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THERMAL RESIDUAL STRESS AND ITS EFFECTS ON MECHANICAL BEHAVIOR OF ALIGNED SHORT FIBER REINFORCED METAL MATRIX COMPOSITES

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SUMMARY: Based on the single fiber model of aligned short fiber reinforced metal matrix composites, the thermal residual stress and its distribution in the composites were analyzed by an axi-symmetrical elastic-plastic finite element method (FEM). The effects of various microstructural parameters on the thermal residual stress were initially discussed. Then, the effects of thermal residual stress on the stress transfer and the initial stress-strain curves of aligned shot fiber composite were analyzed under axial applied stress. It was shown that, the unmatched thermal strain resulted in a compressive fiber's axial stress, tensile matrix's axial stress and compressive interfacial normal stress. The stress transfer between matrix and fiber became to be inadequate due to the thermal residual stress, which was detrimental to the improvement of composite mechanical behavior. The thermal residual stress resulted in the difference between the tensile and the compressive behaviors of the composites.

INTRODUCTION

In the squeeze casting manufacture of short fiber reinforced metal matrix composites, thermal residual stress was produced unavoidably due to the unmatched coefficients of thermal expansion of the short ceramic fibers and the metal matrix. The thermal residual stress influences significantly the mechanical behavior of the composites, and cannot be neglected. At present, according to the Eshelby's inclusion theory [1~3] or using the elastic-plastic finite element method [4~6], the thermal residual stress produced in short fiber reinforced metal matrix composites was analyzed and some significant results had been obtained. However, in the established work, the effects of various microstructural characteristics of the composites on the thermal residual stress were not taken into account systematically. The feature of the thermal residual stress and its effects on the stress transfer and mechanical properties of the composites have not been realized incisively. Elastic-plastic finite element methods are able to deal with accurate geometrical representation of the short fiber reinforced metal matrix composite. The effects of sharp corners or other stress-concentrations can be included in the analysis. The finite element method had been adopted to discuss the thermal residual stress and its distribution in the composites and resulted in a more reasonable conclusion than that obtained by Eshelby's inclusion theory. Thus, in this work, based on the single fiber model of short fiber reinforced metal matrix composites (SFRMMCs), the thermal residual stress and its distribution in the aligned short fiber composites were systematically analyzed using an axi-symmetrical elastic-plastic FEM. The effects of various microstructural parameters on the thermal residual stress were initially discussed. Then, the effects of thermal residual stress on the stress transfer and tensile initial stress-strain curve of aligned shot fiber composite were analyzed under axial applied stress. Some significant results were obtained.

FEM MODEL

In this work, an axi-symmetrical single fiber model of the metal matrix composites reinforced by aligned short fibers was used and shown in Fig. 1. The symmetrical axis was *z*-axis. Only one-fourth part of the single fiber model and its simplified finite element mesh were shown in Fig. 1 due to the symmetry. The elastic-plastic FEM code was ANSYS R5.5/Multiphysics. The size of model was $l_m=l_f+5r_f$, $l_f r_f^2 / l_m r_m^2=V_f$, $l_f/r_f=20$. V_f was fiber volume fraction. An 8-node axi-symmetrical element was used in the calculation. The material properties adopted in the analysis were: the fiber, elastic modulus E_f=300GPa, Poisson's ratio ν_f=0.20, coefficient of thermal expansion $\alpha_f=7.5\times10^{-6}$/℃; the matrix, elastic modulus E_m=70GPa, Poisson's ratio ν_m= 0.33, coefficient of thermal expansion α_m= 23.6×10^{-6}/℃. The fiber was taken to be an elastic material. The matrix was assumed to be a bi-linear material and yielded according to the Von-Mises's rule. In order to discuss the effects of interfacial bond on the thermal residual stress, an interfacial layer was inserted into the single fiber model, as shown in Fig. 1. The thickness of interfacial layer was $t_i=0.05r_f$. The material of interfacial layer was also assumed to be elastic-plastic.

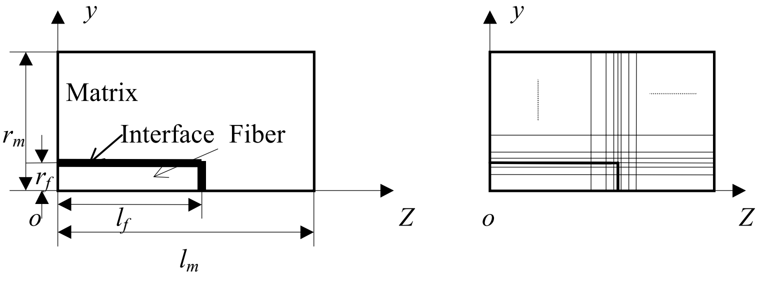
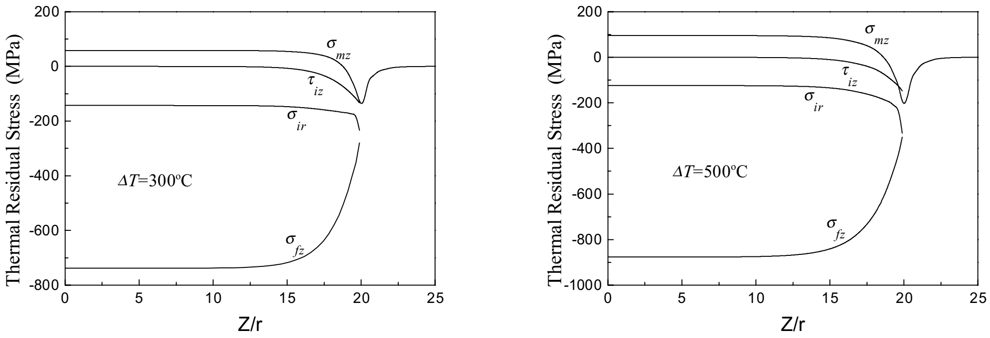


Fig. 1 The axi-symmetrical single fiber model of SFRMMCs and its simplified mesh

RESULTS AND DISCUSSION

Basic Features of Thermal Residual Stress

In this work, the temperature of 525℃(which was about equal to the melt temperature of aluminum alloy) was adopted as the thermal-residual-stress-free referential temperature T_r. In the cooling of the squeeze casting billet, the thermal residual stress was produced. In order to discuss its basic features, the thermal residual stress was analyzed at different temperatures T (which were represented by various temperature differential $\Delta T=T-T_r$). Thus, with ΔT=300℃ (which represented at 225℃) and 500℃(which represented at room temperature), $l_f/r_f=20$, V_f=15%, σ_{my}=200MPa, H'=2Gpa, a perfect interface adopted, the distributions of thermal residual stress components were calculated. In this paper, the axial stress of fiber and matrix, σ_{fz} and σ_{mz}, interfacial shear stress τ_{iz} and normal stress σ_{ir} were mainly considered. The results are shown in Fig. 2. It can be seen that a residual compressive σ_{fz}, a residual tensile σ_{mz} and a residual compressive σ_{ir} are produced in the fiber, matrix and interface respectively, due to the unmatched thermal deformation of the fiber and the matrix. A considerable residual shear stress also occurred at the interface. With the decrease of ΔT, the values of thermal residual stress decreased. However, the decrease is non-proportional due to the elastic-plastic behavior is involved in the calculation. On comparison with an elastic analysis, it is found that the values obtained by elastic-plastic analysis are lower than those gained in the elastic analysis. Especially, the sudden change of the residual matrix stress happened at the fiber end in elastic analysis is significantly alleviated by the plastic deformation of the matrix. This means that the unmatched thermal strain can be abated by the plastic deformation of matrix.



a) ΔT=300℃ b) ΔT=500℃

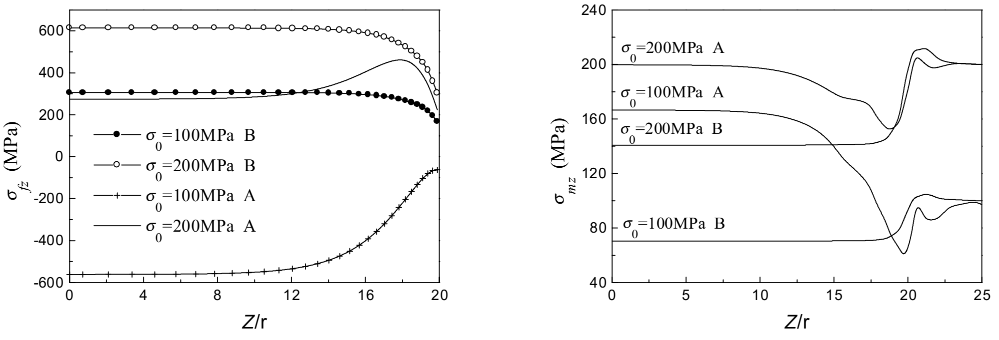
Fig. 2 Distribution of thermal residual stress components with two temperature differentials

Effects of Microstructural Characteristics on Thermal Residual Stress

Further research showed that the thermal residual stress components had close relation to the microstructural characteristics of short fiber reinforced metal matrix composites, such as fiber volume fraction, fiber's aspect ratio, matrix plastic behavior and interfacial bond. Here the absolute values of thermal residual stress components were discussed. With the increase of fiber volume fraction, the fiber axial stress σ_{fz}, interfacial shear stress τ_{iz} and normal stress σ_{ir} decreased, but the matrix axial stress σ_{mz} increased. When the fiber aspect ratio increased, all thermal residual stress components of the fiber, matrix and interface increased. The calculated results had showed that the plastic deformation of the matrix could alleviate the unmatched thermal deformation of the fiber and the matrix and made the thermal residual stress decreased. The extent of the matrix plastic deformation was determined by the matrix yield strength and hardening modulus. With the different matrix yield strengths or the different hardening moduli, the calculated results showed that the thermal residual stress decreased with the decreasing of the matrix yield strength or hardening modulus. This meant that the more easily the plastic deformation occurred in the matrix, the smaller the thermal residual stress in the composites was. With regard to the interface performances, it was concluded that the weaker the interfacial bond was, the smaller the thermal residual stress was. The interfacial plastic behavior resulted in the decrease of thermal residual stress, but its effect was much weaker than that of interfacial elastic modulus that represented the state of interfacial bond.

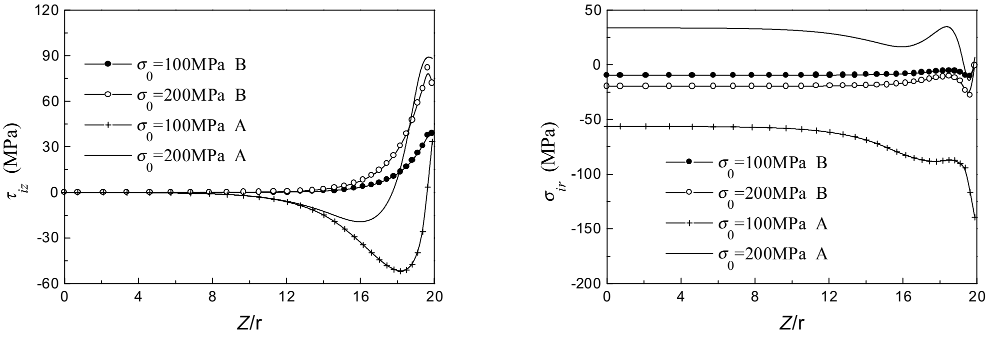
Stress Transfer with Thermal Residual Stress

In order to reveal the effects of thermal residual stress on the stress transfer of SFRMMCs, with ΔT=500℃, l_f/r_f=20, V_f=10%, σ_{my}=200MPa, H′=2GPa, and a perfect interface, the features of stress transfer were discussed under certain applied stress σ_0 with or without thermal residual stress. The calculated results of the axial stress of fiber and matrix, σ_{fz} and σ_{mz}, interfacial shear stress τ_{iz} and normal stress σ_{ir} are shown in Fig. 3.



a) Fiber axial stress σ_{fz}

b) Matrix axial stress σ_{mz}



c) Interfacial shear stress τ_{iz}

d) Interfacial normal stress σ_{ir}

Fig. 3 Stress distribution under applied stress σ_0 with(A) or without thermal residual stress(B)

From Fig. 3, it is found that the thermal residual stress influences significantly the stress transfer in the SFRMMCs. The fiber's axial stress σ_{fz}, matrix's axial stress σ_{mz}, interfacial shear stress τ_{iz} and normal stress σ_{ir} all increase with the increment of the applied stress. However, under a certain applied stress, the σ_{fz} gained without thermal residual stress taken into account is higher than that obtained with thermal residual stress, as shown in Fig. 3a. Correspondingly, the τ_{iz} obtained without thermal residual stress taken into account is also higher than that gained with thermal residual stress, as shown in Fig. 3b. This means that the residual stress degrades the stress transfer carried out by means of interfacial shear stress between the fiber and matrix. Since the fiber's stress decreases with the thermal residual stress taken into account, the proportion of the applied stress shared by the matrix increases. Thus, the σ_{mz} gained without thermal residual stress is lower than that obtained with thermal residual stress, as shown in Fig. 3c. When the unmatched thermal strain is not taken into account, the interfacial normal stress σ_{iy} has little change and remains a small negative value with the increment of the applied stress. However, the σ_{iy} obtained with thermal residual stress is much higher in absolute value than that without thermal residual stress and changes significantly from a compressive stress to a tensile stress when the applied stress increases. This tensile stress is very detrimental to the interfacial bond between the fiber and the matrix. It is also concluded that with an increasing applied stress, the difference resulted from taking the thermal residual stress into account or not decreases. The calculated results showed that when the applied stress reached 350MPa, the difference almost disappeared. This means that the thermal residual stress can be relaxed by the increasing plastic deformation of the metal matrix.

Stress-strain Curve with Thermal Residual Stress

Based on the theory of composite overall effective property [7], with ΔT=500℃, l_f/r_f=20, V_f=10%, σ_{my}=200MPa, H′=2GPa, and a perfect interface, the initial tensile or compressive stress-strain curves of aligned short fiber reinforced metal matrix composite were calculated with or without thermal residual stress taken into account. The simulated results are shown in Fig. 4. There is considerable difference between the two stress-strain behaviors with or without the thermal residual stress taken into account. It is seen that without thermal residual stress, the tensile and compressive initial stress-strain curves are overlapped. However, the tensile elastic modulus and compressive proportional limit increase considerably, and the tensile proportional limit and compressive modulus decrease apparently when the thermal residual stress is considered. The results are similar to that in the established work [4~5].

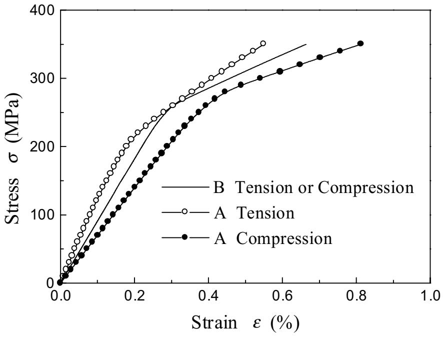


Fig.4 The initial stress-strain curves with (A) or without thermal residual stress (B)

CONCLUSIONS

A residual compressive σ_{fz}, a residual tensile σ_{mz} and a residual compressive σ_{ir} are produced in the fiber, matrix and interface respectively, due to the unmatched thermal deformation of the fiber and the matrix. A considerable residual shear stress also occurred at the interface. With the decrease of ΔT, the values of thermal residual stress decreased. The thermal residual stress components have close relation to the microstructural characteristics of short fiber reinforced metal matrix composites, such as fiber volume fraction, fiber's aspect ratio, matrix plastic behavior and interfacial bond. The increase of fiber volume fraction results in a decrease of the σ_{fz}, τ_{iz} and σ_{ir}, but a increase of the σ_{mz}. All thermal residual stresses increase with the increment of fiber's aspect ratio. The more easily the plastic deformation occurs in the matrix, the smaller the thermal residual stress is. The weak interfacial bond would result in a small thermal residual stress. The residual stress degrades the stress transfer carried out by means of interfacial shear stress between the fiber and matrix, which results the increasing proportion of the applied stress shared by the matrix. It is also concluded that with an increasing applied stress, the difference resulted from taking the thermal residual stress into account or not decreases. The thermal residual stress can be relaxed by the increasing plastic deformation of the metal matrix. The thermal residual stress results in an increase of tensile elastic modulus and compressive proportional limit, and a decrease of the tensile proportional limit and compressive modulus. There is a significant difference between the initial tensile and compressive stress-strain curves of the composites.

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