Investigation of micro-structural and mechanical properties of metal matrix composite A359/B₄C through electromagnetic stir casting

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In recent years, instead of the conventional structural materials, aluminium-based metal matrix composites (MMCs) are being widely used in aerospace and automotive industries because of their valuable engineering qualities, such as, specific strength, light weight and greater stiffness. In the present paper, an attempt has been made to fabricate MMC of an alloy of aluminium A359, reinforced with B₄C micron-size particles using electromagnetic stir casting method. Mechanical stir casting route was also used to fabricate another sample to compare the experimental results. The fabricated samples of MMC are analyzed by the scanning electron microscopy (SEM). X-ray diffraction (XRD), energy dispersive spectroscopy (EDS) and differential thermal analysis (DTA) are also studied to validate the process of fabrication. Different mechanical tests for tensile strength, toughness, hardness and porosity were carried out for both the samples. The results showed that the electromagnetic stir casting could produce uniformly distributed reinforced particles of B₄C particles in A359 alloy as compared to mechanical stirring, which, in turn, could improve mechanical properties.

Keywords: Metal matrix composite, A359, Boron carbide, Electromagnetic stir casting

Aluminium matrix composites, in which hard ceramic particles are dispersed in a relatively ductile Al matrix, have applications in wide areas such as ground transportation (auto and rail), thermal management and aerospace. These composites are a class of materials with an excellent combination of mechanical and physical properties for various applications in the automotive industry. They are also amenable to secondary manufacturing processes, such as, extrusion, rolling, forging, welding, etc. A large majority of these materials are metal matrix composites (MMC) in which metallic matrices are reinforced with high strength and high modulus phases, such as, carbides, nitrides, and oxides. The upgraded characteristics of the MMC such as light weight, high strength, better corrosion resistance, etc, make it the best suitable material for automobile industries. In recent years, the composite materials have been replacing the heavier engineering materials (steel or copper) for better performance in terms of weight reduction and good fuel efficiency. MMCs require embedding of reinforced fibers in a metallic matrix. This involves either melting of the matrix material or hot pressing of the matrix into fibers. In either case, high temperature is required to produce these special composites. In the MMCs, metallic matrices are reinforced with high strength and high modulus phases, such as, carbides, nitrides, and oxides. Particulate MMCs have been proven to improve strength, wear resistance, structural efficiency, reliability and control of physical properties, such as, density and coefficient of thermal expansion. In the process, they ensure improved engineering performance in comparison to the un-reinforced matrix.

There are several fabrication techniques available for manufacturing the MMC materials. The fabrication techniques can vary considerably according to the type of reinforcement. The selection of process depends upon the homogeneous distribution of the particles in the matrix alloy and accuracy of the MMCs. Electromagnetic stir casting is one of the advanced techniques to develop the reinforced casting. In this technique, the stirring of the molten metal is done by increasing the stirring current produced by electromagnetic effect. In the presence of a magnetic field, when electric current flows through a conducting body, whether solid or fluid, there is a force per unit volume (the Lorentz force). The rotational motion of the fluid is achieved...
by the effect of this Lorentz force due to the eddy
current of the alternating field flowing into the molten
metal\textsuperscript{12,15}. In the electromagnetic stirring process, a
vortex or eddy forms where the reinforcing particles
are introduced to the side of vortex and this vortex
helps to mix the reinforcement with the molten
material\textsuperscript{16}. As the process does not use any type of
mechanical stirrer, the possibilities of impurity
creeping into the process is minimum. Many of the
researchers have worked on fabrication process of
aluminium composite through different techniques but
most of them have suggested to use liquid metallurgy
to produce metal matrix composite. Moffatt\textsuperscript{14}
described electromagnetic stirring and stated the
concept of Lorentz force distribution to produce
stirring in a conductor.

Takeuchi \textit{et al.}\textsuperscript{17} investigated the quality and
productivity of the continuous casting process to
prove it a feasible manufacturing process. Rohatgi\textsuperscript{18}
presented an overview on fabrication of metal matrix
composites by incorporation of fly ash particles. Their
results indicated the increase in hardness, abrasion
resistance and overall stiffness. Stefanos\textsuperscript{19} fabricated
the composite of Al-Mg alloy reinforced with SiC particle by stir casting process and investigated the
tensile and fatigue strengths. Rohatgi\textsuperscript{20} examined the
abrasion and frictional resistance of fly ash reinforced composite material of A356 produced by stir casting
process and compared the finding with base alloy
A356. Zhou \textit{et al.}\textsuperscript{21} recommended the two step mixing
method to improve wettability, homogeneous particle
distribution and produced A356 and 6061 matrix alloy
by gravity casting. Modi \textit{et al.}\textsuperscript{22} investigated the
microstructure and wear behavior of Al-Zn alloy
along with mechanical properties produced by stir
casting process. Hashim \textit{et al.}\textsuperscript{15} selected A359 as
a base alloy to produce cast metal matrix composites by
mechanical stirring at two steps before pouring. Das and Mondal\textsuperscript{23} produced the hard particle
composite by pressure die-casting and correlate its
mechanical properties and microstructure with abrasive
wear.

Sritharan \textit{et al.}\textsuperscript{24} observed the SiC and aluminium
reactions while producing MMCs and discussed the
mechanism for pits forming in the microstructure.
Das\textsuperscript{25} developed a composite reinforced with SiC to
examine the wear resistance in addition to weight
saving. Li \textit{et al.}\textsuperscript{26} reported the dynamic response of
A359 aluminum alloy and A359/SiCp MMCs in shear
and observed that the composite is significantly
stronger than the matrix alloy in shear, and retains the
same strain hardening characteristics as the matrix
alloy. Ye \textit{et al.}\textsuperscript{27} developed magnesium matrix
composite and studied the microstructure with respect
to reinforcement distribution, grain refinement and
interfacial characteristics along with mechanical
properties. Saraswathi \textit{et al.}\textsuperscript{28} produced Al-SiC
composite and examined the effect of reinforcement
volume, alloy composition and stirring speed on the
erosion-corrosion behavior. Balasivanandha\textsuperscript{29}
investigated the effect of stirring speed and stirring
time on distribution of reinforcement particles in cast
MMC and suggested that 600 rpm stirring speed and
10 min stirring time were the best suitable
combinations to cast aluminum composites. Zhou \textit{et al.}\textsuperscript{30}
discussed the effect of intensity and frequency of
electromagnetic stirring on the solidification structure of
austenitic stainless steel.

Barbara \textit{et al.}\textsuperscript{31} have done double stir method to
mix the liquid slurry of A359 aluminium alloy with
20% SiC and 7.5% B\textsubscript{4}C. Rohatgi \textit{et al.}\textsuperscript{32} discussed the
processing and synthesis of cast MMCs to emphasize
the incorporation of reinforcement into the liquid
phase of molten and its solidification. Zhu \textit{et al.}\textsuperscript{33}
reported annular electromagnetic stirring (A-EMS), a
newer technique to produce semisolid slurry and
study the effect of stirring time, stirring speed,
cooling rate and solidification behavior of A357 alloy.
In further studies Bai \textit{et al.}\textsuperscript{34} reported the effect of
annulus gap width and pouring on the microstructure of
the semi-solid A357 aluminium alloy slurry prepared by A-EMS technology. Yu \textit{et al.}\textsuperscript{35} optimized the
process parameters in a round billet continuous
casting mold with electromagnetic stirring. Christy
\textit{et al.}\textsuperscript{36} investigated the mechanical properties and the
microstructure of Al6061 alloy with Al-TiB\textsubscript{2} MMC
containing 12% by weight TiB\textsubscript{2} manufactured through
in-situ process. Jokhio \textit{et al.}\textsuperscript{37} developed aluminum
alloy matrix with the addition of Cu-Zn-Mg metals and
reinforced with Al\textsubscript{2}O\textsubscript{3} by using stir casting
process. Behera \textit{et al.}\textsuperscript{38} developed LM6 based
composites reinforced with different weight fraction of
SiC particles by stir cast technique and studied the
effect of reinforced ratios on the forgeability and the
machinability. Mocko \textit{et al.}\textsuperscript{39} investigated the aluminium based MMCs reinforced by silicon carbide of
volume fraction 0%, 10%, 20% and 30% and
conducted tests at wide range of strain rates and large
magnitudes of strains. Prabhkiran\textsuperscript{40} developed
electromagnetic stirring setup and presented the effect
of electromagnetic stirring on microstructure, mechanical properties and wear behaviour of A356-SiC composite. Kayal et al. investigated the solidification behavior of aluminum alloy (LM6) SiCp composites at different sections of five stepped component (composite castings) which was produced by stir cast technique. DasGupta et al. produced the MMC of Al7075 alloy reinforced with 10% SiC particle by stir casting process and evaluated the fabricated composite for their sliding wear properties. Yakobshe et al. investigated that electromagnetic stirring in the continuous casting mold can significantly increase the mass of solidified metal. Altinkok and Coban studied tensile strength and porosity properties of hybrid MMC A332/Al2O3/SiC produced by stir casting technique. Behera et al. observed that mechanical properties of metal matrix composites were deeply influenced by the distribution of reinforcement particulates in the matrix and the morphology of secondary matrix. DasGupta et al. produced the composite of Al2014 alloy by adding 10% SiC of size (20-50 µm) particles using vortex method and have shown uniform distribution of SiC particles. Alaneme and Sanusi produced the hybrid aluminum composite with adding rice husk, alumina and graphite and discussed the mechanical and microstructural properties. Ghasali et al. used microwave sintering to produce Al/B4C composite and investigates the mechanical and microstructural properties. On the basis of above survey it has been concluded that making of composite through stir casting route is still needs modification to improve properties and findings.

**Experimental Procedure**

The criteria for material selection required high strength and good corrosion-resistant aluminium alloys for the matrix materials. In this study, A359 Alloy (Si- 8.5-9.5%, Cu-0.2%, Mg-0.5-0.7%, Mn-0.1%, Fe-0.2%, Zn-0.1%, Ti-0.2% Al -remaining) was used as a base metal. The macrograph of matrix phase of A359 is shown in Fig. 1 captured through optical microscope made of Olympus. Figure 1(a) shows the network structure with less impurity which is formed by super cooling of casting solidification and homogeneously distribution of other elements of alloy. Figure 1(b) was also taken by same machine through particle measurement module. In which the aluminium phase was shown by green color where the other colors represents the next major compositions like silicon. The colors of particles were decided first before starting of measurement. Both the images show the clear homogenous distribution of other alloying elements in the network phase. The reinforcement material B4C of size 20 microns was added in portions of 2%, 4%, 6% and 8% by weight to cushion a wide range of effect of the reinforcement. The thermo-physical properties of A359 alloy and B4C are given in Table 1.

The experimental setup consisted of a Muffle furnace, three-phase auto transformer, three-phase induction motor and thermocouple as shown in Fig. 2. Initially, A359 was melted in the Muffle furnace at nearly 750°C. B4C was also preheated at the temperature upto 350°C. A K-type thermo-couple was fixed inside the casting mould to measure the temperature of the material starting at its liquid state and continuing up to the state of its total solidification. Thereafter, the crucible of molten metal

| Table 1 — Thermo-physical properties of A359 alloy and B4C |
|---------------------------------|----------------|----------------|----------------|
| Density (g/cm³) | Thermal conductivity (W/mK) | Specific gravity | Melting point °C |
| A359 | 2.66 | 152 | 2.68 | 60 |
| B4C | 2.52 | 30 - 42 | 2.51 | 2445 |

Fig. 1 — Macrograph of matrix macrostructure (A359 alloy)
was placed in the three-phase induction motor where voltage and current were supplied to the induction motor with the help of three phase auto transformer to produce the stirring action and it can be measured by control panel. An induction coil bind on the stator was used to generate magnetic field. When the current was supplied from an AC power source, a magnetic field was developed by the action of magnetic flux inducing electric current to flow throughout the molten metal. This current then produced an electromagnetic force in the molten metal as a rotational force. The electromagnetic force produced by the induction motor helped to stir the molten metal at 300 rpm with constant temperature. Stirring speed can be measured by the relation of obtained voltage and current from the control panel, if voltage increases, speed will also increases. Speed variation can also checked by stroboscope. In order to produce a uniform distribution of reinforcement, the speed range was kept between 250 rpm and 350 rpm. Reinforcement was mixed with the help of hopper. It was used to disperse the preheated reinforcement tangentially near to outer layer of molten in the crucible where general stirring helped to transfer particles into the liquid metal and to maintain the particles in suspension. During the process, a certain amount of degasser with good wetability was added into the molten metal. Gas layers are considered to be the main factor behind poor wetability. They can cause buoyant migration of particles, which, in turn, will make it difficult to incorporate the particles into the melt. Electromagnetic stirring of the melt was carried out for nearly 40-45 s in the semi-solid zone in a temperature range of 600°C-612°C. A low viscosity material was produced after the stirring reached a steady state. It was classified as a non-Newtonian fluid.

In case of mechanical stir casting the stirring has been done by mechanical stirrer which rotates with the help of motor attached to it. Figure 3 shows the stirring action of mechanical stir casting process. Composites of A359 alloy reinforced with B₄C were developed by both electromagnetic stir casting and mechanical stir casting process to compare the effect of stirring type, distribution of reinforcement particle in the metal matrix, microstructures and mechanical properties such as tensile strength, hardness, and toughness along with porosity test.

![Electromagnetic stir casting setup](image1)

![Mechanical stir casting process](image2)

![SEM images of electromagnetically stir cast samples at different magnification](image3)
Results and Discussion

Micro-structural Analysis

The samples for micro-structural analysis were prepared by means of a bainpole polisher machine and different types of grit papers. Finally, it was etched by Keller’s reagent chemical solution. Scanning electron microscopy (SEM) was used to find out the microstructure of different prepared samples and the distribution of B\textsubscript{4}C reinforcement in A359 matrix. For most of the applications, a homogeneous distribution of the particles is desirable in order to improve the mechanical properties. The SEM images of the electromagnetic stir cast samples at different magnifications are shown in Fig. 4 while Fig. 5 shows the SEM images of mechanical stir cast samples at same magnification. It shows that the mixing of reinforcement is better in electromagnetic stir casting process as compared to mechanical stir casting. This was achieved by an effective stirring action and also with the use of the appropriate process parameters of electromagnetic process. However, the percentage porosity and other casting defects are higher in the electromagnetic process compared to the mechanical stir process. In the pilot experiments, it was observed that the homogeneous distribution of the particles was affected by the stirring speeds. At higher stirring speed, the distribution of the reinforcement particles was more homogeneous but the same time density will decrease. Due to this low density the possibility of porosity may be increased. Another major factor for casting defects in electromagnetic process was not a suitable arrangement for degasser and lack of effective turbulence in the mixing process. These defects could be minimized by adding some turbulence in the mixing and by use of proper degasser in the matrix phase.

Energy dispersive X-ray spectroscopy test

Energy dispersive X-ray spectroscopy (EDS) was used for the elemental analysis of the composite. This test was conducted on all the produced samples of electromagnetic stir casting. The results of the EDS test are shown in Fig. 6. The image shows a wider inter-facial reaction zone and the presence of boron is evident from the EDS spectra. Results indicated that the main components of the samples were aluminium, silicon and boron. Approximately, 8.5 to 9.5% of the silicon was present in the base metal. Therefore, it was shown by the EDS spectra in a wide range. Oxygen could also be seen in the spectra because of the presence of water vapour on the particle surfaces. Other components of the matrix alloy in the sample could also observe and is shown in Fig. 6.

XRD and DTA analysis

There is a possibility of overlapping of energy peaks in different types of element and also a limitation to not to detect the lighter elements by EDS analysis, XRD method was also analyzed to validate the elements of samples. Concept of Bragg’s law to measure the intensity of peaks in terms of 2\textdegree is performed on Grazing incidence X-ray diffraction (GIXD) machine. Figure 7 shows the pattern formed by GIXD machine for electromagnetic stir cast sample. The graph shows different peak points at 2\textdegree diffraction angle. While comparing with the table of relative intensity, the major peaks are Al\textsubscript{2}O\textsubscript{3}, B\textsubscript{2}O\textsubscript{3}, B\textsubscript{2}O, SiO\textsubscript{2}, FeO, CO\textsubscript{2} etc.

DTA test has been performed to analyze the absorption or extraction of heat under physical and chemical changes in material during heating or cooling. In this method the powder form of fabricated MMC were compared with the thermally inert material in terms of temperature substances during heating or cooling at uniform rate. Endothermic peaks and exothermic peaks were analyzed by comparing at different transformation temperature. Endotherms are plotted downwards to exotherms. The test was performed on electromagnetic stir cast sample at the temperature range of 30°C to 900°C at heating rate of 10°C/minute.

Fig. 5 — SEM images of mechanical stir cast samples at different magnification
20°C/min under nitrogen atmosphere. Figure 8 shows the graph of DTA analysis. The endothermic peak shown in graph represents the negative temperature difference due to absorption of heat. Temperature at maximum peak is 655°C, change in enthalpy 115 mJ/mg and -46.30 µv is the potential of phase difference. DTA analysis also provides the change in mass percentage at different temperatures. DTG curve shows that there is a nearly continuous change in mass percentage with respect to time.

Porosity analysis

Porosity in cast MMC is considered to be a defect that hinders enhancement of strength, particularly in particle-reinforced MMC. Porosity \( P \) is defined as the percentage of the volume of pores with respect to...
the total volume of a substance. It is inversely related to solidity. Porosity present in a material decreases its strength while increasing the fluid absorption. The porosity is defined as:

$$P = \left(1 - \frac{\rho_{\text{experimental}}}{\rho_{\text{theoretical}}}\right) \times 100 \% \quad \cdots (1)$$

Theoretically and experimentally, the porosity level is calculated by the measurement of density. The experimental density of the samples was evaluated by weighing the test samples. The measured weight in each case was divided by the volume of respective samples. Theoretical density of the composite material was then measured by the rule of mixture that is expressed as: $\rho = (\text{volume of base metal} \times \text{density of base metal} + \text{volume of reinforcement} \times \text{density of reinforcement})$. Figure 9 shows the level of porosity for both the stir casting routes. It is clearly shown that with an increase in the percentage of reinforcement, porosity in the MMC also increased. Porosity in electromagnetic stir casting sample was slightly higher than the mechanical stir casting. This was due to the applied casting process, process parameters such as stirring speed, process time. Higher stirring velocity formed a vortex on the surface of the slurry. The vortex was found to be helpful for transferring the particles into the matrix melt as the pressure difference between the inner and the outer surface of the melt pulled the particles into the liquid. It resulted in the formation of porosity in the slurry. Another common possibility of porosity formation was due to the traces of water vapour present on the particle surfaces. When aluminium solidifies, the hydrogen trapped in the solid metal forms bubbles that cause gas porosity. The possibility of porosity in the stir casting process can be reduced by applying the faster cooling rate. It tends to distribute the reinforcement material uniformly while decreasing the porosity formation, which most likely develops during the solidification. Pre-heating of reinforcement material and bottom pouring casting are the principal methods to obtain a minimum level of porosity in the stir casting process.

**Tensile Test**

The sample for the tensile test was prepared with the help of CNC lathe machine as per the ASTM standard (Fig. 10) for both electromagnetic and mechanical stir casting. Three sets of these samples were prepared. The samples were then tested on a
UTM testing machine of capacity 10 kN. Figure 11 shows the graph for comparative study of tensile strength for both type of samples. It is observed from the result that with the increase in reinforcement percentage, tensile strength of both the MMC increased and the ductility decreased substantially. The increase in the tensile strength was due to the increase in hardness of the composite material because of the presence of B₄C particles in the matrix. These particles provide more strength to the matrix material by offering more resistance to tensile stresses. The reduction in ductility can be attributed to the presence of a hard ceramic phase that is prone to localized crack initiation and increased effect of brittleness due to local stress concentration sites at the reinforcement matrix interface. However, results indicate that the tensile strength of mechanical stir cast sample is quite low than electromagnetic stir cast sample. This is due to the fact of more homogenous mixing of electromagnetic stirring. Figure 12 shows the SEM images of fractured surface of A359/8% B₄C for both electromagnetic stirred cast and mechanical stir cast sample. In both the cases the dimple nature of fracture and brittle fracture of B₄C particles are seen. This is due to the decreases in ductility of base material with the addition of hard reinforcement B₄C. There are more micro cracks, voids cleavage surfaces are seen in both images which occurs due to the debonding of B₄C particles in the matrix phases. However the debonding of B₄C particles are seen quite higher in case of electromagnetic stir cast sample this is due to the presence of high porosity and lack of effective turbulence.

**Charpy test for toughness**

The Charpy impact test, also known as the Charpy V-notch test, is a standardized high strain-rate test which determines the amount of energy absorbed by the material during fracture. The standard sample for the Charpy test was prepared and the test was carried out. The comparative Charpy test results for electromagnetic stirring and mechanical stir casting are shown in Fig. 13. The toughness of pure matrix metal was observed as decreases in both type of samples. However, toughness of electromagnetic stirred sample are better than mechanical stir cast samples. It was observed that the toughness decreased further with an increase in the percentage of reinforcement due to the increase in brittleness.

**Hardness test**

Hardness is a measure of a material resistance to surface indentation. It may be considered to be a function of the stress required to produce some specific types of surface deformation. Hardness is an important parameter of the composite material. The hardness test was conducted using a major load of 60
kgf and a steel ball of diameter 1.5 mm as indenter. The reading was calculated on C scale. The hardness results for both types of samples are shown in Fig. 14. The result shows that the hardness increases with the increase in percentage composition of reinforcement. The hardness of pure matrix metal was 46.4 HRC and it increased up to 64.2 HRC for electromagnetic stirring and 60.2 HRC in case of mechanical stirring. The increase in hardness was probably attributed to the hard reinforcement which acts as a barrier to dislocations within the matrix. The presence of reinforcement particles in the melt provides additional surface or layer for the solidification to construct, thereby increasing the nucleation rate and decreasing the grain size.

Conclusions

In this study, the electromagnetic stir casting method and mechanical stir casting method were used to develop a MMC (A359/B₄C). The following conclusions are drawn:

(i) Fabrication of MMC (A359/B₄C) was successfully completed through electromagnetic stir casting and mechanical stir casting routes.

(ii) The mixing of reinforcement in both the processes was uniform and homogeneous as seen by the SEM images. It was observed that in case of electromagnetic stir casting, without using an external mechanical stirrer in the proposed synthesis process, the mixing of reinforcement could be improved. Due to the reinforcement particles were under rotation till the solidification of the molten metal was complete. As a result, the reinforcement was settled throughout the molten metal and improved homogeneous mixture could be prepared.

(iii) The EDS and XRD results revealed the confirmation of elements of MMC (A359/B₄C). The major elements with their percentages are shown in results.

(iv) DTA analysis has been conducted and results indicated the endothermic nature of fabricated composite.

(v) Porosity was observed quiet high in case of electromagnetic stir cast sample, this was due to the pressure difference between the inner and the outer surface of the melt pulled the particles into the liquid.

(vi) The test results also revealed that with an increase in the percentage of the reinforced material, the ultimate tensile strength and hardness could be increased and the toughness was observed to decrease with an increase in the percentage of reinforcement in both types of stir casting route.

(vii) The fractured analysis of tensile testing indicated the dimple nature of fracture as well as brittle fracture of B₄C particle.

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