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# AN INVESTIGATION OF CAVITATION IN A MECHANICALLY ALLOYED 15 VOL% SiCp/IN9021 ALUMINUM COMPOSITE


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# An investigation of cavitation in a mechanically alloyed 15 vol% SiC*p*/IN9021 aluminum composite

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A mechanically alloyed 15 vol % SiC*p*/IN9021 aluminum composite exhibited a maximum elongation of 610 % at a very high strain of 5 $s^{-1}$ at 823 K. Nonetheless, the maximum elongation was obtained at a lower strain rate than that where the maximum m value (about 0.5) was obtained. This discrepancy between the optimum superplastic strain rate for the largest elongation and the strain rate for the maximum m value was believed to be associated with the cavitation behavior. Cavitation behavior of the SiC*p*/IN9021 aluminum composite was, therefore, carried out. It was found that cavities initiated at the ends of particulate reinforcements and parallel to the applied stress direction within initial small strains, and their subsequent growth and coalescence invariably leads to premature failure. Experimental results indicated that cavity growth is plasticity controlled and can be described by a model proposed by Stowell.

## 1. INTRODUCTION

The development of new superplastic aluminum alloys, through recent advances in powder metallurgy technology, has led to a new area of high strain rate superplastic forming in aluminum alloy matrix composites produced by mechanical alloying process [1]. In a mechanically alloyed IN9021 composite reinforced with 15 vol % $SiC_p$, a maximum elongation of 610 % has been previously obtained at a very high strain of 5 $s^{-1}$, which does not coincide with the strain rate range where high m values were observed. Specifically, the largest elongation was obtained at a lower strain rate than that where a maximum m value of about 0.5 was obtained. This discrepancy between the optimum superplastic strain rate for the largest elongation and the strain rate for the maximum m value was also found in other high strain rate superplastic composites [2]. This may be associated with the cavitation behavior in these composites, which is directly related to the presence of the reinforcements.

In this paper, the cavitation behavior of a mechanically alloyed 15 vol % $SiC_p$-IN9021 aluminum composite is investigated under the optimum superplastic conditions, in order to develop a general understanding of the fracture behavior in superplastic composites.

## 2. EXPERIMENTAL PROCEDURES

The nominal compositions of the commercial powders of the IN9021 aluminum alloy used in this work is given as an Al-4.0wt%Cu-1.5wt%Mg-1.1wt%C-0.8wt%O. The mean particle size of SiC is about 2 µm, Nonetheless, some SiC particulates also have a dimension of about 5 to 10 µm, as shown in Figure 1. Grain size in the mechanically alloyed 15 vol% $SiC_p$/IN9021 composite is about 0.5 µm, as shown in Figure 2.

The as-received $SiC_p$/IN9021 aluminum composite was obtained in a sheet form of 1.7 mm thick, which was initially reduced from a 12.7 mm-thick sheet by warm rolling. This warm-rolled sheet was further thermomechanically processed to 1 mm in thickness. Tensile samples with 5 mm gauge length and 4 mm width were machined from the rolled sheets, with the gauge length parallel to the rolling direction. Constant true strain rate tests were carried out in air at strain rates between $10^{-3}$ and 100 $s^{-1}$ at the optimum superplastic temperature of 823 K. Flow stresses for each sample were determined at a fixed true strain of 0.1.

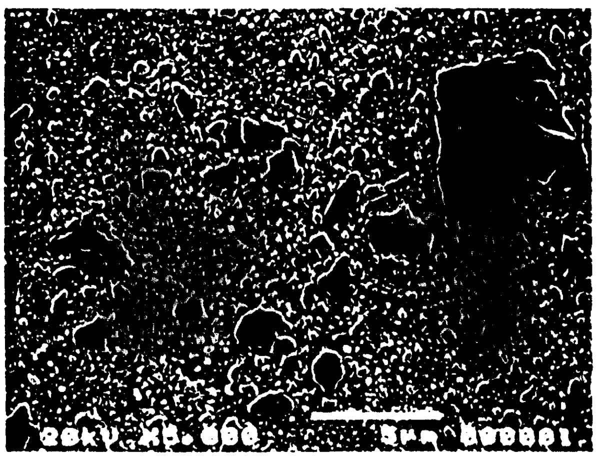


Figure 1 Size distribution of SiC particles.

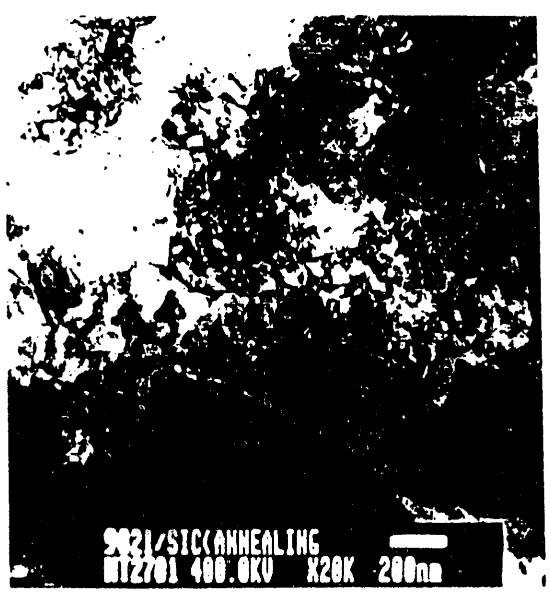


Figure 2 Grain size in a SiC$p$/IN9021 composite.

A number of specimens were deformed to pre-determined strains at two high strain rates of 5 and 100 $s^{-1}$. The volume fraction of cavities in the deformed specimens was determined using density measurements; by hydrostatic weighing in ethyl iodide or water using a corresponding gauge head as a standard. Metallographic studies were also made using scanning electron microscopy.

## 3. RESULTS AND DISCUSSION

### 3.1. Mechanical behavior

A typical log (flow stress) *vs* log (strain rate) plot for the SiC$_p$/IN9021 composite deformed at the optimum superplastic temperature of 823 K is shown in Figure 3. It, revealed that there exists two distinct regions. In the low strain rate regime (below 1 $s^{-1}$), the strain rate sensitivity, $m$, of less than 0.03, with corresponding low elongations (about 100 %). This indicates the existence of an apparent threshold stress. In the high strain rate range (over 10 $s^{-1}$) where superplasticity was obtained, a relatively high $m$ value (more than 0.5) was observed. This m value of 0.5 was noted to retain up to the highest strain rate of 100 $s^{-1}$.

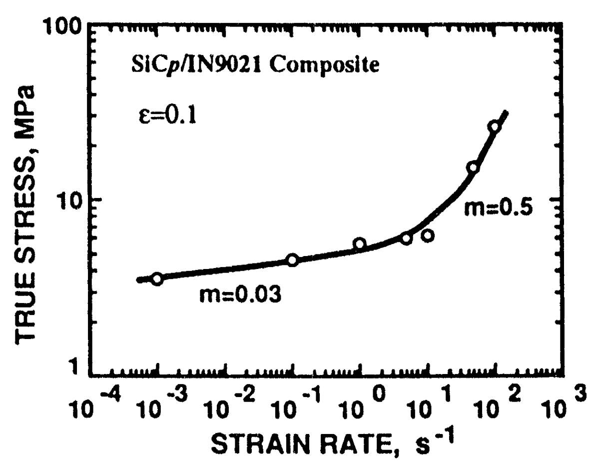


Figure 3: A typical log flow stress *vs* log strain rate plot at 823 K.

Elongation of the SiC$_p$/IN9021 composite deformed at 823 K is shown in Figure 4 as a function of strain rate. The composite exhibits a total elongation of about 400 % in the high strain rate range from 5 to 100 s$^{-1}$. A maximum elongation of 610 % was obtained at a high strain rate of 5 s$^{-1}$. However, it is noted generally that the largest elongations occurs at a strain rate which is lower than that at which the maximum m values was obtained. Beyond the strain rate of 5 s$^{-1}$, the total elongation decreased with strain rate. However, even at these high strain rates, the elongation value still maintains; a large elongation of 440 % was observed at an extremely high strain rate of 100 s$^{-1}$.

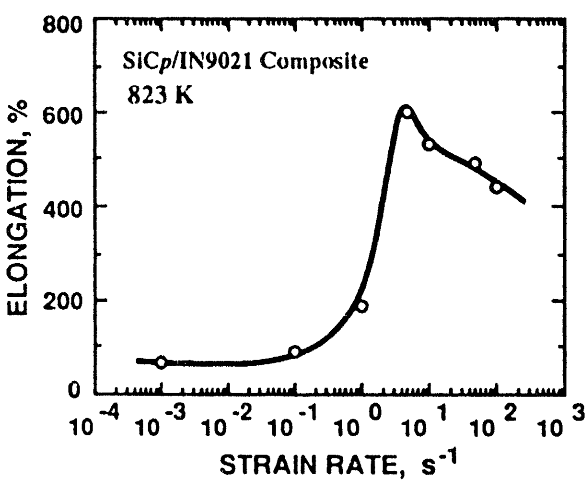


Figure 4 A typical log elongation *vs* log strain rate plot at 823K.

### 3.2. Density measurements

The cavitation behavior of the SiC$_p$/IN9021 composites was investigated and the results are summarized in Table 1. A series of specimens were strained at the optimum superplastic temperature of 823 K, to pre-determined true strains, at two strain rates, *i.e.* 5 and 100 s$^{-1}$. (Cavitation data determined from samples deformed to failure are not included in Table 1.) The maximum volume of cavities is less than 5 %. Cavitation at different strain rates for the SiC$_p$/IN9021 composite are shown in Figure 5 as a function of superplastic true strain. The data showed that the volume of cavities increased with increasing strain and also with increasing strain rate. This is expected since a higher local stress is generated in the matrix or at the matrix/reinforcement interfaces as the strain rate (stress) increases.

Table 1: Cavitation as a function of strain and strain rate.

| | Volume fraction of cavities (%) | | | | | |
|---|---|---|---|---|---|---|
| True strain | 0.53 | 0.62 | 0.77 | 1.06 | 1.38 | 1.61 |
| $\dot{\varepsilon} = 5 s^{-1}$ | -- | 0.063 | 0.101 | -- | 0.499 | -- |
| $\dot{\varepsilon} = 100 s^{-1}$ | 0.118 | -- | -- | 0.586 | -- | 4.579 |

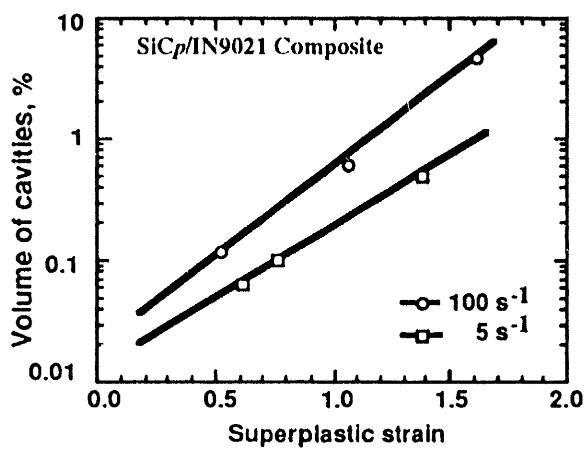


Figure 5 Cavitation at different strain rates as a function of superplastic true strain.

The variation of the volume of cavities with strain in Figure 5 can be best described by an exponential relationship indicating that for the most part cavity growth is plasticity controlled. As the materials is deformed plastically, voids also increase in volume as a result of the increasing level of strain wherein [3,4]

$$\frac{dr}{d\varepsilon} = \frac{\eta}{3}\left(r - \frac{3\tau}{2\sigma}\right) \qquad (1)$$

in which r is the cavity radius; $\varepsilon$ the strain; $\sigma$ the applied stress; t the surface energy; h the cavity growth rate parameter, is dependent on both the applied stress state and the geometry of deformation.

If cavity growth is strain controlled then the volume of cavities would be expected to increase exponentially with strain. A model was developed for cavitation in which it is assumed that (i) all cavities pre-exist at zero strain, (ii) all cavities are the same size and (iii) cavity growth is plasticity controlled by eqn.(1). The analysis predicts that the volume of cavities, $C_v$, should have an exponential dependence on strain, e, according to the relationship

$$C_V = C_{VO} \exp(\eta\varepsilon) \qquad (2)$$

where $C_{vo}$ the volume of cavities at zero strain. The cavity growth rate parameter, h usually has a value in the range 2 to 4 for many superplastic aluminum alloys, is dependent on materials, and on strain rate, temperature and grain size [5]. In the present case, the values of h and $C_{vo}$ for the $SiC_p$/IN9021 composite are 2.7 and 0.03 for 5 $s^{-1}$, 3.4 and 0.04 for 100 $s^{-1}$.

### 3.3. Microstructures

Metallographic observations showing the detail morphologies and the distribution of cavities were obtained from polished etched longitudinal sections of specimens of the $SiC_p$/IN9021 composite deformed at 823 K to given strains at very high strain rates of 5 $s^{-1}$ (Figure 6) and 100 $s^{-1}$ (Figure 7). For the specimens deformed at higher strain rates in the $SiC_p$/IN9021 composite, the level of cavitation is higher and the onset of cavity initiation occurs much earlier as compared to the specimens at lower strain rates. The smallest size of cavities which could be resolvable in this observation would grow from a cavity of initial size of less than 0.2 μm. In general the critical cavity size, $r_c$, which is stable under an applied tensile stress, $\sigma$, is given by

$$r_c \approx 2\tau/\sigma \qquad (3)$$

where $\tau$, in the present case, is $\tau_{SiC} + \tau_{Al} - \tau_{SiC/Al}$, since the matrix/reinforcement interfaces are the preferential sites for cavity nucleation. It is expected from eqn.(3), that as the applied stress increases with increasing strain rate, the critical cavity size at higher strain rates is smaller than that at lower strain rates, resulting from a higher local stress at the matrix/reinforcement interfaces.

For a typical superplastic aluminum alloy such as 7475 alloy, cavities develop along grain boundaries, at triple points, and intergranular particles at a rate which is dependent on the flow stress and cleanliness of the alloy [6]. In the present $SiC_p$/IN9021 composite, in addition to SiCp reinforcement, the alloy contains a large amount (about 5 vol %) of very fine (~20nm) oxide and carbide particles as a result of mechanical alloying. These particles, in particular the larger $SiC_p$ reinforcements, increase resistance to grain boundary sliding and act as stress concentrations, thus increasing the number of cavity nucleation sites. Microstructural observations from the $SiC_p$/IN9021 composite, as shown in Figure 6 and 7, indicate that cavities initiated at the ends of particulate reinforcements and parallel to the applied stress direction within initial small strains. Apparently, all cavities nucleate at the matrix-reinforcement interfaces and their subsequent growth and coalescence invariably leads to premature failure. Also, the interfaces of the larger SiC particulates appear to act as the preferential sites for cavity nucleation than those of the smaller ones. The nucleated cavities grow along the matrix-reinforcement interfaces and parallel to the tensile direction, then larger cavities are developed by cavity coalescence prior to fracture.

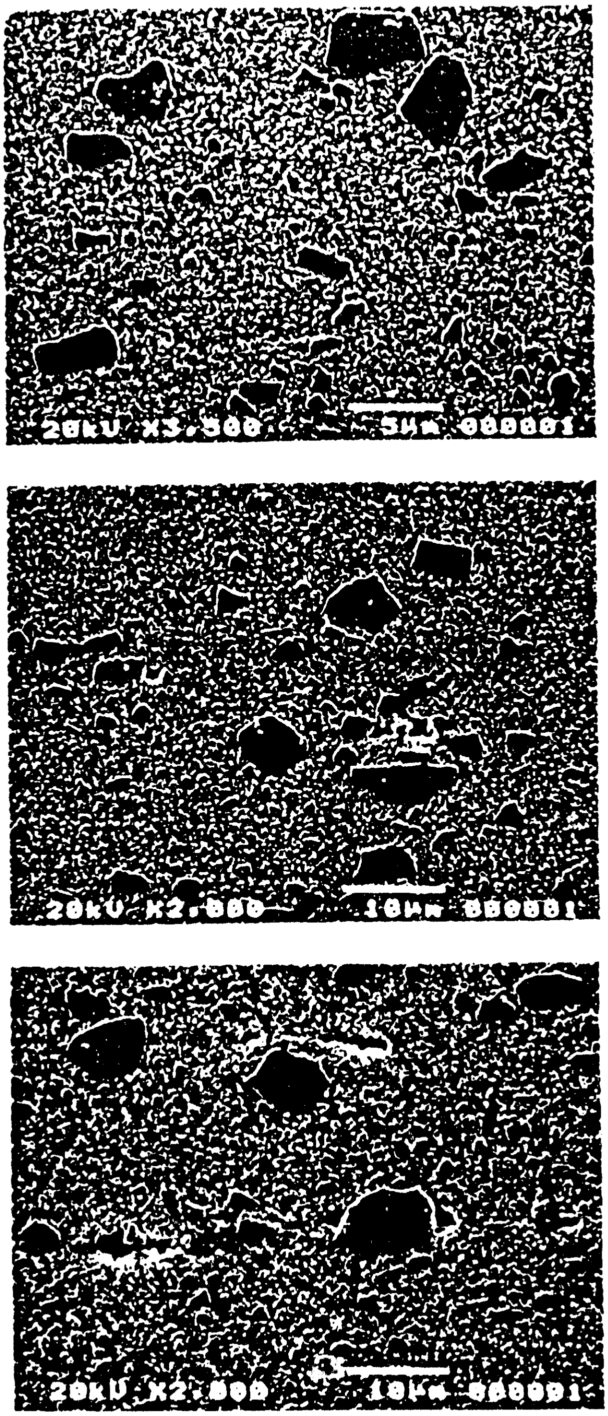


Figure 6 Cavity morphologies in the $SiC_p$/IN9021 composite deformed at 823 K at a very high strain rate of 5 $s^{-1}$ to pre-determined true strains of 0.62 (top), 0.77 (middle) and 1.38 (bottom). The tensile direction is horizontal.

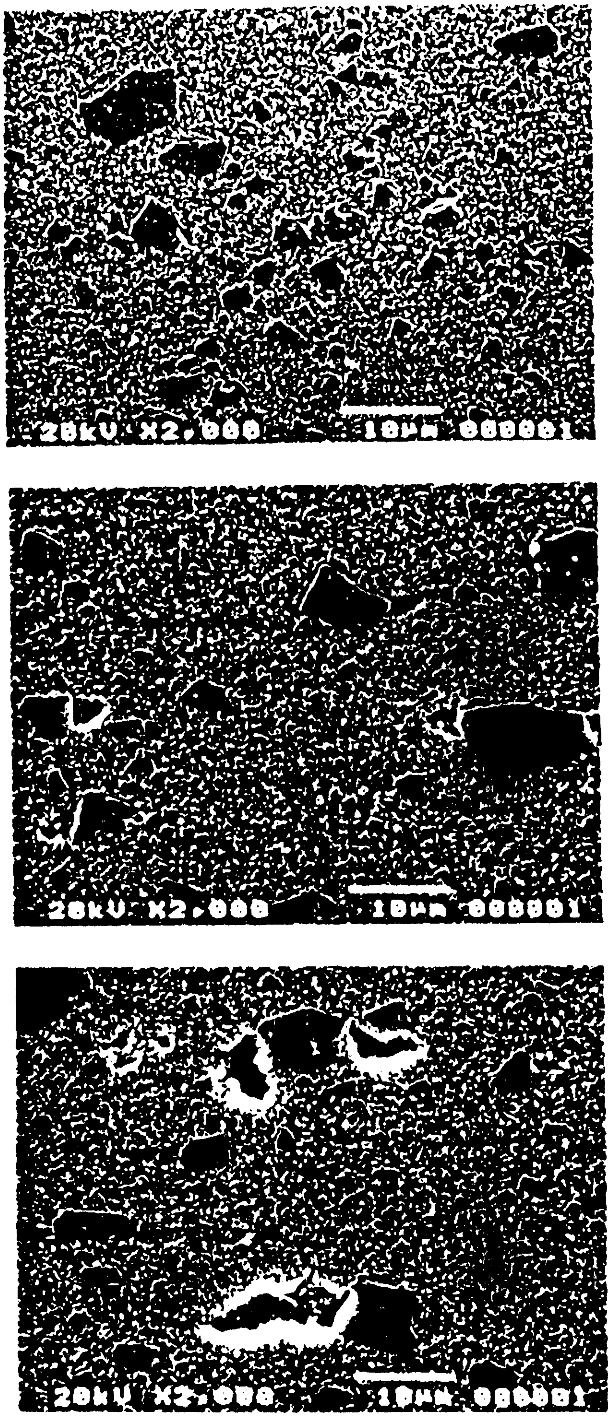


Figure 7 Cavity morphologies in the $SiC_p$/IN9021 composite deformed at 823 K at a very high strain rate of 100 $s^{-1}$ to pre-determined true strains of 0.53 (top), 1.06 (middle) and 1.61 (bottom). The tensile direction is horizontal.

In the present case, plastic deformation of the SiC*p* reinforcements in the SiC*p*/IN9021 composite is impossible at the superplastic temperatures. Since there exists a large volume of reinforcement/matrix interfaces suggesting that interfacial sliding may play as an important role as grain boundary sliding during superplastic deformation. Therefore, plastic deformation of the matrix by interfacial sliding must be accommodated by plastic or diffusional flow of the adjacent matrix, as schematically illustrated in Figure 8. Otherwise, as shown in Figure 6, extensive cavitation would occur near the matrix/reinforcement interfaces. Thus, the optimum superplasticity in a metal-matrix composite (MMC) is achieved under conditions that interfacial sliding rates, rather grain boundary sliding rates, are balanced by the accommodation process rates. because diffusional processes near the matrix/reinforcement interfaces in MMCs, which control the optimum superplastic strain rate are expected to be slower than those on grain boundaries. Therefore, a mechanism to count for the accommodation process to relax the local stresses which is caused by interfacial sliding is required in order to describe fully the high superplastic flow in MMCs under high strain rate conditions.

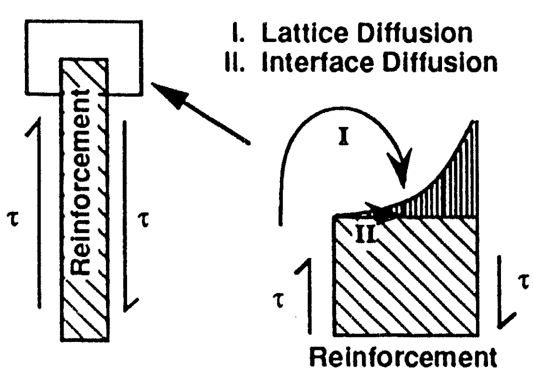


Figure 8 Schematic representation of a sliding reinforcement-matrix interface accommodated by diffusional processes.

## 4. CONCLUSIONS

A mechanically alloyed 15 vol% SiC*p*/IN9021 composite exhibited large superplastic elongations of about 500 % at very high strain rates between 5 and 100 $s^{-1}$. Cavities initiated at the poles of particulate reinforcements and parallel to the applied stress direction a initial small strains, and their subsequent growth and coalescence invariably leads to premature failure. The level of cavitation in the specimen deformed at higher strain rate of 100 $s^{-1}$ is higher and the onset of cavity initiation occurs much earlier as compared to that in the specimen deformed at the lower strain rate of 5 $s^{-1}$. It is clear that, as the applied stress increases with increasing strain rate, the critical cavity size for nucleation at higher strain rates is smaller than that at lower strain rates resulting from a higher local stress at the matrix-reinforcement interfaces.


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