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Superplastic Deformation of 15 vol% SiC_p/LY12 Aluminum Composite under an Electric Field

M.Q. Li, C. Tang, D. Chen, and Y. Chen

In this paper, influence of an external electric field on mechanical performance of deformation, cavity formation, and fracture mechanisms has been investigated during superplastic deformation of 15 vol% SiC_p/LY12 (LY12 matrix corresponds approximately to ASTM 2024) aluminum composite. The experimental results show that the appropriate electric field makes the strain-rate sensitivity index increase and the superplasticity improve. The results obtained by scanning electron microscopy (SEM) show that the nucleation growth and linkage or coalescence of cavities is restrained by applying an external electric field; meanwhile, fracture transforms from intergranular tear to typical superplastic failure, that is, fracture by formation and coalescence of cavities at particles and boundaries.

Keywords aluminum, superplastic composite

1. Introduction

Metal-matrix composites (MMCs) generally have lower plasticity, which restrains their development and application in practice. Conrad and his colleagues (Ref 1, 2) were the first to apply the electric field to the superplastic deformation of 7475 aluminum alloy and found that the electric field increased the strain-rate sensitivity index and reduced the flow stress. Then, Li et al. (Ref 3, 4) found that the electric field improves the microstructure and increases the total elongation during superplastic deformation of Duralumin LY12CZ under an electric field. Now, the electric field is subjected to superplastic deformation of SiC_p-Al composite in order to improve the superplasticity of the metal-matrix composites.

For this article, superplastic deformation of 15 vol% SiC_p/LY12 aluminum composite under an external electric field was investigated. The experimental results show that the electric field promotes the total elongation of this composite, as a result of the increase in strain-rate sensitivity index (m). The improvement of the superplastic properties relates closely to the nucleation and growth of cavities and the interfacial sliding between the matrix and the particulates of the reinforcements, according to the experimental results.

2. Experiments

The 15 vol% SiC_p/LY12 aluminum composite was fabricated by spray atomization and codeposition (Ref 5); chemical compositions of LY12 matrix (corresponding approximately to ASTM 2024) are 4.3% Cu, 1.6% Mg, 0.5% Mn, and the balance aluminum. LY12 aluminum alloy was mixed with SiC particles having an average diameter of 10 μm. After isothermal hot compression and isothermal hot forward extrusion (extrusion ratio: 10.0) of the composite, the uniaxial tension specimens were machined. The gage diameter and length of specimens were 5 × 15 mm. Tensile tests were carried out using a type CSS-1110C material-testing machine, at a constant crosshead speed both with and without the concurrent application of an external direct-current electric field from a commercial power source in Fig. 1. The optimal process parameters of 15 vol% SiC_p/LY12 aluminum composite were superplastic deformation temperature 773 K; initial strain rate, 3.3×10^{-4} s^{-1}; and electric field intensity, 2.0 kV/cm (Ref 6).

The strain-rate sensitivity index (m) was measured with help of the Backofen method under the equivalent strain (true strain) (Ref 7). The mechanical performance of superplastic deformation and total elongation (δ) during superplastic deformation were measured. The measured value is the average of five specimens after superplastic uniaxial tension. The cavity evo-

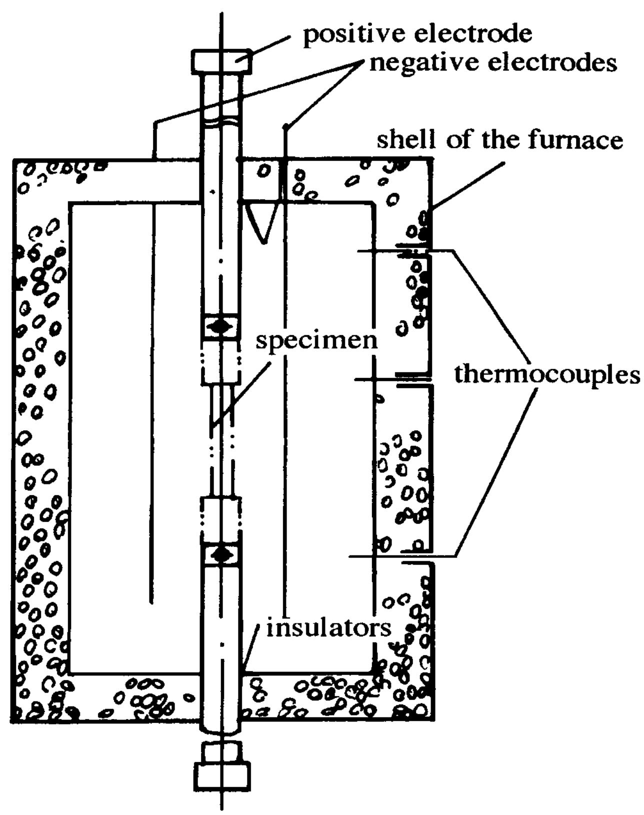

Fig. 1 Schematic of experimental arrangement

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lution and fracture manner had also been investigated by scanning electron microscopy (SEM).

3. Experimental Results and Discussion

3.1 *Electroplastic Effect during Superplastic Deformation*

Figure 2 shows the strain-rate sensitivity index (*m*) during superplastic deformation of 15 vol% SiC_p/LY12 aluminum composite both with and without the application of electric field. It can be seen from Fig. 2 that the strain-rate sensitivity index (*m*) under an optimal intensity of electric field is increased as compared with that without electric field. The strain-rate sensitivity is an important parameter in superplastic deformation. Higher *m*-value is indicative of improvements in superplasticity.

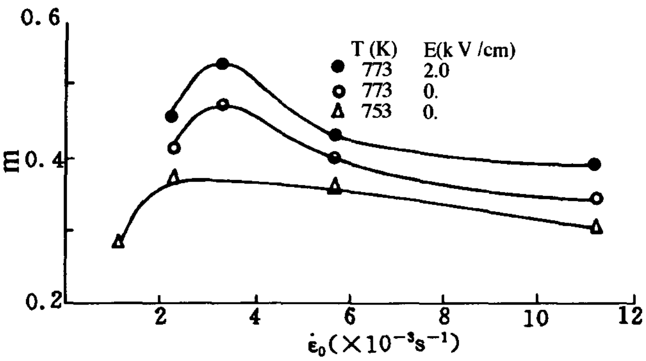

Fig. 2 Effect of electric field on the strain-rate sensitivity index (*E*, electric field intensity)

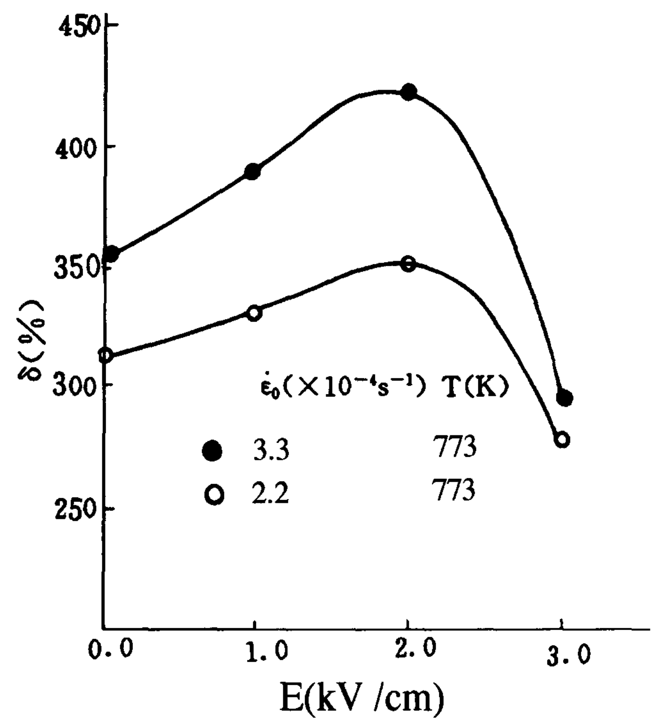

Fig. 3 Effect of electric field on total elongation

The effects of electric field on the elongation (δ) for superplastic deformation of 15 vol% SiC_p/LY12 aluminum composite both with and without the application of electric field is plotted in Fig. 3, which shows that the elongation is sensitive to the intensity of electric field. Optimal intensity of electric field makes the total elongation increase in superplastic deformation. The higher elongation recorded, 420%, was 20% higher than that obtained without the electric field.

Figure 4 demonstrates the true stress (σ)-true strain ($\bar{\varepsilon}$) curves for the superplastic deformation of 15 vol% SiC_p/LY12 aluminum composite both with and without the electric field. Figure 3 shows that the true stress-true strain curves during superplastic deformation of the SiC_p-Al composite are a combination of strain-hardening and strain-softening behaviors. However, the electric field reduces the flow stress during superplastic deformation of this SiC_p-Al composite.

3.2 *Nucleation and Growth of Cavities*

From the observations of cavity nucleation sites in the 15 vol% SiC_p/LY12 aluminum composite, as shown in Fig. 5, cavities are initiated at the poles of particle reinforcements. It is clear from this figure that most cavities tend to be nucleated at the interfaces between matrix and reinforcements, and their subsequent growth and coalescence invariably leads to premature failure. The interfaces of the larger SiC particles seem to act as preferential sites for cavity nucleation rather than those on the smaller particulates in the 15 vol% SiC_p/LY12 aluminum composite. The generated cavities grow along the reinforcements, and then the development of large cavities is achieved by cavity coalescence, which becomes quite extensive prior to fracture. The large isolated cavities were interlinked to each other by propagation of brittle cracks, as clearly shown in Fig. 5(b), which corresponds to the morphology just before the final fracture of the 15 vol% SiC_p/LY12 aluminum composite.

As the material deforms plastically, the void volume also increases as a result of the increasing strain level. The fact that plastic deformation of the reinforcements in MMCs is believed

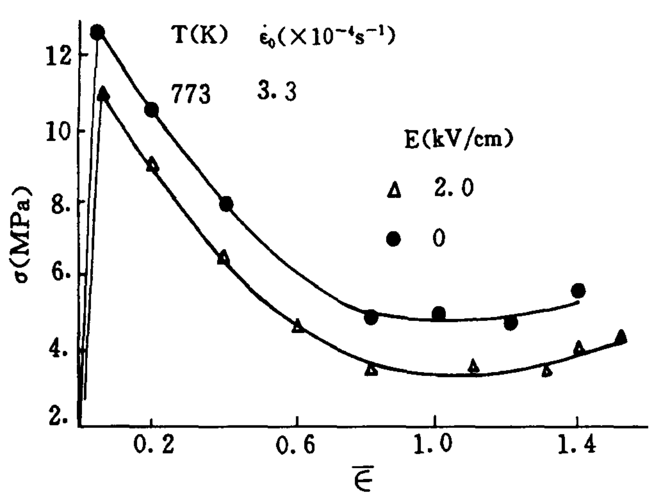

Fig. 4 The curves of true stress versus true strain

to be impossible at superplastic temperatures, as a result of the existence of the reinforcements-matrix interfaces, indicates that interfacial sliding must play as important a role as grain-boundary sliding in superplastic deformation. Therefore, plastic deformation of the matrix by interfacial sliding must be accommodated by plastic or diffusional flow of the adjacent matrix. Otherwise, as shown in Fig. 5, extensive cavitation must take place near the reinforcements. Thus, the optimal superplastic potentials in MMCs can be achieved under the condition that the interfacial sliding rates, not the grain-boundary sliding rates, are similar to the accommodation process rates because the diffusional processes at or around interfaces in MMCs that control an optimal superplastic strain rate are expected to be slower than those on grain boundaries. Therefore, a special mechanism for the accommodation process of relaxation in stress constraints, which is caused by interfacial sliding, is required in MMCs under superplastic flow. It is reported that a liquid phase or a low-melting-point region at grain boundaries could act as lubricants to promote the deformation (Ref 8). When the electric field is applied to the superplastic deformation of this composite, the interfacial sliding required in MMCs under superplastic flow is enhanced as a result of the large liquid phase or low-melting-point region at grain boundaries. This, therefore, improves the superplasticity of 15 vol% SiC_p/LY12 aluminum composite.

3.3 *Fractographs*

Figure 6 shows the fracture mechanism after superplastic deformation of 15 vol% SiC_p/LY12 aluminum composite. It can be seen from Fig. 6 that (1) the fracture mechanism is intergranular tear after superplastic deformation of 15 vol% SiC_p/LY12 aluminum composite without the electric field, and (2) the fracture mechanism is typical of superplastic failure, that is, fracture by formation and coalescence of cavities at particles and grain boundaries for 15 vol% SiC_p/LY12 aluminum composite with the electric field.

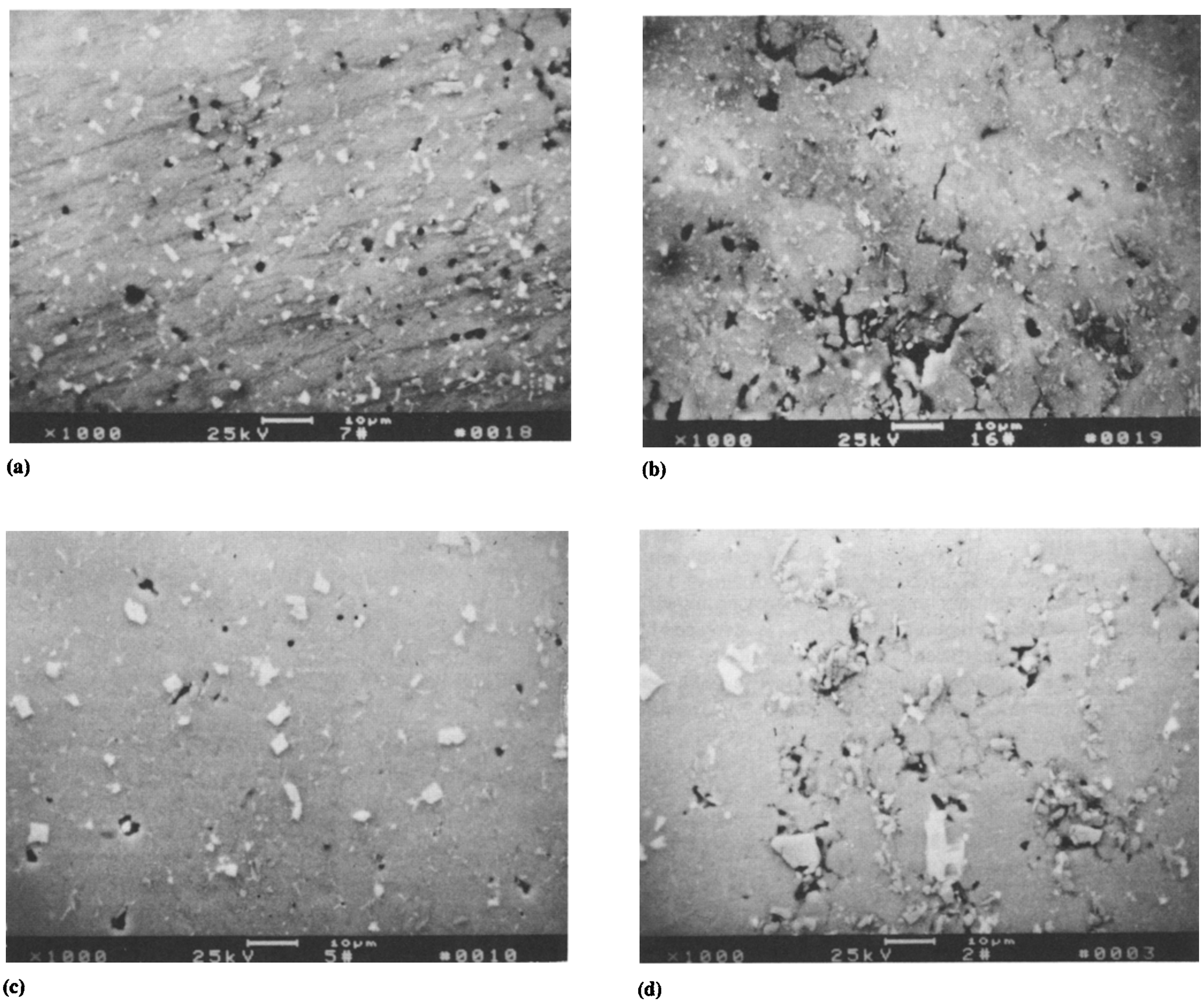

Fig. 5 Nucleation and growth of cavities. (a) 773 K, 3.3×10^{-4} s^{-1}, 0 kV/cm, $\bar{\varepsilon} = 0.74$. (b) 773 K, 3.3×10^{-4} s^{-1}, 0 kV/cm, $\bar{\varepsilon} = 1.22$. (c) 773 K, 3.3×10^{-4} s^{-1}, 2.0 kV/cm, $\bar{\varepsilon} = 0.74$. (d) 783 K, 3.3×10^{-4} s^{-1}, 2.0 kV/cm, $\bar{\varepsilon} = 1.22$.

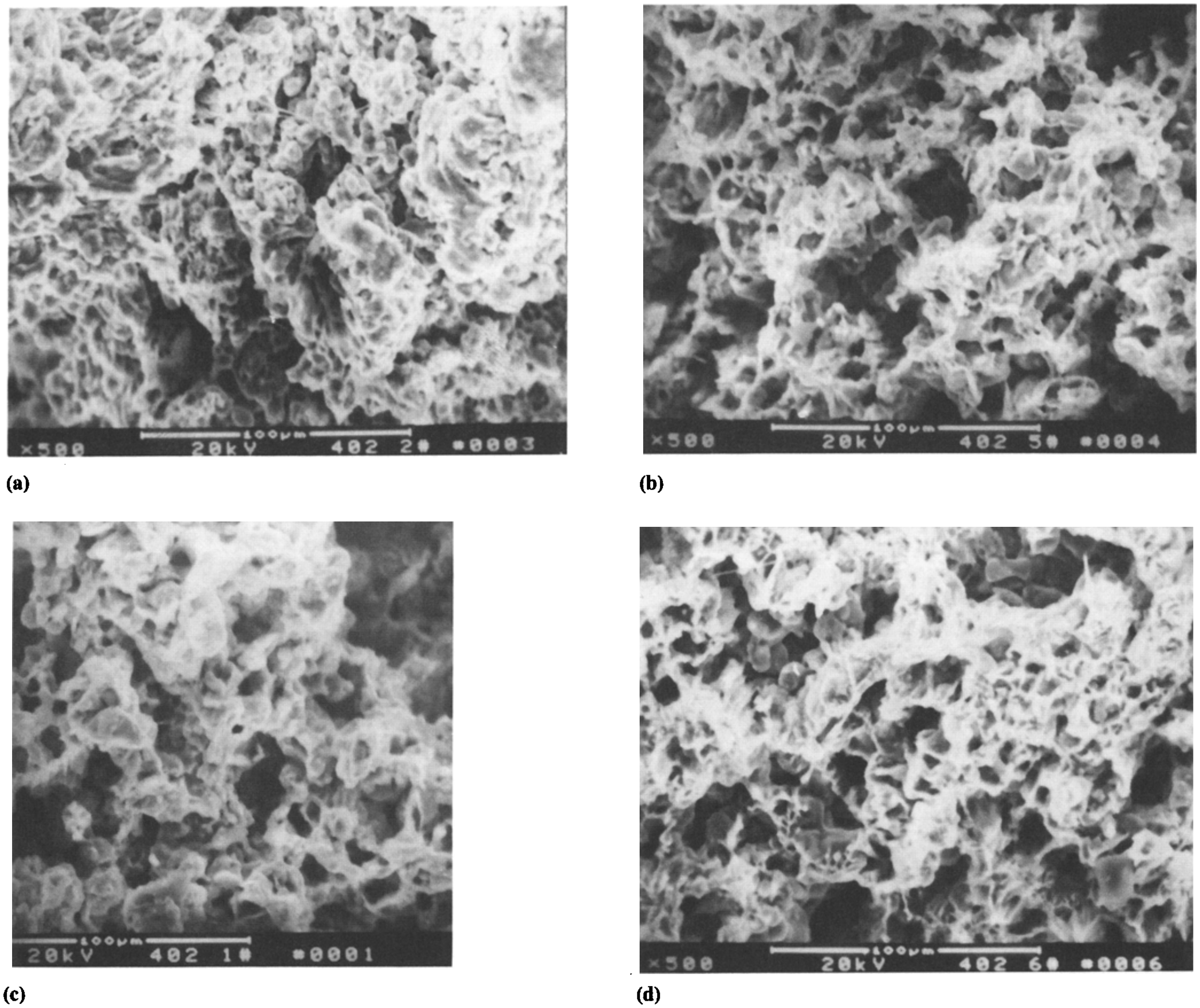

Fig. 6 Fractographs. (a) 753 K, $3.3 \times 10^{-4}\,s^{-1}$, 0 kV/cm. (b) 773 K, $3.3 \times 10^{-4}\,s^{-1}$, 0 kV/cm. (c) 773 K, $3.3 \times 10^{-4}\,s^{-1}$, 2.0 kV/cm. (d) 783 K, $3.3 \times 10^{-4}\,s^{-1}$, 2.0 kV/cm

4. Conclusions

The strain-rate sensitivity index (m) is increased by 0.13 times and the total elongation recorded, 420%, is increased by 0.20 times during superplastic deformation of 15 vol% SiC_p/LY12 aluminum composite under an electric field. According to the observations of cavity evolution and the fracture manner, the electric field restrains the nucleation and growth of cavity. In addition, because of the application of electric field, the interfacial sliding required in MMCs under superplastic flow is enhanced as a result of the large liquid phase or low-melting-point region at grain boundaries. This, therefore, improves the superplasticity of 15 vol% SiC_p/LY12 Al composite.

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