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Effects of the coating system and interfacial region thickness on the thermal residual stresses in SiC$_f$/Ti–6Al–4V composites

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ABSTRACT

A three-dimensional finite element model was developed to study effects of the coating system and interfacial region thickness on the distributions of the thermal residual stresses in continuous SiC fiber reinforced Ti–6Al–4V composite. Three coating systems were applied in this study, that is, C coating, C/TiB$_2$ coating and without coating. The influence of the interfacial region thickness on the thermal residual stresses in the composite was analyzed with concerning the simple case of without coating. Some proposal was given for the interface structure design of the composites. With regard to the thermal residual stresses, the C coating is an advisable choice for the interface structure design of the continuous SiC fiber reinforced Ti–6Al–4V composites. And for the region of the interfacial region thickness from 1 μm to 3 μm, the thicker interfacial region can reduce most of the thermal residual stresses in composites and improve the axial tensile strength of the composite.

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. At the same time, in the composites, an interfacial region (i.e. an interface coating or an interfacial reaction layer) between the fiber and matrix with a finite thickness is known to exist. The thermal residual stresses in the interfacial region have a significant influence on the composite properties [5–10]. Consequently, more attentions have been focused on the thermal residual stresses near the interfacial region in SiC$_f$/Ti–6Al–4V composites. Shaw and Miracle [5] have studied the effect of the interfacial region on the transverse behavior of metal–matrix composites using the finite element analysis (FEA). In their model, Yttria coated, graded carbon coated and without coated interface have been considered independently. Their results shown the thermal residual stresses in the interfacial region strongly depend on the properties of the interfacial region, while the residual stresses in the matrix and fiber are not significantly affected by these properties. And they believed the thickness of the coating has little influence on the thermal residual stresses. Robertson and Mall [6] have examined the effect of the thickness of the interfacial region on transverse properties of titanium-based metal–matrix composites. However, the matrix is assumed to be elastic in the model. Haque and Choy [7] have 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. Numerical modeling of composites with a finite thickness interface has also been carried out by Broutman and Agarwal [8]. However, their analyses are limited by the assumption of linear elastic behaviors of all constituents (i.e. fiber, matrix and interfacial region) and only longitudinal properties are evaluated. Xia et al. [9] investigated the axial stresses in composites by using a three-dimension (3D) finite element model with concerning the interfacial reaction layer thickness. Meinhard et al. [10] obtained the interfacial region 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.

In this paper, the attention is focused on simulating the thermal residual stresses in the SiC$_f$/Ti–6Al–4V composite system by using a 3D model with concerning the different coating systems and thicknesses of interfacial region. Based on this analysis, a guideline for the coating system and interfacial region thickness selections is proposed to improve performances of the composites.

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2. Finite element analysis

2.1. 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 20% and an interfacial region. In this system, the SiC fibers were treated as elastic and transversely isotropic (Table 1), whereas time independent elastic–plastic behavior was used to describe the isotropic Ti–6Al–4V matrix (Table 2). In Table 1, the subscript T and A denote the transverse and axial direction, respectively.

In earlier works, the coated fiber reinforced titanium alloy matrix composites have been studied by using theoretical modeling [7] and experimental [11–14]. The C coating and C/TiB_2 double coating were mostly investigated in these papers. The C coating prevents the direct reaction between the fiber and matrix and produces the brittle TiC between C coating and matrix. Therefore, the interfacial region can be simulated as C/TiC in case of C coating. Mogilevsky [14] obtained the TiB_2/matrix interface may be unstable both thermo-dynamically and kinetically and the kinetic instability manifest itself in the growth of TiB needles at the TiB_2/matrix interface. However, in this analysis, the interfacial region can be simulated as C/TiB_2 in case of C/TiB_2 coating without concerning the TiB needles because TiB needles cannot form a separated layer. In addition, for the fibers without coating, according to Lü [15], the magnitude of TiC is the greatest among the interfacial reaction products. Consequently, the composition of the interfacial region was nearly treated as TiC in case of without coating in the analysis. As described above, the interfacial region can be simulated as C/TiC, C/TiB_2 and TiC in case of C coating, C/TiB_2 coating and without coating, respectively in this analysis. And C, TiC and TiB_2 were treated as elastic and isotropic. Their thermal and mechanical properties are shown in Table 3.

2.2. 3D finite element model

Finite element analysis was implemented using the ANSYS code. A 3D model with a square fiber array included three phases, i.e. the fiber, interfacial region and matrix, and two distinct interfaces, one between the fiber and interfacial region (f/i interface) and the other between interfacial region 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_f/Ti–6Al–4V composite. The global behavior of the composite was assumed to be same as that of RVE. The fiber was 140 μm in diameter. Along the fiber direction, the model thickness was

Table 1
SiC fiber properties used in the model

Material	Young's modulus (GPa)		Shear modulus (GPa)		Poisson ratio		Coefficient of thermal expansion (10^{-6}/°C)	
SiC	E_T 262.6	E_A 403.2	G_T 109.5	G_A 93.1	ν_T 0.194	ν_A 0.148	α_T 2.63	α_A 4.5

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

Temperature (°C)	Young's modulus (GPa)	Poisson ratio	Yield stress (MPa)	Flow modulus (GPa)	Coefficient of thermal expansion (10^{-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

Table 3
C, TiB_2 and TiC properties used in the model

Material	Temperature (°C)	Young's modulus (GPa)	Poisson ratio	Coefficient of thermal expansion (10^{-6}/°C)
C	All temperature	160	0.23	10.0000
TiB_2	All temperature	569	0.113	8.1000
TiC	All temperature	440	0.2	7.6000

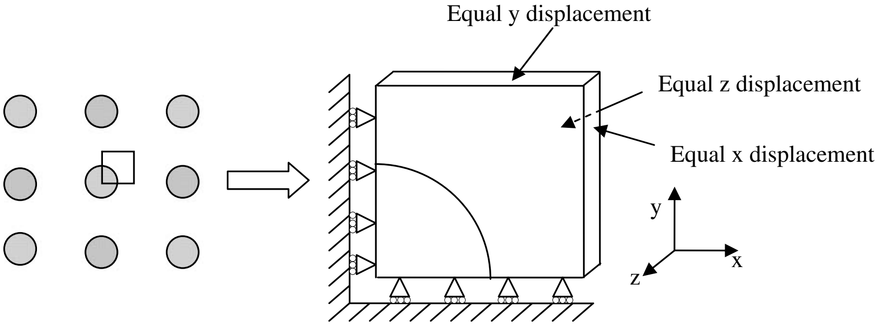

Fig. 1. Fiber arrangement, selected RVE and boundary conditions.