Materials Science and Engineering A 488 (2008) 45–49

MATERIALS SCIENCE & ENGINEERING A

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Finite element design of SiC/C functionally graded materials for ablation resistance application

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Received 31 May 2007; received in revised form 21 October 2007; accepted 31 October 2007

Summary

Elastic finite element numerical models are used to study residual thermal stresses induced during cooling from the sintering temperature of carbon-based SiC/C functionally graded materials (FGMs) for ablation resistance application. Results show that the stresses can be decreased gradually with increasing the layer number (*N*). In a preferred system, the optimum compositional distribution exponent (*P*) and thickness of intermediate graded layers and pure SiC layer are 1.0, 3.6 mm and 1.0 mm, respectively. On basis of the simulated results, SiC/C purpose FGM was fabricated by hot-pressing process. SEM observation shows that this material is characterized by a linearly continuous gradient in the microstructure. Further studies indicate that this material has excellent ablation and thermal shock resistances.

Keywords: SiC/C; Functionally graded material (FGM); Residual thermal stresses; Finite element; Hot-pressing; Ablation

1. Introduction

In functionally graded materials (FGMs), residual thermal stresses were generated during cooling process from the fabrication temperature because of differences in thermal and elastic properties of different materials. The distribution of residual thermal stresses is very important to obtain a soundness FGM system, especially for the FGM used in severe conditions such as ultra high temperature, rapid temperature shift and high velocity gas eroding, etc. [1–3]. So it is necessary to analyze and optimize the distribution of composition and structure in FGMs before preparation.

Modeling study of thermal stress by finite element method (FEM) is one of the main research directions in the optimum design of FGMs [4–6]. Sarikaya, Chen et al. [7–10] had studied residual thermal stresses of the representative metal/ceramic FGM systems. As thermal-structural material for needs of aerospace, fusion and high temperature engine applications, ceramic/carbon FGM system has been developed in present years [11–13]. However, little systematic work on residual stress distribution of this kind of material, especially used as ablation resistance material, has been reported in the open literatures.

In this paper, the distribution of the residual stresses of carbon-based SiC/C FGM with different technical parameters was systematically investigated by FEM. Furthermore, the SiC/C purpose FGM with the optimized parameters was fabricated and its structure and some properties were studied for ablation resistance application.

2. Finite element analysis

According to the cylinder shape of the sample prepared by power stacking and hot-pressing techniques, a two dimensional (2D) model with axial symmetry was used as an analysis model, shown in Fig. 1. The pre-designed SiC/C FGM specimen had a diameter of 50 mm and consisted of pure carbon layer, SiC/C intermediate transition layers and pure SiC protective layer. Furthermore, carbon layer was determined as the main body of the FGM due to its excellent thermal physical property at high temperature and its thickness was determined at 25.4 mm. Relatively speaking, SiC/C intermediate graded layers and pure SiC layer were thin and their thicknesses were variable. In the thickness direction, the volume percentage of SiC in different

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doi:10.1016/j.msea.2007.10.078

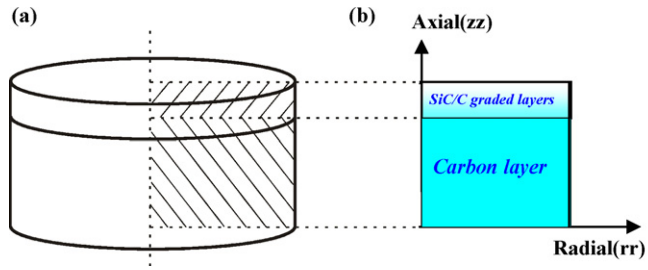

Fig. 1. Geometrical model of the cylindrical SiC/C FGM specimens used in finite element analysis (a) 3D view; (b) axi-symmetrical cross-section.

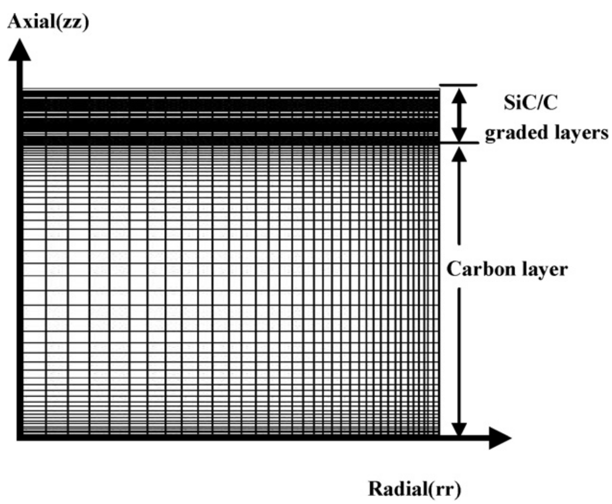

Fig. 2. Computational mesh division model for finite element analysis, the mesh area is corresponding to the colorized area in Fig. 1(b).

layer increased gradually from the bottom carbon layer to the top SiC layer. The FGM systems with different layer number (N), compositional distribution exponent (P) and thickness of graded layers were modeled and simulated. The FGM models were meshed using the 2D axi-symmetric, four-node, thermal-structural coupled element package (Plane 13) of ANSYS finite element software. Moreover, fine meshes were introduced at the layer interfaces and the boundary regions of the specimen models shown in Fig. 2. The number of elements and node points was 16,000 and 16,261, respectively. The analytical model was assumed as a perfect elastic body without plastic deformation. The structural and thermal boundary conditions were given as follows: (1) in Fig. 2, the left boundary of the mesh corresponds to the axis of symmetry and therefore the displacements of all nodes at the boundary were fixed in the radial (r) direction. All other boundaries were free; thus, thermal-induced bending was permitted during cooling process. (2) The initial stresses of all nodes were assumed as zero at the sintering temperature, and residual thermal stresses generated in the succedent cooling process. (3) The model was assumed to cool from sintering temperature (2273 K) to room temperature (298 K), with a uniform temperature field.

Some conventional properties of carbon and SiC materials for numerical simulation are listed in Table 1 [14–17]. The elastic modulus (E) and thermal expansion coefficient (α) of each graded layer were calculated by the modified rule of mixtures as the formula (1) and (2):

$$E = \frac{eV_C E_C + V_{SiC} E_{SiC}}{eV_C + V_{SiC}}, \quad e = \frac{q + E_{SiC}}{q + E_C} \tag{1}$$

$$\alpha = V_C \alpha_C + V_{SiC} \alpha_{SiC} - \frac{\Lambda - 1/\bar{K}}{1/K_C - 1/K_{SiC}}(\alpha_C - \alpha_{SiC}), \quad \Lambda = \frac{V_C}{K_C} + \frac{V_{SiC}}{K_{SiC}} \tag{2}$$

where α_i, V_i, E_i, K_i and $\bar{K}$ are the CTE, volume fraction, elastic modulus, bulk modulus of i component and that of graded region, respectively. Moreover, q is defined by the stress–strain transfer ratio and mostly determined at 500 MPa. $\bar{K}$, Poisson's ratio and thermal conductivity of each graded layer were calculated by the linear rule of mixtures [18,19].

3. Results and discussion

3.1. Effect of the layer number

Fig. 3 shows the calculated residual stress distributions in the graded layers of SiC/C FGMs with different layer number. Table 2 shows the maximum stress jumps at the interface between the adjacent layers and maximum residual stresses of the specimens. Results indicate that with increasing the layer number, the maximum stress jump and maximum residual stress of the corresponding FGM specimen decreased gradually, the main reason of which may be the decrease of component concentration difference between the adjacent layers. Furthermore, compared with the maximum residual stresses, the maximum stress jumps decreased rapidly. This is beneficial to the structural integrity of the layer interfaces, which are the worst bonding regions in the samples. In theory, bigger layer number is reasonable in order to relax the residual stresses more greatly. Considering the practical workload and the controllability of the experiment, the layer number should not be bigger. From the result of the thermal stress simulation, the optimized layer number was $N \geq 8$.

Table 1
Some conventional properties of carbon and SiC materials for numerical simulation

Material	Elastic modulus, E (GPa)	Poisson's ratio, υ	Coefficient of thermal expansion (CTE), α (K^{-1})	Thermal conductivity, λ ($W\,m^{-1}\,K^{-1}$)
C	11.5	0.25	3.5×10^{-6}	106
SiC	410	0.21	4.55×10^{-6}	49