Scientia Iranica, Vol. 11, No. 4, pp 392–397
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SCIENTIA
IRANICA

Research Note

Aging Behavior and Tensile Properties of Squeeze Cast AL 6061/SIC Metal Matrix Composites

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In this work, the production and properties of Al 6061/SiC composites, made using a squeeze casting method, were investigated. SiC preforms were manufactured by mixing SiC powder, having a 16 and 22 μm particle size, with colloidal silica as a binder. 6061 Al melt was squeeze cast into the pores of the SiC preform to manufacture a DRA composite containing 30v/o reinforcement. The aging behavior, tensile properties and fracture mechanism of the cast material were studied. The results show that higher hardness, yield strength, tensile strength and Young's modulus can be obtained by the addition of SiC particles to 6061 Al alloy, whereas tensile elongation decreases. This is mainly caused by a thermal mismatch between the metal matrix and the reinforcement, which leads to a lower grain size of the matrix with more dislocation density. It was also found that the precipitation kinetics of GP zones in the composite material was accelerated, owing to the heterogeneous nucleation capability of metastable phases on the SiC particles. Decreasing the SiC particle size resulted in better mechanical properties and a faster aging response. Nevertheless, the decohesion of the interface between the metal matrix and SiC particles led to the formation of voids which, subsequently, coalesced to generate the ductile rupture of the metal matrix.

INTRODUCTION

The demand for high performance materials in aerospace and automobile applications has led to the development of numerous structural composite materials [1-8]. Amongst different kinds of the recently developed composites, particle-reinforced metal matrix composites and, in particular, aluminum base materials, have already emerged as candidates for industrial applications. This is due to their excellent combination of properties such as high specific strength and stiffness, improved wear resistance and the additional advantages of being machinable and workable [9-12].

So far, different techniques have been developed for manufacturing Discontinuous Reinforced Aluminum alloys (DRA) [13,14]. However, the fabrication of these composites via a squeeze casting method has become known as a very promising way of manufacturing near net shape components at a relatively low cost [13]. In addition, the microstructure of the composite is relatively homogeneous and fine. Furthermore, the procedure enhances bonding strength between the metal matrix and the reinforcement. In fact, the implementation of high pressure during the squeeze casting process not only pushes the liquid metal into pores of the SiC preforms, but also improves the wetability of the molten metal by the reinforcement [13,14,16].

Besides the aforementioned impact of the manufacturing method on the characteristics of DRA composites, it has been found that reinforcement has a great influence on the properties of the aluminum metal matrix. For instance, it was shown that addition of ceramic particles results in increasing the dislocation density and decreasing the grain size of the metal matrix [9,15,16]. These phenomena certainly affect aging behavior and the mechanical properties of the DRA composite [10,17-19].

However, it is obvious that the impact of the influence of reinforcement on the properties of DRA composites depends both on the manufacturing method and the characteristics of SiC particles (volume percent and particle size). On the other hand, when usual

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casting methods, such as the vortex procedure, are used for fabrication of DRA composites, it is barely possible to obtain composites with more than 20v/o of the reinforcement. In this study, the squeeze method was successfully implemented for manufacturing high content SiC particles using a special procedure for fabricating the preforms. Good adhesion between the metal matrix and the reinforcement was obtained. The influence of adding SiC particles and, in particular, the size of the reinforcement particles on the aging behavior of the materials was then studied. This investigation for composite materials, with high amounts of the reinforcement made by squeeze casting, has not been done exclusively, i.e., in addition to the valuable mechanical strengths which were obtained, the impact of the reinforcement, at such a high level, on the aging behavior, is addressed and discussed. This article presents the influence of reinforcement on the precipitation kinetics of GP zones during aging and its resulting impact on the mechanical properties of the investigated DRA composites.

EXPERIMENTAL PROCEDURE

Materials

Commercial 6061 aluminum alloy was used as the metal matrix and SiC particles as the reinforcement. The metal matrix alloy consists of (in weight percent) 0.99 Mg, 0.73 Si, 0.5 Fe, 0.4 Cu, 0.11 Zn, 0.07 Cr and the rest being aluminum. SiC particles were of an abrasive grade with median particle sizes of 16 and 22 μm. Figure 1 shows a SEM micrograph of the SiC particles.

Fabrication of SiC Preform

Colloidal silica was used as the binder for the manufacturing of SiC preform. At first, 150 g of SiC particles were mixed with the silica in a container. Two SiC particle sizes of 16 and 22 μm were used. Then, this mixture was poured into a cylindrical mold of 20 mm height and 100 mm diameter. After baking this mixture at 120°C for 24 hrs, the dry preform was sintered at 1000°C for 4 hrs. The volume fraction of SiC in the preform was 30v/o.

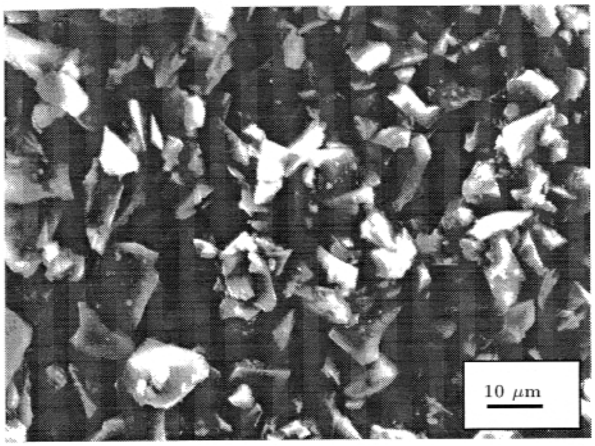


Figure 1. SEM micrograph of SiC particles used in this study.

Squeeze Casting

The composite samples were produced via a squeeze casting method. Figure 2 shows the schematic of the apparatus used in this study. At first, the mold and the SiC preform were preheated to 300°C. Then, the molten 6061 aluminum alloy was poured into the mold at 800°C. Subsequently, a 100 MPa pressure was applied to the mixture using a hydraulic press. The molten aluminum alloy was, therefore, infiltrated into the preheated reinforcement preform and solidified. Since the solidification time is very short when using a high pressure (70-100 MPa) for squeezing the liquid metal, it is expected that a no reaction zone would develop on the interface of the matrix and the reinforcement, giving void free and high strength composites as cited in [9,13,14,20].

Heat Treatment

After squeeze casting, all specimens were homogenized at 530°C for 3 hrs. Then, the solution heat treatment was employed for 2 hrs at 557°C, followed by water quenching. Finally, all specimens were aged at 175°C at varying times.

Material Characterization

Tensile test specimens were machined from the cast block according to ASTM-E8M Standard. The length and diameter of the gage were 30 and 6 mm, respectively. Here, it is pertinent to point out that three

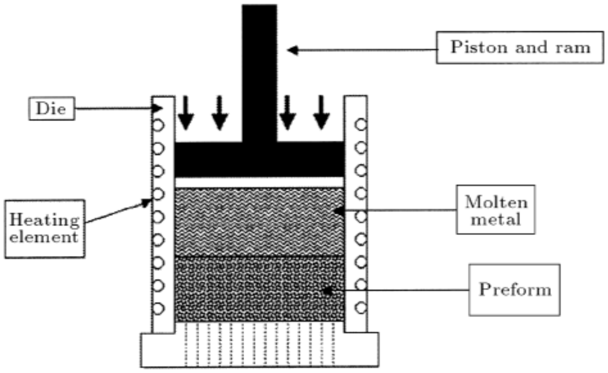


Figure 2. Schematic diagram of the squeeze casting apparatus.

tensile tests were done for each run and the results were reported using the mean square method. The scatter among the experimental data is less than 5%. After machining, the gage surface of the specimens was mechanically polished using 100, 200 and 500 mesh abrasive papers to remove scratches and machining marks.

The apparent hardness of the composite material was evaluated using the Brinell method, employing a 2.5 mm ball at 15 and 30 g loads. Sample tests for microstructural examinations were prepared using the standard metallographic method. Scanning Electron Microscopy (SEM) and Optical Microscopy (OM) were performed to evaluate the distribution of the SiC particles and the degree of perfection of the infiltration process. The fracture surface of the composite was also examined using SEM.

RESULTS AND DISCUSSION

Microstructure

The most important factor in the fabrication of DRA composites is the uniform dispersion of the reinforcement. So, the appearance of the microstructure could give an insight into the quality of the composite. Figure 3 shows the microstructure of the Al 6061/SiC$_p$ composite made by the squeeze casting method. One can see that the distribution of SiC particles is relatively uniform and the infiltration of Al 6061 alloy is virtually complete.

Aging

The strength of Al 6061/SiC composites can be further improved via precipitation hardening, i.e., the precipitation of metastable phases during the aging of a supersaturated solid solution. The generally admitted precipitation sequence in Al 6061 alloy is:

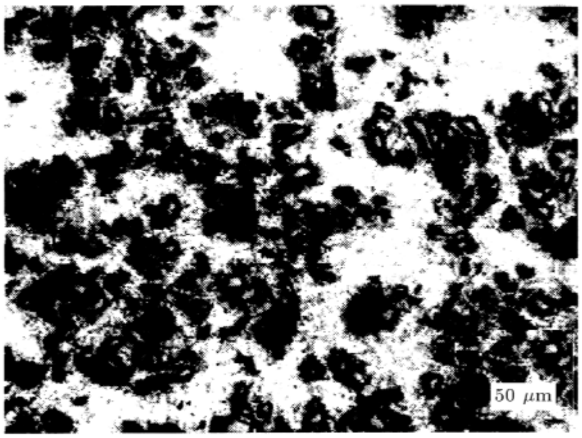


Figure 3. Characteristic microstructure of 6061Al/SiC (22 μm) composite.

1. Super saturated solid solution,
2. Vacancy silicon clusters,
3. GP zones,
4. β'' coherent needle phase precipitates,
5. β' semicoherent rods,
6. Equilibrium β plates [18].

Figure 4 shows the effect of aging time on the hardness of reinforced and unreinforced Al 6061 alloy. One can notice that an increase in the hardness of the composite materials occurred after the aging treatment. However, it is of interest to note that peak hardness was observed at lower aging times for the DRA composite compared to the Al base alloy (125 min for the composite and 185 min for the Al alloy). In addition, using smaller SiC particle size resulted in a faster aging response, i.e., the time of peak hardness decreased from 125 to 106 min. These results indicate that the addition of reinforcement to the aluminum matrix accelerates the aging kinetic. This behavior can be related to the high matrix dislocation density induced by the mismatch between the matrix and the reinforcement [15,17,19]. It is well known that high dislocation density in the metal matrix promotes dislocation-assisted diffusion of the aging elements. On the other hand, the influence of the reinforcement on the aging behavior can be attributed to the heterogeneous nucleation capability of metastable phases on the SiC particles [9,10,18,19]. It can, therefore, be concluded that both nucleation and growth of the GP zone are influenced by the ceramic particles. Here, if smaller SiC particle size is used, the total interface area between the metal matrix and the reinforcement would be higher, while the mean intercept distance between the particles would be lower. So, the dislocation density of the matrix increases, whereas the diffusion distance decreases. This results in a faster aging response, as cited above.

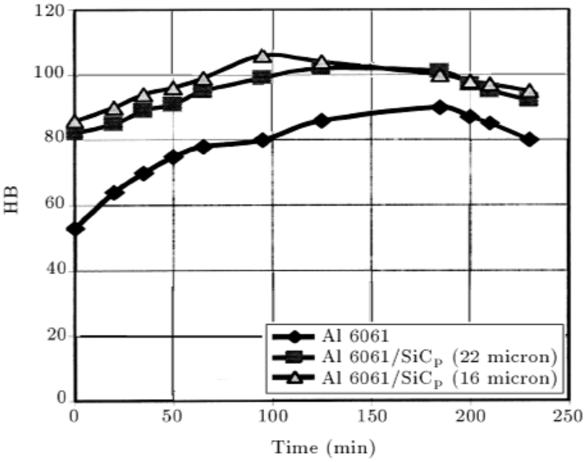


Figure 4. Brinell hardness versus the aging time for the investigated materials.

Tensile Properties

The tensile properties of the 6061 aluminum alloy and the DRA composite materials were evaluated according to the ASTM-E8M Standard at peak-age condition. Three test specimens were used for each run. The engineering stress-strain curves of the examined materials are shown in Figure 5. The tensile properties, such as yield strength (Ys), tensile strength (Ts), elastic modulus (E) and elongation (%EL), were extracted from the stress-strain curves. The results are shown in Figure 6. From this figure, one can see that the Ys, Ts and E of the DRA composites are greater than those of the aluminum base alloys. As mentioned above, a thermal mismatch between the metal matrix and the reinforcement is a major mechanism for increasing the dislocation density of the matrix and, therefore, increasing the composite strength. Here, it should be noted that using a smaller SiC particle size resulted in better mechanical strength, in convincing agreement with the previous investigations [9,20]. Again, at a constant volume fraction of the reinforcement, the smaller SiC particle size provides more interface area, which serves as the nucleation site for grain formation during squeeze casting and as a barrier for grain growth during the subsequent heat treatment. Therefore, it is not generally surprising that decreasing the grain size of the reinforcement, in addition to the effect of less intercept length between ceramic particles (smaller particles exert more restriction on plastic flow during deformation), as well as a higher dislocation density of the metal matrix, results in higher mechanical strength. In addition, it is known that the more interface between the metal matrix and the reinforcement in the DRA composites leads to higher elastic modulus, if good interfacial contact exists [21]. This is mainly due to the improvement of the load-bearing capacity of the reinforcement, as a result of more interface area.

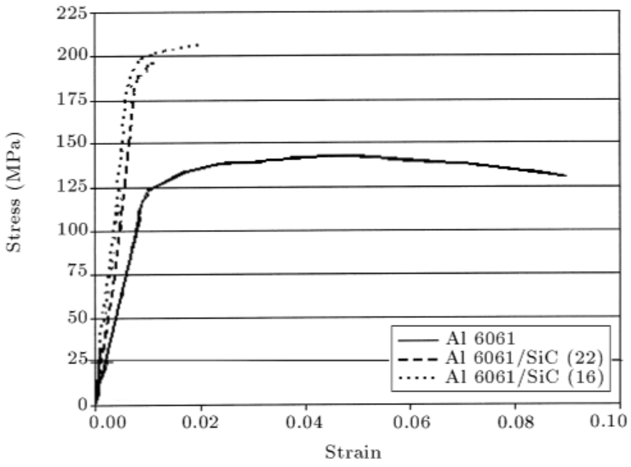


Figure 5. Stress-strain curves of the investigated materials at the aged condition (the number in the parenthesis gives the size of SiC particles).

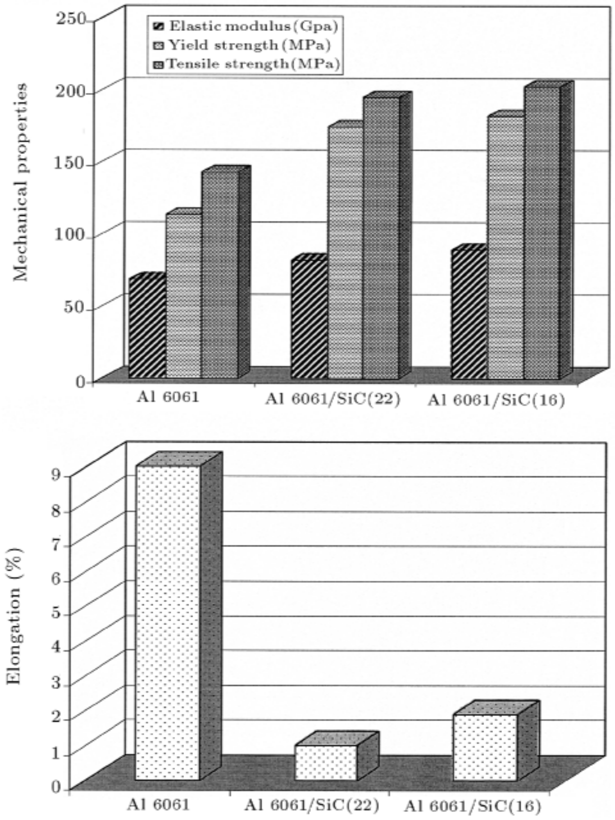
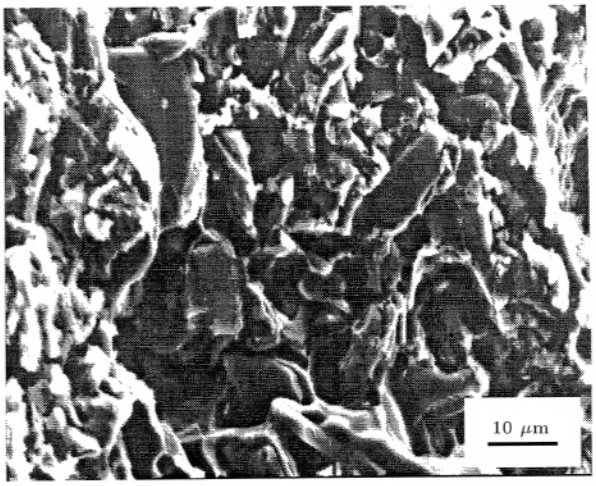


Figure 6. Mechanical properties of the investigated Al 6061 and DRA composites produced by squeeze casting (the number in the parenthesis gives the size of SiC particles).

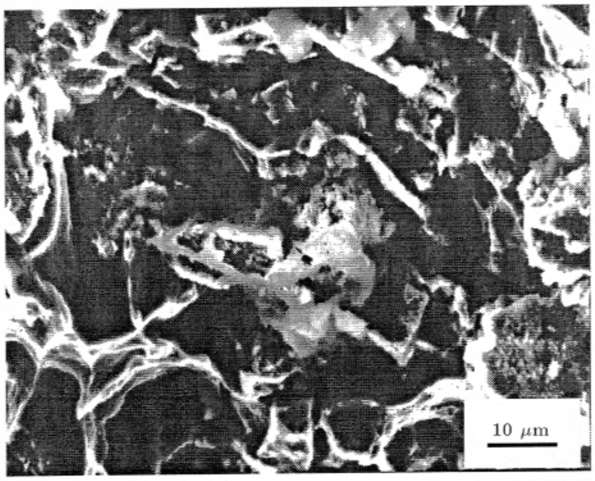
However, as shown in Figure 6, the DRA composite materials exhibit lower elongation than that of unreinforced specimens. It is obvious that plastic deformation of the mixed soft metal matrix and the non-deformable reinforcement is more difficult than the base metal itself. Therefore, the ductility of the DRA composite must be lower than that of unreinforced material.

Fractography

Fractographic study has been done on the tensile specimens. Figure 7 shows the fracture surface of the composite specimens taken by SEM. Areas of brittle fracture, dimples and voids are clearly visible. The latter were generated as a consequence of decohesion of the SiC particles from the aluminum matrix. In fact, strain localization at sharp corners of the reinforcement particles has been regarded as a dominant fracture initiation mode in these composites [20]. Consequently, the ductile fracture of the matrix was due to a void coalescence mechanism, which resulted in the formation of dimples, as observed at the fracture surface (Figure 7).



(a) 16 μm SiC particles



(b) 22 μm SiC particles

Figure 7. The fracture surface of the tensile tests for the Al 6061/SiC composites.

CONCLUSION

In this investigation, the squeeze casting process was successfully implemented for producing high quality DRA composites containing 30v/o SiC particles. SiC preforms were manufactured by mixing SiC powder, having 16 and 22 μm particle sizes, with colloidal silica as a binder. It was found that in comparison to the 6061 aluminum alloy, the precipitation kinetic was accelerated by adding the reinforcement. This effect reduced the time for obtaining the maximum hardness by the aging heat treatment. The reason for the improvement of the kinetics of GP zone formation is related to the higher dislocation density of the metal matrix, due to the thermal mismatch. This not only enhances the nucleation rate (heterogeneous nucleation), but also affects the diffusion rate of the solute elements. Decreasing the SiC particle size improved the impact of this phenomenon, i.e., the peak hardness was shifted to a shorter time. Consequently, better mechanical strength and stiffness were obtained. However, the ductility of the composite material was lower than that of the unreinforced specimen. Here, using the smaller SiC particle size resulted in better tensile ductility and stiffness. The fracture surface of the composite material consisted of voids, which were formed by the strain localization at sharp corners of the SiC particles. These voids were then coalesced during tensile loading, resulting in the formation of a dimple appearance at the fracture surface.

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