Compressive stress-strain response of directionally aligned SiC_w/Al composite

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A SiC_w/6061Al composite was fabricated through a squeeze-casting route and hot extruded to obtain a composite with directionally aligned whiskers. Based on observed changes in whisker orientation and length before and after deformation, compressive deformation behaviour of the directionally aligned SiC_w/Al composite was investigated. It is found that when the compressive temperature is much lower than the solidus of the matrix alloy, the compressive flow stress of the directionally aligned composite is increased with compressive strain first and then decreased. When the compressive temperature equals the solidus of the matrix, however, the compressive flow stress of the directionally aligned composite is increased monotonously with compression strain. During compression, whisker rotation and breakage occurred, and the higher the compressive temperature, the easier the whisker rotation and hence the smaller the degree of whisker breakage. When the compressive strain was quite high, the degree of whisker breakage was serious even at the temperature as high as the solidus of the matrix. Analyzing changes in whisker orientation and breakage before and after compression indicates that the decreased compressive flow stress with compressive strain is the result of the decreased load carrying ability of whiskers caused by whisker rotation and breakage. Compared with whisker rotation, whisker breakage has a bigger contribution to the decreased compressive flow stress. No strain softening in the composite compressed at 580°C can be thought to be a result of the very low strengthening effect of whiskers at such a high temperature. From the point of view of whisker breakage, to get higher properties of SiC_w/Al composite parts made by means of plastic forming, too high plastic strain should not be suffered by SiC_w/Al composites during the plastic forming.

1. Introduction

Plastic forming is one of the most important techniques in discontinuously reinforced aluminum matrix composite (DRA) applications. To provide useful information to plastic forming of DRAs and also to understand deformation mechanisms of DRAs, compressive deformation behavior of DRAs has been widely investigated in recent years [1–4]. However, almost all the studies that have been made on the compression behavior focus their attention on DRAs with randomly aligned reinforcements but not on DRAs with directionally aligned reinforcements. In fact, directionally aligned DRAs, especially the ones reinforced with whiskers or short fibers, sometimes have larger advantages in practical applications as compared with the randomly aligned ones.

Stanford-Beale *et al*. [1] investigated the compressive deformation of randomly aligned short fiber reinforced aluminum matrix composites. It was found that strain softening, matrix metal flow and whisker rotation occurred during compression, and the matrix metal flow and whisker rotation during compression

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related only to specimen shape. For solid cylindrical specimens, hoop and radial strains were equal during compression, so there was no systematic change in the whisker orientation distribution of planar random array (with the plane initially normal to the compression axis). For ring specimens, however, different regions were not constrained to increase their radial location in inverse proportion to the square root of the height ratio, so there was a systematic change in the whisker orientation distribution [1]. Because randomly aligned composites were used, the effect of directional alignment of reinforcements on compressive deformation behavior could not be investigated.

Geng *et al*. [4] investigated the compressive deformation of a SiC_w/Al composite at temperatures close to and above the solidus of the matrix alloy and found that whisker reorientation and breakage affected the work hardening behavior of the composite and the whisker breakage was a result of whisker interaction. By analyzing the whisker strengthening effect, temperatures above the solidus of the matrix were suggested for the plastic forming of SiC_w/Al composites. Also, the effect of directional alignment of reinforcements on compressive deformation behavior was not investigated.

With directionally aligned reinforcements, directionally aligned DRAs are anisotropic and different in structure and property from randomly aligned ones. In our paper [5], we studied the compressive deformation of a directionally aligned SiC_w/Al composite, in which whisker alignment direction is perpendicular to the compression direction. It was found that the matrix metal flow and whisker reorientation during compression of the directionally aligned SiC_w/Al composite depended not only on the specimen shape and but also on the deformation temperature, and the whisker reorientation could occur only at high temperatures and in ring specimens. Since the whiskers aligned horizontally in the plane perpendicular to the compressive direction, all the whiskers would be perpendicular to the compressive direction during the compression. Therefore, the influence of the whisker rotation from compressive direction to horizontal direction on compressive behavior of SiC_w/Al composites could not be investigated. According to [3], the change in the inclined angle of whisker from compressive direction to horizontal direction should be more important to the stress-strain response of SiC_w/Al composites.

In addition, although whisker rotation and whisker breakage have been found to be the reason that results in the softening behavior of SiC_w/Al composites, it still remains unclear, to date, which one, whisker rotation or whisker breakage, is more important to the softening behavior of SiC_w/Al composites.

The objective of this paper is to quantitatively investigate the degrees of the respective contributions of both whisker rotation and whisker breakage to the softening behavior of SiC_w/Al composites by analyzing the compressive deformation behavior of directionally aligned SiC_w/Al composites, in which whisker alignment direction is parallel to the compression direction. In order to understand the effect of temperature on the compressive behavior of the directionally aligned SiC_w/Al composites, two test temperatures, one is much lower than the solidus of the matrix and the other is equal to the solidus of the matrix, are used in the compression tests. For a better formability of SiC_w/Al composites, high temperatures could be chosen as forming temperatures [3]. However, deformation at temperatures above the solidus of the matrix may deteriorate the composite properties due to superburning of the matrix alloy. To reduce the effect of superburning of matrix, in this research, only the solidus of the matrix alloy was chosen as the upper limit temperature.

2. Experimental procedure

A SiC_w/6061Al composite was fabricated by a squeeze casting technique using the β-SiC whisker (TWS-100) as the reinforcing element and the commercial 6061 alloy as the base metal. Mold and whisker perform temperature, pouring temperature and applied pressure were 450°C, 750°C and 60 MPa, respectively. The whisker volume fraction, V_f, was about 20%. The as-cast SiC_w/Al composite was then extruded to obtain a directionally aligned material for use in compression tests. The solidus of the matrix 6061 alloy in the directionally aligned composite was measured to be 580°C by differential scanning calorimetry (DSC). Based on this result, compression tests of directly aligned SiC_w/Al composites were conducted in air at 380 and 580°C with a constant platen velocity of 0.2 mm s^{-1}. In this research, only the solidus of the matrix alloy was chosen as the upper limit temperature to reduce matrix superburning. To decrease the frication between the specimens and the platen, all tests were carried out using graphitic oil as the lubricant. Solid cylindrical specimens were used with the diameter of 8 mm and height of 12 mm, and the compression direction was the extrusion direction. For comparing purpose, unreinforced 6061 Al was also compressed under the same condition as the composite.

Microstructures of the deformed and undeformed specimens were observed using SEM on vertical-sections of the specimens. Quantitative analyses of whisker orientation and aspect ratio were carried out using Leica MEF4M image analyzer. The reference direction for measuring the whisker orientation was the extrusion direction and at least 200 whiskers were measured for each specimen. In order to determine the whisker aspect ratios, samples of compressed and uncompressed composites were digested with a 50% HCl + 50% HNO_3 solution to remove the matrix.

3. Results and discussion

3.1. Compressive stress-strain curves

Fig. 1 shows true stress-strain curves of the directionally aligned SiC_w/Al composites and unreinforced Al compressed at 380 and 580°C, respectively. It can be seen that the stress-strain behavior at 380°C is different from that at 580°C and the flow stress is much higher for the composites compressed at 380°C than at 580°C. When compressive temperature is 380°C, the

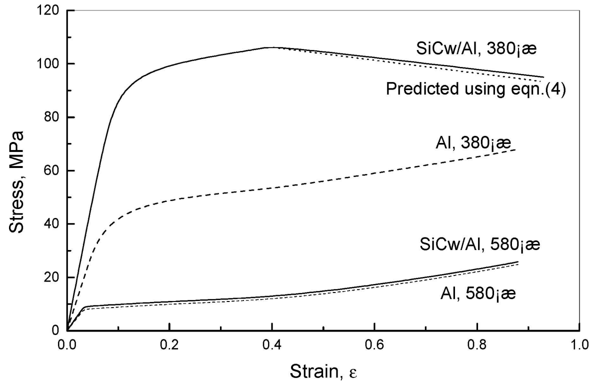

Figure 1 True stress-strain curves of directionally aligned SiC_w/Al composites and unreinforced Al compressed at 380°C (much lower than the solidus of matrix) and 580°C (equal to the solidus of matrix), respectively.

compressive flow stress of the directionally aligned composite increases with compressive strain first and then decreases. That is to say, at 380°C, the stress-strain curve of the composite can be divided into two steps. The first one is strain hardening ($\varepsilon \leq 0.4$) and the second is strain softening ($\varepsilon > 0.4$). When compressive temperature was 580°C, however, the compressive flow stress of the directionally aligned composite increased monotonously with compression strain. That is to say, no strain softening occurs. In addition, at 580°C, the flow behavior of the composite is similar to that of the unreinforced matrix alloy.

3.2. Whisker rotation

Fig. 2 shows some typical SEM photos of whisker morphology in SiC_w/Al composites compressed at different temperatures to different strains. Each photo only corresponds one point in each specimen. It can be seen that, during compression, all the whiskers in the composites rotated and broke regardless of the compressive temperatures. From all the photos of whisker morphology we took including those shown and unshown in Fig. 2, whisker orientation distributions of SiC_w/Al composites compressed at different temperatures to different strains are obtained and shown in Fig. 3. The compressive direction is taken as the reference direction i.e. 0° direction. From Fig. 3a it can be seen that, before compressive deformation, the major direction of whisker distribution in the SiC_w/Al composites is 0°. That is to say, most of the whiskers in the composites align in the extrusion direction before compression. When compressive strain is about 0.4, the major directions of whisker distribution are 20° for the composite compressed at 380°C (Fig. 3b) and 35° for the composite compressed at 580°C (Fig. 3d). While when compressive strain is about 0.93, the major directions of whisker distribution are 40° for the composite compressed at 380°C (Fig. 3c) and 45° for the composite compressed at 580°C (Fig. 3e). Because the major whisker distribution directions of the composites with the strains of 0, 0.4 and 0.9 are different, it can be thought that whisker rotation took place during the compression.

TABLE I Whisker orientation function $f(\phi)$ in SiC_w/Al composites compressed at different temperatures to different strains

	$f(\phi)$	
Strain	380°C	580°C
0	0.45	
0.4	0.36	0.16
0.9	0.05	0.01

The whisker orientation can better be described using the orientation function f [6]:

$$f = (2\langle\cos^2\phi\rangle - 1)/2 \tag{1}$$

with

$$\langle\cos^2\phi\rangle = \frac{\sum N_i \cos^2\phi_i}{\sum N_i} \tag{2}$$

where ϕ_i is the angle between the major axis of a whisker and the compression direction, N_i the number of whiskers with the angle of ϕ_i.

From Equation 1, it can be found that the more the degree of whisker orientation along the compression direction, the more the value of orientation function $f(\phi)$. If all whiskers align in the compressive direction, $f(\phi) = 0.5$; if all whiskers align in the direction perpendicular to the compressive direction, $f(\phi) = -0.5$; if all whiskers are aligned in the direction of 45° to the compressive direction or in randomly aligned manner, $f(\phi) = 0$.

According to Equations 1 and 2 and the results in Fig. 3, values of orientation function f of the composites compressed at different temperatures to different strains are calculated and listed in Table I. It can be more clearly seen that whisker rotation took place during the compression for all the composites. Because the values of orientation function f are smaller for the composites compressed at 580°C than at 380°C, the degree of whisker rotation is larger for the composites compressed at 580°C than for 380°C, especially within the strain range of less than 0.4. Because a whisker rotation in a SiC_w/Al composite during compression is a result of strain coordination between the whisker and the matrix, it is easy to understand that with decreasing resistance to the matrix deformation, the whisker rotation becomes easier. The decreased matrix flow stress at the higher temperature in the unreinforced matrix Al (Fig. 1) indicates that the resistance of matrix to whisker rotation should be lower in the SiC_w/Al composite compressed at the higher temperature, and hence the SiC_w/Al composite compressed at the higher temperature has a higher degree of whisker rotation.

3.3. Whisker breakage

Another important phenomenon during compressive deformation is whisker breakage. Table II shows the average aspect ration of whiskers in the SiC_w/Al composites compressed at different temperatures to different strains. It can be seen from Table II that the whisker

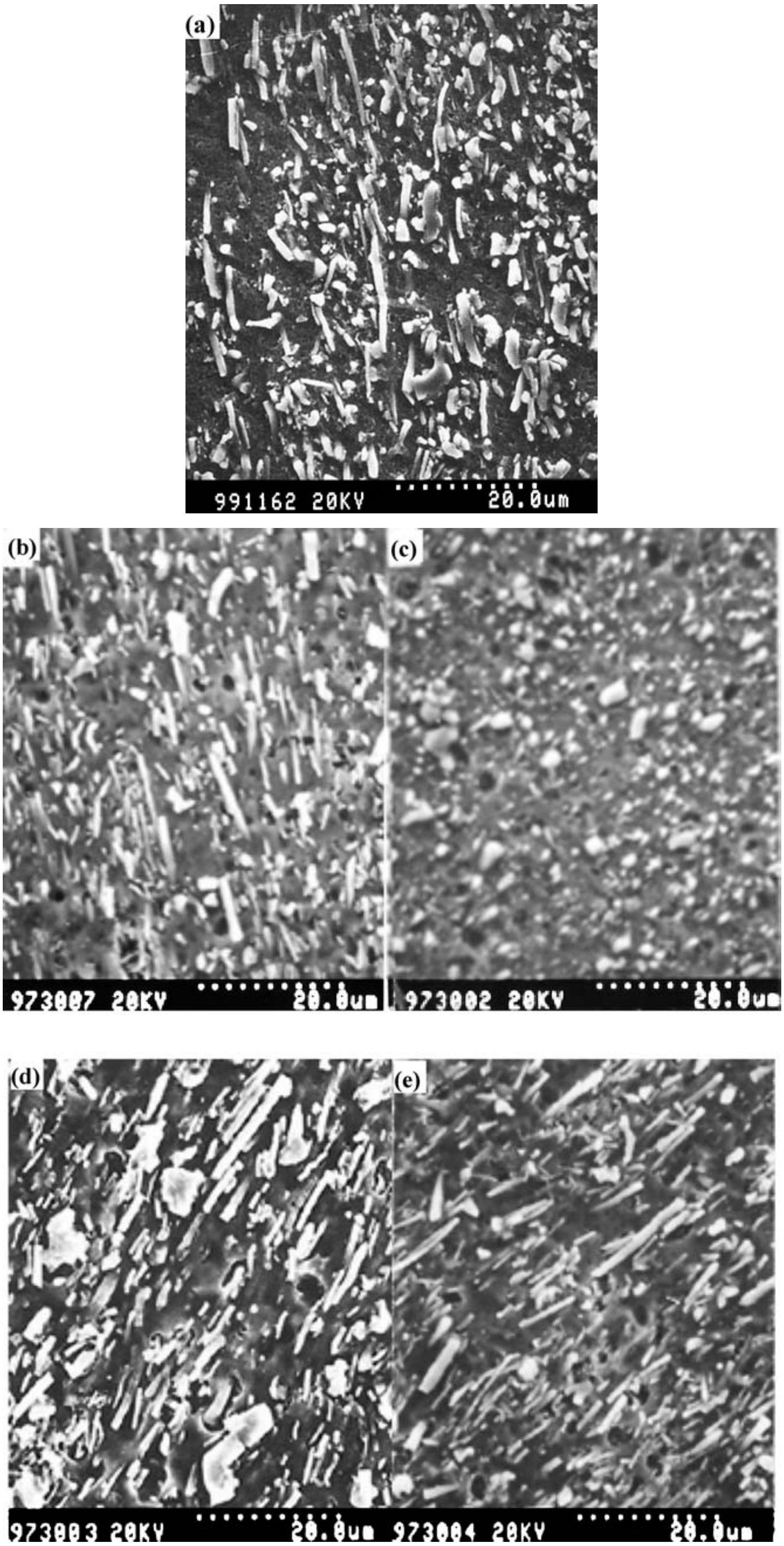

Figure 2 Whisker morphology in SiC_w/Al composites compressed at different temperatures to different strains: (a) $\varepsilon = 0$, (b) $\varepsilon = 0.4$, 380°C; (c) $\varepsilon = 0.93$, 380°C; (d) $\varepsilon = 0.4$, 580°C; (e) $\varepsilon = 0.93$, 580°C.

aspect ratio in the composites with the strain of 0.4 is smaller than that in the composites with the strain of 0.9, indicating that the degree of whisker breakage is more serious as compression strain increases. At the same time, the degree of whisker breakage in the composites compressed at 580°C is smaller than that in the composites compressed at 380°C, indicating that higher temperatures can reduce the degree of whisker breakage during the compression. Since the difference in whisker aspect ratio between the composites with the

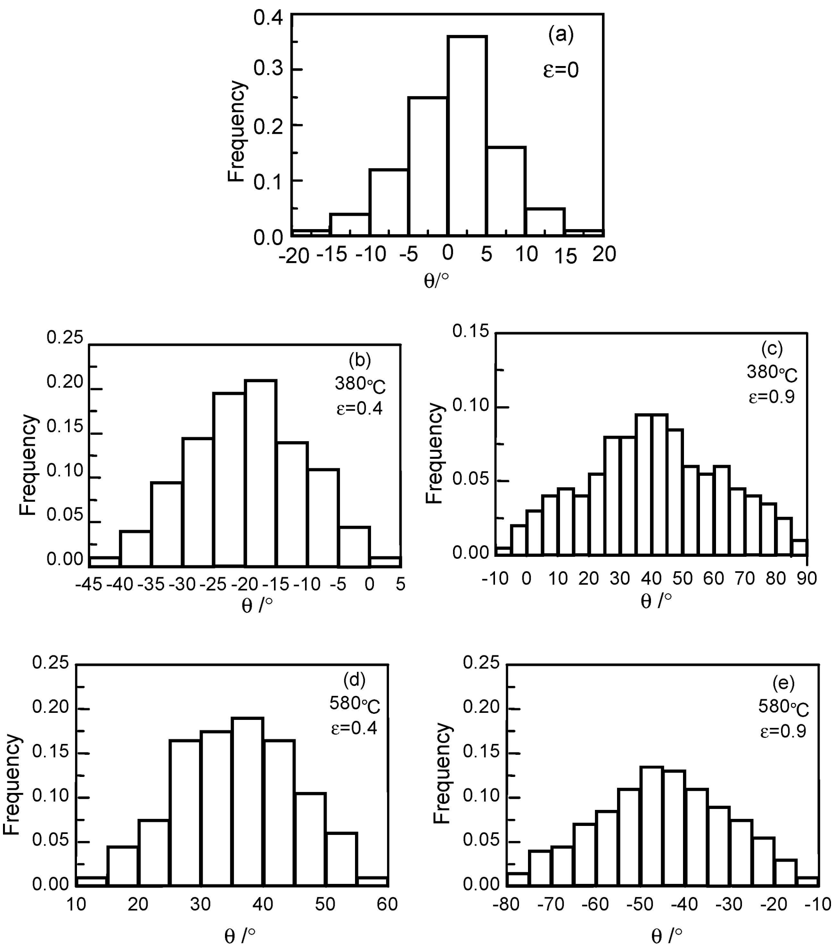

Figure 3 Orientation distributions of whiskers in SiC_w/Al compressed at different temperatures to different strains: (a) ε=0; (b) $\varepsilon = 0.4$, 380°C; (c) $\varepsilon = 0.93$, 380°C; (d) $\varepsilon = 0.4$, 580°C; (e) $\varepsilon = 0.93$, 580°C.

strains of 0.4 and 0 is far smaller than that between the composites with the strains of 0.4 and 0.9, it can be said that the degree of whisker breakage during compression with the strain range from 0.4 to 0.9 is higher than that with the strain range from 0 to 0.4. This indicates that when compressive strain is more than 0.4, the degree of whisker breakage becomes more and more serious with compressive strain even when deformation temperature is as high as 580°C. It was reported that whisker breakage in SiC_w/Al composites compressed at temperatures close to and above the solidus of the matrix alloy could be seen as a result of whisker interaction [4], therefore it can be said that, in the present research, the interaction between whiskers in the SiC_w/Al composites compressed to high strain (such as 0.9) is quite serious even at the solidus of the matrix alloy. The result that the flow behavior at 580°C is similar for the composite to for the unreinforced matrix alloy (Fig. 1) implies that the solidus of the matrix could be used to improve the plastic forming ability of SiC_w/Al composites. This is consistent with that reported in Ref. [4] However, it must be pointed out that the serious whisker breakage can also deteriorate composite properties due to the decreased load carrying ability of whiskers caused by the whisker breakage. Therefore, from the point of view of whisker breakage, to get higher properties of SiC_w/Al composite parts made by means of plastic forming, SiC_w/Al composites should not suffer from too high plastic strain for plastic forming purpose even though the deformation is carried at temperatures close to the solidus of the matrix.

3.4. Strain softening behavior

The flow stress of a SiC_w/Al composite under a constant strain rate can be expressed by [3]:

$$\sigma_c = \sigma_m(\bar{l}/d)v_f \sum_{i=1}^{n} \cos\alpha_i/n + \sigma_m \tag{3}$$

where $\bar{l}/d$ is average aspect ratio of whisker, α_i the angle between the long axis of a whisker and the compressive direction, n the whisker number, σ_m the flow stress of the matrix, v_f the whisker volume fraction.

For materials with high fault energy such as aluminum and its alloy, dynamic recovery is considered to be the only softening mechanism [2]. That is to say,

TABLE II Average aspect ratio of whiskers in SiC_w/Al composites compressed at different temperatures to different strains

	Aspect ratio, $\bar{l}/d$	
Strain	380°C	580°C
0	7.3	
0.4	6.8	7.1
0.9	3.0	4.0

TABLE III $\sum_{i=1}^{n}\cos\alpha_i/n$, matrix flow stress ($\sigma'_m$), calculated and experimentally-obtained flow stresses σ_c^c and σ_c^m in SiC_w/Al composites tested at 380°C to different strains

Strain	0.4	0.9
$\sum_{i=1}^{n}\cos\alpha_i/n$	0.75	0.56
σ'_m	52.86	65.64
σ_c^c	106.78	87.70
σ_c^m	107.05	95.10

TABLE IV Strengthening factor (Φ)

Strain	0.4	0.9
Strengthening factor, Φ	5.12	1.68

during compression with a constant strain rate, flow stress of the materials can be considered to be constant when dynamic recovery takes place. With the increase in strain rate, dynamic recovery will take place at higher stresses and hence the flow stress of a SiC_w/Al composite under an increasing strain rate can be expressed as:

$$\sigma_c = \sigma'_m(\bar{l}/d)v_f\sum_{i=1}^{n}\cos\alpha_i/n + \sigma'_m \qquad (4)$$

where σ'_m is matrix flow stress varying with strain rate and represents work-hardening effect of the matrix. In this research, since the platen move velocity is 0.2 mm s^{-1} and kept constant during each compression test, the strain rate during compression should increase monotonously with time.

In this research, $v_f = 0.2$, σ'_m depends on temperature and can be obtained from the true stress-strain curves of unreinforced matrix alloy, $\bar{l}/d$ and α_i are from Fig. 3 and Table II, respectively. With these values, two flow stresses at 380°C of the composites with two typical strains of 0.4 and 0.9 are calculated and shown in Table III, in which two measured flow stresses at 380°C are also listed.

Table III indicates that the calculated flow stress values are close to the corresponding experimentally obtained ones. The predicted strain softening behavior is also shown in Fig. 1. The predicted strain softening behavior is also close to the experimentally obtained one. Hence, Equation 4 can be used to predict the strain softening behavior of the SiC_w/Al composite during compression at 380°C.

From Equation 4, it can be known that σ'_m, $\bar{l}/d$, α_i are three factors influencing the flow stress of a SiC_w/Al composite. σ'_m increases with strain and hence is a factor causing strain hardening. $\bar{l}/d$ and α_i are two factors causing strain softening. So far, it still remains unclear that which one of the two factors, $\bar{l}/d$ or α_i has a larger effect on the strain softening behavior. To make it clear, the dot product, $(\bar{l}/d)\sum_{i=1}^{n}\cos\alpha_i/n$, is chosen as a strengthening factor and denoted as Φ:

$$\Phi = (\bar{l}/d)\sum_{i=1}^{n}\cos\alpha_i/n \qquad (5)$$

$\bar{l}/d$ and $\sum_{i=1}^{n}\cos\alpha_i/n$ can be obtained from Tables II and III, respectively. The calculated values of Φ are listed in Table IV. It can be found that the strengthening factor Φ changes from 5.12 to 1.68 when the strain changes from 0.4 to 0.9, indicating that whisker rotation and breakage are two factors leading to the strain softening.

Considering an incremental strain $d\varepsilon$, then from Equation 5 we can obtain:

$$\begin{aligned} d\Phi &= \frac{\partial\Phi}{\partial(\bar{l}/d)}d(\bar{l}/d) + \frac{\partial\Phi}{\partial\left(\sum_{i=1}^{n}\cos\alpha_i/n\right)}d \\ &\quad\times\left(\sum_{i=1}^{n}\cos\alpha_i/n\right) \\ &= \left(\sum_{i=1}^{n}\cos\alpha_i/n\right)d(\bar{l}/d) + (\bar{l}/d)d \\ &\quad\times\left(\sum_{i=1}^{n}\cos\alpha_i/n\right) \end{aligned} \qquad (6)$$

Integrate Equation 6 from $\varepsilon = 0.4$ to $\varepsilon = 0.6$, then the corresponding increment in strengthening factor Φ is:

$$\begin{aligned} \Delta\Phi &= \int_{\Phi_{0.4}}^{\Phi_{0.9}} d\Phi = \int_{6.8}^{3}\left(\sum_{i=1}^{n}\cos\ \alpha_i/n\right)d(\bar{l}/d) \\ &\quad + \int_{0.75}^{0.56}(\bar{l}/d)d\left(\sum_{i=1}^{n}\cos\ \alpha_i/n\right) \end{aligned} \qquad (7)$$

To integrate Equation 7, the relationship between $\bar{l}/d$ and $\sum_{i=1}^{n}\cos\alpha_i/n$ must be known. To do this, the measured values of $\bar{l}/d$ and $\sum_{i=1}^{n}\cos\alpha_i/n$ of the composites compressed at 380°C to strains ranging from 0.4 to 0.9 are shown in Fig. 4.

Form Fig. 4, it can be found that the relationship between $\bar{l}/d$ and $\sum_{i=1}^{n}\cos\alpha_i/n$ within the strain range from 0.4 to 0.9 is basically linear and can be

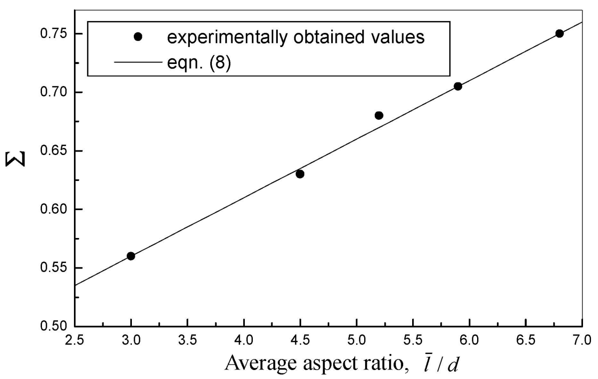

Figure 4 Relationship between $\bar{l}/d$ and $\sum_{i=1}^{n}\cos\alpha_i/n$ (denoted as $\sum$) in strain range from 0.4 to 0.9

approximately expressed as:

$$\bar{l}/d = 19.60 \sum_{i=1}^{n} \cos \alpha_i / n - 7.96 \qquad (8)$$

Combining Equation 8 into Equation 7 and integrating it, we can obtain:

$$\begin{aligned}\Delta\Phi &= \int_{\Phi_{0.4}}^{\Phi_{0.9}} d\Phi \\ &= \int_{6.8}^{3} \left(\sum_{i=1}^{n} \cos \alpha_i / n \right) d(\bar{l}/d) \\ &\quad + \int_{0.75}^{0.56} (\bar{l}/d) d \left(\sum_{i=1}^{n} \cos \alpha_i / n \right) = -3.44\end{aligned}$$

where $\Delta\Phi_1 = \int_{6.8}^{3} \left(\sum_{i=1}^{n} \cos\alpha_i/n\right) d(\bar{l}/d) = -2.51$, representing the contribution from whisker breakage to the drop in strengthening factor. $\Delta\Phi_2 = \int_{0.75}^{0.56} (\bar{l}/d) d \left(\sum_{i=1}^{n} \cos\alpha_i/n\right) = -0.93$, representing the contribution from whisker rotation to the drop of strengthening factor. Then, the percent drops in strengthening factor due to whisker breakage and whisker rotation, $\Delta\Phi_1/\Delta\Phi$ and $\Delta\Phi_2/\Delta\Phi$, is 73% and 27%, respectively, indicating that, in this research, whisker breakage has a larger contribution to the strain softening compared with whisker rotation.

The fact that no strain softening occurred in the composite compressed at 580°C can be thought to be a result of the low strengthening effect of whiskers at such a high temperature due to the very low strength of the matrix at such a high temperature.

4. Conclusions

By observing changes in whisker orientation and length before and after deformation, the compressive deformation behaviour of directionally aligned SiC_w/Al composites was investigated. It can be concluded as follows:

(1) Whisker rotation and breakage took place during compression of the directionally aligned SiC_w/Al composite. The higher the compressive temperature, the easier the whisker rotation and hence the smaller the degree of whisker breakage. When compressive strain was quite high, degree of whisker breakage got more and serious with strain even at the temperature as high as the solidus of the matrix.

(2) When compressive temperature is much lower than the solidus of the matrix alloy, the compressive flow stress of the directionally aligned composite increases with compressive strain first and then decreases, i.e. strain softening occurs. When compressive temperature is equal to the solidus of the matrix, however, the compressive flow stress of the directionally aligned composite increases monotonously with compression strain, i.e. no strain softening occurs.

(3) By analyzing changes in whisker orientation and breakage before and after compression, the strain softening behavior can be thought to be the result of whisker rotation and breakage. Compared with whisker rotation, whisker breakage has a larger contribution to the strain softening behavior. No strain softening occurred in the composite compressed at 580°C can be thought as a result of the very low strengthening effect of whiskers at such a high temperature.

(4) From the point of view of whisker breakage, to get higher properties of SiC_w/Al composite parts made by means of plastic forming, too high plastic strain should not be suffered by SiC_w/Al composites during the plastic forming.

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