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Deformation and cracking near a hole in an oxide forming alloy foil subjected to thermal cycling. Part II: Effects of remotely applied stress

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Abstract

The main protection for the turbine blades in a hot section of a gas turbine are thermal barrier coatings and the cooling air fed through holes distributed on the surfaces of the turbine blades. The predecessor of this work investigated an idealized model of the holes on the surfaces of the blades and the behavior of a hole in a heat-resistant alloy coupon subject to purely thermal cyclic loading. The stress near the hole and the consequent deformation or cracking of the hole were analyzed and traced according to the loading cycles by theoretical and numerical approaches using realistic material properties. In this work, similar approaches were used to investigate the effect of remotely applied stress in addition to thermal cyclic loading, which simulated the loading condition of the turbine blades subjected to not only the high temperature but also the centrifugal force generated by the high-speed revolution in a hot section, on the stress near the hole and the consequent deformation or cracking. The behavior of the hole under the thermomechanical cyclic loading was analyzed by the experiments and theoretical solution. It was revealed that the remotely applied stress substantially enhanced the deformation near the hole, although the stress level was very low. The experimental observation was theoretically explained by superimposing the stress concentration near the hole due to the remotely applied stress over that due to thermal cyclic loading with consideration of the creep properties of the materials.

Keywords: Thermal barrier coating; Thermally grown oxide; Thermomechanical cycling; Hot corrosion; Creep

1. Introduction

Film cooling and thermal barrier coatings (TBCs) have been used to protect turbine blades in gas turbine engines from hot corrosion and other damages. In film cooling, cool air is discharged through small holes on the blade surface, creating a film of cooling air that protects the blade surface from the hot mainstream flow [1]. The TBC system 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 [2]. The dense TGO layer helps protect the underlying substrates from high temperature corrosion. During service, however, a substantial level of stress is generated within the TGO layer. There are two sources of the stress created in the TGO layer: one is the mismatch of the coefficients of thermal expansion (CTE) between the TGO and the metal substrate, when the TBC system is subjected to thermal cycling, and the other is the TGO formation in the lateral (in-plane) direction at high temperatures. TGO instability is also affected by initial geometric imperfections such as undulations or grooves pre-existing on the interface between the TGO layer and the BC.

In the predecessor of this work [3], the cooling hole was regarded as another major source of TBC failure in addition to the surface groove or unevenness because a circular hole is a well-known stress concentrator. As an idealized model of the cooling holes on the surfaces of the blades, the behavior of a hole on a heat-resistant alloy (Fecralloy,

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Fe72.8/Cr22/Al5/Y0.02/Zr0.09 in wt.%) coupon subject to thermal cyclic loading was investigated. The experiments performed with a noble small-scale material tester [4,5] revealed that a thermal loading with more frequent cycling resulted in more deformation and cracks around the hole, although the duration at the high temperature portion during more frequent cycling was shortened in order that the final thickness of the TGO layer formed on the surface was kept constant regardless of cycling rate.

To explain the phenomena, the stress near a hole and the consequent deformation or cracking near the hole were analyzed and traced according to the thermal loading cycles by theoretical and numerical approaches. Specifically, based on the material properties of TGO and the substrate including creep deformation, oxidation rate and growth strain (some of which were also measured by the small-scale material tester while others such as the temperature-dependent material properties were realistically assumed), the stress in the TGO layer and the strain at the interface were estimated by an analytic solution derived for a two-dimensional (2-D) model, and by finite element analysis for a more realistic three-dimensional (3-D) model. The 2-D model had the TGO layer only on the inner surface of the hole, while the 3-D model had the TGO layer on the lateral surfaces as well as the inner surface. The analytic solution gave fairly good estimations of the mechanical behaviors of the hole in comparison with the experimental observations and the results of the finite element analysis.

Turbine blades usually experience not only thermal cycling but also mechanical loading due to the centrifugal force generated by high speed revolution during operation. Mechanical loading can lead to additional deformation, which can increase the TGO displacement instability. Bartsch et al. [6] and Shi et al. [7] developed a strategy to simulate the relevant service conditions of a turbine blade. A mechanical load was imposed on a hollow, cylindrical specimen by a servohydraulic testing machine. To heat the specimen, radiation from four quartz lamps was focused onto the specimen with elliptical mirrors. This test setup made it easier to assess the durability of a TBC on the turbine blade with a thermal gradient between the inner and outer surfaces. However, the heating and cooling process was complicated and expensive. Also, it was impossible to observe the surface morphology of the specimen in situ. On the other hand, the small-scale material tester used in the previous work [3] could measure the mechanical properties of an alloy at high temperature by using a ribbon specimen and Joule heating. In addition to the benefit of in situ observation on the specimen under static loading, the tester has been successfully used to investigate the material behavior under cyclic mechanical loading. In fact, using the small-scale material tester, Li et al. [8] investigated the morphological changes near a surface groove on an alumina-forming alloy under thermal and thermomechanical cycling.

In this work, the mechanical behavior near a hole in a foil subjected to thermomechanical cycling is investigated.

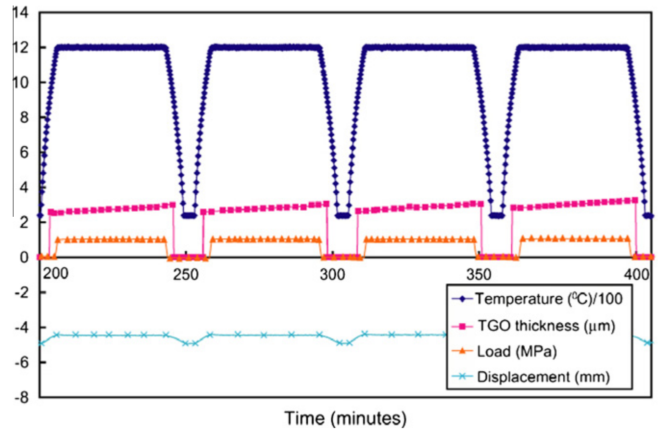

Fig. 1. Example of data measured during a thermomechanical cyclic test.

To simulate the centrifugal force acting on turbine blades, mechanical stress was remotely applied to the specimen in addition to thermal cycling, and the deformation and cracking near the holes of the specimens were monitored upon cycling. To explain the experimental observations, the maximum stress and strain around a hole were theoretically analyzed and traced according to loading cycles.

2. Experiments

The specimens and the test system were the same as those in the previous work [3]. The load, displacement, temperature and the TGO thickness being formed on the surface were measured in situ. Technical details about the loading and measuring system are described in the authors' previous papers [4,5]. Fig. 1 shows an example of the experimental data.

In the previous work [3], the specimens were subjected to three different thermal loading conditions, i.e., isothermal cycle, slow 20 cycles and fast 200 cycles. To ensure that all the specimens had an almost constant thickness of the TGO layer at the end of each experiment regardless of the loading condition, the periods of dwelling at the maximum temperature were set to 10 h, 30 min and 3 min for the loading conditions of the isothermal cycle, the slow 20 cycles and the fast 200 cycles, respectively [9]. In this work, another set of specimens were subjected to thermomechanical loading, in which a mechanical load was additionally applied so that the specimens would experience a stress level of 0.18 MPa or 0.5 MPa only during the periods of dwelling at the maximum temperature. The slow 20 cycles of thermomechanical loading with the stress level of 0.5 MPa applied at 1200 °C induced substantial overall plastic deformation on the specimen. Hence, the experiment of the fast 200 cycles with the same stress level was skipped. The experimental conditions are summarized in Table 1.

3. Experimental results

Fig. 2 shows the SEM photos of the morphology near the holes after the three different thermomechanical loadings