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Excellence of Al-metal matrix composite fabricated by gas injection bottom pouring vacuum stir casting process

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The present study has envisaged an advance technique, gas injection bottom pouring vacuum stir casting process, for the casting of metal matrix composite (MMCs). This process has been eliminated several manual processing steps of conventional stir casting hence concerns about the workers' safety and its bottom pouring mechanism & vacuum mould chamber improve the properties of the fabricated MMC. An Al/(10wt% Al_2O_3) MMC has been fabricated by the proposed technique and characterized for the mechanical and microstructural properties. An experimental plan based on Taguchi L_{16} orthogonal array has also been used to investigate the factors affecting the wear behaviour. The fabricated Al-MMC has a density of 2.65 gm/cc, micro-hardness of 73.3 HV, tensile strength of 220 MPa and wear rate of 0.0137736 mm^3/m, implying in substantial improvements from the matrix Al-alloy. A comparative study with the available literature has been carried out to investigate the possibilities of the proposed method in today's manufacturing world. The results concluded that the fabricated MMC has significantly enhanced the properties of MMCs when compared to the existing casting techniques. From the results of present study, it has been suggested to employ the process in industrial & allied applications and especially in the research institutes where the researchers are not very skilled for the casting operations.

Keywords: Al-MMC, Bottom pouring vacuum stir casting, Mechanical properties, Dry sliding wear, ANOVA

1 Introduction

The invention of Metal Matrix Composites (MMCs) has appeared as one of the significant development in the field of materials science[1,2]. These composites have numerous advantages as compared to monolithic metals and alloys. In MMCs, a metal matrix contains reinforcements of different ceramic materials with varying composition. The type, shape, size and percentage composition of reinforcement depends upon the required properties of the MMC. The MMCs are fabricated by three types of processes *viz.* liquid state, solid state and vapour state. In past few decades, numerous low-cost MMCs fabrication techniques have been developed which are based on casting methods such as stir casting, squeeze casting, compo-castings and continuous casting. The MMCs fabricated using conventional ex-situ techniques are having separately prepared reinforcements in the matrix which ensued inporosity, particles clustering, improper wetting, poor bonding and undesired interfacial reaction products[3-5]. In-situ techniques of MMC fabrication involve producing desirable reinforcements during the processing itself. These techniques have distinct advantages over the conventional ex-situ techniques because of its ability of producing finer grain size with excellent thermodynamic stability[6].Available literature revealed that liquid state route of MMC fabrication *i.e.* foundry techniques, having particulates reinforcement is the mostly used fabrication processes[7-11].This route has the potential for specifically weight-critical engineering applications[12]. Nowadays, 3D printing is under extensive exploration and is being used to fabricate MMCs and the results proved the efficacy of this technology in Al based MMC fabrication[13]. Fabrication based on friction stir welding process has also been established for Local Metal Matrix Composites (LMMCs) in light alloys. In this process, the LMMCs are produced contextually in the friction stir welded region. The results for shear testing publicised an increase in the maximum load capacity of the joint having LMMCs as compared to the joint without LMMCs[14]. Hot rolling process is also used for multilayer-MMC fabrication. It his process, metal foils having sandwiched reinforcement were hot rolled to form multiple layers. MMCs fabricated using this process has better modulus of elasticity as well as strength, but low in ductility[15].

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The MMCs having particulate reinforcement shows improvements in tensile and compressive strengths, structural efficiency, wear resistance, and controlled physical properties like density and coefficient of thermal expansion. So these MMCs provide an improved industrial performance of the material[16-19]. The improvement in one property is usually attained at the cost of some other one. Therefore, the selection of a reinforcement which is to be added to the matrix is based on the properties required for the specific application of that material and the environmental conditions of the operation. In conventional MMCs, ceramics like alumina, silicon carbide, silicon nitride, boron, boron nitride, boron carbide, titanium carbide etc. are being used extensively as reinforcement particulates[10-24]. A number of metal oxides can also be inoculated in the molten matrix to manufacture in-situ MMCs. These metal oxides react chemically and produce nanoparticles which act as the reinforcement[25]. A number of salts are also be used for the growth of reinforcement in the molten matrix to form MMCs. These salts react chemically with the molten matrix to produce particulate reinforcements[26]. The physical characteristics of reinforced particulates like shape and size also plays a significant role in deciding the overall properties of the MMCs. Fatigue life of the composites having large sized reinforcement particulates is lesser as compared to the composites having fine reinforcement particulates[27].Several authors have reviewed the applications of MMC and major markets have been found to be in ground transportation, thermal management, aerospace, industrial, recreational and infrastructures[16-17]. The major advantage of the MMCs is their alterable physical as well as mechanical properties that can be improved to the required level by transforming the microstructure. It is reported that by a proper selection of matrix-reinforcement combination and fabrication method, attractive properties can be achieved.

Among all the available MMCs, Aluminium based MMCs are broadly used in automobile, aerospace and other engineering industries[28-30]owing to their high specific strength, good thermal stability, higher Young’s modulus, better corrosion resistance, wear, creep and fatigue[31-32].The viscoelastic properties of these Al based MMCs confirms a stable behaviour and rapid diminution in stiffness is observed only at very high temperatures. These MMCs also have higher mechanical damping and internal friction as compared to pure Al alloy[33]. Due to these properties, Al-MMCs are difficult to machine by convention methods, and various researchers used different non-conventional methods for machining[34]. The successful applications of aluminium metal matrix composites in the automotive industry are investigated in the countries of Europe, USA and Japan[35, 36]. Hyper-eutectic Al-Si based MMCs such as A356 that containsalumina (Al_2O_3), zirconium oxide (ZrO_2) and silicon carbide(SiC) particles reinforcements were used in the fabrication of automotive engine components[30].The low weight of these Aluminium MMCs has led to reduction of weight which ultimately resulting in considerable economic advantages specifically for aerospace industries[37-40].

The loss of material from its surface in contact because of relative motion between two sliding surfaces is known aswear[5]. This progressive loss is because of the relocation of material from one moving surface to another by localised bonding between contacting surfaces. In this process, the particles detached from one surface are either temporarily or permanently amalgamated to another surface. Both the sliding surfaces are damaged by these processes due to sliding friction[40, 41]. The loss of material because of wear depends on the load between the contacting surfaces, sliding distance & speed, surface characteristics, environmental conditions and the properties of material[42, 43]. Wear Behaviour and working properties of Aluminium pistons for engines are significantly improved by piston rings made up of Aluminium-MMCs[30].It is clear from the literature that materials having high wear resistivity are mandate for the current industrial scenario, so researches in this field has a significant importance from industrial point of view.

In this research work, a gas injection bottom pouring vacuum stir casting process is envisaged for the fabrication of Al alloy based MMCs. This used technique of MMC fabrication is one of its kind. For the validation of the proposed casting process different physical and mechanical properties of the fabricated Al-MMC have been determined. Wear behavior of the fabricated MMC has also been investigated using DOE and ANOVA. The performance of the MMC is compared with the available literature, and it is concluded the adopted fabrication method has provided a homogenously reinforced Al-MMCs with excellent mechanical &wear-resistant properties.

2 Gas injection bottom pouring vacuum stir casting process

The stir casting process is one of the low-cost and highly productive method of MMC fabrication. The process is having a wide range of processing conditions which can be used as per the specific requirements. But this method of fabrication consists of many steps *viz.* separate pre-heating of reinforcement particles, manual stirring, separate pre-heating of mould, manual pouring *etc*. which induces various defects in the fabricated MMCs. Keeping in view the above, a new gas injection bottom pouring vacuum stir casting process is utilized for the fabrication of Al/Al_2O_3 MMC. This is an advanced stir casting process, which not only reduces the human efforts and activities but its vacuum chamber and bottom pouring mechanisms fabricates a sound casting as compared to the conventional stir casting process. The main objective of the new gas injection bottom pouring vacuum stir casting process is to eliminate the accidents happened during the conventional stir casting process hence providing a safer working environment without compromising with the quality of fabricated MMCs. Figure 1(a) is the schematic representation of the utilized process setup showing its various components as well as inside mechanisms which are not visible in the actual image and Fig. 1(b) shows the actual image of the setup. The setup mainly consists of the following components:

- An induction resistance furnace with temperature regulator cum indicator
- Two reinforcement particulate chambers
- Automatic stirring mechanism with graphite impeller
- Vacuum chamber
- Mould preheater
- Temperature sensors
- Inert gas supply system

The setup consists of an induction resistance for melting of the metal matrix. The furnace can regulates the temperature as per requirement and has a capacity of 1500 ºC with an accuracy of ±2 ºC. The temperature regulator cum digital recorder maintain a proper required temperature inside the furnace. Metal is melted in graphite crucible which is fixed inside the furnace. The crucible has a bottom opening for pouring purpose which is controlled by a switch provided on the control panel.

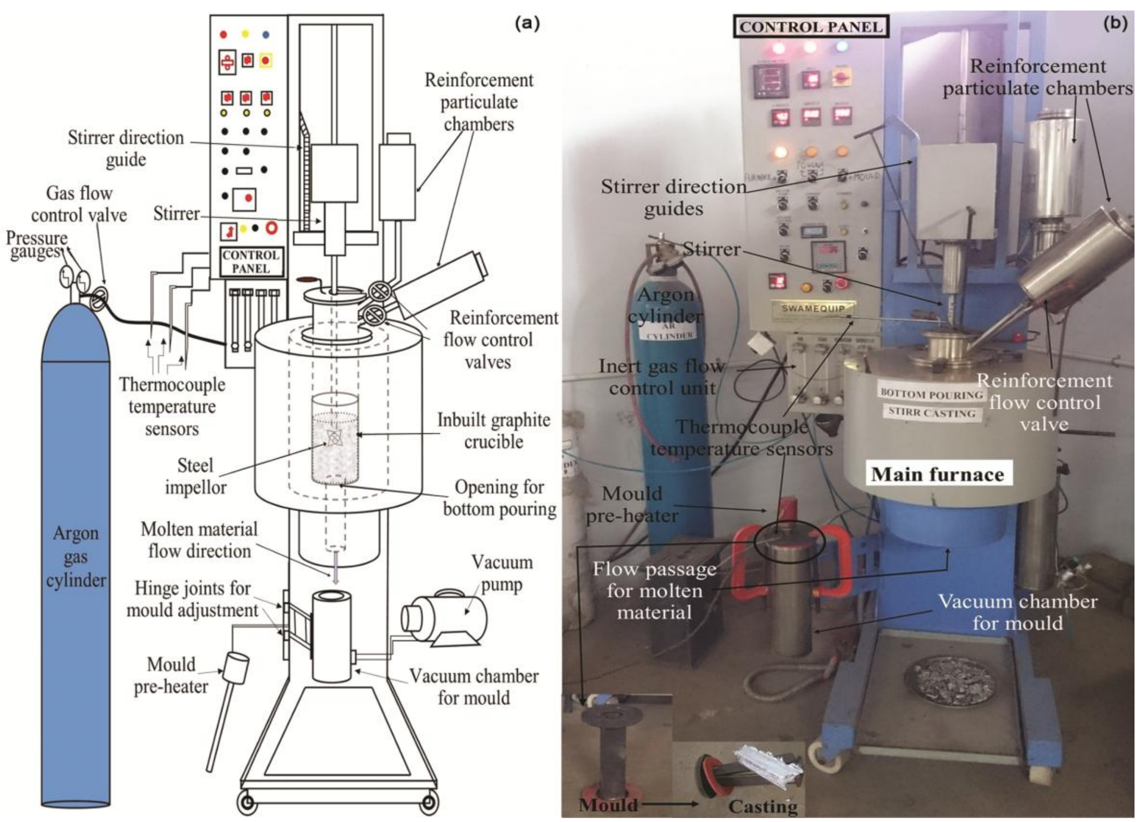

Fig. 1 — (a) Schematic of gas injection bottom pouring vacuum stir casting setup and(b) actual image of casting setup used for fabrication of $Al/(Al_2O_3)$-MMC inset showing the mould used for along with the fabricated casting[44].

The setup consists of two reinforcement particulate chambers for containing the reinforcements. These two chambers facilitate the fabrication of hybrid MMCs having more than one reinforcements. These reinforcement particulate chambers are installed with induction heating mechanism (capacity 800 ºC with an accuracy of ±2 ºC) for preheating of particles to remove its moisture, hydroxide and other gases. These chambers are connected to the matrix melting furnace with a tube having a valve mechanism to control the flow rate of the reinforcements. The setup facilitates both melting of the metal matrix and preheating of the hard reinforcement particulates simultaneously for the casting of the composites.

The hard reinforcement particulates are uniformly distributed in the molten matrix by using a stirring mechanism having graphite impeller. The stirrer has a speed regulator and tachometer to control stirring speed. The stirrer has an automatic downward and upward movement which can be controlled through the control panel of the setup. The automatic stirring mechanism plays an important role in a homogenised distribution of the hard reinforcement particles by agitating the mixture during stirring.

Vacuum chamber of the setup is used to create the desired vacuum in the mould with the help of a vacuum pump. The mould is specially designed to fit in the chamber as it requires a proper adjustment for creating the desired vacuum. The vacuum is created before pouring of the molten material. A heating arrangement for baking and pre-heating of the mould is also provided in the setup which can heat it to a temperature of 400 ºC.

Three temperature sensors of the setup are used to measure the temperature of the furnace, particulate chamber and mould simultaneously. These sensors are movable and can be placed where-ever required.

The setup has an inert gas supply system which removes oxygen from the furnace resulting in making the surroundings oxygen-free, which is necessary to prevent the molten matrix from the oxidation. This system can effectively be utilised for castings which are very sensitive to operate in their molten state (e.g. magnesium) under oxidized condition but for preventing the metal matrixes from the oxidation as it causes material loss, it can be used for every casting.

3 Fabrication of Al-MMC

Alumina (Al_2O_3) reinforced Aluminium Metal Matrix Composite (Al-MMC) is fabricated for this experimental research. Pure alumina particles with ≤ 10 µm average particle size (shown in Fig. 2) is used as reinforcement whereas Aluminium alloy-6063 is the metal matrix. Table 1 shows the chemical composition of the Aluminium alloy 6063. The MMC with 10% by weight of alumina reinforcement is fabricated in the present analysis.

Before starting the fabrication process, graphite crucible of the furnace, the stirrer impeller and the mould is coated with Zirconia paste and baked for 3 to 4 hours a-day-before the casting is to be made. This process makes the components non-sticky with the molten material.

Firstly aluminium alloy AA6063 is first preheated to a temperature of 500 ºC for 2 hours in the main induction furnace and there after the temperature is raised to 710 ºC *i.e.* above the liquid us temperature of Al. The temperature is maintained at this level for 30 min to melt the Al-matrix completely. Simultaneously, reinforced alumina is also preheated

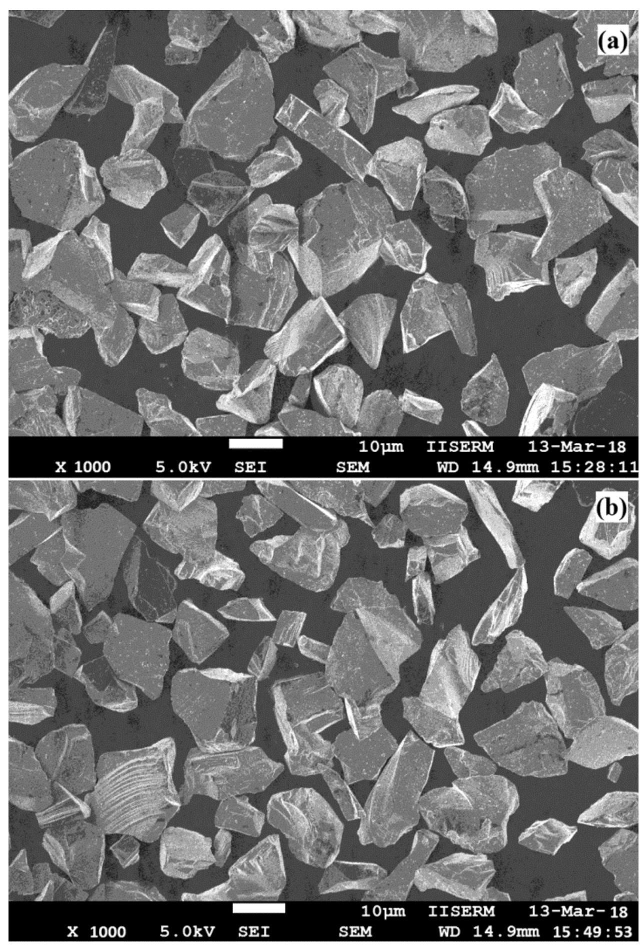

Fig. 2— SEM micrographs of Al_2O_3-reinforcement particulates at 1000× magnification.

Table 1 — Composition of aluminium AA6063 T6 alloy.

Weight %	Al	Si	Fe	Cu	Mn	Cr	Mg	Zn	Ti	Others
AA6063	97.5	0.2-0.6	0.35	0.1	0.1	0.1	0.45-0.9	0.1	0.1	0.15

in the reinforcement particulate chamber at 650 ºC for 2 hours to remove its moisture, hydroxides and other gases to improve its wettability with Al matrix. After complete melting of aluminium, 1.0 wt% magnesium is also added to the aluminium melt improve the wettability of the reinforcement particles further. The melting temperature of aluminium is observed to be 657 ºC. The furnace temperature is then kept a little below the liquid us temperature at *i.e.* 630 ºC for allowing the molten metal to convert into a semi-solid state. At this stage, the pre-heated reinforcementAl_2O_3 particulate is added slowly and mixed by continuous stirring at 350 rpm for around 10 min to ensure homogenous scattering of the particulate in the molten matrix. The slurry is heated above its melting temperature to a fully liquid state and again stirred thoroughly. The stirring process is repeated thrice which results in more uniform distribution of alumina and better microstructure when compare with the conventional. The effect of the multi-step mixing process is that the turbulence created in the slurry by stirring breaks of the interfacial gas buffer present around the surface of particle which otherwise hinders wetting between the reinforcement particles and molten metal. Now, the furnace temperature is increased to 670 ºC during pouring to improve the fluidity of the mixed slurry when it flows into the mould. At the same time vacuum is created inside the mould, which is aligned with the bottom flow passage of the furnace. The pouring is done automatically using a switch provided on the control panel. After 15 minutes of pouring the mould is removed from the vacuum chamber and the casting is taken out by dissembling it. Inset of Fig. 1(b) shows the mould and the fabricated Al-MMC casting[44].

The reason for selecting 10% wt fraction of Al_2O_3 reinforcement is because of the mechanical properties of the fabricated Al-MMC. It has been observed in the previous study of the casting process that upto 10% wt of Al_2O_3reinforcement the tensile strength increases but beyond that it decreases considerably. Although the hardness and density increases even after 10% wt of Al_2O_3 reinforcement but when compared to the tensile strength the increment is not significant[44]. Figure 3 shows the SEM micrographs of the fabricated Al-MMC showing grain boundaries and uniformly distributed reinforced Al_2O_3 particulates.

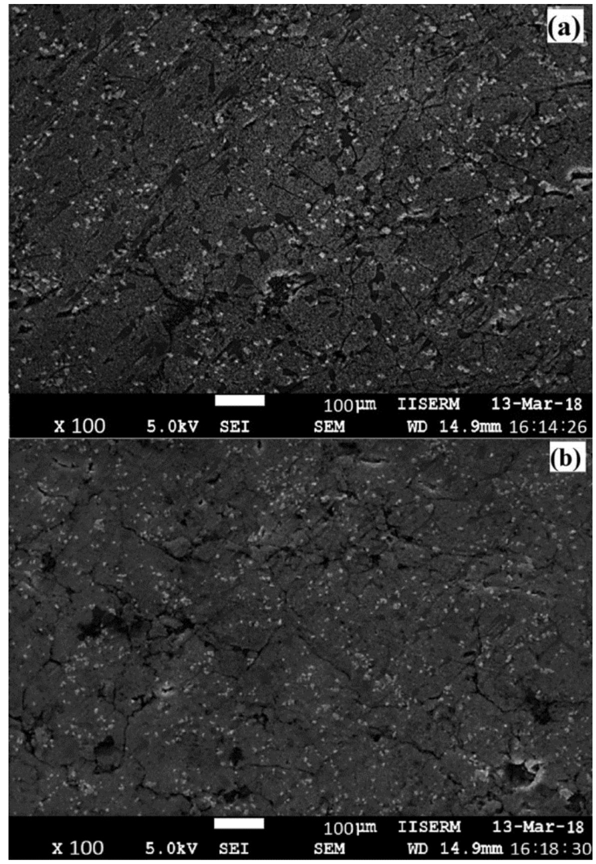

Fig. 3 — SEM micrographs of Al-MMC reinforced with 10 wt.% ofAl_2O_3 particulates.

The homogeneity of reinforced particulates in the matrix is also because of the intensive shear generated by the multi-step stirring, which is otherwise very difficult to achieve in conventional stir casting processes. The micrographs clearly represent a good interfacial bonding of metal matrix with reinforced particles.

4 Results and Discussion

4.1 Density

To measure the density, a rectangular piece of size 6.0 cm×2.5 cm×2.0 cm is used. Density of the prepared sample (ρ_s) is then determined by utilizing the Archimedes's principle given as:

$$\rho_s = \frac{W_1(\rho_w)}{W_1 - W_2} \quad \dots (1)$$

where, $W_1$is weight of the sample in air, ρ_w is the density of water and W_2 is weight of the sample in water. Density of Al/Al_2O_3-MMC is came out to be 2.65 g/cc which is about 1.08 times of the experimental value of Al-metal-matrix density. Hence, the higher density of Al_2O_3has found to have influence on the density of fabricated Al/Al_2O_3-MMC. A higher density of the Al/Al_2O_3-MMC is also because of noporosity in the casting which has resulted in a sound casting.

4.2 Hardness test

Vicker Hardness test is performed on HUAY IN HV-1000B model 2011 at micro level. The indenter used for the test is made of diamond and have a shape of square pyramid with 136º angle (θ) between opposite faces. The load applied to the sample is 200 gm for a dwelling time of 15 seconds. The micro-hardness is evaluated by measuring the diagonals of residual indentation. The Vickers hardness number is a function of the load applied (test force) and the surface area of the indent. The average of the two diagonals is used to calculate the Vickers hardness using the following formula:

$$HV = \frac{2P}{L^2} Sin\frac{\theta}{2} = 1.8544\ \frac{P}{L^2} \quad \ldots(2)$$

where, P is the test force in kgf and L is the average of indent diagonals length in mm. The measured value of the micro-hardness is 73.3 HV.

4.3 Ultimate tensile strength test

The effect of wt% of Al_2O_3 particulate reinforcement on the ultimate tensile strength (UTS) is investigated for the fabricated Al-MMC. The test specimen is prepared as per the ASTM-B-557M standard (Fig. 4(a)). The experiments are conducted

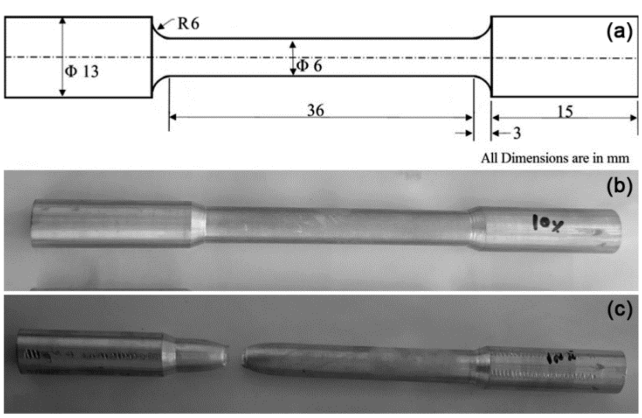

Fig. 4 — (a) Geometry of the tensile test specimen as per the ASTM-B-557-M standards, (b) tensile test specimen of casted Al/Al_2O_3p-MMC samples and(c) the fractured specimen after tensile testing.

by using a universal testing machine (UTE 40 model) from Fuel Instruments and Engineers Pvt. Ltd. Figure 4(b) shows the prepared sample for UTS testing and Fig. 4(c) shows the fractured sample after UTS testing. The UTS of fabricated Al-MMC sample has found to be 220 MPa at 22 kN load having a corresponding displacement of 10.8 mm. It is 1.27 times of Al metal matrix *i.e.* Aluminium alloy 6063. Figure 5 shows the SEM images of the fractured specimen of Al-MMC sample. Analysis of the fractured surface of the composite by SEM shows cracked Al_2O_3 particles and ductile tear ridges indicating both brittle and ductile fracture mechanism which is caused by the decrease in the ductility of the matrix after Al_2O_3 reinforcement.

4.4 Wear testing

In dry sliding wear testing of a material, the wear loss is mainly influenced by three parameters *viz.* sliding speed, normal load applied and sliding distance[28] so these three parameters are chosen in the

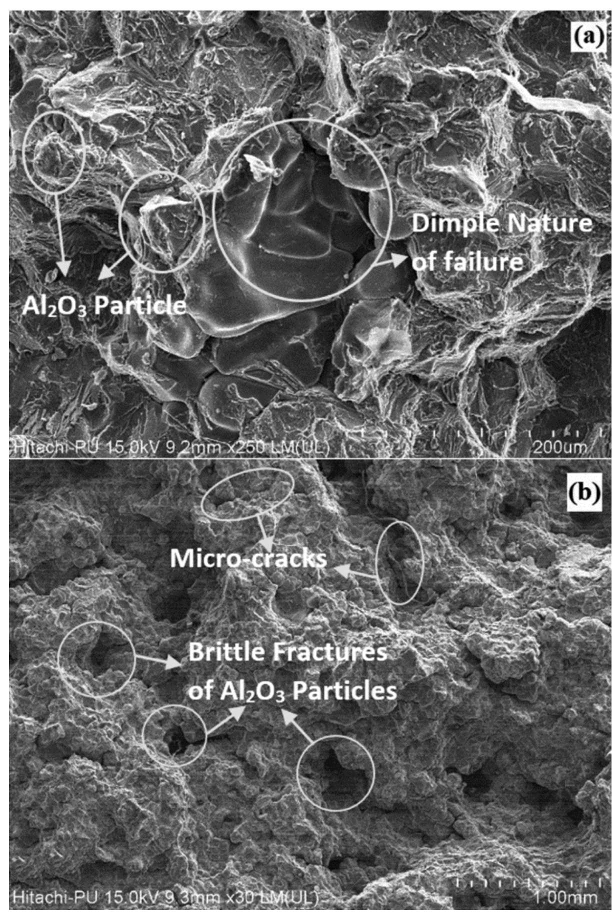

Fig. 5 — SEM images of the fabricated MMC samples showing fracture mechanisms (a) at 250 × magnification and (b) at 30 × magnification.

present study. A detailed study has been carried out to assess the effect of parameters on the response characteristic *i.e.* wear loss. The experiments are planned by Taguchi's design of experiment L-16 orthogonal array. The input parameters and their respective levels for the wear test experimentation are shown in Table 2. The plan of experimentation and summary of response parameters are shown in Table 3. The results of wear test experimentation are then subjected to the analysis of variance.

4.5 Experimental setup and procedure for wear testing

Friction and wear are not intrinsic properties of a material but are the properties of the system in which the materialis used. The wear characteristic of the Al/Al_2O_3MMC has been studied on a pin-on-disk tribometer. The disc of the tribometer is made of hard steel material (EN31 steel disc). Cylindrical shaped test samples of Aluminium MMC has been prepared according to ASTM, D-91 standards with 30 mm in length and 8 mm in diameter. Figure 6 shows the rotating steel disk of the pin-on-disk friction wear tester. Both the disk and the pin are pressed together by applying load. The wear tests are conducted in dry sliding condition at room temperature. The contact surface of the pin samples is flattened using emery papers before testing to ensure proper contact with the rotating steel disc. The composite samples are thoroughly cleaned with acetone, dried and then weighed on anelectronic analytical weighing scale with accuracy of ± 0.1 mg, before and after every wear test. The difference between the initial weight (*i.e.* before test) and final weight (*i.e.* after test) of the pin specimen gives the weight loss caused by sliding wear. The wear rate is calculated using the relation:

$$\text{Wear rate} = \text{Volume loss / Sliding distance} \quad \ldots (3)$$

or

$$\text{Wear rate } (mm^3/m) = \text{weight loss}/\ \rho \times \text{Sliding distance} \quad \ldots (4)$$

where, ρ is the density of the fabricated Al-MMC.

Table 2 — Coded levels and corresponding absolute values of wear analysis parameters.

Control Factor (code used)	Unit	Levels I	II	III	IV
Normal Load (N)	N	10	20	30	40
Sliding Speed (S)	m/s	2	4	6	8
Sliding Distance (D)	m	1000	2000	3000	4000

Table 3 — Plan of experimentation and summary of response parameter.

Exp. No.	Parameters			Response	
	N	S	D	Wear loss (g)	Wear rate (mm^3/m)
1	10	2	1000	0.0018	0.0006792
2	10	4	2000	0.0089	0.0016792
3	10	6	3000	0.0227	0.0028553
4	10	8	4000	0.0378	0.0035660
5	20	2	2000	0.0063	0.0011887
6	20	4	1000	0.0041	0.0015472
7	20	6	4000	0.0388	0.0036604
8	20	8	3000	0.0349	0.0043899
9	30	8	3000	0.0401	0.0050440
10	30	4	4000	0.0432	0.0040755
11	30	6	2000	0.0157	0.0029623
12	30	2	1000	0.0199	0.0075094
13	40	2	4000	0.0449	0.0042358
14	40	4	3000	0.0491	0.0061761
15	40	6	2000	0.0437	0.0082453
16	40	8	1000	0.0365	0.0137736

4.6 Analysis of wear loss

Experiments are conducted to correlate the input parameters *viz.* sliding distance, sliding speed and applied load with the wear loss of Al/Al_2O_3 MMC. Analysis of Variance (ANOVA) has also been carried out to determine the contribution of each input parameter. Percentage contribution of each input factors on wear lossis shown in Fig. 7. The ANOVA results revealed that sliding distance has the maximum contribution with 49.65% while the least

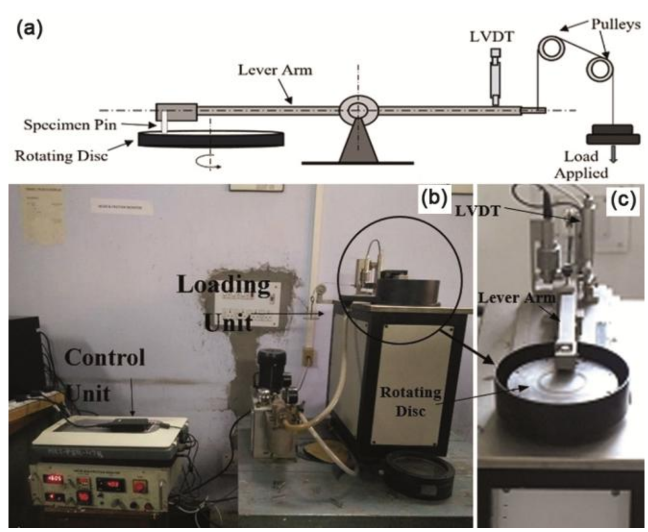

Fig. 6 — (a) Schematic representation of pin on disk wear mechanism, (b) the pin on disc wear tester used for the experimental study and(c) lever arm holding the specimen pin against the steel disc.

effect is of the sliding speed having 4.79% contribution. The normal load has found to have in-between effect with 39.49% contribution. The error associated with experimental results has found to be 6.07%.Table 4 shows the detailed ANOVA results of the conducted wear analysis. Figure 8 depicts the plot of main effect for the wear loss. The analysis has been made with a quality characteristic "smaller the better". The S/N ratio analysis illustrates that sliding distance is the factor having the highest influence on wear loss. This is due to an increase in time with an increase in distance of sliding. The normal load is another influential factor for wear of Al-MMC as the pressure at the point of contact increases with normal load.

4.7 Regression analysis

Regression analysis is an imperative tool for modeling and analysing experimental data. Various researchers have used regression analysis to model a relationship between the process parameters and output quality characteristics. In the present work, a regression equation is developed for the investigation of wear loss during dry sliding wear testing of Al-MMC and is given as:

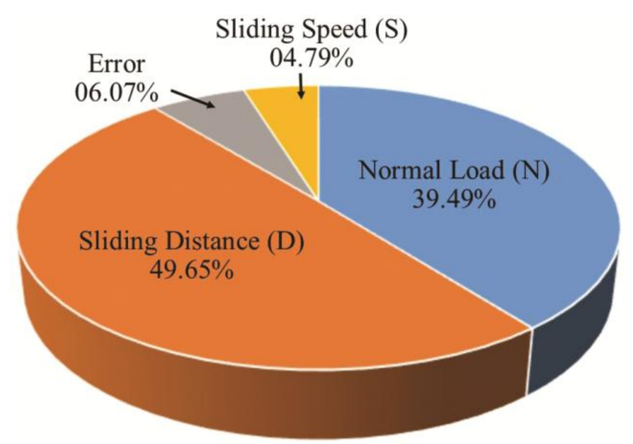

Fig. 7 — Percentage contribution of input factors on response wear loss.

$$\text{Wear Loss} = 0.02802 - 0.01022\,N_1 - 0.00700\,N_2 + 0.00170\,N_3 + 0.01552\,N_4 - 0.00475\,S_1 - 0.00170\,S_2 + 0.00220\,S_3 + 0.00425\,S_4 - 0.01350\,D_1 - 0.00832\,D_2 + 0.00867\,D_3 + 0.01315\,D_4 \quad \ldots (5)$$

where, subscripts represent the level of that process parameter.

4.8 Microstructure analysis

The microscopic analysis is done ona field emission scanning electron microscope (FESEM)

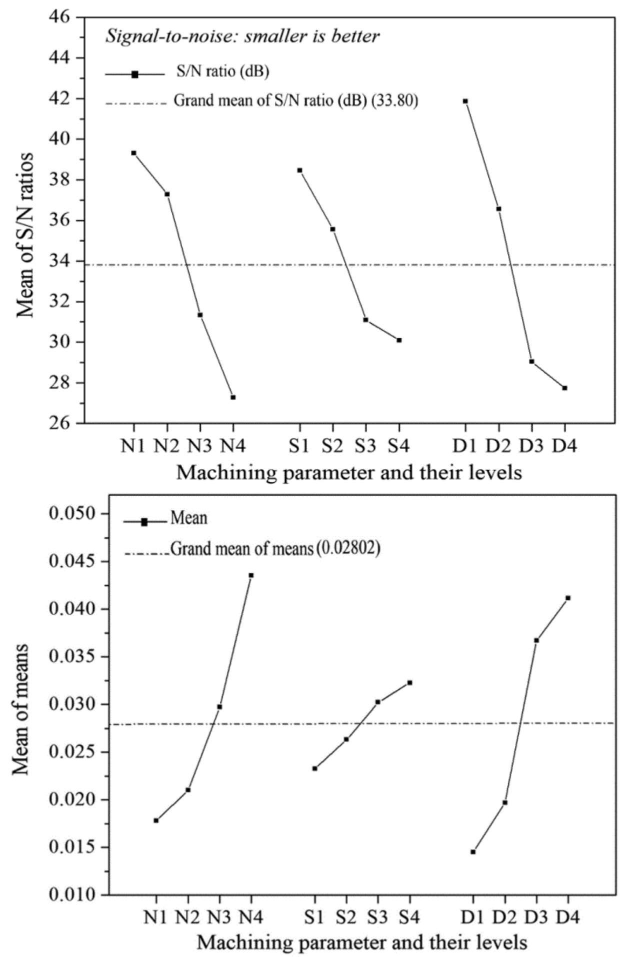

Fig. 8 — Main effect plots: (a) for S/N ratios and (b) for means, with wear loss as an output response parameter.

Table 4 — ANOVA for wear loss.

Source	DF	Adj SS	Adj MS	F-value	p-value	Remark
Normal Load (N)	3	0.001590	0.000530	13.06	0.005	Significant
Sliding Speed (S)	3	0.000193	0.000064	1.59	0.288	
Sliding Distance (D)	3	0.001999	0.000666	16.42	0.003	Significant
Error	6	0.000243	0.000041			
Total	15	0.004026				

DF: Degree of freedom; SS: Sum of squares
Model Summary
Std. Dev. = .0063; R-square = 93.95%; R-square (adj.) = 84.88

model: Hitachi SU-8010. Figure 9 shows SEM images and the mapping images illustrating surface topography and the element distribution of the worn surface of Al-MMC. Presence of deep groves is clearly visible in Fig 9(a) which shows the direction of sliding. Mapping of the images of Fig 9(b) & (d) clearly shows the homogenous distribution of the reinforcement in Al-matrix. Figure 10 represents the energy-dispersive X-ray spectroscopy (EDX) of the two mapped SEM *i.e.* Fig. 9(a) & (c). The EDX testing investigates the percentage of the elements present on the surface and the testing results reveal the presence of the elements of Al-6063 alloy *i.e.* dominantly Al with Fe, Zn, Mn, Si, C, etc. The presence of oxygen shows that the aluminium in oxide form (Al_2O_3) is also present which represents the reinforcement alumina whereas no contamination is observed in the SEM, mapping and EDX results.

5 Comparison of gas injection bottom pouring vacuum stir casting technique with other methods

Table 5 represents the mechanical characteristics of Al-MMC made by other techniques *e.g.* squeeze casting, stir casting, double stir casting and powdered metallurgy routes *etc*. The comparison is based upon the properties *viz.* tensile strength, hardness and density of the Al-MMCs. It is clear from the study that the proposed bottom pouring vacuum stir casting process is not available. However, the Al-MMC fabricated by this process has a density of 2.65 gm/cc, micro-hardness of 73.3 HV and tensile strength of 220 MPa which is analogous with the available literature. The unique features of the bottom pouring vacuum stir casting process, *viz.* automatic stirring mechanism with controllable speed results in uniform distribution of reinforcement; bottom pouring & vacuum created in the mould while pouring results in avoiding pouring defects *like* void formation & porosity; mixing of preheated reinforcement particles from reinforcement particulates chamber without any manual interference results in a homogenous MMC, *etc.* strongly recommend it in various engineering and industrial applications.

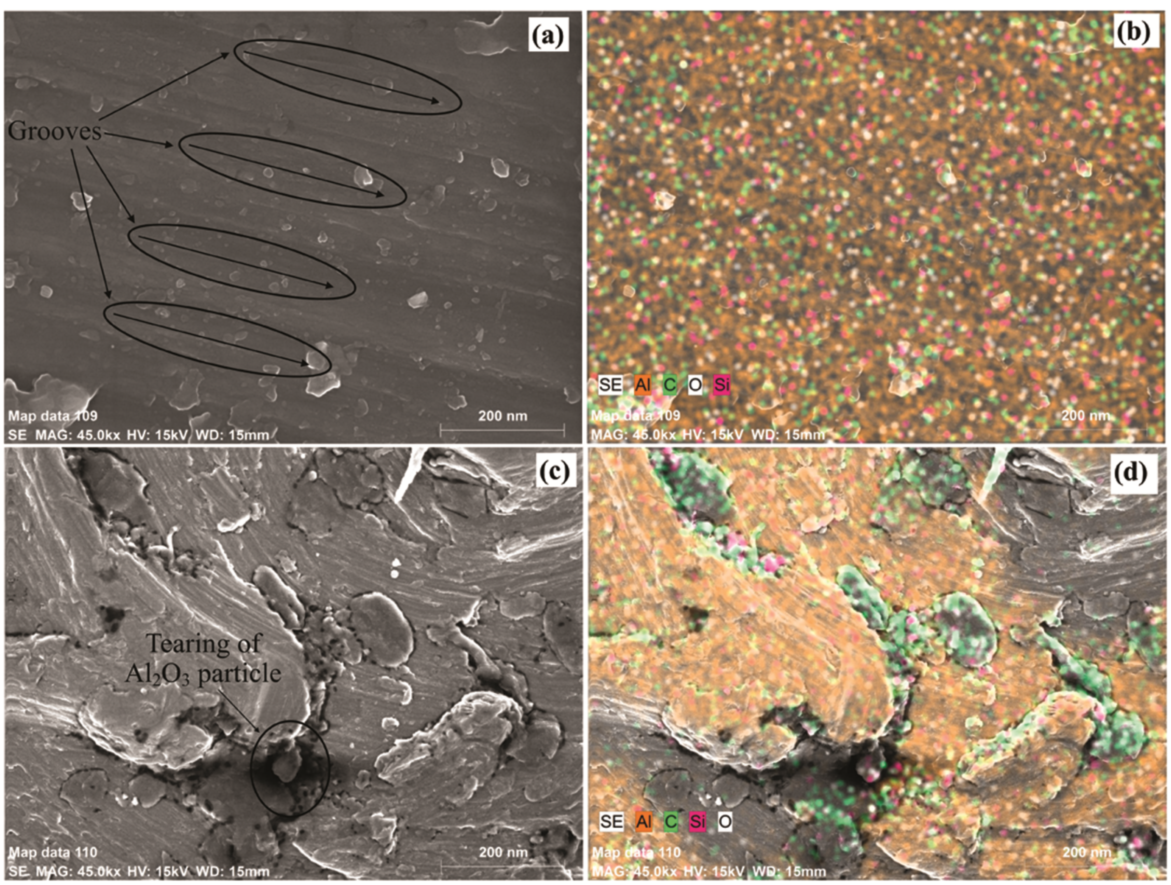

Fig. 9 — Wear surfaces of the Al-MMC: (a) showing permanent grooves after testing no #16 having lowest wear rate at 12000 × magnification, (b) the mapping of Fig. 9 (a) showing distribution of elements, (c) at a magnification of 45000 × and (d) mapping of Fig. 9 (c).

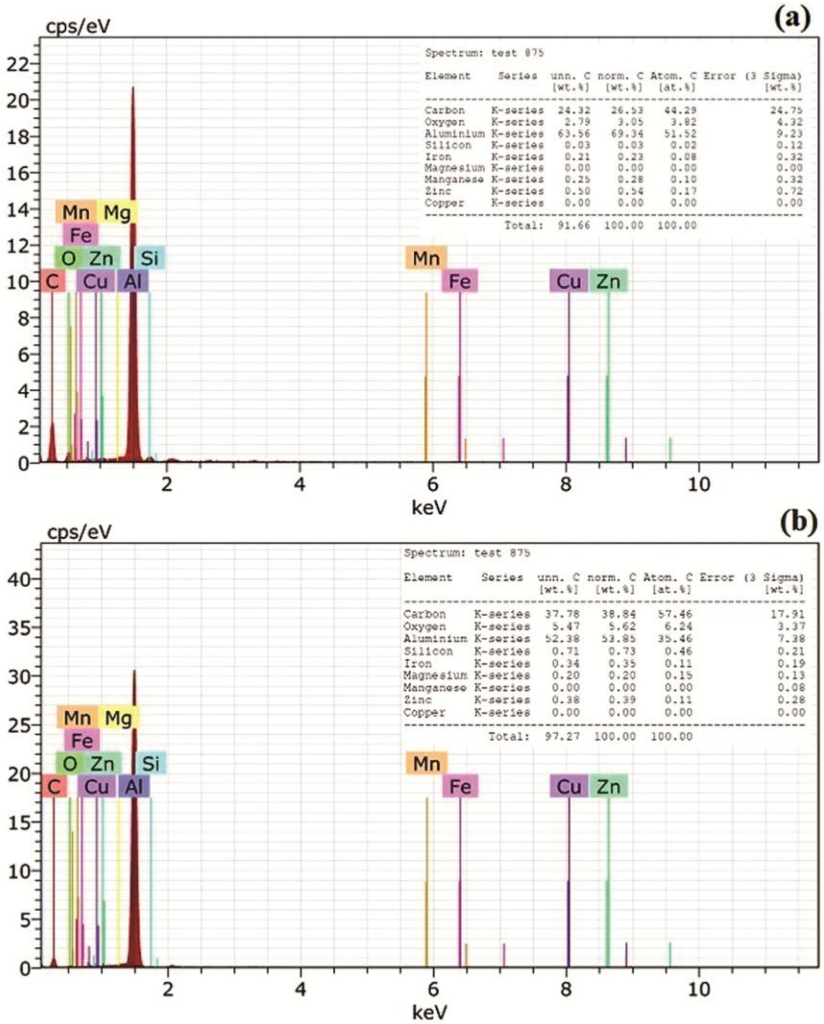

Fig. 10 — Energy dispersive X-ray spectroscopy (EDX) of the SEM images, shown in Fig. 9, showing the elemental composition present on the surface (a) EDX for Fig. 9(a) and(b) EDX for Fig. 9(c).

Table 5 — Comparison of Al/MMC fabricated with other methods.

S. No.	Material	Density (g/cc)	Tensile Strength (MPa)	Hardness	Process
1.	AlSi7Mg2/SiC	2.80	270	98 HB	Squeeze casting[45]
2.	Al-A356.2/RHA/SiC	2.73	356	104 BHN	Double stir casting[46]
3.	Al-2014/SiC	2.42	-----	50 BHN	Powder metallurgy[47]
4.	Al/SiC	-----	77.56	45.40 HV	Stir casting[48]
5.	Al-6061/SiC/TiB_2	-----	150.1	73.00 HV	Stir casting[49]
6.	Al-6061/SiC/Gr	2.66-2.73	192.45	-----	Stir casting[50]
7.	Al-2014/TiC	-----	118-147	61-94 HV	Stir casting[51]
8.	Al-6061/Al_2O_3	2.35-2.57	149.76-193.47	76-186 HV	Stir casting[52]

6 Conclusions

This work has highlighted the possibility for the application of bottom pouring vacuum stir casting process for the fabrication MMCs for different engineering application. The following conclusions are drawn from the present work:

(i) The utilized gas injection bottom pouring vacuum stir casting machine for MMC casting has fabricated a sound and robust Al/ Al_2O_3-MMC.

(ii) The method of fabrication of Al-MMC *i.e.* bottom pouring vacuum stir casting process and incorporation of Al_2O_3 particles as a primary reinforcement has significantly affected the mechanical and the micro structural properties of the MMC.

(iii) The fabricated Al-MMC has a density of 2.65 gm/cc, micro-hardness of 73.3 HV and tensile strength of 220 MPa which is higher than the Al-alloy.

(iv) The highest wear rate of the MMC is 0.0137736 mm^3/mis noted at 40 N load, 8 m/s sliding speed and 1000 m sliding distance.

(v) From ANOVA of the wear test data, sliding distance is found to have the highest physical and statistical effect on the wear of the MMC.

(vi) Further, the contribution of sliding distance by 49.65%, load by 39.49%, and sliding speed by 04.79% for wear loss of the fabricated Al-MMC.

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