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Research Article

Experimental Investigation on A356.1 Aluminum Composite Reinforced with Zirconia Nano Metal Matrix Composites Fabricated via Stir Casting Technique

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Abstract:
Aluminum amalgams are used in self-impelled productions because of their longevity strength and mechanical behavior, alloys of aluminum have numerous interests while used in engineering determinations, in spite of their better formability and malleability, low density, high electrical and thermal comductivity. In this work, ZrO_2 Nanoparticles with particle size of 50nm reinforced A356.1 aluminum alloy, Nano Metal Matrix Composite were prepared through liquid state casting i.e. stir casting method with varying weight proportion ratios of 1.0, 2.0, 3.0, and 4.0% at a constant speed of 100rpm for 30 minutes. Fabricated Nano Aluminum metal were characterized using Powder X-ray Diffraction (PXRD), Energy Dispersive X-ray Analysis (EDX) and Scanning Electron Microscope (SEM) which showed their distribution of surface structure, crystalline phase and elemental compositions. Hardness tests were carried on Brinell hardness, tensile tests were carried on electronic tensometer and also tribological behavior of fabricated material was conducted by computerized pin on disc wear testing apparatus. As the reinforcement wt. % percentage increases, more load is transferred to these strong reinforcing elements, resulting in higher hardness and tensile strength for the composite. Results revealed that the NMMCs with 4.0 % reinforcement exhibit superior mechanical and tribological properties.

Keywords: *NMMCs, Stir casting, Characterization, Hardness, UTS, Wear rate*

1. Introduction

The engineering community and material scientists are paying more attention to the transition from monolithic to composite materials as a result of the advancements made in the production of lighter, more environmentally friendly, and more functional appliances. A composite material is made up of two or more macro, micro or nano elements that are largely insoluble in one another and vary in chemical composition and structure, with an interface separating them [1-3]. It includes two components, including a reinforcement matrix. The continuous phase or component known as matrix and the discrete or discontinuous component known as reinforcement. Composites are categorized into three groups on the basis of matrix i.e. metal matrix composites, ceramic matrix composites, and polymer matrix composites. Composites of metal matrix offer a number of desirable properties, including wear resistance, good

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abrasion resistance and elevated temperature behavior in addition to high specific modulus and strength. Due to its better mechanical and tribological qualities, composites are often employed in automobiles, trades, and the aerospace industry.

From their inception to the present, MMCs have occupied a notable position in high-tech research and applications, and they have demonstrated significant promise in the aerospace, electronic instruments, automotive, military, and other industries. The primary characteristic of MMC that sets it apart from other materials is its ability to be customized to meet specific needs [4]. Aluminum is a material that is very significant in these composites due its stiffness, high strength, ductility, low density and low cost. Nano-composite materials have recently come into use as viable alternatives to alleviate the drawbacks of monolithic-composites and micro composites, as well posing research difficulties correlated to the control of fundamental stoichiometry and arrangement in the phase of nano cluster. In comparison to monolithic materials, Nano composites also improve better properties. To obtain the expected effect of strengthen, elements of reinforcement remains stiffer and stronger than the matrix. To attain the required qualities, though, the reinforcement's material, size, type and volume proportion, as well as their interaction with the matrix must be taken in account. The most attractive ceramic reinforcements with strong thermal stability include oxides, carbides, nitrides, borides and alumina, such as Al_2O_3, ZnO, Gr, SiC and ZrO_2. ZrO_2 is the best, cheapest, and very readily available less density strengthening reinforcement when different dispersions are utilized by the matrix because of hardness, high toughness, low thermal conductivity, and phase transformation toughening. Tensile and hardness values have significantly changed, and the composite's density has decreased. Any of these values can be used to increase the proportion of base metal weight that is made up of zirconium dioxide particles, or reinforcement [5] Because stable reinforcement particles formed in the composites, aluminumMMCs showed excellent mechanical and wear characteristics [6] ZrO_2 and nanographene particles in the aluminumalloy were successfully used to create hybrid composites using a liquid metallurgy course [7]. From their early stages to their advanced stages, composites have undergone constant development. Because metal matrix composites (MMCs) have so many uses, their demand and consumption are growing steadily on a global scale. There is a persistent need in industries to develop lighter, stronger materials with excellent performance and efficiency in a range of industries [4]. Brittle and hard ceramic particles found in the aluminum alloy matrix were blamed for the decrease in elongation. For samples with 5% ZrO_2, the compressive test increased by 23% when compared with unreinforced sample [8]. Impacts of mono metallic ZrO_2 particles at the nanoscale on the tribological and mechanical performance of aluminum alloys. The function of zirconia nanoparticles as reinforcements and aluminum alloys as the base matrix is crucial [9]. The impact of ZrO_2 concentration on the wear and hardness properties of composites made of Al7075, increasing behavior in the mechanical behavior of the composites [10]. Aluminum is a prominent material due to its low density and high stiffness. Numerous series have been created to address the upcoming challenges of modern life. Because of their unique properties, aluminum-based composite materials are important components in many industries, particularly the automotive and aeronautical sectors [11]. Tensile and compressive strength mechanical analyses were performed for each of different ZrO_2 weight proportions [12].

The utilization of Aluminum 356.1 reinforced with zirconium oxide nanoparticles has great motivation and potential benefits for the fields of materials science and engineering. Advanced materials with better performance for structural, automotive, and aerospace applications are in greater demand. This need is satisfied and material science frontiers are pushed by studying the reinforcing of aluminum alloys with nanoparticles.

2. Experimental Setup

Aluminum 356.1 with atomic number 13, atomic weight 26.8, FCC crystal structure, 2.67 g/cm^3 density was chosen as the matrix material because of density, excellent resistance to corrosion, better mechanical properties. Due to itsdensity, wettability, and reactivity in conjunction with the matrix material ZrO_2 Nano with a particle size of 50nm with a range of 30-50 nm Nanoparticles have an elevated ratio of surface area to volume in contrast to larger particles. This increased surface area enhances their reactivity and makes them suitable for applications such as catalysis, adsorption, and sensing, cubic crystal structure which are obtained above the 2370°C temperature with 5.89 g/cm^3 was chosen as reinforcement material. It reveals high strength, high hardness which increases its resistance to abrasion and wear. The performance of ZrO_2 in different applications may be influenced by its crystalline structure and phase composition.

2.1 Fabrication Process

A356.1and ZrO_2 chemical composition and elemental composition is displayed in Tables 1, 2 and 3.

Table 1: Aluminum 356.1 Chemical Composition

Constituent	Aluminum	Silicon	Magnesium	Iron	Copper	Zinc	Nickel	Manganese
Weight %	91.7	7.2	0.38	0.32	0.18	0.05	0.05	0.02

Table 2: ZrO_2 Chemical Composition

Constituent	ZrO_2	SiO_2	TiO_2	FeO_3	Other
Weight %	99.5	0.10	0.007	0.002	0.39

Table 3: Elemental Composition of EDX

Elements	Weight (%)	Atomic (%)	Error (%)	K Ratio
OK	6.11	9.11	11.85	0.0365
AlK	93.69	90.04	2.92	0.9181
ZrL	0.19	0.05	14.81	0.0012

(a) (b) (c)

Fig. 1. (a) Metal Melting furnace and stirrer (b) Molten metal poured into mold cavity (c) Casted material

From commercially available Aluminum 356.1, the composites are prepared, Nano particles of ZrO_2 are reinforced with A356.1. The Nano powder's size of the particle was found to be an average of 30-50nm respectively. ZrO_2 nanoparticles are typically 50 nm in size to balance mechanical, thermal, and optical properties, as well as ease of manufacturing and processing. The heated three phase electric resistance furnace is fundamentally used for the composite preparation. The furnace temperature range is about 1200℃ to 1500℃, with an accuracy control of ± 5℃ fixed with partially integrated differential digital temperature controller and seven segmented light emitting diode. The furnace's shooting capacity is 500℃ per hour. Crucible is made of graphite is placed in middle of the furnace. Stir casting technique was used to prepare composites with a 100 rpm speed of stirring and blades of stirrer is made of ceramic coating. At constant speed with a duration of stirring time about 20 to 30 min stirring process was carried out. The reinforcement variable weight percentage was 1.0wt, 2.0wt, 3.0wt and 4.0wt% to prepare the composites. Molten metal of composite was discharged into the pre heated cast iron cylindrical mould cavity of 170 mm height and 12mm diameter as shown in Fig. 1. Then the fabricated NMMCs was machined as per the American Society for Testing and Materials (ASTM) standards for tensile ASTM E8, Hardness ASTM E10 and wear test ASTM G99.

3. Outcomes

3.1 Characterization

3.1.1 PXRD

Powder X-ray diffraction (PXRD) is used to examine the structure of crystals of various materials. Usually, the material to be examined is finely powdered. This guarantees that a huge number of crystallites will be inter acting with the X-rays as they penetrate the sample. The powdered sample is the focus of the X-ray beam. The Wavelength of these X-rays is on the order of Angstroms (10^-10 meters), which is equivalent to the atomic spacing in a crystal lattice. The crystal lattice in the sample causes X-rays to be diffracted when they hit it. The type of atoms in the lattice and the distance between the crystal planes determine the angle and intensity of the diffracted X-rays. X-ray diffraction of powdered samples was conducted through Rigaku Miniflex 600 model. The crystalline phase of the Nano-ZrO_2 powder is confirmed by the diffraction of X-ray arrangement, furthermore reveals the crystal size. It is decides the measured peak view. Peaks occurs by inter planing spacing. In this observation, for angles of 38.66°, 44.91° and 65° peaks were obtained with heights i.e 8389, 3592 and 2282 of peaks 2, 3 and 4 correspondingly. The more intense familiar peaks indicate that the products should have longer crystalline lives. The absence of impurity-related peaks demonstrates that the finished product is only ZrO_2 Nano powder as shown in Fig. 2.

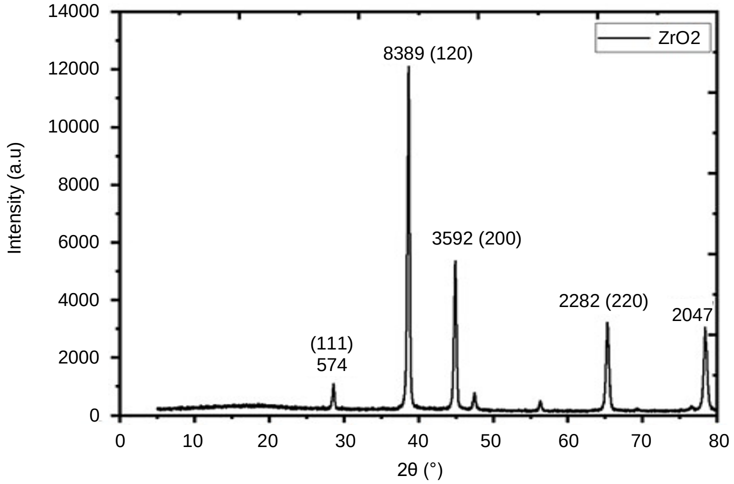

Fig. 2. PXRD of ZrO_2

3.1.2 EDX

An Energy Dispersive X-Ray (EDX) on a composite material showed that Zirconium and oxygen emanation vitality pinnacles are visible in the analysis of the EDX peaks, and this connects to the ZrO_2 support. Al, Zr, and O elements, carbon peak level are present in the Aluminum 356.1 fabricated composite, according to the analysis. ZrO_2 scatter uniformly in the aluminum framework material, as can be seen by analyzing the composite's elemental composition analysis as shown in Fig. 3. The uniform scattering of ZrO_2 within the matrix of aluminium maintains consistent mechanical properties including stiffness, strength, wear and corrosive resistance.

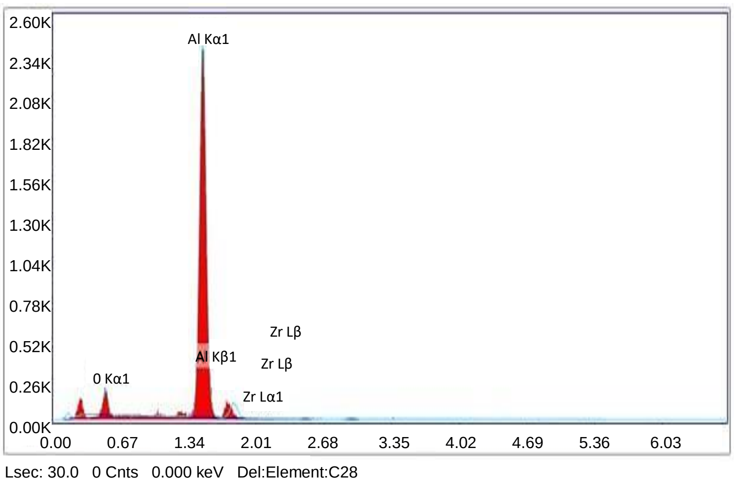

Fig. 3. EDX of ZrO_2

3.1.3 SEM

The powders were characterized for their microstructure and distribution of ZrO_2 nano particles in Aluminum 356.1 matrix using JEOL JSMIJ300LV. The main purpose of this investigation was to confirm that homogeneous distribution of ZrO_2 in Al 356.1 matrix after stir casting. Uniform reinforcement distribution may lead to improved mechanical properties in composites. A356.1 reinforced with ZrO_2 for different weight proportion ratios of SEM images as shown in Fig. 4. ZrO_2 nanoparticles are clearly visible embedded in the aluminum alloy matrix's grains, which indicates that the structure is getting closer together and the grains are getting more compact. SEM image shows a few cavities in the structure in as cast A356.1 aluminum alloy, randomly distribution of Nano particles in the reinforced ZrO_2 Nano metal matrix composites are seen. In case of a lesser wt%.of reinforcement, ZrO_2 Nano particle's small agglomerations is noticeable with white particles as depicted in Fig. 4(a). The SEM images determines that the samples have a uniform assembly and accomplish well at less than 1.0% reinforcement rate. ZrO_2 Nano particle's agglomerations occurs often in the alloys of aluminium, at higher wt% ratio (3.0 and 4.0%) the particles are not evenly allocated as shown in the images. The agglomeration and uneven distribution of Nano particles in A356.1 results in density variations. Identical examination of SEM micrographs were made for other samples comprising varying wt% of Aluminium 356.1 allo with ZrO_2 reinforced Nano particles. Fig. 4(e) depicts SEM micrographs of 4.0wt% Aluminum 356.1 alloy with ZrO_2 nanoparticles at higher magnification.

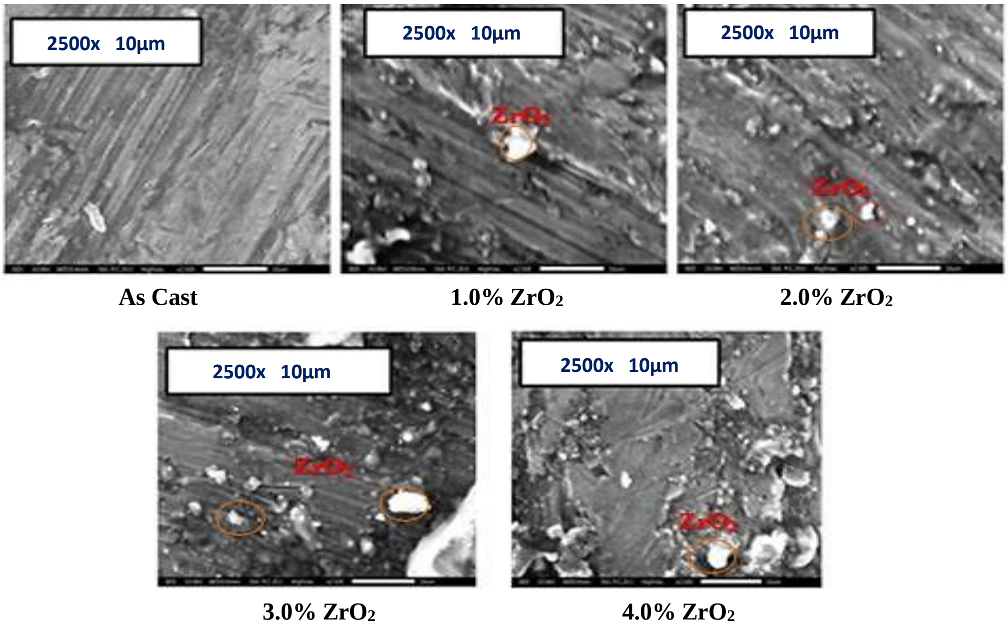

Fig. 4. SEM images of Aluminum 356.1 Reinforced with ZrO_2 Nanoparticles

3.2 Hardness Test

Brinell hardness test with ball indentation performed on NMMCs samples. The load applied during the hardness test is a critical parameter that influences the depth or size of the indentation produced on the material's surface. Tests indicated that as the 4.0% reinforcement increases, matrix hardness increases. Outcomes demonstrate that as the reinforcement weight percentage ratio increases hardness increases significantly because of the presence of ZrO_2 Hardness for as cast is 50.23BHN and for 4.0% hardness is 71.23BHN. The main reason for this is the existence of tougher ZrO_2 Nanoparticles, whose smaller grain size and presence offer an improved limitation on confined deformation during indentation. The findings show that the mechanical characteristics shown in Fig. 5.

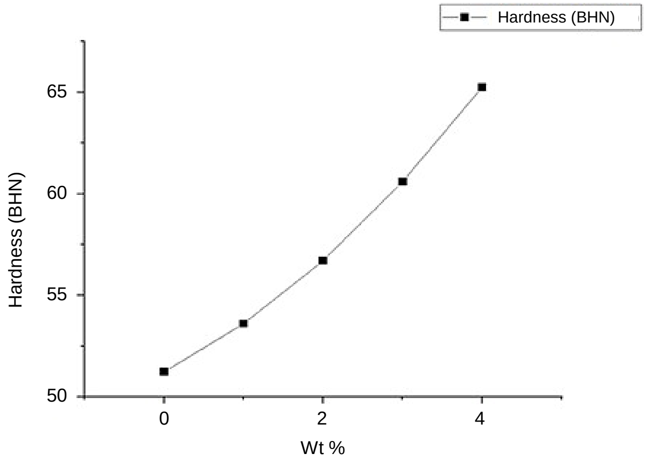

Fig. 5. Hardness vs. Reinforcement wt. %

3.3 Tensile Test

An electronic tensometer with MMT 2000 bench model of 20KN capacity, accuracy of ±0.05, motor speed of 1600rpm, displacement measurement of 0 to 500mm, displacement least count 0.1mm standard with PC 0.1mm with software is used to perform tensile tests on materials as shown in Fig. 6. As per American society for testing and materials (ASTM) E8 standard specimens were prepared, mount the specimen on the electronic tensometer holder, enter the initial data as required, start the machine, and enter the readings after obtaining the weak point material breakdown and noting the final data.

Fig. 7 shows the specimen dimensions which are required for testing. Fig. 8 displays testing specimens that were breaked down after testing.

Fig. 6. Tensometer

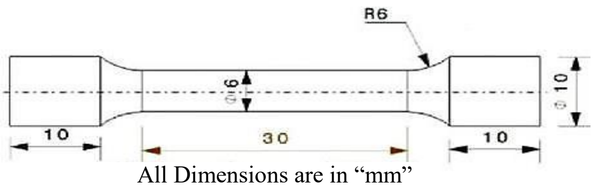

Fig. 7. Specimen Dimensions

Fig. 8. Tested Specimens at Different wt. % Ratios

Fig. 9 shows the tensile strength variant of ZrO_2 nanoparticle reinforced with A356.1 for varying wt% ratios. At 4.0% weight ratio the ultimate tensile strength is 337.54MPa, for as cast A356.1 the ultimate tensile strength, or 215MPa, increasing as the percentage of reinforcement weight increases at load of 6680N.

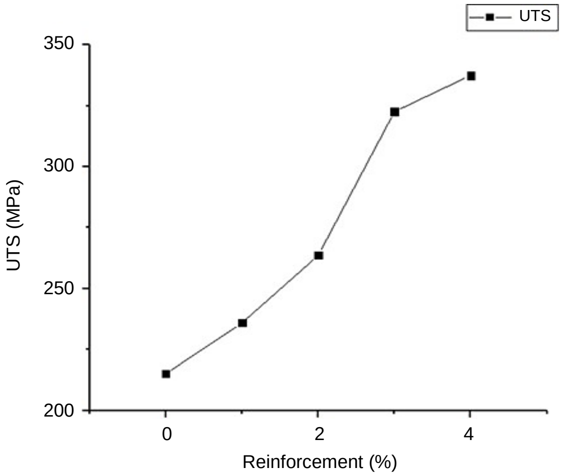

Fig. 9. UTS vs. Reinforcement wt. %

The reinforced ZrO_2 Nano particles with different wt% ratio and peak load modulation is showed in Fig. 10. It showed that the as the reinforcement weight percentage increases, peak load increases because peak load refers to the maximum load that the material can withstand before failure. The peak load helps to assess the effectiveness of reinforcements of materials. A higher peak load often indicates that the Nano-reinforcements are well-distributed and effectively contributing to load-bearing.

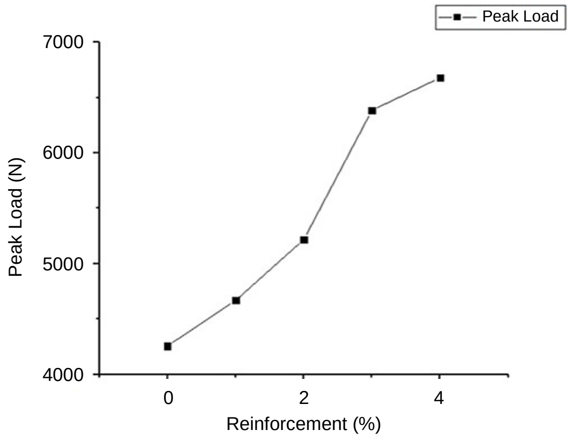

Fig. 10. Peak load vs. Reinforcement wt. %

Fig. 11 shows stress and strain of aluminum 356.1 reinforced with ZrO_2 with various percentage ratio such as 1.0%, 2.0%, 3.0% and 4.0%. It shows that the strain increases stress will increase. It is clear that, at 0.05 stress is 215MPa as the weight percentage ratio increased, the stress also increases upto 355MPa at 0.10 because of the linear relationship, stress rises with strain inside the elastic portion of a material's behaviour. This is a reflection of the material's natural resistance to deformation, which increases with applied strain.

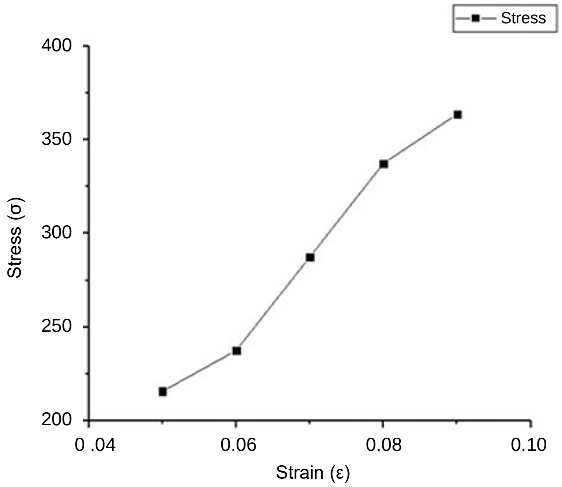

Fig. 11. Stress vs. Strain

3.4 Wear Test

Wear and friction test was carried out by using computerized pin on disc apparatus as per the ASTM standard G99 as shown in Fig. 12.

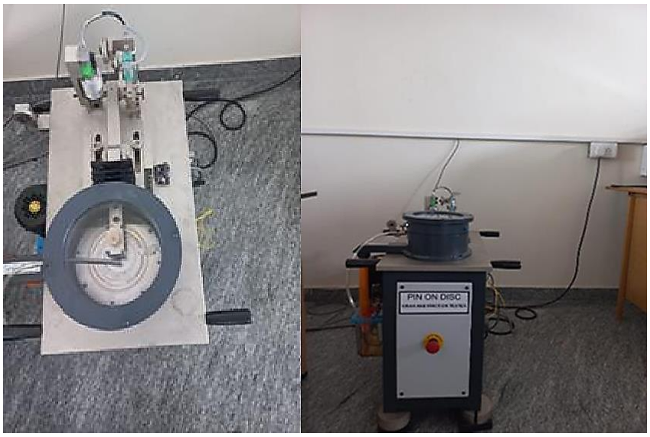

Fig. 12. Pin on Disc Apparatus

In the present work, as per the American society for testing and materials (ASTM) G99 standard specimens were prepared with dimension of 8mm*30mm for different weight percentage ratio. This test simulates the contact and relative motion of two surfaces, one of which is a stationary pin and the other a rotating disc. The test measures wear rate and frictional force as the pin is pressed against the rotating disc under controlled conditions, such as a specific load, speed, and environment. When the disc rotates non-edible vegetable oil i.e pongamia oil is circulated through drop by drop with viscosity of 40cst and density of 0.924 g/cm^3. At the contact zone of the pin on disc, load of 10N, 20N, 30N and 40N is applied. The disc is rotated at 100, 200, 300, and 400 rpm for duration of 300, 600, 900 and 1200 seconds. For every 5 minutes i.e. 300 seconds the wear and frictional force are recorded. In the data acquisition system observations are noted down. Results showed that as the increase in test parameters like load, time and speed wear decreases due to a higher loads, fine debris particles form to participate in the tribo-layer formed on the rubbing surfaces as shown in Figs.13, 14 and 15.

3.5 Effect of Wear Rate on Load

Fig. 13 shows when load at 10N the wear rate is 26.47X10-6 g/m for as cast A356.1 alloy, and for the same load 4.0wt% of ZrO_2 Nano particle added to alloy shows a decrease of wear rate to 2.01X10-6 g/m. This reveals that addition of ZrO_2 Nano particle in to the base material reduces the wear rate gradually, thus ZrO_2 Nano particles play a significant role as reinforcement in the developed composites. As reinforcement content increases, the wear rate decreases due to presence of ZrO_2 hard Nano particle in the Aluminum 356.1 alloy.

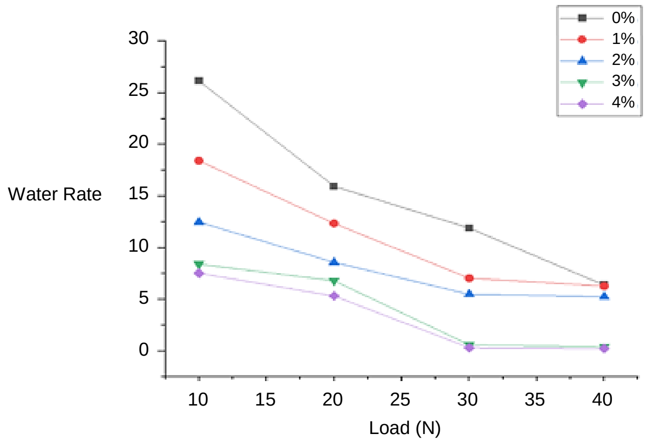

Fig. 13. Wear vs Load (Speed 100 rpm and test duration 300 Sec)

3.6 Effect of Wear Rate on Speed

From the Fig. 14 it is observed when the speed of 100rpm, the wear rate is 26.16X10-6g/m for as cast A356.1 alloy and for the same speed wear rate is 7.52X10-6g/m for A356.1 alloy with 4.0Wt% reinforcement. As the speed increases from 100rpm to 400 rpm wear rate also increase gradually. Graph shows that at 400rpm the wear rate is 12.37X10-6g/m and 3.23X10-6g/m for as cast and 4.0 Wt% reinforcement respectively.

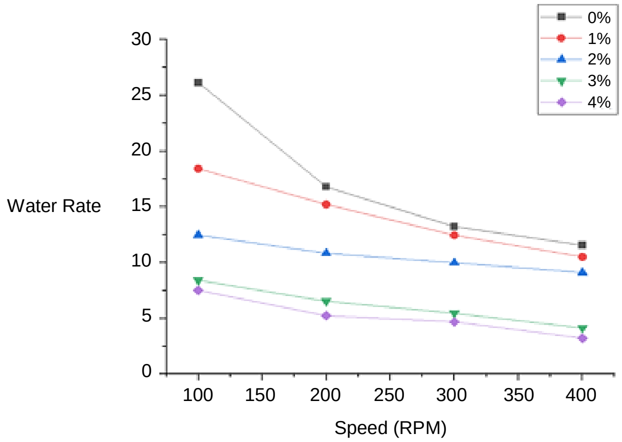

Fig. 14. Wear vs. Speed (Load 10 N and test duration 300 Sec)

3.7 Effect of Wear Rate on Time

From the Fig. 15 it is clear that at 300 secs, the wear rate is 26.16x10-6g/m for alloy without reinforcement and for the same time duration the wear rate decreases to 7.52x10-6g/m for 4.0 wt% reinforcement. Similarly when the test duration is 1200 sec, the wear rate is 13.23 x10-6 g/m and 4.69x10-6g/m respectively.

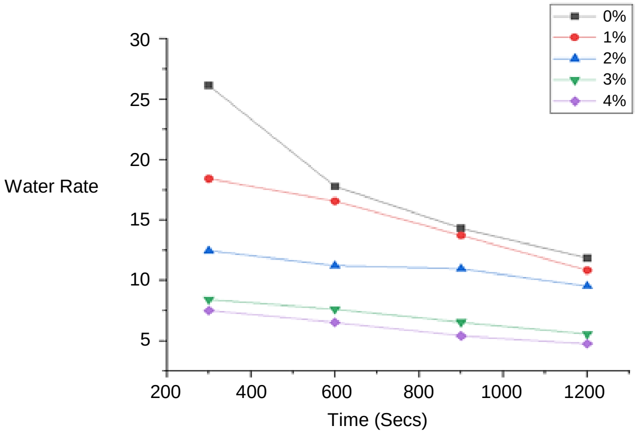

Fig. 15. Wear vs. Time (Load 10 N and speed 100rpm)

4. Conclusion

In the present investigation Zirconium oxide Nano particle were effectively reinforced with A356.1 aluminium alloy through Stir casting method with 100 rpm stirring speed and 30 min constant stirring rate at a constant temperature 650℃ for varying weight percentage ratios. Prepared Zirconium Nano particle morphology was analyzed using PXRD, EDX and SEM and it shows Nano particles are in spherical shape, crystalline phase and elemental composition. SEM images of Nano metal matrix composites show Nano particles are well agglomerated random distribution. When compared to Aluminum 356.1 alloy hardness of the reinforced Nano composites exhibits higher hardness, with increasing the Nano particle's weight percentage ratio hardness is steadily increased, and from the data result reveals that reinforcement content shows increased of hardness for 4.0 Wt% compared to other reinforcements because of the maximum amount of Nano particles present in the Nano metal matrix composites. As the reinforcement increases the tensile strength was steadily increasing. Wear resistance of the composites with pongamia oil was reduced with different wt% ratio than that of the aluminum 356.1; when the amount of hard nanoparticles in the composite increases, the hard nanoparticles resist the abrasive's destructive effect and shield the surface. When compared to base alloy, 4.0Wt% reinforced ZrO_2 shows better wear resistance and enhances wear rate of 21%.

Nomenclature

NMMCs	Nano Metal Matrix Composites
PXRD	Powder X-Ray Diffraction Analysis
EDX	Energy Dispersive X-Ray Analysis
SEM	Scanning Electron Microscope
UTS	Ultimate Tensile Strength

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