Article ID: 1003 - 6326(2004)02 - 0330 - 05

Effect of fiber distribution on residual thermal stress in titanium matrix composite ①

MA Zhi-jun(马志军), YANG Yan-qing(杨延清), ZHU Yan(朱 艳), CHEN Yan(陈 彦)
(Department of Materials Science and Engineering, Northwestern Polytechnical University, Xi'an 710072, China)

Abstract: Residual thermal stresses (RTS) of SCS-6 SiC/Ti-24Al-11Nb composite were analyzed by using finite element method (FEM). Three models of fiber array in the composite and the effect of fiber distance on the RTS were discussed. In all the three models compressive stress was found in the radial direction and tensile stress in the tangential direction. It is pointed out that, in real composite system, hexagonal fiber geometry is superior because the distribution and the magnitude of the residual stress are similar to those in single fiber model. In square fiber geometry, it is easier to make the matrix crack due to the larger residual tangential stress. RTS becomes very large and changes violently when the fiber distance is less than 15 μm or so, therefore too high fiber volume is apt to result in matrix crack.

Key words: titanium matrix composite; SiC fiber; residual thermal stress; finite element method
CLC number: TG 146.23 **Document code:** A

1 INTRODUCTION

With the rapid development of aerospace industry, more and higher demands have been presented on materials. The continuous SiC fiber reinforced titanium matrix composite is regarded as the ideal material of next generation aerospace engines in many developed countries, and more attention has been put on them for its superior properties at elevated temperature[1-3] and its designability of flexibility.

It is well known that different fiber geometry and fiber volume can be derived from different composite fabrication condition, for example, fiber volume may reach 80% by fiber coating method. Sometimes the properties of composite are not changed regularly, and RTS in composite generated when they are cooled from the processing temperature to room temperature due to the coefficient of thermal expansion (CTE, α) mismatch[4,5] between the fiber and matrix[6], is one of the main reasons. To some extent a great deal of investigation[7-11] already make people know the distribution and influencing factor of RTS around the interface. However, the effect of different fiber geometries on RTS is seldom involved, especially the effect of fiber distance factor.

RTS of SCS-6 SiC/Ti-24Al-11Nb composite is simulated by FEM in this paper. The objective is to discuss the effect of fiber geometry and fiber distance on RTS, and then to find better fiber geometry and appropriate fiber volume in composite from the perspective of RTS in order to provide technical supports for composite fabrication.

2 FINITE ELEMENT MODEL

Firstly, three typical fiber geometries are shown in Fig. 1. Although the single fiber model can't be repeated infinitely to compose the entire material volume, it can be compared with the other two models as the reference. Commonly, square fiber geometry can be derived from foil-fiber-foil layer technique, and hexagonal fiber geometry from fiber coating method[12, 13].

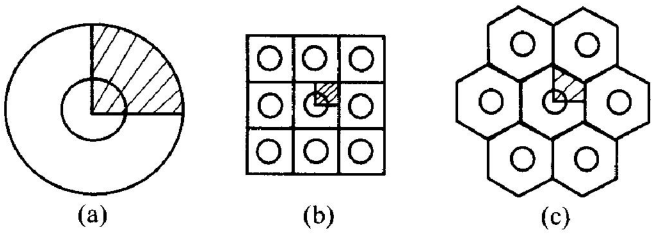

Fig. 1 Fiber geometry in composites
(a) —Single fiber model; (b) —Square fiber geometry model; (c) —Hexagonal fiber geometry model

In general, finite element model of composite should meet three basic requirements: 1) the model must have appropriate dimension which can demonstrate the size relationship between the reinforcement

① **Foundation item:** Project(50371069) supported by the National Natural Science Foundation of China; project (J1500E002) supported by the National Defense Fundamental Research Program of China; project (51412020401HK0302) supported by the Advanced Research Foundation for Weapon Equipment of China
Received date: 2003 - 06 - 16; **Accepted date:** 2003 - 12 - 02
Correspondence: MA Zhi-jun, PhD; Tel: +86-29-88486091; E-mail: zhijun_ma@hotmail.com

and the matrix at least; 2) the model must characterize periodicity of composite; 3) interface between fiber and matrix should be bonded perfectly. According to the symmetry of fiber array in the composite, analytical unit cells can be taken out from the shadow parts in Fig. 1. The corresponding finite element models (called 1/4 fiber model) are shown in Fig. 2, in which generalized plane strain state is assumed. Fig. 2(b) exemplifies the schematic diagram of finite element mesh with the specified boundary conditions. X-displacement on the Y-axis and Y-displacement on the X-axis are kept zero to maintain the symmetry condition. Since the research emphasis are stress distribution near the interface and the effect of fiber array on RTS in the engineering perspective, and in order to simplify the calculation, the other two sides are supposed to be free boundary condition.

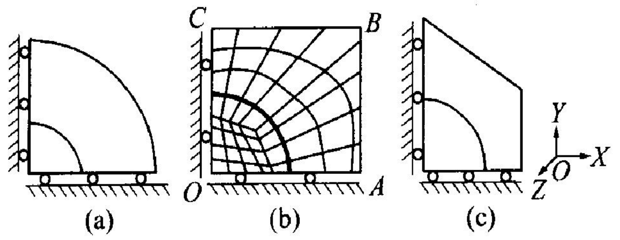

Fig. 2 Schematic diagram of 1/4 fiber model for finite element analysis
(a) —Single fiber model; (b) —Square fiber geometry model; (c) —Hexagonal fiber geometry model

Secondly, multi-fiber model should be built in order to find out the effect of fiber distance on RTS because 1/4 fiber model can't characterize the influence of surrounding fibers. Fig. 3 shows the schematic diagram of a multi-fiber model for square fiber geometry. According to the symmetry of composite, the shadow part in Fig. 3(a) is taken out as analytical unit cell. The assumption and boundary conditions of multi-fiber model are similar to those of 1/4 fiber model, as shown in Fig. 3(b).

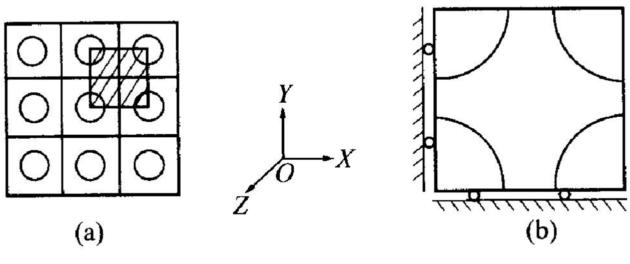

Fig. 3 Schematic diagram of a multi-fiber model
(a) —Fiber geometry; (b) —Finite element model

3 MATERIAL PROPERTIES AND FABRICATION CONDITIONS

RTS is caused by the inherent properties of the composite and influenced by the fabrication conditions. Tables 1 and 2 show the properties of SCS-6 SiC fiber and Ti-24Al-11Nb matrix used in finite element analysis[14]. The fiber is modeled as a linear elastic material and the matrix as an elastic-plastic-strain hardening material with temperature dependent properties. In addition, the composite is consolidated at 196 MPa and 920 ℃ for 1 h, the fiber volume fraction of composite is supposed to be 35%.

Table 1 Properties of SCS-6 SiC fiber

t/ ℃	α/ (10^{-6} ℃$^{-1}$)	E/ GPa	υ	ρ/ (kg·m^{-3})
25	3.53	400	0.25	2 550
203	3.62	400	0.25	2 550
400	3.87	400	0.25	2 550
500	4.03	400	0.25	2 550
702	4.36	400	0.25	2 550
900	4.59	400	0.25	2 550

Table 2 Properties of Ti-24Al-11Nb matrix

t/ ℃	α/ (10^{-6} ℃$^{-1}$)	E/ GPa	σ_y/ MPa	H/ GPa	υ	ρ/ (kg·m^{-3})
23	9.0	110	372	2.3	0.26	4 200
200	9.36	100	407	3.0	0.26	4 200
425	10.3	76	370	2.2	0.26	4 200
600	10.5	86	291	1.29	0.26	4 200
650	10.6	68	270	0.67	0.26	4 200
815	11.0	43	165	0	0.26	4 200

4 RESULTS AND DISCUSSION

4.1 Effect of fiber geometry on RTS

Fig. 4 shows the distribution of radial and tangential RTS in single fiber model. For a composite system whose matrix contracts larger than the fiber under a uniform reduction, residual radial stress is compressive stress as shown in Fig. 4(a). Maximal compressive stress about 106 MPa is homogeneous inside the fiber and extends to the interface next to the matrix. Consistent with the compressive radial stress is the state of tensile tangential stress in the matrix as shown in Fig. 4(b). The maximal tensile tangential stress is about 191 MPa near the interface next to matrix. At the same time tangential stress inside fiber is compressive. Therefore there is a larger tangential stress gradient at the interface. Many microcracks perpendicular to the interface would be found if the fabrication conditions were not appropriate, especially when the fiber distance was shorter. Obviously, the large tangential stress gradient[15] and the maximal tensile tangential stress near the interface are the impossible main reasons for matrix cracking.

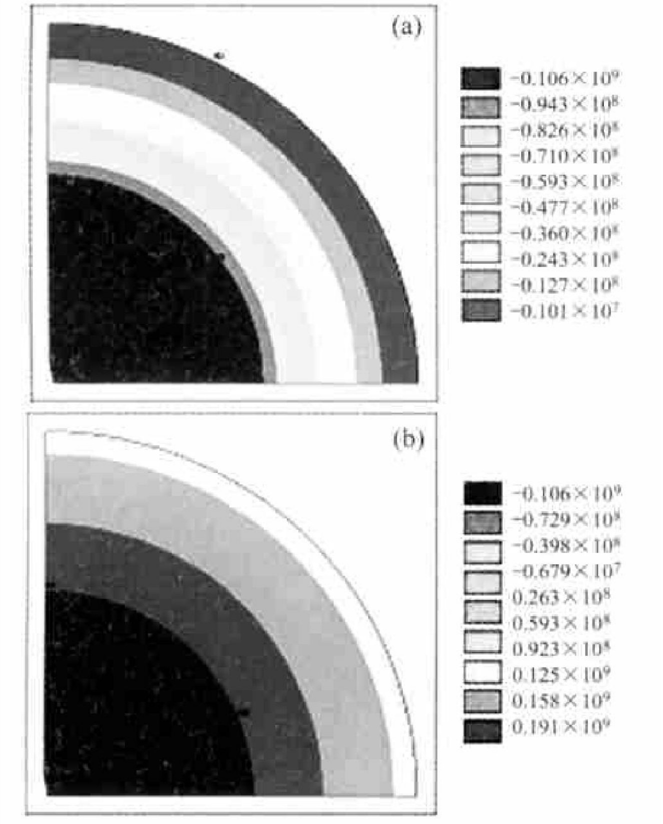

Fig. 4 Residual stress nephogram of single fiber model(Pa)
(a) —Radial stress; (b) —Tangential stress

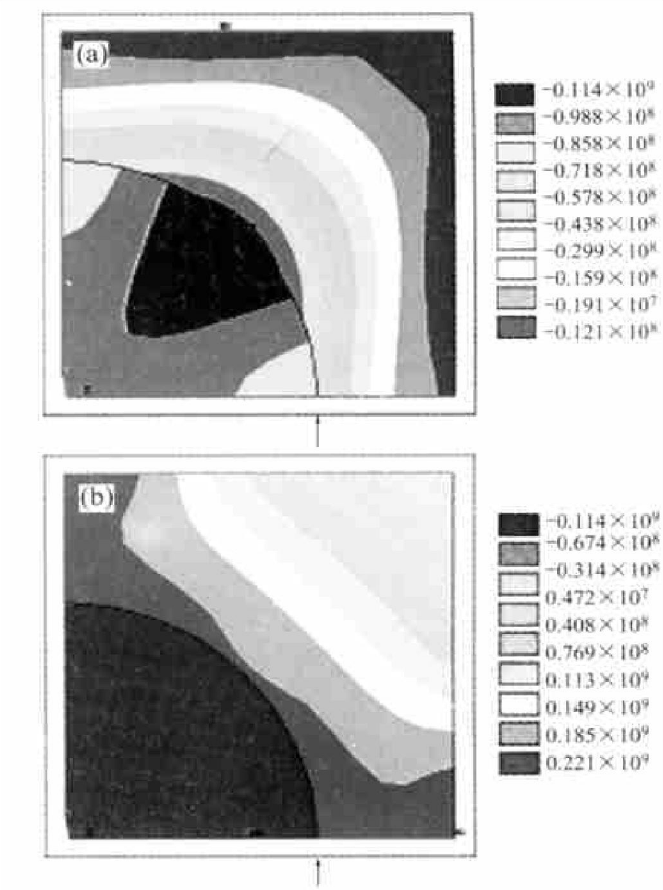

Fig. 5 Residual stress nephogram of square fiber geometry model(Pa)
(a) —Radial stress; (b) —Tangential stress

The single fiber model is an ideal model and its RTS distribution is almost with regularity, but in fact this kind of fiber geometry don't exist in real composite system. Square and hexagonal fiber geometry are the emphasis of this research because they are close to practical cases.

Compared with the single fiber model, the RTS of square fiber geometry model is very irregular, especially near the interface. The stress magnitude varies with the location as shown in Fig. 5. The radial stress is primarily compressive as shown in Fig. 5(a). In diagonal direction there exists maximal compressive radial stress of about 114 MPa in the vicinity of the interface, and in horizontal or vertical direction the relative small compressive radial stress is about 85.8 MPa. Because stress distribution is inhomogeneous, the interface is liable to separate in horizontal or vertical direction when the composite is sustained transverse load. As for the tangential stress shown in Fig. 5(b), the maximal tensile stress is about 221 MPa at the interface next to matrix. Furthermore, in horizontal or vertical direction the zone as well as the magnitude of maximal stress is larger than that of the single fiber model. In other words, matrix cracks perpendicular to the interface tend to extend in the direction of the line that connects centers of two nearest fibers.

Fig. 6 shows the residual stress nephogram of hexagonal fiber geometry model. It can be seen that the distribution of residual stress, especially the compressive radial stress, is relatively homogeneous and almost similar to that of the ideal single fiber model compared to the square fiber geometry model. Furthermore, the maximal compressive radial stress (see Fig. 6(a)) and tensile tangential stress(see Fig. 6(b)) are smaller than those of square fiber geometry model, which are about 108 and 196 MPa, respectively. Therefore to some extent the effect of fiber geometry on RTS is obvious, and compared with square fiber geometry, in composite hexagonal fiber geometry, this effect is better and not liable to lead to matrix cracking.

4.2 Effect of fiber distance on RTS

It is well known that the fiber volume in composite can't increase infinitely. In other words, fibers are not arranged too close, otherwise comprehensive properties of composite will be degraded severely. In this section, in order to investigate the effect of fiber distance on RTS, the distribution of RTS in multi-fiber model is simulated when fiber distance is assumed to be 1, 2, 4, 6, 8, 10, 15, 20, 25, 30, 35, 40, 50, 60, 70, 80, 100 μm, respectively.

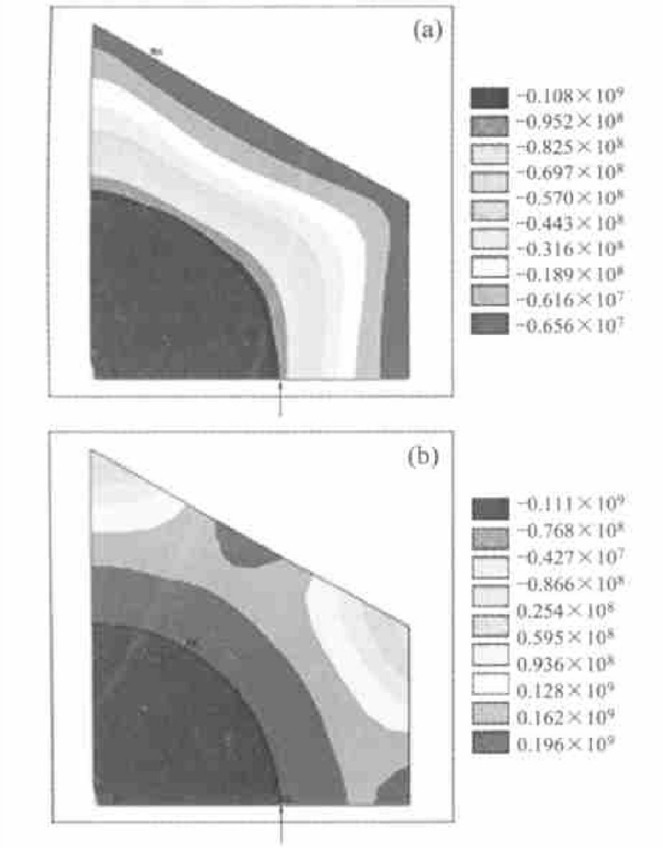

Fig. 6 Residual stress nephogram of hexagonal fiber geometry model(Pa)
(a) —Radial stress; (b) —Tangential stress

The distribution of RTS in multi-fiber model is shown in Fig. 7 when fiber distance is 70 μm and the fiber volume fraction is 35%. There exists similar stress distribution with the square fiber geometry model around the lower left-hand fiber. However, because of the influence of the other fibers the maximal compressive radial stress (127 MPa) and tensile tangential stress (243 MPa) of the multi-fiber model are larger than those of the square fiber geometry model under the same fiber volume fraction(See Fig. 5) .

Fig. 8 shows the RTS of points a and b (see Fig. 7) near the interface as a function of fiber distance. It can be seen that the RTS is very large and changes violently before the fiber distance reaches 15 μm (fiber volume fraction 62. 4%) . Furthermore, the radial stress of point a is largely tensile when the fiber distance is less than 6 μm, that is different from the distribution of RTS in square fiber geometry model and easily results in debonding of the interface. And then the curve becomes even after fiber distance exceeds 15 μm. Therefore the fiber distance of 15 μm is a critical distance which had better not to be exceeded in composite.

Fig. 7 Residual stress nephogram of multi-fiber model with fiber distance of 70 μm(Pa)
(a) —Radial stress; (b) —Tangential stress

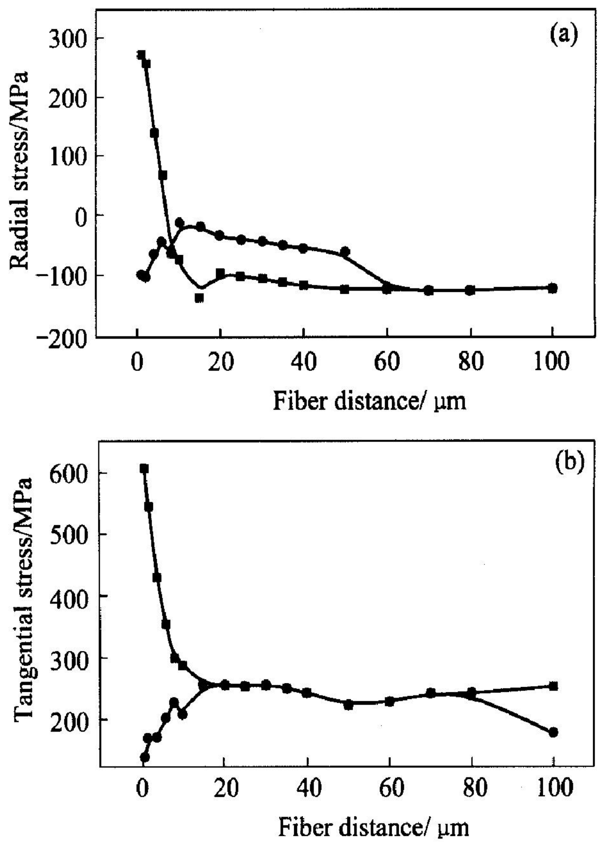

Fig. 8 RTS of points a(■) and b(●) as function of fiber distance in multi-fiber model
(a) —Radial stress; (b) —Tangential stress

5 CONCLUSIONS

1) The stress distribution in hexagonal fiber geometry model is more homogeneous than that in square fiber geometry model. Therefore the hexagonal fiber geometry is superior, and fiber coating method is better than foil-fiber-foil layer technique for composite processing if only considering the factor of RTS.

2) The variation of fiber distance remarkably influences the magnitude and distribution of RTS in composite. Since there is a distinctive knee in the curve between stress and fiber distance, the fiber distance had better not to exceed this threshold level, that is to say, the fiber volume in composite can't be increased infinitely.

REFERENCES

[1] Weber C H, Chen X, Connell S J, et al. On the tensile properties of a fiber reinforced titanium matrix composite —Ⅰ. unnotched behavior[J]. Acta metall Mater, 1994, 42(10): 3443 - 3450.

[2] Smith P R, Graves J A, Rhodes C G. Preliminary mechanical property assessment of a SiC/orthorhombic titanium aluminide composite[A]. Proceedings of Structural Intermetallice[C]. Pennsylvania: TMS, 1993. 765 - 770.

[3] Sandhu S, Tsakiropoulos P, Wood M J, et al. Interfacial studies in titanium aluminide/SiC composites[J]. Key Engineering Materials, 1997, 127 - 131: 671 - 678.

[4] CHU Cheng-lin, ZHU Jing-chuan, YIN Zhong-da, et al. Preparation and thermal stress relaxation characteristics of HA-Ti/Ti/HA-Ti axial symmetrical functionally graded biomaterial[J]. The Chinese Journal of Nonferrous Metals, 1999, 9(S1): 57 - 62. (in Chinese)

[5] ZHAO Yin-fu, LI Wei-geng. Heating effect on binding strength of interface of Cu/Ti composite plates[J]. The Chinese Journal of Nonferrous Metals, 1997, 7(2): 118 - 121. (in Chinese)

[6] Brunet A, Valle R, Vassel A. Intermetallic TiAl-based matrix composites: investigation of the chemical and mechanical compatibility of a protective coating adapted to an aluminide fiber[J]. Acta Mater, 2000, 48: 4763 - 4774.

[7] Meinkard K, Bernhard M, Georg G. Residual stresses in fiber-reinforced ceramics due to thermal expansion mismatch[J]. J Amer Cera Soc, 1993, 76(10): 2607 - 2612.

[8] Partha R, Jayaraman N. Residual stresses in SCS-6/Ti-24Al-11Nb composite(Ⅱ) —finite element modeling[J]. J Comp Tech Res, 1994, 16(1): 54 - 67.

[9] Chandra N, Ananth C R, Garmestani H. Micromechanical modeling of process-induced residual stresses in Ti-24Al-11Nb/SCS-6 composite[J]. J Comp Tech Res, 1994, 16(1): 37 - 46.

[10] Ronald P N. Fiber-matrix interface effects in the presence of thermally induced residual stresses[J]. J Comp Tech Res, 1990, 12(2): 65 - 75.

[11] Durodola J F, Derby B. An analysis of thermal residual stresses in Ti-6-4 alloy reinforced with SiC and Al_2O_3 fibers[J]. Acta Metall Mater, 1994, 42(5): 1525 - 1534.

[12] Yang Y Q, Zhu Y, Chen Y, et al. Processing and property of SiC fiber reinforced Ti - matrix composite [J]. Rare Metal Mat Eng, 2002, 31 (3): 201 - 204.

[13] Dudek H J, Leucht R, Kaysser W A. Development of metal matrix composites by fiber coating and hipping [A]. Proceedings of ICCM-10[C]. Canada: Whistler B C, 1995. 695 - 702.

[14] Arnold S M, Arya V K, Melis M E. Reduction of thermal stresses in advanced metallic composites based upon a compensating/compliant layer concept[J]. Journal of Composite Materials, 1992, 26(9): 1287 - 1309.

[15] Warrier S G, Gundel D B, Majumdar B S, et al. Interface effects on the micromechanical response of a transversely located single fiber SCS-6/Ti-6Al-4V composite [J]. Metallurgical and Materials Transactions A, 1996, 27A: 2035 - 2043.

(Edited by LONG Huai-zhong)