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Optimal design of deformation near a hole in an oxide forming alloy foil under thermal cycling using taguchi method

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ABSTRACT

Recently, an idealized cooling hole was studied to evaluate the durability of gas turbine blades. A theoretical model was derived and the results were close to experimental measurement. In this work, the effects of various design parameters on the hole deformation under thermal loading were evaluated using validated analytical model. Specifically, a sensitivity study of the growth strain of thermally grown oxide (TGO), the yield strength of TGO and the substrate, and the hole diameter were performed using the taguchi method. The sensitivity study revealed that the growth strain, ε_g, was the dominant influential design parameter on the final hoop strain near the hole during the 20 thermal cycles, followed by the compressive yield strength of the TGO layer at RT and the tensile yield strength of the TGO layer at 1200 °C. The yield strength of the substrate layer at RT was the least influential design parameter.

1. Introduction

Gas turbine components in the hot section are protected by a thermal barrier coating (TBC) system, which covers a superalloy substrate. As shown in Fig. 1, the TBC system consist of four primary constituent materials which combine together to form a well-performed thermal protection system from the environment. They are (i) the column TBC itself, (ii) bond coat (BC), which contains aluminum for TGO forming, (iii) the superalloy substrate (iv) thermally grown oxide (TGO), a dense aluminum oxide layer grows between the top coating and BC during at the high temperature [1]. The fourth layer, i.e., the thermally grown oxide (TGO) layer helps protect the underling substrates. However, the lateral growth of TGO and the expansion mismatch between TGO and the BC substrate can induce substantial level of stress that associated with TBC failure [1–4]. The stress within TGO induces displacement instability of the TBC system under thermal cycling and consequently, the separation of the top zirconia coat, which results in the hot corrosion attack into the substrate [1,5,6]. TBC instability is also affected by initial imperfections on the surface of BC with the cyclic loading [7]. The durability of the TBC system is enhanced by polishing the imperfections on the BC substrate [8]. The cooling holes on the surfaces of the blades, potential stress concentrators, might accelerate the displacement instability of a TBC system. In fact, a number of failures near the cooling holes have been reported [9–12]. Another factor affecting TBC instability is the mechanical strength of BC or TGO. According to Evans et al. [13,14], the displacement of a surface groove substantially depends on the yield strength of BC or TGO. Groove deformation is suppressed by increasing the BC strength at the high temperature or decrease the TGO strength.

Recently, a theoretical model was derived to study the stress and displacement distribution on an idealized cooling hole using oxide forming alloy during thermal loading cycles [15]. The thermal cycling test was performed using a micro-creep tester [16,17]. As shown in the results, the hole deformation was increased with the larger number of cycles, although the final TGO thickness was set constant. To explain the experimental results, a two-dimensional (2D) theoretical model was derived. The material behaviors for TGO and the substrate at the high temperature were obtained from micro-creep tester. These material properties includes the yield strength of TGO and the substrate at the high temperature, growth rate of TGO and creep strain. While other properties were realistically assumed such as that the yield stresses of TGO and the substrate are linearly changed with temperature. The stress and strain distribution near a hole were estimated during thermal cycling. The theoretical results were close to experimental measurement. To prove the validity of the 2D theoretical model, finite element analysis was performed with a more realistic 3D model [15]. From the comparison between numerical and theoretical results proved the validity and the accuracy of the theoretical approach.

In this paper, the sensitivities of the yield strengths of the TGO layer and the substrate, and the growth strain of the TGO layer are

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Nomenclature

D	diameter of the hole
e	virtual parameter
E	Young's modulus
G	shear modulus
h	initial thickness of TGO
n	number of experimental points
p	pressure
R	radius of the hole
R_P	the radius of the plastic zone
ΔR	radial variation
T_o	maximum temperature
T_{RT}	room temperature
u_{r_sub}	radial displacement of the substrate
ν	Poisson's ratio
y_i	the optimal design value
α_{sub}	coefficients of thermal expansion of substrate
α_{tgo}	coefficients of thermal expansion of TGO
$\Delta\alpha$	CTE mismatch between the TGO layer and the substrate
ε_g	growth strain of the TGO layer
$\Delta\varepsilon_g$	increasing growth strain of the TGO layer
ε_T	the strain during cooling, reheating or dwelling at maximum temperature
$\varepsilon_{\theta\theta}$	strain on the interface between TGO and the substrate
$\varepsilon_{\theta\theta\_sub}$	hoop strain in the substrate
$\varepsilon_{\theta\theta\_tgo}$	hoop strain in the TGO layer
$\sigma_Y^{sub\text{-}RT}$	yield strength of the substrate at the room temperature
$\sigma_{TY}^{TGO\_HT}$	tensile yield strength of the TGO layer at 1200 °C
$\sigma_{CY}^{TGO\_RT}$	compressive yield strength of the TGO layer at the room temperature
$\sigma_{\theta\theta\_tgo}$	hoop stress in the TGO layer
$\sigma_{\theta\theta\_sub}$	hoop stress in the substrate
σ_{rr_sub}	radial stress in the substrate
u_{r_tgo}	radial displacement of TGO
σ_Y^{sub}	yield strength of the substrate
σ_Y^{tgo}	yield strength of TGO

investigated using the taguchi method. The results are expected to be useful in practical engineering design and material selection for suppressing deformation near the cooling holes and for enhancing the durability of the TBC systems in gas turbine blades.

2. Problem and analytic solution

2.1. Specimen & experiments

The following describes the experiments performed in the authors' previous work [15,18]. To simulate the mechanical behaviors of BC layers, the Fecralloy was used as the model material. The specimen was cut into a number of ribbons with 50 mm length, 5 mm width, and 0.35 mm thickness in size. A small hole (φ = 1mm) was machined using a mini-drill into the center of each specimen, and the inner and outer surfaces of the hole were mechanically ground and polished to a 1 µm finish. A small scale material tester [16,17] was used to apply thermal cyclic loading to the Fecralloy specimen. Fig. 2 shows the schematic of the tester, a specimen, an enlarged SEM photo, and a 2D model used for obtaining the analytic solution. The SEM photo can be used to show the TGO thickness, the level of crack and etc. Two infrared pyrometers (OMEGA, OS554-V1-E and CHINO, IR-FA1NNN) were used to monitor the TGO thickness and the temperature *in-situ*. The TGO thickness is determined from the difference between the temperature indications from the two pyrometers with the emissivity level fixed [16,17]. Technical details about the micro-creep tester are described in [16,17].

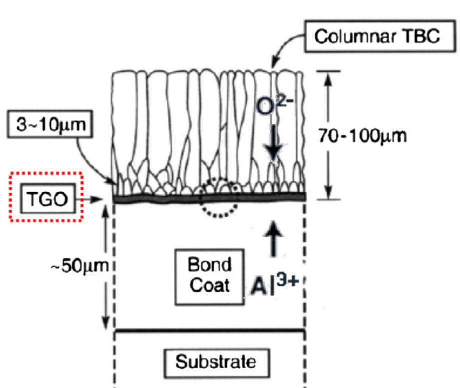

Fig. 1. TBC system.

The specimens were subjected to 20 thermal loading cycles, as shown in Fig. 3. Each thermal cycle consisted of a 30 min hold at the maximum temperature of 1200 °C, a 5 min ramp-down to the room temperature, a 2 min hold at the room temperature, and a 5 min ramp-up to the maximum temperature. Although this kind of simple cycle cannot fully show the characteristics of the TBC system, but the research results can make a scientific basis for designing a high performance TBC system. Digital Image Correlation (DIC) method were proposed to measure the displacement fields occurring near the holes [19].

2.2. Analytic solution

In the authors' previous work [15,18], the theoretical solution for the hole deformation was derived. Specifically, a thin cylindrical TGO shell with radius R and initial thickness h fitted to an infinite substrate with a hole in the 2D model, as shown in Fig. 2. First, each phase is considered to undergo unconstrained strains, and then constraint is imposed, equations of the TGO stress and strain along the interface with the substrate were derived. The material properties includes the yield strength of TGO and the substrate at the high temperature, growth rate of TGO, creep strain and etc can be obtained from the experiments. The TGO layer and the substrate were considered to be elastic-perfectly plastic with temperature dependent properties respectively. At the maximum temperature, T_o, the system was driven by increasing growth strain of the TGO layer, $\Delta\varepsilon_g$. During ramp-down to the room temperature, T_{RT}, and ramp-up to T_o, the system was driven by the thermal expansion mismatch between the TGO layer (Typical value of 6×10^{-6}/°C) and the substrate(Typical value of 12×10^{-6}/°C), $\Delta\alpha\Delta T = (\alpha_{sub} - \alpha_{tgo})\Delta T$.

Along the cyclic thermal history, as shown in Fig. 3, the theoretical solutions were applied step by step to study the stress and strain distribution in the TGO layer and the substrate.

Because the thickness (0.35 mm) of the specimens are relatively thin compared to the hole diameter (1 mm), a plane stress condition was applied to the theoretical model. First, when the TGO layer and the substrate both deform elastically, the stress and strain in the TGO layer and the substrate are given as functions of p, the pressure acting between the substrate and the TGO layer as follows;

$$\sigma_{\theta\theta\_tgo} = -p\frac{R}{h} \quad (1)$$

$$\sigma_{\theta\theta\_sub} = p \quad (2)$$

$$\sigma_{rr\_sub} = -p \quad (3)$$