

# AGING BEHAVIOUR OF PARTICULATE REINFORCED ALUMINUM ALLOY MATRIX COMPOSITES<sup>①</sup>

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## ABSTRACT

The process of aging precipitation in SiC<sub>p</sub>/6061 and Al<sub>2</sub>O<sub>3</sub>/6061 composites were investigated. Hardness testing, differential scanning calorimetry (DSC) and transmission electron microscopy were employed. Results showed that the precipitation phase form directly along dislocation lines in the composites because the particles produce high densities of dislocations which makes vacancy densities in the composites decrease, and the main precipitation phase at peak hardness was β' phase.

**Key words:** particle composite aging precipitation phase

## 1 INTRODUCTION

With the development of new processing techniques, the technological interest and research activity in the development of metal matrix composites have increased rapidly in recent years. Particulate reinforced metal matrix composites (MMC) offer many advantages in applications where low density, high strength and high stiffness are of prime concern. However, in order to obtain the best balance of mechanical properties, it is necessary to optimize the matrix microstructure, and to be able to do this by the engineering metallurgy. It's important to understand how precipitation reactions may be affected by the presence of the reinforcing phase.

In order to clarify the effect of the SiC and Al<sub>2</sub>O<sub>3</sub> particulate reinforcements on the aging behaviour of SiC<sub>p</sub>/Al and Al<sub>2</sub>O<sub>3</sub>/Al composites, here we study the precipitation behaviour of SiC<sub>p</sub>/6061 and Al<sub>2</sub>O<sub>3</sub>/6061 composites using hardness tests, DSC and

TEM techniques.

## 2 MATERIALS AND EXPERIMENTAL METHODS

The composite material selected for investigation were 6061 aluminum alloy containing 35 vol.-% SiC particles and 6061 aluminum alloy containing 20 vol.-% Al<sub>2</sub>O<sub>3</sub> particles. The mean SiC particle diameter is 3.5 μm and Al<sub>2</sub>O<sub>3</sub> particles is 0.3 μm. SiC or Al<sub>2</sub>O<sub>3</sub> particles distributes homogeneously in matrix alloy (Fig. 1). The materials were manufactured using a squeeze casting techniques. Specimens were solution treated at 530 °C for 1 h, water quenched and subsequently aged at 180 °C, 160 °C for various times. Hardness measurements were made on the specimens of reinforced and unreinforced 6061 aluminum alloys immediately after aging on a Vickers Hardness Testing Machine with a load of 10 kg. At least 10 hardness measurements were made for each aging con-

**Fig. 1 Appearance of reinforced particles**  
(a)—SiC particles; (b)—Al<sub>2</sub>O<sub>3</sub> particles

dition to ensure accurate results. Microstructures of both the MMC and the control alloy were carefully observed on a Philips CM-12 Scanning Transmission Electron Microscope (STEM) operating at 120 kV. TEM foils were prepared by grinding discs to a thickness of <10 μm. The argon ion beam table was cooled by liquid nitrogen to avoid possible damage during specimen preparation. A Perkin Elmer II DSC analyzer was used.

### 3 EXPERIMENTAL RESULTS AND DISCUSSION

#### 3.1 *The Effect of Particles on Aging Behaviour of Composite*

Fig. 2 shows the variation of hardness with the aging time for both the reinforced and the control alloy aged at 20, 160, 180 °C respectively. Clearly, the hardness value of the composites is higher than that of the control alloy. During natural aging (Fig. 2 (a)), the hardness of the SiC<sub>p</sub>/6061 composite doesn't change with the aging time and the peak-time for the Al<sub>2</sub>O<sub>3</sub>/6061 composite

is about 500 h, whereas the peak-aging time for the unreinforced alloy is about 300 h; during 160 °C aging, the peak-aging time of the SiC<sub>p</sub>/6061 composite equals that of the control alloy which is about 7 h, that of the Al<sub>2</sub>O<sub>3</sub>/6061 composite is about 6 h; during 180 °C aging that of the SiC<sub>p</sub>/6061 or Al<sub>2</sub>O<sub>3</sub>/6061 composites is about 5 h, whereas that of the control alloy is about 7 h. As a result, the effect of particles on aging behaviour of the composite relates to aging temperature.

We know that, for 6061 aluminium alloy, precipitation is generally considered to take place in the following sequence:

Supersaturated solid solution → Guinier-Preston Zones (GPZ) → Transition phase β' → Equilibrium phase β (Mg<sub>2</sub>Si).

The GPZ is a segregation zone of solute atoms, which is formed by segregation of quenched-in vacancies, and is normally fully coherent with the matrix; β' phase is semicoherent with the matrix, it is formed by nucleating at lattice defects zones or growing on the base of GPZs; β phase is an equilibrium phase, which is incoherent with the matrix,

and is formed by growing along the  $\beta'$  phase. The main microstructure of 6061 aluminum alloy at the highest hardness is a large number of GPZs. Because GPZ is coherent with the matrix, the elastic coherent

strain field is produced in the matrix when GPZ forms, which inhibits dislocation movement. So material is hardened<sup>[1]</sup>.

In the composites, which has large difference in the expansion coefficients of particles and matrix, large stresses generated at the interfaces between reinforcement and matrix on cooling give rise to a high dislocation density in the matrix. Both the presence of the lattice defects and the way they move through the matrix during stress relaxation will greatly increase the rate at which the matrix gets rid of excessive quenched-in vacancies. Nonequilibrium levels of quenched-in vacancies are very important in the formation of GPZs, and it is on this basis we suggest that the different kinetics observed for the formation of such phases on low temperature aging in the composites and controls can be explained. The fascinating point is that while in the composites the nucleation of GPZs is inhibited, that of  $\beta'$  is encouraged<sup>[2,3]</sup>. This is initially surprising considering that all of these phases are of homogeneous nucleation. Of course, the formation temperature of  $\beta'$  must be high enough although there is a low room temperature vacancy concentration in the composites ma-

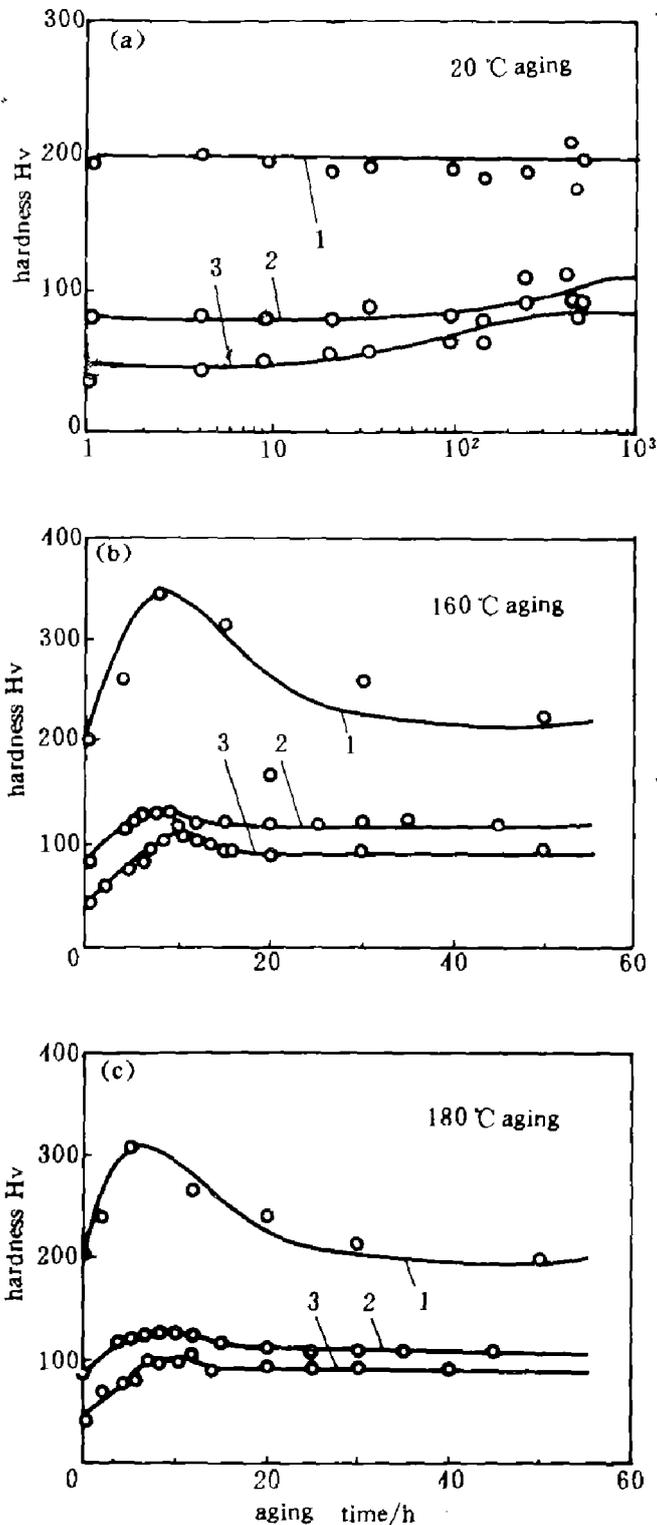


Fig. 2 The variation of hardness with the aging time for both the reinforced and the control alloy  
1—SiC<sub>p</sub>/6061; 2—Al<sub>2</sub>O<sub>3</sub>/6061; 3—6061

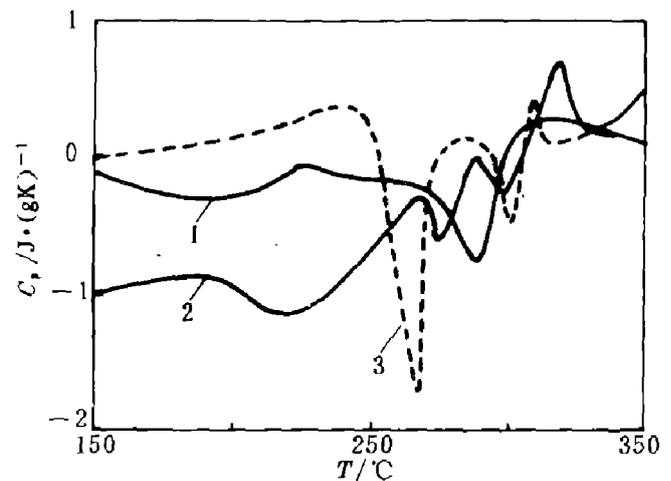


Fig. 3 The DSC scans for the reinforced and unreinforced 6061 alloys  
1—SiC<sub>p</sub>/6061; 2—Al<sub>2</sub>O<sub>3p</sub>/6061; 3—6061

trix, this, has no effect on  $\beta'$  precipitation.

The DSC scans for the reinforced and unreinforced 6061 alloys are shown in Fig. 3. Two large exothermic reaction peaks are evident in the control alloy. Peak I, near 268 C, is due to the formation of GPZ, while peak II, near 301.2 C, is due to the formation of  $\beta'$  phase. Only one exothermic reaction peak is evident in a  $\text{SiC}_p/6061$  composite at the temperature of 289.1 C, it is due to the formation of  $\beta'$  phase, two exothermic reaction peaks are evident in a  $\text{Al}_2\text{O}_3/6061$  composite. Peak I, near 275.5 C, is due to the formation of GPZ, while peak II, near 297.3 C, is due to the formation of  $\beta'$  phase. These results are the same as that of Fig. 2, that is, when aged at lower temperature (Fig. 2 (a)), the rise in hardness of the unreinforced control alloy is faster than that of the composite because the formation of GPZ is inhibited in composites; while when aged at higher temperature (Fig. 2 (c)), the rise in hardness of the unreinforced control alloy is lower than that of the composite because of the formation of  $\beta'$  phase. Further evidence for the acceleration of the transition  $\beta'$  phases in composites can be seen in Fig. 4, at peak hardness, where the microstructure for

composites consists of GPZ and  $\beta'$  phase, but the GPZ density is much less than the  $\beta'$  phase.  $\beta'$  was however observed to form earlier in the composite matrix by TEM. The  $\beta'$  phase is thought to nucleate homogeneously and independent of the density of lattice defects, the dislocation density is of course considerably higher in composite than in the control alloy.

### 3.2 The Effect of Different Aging Temperature on Composites

Compared with the variations of hardness as a function of aging time for both the reinforced and control alloy aging at 160 and 180 C respectively (Fig. 5), we found that, the increase of the hardness is the same at the initial state of aging, but, with the increase of aging time, the hardness of the composite aged at 160 C increases faster than that of 180 C.

From the analyses above, we know that a large number of  $\beta'$  phase nucleation positions are provided by high density dislocations. So, as the numbers and the dispersity of  $\beta'$  phase increases, the hardness of the composites is higher. At the beginning of aging, the dislocation density at 160 C is the

Fig. 4 A lot of  $\beta'$  phases precipitate on composites at the aging condition  
(a)— $\text{SiC}_p/6061$ ; (b)— $\text{Al}_2\text{O}_3/6061$

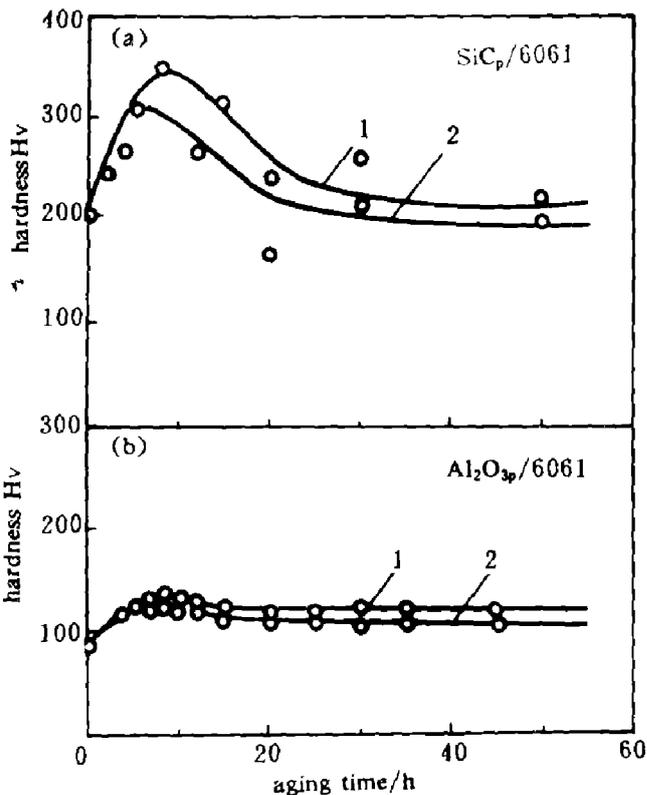


Fig. 5 The variations of hardness as a function of aging time for both the reinforced and control alloys  
 1—160 °C aging; 2—180 °C aging

same as that of aging at 180 °C, so the hardness increase of them is almost the same; with the increase of aging time, the dislocation density of aged at 180 °C decreases quickly, precipitation of  $\beta'$  phase also decreases, and  $\beta'$  phase grows up easily at higher temperature, so that the hardness of peak aging is lower. As contrasted to aging at 180 °C, when aging at 160 °C,  $\beta'$  phase

precipitates fully, and also homogeneously, which results in higher hardness.

#### 4 CONCLUSIONS

(1) The precipitation mechanism of composites and 6061 aluminum alloy is different. Supersaturated vacancy produced by quenching results in the GPZ precipitation in a 6061 aluminum alloy. But the precipitation phases form directly along dislocation lines in composites because particles produce high densities of dislocations which makes vacancy density in composites decrease.

(2) In composites, GPZ formation is inhibited, but precipitation reactions which involve  $\beta'$  phases at dislocations are accelerated, and the main strengthening phase is transition  $\beta'$  phase.

(3) In composites, the hardness of aging at 160 °C is higher than that of aging at 180 °C. This is because high aging temperature makes the density of dislocations decrease, which results in the decrease of  $\beta'$  phase.

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