Effect of Heat Treatment on Mechanical Properties of Particulate Reinforced Al6061 Composites

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Mechanical tests were carried out to study the behavior of albite reinforced Al 6061 matrix composite produced through the liquid vortex method and heat treated to T6 treatment. The matrix material Al 6061 was also tested as a control material for comparison. The hardness, ultimate tensile strength (UTS), compression strength, and Young's modulus were found to be higher than those of the control alloy. The reinforcement noticeably enhances the dislocation density in the matrix upon cooling from the solutionizing temperature. The dislocations that serve as heterogeneous nucleation sites for strengthening precipitates during subsequent aging treatments, after the precipitation kinetics of the matrix of the composite, were compared to the control alloy. A higher density of dislocations and a higher density of intermediate precipitates were observed. There was a marginal improvement of tensile strength, compression, and hardness with aging.

Keywords aluminum composite, composites, heat treatment

1. Introduction

In recent years, there has been considerable interest in metal matrix composites (MMCs). This is because of the potential improvements in mechanical properties such as tensile strength, compression strength, and hardness and also an increase in high-temperature properties. Such improvements are countered by a reduction in ductility and toughness. Fiber-reinforced composites enhance properties to a greater extent. However, they are anisotropic and cannot be formed by conventional mechanical processing. Particulate-reinforced composites are more isotropic, and modest improvements in properties are obtained and can be processed conventionally.[1]

An accelerated aging response in ceramic-reinforced aluminum alloy composites has been acknowledged for several years. This mechanism can be due to increased dislocation density in the vicinity of the ceramic reinforcement, which is due to a difference in coefficient of thermal expansion between the ceramic particles and the matrix. The higher dislocation density can both aid the diffusion of solute atom and serve as nucleation sites, thereby leading to a more rapid precipitation process.[2,3] Excess vacancy concentration introduced by quenching from the solution temperature plays an important role in decomposition of supersaturated solid solution.[3,4] It has been reported that higher vacancy concentration retained by fast quenching will promote the formation of Guinier-Preston (GP) zones and metastable precipitates in Al-Si and Al-Mg-Si alloys.[5] The present work attempts to clarify the influence of vacancy concentration and dislocation density due to artificial aging on the mechanical properties of Al-6061/albite ceramic-reinforced composites.

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2. Experimental Procedure

The material used in the present study was Al 6061 having Si-0.6, Mg-1.11, Cu-0.3, Fe-0.4, Cr-0.2, Mn-0.001, and Al-balance and reinforced with albite ($NaAlSi_3O_8$); a plagioclase feldspar appears as glassy while having a Mohr's hardness of 6 to 6.5. The matrix was melted in an electrical resistance furnace to a superheat of 710 °C and stirred at 550 rpm with a turbine-type rotor submerged in molten matrix to 60%. The albite reinforcement (90 to -150 μm) was introduced into the vortex, which was preheated to 400 °C and precoated with silver.[6,7] The composites were cast in permanent molds of 25 $\times$ 300 mm with varying albite reinforcement of 0, 1, 2, 3, and 4 wt.%. The obtained castings were machined in accordance with ASTM standards for various mechanical tests.

Three aging conditions were selected for mechanical testing. The heat treatment used to achieve these conditions was a solution treatment of 10 h at a temperature of 532 °C followed by water quenching in hot water (80 °C) aged at room temperature for 12 h followed[8,9] by aging at 175 °C for 1, 3, and 5 h. Specimens are polished to observe particle distribution by optical microscopy. Hardness tests were systematically conducted at fixed points within the composite following each heat treatment stage. Hardness was characterized by a Brinell hardness tester. The tensile and compression tests were conducted on a 20 T Shimadzu universal testing machine. Fracture surfaces of tested tensile specimens of both MMC and Al-6061 were observed using a scanning electron microscrope (SEM). For each of the parameters mentioned, at least ten samples were employed to ensure reliable results. To study the effect of the addition of albite particulate reinforcement, Al-6061 alloy specimens were also tested as a control alloy for comparison. The experimental procedures were identical to those for the composite material.

Thin foils for transmission electron microscopy (TEM) were prepared after mechanical grinding to 100 μm followed by twin jet polishing at 40 °C to study the microstructural changes, and

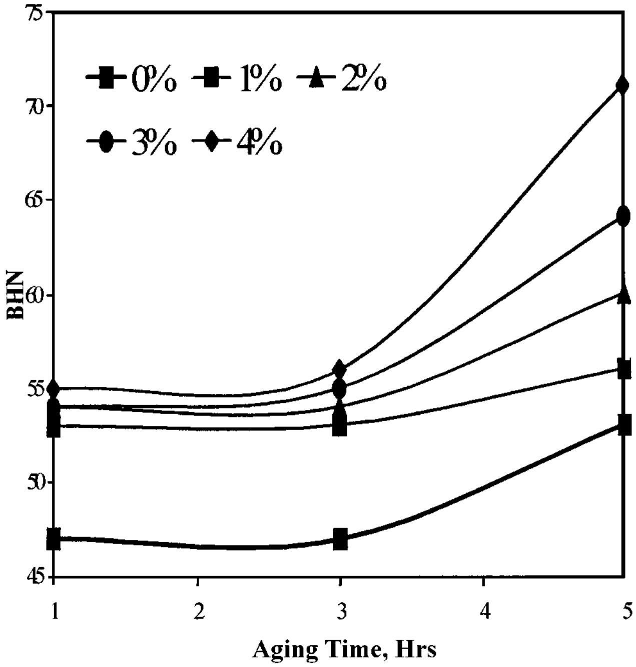

Fig. 1 Matrix hardness, indicating the aging response of the various weight percents of reinforcement of particulate composites

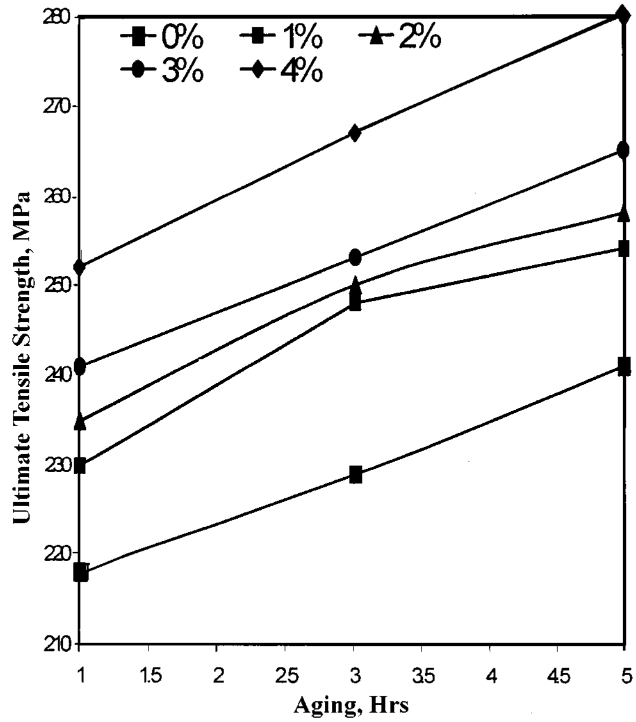

Fig. 2 UTS, indicating the aging response of the various weight percents of reinforcement of particulate composite

spot analysis was done using energy dispersive x-ray analysis (EDAX) of these intermediate particles.

3. Results

3.1 Hardness Results

The results of the hardness tests of aged alloy as well as the composites containing 0, 1, 2, 3, and 4% albite particulate by weight are represented graphically and are as shown in Fig. 1. It has been reported previously[3,9,10–12] that the addition of albite particulate brings about a considerable increase in hardness of the composite. Changing the solution treatment temperature[3] does not influence the accelerated aging response observed for the composites. The increase in hardness is to be expected because albite particulates are very hard and act as a barrier to the movement of dislocations within the matrix and exhibit greater resistance to indentation of the hardness tester. The difference in hardness was marginal with increasing aging time from 1 to 5 h. Various researchers[3,12] have reported accelerated aging responses of the composites in comparison with the base alloy, decreases beyond the peak hardness aging time period. However, in the present study, the three aging conditions considered within peak aging conditions showed an increase in hardness with the aging time period.

3.2 Ultimate Tensile Strength

Figure 2 shows the effect of aging on the ultimate tensile strength (UTS) of composites containing various amounts of albite particles. It can be seen that as the albite content increases, the UTS of the composite material increases monotonically. Various researchers found[12,13] remarkable improvements in both UTS and Young's modulus ranging from 50 to 100% by incorporation of reinforcement. In the present investigation, aging and the addition of albite reinforcement were found to increase UTS and Young's modulus substantially. As more albite particulates were added, decreases in inter-particulate distance between hard albite particles caused an increase in dislocation pileup. Moreover, improvement in UTS may be[13] due to the matrix strengthening that might have occurred as a result of the grain size strengthening following a reduction in composite grain size and the generation of a high dislocation density in the matrix as a result of the difference in coefficient of thermal expansion between the matrix and albite reinforcement.[11,15] One great advantage of this dispersion strengthening effect is that it is retained even at elevated temperature, as particulates are not reactive with the matrix phase.[12,14]

Artificial aging at 175 °C seems to increase UTS monotonically by a significant amount for composites of various albite percentage contents. A similar trend was seen for the Young's modulus, which is evident from Fig. 2.

3.3 Ductility

Figure 3 shows the effect of aging on the ductility of composites containing various amounts of albite particles. There was not much significant change in hardness with the addition of albite particles; ductility decreased significantly, and with the increase in aging time, the ductility increased by a slender margin. All of these results are in close agreement with many previous researchers,[15–18] who believe that the ductility of discontinuous reinforced MMCs decreases with an increase in

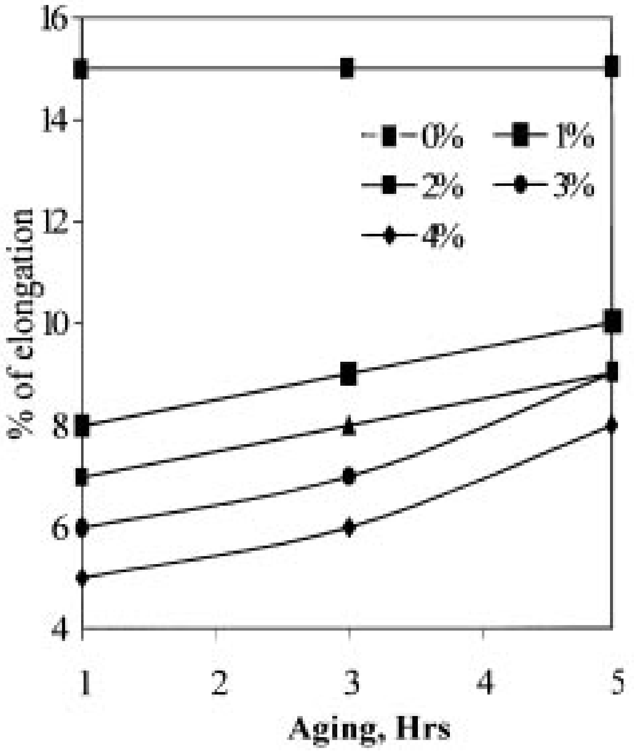

Fig. 3 Ductility, indicating the aging response of the various weight percents of reinforcement of particulate composite

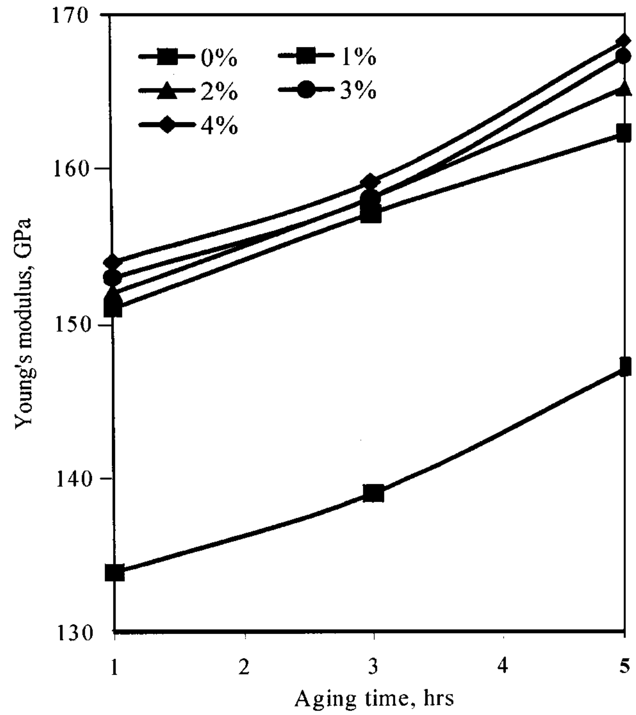

Fig. 4 Young's modulus in compression, indicating the aging response of the various weight percents of reinforcement of particulate composite

reinforcement content. The particulate reinforcement induces stress sites and also large differences in elastic behavior between the matrix and the reinforcement.

Increased aging seems to increase ductility, which is due to the fine dispersion of precipitate clusters formed during quenching, and a more stabilized β-precipitate phase was reached. The GP zone formed deteriorates with aging.

3.4 Compression Strength

Figure 4 shows the effect of aging on the Young's modulus in compression of composites containing various amounts of albite particles. It can be seen that as the albite content increases, the Young's modulus of the composite material increases monotonically. In the present investigation, three aging conditions, namely, for 1, 3, and 5 h, were selected to study the compression behavior for different weight percents of albite composites. Upon heat treatment, the composite behaved as a ductile material, which may be due to the influence of dislocation of substructure on the precipitation process. The increase in dislocation density and dislocation acts as preferential nucleation sites for precipitates obtained during aging.

Due to dislocation, finer precipitate distribution would be expected in the composite, which is at par with Song and Baker.

3.5 Microstructure

Figure 5 shows an optical micrograph of the transverse section of the as-cast material. The distributions appear to be reasonably homogeneous. The same dispersion was observed by Doet *et al.*[13]

4. Discussion

It is now well established that the development of significant levels of hardness in Al-6061 is associated with the formation of βMg_2Si. However, the level depends on the size and spacing of the β precipitates. The latter is controlled by the nature of β nuclei (which are normally GP zones) and their temperature of formation.[11] The absence of GP zone formation in the composite therefore has a significant effect on the size and morphology of the β precipitates and resultant age hardening. The material contained βMg_2Si in a coarse Widmanstätten morphology; homogeneously nucleated precipitates in peak-aged condition were found by many researchers[11,14] in unreinforced alloys.

Microstructural examination *via* TEM showed uniform distribution of inter-metallic compounds in both Al-6061 and composites. Figure 6 shows spectra obtained *via* EDAX of these small particles in the form of needles showing the presence of Mg_2Si. Examples of preferential precipitation of Mg_2Si along the grain boundaries and sub-boundaries have been documented by Song *et al.*;[2] the same results were obtained by Bhaduri *et al.* for Al-7075 alloy composite.[10] In 4% albite reinforced composite, a higher density was observed around the albite particulate compared to the unreinforced alloy. During the beginning of aging, needles of precipitates were normally made visible as a result of a higher density of dislocation, which is evident from the results observed by Song *et al.*[2] Previous work on Al-Mg-Si has provided some evidence of clusters of silicon atom formed after quenching; however, precipitates

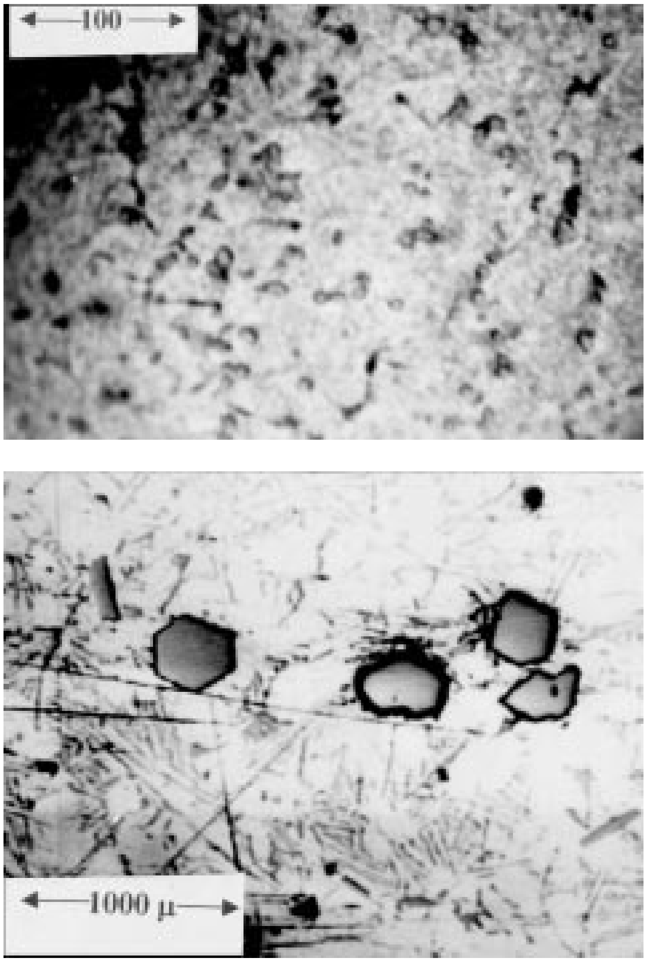

Fig. 5 Optical micrograph showing uniform distribution of albite particulate in Al-6061/albite composite (4 wt.%)

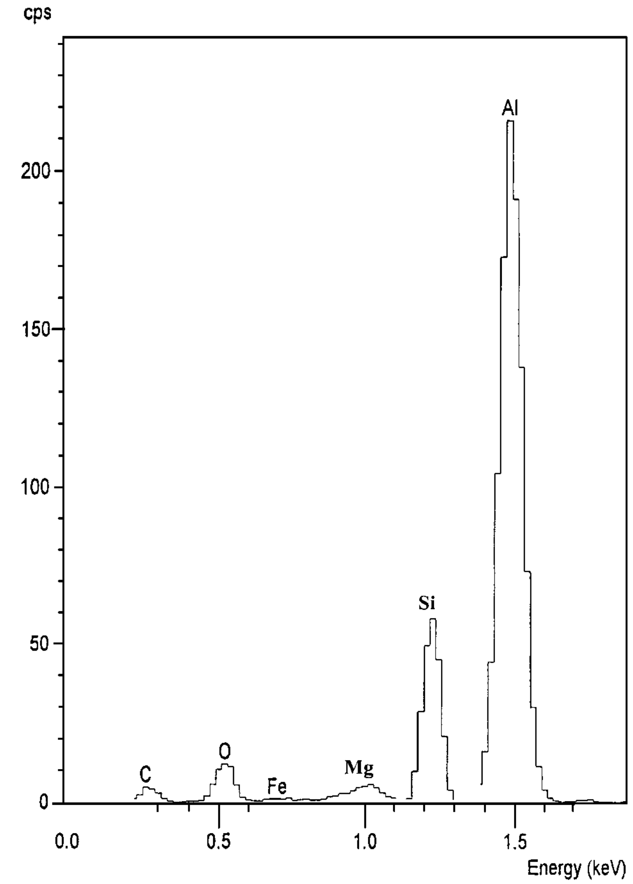

Fig. 6 Point EDAX of precipitates obtained during T-6 heat treatment

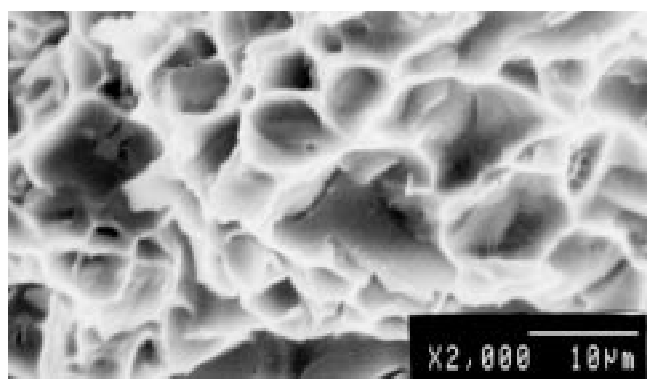

Fig. 7 Micrograph shows dimples on the fracture surface of Al-6061/albite composite

formed at 175 °C are needle shaped, which is at par with Song *et al.*[2]

Hant *et al.*[19] has also reported an accelerated aging response in SiC particle-reinforced Al-8090 alloy composites; they found that the δ precipitates in composites were essentially the same as those of the unreinforced alloy. They conclude that the rapid hardening response in MMC must be explained by dislocation interactions other than an enhanced precipitation reaction. The precipitate density appears to be greater in the composite than in the base alloy, and peak hard aging is attained when most of the solute precipitates on a fine scale. The lower apparent activation energy for the composites calculated at the aging temperature at about 170 °C could be attributed to a dislocation assisted nucleation process in the composites.[2]

Figure 7 shows many dimples on the matrix aluminum alloy, which prove that fracture is ductile. The dimples formed due to the debonding of particles. This means that the microcracking at the interface occurs as a result of the ductile limit of the matrix alloy adjacent to the albite particles.[20] However, part of the incompletely bonded interface also exists in the composite, which is evident from the original surface seen on the albite particles. Microcracking can initiate at an incomplete interface, which is aligned normal to the tensile direction. Interface bonds were complete all over the particle; no debonding was observed, but particle cracking did occur, as shown in Fig. 8. The dimples observed using an SEM were circular-shaped and uniformly distributed with an average size of 90 to 120 μm.[6]

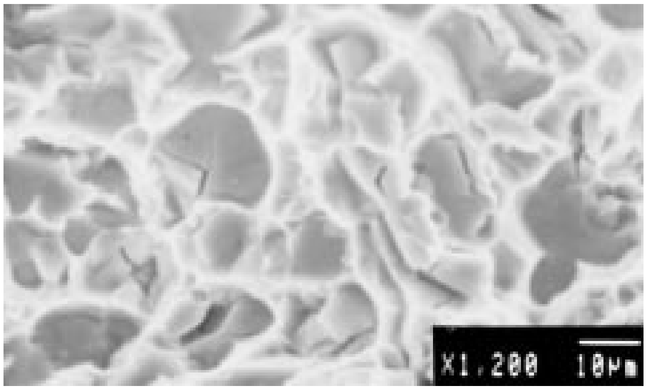

Fig. 8 Micrograph shows particle cracking in fracture for Al-6061/albite composite

5. Conclusions

- New MMCs can be synthesized by liquid metallurgy technique successfully with enhanced properties using a low cost albite particulate reinforcement.
- The additions of reinforcement noticeably enhance dislocation density due to the variation of coefficient of thermal expansion.
- These dislocations act as nucleation sites for strengthening precipitates formed during quenching.
- With an increase in reinforcement, there was substantial improvement in UTS, Young's modulus, hardness, and compression strength.
- With an increase in reinforcement content, ductility decreased substantially.
- With aging, the βMg_2Si precipitate transformed into a more stable state and a fine dispersion precipitate was observed.
- The fracture was ductile, with the dimple surface showing particles debonding and particle cracking.

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