

Influence of pre-plastic deformation on thermal residual stress and yield strength of SiC_w/Al composites^①

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Abstract: With a micro-mechanical model, the feasibility of modification of thermal residual stress of the composites treated by tensile pre-plastic deformation was analyzed. The relationship between pre-plastic strain and variation of thermal residual stress was established. By using the method of tensile pre-plastic deformation, the thermal residual stress in 20 %SiC_w/6061 Al composites was modified. The results show that, with increasing tensile pre-plastic strain, the tensile residual stress in the matrix was decreased to zero gradually, and then it was turned into compressive stress. By comparison, it was found that the changing tendency of the test results is similar to that of theoretical analysis. In addition, due to pre-plastic deformation, the dislocation density in the matrix was increased, and the yield strength of the composites was improved. The increasing yield strength is mainly due to the decreasing tensile residual stress and the changing of distribution of dislocation in the matrix.

Key words: SiC_w/Al; pre-plastic deformation; residual stress; yield strength

Document code: A

1 INTRODUCTION

Due to the difference of coefficients of thermal expansion between reinforcement and the matrix in SiC_w/Al composites, the thermal residual stress is not avoided when the temperature is changed^[1,2]. The thermal residual stress can largely affect the properties of the composites, such as strength, deformation and fracture. However, there are only a limited number of investigations on the modification of thermal residual stress in composites.

The plastic deformation usually presents in the matrix, while the reinforcement constantly keeps elastic state. When the composites are unloaded after plastic deformation, the misfit strain between the two phases will change, thus resulting in the change of misfit residual stress. According to the reasons mentioned above, the thermal residual stress of composites can be modified by pre-plastic deformation, which has important practical value in engineering for tapping the latent of material properties.

2 MODEL AND ANALYSIS

The whiskers in composites are assumed to be cylindrical, and distribute in the matrix uniformly. A unit is selected as the analytical object, as shown in Fig.1. The diameter of the whisker cylinders is a , and the diameter of the matrix is b . The length of unit is much bigger than its diameter.

The approximate volume fraction ($\bar{\varphi}$) of

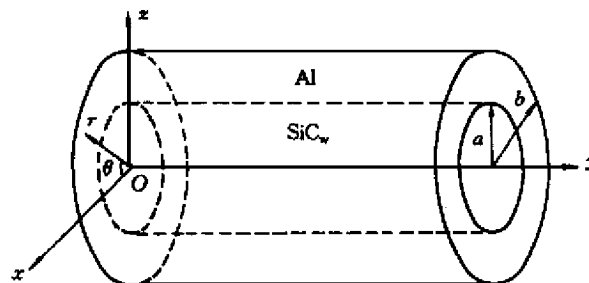


Fig.1 Analytical unit of whiskers and matrix in composites

whiskers in composites is as follows:

$$\bar{\varphi} = a^2/b^2 \quad (1)$$

When the analytical unit bears a tensile stress σ_y along y axis in Fig.1, the matrix stress tensors satisfy $\sigma_y > \sigma_\theta > \sigma_r$. That is, σ_y is the maximum axial principal stress, σ_r is the minimum radial principal stress, and σ_θ is the middle tangential stress^[3]. It is considered that the plastic volume of material cannot be compressed. According to the rule of Tresca, when axial tensile plastic strain of ε_p occurs in the matrix, radial compressive plastic strain of $-\varepsilon_p$ occurs in the matrix at the same time.

When the composites are unloaded after pre-plastic deformation, the relations between stress and strain in the matrix are:

$$\varepsilon_y = (\sigma_y - \nu_m(\sigma_r + \sigma_\theta))/E_m + \varepsilon_p \quad (2)$$

$$\varepsilon_r = (\sigma_r - \nu_m(\sigma_\theta + \sigma_y))/E_m - \varepsilon_p \quad (3)$$

$$\varepsilon_{\theta} = (\sigma_{\theta} - \nu_m(\sigma_r + \sigma_y))/E_m \quad (4)$$

where ε_y is the axial strain of the matrix, ε_r and ε_{θ} are the radial strain and tangential strain of the matrix respectively, and E_m and ν_m are the elastic modulus and Poisson's ratio of the matrix respectively.

Since the whiskers constantly keep elastic state during deformation, the relationship between stress and strain in the whiskers after unloading of the composites can be written as

$$\varepsilon_y^e = (\sigma_y^e - \nu_c(\sigma_r^e + \sigma_{\theta}^e))/E_c \quad (5)$$

$$\varepsilon_r^e = (\sigma_r^e - \nu_c(\sigma_{\theta}^e + \sigma_y^e))/E_c \quad (6)$$

$$\varepsilon_{\theta}^e = (\sigma_{\theta}^e - \nu_c(\sigma_r^e + \sigma_y^e))/E_c \quad (7)$$

where σ_y^e is the axial stress of the whiskers, σ_r^e and σ_{θ}^e are the radial stress and tangential stress of the whiskers respectively, ε_y^e is the axial strain of the whisker, ε_r^e and ε_{θ}^e are the radial strain and tangential strain of the whiskers respectively, and E_c and ν_c are the elastic modulus and Poisson's ratio of the whiskers respectively.

The common solutions of the matrix stress tensors in this kind of axial symmetry system are^[3]

$$\sigma_y = C \quad (8)$$

$$\sigma_r = A - B/r^2 \quad (9)$$

$$\sigma_{\theta} = A + B/r^2 \quad (10)$$

The stress tensors satisfy the following equations:

$$\sigma_y^e = P_y \quad (11)$$

$$\sigma_r^e = \sigma_{\theta}^e = P \quad (12)$$

where P_y is the axial stress of the whiskers, P is the radial stress and tangential stress of the whiskers.

If the interfacial bonding between the matrix and the whiskers is good, the axial and radial strains are continuous at the point of $r = a$.

$$\varepsilon_y = \varepsilon_y^e|_{r=a}, \quad \varepsilon_{\theta} = \varepsilon_{\theta}^e|_{r=a} \quad (13)$$

The axial resultant force of the matrix and the whiskers becomes zero after unloading of the composites. The stress balance equation is

$$\sigma_y \cdot (b^2 - a^2) + P_y \cdot a^2 = 0 \quad (14)$$

According to equations (1) ~ (14), the stress tensors of the matrix can be obtained as follows:

$$\sigma_y = -P_y \bar{\varphi}/(1 - \bar{\varphi}) \quad (15)$$

$$\sigma_r = -P(\bar{\varphi} - a^2/r^2)/(1 - \bar{\varphi}) \quad (16)$$

$$\sigma_{\theta} = -P(\bar{\varphi} + a^2/r^2)/(1 - \bar{\varphi}) \quad (17)$$

$$P = P_y \left[\frac{\nu_m \bar{\varphi}}{E_m (1 - \bar{\varphi})} + \frac{\nu_c}{E_c} \right] \left/ \left[\frac{1}{E_m} \frac{1 + \bar{\varphi}}{1 - \bar{\varphi}} + \frac{\nu_m}{E_m} + \frac{1 - \nu_c}{E_c} \right] \right. \quad (18)$$

$$P_y = \frac{\varepsilon_p \cdot \rightarrow}{(1 + \nu_m) \bar{\varphi} + (1 - \nu_m - 2\nu_m^2) \bar{\varphi} + \rightarrow} \frac{E_m^2 (1 - \bar{\varphi})^2}{\left[\frac{1}{E_m} \frac{1 + \bar{\varphi}}{1 - \bar{\varphi}} + \frac{\nu_m}{E_m} + \frac{1 - \nu_c}{E_c} \right] \cdot \rightarrow} \left[\frac{1 + \nu_m + (2 - \nu_m - \nu_c - 4\nu_m \nu_c) \bar{\varphi}}{E_m E_c (1 - \bar{\varphi})} + \rightarrow \right]$$

$$\left[\frac{1}{E_c} + \frac{1 - \nu_c - 2\nu_c^2}{E_c^2} \right] \quad (19)$$

Eqn.(15) is actually the variation of the thermal residual stress of the matrix along the y -axis due to pre-plastic strain in the composites. Eqns.(15) and (19) show that, when the composites are unloaded after pre-plastic strain of ε_p along the y -axis, the variation of thermal residual stress of the matrix is negative in this direction, that is, the residual stress of the matrix is decreased.

3 EXPERIMENTAL

Squeeze cast and extruded 20 %SiC_w/Al composites were selected, respectively. The tensile specimens in plate shape were machined. The specimen's total length is 50 mm, effective length 20 mm, thickness 2 mm and effective width 6 mm, respectively. The whiskers distributed at random in the squeeze cast composite, while they were aligned in the extruded composite. The tensile direction of the specimens of the extruded composite was along the direction of extrusion. All the specimens were annealed at 500 °C to eliminate the macro residual stress.

With the Instron1186 electronic mechanical testing equipment, the specimens were treated by tensile pre-plastic deformation at a strain rate of $2 \times 10^{-4} \text{ s}^{-1}$. The electronic resistance gage of strain stuck on the middle of the specimen surface so as to measure the dynamic strain of the specimens. According to the curves of "stress ~ strain" during loading and unloading, the plastic strain of each specimen was obtained.

With X-300 type of X-ray stress analyzer, the matrix stresses along the direction of tensile pre-plastic strain in the specimens after pre-plastic deformation were measured. The method of stress measurement is the same as that in Ref.[4]. The dislocations in the matrix of the composite after pre-plastic deformation was observed by a Philips CM12 TEM. In addition, the tensile tests were conducted again for the pre-plastically deformed specimens to investigate the influence of pre-plastic deformation on the tensile strength of composites.

4 RESULTS AND DISCUSSION

4.1 Residual stress

The relationship between the residual stress (σ_{res}) in the matrix of 20 % SiC_w/Al composites and the tensile pre-plastic strain (ε_p) is shown in Fig.2. It can be seen that, for the squeeze cast or extruded composites, the residual stress has a monotonous decreasing tendency. For two types of composites, the decreasing tendency in the extruded composite is more

evident.

The calculated stresses in Fig.2 are from Eqns. (15) and (19). It is assumed that, the plastic strain in the matrix is the same as that of the composite, and $E_m = 70$ GPa, $\nu_m = 0.33$, $E_c = 450$ GPa, $\nu_c = 0.17$ and $\bar{\varphi}_r = 0.2$. According to Eqns. (15) and (19), the variation of thermal residual stress in the matrix due to pre-plastic strain can be calculated, and then it is added to the residual stress in the primary state ($\varepsilon_p = 0$) of the extruded composites, the calculated residual stress after pre-plastic deformation can be obtained.

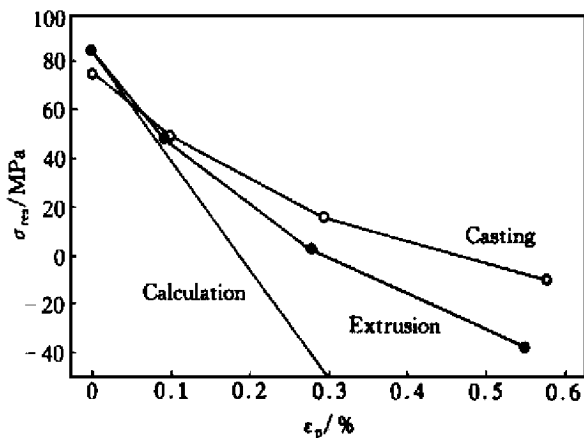


Fig.2 Residual stress (σ_{res}) of matrix vs pre-plastic deformation (ε_p) in SiC_w/6061 Al composites

The model in Fig.1 is aimed at the extruded composite, in which the whiskers are aligned. Fig.2 shows that, the varying tendency of calculated value is similar to that of experimental, but they are not identical. During the tensile pre-plastic deformation, although the average strain can be measured, the distribution of plastic strain in the matrix is not much uniform^[5,6]. In the initial stage of plastic deformation, the matrix plastic strain arises mainly in the

near interface area. If the composite has a great plastic strain, then the plastic deformation will take place in all the area of the matrix. With increasing plastic strain in composite, the effect of strain hardening in the matrix and the resistance of plastic strain are enhanced, which result in that the tendency of plastic strain in the area near the interface is reduced. Since the effect of plastic strain in the matrix near the interface on misfit stress between two phases is greater than that in the other areas, the reduced tendency of the matrix plastic strain in this area will lead to decreased slope of curve of residual stress (σ_{res}) with the variation of pre-plastic strain (ε_p). The difference between theoretical values and experimental results in Fig.2 is mainly due to the very simple model in this paper.

The orientation of whiskers in the squeeze cast composite is at random. If the whiskers are along the tensile direction of the specimens, the matrix plastic strain will be parallel to the axis of the whiskers, and the matrix residual stress can be reduced effectively by tensile pre-plastic deformation. If the whiskers are perpendicular to the tensile direction of the specimens, the matrix plastic strain will be perpendicular to the axis of the whiskers, and the matrix residual stress is not severely reduced after tensile pre-plastic deformation. Most whiskers in the squeeze cast composite are in the state between the two cases above, so the effect of pre-plastic strain on the residual stress in the squeeze cast composite is less evident than that in the extruded composite.

4.2 Dislocation distribution

Fig.3 gives the typical dislocation photographs in the matrix before and after tensile pre-plastic deformation in the squeeze cast 20 %SiC_w/6061 composite. The tensile pre-deformation is along the horizontal direction of the photograph in Fig.3(b). It is found

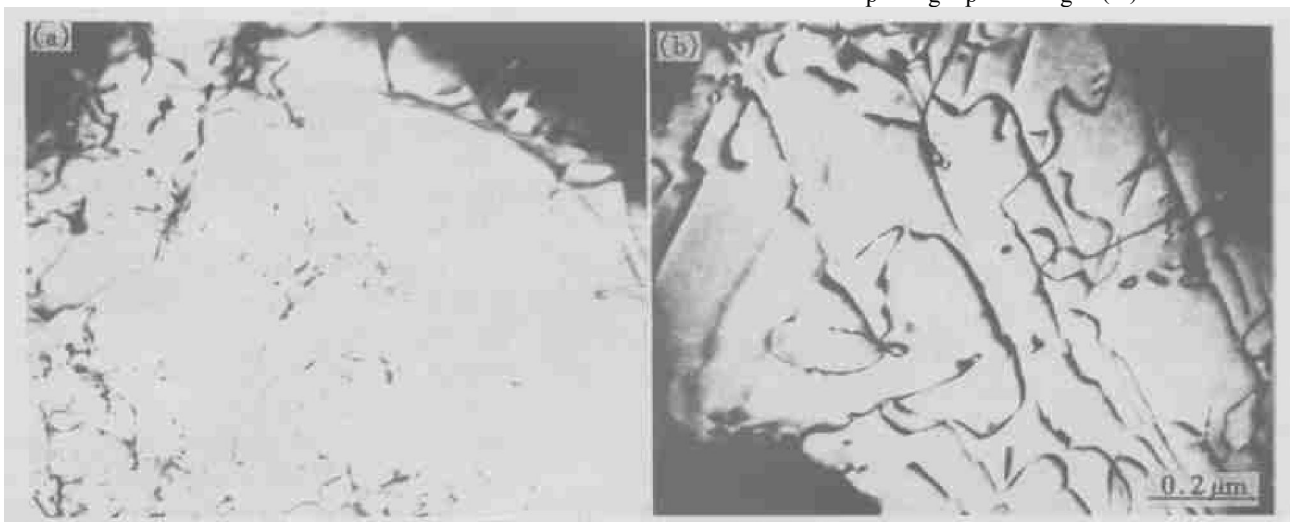


Fig.3 Typical photographs of dislocations in matrix of SiC_w/6061 Al composites
(a) —Original state ($\varepsilon_p = 0$) ; (b) —After pre-plastic deformation ($\varepsilon_p = 0.58\%$)

that the density of dislocations is increased in the matrix after plastic deformation, and there are evident bent and crossed dislocations, and dislocation nets.

4.3 Yield strength

Fig. 4 gives the relationship between tensile yield strength and tensile pre-plastic strain of the composites. It can be seen that, in the range of tensile pre-plastic strain of this paper, the yield strength keeps a monotonous increasing tendency with increasing pre-plastic strain of squeeze cast or extruded composites.

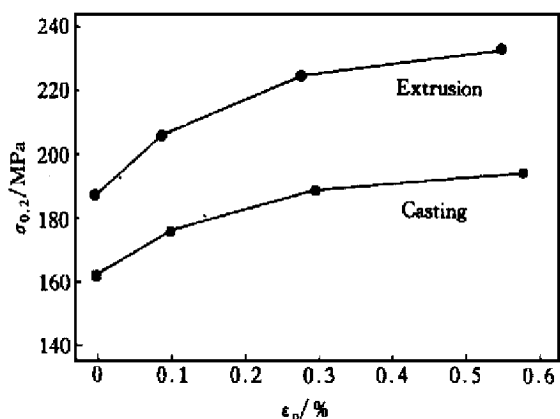


Fig. 4 Yield strength ($\sigma_{0.2}$) of SiC_w/6061 Al composites vs pre-plastic deformation (ϵ_p)

The effect of pre-plastic deformation on tensile yield strength of composites can be explained from the decreasing of residual stress and the changing of dislocation distribution in the matrix. It is well known that tensile residual stress exists in the matrix, which can enhance the plastic strain of the matrix, and lead to decreasing the tensile yield strength. That is, tensile yield strength is improved with decreasing residual stress. On the other hand, due to the increasing of dislocation density in the matrix by pre-plastic deformation of the composites, the resistance to the movement of dislocations is enhanced during the tensile test again, thus leading to increasing yield strength of composites^[7].

Fig. 4 also shows that, the effect of pre-plastic deformation on the yield strength of the extruded composite is greater than that of the squeeze cast composite. Because the extent of decreasing of residual stress in the extruded composite by pre-plastic deformation is greater than that in the squeeze cast composite, its influence on the yield strength in the extruded composite is more evident than that in the squeeze cast composite.

Comparing the data in Fig. 2 and Fig. 4, it is found that the residual stress in the extruded composite is decreased from 84 MPa to -38 MPa after pre-

plastic strain of $\epsilon_p = 0.55\%$, while the yield strength is increased from 187 MPa to 233 MPa. The residual stress in the squeeze cast composite is decreased from 75 MPa to -8 MPa after preplastic strain of $\epsilon_p = 0.58\%$, while the yield strength is increased from 162 MPa to 193 MPa. The extent of increasing of the yield strength is lower than the extent of decreasing of residual stress. The composites have large residual stresses at three-dimensional state before pre-plastic deformation^[2,8], and the Mises effective stress is lower than the one-dimensional stress. In addition, although the composites bear one-dimensional stress totally, the matrix bears three-dimensional stress and the stress distribution is very complex. In a word, because of the complication of stress state^[9,10], the content of decreasing of residual stress in the matrix can not be simply considered the content of variation of yield strength of composites.

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(Edited by PENG Chao-qun)