Computational Materials Science 49 (2010) 603–608

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Finite element modeling of residual stress around holes in the thermal barrier coatings

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ARTICLE INFO

Article history:
Received 23 April 2010
Received in revised form 17 May 2010
Accepted 27 May 2010
Available online 26 June 2010

Keywords:
Thermal barrier coatings
Residual stress
Finite element method

ABSTRACT

The distribution of residual stresses in the sprayed coating is discussed by finite element method (FEM). With the increasing of coating thickness, residual stresses in the coating tend to change from compressive to tensile, the stress distribution along the radius of the specimen is smoother, but the concentration near the edge of coating, especially near the edge of hole, is sharper, which lead to failure of the coating. The hole radius of specimens took great effect on the distribution of residual stress near the inner radius, however, little effect on the distribution near the outer radius.

1. Introduction

Plasma-sprayed thermal barrier coatings have been utilized to prolong the operating life of turbine engines. However, due to the difference of the coefficient of thermal expansion (CTE) between the substrate and thermal barrier coatings (TBCs), residual stresses are inevitable within the coating during the preparation of TBCs. The severe stress concentration in the interface between the coating and substrate would result in the failure of coatings [1]. Many kinds of components such as turbine blades and vanes [2] are cooled by passing a portion of the air from the compressor portion of the engine through internal cooling passages and out of the blades through holes in their surfaces, so the distribution of residual stresses around the hole in the coatings are important. In this paper, The ZrO_2/NiCoCrAlY coatings, which are widely applied in aerospace industry [3], are analyzed by using ANSYS software. The distribution of residual stress in the coatings is predicted. Most of failures in the coating occur in the interface, and the distribution residual stresses at the interfaces of ZrO_2 topcoat-NiCoCrAlY bondcoat and coating–substrate is important to the appliance of the ZrO_2/NiCoCrAlY coating. So the influence of the hole dimension and the coating thickness to residual stresses at two interfaces was discussed.

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doi:10.1016/j.commatsci.2010.05.057

2. Analytical model

The distribution of coating residual stresses around the hole was analyzed by finite element code ANSYS (revision 8.0). The thermal–structural element PLANE 55 was selected. For the modeling of residual stress after plasma spraying, the model (shown in Fig. 1) represents a hollow cylinder for the nickel substrate of 10 mm, 10 mm annular thick between the outer diameter and the inner diameter. The coating and substrate are assumed to be isotropic for simplicity in this study. The analytical model is a perfect elastic body without plastic deformation. An axisymmetric element mode is chosen to reduce computer calculation and data manipulation time, *Y* axis, shown in Fig. 1, was chosen as the symmetric axis. Two-layer duplex NiCoCrAlY/ZrO_2 coatings with a hole of different dimensions of diameter and the coating thickness are computed, a schematic cross-section of the ZrO_2/NiCoCrAlY coating system is shown in Fig. 2. A dense mesh is used at the edge of specimen and mesh elements along the coating–substrate interface are refined, as shown in Fig. 3. The material properties of ZrO_2 topcoat, NiCoCrAlY bondcoat and Ni-alloy substrate as functions of temperature from 25 to 800 °C are shown in Table 1. Then the influence of the radius of the hole on the distribution of residual stresses in the coatings is reflected. In order to reduce the concentration of the residual stress in the interface between the topcoat and the bonded coat, the interlayer is added. As shown in Fig. 2.

In order to investigate the effects of coating size and interlayer on the residual stresses level, four aspects of this investigation are shown as follows [4–6].

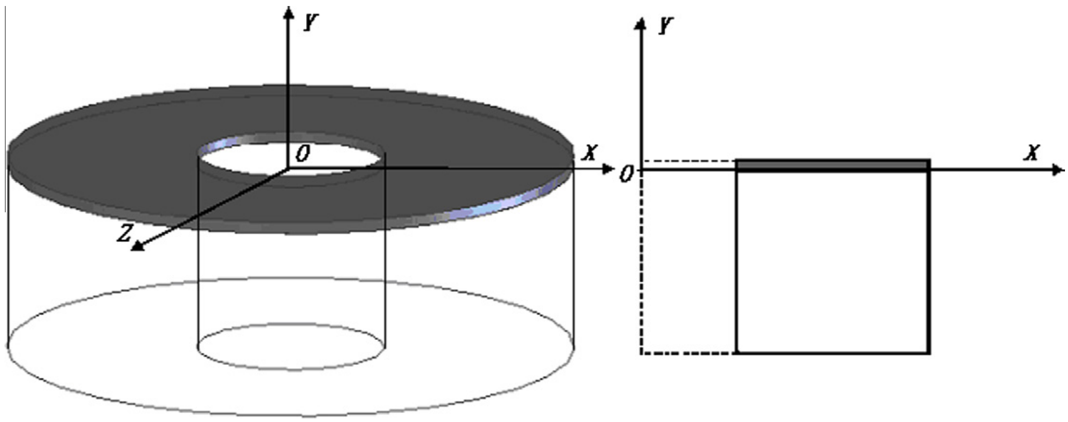

Fig. 1. Schematic description of the geometry used in the finite element modeling.

1. Calculation of residual stresses owing to a uniform cooling from an assumed uniform stress-free manufacturing temperature of 427 °C to room temperature;

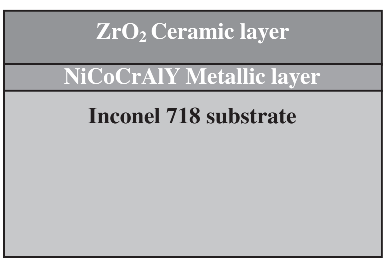

Fig. 2. The cross-section of a TBC including a ZrO_2 ceramic layer and a NiCoCrAlY metallic layer on Inconel 718 substrate.

2. Calculation of residual stresses owing to a uniform cooling of two-layer duplex ZrO_2/NiCoCrAlY coating–Inconel 718 substrate systems with different ZrO_2 topcoat to substrate thick ratios using stead state analysis type of FEM.
3. The analysis is performed to model the effect of cooling rate on the residual stresses distribution within coating, the convection coefficients to environment were taken to be 1000 W/m^2 K.

3. Modeling results and discussions

3.1. Concentration of residual stresses at the edge of the coating

Due to edge effect [7], residual stresses would be concentrated severely at the edge of the coating, especially near the interface between coating and specimen. Although bondcoat can reduce residual stresses within the coating, concentration of residual stress

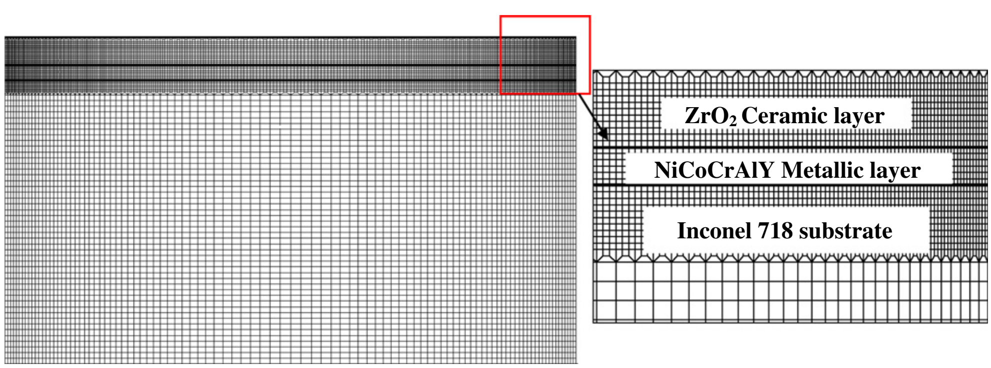

Fig. 3. Mesh of the model and the coating edge area.

Table 1
Materials properties of coating and substrate [4–6].

Materials	Temperature T (°C)	Elastic modulus E (GPa)	Density ρ (kg/m^3)	CTE α (10^{-6}/K)	Poisson's ratio υ	Thermal conductivity k (W/m K)	Specific heat C (J/kg K)
Ni-alloy substrate	25	200	8220	14.4	0.3	11.7	431
	400	179		14.4		17.3	524
	800	149		14.4		23.8	627
NiCoCrAlY	25	225	7320	14	0.3	4.3	501
	400	186		24		6.4	592
	800	147		47		10.2	781
ZrO_2	25	53	6037	7.2	0.25	1.5	500
	400	52		9.4		1.2	576
	800	46		16		1.2	637