[文章编号] 1004-0609(2001)S1-0125-04

Effects of residual stress and dislocation on tensile deformation behavior of SiC_w/Al composites ①

HU Ming(胡 明), HU Jin(胡 津), FEI Wei-dong(费维栋), YAO Zhong-kai(姚忠凯)
(School of Materials Science and Engineering, Harbin Institute of Technology, Harbin 150001, P. R. China)

[Abstract] By means of XRD, Instron electronic tensile machine and TEM, the dislocation states and strengthening mechanisms of SiC whisker reinforced pure aluminum matrix composites were studied with different annealing treatment processes and matrixes. The results showed that the strengthening mechanisms of $SiC_{w/p}$-Al composite and SiC_w/6061Al composites are different. For the $SiC_{w/p}$-Al composite, the thermal residual stress plays more important role in strengthening than the high density dislocations in matrix; for the SiC_w/6061Al composite, the dislocation strengthening and precipitation are main strengthening factors.

[Key words] SiC whisker; yield strength; dislocation; thermal residual stress
[CLC number] TG 132.3 **[Document code]** A

1 INTRODUCTION

The residual thermal stress caused by the mismatch of coefficients of thermal expansion (CTE) between reinforcement and matrix alloy and high density dislocations in the vicinity of the interfaces resulted from the relaxation of residual stress on cooling have great influences on the properties of SiC_w/Al composites[1-4].

Recently, our research[5] indicated that both thermal residual stress and dislocation density in matrix around whiskers can be changed by annealing treatments and compositions of matrix alloy. However, up to now, few literatures have been related to the effects of thermal histories on the tensile deformation behaviors of SiC_w/Al composite. The present study aims to examine the tensile behaviors and strengthening mechanisms through the changing of residual stresses and dislocation states in the matrix of SiC_w/Al composites.

2 EXPERIMENTAL

The SiC whisker reinforced aluminum composites used, with volume fraction of 20%, were fabricated by squeeze casting technique, the matrix were pure aluminum of 99.99% Al (mass fraction) and 6061aluminum alloy (composition: 0.15% ~ 0.4% Cu; 0.8% ~ 1.2% Mg; 0.4% ~ 0.8% Si; and balanced Al). The pure Al and 6061 Al matrix composites are referred to as $SiC_{w/p}$-Al and SiC_w/6061Al, respectively. The heat treatment processes for both the tensile experiment and transmission electron microscope (TEM) observation are shown in Table 1. The

Table 1 Processes of $SiC_{w/p}$-Al and SiC_w/6061Al composites

Composites	Temperature / ℃			Time / h	Cooling rate / (℃·min^{-1})
$SiC_{w/p}$-Al	250	350	600	2	1
SiC_w/6061Al	as cast	250	580	2	1

X-ray diffraction (XRD) test was conducted on a D/max-γB type X-ray diffractometer with Cu K_α radiation. The method, proposed by WANG[6] for analysis of X-ray diffraction profile, was employed for measurement of dislocation density of the specimens. The specimens for TEM observation were thinned by ion milling, and the microstructure was observed using a CM-12 type transmission electronic microscope.

3 RESULTS AND DISCUSSION

3.1 Dislocation state and yield strength of $SiC_{w/p}$-Al composite

The dislocation states and density of $SiC_{w/p}$-Al composite subjected to the above treatments at different temperature are shown in Figs. 1 and 2. It can be seen that the dislocation states in matrix around whiskers of $SiC_{w/p}$-Al composite is changed greatly by treatments. First, the dislocation density in matrix of $SiC_{w/p}$-Al annealed at 250 ℃ is much higher than that in the composite annealed at 350 ℃. Second, the dislocation states are quite different in the above specimens. The dislocation tangle is the main feature in matrix of the composite annealed at 250 ℃, but only a few dislocations of $SiC_{w/p}$-Al composite with straight state can be seen in the matrix of composite annealed at 350 ℃.

① **[Received date]** 2001-08-31; **[Accepted date]** 2000-10-13

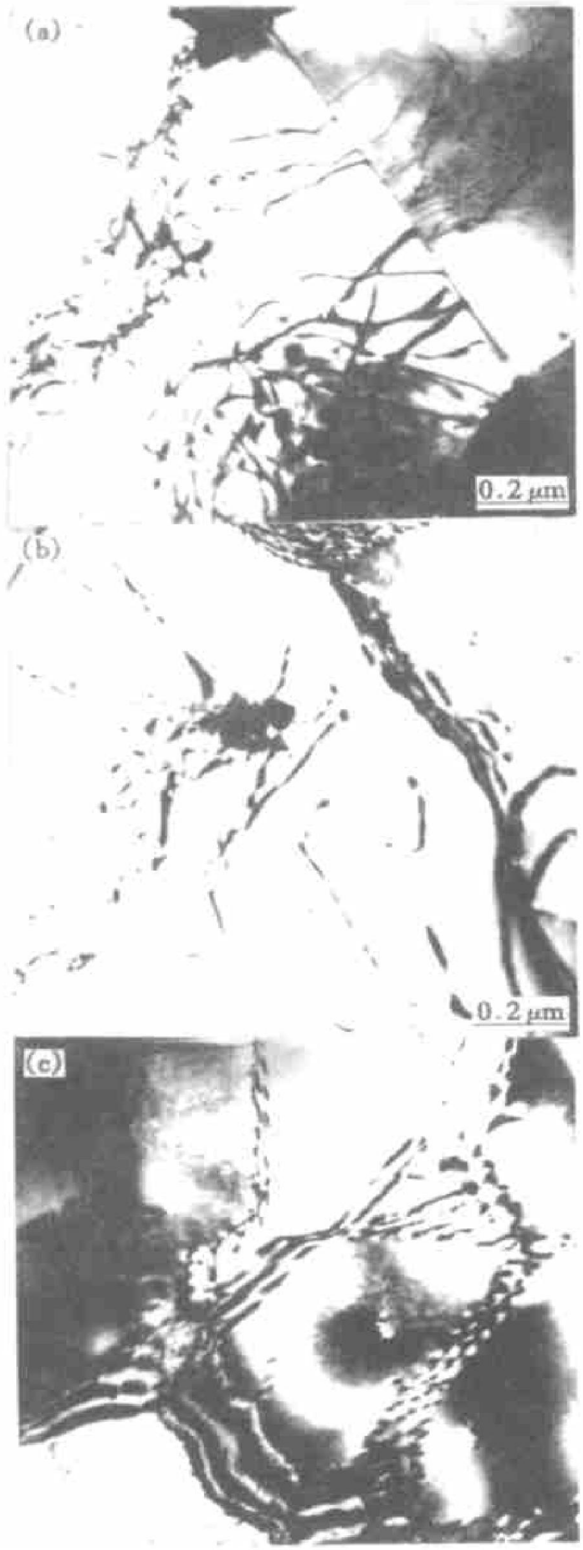

Fig. 1 TEM micrographs of dislocation state of $SiC_{w/p}$-Al composite
(a) —Annealed at 250 ℃ for 2 h;
(b) —Annealed at 350 ℃ for 2 h;
(c) —Annealed at 600 ℃ for 2 h

When the specimens of $SiC_{w/p}$-Al composite were held at elevated temperature, the dislocations generated in the matrix by fabricating process can be decreased by recovery and recrystallization, the driving force for recovery and recrystallization are residual stress. It is easy to understand that the higher the annealing temperature, the heavier the degree of

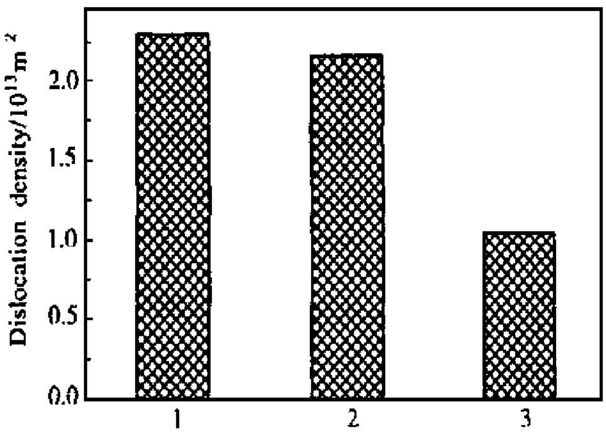

Fig. 2 Dislocation densities of $SiC_{w/p}$-Al composites
1 —Annealed at 250 ℃ for 2 h;
2 —Annealed at 350 ℃ for 2 h;
3 —Annealed at 600 ℃ for 2 h

recovery and recrysatllization. Therefore the dislocation density in the matrix of the composite annealed at 350 ℃ is much lower than that annealed at 250 ℃. Almost all dislocations in the matrix near the whiskers of $SiC_{w/p}$-Al composite disappear when the composites are annealed at 600 ℃ for 2 h. On the one hand, the dislocations can be generated because of thermal mismatch stress relaxation on cooling. On the other hand, owing to low cooling rate the dislocations in matrix of $SiC_{w/p}$-Al composite can be annihilated by recovery process during cooling.

Both the microyield strength $\sigma_{0.005}$ and yield strength $\sigma_{0.2}$ of $SiC_{w/p}$-Al composite increase with temperature, as contrast with dislocation density change, see Fig. 3.

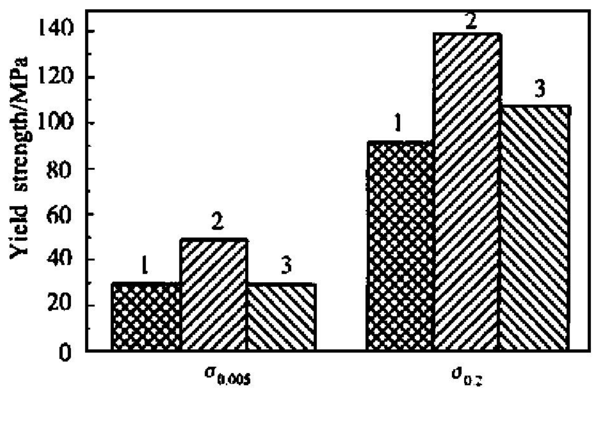

Fig. 3 Microyield strength $\sigma_{0.005}$ and yield strength $\sigma_{0.2}$ of $SiC_{w/p}$-Al composite
1 —Annealed at 250 ℃ for 2 h;
2 —Annealed at 350 ℃ for 2 h;
3 —Annealed at 600 ℃ for 2 h

In order to probe the change trend of residual stress with annealing temperature, the XRD technique was used to determine the lattice constant of matrix aluminum. The results show that the lattice constants of matrix aluminum are 0.407 53 nm and 0.404 27 nm as the specimens of $SiC_{w/p}$-Al are treated at 250 ℃ and 600 ℃ for 2h with a slow cooling rate, respectively. Because the thermal residual in matrix of $SiC_{w/p}$-Al composite is tensile[7~9], the decrease of lattice constant of matrix aluminum implies that the residual thermal stress of $SiC_{w/p}$-Al composite decreases with annealing temperature.

It can be judged that the residual thermal stress plays more important role in micro and macro tensile deformation stages than dislocation density in matrix for $SiC_{w/p}$-Al composite.

3.2 Dislocation state and yield strength of SiC_w/6061 Al composite

The microstructures of SiC_w/6061 Al composite are shown in Fig. 4. It can be found that the dislocation density in the matrix of composite annealed at 250 ℃ for 2 h is slightly higher than that of as-cast composite, which may result from the fine and homogeneous precipitation in 6061 Al matrix. As shown in Fig. 5(d), they are Mg and Si rich phase which are well studied. It is obvious that the dislocations can be pinned out by the precipitate phases, which results in that the movement and annihilation of dislocations are very difficult. Therefore, in the case of presence of fine and homogeneous precipitation, the higher density dislocations were kept to the room temperature, which is quite different from that in $SiC_{w/p}$-Al composite. When the composite is annealed at 580 ℃, the dislocation density also decreases due to no precipitation at the annealing temperature with same mechanism of the $SiC_{w/p}$-Al composites annealed at 600 ℃. Above analysis is also confirmed by XRD tests as shown in Fig. 5.

That effect of annealing treatment on the microyield and macroyield strengths of $SiC_{w/p}$-Al composite is shown in Fig. 6. Compared with the yield strength of $SiC_{w/p}$-Al composite, the maximum values of both microyield and macroyield strength are attained at the annealing treatment at 250 ℃. Combining the dislocation and precipitation observation, one can conclude that the higher yield strength of SiC_w/6061Al composite should be contributed to both high-density dislocations and lower residual stress, which provide high dislocation and dispersion strengthening effect on the matrix of composites. Although the yield strength of SiC_w/6061Al composite annealed at 580 ℃ is higher than that of as-cast SiC_w/6061 Al composite, the increasing quantity of yield strength for SiC_w/6061 Al composite is smaller than that for $SiC_{w/p}$-Al composite, which suggests that increasing

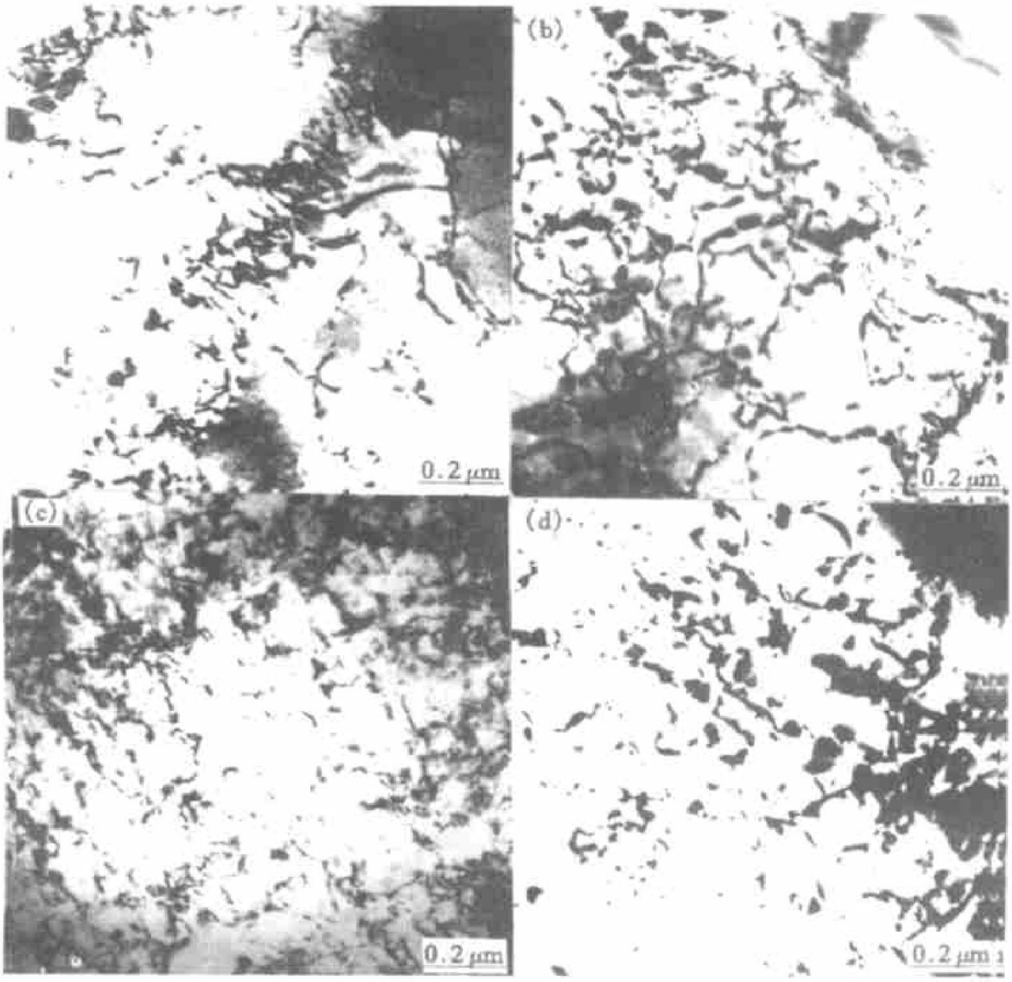

Fig. 4 Dislocation states of SiC_w/6061-Al composite
(a) —As cast; (b) —Annealed at 250 ℃ for 2h; (c) —Annealed at 580 ℃ for 2h; (d) —Precipitation phase

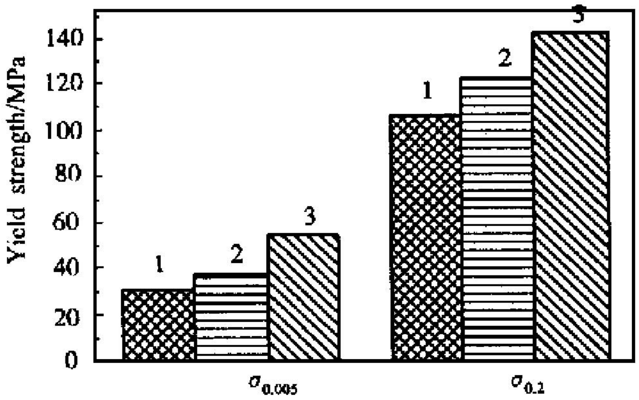

Fig. 5 Microyield and yield strength of $SiC_w/6061Al$ composite

1 —As-cast; 2 —Annealed at 250 ℃ for 2 h; 3 —Anealed at 580 ℃ for 2 h

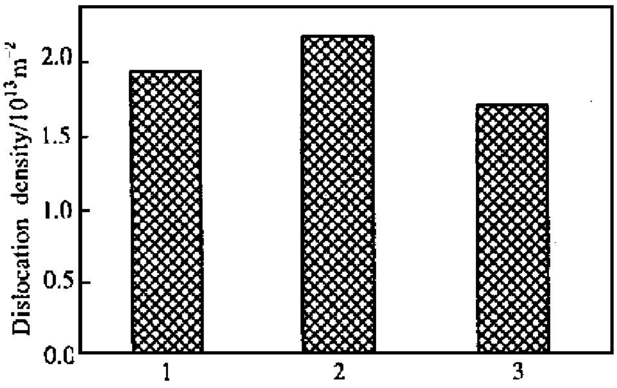

Fig. 6 Dislocation states in matrix of $SiC_w/6061$ Al composite

1 —As-cast; 2 —Annealed at 250 ℃ for 2 h; 3 —Anealed at 580 ℃ for 2 h

of dislocation density for enhancement of yield strength of $SiC_w/6061$ Al composite is more important than that for $SiC_{w/p}$-Al composite.

The measurement results of work hardening indexes in the strain range from 5×10^{-4} to 2×10^{-3} show that the work hardening indexes are 0.38, 0.41 and 0.30 for as-cast, annealed at 250 ℃ and 580 ℃ $SiC_w/6061$ Al composites, respectively. The highest work hardening indexes of $SiC_w/6061$ Al composite annealed at 250 ℃ also suggest that the dislocation mobility is decreased by high density dislocation and fine precipitation.

On the basis of the above results, it can be found that annealing treatment with lower cooling rate is an efficient technique to change the microstructure of the matrix in whisker reinforced aluminum matrix composite and reduce the residual stress of the composite. However, to enhance the yield strength of composite, all factors, such as matrix strength, precipitation, dislocation density in matrix and residual stress must be taken into consideration.

4 CONCLUSIONS

1) For $SiC_{w/p}$-Al composite, the dislocation density in the matrix decreases with annealing temperature, while the microyield strength ($\sigma_{0.005}$) and macroyield strength ($\sigma_{0.2}$) increase.

2) For $SiC_w/6061Al$ composite, the dislocation density is a little high in $SiC_w/6061Al$ composite subjected to annealing treatment at 250 ℃ for 2 h, and the change of microyield strength and yield strength of $SiC_w/6061Al$ composite agrees better with the change of dislocation density.

3) For the $SiC_{w/p}$-Al composite, the thermal residual stress plays more important role in strengthening than the high density dislocations in matrix; for the $SiC_w/6061Al$ composite, the dislocation strengthening and precipitation strengthening are main strengthening factors.

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(Edited by ZHU Zhong-guo)