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Thermo-mechanical stress analysis of thermal barrier coating system considering thickness and roughness effects

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ABSTRACT

Cast aluminium–silicon alloy, A356.0, is widely used in automotive and aerospace industries because of its outstanding mechanical, physical, and casting properties. Thermal barrier coatings can be applied to combustion chamber to reduce fuel consumption and pollutions and also improve fatigue life of components. The purpose of the present work is to simulate stress distribution of A356.0 under thermo-mechanical cyclic loadings, using a two-layer elastic-visco-plastic model of ABAQUS. The results of stress–strain hysteresis loop are validated by an out of phase thermo-mechanical fatigue test. Different thicknesses from 300 to 800 μm of top coat and also roughness of the interfaces are simulated to get best stress gradient. Results show that increasing top coat thickness causes stress increase. The realistic interface model is useful for identifying critical areas in stress development. Two important factors having considerable effect on development of high stress in TBC, are the severity of undulations relating to amplitude and wavelength of interface waves; and the thickness of BC layer relating to mutual positioning of either interfaces. However the realistic model has some limitations including long calculation time and difficulties of generating a suitable mesh. To diminish these limitations, after recognizing critical area, in second stage of the study, a periodic unit cell is used instead . Eight models considering different mutual positioning of interfacial asperities along with different penetration in adjoining layers are simulated and compared. Results show that detachment of the thermal barrier coating system from substrate is more probable Results show that IP positioning of mutual waves produce more severe stress but contour pattern is less likely to promote crack propagation.

1. Introduction

Thermal Barrier Coatings (TBCs) can be applied to the combustion chamber of diesel engines in order to allow higher combustion temperatures, increasing the thermal efficiency, or to achieve lower base metal temperatures. Both can cause an increase in fatigue life of high temperature components and also reduction in fuel consumption and some emissions such as hydrocarbons [1–4]. A TBC consists of two-layer systems which are a heat resistant ceramic top coat (TC), mostly Yttria stabilized Zirconia (YSZ) with typical composition ZrO_2-8%Y_2O_3 and also a metallic bond coat (BC), mostly made of Ni–Cr–Al–Y. These layers are applied by Air Plasma Spraying (APS) to the substrates.

Aluminum alloy cylinder heads, as a part of combustion chamber, are expected to meet two essential material requirements including resistance to deformation under combustion pressure and assembly loads and also toughness at high temperatures of flame to prevent cracking [5]. These thermo-mechanical loading conditions can only be handled by a combination of modern cooling methods or protective coatings such as TBCs, leading to lower thermal stresses due to lower temperature gradient. The TBC provides a temperature drop of 100–200 °C due to its low thermal conductivity [6].

Different aspects of exposure conditions and failure mechanisms of TBC systems must be considered in order to model and predict the fatigue life. A major weakness is the interfaces between the bond coat and the substrate and also between the bond coat and the top ceramic coat. These interface regions undergo high stresses due to the mismatch of thermal expansion between materials and due to interface roughness [6]. Another failure mechanism is the development of thermally grown oxide (TGO) at the interface formed as a result of bond coat oxidation at about 900 °C [7].

One of the key issues of the present paper is to investigate the influence of top coat thickness and the interface roughness effect on stress distribution by using finite element (FE) modeling of TBC systems. FE simulation of TBC systems on aluminum alloys is rare and most researches are about modeling of coating on super alloys. Finite element analysis for the development of residual stresses during spraying of zirconia based thermal barrier coatings was presented by Bengtsson and Persson [8] and also Widjaja et al. [9]. To simplify the approach, a flat interfaces hypothesis was assumed between dissimilar materials.

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Table 1
Thermal shock test conditions.

Cycle type	Coat-face temperature (°C)	Back-face temperature (°C)	Duration (sec)	Cycle number
Normal	325	225	35	1–200
Hot	525	425	65	201–300
Ultra Hot	580	480	95	301–400

Table 2
The life times of specimens in thermal shock test.

Specimen No.	TC thickness (μm)	BC thickness (μm)	Cycles to surface crack initiation	Cycles to crack initiation on interface of coating and the substrate	Cycles to separation
TBC_SPC_L_01	300	150	230	309	333
TBC_SPC_L_02	550	150	185	302	304
TBC_SPC_L_03	800	150	185	303	306

The time dependent model of CMSX-4 was presented by Schubert et al. [10]. The oxidation process has been simulated by growth the thickness of TGO elements. The development of cracks at the TGO/BC interface has been simulated using cohesive zone elements. Hsueh and Fuller [11] examined the effect of curvature and height of the interface asperity on stresses formation during the service.

Bialas [6], Ranjbar-Far et al. [7] and Sfar et al. [12] modeled the top coat and bond coat interface roughness, the volume growth of the oxide layer, the cyclic loading and the creep relaxation to predict their effects on the stress distribution by considering a homogenous type for the temperature distribution. Liu et al. [13] performed experimental and numerical life prediction of thermally cycled thermal barrier coatings by considering different thicknesses for top coat. Moridi et al. [14] simulated stress distribution in aluminum alloys under thermo-mechanical cyclic loads to investigate ceramic coating thickness and interfaces roughness effect. Bialas [6] performed a numerical simulation of crack development within APS TBC systems. The TGO thickening and creep deformation of all system constituents is modeled. Two dimensional periodic unit cell is used to examine the effect of interfacial asperity on stress distribution and subsequent delamination of APS TBC. The finite element analysis shows that the development of the interfacial crack allows for a micro crack formation within APS TBC. In another paper, Ranjbar-Far et al. [15] presented a new step in the objective to continue the development of the TBCs performance by considering a non-homogenous temperature model and using the finite element code ABAQUS to study the thermo-mechanical behavior of the thermal barrier coating systems. The results show that the oxide formed on rough TC/BC interface during service has an intrinsically different morphology and different growth rate compared to those formed when considering a homogenous temperature.

In the present work, coating thickness effect on stress distribution of A356.0 -T7 is studied under thermo-mechanical loadings. The development of TGO is neglected due to temperature range below 500 °C, but the surface roughness of the interfaces between substrate and BC and also between BC and TC layers is considered. As a result, thermo-mechanical stress distributions for different top coat thicknesses are drawn in the figures. To find a better knowledge on the roughness effect, mutual wave positioning of substrate/BC and BC/TC interfaces, in phase (IP) and out of phase (OP) with different penetration of undulations in adjoining layers, are studied and the results are demonstrated in the figures.

2. Material

A356.0 -T7 (8 h solution at 525 °C, water quench and 3 h aging at 230 °C) is studied under thermo-mechanical loadings. The alloy composition is 7.03% Si, 0.35% Mg, 0.26% Fe, 0.17% Cu, 0.01% Mn, and 0.01% Ti, reminder Al. The metallic bond coat is made of Ni–Cr–Al–Y and ceramic top coat is made of yttria stabilized zirconia (YSZ) with typical composition of ZrO_2-8 wt.%Y_2O_3.

3. Finite element simulation

FE simulation has been employed to study stress distribution in TBCs and thus evaluating the optimized thickness. Many efforts have been done to numerically investigate stress development in TBC systems. Many times a two dimensional unit cell symbolizing a single asperity has been used to be representative for the entire surface area stress field [6]. For the reason that interface profile between substrate/BC and BC/TC has a random nature, the idealized simulation of a single asperity may not predict the real behavior of TBC system. Furthermore, the substrate/BC roughness has not been considered in former simulations. The reason is that, in gas turbine application for TBC systems, temperature ranges are high and predominant failure mechanism is the development of TGO at about 900 °C in BC/TC interface [7]. In the present paper, the cylinder heads application for TBC system is studied where the working temperature is below 500 °C and therefore TGO growth is not taken into account. A thermal shock test has been performed on 3 different thicknesses of TC. Specimens have 30 mm length, 25 mm width and 10 mm thickness with 150 μm bond coat thickness and 300, 550 and 800 μm top coat thickness for TBC_SPC_L_01, TBC_SPC_L_02 and TBC_SPC_L_03, respectively. All coating processes are performed by air plasma spraying method,

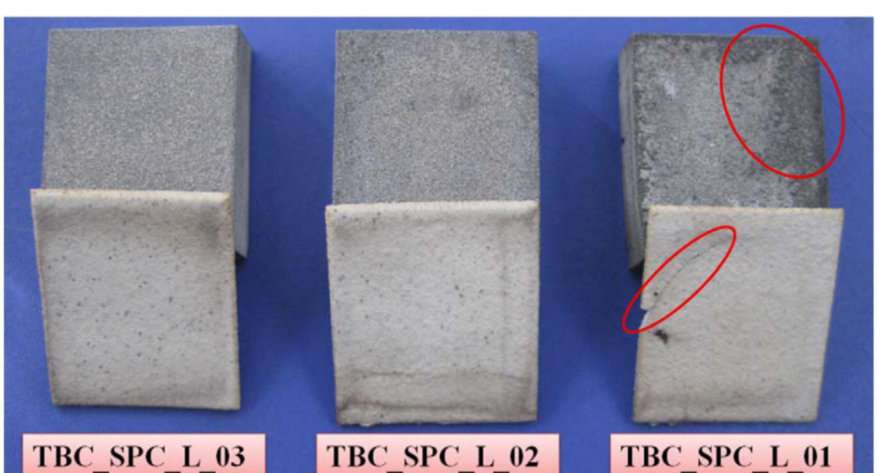

Fig. 1. The specimens after separation of coating layers from substrate in thermal shock test.