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Effects of Mg content on microstructure and mechanical properties of SiC_p/Al-Mg composites fabricated by semi-solid stirring technique

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Abstract: 10% (volume fraction) SiC_p/Al-Mg composites with different Mg contents were successfully fabricated by semi-solid mechanical stirring technique under optimum processing conditions. Effects of Mg content on microstructure and mechanical properties were studied by scanning electron microscopy (SEM), X-ray diffractometry (XRD) and transmission electron microscopy (TEM). The results indicate that SiC particles disperse homogeneously in Al-Mg matrix and interfacial reaction between Al matrix and SiC particles is effectively controlled. Distribution of SiC_p reinforcement and interfacial bonding are improved by adding Mg. Additionally, the mechanical properties of composites are remarkably improved with the Mg content increasing.

Key words: metal matrix composites; SiC; Al-Mg alloy; microstructure; mechanical properties; interface

1 Introduction

Metal matrix composites (MMCs), especially SiC_p/Al composites, attract more and more attentions because of their low expansion coefficient, excellent dimension stability, high specific strength and stiffness, as well as low cost and extensive resources[1]. Great progress for processing and properties of MMCs has been made on various composites in recent decades[2]. Many processing techniques, such as melt infiltration and semi-solid stirring, have been developed to fabricate SiC particles reinforced MMCs. Among these techniques, semi-solid stirring is considered to be the best method to commercially prepare large quantity of composites due to its processing simplicity, flexibility and low cost[3]. The problem of unwettability between reinforcement and matrix of SiC_p/Al composites can be effectively solved by adopting the stirring technique, resulting in homogenous reinforcement distribution and enhanced mechanical properties of the composites.

In semi-solid stirring process, particles are added into semi-solid alloys with stirring, and then cast into a mould for solidification[4]. The mechanical properties of SiC_p/Al composites are strongly related to particles distribution as well as interfacial bond strength between particles and matrix[5−6]. This can be achieved by optimizing stirring parameters[7−8], such as stir temperature and speed. Furthermore, during the stirring casting of SiC_p/Al composites, the addition of Mg into the aluminum melt also helps to improve the wettability of reinforcement with matrix, increasing interface bonding strength and preventing deleterious interfacial reaction[9−11]. Therefore, systematic study on the effects of Mg content on the microstructure and mechanical properties of SiC_p/Al-Mg composites is important to reveal the performance improvement of MMCs.

In this work, SiC_p/Al-Mg composites with different Mg contents were successfully fabricated by semi-solid stirring technique. The effects of Mg content on the microstructure and mechanical properties of composites were investigated.

2 Experimental

Al and Mg ingots with a purity of 99.7% (mass fraction) and α-SiC particles with average size of 10 μm were used to fabricate the composites. SiC particles were calcined at 800 °C for 2 h in air before stirring process in order to form an oxide layer on the surface of particles.

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The SiC_p/Al-Mg composites with 10% (volume fraction) SiC particles and 2.5%, 4.2% and 6.8% (mass fraction) Mg content, respectively, were fabricated by semi-solid stirring technique. Firstly, SiC particles were preheated in a stainless steel crucible in a furnace. Secondly, the molten Al-Mg alloy was quickly poured into the crucible and then the melt temperature was dropped to the semi-solid temperature range. Thirdly, semi-solid alloy and preheated SiC particles were stirred at 612−640 °C with the speed of 500 r/min for 30 min[8]. Fourthly, the semi-solid mixture temperature was raised to 650 °C and further stirred at 250 r/min for 10 min. Finally, the mixture was poured into a mould preheated at 450 °C, and a pressure of 100 MPa was applied by a compressive machine. The pressure was maintained for 3 min, allowing for solidification. The crucible and furnace was filled with pure argon atmosphere to prevent oxidation of aluminum and magnesium.

Tensile tests were carried out using an Instron−5569 universal testing machine at a constant crosshead speed of 0.5 mm/min, with plate-like specimens of 20 mm × 5 mm × 2.0 mm. Five samples were tested for each composition. Microstructural examination was performed by scanning electron microscopy (SEM), X-ray diffractometry (XRD) and transmission electron microscopy (TEM).

3 Results and discussion

3.1 Establishment of semi-solid stirring temperature corresponding to different matrix alloy

Fig.1 shows the solid-liquid zone of Al-Mg alloys with various Mg contents. It is indicated that the semi-solid temperature ranges of Al-2.5Mg, Al-4.2Mg and Al-6.8Mg alloys are 649−620 °C, 640−603 °C and 628−567 °C, respectively.

Fig.2 shows the SEM micrographs of 10% SiC_p/Al-6.8Mg composites fabricated by mechanical stirring at 650 °C (above liquidus) and 612 °C (in solid-liquid range) with the same stirring speed of 500 r/min and time of 30 min. It can be seen from Fig.2(a) that SiC particles agglomerate obviously in composites fabricated at stirring temperature of 650 °C. In contrast, SiC particles distribute homogeneously in the composites fabricated at 612 °C (Fig.2(b)). This is due to the lower viscosity and friction resistance of the melt at the temperature of 650 °C, and thus the friction between reinforcement and matrix is decreased. In this case, it is difficult to disperse SiC particles homogenously in the matrix. However, when the melt temperature is decreased to the semi-solid range of 612 °C, the semi-solid slurry owns a higher viscosity, but maintains a better liquidity at stirring speed of 500 r/min. The vortex generated in the stirring process smashes the solid dendrite in semi-solid slurry, which further improves the distribution of reinforcement in the matrix by enhancing the friction between reinforcement and matrix. However, when the stirring temperature is too low, the solid fraction in the semi-solid slurry increases and liquid viscosity rises rapidly, which probably makes it difficult to carry out the stirring process[7].

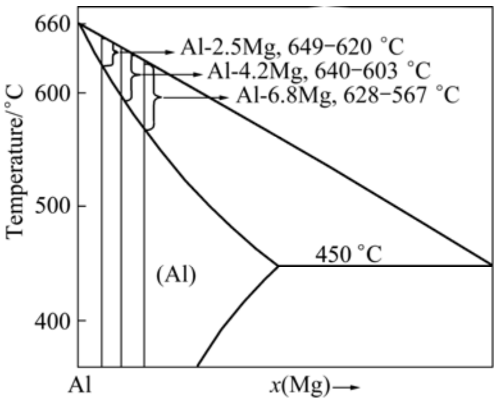

Fig.1 Solid-liquid zones of Al-Mg alloys with various Mg contents

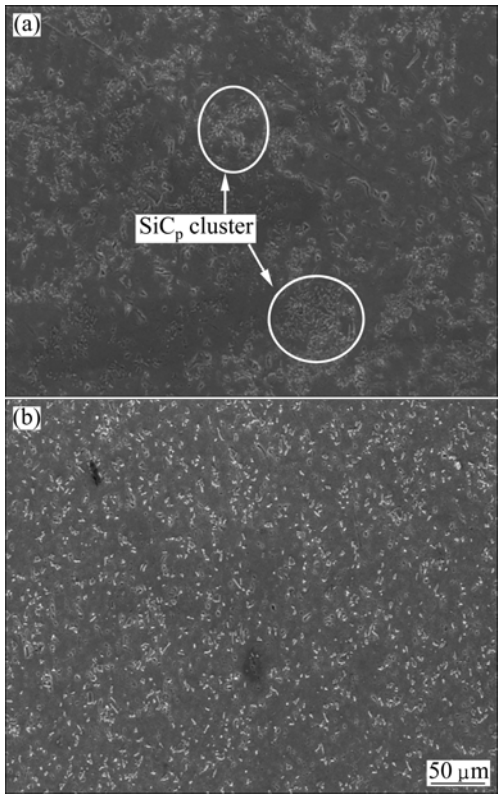

Fig.2 SEM images of 10% SiC_p/Al-6.8Mg composites fabricated at different stirring temperatures: (a) 650 °C; (b) 612 °C

Further systematic study shows that the optimal stirring temperatures are 640 °C, 630 °C and 612 °C for Al-2.5Mg, Al-4.2Mg and Al-6.8Mg, respectively, which corresponds to 45% of solid fraction. Composites with homogeneous microstructure and superior properties can be obtained by semi-solid stirring technique at the optimal temperatures corresponding to 45% solid fraction.

3.2 Phase constitution of SiC_p/Al-Mg composites

In semi-solid stirring process of SiC/Al composites above 650 °C, SiC particles tend to react with aluminum, leading to the formation of Al_4C_3 and Si[10]. Fig.3 shows the XRD result of the 10% SiC_p/Al-2.5Mg composite. It can be seen that only Al, SiC, MgO and $MgAl_2O_4$ exist in the prepared composite and no reflections corresponding to Al_4C_3 are observed. Fig.4 shows the TEM micrograph of the 10% SiC_p/Al-2.5Mg composite and diffraction pattern of $MgAl_2O_4$. It testifies that $MgAl_2O_4$ layer appears on SiC_p surface. The same result is also obtained for 10% SiC_p/Al-4.2Mg and 10% SiC_p/Al-6.8Mg composites. The appearance of $MgAl_2O_4$ layer is related to SiO_2 on SiC surface, which is formed during calcinations of SiC particles in air[9]. The SiO_2 layer also restricts the reaction between Al and SiC. During the stirring process, Al reacts with SiO_2 to form Al_2O_3 through the following reaction:

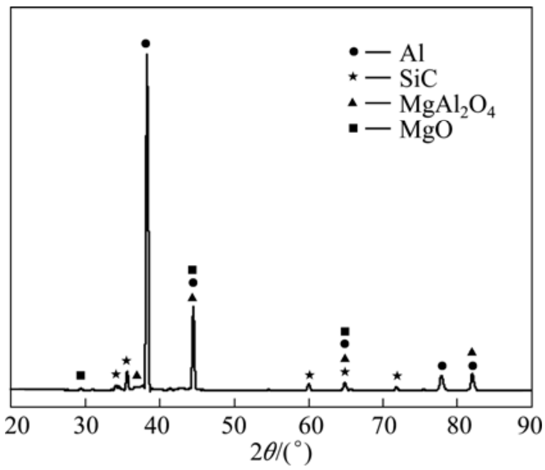

Fig.3 XRD pattern of 10% SiC_p/Al-2.5Mg composite

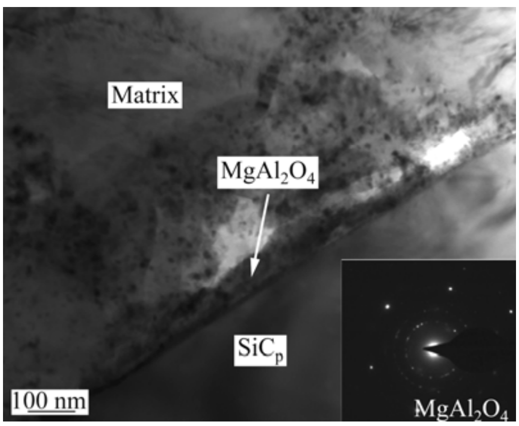

Fig.4 TEM image of 10% SiC_p/Al-2.5Mg composite

$$4Al + 3SiO_2 \rightarrow 2Al_2O_3 + 3Si \quad (1)$$

Meanwhile, Mg reacts with Al_2O_3 by the following reactions[10]:

$$3Mg + Al_2O_3 \rightarrow 3MgO + 2Al \quad (2)$$

$$MgO + Al_2O_3 \rightarrow 2MgAl_2O_4 \quad (3)$$

Because of the above reactions, the wettability between molten Al-Mg matrix and SiC particles is improved and the surface tension of molten Al-Mg alloy with SiC particle is reduced[12−13], which helps in achieving homogeneous particles distribution in the matrix and high interfacial bond strength.

3.3 Microstructure of SiC_p/Al-Mg composites

Fig.5 shows the SEM images of 10% SiC_p/Al-Mg

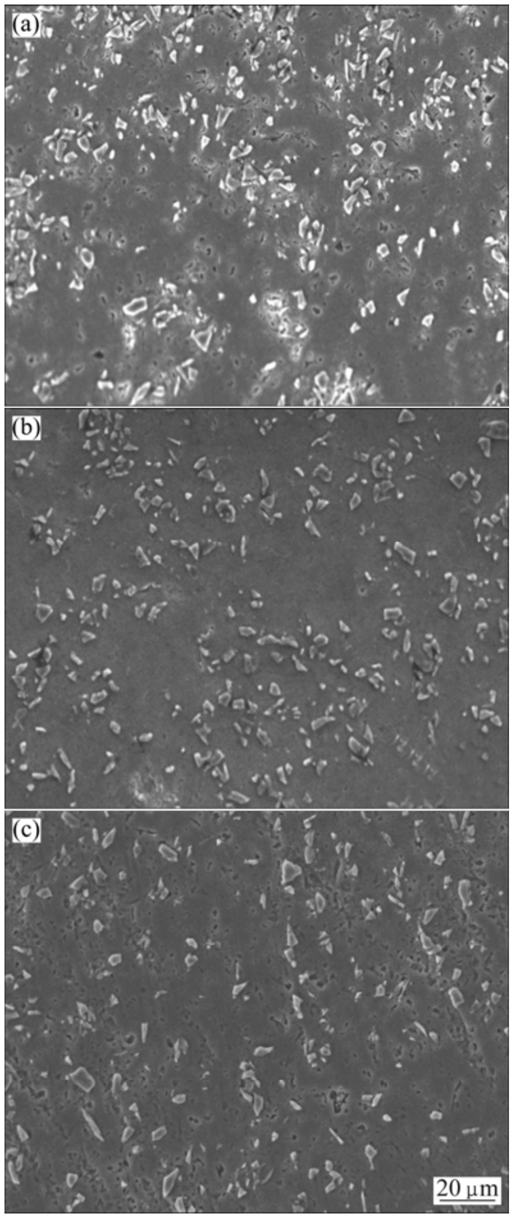

Fig.5 SEM images of 10% SiC_p/Al-Mg composites: (a) SiC_p/Al-2.5Mg; (b) SiC_p/Al-4.2Mg; (c) SiC_p/Al-6.8Mg

composites with different Mg contents. It can be observed that SiC particles distribute homogenously in the composites. SiC particles distribute more homogenously in composites with higher Mg content. The mechanical stirring under the semi-solid state accelerates the dispersion of the particles in the matrix due to a great friction force generated between solid matrix particles and SiC particle reinforcement. By comparison, it can be seen that with increasing Mg content, the particles distribution can be further improved because of the better wettability between matrix and reinforcement[9].

Fig.6 shows the TEM micrographs of 10% SiC_p/Al-Mg composites. Fig.6(a) shows that porosity is not observed at the interface between particles and Al-4.2Mg matrix, and SiC particles are almost perfectly embedded inside the Al-4.2Mg matrix without any interface debonding. Fig.6(b) shows that there is no porosity in the hollow of anomalistic particles due to the better wettability between SiC particles and Al-6.8Mg matrix. This indicates that the matrix can flow into the hollow of anomalistic particles and a good interfacial bonding is formed during the solidification.

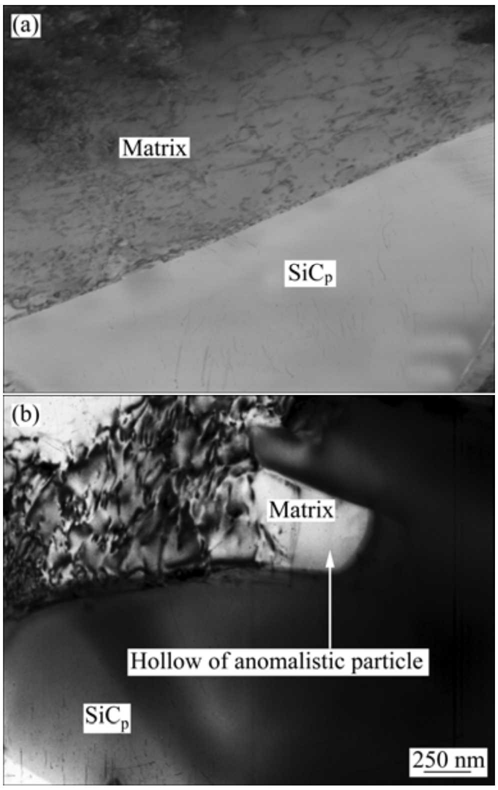

Fig.6 TEM images of 10% SiC_p/Al-Mg composites: (a) SiC_p/Al-4.2Mg; (b) SiC_p/Al-6.8Mg

3.4 Mechanical properties of SiC_p/Al-Mg composites

Table 1 summarizes the tensile properties of Al-Mg alloys and SiC/Al-Mg composites in order to further investigate the contribution of Mg element and SiC_p reinforcement. As expected, the tensile strength (σ_b) of the Al-Mg matrix alloys increases from 223, 232 and 240 MPa to 290, 314 and 344 MPa, respectively, by adding 10% SiC_p reinforcement. The tensile strengths of the composites are 30.0%, 35.3% and 43.3% higher than that of the Al-Mg alloys, respectively. Furthermore, the yield strength ($\sigma_{0.2}$) and elastic modulus (E) of the composites are significantly improved compared with the corresponding Al-Mg matrix alloys. This properties improvement is attributed to the load transfer from matrix to SiC particle and dislocation strengthening of the matrix induced by the addition of SiC particles. However, the elongation of composites decreases because particles impede the slipping of dislocation[14−16].

Table 1 Mechanical properties of 10% SiC_p/Al-Mg composites and Al-Mg alloys

Material	Yield strength/ MPa	Tensile strength/ MPa	Elastic modulus/ GPa	Elongation/ %
Al-2.5Mg	88±2	223±3	62±2	22.6±1.0
Al-4.2Mg	99±3	232±4	64±1	20.4±1.0
Al-6.8Mg	119±3	240±3	65±2	18.8±1.0
SiC_p/Al-2.5Mg	134±2	290±3	76±1	6.8±0.8
SiC_p/Al-4.2Mg	165±3	314±4	82±2	7.1±0.6
SiC_p/Al-6.8Mg	194±4	344±6	84±2	6.7±0.5

In addition, the strength of the composites is significantly improved with Mg content increasing. It can be attributed to the following reasons. 1) The addition of Mg raises the strength of the matrix by the solid solution hardening, resulting in the improvement of mechanical properties of the matrix. 2) Based on the reactions (1)−(3), Mg reacts with SiO_2 to form the $MgAlO_4$ spinel on the surface of oxidized SiC particles. The reaction inhabits the formation of Al_4C_3, which is brittle and deleterious to composites properties. 3) The addition of Mg enhances wetting of SiC particle with matrix alloy, which improves the uniform distribution of SiC particles in the matrix and thus the properties of the composites. The mechanism of improvement of wettability has been discussed in previous section. 4) With increasing the content of Mg, the interfacial bonding between matrix and SiC particles is enhanced, resulting in the increase of interfacial bonding strength[11].

However, higher Mg content in Al-Mg alloy is not suitable due to the poor corrosion resistance of Mg. And when the content of Mg is higher, a brittle compound Al_3Mg_2 forms in the Al-Mg alloy because of the reaction between Mg and Al, resulting in the decrease of mechanical properties for application. Therefore, the maximum Mg content in Al-Mg alloy is about 6%. In addition, previous investigation[11] indicates that with further increasing the Mg content, SiC_p will be degraded and some defects will arise in composites during the fabrication of composites by liquid phase technique.

4 Conclusions

1) The 10% (volume fraction) SiC_p/Al-Mg composites with homogeneous particle distribution and superior mechanical properties are successfully fabricated by semi-solid mechanical stirring technique.

2) The distribution of SiC_p reinforcement in matrix is further improved by the superior wettability between reinforcement and matrix, with increasing Mg content.

3) The prepared composites exhibit superior tensile strength compared with Al-Mg alloys. In addition, the mechanical properties of the composites increase with increasing Mg content.

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