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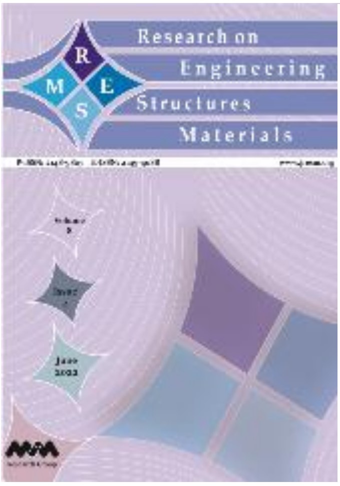

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Research Article

Influence of alumina and zinc oxide nanoparticles on microstructure and electro-mechanical properties of aluminum metal matrix composites fabricated by customized two-step stir casting method

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Abstract

The present paper reports the influence of Alumina (Al_2O_3) and Zinc Oxide (ZnO) nanoparticles on the microstructure and electro-mechanical properties of aluminum metal matrix composites (Al MMCs) fabricated by a customized two-step stir casting method. Two types of Al MMCs were developed, (i) Al MMC-01 having 97.5 wt. % of Al and 2.5 wt. % of Al_2O_3 and (ii) Al MMC-02 having 95 wt. % of Al, 2.5 wt. % of Al_2O_3 and 2.5 wt. % of ZnO. The microstructures of Al MMC-1 and Al MMC-2 observed in a Scanning electron microscope (SEM) have affirmed the uniform distribution of Al_2O_3 and ZnO in the metal matrix composites. It has been observed that the addition of 2.5% Al_2O_3 has improved the hardness, flexural strength, and impact toughness of Al composite significantly compared with pure Al. Furthermore, both bulk and micro hardness of Al MMC-02 have also increased significantly. However, impact strength, flexural strength, modulus of elasticity, and electrical conductivity of Al MMC-02 have been reduced by 12%, 52.5%, 60.8%, and 9.81% respectively in comparison with Al MMC-01 as it becomes brittle in nature for the presence of cleavage cracks, deep shear dimples, and crystallographic planes than that of Al MMC-01 as revealed by fractured surface analysis through SEM.

1. Introduction

Aluminum (Al) has been becoming increasingly popular across a variety of industries, including aerospace, automotive, space, etc. due to their superior strength-to-weight ratio, cost-effectiveness, and ample supply of Al on a worldwide scale [1-2]. However, pure Al cannot be used directly in aforesaid industries as many of its properties do not meet the requirements and concerned industries are looking for those composites which are having enhanced electro-mechanical properties. In this regard, researchers around the world are continuously applying different innovative techniques to develop aluminum-based metal matrix composites with the inclusion of various reinforcement particles in nano and micro sizes.

Al MMCs can be fabricated using a variety of processing methods, including stir casting, ultrasonic assisted casting, compo-casting, powder metallurgy, etc. [3-5]. Among these techniques, stir casting is relatively easy to use and inexpensive for the production of Al composites. Up to 30% volume fractions of reinforcement, aluminum composites can be developed using the stir casting method [6-7]. However, the wettability of the reinforcement with the matrix, porosity, and homogeneous reinforcement dispersion are

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the technical difficulties in stir casting. When creating Al MMCs by stir casting, these problems must be resolved in order to get the necessary characteristics [8-11]. The non-homogeneous dispersion of reinforcement particles in the matrix reduces the material properties of the composite in many aspects. Few techniques, such as two-step stir casting, can mitigate or at least reduce the drawbacks of single stir-casting [12-13]. These criteria led to the two-step stir casting method being chosen as the fabrication method to develop Al composites.

The stir-casting process and parameters such as stirring speed, stirring duration, casting temperature, preheating temperature, the effect of squeeze pressure, reinforcement size, etc. can have effects on developed Al composites, which need to be identified and addressed. Numerous studies have examined the creation of metal matrix composites using the stir-casting method while varying various process variables. However, it is still unclear how stirrer blade angle and rpm affect the uniform dispersion of reinforcement particles in the molten matrix. Research on the dispersion of reinforcement particles during the stir-casting process to create MMCs has been conducted by Hashim et al. [14–16]. Mehta and Sutaria [17] looked at the effects of stirrer geometry, position, and speed on particle dispersion into the molten matrix. They investigated the effects of stirrer speed and geometry and discovered a strong association with the outcomes of the experiments. Singh et al. [18] demonstrated that the stirring speed, duration, and angle of the stirrer's blade are crucial factors in ensuring uniform dispersion of reinforcement particles. The effect of stirring speed on the homogenous dispersion of particles in a comparable Al-SiC composite has been simulated by Naher et al. [19].

Literature survey also indicates that relentless efforts are being made to improve the electro-mechanical properties of Al composites by adding different reinforcement particles such as Alumina (Al_2O_3), Silicon Carbide (SiC), Graphite (Gr), Boron carbide (B_4C), and Titanium Carbide (TiC) [20-25]. Among them, Al_2O_3 is the most frequently utilized reinforcement material due to its superior interfacial affinity and resistance to chemical degradation by molten aluminum alloys [26-27]. Aybarç et al. [27] observed that aluminum composites with nano- Al_2O_3 particles exhibited higher mechanical properties than the ones with micro- Al_2O_3 particles. Akbari et al. [28] investigated TiC-reinforced Al matrix composite developed via friction stir processing (FSP) and found uniform particle distribution of TiC particles in the Al matrix resulted in higher mechanical and wear properties. Kandpa et al. [29] developed an aluminum composite using the stir casting method and observed the clustering of Al_2O_3 particles in a few places through SEM for higher wt. % of reinforcement particles.

To improve further on the mechanical qualities and wear characteristics of Al composites, Jasim et al. [30] added different wt. % of ZnO and observed an increase in compressive strength and wear characteristics. They also exhibited a progressive rise of the hardness of Al composites reinforced with a higher percentage of ZnO particles. As per the literature review, ZnO received very rare attention in making hybrid Al-based composites. Moreover, the combined effect of using Al_2O_3 and ZnO in aluminum composites is yet to be investigated. Therefore, there is a prospective research scope of developing a novel hybrid Al composite reinforced with Al_2O_3 and ZnO particles together. As such, two aluminum composites: (i) one having 2.5 wt. % of Al_2O_3 nano-particles and (ii) another having 2.5 wt. % of Al_2O_3 and 2.5 wt. % of ZnO nano-particles in the aluminum matrix. The current research has focused on the selection processes and parameters for customization of stir casting technique and characterization of a few mechanical properties like hardness, impact strength, flexural strength, and electrical conductivity of the developed two Al composites so that their significant usefulness in the aerospace and automotive industries can be explored.

2. Material Under Study

The base metal used for the casting of composites is aluminum ingots collected from RUSAL of Russia. The reinforcement particles used for the fabrication of composites are nanoparticles such as Alumina (Al_2O_3) and Zinc Oxide (ZnO) provided by Hebei Suoyi New Material Technology Co. Ltd. in China. The details of these components/ingredients used for the present study are briefly described below.

2.1 Pure Aluminum

The chemical composition analysis of the pure aluminum has been done by the XRF Analyzer of Olympus, Model: Vanta C Series and the results are presented in Table 1.

Table 1. Composition of Pure Aluminum

Element	Al	Si	Fe	Cu	Zn	Zr	Pb
Percentage (%)	99.052	0.614	0.323	0.002	0.008	0.0007	0.0009

2.2 Alumina (Al_2O_3)

Aluminum oxide commonly named as Alumina is a chemical compound of aluminum and oxygen with the chemical formula Al_2O_3. It has significant uses to produce Al metal matrix composite, as it has an abrasive owing to its hardness, and has a refractory material owing to its high melting point. As per the maker's manual of Al_2O_3, the Melting point is 2072^{0}C, Boiling point is 2977^{0}C, Limit of application is 1175^{0}C, Hardness as per Moh's Scale is 7.5, the Linear coefficient of expansion is 4.5 μm/m^{0}C, the Molecular weight is 101.96 g/mol, Bulk Density is 0.1-0.3 g/cm^3 and Thermal conductivity is 30 W.m^{-1}-K^{-1}. Fig. 1 shows the SEM image of Al_2O_3 collected for the study.

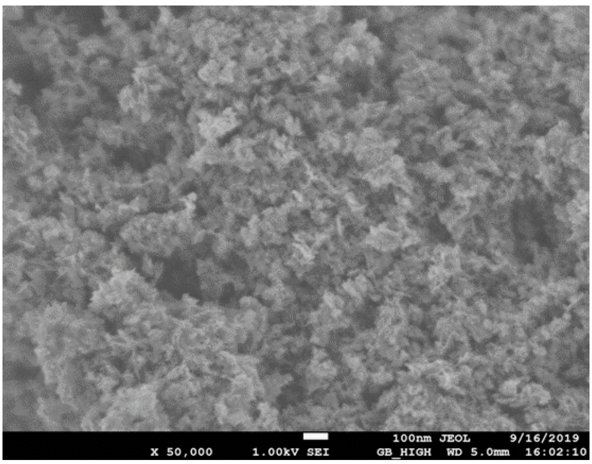


Fig. 1. SEM of Reinforcement particles Al_2O_3 with grain size of 20 nm

2.3 Zinc Oxide (ZnO)

ZnO is a white powder that is essentially water-insoluble. To customize the mechanical properties of several materials, ZnO is employed as reinforcement. As per the maker's manual of ZnO, the Melting point is 1974^{0}C, the Flashpoint is 1436^{0}C, the Hardness as per Moh's Scale is 4.5, the Linear coefficient of expansion is 4.5 μm/m^{0}C, the Molecular weight is 81.406 g/mol, Bulk Density is 0.15-0.3 g/cm^3 and Thermal conductivity is 50 W.m^{-1}-K^{-1}. Fig. 2 shows the SEM image of ZnO collected for the study.

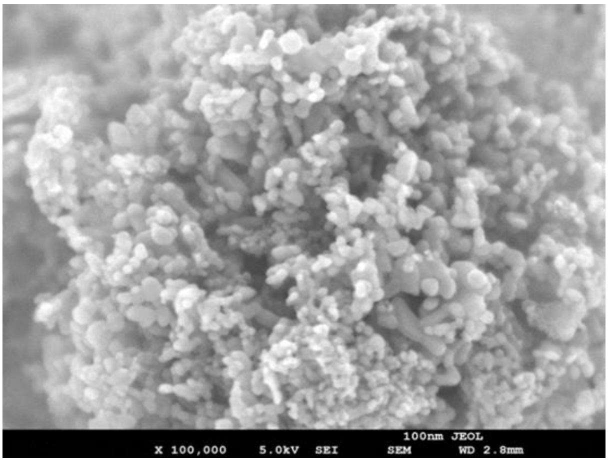


Fig. 2. SEM of Reinforcement particles ZnO with grain size of 30 nm

3. Experimental Details

3.1 Selection Criteria for Process and Parameters of Stir Casting

The stir-casting process and associated parameters such as stirring speed, stirring duration, casting temperature, preheating temperature, the effect of squeeze pressure, reinforcement size, etc. have a variety of effects on developed Al composites which will be discussed here sequentially. In the case of stirring speed, there is no room for the reinforcement particles (dispersed phase) to scatter evenly throughout the matrix due to reduced shearing force [31]. With a faster stirring speed, there is a potential that the matrix's porosity will increase as the gas particles move around inside it. Therefore, an optimum stirring speed of 400 RPM has been chosen to avoid such circumstances. The duration of stirring is crucial in ensuring that the dispersed phase is distributed evenly throughout the matrix. The clustering of reinforcement particles is brought on by shorter stirring times [32]. Therefore, stirring of 5 minutes in two steps has been selected to avoid such agglomeration.

The casting temperature is one of the factors that have the biggest impact on the stir casting process. The viscosity of the matrix metal reduces as the temperature rises, and the particle distribution is also impacted. By raising the melt temperature, the chemical reaction between the metal matrix and the reinforcing particles is sped up [33]. According to the microstructure analysis of numerous study articles, the reinforcing particles were discovered to be evenly distributed between 750°C and 800°C for casting. Due to variations in the viscosity of the liquid Al matrix, the particle agglomerations were seen at processing temperatures of 700°C, 850°C, and 900°C [34]. To keep the optimum viscosity and minimum chemical reaction between the metal matrix and reinforcement particles, 800°C has been selected as the casting temperature.

Preheating the base metal and reinforcing material is essential to reducing porosity [35]. Base metal is preheated at 500^{0}C for an hour and reinforcing particles at 300^{0}C for two hours because preheating is needed to release the trapped gases from the metal and reinforcing particles. The MMC strength is impacted by the size of the reinforcement. The size of the reinforcement has an inverse relationship with strength. Strength improves as reinforcement size decreases [36]. With the heat being dissipated from various dies, the squeeze pressure accelerates cooling [34]. Additionally, it reduces the nucleation of gas bubbles, which decreases porosity [37].

On the basis of the notable factors and their parameters on the effects of stirring casting after studying the various research works [31-37], the finalized parameters for the development of Al composites are shown in Table 2.

Table 2. Selection of Stir Casting Parameters with Arrangements

SL No	Casting Arrangement	Casting parameter
1	Base Metal	99% pure Al
2	Casting Method	Two Step Stir Casting
3	Base Metal Preheat	500°C
4	Base Metal Preheat Time	60 minutes
5	Casting Temperature	800°C
6	Reinforcement	Al_2O_3 and ZnO
7	Reinforcement Particle Size	Al_2O_3: 20 nm and ZnO: 30 nm
8	Reinforcement Preheat	300°C
9	Reinforcement Preheat Time	120 minutes
10	Stirrer RPM	400 RPM
11	Stirring Time	05 minutes in two steps

3.2 Design and Development of Customized Stirring Mechanism

A dedicated small version of the stirring mechanism has been designed and developed to apply the effects of selected casting parameters such as stirring speed, stirring time, Squeeze Pressure, etc. during the fabrication of Al composites for the present research purpose. The stirring mechanism was developed using two major parts, i.e., a power drive and a stirring rod with an impeller (mixer head).

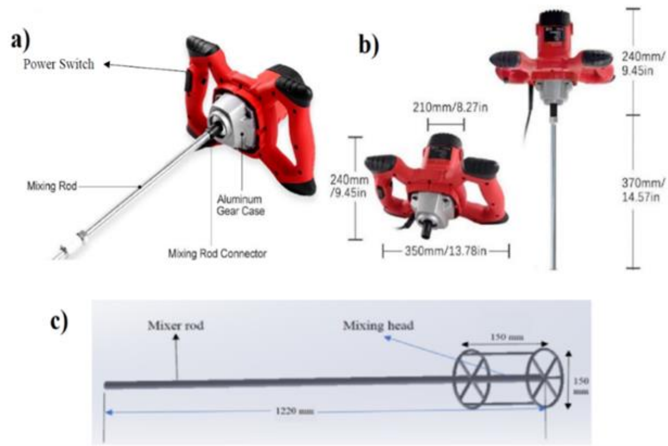


Fig. 3. (a) Component details of Stirrer (b) Dimensions of Stirrer machine (c) Dimension of mixer rod & head

For the power drive part, one multi-speed handheld mixer machine motor was used having a rated voltage of 220V, power of 2100w, frequency of 50/60 Hz and for the stirring part, a rod of about 1220 mm length was connected with an impeller of 150 mm diameter. This mixer machine had 6 gears to operate at different rotational speeds, i.e., 100 rpm to 600 rpm with an interval of 100 rpm for each gear. For the present work of the fabrication process, the 4th gear having 400 rpm was selected as the optimum one after a few trials with speed variations. A detachable arrangement was made to remove the mixer head from the motor part for cleaning purposes.

Since the crucible furnace was supposed to be set at 800°C for casting the metal matrix composite, the materials were selected in such a way that the stirring rod and mixer head could sustain at such an elevated temperature. Therefore, the mixer head was made of stainless steel (SS) and the mixer rod was made of mild steel (MS) as their melting point are about 1500°C and 1300°C, respectively. Fig.3 shows the driving part and the stirring part along the dimensions of the developed stirring gear used for casting purposes in the crucible furnace.

3.3 Fabrication Procedure of Al Composites

The stir casting was done in a gas-fired crucible furnace which could sustain very high temperatures even more than 3500°C. An external air blower was used to supply a sufficient amount of air for maintaining a steady temperature during gas burning. The step-by-step process of Stir casting is shown in Fig. 4. Firstly, Al metal was kept in the crucible and fired up the furnace without activating the blower which generates heat at the temperature of about 300°C heat. After 15 minutes, an electric blower was activated and maintained a temperature of 500°C for preheating the base metal for 60 minutes. Simultaneously the preheating of reinforcement particles is done in the oven at 300°C for 120 minutes. It takes nearly 60 minutes to melt the metal completely at a casting temperature of 800°C. Then, the stirring machine was used for 05 minutes in two steps to mix the molten metal properly with Al_2O_3. When the metal is ready, it was poured into the empty sand mold. After pouring 1st mold with Al composite reinforced Al_2O_3 (Al MMC-01) into the 1st mold, the 2nd reinforcement particle ZnO was added in the crucible and mixed similarly with a two-step stirring mechanism for 05 minutes. When the metal is ready again, Al composite reinforced with Al_2O_3 and ZnO (Al MMC-02) was poured into another sand mold. Mixing of Al_2O_3 and ZnO in the crucible was maintained 20 gm/minute.

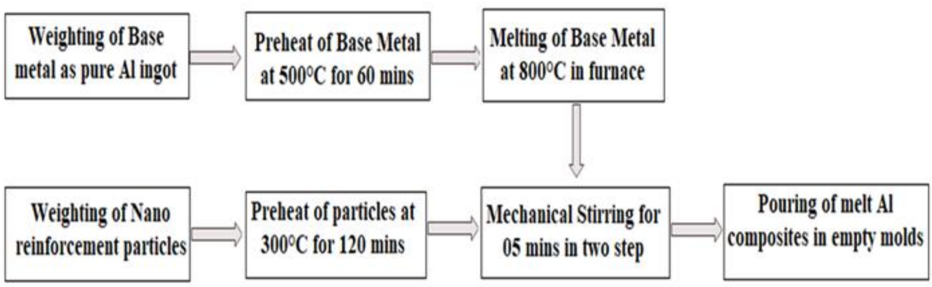


Fig. 4. Flowchart of the Stir casting process

3.4 Preparation of Test Specimens

Test specimens were prepared by a CNC machine, Model VF-2 type as shown in in Fig. 5(a). The cutting tools used for surfacing and machining were respectively 12 mm and 6mm coated with bronze as shown in Fig. 5(b). The finished smooth surface of the Al composite is shown in Fig. 5(c). Test specimens for Impact Charpy and flexural were prepared respectively as per ASTM standards E23-18 and D790-10 as shown in Fig. 5(d)-5(e). The dimension of Impact Charpy and flexural test specimens are respectively 55 mm×10 mm×10 mm and 80 mm×10 mm×04 mm. Test specimens for hardness (Rockwell and Vickers micro) and electrical conductivity were prepared respectively as per ASTM standards E10-18, E18-20, E92-17, and E1004-17 with the dimensions of 20 mm×20 mm×08 mm. The specimens are demonstrated sequentially in Fig. 5(f).

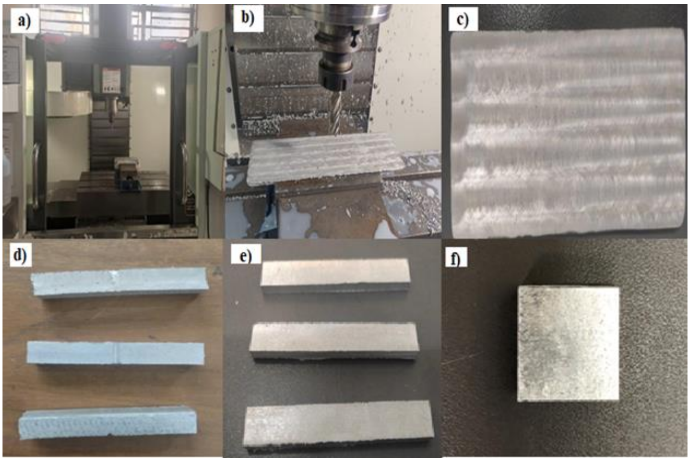
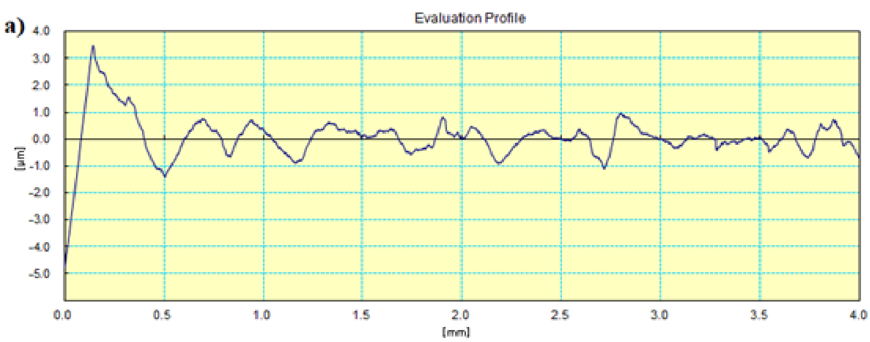


Fig. 5. (a) CNC machine set up (b) End Mill cutter (c) Finished Al composite, Sample specimens for (d) Impact (Charpy) (e) Flexural (f) Hardness and Electrical Conductivity

3.5 Surface Roughness of Test Specimens

The cutting speed, feed rate, and depth of cut for the CNC machining were maintained as 375m/min, 400m/min, and 1 mm respectively during facing and preparation of test specimens for hardness, flexural & impact strength and electrical conductivity. The surface roughness of a test specimen is the prediction factor for mechanical performance. Mainly surface irregularities contribute to the breakage and initial formation of corrosion. A sample of test specimen from Al MMC-01 has been taken to conduct the surface roughness test by a Mitutoyo roughness tester, Model SJ-210 to identify the possible imperfection and obtained an overall Ra of 0.492 μm. The evaluation profile of measured surface roughness is shown in Fig. 6(a).

The microstructure of the same test specimen from Al MMC-01 was also observed by Scanning Electron Microscope (SEM), Model: TESCAN VEGA 4 from the Czech Republic. As shown in Fig. 6 (b), a sample of test specimen with a dimension of 05mm×05mm×05mm was observed in SEM with FoV: 109 μm, WD:11.57 mm, Speed: 7:19, Energy: 30KeV, Mag: 2.56Kx, Pixel Size: 107 nm, DoF: 74.1 μm. As shown in Fig. 06 (b), we identified a few discontinuities and a few holes with elliptical sizes of 2.09 μm & 1.28 μm.



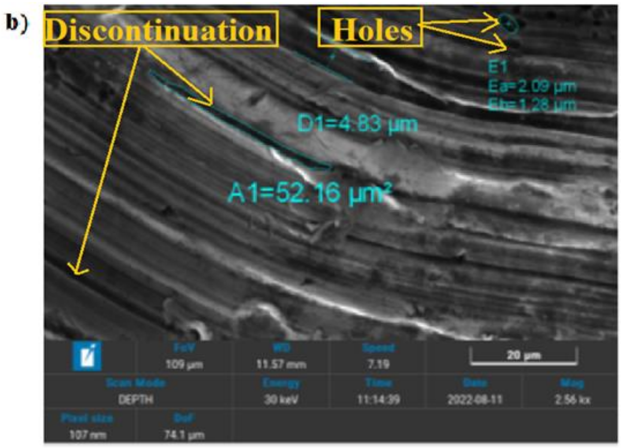


Fig. 6. (a) Evaluation profile of Surface roughness (b) Microstructure observation by SEM of a test specimen from Al MMC-01

4. Microstructure Observation

After the preparation of the aluminum metal matrix composite by two-step stir casting, microstructure observation was carried out by SEM in order to confirm the mixing of reinforcement particles (Al_2O_3) and (ZnO) into a base material (99% Al). A sample of Al-Al_2O_3 (Al MMC-01) and Al-Al_2O_3-ZnO (Al MMC-02) with a dimension of 05mm×05mm×05mm prepared for microstructure observation by Scanning Electron Microscope (SEM), Model: TESCAN VEGA 4.

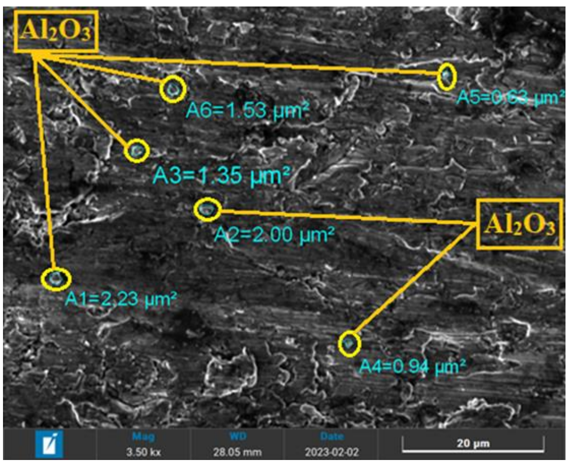


Fig. 7. Microstructure observation by SEM of Al composite having 97.5% of Al and 2.5% of Al_2O_3 (Al MMC-01)

For Al MMC-01, the morphology of Al_2O_3 particles is mainly irregular or nearly elliptical shown in Fig. 7. The Al_2O_3 particles were uniformly distributed in the Al/ Al_2O_3 as casted-condition. The elliptical area immersed by the reinforcements (Al_2O_3) in Al MMC-01 are approximately 5.45 µm^2 and 6.29 µm^2 which is investigated through image processing as shown in Fig. 7. Also, a few clustering or agglomerations of Al_2O_3 particles were perceived in Al MMC-01.

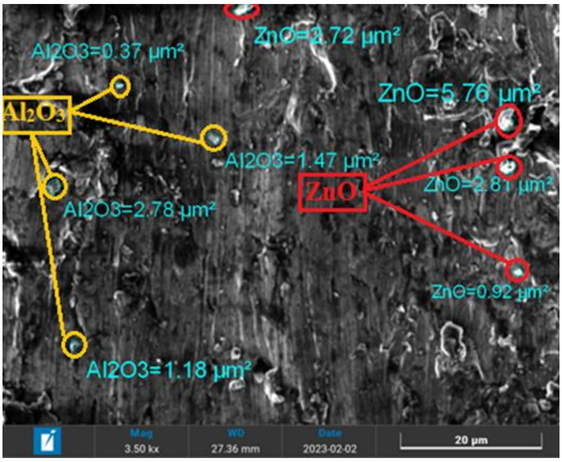


Fig. 8. Microstructure observation by SEM of Al composite having 95% of Al, 2.5% of Al_2O_3, and 2.5% of ZnO (Al MMC-02)

Fig. 8 exhibits the distribution of Al_2O_3 and ZnO particles in Al MMC-02 where the morphology of both nanoparticles is also irregular or nearly elliptical in shape. As shown in Fig. 8, both nanoparticles were also uniformly distributed in Al MMC-02 as a casted condition. The elliptical area immersed by the reinforcements Al_2O_3 and ZnO in Al MMC-02 are respectively 0.37 to 2.78 µm^2 and .92 to 5.76 µm^2 which was investigated through image processing. We also observed a few agglomerations of Al_2O_3 and ZnO particles perceived in Al MMC-02.

Singla et al. [38] applied a two-step stirring technique during the fabrication of Al composite reinforced with SiC particles by the stir casting method. This experimental method had an effective contribution to the improvement of the strength and hardness of fabricated Al MMCs for the uniform dispersion of SiC particles in the matrix. The uniform dispersion of Al_2O_3 in Al MMC-01 and Al_2O_3 and ZnO in Al MMC-02 was achieved by the selection of process and parameters of two-step stir casting which goes in line with Singla et al. [38].

The introduction of Al_2O_3 nanoparticles in Al MMC-01 and Al_2O_3 and ZnO nanoparticles in Al MMC-02 leads to a decrease in the grain size of primary Al as shown in the microstructure of both MMC as per Fig. 7 and Fig.8. This decrease in grain size of primary Al was highly observed in both Al MMC-01 and Al MMC-02 at high concentrations of nanoparticles. Wazery et al. [39] observed similar microstructure during the investigation of mechanical properties for Al composites reinforced with 3 wt.% of ZnO nanoparticles.

5. Investigation Procedure

5.1 Rockwell Hardness

Rockwell hardness test was carried out by a hardness tester from Brooks Inspection Equipment Ltd, United Kingdom at a room temperature of 26^{0}C. The test specimens were prepared as per ASTM standard E10-18 with dimensions of 20 mm×20 mm×08 mm where a 1.58 mm diameter hardened steel ball subjected to a load of 100kg was applied. The diameter of the impression is the average of five readings.

5.2 Vickers Micro Hardness

The test specimens for Vickers microhardness were prepared as per ASTM standard E92-17 with a dimension of 20 mm×20 mm×08 mm. The tests were carried out by a Vickers hardness tester model: TMHV-10MDT auto turret Vickers hardness tester with 500 gm load for 10 seconds duration. The average value of HV was taken from ten readings.

5.3 Impact Toughness

The Impact Charpy test was carried out to investigate energy being absorbed and ascertain the durability of the developed composite samples. The tests were carried out by an Impact testing machine of Model: AIT300 from Turkey at a room temperature of 26^0C. The specimens used for the Charpy test had a dimension of 55mm×10mm×10mm as per ASTM E23-18. The average value of impact toughness was taken from three readings.

5.4 Flexural Strength

The flexural test was done to determine the flexural behavior based on simple beam load-bearing capacity of developed two Al composite materials, i.e., Al MMC-01 and Al MMC-02. It was conducted using the Universal Testing Machine at a room temperature of 26^0C under three-point bending conditions. The dimension of the test specimens was 80mm×10mm×4mm as per ASTM D790-17. The flexural strength, elastic modulus, etc. were obtained on average values taken from three tests' readings.

5.5 Electrical Conductivity

The electrical conductivity of developed Al MMC-01 and Al MMC-02 are tested by Eddy Current Conductivity meter, model: 12Z from ZAPPITEC PTY LTD, Australia at a room temperature of 26^0C. The test specimens were prepared as per ASTM E1004-17 with a dimension of with dimension of 20 mm×20 mm×08 mm. The electrical conductivity of a metal depends on several factors, such as its chemical composition and the stress state of its crystalline structure. Also, the conductivity of metals changes significantly with temperature. To allow easy comparison between different metals, conductivity values were taken with a standardized temperature of 20^0C. The measurement is made in %IACS units, an acronym that means "Percent of International Annealed Copper Standard".

6. Results and Discussion

6.1 Hardness

The Rockwell hardness values (HRB) of developed Al MMC-01 were observed to be 24.33 kg/mm^2 with a standard deviation of 1.22 and Al MMC-02 was 29.2 kg/mm^2 with a standard deviation of 1.3. The diameter of the impression is the average of five readings at right angles. As per Fig. 9, there is a 20% improvement in Rockwell hardness in Al MMC-02 from that of Al MMC-01 due to the addition of 2.5% ZnO as reinforcement particles.

The Vickers mirco-hardness (HV) of Al MMC-01 was 35.72 with a standard deviation of 1.46 and that of Al MMC-02 was 50.23 with a standard deviation of 2.50. The average value of HV was taken from ten readings. As per Fig. 9, there is a 41% improvement in Vickers micro-hardness in Al MMC-02 from Al MMC-01 due to the addition of 2.5% ZnO as reinforcement particles.

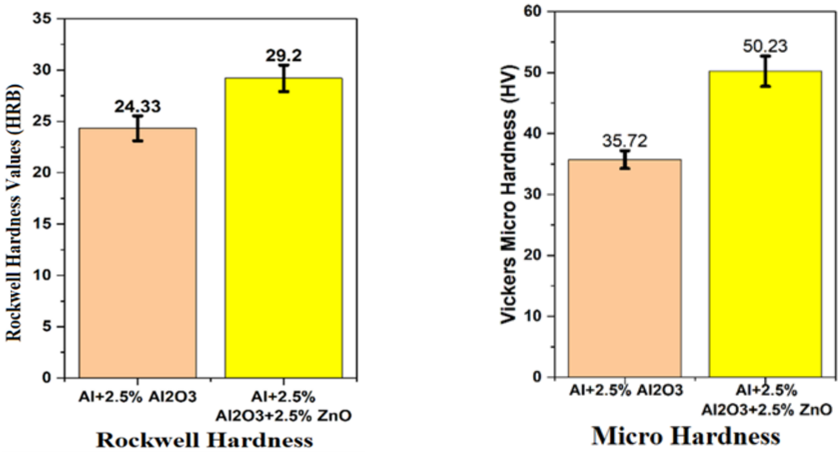


Fig. 9. Hardness test results of Al MMC-01 (Al+2.5% Al_2O_3) and Al MMC-02 (Al+2.5% Al_2O_3+ 2.5% ZnO)

With the insertion of ZnO nanoparticles in Al MMC-02, the strength of the grain boundaries may be increased because ZnO and Al's reaction polished the microstructure can be seen in Figure 9 which contributed to the higher hardness readings of Al MMC-02. A high interfacial zone between aluminum and ZnO nanoparticles causes a strong reaction between them. The reaction reaches a high value for high ZnO nanoparticle concentrations (2.5%), leading to the sample with the highest microstructural refinement. Growth restriction factor and heterogeneous nucleation are responsible for Al refining by the addition of various elements [40-41].

More specifically, the addition of ZnO nanoparticles to an Al matrix solution at a high temperature causes the ZnO nanoparticles to break down into Zn and O. After decomposing from ZnO, almost all of the oxygen was coupled with aluminum oxide. formation is hampered by the presence of oxygen that has been broken down from ZnO at the interface between liquid and solid aluminum during the formation of the primary aluminum alloy. The diffusion of solute Zn at the interface between solid and liquid aluminum can be blamed for limiting aluminum growth during solidification. Additionally, the breakdown of Zn and oxygen yields significant amounts of Zn for the heterogeneous nucleation of primary aluminum grains. Therefore, it can be deduced that addition ZnO has the potential to increase the hardness of aluminum composites at both bulk and micro levels.

Jasim et al. [30] developed ZnO-reinforced Al MMC using the stir casting method for the investigation of mechanical properties and wear characteristics. Their investigation exhibited an increment of hardness from 23 kg/mm^2 to 30 kg/mm^2 for (2, 4, 6, 8, 10) wt.% of ZnO along with Al. In the present study, Rockwell hardness values have been found as 24.33 kg/mm^2 for Al MMC-01 and 29.2 kg/mm^2 for Al MMC-02. Therefore, the present results are quite agreeable with Jasim et al. [30] on an incremental aspect of hardness in the presence of ZnO in aluminum composites.

6.2 Impact Toughness

The effects of Al_2O_3 and ZnO on the impact strength of developed two Al MMCs are shown in Fig. 10. The average value of impact toughness energy of Al MMC-01 is 13.47J with a standard deviation of 0.64J and that of Al MMC-02 is 11.77J with a standard deviation of 0.25J respectively. The result brings forward the limitations of energy absorption capacity while ZnO is added along with Al_2O_3 in developing aluminum composites.

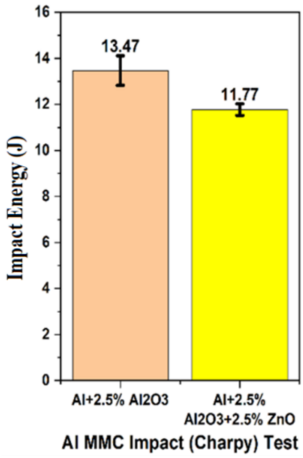


Fig. 10. Impact Toughness of Al MMC-01and Al MMC-02

Verma et al. [42] developed Al MMC reinforced with 10% Al_2O_3 and observed an impact toughness of 6.97J with a standard deviation of 0.85 [42]. The present study reveals that there is an increase in impact toughness in Al MMC-01 in comparison with pure Al due to the addition of 2.5% Al_2O_3 in the metal matrix. However, there is a decrease of 12% impact energy for Al MMC-02 in comparison to that of Al MMC-01 due to the insertion of 2.5% ZnO with 2.5% Al_2O_3 in aluminum composite. The addition of ZnO in aluminum alloy increased its hardness, thus turning it brittle in nature. As a result, the degree of plastic deformation energy for the composites is reduced. This deformation energy increases the chances of debonding during the fracture which leads to a reduction in impact strength [43]. The brittleness of the material decreases the plastic deformation energy thereby reducing the impact strength.

6.3 Flexural Strength

The flexural test results of the developed metal matrix composites, i.e., Al MMC-01 and Al MMC-02 conducted using a Universal Testing Machine on three-point bending conditions are presented in Fig.11. Fig.11 (a), show that the ultimate flexural strengths (UFS) of Al MMC-01 and Al MMC-02 are 320.06 MPa and 151.94 MPa respectively. Fig.11 (b) illustrates that the modulus of elasticity (MoE) values of Al MMC-01 and Al MMC-02 are 81.36 GPa and 31.84 GPa respectively. It is depicted that both strength and elastic modulus for the inclusion of 2.5% Al_2O_3 in Al MMC-01 have increased significantly compared to pure aluminum. This result agrees fully with the findings of Saravanakumar and Sasikumar where the flexural strength was found to be 250 MPa for the Al MMC with 3% of Al_2O_3 [44]. However, the addition of ZnO in Al MMC-02 has not shown any positive impact on UFS or MoE compared to that of Al MMC-01. Rather, the inclusion of only 2.5% ZnO in Al MMC-02 has reduced UFS and MoE from Al MMC-01 by 52.5% and 60.8% respectively. These results thus lead to limitations in specific requirements for the use of ZnO in aluminum composites.

The flexural test findings show that the flexural strength significantly changes by adding the weight % of the nanoparticles. Good particle-particle bonding, which leads to internal stress transmission, plastic deformation, and movement towards reinforcing nanoparticles, is responsible for improved strength. The nanocomposite samples' fracture is delayed and their flexural strength rises as a result of the nanoparticles' presence, high stiffness, and the high force required to break them.

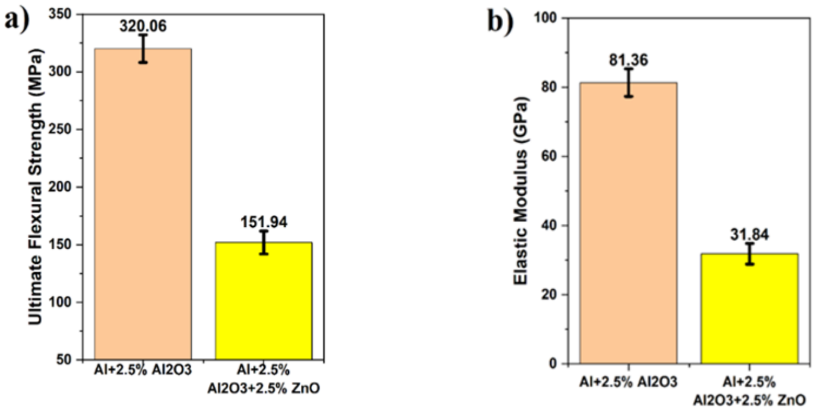


Fig. 11. (a) Ultimate Flexural Strength (UFS) and (b) Modulus of Elasticity (MoE) of Al MMC-01and Al MMC-02

Al_2O_3 is one of the strongest reinforcing nanoparticles, and samples containing it have much higher flexural strengths than samples without it. The lowest flexural strength among all reinforced samples is provided by ZnO nanoparticles, which are weaker than other nanoparticles [45]. As a result, the presence of Al_2O_3 in Al MMC-01 improved the flexural strength of Al MMC-01. Increasing the percentage of nanoparticles results in higher local ductility because the mixing of the nanoparticles was done successfully and good distribution between the nanoparticles and Al was achieved [46]. However, adding ZnO nanoparticles along with Al_2O_3 in Al MMC-02 has reduced the flexural strength, making the metal matrix from ductile to brittle in nature. SEM imaging from the fracture cross-section of the Al MMC-01 and Al MMC-02 samples was performed to ensure the results.

6.4 SEM Observation of Fractured Surface

The fractured surfaces obtained through flexural tests of Al MMC-01 and Al MMC-02 were examined using a Scanning Electron Microscope (SEM) to identify the mode of failure. The SEM micrographs presented in Fig. 12 exhibit the characteristics of a brittleness fracture pattern.

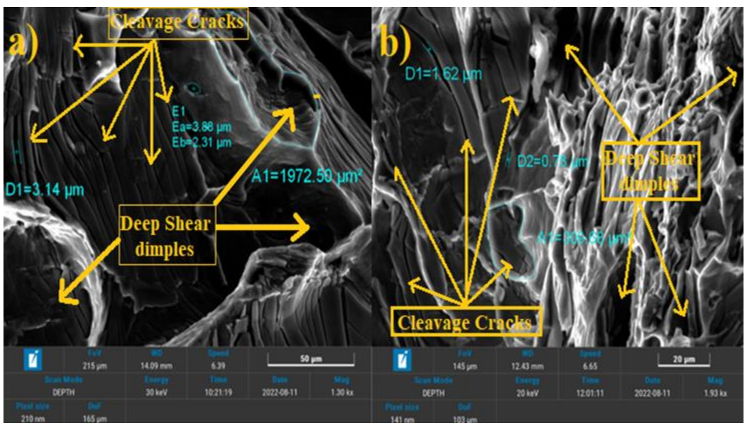


Fig. 12. SEM images of the fractured surface of: (a) Al MMC-01 & (b) Al MMC-02

The cleavage cracks and deep shear dimples of Al MMC-01 and Al MMC-02 are shown respectively in Fig. 12 (a) and 12 (b) respectively. The presence of cleavage cracks and deep shear dimples in the fractured surface of Al MMC-02 are higher than that from the fractured surface of Al MMC-02. The existence of multiple cleavage cracks, shear dimples, and crystallographic planes within one specific grain as shown in Fig. 12 (b) in the fracture surface of Al MMC-02 is also an indication of the brittle features at the fracture surface [47].

As a whole the mechanical properties such as hardness, impact toughness, and UFS were increased a lot compared with pure Al. Bakshi et al. [48] investigated the factors which affect the strengthening mechanism of aluminum composites. According to their study, the strength mainly depends on the volume fraction of constituents and the aspect ratio of the reinforcement. In the current investigation, the findings are similar to the flexural & impact strength and Hardness of Al MMC-01 and Al MMC-02, i.e., the values have been increased in comparison to that of pure Al. However, the impact toughness, UFS, and MoE of Al MMC-02 are less than that of Al MMC-01 as shown in Fig. 10 and Fig. 11 due to the insertion of 2.5% ZnO in the metallic matrix being affirmed by SEM images shown in Fig.12.

6.5. Electrical Conductivity

The electrical conductivity of Al composite is different from pure Al. As shown in Figure 13, Al MMC-01 having a composition of 97.5% Al and 2.5% Al_2O_3 nanoparticles has an electrical conductivity of 45.15 % IACS with a standard deviation of 1.29% IACS and Al MMC-02 has a composition of 95% Al and 2.5% Al_2O_3 & 2.5% ZnO nanoparticles has an electrical conductivity of 40.72% IACS with a standard deviation of 1.97% IACS. Both Al MMC-01 and Al MMC-02 possess lower values of electrical conductivity because of the non-conducting Al_2O_3 and ZnO reinforcement materials present in MMCs.

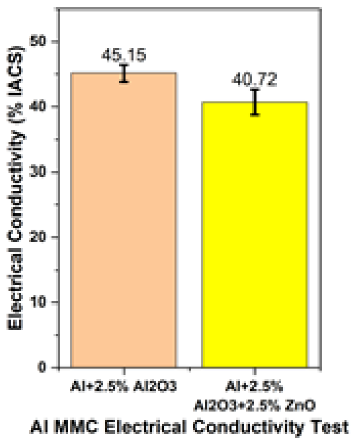


Fig. 13. Electrical Conductivity of developed two Al MMCs

As shown in Fig. 13, the electrical conductivity is observed to be reduced by 9.81% from Al MMC-01 to Al MMC-02 due to the addition of 2.5% ZnO as reinforcement particles change the crystal structure of the metal matrix. Though it is not desirable in some aerospace applications, however, there are many other applications such as heat sinks, bearings, etc.

As the Al MMCs are developed with Al_2O_3 and ZnO reinforcement particles, the electrical conductivity typically decreases. This can be attributed to several factors such as the Insulating nature of nanoparticles, increased scattering of electrons, reduced electron mobility, dilution effect etc.

Both Al_2O_3 and ZnO are ceramic materials that have inherently low electrical conductivity. When these nanoparticles are dispersed within the aluminum matrix, they act as insulating barriers, impeding the flow of electrical current through the composite. Also, the presence of these nanoparticles creates interfaces and irregularities within the composite structure. As electrons move through the material, they scatter off these interfaces, resulting in increased resistance to the flow of current. This scattering effect further reduces the electrical conductivity of the composite. Thus, the addition of these nanoparticles also disrupts the electron mobility within the composite as these particles introduce grain boundaries, which can impede the movement of electrons. These grain boundaries act as barriers to the free flow of charge carriers, reducing the overall conductivity. It's important to note that the specific impact of nanoparticles on electrical conductivity varies depending on factors such as particle size, distribution, volume fraction, and processing techniques. Different combinations of nanoparticles and matrix materials yield different conductivity behaviors in MMCs. Babalola et al. [49] developed Al MMC with different wt. % of Al_2O_3 and investigated the electrical conductivity. As per their study, it was observed that a similar decreasing pattern of electrical conductivity of samples for each incremental wt. % of reinforcement particles in Al MMC.

6. Conclusion

In the current research, we investigated the effect of nano reinforcement particles Al_2O_3 and ZnO on microstructure and electro-mechanical properties like hardness, impact toughness, flexural strength and electrical conductivity of Al MMC fabricated by customized Two-step stir casting method. The notable outcome and findings of the investigations are summarized as follows:

- Two Al MMCs developed having compositions of 97.5% Al and 2.5% Al_2O_3 (Al MMC-1) and 95% Al, 2.5% Al_2O_3 and 2.5% ZnO (Al MMC-2) by a customized two-step stir casting method with selected process parameters.
- The microstructure observation of specimens determines an almost uniform distribution of Al_2O_3 & ZnO nano particles Al MMC-01 and Al MMC-02 with fewer agglomeration. The selection of process parameters was observed to influence the properties of developed Al MMCs.
- Al MMC-01 has displayed distinct mechanical properties such as flexural strength and impact toughness. Therefore, it can be considered for aircraft parts such as wing ribs, spars, wing-to-fuselage attachment points, control surfaces (i.e., flaps, slats, elevators, and rudders) and structural attachments such as brackets, fasteners, and joints, exposed to bending and flexing forces.
- The inclusion of 2.5% ZnO nano-particles has increased the bulk hardness (Rockwell) and surface hardness (Vickers Micro) of Al MMC-02 by 20% and 41% respectively in comparison with Al MMC-01. However, the flexural strength, impact toughness, modulus of elasticity, and electrical conductivity values of Al MMC-02 were reduced by 12%, 52.5%, 60.8%, and 9.81% in comparison to Al MMC-01 due to the presence of multiple cleavage cracks, deep shear dimples, etc. The presence of these multiple cleavage cracks and deep shear dimples indicate a mode of failure associated with brittle fracture in Al MMC-02. As these characteristics are not desirable for aerospace applications, AL MMC-02 is not getting preference to aerospace applications to meet the required high structural integrity, reliability, and fatigue resistance in aerospace applications.

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