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Mechanical, Physical and Thermal Behaviour of SiC and MgO Reinforced Aluminium Based Composite Material

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Abstract: The increased demand of aluminium metal matrix composite in automobile and aerospace industries had enabled to manufacture the aluminum based composites. In this study, aluminium based composite material is fabricated using SiC and MgO reinforced particles. The stir casting technique is used to make the composite material. Attempts have been made to obtain the best composition by mixing SiC and MgO particles with different percentage. Looking at the microstructure image, it was found that both SiC and MgO particles are well combined with the matrix material. The addition of preheated SiC and MgO led to increase in tensile strength and hardness. However, the toughness of the composite material is reduced. Behavior of thermal expansion and corrosion weight loss of the composite material has reflected the presence of SiC and MgO content in the aluminum alloy. Minimum corrosion loss was found for Al/12.5 wt. % Preheat SiC/2.5 wt. % MgO composite material. Minimum dimension change was found to be 4.12 mm^3 for Al/12.5 wt. % Preheat SiC/2.5 wt. % MgO composite material.

Keywords: Al/SiC/MgO composite material; Mechanical properties; Corrosion loss; Thermal expansion

1. Introduction

World's most important metal is the Aluminum and most commonly found in the 8% of the earth crust. After steel, it is most extensively used. Aluminium is extensively used in automobile industries because of its mass and strength considerations.[1,2)] It is widely demanded metal in the earth per year, approximately 29 million tons per year due to its lightweight, durable and functional properties. About 22 million tones of new aluminium are used worldwide in different applications whereas 7 million tones aluminium scrap is reused. Recycled aluminium scrap has comprehended the issue of environment and also economically in manufacturing. Because around 14,000 kWh is expended to create 1 ton of new aluminium.[3,4,5)] While changing over it takes to remelt and recycled aluminium because of which there is no distinction has come in quality among new and recycled aluminium alloys. Aluminium is intrinsic properties like soft, ductile, high electrical conductivity and highly corrosion resistant. Therefore, it is extensively used in many applications but mainly it is used for making conductor cable and foils. In some applications where high strength is desired aluminium alloy is used with other elements.[6-8)].

In many engineering applications, composite materials were popularly used since 1000 years before. Composite material has intrinsic properties due to which composites are very useful many practical and engineering applications mainly this material is most suitable for the high strength applications in comparison to the weight. The composite material is fabricated and selected specifically as per the multiple loading conditions and optimally designed. However, in may critical applications where other materials like titanium, hard steels have used, these materials can be most suitable due to its availability and easy manufacturing processes. Another advantage of the composite material is its flexibility in the design because composite can be molded easily in complicated shapes and sizes. Many researchers have designed composite materials to suit many applications. It was found that composite material exhibit very good strength in comparison to the other metals. Pure aluminium cannot give a required tensile strength whereas by adding some other materials like silicon, manganese, copper and magnesium can give a proper strength and converted into a composite with adequate properties which is most suitable for the specific applications[9-12)]. Aluminium is best suited to a cold environment because if the temperature decreases its tensile strength will increase. The composite material is a combination of two or more metals having different chemical compositions and physical properties resulting in a new material formation. This has been examined that a composite performance is much superior to the base alloy.[13-14)]

Aluminium based composite materials are one of the interest area of many researchers to fulfil the requirement of engineering applications. In many sectors the designing of material is for the improvement of strength and cost saving. In fulfilment of this industrial requirement addition of alloy, modification of grains, heat treatment, corrosion resistance etc a certain trends has been followed. Due to the lightweight property of the aluminium based alloy, it has been one of the important applications in many industrial sectors, automobile applications and biomedical instruments fabrications. Advanced technology for the development of aluminium based composites like Metal matrix composite (MMCs) is widely used by the engineers and material scientist. Many researchers are used MMCs is one of the most useful technique which used worldwide. Just because of easy of fabrication, cost involved in the process, size, shape and wetability between the second phase and matrix alloy, MMCs is one of the first choice of many researchers to satisfy its working conditions in the engineering field. Aluminium alloy composites also possessed an important consideration when it require for a mass production, repeatability operations, and good surface finish. In comparison of cast iron aluminium alloy can give best results in terms of strength and weight ratio, heat transfer rate, corrosion resistance, energy efficiency and stiffness. More development of the aluminium alloys have been observed in the structural, aerospace industries, automobile and railway sectors. In the literature review many authors have revealed that a high wear resistance property of the aluminium based composite material at high speed. It was also reported that at higher volume fraction and size of the particulates the wear resistance property of the AMMCs increases. In the presence of SiC particles in the aluminium alloy the wear resistance property has significantly increases. Therefore, for the application of many mechanical sliding and rolling elements, the uses of aluminium composites are the final choice of the engineers.[15, 16)]

In many structural applications, a lighter metal such as titanium, aluminium and magnesium are used in the matrix. For the high temperature applications other material like cobalt and cobalt-nickel alloy materials, silicon carbide, or ceramic fibers are used in the matrix. In the automobile industry, MMCs is commonly used for the fabrication process. In the manufacturing of the automobile elements aluminium is used as a matrix and it reinforced with the fibbers material like silicon carbides. MMCs have a high specific stiffness and less thermal expansion coefficient. Due to which this method is best suited for the manufacturing of automobile components like pushrods for racing engines, disc brakes, engines, driveshaft etc. MMCs have long time resistance at different environments over polymeric matrices. Another advantage of the metal is that it can be easily deformed plastically and strengthened with the help of mechanical and heat treatment. There are many methods are adopted for manufacturing of aluminium based composite materials other than metal matrix composite method, e.g. powder metallurgy method with the help of hot extrusion. Major advantage of the powder metallurgy process is easy control of the properties of mixing material with different proportions.

Metal-Matrix Composites(MMC) are made of by adding some reinforced material like fibres of boron, alumina, carbide, graphite and tungsten, etc., in the different matrix of aluminium, magnesium, titanium super alloy, etc. It has a high resistance at high temperatures with high elastic modulus ductility. To prevent any chemical reactions with the matrix the surface of the composite can be coated. The matrix is a single-crystal material and formed a continues material by adding a reinforcement of other materials.[17-19)] Composite has a high heat resistance property. Some more important properties like toughness and fatigue resistance are very well improved. While making the composite the quality of the end product is increased with its mechanical and physical properties.[20-22)]

The stir casting technique is used to make composite material or electromagnetic stir casting technique. When one reinforcement is used to make composite, it is called monolithic composite. The same when two or more reinforcement is added to the matrix, it is called hybrid composite. There are often problems in making hybrid composite. One of these is to have different density of two different reinforcement. However, hybrid composite also has several advantages. Therefore, in this study SiC and MgO are used made aluminum based composite using two different reinforcement.

The main reason for making composite material is to increase the properties of matrix material. For this reason, either one reinforcement is added to it or more than one. It is also taken into consideration that the overall cost and density should not increase too much while making the composite material. Because, if the density and cost will also increase, then it becomes difficult to bring the composite into the application. As everyone knows that iron strength is much higher than aluminum. But still it is not used in many places. The main reason for this is its density. Its density is much higher than aluminum. Because of which iron is not used where light material is required. In such places aluminum based composite material is used. Many ceramic particles are used when making aluminum based composite.

While selecting a material one of the most essential factors is the ability to sustain the material in the condition of the high-temperature environment. It was observed various times that good strength material could not sustain a high-temperature environment. It has been also noticed that material having good strength corroded early. Further, from the background, it has been noticed that very limited researchers used SiC and MgO particles simultaneously in development of aluminium based composite material. Less work is performed by varying these reinforcements. Keeping these realities in the mind, in the present investigation, an attempt was made to identify the optimum combination of SiC and MgO as reinforcement material in the manufacturing of aluminium based composite material for superior mechanical properties with least thermal expansion of composite and corrosion failure.

2. Materials and methods

2.1 Matrix Material

In the present study, commercially available pure aluminium was selected as metal matrix material. Aluminium matrix composites are highly used in various engineering applications because it possesses some important properties like formability, recyclability corrosion-resistant and re-melted with the result of that this is available in various forms[23-24)]. One of the most disadvantages of aluminium is its low strength as compared to iron. However, by using various reinforcement particles with aluminium, its mechanical properties can be improved [25)]. Chemical composition of aluminium was about 0.12–0.5% of Cu and 99.5%–99.9% of Al. The reinforcing material is added to the matrix. The reinforced material not only changes the structure but also improves the physical properties such as thermal conductivity, wear resistance, friction coefficient. The reinforced material can be chosen as continuous or discontinuous. Discontinuous material is most useful for some manufacturing applications like extrusion, forging and rolling. Commercially available reinforcements were used in the experiment.

Table 1: Composition Selection

S. No.	Sample Designation	Composition	Wt. % SiC	Wt. % of Preheat SiC	Wt. % of MgO Powder
1	G1	Al + 2.5 % SiC	2.5%	-	-
2	G2	Al+ 5 % SiC	5%	-	-
3	G3	Al+ 7.5 % SiC	7.5%	-	-
4	G4	Al+ 10 % SiC	10%	-	-
5	G5	Al+ 12.5 % SiC	12.5%	-	-
6	G6	Al+ 2.5 % Preheat SiC	-	2.5%	-
7	G7	Al+ 5 % Preheat SiC	-	5%	-
8	G8	Al+ 7.5 % Preheat SiC	-	7.5%	-
9	G9	Al+ 10% Preheat SiC	-	10%	-
10	G10	Al+ 12.5 % Preheat SiC	-	12.5%	-
11	G11	Al+ 0% Preheat SiC + 15 % MgO	-	0	15%
12	G12	Al+ 2.5 % Preheat SiC + 12.5 % MgO	-	2.5%	12.5%
13	G13	Al+ 5 % Preheat SiC + 10 % MgO	-	5%	10%
14	G14	Al+ 7.5 % Preheat SiC + 7.5 % MgO	-	7.5%	7.5%
15	G15	Al+ 10 % Preheat SiC + 5 % MgO	-	10%	5%
16	G16	Al+ 12.5 % Preheat SiC + 2.5 % MgO	-	12.5%	2.5%
17	G17	Al+ 15 % Preheat SiC	-	15%	0

2.2 Primary Reinforcement Material

In the fabrication of aluminium based composite material, commercially available silicon carbide (SiC) has been selected as primary reinforcement material to enhance the physical properties of the composite material. SiC is preferred as reinforcement material due to its excellent wettability with aluminium alloy. The mechanical properties of the composite have increased by adding SiC in aluminium alloy. The density, bonding strength and elastic modulus lies in the range of 3.02 g/cm^3, 250-280 MPa and 300 GPa at 1200^0C. The main reason for using it most is to make it good wettability with aluminum. Also SiC builds good bond strength with aluminum. For all these reasons, SiC has been taken as the primary reinforcement in this study.

2.3 Secondary Reinforcement Material

In order to further improvement of the properties, secondary reinforcement was added to the composite material. Such type of composite is called a hybrid composite. In the fabrication aluminium based composite, commercially available MgO powder consist of SiO2, CaO, Fe_2O_3 and Al_2O_3. The purpose of selecting powder of MgO as secondary reinforcement material is to improve the wettability of primary reinforcement particles with aluminium alloy. MgO powder was accountable for the improvement of mechanical properties of the composite.

2.4 Development of Composites

In this study aluminum based composite is made using SiC and MgO together. Various problems encountered from literature while making composite. It has been seen many times that a composite is formed, but many defects appear in it. These defects affect the property of the composite in many ways. Due to this effect, tensile strength and hardness affected. The main defect which comes in composite has many reasons. The first reason is the lack of reinforcement particles in the matrix. When reinforcement particles do not mix well in aluminum, they either get collected in one place. Because of which the property of a composite does not come the same everywhere. And this composite is no longer usable. The second reason is the stirrer brought into the composite. Even if the design of the stirrer is not correct, the composite may not mix well. Hence it becomes very important that the design of the stirrer is correct. Another factor comes up when making hybrid composite is the different density of reinforcement particles. Due to different density, many times there is a lot of problem. In this case, the lighter reinforcement particle floats on the surface of the molten matrix and the heavier reinforcement particles get collected at the bottom of the molten matrix. Because of which the stirrer is not able to mix both these reinforcement particles properly. The preheat temperature of reinforcement particles also greatly helps in increasing the mechanical property of the composite. Reinforcement particles have a good wettability with the matrix material if it is necessary to increase the mechanical property of the composite. Here if the reinforcement particles are preheated with proper temperature then it makes good wettability with the matrix. The same does not create proper wettability with the matrix material if reinforcement particles are not preheated well. Because of which the mechanical property of the composite does not increase well.

In this study, metal matrix composites were prepared by the mechanical stir casting technique. MMCs are developed at a varying temperature which is an important consideration for bonding diffusion of the composite interface.[26] After that, it is cooled down at ambient temperature. Before melting in the furnace, aluminum and SiC particles was preheated to remove the moisture content. For the fabrication of the composite, aluminum alloy was melted in the muffle furnace. SiC and MgO particles kept in aluminum foil were incorporated (5 to 7 gm/min) in the melt to avoid clusters of reinforced particles. Stir casting set up is shown in Figure 1. Stirring was done for 12 minutes at 480 rpm. The melt slurry was poured in the preheated permanents steel mold at 310°C for 100 minutes having 34 mm diameter and 78 mm length. The melt was permitted to cool in atmospheric air. Once composite material has solidified then it is prepared for the different testing. Composition Table of different composition is shown in Table 1.

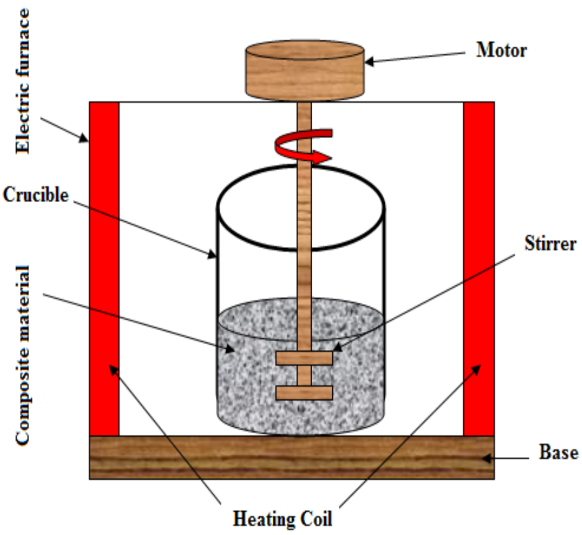

Fig 1: Line diagram of Stir Casting Set-Up

2.5 Measurement of mechanical properties

Micro-structural analysis had confirmed the presence of reinforced particles in the prepared composite material. Mechanical properties such as tensile strength, corrosion, hardness, toughness and thermal expansion has been studied. UTM was used to perform the mechanical test. NaCl solution was used to conduct the corrosion test.

3. Results and Discussion

3.1 Microstructure Analysis

The analysis of microstructure is one of the most important considerations in the fabrication of composite material. Scanning electronic microscopy was employed to study the microstructure. If reinforcement particles are uniform, then it provides better mechanical properties. But, if its distribution is not uniform then, it does provide lower mechanical properties. Figure 2 shows the microstructure of Al/12.5 wt. % Preheat SiC/2.5 wt. % MgO composite material. A uniform distribution of SiC and MgO particles showed an aluminium base matrix material in the microstructure results. Uniform distribution of preheated SiC particles and MgO powder was the main reason for improving the property of mechanical, physical and thermal behaviour of composite material. The strength of the composite material always depends on the distribution of reinforcement particles. However, the interfacial reaction layer made with the matrix of reinforcement particles along with the distribution of reinforcement particles also makes a very significant contribution. Hence, these things are always taken care of when making composite. Here also the distribution of SiC and MgO inside the matrix was found to be good. Also, when SiC and MgO were added to the matrix after preheat a good interfacial reaction layer with the matrix of reinforcement particles also developed [27]. Figure 3 shows the microstructure image of composite with the lowest (Al/5 wt. % Preheat SiC/10 wt. % MgO composite) tensile strength. Non-uniform distribution of reinforcement particles and some cracks can be observed.

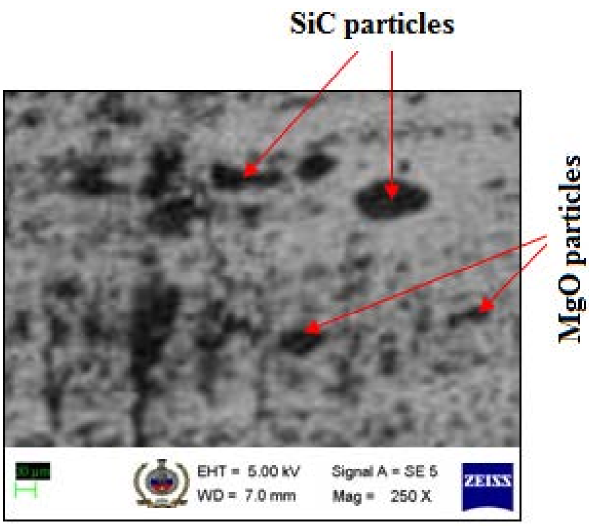

Fig. 2: Microstructure of composite with the highest tensile strength

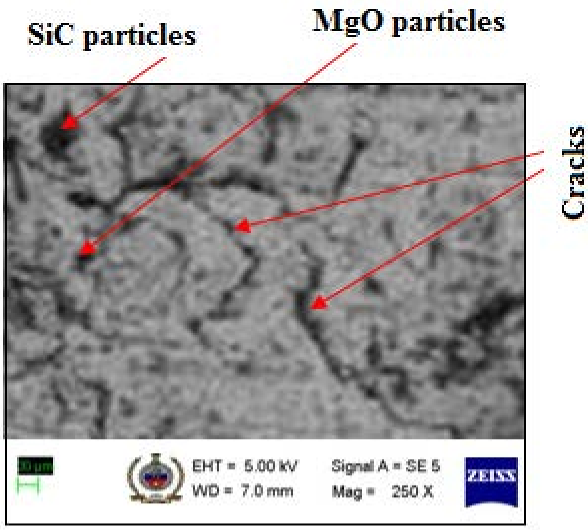

Fig. 3: Microstructure of composite with the lowest tensile strength

3.2 Tensile Strength Analysis

A tensile test was performed for different composite material. Specimens were prepared as per ASTM E8-E8M-13a standard. The variation of the tensile strength of different composite material developed by the stir casting process is shown in the figure 4. It was noticed that preheated SiC particles used as reinforced material have been demonstrated better tensile strength as compared to without preheated SiC particles. Incorporation of MgO particles in Al/preheated SiC particles enhanced the tensile strength of composite material. In comparison to other composite materials, the tensile strength for composition Al/12.5 wt. % Preheat SiC/2.5 wt. % MgO is found maximum as shown in Figure 3. The other composite material have not got much tensile strength. This may be due to agglomeration of reinforcement materials or poor bonding between the alloy and reinforcement. It was also noticed that the uniform distribution of reinforcement particles in the aluminium alloy was accountable for improvement in the tensile strength of composite material. However, strong bonding between the molecules after the solidification process in the composite also enhances the tensile strength of the composite material. Incorporation of MgO particles with SiC ceramic particles improved the bond strength of aluminium based matrix material. Improved bond strength of composite material was responsible for enhancing the tensile strength of composite material significantly. Tensile strength increases when composite materials were made by adding reinforcement particles. However, there are several reasons for increasing tensile strength. But the main reason is wettability with the matrix of reinforcement. Wettability always depends on the reinforcement and bonding strength of the matrix material. Here also the reason for increasing tensile strength is the good wettability of SiC and MgO particles with aluminum [28]. Figure 5 shows the tenaile fracture image of composite material. Fractured image of the Al/12.5 wt. % Preheat SiC/2.5 wt. % MgO composite material showed the pulled regions tiny dimples which balanced between strength and ductility of the prepared hybrid composite material. However, some agglomeration of reinforcement particles can be also observed from fracture SEM image.

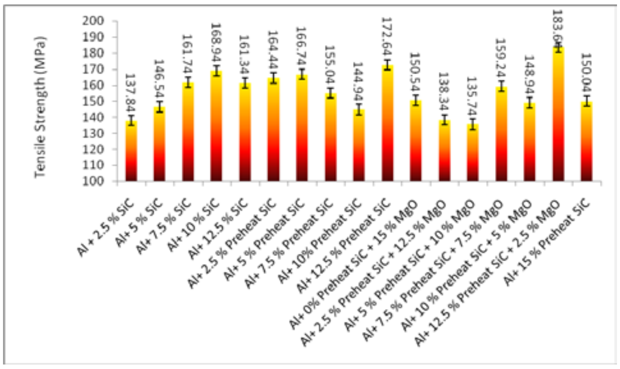

Fig. 4: Tensile strength of Composite Materials

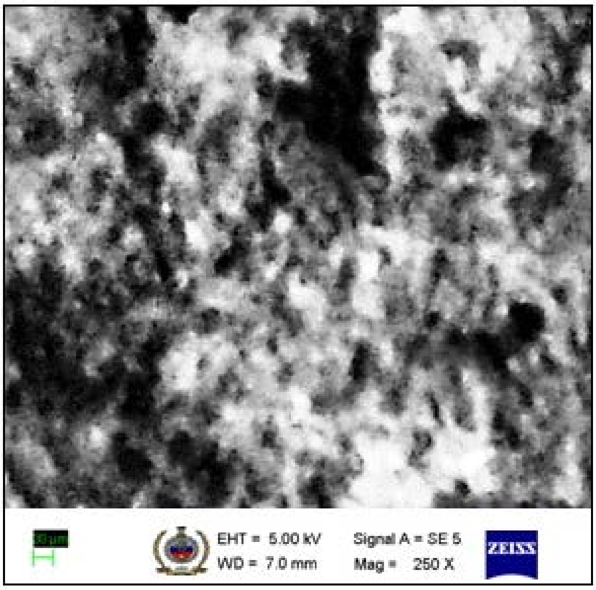

Fig. 5: Tensile fracture image of Composite Materials

3.3 Hardness

Brinell hardness test was performed to evaluate the hardness of various composite materials reinforced with SiC and MgO particles in Al alloy. The variation of hardness of different composite materials is shown in the figure 6. It can be easily determined that maximum hardness was noticed to be 79.24 BHN for composition Al/15 % Preheated SiC composite material. Results of hardness test clearly showed that preheated SiC particles with 15 wt. % in aluminium alloy have demonstrated better hardness as compared to selected other composition. It can be noticed that maximum hardness was found for composition Al/15 % Preheated SiC composite material due to the hard phase of SiC particles. The hardness of the composite materials were improved just because of the proper wettability of the preheated reinforcement particles with the aluminium alloy. The property of materials wettability normally depends on the interfacial reaction layer between the reinforcement particles and matrix material. Proper interfacial reaction layer had reduced the porosity of various composite materials produced by the variation of reinforcement. Resulting, the hardness of composite increased. The hard material is added to the matrix material to increase hardness. However, many times it has been observed that when reinforcement particles are added to molten aluminum, porosity is produced inside the composite when it begins to solidify. This porosity reduces the hardness of the composite. But here when SiC and MgO were added to the aluminum, the hardness increased [29]. Some interfacial reactions may occur as variation in hardness is observed on preheated and non pre heated SiC content.

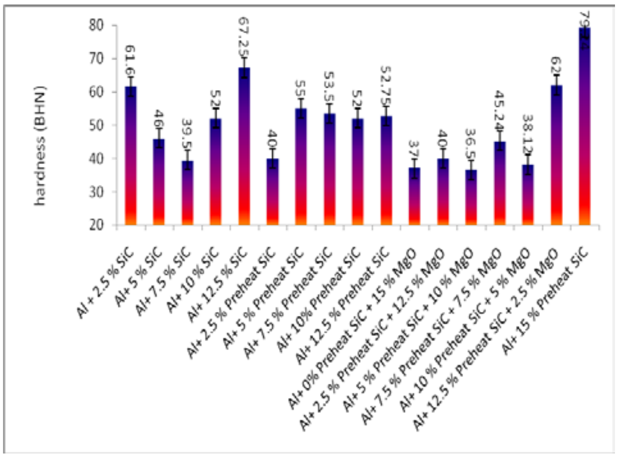

Fig. 6: Hardness of Composite Materials

3.4 Toughness Analysis

The intention of a toughness test is to measure the resistance of a material in terms of the load required to cause brittle or ductile crack extension (or to reach a maximum load condition) in a standard specimen containing a fatigue precrack. From figure 7, it was found that the addition of reinforcement particles in aluminium alloy has been reduced the toughness of composite material. However, maximum toughness was found to be 16 Joule for composition Al/2.5 wt. % preheated SiC composite material among the selected compositions. Toughness behaviour is also an important property of a material along with tensile behavior. However, in most cases Toughness decreases when hard ceramic material is mixed with aluminum. The main reason for decreasing Toughness is the opposition to the plasticity behavior of the material. Also seen here, when

SiC and MgO were mixed together, the Toughness of the composite decreased compared to aluminum [30].

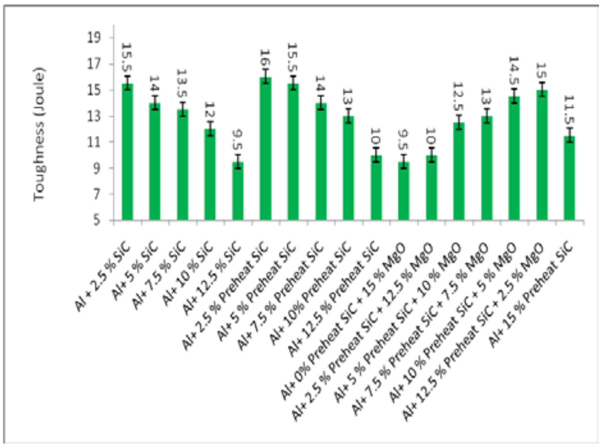

Fig 7: Toughness of Composite Materials

3.5 Corrosion Analysis

Corrosion in the material is a normal phenomenon. Although some material has very high corrosion rate, while some material is very low. For example, if we talk about iron, it has a high corrosion rate. If we talk about aluminum, then it is very less in comparison to iron. This is the reason why nowadays aluminum based composite is being used more in industries. However, after the composite material is formed, there are many factors that affect the corrosion rate. One of the factors is porosity. That is why after making composite material, it is necessary to find out the corrosion behavior of each composition.

Corrosion in the materials relies upon the variety of the capability of the two regions. This is occurred due to structural defects. Sometimes, it was observed that very good property of the material is corroded earlier. This corroded material is then useless for industrial application point of view. The present study deals with the minimum corrosion loss in the composite material by selecting the various compositions of SiC and MgO with aluminium base matrix material. Accelerated corrosion test, that was 5% salt spray test and alternate immersion test in 4.7% $CaCl_2$ solution and 5% NaCl solution was performed for 120 hours. Results exhibited that with the addition of the SiC and MgO particles in aluminium alloy, corrosion loss of material decreases. In the graph it has been clearly noticed that the minimum corrosion loss was found for composition Al/2.5 % SiC composite material and Al/12.5 wt. % Preheat SiC/2.5 wt. % MgO composite material as shown in Figure 8.

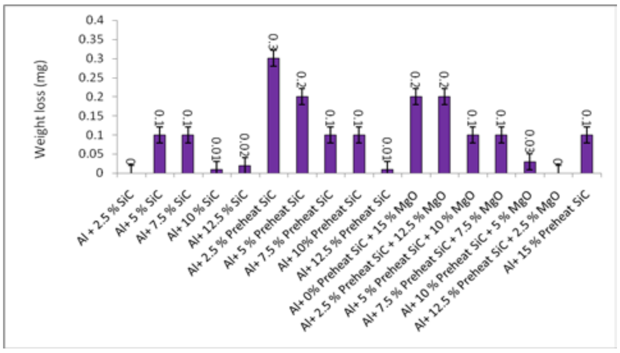

Fig 8: Weight Loss of Composites after Corrosion Test

3.6 Thermal Expansion Analysis

In industries, most parts have utility in high temperature. Many times it has been seen that materials with good strength and hardness also shrink at higher temperatures. Because of which it also affects the rest of the parts. Therefore, it becomes very necessary to check the utility of the composite made in high temperature. Especially in more temperature of aluminum based composite, it is more important to check the utility. Because its melting temperature is very less compared to the rest of the material like iron.

The composite materials are having many applications where the thermal gradients are unexpected and unavoidable. Thus the performance of the composite is very important at varying temperature environment. The behavior of thermal expansion of composite material has been recognized to perceive material sustainability in a high-temperature situation. A uniform sample of dimension (Volume: 2500 mm^3 (25 x 10 x 10)) was kept for each sample. The behavior of thermal expansion of the composite material was recorded with the heating of the composite at 450^0C in an electric furnace for the duration of 72 hours. Due to the formation of appropriate interfacial reaction layer between the matrix material and reinforcement particles, a minimum thermal expansion in this composite was recorded. It was noticed that minimum dimension change was found to be 4.12 mm^3 for composition Al/12.5 wt. % Preheat SiC/2.5 wt. % MgO composite material as shown in Figure 9.

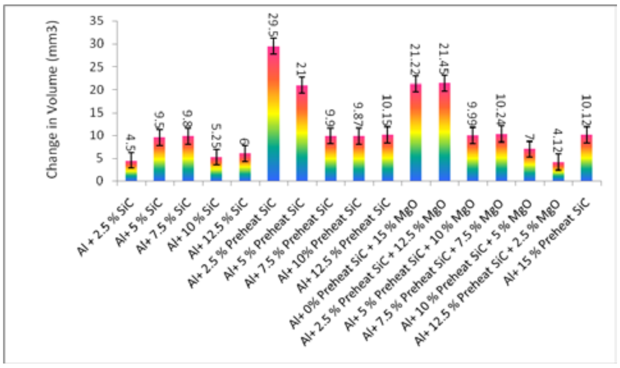

Fig 9: Change in Volume after Thermal Expansion Test

3.7 Density and Porosity Analysis

Porosity (P) is the percentage of the pores volume to the total volume with the volume of a substance. Theoretical density of the composite was calculated by the rule of mixture. Fig. 10 represents the schematic setup for the experimental density measurement Archimedes principle. It is defined by

$$P = \left(1 - \frac{\rho_{Experimental}}{\rho_{Theoratical}}\right) \times 100\ \%$$

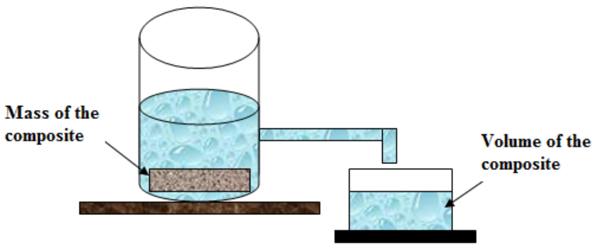

Fig. 10: Experimental density measurement of composite by Archimedes principle

Density of the aluminum was 2.7 g/cm^3. Density of the SiC and MgO were found to be 3.21 g/cm^3 and 3.58 g/cm^3 respectively. Theoretical density and experimental density can be observed from Figure 11. From the density analysis minimum porosity was found for the composition Al/12.5 wt. % Preheat SiC/2.5 wt. % MgO composite material. Figure 12 shows the percent porosity of composite materials. Minimum percent porosity was found to be 0.57 % for the composition Al/12.5 wt. % Preheat SiC/2.5 wt. % MgO composite material.

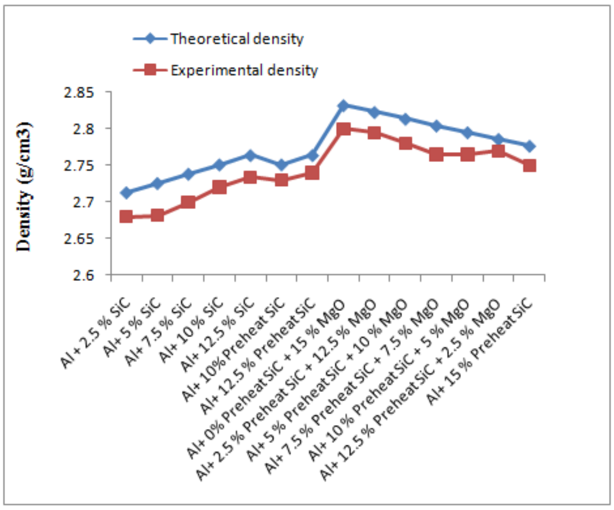

Fig. 11: Theoretical and Experimental density of composite

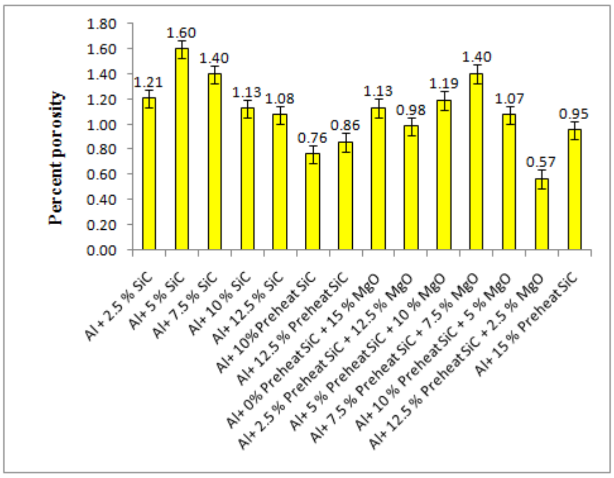

Fig. 12: Percent porosity analysis of composite

4. Conclusions

Following conclusions are drawn from the analysis.

1. The aluminium based composite material can be fabricated using SiC as primary reinforcement particles and MgO as secondary reinforcement particles by stir casting technique.
2. The microstructure of composite material demonstrated a uniform distribution of reinforcement particles in aluminium alloy.
3. Preheated SiC particles as reinforcement in development of aluminium based composite material showed better tensile strength as compared to the addition of without preheated SiC particles.
4. Tensile strength of Al/SiC composite further improved after adding the MgO particle as secondary reinforcement. Al/12.5 wt. % preheat SiC/2.5 wt. % MgO composite material had maximum tensile strength.
5. Corrosion loss and thermal expansion of composite have been decreased by adding SiC and MgO in aluminium alloy. Minimum corrosion loss was found for Al/12.5 wt. % preheat SiC/2.5 wt. % MgO composite material.
6. Minimum percent porosity was found to be 0.57 % for the composition Al/12.5 wt. % Preheat SiC/2.5 wt. % MgO composite material.
7. Future research can be performed by conducting more experiments by varying process parameters and weight percentage of reinforcement.

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