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Effects of heat treatment on the microstructure and microplastic deformation behavior of SiC particles reinforced AZ61 magnesium metal matrix composite

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ABSTRACT

In this paper, solution and ageing heat treatment processes were used to improve microplastic deformation behaviors of as-cast SiCp/AZ61 magnesium metal matrix composites (Mg MMCs) fabricated by stir casting method. Higher percentages of SiC particle reinforcements showed higher microhardness values. Ageing heat treatment process was seen significant on the 12 h aged 2 wt% SiCp/AZ61 Mg MMC which induced lower microhardness value. At the 12 h ageing of 2 wt% SiCp/AZ61 Mg MMC the formations of particle free regions and discontinuous secondary phases were observed. For a higher ageing time, the secondary phases distribution became continuous and laminar structure. The addition of 5 wt% SiC particles resulted in the formation of Mg_2Si phase throughout the whole heat treatment processes. The addition of SiC particles reinforcements increased the phase heterogeneity during ageing heat treatment processes. XRD patterns revealed the presence of nanocrystalline $MgSiO_3$ phase on the 12 h aged 2 wt% SiCp/AZ61 Mg MMC. Using reference intensity ration (RIR) method a 51.6% of $MgSiO_3$ phase was determined which can cause the formation of microplastic deformation behavior. And also, the maximum average crystallite size, compressive microstrain and microcrack-free phase boundaries were observed on the 12 h aged 2 wt% SiCp/AZ61 Mg MMC.

1. Introduction

Magnesium alloys are becoming increasingly attractive structural materials in aerospace, automotive and electronics applications because of the lowest density of magnesium compared to structural metals (approximately two third of aluminum), their high specific strength and good casting properties [1]. However, the low performance of magnesium alloys in strength, creep resistance, corrosion resistance, and wear resistance behavior can impose constraints on their structural applications [2,3]. Therefore, magnesium alloys need to be subjected to different cold working, thermomechanical forming and solution heat treatment processes to enhance good mechanical properties based on the service requirements. It is a common practice to optimize the mechanical properties of magnesium alloys by considering parameters like grain size, the percentage of inclusions, grain boundary morphologies, precipitation processes, the coefficient of thermal expansion (CET) and so on. Severe plastic deformation (SPD) process is one of the most commonly used processes to refine grain size which can improve ductility and strength for more than twice of the as-cast form [4,5]. However, the complex nature of hexagonal closed packed crystal structure is another issue on the plastic deformation characteristics of magnesium alloys. Magnesium alloys with the higher volume fraction of basal orientations have higher hardness value because the dislocation density and stored energy of basal orientations are smaller compared to off - basal orientations [6].

The other method of improving the mechanical properties of magnesium alloys is by using reinforcing hard particles which can increase the strength, creep resistance, wear resistance and corrosion resistance behavior of magnesium alloys. Metal matrix composites (MMCs) can be considered as isotropic materials and its fabrication processes are similar to monolithic materials. It is also an effective approach to attain the two basic requirements, light weight, and improved mechanical properties, which were a trade-off in monolithic materials. Depending on the type, size, content and shape of reinforcing particles the mechanical properties of light weight matrix materials can be improved considerably with the addition of reinforcements [7]. Furthermore, the presence of reinforcing particles in the matrix can facilitate the early stage nucleation of dynamic recrystallization processes and reduce the average grain size of the matrix materials [8].

The overall structural performance of MMCs is significantly affected

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by the percentage of defects included during the fabrication processes. Nowadays, different fabrication processes are being used to produce MMCs such as powder metallurgy, stir casting, squeeze casting, spray deposition, electroplating, and physical vapor deposition [9]. Different factors can be considered to select the most relevant fabrication method of MMCs such as fabrication cost, uniform distribution of reinforcements, minimum porosity level, less chemical reactivity during casting, casting capacity and easy adaptability of fabrication processes. Stir casting fabrication process is easy, flexible, has large scale casting capacity, commercially applicable and has high conventionality which results in low production cost [10]. In this research, stir casting method was used to fabricate SiCp/AZ61 Mg MMCs cast ingots with different weight percentage of SiC particles.

However, it is less practical to use the cast composites for direct applications, especially for load critical structural applications because the addition of SiC particles (SiCp) reinforcements can induce higher porosity level compared to monolithic materials. It requires further processing to enhance much better mechanical properties. Severe plastic deformation (SPD) process is an advanced approach to enhance superior mechanical properties on Mg MMCs to meet a number of requirements in engineering applications. SPD process can produce ultrafine grain structure and also uniformly distributed grain sizes throughout the whole volume of the processed material to provide stable mechanical properties. Equal channel angular pressing (ECAP) extrusion process is one of the SPD processes and used to refine the particle size to the submicron and nano levels. However, ECAP processing of Mg MMCs with the same preheats treatment conditions (homogenization heat treatment condition) of magnesium alloys was not effective, as shown in Fig. 1. Because pre-deformation heat treatment processes are applied to magnesium alloys plastic deformation processes to homogenize $Al_{12}Mg_{17}$ secondary phases formed during casting. And also, MMC is a combination of two extremely different constituents, hard reinforcing particles, and ductile matrix. During ECAP process the hard reinforcing particle crystalline structures can induce damage on the crystallites of the ductile matrix which can increase the formation of micro cracks and debonding fracture. Therefore, it needs different heat treatment conditions to develop phase heterogeneity which can stimulate local inhomogeneity by developing microplastic zones between the hard and ductile phases to facilitate the ease of crystal structure slip systems during ECAP processes. The effective stress in Mg MMCs can be represented as follows by assuming constant deformation process of each phase, [11].

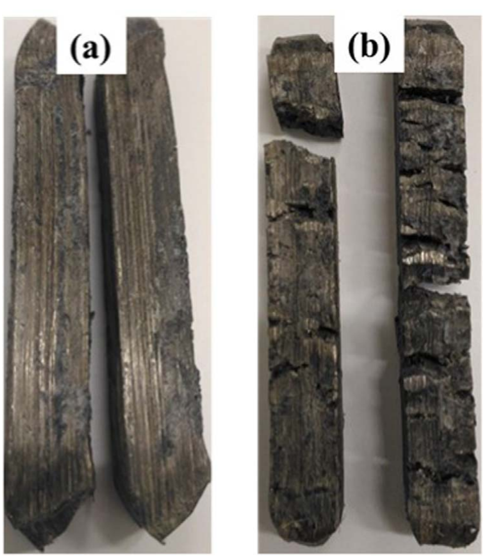

Fig. 1. Equal channel angular pressing (4 pass) severe plastic deformations of homogenized (at 200 °C for 24 h). (a) as-cast AZ61 magnesium alloy and (b) as-cast 2 wt% SiCp/AZ61 Mg MMC.

$$\sigma = \sum_{i}^{n} f_i \sigma_i \sum_{i}^{n} f_i = 1 \tag{1}$$

Where σ_i are the stresses in each phase and f_i are each phase volumetric fractions.

In this paper, heat treatment processes were applied on SiCp/AZ61 Mg MMCs to develop precipitates of heterogeneous phases to enhance microplastic deformation behaviors. The difference in the physical and mechanical properties of heterogeneous phases can create stress-strain inhomogeneity along the grain boundaries and on the microvolumes of nanocrystalline ductile secondary phases. The formations of precipitate phases, their distributions along the grain boundaries of the matrix materials and their microstructural behaviors depend on the optimal heat treatment conditions and SiC particles weight percentage. The crystallite size, quantitative value and microstructural behavior of each constituent phase have a significant influence on the formations of inhomogeneous stress-strain states. Therefore, to understand the cumulative effects of each precipitate, first the quantitative, qualitative and microstructural behaviors of the newly formed heterogeneous phases were investigated by using, scanning electron microscope (SEM), energy dispersive spectrometry (EDS) and X-ray diffractometer (XRD) analysis. Their cumulative effects were investigated by using microhardness test, fracture morphologies, crystallite size and microstrain distribution analysis.

2. Experimental procedure

AZ61 magnesium alloy with the chemical composition (wt%) of Al-5.95, Zn-0.64, Mn-0.26, Fe-0.005, Si-0.009, Cu-0.0008, Ni-0.0007 and Mg balance was used as a matrix material. Approximately, 10 µm diameter size of SiC particles (SiCp) was used as reinforcement. The weight percentage of SiCp was 2 and 5, as shown in Table 1. Stir casting method was used to fabricate AZ61 magnesium alloy and SiCp/AZ61 Mg MMCs casts, as shown in Fig. 2. During casting, CO_2 and SF_6 gases were used at 400 °C to prevent burning of AZ61 magnesium alloy, and also argon gas was used at 700 °C to avoid oxidation. During casting processes there were 15 min stabilizing time for each step of 100 °C temperature increments up to 700 °C for both pure AZ61 and SiCp/AZ61 casts. After a 30 min stabilization at 760 °C the SiCp/AZ61 melt was stirred at 300 rpm for 3 min to have uniformly distributed SiCp throughout the magnesium matrix. Finally, the mixed melt was poured down to the mold placed inside the lower chamber of the furnace to get the final cast ingot as shown in Fig. 2.

Two different batches of sample sizes were cut from the three types of cast ingots (Table 1). First, a 10 mm × 5 mm × 5 mm sample sizes were cut from each type of cast ingots for microhardness test, SEM, and XRD analysis. Secondly, a 55 mm × 10 mm × 10 mm sample sizes were cut from each type of cast ingots for Charpy impact test as shown in Fig. 3. From the first category, some of the 10 mm × 5 mm × 5 mm sample sizes were solution heat treated (homogenized) at 410 °C for 24 h and some of them left as-cast. In the case of Charpy impact test samples, all the 55 mm × 10 mm × 10 mm sample sizes were solution heat treated (homogenized) at 410 °C for 24 h. Finally, for both first and second batches, some of the solution heat treated samples were artificially aged at 200 °C for different periods of ageing time.

Microhardness tests were conducted by using MicroVickers Hardness Testing Machine (Akashi MVK-H1) for all types of specimens

Table 1
Weight percentage and particle size of SiCp in SiCp/AZ61 Mg MMCs casts.

Types of cast ingots	SiCp wt%	SiCp size (µm)
Pure AZ61	0	–
SiCp/AZ61	2	10
SiCp/AZ61	5	10