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Probabilistic lifetime model for atmospherically plasma sprayed thermal barrier coating systems

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ABSTRACT

Calculations of atmospherically plasma sprayed thermal barrier coating durability were facilitated by the development of a numerical lifetime model including probabilistic fracture mechanical analyses of thermally induced topcoat stress field evolutions. The stress distributions were determined in finite element analyses taking into account oxide scale growth and topcoat sintering as transient degradation effects. The influence of interface microstructure was investigated by implementing two different interface approximation functions. Subsequent fracture mechanical analyses of subcritical crack growth were performed at numerous different and permanently assigned abstract crack positions. A comparison of the transient energy release rate to its critical value, which depends on crack length and therefore position, results in statistical distributions of system lifetime as a function of simulated thermal cycling conditions. The model was calibrated by presetting an experimental lifetime distribution which was determined in thermal cycling experiments performed at a burner rig facility. The associated cycle-dependent calibration parameter reflects the effect of fracture toughness increase for increasing crack lengths. Experimental reference values for system lifetime were found to be reproduced by the lifetime model. The stress field inversion directly correlated to oxide scale growth rate was identified as the main failure mechanism. The expectation values and standard deviations of the calculated lifetime distributions were found to be in accordance to the experimentally obtained lifetime data and the data scattering typically observed in thermal cycling.

1. Introduction

State-of-the-art gas turbine designs rely on heat exposed components to resist progressively higher gas inlet temperatures, which are strongly requested for achieving higher efficiencies of power generation (Padture et al., 2002). In land-based gas turbines, an increased heat resistivity of these components is implemented by internal vane and blade cooling and the application of thermal barrier coatings (TBCs) by atmospheric plasma spraying (APS). TBC systems are composed of the ceramic APS topcoat providing low thermal conductivity and a metallic bond coat (BC) often produced by vacuum plasma spraying, which ensures sufficient bonding of the topcoat to the substrate and protects the latter against oxidation. The typically high aluminum content of the BC alloy leads to the formation of a dense oxide layer (thermally grown oxide, TGO) mainly consisting of alpha alumina at the topcoat–BC interface during system operation under extreme thermo-cyclic loads.

TBC systems are prone to stress induced failure due to the mismatch of the thermal expansion coefficients of the individual layers (Evans et al., 2001). The failure results in a complete loss of the protective function endangering the secure operation of the entire turbine system. Reliable assessments of TBC system durability under service conditions are therefore highly demanded. Resorting to experimental findings,

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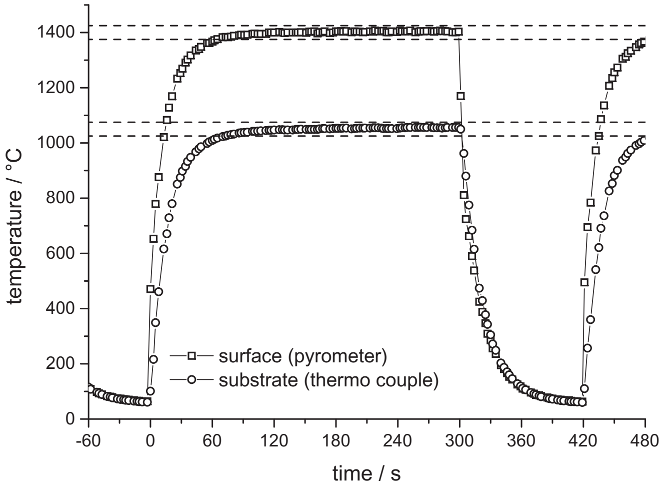

Fig. 1. Typical temperature readings for surface and substrate temperature during heating phase (start at 0 s) and cooling phase (start at 300 s). Dashed lines indicate the tolerance level of +/− 25°C of the target temperatures in the heating phase of the experiment.

TBC lifetime models are developed simulating failure correlated to crack propagation as consequence of thermo-cyclic loading. These models enable to calculate the expected secure service time. Moreover, the modeling involves the identification of lifetime limiting mechanisms contributing to exploration of approaches for an optimization of system performance.

By the majority, these lifetime models include finite element (FE) analyses of thermally induced stress fields comprising analytical approximation functions for interface topography. Within these models, different failure criteria are used formulating critical quantities to determine system failure on the theoretical level. Some of the studies deal with comprehensive parameter variations with regard to creep rates, interface approximations, oxide scale growth, and their effects on FE results contributing to an essential basic knowledge about stress field determination methodology (Ahrens et al., 2002; Seiler et al., 2010; Träger et al., 2003; Rösler et al., 2004; Bäker et al., 2005; Rösler et al., 2001; Martena et al., 2006). Conclusions regarding the system lifetime are partly drawn directly on the basis of stress field calculation results (Rösler et al., 2001; Martena et al., 2006; Busso et al., 2001; Busso et al., 2001; Kyaw et al., 2013; Schwarzer et al., 2004). Advanced lifetime models include fracture mechanical approaches which enable to calculate subcritical crack growth subsequent to the stress field calculations (Träger et al., 2003; Vaßen et al., 2001; Kerkhoff, 2000; Oechsner, 2001; Vaßen et al., 2009). These modeling approaches have in common, that crack propagation initiated by oxide scale growth leads to topcoat spallation. Failure of the systems is often determined by an energy release rate criterion (Oechsner, 2001; Vaßen et al., 2009; Bäker, 2012; He et al., 2003; Shinozaki and Clyne, 2013).

The present study introduces a statistical interpretation of the thermally induced transient stress fields. Topcoat stress distributions are calculated in FE analyses including microstructural effects and transient thermally induced processes enforcing crack propagation. These distributions are considered in fracture mechanical analyses of subcritical crack growth leading to a probabilistic analysis based on an energy release rate criterion. The theoretically obtained results are compared to reference lifetimes observed in experiments using a thermal gradient burner rig facility.

2. Experiments

Disk-shaped samples with a diameter of 30 mm and 3 mm thick IN 738 substrates were coated by vacuum plasma spraying with 150 μm thick Amdry 386 (Oerlikon Metco, Wohlen, Switzerland) NiCoCrAlY BCs and by APS with 400 μm thick yttria-stabilized zirconia (7 wt% YSZ) topcoats. Before topcoat deposition, the mean surface roughness S_a and the root mean square gradient S_{dq} were measured by using a confocal laser scanning microscope (Keyence VK-9700K, Neu-Isenburg, Germany).

For lifetime determination, the TBC-system samples were cycled in burner rig test facilities (Steinke et al., 2010; Träger et al., 2003), in which recurrent temperature gradients between alternately heated and cooled sample front and permanently cooled substrate rear side were generated. During the experiments, temperature evolutions were tracked at two positions. The topcoat surface temperature was measured by a pyrometer and a thermocouple was used to measure the temperature at the substrate center. One cycle comprised 5 min of heating and 2 min of cooling. Fig. 1 shows a typical evolution of surface and substrate temperatures. In the heating phase, stationary conditions are typically reached within 1 min with temperatures in a range of target temperature +/− 2% (e.g. surface temperature 1400°C +/− 25°C). At the end of the high-temperature phases, cool down takes place with an initial sudden temperature decrease and a final state with temperatures well below 100°C (typically below 70°C) and with negligible temperature gradients. Acoustic emission analyses (Ebert et al., 2013) revealed that enhanced crack propagation proceeds during rapid cooling. Topcoat spallation as consequence of stress induced crack propagation within the topcoat and in the vicinity of the BC interface was the most prevalent failure type.