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Deformation and cracking near a hole in an oxide-forming alloy foil subjected to thermal cycling

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Abstract

This work investigates the behavior of a hole on an alumina-forming alloy coupon subjected to thermal cyclic loading. The experiments, performed using a unique facility, revealed that a hole often deformed and cracked. To explain the phenomenon, the stress near a hole and the consequent deformation or cracking were analyzed and traced according to the loading cycles by theoretical approaches based on material properties of thermally grown oxide (TGO) and the substrate, including creep deformation, oxidation rate and growth strain, some of which were also measured by the facility, while others, such as the temperature-dependent material properties, were realistically assumed. The analytic solution for a two-dimensional model gave fairly good estimations of the mechanical behavior of the holes in comparison with the experimental observations, and the analytic solution was validated by numerical analysis for a three-dimensional model with TGO on the lateral surfaces. These results demonstrated that, without the cooling air flow, the subsequent thermal gradient or underlying bond-coated superalloy, deformation or cracking may occur near the cooling holes in turbine blades in gas turbine engines purely by thermal cycling, depending on the number of loading cycles.

Keywords: Thermal barrier coating; Thermally grown oxide; Gas turbine; Hot corrosion; Crack

1. Introduction

To protect turbine blades in gas turbine engines from hot corrosion and other damage, thermal barrier coatings (TBC) and film cooling have been used. In film cooling, cool air is bled from the compressor stage, ducted to the internal channels of the turbine blades, and discharged through small holes on the blade surface, creating a film of cooling air that further protects the blade surface from the hot mainstream flow [1]. Many studies have been reported on the thermal distribution near a cooling hole [1–5]. The TBC system shielding the metal substrate against high temperatures typically consists of four layers: the top porous zirconia coating; the thermally-grown oxide (TGO) layer; the bond coat (BC); and the underlying superalloy substrate [6]. As a result of the chemical reaction between metal cations and oxygen anions, which diffuse outwards from BC and inward from the air at high temperatures, respectively, the TGO layer forms to help protect the underlying substrates from high-temperature corrosion. During service, however, a substantial level of stress is generated within the TGO layer, as the TBC system is subjected to thermal cycling. The induced stress can cause the TGO layer to separate, buckle and even crack [7–9].

Two sources of the stress created in the TGO layer can account for the TBC failure mechanism. One is the mismatch of the coefficients of thermal expansion (CTE) between the TGO and the metal substrate. The other is the TGO formation in the lateral (in-plane) direction. At high temperatures, a portion of the new TGO forms along the boundaries between the existing TGO grains that grew vertically from the interface and pushes the neighboring, existing TGO grains toward two lateral sides. This pushing results in compressive stress in the TGO layer. When cooled to room temperature, this stress may increase up

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to 3–6 GPa because of the added stress due to the mismatch of the CTE [6,10–12].

TGO instability is also affected by initial geometric imperfections such as undulations or grooves pre-existing on the interface with the BC. According to the experiments of Mumm et al. [13], the amplitude of a surface undulation was increased as the TGO thickened upon thermal cycling. Spitsberg et al. [14] extended theses experiments and investigated the effects of various grit-blasting processes of the initial BC surface on the TGO instability. TBC durability was significantly enhanced by the pretreatment that removed the imperfections on the BC surface. Rebollo et al. [15] used Fecralloy™ coupons with a single groove on the surface and showed that the edges of the groove displaced upwards, while the base displaced downwards during each thermal cycle accompanying oxidation. In contrast, in the isothermal case, the displacements were minor.

For analysis of the thermal stress occurring near an imperfection on the substrate subjected to thermal cycling, Hsueh and Fuller [16] and Hsueh [17] used a model consisting of three concentric spherical (or cylindrical) shells of TBC, TGO and BC. Then, the residual radial stresses at the TBC/TGO and the TGO/BC interfaces as functions of the TGO thickness were presented. Karlsson et al. [18,19] explored a more fundamental understanding for the one-way displacement of TGO by devising a spherically symmetric model with a thin shell and the surrounding medium, which represented the TGO and the BC, respectively. In the model, the displacement of the TGO was monitored as the system was subjected to various thermal cycling histories. Segments of the cyclic thermal history were defined by the occurrence of yielding in the BC and TGO. A numerical simulation by the finite element method was used to verify the main implications of the results obtained from the analytic model. However, in their studies, several important material properties were assumed or idealized, not based on experimental measurements. For example, the yield strengths of TGO and BC were assumed to be constant, regardless of temperature and regardless of whether they were in a state of tension or compression.

Recently, Kang and his colleagues [20,21] developed a noble small-scale material tester that can measure the mechanical properties of an alloy at high temperature, using a ribbon specimen. The high temperature was achieved by Joule heat, which was generated by the electricity passing through the specimen. With this method of heating, the specimen did not have to be enclosed by heating elements, so it was exposed for in situ observation. A loading device taken from a precision balance varied the load level by moving a counter-mass, which was controlled remotely. This tester has been used successfully to measure the creep properties of alumina or chromia TGO and substrate metals at high temperature [22–25]. And also the measured tensile or creep properties of TGO and substrate alloys were used for finite element analysis (FEA) of the morphological changes near a surface groove [26,27]. The result showed fairly good agreement with the experimental observations, validating the material property data and the effectiveness of this tester.

The present authors suspect that the cooling hole could be another major source of TBC failure, in addition to the surface groove or unevenness. In fact, a number of papers have reported cracking near cooling holes in turbine blades. Mostly, temperature gradients associated with air passing through the holes are regarded as a main source of stress or failure occurring near the holes [28,29]. However, it has been also reported that the holes could be stress concentrators inducing cracks, regardless of air flow through them [30,31]. Whatever the cause, if excessive deformation or cracks occur near a cooling hole and, consequently, the TGO layer and the over-laying zirconia top coat fail, hot corrosion will concentrate in the region and, finally, cracks will initiate in the underlying superalloy. In this work, as a preliminary model study of the cooling holes as stress concentrators without consideration of the cooling air flow, the subsequent thermal gradient or underlying bond-coated superalloy, the mechanical behavior near a hole in a foil subjected to thermal cycling is investigated. Coupons of an alumina-forming alloy with a circular hole at the center were used as specimens. Deformation and cracking occurring near the holes of the specimens were monitored upon cycling. With more realistic material properties, such as the temperature-dependent yield strengths, taken into account, the interaction between TGO growth and thermal cycling, and the subsequent deformation were theoretically analyzed and validated by comparison with the results of the experiments and numerical analysis.

2. Experiments

2.1. Specimens and test system

BC alloy is not commercially available. Fecralloy (Fe72.8/Cr22/Al5/Y0.02/Zr0.09 in wt.%) forms a uniform α-Al_2O_3 scale without voids at the interface between the oxide and alloy, just as the BC alloy does in a TBC system. Therefore, as in a number of previous works [15,20,21,23,32], Fecralloy was used as the model material in this experiment, to simulate the behavior of the BC alloys. A Fecralloy foil was cut into a number of coupons 50 mm long, 5 mm wide and 0.35 mm thick. A small hole 1 mm in diameter was machined into the center of each specimen, using a mini-drill, and the surfaces were mechanically ground and polished to a 1 μm finish. Field emission scanning electron microscopy (FE-SEM; S-4700 instrument) was used to measure the initial morphology of the holes. Fig. 1 shows an SEM image. Before testing, each specimen was cleaned in acetone, and its dimensions and weight were measured within accuracies of ±10 μm and ed wμg.

A small-scale material tester designed for foil specimens [20,21] was used in this research. Fig. 2 shows a schematic