-cyclic and under thermo-mechanical loading conditions has to be developed.

The aim of the presented work is to determine the critical strain, i.e. the strain at which cracking initiates, and to analyse the evolution of a network of cracks for widely used atmospheric plasma sprayed (APS) thermal barrier coating (TBC) systems. The TBC system has been exposed in our study to service relevant loading conditions, namely to thermal gradient mechanical fatigue (TGMF). TGMF tests for in-phase as well as out-of-phase loading cycles were performed on hollow cylindrical specimens made of the single crystal super alloy CMSX-4, loaded mechanically in ⟨001⟩ orientation, and being coated with a duplex system comprised of a CoNiCrAlY bond coat and a 8 wt.% Yttria partially stabilized Zirconia (YSZ) TBC. The CoNiCrAlY bond coat was deposited by Low Pressure Plasma Spraying (LPPS), while the ceramic top coat was deposited using the APS process. The loading cycles were chosen to represent an industrial gas turbine engine. Critical strains measured for delamination (within the ceramic coating or at the CoNiCrAlY – TBC interface) and through cracking, i.e. segmentation of the ceramic top coat was determined using a special compression test equipped with in situ acoustic emission technique. The mechanical testing was performed at room temperature after TGMF exposure. In order to study the impact of thermally grown oxide (TGO), specimens have been TGMF tested in the "as received" conditions as well as after isothermal aging (up to 3000 h at 1000 °C). To correlate the signal obtained by acoustic emission (AE) with the evolution of (micro-) cracks, the specimens have been carefully sectioned and investigated by standard metallographic means.

The measured critical strains are used as a data basis for a strain-based lifetime model developed for isothermal and cyclic oxidation as well as thermo-mechanical loading. The lifetime model considers two failure modes, namely delamination and (vertical) through cracking.

Metallographically obtained crack patterns within the TBC system have been incorporated into finite element models to quantify stress–relaxation as a consequence of damage evolution in the TBC system.

The observations show that thermal gradient fatigue loading under in-phase loading leads to a shorter lifetime compared to out-of-phase loading.

For the delamination mode, the critical strain values of the model are in good agreement with the experimental data of the TGMF experiments. The modeled critical strain for through cracking, on the other hand, is consistently lower than the experimentally determined failure strains, implying that the model describes the failure situation in a conservative manner.

1. Introduction

Turbine blades with thermal barrier coatings are under service condition exposed to high thermal and mechanical loading, which might lead to degradation and ultimate failure of the TBC system. There are still significant knowledge gaps in the description of crack

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Nomenclature

$\Delta\varepsilon_m$	mechanical strain range (%)
ε_C	critical strain
σ	stress (MPa)
t_1	time at start-up (min)
t_2	hold time at T_{max} (min)
t_3	time at shut-down (min)
t_4	hold time at T_{min} (min)
t_c	cycle period (min)
t_{ox}	pre-oxidation time (h)
R_a	bond coat roughness (μm)
ε_{11}	radial strain
σ_{11}	radial stresses (MPa)
ε_{22}	axial strain
σ_{22}	axial stresses (MPa)
N	number of cycles
IGC	industrial gas turbine cycle
TBC	thermal barrier coating
TGO	thermally grown oxide
BC	bond coat
TGO/TBC	interface cracks between the TGO layer and TBC layer
TGO/BC	interface cracks between the TGO layer and BC layer
TGO + TBC	cracks in TGO layer and in TBC layer, who are connected together

initiation and crack growth up to the delamination of thermal barrier coating systems as well as crack arrest effects in interaction with load and component. The modeling of crack propagation processes to the point of life prediction is therefore an important task for future development of thermal barrier coatings in stationary gas turbines. Different approaches to describe the damage process can be used.

Investigations suggest that the reliability of a TBC system is influenced by the roughness of the bond coat – TBC interface [1–3] and by the TGO-thickness. The evolution from microscopic cracks to macroscopic cracks was described in [5–8] by introducing a critical TGO-thickness, which varies with the surface roughness, the TBC system and the loading type. It was found that a sufficiently large TGO-thickness can lead to large-scale delamination of the TBC [4–6]. Furthermore, investigations demonstrated that a bond coat roughness of R_a = 10 μm contributes to higher lifetimes than a bond coat roughness of only R_a = 7 μm [2].

The aim of this work is to determine the critical strain for delamination and through cracking from experiments under thermal gradient mechanical fatigue loading (TGMF) to obtain a characteristic strain value for the failure of APS TBC systems. The results of critical strain data are presented and compared with respect to the thermo-mechanical cycle type (IP: in-phase, OOP: out-of-phase). Furthermore, the evolution of a network of cracks in thermal barrier coating systems is analyzed. Dependent on the loading type the cracks are quantified and classified by measuring the maximum crack length in each layer. Finite element analysis should reveal the local stress contribution in TBC systems claimed for TGMF under in-phase and out-of-phase loading, in order to get a better understanding of the damage process and the corresponding crack analysis.

2. Material and specimen preparation

In order to obtain a geometry resembling the leading edge of a turbine blade, a thin-walled hollow specimen was designed (Fig. 1).

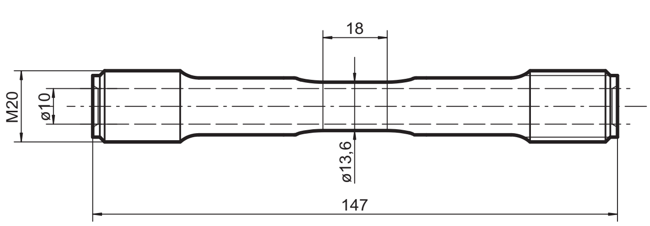

Fig. 1. Hollow specimen for the thermal gradient mechanical fatigue (TGMF) experiments.

The specimens were machined from bars out of the single crystal super alloy CMSX-4 (crystallographic orientation ⟨001⟩ in axial direction) and coated by Low Pressure Plasma Spraying (LPPS) with a metallic (CoNiCrAlY) bond coat in thicknesses between 230 and 260 μm. The chemical composition is given in Table 1.

The 8 wt.% Yttria (Y_2O_3) partially stabilized Zirconia (ZrO_2) ceramic top coat was deposited by means of air plasma spraying (APS) in thicknesses between 300 μm and 350 μm. In order to reduce the amount of time that one single specimen remains in the TGMF test rig, the specimens were isothermally pre-oxidized at 1000 °C in air (pre-oxidation time t_{ox}) prior to the TGMF experiments. The specimens were oxidized for 1000 h in order to establish values of the TGO-thickness of approx. 5 μm. Only one hollow specimen was oxidized isothermally for 3000 h at the same temperature (1000 °C) (Table 2).

3. Experimental procedure

The isothermally pre-oxidized hollow specimens were tested in a TGMF test rig for significant test durations (Table 2). Subsequently, the TGMF specimens were loaded under compression load at room temperature to determine the critical strain for delamination and through cracking.

3.1. TGMF test condition

TGMF-tests on hollow specimen under in-phase (IP) and out-of-phase loading (OOP) were performed in a strain control mode for industrial gas turbine cycle as shown in Fig. 2. The cycle temperature represents the bond coat surface. The cycle starts at a minimal temperature of T_{min} = 60 °C followed by heating period of 4 min until the maximum dwell temperature of T_{max} = 930 °C is reached. The hold time at this temperature is 8 min in order to enable a stress reduction in the TBC system by relaxation. The shut down is 4 min followed by a dwell time of 4 min at minimum temperature. The TGMF-tests were performed under strain control with a mechanical strain range $\Delta\varepsilon$ of 0.3%.

The mechanical load was applied by a servo-hydraulic testing machine and the thermal loading with a radiation furnace powered by halogen lamps (Fig. 3). The bond coat temperature was measured at the shoulder of the sample with a thin wire thermocouple (∅0.5 mm, type S) attached by means of a specially designed mounting device [2]. A pyrometer was also used to monitor the surface temperature. The specimen displacement was measured by a dual acting side-contact extensometer. At the contact points of the thermocouple and the extensometer, the ceramic coating was removed by grinding to measure displacement and temperature at the surface of the metallic bond coat. High cooling rates were achieved with external air cooling initiated during the