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COMPOSITES THEORY AND PRACTICE

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EFFECT OF MAJOR ALLOYING ELEMENTS ZN AND MG ON MICROSTRUCTURE AND MICROHARDNESS OF AA7075 ALLOYS AND THEIR COMPOSITES

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The present research work focuses on studying the effect of the major alloying elements on the microstructure and hardness of 7xxx series aluminium alloys and their composites. AA7075 aluminium alloy was used as the base material and different weight percentages of alloying elements zinc (Zn) and magnesium (Mg) were added at ratios 1:1, 2:1 and 3:1 to the base material. Afterwards, the modified aluminium alloys were used as matrix materials for the fabrication of aluminium alloy matrix composites (AAMCs) by adding different weight fractions of silicon carbide (SiC) as reinforcement material. Both the alloys and the AAMCs were fabricated by means of stir casting. XRD, SEM and EDX analysis of the modified aluminium alloys and their composites were carried out. Microstructures of the modified aluminium alloys and AAMCs were observed and the grain sizes were measured according to ASTM standards. Hardness tests of the fabricated specimens were carried out using Vickers microhardness testers and the hardness values were measured utilising the integrated software. It was observed that equiaxed grain structures were formed in both the modified Al alloys and their composites, indicating successful fabrication by means of the casting process; however, the average grain sizes of the fabricated specimens are dependent on the combination of wt% of reinforcement and the composition of the Al alloys. Interestingly, a positive correlation with the weight percent ratio of Zn and Mg in the AA7075 was observed, indicating the potential for fine-tuning of the mechanical properties through proper selection of the alloying elements. It was also observed that the microhardness of the AAMCs fabricated with the modified Al alloys exhibits consistent improvement with an increasing weight fraction of SiC reinforcement, irrespective of the weight percentage ratio of the added Zn and Mg combination.

Keywords: metal matrix composites, AA7075, stir casting, microstructure, microhardness

INTRODUCTION

Metal matrix composites (MMCs) are known for their enhanced mechanical properties, which are influenced by factors such as the fabrication techniques, choice of matrix material, type and weight percentage of reinforcement as well as uniform distribution of reinforcements within the matrix [1–4]. These efforts have led to the continual introduction of new materials tailored for diverse applications. MMCs are widely used in automobile and aerospace applications due to their exceptional properties. Various reinforcements such as boron carbide, titanium chloride, silicon carbide, aluminium oxide, silicon nitride and titanium diboride are employed to improve the strength in the resulting materials. Owing to their high strength-to-weight ratio, 7xxx series aluminium alloys are widely regarded as ideal materials for applications in the aerospace, space and defence industries

[5–7]. Among them, AA7075 is one of the most extensively utilised alloys. Recent studies have investigated a range of matrix materials among aluminium alloys such as A356, AA6061 and AA7075, employing composite fabrication methods including centrifugal casting, stir casting, squeeze casting and other similar techniques [8–12].

Manufacturing advanced metal matrix composites (MMCs) typically follows three primary pathways: liquid-state (liquid metallurgy), solid-state (powder metallurgy), and deposition processes. In the liquid-state approach, reinforcements are introduced into the molten alloy while stirring. Conversely, powder metallurgy involves consolidating and fusing the matrix and reinforcing particles (powder) by sintering, creating a solid metal matrix under high pressure and temperature, all without reaching the alloy's melting point in an inert environment [13–14]. In the deposition method, reinforcements are deposited onto the matrix utilising physical vapor deposition or spray deposition techniques. Additional methods such as squeeze casting, pressure infiltration, pressureless infiltration, friction stir processing (FSP), and ultrasonic-assisted casting are also used in MMC fabrication.

AA7075 is a type of aluminium alloy that is used in a wide field of applications. Nevertheless, sometimes it needs to be made even stronger. Therefore, researchers mix it with other materials as reinforcement like SiC, Al2O3, Gr, TiO2, B4C, AIN and even fly ash to make it much harder and stronger [15–19]. These mixtures are termed as aluminium alloy matrix composites (AAMCs). Several authors [20–22] have reported that by increasing the reinforcement content, the mechanical properties improve greatly. Balaji et al. [23] demonstrated the successful fabrication of Al7075-SiC composites using liquid metallurgy techniques, achieving a reinforcement content of up to 6 wt%. They stated that the microhardness grows by approximately 10% with reinforcement content and the wear resistance improved significantly, which was attributed to the addition of the hard SiC particles, resulting in superior mechanical and tribological properties of the Al7075-SiC composites. Kumar et al. [24] experimentally observed the uniform dispersion of reinforcement particles in AA7075 matrix composites fabricated by the conventional casting process. They stated that with the increase in wt% of BN, the strength of the composites grew extensively, surpassing other composite materials. Notably, the composites with 9 wt% BN exhibit superior toughness and strength, which is promising for applications in structural materials. Gosavi et al. [25] also experimentally investigated the mechanical properties of AA7075-SiC composites fabricated by means of the stir casting process.

It is clear from the research works available in the open literature domain that several authors have investigated the mechanical properties and wear resistance of AA7075-SiC composites fabricated by adding SiC powder materials to commercially available AA7075 matrix material by the stir casting process. Nonetheless, they used the commercially available AA7075 alloy directly instead of further improving its mechanical properties by either modifying the alloy composition or with further heat treatment processes. In this context, the present investigation is aimed at improving the mechanical properties of commercially available AA7075 alloy by adding major alloying elements at different weight percentages, followed by the fabrication and characterization of their SiC reinforced composites.

EXPERIMENTAL PROCEDURE

Materials

Aluminium alloy AA7075, pure Zn and pure Mg were selected as the materials for the present investigation. The commercially available AA7075, 99.97% purity Zn and 99.5% purity Mg materials were purchased from M/S MATRICS, Kanyakumari, Tamil Nadu – 629204 in the form of ingots. Silicon carbide (SiC) powder materials having an average particle size less than 40 micron were purchased from M/S Nano Research Elements, Haryana – 136132, India. The chemical composite of the purchased materials is listed in Table 1.

Table 1. **Chemical composition of AA7075, Zn and Mg materials**

Raw Materials	Constituent (%)														
	Al	**Zn**	**Mg**	**Cu**	**Cr**	**Mn**	**Si**	**Pb**	**Ti**	**Sn**	**Fe**	**Ni**	**C**	**O**	**Mo**	**Mg**
AA7075	Bal.	5.3	2.1	1.1	0.18	0.3	0.4	0.029	0.2	0.012	0.5	--	--	--	--	--
Pure Zn	0.01	99.97	0.003	0.002	--	0.003	0.003	--	--	--	0.009	--	--	--	--	--
Pure Mg	0.006	0.005	99.5	0.007	--	--	0.042	--	--	--	0.006	0.001	--	--	--	--
SiC Powder	--	--	--	--	--	--	69.5	--	--	--	0.10	--	29.5	0.3	0.2	0.3

Fabrication of modified aluminium alloy

The flow diagram of the complete methodology used in the present research work is shown in Figure 1. Modification of the aluminium alloys was performed by means of an HMI controlled stir casting machine (SwamEquip; SCM-A101) as shown in Figure 2(a). The modified Al alloys were fabricated by adding 10 weight percent Zn and Mg to AA7075 at 1:1, 2:1 and 3:1 ratios using the stir casting machine. Initially, the necessary amount of AA7075 alloy in small pieces was heated at 800±5°C in the melting furnace of the stir casting machine to completely melt the materials. After melting, the required amount (total 10 wt%) of Zn and Mg at 1:1, 2:1 and 3:1 ratios were added; after both Zn and Mg were completely melted, the molten material was continuously stirred with a mechanical stirrer blade. The stirrer was rotated at a speed of 650 rpm for 6-8 min and the auto-jog option was switched on in order to achieve uniform mixing of the alloying elements into the molten metal. After uniform mixing, the molten mixture was poured into a preheated cast iron mould with a circular cross section cavity. Once solidified, the cast metal was removed from the mould cavity and cut into the required shapes and sizes for further processing. The modified aluminium alloys are shown in Figure 2(b) and the specimen codes (1-1 AA, 2-1 AA and 3-1 AA) are listed in Table 2.

Fabrication of aluminium alloy matrix composites

Fabrication of the aluminium alloy matrix composites (AAMCs) was also carried out utilising the same stir casting machine. In this process, the modified AA7075 alloys (1-1 AA, 2-1 AA and 3-1 AA) were used as the matrix materials and silicon carbide (SiC) powder as the reinforcement material. Firstly, the required amount of modified aluminium alloy in small pieces was heated at 800±5°C in the same melting furnace of the stir casting machine and the temperature of the molten metal was maintained at 750±10°C. The slag was removed from the molten material, followed by stirring and auto-jogging of the molten metal by the stirrer blade at 600 rpm, then adding the preheated SiC powder materials at a slow flow rate. In the present investigation, three different wt% (2.5, 5 and 7.5) of SiC reinforcement were added to the individual modified Al alloys. After 7-8 minutes of stirring the mixture of the molten matrix and reinforcement particles, it was immediately poured into a 350°C preheated cast iron mould having a rectangular cross-section cavity. The AAMC sample was extracted from the mould cavity after complete solidification and cooling down to room temperature.

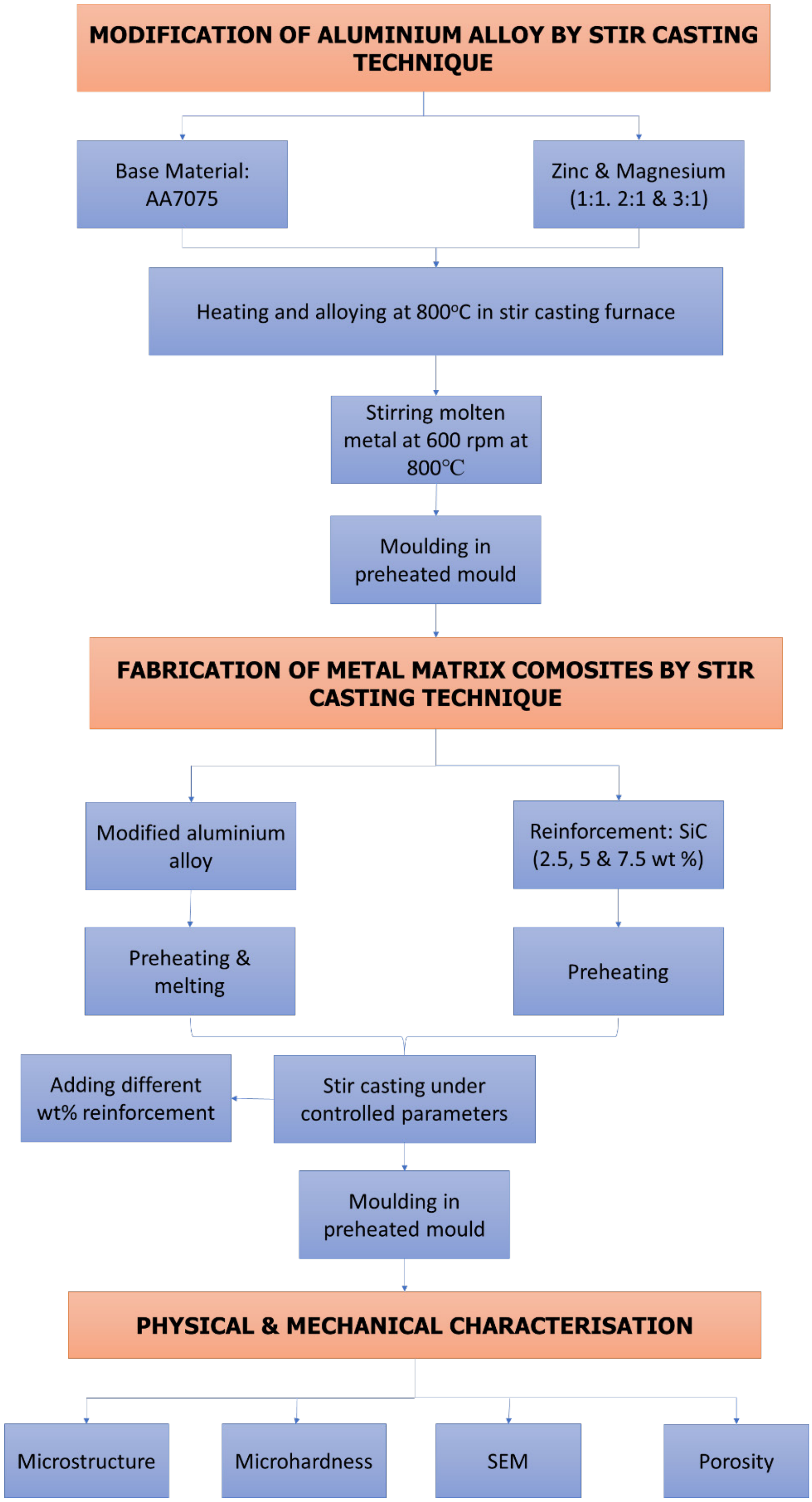

Fig. 1. Flow diagram of complete methodology used in present research work

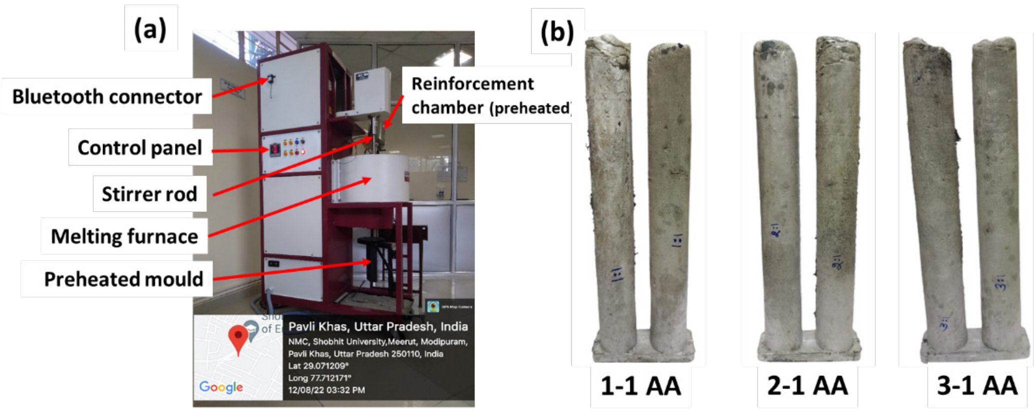

Fig. 2. Photographs of (a) experimental set-up used for fabrication of modified Al alloys and their composites (b) fabricated Al alloy samples

Table 2. **Test matrix with sample codes and corresponding experimental results**

Sample code	Ratio/ wt% (Zn: Mg) / (AA-SiC)	Average grain size (μm)	Average micro-hardness HV	Surface pores area (%)
AA7075	-	30	62	-
1-1 AA	1-1	79	72	-
2-1 AA	2-1	40	85	-
3-1 AA	3-1	53	88	-
1-1 AA-SiC 2.5	2.5	63	86	8
1-1 AA-SiC 5	5.0	57	97	8
1-1 AA-SiC 7.5	7.5	45	93	10
2-1 AA-SiC 2.5	2.5	30	90	15
2-1 AA-SiC 5	5.0	48	95	20
2-1 AA-SiC 7.5	7.5	45	97	15
3-1 AA-SiC 2.5	2.5	31	110	8
3-1 AA-SiC 5	5.0	40	104	8
3-1 AA-SiC 7.5	7.5	60	111	7

Microstructure observations and microhardness test

The microstructure of the Al-Zn-Mg base alloy and Al-Zn-Mg alloy/SiC composites with different weight percentages of reinforcement were observed in an inverted metallurgical microscope (TRUEMET; RIM-5). First, specimens 15 mm x 15 mm in size were cut. Then, the specimens were polished on a single dish polisher employing successive grades of emery papers starting from 600 grade to 2500 grade, followed by cloth polishing with micro polish alumina (1-3 μm). The polished specimens were etched in Keller's agent for 30 seconds, followed by the application of ethanol and drying of the surface by means of a drier.

The microhardness tests of Al-Zn-Mg based alloy and Al-Zn-Mg alloy/SiC composites with different fraction percentages were performed utilising a semi-automatic Vickers microhardness tester (TRUEMET; BHT-1000) and the hardness values were measured by the integrated software, VIDAS 2.0. The specimens were placed properly on the stage of the Vickers microhardness tester, followed by an applied 50 gm load for a dwell time of 10 seconds by a diamond type indenter. A minimum of 10 hardness values were taken for every specimen at different locations.

RESULTS AND DISCUSSIONS

XRD analysis

The XRD analysis was carried out at the National Physical Laboratory, New Delhi. The XRD analysis of the 1-1AA, 2-1AA, 3-1AA alloys and 1-1AA-SiC-7.5 AAMC are shown in Figure 3. From Figure 3 it can be confirmed that the matrix material Al and the alloying elements Zn and Mg are present in the 1AA, 2-1AA, 3-1AA alloys, while Al, Zn, Mg and SiC are present in the 1-1AA-SiC-7.5 alloy.

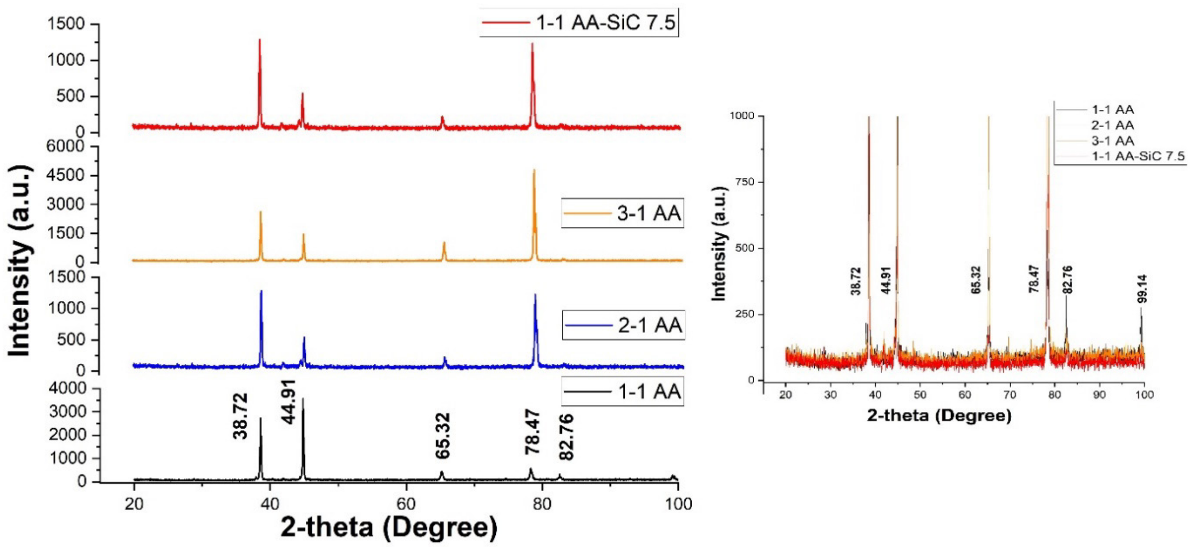

Fig. 3. XRD patterns of 1-1AA, 2-1AA, 3-1AA alloys, 1-1AA-SiC-7.5 AAMC and its magnified view

SEM observation and EDX analysis

The scanning electron microscopy (SEM) micrographs of the 1-1 AA and 3-1 AA alloys are displayed in Figure 4(a) and Figure 5(a) respectively. It is clearly observed from Figure 4(a) and Figure 5(a) that secondary phases of MgZn2 having dendritic morphology are distributed at the grain boundaries. These secondary phases are undissolved phases of Al, Zn and Mg that formed during the casting process [26]. Similar findings were reported by Zhang et al. [26–27]. They stated that these phases have different crystallographic characteristics. Additionally, they observed that at higher magnification these phases resemble a group of fish skeletons with sharp spines and lumps of bone. It is also clear from Figure 4(a) and Figure 5(a) that with increases in the Zn content, the density of the secondary phases grows. Zhang et al. [27] also reported similar observations. They have found that Al-Zn-Mg alloys mainly consist of an α-Mg phase and a small amount of Mg32(Al, Zn)49 phases, which are known as the T phase. They also stated that with an increase in Zn content the grain boundary becomes thicker as the grain boundary areas of the alloy are dominated by wide parallel structured eutectic phases.

The elemental analysis of the 1–1 AA and 3–1 AA alloys by the energy dispersive X-ray (EDX) technique are presented in Figure 4(b) and Figure 5(b), respectively. It is observed that Al, Zn and Mg are present as major elements in the both the1-1 AA and 3–1 AA alloys. The calculated weight % of the Zn and Mg elements from the EDX analysis as shown in Figure 4(b) and Figure 5(b) is almost same as the wt% of Zn and Mg that were added during the casting process.

An SEM micrograph of an aluminium alloy matrix composite (1-1AA-SiC-7.5) is shown in Figure 6. From Figure 3(b) is it clearly observed that the SiC particles are uniformly distributed in the matrix material (1-1 AA). Such uniform distribution of SiC reinforcement particles in the matrix material is acheived by using a stir casting machine with optimum control of the stirring speed and auto-jogging of the stirrer blade in addition to the duration of stirring.

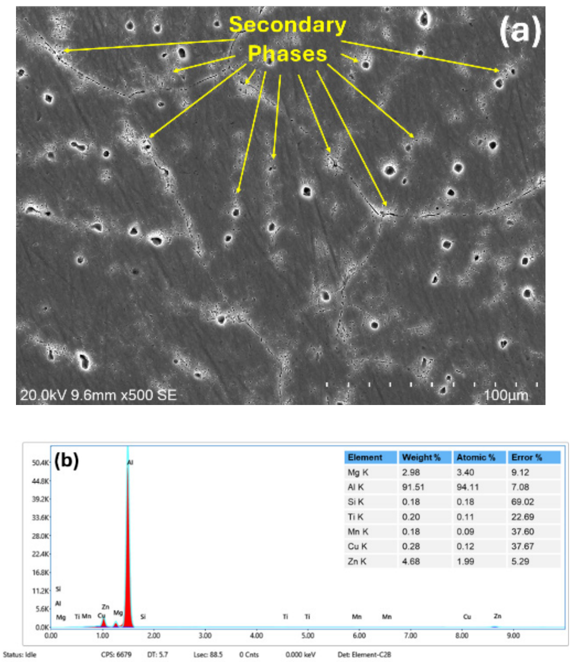

Fig. 4. (a) SEM micrograph and (b) corresponding EDX analysis of 1-1AA alloy

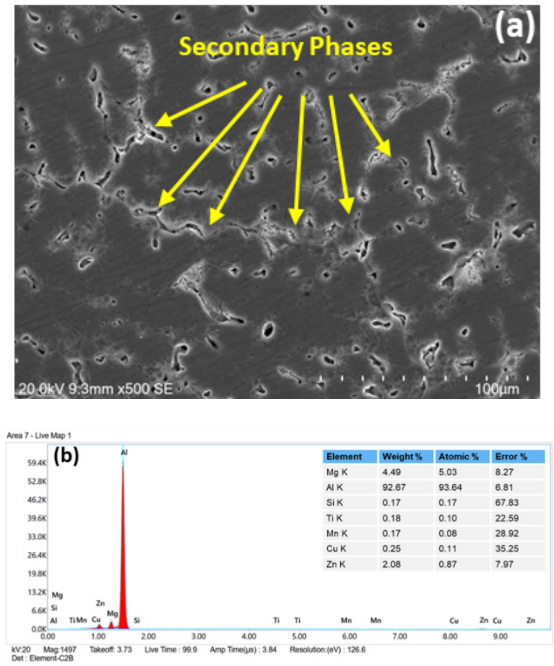

Fig. 5. (a) SEM micrograph and (b) corresponding EDX analysis of 3-1AA alloy

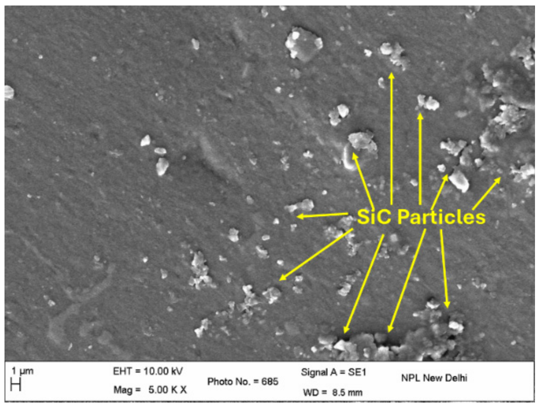

Fig. 6. SEM micrograph of fabricated 1-1AA-SiC 7.5 metal matrix composite

Microstructure observation

The microstructures of the modified aluminium alloy and their metal matrix composites (AAMCs) having 2.5, 5.0 and 7.5 wt% SiC reinforcement are displayed in Figures 7(a-l). It is clearly observed that equiaxed type grain structures are formed regardless of the ratios of Zn and Mg in the modified alloy and weight percentage of SiC reinforcement. This observation confirms the successful fabrication of the modified Al alloys and AAMCs by means of the casting process. The average grain sizes were measured in every micrograph to deeply understand the correlation between the average grain sizes and hardness properties of the fabricated specimens. The average grain size of each specimen was measured according to the ASTM E112 standard and listed in Table 2. The average grain size variation with respect to the different material compositions is shown in Figure 8. It was observed that an increase in the Zn-Mg ratio in the modified aluminium alloy leads to a reduction in the average grain size of the microstructure. It is also clearly observed from Figure 7(d-i) and Figure 8 that the average grain size decreases with an increase in wt% of reinforcement. This trend underscores the refining effect exerted by the SiC particles on the grain structure of the composite material. Such an observation may be attributed to the increase in the hard SiC particle content, which hinders the growth of grain boundaries. Conversely, in the case of the AAMCs fabricated with the 3-1AA alloys, they have an opposite trend in grain size variation with respect to the wt% of SiC; with an increase in the SiC content the average grain size grows. This interesting observation suggests that the impact of SiC reinforcement on grain refinement may vary depending on the specific alloy composition, emphasizing the complexity of the composite fabrication process.

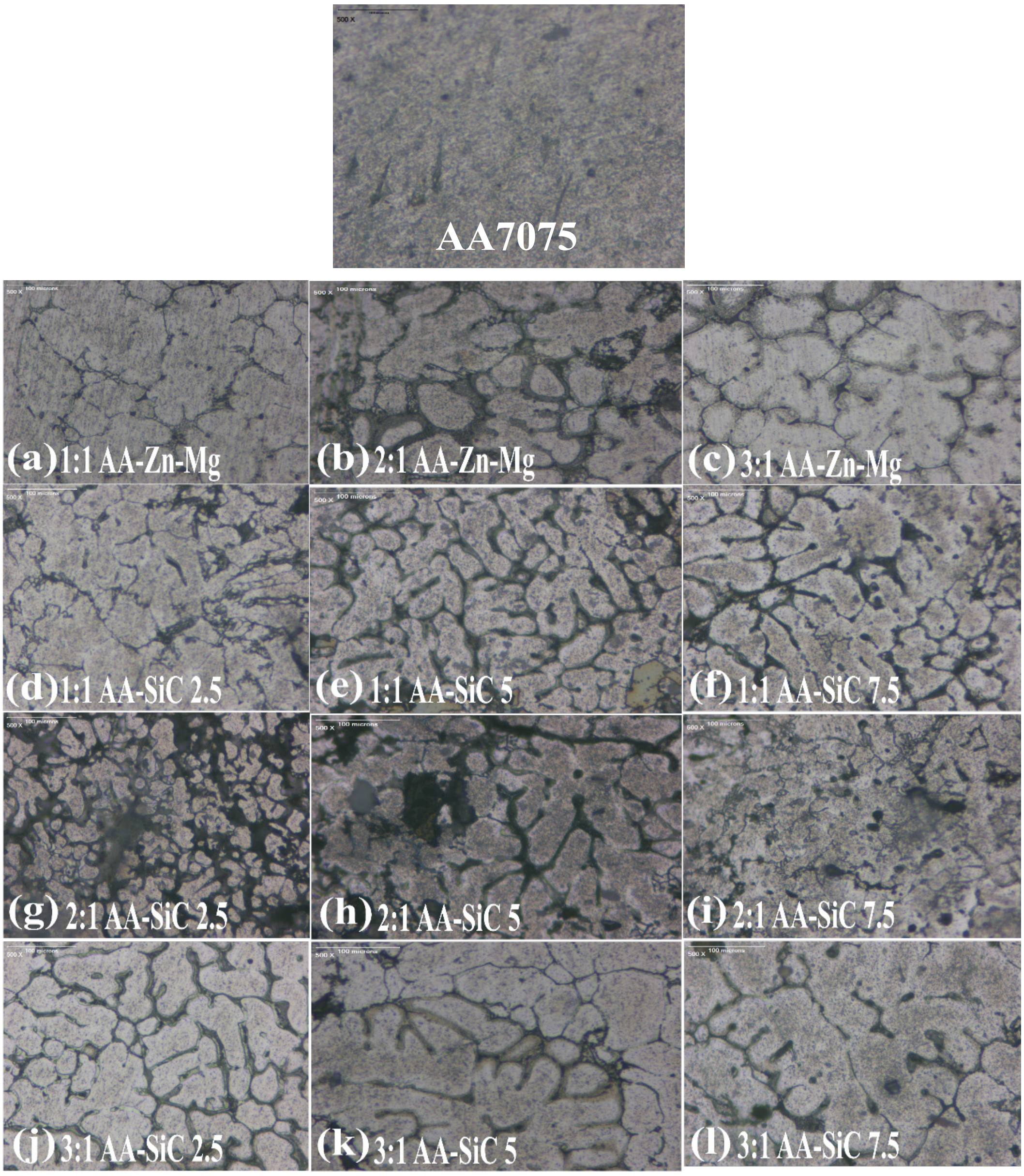

Fig. 7. Microstructure of modified aluminium alloy AA7075, (a-c) 1-1AA, 2-1AA & 3-1AA, respectively and (d-l) 2.5, 5.0 and 7.5 wt% SiC reinforced AAMCs

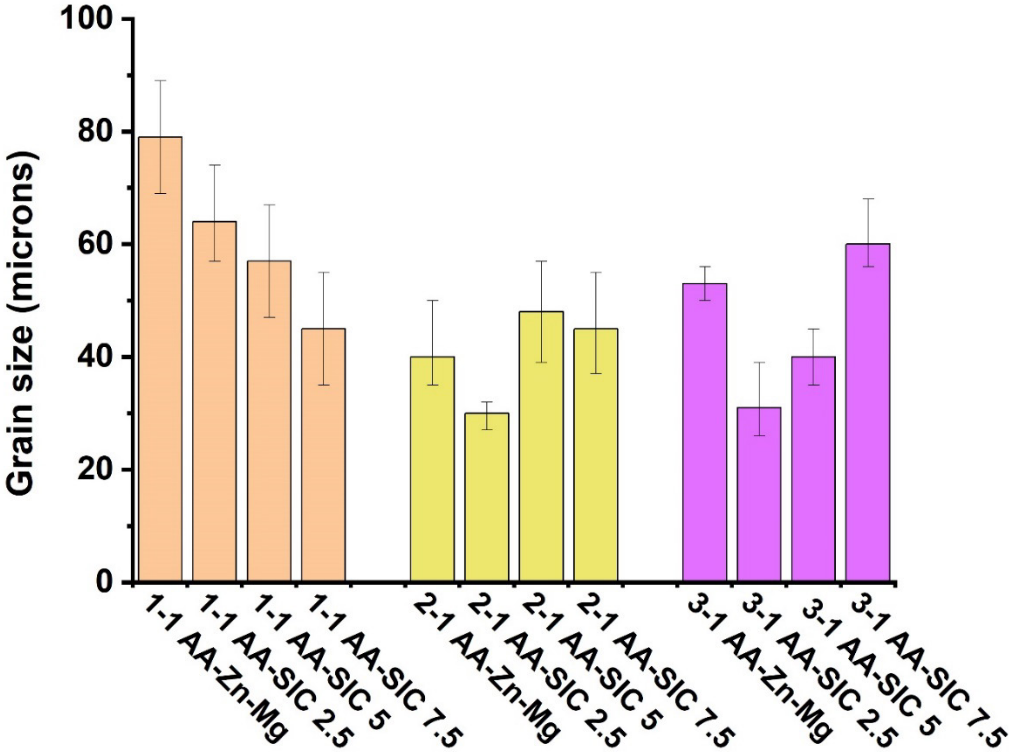

Fig. 8. Average grain size variation with respect to different compositions of specimen

Microhardness study

In the present research work, microhardness measurements were conducted at 10 distinct locations on each sample to ensure comprehensive characterisation. The average microhardness values are presented in Table 2. Furthermore, Figure 9 illustrates the comparison error bar diagram of the average microhardness concerning different ratios of Zn and Mg alloying elements and the weight percentage of SiC reinforcement. It is interesting that by increasing in the Zn to Mg ratio but keeping the wt% of the alloying additive constant, the average hardness of AA7075 notably rises. Such an observation may be attributed to the effect of Zn on the mechanical properties of the Al alloy, which is considerably more as compared to Mg [28]. Zn enhances the mechanical properties by following the strengthening principles like solid solution strengthening, dislocation strengthening, precipitation strengthening and crystal boundary strengthening [29].

Moreover, the investigation extends to the microhardness analysis of the AAMCs fabricated with the modified Al alloys (1-1AA, 2-1 AA and 3-1 AA) containing different wt% of SiC reinforcement. Regardless of the specific ratio of Zn and Mg combination employed, the microhardness consistently grows with the increase in the weight fraction of SiC reinforcement. This observation underscores the impact of SiC reinforcement on enhancing the mechanical properties of the composite material, irrespective of the alloy composition.

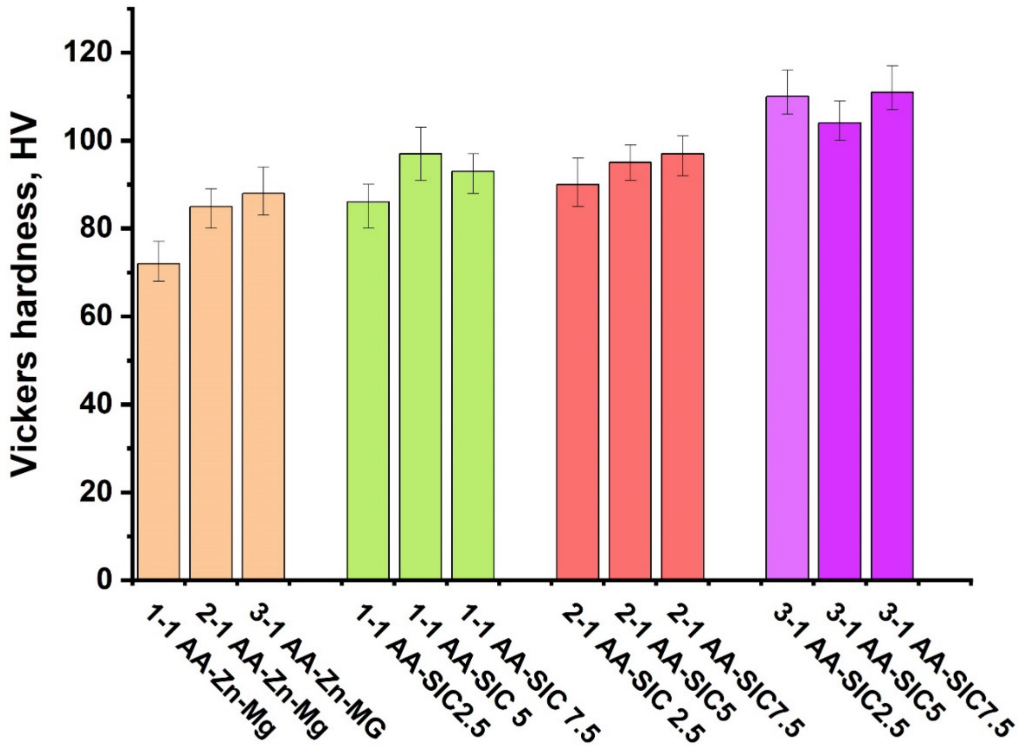

Fig. 9. Comparison error bar diagram of average microhardness with respect to material compositions

CONCLUSIONS

In the present research work, modified aluminium alloys were fabricated via the stir casting process by incorporating various proportions of zinc and magnesium into the base alloy AA7075 as major alloying elements. AAMCs were then fabricated from the resulting alloys, reinforced with SiC in different weight percentages. The investigation focused on analysing the microstructural characteristics and microhardness properties of both the fabricated alloys and their composites. Through rigorous experimental evaluation, the following conclusions were drawn:

1. Utilizing a controllable stir casting machine facilitates uniform distribution of the SiC reinforcement within the modified Al alloy matrix, ensuring improved properties throughout the material.
2. The microhardness demonstrates a positive correlation with the weight percentage ratio of Zn and Mg in the modified AA7075 alloys, indicating the potential for fine-tuning of the mechanical properties through the effect of alloying elements.
3. The microhardness of the AAMCs fabricated with the modified Al alloys exhibits consistent improvement with an increasing weight fraction of SiC as reinforcement, irrespective of the weight percentage ratio of Zn and Mg combination employed.
4. Fabricating advanced lightweight, high-strength Al alloy composites is achievable through strategic selection of the alloying elements and appropriate weight fractions of the reinforcing materials, offering a pathway to tailored material properties for diverse applications.

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