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Prediction of dynamic recrystallization condition by deformation efficiency for Al 2024 composite reinforced with SiC particle

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Hot torsion test has been carried out for Al 2024 composite reinforced with 8 μm SiCp (15 vol.%) to suggest optimum hot working condition for dynamic recrystallization (DRX) at the temperature range of 320 to 520 °C and strain rate range of 0.1 to 3.0/sec. Flow curve and deformed microstructure have been analyzed to identify the hot restoration mechanism of DRX. Processing map showing the variation of the deformation efficiency expressed by $[2m/(m+1)]$, where m is the strain rate sensitivity, with temperature and strain rate has been described for the composite. The characteristics of domain of DRX and peak efficiency of the composite have been analyzed by observing deformed microstructure. The composite showed 40–50% efficiency at the DRX domain (370–460 °C, 0.1–0.5/sec). Also, the variation of deformation efficiency with Zener-Hollomon parameter($Z = \dot{\varepsilon}\exp(Q/RT)$) were discussed to find out optimum hot working condition for DRX of the composite. It is found that the optimum temperature and strain rate condition for DRX of the composite is 430–450 °C and 0.5/sec.

1. Introduction

Al-based composites reinforced with particles, whiskers or short fibers have emerged as an advanced materials owing to their good wear resistance, high specific strength, and low thermal expansion properties [1, 2]. Hot working processes like rolling, forging, and extrusion have been considered an important part in the automotive, steel-making, and aircraft industries. High strain rate and large strain are frequently involved in order to control the shape and microstructure of materials during the proscessing. Many results have been reported on the hot deformation behaviors of Al-based composites reinforced with ceramic reinforcement [3, 4]. It is found that hot restoration mechanism and matrix flow behaviors of Al-based composites are quite different from those of unreinforced monolithic alloy.

In the meanwhile, conventional hot working processes for unreinforced monolithic alloy are used to produce composite's product. One of the important thing in the hot deformation is to obtain the composites with sound microstruture without micro- or macrodefects or flow instabilities. Therefore, it is very important to understand hot deformation behaviors of the Al-based composites, because the composites will show different characteristics by the ceramic reinforcement during hot working.

The aim of this work is to study the hot deformation behavior of SiCp/Al 2024 composite under hot working condition and to generate a processing map for optimization of hot workability. Many workers have established deformation map, which is based on the dynamic material model [5, 6], to reveal relationship between deformation efficiency and their microstructure. In this model, the workpiece subjected to hot working is considered as a nonlinear dissipator of power and the instantaneous power dissipated at a given strain rate may be considered to consist of two parts: G content, representing the temperature rise and J co-content, representing the dissipation through microstructural changes. The J co-content is given by

$$J = \frac{\sigma\dot{\varepsilon}m}{(m+1)}$$

For an ideal linear dissipator, $J = J_{\max} = \sigma\dot{\varepsilon}/2$. The deformation efficiency (η) of a nonlinear dissipator can be expressed as a dimensionless parameter $\eta = J/J_{\max}$. The variation of η with temperature and strain rate represents the characteristics of deformation efficiency through microstructural changes in the materials and constitutes a processing map. In this study, the hot workability of the composite is evaluated to correlate deformation efficiency with the microstructural changes during hot deformation.

2. Experimental procedure

The materials used in this work are SiCp reinforcements (∼8 μm) and Al 2024 alloy powders (∼44 μm diameter). The composite were fabricated by powder metallurgy. For the fabrication of the composite, the Al powders and SiCp were ball-milled for 72 hours and the resulting mixtures were compacted by hot-pressing at 520 °C and 120 MPa in vacuum before cooling. The hot-pressed billets with a diameter of 50 mm and a length of 50 mm were hot-extruded with an extrusion ratio of 25 : 1 at 430 °C. The torsion specimens with a gauge length of 10 mm and a diameter of 7 mm were machined from the extruded composite bars. The samples for torsion tests were heated up to 370–500 °C using dual elliptical radiant furnace and then kept for 10 min.

To investigate the hot deformation behavior of 15 vol.% SiCp/Al 2024 composite reinforced with SiCp reinforcement, hot torsion tests were conducted in the temperature range 370–500 °C and in the strain rate range 0.1–3.0/sec along the extrusion direction. Subsequently, the torsion-tested specimens were quenched immediately in the water at 25 °C. The strain rate sensitivity of the composite was obtained from the relationship between the torque moment and strain rate under an equivalent deformation strain. The effective stress (σ) and effective strain (ε) of the composite were calculated by the von Mises criterion [7] using the torque moment (M) and angular displacement (θ) measured from the torsion tests. The microstructures of the hot-deformed composite were investigated by the scanning electron microscopy (SEM). The specimens for SEM were prepared by the conventional metallographic method. Transmission electron microscopy (TEM) was used to examine the microstructures of hot deformed composite. The specimens for TEM observation were sectioned perpendicular to the extrusion axis. The TEM specimens were mechanically ground to $\sim$60 μm and then jet-polished with a solution of 25% nitric acid and 75% methanol under a condition of 30 V and 60 mA at about -40 °C.

3. Results and discussion

Fig. 1a and b show variation of deformation efficiency with pass strain for the composite deformed at 370 and 470 °C under different strain rates, respectively. The efficiency varied with strain rate ($\dot{\varepsilon}$) and pass strain (ε_i). In Fig. 1a, the composite showed 20–45% efficiency under the strain rates of 0.1, 0.5, and 1.0/sec and showed a higher efficiency of $\sim$44% at the strain rate of 0.5/sec and pass strain of 0.1. At the strain rate of 0.5/sec, the efficiency ($\sim$20%) of the composite obtained at the strain of 0.05 was lower than that ($\sim$44%) at the strain of 0.1. This is because the work hardening behavior at the strain of 0.05 is more predominant at an earlier strain stage than at the strains of 0.1, 0.2, and 0.4, corresponding to steady state regime in flow stress-strain curve. After at the strain of 0.1, dynamic recrystallization (DRX) occurred in the composite and the composite exhibited a $\sim$35% efficiency, which is similar to that of at the steady state regime.

In the privious work [4], flow curves of the Al 2024 composite have been analyzed in order to identify hot restoration mechanism. Upon decreasing deformation temperature, flow stress of the composite increased and flow strain decreased. The composite showed a flow curve of dynamic recrystallization (DRX) having a single peak followed by low steady state. Also, the critical and peak strains for DRX of the composite were mentioned in an earlier work [8]. The critical strains for DRX of the composite deformed at 370 °C, 0.5/sec and 470 °C, 0.5/sec were $\sim$0.07 and $\sim$0.06, respectively. It is found that the composite exhibited small equiaxed grains with high dislocation density at temperature of 320–460 °C, indicating that the DRX occurred during hot deformation. The added SiC reinforcement promoted the nucleation of DRX by increasing dislocation density in the matrix [8, 9]. Therefore, the efficiency of the composite obtained at the strains for DRX condition was higher than that of at the strains of work hardening stage.

In Fig. 1b, the efficiency of the composite was higher than that at 370 °C. The composite deformed at 470 °C under a strain rate of 0.1/sec exhibited the highest deformation efficiency among other strain rates used and there is no significant effect of strain on the efficiency. With increasing the pass strain, the variation of efficiency became small at the strain rates of 0.1 and 0.2/sec. On the other hand, at the strain rates of 0.5, 1.0, and 3.0/sec, the composite showed a different value of efficiency with pass strain. It is also found that the difference in efficiency of the composite deformed at 470 °C obtained at the strains of 0.05 and 0.1 was quite small. This is due to the fact that the work hardening rate of the composite is decreased at high temperature and low strain rate. The decrease in work hardening rate at high temperature deformation results in decrease in critical strain for DRX [8, 9] and leads to increase in deformation efficiency.

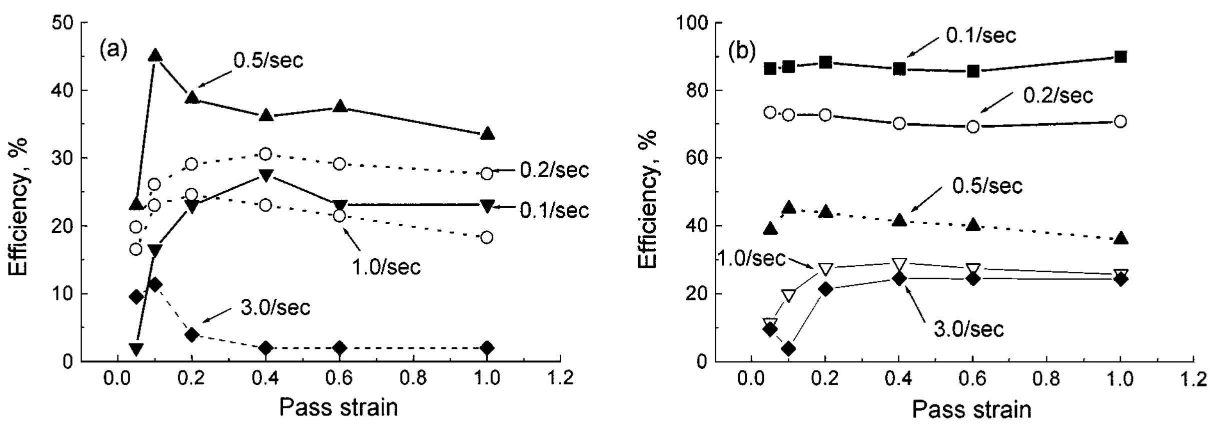

Figure 1 Variation of deformation efficiency with pass strain for the composite deformed at (a) 370 and (b) 470 °C under different strain rates.

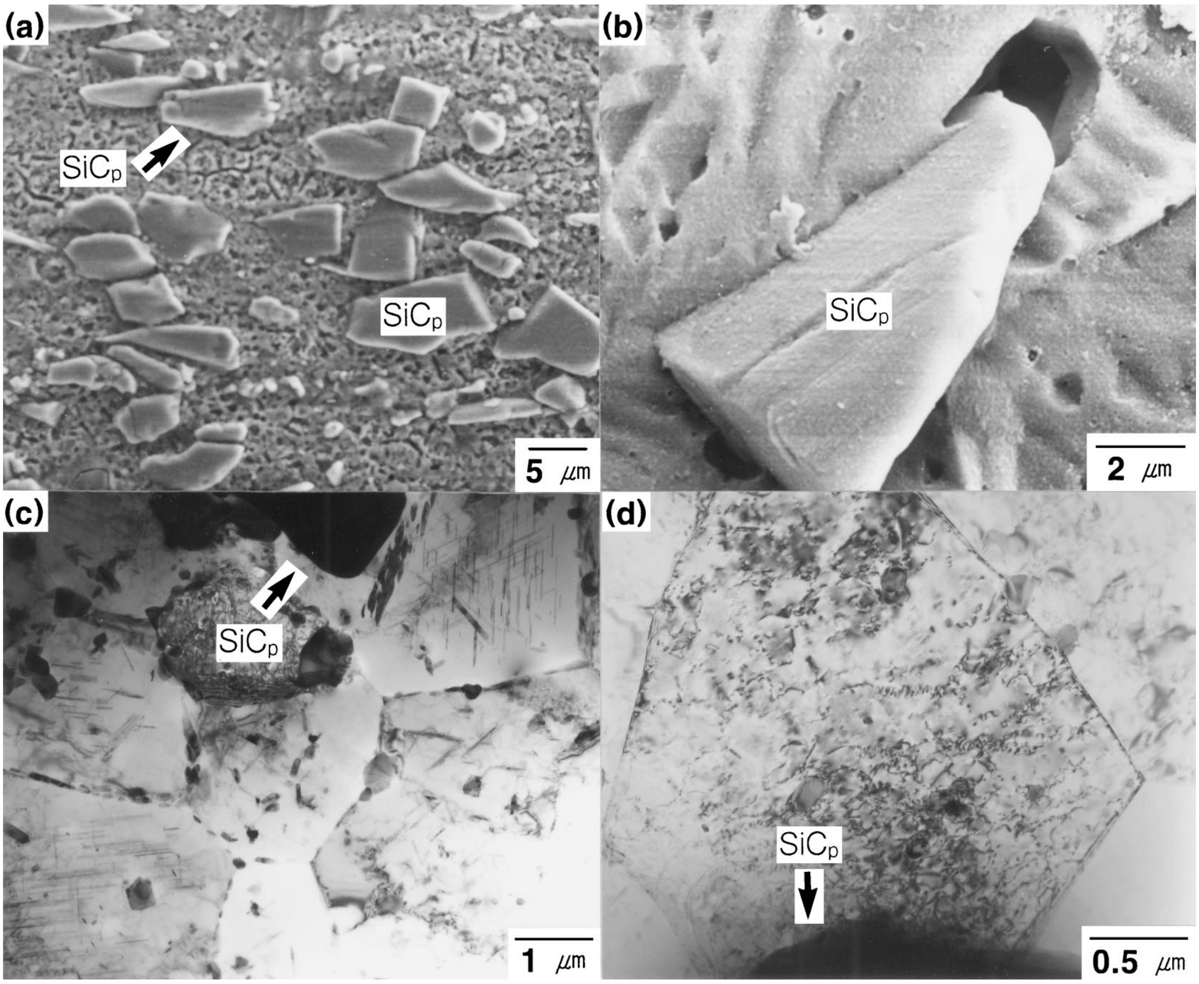

Figure 2 SEM micrographs (a) and (b) and TEM bright field images (c) and (d) of the composite deformed at different deformation conditions : (a) and (c) 370 °C, 0.5/sec (pass strain = 0.05) (b) 470 °C, 0.1/sec (pass strain = 0.4) (d) 470 °C, 0.5/sec (pass strain = 0.4).

To analyze the effect of temperature, pass strain, and strain rate on the deformation efficiency of the composite, hot-deformed microstructure was observed by SEM and TEM. Fig. 2a and c are the SEM and TEM micrographs of the composite deformed at 370 °C under a strain rate of 0.5/sec, respectively. The micrographs are obtained at the strain of 0.05. Also, SEM and TEM micrographs of the composite deformed at 470 °C, 0.1/sec and 470 °C, 0.5/sec are shown in Fig. 2b and d, respectively. The micrographs are obtained at the strain of 0.4. In Fig. 2a, any voids or microcracks were found near the SiCp, indicating that the composite is under work hardening stage and the DRX didn't occur during hot deformation. In Fig. 2b, the round-shaped voids were formed at the matrix/reinforcement interface, indicating that interfacial debonding occurred predominantly at high temperature and low strain rate. It is also found that at 370 °C, dynamic recrystallized grains with small equiaxed subgrains containing precipitates were formed in the composite and the dislocation density was very high as shown in Fig. 2c. On the other hand, at 470 °C, dislocation density in the matrix of the composite was very low and the strengthening precipitates Al_2CuMg at the grain boundary and grain were dissoluted into the matrix. Any precipitates were found at the grain boundary. These results imply that interfacial debonding, low dislocation density, and precipitates dissolution give rise to increase in deformation efficiency of the composite during hot deformation.

It has been reported that the damage process such as grain boundary cracking is very efficient in dissipating power through the generation of new surfaces [10, 11]. The interfacial debonding between the SiCp reinforcement/matrix mainly occurred above at 470 °C and the efficiency of the composite deformed at 470 °C, 0.1/sec, and 40% pass strain was ∼86%. On the other hand, the safe processes like DRX is less efficient in dissipating power even though climb of dislocations will be involved. Many workers have reported deformation efficiency for DRX depending on alloy composition, crystal structure, and deformation history as well as stacking fault energy of alloy [10–13]. Normally, the alloy with high stacking fault energy shows more higher efficiency than that of with low stacking fault energy. For examples, the efficiency of pure Al (2 to 5 N) with high stacking fault energy of ∼200 mJ/m^2 has been reported ∼55% at 375–600 °C and 0.001/sec [12]. The efficiency of α-Zr alloy was ∼42% at 800 °C, 0.1/sec [10] and the AISI 304L with low stacking fault energy of ∼18 mJ/m^2 was ∼34% at 1150 °C, 0.1/sec [13]. Prasad suggested that during DRX process of Al alloys and Al-based composites with high stacking fault energy, the rate of interface formation is much higher than

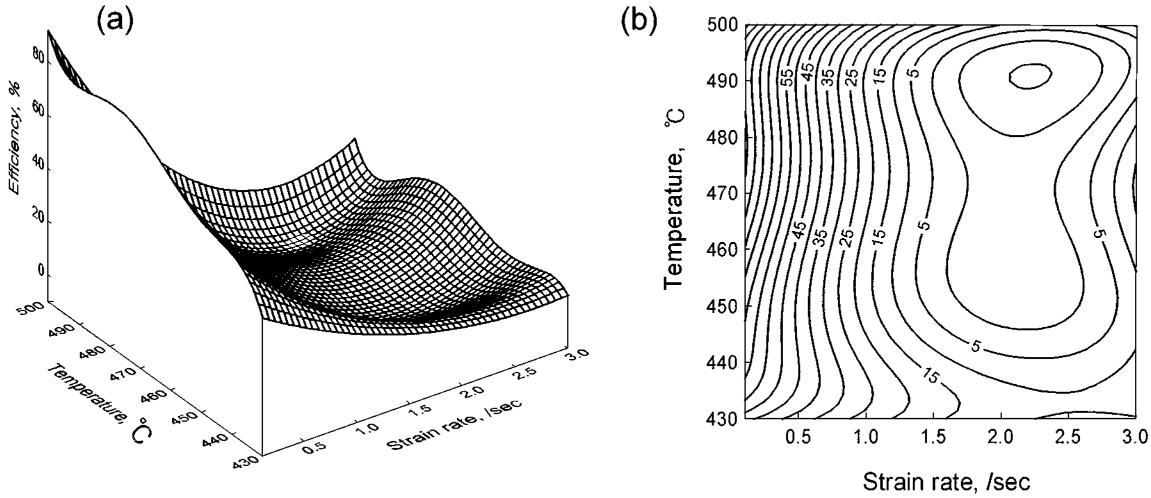

Figure 3 (a). 3-D view of the variation of deformation efficiency with temperature and strain rate for the composite obtained at the strain of 0.1. (b) is the contour map with iso-efficiency contour of the efficiency corresponding to Fig. 3a.

the rate of migration, indicating the DRX is controlled by the interface migration process [11, 12].

Fig. 3a is the 3-D view of the variation of deformation efficiency with temperature and strain rate for the composite obtained at the strain of 0.1. Fig. 3b is the contour map with iso-efficiency contour of the efficiency corresponding to Fig. 3a. The number in these figures shows the efficiency value. In Fig. 3a and b, the deformation efficiency obtained at higher temperature and lower strain rate was higher than that at lower temperature and higher strain rate. For example, the efficiency of the composite deformed at 470 °C and 0.1/sec was higher that of at 320 °C and 3.0/sec. The efficiency increased with increasing temperature and decreasing strain rate. Similarly, the failure strain of the composite increased with temperature up to 480 °C and then decreased [8].

In Fig. 3b, the efficiency values are largely divided into three regions. First, in the upper right corner of the map, the efficiency was so low thus it is not preferrable for hot working of the composite. Second, in the left hand side of the map, the efficiency was high thus the microstructure of DRX could not be expected. Finally, between the upper right corner and left hand side of the map, the composite showed 40–50% efficiency having a DRX microstructure. Therefore, the efficiency of 40–50% is preferrable hot working for DRX of the composite because it leads to a defect free microstructure with fine uniform grains.

Fig. 4 shows the variation of deformation efficiency (solid line) with Zener-Hollomon parameter ($Z = \dot{\varepsilon}\exp(Q/RT)$) for the composite. The activation energies, which were obtained by using the ralationship between the peak stress and temperature, were ~294.8 kJ/mol at the temperature of 320–460 °C and ~263.5 kJ/mol at the temperature of 470–520 °C, respectively [4]. The failure strain (dotted line) also added into Fig. 4. The composite showed low values for both efficiency and failure strain at high Z condition. Upon decreasing the Z value, the efficiency and failure strain increased. The highest failure strain of the composite was obtained under the Z value of 3.7×10^{15}/sec. At the Z value of 3.7×10^{15}/sec, the composite would

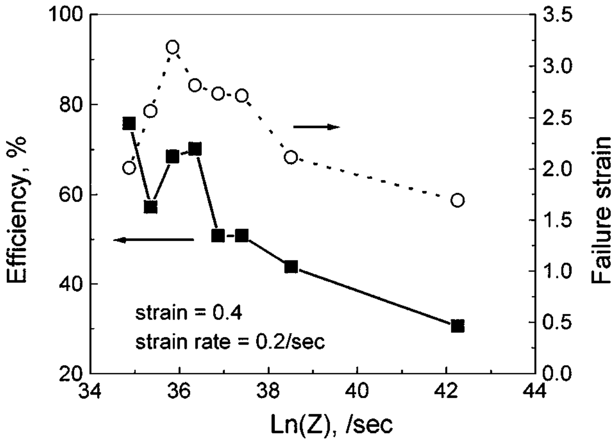

Figure 4 Variation of deformation efficiency (solid line) and failure strain (dotted line) for the composite with Zener-Hollomon parameter obtained at the strain of 0.4.

not have high strength after hot working due to the large grains with few dislocations and strengthening precipitates, even though larger strains can be applied to the composite during hot working. The efficiency corresponding to the Z values is ~68%. The composite showed 40–50% efficiency under the Z values from 1.0×10^{16}/sec to 5.3×10^{16}/sec. Therefore, in order to obtain the composite with superior mechanical properties by DRX after hot working, a strain rate and temperature showing 40–50% efficiency should be considered.

4. Conclusion

The SiCp/Al 2024 composite showed 40–50% efficiency in the dynamic recrystallization (DRX) region (370–460 °C, 0.1–0.5/sec), showing microstructure of equiaxed grains and high dislocation density. The deformation efficiency obtained at high temperature and low strain rate was larger than that of at low temperature and high strain rate. Moreover, there is no significant effect of strain on the efficiency at the steady-state strain. The interfacial debonding initiated by SiCp mainly occurred above at 470 °C, contributing a high efficiency during hot deformation. From using relationship among the deformation efficiency, deformed microstructure, and failure strain, optimum hot working condition for DRX could be suggested for the SiCp/Al 2024 composite.

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