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Elastic modulus of SiC_w/6061Al alloy composites as-squeeze-cast ①

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[Abstract] By using the system of image analyzer connected with scanning electron microscope, the whisker orientation in the SiC_w/6061Al alloy composite as-squeeze-cast was measured. According to the shear lag model and the actual distribution function of whisker in composite, the inhomogeneity of elastic modulus in composite was analyzed. With the method of ultrasonic velocity, the elastic modulus of composite was measured. The results showed that, the whiskers of composite are preferred in an orientation normal to the direction of squeeze cast. The higher the volume fraction of whisker, the more extent of preferred orientation of it, and the inhomogeneity of elastic modulus is mainly due to the differences of whisker distribution in composite.

[Key words] SiC-whisker; composite; whisker orientation; elastic modulus; ultrasonic wave
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1 INTRODUCTION

Composite of silicon carbide whisker reinforced aluminum (SiC_w/Al) as a new type of structural material not only has some advantages such as high specific strength, high specific modulus, low thermal coefficient of expansion and so on[1,2], but also can be secondarily shaped by the conventional working method[2,3]. So this composite can be widely applied in many industrial fields. The distribution of whisker orientation in the composite is a main factor affecting the composite elastic modulus, so it has been greatly noticed. When the reinforcements are distributed as aligned, the elastic modulus of composite can be theoretically calculated by the shear slag model[4,5]. However, the whiskers were not aligned in the actual composite as-squeeze-cast, it is difficult to calculate the elastic modulus of composite. Due to the probability difference of whisker orientation in different directions, this fact must bring on the inhomogeneity of elastic modulus in various directions of composite, and it must be fully considered in engineering application of composite. With the improved shear slag model and the actual orientation distribution of whisker in this paper, the inhomogeneity of elastic modulus in the SiC_w/Al composite as-squeeze-cast was analyzed. By using the method of ultrasonic velocity, the elastic moduli of composite in different directions were measured, and the results from experiment were compared with those from theoretical calculation.

2 MODEL AND ANALYSIS

Fig. 1 gives a model standing for a representative volume of whisker (SiC_w) and matrix (Al). In this figure, the Z-axis is the direction of squeeze cast for composite, θ is the orientation angle of whisker, α is the angle between the OL direction and Z-axis.

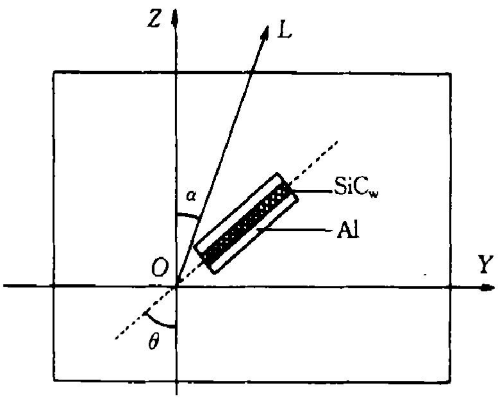

Fig. 1 Model standing for representative volume of whisker (SiC_w) and matrix (Al) in composite

When a loading stress was applied on the model of Fig. 1 along the direction of OL, the following equations. can be obtained by using the improved shear slag model[6],

$$\sigma_\theta^w = \left[E_w - \frac{E_w - E_m}{2\cosh(ns) - 1}\,\frac{\sinh(ns)}{ns}\right]\varepsilon_\alpha^{com}\cos^2(\theta-\alpha) \quad (1)$$

$$n = \{2E_m/[E_w(1+\upsilon_m)\ln(1/\varphi)]\}^{1/2} \quad (2)$$

$$\sigma_\alpha^m = E_m\varepsilon_\alpha^{com} \quad (3)$$

$$\sigma_\alpha^{com} = [\sigma_\theta^w\cos^2(\theta-\alpha)]\varphi + \sigma_\alpha^m(1-\varphi) \quad (4)$$

where σ_α^{com} is the average stress of the representative

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volume along the direction of OL, σ_0^w is the axial stress of whisker, σ_α^m is the stress of matrix along OL direction, ε_α^{com} is the average strain along OL direction, n is a constant, φ is the volume fraction of whisker, E_w is the elastic modulus of whisker, s is the aspect ratio of whisker, E_m is the elastic modulus of matrix, υ_m is the Poisson ratio of matrix.

To combine Eqns. (1) ~ (4), the elastic modulus of model in Fig. 1 along the direction OL can be expressed as,

$$E_\alpha^{com} = \frac{\sigma_\alpha^{com}}{\varepsilon_\alpha^{com}} = \left[E_w \frac{E_w - E_m}{2\cosh(ns) - 1} \frac{\sinh(ns)}{ns} \right] \cdot \cos^4(\theta - \alpha)\varphi + E_m(1 - \varphi) \quad (5)$$

For the actual composite, the whiskers are distributed within a certain range of orientation angles. So the whisker orientation function $g(\theta)$ was defined, which is the whisker probability per angle of orientation at θ region. The whisker orientation can be determined by experiment, and satisfied the following equation,

$$\int_{-\pi/2}^{\pi/2} g(\theta)\mathrm{d}\theta = 1 \quad (6)$$

The elastic modulus of integral composite along the OL direction is,

$$E_\alpha^{com} = \int_{-\pi/2}^{\pi/2} \left\{ \left[E_w \frac{E_w - E_m}{2\cosh(ns) - 1} \frac{\sinh(ns)}{ns} \right] \cdot \cos^4(\theta - \alpha)\varphi + E_m(1 - \varphi) \right\} g(\theta)\mathrm{d}(\theta) \quad (7)$$

Therefore, the elastic modulus of composite along OL direction can be calculated by Eqn. (2), Eqn. (7), actual orientation function and aspect ratio of whisker.

3 MATERIAL AND EXPERIMENT

The SiC_w/6061Al alloy composite was fabricated by the squeeze casting, including the processes of making whisker preform and casting composite[7, 8]. The process of making preform can be described as follows: washing whisker → adding glue solution → shaping by pressure → drying and sintering, to obtain the preform with high strength and uniform for whisker distribution. The process of squeeze casting for composite can be described as follows: preheating of whisker preform → pouring Al-liquid → penetration by pressure → cooling to room temperature. The whisker volume fraction of fabricated composite is 16%, 25% and 35%, respectively.

The orientation angle and aspect ratio of whiskers in composite were measured statistically by the system of image analyzer combined with scanning electronic microscope[9], in which the orientation angle is provided as the angle between whisker axis and the direction (Z-axis) of squeeze casting, and the distribution function of whisker orientation $g(\theta)$ and the average aspect ratio of whisker were determined. With an ultrasonic velocity analyzer and the method of echo pulse, the ultrasonic velocities of shear wave and longitudinal wave were measured, respectively. The ultrasonic test parameters can be given as follows: transducer diameter of 5 mm, ultrasonic frequency of 10 MHz and coupling solution of glycerin.

The relation among the elastic modulus (E) of the composite, the ultrasonic velocity of the shear wave (u_S) and longitudinal wave (u_L) can be expressed as[10, 11],

$$(u_S)^2 = E/[2\rho(1 + \upsilon)] \quad (8)$$

$$(u_L)^2 = [E(1 - \upsilon)]/[\rho(1 + \upsilon)(1 - 2\upsilon)] \quad (9)$$

where ρ is density of composite, υ the Poisson ratio of the composite.

Combing Eqns. (8) and (9), the following equation is obtained,

$$E = \rho[3(u_L)^2 - 4(u_S)^2]/[(u_L)^2/(u_S)^2 - 1] \quad (10)$$

Therefore, if the composite density (ρ), the ultrasonic velocity of shear wave (u_S) and longitudinal wave (u_L) were known, the elastic modulus of composite would be determined by Eqn. (10).

4 RESULTS AND DISCUSSION

The statistical results measured for the orientation function $g(\theta)$ of whisker in the SiC_w/Al alloy composite as-squeeze-cast was shown in Fig. 2. It can be seen that, the whisker orientation of composite is preferential in certain directions, the whisker numbers in the direction ($\theta = 0$) along Z-axis is fewer than those in the direction ($\theta = \pm\pi/2$) normal to Z-axis. Compared with the curves of this figure, it can be found that the higher the volume fraction of whisker in composite, the larger the extent of the whisker preferred in orientation. In fact, the pressure was applied along the Z-axis during the process of making whisker preform and squeeze casting for com-

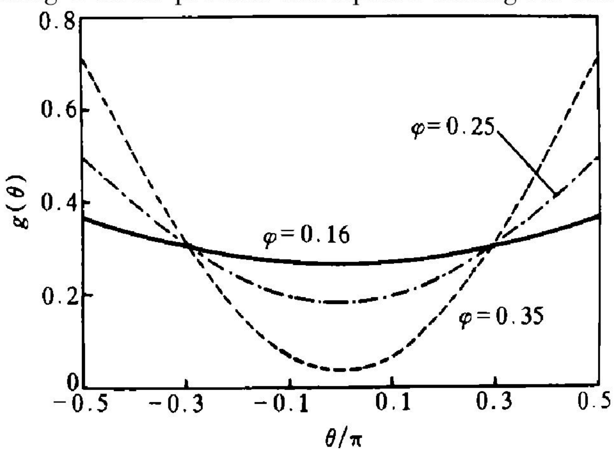

Fig. 2 Actual orientation function of whisker in SiC_w/6061Al composite as-squeeze-cast

posite, the whiskers were rotated normal to Z-aixs, as a result, it leads to the preferred orientation of whisker normal to the direction of Z-axis. The higher the volume fraction of whisker in composite is, the higher the applied pressure during the process of making whisker preform and squeeze casting for composite is, the larger the rotated angle is and the more obvious the preferred orientation of whisker is.

The results of image analysis showed also that when the volume fraction of whisker in composite is 0.16, 0.25 and 0.35, the average aspect ratio of whisker is 16.5, 13.6 and 10.9 respectively. This fact means that the higher the volume fraction of whisker is, the lower the aspect ratio of whisker is. Because the pressure was applied during the process of making whisker preform and squeeze casting for composite, it is unavoidable for the pressure to break the whisker. The higher the volume fraction of whisker in composite is, the higher the applied pressure during the process of making whisker preform and squeeze casting for composite is, the more the broken whiskers are and the lower the aspect ratio of whisker is.

With $g(\theta)$ datum of Fig. 2 and the measured results for average aspect of whisker, the distribution of elastic modulus in $SiC_w/6061Al$ alloy composite as-squeeze-cast can be calculated by using Eqns. (2) and (7), as shown in Fig. 3. In Fig. 3, the material constants used can be given as follows: $E_w = 450$ GPa, $E_m = 70$ GPa and $\nu_m = 0.33$. It can be seen that, the elastic modulus in each direction of composite is obviously higher than that in the matrix alloy (70 GPa), so the composite was strengthened in various directions. In addition, there is certain inhomogeneity of elastic modulus in different directions of the composite. The elastic modulus is the lowest along the direction of $\alpha = 0$, and it is the largest along the direction of $\alpha = \pm\pi/2$ in the composite. Furthermore, the higher the volume fraction of whisker is, the larger the average elastic modulus of composite is, and the larger the differences of elastic modulus among different directions are.

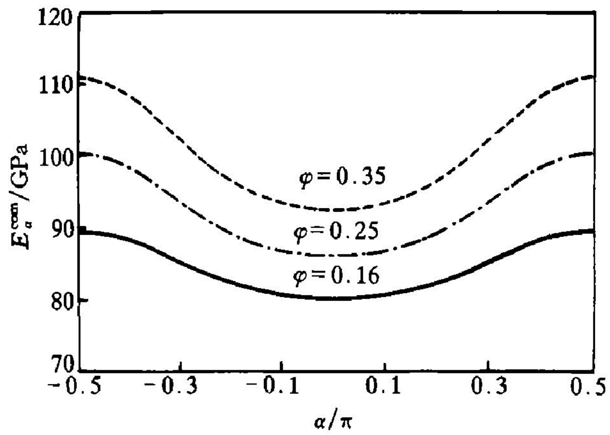

Fig. 3 Distribution of elastic modulus in $SiC_w/6061Al$ composite as-squeeze-cast

The inhomogeneity of elastic modulus in different directions of the composite is mainly due to the distribution differences of whisker orientation. Because of the lowest of whisker orientation function in the direction of $\alpha = 0$, the effect of loading transfer in this direction is lower than that in other directions, and the elastic modulus of composite in this direction is the lowest. On the contrary, because of the largest whisker orientation function in the direction of $\alpha = \pm\pi/2$, the effect of loading transfer in this direction is larger than that in other directions, and the elastic modulus of composite in this direction is the largest. According to the rule of mixtures[12], the larger the volume fraction of whisker is, the higher the bearing stress of whisker is, and the larger the elastic modulus of composite is. From the orientation function of whisker, it can be found that the larger the volume fraction of whisker is, the larger the extent of whiskers preferred in orientation is, the larger the extent inhomogeneity of elastic modulus in composite is.

The conventional method of measuring elastic modulus for composite is tensile testing, namely the elastic modulus of composite is determined from the slope of the initial tensile deformation curve. However, due to a lower proportional limit of the metal matrix composite, the method of tensile test is not reliable for measuring the elastic modulus of composite. By using the method of ultrasonic velocity, the elastic modulus of composite can be measured nondestructively. In this paper, it was found that the standard deviations of measured ultrasonic velocity for the $SiC_w/6061Al$ alloy composite are $\Delta u_L < 8$ m/s and $\Delta u_S < 15$ m/s respectively, and the standard deviations of elastic modulus is $\Delta E < 0.5$ GPa correspondingly. So the standard deviations of measured elastic modulus by the ultrasonic velocity is far lower than that by tensile test.

Table 1 gives the experimental results of ultrasonic velocity and elastic modulus of the $SiC_w/6061Al$ alloy composite as-squeeze-cast. In Table 1, the relation between the ultrasonic velocity and elastic modulus of composite was shown in Eqn. (10), and the density of composite is $\rho = 2.8$ g/cm^3. It can be seen

Table 1 Test results for ultrasonic velocity and elastic modulus of $SiC_w/6061Al$ alloy composite as-squeeze-cast

φ	α	u_S/(m·s^{-1})	u_L/(m·s^{-1})	E_α^{com}/GPa
0.16	0	3310.8	6194.0	79.8
	π/2	3502.4	6552.3	89.3
0.25	0	3447.0	6448.8	86.5
	π/2	3710.0	6940.7	100.2
0.35	0	3568.4	6675.9	92.7
	π/2	3929.3	7351.1	112.4

that, there is obvious inhomogeneity of ultrasonic velocity in different directions of the composite. The higher the volume fraction of whisker is, the higher the ultrasonic velocity is, and the larger the difference of ultrasonic velocity among different directions is. Compared with the data of Fig. 1 and Table 1, it can be also found that the elastic modulus of the composite as-squeeze-cast from the theoretical calculation was close to that from the experiment.

The advantage of SiC_w/Al composite is that the properties can be artificially designed. The integral properties of composite are improved by increasing the volume fraction of whisker, while the distribution of whisker can directly affect the property inhomogeneity of composite. The whisker orientation in the composite as-squeeze-cast is neither totally preferred nor totally random. There is an obvious difference of strengthening effect in different directions of the composite as-squeeze-cast, although this material was strengthened in each direction. Therefore, the property inhomogeneity must be considered in engineering application of the SiC_w/Al alloy composite as-squeeze-cast, to understand the potential property of the composite fully.

5 CONCLUSION

The whisker orientation of the composite is preferable normal to the squeeze casting direction. The higher the volume fraction of whisker, the more the extent of preferred orientation of it. According to the shear lag model and the actual orientation distribution function of whisker in the composite, the elastic modulus of composite is theoretically analyzed. There is obvious inhomogeneity of elastic modulus in the composite as-squeeze-cast. The higher the volume fraction of whisker is, the more obvious the inhomogeneity of elastic modulus in composite is. The elastic modulus of composite can be precisely measured by the method of ultrasonic velocity, and the results from the experiment are close to those from the theoretical calculation.

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