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Effect of aging treatment on mechanical properties of (SiC_w+SiC_p)/2024Al hybrid nanocomposites

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Abstract: 2024Al based composites reinforced by a hybrid of SiC whisker and SiC nanoparticle were fabricated by a squeeze casting route. In the (SiC_w+SiC_p)/Al composites, the volume fraction of SiC whisker is 20% and that of SiC nanoparticle is 2%, 5% and 7%, respectively. The as cast composites were solution treated followed by aging treatment. The experimental results show that the SiC nanoparticles are more effective in improving the hardness and tensile strength of the composites than SiC whiskers. The hardening kinetics of the composites is enhanced by reinforcements addition and the peak aging time is 4-5 h. The hardness of all the hybrid composite decreases at the initial aging stage, suggesting that dislocation recovery softening process coexists with precipitation hardening. DSC study shows that the GP zone formation of the hybrid composites is suppressed.

Key words: (SiC_w+SiC_p)/2024Al; SiC_w/2024Al; SiC_p/2024Al; hybrid composites; SiC nanoparticle; mechanical properties

1 Introduction

Metal matrix composites(MMCs) have received much attention because of their improved specific strength, good wear resistance and higher thermal conductivity [1−3]. Up to now, most investigators have studied the fabrication process and mechanical properties of SiC_w/Al or SiC_p/Al composites[4−6], but very few studies on the (SiC_w+SiC_p)/Al hybrid composites have been available in literatures[7, 8]. The addition of SiC particles leads to an increase in the wear resistance, elastic modulus, and a decrease in the thermal expansion coefficient. The addition of SiC whiskers is more effective in improving the strength and ductility than the addition of SiC particles[7].

The age-hardening behavior of discontinuously reinforced aluminium matrix composites has been a subject of great interest from both scientific and technological view-points. In view of the inherent characteristics of dislocation aided precipitation in AA2024 it appears that reinforcing the alloy with nanoparticles would have a significant influence on the overall strengthening. The study on the aging behavior is beneficial to optimizing the aging treatment and provide the experimental and theoretical information for designing the properties of composites[9, 10].

In the present work, the effect of the volume fractions of SiC nanoparticles on the aging behaviour of the (SiC_w+SiC_p)/Al hybrid composites is studied by means of hardness measurement and TEM observation. A DSC study is carried out to understand the influence of nanoparticle reinforcement on the aging kinetics of the hybrid composites. The aim of this work is to investigate the aging behavior of hybrid composites and the effect of aging on the mechanical properties of the hybrid composites.

2 Experimental

The nominal composition of the matrix alloy (AA2024) used in the present study was (mass fraction): 4.6%Cu, 1. 2%Mg, 0.5%Si, 0.5%Fe, 0.3%Mn and Al (balance). SiC whiskers (0.3-0.6 μm in diameter and 10−28 μm in length) and SiC nanoparticles with an average diameter of 35 nm were selected as the reinforcement phase.

The composites were fabricated by a squeeze casting technique. The hybrid preform was prepared by mixing up SiC whiskers, SiC particles and pure alcohol in a slurry. The reinforcements were dispersed by ultrasonic waves, and the blend was mechanically stirred

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up to obtain a homogenous distribution of the nanoparticle in the preform. The AA2024 was melted and heated up to 800 ℃, meanwhile, the preform was heated to 520 ℃. The melt AA2024 was then infiltrated into the preform under a low pressure (about 2 MPa) and solidified under a high pressure (about 50 MPa). In the hybrid composites, the volume fraction of SiC whiskers was 20% and the volume fractions of SiC nanoparticles was 2%, 5% and 7%, respectively. In the SiC_w/Al composites, the volume fraction of SiC whiskers was 27%.

The as cast samples were solution treated at 495 ℃ for 1 h, water quenched and then aged at 190 ℃. The optimum aging conditions for the hybrid composites were found by measuring the hardness of the samples at different aging times using a Vickers hardness testing machine with an applied load of 49 N. For the DSC analyses, the samples were solution treated at 495 ℃ for 1 h and quenched in water at room temperature. They were stored in liquid nitrogen before DSC analysis. A constant heating rate of 15 ℃/min was used. The microstructure of the composite was analyzed using a Philips CM-12 transmission electron microscope(TEM). The tensile tests were carried out at room temperature using a 100 kN Instron 5569 with a crosshead speed of 0.5 mm/min.

3 Results and discussion

3.1 Aging kinetics

Figs.1(a) and (b) show the reinforcements distribution in the hybrid composites observed by SEM and TEM, respectively. The SiC whiskers are all relatively uniformly distributed in the matrix. A large amount of SiC whiskers, compared with the low content of the SiC nanoparticles, contribute to the dispersancy of the SiC nanoparticles. Voids can be hardly detected within the microstructure, indicating a higher densification of the composite. It is also found that the matrix has successfully infiltrated into the pores formed by the SiC clusters.

Fig.2 shows the hardness of unreinforced 2024Al and composites as a function of aging time during aging at 190 ℃. It is clearly evident that the aging behaviour of the composites is quite different from that of the unreinforced alloy. The peak aging time of AA2024 is 12−13 h, however, the peak aging time both for SiC_w/Al composites and (SiC_w+SiC_p)/Al composites is 4−5 h. The hardness of the hybrid composite decreases at the initial stage of aging. After the peak aging time, the hardness of the hybrid composites decreases slightly with increasing aging time. In addition, the level of peak hardness achieved in the hybrid composites is much higher than that of SiC_w/Al composites. The peak hardness of the hybrid composites increases with increasing volume fraction of the SiC nanoparticle. The (20%SiC_w+7%SiC_p)/Al composite, among the hybrid composites, shows the highest peak hardness value (about HV348). From the hardness measurement, it can be determined that the optimum aging condition for the composites is 4−5 h at 190 ℃ when the volume fraction of the reinforcements varies from 20% to 27%. The peak hardness for the (20%SiC_w+2%SiC_p)/Al composite is about HV316, which is much higher than that of 27%SiC_w/Al composite (about HV257). This result indicates that the SiC nanoparticle is more effective in enhancing the composite hardness than the SiC whisker, which is contrary to the study of KO et al[7]. The reason for this is the size of SiC particles used in the present study is in nanoscale. It is concluded that particles less

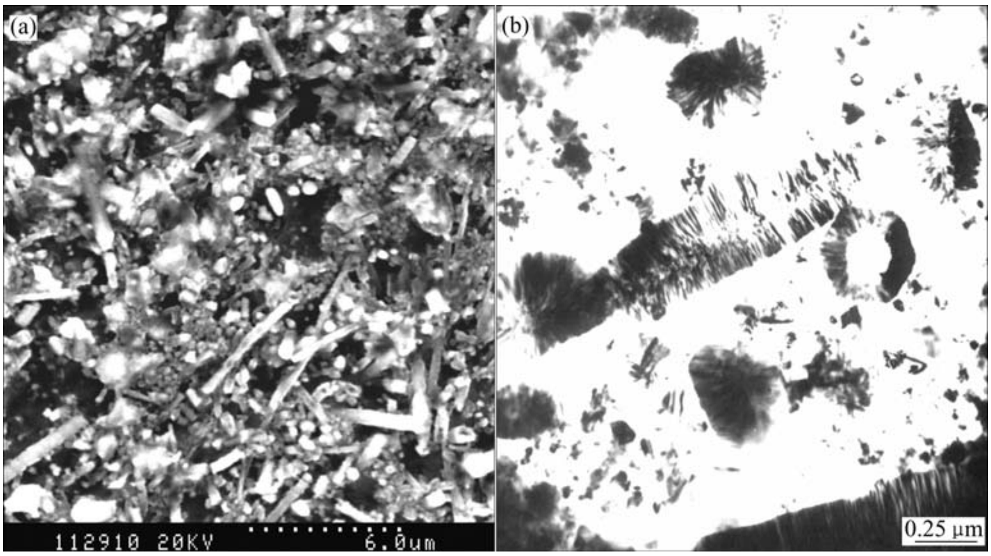

Fig.1 Microstructures of hybrid composites showing distribution of whiskers and nanoparticles by SEM(a) and TEM(b)

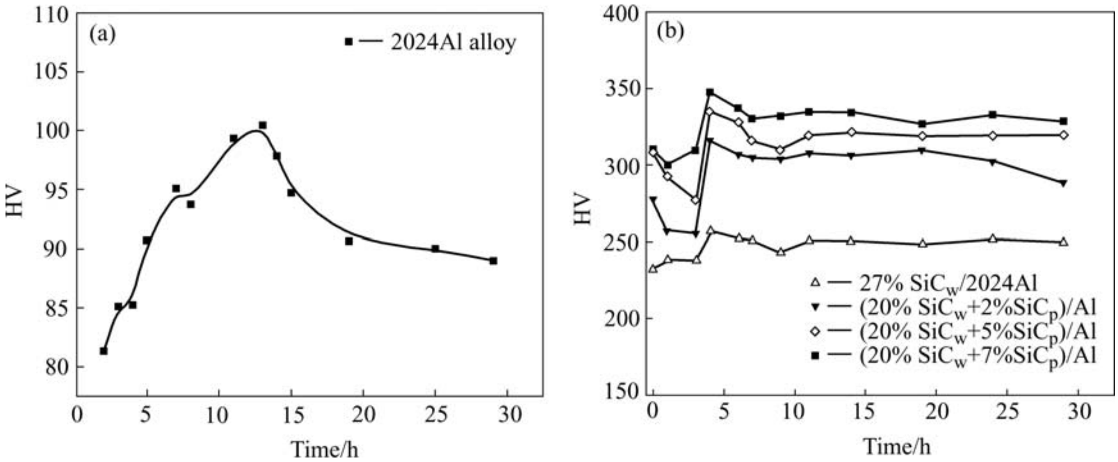

Fig.2 Variation of hardness of 2024Al and composites with time during 190 ℃ aging

than 100 nm in size are advantageous to achieving more attractive properties in the aluminium matrix composites[11]. Better distribution, relatively finer sizes of reinforcement and finer sizes of precipitates in the composite tend to achieve higher hardness, accordingly the mobility of dislocation reduces as Orowan theory described[12, 13].

Two interrelated factors mainly affect the precipitation behaviour of aluminium alloy matrix composites. The first one is the reduction of the retained vacancy sites in composites. The absorption of quench-in vacancies in the high dislocation density matrix inhibits the GP zone formation because the nucleation of the GP zone requires vacancy clusters. Fig.3 presents the DSC thermograms for 2024Al and the hybrid composites. Two exothermic peaks are observed in the unreinforced alloy. The DSC curve of the unreinforced alloy exhibits a weak exothermic peak at 110 ℃ that is in the temperature range for GP zone formation. The DSC trace shows the second exothermic peak at 306 ℃. This peak is indicative of precipitate formation of S' and denotes that the maximum rate of precipitation is achieved at 306 ℃. The DSC curves of the composites are very different from that of the unreinforced 2024Al alloy, exhibiting a reaction peak with no obvious separate GP zone peak.

The second one is the increased dislocation density, which is caused by the large differences in thermal expansion coefficient of matrix alloy and SiC reinforcement. Peak aging times for the hybrid composites are reduced because dislocations afford more nucleation sites for S' precipitation. These results indicate that the addition of both SiC whiskers and SiC nanoparticles accelerates the aging kinetics because of an increase in the dislocation density of the matrix. The high density dislocation can provide a rapid diffusion path, thus accelerating the precipitation rate of S' phase which accounts for the peak hardness[14−17].

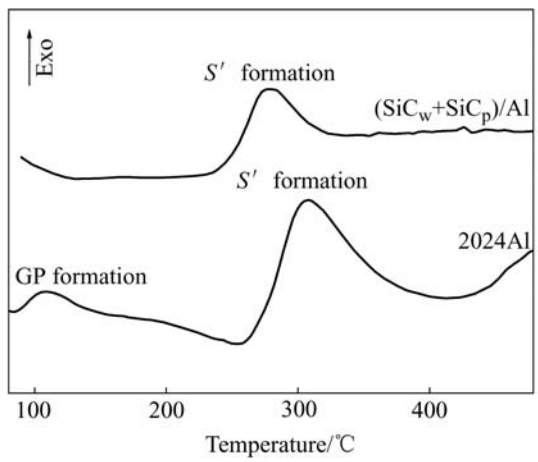

Fig.3 Comparison of DSC traces of solutionized 2024Al and hybrid composites

The hardness of all the hybrid composite samples decreases at the initial stage of aging. This softening trend indicates that some softening mechanism occurs during aging. The overall age-hardening behaviour of the composites can be attributed to a competition between precipitation hardening and recovery softening, both of which are related to the matrix dislocation density[9]. The addition of nanoparticles leads to more interface and higher dislocation density in the matrix than that of SiC_w/Al composite. A high dislocation density means a high strain energy, resulting in a high driving force for recovery. At the beginning of aging, the S' phase has not formed, meanwhile recovery softening occurs. By increasing the aging time, S' phase forms at a higher rate because of the presence of high density dislocation, which are considered favorable sites for S' phase nuclei formation. The observation results also show that S' phase could hardly be observed in the matrix when the aging time is about 2 h, as shown in Fig.4(a). Until the peak aging time, the amount of S' phase with needle type comes to the maximum, as shown in Fig.4(b).

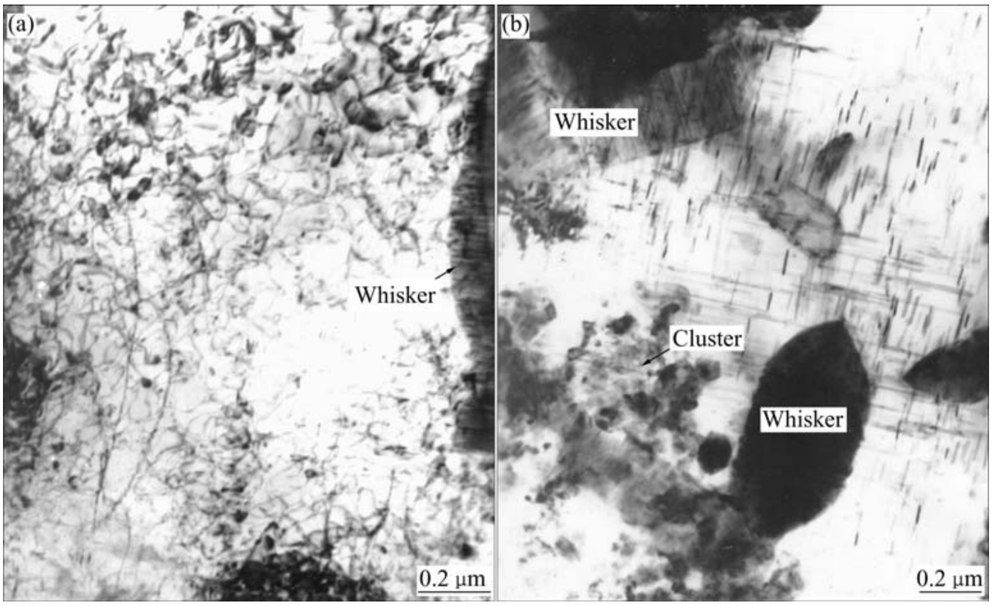

Fig.4 TEM micrographs of (SiC_w+SiC_p)/2024Al composites aged at 190 ℃ for various times: (a) 2 h; (b) 5 h

3.2 Mechanical properties

It is known that the optimum aging conditions are strongly dependent upon the amounts of reinforcements. It can be obtained in this paper that the optimum aging conditions are 4−5 h at 190 ℃ when the amount of reinforcements is from 20% to 27%(volume fraction). On the other hand, the optimum conditions for aging 2024Al alloy is 12−13 h at 190 ℃ after solution treatment. From these results, the microstructure and mechanical properties of these composites can be altered by a suitable aging treatment.

The mechanical properties determined by tensile tests are shown in Table 1. The tensile strength of the composites is found to be sensitive to the content of SiC nanoparticles. As can be seen, the addition of SiC whiskers into the 2024Al alloy greatly increases the elastic modulus and the strength. An increase in volume fraction of SiC nanoparticles from 2% to 7% causes an overall improvement of strength and elastic modulus and a decrease of elongation. These results are in good agreement with the composite theory.

Table 1 Mechanical properties of composites under T6 condition

Material	Tensile strength/MPa	Elastic modulus/GPa	Elongation/ %
AA2024	296	70	17
(20% SiC_w+ 2% SiC_p)/Al	513	124	0.83
(20% SiC_w+ 5% SiC_p)/Al	540	126	0.80
(20% SiC_w+ 7% SiC_p)/Al	620	127	0.77
27% SiC_w/Al	613	126	0.80

The strength of the hybrid composites reflects a cooperative strengthening effect of SiC whiskers and SiC nanoparticles. Dispersion strengthening becomes more obvious with increasing nanoparticle content. With increasing the content of SiC nanoparticles, the strength of the (SiC_w+SiC_p)/Al composites increases not only because of the dispersion strengthening of SiC particle, but also because of the grain fining and high density of dislocation in the matrix due to the addition of SiC nanoparticles. A fine dispersion of SiC particles in the matrix may prevent the grain growth of the matrix alloy during squeeze casting process. Besides, a high density of dislocations, caused by the difference in the thermal expansion coefficient between matrix and reinforcements, were observed in the matrix near to SiC whiskers and SiC nanoparticles, and the dislocation density increases with increasing the content of SiC nanoparticles.

The nanoparticles are more effective in improving the tensile strength than whiskers. In the same volume fraction, finer particles will lead to more amount of interface which increases the dislocation density of the matrix. These dislocations act as the nucleation sites for precipitation during aging. Moreover, the addition of nanoparticles in the composites refines the grain size of the matrix, and the fine space between the nanoparticles prevents the precipitation coarsening in the composites.

4 Conclusions

1) The precipitation behavior of the composite is greatly different from the unreinforced 2024 Al alloy. The addition of both SiC whisker and SiC nanoparticle in 2024Al promotes the nucleation of the S' precipitates and

generally enhances the hardening of composites with respect to the unreinforced alloy. SiC nanoparticles are more effective in enhancing the composites hardness than SiC whiskers.

2) All the hybrid composites investigated here show the peak aging time of 4−5 h. The decrease in hardness during aging in the early stages can be attributed to the dislocation recovery, which is more predominant in the initial stage.

3) The SiC nanoparticles effectively improve the tensile strength of the hybrid composites than the SiC whiskers.

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