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Relaxation of residual stresses in 20%SiC$_w$/6061Al composite as-extruded at high temperature①

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[Abstract] The residual stress in a 20% SiC$_w$/6061Al composite as-extruded was investigated by using X-ray stress measurement method. It was found that, high residual stress existed in the composite and residual stress distribution in each direction are not uniform. Relaxation process of residual stress in the composite was dynamically measured during annealing at high temperature. It is verified that the relaxation of residual stress obeys the power law at high temperature. With the creep mechanism, the relaxation behavior of residual stresses at high temperature was analyzed. The results show that, the stress exponent and activation energy for stress relaxation of the composite are obviously higher than those of the matrix alloy.

[Key words] SiC-whisker; Al-matrix composite; residual stress; stress relaxation; X-ray diffraction
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1 INTRODUCTION

Aluminum matrix composite reinforced with silicon carbide whisker (SiC$_w$/Al) as a new type of structural material not only has certain advantages such as high specific strength, high specific modulus, low coefficient of thermal expansion (CTE) and so on, but also can be secondarily shaped by the conventional working method. So this composite can be of potentiality to be widely applied in many industrial fields[1, 2]. Through the development and research for many years, the SiC$_w$/Al composite has applied in several engineering areas, and several types of aerospace structural parts have been successfully fabricated with this composite, which presents a good developing future.

In general, the thermal residual stress and macro residual stress existed in the SiC$_w$/Al composite at same time. Firstly, due to a mismatch in CTE between the reinforcement and matrix, when the temperature changes the thermal residual stress between the two phases is unavoidable[3, 4]. Secondly, due to the secondary working, the inhomogeneity of macro plastic deformation in the composite must induce the macro residual stress[5]. The two types of residual stress can affect the composite properties harmfully, but only the macro residual stress is a key factor affecting the dimensional stability of material. The conventional method of stress relieving is to anneal the material at high temperature, but only a limited number of literatures about this subject for composite material have been reported. Therefore, the macro residual stress in a 20% SiC$_w$/6061Al (SiC$_w$ reinforced 6061 aluminum alloy of which whisker volume fraction is 20%) as-extruded and its high temperature relaxation process were investigated by the method of X-ray stress measurement, and the relaxation behavior of residual stress at high temperature was analyzed using the creep mechanism.

2 MATERIAL AND EXPERIMENT

The 20% SiC$_w$/6061Al composite was fabricated by the squeeze casting, in which the pouring temperature and the solidification temperature of the 6061Al-liquid are 800 ℃ and 600 ℃ respectively. Then the original composite as-cast was extruded with an extrusion ratio of 1∶20 at 450 ℃, and a composite tube was obtained. The outer and inter diameter of the composite tube are 34 mm and 20 mm respectively.

Fig. 1 gives the scheme of X-ray stress measurement. In this figure the point O is the position of stress measurement, P and O stand for the incident direction of X-ray, Φ and Ψ for two of space angles, σ_{22} and σ_{11} for the longitudinal residual stress and transverse residual stresses respectively. According to the basic principle of X-ray stress measurement[6], two tensors of residual stress can be expressed as follows,

$$\sigma_{22} = K[\partial(2\theta_{\Phi=90°})/\partial(\sin^2\Psi)] \quad (1)$$

$$\sigma_{11} = K[\partial(2\theta_{\Phi=0°})/\partial(\sin^2\Psi)] \quad (2)$$

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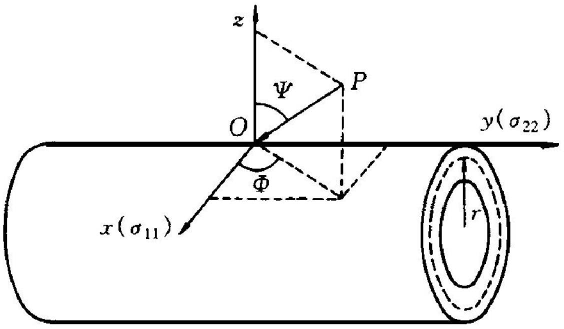

Fig. 1 Scheme of X-ray stress measurement for 20% SiC$_w$/6061Al composite tube

where 2θ is the diffraction angle of matrix in composite, K is the constant of X-ray stress measurement.

It must be pointed out that the field of the thermal residual stress between two phases of discontinuous whisker reinforced composite characterizes a triaxial stress field near the surface of the composite[7,8], it can not obviously affect the $\partial(2\theta)/\partial(\sin^2\Psi)$, although it can led to the movement of diffraction peak. In addition, the macro residual stress field of the composite presents some behaviors of plane stress field near the surface of the composite, it can greatly affect the $\partial(2\theta)/\partial(\sin^2\Psi)$. So the stresses in Eqns. (1) and (2) are two tensors of macro residual stress of the composite.

The residual stresses of 20% SiC$_w$/6061Al composite as-extruded were measured with the X-ray stress analyzer of X-350 type. The parameters and conditions of stress measurement are given as follows: tube voltage 26 kV, tube current 8 mA, radiated area 2 mm × 2 mm, diffraction plane Al(222), Cr-K$_\alpha$ radiation. A cross correlation method was used for determining peak positions. With the method of machining and corrosion in 20% NaOH solution, the composite tube was peeled off from its outer surface ply by ply to measure the distribution of residual stress, meanwhile the relieved stress due to the material peeled was corrected. The correcting method of relieved stress in the material is the same as that in Ref. [6]. Each ply peeled off from the composite surface is of a thickness about 1mm. The composite was annealed at high temperature, and the relaxation process of residual stress was dynamically measured at the same time.

3 RESULTS AND DISCUSSION

The distribution of residual stress in the extruded tube of 20% SiC$_w$/6061Al composite is shown in Fig. 2. It can be seen that high stresses exist in this composite. Near the inner surface (r = 10) and outer surface (r = 17) of the tube, the longitudinal residual stress (σ_{22}) is compressive, while the transverse residual stress (σ_{11}) is tensile. On the contrary near the middle area of the tube, the longitudinal residual stress is tensile, while the transverse residual stress is compressive. This obvious inhomogeneity of residual stress in composite is mainly due to a difference of plastic deformation in different areas of the material during hot extrusion. Since the symbol of two stress tensors is opposite to each other, the Mises effective stress must be at a high level, and it is very harmful for the composite.

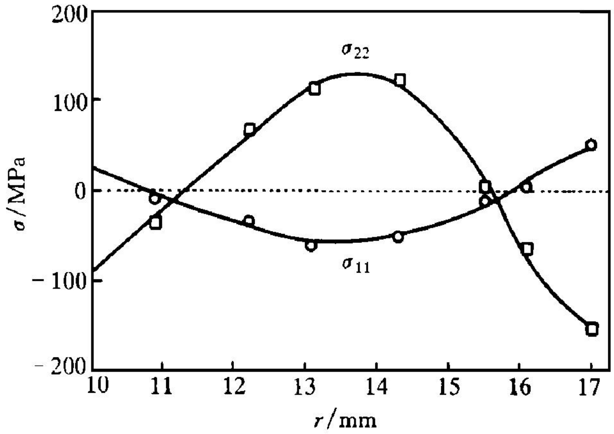

Fig. 2 Distribution of residual stress (σ) in radial direction (r) of 20% SiC$_w$/6061Al composite as-extruded

In order to explore stress relieving mechanism for the composite by annealing technology, it is necessary to investigate the relaxation behavior of residual stress at high temperature. Fig. 3 gives the relaxation process of the longitudinal residual stress near the outer surface of the extruded composite tube at high temperature. It can be found that with increase of annealing time at high temperature, the relaxation of residual stress in the composite obeys the form of power law. The higher the annealing temperature, the more obvious the relaxation extent of the residual stress is.

Due to the residual stress, the stress reliving and

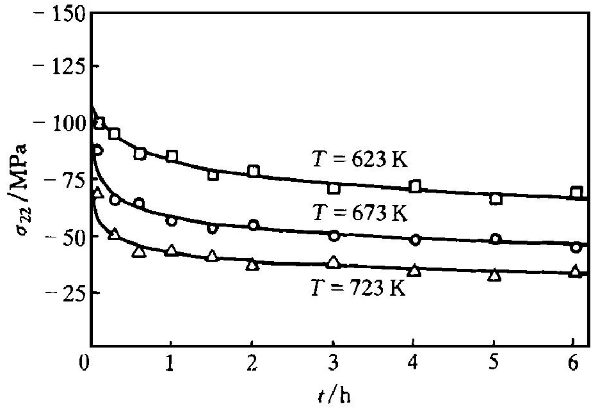

Fig. 3 Residual stress (σ_{22}) of 20% SiC$_w$/6061Al composite as-extruded vs annealing temperature (T) and time (t)

creep phenomenon must occur in some area of the composite at high temperature[9], and the relation between creep rate ($d\varepsilon_{22}/dt$) and residual stress (σ_{22}) of the composite can be expressed as follows[10],

$$d\varepsilon_{22}/dt = A(\sigma_{22})^n \exp[-Q/RT] \qquad (3)$$

where ε_{22} is the creep strain, t is the time, s; A is a constant, n is the stress exponent, Q is the creep activation energy also named relaxation activation energy of composite, $J \cdot mol^{-1}$; $R = 8.31 J \cdot mol^{-1} \cdot K^{-1}$ is the gas constant, T the absolute temperature, K.

The elastic strain of the composite would obtain a decrement of $d\varepsilon_{22}$ when the creep strain also named plastic strain obtains an increment of in some area, and the residual stress would be reduced at the same time. The relation between residual stress change ($d\sigma_{22}$) and creep strain change ($d\varepsilon_{22}$) of the composite can be expressed as[11],

$$-d\sigma_{22} \propto d\varepsilon_{22} \qquad (4)$$

To combine Eqns. (3) and (4), the follow equation can be obtained,

$$d\sigma_{22}/dt = B(\sigma_{22})^n \exp[-Q/RT] \qquad (5)$$

where B is a constant.

The integration of Eqn. (5) can give Eqn. (6) as follows,

$$1/(\sigma_{22})^{n-1} - 1/(\sigma_{22}^0)^{n-1} = Bt(n-1)\exp[-Q/(RT)] \qquad (6)$$

where σ_{22}^0 is the residual stress in the composite at beginning ($t = 0$), σ_{22} the residual stress in the composite after the relaxation at any time (t).

According to Eqn. (6), a regression analysis for the datum in Fig. 3 can be carried out by using the computer program. The regression analysis results are given as follows: the constant $B = 1.82 \times 10^{-3}$, the stress exponent $n = 8.6$, and the activation energy for stress relaxation $Q = 195 kJ \cdot mol^{-1}$. Those results show that, the stress exponent and activation energy for stress relaxation of the composite are obviously higher than those of matrix alloy[12].

It is well known that the creep behavior and stress relaxation at high temperature are usually related to the motion and climb of dislocation in materials. Due to the reinforcement of whiskers, the stress exponent and activation energy for stress relaxation will increase when the resistance to motion and climb of dislocation in materials increase, so that it leads to that the stress exponent and activation energy for stress relaxation of composite are obviously higher than those of matrix alloy.

Therefore when selecting the annealing technology of stress relieving for the composite, the annealing temperature of the composite will be higher than that of matrix alloy, while the annealing time of the composite will be longer than that of matrix alloy.

With Eqn. (6) and the values of R, n, B and Q above indicated, the follow equation can be obtained,

$$1/(\sigma_{22})^{7.6} - 1/(\sigma_{22}^0)^{7.6} = 0.0138\, t \exp[-23466/T] \qquad (7)$$

Eqn. (7) stands for the relaxation principle at high temperature for residual stress in the 20% SiC_w/6061Al composite as-extruded, and is also the theoretical foundation to select the annealing technology of stress relieving for this composite. It can be found from this equation that, if the annealing temperature increases and annealing time lengthens, the residual stress of the composite can be fully reduced.

Fig. 4 gives the distribution of residual stress in the 20% SiC_w/6061Al composite after annealing at 450 ℃ for 6 h. This figure shows that although there is a certain degree of residual stress in the composite, the residual stress level reduces markedly and the difference between two tensors of residual stress obviously decreases, meanwhile the distribution of residual stress is also improved after annealing. Because the residual stress decreases and its distribution improves, the properties especially dimensional stability of the composite will be certainly enhanced.

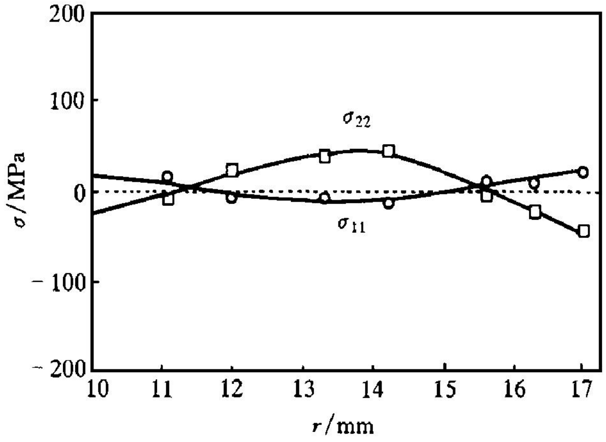

Fig. 4 Distribution of residual stress (σ) in radial direction (r) of 20% SiC_w/6061Al composite as-annealed at 450 ℃ for 6 h

4 CONCLUSIONS

From the X-ray stress measurement in this paper, it is verified that the high residual stresses exist in the 20% SiC_w/6061Al composite as-extruded, and the distribution of residual stress in each direction is not uniform. During the annealing at high temperature for stress relieving, the relaxation of residual stress obeys the form of power law at high temperature. With the creep mechanism, the relaxation behavior of residual stress at high temperature is analyzed. It is found that, the stress exponent and activation energy for stress relaxation of composite are obviously higher than those of matrix alloy. The relaxation behavior of residual stress at high temperature can be expressed as an equation of $1/(\sigma_{22})^{7.6} -$

$1/(\sigma_{22}^{0})^{7.6} = 0.0138\, t \exp[-23466/T]$, which is the theoretical foundation to select the annealing technology of stress relieving for this composite.

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