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Deformability of a SiCw/6061Al composite during high strain rate compression at elevated temperatures

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The deformability of SiCw/6061Al composite during high strain rate compression has been investigated at elevated temperatures around the solidus of the matrix alloy. The results show that the maximum deformability was obtained at 580°C which is near the solidus of the matrix. Analysis of the results indicates that the composites deformed at 580°C have the largest strain rate sensitivity (m value) and the lowest threshold stress, both of which lead to the maximum deformability. Microstructure observation shows that microcracks were formed at the interfaces in the composites deformed at 540°C and 620°C, whereas, in the composite deformed at 580°C, microcracks were rarely found because of the low stress concentration at the interfaces due to the presence of a small amount of liquid. It is suggested that the presence of an adequate amount of liquid phase gives rise to the effective accommodation required for grain boundary sliding for the composite, and thus directly affects the deformability of SiCw/6061Al composite.

1. Introduction

It has been demonstrated that aluminum matrix composites reinforced with various discontinuous reinforcement materials have potential for applications in both the automotive and aerospace industries [1–4]. However, the poor machinability of the composites have limited their development. To solve this problem, near–net shape forming technology has been proposed and in particular, forming, in which high strain rate superplasticity plays a most important role.

High strain rate tensile superplasticity of metal matrix composites has been well documented, including tensile deformation behavior, proposed deformation mechanisms [5, 6], and cavitation characteristics during deformation process [7, 8]. However the experimental method of high strain rate compression of the composites, which is more suitable for simulating the actual forming conditions than tensile deformation is seldom reported.

The aim of the present paper is to investigate the deformability of SiCw/6061Al composite during high strain rate compression at elevated temperatures. Specific attention is paid to the effect of deformation temperature and the presence of liquid phase on the deformability of the SiCw/6061Al composite, including critical reduction (maximum reduction before specimen surface cracks are formed), strain rate sensitivity (m), and threshold stress.

2. Materials and experimental procedures

The SiCw/6061Al composite used in the present study was fabricated by squeeze casting. The composite was reinforced with 20 vol% β-SiC whiskers having an average diameter of 0.5 μm and length of 25 μm. The partial melting temperature of the SiCw/6061Al composite was determined by STA449C DSC (Differential Scanning Calorimetry). Compression tests of the composites were conducted in a Gleeble-1500. The compressive specimens, with a size of $\phi 6 \times 9$ mm, were compressed at three different temperatures around the partial melting temperature of the composite. After testing, each specimen was sectioned, polished, and then examined using a high resolution SEM (scanning electron microscopy).

3. Results and discussion

Fig. 1 is the DSC result showing the partial melting temperature of the SiCw/6061Al composite. During this test, the composite sample was heated in an Al_2O_3 crucible from room temperature to 700°C at a heating rate of 10°C/min. The DSC result shows that the partial melting temperature of the present composite is 579.5°C. Based on the DSC result, the compressive tests were conducted at 540°C, 580°C and 620°C, respectively.

Fig. 2 shows the effect of deformation temperature on the critical reduction, i.e., the percent reduction height

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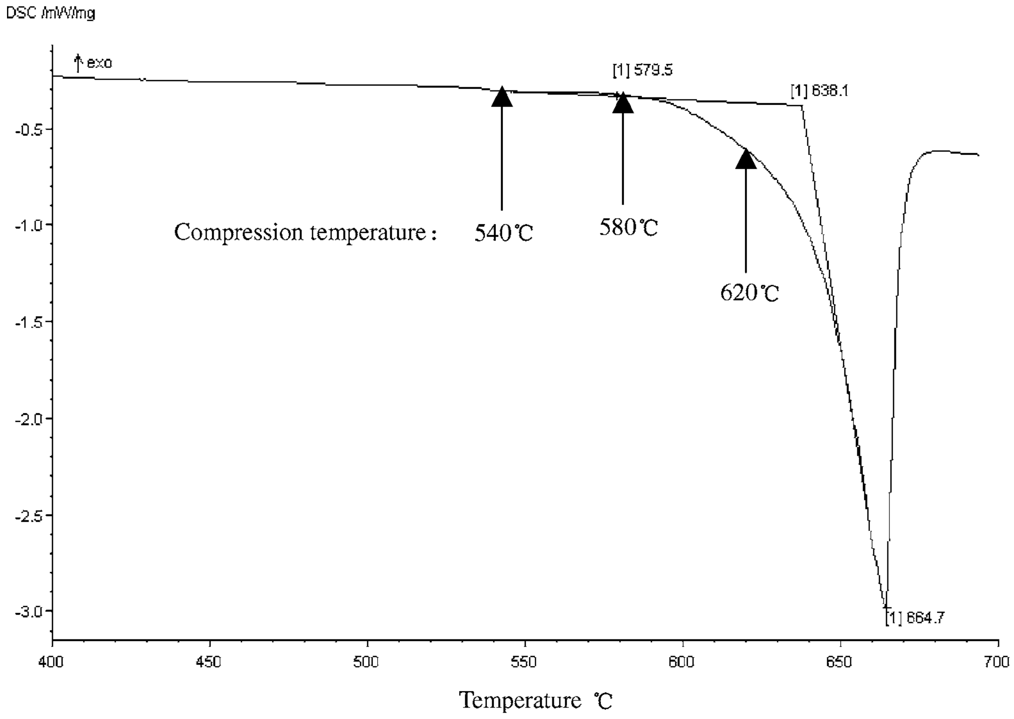

Figure 1 Typical DSC curve of the SiCw/6061Al composite at a temperature range from 400–700°C.

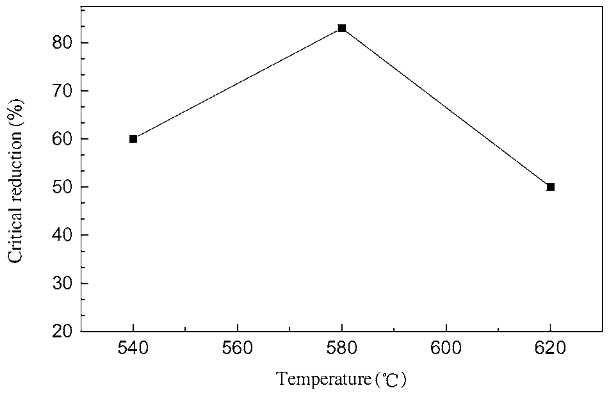

Figure 2 Dependence of critical reduction and compression temperature of SiCw/6061Al composite.

prior to cracking, of the SiCw/6061Al composite. It can be seen that when the composite is deformed at 540°C, which is 40°C lower than the partial melting point of the composite, a small critical reduction of 60% was obtained. At 580°C, which is a little higher than the partial melting point, a large critical reduction of 83% was obtained. When the composite is deformed at 620°C, which is 40°C higher than the partial melting point, the critical reduction is only 50%.

An optical micrograph and a scanning electron micrograph of the SiCw/6061Al composite in the as-cast state are shown in Fig. 3a and b, respectively. They show that the whiskers are distributed homogeneously and no cavitation is found in the composite.

Fig. 4 shows the relationship between the flow stress and the strain rate of SiCw/6061Al composite. There is a linear function between ln σ and ln $\dot{\varepsilon}$. The strain rate sensitivity (*m* value) of the SiCw/6061Al composite compressed at 540°C is 0.323 in the studied strain rate region. The composite tested at 580°C, however, indicates an *m* value of 0.5, whereas, the *m* value decreases to 0.28 for the composite tested at 620°C in the same strain rate range. The strain rate sensitivity is an indicator of the superplastic deformability of the material. When the deformation temperature is below the solidus of matrix alloy, e.g., 540°C, a solute-drag controlled dislocation motion mechanism is considered to be the superplastic deformation mechanism of aluminum

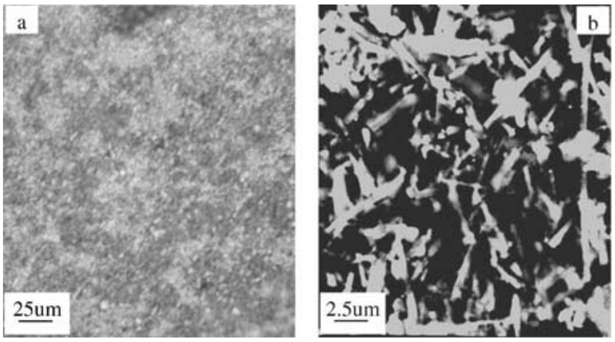

Figure 3 Optical micrograph (a) and SEM photograph (b) of the as-cast SiCw/6061Al composite.

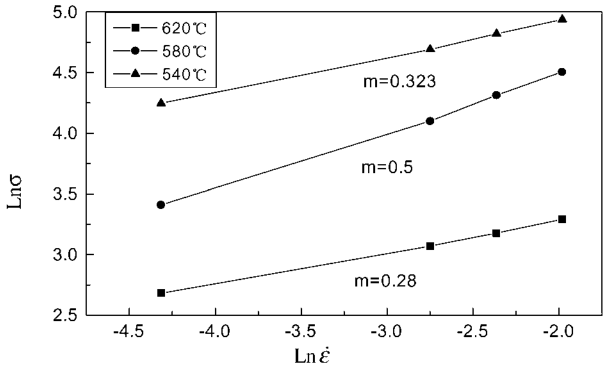

Figure 4 The variation in the true stress as a function of strain rate for the SiCw/6061Al composite.

TABLE I Aluminum matrix composites high strain rate superplasticity [12–16]

Material	T (K)	T_s (K)	$\dot{\varepsilon}$ (S^{-1})	m	El (%)	Ref
17.5 vol%SiCp/6061Al	853	852	10^{-1}	0.5	375	[12]
17.5 vol%SiCp/6061Al	853	853	10^{-1}	0.5	200	[12]
17.5 vol%SiCp/8090Al	848	833	0.18	0.5	300	[13]
20 vol%SiCp/6061Al	853	853	0.24	0.5	340	[14]
20 vol%Si_3N_4/Al-Cu-Mg	788	784	0.04	0.5	840	[15]
AlNp/6061Al	873	853	0.8	0.5	500	[16]

matrix composites [7, 8], and the deformability is relatively low in this temperature region as shown in Fig. 2. It is proposed that when $m = 0.5$, grain boundary sliding and interfacial sliding accommodated by dislocation movement along the grain boundaries would be the major deformation mechanism for some fine grained superplastic aluminum matrix composites [9–11]. Similar results are shown in Table I, from which it can be seen that large elongations were obtained for the composites at temperatures a little higher than the solidus of the matrix. In this research, when the SiCw/6061Al composite was deformed at 580°C, a small amount of liquid phase appeared, especially at the SiC-Al interfaces and grain boundaries of the matrix [17], which improved the interfacial and grain boundary sliding during compression, resulting in a high critical reduction of the composite as shown in Fig. 2. When the testing temperature is much higher than the solidus of the matrix (such as 620°C in this test), the deformation is related to liquid flow. The deformation at this temperature is likely to be one of lubricated flow in a semi-solid state containing a continous liquid. However, deformability is low at this temperature. This is probably because of decohesion at boundaries with a thick liquid phase. The continuous liquid is squeezed out of the specimen during compression, decreasing the uniformity of the deformation and leading to a rapid decrease in formability. The analysis above indicates that the maximum deformability of the SiCw/6061Al composite is attained at the temperature close to or slightly above the partial melting temperature.

Compared with an unreinforced aluminum alloy, the aluminum matrix composite usually shows a lower m value and a higher stress exponent ($n = 1/m$). Therefore the concept of a threshold stress is commonly invoked to evaluate the deformability of the aluminum matrix composite. In order to calculate the threshold stress the following power law equation has been used

$$\dot{\varepsilon} = \frac{ADGb}{KT}\left(\frac{b}{d}\right)^p\left(\frac{\sigma - \sigma_0}{E}\right)^n \tag{1}$$

where $\dot{\varepsilon}$ is the strain rate, D the appropriate diffusivity, G the shear modulus, b the Burgers vector, k the Boltzmann constant, T the test temperature, d the grain size, p the grain size exponent, σ the applied stress, σ_0 the threshold stress, E the Young's modulus, n the stress exponent, and A a dimensionless constant. According to the above equation the threshold stress can be determined by plotting $\dot{\varepsilon}^{1/n}$ against flow stress σ and then extrapolating the plot to zero strain rate. The stress exponent of 2, commonly found in conventional superplastic alloys, has been used in this study to calculate the threshold stress. Fig. 5 shows plots of $\dot{\varepsilon}^{1/2}$ versus stress for various temperatures. The data points give a reasonable fit to a straight line, although some systematic deviation is evident. The threshold stress is dependent on the compression temperature. The results show that threshold stresses of SiCw/6061Al composite compressed at 540°C, 580°C and 620°C are 61 MPa, 24 MPa and 13 MPa, respectively. The threshold stress decreases gradually with increasing deformation temperature. From this point of view, the deformability of the composite should increase with increasing deformation temperatures. However, when the deformation temperature is much higher than the partial melting point of the composite, a continuous liquid is formed, leading to a lower deformability as shown in Fig. 2. When large amounts of liquid phase appears during deformation, more cavities are formed, which also accounts for the decreasing deformability of the composite deformed at 620°C.

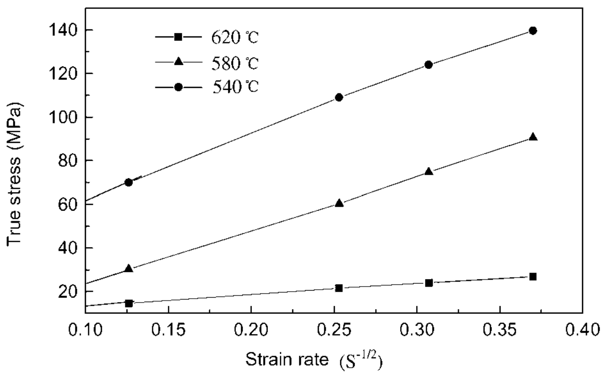

Figure 5 Calculation of the threshold stress for temperatures 540, 580 and 620°C for a SiCw/6061Al composite.

Fig. 6 shows the microstructure of the SiCw/6061Al composite deformed by a thickness reduction of 50% at various temperatures. It can be seen that cavities are formed easily when the temperature is much higher than the solidus temperature of the matrix or much lower than it, and the cavities are located at the interfaces between the reinforcement and the matrix. But, when the compression temperature is near the solidus of the matrix, such as 580°C cavitation is seldom seen. This is because when the composite is compressed at 540°C, it leads to stress concentrations at the interfaces of the composite and gives rise to cavity nucleation. As a result of increasing stress concentrations, the number of potential nucleation sites increases and consequently the number of cavities increases with increasing strain. The presence of a liquid phase at grain boundaries with high misfit angles, and at reinforcement-matrix interfaces, in the composite has been proved by *in situ* observation using transmission electron microscopy (TEM) at elevated temperature [17]. Therefore, the stress concentration level at the interface containing a liquid phase may be much lower than in interfaces without a liquid phase. Therefore, the accommodation required to relax the stress concentration by sliding can be much more easily achieved through rapid mass transport within a liquid phase. It is likely that high

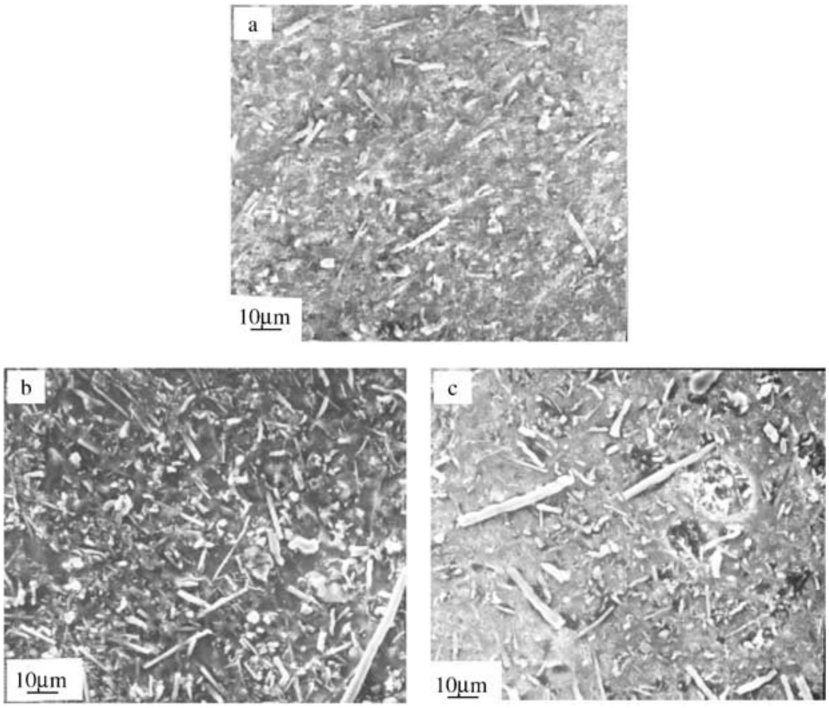

Figure 6 Micrograph showing microstructure in the SiCw/6061Al composite compressed at 540°C (a), 580°C (b) and 620°C (c).

deformability in the composite can be attributed to the presence of a liquid phase. However, at 620°C, cavity nucleation occurs much more easily at these interfaces, since the continuous liquid phase in the composite leads to a weak bonding force between the liquid and the solid. In addition, the increasing amount of the liquid phase tends to aggregate or is even squeezed out of the samples. The liquid phase is solidified after compression and some casting defects (cavities) may appear. All this will affect the deformability of SiCw/6061Al composite.

4. Conclusions

1. When the SiCw/6061Al composite is compressed at 540°C, which is 40°C lower than the solidus temperature of the matrix , the deformability of the composite is low because of the small m value, the large threshold stress, and the cavitation that forms at the SiC-Al interfaces due to a high stress concentration.

2. When the compression temperature is near the solidus of the matrix, the maximum critical reduction of 83% is obtained. This is a result of the existence of a small amount of liquid phase which relaxes stress concentrations and then improves the deformability of the composite. At this temperature the m value is higher and the threshold stress is lower, which also contribute to the maximum deformability.

3. When the compression temperature is 620°C, too much liquid phase appears, which promotes the formation of the cavities and results in a low m value and a decreased critical reduction.

4. In order to obtain high strain rate superplasticity, the proper amount of liquid phase is necessary for the compression of the SiCw/6061Al composite.

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