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IJIE

http://penerbit.uthm.edu.my/ojs/index.php/ijie
ISSN : 2229-838X e-ISSN : 2600-7916

The International Journal of Integrated Engineering

Microstructural Evolution and Mechanism of Strengthening in Al-Zn/fly ash/ ZrO2 Composites Fabricated Through a Vortex

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DOI: https://doi.org/10.30880/ijie.2022.14.07.007
Received 26 April 2022; Accepted 1 July 2022; Available online 31 December 2022

Abstract: This paper describes the fabrication of aluminum-zinc (Al-Zn) alloy (AZ91E) metal matrix composites augmented with Fly Ash (FA) and zirconium dioxide (ZrO2) particulate utilizing the vortex method and a stir casting process. The researchers introduced composites with ZrO2and fly ash at varied weight % ranging from 0 to 10 with 53 µm particle sizes. The inclusion of ZrO2 particle reinforcement increased the hardness significantly, whereas the ultimate yield and tensile strengths increased somewhat. As the weight % of ZrO2 particles was increased, the permeability and density of Al-Zn alloy based composites increasing. When compared to the comparable alloy, composite densities were lower, which might be attributed to the low density of the FA. Additionally, the compressive and tensile crack properties of the composites produced were investigated. Microstructural analyses confirmed the presence of evenly dispersed FA and ZrO2 particles throughout the matrix, but an EBSD study revealed that this led to the diminished reduction. The inclusion of FA particles enhanced the material's tensile properties and hardness including ultimate yield and tensile strengths. The strengthening mechanisms underlying the enhanced properties were discussed. At the point when ZrO2 and FA fortifications were applied, a definite tensile and yield strengths raised in contrasted with the basic compound. As revealed by the aftereffects of the examination, the grain size of the Al-Zn composite built up with FA and ZrO2 particulates is a lot of lower than the grain size of the lattice compound.

Keywords: Fly ash, ZrO2, Al-Zn, scattering electron microscope, tensile strength

1. Introduction

The most often utilized nonferrous metals are aluminum alloys, which are being used due to their abundance of attractive material qualities and low cost. As a consequence of the substantial research that has been done, several aluminium alloys have been developed to improve the specific material characteristics that have been determined as important. Composites are multiphase materials that are made of a reinforcement and matrix to meet the raising need for captivating technical materials in the construction industry. Composites, in general, have good thermal qualities as well as remarkable mechanical features, such as stronger fracture toughness, improved resistance to wear and corrosion, hardness and strength, [1, 2]. Because of these favorable features, composite materials have become increasingly popular in industrial used.

They are used in aviation applications because of their great strength, remarkable thermal characteristics, and extraordinary mechanical features like as fracture endurance, wear and erosion resistance. [22-25] Composite materials are made up of reinforcement materials or reinforcing elements that are spread in a continuous phase known as a matrix. Neeraj k bhoi et.al worked on aluminium metal matrix and explained how the mechanical properties like

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strength, stress improves based on reinforcement of Al2O3, AlN, CeO2, CNT, SWCNT, MWCNT, Gr, GNP, Cu, TiC, TiN, TiB2, TaC, SiC, Si3N4, ZrO2, ZnO, ZrB2, WS2, etc [20]. Priyaranjan Samal etc. all worked on Alloys of aluminum have a unique combination of qualities that makes it an excellent material for making composites. Based on their reactivity to precipitation hardening, aluminum alloys may be divided into two categories: heat treatable alloys and non heat treatable alloys. Alloys that are not heat treatable, on the other hand, get their best properties via the cold working procedure [21].

Matrix composites of ceramic reinforced aluminium have received substantial consideration in the automobile, defense, aerospace and other vital structural uses because they are lightweight and fuel-efficient advanced materials employed in aircraft and missiles. Metal Matrix Composites (MMC) are propelled materials made up of a hard ceramic reinforcements and metallic grid, such as silica, boron carbide, titanium carbide, aluminum oxide, and soft reinforcement to manufacture composite materials. The combination of reinforcements and alloy matrix gives MMCs their combined physical and mechanical qualities. When compared to wear resistance, the specific strength, base metal, fatigue resistance, corrosion resistance, stiffness, and aluminium metal matrix (AMC) composites creep are estimated to be higher [3-5]. This is owing to the composite's larger reinforcement volume % and the higher reinforcement blended into it. As a result of these improvements in characteristics, AMCs are becoming increasingly important in the aviation, space, and automotive industries. Various commercially available metal alloy systems, including Al, Mg, Cu, Zn, Fe, Ni, Ti, Si, and Ag, are employed as matrix materials in manufacturing reinforced particulate metal matrix composites (DRPMMC). DRPMMC are often manufactured discontinuously utilising an aluminium alloy supplemented with high modulus ceramic particles such as SiC or Al2O3. Ceramic particulate metal matrix composites exhibit superior properties to matrix materials. Researchers have concentrated their efforts mostly on commercially accessible aluminium alloy matrix systems such as A2024, A356, and AA 7075 due to their unique characteristics.

In various heavy industries, such as cement, petroleum, and coal-fired power plants, fly ashes are a highly plentiful synthetic substance that is created as a byproduct. Coal-fired power stations, for example, create unusually large volumes of fly ash, which is the residue left over after coal is burned in the power plant. Coal consists mostly of silica and alumina oxides, which are converted to FA after the coal is completely consumed by combustion. In electrostatic precipitators or bag filters, approximately 80% of the ash flies and flue gases become trapped and classified as "Fly Ash” [6, 7]. A large amount of FA produced has negative consequences on the ecosystem, contributing to the severity of global climate change. For example, improper dumping of FA into settling ponds could pollute the environment because of the heavy metals in FA are phytotoxic if they are contained in high concentrations, while others are toxic to aquatic species and fish in high concentrations. The following types of environmental contamination are caused by the heavy metal leaching from coal FA ponds: soil and contamination of vegetation, phytotoxicity, ground and surface water pollution [8-11]. It was discovered that, out of the several ways studied, alloying was the most successful strategy for altering the microstructure and increasing the mechanical characteristics of the AZ91E alloy. The addition of elements like as Sn, Sb, Bi, and others to AZ alloys during the alloying process is routinely done to improve their mechanical performance. Research in the past revealed that rare earth elements were more effective than other elements at maximizing the mechanical performance of AZ91E than other elements. Rare earth elements (RE) may form Al-RE intermetallic in the matrix of the AZ91E alloy, which improves the ultimate strength and creep resistance of the alloy significantly. Zinc is a well-known low-cost RE element that is well-suited for large-scale industrial applications due to its cheap cost. Lanthanum alloying has another benefit in that it promotes the production of Al-Zn intermetallic inside the alloy matrix, which helps to preserve the alloy's excellent thermal conductivity. After a period of time, both the Al-Zn intermetallic and the ZrO2 phases precipitated and greatly strengthened the alloy, which was previously weak.

V. Ramakoteswara Rao and colleagues investigated the tensile properties of a titanium carbide-reinforced Al-Zn alloy. Their findings show that increasing TiC particulates improves the alloy's wear and tensile characteristics while increasing the weight percentage and sliding velocity of TiC carbide particles decreases the frictional coefficient [12]. Baradeswaran et al. investigated the AA 7075/Al2O3/graphite hybrid composite’s tribological and tensile characteristics. They concluded that the frictional coefficient of AA7075 lowers when 5 percent graphite and 2, 4, 6, and 8 percent Al2O3 are added to the composite [13].

This research is primarily concerned with investigating the hybrid particle reinforced composite’s grain structures and microstructural characterization including the Al-Zn alloy AZ91E. The impacts of hybrid particle reinforcement on mechanical properties, grain refinement and microstructure of the particulate reinforced composites are discussed in this work, which was carried out at standard room temperature. In section 2, materials and methods are explained clearly. Section 3 gives the detailed explanation on results and discussions. Section 4 of the paper includes conclusion.

2. Materials and Methods

2.1 AZ91E Aluminium Alloy

There are now several distinct types of aluminum alloys available on the market, each with its own set of advantages and applications. This study focuses on AZ91E aluminum alloys, which are resistive to heat may be greatly strengthened and they are employed in a range of applications requiring corrosion resistance, strength and weldability. The AZ91E alloy’s chemical composition is listed in table 1.

Table 1 - AZ91E alloy's chemical composition

Element	Composition (Mass Percentage)
Al	8.93
Mg	Balance
Si	0.13
Cu	<0.01
Zn	0.86
Mn	0.28

Aluminum alloys (AZ91E) are largely used in aviation and automotive industries for the production of lightweight components. A broad range of reinforcements has been employed in the fabrication of the MMC utilising the AZ91E matrix, including compounds such as ZrO2, Al2O3, Si3N4, B4C, BN, SiC, TiC and others [14-16]. In this research work, ZrO2 has been used as reinforcements. Recently, other nanocomposites based on the AA 6061 alloy matrix have been manufactured on a larger scale as well.

2.2 Stir Casting Process

Over the last decade, a wide range of technologies for manufacturing MMCs has been established. The kind of fabrication technology used has a considerable impact on the composite's mechanical characteristics and production cost. These manufacturing techniques are divided into the processing of liquid and solid state depending on metal matrix condition during the primary process. Other semi solid state methods such as recasting, spray deposition, in situ manufacturing and composting are also available, although they are not as widely used as liquid or solid state procedures.

In solid state manufacturing, the matrix bonding with reinforcements occurs because of mutual diffusion in the solid state at high pressures and temperatures. In liquid state manufacturing, reinforcements are dispersed in the molten matrix and then solidified by infiltration or casting techniques. When compared to solid-state technologies, these approaches are more cost-effective. The most common casting is stirred casting and widely utilized liquid state processing technology because it is less expensive than other methods. It also has reasonably homogeneous reinforcement dispersion in the improved wettability, matrix, and lower porosity.

Stir casting is the method of mixing a layered structure into a matrix phase with the use of a stirring device. Electrical energy is typically utilized to power the stir-casting furnace, and a popular form of heat generation is electrical resistance heating. The procedure involves heating the matrix in a crucible until it melts. To facilitate the mixing of the ingredients the reinforcements are frequently preheated. Mixing takes done in a molten state to reduce the risk of casting faults, and an inert state can be maintained during the charge’s pouring and stirring. To avoid gas entrapment, particulate reinforcements are often fed by an injection gun. Stepper motors are widely used to change the stirrer's spinning speed. The wettability of the matrix and reinforcement should be adequate to achieve a homogeneous mixture through this procedure. The schematic representation of the stir casting process of AZ91E composites are represented in figure 1 [17].

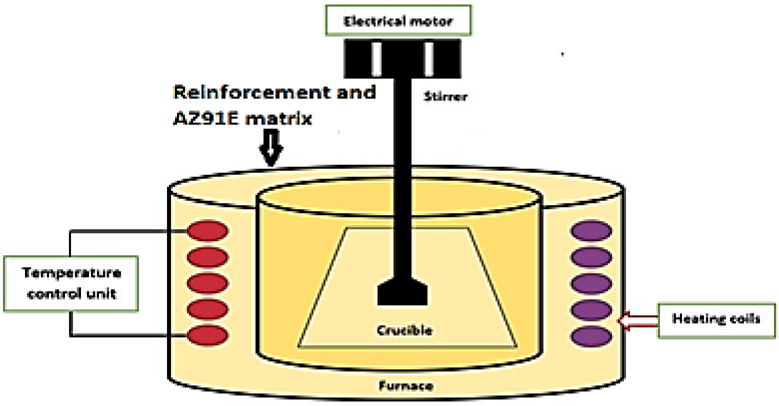


Fig. 1 - Schematic representation of the stir casting process of AZ91E composites

2.3 Fabrication of Hybrid Composites

Figure 2 shows the experimental setup for making hybrid composites using an Al-Zn based alloy reinforced with FA and AZ91E loaded with heat higher than the liquid temperature in a muffle furnace. In a cast cylindrical iron die with an 18mm diameter and a 90mm length, molten metal is poured. The stir casting process is utilized to strengthen the base alloy with varied mixtures of FA and ZrO_2 particulates with 53m average particle size. To minimize agglomeration, the particles were injected during the vortex while preserving flow homogeneity. Fly Ash and ZrO_2 concentrations ranged from 0 percentage to 15 percentage. For 24 hours, all of the constructed specimens were homogenized at 100°C. To determine the stirrer time, temperature and speed, tests were conducted with 450 rpm final speed being selected for smooth particle flow [18].

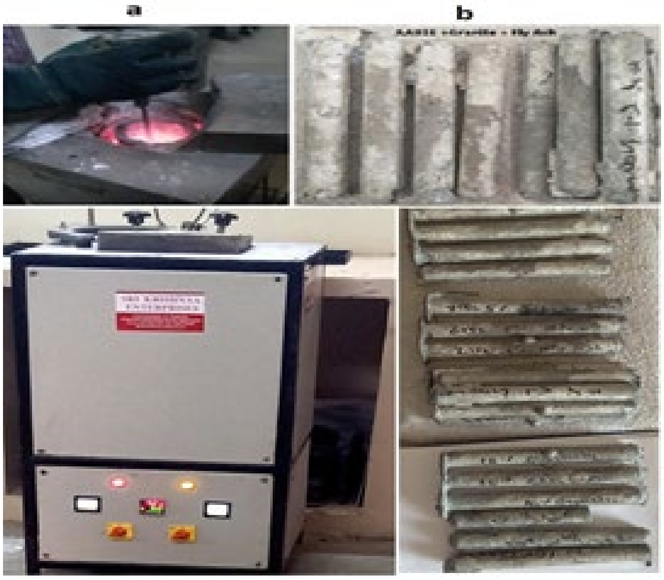


Fig. 2 - (a) Stir casting machine (vortex); (b) casted fingers

3. Results and Discussion

Fly ash powders were sieve-screened as soon as they arrived to remove any big particles. Previous research has shown that adding more than 10% fly ash to fly ash composites boosts their tensile modulus, but at the detriment of tensile strength. Because all of these mechanical qualities are significant, the present investigation utilizes 10 percent FA as it has a great tensile modulus and tensile strength [19].

Zirconium dioxide (ZrO2)-reinforced composites have good bonding properties, particularly with aluminum and have been identified for improving the properties of material such as wear resistance, compressive strength and micro hardness. ZrO2 particles have also been identified as a potential reinforcement for increasing corrosion resistance. To increase the wettability, magnesium was added during the stirring process in this approach. In addition, argon gas was used to prevent the liquid framework material from interacting with the surrounding environment throughout the manufacturing process. The researchers developed defect-free composites that included varying amounts of reinforcing material. As the concentration of ZrO2 in the material was increased, the specific strength of the material increased dramatically as a result of ZrO2's resistance to plastic deformation. The AMC's wear resistance was also enhanced. Stir casting was also used to make an AZ91E alloy- ZrO2 composite with good ZrO2 dispersion. Figure 2 (a) and (b) show FA and ZrO2 particle's SEM micrographs with ZrO2 particles having crystal structure and FA particles having a spherical form.

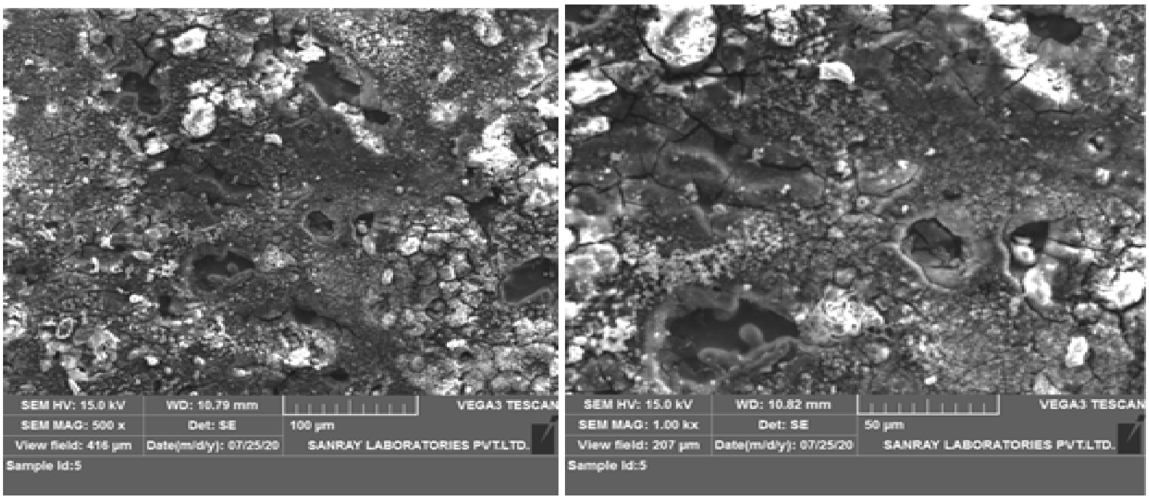
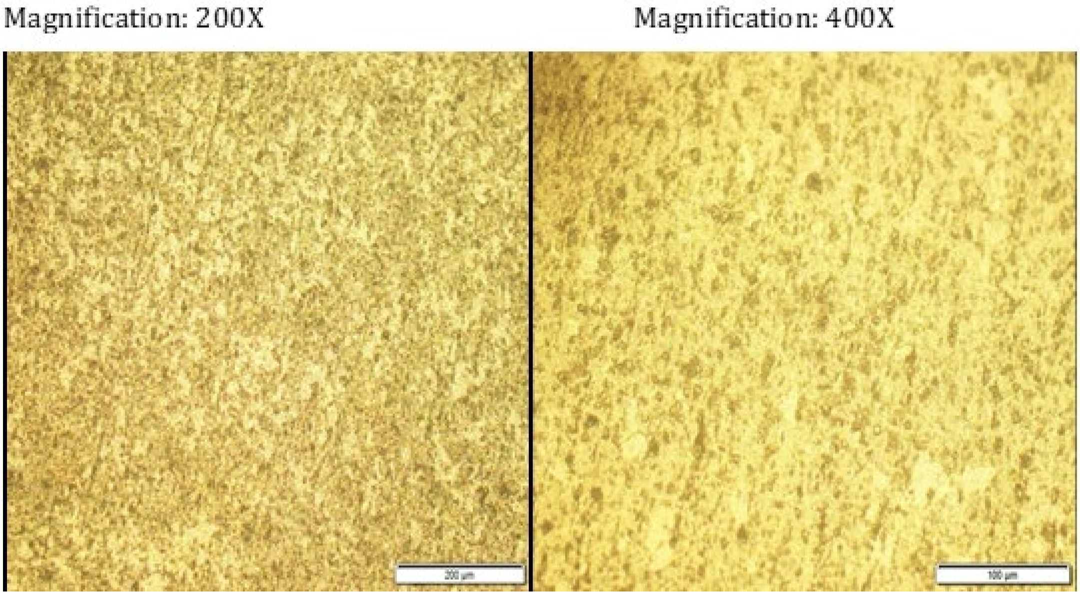
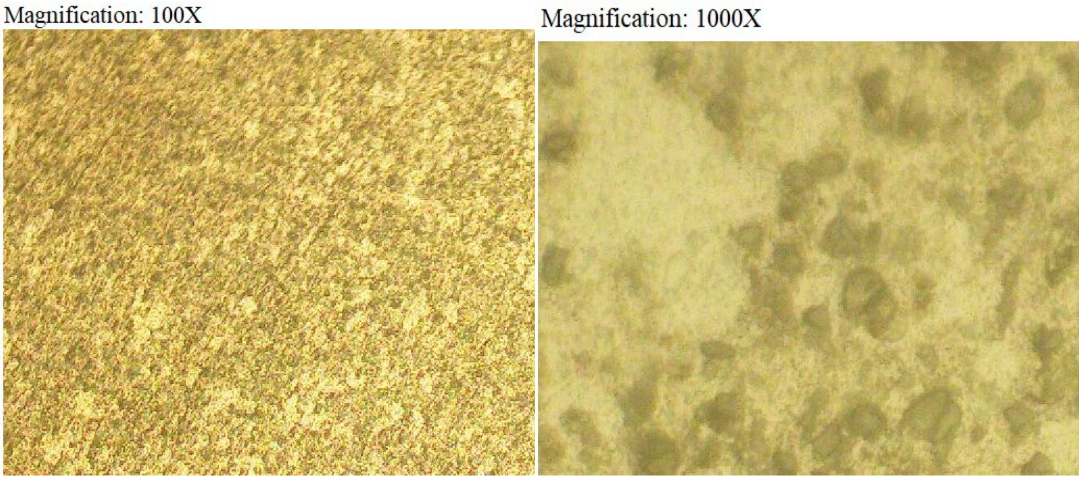


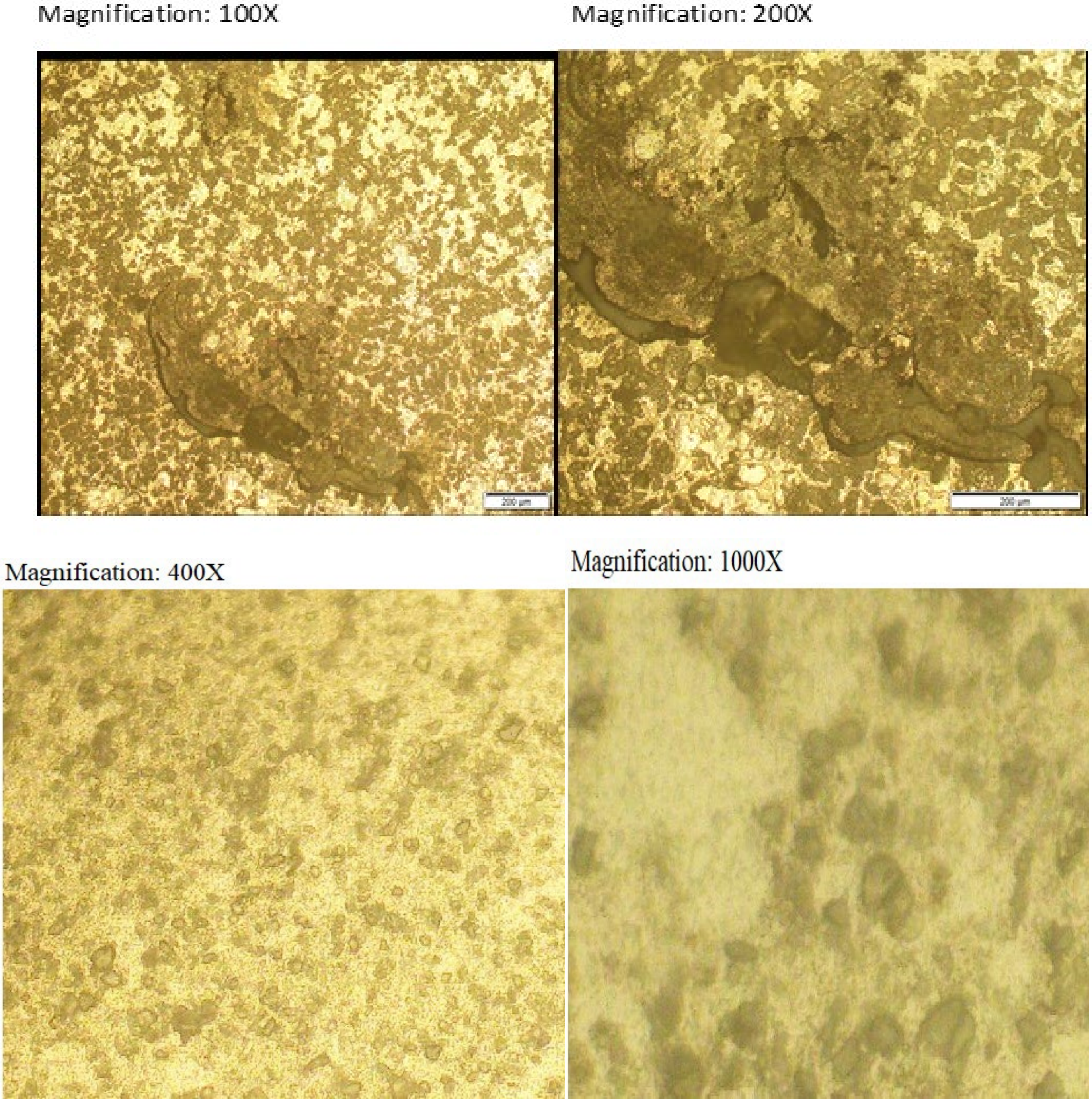
Fig. 3 - X-ray images of A-Zro2 particles taken using a scanning electron microscope

An optical microscope was used to analyses the Al-Zn base alloy’s microstructure, FA/Al-Zn alloy/ZrO2 hybrid composites in varied reinforcing % as represented in Figure 3(a–c). The alloy’s microstructure is shown in Figure 3 (a) as an interdimeric network without vacancies. The Al-Zn/ ZrO_2/fly ash hybrid composite’s microstructures are shown in Figure 3(b and c). There is no indication of fracture development, indicating arbitrarily scattered secondary phase particles. This could be due to the inclusion of the necessary process parameters for casting manufacture.

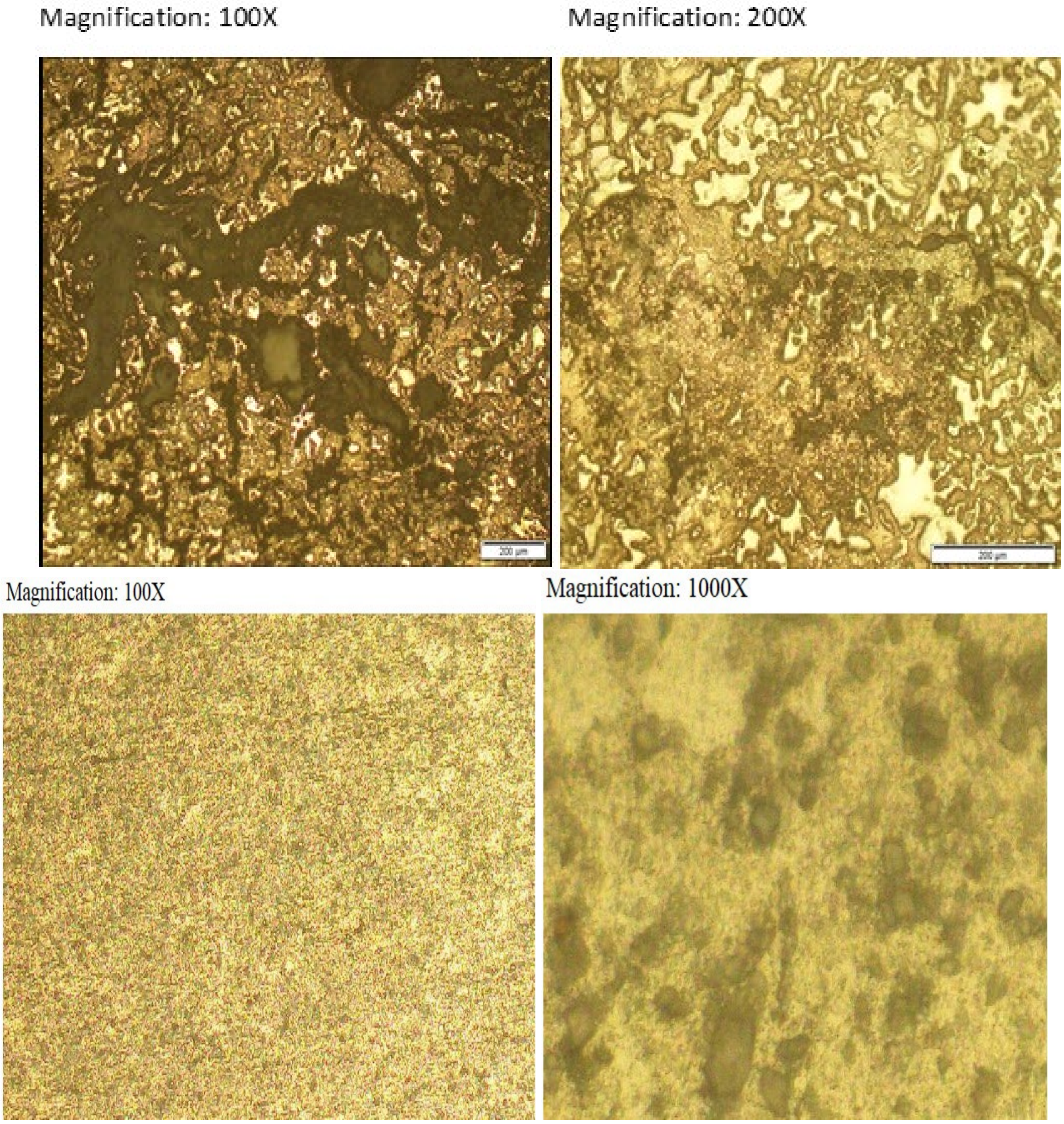




(a) The microstructure of the alloy was examined with magnifications of 100x, 200x, 400x, and 1000x.



(b) Microstructure of a 5 percent composite at 100x, 200x, 400x, and 1000x magnifications



(c) Microstructure of a 10 percent composite at 100x, 200x, 400x, and 1000x magnifications

Fig. 4 - Microstructure for alloys

Average values were used to explore the densities of basic alloys and composites and the density changes are reported in table 2, with a graphical illustration in Figure 5. When compared to the base alloy, the composite densities were identified to be lower, which could be because of the reduced density of FA. The Theoretical and actual densities are compared.

Table 2 - Densities of Al-Zn alloys and composites, both theoretical and measured

S.No	Composition of reinforcements	Theoretical Density (Rule of Mixture)	Theoretical Density (Archimedes Drainage method)	Measured Density (g/cm^3)
1	AZ91E	1.81	1.8	1.96
2	AZ91E + 2.5% Fly ash + 2.5% Zro2	1.88	1.76	1.64
3	AZ91E + 5% Zro2 + 5% Fly ash	1.96	1.74	1.69

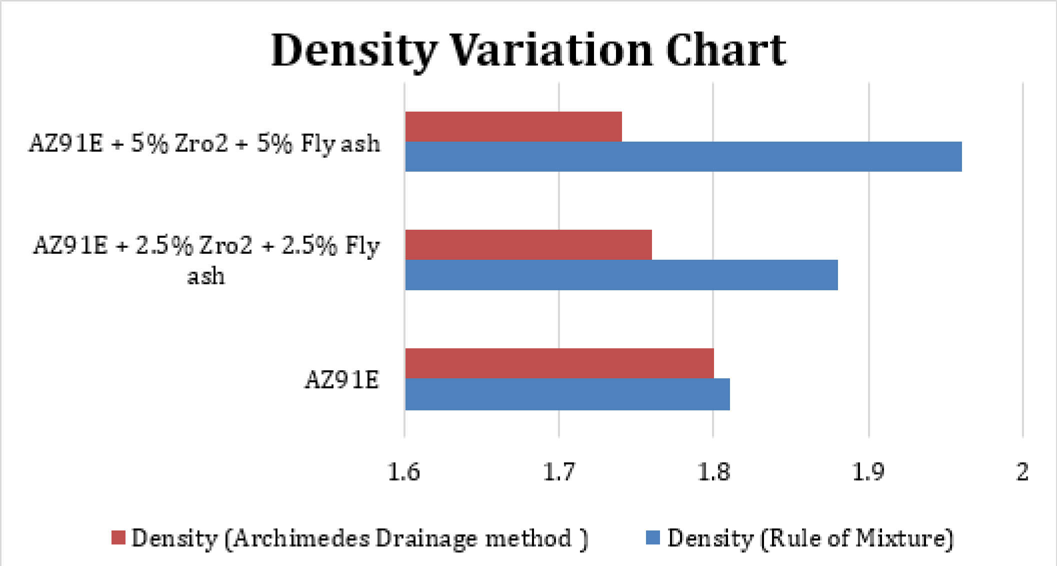


Fig. 5 - Variations in density graph

A micrograph exhibiting the indentation’s aspect is represented in Figure 6. To avoid the effects of particle segregation, an average of six measurements were recorded at various sites for each hardness value. For composites reinforced with FA and ZrO2, the Vickers hardness number was established to be greater when base matrix is compared with it. The presence of stiff, strong ZrO2 and Al2O3 in the FA and zirconium dioxide may account for rise in hardness. One of the reasons for the hardness increase is the refining of grain size. Several writers found similar findings. A material's hardness is a physical property that indicates its capacity to withstand local plastic deformation. The hardness of the Al-Zn (AZ91E) alloy was enhanced from 102 VHN to 120 and 125 VHN for composite 1(with 5%) and composite 2 (with 10%) as illustrated in Figure 7. This might be owing to the occurrence of hard ZrO_2 particles as well as the existence of FA particulates, which contain bulk zirconium dioxide and alumina both of which are hard in nature.

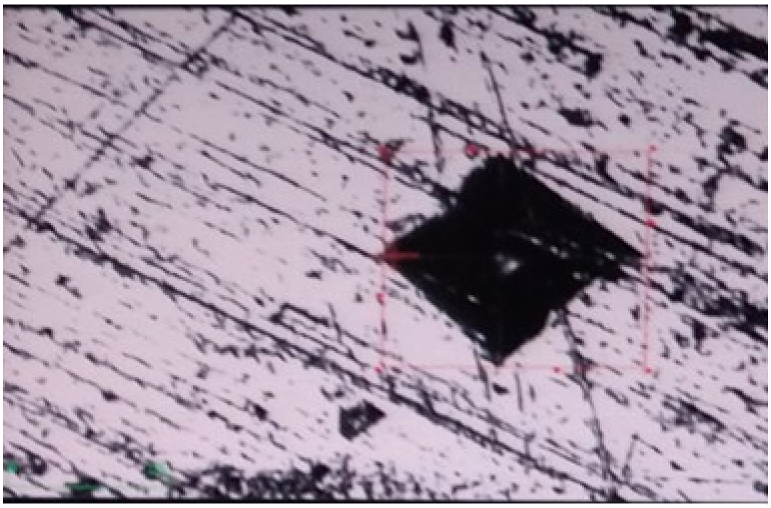


Fig. 6 - Micrograph demonstrating the indentation's aspect

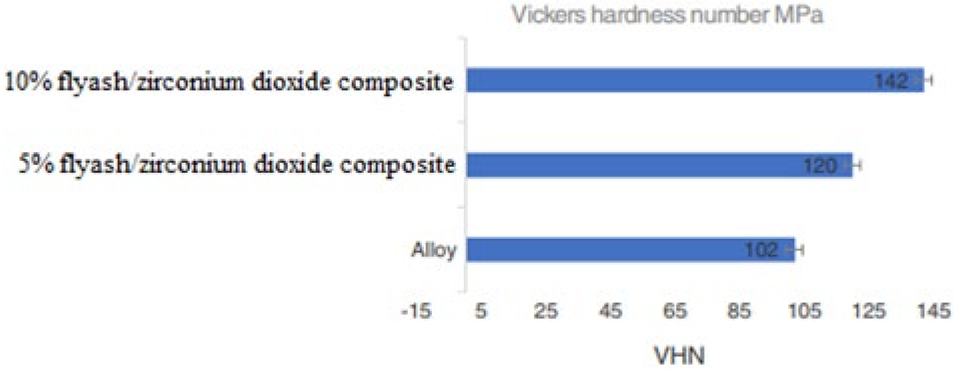


Fig. 7 - Hardness as a factor of reinforcement content

4. Conclusion

The vortex approach was effective in producing hybrid metal matrix composites with light weight. In an Al-Zn (AZ91E) alloy matrix, FA and ZrO2 particles were assorted in equal amounts and reinforced equally. Microstructures demonstrate a constant distribution of FA and ZrO2 particles, with no voids or discontinuities visible in the matrix or composites. Since inert gas was used throughout the casting process, no oxygen peaks or other impurities were found in the matrix or composites. The composite densities were found to be lower than the basic alloy, which could be due to the fly ash's low density. Theoretical densities and actual densities were compared. For composites reinforced with FA and ZrO2, the Vickers hardness number was established to be greater when base matrix is compared with it. The presence of stiff, strong ZrO2 and Al2O3 in the FA and zirconium dioxide may account for rise in hardness. In comparison to the basic alloy, the ultimate yield and tensile strengths rose as ZrO2 and fly ash reinforcements were added.

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