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Characterization of Aluminium-Magnesium (Al-Mg) Alloy Reinforced with Strontium (Sr) by Casting Technique

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ABSTRACT

Aluminium-metal matrix composites (Al-MMCs) are quite attractive due to their low density, ability to be reinforced by precipitation, good corrosion resistance, high thermal and electrical conductivity, and high damping capacity. In this study, the aluminium-magnesium (Al-Mg) master alloy was reinforced with 0.5 to 1.0 wt% strontium (Sr) by casting technique. Then, the Al-Mg-Sr composite alloy was characterised by its mechanical properties and microstructure characterization. An Instron tensile machine and a Vickers hardness tester were used to determine the tensile strength and hardness of the Al-Mg-Sr composite alloy. The Gamry potentiometer electrode was used to determine the corrosion rate of this composite alloy. From the results, increased Sr content increases the tensile strength and hardness of the Al-Mg alloy. Field emission scanning electron microscope (FESEM) results show that the synthesised composite alloys have a uniform distribution of reinforcement, which tends to be fine and associated with a clean interface with the metal matrix. X-ray diffraction (XRD) analysis confirms that only the elements Al, Mg, and Sr were detected during characterization. The morphology shows that the particles of the Sr phase have a dendritic structure. In the corrosion test with the Gamry potentiometer electrode, Al-Mg with a composition of 1.0 wt% Sr showed the best results in terms of corrosion rate compared to cast Al-Mg with 0.5 wt% and the Al-Mg alloy itself. All the summarised results show that Al-Mg alloy composites containing different weights of Sr phase were successfully fabricated and the particles were uniformly distributed in the matrix of the composites.

1. Introduction

Aluminium-metal matrix composites (Al-MMCs) are widely used in engineering structures and components with low requirements for weight, density, tensile strength, workability, and corrosion resistance [1,2]. Aluminium has been widely used in aerospace and automotive applications because of its good strength-to-weight ratio. On the other hand, pure aluminium metal is too soft for use and does not have the tensile strength required for aircraft and helicopters. Aluminium alloys have played

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a crucial role in the aerospace industry since the introduction of metal-skinned aircraft. Aluminium-magnesium (Al-Mg) alloys are lighter and less explosive than other aluminium alloys with a high magnesium content [3].

Aluminium-magnesium alloys are most commonly used in engineering due to their high properties such as lightness, temperature and heat resistance, flexibility at low temperatures, non-toxicity and many more. Some aluminium alloys are as strong as steel, in some cases even stronger than steel. Aluminium products can recover both shape and size under static and dynamic conditions, which is advantageous when flexible strength is required [4].

Grain size is a critical factor in determining the properties and durability of some materials. The Hall-Petch equation states that the yield strength is inversely proportional to the square root of the grain size [5]. A grain size distribution with two separate peaks in the coarse grain and nanofine grain ranges has such a large difference that it can significantly affect the material. For example, bimodal materials are developed to maximise the strength and ductility of the material. Bimodal aluminium materials are reinforced with ceramic particles to create complicated metal matrix composites and achieve better strength. The development of MMC was noted at the time for its high strength modulus and increased temperature resistance, but also for its light weight. Not only because of their properties, but also because of their low manufacturing cost, easy processing, and little difference from fibre reinforced materials [6].

Most studies have found that the addition of inoculants can improve the properties. Inoculation is a grain refinement technique that increases the number of grains formed during solidification. The addition of boron (B) is the most widely used method for seeding Al-MMC alloys. By adding a small amount of strontium (Sr), the researchers found that these particles can form α- or β-phases depending on the alloy composition. A good distribution between inoculant and nucleating phases was found; however, the borides that form can have flakes or needle-like morphologies. The effects of the flakes included decreased creep, resistance, and tensile strength.

2. Methodology

Aluminium-magnesium (Al-Mg) was melted with Sr in a casting process. Microstructural and mechanical analyses were performed to determine the properties and characterization of the Al-Mg-Sr composite alloy.

Al-Mg-0.5 wt% Sr and Al-Mg-1.0 wt% Sr composite alloys were prepared by casting. For the base alloy, Al-7 wt% Mg was melted in a furnace at 720 °C. After melting the alloy, the homogenization process was carried out for about 15 minutes. Finally, the alloy was poured into a stainless steel mould and cooled at room temperature. The same method is used as standard for different Sr contents of 0.5 and 1.0%. First, the melting process of Al-Mg was carried out. Then, the homogenization process was initiated 15 minutes before the addition of Sr. Then Sr was gradually mixed in the furnace, and finally the mixture was poured into the mould [9].

Hardness and tensile tests were carried out to determine the properties of Al-Mg with Sr addition. The hardness test is analysed by Vickers microhardness. The microhardness test method [10] specifies a series of light loads where a diamond indenter is used to create an indentation that is measured and converted to a hardness value. Tensile testing is analysed using Instron's ultimate tensile testing machine (UTS). In this test method, a tensile force is applied to a specimen, and the measurement is made by responding to the stress. The data that can be collected are the final t ensile strength and hardness [11].

Field emission scanning electron microscopy (FESEM) was used to observe the microstructure of Al-Mg alloy reinforced with Sr. FESEM is an analytical method that scanning tiny topographic details on the surface of whole or fractionated objects, providing topographic and elemental information at magnifications from 10x to 300,000x and unlimited depth of field. Simultaneously, XRD shines X-rays, also known as wavelength, through a material sample to analyse the structure of crystalline materials [12].

3. Results

3.1 Mechanical Properties of Al-Mg-Sr Composite Alloy

Different Sr compositions were used for grain refinement, resulting in two alloy types with different compositions, 0.5 and 1.0 wt% Sr. The results are shown in Figure 1(a) and Figure 1(b). By adding a small amount of Sr, the hardness and tensile strength of the alloy gradually increase. The tensile strength of the alloy was determined using the machine UTS. Figure 1(a) shows the result of tensile test on Al-Mg alloy with different Sr compositions. The result shows that with the addition of 0.5 and 1.0 wt%, the value of tensile strength was 312.3 and 344.3 MPa, while for Al-Mg itself (without Sr), the value was 292.7 MPa.

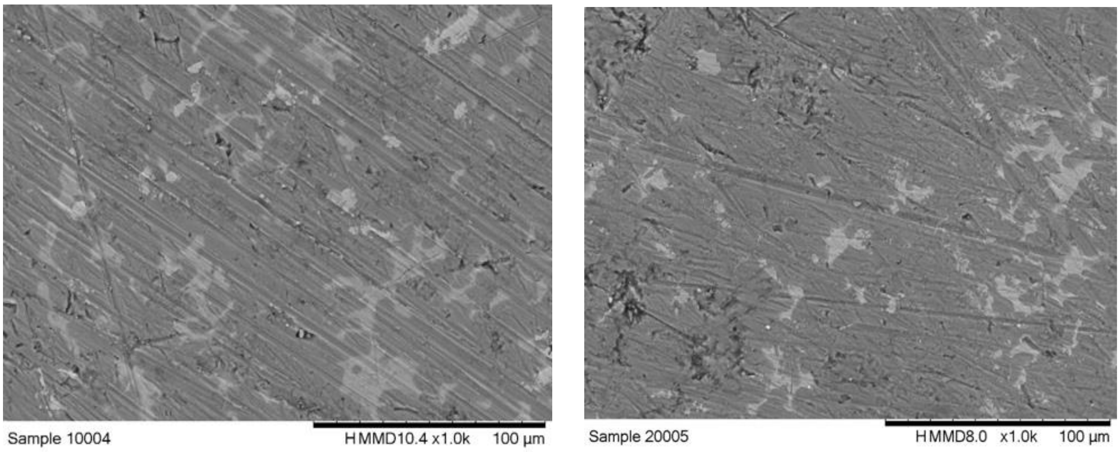
(a) (b)

Fig. 1. Histogram of (a) tensile strength, and (b) hardness properties of Al-Mg alloy reinforced with different Sr contents

3.2 Microstructure of Al-Mg-Sr Composite Alloy

Figure 2 shows that the microstructure of the grains becomes more with a higher concentration of Sr. The increasing concentration of Sr will help avoid forming pores and, as a result, reduces the alloy's flaws. Based on previous research, adding Sr as grain refinement will enhance alloys' tensile strength and microstructure stability. Sr would also make the porosity of the grain structure decrease [13]. The difference in porosity characteristics thus depends on the amount of Sr oxides present in the solidified structure [14]. Porosity often causes a reduction in mechanical properties and results in low-quality castings. Sr additions also interact with the grain refinement of aluminium foundry alloys [15-18]. Sr tends to react with boron (B) in aluminium melts to form the strontium boride SrB_6 compound [19].

Figure 2(a), which contains 0.5% Sr, shows that the grain boundaries are more distinct and broader than in Figure 2(b). The volume fraction of the particles is lower. The lower volume fraction of particles is most likely due to the higher Sr content in the alloys. Farahany *et al.,* [20] found that the coarse and dendritic structures of the magnesium silicide (Mg_2Si) reinforcement particles were converted to a polygonal shape and that the mean size and aspect ratio decreased by 30% and 7%, respectively. In comparison, the particle density increased to about 182.4%. They also observed that more cracked particles and fewer decohered particles were observed after the addition of 0.01 wt% Sr.



(a) (b)

Fig. 2. Morphology of Al-Mg alloy reinforced with (a) 0.5 wt.% and (b) 1.0 wt.%Sr observed by FESEM with 1000X magnification

3.3 Corrosion of Al-Mg-Sr Composites Alloy

Polarisation is the displacement of an electrode potentiometer from its equilibrium value. The magnitude of this displacement is the overvoltage expressed in plus or minus volts (or mV) with respect to the equilibrium potential [21]. Potentiostatic polarisation was used to calculate the electrochemical parameters. Anodic and cathodic polarisation potentials were measured on a reference sample and on Al-Mg alloys in 0.5 M NaCl solution in the current density range of 2 to 6 mA/cm^2 [22].

The electrochemical parameters such as corrosion potential (E_{corr}), corrosion current (I_{corr}) and corrosion current density were calculated and summarised in Table 1. Based on the results, the difference between Al-MMCs (Al-Mg) with 0.5% Sr and 1.0% Sr composition was investigated. The I_{corr} value of Al-Mg with 0.5% Sr is 21.00 mA, while Al-Mg with 1% Sr is 19.70 mA. However, the E_{corr} value remained the same and is -737.0 mV. On the other hand, the corrosion rate of Al-Mg with 0.5% Sr composition gave the best corrosion rate, which is 5.340×10^3 m/y.

Farahany *et al.,* [20] investigated the corrosion behaviour of Al-Mg-Si alloys reinforced with 0.01 wt% Sr using polarisation corrosion tests in sodium chloride solution. They found that the corrosion current density increased from 0.58 $\mu A/cm^2$ to 1.8 $\mu A/cm^2$ with the addition of 0.01 wt% Sr, which was attributed to the extended boundaries between the Al and Mg_2Si reinforcement particles. The polarisation test also showed that the addition of Sr resulted in a shift of the corrosion potential in a more negative direction. The corrosion current density also increased with the addition of Sr.

Table 1
I_{corr}, E_{corr}, Corrosion rate of Al-Mg alloy

	Al/Mg + 0.5 wt%Sr	Al/Mg + 1.0 wt%Sr
I_{corr} (mA)	21.00	19.70
E_{corr} (mV)	-737.0	-737.00
Corrosion rate (m/y)	5.702×10^3	5.340×10^3

In comparison to other Sr compositions, Figure 3 shown Al-Mg alloy with 0.5 wt.% Sr displayed the best corrosion resistance. Corrosion rate was 5.340 x 10^3 m/y at 0.5 wt.% Sr, but it dropped to 5.702 x 10^3 m/y at 1.0 wt.% Sr for Al-Mg alloy. The alloy's ability to resist corrosion is demonstrated by the alloy's lowest corrosion rate that was shown in equation below. The Al-Mg alloys are less susceptible to corrosion in the following order:

Al-Mg-0.5 wt.% Sr > Al-Mg-1.0 wt.% Sr

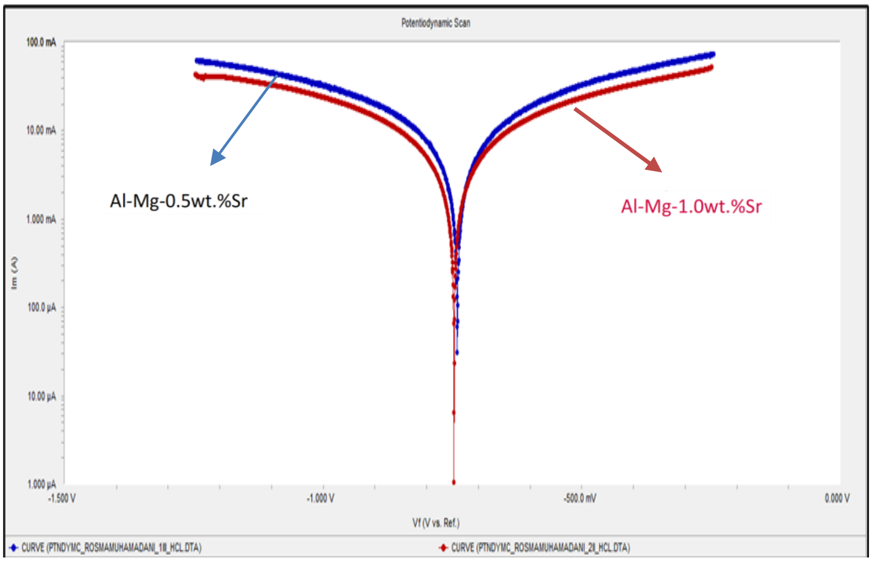


Fig. 3. Anodic and cathodic polarized curves of Al-Mg alloy reinforced with 0.5 and 1.0 wt.% Sr

4. Conclusions

The addition of Sr to Al-Mg makes the grain finer by reducing the size of the grain. The Al-Mg-Sr composite alloy sample has a finer grain size, resulting in higher tensile strength and improved hardness properties. The addition of Sr to Al-Mg is the most efficient technique for producing an alloy with good properties. To achieve further exceptional properties, Sr can be added to Al-MMCs to modify their microstructure while improving their mechanical properties.

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