Available online at www.sciencedirect.com
ScienceDirect
Materials and Design 28 (2007) 2336–2343
Materials & Design
www.elsevier.com/locate/matdes

Residual stress redistribution within high-temperature coatings due to surface cracks

X.C. Zhang [a,b,*], B.S. Xu [b], H.D. Wang [b], Y. Jiang [b], Y.X. Wu [a]

[a] State Key Laboratory of Metal Matrix Composites, Shanghai Jiaotong University, Shanghai 200030, China
[b] National Key Laboratory for Remanufacturing, Beijing 100072, China

Received 17 January 2006; accepted 13 July 2006
Available online 2 October 2006

Abstract

Residual stress is one of the important mechanical properties of high-temperature coatings and it will be redistributed if the physical discontinuities are presented. The objective of this theoretic study was to investigate the residual stress redistribution within a high-temperature ZrO_2/NiCoCrAlY coating due to the presence of surface crack. Results indicated that the shape and dimension of crack had significant influences on the magnitude and distribution of the residual stresses within coatings. When the surface crack was absent, there was a remarkable stress concentration near the edge of the coating. However, the location of the stress concentration may be changed due to the presence of surface crack. The effect of multi-surface crack on the residual stress redistribution within the coating was also discussed.

Keywords: Residual stress; Coatings; Stress redistribution; Stress concentration; Surface crack

1. Introduction

1.1. Background

Many practical advantages of high deposition rates and low cost have enabled thermal spray coatings to become an integral part of aerospace industry. Among the family of coatings, high-temperature coatings such as thermal barrier coating (TBC) are often used to provide high-temperature protection to machine parts and improve their efficiency [1]. For TBCs, one of the more common fabrication techniques is plasma spraying process where ceramic powder is melted and sprayed onto a substrate. It is well known that the performance of a TBC is dependent on application and upon the overall properties of the coating and substrate combination. During the deposited process of a TBC, difficulties arise due to the mismatches in elastic moduli, coefficients of thermal expansion (CTEs) between the coating and the substrate, and the elastic–plastic deformation of bondcoat and substrate [2,3]. Because of these differences, residual stresses are generated inevitably.

The thermo-mechanical integrity of TBCs is often influenced by residual stresses. For instance, the tensile residual stress in coating can result in the through-thickness cracking [4,5]; while the compressive residual stress can cause the spallation failure at the interface between the coating and substrate [6–8]. In order to predict the magnitude and distribution of residual stresses within TBCs, several experimental methods have been developed so far, such as diffraction method, flection method and material removal method, etc. However, most of these techniques impose severe limitations on specimen geometry [9] and the testing procedure is very dull. With the development of computer techniques, the finite element method (FEM) has been utilized and is being an important tool to analyze the thermo-mechanical behaviors and predict the residual stresses within TBCs [10–12].

* Corresponding author. Present address: National Key Laboratory for Remanufacturing, Beijing, China. Tel.: +86 10 66718541; fax: +86 10 66717144.
E-mail address: zhangxc@sjtu.edu.cn (X.C. Zhang).

0261-3069/$ - see front matter
doi:10.1016/j.matdes.2006.07.007

However, up to now, most of these studies were limited to the TBCs without any micro-defect. In fact, residual stresses distribution will be changed if the physical discontinuities within coating are presented [13].

1.2. Previously relative studies

The stress magnitude and distribution will be changed significantly due to the presence of cracks in coating. Under the linear elastic condition, the stress distribution parallel to the interface between two adjacent cracks can be evaluated based on the shear-lag analysis: thus for a fragment centered at the origin, with the normal residual stress, σ_0, along the x direction, it follows that [14]

$$\frac{\sigma_{xx}(x)}{\sigma_0} = 1 - \frac{\cosh(x/\xi)}{\cosh(L/2\xi)} \quad (1)$$

where L is the separation between the cracks, ξ is a constant which depends on the elastic properties and thicknesses of coating and substrate. The in-plane stress is zero normal to the surfaces of the cracks and the maximum stress value will be at the mid-point of the segment. If $\xi \gg L$, the function $\sigma_{xx}(x)$ can be parabolic,

$$\sigma_{xx}(x) = \sigma_0 L^2(1 - 4x^2/L^2)/(8\zeta^2) \quad (2)$$

In the case of non-linear stress transfer between the coating and the substrate, the normal stress on the coating is coupled to the shear stress at or near the interface through at integral equation [15],

$$\mathrm{d}\sigma/\mathrm{d}x = \tau/t_c \quad (3)$$

where τ is the shear stress developed in the vicinity when a load is applied to the substrate, t_c is the coating thickness. However, these analytical approximations are obtained based on some assumptions.

Qian et al. [1] investigated the effects of thermal gradient and residual on the fracture behavior of TBCs. In their paper, a small quantity of investigation was performed to study the residual stress fields within the TBCs containing cracks at different locations. It was found that when cracks were parallel to the coating, the residual stresses predicted by elastic–plastic FEM are shown to be small. Recently, Peng et al. [16] measured the residual stresses distribution in the thermally grown oxide around holes in thermal barrier coatings using luminescence piezospectroscopy. The characteristic distance, over which the stresses vary, was of the order the half the hole radius consistent with a shear-log model for stress redistribution. In the vicinity of the hole, the mean stress decreased monotonically towards the edge of the hole.

In this paper, residual stress redistribution within high-temperature ZrO_2/NiCoCrAlY coatings due to the presence of surface cracks was investigated by FEM. Effects of the shapes and dimensions of surface cracks on the residual stresses in coatings were studied. The multi-surface crack was also used to investigate the effect of inaction between cracks on the residual stresses.

2. Thermo-mechanical model description and materials

Spraying residual stresses were calculated by non-linear thermo-mechanical analysis using finite element code ANSYS 6.0. At first, a thermal model was used to determine the temperature through the specimen during cooling. And then, the result of thermal history was transferred to the mechanical model to compute the residual stresses both in the coating and in substrate.

The used model represents a shape Ni-alloy substrate of 16 mm in diameter and 10 mm in height with a 200 μm NiCoCrAlY bondcoat and a 400 μm ZrO_2 topcoat orderly depositing to the top surface. In order to determine the effect of surface crack on the residual stress redistribution, it is assumed that a surface crack exists at the center of the topcoat surface, as shown in Fig. 1a. The geometrical condition allows the stress and deformation near the crack and within the specimen to be axisymmetrical and then costly three-dimensional analysis can be avoided. The axial symmetric model was shown in Fig. 1b. The meshes in the zone near the coating/substrate interface and crack were refined to improve the accuracy of calculation. The constraints were imposed on the axial line and the bottom sides of the substrate. The 100 W/m^2 K heat transfer was only allowed from the top surface of topcoat. The analytical model was assumed to be a perfect elastic body without plastic deformation in the whole analysis procedure. Four-node thermal-structure couple element PLANE13 was used. During the whole thermal analysis, thermal radiation was not considered.

Because the used coating specimens in the present investigation were relatively small, all specimens were assumed to be stress free at the temperature of 700 K (i.e., reference temperature), at which the spraying process was assumed to end [17]. So to all analyzed systems, the final residual stresses are only generated due to the cooling of the whole coating specimens from the reference temperature to home temperature (i.e., 298 K).

Residual stress components resulting from the FEA are obtained in the following directions: (1) radial stress, σ_{xx}, corresponding to stress value along the radial direction; (2) axial stress component, σ_{yy}, that refers to stress profile through the thickness of coatings and (3) shear stress com-

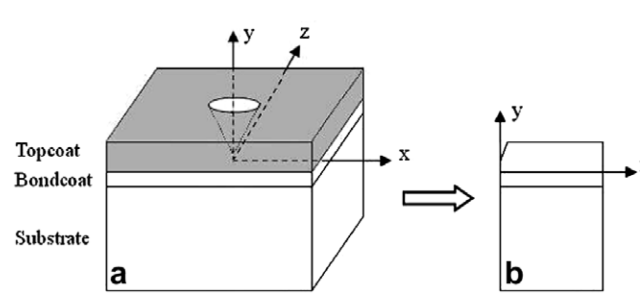

Fig. 1. (a) Schematic of surface crack in the thermal barrier coating consisting of a ceramic topcoat, a metallic bondcoat and a Ni-alloy substrate. (b) Cross-sectional view of axisymmetrical model used for analysis.