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Effect of the interfacial reaction layer thickness on the thermal residual stresses in SiCf/Ti–6Al–4V composites

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Abstract

A three-dimensional finite element model was developed to study the effects of the interfacial reaction layer thickness on the distribution of the thermal residual stresses near the interfacial reaction layer in continuous SiC fiber reinforced Ti–6Al–4V composite. The interfacial reaction layer thicknesses in real composites were adopted in the present analysis. The hoop, radial and axial stresses at the fiber and interfacial reaction layer (f/i interface), middle of the interfacial reaction layer and interfacial reaction layer and matrix (i/m interface) were studied for each thickness. The results show the interfacial reaction layer thickness has a significant influence on the distribution of the thermal residual stresses near the interfacial reaction layer. X-ray stress measurements indicate that the prediction data have a good agreement with the experimental results. The interfacial radial cracks appear not only in the as-processed sample but also in the heat-treated samples. Experimental observations suggest that the f/i interfacial debonding is not significant during the transverse tensile loading.

Keywords: SiC/Ti–6Al–4V composite; Interfacial reaction layer thickness; Thermal residual stress; Finite element analysis; X-ray diffraction

1. Introduction

Continuous SiC fiber reinforced Ti alloy matrix composites (Ti-MMCs) are potential materials for using in the aerospace industry and other high-technology fields owing to their low density, high performance and high specific strength at room and elevated temperature [1–3]. However, the thermal residual stresses caused by the mismatch in the coefficient of thermal expansion (CTE) between the Ti alloy matrix and the SiC fiber reinforcement during the cooling from the consolidation temperature influence the overall mechanical properties of the composites [4]. Therefore, there has been considerable interest in the thermal residual stresses of the Ti-MMCs. Especially, more attention have been focused on the thermal residual stresses near the interfacial reaction layer in SiC/Ti–6Al–4V composites. Shaw and Miracle [5] studied the effect of the interfacial region on the transverse behavior of metal-matrix composites using the finite element analysis (FEA). But, the interfacial region was the coating instead of the interfacial reaction layer in their work. Haque and Choy [6] investigated the effect of the coating on thermal residual stresses generated at the fiber/matrix interface due to differences in the CTE mismatch between the various materials within the coating system. Although the interfacial reaction layer thickness and the type of C-coating were concerned, the effect of the coating system for SiC monofilament on the thermal residual stresses is obviously different from that in the real composites. Xia et al. [7] investigated the axial stresses in composites by using a three-dimensional (3D) finite element model with concerning the interfacial reaction layer thickness. Aghdam and Falahatgar [8] demonstrated that a better estimate for the stress–strain curve of the composites can be achieved by introducing the failures of fiber/coating interface and coating/matrix interface. Meinhard [9] obtained the interfacial reaction layer has an outstanding effect on the thermal residual stresses in composites by introducing a four-phase model consisting of concentric cylinders which represent fiber, interfacial layer, matrix and composite. However, Shaw and Miracle [5] conjectured that the thickness of the coating has little influence on the thermal residual stresses.

In this paper, the attention is focused on simulating the thermal residual stresses near the interfacial reaction layer in the SiC/Ti–6Al–4V composite system by using a 3D finite element model. In doing so, the stress distribution for different interfacial reaction layer thicknesses is examined. Based on the results, the

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Table 1
X-ray stress measurement conditions

Term	Content
Characteristic X-rays	Cu Kα (filter: Ni foil)
Reflection	HCP-α(114)
Tube voltage, current	40 (kv), 35 (mA)
Ψ Angle (°)	0, 20.7, 30, 37.76, 45
Correction	Lorentz, polarity, absorption

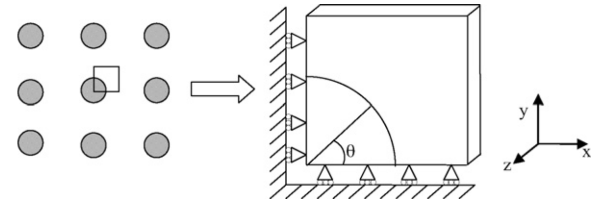

Fig. 1. Fiber arrangement, selected RVE and boundary conditions.

interfacial cracks and debonding during the transverse loading were discussed. The stress experiments were conducted to verify the FEA data.

2. Experimental procedure

A Ti–6Al–4V matrix composite reinforced continuously with 18 vol.% SiC fibers was employed in this experiment. These fibers have a diameter of approximately 140 μm. By means of foil-fiber-foil layer method, the 5-ply composite was assembled and subsequently hot pressed at 925 °C for 1 h under 72 MPa pressure. The specimens were subjected to heat treatments which were designed to prepare the specimens for X-ray analysis. For the sake of obtaining the different interfacial reaction layer thickness, the composites were heat treated in vacuum at 900 °C for 25 h and 900 °C for 75 h. And in order to research the distribution of the thermal residual stresses along the normal direction in specimens, the specimens need to be removed by mechanical polishing and chemical etching layer by layer. Chemical etching was used to remove the surface strain layer caused by the mechanical polishing. Only the matrix transverse stresses were measured due to the limitations of the specimen dimension and the instrument condition.

X-ray measurements were conducted on the PANalytical X'Pert MPD Pro X-ray diffractometer and used the $\sin^2\psi$ method with Cu kα radiation in the α(HCP) phase of the matrices. Only h k ls in the high 2θ were used for the analysis because of the greater sensitivity implicit at large angle. So the h k l 1 1 4 which scatter at 114°of 2θ was examined. Table 1 shows the detail X-ray measurement conditions.

3. Finite element analysis

3.1. Properties of the composite constituents

The composite system consists of a titanium alloy matrix, Ti–6Al–4V, reinforced by SiC fibers with a volume fraction of 18% and an interfacial reaction layer. In the system, the SiC fibers were treated as elastic, whereas time independent elastic–plastic behavior was used to describe the Ti–6Al–4V matrix (Table 2). According to Lü [10], for uncoated fiber, the composition of the interfacial reaction products consists of TiC, Ti_5Si_3, Ti_3Si, Ti_3SiC_2 and so on. And the magnitude of TiC is the greatest among the interfacial reaction products. Consequently, the composition of the interfacial reaction was nearly treated as TiC in the analysis. The SiC fibers and TiC properties are shown in Table 3.

3.2. 3D finite element model

Finite element analysis was performed using the ANSYS code. A 3D model with a square fiber array includes three phases, i.e. the fiber, interfacial reaction layer and matrix, and two distinct interfaces, one between the fiber and interfacial reaction layer (f/i interface) and the other between interfacial reaction layer and matrix (i/m interface). As shown in Fig. 1, the representative volume element (RVE) was selected to predict the thermal residual stresses in SiC/Ti–6Al–4V composite. The global behavior of the composite is assumed to be same as that of RVE. The nodes on the bottom face of the model (i.e. the x–z plane at $y=0$) were not allowed to move in the y-direction, while the nodes on the top face of the model were coupled together to shift an equal amount of displacement in the y-direction. Similarly, the nodes on the front face of the model (i.e. the y–z plane at $x=0$) and on the left face of the model (i.e. the x–y plane at $z=0$) were not allowed to move in the x-direction and z-direction, respectively, while the nodes on the back and right face of the model were coupled together to shift an equal amount of displacement in the x-direction and z-direction, respectively. Furthermore, the node at the origin of the model was not allowed to move in any direction to prevent rigid body displacement.

Three-dimensional eight-node elements were used to construct all the meshes in the analysis. Meshes for all the interfacial

Table 2
Ti–6Al–4V mechanical properties used in the model

Temperature ((C)	Young's modulus (GPa)	Poisson ratio	Yield stress (MPa)	Flow modulus (GPa)	Coefficient of thermal expansion ($\times10^{-6}$/°C)
23	125	0.31	1000	0.7	8.7800
260	110	0.31	630	2.2	9.8300
427	100	0.31	525	2.2	10.710
538	74	0.31	446	1.9	11.220
650	55	0.31	300	1.9	11.680
800	27	0.31	45	2	12.210