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Effect of low temperature treatment on tensile yield strength of SiC_w/6061 Al alloy composites ①

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Abstract: The effect of the low temperature treatment at - 78 ℃ and - 196 ℃ on the microstructure and properties of 18 %SiC_w/6061 (volume fraction) Al alloy composites of as-squeeze-casting were studied. The results show that, after the low temperature treatment, the dislocation density in matrix increases, and the residual stress of the matrix decreases, as well as the tensile yield strength of the composites improves. The high residual stress exists in the matrix of the composites of as original squeeze casting. The mismatch degree between the matrix and SiC_w phases increases during the low temperature treatment. The matrix undergoes the tensile plastic deformation during the cooling procedure. On the contrary, the matrix encountered an elastic unloading procedure during the heating up process from low temperature to room temperature. The increase of dislocation density and the decrease of residual stress in the matrix are the main reason of the improvement for tensile yield strength of the composites.

Key words: SiC_w/6061 composites; dislocation; residual stress; tensile yield strength **Document code:** A

1 INTRODUCTION

In SiC_w/6061 composites, the difference of the thermal expansion coefficient between reinforcement (SiC_w) and matrix (Al alloy) is very large. As a consequence, when the composites is cooling down from the manufacturing temperature to room temperature, a large mismatch tensile stress will present in the matrix of composites due to the large shrinkage of the matrix. When the mismatch stress is larger than the yield strength of matrix, its relaxation will occur and the high-density of dislocation will present[1]; partial stress will be kept, as the residual tensile stress, in the matrix[2]. As it is known, the high-density of dislocation and the residual tensile stress in matrix are two of the important characteristics of SiC_w/6061 composites. Among them, the former has a certain contribution to the strengthening of composites[3], while the later will decrease the tensile strength of the composites[2,4,5].

During the past several years, some primary results have gained on the adjustment of the residual stress by the technique of low temperature treatment[6,7]. However, some studies should be made for the influence of low temperature treatment on the microstructure and tensile properties of the composites.

2 EXPERIMENTAL PROCEDURE

The SiC_w/6061 composites was manufactured by squeeze casting procedure. The volume fraction of β-SiC_w was 18 %. The gauge of the β-SiC_w was 3 ~ 15 μm in length and 0.1 ~ 1.0 μm in diameter. After producing of preform and squeeze casting of composites, SiC_w had some extent of preferable orientation in the vertical plane of the direction of squeeze casting. The chemical composition (mass fraction) of 6061 matrix is 1.0 %Mg, 0.70 %Si, 0.19 %Cu, 0.06 %Mn, 0.50 %Fe and balance Al. The yield strength ($\sigma_{0.2}$) of as-cast 6061 Al alloy is 85 MPa.

The original squeeze casted composites were treated at - 78 ℃ and - 196 ℃, respectively.

The pattern of dislocation in matrix of the composites was diffracted by Philips-CM12 TEM and 20 typical images of dislocation in the matrix were taken from each state of composites. All the images of dislocation were analyzed by Magiscan-2A image analyzer. The average value of dislocation density was calculated by the formula of Ref.[8].

The residual stress was measured by X-300 stress analyzer. The thickness and diameter of specimen was 1 mm and 10 mm, respectively. The specimen was chemically polished in 20 %NaOH solution. Typically, more than about 100 μm was removed from the studied surface of specimen. Due to the existence of triaxial residual stress in the surface of composites[6,7,9,10], the triaxial stress measured should be taken[10]. The Z axle is the direction of squeeze casting for composites, while the X and Y axle are the vertical direction of squeeze casting for composites. Each specimen was measured for 5 times and the mean value was taken as the measurement.

Three tensile specimens were prepared for each

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state of the composites. By using the Instron-1186 mechanical testing equipment, the tensile tests were taken. The typical tensile curves were chosen to estimate the tensile properties of the composites. The tensile direction is along the *Y* axle. The tensile specimen is 50 mm long, and 2 mm thick. The effective length and width is 20 mm and 6 mm, respectively. The strain gages were stuck on the middle of the surface of specimen. The test temperature is 25 ℃. The rate of tensile strain of specimen is $2\times10^{-4}s^{-1}$.

3 RESULTS AND DISCUSSION

3.1 Dislocation density

The typical dislocation images of the matrix of as-cast and treated at -196 ℃ SiC_w/6061 Al alloy composites is shown in Fig.1. It is found that the dislocation increases in matrix of composites after low temperature treatment. The distribution and configuration of the dislocation line in the matrix near the interface between the matrix and reinforcement phases were also changed. The dislocation net was formed, and there is an increasing trend for the curvature of dislocation line.

The relation between treatment temperature and the mean density of dislocation of the matrix of SiC_w/6061 Al alloy composites is shown in Fig.2. The lower the temperature of treatment, the higher the dislocation density in matrix of the composites. The mean dislocation density in the matrix of the composites of as-squeeze-cast is 5.58×10^{13} m^{-2}. After the composites was treated at -78 ℃, the mean dislocation density is 7.17×10^{13} m^{-2}, and it is 8.26×10^{13} m^{-2} when the composites was treated at -196 ℃.

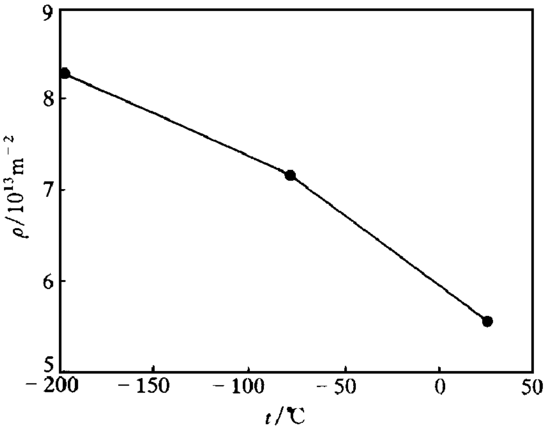

Fig.2 Dislocation density (ρ) of matrix of SiC_w/6061 Al composites vs temperature (*t*)

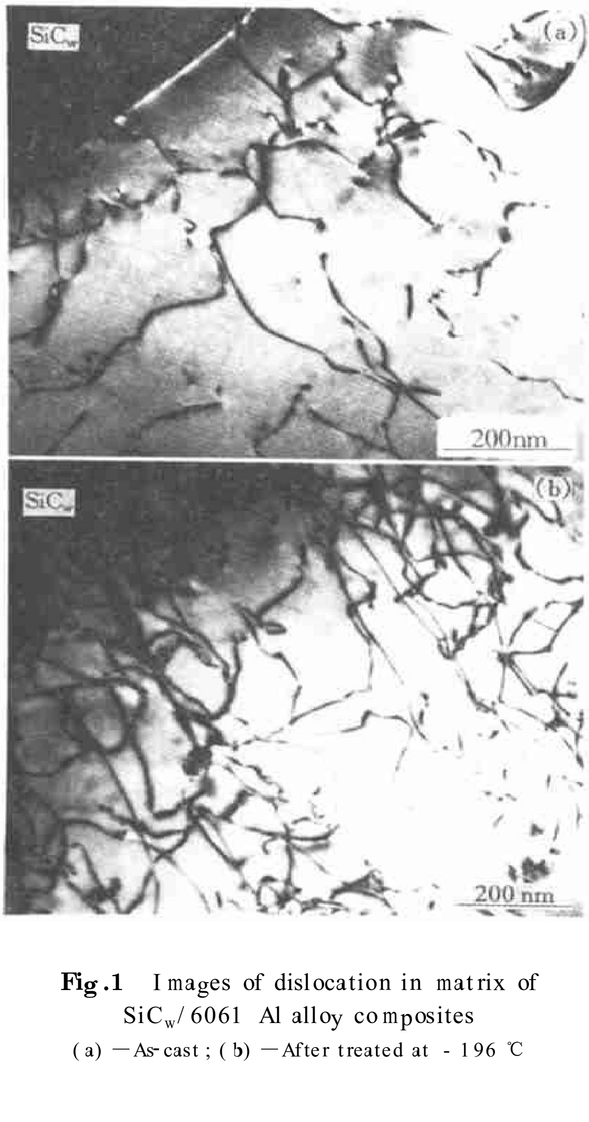

Fig.1 Images of dislocation in matrix of SiC_w/6061 Al alloy composites
(a) —As-cast; (b) —After treated at -196 ℃

In manufacture of SiC_w/6061 Al alloy composites, the casting temperature of 6061 Al alloy is 800 ℃, and the solidification temperature of 6061 Al alloy is 600 ℃. Due to the large thermal expansion coefficient of matrix, the shrinkage of matrix far exceeds that of SiC_w during the cooling procedure from manufacturing temperature of composites to room temperature, which leads to a fast increase of the mismatch tensile stress in matrix. By the theoretical analysis[9,11~13], the stress reaches the yield strength in local area of the matrix near the interface between two phases before the composites was cooled down to room temperature. When the temperature cooled down to room temperature, the matrix near the interface between two phases have already encountered the marked local tensile plastic strain and work hardening.

When the composite was cooled down from room temperature to -78 ℃ or -196 ℃, the mismatch degree between the matrix and the SiC_w went on increasing, the local area near the interface went on encountering the tensile plastic strain and work-hardening. The dislocation density in matrix as well as the change of configuration of dislocation line went on increasing. The lower the temperature, the higher the dislocation density. However, the composites encountered an elastic unloading procedure of the mismatch stress in matrix during heating from the low temperature to room temperature, the density and configuration of the dislocation in the matrix have not any marked changes.

3.2 Residual stress

The relation between the residual stress of matrix at room temperature and the temperature of treatment is shown in Fig.3. The triaxial residual stress exists in the matrix of the as-squeeze-cast composites. Among them, σ_Z is the lowest component of stress, which is mainly due to the preferable orientation of SiC_w on the XOY plane. With decreasing the temperature, the triaxial residual stress decreases in proportion. The residual stress of matrix of as-squeeze-cast composites of σ_X, σ_Y and σ_Z is 75 MPa, 73 MPa and 49 MPa, respectively. After treated at -78 ℃, the residual stress is 34 MPa, 37 MPa and 25 MPa, respectively, and it is 10 MPa, 9 MPa and 6 MPa, respectively, after treated at -196 ℃.

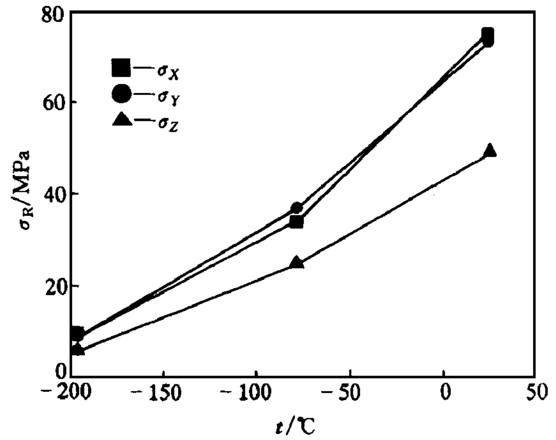

Fig.3 Residual stress (σ_R) of matrix of SiC_w/6061 Al alloy composites vs temperature (t)

To explain the influence of low temperature treatment on the residual stress, Fig.4 shows the changing process of mismatch stress with the temperature. In Fig.4, point A is corresponding to the solidification temperature of 6061 Al alloy, at this temperature, there is no mismatch stress between SiC_w and 6061 Al alloy. Both two phases shrunk when the temperature cooled down. Among them, the shrinkage of the matrix is larger, which leads to the presence of mismatch tensile stress in matrix. With the cooling down of the temperature, the tensile residual stress increases to the yield strength of matrix at point B. After that, the mismatch stress changes with work-hardening. When the temperature cooled down to the room temperature at point C, some extent of plastic deformation occurred, and the mismatch stress at this point is the residual stress of the matrix of as-squeeze-cast composites. If the composites is treated at low temperature, the mismatch stress in the matrix will change with work-hardening to point D. When the composites go back from low temperature to room temperature, both SiC_w and matrix encounter expansion. The expansion extent of matrix is larger than that of SiC_w during heating from low temperature to room temperature, the mismatch stress of matrix of composites encountered the elastic unloading procedure, and changes along the line $D \sim E$. The mismatch stress at point E is the residual stress of the matrix of the composites treated at low temperature. The residual stress is decreased markedly.

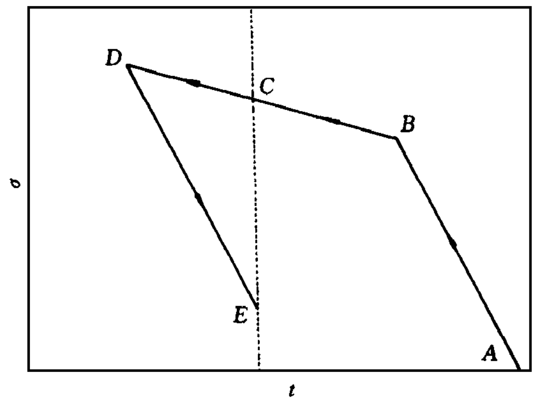

Fig.4 Diagram of mismath stress (σ) of matrix of composites vs temperature (t)

By the analyses above mentioned, it is found that the low temperature treatment can lead to the mismatch pre-tensile plastic strain of matrix of the composites, while SiC_w is in the state of elastic. When the composites goes back from low temperature to room temperature, the degree of mismatch between two phases will be relaxed, and lead to decrease of the residual stress. The lower the temperature of the composites is, the larger the mismatch pre-tensile plastic strain near the interface will be, and the lower the residual stress in the matrix at room temperature is.

3.3 Tensile properties

The tensile yield strength is one of the main properties data for design of aerospace construction parts. It is necessary to study the effect of low temperature treatment on the tensile yield strength of the composites. Fig.5 is the tensile "stress-strain" curves at room temperature of as-squeeze-cast composites, treated at -78 ℃ and -196 ℃. As shown at the early stage of tensile deformation, three curves are primary coincident, when the deformation exceed 0.1 %, they separated. The tensile yield strength ($\sigma_{0.2}$) of the as-squeeze-cast composites is 157 MPa. After being treated at -78 ℃, the yield strength is 169 MPa, and reaches 182 MPa after treated at -196 ℃. The lower the temperature, the higher the tensile yield strength of the composites.

The high density of dislocation in the matrix is one of the typical strengthening mechanism of the metal matrix composites. The effect of the dislocation density(ρ) in the matrix on the tensile yield strength ($\sigma_{t(0.2)}$) of the composites can be expressed approximately as follows[3]:

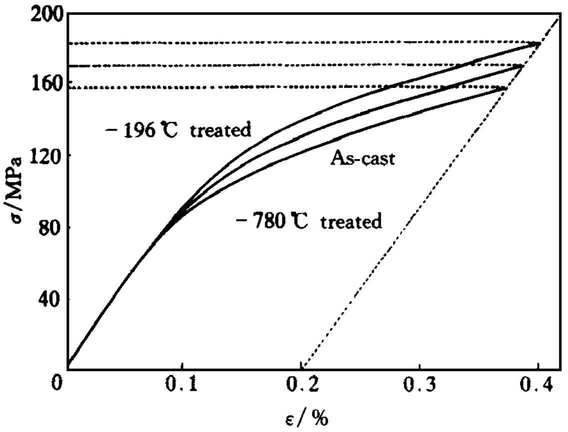

Fig.5 Effect of low temperature treatment on "stress(σ)-strain(ε)" curves of $SiC_w/6061$ Al alloy composites under tension

$$\sigma_{t(0.2)} = \alpha\mu b\sqrt{\rho}$$

Where α is a constant, μ is the shear modulus, and b is the Burgers vector of dislocation of the matrix. This formula shows that, the larger the dislocation density in matrix, the higher the tensile yield strength of composites. The low temperature treatment can make the dislocation density of matrix of composites increase. As a result, the tensile yield strength of the composites also increases.

The residual stress in the matrix phase is a key factor which affects the tensile behavior of the composites. The tensile residual stress in matrix can increase the tensile strain of matrix and decrease tensile strength of composites[2,4,5,14,15]. The higher the residual stress level, the larger the degree of the effect on the tensile properties of the composites.

Due to the complication of the system in the $SiC_w/6061$ composites, to accurately calculate the effect of residual stress on the tensile yield strength by the micro-mechanical method is difficult. Here just give a simple analysis. Considering the component of the residual stress $\sigma_X \approx \sigma_Y$, the Mises effective stress of triaxial residual stress is $\sigma_e = \sigma_Y - \sigma_Z$. According to this formula and the data given by Fig.3, the effective residual stress in the matrix of as-squeeze-cast composites is 24 MPa. It is 12 MPa after treated at -78 ℃, and 3 MPa after treated at -196 ℃. As a result, the lower the effective residual stress, the higher the tensile strength of the composites.

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