



Research article

Investigation of physical, mechanical and tribological properties of Al6061–ZrO₂ nano-compositesG.B.Veeresh Kumar^{a,*}, R. Pramod^b, Ch Guna Sekhar^b, G.Pradeep Kumar^b, T. Bhanumurthy^b^a Department of Mechanical Engineering, National Institute of Technology - Andhra Pradesh, Tadepalligudem, Andhra Pradesh, India^b Department of Mechanical Engineering, Amrita School of Engineering, Bengaluru Campus, Amrita Vishwa Vidyapeetham, India

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ABSTRACT

The present investigation mainly concentrates on work done in order to explore physical, mechanical & tribological characteristics of Al6061 alloy reinforced with nano-sized zirconium dioxide particulates. Four casts of different percentages of reinforcement from 0 to 6 wt% in the steps of 2 are fabricated using liquid metallurgy technique (stir casting). The prepared composites later subjected to various physical, mechanical & wear tests and results were studied. The tests were carried out in accordance with the ASTM standards on the alloy and nano-composites. In the present investigation the physical and mechanical properties like density, hardness and tensile strength increased significantly with the increase in percentage of reinforcement in the matrix alloy, while the percentage elongation found to be decreased. The sliding wear tests were performed by using pin-on-disc the tribometer and results indicated that wear resistance of composites was higher. Of the four compositions, there were improved properties of composites with higher weight percent of reinforcement. Scanning Electron Microscope (SEM) micrographs was used after tensile testing to study fractured surfaces of specimens and wear morphology after wear testing. Overall the investigational outcomes are very interesting and motivates to do further more research.

1. Introduction

The Metal Matrix Composites (MMCs) were extensively used for various applications such as aircrafts, space shuttles and automobiles because of their improved properties. These characteristics include light weight, high rigidity, high strength, flexibility of design, high resistance to corrosion and crack. Composites can be used to replace other alloys such as cast iron and bronze due to the above-mentioned properties. Their unique properties are the reason for the need to develop more and more of new composite materials [1, 2]. The composites formed by adding earthen wear particulates as reinforcement possess high resistance to scratch and thus can be used as parts of a car engine such as cylinders, pistons, cylinder rings etc., [3]. Mostly Aluminum (Al) alloys were used as materials in automobile and aircraft industries owing to their excellent properties which comprise low density, good mechanical and thermal properties. Al matrix composites are candidate materials for dental prostheses, total joint arthroplasty, biomedical gadgets and cutting tools, owing to their strength, dimension accuracy, machinability and wear resistance [4]. Of all the Al alloys, Al6061 alloy has a lot of importance because of its exceptional properties. Al6061 alloy has been

widely used in aeronautical industries and construction field because of its high strength and corrosion resistance [5]. When subjected to high temperature conditions Al composites having ceramic reinforcement show outstanding properties. The sliding wear of Al6061-Aluminum Oxide (Al₂O₃) composites can be influenced by the hardness of the composite material [6]. Compared to all others MMCs, Al based MMCs have good mechanical properties [7]. The wear rate of Al6061-Titanium Dioxide composite depends on various parameters such as load, rpm, sliding distance and the amount of reinforcement [8]. Most of the machine breakdowns are due to component wear [9]. When Al6061–Al₂O₃ composite materials was made to undergo dry condition sliding wear testing, a very different mechanism was observed [10]. Applied load and temperature also affect wear rate of Al6061-Silicon Carbide (SiC) composite materials. Literatures suggests that the composites of Al6061–SiC will have lesser wear rates when applied load increases [11]. When wear tests on Al6061 alloy and short fiber saffil filled composites was performed, it was noted that they have increased wear resistance [12]. It was evident from publications that MMCs filled with 15% of SiC as reinforcement and fabricated through the powder metallurgy have shown good resistance to wear [13]. The parameters like sliding distance,

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microstructure, sliding velocity and applied load have greater effect on composites wear. For Al2219-SiC composites, wear and cracking resistance increased as load applied increased [14]. However, variables such as sliding wear reasons for composites highest wear loss when exposed to various speeds and applied loads [15]. Under dry sliding, there was shift in wear rate from slight to severe due to the increase in Al6061 temperature [16]. Research on the characteristics of Al6061-Albite and Al6061-Graphite (Gr) found that the characteristics such as elongation and strength improved with increase in proportion of Gr filler, whereas hardness decreased. Increased Albite proportion in Al6061-Albite composite has resulted in increased hardness and reduced ductility [17]. The primary goal of this job is to manufacture composites comprising alloy Al6061 reinforced with nano-sized zirconium dioxide (ZrO₂). It correspondingly involves inquiry of composites physical, mechanical & tribological studies through different trials.

2. Production & investigational particulars of MMCs

2.1. Matrix & reinforcement materials particulars

Fenfee Metallurgicals, Bangalore, India provided the matrix material Al6061 alloy in the form of ingots. The Table 1 below shows the Al6061 alloy details related to composition. The material chosen for reinforcement was nano-powder ZrO₂ and its size is 200 nm. Triveni chemicals, Gujarat and Sigma-Aldrich, India, from where the materials procured. The ZrO₂ nano-powder particulates used are irregular shaped. The Table 2 highlights the characteristics of both matrix and reinforcement materials.

2.2. Fabrication of Al6061-ZrO₂ MMCs

The liquid metallurgy route of fabrication is economical and allows composites manufacturing with uniform distribution. Liquid metallurgy method of casting was used to manufacture the composite. The Al6061 alloy ingots were placed in a furnace's crucible and heated to 710 °C. After alloy was obtained in the molten form, Magnesium chips as catalysts, Hexachloroethane as degassing tablets and Coverall were introduced to enhance wettability, eliminate gasses from molten alloy and form a thin layer between molten material and atmosphere respectively. The molten material was stirred by a graphite-coated steel stirrer at a steady velocity of 400 rpm. Now ZrO₂ nano powder has been wrapped in aluminum foils and preheated with a muffle furnace to 350 °C before being added to the vortex created by stirring and was achieved for 10 min towards guarantee the uniform reinforcement allocation. The molten material was then transmitted to a 150 mm long, 25 mm diameter cast iron mold box. By adding distinct percentages (0–6 percent) of ZrO₂ powder, four cast composites were achieved.

2.3. Experimental studies details

The cast Al6061-ZrO₂ composites acquired using stir casting was machined to the needed specifications in accordance with ASTM standard using lathe machine. The machined samples then used to investigate characteristics such as hardness, microstructure, density, tensile strength and dry condition wear. The density was discovered by means of rule of mixture and then values compared with those of practical values. To obtain microstructural pictures of samples, metallurgical microscope (NIKHON Japan model 150 ECLIPSE) was used. Hardness testing is performed using the hardness testing machine MRB 250 Brinell. A tensometer was used to detect specimen's tensile strength and percentage

Table 2

Al6061 and ZrO₂ materials properties.

Material	Hardness (HB500)	Density (g/cc)	Tensile Strength (MPa)
Al6061	30	2.7	115
ZrO ₂	5500 ^a	5.68	5200 ^b

^a Knoop Hardness, Kg/mm².

^b Compression Strength.

elongation. The tensile test samples were machined to the norms of ASTM E8 M15a. Ducom, Bangalore make a computerized pin-on-disc tribo-machine to discover wear of composites on three distinct applied loads such as 10 N, 20 N and 30 N. ASTM-G99 requirements were followed for this exam. The velocity of sliding remains continuous at 3.14 ms⁻¹. The size of the used cylindrical samples was 10 mm length and 10 mm diameter. The samples were produced to dry slide with a hardness of 60 HRC against EN31 steel counter disk. The 10 mm × 10 mm diameter and height composites, EN31 steel counter disk of 60 HRC hardness, were accepted. During each experiment, wear height loss was registered for each 30 s using a LVDT transducer of 1.0 μm precision for plotting charts between sliding distance and volumetric wear loss. EN31 steel disk was rotated at 500 rpm and 2.5 km sliding distance. To study the sort of wear and the type of fracture, the SEM pictures of the worn surfaces and the broken samples were considered.

3. Results and discussions

3.1. Density of Al6061-ZrO₂ MMCs

The theoretical densities for distinct compositions were calculated using mixture rule and weight to volume ratio was used to calculate practical densities. The bar graph shown in the Fig. 1 compared the theoretical and practical density values. It is apparent from the graph that theoretical density surpasses that of practical density. This may be due to casting deficiencies. However, in both cases, as percentage filler of ZrO₂ reinforcement increase, the density found to increase. This density rise is owing to the addition of strengthening of higher density (5.68 g/cc). From the figure it was clearly confirmed that density of MMCs was higher than the matrix material [18].

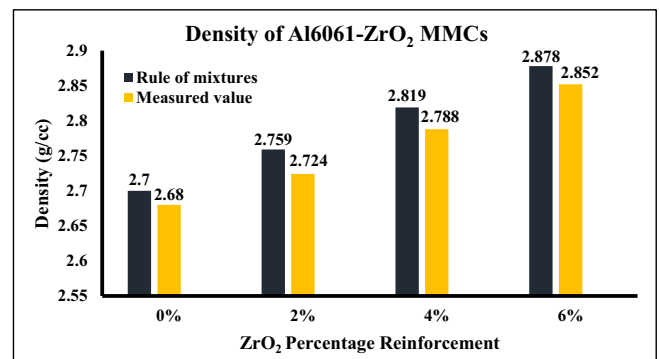


Fig. 1. Graph comparing weight-to-volume ratio and rule of mixtures density values of Al6061-ZrO₂ MMCs.

Table 1

Weight percentage chemical composition Al6061 alloy.

Chemical composition	Cu	Zn	Mn	Mg	Si	Fe	Cr	Ti	Al
Al6061	0.22	0.10	0.03	0.84	0.62	0.23	0.22	0.01	Bal

3.2. Microstructural images Al6061–ZrO₂ MMCs

Fig. 2 a-d, depict optical images of Al6061 alloy and ZrO₂ filled MMCs. From the images, one can infer from the images that the grain boundaries are in the form of dendrite regions. These dendrite regions represent that there is a uniform distribution of the reinforcements with minimum porosity and good bonding between the matrix and reinforcement materials. From the images it is also evident that off the four composites fabricated Al6061-6% ZrO₂ has more dendrite regions because of the presence of more amount of ZrO₂ reinforcements.

The Fig. 3, is presented with the fabricated Al6061-2 wt.% ZrO₂ composite material was subjected to study the elemental mapping using SEM of model RUSK microscope. The micrographs and corresponding elemental mapped images are presented in Fig. 3a, and it shows the presence of ZrO₂ reinforcement, few particulates are indicated with arrows in red colour in the Al6061 alloy. Fig. 3a shows the SEM image of the composite, Figs. 3b and 3c shows the elemental mapping images of the composites showing the presence of 'O' (green dots) and 'Zr' (blue dots) respectively. Hence with the help of density values, optical microscope and SEM images it is clear the fabrication of the Al6061–ZrO₂ reinforced MMCs was successful and also indicates at the suitability of the liquid metallurgy process.

3.3. Hardness of Al6061–ZrO₂ MMCs

The hardness of the composite was found using Brinell's hardness testing machine. The hardness was done based on ASTM E10-07a standards. A load of 250 N was applied for finding the hardness of the composites. Fig. 4 below shows that the increase in the hardness with the increase in the reinforcement percentage from 0% to 6%. It is apparent from the bar graph that the hardness of Al6061–ZrO₂ composite is higher compared to that of the matrix material alone. The increase in hardness property directly proportional to increase in density. Also, from it is evident from Fig. 4, that the hardness of the MMCs increased by 39.88% as reinforcement percentage raised from 0% to 6%.

3.4. Ultimate tensile strength of Al6061–ZrO₂ MMCs

The specimens for tension test was discovered using a tensometer. A lathe was used to machine the samples used for the tensile test to the necessary sizes. The tensile sample sizes were drawn in-line with norms of ASTM E8-M15a. The enhancement in tensile strength with rise in the reinforcement proportion is shown in Fig. 5. The test was conducted at room temperature and the findings were found to be comparable to the researchers' studies [19]. The Results of tensile test indicate that specimens' tensile strength improved by 47.13% with the rise in the reinforcement proportion varying from 0% to 6%. As a consequence of increased hardness and density, the increase in tensile strength also results. Also, the matrix has been toughened by the addition of ZrO₂ through transformation toughening.

Absence of temperature gradient and proper stirring helps in achieving refine and homogeneous structure via redistributing particle within metal matrix. The ultimate tensile strength, yield strength and hardness of composite increase with increased wt% of ZrO₂ particles evenly distributed in the matrix. Increased volume percentage of ZrO₂ particles will also impart brittleness which will reduce ductility due to the segregation of nanoparticles. So, it is very important to add optimum amount of ZrO₂ reinforcement particle so that composite will possess balanced mechanical and tribological properties.

3.5. Ductility of Al6061–ZrO₂ MMCs

With rising quantity of reinforcement, all the characteristics of the composite material gradually improve, but ductility decrease with rise in reinforcement. Fig. 6 demonstrates reduction in proportion of MMCs elongation as strengthening increased from 0% to 6%. This reduction in ductility is due to higher hardness. From the outcomes, it was found that the percentage elongation of the MMCs decreased by 50.2% as the proportion of strengthening rose from 0% to 6%. These findings were comparable to those of many researchers [20, 21].

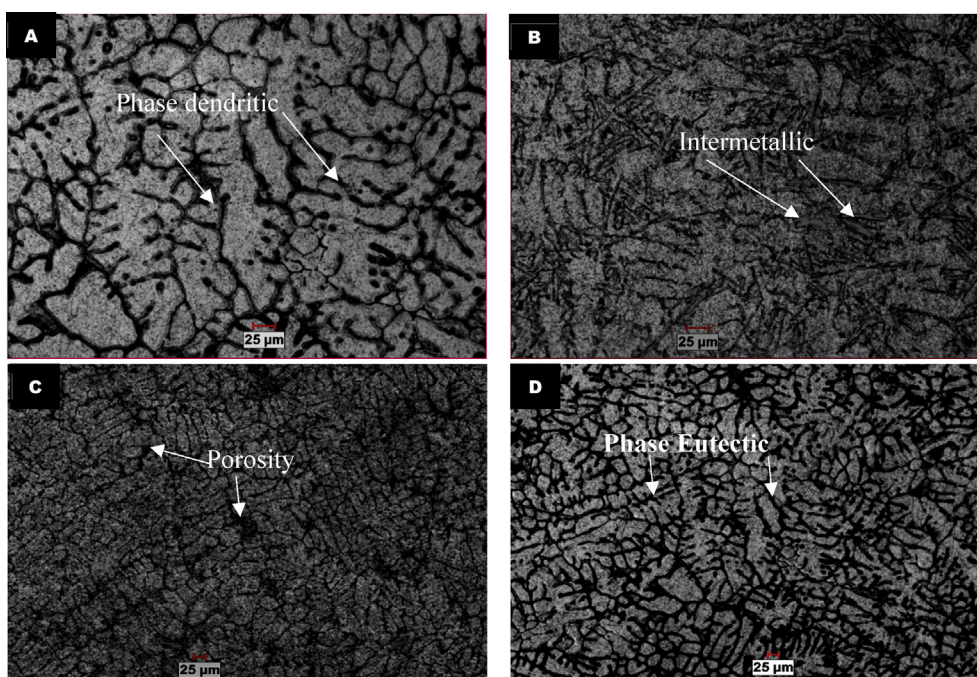


Fig. 2. Micrograph images of Al6061 a) Al6061 Base Alloy, b) Al6061-2% ZrO₂ MMCs, c) Al6061-4% ZrO₂ MMCs, d) Al6061-6%ZrO₂ MMCs.

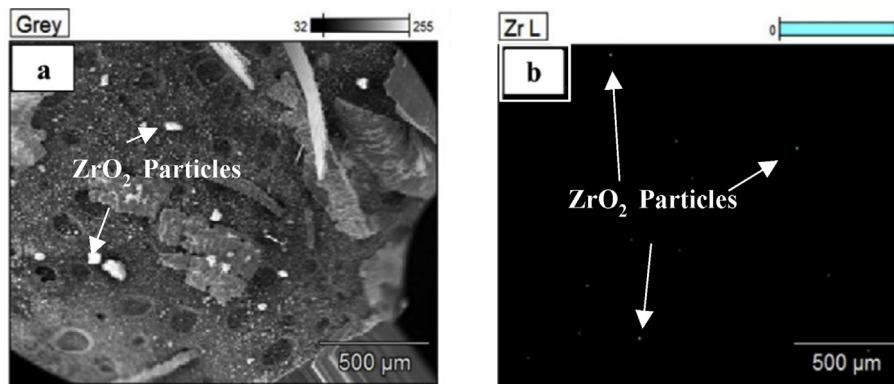


Fig. 3. Optical Micrographs of Al6061-2 wt.% ZrO₂ reinforced MMCs - a) SEM image, b) EDS Elemental Mapping.

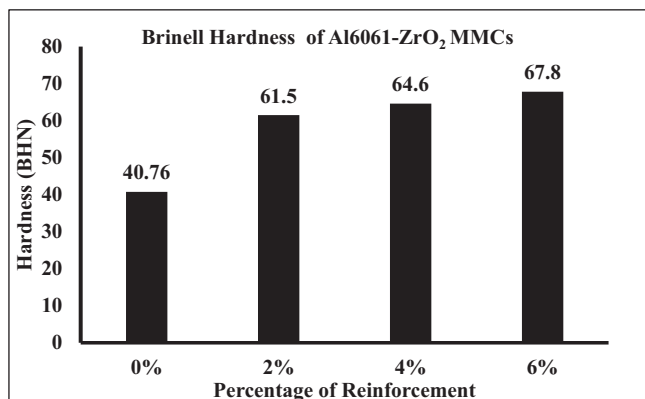


Fig. 4. Hardness of Al6061-ZrO₂ MMCs with increased reinforcement percentage.

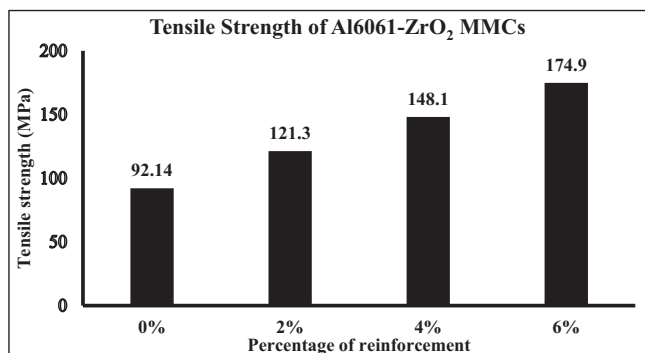


Fig. 5. Results of UTS on Al6061 and its ZrO₂ MMCs with rise in the percentage of reinforcement.

3.6. The dry condition sliding wear studies of Al6061-ZrO₂ MMCs

Al6061-ZrO₂ MMCs wear resistance were explored using pin-on-disc tribometer. Countless studies on Al MMCs have been performed to determine wear characteristics of composites and countless reports have been presented over previous 25 years concerning these. The dry sliding wear test is carried out at room temperature on the MMCs in this document. ASTM-G99 requirements were followed for this exam. The velocity of sliding maintained at 3.14 ms⁻¹.

The wear experiments outcomes were used to plot graphs between the volumetric wear loss and dry sliding distance when three distinct loads 10, 20 and 30 N were applied. Fig. 6a-d represent the volumetric wear loss that occurs when three distinct loads are applied at distinct sliding

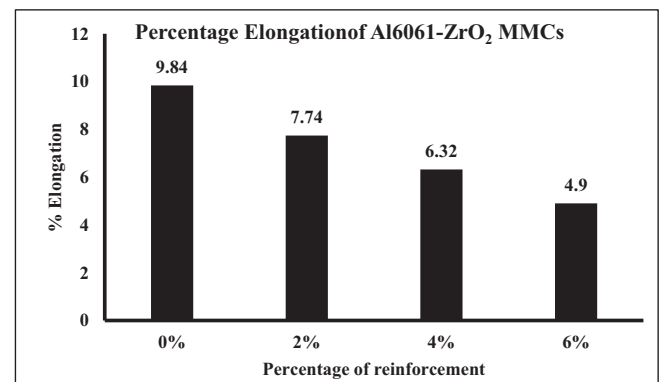


Fig. 6. Al6061 and its ZrO₂ MMCs percentage elongation with rise in percentage with increase in reinforcement.

range. It was found from the statistics that the volumetric wear improves as the sliding range rises. This is because there has been a shift in frictional force as the sliding range rises, which has led the MMCs to increase in temperature. As the temperature rose, the composite becomes softer and the loss of volumetric wear increased. In Fig. 7a, the volumetric wear loss gradually decreased with the increase in the amount of reinforcement upon application of 10 N load. This indicates that the hardness is increasing.

Similarly Figs. 7b and 7c represent the same for 20 N and 30 N loads respectively, as the hardness increases the resistance to wear also increases [22]. Load is a very important factor that decides wear rate of Al6061 and Al6061 based composites [23]. On comparing three graphs it was concluded that there will be an increase in the wear rate as the load was increased from 10 to 30 N. These enhanced wear properties of Al6061-ZrO₂ MMCs is due their increase in hardness on addition of reinforcement. The sliding wear under dry conditions of the composites obtained are in agreement with the with WC reinforcement Al6061 composites which displayed greater resistance to wear [24, 25].

Fig. 8 is shown with Al6061-ZrO₂ MMCs volume wear loss with ZrO₂ content rise. The volume wear loss of MMCs decreased from figure as the quantity of ZrO₂ filler in alloy increased. In contrast, MMCs showed wear loss decrease after the continuous phase. The increased strength provided to increased wear resistance of composites can be attributed to greater composite hardness values with the rise in ZrO₂.

3.7. Scanning Electron Microscope micrographs

Figs. 9, 10, and 11 illustrate the SEM images of the fracture surfaces of Al6061-ZrO₂ specimens. From all the figures below, we can infer that there is good bonding between the matrix material (Al6061 alloy) and the reinforcement (ZrO₂). From the Fig 9a and b below, represents the

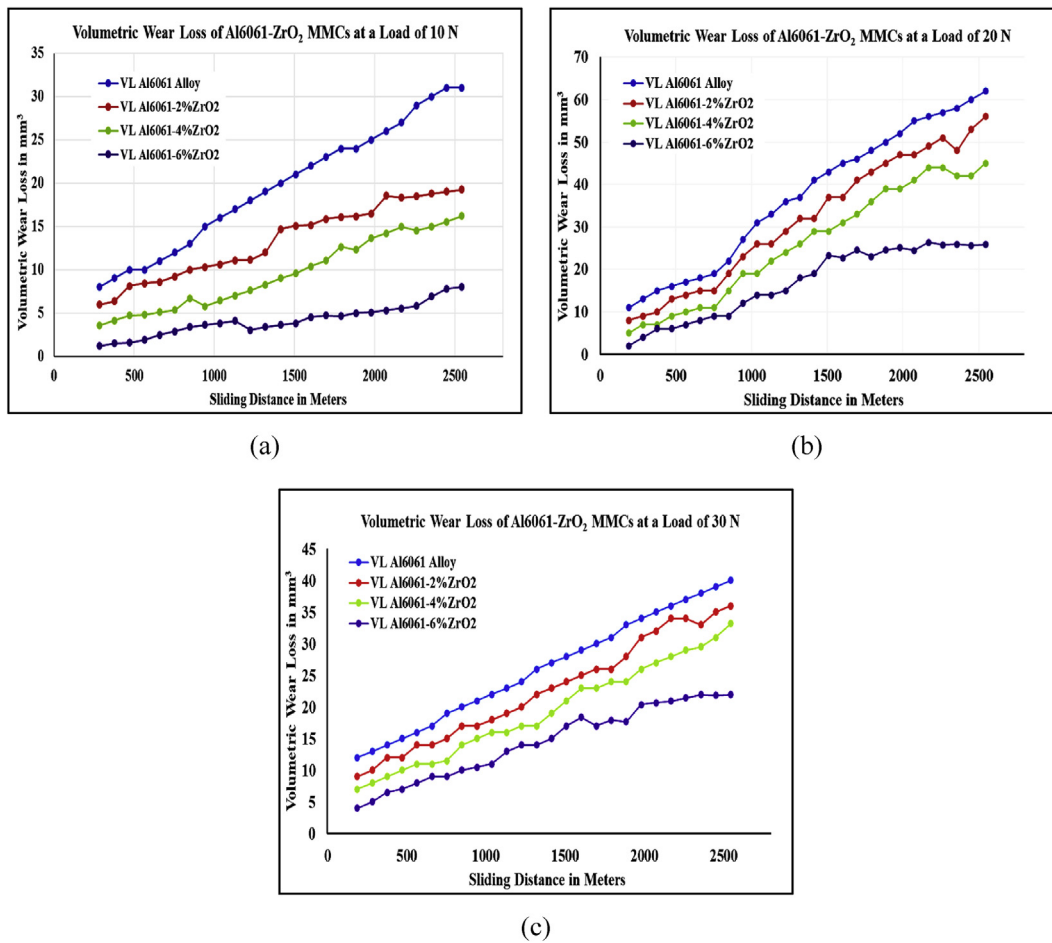


Fig. 7. Volumetric loss vs sliding distance graphs for (a) 10N load, (b) 20N load, (c) 30N load.

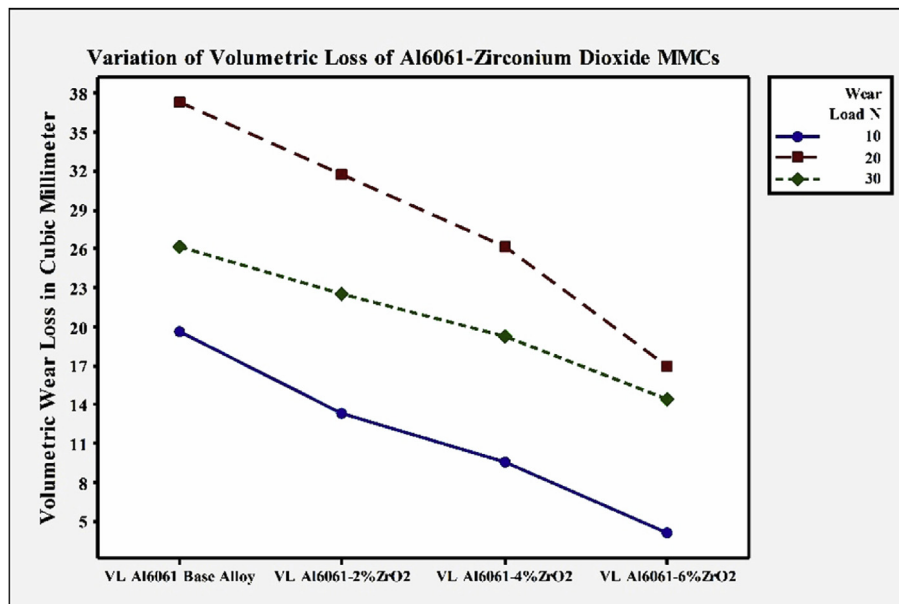


Fig. 8. Disparity in volume wear loss with rise in ZrO₂ filler in Al6061– ZrO₂ composites.

fractures surfaces of 500X magnification images of Al6061–2%ZrO₂ composite. The similar inferences were made to the remaining fractured surfaces. Further as the ZrO₂ reinforcement increased there is increased brittleness of the composites.

The SEM images of the specimens is taken after dry sliding them for a distance of 2.5 km with a constant speed of 500 rpm Fig. 12 a, b and c represents the SEM micrographs of Al6061-2% ZrO₂, Al6061-4% ZrO₂ and Al6061-6% ZrO₂ composites respectively. From the images it is clear

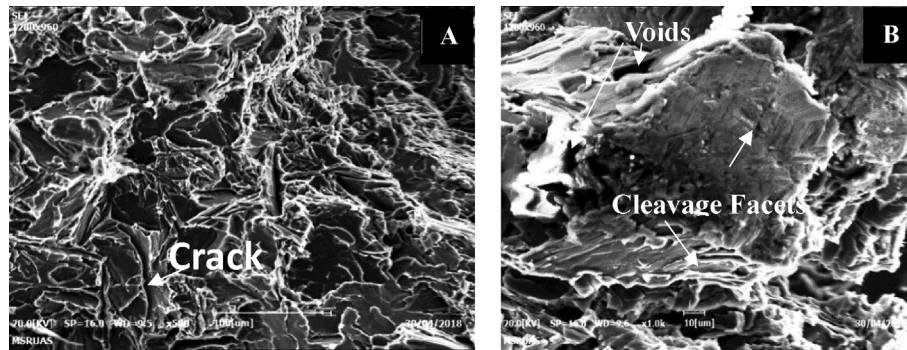


Fig. 9. Fracture surface of Al6061-2%ZrO₂ - a) 500x magnification, b) 1000X magnification.

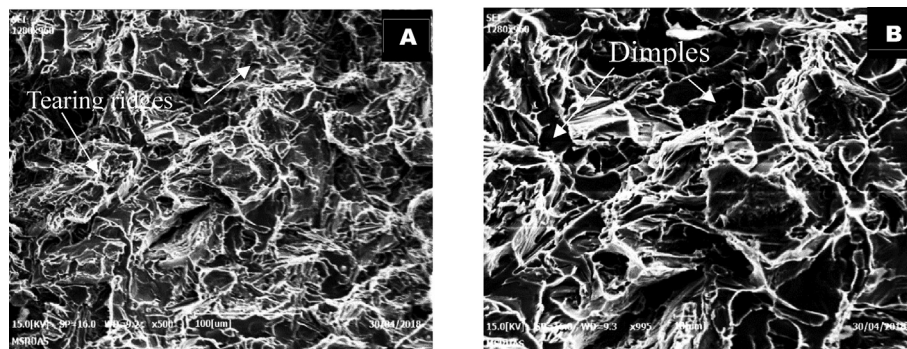


Fig. 10. Fracture surface of Al6061-4%ZrO₂ - a) 500x magnification, b) 1000X magnification.

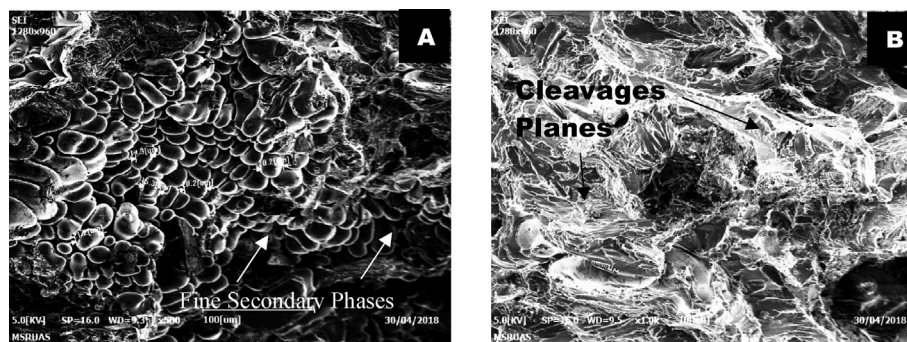


Fig. 11. Fracture surface of Al6061-6%ZrO₂ - a) 500x magnification, b) 1000X magnification.

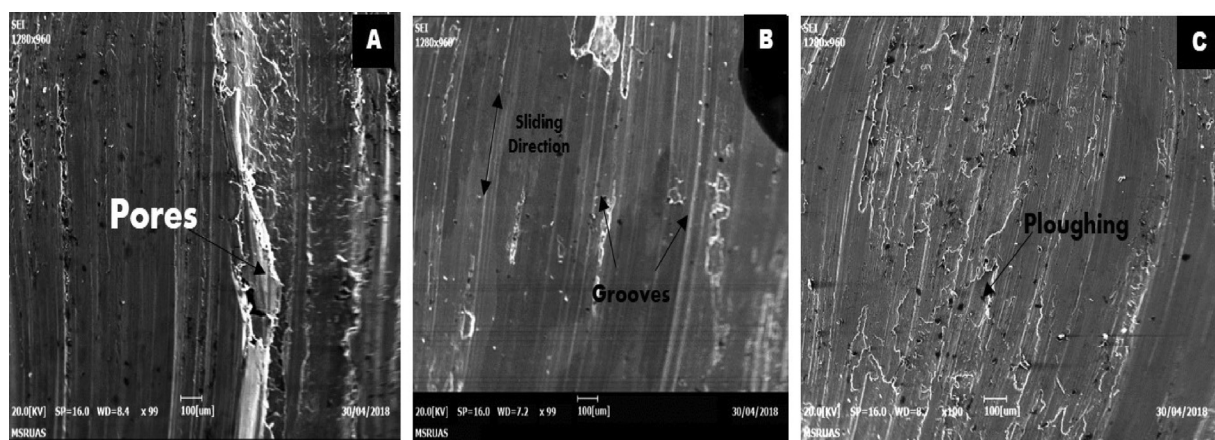


Fig. 12. SEM images of worn out surfaces - a) Al6061-2%ZrO₂ MMCs, b) Al6061-4%ZrO₂ MMCs, c) Al6061-6%ZrO₂ MMCs.

that the composite with 6 wt.% reinforcement has less wear rate. From the results obtained and the SEM images of worn out surface composites of Al6061–ZrO₂, it can be understood that the dominant wear mechanism was oxidation at low load and at high load adhesion and delamination in the composite with low volume reinforcement fraction. As the reinforcement content increased in the matrix material the wear mechanism is abrasive and adhesion at higher speeds, due to increase in the temperature. We can observe from the images that the number pits and grooves are more in composite having 2 wt.% reinforcement and a bit less in that of the composite having 4 wt.% reinforcement. Whereas there are more tracks in the image of the composite having 6% reinforcement. This absence of grooves suggests that very less amount of material is removed during wear test.

3.8. Regression analysis of Al6061–ZrO₂ MMCs

Regression analysis used for statistical approximation for the relationships between the variables by for modeling and analyzing variables, when the focus is on the relationship between a dependent variable and independent variables.

Fig. 13 a to d, are provided with residual plots taken to confirm regression goodness-of-fit and ANOVA assessment used in this research to evaluate the impact of various weigh. percentage of ZrO₂ nano reinforcement in MMCs.

To verify suitability, residual assessment was performed and regression model were developed and permitted to relate experimental

variables to the answers. After experimental confirmation, model was observed to be good. The residual analysis graphs shown in Fig. 13a–d, do not show any specific pattern in the residuals which is characteristic of good model.

The primary factors in tribology governing the behavior of wear in reinforced composite specimens were the physical and mechanical factors. Extrinsic to surface-level material interactions such as impact wear ordinary tribo-contact load, sliding speed, reinforcement orientation, sliding wear distance, climate, surface finish, temperature and counter-part material variables inherent to surface-level material interactions such as filler distribution, reinforcement type, shape, size, matrix microstructure and reinforcement volume fraction [26, 27].

ZrO₂ has comparable mechanical characteristics to stainless steel. Its traction strength can be as high as 900–1200 MPa and its resistance to compression is approximately 2000 MPa. This material also tolerates cyclic load stresses well. As a consequence of a physical property known as toughening conversion, Zirconia is defined by elevated flexural strength and fracture toughness. It also displays corrosion resistance along with this distinctive property. The composite may be handled thermally [28].

4. Conclusions of studies on Al6061 and ZrO₂ composites

The Al6061–ZrO₂ MMCs were effectively manufactured using stir casting method following the liquid metallurgy path. The composite density gradually improved as the reinforcement proportion rose from

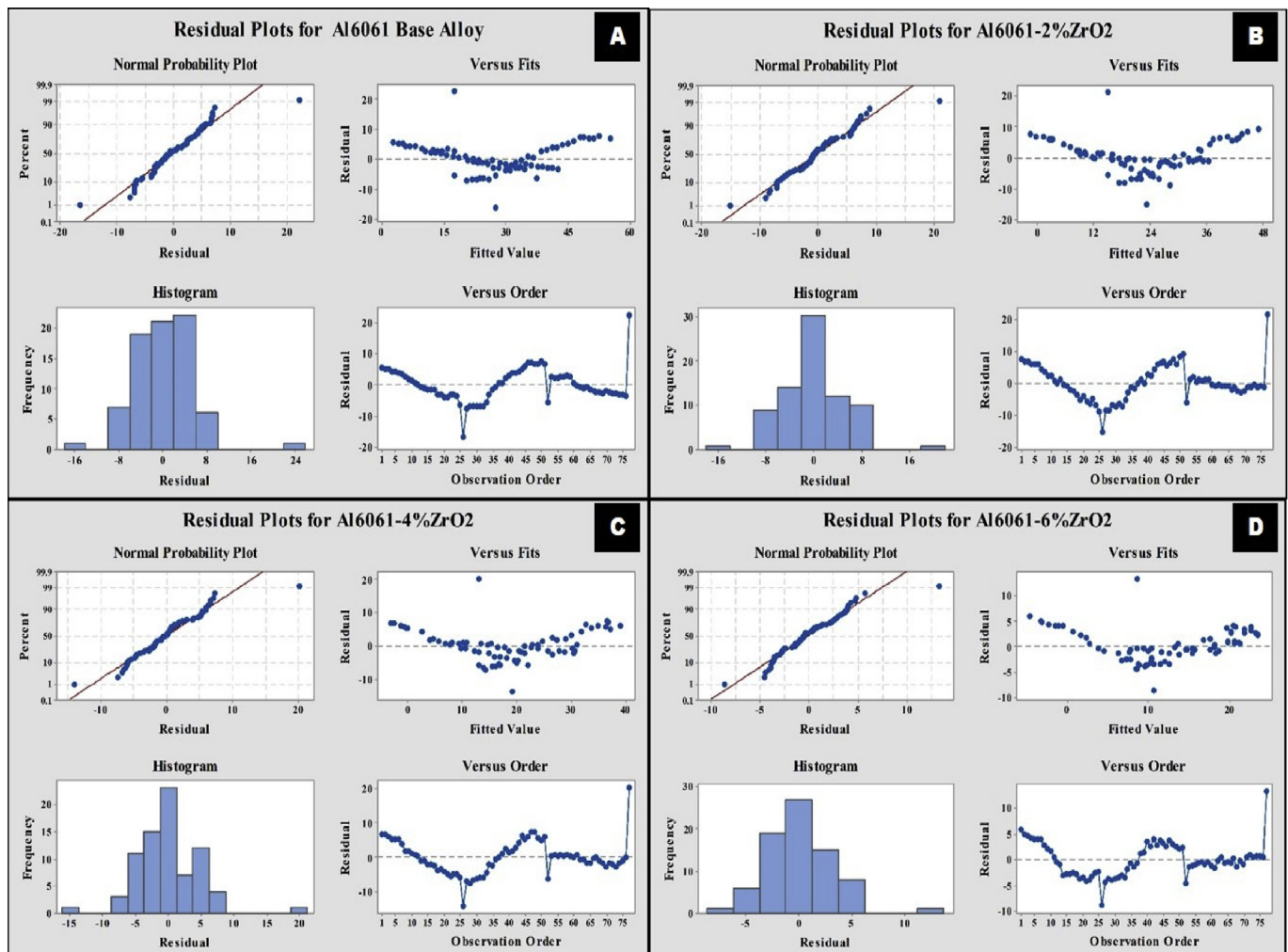


Fig. 13. The Residual analysis plot - a) Al6061 base alloy, b) Al6061- 2 wt.% ZrO₂ MMCs, c) Al6061- 4 wt.% ZrO₂ MMCs, d) Al6061- 6 wt.% ZrO₂ MMCs.

0% to 6% wt. The optical micrographs of all MMCs noted excellent bonding between matrix and nano-reinforcement materials with dendrite areas. It was evident from the outcomes that as the nano-reinforcement expanded, the tensile strength of MMCs also increased. Al6061–ZrO₂ MMC has been discovered to have greater UTS among the four MMCs with 6 wt. percent nano-reinforcement. Wear experiment findings indicate that as the content of nano-reinforcement increased, the wear resistance of the MMCs improved. With the increase in the sliding distance and applied load, the wear rate increased in all MMCs. The addition of ZrO₂ enhanced all characteristics with the exception of ductility.

Declarations

Author contribution statement

Veeresh Kumar: Conceived and designed the experiments; Analyzed and interpreted the data; Wrote the paper.

R Pramod: Performed the experiments; Contributed reagents, materials, analysis tools or data.

Ch Guna Sekhar, G Pradeep Kumar & T Bhanumurthy: Performed the experiments; Analyzed and interpreted the data.

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Competing interest statement

The authors declare no conflict of interest.

Additional information

No additional information is available for this paper.

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