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Processing, microstructure and mechanical properties of micro-SiC particles reinforced magnesium matrix composites fabricated by stir casting assisted by ultrasonic treatment processing

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ABSTRACT

The novel stir casting assisted by ultrasonic treatment processing was studied. Unlike traditional stir casting, short semi-solid stir time was needed for addition and pre-dispersion of the particles in the novel processing. For ultrasonic treatment, there existed an optimal time. Both too short and too long time for the treatment resulted in nonhomogeneous particle distribution. Furthermore, the liquid stirring after ultrasonic treatment was proved to be necessary to further improve particle distribution. The mechanical properties of the composites fabricated by different parameters indicated that ultrasonic treatment evidently improved the mechanical properties compared with traditional stir casting. 5–20% SiCp/AZ91 composites were fabricated by the novel processing. The particle distribution was uniform in these composites. The grains were refined by addition of SiC particles. Grain sizes of composites decreased with the increases of particle contents. The ultimate tensile strength, yield strength and elastic modulus were enhanced as the particle contents increased.

1. Introduction

Magnesium matrix composites have become of great interest in the lightweight fields because of their high specific stiffness and high specific strength [1–3]. However, magnesium matrix composites are limitedly used due to their high cost. Their high cost usually comes from three aspects: reinforcements, fabrication processing and secondary deformation. Thus, economical particles and high efficient production methods should be developed.

Micro-particles are very economical because of their low prices and easy dispersion during fabrication. The micron-particle reinforced Mg matrix composites own the potential commercial use for its relatively low cost and good mechanical properties. Micron-particle reinforced metal matrix material is usually produced by powder metallurgy [4,5], high-energy ball milling [6], sputtering [7] and stir casting [8–10], etc. Among all of these methods, stir casting is regarded as the most productive and economical. However, long stir time is necessary to obtain uniform particle distribution. This often results in too much gas and oxidation to Mg matrix. Thus, it is necessary to reduce the stir time in order to fabricate high-quality composites. Recently, ultrasonic treatment is used to disperse nano-particles because of ultrasonic cavitation effect [11]. The cavitation effect would produce a lot of ultrasonic cavitation in the melting metal, which would collapse with high pressure (above 1000 atm), temperature (~5000 °C) and heating and cooling rates (above 10^{10} K/s) [12]. This would disperse the existed agglomeration consisted of micro-SiC and clean the surface of SiC particles. In addition, ultrasonic treatment can effectively degas Mg melt. Therefore, ultrasonic treatment is very effective to reduce gas and oxidation as well as dispersing particles. However, it is very difficult or time-consuming to add particles to melt in the single ultrasonic treatment processing. This evidently raises the cost of Mg matrix composites. Besides, the effect of ultrasonic treatment is very micro-localized. Thus, single ultrasonic treatment may be not a good method to fabricate micron-particle reinforced Mg matrix composites. If mechanical stir is combined with ultrasonic treatment, the disadvantages of both mechanical stir and ultrasonic treatment can be well overcome. Thus, in this work, we combine stir casting with ultrasonic treatment to fabricate micron-particle reinforced Mg matrix composites.

Although ultrasonic treatment has been successfully used to fabricate metal matrix nanocomposites, up to now, there are no proper methods using ultrasonic treatment to fabricate

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Table 1
Chemical composition of AZ91D magnesium alloy.

AZ91D	Al	Zn	Mn	Si	Cu	Ni	Fe	Be	Mg
Mass percentage	9.29	0.71	0.23	0.019	0.001	0.001	0.0019	0.0014	Balance

micron-particle reinforced magnesium matrix composite. Thus, in this work, the stir casting assisted by ultrasonic treatment processing was studied in order to develop a good processing to fabricate the micron-SiC particulate reinforced magnesium matrix composite.

2. Experiments

In this study, AZ91D magnesium alloy was selected as the matrix, whose chemical composition is listed in Table 1. SiC particles in the average diameter of 10 μm were selected as the reinforcement. 10 μm 10 vol% SiCp/AZ91D magnesium matrix composites were chosen as the example to study the fabrication processing, and then magnesium matrix composites with different volume fraction were fabricated. The device producing ultrasonic waves consists of a transducer coupled with a maximum power of 2 KW and frequency of 20 kHz. Six fabrication parameters were conducted in order to investigate the effects of semi-solid stirring, ultrasonic treatment and liquid stirring on the mechanical properties and particles distribution, as shown in Table 2. The temperature–time sequence for the stir casting assisted by ultrasonic treatment was shown in Fig. 1. In the beginning, AZ91 alloy was melt under the protection atmosphere of mixed CO2/SF6. Then, it was cooling down to the semi-solid condition. The melt was stir in the semi-solid condition. At the same time, the preheated SiC particles were added into the melt. After semi-solid stirring, the melt were heated up to 700 °C and then ultrasonic probe was imposed to the melt. After ultrasonic treatment, the melt was stirred in the liquid condition without vortex formation. Finally, the melt was poured into a preheated metal mould (400 °C) and solidified under about 100 MPa. It should be noted that the ultrasonic treatment was only used in molten metals, not in solidifying melts. Thus, the ultrasonic treatment does not significantly change the distribution and size of the $Mg_{17}Al_{12}$ [13].

Optical microscopy (OM), scanning electron microscopy (SEM) (Quanta 200FEG) and transmission electron microscopy (TEM) (Tecnai F30) were used to study the microstructure of the composite and the distribution of the micron particles. The specimens for microstructure analysis were mechanical polished and etched by picric acid [5 ml acetic acid + 5.5 g picric acid + 100 ml H_2O + 90 ml ethanol]. Specimens for TEM observation were firstly prepared by grinding-polishing the sample to produce a foil of 50 μm thickness followed by punching 3 mm diameter disks and then thinned by ion beam.

The tensile mechanical properties of SiCp/AZ91 composites were measured by using an Instron 5569 universal testing machine at a constant cross-head speed of 0.5 mm/min. The tensile tests were in accordance with ASTM: E8/E8M-13a (http://www.astm.org/Standards/E8.htm) standards. The tensile property data (yield strength/YS, ultimate tensile strength/UTS, elastic modulus/E and elongation/δ) were based on the average of 3–5 tests.

3. Results and discussion

3.1. The effect of semi-solid stir time to particle distribution

Fig. 2 shows the distribution of SiC particles in the composite fabricated by different semi-solid stir time (EXP-1, EXP-2). Obvious particle clusters were not observed in the composite fabricated by EXP-1, and some clusters were observed in the composite fabricated by EXP-2. The semi-solid stir time of EXP-1 was shorter than that of EXP-2. The viscosity of Mg melt increased with the increase of the semi-solid stir time. The high viscosity will decrease the effect of ultrasonic cavitation [14]. In term of particle distribution, short semi-solid stir time should be employed. In addition, for stir casting assisted by ultrasonic treatment, the function of semi-solid stir is fast-addition of particles into the melt and pre-dispersion of particles before ultrasonic treatment. More gas and oxidation is entrapped to the Mg melt after long time stir. Thus, short semi-solid stir time should be better for stir casting assisted by ultrasonic treatment. For this study, the semisolid stir time was 5 min.

From Fig. 2(c) and (d), most particles were segregated along grain boundaries in the micro-scale level. Many particles distributed along grain boundaries, like necklaces. This is very normal for metal matrix composites fabricated by stir casting. This kind particle distribution is called "necklace-type" [15], which is caused by the "push" effect of solidification front.

3.2. The effect of ultrasonic treatment time to particle distribution

Fig. 3 shows particle distribution in the composite fabricated with different ultrasonic treatment time (EXP-1, EXP-3, EXP-4 and EXP-6). It should be noted that EXP-6 is traditional stir casting processing. The particles distribution was better in the composite fabricated by EXP-1, as shown in Fig. 3(a). As shown in Fig. 3(g), particle clusters and oxidation were observed in the composite fabricated by EXP-6. By comparing EXP-1 and EXP-6, it indicates that ultrasonic treatment can effectively eliminate particle clusters and disperse particles. During the ultrasonic treatment, the Mg melt was subjected to the effect of random compression–expansion cycles and the ultrasonic cavitation was formed. In general, the cluster of micron SiC particles was lose and filled with air, metal vapor or inert gas, which consequently was served as nuclei for ultrasonic cavitation [16]. Then, the cavitation gradually grew and collapsed

Table 2
Different fabrication parameters for 10 μm 10 vol% SiCp/AZ91D composites.

Experiment number	Semi-solid stir		Ultrasonic treatment		Liquid stir	
	Time/min	Speed/rpm	Time/min	Power/watt	Time/min	Speed/rpm
EXP-1	5	1000	20	600	0	200
EXP-2	10		20		0	
EXP-3	5		10		0	
EXP-4	5		30		0	
EXP-5	5		20		5	
EXP-6	20		0		15	