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RESEARCH

Parametric Optimization of Dry Sliding Wear Behavior of A356 Alloy-Zircon Composites

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A B S T R A C T

A356 Aluminium Alloy-Zircon composites were synthesized through the stir casting technique by introducing different volume fractions of zircon particles (3, 6, and 9 %). Stir casting process was carried out at the stirring speed of 600 rpm and stirring time of 10 minutes. The microstructure of the composites showed an even distribution of zircon particles. The composites' hardness improved with an increase in vol.% of zircon constituent part. Wear loss against different sliding distances and load was investigated through a Pin-on-Disc wear testing apparatus with an L16 orthogonal array. Taguchi's parameter optimization demonstrated that material loss was influenced to a significant extent by adding Zircon. Wear resistance of the synthesized composite was investigated and verified using Analysis of Variance (ANOVA). Zircon content (39.33%) was found to be the most influencing factor on wear loss, followed by the applied load (36.80%) and sliding distance (21.54%). Zircon improves the properties of the composite through restricting the growth of dendritic arms in A356 alloy. In addition, reinforcement particles enhanced the strengthening of the composites through Orowan mechanism by inhibiting the movement of dislocations. ANOVA technique was successfully used to examine the effect of individual parameters on wear loss of A356 alloy-Zircon composites MMCs.

1. INTRODUCTION

Metal Matrix Composites (MMCs) exhibit a perfect blend of properties, including enhanced specific strength, modulus, high-temperature properties, abrasion, and wear resistance properties. Among various MMCs, aluminium MMCs (AMMCs) becomes the significant material of current research interest owing to its light weight [1]. However, AMMCs has not been utilized for wear application extensively [2]. Hence there is a need for improvement of wear resistance of AMMCs for enhancing its application potential [3]. Various factors that affect the wear performance of the AMMCs are the choice of fabrication method, matrix and reinforcement [4].

Researchers have tried out a wide variety of fabrication techniques for the development of various AMMCs, which includes stir casting [5-12], compo-casting [13], squeeze casting [14], spray forming [15], liquid metal infiltration [16], powder metallurgy [17,18], mechanical alloying [19], in-situ techniques [19,20], etc. Many researchers adopted the ex-situ composite fabrication method for dispersing reinforcement particles onto the matrix metal as the developed composite material possessed enhanced mechanical properties. Among the foresaid fabrication techniques, the stir casting method is vastly adopted in order to achieve near uniform dispersion of reinforcement in the AMMCs [21].

Among various aluminium alloys, A356 is preferred as the matrix since it can be used in a variety of applications, such as cylinder heads, cylinder blocks, cylinder liners, transmission cases, aero frame castings, machine parts, truck chassis parts, aircraft components, missile components, and structural components, requiring higher mechanical strength [22]. In terms of strength, ductility, hardness, fatigue strength, pressure tightness, fluidity, and machinability, it meets all requirements [23]. However for the improvement of wear resistance, ceramic particles have to be introduced into the matrix [24, 25].

Various ceramic particles have been experimented with as reinforcing particles to analyze each particle's effect on the properties of thus developed composite materials [26]. Carbides, oxides, and nitrides-based ceramic particles have been found to greatly influenced the mechanical and tribological properties of developed MMC[27]. Among various reinforcements, zircon ($ZrSiO_4$) had a major impact on the property enhancement due to its excellent refractoriness, resistance to impact load, chemical attack, wear and abrasion [2-7]. Among the various ceramic reinforcements available, zircon has been identified as a potential candidate with exceptional characteristics such as high elastic modulus, better hardness (With a Mohs hardness of 7.5) and high thermal stability[28]. Zircon also offers very low thermal expansion coefficient when compared to other ceramic materials [28]. In this study, zircon has been preferred as the reinforcement for manufacturing of the composite instead of zirconia being slightly harder (With a Mohs hardness of 8.5). This is due to the abundance of the zircon and its excellent thermal stability since composite fabrication processes undergo immense temperature changes, and phase transformations which can cause large volumetric changes that result in debonding at interfaces [10]. In addition to the reinforcement influence on the wear behavior, factors such as load and distance also has to studied [29-31]

Design of Experiments method is employed by several researches to investigate the wear behavior of the aluminium composites considering the influence of various factors [32]. Several optimization techniques are also used for this purpose [33]. Among them, Taguchi method is one of the most used Design of Experiments (DoE) technique to optimize the control aspects effectively by way of approach and also to analyze the result of various control factors on performance behavior [34]. Several studies have been conducted on optimizing the wear loss of composites using the Taguchi technique. ANOVA, a statistical model, based on the least square method, is useful for developing and confirming the experimental values. Taguchi's technique was used to examine the importance of each process parameter on the performance features of an alloy or composites [35, 36]. Palanisamy et al. [37] investigated the wear behavior of Al-fly ash composites by the Taguchi approach. They proposed that fly ash weight fraction dominates to be the main factor influencing wear loss, followed by sliding speed and load. It was also observed that minor wear occurs at low and high speeds, while rigorous wear occurs at high loads and speeds. Wear performance of composites AA6082-T6/B_4C and AA6082-T6/SiC using ANOVA and RSM. ANOVA results expressed that reinforcement content exerted the most negligible contribution of 4.31 %, followed by a load of 11.88 % sliding speed of 14.28 %. The sliding distance has the highest contribution (60.24 %) to AA6082-T6/SiC wear, and a similar trend was also detected for composites AA6082-T6/B_4C [38]. Vetrivel et al. [39] analyzed the effect of tribological processing parameters employing the Taguchi method, wherein the output response considered in this research was wear resistance of the developed aluminum composites. Results demonstrated that reinforcement percentage, load, and sliding distance significantly influenced the wear behavior of the developed aluminum hybrid MMC. Radhika et al. [40] optimized the wear process parameters of LM25/SiO_2 metal matrix composites using experiment L16 orthogonal array design. The 69.17 % load had the maximum impact on the wear loss trail by the sliding velocity (18.04 %) and sliding distance (1.5 %).

Amongst the studies carried out on the different behavior of various aluminum–ceramic combination composites, studies were not done on aluminum–zircon composite as there is a significant difference between their density values. Hence, in this study an attempt has been made in fabricating the zircon reinforced A356 alloy composites. In the present study, Taguchi's method was applied to understand the outcome of sliding distance, load, and zircon content, on the wear behavior of the Zircon reinforced A356 composite samples. ANOVA was conducted to categorize the % of involvement and importance of testing conditions.

2. EXPERIMENTAL METHODOLOGY

2.1 Materials

Elemental analysis of the Aluminium A356 alloy was conducted with optical emission spectroscopy, and the attained chemical composition is tabulated in Table 1.

Table 1. Elemental composition of Aluminium A356 alloy.

Composition	Si	Mg	Fe	Ti	Cu	Mn	Zn	Al
wt %	7.5	0.4	0.3	0.2	0.2	0.1	0.1	91.2

2.2 Synthesis of A356 alloy - zircon composites

Aluminium alloy of grade A356 was weighed for 500 g and melted at a temperature of 750°C in a graphite crucible. Commercially available zircon particle (99.5 % pure) was used as reinforcement with particle sizes ranging from 37 μm-44 μm. Before introducing zircon particles into the molten metal, it was preheated for two hours at 400°C to eradicate the particles' moisture content and to promote wettability of the reinforcement by the molten aluminum alloy. A mechanical stirrer was introduced into the crucible carrying molten metal. The speed was steadily raised to 600 rpm, leading to the formation of a vortex in the melt owing to the stirring action of the stirrer. The preheated (400°C) zircon particles were then introduced into the metal through the vortex at 5 g/min, manually with spoon. To guarantee the proper dispersion and uniform reinforcement distribution, melt stirring was carried out for an optimized time of 10 minutes. To reduce melt porosity, tablets of Hexachloroethane were added to the melt, and the composite mixture was tapped into a mold. Introducing ceramics into molten metal would lead to various chemical reactions and metallographic variations, thereby changing its properties. So, analyzing the metallographic variation is considered to be a primary assessment in the case of composite materials. To attain the microstructural variation, samples were cut from composites through wire cut electric discharge machining, mechanically polished, and etched via Keller's reagent. The metallographic modifications were observed using optical microscopy (Nikon, Eclipse MA-100), and the same was documented. To ensure the phases indicated by metallography, an X-ray diffraction examination of the as-cast composites was carried out at a scanning range from 10°to 80° using Cu Kα radiation (λ=1.54 Å), using an XRD-6000 diffractometer (Make: Shimadzu). Density was evaluated both theoretically and by Archimedes' principle. Rule of Mixtures (ROM) was used to evaluate the theoretical density of the composite, while actual density was measured using a density meter. A Brinell hardness tester was employed to measure the hardness of the base metal and the developed composite metals. The tests were carried out according to the ASTM E10 standard using a 10 mm steel ball indenter with a load of 500 kg. A Pin-on-disc tribometer (DUCOM, Model TR- 20) was employed to study the wear behavior of the developed composite and its base metal. Based on ASTM Standard G99-04, wear testing on specimens was carried out [41]. Cylindrical specimens with a diameter of 10 mm and a height of 30 mm were prepared from A356 alloy and the fabricated composite. A hardened EN32 steel disc was considered the counterpart disc with a hardness of 65 HRC. Wear testing was carried out with varying load and sliding distance sets for each set of specimens attained from an established design of experiments. Worn-out specimens after testing were cleaned using acetone and weighed with an accuracy of ±1 mg to determine the weight loss or wear loss. The worn-out surface of wear samples was observed through a Scanning Electron Microscope (JEOL, model JSM-6510LV) to study the wear mechanism during wear testing. Wear loss data attained from wear testing was then analyzed through Taguchi's method to recognize the effect of zircon vol %, sliding distance, and load on the wear behavior of the composites. ANOVA was also carried out to study the % of contribution and importance of the testing parameters.

2.3 Wear analysis

Taguchi's method is a conservative and proficient optimization method widely used in industries for multiple sample comparisons. One can design an excellent-quality system based on the Orthogonal Array (OA), which provides the best possible setting for control process parameters through limited test quantity. The test results are converted into a Signal-to-Noise (S/N) ratio. Generally, the signal-to-noise ratio can be classified into nominal the better, higher the better, and lower the better. S/N ratio for the present study was carried out using the smaller-the better feature since the explicit intention is to minimize the wear loss. S/N ratio can be expressed as the algorithmic alteration of the loss function, as revealed in Equation (1).

$$\frac{S}{N_B} = 10\log\left(\frac{1}{n}\sum_{i=1}^{n} y_i^2\right) \tag{1}$$

Where *y* and *n* represents observed data and the number of observations, respectively. Three process parameters such as vol % of zircon (0, 3, 6 and 9 %), load (5, 10, 15 and 20 N) and sliding distance (500, 1000, 1500 and 2000 m) were taken with four different levels, as shown in Table 2. These parameters and their levels are given as input in the Minitab software. Based on the number of parameters and levels, L_{16} OA was chosen for this study as per the Taguchi method, and the tests were conducted as per the OA.

Table 2. Control factors.

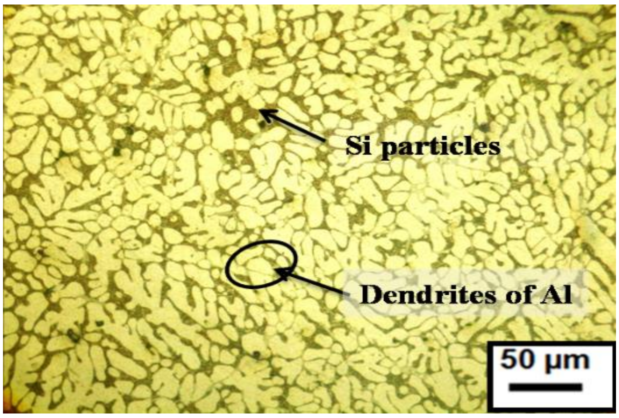
Control factor	Code	Level 1	Level 2	Level 3	Level 4
Vol % of Zircon	A	0	3	6	9
Load- N	B	5	10	15	20
Sliding distance, m	C	500	1000	1500	2000

3. RESULTS AND DISCUSSION

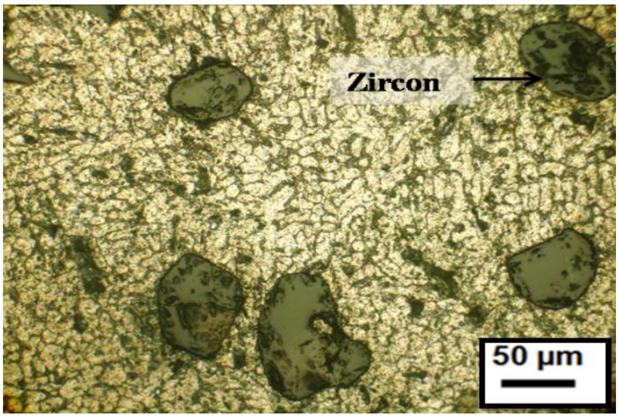
3.1 Metallurgical Analysis

Zircon reinforced A356 alloy composite was produced successfully through stir casting techniques. The casting defects generally associated with the fabrication of the aluminium composites is gas porosities, oxides and inclusions [42]. The method to eradicate such defects is to optimize the casting technique and enhance the sound of the casting. Mainly in aluminum castings, hydrogen is the only gas that dissolves in major quantity, which consequences in hydrogen gas porosity [43]. In the current research, to reduce melt porosity, tablets of Hexachloroethane were added to the melt, and the composite mixture was tapped into a mold. As a result, composites cast part is observed visually and it is found with absence of surface defects. Upon sectioning or machining of the samples for various testing purpose such as for metallographic examination, density measurement, hardness testing and wear testing, the presence of internal defects was also not found.

The distribution of Zircon particles into the A356 alloy matrix is evident from the optical microstructure confirming the successful dispersion of particles into the matrix metal. The optical micrograph of the As-Cast A356 alloy demonstrated a coarse eutectic phase between aluminum dendrites (Fig. 1a). The optical microstructures of A356 composites are represented in Fig. 1 (b-d). It is clear from Fig. 1b that uniform distribution of zircon particles has occurred in the 3 vol % Zircon reinforced composites. It can also be observed that a refinement of α-aluminum dendrites occurred for MMC dispersed with 3 vol % zircon compared to As-Cast monolithic A356 alloy. This refining can be attributed to the heterogeneous nucleation triggered due to the high-temperature difference between the introduced zircon particles and the melt [44]. The dendrites appear as rosettes in Zircon reinforced composites [45].



(a)



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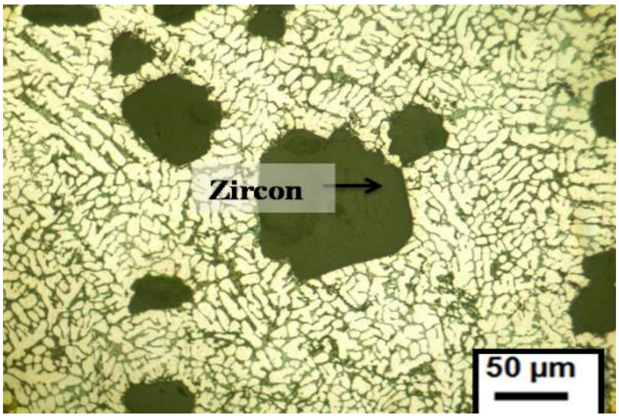

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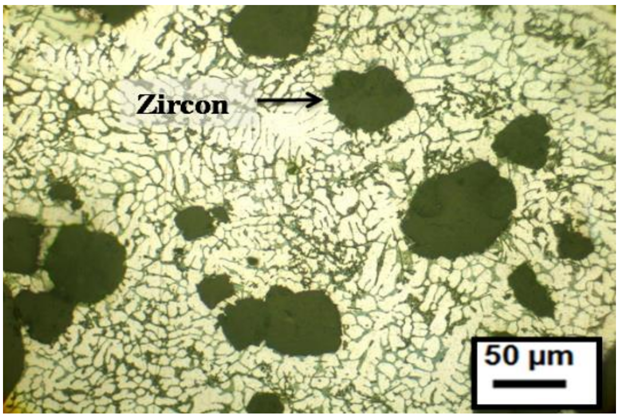

(d)

Fig.1. Microstructure of (a) A356 alloy, (b) 3, (c) 6, (d) 9 vol. % zircon reinforced composites.

A356 alloy dispersed with 6 volume fraction of zircon particles also exhibits a uniform distribution of reinforcement particles and a refinement in α-aluminium dendrites. Results were similar in the case of A356 alloy - 9 vol % zircon reinforced composites, but clustering of zircon particles at specific locations was observed.

The other possible mechanism for refinement of α-Aluminium dendrites is the growth restriction theory [46]. The incorporation of the zircon particles inhibits the growth of the α-Aluminium dendrites by growth pinning effect thereby refining it [47]. Thus it can be concluded that α-Aluminium dendrites refined by synergic effect of heterogeneous nucleation and growth pinning effect [48].

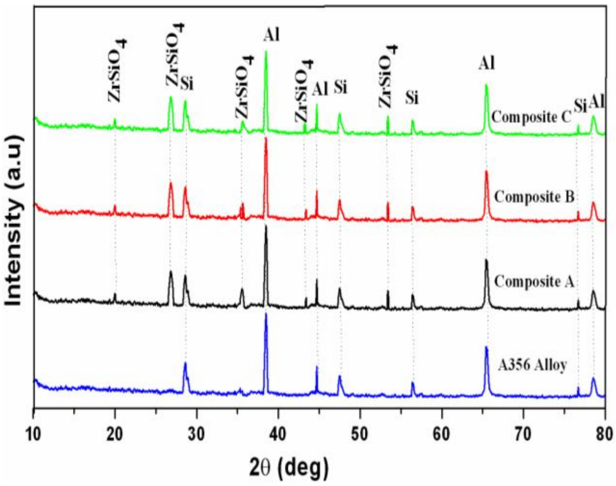

Fig. 2. X-ray diffraction patterns for all the A356 alloy and composites.

The X-ray diffraction pattern of the base metal and fabricated hybrid MMCs with varying zircon particles is shown in Figure 2, wherein the presence of $ZrSiO_4$, Al, and Si [49] was revealed through the pattern. It is evident from XRD patterns that apart from $ZrSiO_4$, Al and Si, no other peaks were observed; thus confirming the excellent chemical bonding between zirconium and aluminium matrix metal.

3.2. Density

Synthesized composite density was evaluated theoretically and through Archimedes' methods. A gradual increase in density values for introducing zircon particles was observed for the developed set of aluminum composites and is expressed in Figure 3.

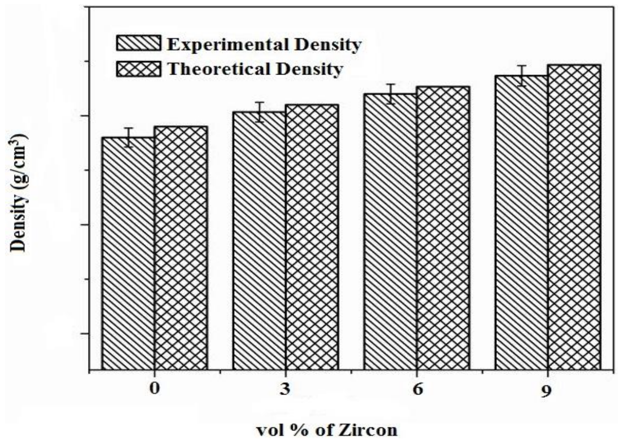

Fig. 3. Experimental and theoretical density of A356 alloy and zircon reinforced composites.

This increment in the density of developed aluminum-zircon composites for the substrate metal A356 alloy (2.73 g/cm^3) can be attributed to dense zircon ceramic particles (4.7 g/cm^3) in the aluminum metal. A close variation can only be observed between the density values evaluated via the theoretical method and Archimedes method from Figure 3, which substantiate the minimal presence of defects within the fabricated composites.

3.3. SEM/EDS analysis

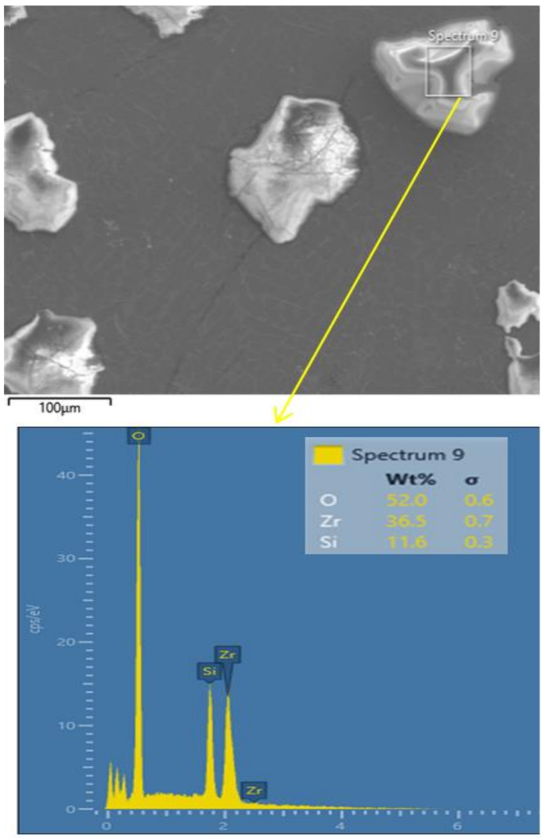

Fig. 4. SEM micrograph of A356/zircon composite and EDS spectra of zircon.

SEM micrograph of A356/Zircon composite is shown in Figure 4a. SEM examination of the sample showed the presence of zircon particles and has excellent interfacial bonding with the matrix. Further, the presence of zircon is confirmed with EDS as shown in fig 4b. It is anticipated that presence of zircon can lead to an increase in hardness and wear resistance of the composites.

3.4. Hardness

The introduction of hard ceramic particles into a metal tends to enhance the hardness of formed material. Despite this, metal's hardness greatly influences the wearing out of metal specimens. Analysing hardness is a mandatory procedure for composite materials for tribological application. A detailed overview of the hardness attained by fabricated composites in contrast to substrate metal is provided in Figure 5. The hardness of the developed metal matrix composites was enhanced by introducing zircon particles exposed to a higher hardness value when compared with substrate metal. Hardness value tends to enhance from 70 BHN for A356 alloy to 94 BHN for 9 vol% zircon addition.

This significant improvement in hardness can be credited to the uniform distribution of hard zircon particles in matrix metal and generation of dislocations at the matrix particle boundary for the period of the solidification owing to the coefficient of thermal expansion difference among Al matrix and Zircon Particles [50-53].

A study reported that due to the increased dislocation density of Al-Zn-Mg alloy matrix, composites have a higher hardness than unreinforced alloys. Also, reinforcement particles tend to refine the matrix grain size, improving the composite's hardness [54].

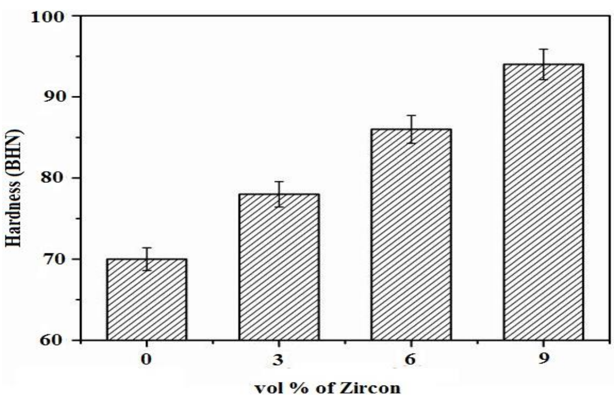

Fig. 5. Hardness of A356 alloy 6 and 3, 9vol % zircon reinforced composites.

3.5 Wear characteristics of composites

Pin-on-disc wear test was conducted for varying vol. % zircon, sliding distance, load indicated by L_{16}, and wear loss were represented in Table 3. Wear loss values in conjunction with their respective S/N ratios of A356 alloy showed a relatively higher wear loss than A356-zircon MMCs. The higher wear loss confirms that vol. % of Zircon in the A356 alloy matrix significantly influenced the composites' wear behavior. In another study, Panwar et al. [55] investigated the effects of zircon sand on Al-Si alloy composites reinforced in various ratios and reported similar findings.

Table 3. Testing parameters and wear loss values in conjunction with their S/N ratios.

Trail No.	Vol. % of Zircon	Load (N)	Sliding distance (m)	Wear loss-(gm)	S/N ratio
1	0	5	500	0.1319	17.5951
2	0	10	1000	0.2037	13.8202
3	0	15	1500	0.2781	11.1160
4	0	20	2000	0.3456	9.2285
5	3	5	1000	0.122	18.2728
6	3	10	500	0.1449	16.7786
7	3	15	2000	0.2353	12.5676
8	3	20	1500	0.2382	12.4612
9	6	5	1500	0.124	18.1316
10	6	10	2000	0.1665	15.5717
11	6	15	500	0.14	17.0774
12	6	20	1000	0.1686	15.4629
13	9	5	2000	0.123	18.2019
14	9	10	1500	0.1356	17.3548
15	9	15	1000	0.138	17.2024
16	9	20	500	0.1567	16.0986

Figure 6 depicts the main effect plots for the composite's S/N ratio of wear loss. From the plot, the parameter with a higher inclination expresses the dominant effect. ANOVA was employed to recognize the importance as well as involvement % of various factors.

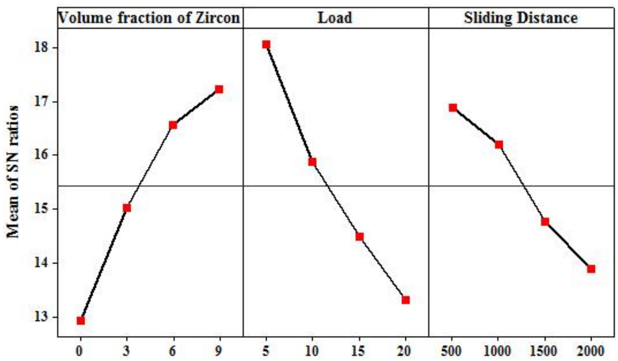

Fig. 6 Main effect plots for S/N ratio in wear loss.

The wear loss of the composites is affected by various testing parameters, which can be seen in Figure 6. Thus, it is evident from the major effect plot that parameter A (Zircon vol%) is the main factor. Wear loss decreased while vol.% of Zircon increased to 9 %. The decrease in wear loss is due to a more significant amount of zircon particles. The higher hardness of composites minimizes the chance of plastic deformation to a limit, consequently reducing wear loss to a great extent. An increase in zircon particle amount increases the hardness of the composite.

Parameters B (load) and C (sliding distance) showed a limited effect on composite wear loss compared to zircon content. From Figure 6, it can be noted that the composite's wear loss increases with an increase in load; as the load increases, the contact pressure among the rotating disc and pin increases. Vetrivel et al. [39] observed a similar trend in the wear behavior of Al hybrid composites. From Fig. 6, it can also be noted that the wear loss increases with the sliding distance primarily due to the increase in contact time among the pin and rotating disc. With an increase in sliding distance, temperature also rises, thus softening the pin material and increasing wear loss. Similar results in the wear performance of AA6082-T6/B_4C and AA6082-T6/SiC composites [38].

A higher delta value has the uppermost effect over the resultant variable between considered parameters. From Table 4, it is clear that load ranked as 1 has a more excellent delta value and has the highest effect on the Al− zircon composite wear loss.

Table 4. Response table for S/N ratio.

Level	Vol. (%) of zircon	Load (N)	Sliding distance (m)
1	12.94	18.05	16.89
2	15.02	15.88	16.19
3	16.56	14.49	14.77
4	17.21	13.31	13.89
Delta	4.27	4.74	3
Rank	**2**	**1**	**3**

Table 5 shows that the volume fraction of Zircon is the most significant factor compared to sliding distance and applied load. ANOVA outcome pointed to the involvement of every factor in the composites' wear loss, and its importance is shown in Table 5. The parameter containing a P ratio < 0.05 is an important factor; hence it can be confirmed in Table 5 that parameter A is the most significant variable. Relationship among the control factors (vol.% of reinforcement (A), load (B) and travel distance (C)) and wear loss (W) was obtained by multiple linear regression method is as follows:

$$\text{Wear loss} = 0.079255 - 0.0113275\ \text{Volume fraction of Zircon} + 0.0068265\ \text{Load} + 5.1715\text{e-}005\ \text{Sliding Distance} \quad (2)$$
$$R = 94.14\%$$

A validation experiment is essential to validate the theoretical model; therefore, two sets of parameters were selected for the validation test. Table 6 compares experimental wear losses and predicted wear loss results. Since deviation among experiment and predicted wear loss is well below 5%, it can be concluded that the attained statistical model can be used for predicting wear loss of Al−Zircon composites accurately.

In the case of composites, hard zircon particles carry the applied load much more effectively and limit the counter face from ploughing into the relatively soft matrix, resulting in reduced wear. With an increase in zircon 3 vol %, the hardness of the composite increases and helps to minimize the wear loss significantly.

Table 5. ANOVA table.

Source	Degree of freedom	Sum of square	Mean square	F -Value	P-Value	Contribution %	Affecting degree
Volume of zircon (%)	3	0.0250	0.00832	33.88	0	39.33	Significant
Load (N)	3	0.0234	0.00779	31.7	0	36.80	Significant
Sliding distance (m)	3	0.0137	0.00456	18.55	0.002	21.54	Significant
Error	6	0.0015	0.000246			2.32	
Total	15	0.0635					

Table 6. Validation test parameters and results.

Experiment No.	Vol. % of zircon	Load (N)	Sliding distance (m)	Experiment wear loss (g)	Predicted wear loss(g)	Error (%)
1	6	15	1000	0.1354	0.1326	2.06
2	9	5	500	0.0357	0.0373	4.48

Worn surface of 3 vol. % Zircon reinforced composite (Fig. 7b) shows the development of abrasive grooves along the sliding direction. In this case, delamination is not observed as likely in unreinforced alloy. However, grooves were identified as the major form of material removal and the grooves are appearing deeper in the worn out surface. Compared to the worn surface of 3 vol. % zircon reinforced composite, shallow abrasive grooves can be observed by the side of the sliding direction for the aluminum composite reinforced with 6 vol. % Zircon reinforced composite (Fig. 7 c). The 6 vol % zircon reinforced composite is observed with the transition in the wear mechanism where it started to change into mild type of wear from severe form. Fig. 7d depicts the worn-out surface of MMC with 9 vol.% of zircon particles dispersed into it.

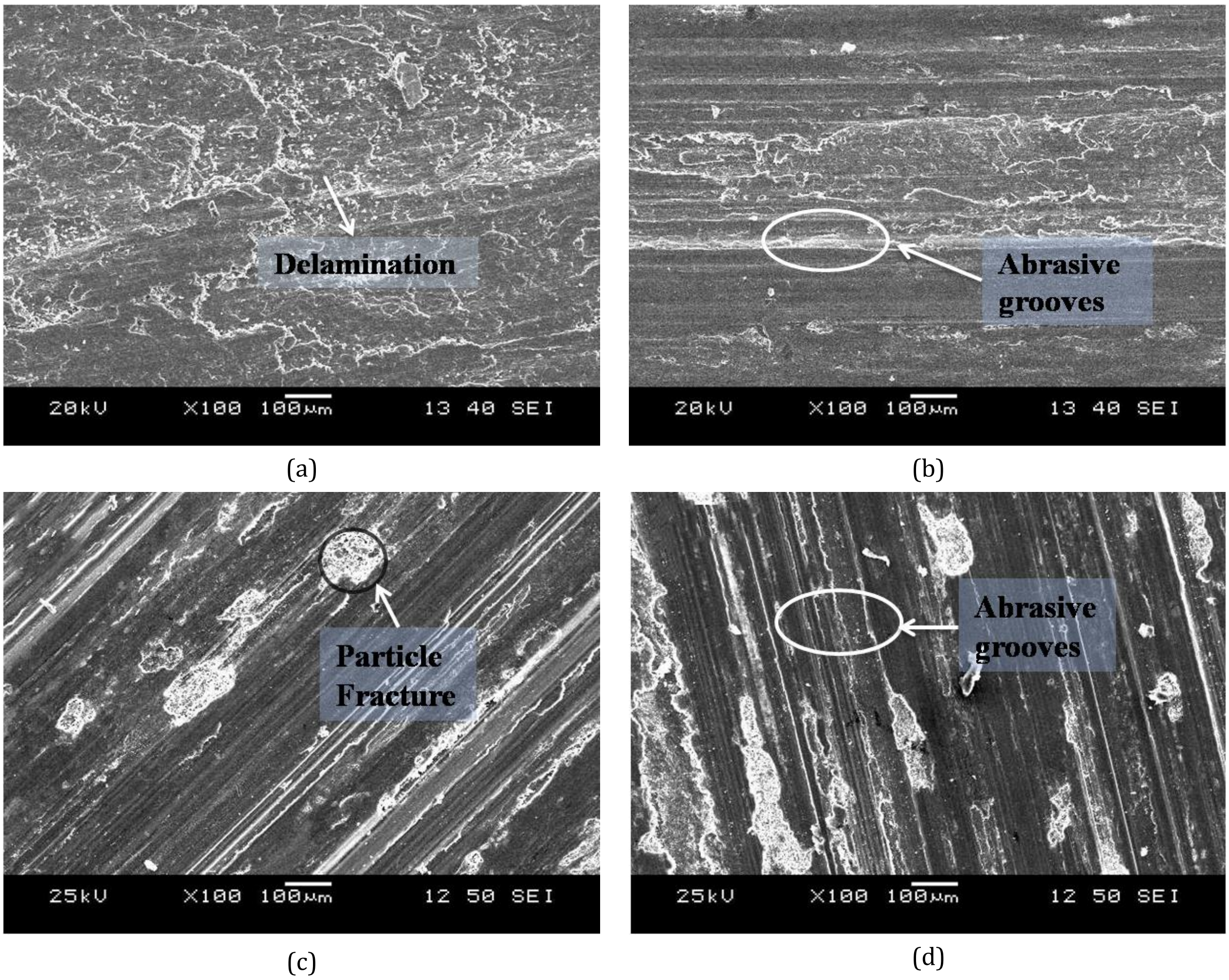

Fig. 7. SEM mages of wear track of A356 alloy (Trial No. 4) (a), 3 vol % zircon (Trial No. 8) (b), 6 vol % zircon(Trial No. 12) (c) , 9 vol % zircon (Trial No. 16) (d).

A smooth surface with thin abrasive grooves was observed, signifying the minimal material loss during the wear test indicating mild type of wear. Thus, it can be concluded that the wear has been transitioned from severe type in unreinforced alloy with delamination to mild type of wear with thin abrasive grooves in higher percentage zircon reinforced composite. Abrasive wear is the main wear mechanism feature viewed from all Zircon reinforced composites. Thus, it can be concluded that adding zircon particles enhances the alloy's wear resistance.

4. CONCLUSIONS

- A356 alloy with Zircon reinforced composites have been successfully produced by stir casting route.
- The microstructure of the synthesized composite shows an even distribution of zircon particles.
- A356 alloy hardness and wear resistance have significantly improved due to the addition of the zircon particles.
- ANOVA results show that Zircon content (39.3 %) was the main deciding factor on wear loss, trailed by load (36.8 %) and travel distance (21.54%).
- The developed composite with better wear performance can be utilized for the automotive application such as in cylinder liner where higher wear resistance is essential.

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