# The Effect of Reinforcement Ratio on Mechanical Properties of AA2024 Matrix MgO+SiC Reinforced Hybrid Composites

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***Abstract*—In today's rapidly developing technologies, the place and importance of composite materials is gradually increasing and the studies carried out in these fields are continuing rapidly. While metal matrix composite materials form part of these studies, especially the applications of ceramic particle reinforced aluminium composites are expanding. Generally, different types and amounts of SiC, $B_4C$, $SiO_2$, $Al_2O_3$, TiC, MgO, TiB, etc. are added into the aluminium alloys of different quality ceramic reinforcement materials are added. However, composite materials are generally produced by using a variety of these reinforcing materials and are subject to scientific studies. In this experimental study; two different ceramic-based reinforcing materials, SiC and MgO, were mixed equally and then hybrid composite materials were produced with 3%, 6% and 12% (weight) reinforcements in 2024 quality aluminium alloy by vortex method. Density, hardness, transverse fracture and abrasive wear tests were carried out and as well as the microstructures of the composite materials were examined. According to the results, the porosity in the composite structure increased and the density decreased due to the increasing reinforcement ratio. On the other hand, the hardness of the composites increased with increasing reinforcement ratio. However, their cross fracture, and abrasion resistance decreased. It was concluded that it is useful to try different process parameters in order to obtain better mechanical properties in such composites produced by vortex method.**

***Keywords*— Hybrid composite, Microstructure, Mechanical Properties, AA2024, SiC, MgO**

## I. INTRODUCTION

Metal matrix composites (MMC) play an important role in all composites. MMCs are consist of at least two component materials metal matrix which are usually a lighter metal, such as aluminium, magnesium, or titanium and reinforcement material which could be metal or different from metal, such as ceramic or organic based compound. Reinforcement materials are generally ceramic-based materials such as SiC, B4C, SiO2, Al2O3, TiC, MgO, TiB which are embedded in the matrix. Reinforcements not only reinforce the composite structure, but are also used to enhance the physical properties. MMCs are characterized by lightweight, high strength and abrasion resistance compared to conventional materials [1]. An important part of MMC materials is aluminium matrix composites (AMC). AMCs represent a class of lightweight high-performance aluminium-centred material systems. Thirty years of intensive research has created a wealth of information that explains the effects of ceramic reinforcements on the physical, mechanical, thermo-mechanical and tribological properties of AMCs. In recent years, AMCs have been used in high-tech structural and functional applications including aerospace, defence, automotive and thermal management, and sports and recreation [2]. Aluminium matrix and SiC reinforced composites are widely used in automotive and transportation sectors, especially brake disc, cylinder liners, engine blocks and connecting rods. Another application area is the aviation and defence industry sectors. Especially SiC reinforced 6XXX series aluminium matrix composites are used in some parts of combat aircraft and helicopter flight systems. MgO, also called Magnesia is widely used as a reinforcing element in electrical applications, contactors, electric heaters, furnaces, ignition systems of diesel engines and valves due to its good refractory properties [3].

Molten metal mixing, which is one of the production methods of particle reinforced MMC materials, has good potential for low cost MMC material production in general purpose applications [4]. As a result of the literature research, it was found that the selection of the appropriate method and material pair was effective for the successful addition of reinforcing elements used in the production of MMC materials [5]. In addition, it is stated that the production process becomes more difficult with the increase in the percentage of particles and the decrease in particle size in MMC material production by the molten metal mixing method and that pore and particle agglomeration increases in post-production investigations [6, 7]. Sur et al. (2005) in their study, 2014 grade aluminium alloy matrix and 29, 45 and 110 μm particle size in average or mean SiC reinforced composites obtained by mixing casting method. They stated that increasing particle size and decreasing reinforcing weight ratio in the production process of the composites facilitated the mixing casting production process. The hardness value of the composite structure increased with decreasing particle size and increasing reinforcement weight ratio. However, in the same case, it has been reported that porosity and reinforcement agglomeration increase and homogeneous distribution is reduced [4]. It is seen that MMC materials with different properties are produced by mixing casting and other casting methods. In the studies; different matrix materials and reinforcing elements have been used and it has been observed that the effects of the reinforcement on mechanical properties such as distribution of the reinforcing element in the composite, its effect on microstructure, porosity, hardness, abrasion behaviour, and breaking strength, the effect of mixing time and speed [8-15]. Hybrid metal matrix composites are formed by adding more than one reinforcing element with different properties in the matrix. These composites having a mixture of two or more reinforcing particles can enhance the mechanical properties of the composite. Silicon carbide (SiC), alumina ($Al_2O_3$), boron carbide ($B_4C$), tungsten carbide (WC), graphite (Gr), single or multiple carbon nanotubes (CNT) and silica ($SiO_2$) are some of the reinforcing materials used in hybrid MMC [16].

In this experimental study, two different ceramic based reinforcing materials, SiC and MgO, were added into the AI 2024 alloy and hybrid MMCs were produced by using 3%, 6% and 12% (weight) vortex method (stir casting). The measurements of density, and hardness, tests of cross fracture, and abrasion were carried out on the prepared hybrid composites. The microstructures were examined under optical microscope and scanning electron microscope (SEM) and the results were considered together with the results of mechanical experiments. Thus, the effect of reinforcement ratio on the microstructure and the mechanical properties of hybrid MMC was investigated.

## II. MATERIALS AND METHODS

In this study, 2024 grade aluminium alloy as ingot and two different ceramic based powders, namely MgO (-88 μm) and SiC (-105 μm), were used to prepare MMC. Firstly, according to the determined reinforcing volume ratios, the reinforcing powders were weighed on the precision scale. Three different reinforcing materials were stir in the drum mill for 2 hours at 350 rpm, with 1/5 (material/ball) steel ball into the mixing vessel. After the mixing process, it was observed that the particles of MgO and SiC reinforcing elements were distributed homogeneously within each other.

Vortex method (stir casting) was used to prepare of the composites. The ingot Al2024 matrix material was placed into the crucible in the electric melting furnace and the melting process was started. Melting was continued until the liquid metal temperature rose up to 750°C. Meanwhile, the mixing impeller was immersed in liquid metal and the mixing process was started. The stirring speed was gradually increased to 500 rpm within 3 minutes. Within 3 minutes of the mixing speed; powdered MgO+SiC reinforcing mixtures which were prepared previously and annealed for 1 hour at 300°C were added to the liquid Al2024 matrix in the crucible. Stirring was continued at 500 rpm for 10 minutes and then slowed down again, gradually. Without wasting time, the liquid composite mixture was poured into steel moulds of 30 mm diameter heated up to 300°C. Cooled composite materials in the mould were removed and made ready for experiments. Figure 1 shows the vortex apparatus for preparing hybrid composites and the moulds used in the casting. Table 1 shows the mixing ratios of the composites were produced.

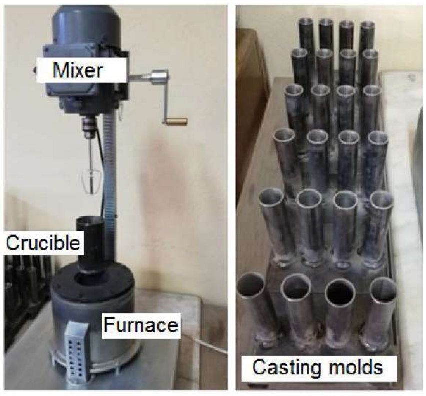



Fig. 1 Vortex apparatus and casting moulds

TABLE I
HYBRID COMPOSITE MIXING RATIOS

| Samples | *MgO + SiC (%) | AI 2024 % |
|---|---|---|
| 1 | 3 | 97 |
| 2 | 6 | 94 |
| 3 | 12 | 88 |

**MgO 50 % and SiC 50 %*

Firstly, surface preparation process of the samples of the required size was made for the microstructure examination of the composite samples prepared in three different reinforcement ratios. For microstructure studies, images were taken at different magnifications on optical microscope and SEM. Then, density measurements and mechanical tests of hybrid composites were performed. Densities were measured according to the Archimedes principle. Hardness measurements were carried out by using *Brinell* method, which using 2.5 mm ball diameter and 31.25 kg measuring load in accordance with TS EN ISO 6506-1 [17]. In the hardness measurements, arithmetic means of the hardness values measured from five different regions of each composite sample were calculated and final hardness values were determined.

Transverse fracture tests were carried out according to ASTM-B 528-05 [18] standard considering the three-point bending principle. The experiments were performed by using

*ELE* hydraulic press with a loading speed of 0.05 kN/sec. The transverse fracture tests were repeated three times for each composite sample and the arithmetic mean of the obtained values were calculated.

At the final stage of the mechanical tests, abrasion losses of hybrid composite samples were recorded by using abrasive abrasion tests with 10, 20 and 50 Nevton loads on a 400 mesh size abrasive paper based on $Al_2O_3$. Fig. 2 shows the abrasion tester in which wear tests were performed.

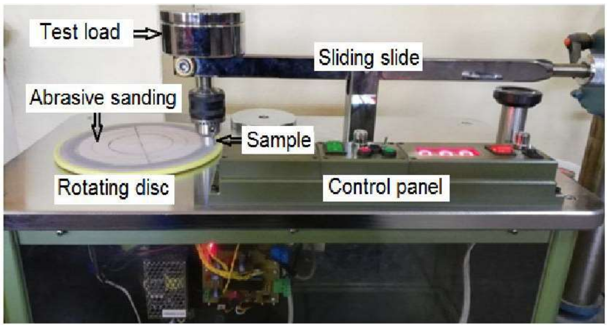



Fig. 2 Pin on disc wear tester

## III. RESULTS AND DISCUSSION

*Microstructures*

The images of optical microscopy, and SEM obtained from the surfaces of the hybrid composites were shown in Figure 3. According to optical microscope images in Figure 3, it is clear that the MgO and SiC reinforcing powders show an irregular distribution. It could also be mentioned that with the increase of the reinforcement ratio, the reinforcing particles tend to agglomerate and the homogeneity was going to be worse. Poor homogeneity and the powder agglomeration have been shown for the hybrid composites as obtained from this study. Root (2005), Hashim et al. (2002) and Pul (2013) pointed out similar results in their studies [11, 19, 20]. One of the major problems of particle reinforced metal matrix composites are that the liquid matrix is often unable to wet the ceramic-based reinforcing element particles, sufficiently. Wetting problem in composite structure causes porosity because of that the matrix material does not envelop the reinforcing particle and a gap, i.e. porosity, occurs at the interface between the matrix and the reinforcing particle.

Due to the density differences between the liquid matrix and the ceramic-based reinforcing particles, the particles aggregate and precipitate into the crucible with the effect of vortex in the liquid metal during mixing. Sur et al. (2005) noted similar results [4]. Since it is difficult to define the MgO and SiC particles aggregated in the composite structure on the optical microscope images, the SEM image (Figure 3d) was taken. On all images shown in Figure 3, it is understood that the pores are formed in the regions where have been the aggregated MgO and SiC particles. It can be said that, the penetration of the liquid metal among aggregated reinforcing particles decreases and causes porosity. Under normal conditions, there are difficulties in wetting liquid aluminium with MgO and SiC particles. The most important reason for this is that ceramic based MgO and SiC particles have a much lower thermal conductivity coefficient than aluminium and very different surface tension values of materials. Therefore, it is even more difficult to wet the aggregated reinforcing particles while during the solidification of liquid metal. Thus, gaps were formed among the reinforcing particles. Hashim et al. (2001) reported similar results in their studies [19].

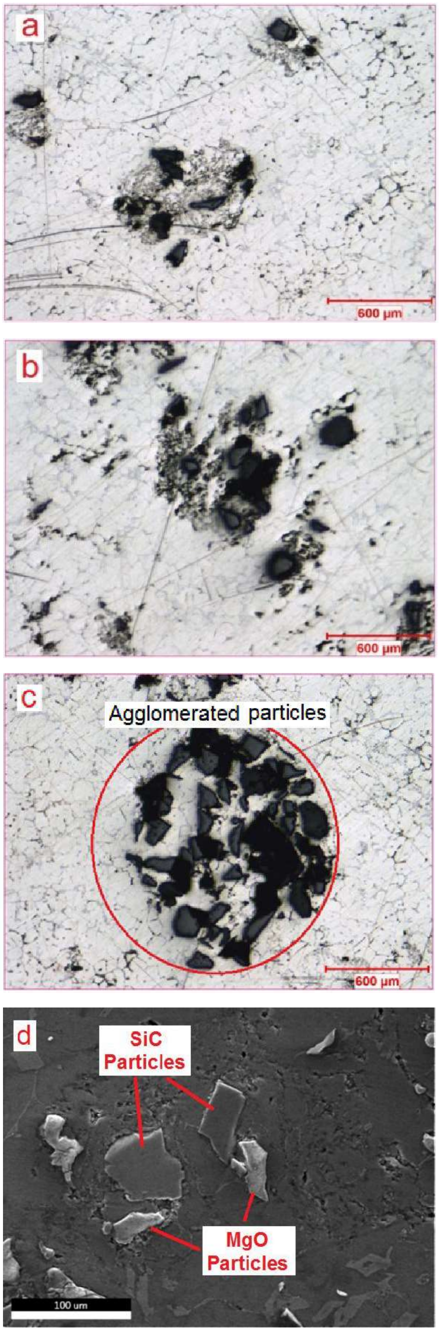



Fig. 3 (a) 3%, (b) 6% and (c) 12% MgO + SiC reinforced AI 2024 matrix hybrid composites, (d) SEM image for MgO and SiC particles

Another issue is the oxidation that occurs during the application of the vortex method. During the mixing process, the vortex formed by the impeller. The impeller alters a continuous airflow into the liquid metal in the crucible during mixing and oxidation occurs because of the property of pure aluminium. The oxidation could be another reason to prevent the wetting and thus the porosity.

*Density*

Theoretical densities of the composites were determined by Archimedes Principle and given in Figure 4 as graphs. In the figure, the first point is that the density is slightly decreasing by increasing of MgO/SiC reinforcement particles. As well as, this situation pointed out that the porosity in the composite structure increases while increasing the reinforcement ratio. Ayvaz and Çetinel (2014) reported similar results obtained in this study [21]. According to the density results, it is clear that the bonding between MgO/SiC reinforcement particles and Al 2024 matrix material has been weaker by increasing the reinforcement ratios. In addition, the density decreased by 4 % as the reinforcement ratio increased from 3 % to 6 %, while it decreased by approximately 10 % as the reinforcement ratio increased from 6 % to 12 %. According to these results, it can be stated that the increase of the reinforcement ratio higher a certain amount (more than 6 %) is more effective on the porosity and density.

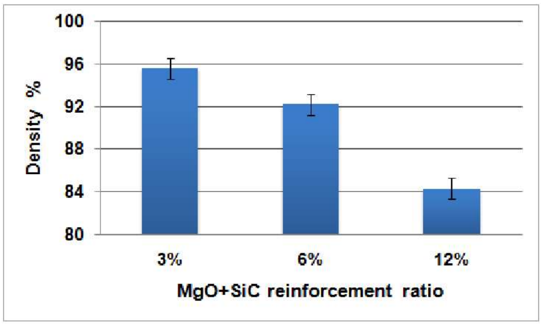



Fig. 4 Densities of hybrid composite samples

*Hardness*

Hardness results of the composite samples were given in Figure 5. It can be observed in the figure that the hardness of the composites increased with increasing MgO and SiC reinforcement amounts. As the harder phases, while increasing MgO/SiC particles ratio, the hardness of the composites increased. A large increasing was obtained, when the reinforcement particles amount up from 3 % to 6 %. However, there is a small increasing from 6 % to 12 %. That result could be explained by increasing of inhomogeneity, and the porosity depending on agglomeration, which getting high by reinforcement ratio. When Figure 3c is reviewed, it is clear that the agglomeration and porosity is higher in the composite structure, which has 12 % MgO/SiC reinforcement. Sur et al. (2005), Kök (2005), and Stamp (2013) pointed out similar results in their studies [4, 11, 20]. Ray (1993) stated that porosity undermines the mechanical properties of the composite structure [13]. In addition, it has been stated in different studies that the agglomeration of the reinforcing particles is adversely affected the mechanical properties of the composite structure [6, 11, 20].

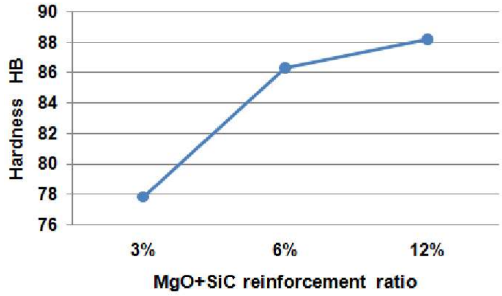



Fig. 5 Hardness values of hybrid composites

*Transverse Fractures*

Figure 6 shows the results of transverse fracture (three-point bending) tests. In the figure, it is seen that the fracture strength of the hybrid composite decreases with an increase of the reinforcement ratio, almost linear. By the increase of MgO/SiC content in the composite structure, fracture strength was negatively affected. The lowest, and the highest fracture strengths were 1010 N at 12 %, and 2250 N at 3% reinforced hybrid composite sample. The possible reason of that result is the porosity, which was being higher depending on MgO/SiC content in the composites. Chong et al. (1993), similar results are expressed [22]. Tekmen et al. (2003) stated that high porosity affects the fracture behaviour of the composite [23]. At the same time, it is considered that SiC particles have sharp corners and could be effective on notching and facilitate fracture by preparing the ground for the formation of micro cracks. If the fracture load values and hardness values were considered together, it is clearly seen that while the increasing of the hardness values, the fracture load value decreases. And there is an inverse relation between them. High hardness decreased the fracture strength by increasing the brittleness of the composite structure. When the literature is reviewed, it is seen that similar results have been revealed in the studies conducted on the subject [4, 6, 7, 9, 20].

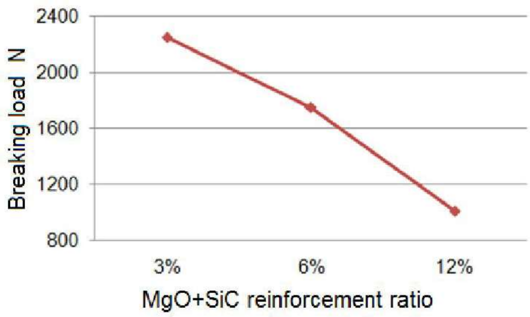



Fig. 6 Breaking loads of hybrid composites

E-ISBN: 978-605-68537-4-6 

*Wear Strength*

The graph of the results of abrasive wear tests have been drawn according to the wear losses, and reinforcement particles ratio and shown in Figure 7. Wear loss values have increased due to the increase of MgO/SiC reinforcement in the composite structure. The most important reasons for this are increasing the amount of MgO/SiC reinforcement and increasing the porosity and decreasing of the composites. During the abrasive wear tests, the pores and voids in the composite structure facilitated the work of abrasive sanding particles. In addition, the agglomeration of the particles that occur with increasing reinforcement ratio can also have a domino effect on increasing wear losses. MgO/SiC particles increase wear losses how by breaking up from the agglomerated regions. An increase at the wear loss between 6 % and 12 % reinforcements also supports that evaluation. There are studies in the literature indicating that wear losses increase with increasing amount of reinforcements in the structure [24, 25]. As a result of these evaluations, it can be said that the high pore amount in the hybrid composite structure directly affects the wear losses and reduces the mechanical strength. Similar results have been reported in some studies in the literature [26-28].

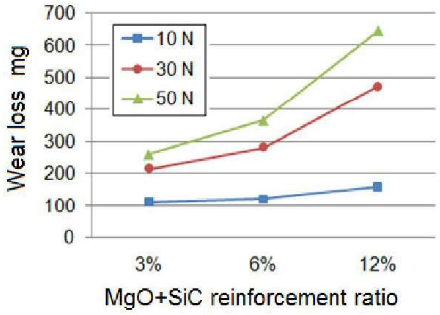
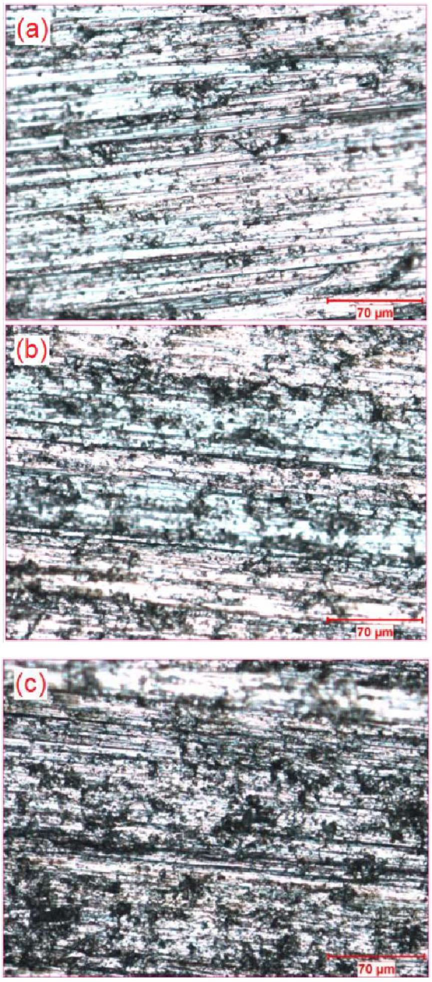



Fig. 7 Wear loss values of hybrid composites

In addition, 10 N abrasion load was not very effective in abrasion tests under three different loads. There was no significant difference between the 3%, 6% and 12% reinforcement ratios in terms of wear loss in the experiments with 10 N load. Consequently, abrasive wear tests of such composites can be performed under loads of 30 N and more, which can provide better results.

Optical microscope images of hybrid composites taken from surfaces after 30N load wear tests are given in Figure 8 to help the investigation of abrasion test results. In the figure, the black areas are particles and light grey areas are Al 2014 matrix. The large black areas pointed out the agglomeration of the particles. In Figure 8d, the pores can be easily seen by high magnification. In particular, the black areas on the worn surface of the 12 % MgO/SiC reinforced composite in Figure 8c refer to both the porous structure and the agglomeration of the reinforcing particles. The other notable is the deep scratched areas on the surfaces. These scratches are not the scratches caused by the $Al_2O_3$ particles on the abrasive sandpaper, but rather the deep scratches of the broken reinforcing element SiC and MgO particles. As could be seen in Figure 8d, especially in areas where reinforcement agglomeration is present in the composite structure, a plurality of particles has broken off together and cause scratches on the surface as they move away from the composite material.

Another noteworthy point in worn surface images is the smearing of the matrix material Al2024. There is an evident in the 3 % reinforced composite in Figure 8a. During abrasion tests, it is understood that the soft phase aluminium has been filled up among abrasive sanding grains and smeared on to the surface. Thus, the wear loss value reduced because of the filling and losing the sharpness of sand paper.



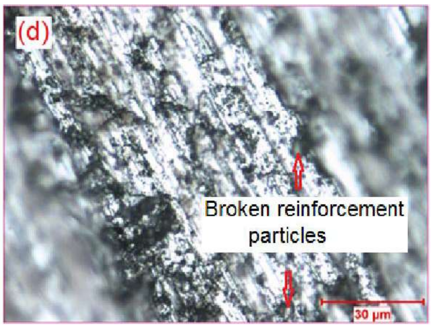



Fig. 8 Wear surface images of (a) 3 %, (b) 6 % and (c) 12 % MgO/SiC reinforced hybrid composites, (d) Reinforcing particles in the structure.

## IV. CONCLUSIONS

The results obtained from the experimental study were listed below:

The better microstructure observed in the composite has less amount MgO/SiC particles with slightly higher homogeneity and less porosity. The reason of the inhomogeneity is agglomeration of the particles and weak wetting property between the matrix and the particles because of surface tensions.

It has been found that the main parameter determining the mechanical properties of such aluminium matrix and ceramic particle reinforced composites is the reinforcement ratios. The distribution of the reinforcing particles in the composite structure, which is not very homogeneous, caused an undesired porous structure and reinforcement agglomeration in some places.

With the increase of the reinforcing element ratios in the hard phase in the composite structure, the hardness of the composites increased while their density, transverse fracture and wear resistance decreased. It has been concluded that the most important reason for the negative effect of mechanical properties is the pores formed in the composite structure and the agglomeration of the reinforcing elements.

The reason of the weak composite structure is that the liquid matrix material Al2024 could not wet enough the reinforcing particles MgO/SiC.

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