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ARTICLE

Effect of Interface Reaction on Interface Shear Strength of SiC Fiber Reinforced Titanium Matrix Composites

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Abstract: The finite element model, which considered the interfacial reaction layer was developed to evaluate interfacial shear strength of titanium matrix composites (TMCs) and analyze the effect of interface reaction on interfacial mechanical properties. The results show that the interfacial shear strength of SiC/Timetal-834 evaluated is about 500 MPa, and that the interfacial shear strength increases as the interfacial reaction enhances. Moreover, the relationship between the thickness of the interfacial reaction layer and the interfacial shear strength is built.

Key words: metal matrix composites; finite element method; interfacial shear strength

SiC fiber reinforced titanium matrix composites (TMCs) are the potential light-mass structural materials for use in aircraft and aerospace industries because of their high specific stiffness and specific strength. However, the serious interfacial reaction, which significantly influences the interfacial mechanical properties of composites, appears between the fiber and the matrix during fabrication or service of composites at high the temperature[1-4]. It is an urgent problem to analyze the effect of interfacial reaction on the interfacial mechanical properties of TMCs.

The finite element modeling of the push-out test is appropriate one to characterize interfacial mechanical properties of composites. In modeling of the push-out test, it is a critical issue to select an appropriate interface model. In previous finite element studies, three types of interface models have been used to describe interfaces, namely interphase layer model[5,6], cohesive zone model[7-9], and spring element model[10]. The interphase layer model considers that the interface is a distinct layer with specified thickness between the fiber and the matrix, while the failure of interface is difficult to realize. In contrast, the cohesive zone model and the spring layer model are suitable for modeling the interface failure behavior. However, the initial thicknesses of cohesive elements and spring elements are zero[10]. In reality, the interphase (i.e. interfacial reaction layer) has some thickness which significantly affects the properties of composites[11].

In the current work, the interface model, which considers the interfacial reaction layer and chemical bond strength, is developed to evaluate the interfacial shear strength of TMCs. Moreover, the effect of the interfacial reaction layer on the interfacial shear strength is analyzed.

1 Finite Element Analysis

1.1 Finite element model considering interfacial reaction

The push-out test was analyzed using an axi-symmetric cylindrical model, as shown in Fig.1. In the model, the main interfacial reaction product TiC is taken into consideration[11]. The height of the specimen is 500 μm. The radius of SiC fiber is 70 μm. The radius of TiC is 76 μm (implying the thickness of the TiC is 6 μm), and the radius of titanium matrix is 118 μm. Two groups of spring elements are used to describe the chemical bond between SiC fiber and TiC and between TiC and titanium matrix, respectively. Fig.2 is the details of the spring elements. The elements of SiC fiber, interphase and titanium matrix are iso-parametric 4-noded quadrilateral elements. The element size chosen (in *Z*-direction) is 12.5 μm, whereas the size in the *R*-direction is 7 μm. The interphase element size in *R*-direction is 6 μm, and in *Z*-direction is 12.5 μm.

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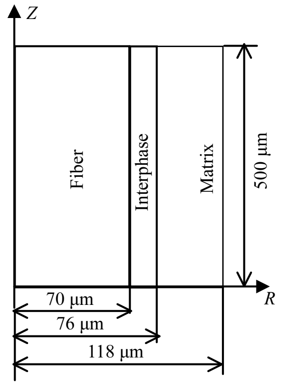

Fig.1 Axi-symmetric finite element model

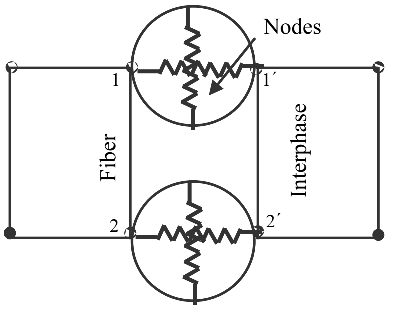

Fig.2 Details of spring model of the interface

1.2 Finite element modeling procedure

The finite element analysis consists of two steps: (1) modeling of the cooling process of TMCs; and (2) modeling of the push-out test process. When TMCs is cooled from high temperature to room temperature, thermal residual stress is induced due to the mismatch of the coefficient of thermal expansion (α). In finite element analysis, this cooling process is modeled using thermal load, and a reference temperature (T_{ref}) is assumed above which the composites is stress free. In addition, the free end surface of the model can be simulated via removing the existing tying constraint and spring elements[12,13].

For the push-out test, the prescribing displacement is applied to a rigid punch to push the fiber out completely. A special subroutine is designed to control the interfacial failure. The interface failure process is based on maximum shear stresses failure criterion given by:

$$|\tau| \geqslant \tau^* \qquad (1)$$

where τ is the shear stress and τ* is the interfacial shear strength. When the interfacial shear stresses are larger than the interfacial shear strength, the stiffness of the spring element is reduced to zero, and the debonding appears under the control of the subroutine. Once the interfacial debonding occurs, the frictional sliding is introduced at the debonding interface. The frictional sliding behavior of the interface is described by the Coulomb's law:

$$\tau_{\mathrm{f}} = \mu \tau_{\mathrm{rr}} \qquad (2)$$

where τ_{f} is the interfacial frictional stress, μ is the friction coefficient and τ_{rr} is the radial residual stress at the sliding interface.

1.3 Material properties

SiC fiber and TiC are treated as perfectly isotropic elastic materials. The matrix is assumed to be elastic-plastic material. The property dependency on temperature is included in the analysis. Table 1 shows the variations of the thermo-mechanical properties of Timetal-834, TiC and SiC fiber. E, ν, and α represent Young's modulus, Poisson's ratio and thermal expansion coefficients, respectively.

2 Results and Discussion

2.1 Evaluation of interfacial shear strength

The push-out test was modeled using the finite element method as described above. When the numerical analysis load-displacement curve has a good agreement with the experiment curve, the interfacial shear strength of TMCs can be obtained. In this paper, SiC/Timetal-834 is taken as the model material. Fig.3 shows the experimental load-displacement curve of the push-out test for SiC /Timetal-834[13]. The specimen of the push-out test is the same as the finite element model. More information about the push-out equipment and test procedure are given in Ref. [14].

Upon modeling the push-out test of SiC/Timetal-834, different interfacial frictional coefficients and the same interfacial shear strength are assumed. The interfacial frictional coefficients are assumed to be 0.2, 0.3 and 0.4 respectively. The interfacial shear strength is assumed to be 450 MPa. Fig.4 presents the numerical analysis load-displacement curves for SiC/ Timetal-834. From Fig.4, it can be seen when the interfacial frictional coefficient is assumed to be 0.3, the frictional force evaluated by the finite element analysis is equal to the experimental one. So the interfacial frictional coefficient of SiC/Timetal-834 is equal to 0.3. Then, the push-out test is modeled with different interfacial shear strengths and the same interfacial frictional coefficient (μ=0.3), as shown in Fig.5. From Fig.5, it can be seen,when the interfacial shear strength is assumed to be 500 MPa, good agreement is found between the numerical analysis load-displacement curves and the experimental one. Therefore, the interfacial shear strength of SiC/Timetal-834 is about 500 MPa.

It is noted that the interfacial shear strength of SiC/ Timetal-834 ($\tau_{\exp}^{p} = P_{\max}/\pi dL$) evaluated from the peak load is only 140 MPa. The value evaluated by the finite element method is four times as big as the one evaluated by the peak load[12]. The reason is that for the interfacial shear strength evaluated by the peak load, the shear residual stresses and the

Table 1 Thermo-elastic parameters of Timetal-834, SiC, and TiC

Material	E/GPa	ν	$\alpha/\times10^{-6}\cdot℃^{-1}$
Timetal-834, 28 ℃	115	0.3	11.24
Timetal-834, 300 ℃	96.4	0.3	11.24
Timetal-834, 530 ℃	84.	0.3	11.24
TiC (all temperature)	440	0.19	7.6
SiC (all temperature)	469	0.17	4.0

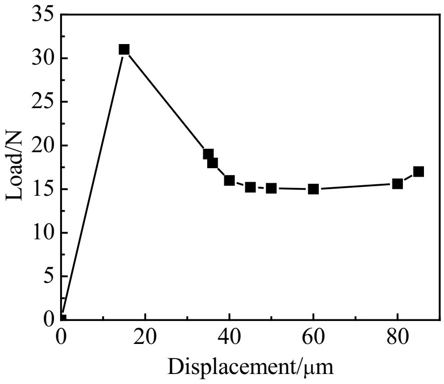

Fig.3 Load-displacement curves of the push-out test[13]

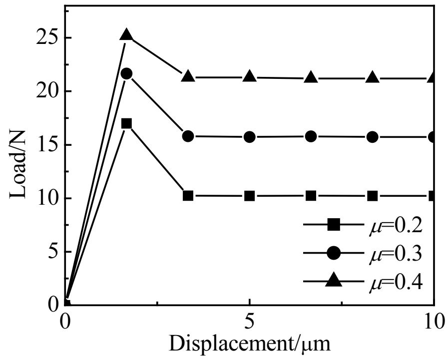

Fig.4 The numerical analysis load-displacement curves with different interfacial frictional coefficients

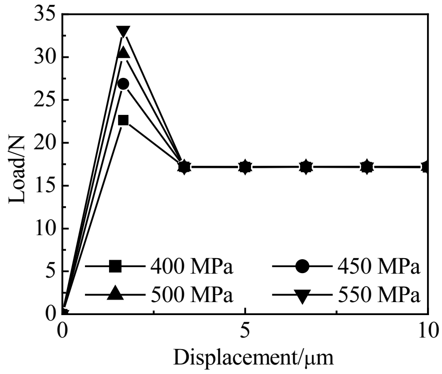

Fig.5 The numerical analysis load-displacement curves with different interfacial shear strengths

frictional stresses are all ignored. The shear stresses acting on the debonding interface is schematically shown in Fig.6. It is indicated that the shear residual stresses (τ_r), the frictional stresses (τ_f) and the shear stresses introduced by the applied load (τ_P) result in the interface debonding. Therefore, the interfacial shear strength can be expressed as:

$$\tau^* = \tau_f + \tau_r + \tau_P \tag{3}$$

Fig.7 presents the distribution of residual shear stresses of SiC/Timetal-834. It can be seen that the residual shear stress is about 300 MPa at the crack tip. The frictional shear stress evaluated from the peak load ($\tau_{fr} = P_{fr}/\pi dL$) is about 80 MPa. According to equation (3), it can be deduced that the interfacial shear strength of SiC/Timetal-834 is 520 MPa. The prediction from equation (3) is in good agreement with the finite element result.

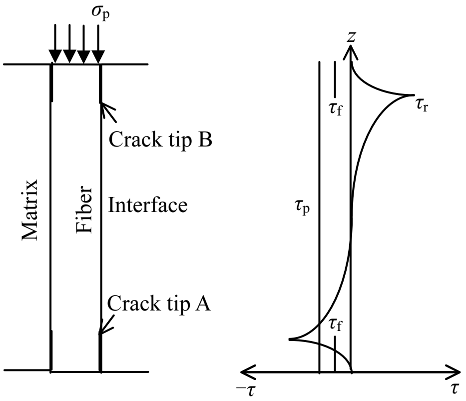

Fig.6 Schematic of interfacial shear stress analysis

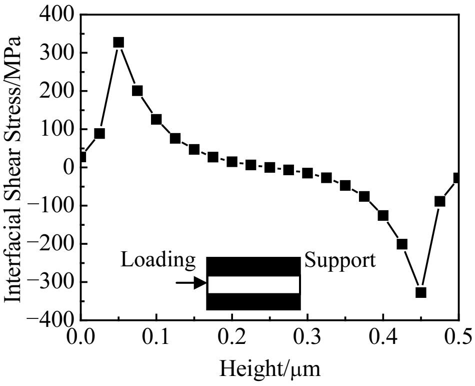

Fig.7 The distribution of interfacial shear stress

2.2 Effect of interfacial reaction on the interfacial shear strength

According to the shear-lag theory, Tsai[15] deduced an equation for evaluation of interfacial shear strength:

$$\tau^* = -\frac{\bar{\sigma}}{2^{\frac{1}{2}}}\left(\frac{G_m}{E_f}\right)^{\frac{1}{2}} \times \frac{\tan(\alpha l)}{\left\{\left(\frac{G_m}{G_i}\right)\ln\left(\frac{r_i}{r_f}\right)+\ln\left(\frac{r_m}{r_i}\right)\right\}^{\frac{1}{2}}} \tag{4}$$

$$\alpha = \left(\frac{2\frac{G_i}{E_i}r_f^2\ln\left(\frac{r_i}{r_f}\right)}{1+\frac{G_i\ln\left(\frac{r_m}{r_i}\right)}{G_m}\ln\left(\frac{r_i}{r_f}\right)}\right)^{\frac{1}{2}} \tag{5}$$

where τ^* is the interfacial shear strength, $\bar{\sigma}$ is the applied maximum stress, G_m and G_i are the shear modulus of matrix and interface, respectively, E_f is the Young's modulus of fiber, r_i, r_f and r_m are the radius of the interface, SiC fiber and titanium matrix, respectively and l is the height of the specimen. ln (r_i/r_f) is equal to 0, because (r_i/r_f) is about 1. With the substitution of equation (5) and ln(r_i/r_f)=0 in equation (4), equation (4) can be modified as:

$$\tau^* = -\frac{\bar{\sigma}}{2^{\frac{1}{2}}}\left(\frac{G_\mathrm{m}}{E_\mathrm{f}}\right)^{\frac{1}{2}} \times \frac{\tan\left(\left(\dfrac{2G_\mathrm{m}}{E_\mathrm{f} r_\mathrm{f}^2 \ln\dfrac{r_\mathrm{m}}{r_\mathrm{i}}}\right)^{\frac{1}{2}} \times l\right)}{\left\{\ln\left(\dfrac{r_\mathrm{m}}{r_\mathrm{i}}\right)\right\}^{\frac{1}{2}}} \tag{6}$$

With thickening of the interfacial reaction product, i.e. the r_i increasing, both $\left\{\ln\left(\frac{r_\mathrm{m}}{r_\mathrm{i}}\right)\right\}^{-\frac{1}{2}}$ and $\tan\left(\left(\frac{2G_\mathrm{m}}{E_\mathrm{f} r_\mathrm{f}^2 \ln\frac{r_\mathrm{m}}{r_\mathrm{i}}}\right)^{\frac{1}{2}} \times l\right)$ increase. G_m and E_f are constant.

In order to study the effect of interfacial reaction on the applied maximum stress ($\bar{\sigma}$), the finite element models with different interphase thicknesses are presented. The interphase thicknesses are assumed to be 4, 6, 8, 10 and 12 μm, respectively. Fig.8 shows the relationship between the interphase thickness and the peak load. It is indicated that the peak load increases with increasing of the interphase thickness, that is to say, the applied maximum stress ($\bar{\sigma}$) increases with enhancing of interface reaction. Therefore, according to equation (6), we can deduce that the interfacial shear strength of TMCs increases with enhancing of interface reaction.

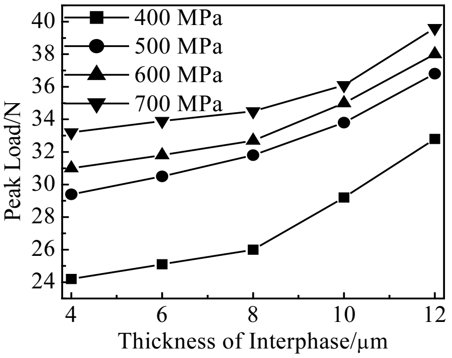

Fig.8 Variation of the peak load as a function of interphase thickness

3 Conclusions

1) The finite element model considering the interfacial reaction layer is used to evaluate interfacial shear strength of TMCs.

2) The interfacial shear strength of SiC/Timetal-834 evaluated by the finite element analysis is about 500 MPa, while the shear strength evaluated by the peak load of the push-out test is only 140 MPa.

3) Interface shear strength increases as interface reaction enhances.

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界面反应对 SiC 纤维增强钛基复合材料界面剪切强度的影响

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摘　要：利用考虑界面反应层的有限元模型，分析了界面反应对复合材料界面剪切强度的影响。有限元预测得出，界面剪切强度随着界面反应增强而增大。并且，建立了界面反应层厚度和界面剪切强度的关系式。

关键词：金属基复合材料；有限元分析；界面剪切强度

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