RESEARCH PAPER

Microstructure and Mechanical Behaviour of Stir Casting Al/SiCp/Mg/Cu Composite with Varying Pouring Temperatures

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Received: June 2021 Revised: August 2021 Accepted: September 2021

DOI: 10.22068/ijmse.2121

Abstract: *The effect of pouring temperature while preparing Aluminium SiC metal matrix composites, with additional benefits of magnesium and copper through stir casting technique was investigated. The composites were fabricated by mixing 12 wt% of SiC reinforcements, 4 wt% magnesium, and 2 wt% copper into 6061 aluminum alloy melt at different pouring temperatures (630℃, 670℃, and 710℃). The addition of magnesium will enhance the wettability of the SiC particles with the Al matrix. The inclusion of copper has considerable improvement in the strength and hardness of the composite. The microstructure and mechanical properties (tensile strength and hardness) of the Al MMC are evaluated with the corresponding processing parameter, specifically the pouring temperature of the cast composites. The metallurgical characterization utilizing optical and scanning electron microscope were observed for the prepared composites. The coarse microstructure and homogenous distribution of SiC particles appeared within the dendrite structures of the composites. The SiC particles have effectively distributed, and higher tensile strength and maximum hardness have occurred in composite at a pouring temperature of 670℃ as compared to other composites. The mechanical properties were lower in composites prepared using lesser pouring temperature (630℃) and significantly decreased for higher pouring temperature (710℃) of the composites.*

Keywords: *AlMMC, SiC, pouring temperature, microstructure, stir casting.*

1. INTRODUCTION

Metal matrix composites (MMC) have more beneficial mechanical and tribological properties and are advantageous when compared to monolithic materials. Aluminum-based MMC have significant strength, hardness, and tribological properties when compared to its matrix materials. However, the aluminum metal matrix composites (Al MMC) are poor in ductility which limits their applications. To enhance its ductility, other alloying elements can be added and fabrication procedure parameters can be investigated to improve its performance. Al MMC's are generally prepared by casting, with ceramic materials reinforced through blending in molten alloy matrix by dispersion method [1]. Stir casting is a mechanical process to prepare composites with motorized stirring imposed to form a vortex that mixes reinforcements into the molten matrix. Among the different processing procedures available for MMC, stir casting is the most economical and beneficial technique [2]. Currently, Al SiC composites have been successfully used in many automobiles, electronics, and aerospace components based on their advantages related to mechanical properties [2–5].

A broad selection of ceramic reinforcements such as SiC, B_4C, ZrO_2, Al_2O_3, TiC, and graphite have been assisted into aluminum composites. The composites face few crucial problems such as poor wettability of ceramic particles with matrix and higher porosity defects. Low wettability decreases the interface bonding quality among matrix and SiC particles. Higher porosity levels were found in the composite with the increasing inclusion of ceramic particles [6]. The addition of SiC particles to aluminum has gained much attention among researchers, because of its great bonding nature and admirable physical properties, which makes it a desirable reinforcing material [5].

To produce Al MMC certain considerations to be made, such as no negative reaction formed between the matrix and reinforcement particles, lesser porosity in the cast, uniform distribution of reinforcement, and good wettability [2]. These considerations greatly affect the properties of the composite. The addition of magnesium is used to strengthen and harden aluminum casting through solid solution strengthening along with its strain hardening ability and increase wettability between Al and SiC interface. The magnesium

(Mg) and copper (Cu) alloying additions create an impermanent layer between particle and matrix. This layer causes a low wetting point reducing the surface tension of the liquid and surrounds the particles with a phase combined with both matrix and particle. The hardness and wear resistance of the composites increases considerably and facilitates precipitation hardening, with the addition of copper [4]. In composites prepared at 750ºC pouring temperature, reinforcement distribution is better than other composites, which decides the final property of the composite. The SiC particle reacts with aluminum to form a brittle reaction at the matrix-particle interface [6]. The gradual increase in the addition of SiC/ceramic particles as reinforcement reduces the ductile capacity of the aluminum alloys [5, 7].

Previous researchers have reinforced the SiC ceramic particles with different types of Al alloys and evaluated them based on their properties. The SiC particles were reinforced in Al-Si-Fe alloy and analysis based on its mechanical properties showed higher tensile strength and hardness values but porosity defects levels were also increased [8]. The addition of SiC particles was varied with different levels while preparing Al composites and reported high mechanical properties were achieved with 20% SiC inclusion [9]. It was also noticed that Al 5% SiC developed better tensile strength compared to Al 10% SiC. The average size of SiC particles added in Al composites was varied and the results of bending strength were proportionally decreasing with an increase in average particle size [10]. The composites can be prepared by including 30 wt%SiC, only along with the incorporation of graphene nano platelets (up to 0.5 wt%), which will increase the hardness and compressive strength [11].

With larger reinforcement dimensions and higher volume proportion, the wear resistance of the composites has improved [12, 13]. Slower stirring speed and duration will lead to SiC particle clustering in few locations and some places without SiC particles. Increasing the speed and time will create a uniform distribution of particles. The hardness of the composites was influenced by the stirring speed and time of stir casting [14]. The ductility of the composites can be improved by using blunted SiC particles to reinforce in the matrix alloy [15]. SiC particles with various quantity addition (5-40 wt.%) and different mesh size (150 and 600 μm) were added in Al 6061 alloy to prepare composites which had significant improvement in wear performance [16]. Al 6061 alloy reinforced with 5% SiC exhibited better wear performance and enhanced hardness values in comparison with the base alloy [17]. Al 6061-SiC (2-6 wt.%) MMC was prepared using a liquid metallurgy process (stir casting). The SiC reinforcement distribution was homogeneous in the matrix and the mechanical properties of the composites were noticed to surge as the particulate content was increased [18]. Mechanical behavior of nano SiC reinforced Al alloy was researched. Hardness and tensile strength values were enhanced by nearly 66% and 20%, respectively, with the inclusion of nano SiC particles. It was noted that adding above 2 % nano SiC with aluminum composites was not feasibly effective for incorporation [19].

The present work was performed to evaluate the impact of pouring temperature conditions on mechanical and microanalysis while preparing MMC with 6061 Al, 4 wt.% Mg, 2 wt.% Cu and 12% micron level SiC particles through conventional stir casting technique. The aim is to increase the quality of the composites by reducing the defects by varying the pouring temperature on composites produced from the stir casting method. Hence, the mechanical properties of the composites were investigated concerning the microstructure and its defects. The mechanical characterization of aluminum composites was performed to find tensile strength, percentage elongation, and micro-hardness. Further, the distribution and bonding strength of SiC particles were investigated using optical and scanning electron microscope along with elemental analysis using the EDX technique.

2. EXPERIMENTAL PROCEDURE

The 6061 aluminum alloy is used to prepare the aluminum MMC and its chemical compositions are 0.93 wt% Mg, 0.63 wt.% Si, 0.52 wt.% Mn, 0.2 wt.% Cu, 0.17 wt.% Fe and remainder Al. Silicon carbide (SiC) is chosen as the primary reinforcement particle as it forms good chemical bonding with aluminum matrix and also has admirable physical properties. Also, pure magnesium powder and copper powder are added while preparing the composite to increase the strengthening mechanism. The aluminum 12% SiC metal matrix composite with 4% Mg and 2%

[DOI: 10.22068/ijmse.2121]

Cu quantity are prepared through the stir casting method using a mechanical stirrer blade.

The stir casting setup and die used to prepare the composites are shown in Fig. 1. Initially, to fabricate composite, aluminum alloy 6061 plates are melted at 750ºC using an electric furnace. Following, 120 g of SiC with an average size of 30 µm are added gradually in a preheated condition of 350ºC. Further 40 g of Mg and 20 g of Cu are added in exact quantity into the molten metal. The stir casting parameters were 700 RPM stirring speed and 12 minutes stirring time while adding the reinforcement gradually [20]. Finally, the Al MMC in the molten condition is poured into the preheated mold maintained at a temperature of 350ºC. The whole melt is poured at 630ºC into the permanent mold of dimensions (120 mm L x 120 mm W x 25 mm T) and allowed to be solidified and then removed. Likewise, the above process was followed for the other two composites processed at pouring temperatures of 670ºC and 710ºC. Three different composites samples are prepared in various conditions of pouring temperatures at 630ºC, 670ºC, and 710ºC. The temperature of the furnace is precisely measured and controlled with thermocouples and PID controllers, respectively. This purpose was to produce good-quality composites.

Fig. 2 shows the cast composites samples prepared at various poring temperatures. Tensile samples of ASTM standard E8M shown in Fig. 3 and hardness test samples of ASTM-E92-82 are prepared accordingly from the solidified cast Al MMC using wire-cut EDM process.

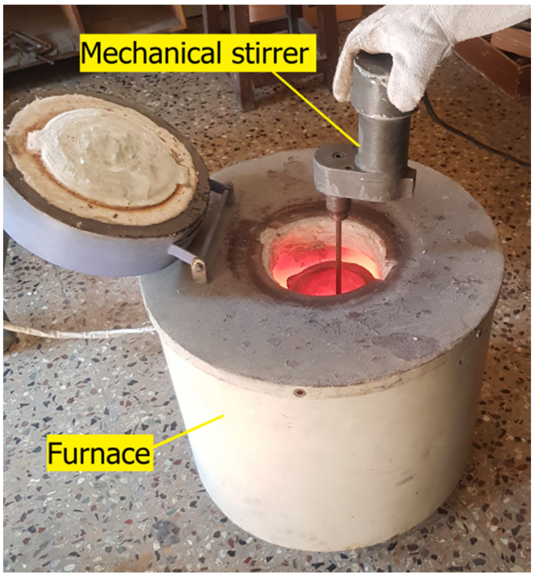

Fig. 1. Stir casting setup and Die used for preparing MMC

Fig. 2. Cast samples of composite prepared at different temperatures.

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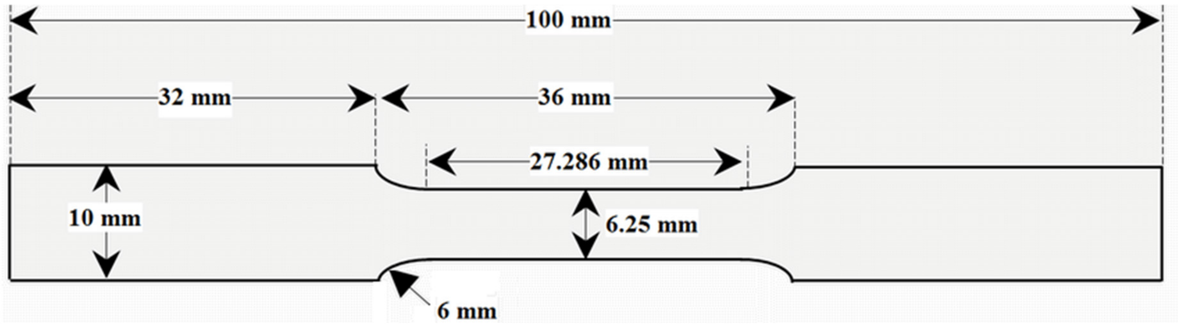

Fig. 3. ASTM E8 – sub size tensile specimen dimensions

Three tensile samples of standard size were tested for each composite in Universal Testing Machine and average values were calculated. Wilson Wolpert Vickers hardness tester was used to measure hardness values with pyramidal diamond intender for 15 seconds dwell time at 0.5 kg loading condition in three different locations for each composite and average values were specified. Keller's reagent etchant was applied for preparing OM and SEM samples after polishing and grinding for microstructural analysis.

3. RESULT AND DISCUSSION

3.1. Microstructure studies

Fig. 4 (a-c) shows the macrostructures of the cast composites prepared at three different pouring temperatures. Macro analysis in this study is to compare the grain size and distribution of reinforcement of the composite. Macro images show the distribution of particles is more uniform in composites fabricated at 670ºC pouring temperature. The clusters of SiC reinforcements are visible in the composites prepared at other pouring temperatures. Solidification behavior from higher pouring temperature results in smaller grain size. Lower pouring temperature (630ºC) leads to rapid and improper solidification which results in the formation of defects. Lower pouring temperatures are expected to form larger grain sizes, which could affect the mechanical properties as per the Hall-Petch equation.

Fig. 5 (a-c) shows narrow variations in fabricated Al SiC composites cast with the varied pouring temperature of 630ºC, 670ºC, and 710ºC, respectively. The influence of pouring temperature on the microstructure is clearly visible with the size and formation of dendrites varied, depending on the pouring temperature. The aluminum cast grain had little variation in size by the different pouring temperatures and the effect of the addition of magnesium and copper has also varied [6]. Dendrites formed are continuous in lower pouring temperature and as the pouring temperature was increased, the size reduces between the dendrites and discontinuity also increases. The clustering of SiC particles is more in composites owing to its higher density and it hovers in the lower region and middle region of the molten metal mixture.

The uniform distribution of reinforcing particles was obvious, but a few localized disorganizations were formed in the composites [6]. Fig. 5 (a) displays the clustering of particles visible along with the Al matrix corresponding to lower pouring temperature 630ºC. The accumulation of SiC reinforcement particles at few locations could be due to less fluidity as the result of insufficient pouring temperature.

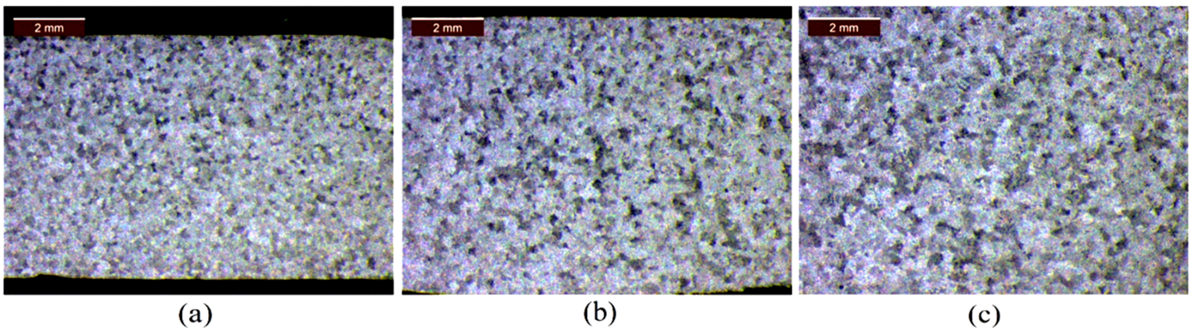

Fig. 4. Macro images of composites prepared at pouring temperatures a) 630ºC b) 670ºC and c) 710ºC

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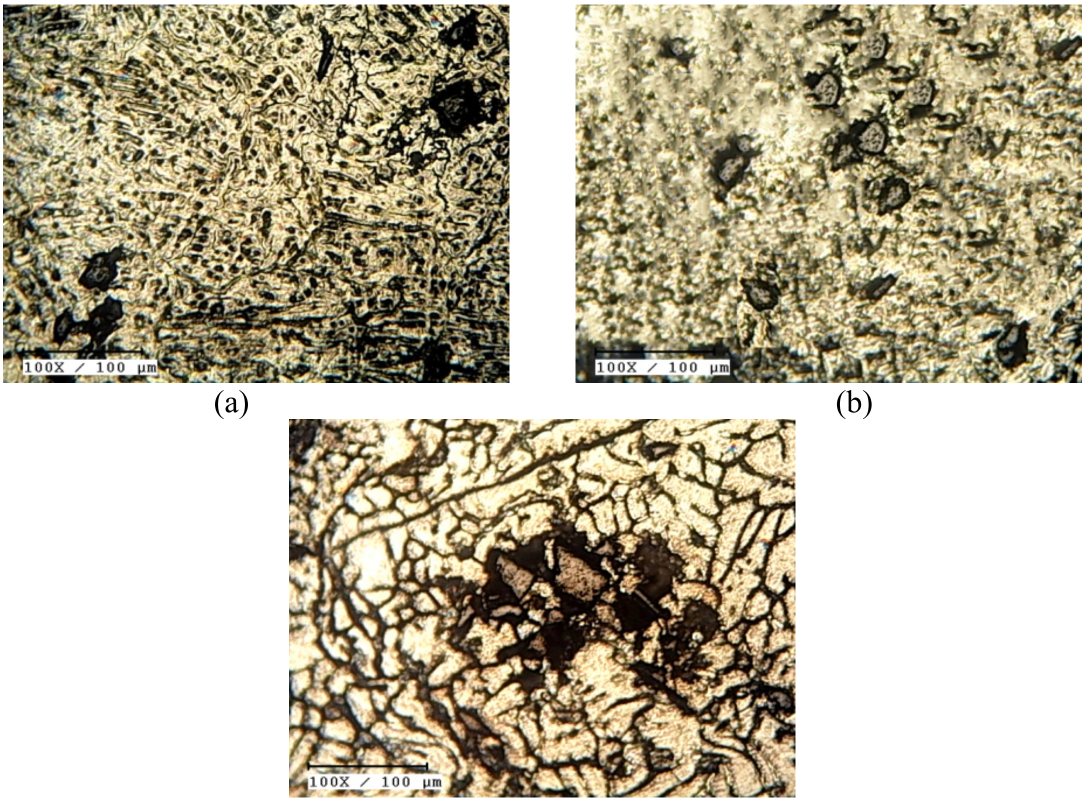

Fig. 5. Optical Microstructure images of stir casted composites with three different pouring temperature a) 630ºC b) 670ºC and c) 710ºC

The distribution of ceramic particles was improved for composite synthesized at 670ºC pouring temperature than other composites. The quantity of entrapped SiC particles was significant in composite, showing that 670ºC pouring temperature is contributing factor for enhanced ceramic particle inclusion in a molten matrix. Fig. 5(c) shows the microstructure of composite with pouring temperature 710ºC, with a minimum quantity of SiC particles incorporation. The formation of cast defects (solidification shrinkage) and improper incorporation of SiC particles has reduced the strength of this composite. Another important identification was gas pores are not visibly noticed in these images. Preheating SiC reinforcement particles, high stirring time, and fluid flow have allowed entrapped gas to escape.

3.2. SEM and EDX analysis

The SEM micrographs of the composites prepared with 670ºC pouring temperatures are seen in Fig. 6, with a distribution of SiC particles being significantly homogenous. SiC particles distribute homogeneously in composites with higher Mg content by increasing their wettability [21]. Further, the SiC particles have more wettability with the Al matrix, when prepared at optimum pouring temperatures [22]. In the 670ºC pouring temperature composites, the particles are well settled into the matrix during the solidification of the cast composites. No major defects such as voids, pits, or solidification shrinkage were observed from the composites prepared at 670ºC pouring temperature. The Al_4C_3 compound phase formation must have varied intensively based on pouring temperatures. Increasing pouring temperature can form more such brittle compound phases [6].

Line energy-dispersive X-ray spectroscopy (EDX) microanalysis was used to evaluate the chemical characterization around the ceramic particle in the composite. Fig. 6 shows the SEM elemental line scan data of composite to confirm the presence of SiC particles. The spectrum shows expected major elements such as Al, Mg, Si, and C. The signal of Al is at maximum outside the particle boundary and it decreases sharply as the particle's location approaches. The silicon (Si) signal significantly increases at the SiC particles region.

[DOI: 10.22068/ijmse.2121]

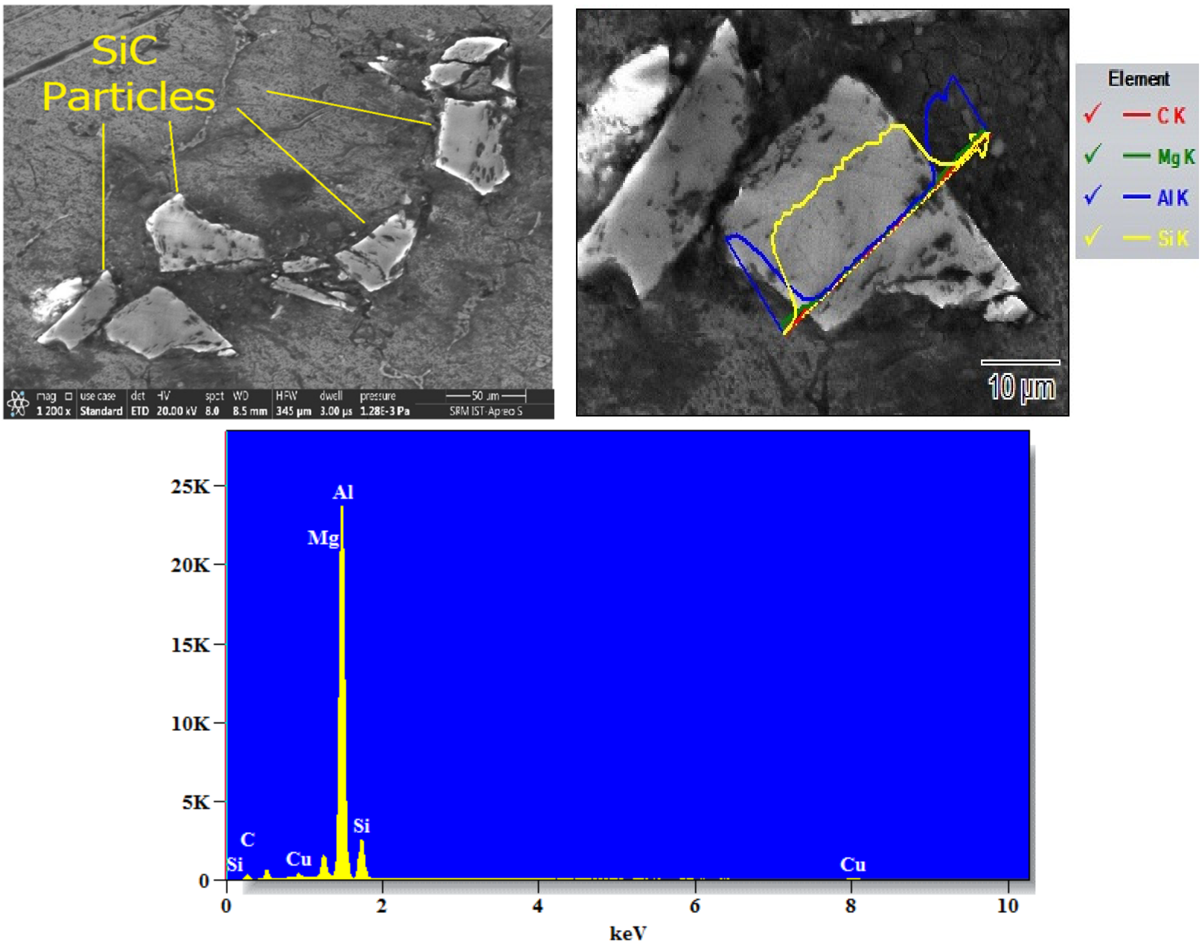

Fig. 6. SEM and Line energy dispersive X-ray spectroscopy (EDX) data with Spectrum of the composite (670ºC pouring temperature).

Mg was present at the SiC/matrix interface and in the matrix region of aluminum with the same intensity, revealing the high quality of composite fabrication [2, 6]. Fig. 7 illustrates the SEM and EDX mapping images of the composite prepared at 670ºC pouring temperature. From the SEM-EDX mapping analysis, it was seen that the SiC particles are located in the matrix, and confirms the existence of SiC particles addition in the composite. As given in Fig. 7, well-distributed SiC particles (green region) can be observed in the matrix. Also, the Si region was clearly visible; the Al matrix region was visible overall except the SiC particle region. Mg (blue region) was evenly distributed in the Al matrix as it provides a solid solution strengthening effect. The Mg was also visible in the SiC particle region, which is because Mg addition helps to increase the wettability between particle and matrix.

Premature solidification due to reduced fluidity by lower pouring temperature leads to casting defects [6]. Fig. 8(a) shows SiC particle surrounded with hollow matrix region, due to lesser fluidity, premature solidification, and formation of a thin brittle compound in the interface. Although the pouring temperature of 630ºC was used for composite, no occurrence of strong bonding reaction was between the particle and matrix. The SiC particles are strongly attached with the matrix and no detachment is noticed in composite poured at 670ºC. The SiC particles eruption while polishing indicates poor bonding between reinforcement particles and matrix caused by higher pouring temperature (710ºC). The SiC particle should not disengage from the matrix, identically to produce a better bonding among matrix and particles. A faster solidification rate has created a shrinkage gap between matrix and particle interface as seen in Fig. 8(b). However, the particles have not detached from the matrix, which could be due to good interface bonding strength caused by the formation of thick brittle compounds.

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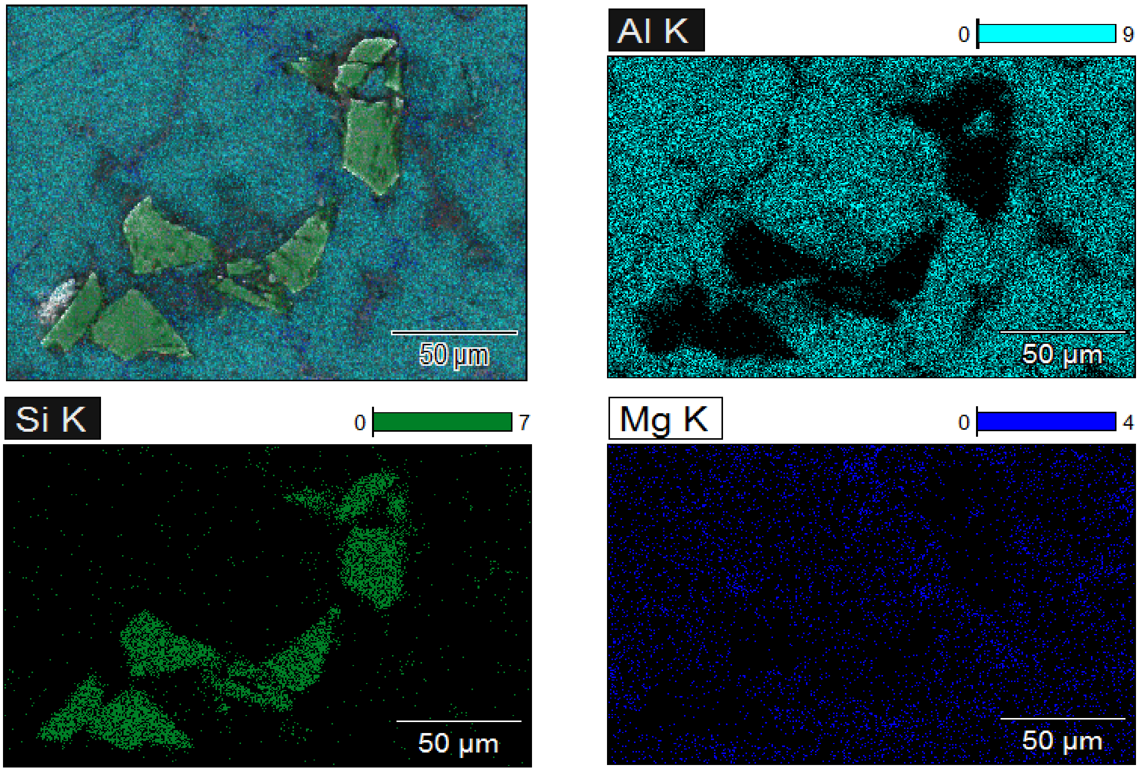

Fig. 7. SEM EDX data analysis on SiC particles region of the composites

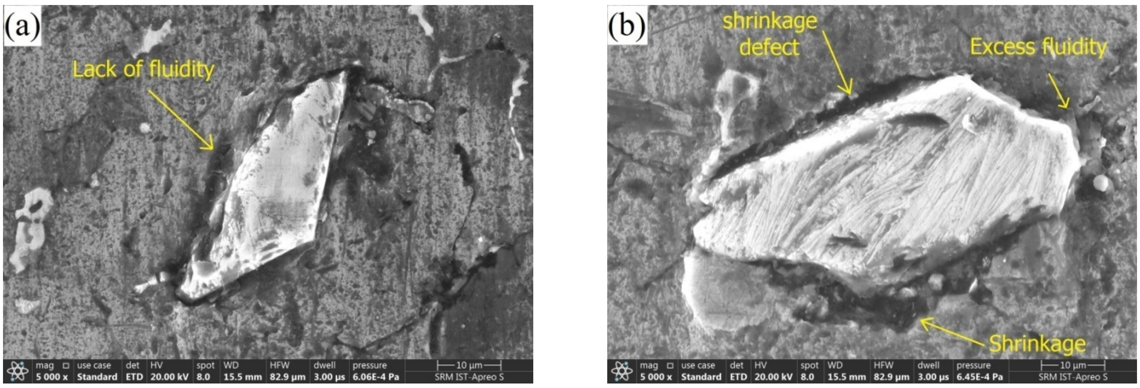

Fig. 8. SEM images of composites prepared at pouring temperatures (a) 630ºC and (b) 710ºC showing interface formed between particle and Al matrix

3.3. Mechanical properties

In general, SiC particles increase the stiffness value and capacity to share more load during deformation along with the Al matrix to increase the tensile property. Minor differences in dendrite structure will not result in unfavorable outcomes in tensile properties [6]. Mechanical testing was done to assess the impact of the pouring temperatures on the strength of composites. Fig. 9 shows the tensile tested samples of composites prepared with varying pouring temperatures. Fig. 10 shows the results of mechanical properties of the composites. As it can be seen, 670ºC poured composite produced a higher result comparatively. When the cast metal was poured at 670ºC, the distribution and presence of reinforcement particles were observed to be better homogeneous when compared to other composites poured at different temperatures, hence higher mechanical properties were attained. The maximum tensile strength of Al SiC composites was 208 MPa for the composite prepared at 670ºC pouring temperature. The SiC particles inclusion along with Mg and Cu alloying indicates considerable improvement in the composites. Premature solidification, fewer particles incorporation, shrinkage defects, and clustering of particles due to reduced fluidity can be related to the reduction in tensile properties of the composite poured at 630ºC. In the case of 710ºC pouring temperature, formation of intense brittle phase, shrinkage defects, and high internal stress have played a considerable role in declining the tensile properties of the composite. The increase of pouring temperature results in better bonding of SiC particles, but beyond a certain temperature, Al_4C_3 compound formation is higher. These phases can affect the mechanical properties of the composites. But still, there is no significant information about Al_4C_3 that could affect the strength of the composite [2].

The percentage elongation of the composites was observed with reduction as a consequence of reinforcement particles resisting the flowability of the matrix. Ductility relies on the quantity of SiC particles reinforced in the composite material and particle bonding strength. The decrement of elongation is high in composites prepared at pouring temperatures 630ºC and 710ºC. Further, the development of shrinkage defects is a crucial aspect reducing the ductile values of the composite.

The composite prepared with 670ºC pouring temperature has produced better elongation values. Furthermore, the ductility of the composites was also reduced by the pointed edges of the SiC particles reinforced in the matrix alloy. SiC particles with pointed shapes have serious stress concentration, causing deformation near the sharp corners of the particles elongated along the tensile direction [15].

Fig. 9. Tensile tested samples of composites prepared at various pouring temperatures.

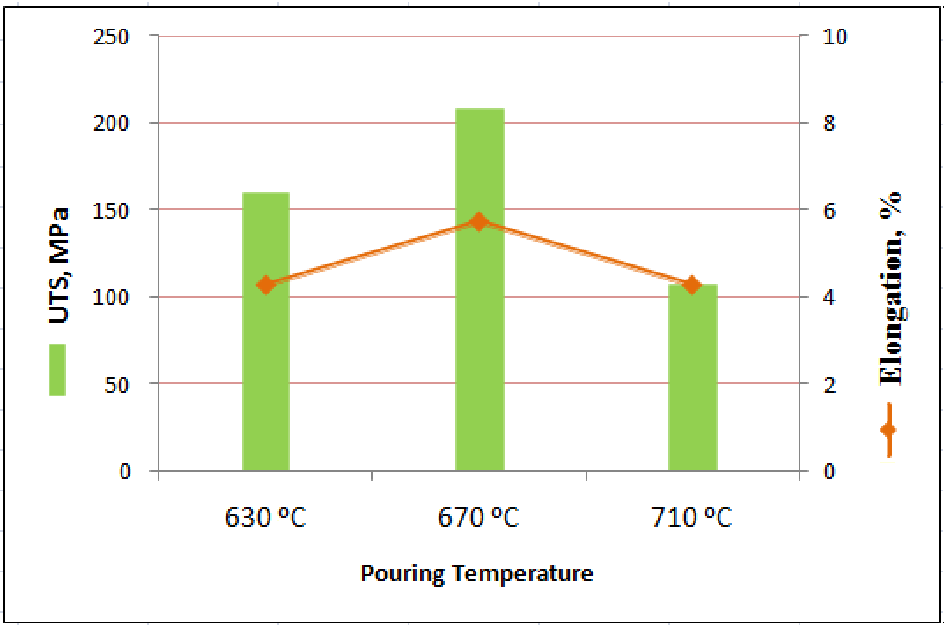

Fig. 10. Mechanical properties of the composites

[DOI: 10.22068/ijmse.2121]

Fig. 11 shows the result of Vickers micro-hardness tests results taken for the composites. In general, the hardness quality improves, as the amount of SiC particles added are increased within limits. The hardness improves due to the deformation resisted by the high solidness of the reinforced SiC particles in comparison with the softer aluminum matrix [5]. But the difference in hardness by varying pouring temperatures was identified, which is determined by solidification behavior leading to variation in the incorporation of SiC particles in the composites. The hardness of the composites has further increased with the addition of copper and magnesium alloying elements.

The maximum enhancement of hardness was recognized in Al SiC composite poured with temperature 670ºC and the distribution of reinforcing particles was more homogenous to correlate with other pouring temperatures. It was due to the reason that required fluidity was achieved by this pouring temperature, leading to good quality of composite.

The strong interface bonding between Al and reinforcement has penetrated the load transfer to SiC particles, so the resistance to penetration increased in a composite made with pouring temperature 670ºC. But at a certain pouring temperature, the hardness of the composite increases and reduces again as the pouring temperature is increased. The hardness reduction was due to clustering and uneven distribution of SiC particles.

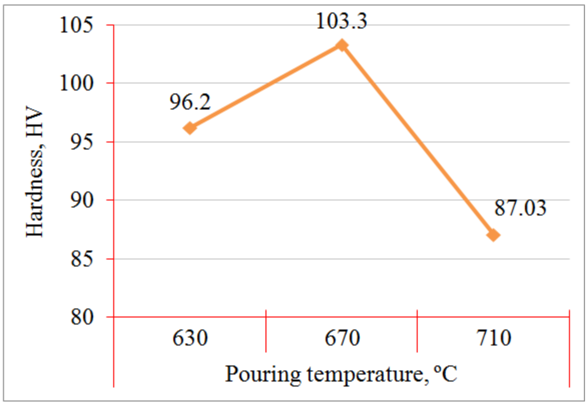

Fig. 11. Hardness plot of three composites

3.4. Fractographic studies

Figs. 12 (a-c) show the fractographic images of tensile samples with brittle nature in common with all three composites. No dimples were visible in the fracture location, evident for the brittle nature of the fracture.

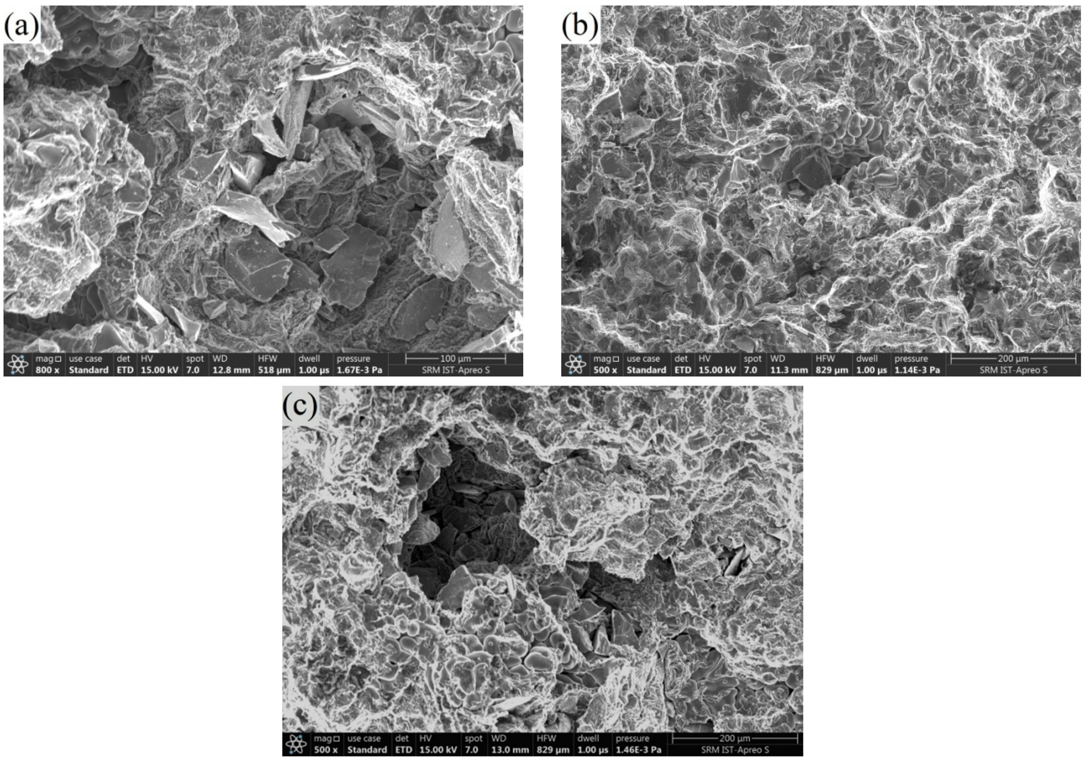

Fig. 12. Fractography images of tensile failure samples of the composites prepared at pouring temperatures a) 630ºC b) 670ºC and c) 710ºC

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The composite prepared at 670ºC pouring temperature shows particle fracture mode with strong bonding. The matrix deformation has appeared first and is followed by Al SiC interface location fracture. The SiC particles were evenly distributed in composite poured at 670ºC temperature, hence fracture was uniform, and no uneven deformation was visible in Fig. 12 (b), like other composites where cluster fracture was seen. Fracture location shows clustering of particles in Fig. 12 (a) and it is the fracture initiation site. Clustering of particles can make the zone weaker as the bonding of particles with the matrix will be weaker. Hence the tensile values of the composites have decreased. Cracks are visible in fractured composite prepared at higher pouring temperature, shown in Fig. 12(c). When casting is poured at a higher temperature, sudden reduction to room temperature leads to crack formation. In the case of poor interface bonding, the breaking of composite is initiated from particles before the deformation of the Al matrix. The SiC particles are located in the fractograph clearly, which shows the fracture has initiated from the pointed corners of the particles, reducing the ductility of the composites. Sharp corners of the SiC particles tend to have lower bonding strength due to high-stress concentration [15]. Hence the strength of the composites depends on bonding strength between the particles and matrix due to varying pouring temperatures.

4. CONCLUSIONS

The Al/SiC/Mg/Cu composites were successfully fabricated with three different pouring temperatures of molten metal, to study the microstructure and mechanical performance of the composites, and the conclusion is listed below.

- The presence of SiC particles in the aluminum matrix was confirmed using SEM-EDX analysis. At a pouring temperature of 670ºC, the Al SiC composite with higher SiC particles incorporation was formed and good interfacial bonding with better distribution of particles guided to the success of best tensile properties.
- At lower pouring temperature (630ºC), a cluster of reinforcement particles has been noticed, because of insufficient temperature for solidification and less fluidity, hence mechanical properties output were lower.
- When the pouring temperature (710ºC) was higher, brittle compound formation between interfaces was intensive and solidification shrinkage defects caused lower mechanical properties.
- It was found that the hardness of the composites changes based on pouring temperature, as it was high when poured at 670ºC temperature.
- Reduction in percentage elongation was seen in all composites prepared at various pouring temperatures because of resistance created by the hard ceramic reinforcement particles in the flowability of the Al matrix.
- The SEM fractographic studies on the fracture surface of the tensile tested samples explained the brittle failure nature of composites.
- Finally, it was concluded that pouring temperature, has an adverse effect on microstructure and mechanical behaviour, making it as vital parameter for preparing Al/SiC/Mg/Cu composites.

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