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Tribological Behavior of SiC and Al_2O_3 Reinforced Aluminium Metal Matrix Composite

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Abstract: Stir casting offers greater benefits than other techniques for creating metal matrix composites. Using the high-energy stir casting process, the aluminium alloy Al5052 was strengthened with SiC and Al_2O_3 particles in varied weight percentages (0, 2, 4, and 6 wt.%). Through the use of XRD and SEM, the structural characterization was carried out. Investigations were made into mechanical characteristics such as hardness, tensile strength, and wear. To conduct wear studies, the load was changed while all other factors remained constant. SEM analysis was used to study the wear process. This study found that SiC and Al_2O_3 added to aluminium composites made them more resistant to wear. The findings demonstrated that when compared to base materials, the percentage of SiC and Al_2O_3 contained in the samples enhanced the mechanical characteristics, wear resistance, and hardness.

Keywords*: Metal matrix composites, Aluminium, SiC and Al_2O_3, Stir casting, Friction and Wear.*

1. Introduction

With the advent of MMCs, the automotive industry's growing need for fuel-efficient vehicles, together with efforts to reduce air pollution and energy use, made progress. The enhanced properties of MMCs, which are a designed fusion of metal matrix material and reinforcement particles, include high strength, extremely low weight, stiffness, excellent resistance to wear, and improved resistance to corrosion. The usage of MMCs in the automotive, electronics, nuclear, marine, and aviation sectors has increased because of all these customized qualities. HMMCs, or hybrid metal matrix composites, are now the subject of many studies [1-3]. HMMCs are capable of withstanding corrosion conditions at high temperatures and have a high fracture toughness. As opposed to other lightweight magnesium and monolithic titanium alloys, MMCs/HMMCs of aluminium are readily capable of achieving all these qualities. Additionally, aluminium is widely used in numerous technical applications because of its inexpensive cost of manufacture, great strength, and corrosion resistance. Because of their effective mechanical and Tribological qualities, Al and Al_2O_3 composites are frequently employed in engine blocks and crankshaft bearings to increase resistance to wear [4–7]. Al-MMCs may be used to provide fatigue resistance, which is the most crucial feature for automotive applications. Aluminium can be reinforced with ceramic particles such as SiC and Al_2O_3, etc. to boost its mechanical strength and wear resistance. Isotropic characteristics are seen in composites formed from particulate metal matrices.The size and weight fraction of the particles as well as the method used to create the composite are two significant aspects that affect the mechanical characteristics of the metal matrix composite [8–11]. Based on the research conducted by Bansal and Saini [12], the fabrication process used in the current study is taken into consideration. The stir-casting method is regarded by them as being straightforward, adaptable, and affordable. SiC/graphite and SiC/Al359 alloy fabricated specimens were examined for tensile strength, wear resistance, and surface hardness. Higher weight percentages of SiC/Gr in the specimen led to better wear and hardness characteristics, "greater tensile strength, and a steady decline in elongation and ductility[13].Investigated the effects of adding silicon and titanium carbides to the metal matrix of Al5052 and found that the mechanical characteristics of the aluminium alloy were improved. The wear on the composite has steadily decreased as the TiC weight percentage has increased. The SEM pictures show a consistent dispersion of carbide particles and a decrease in voids and grooves. The experimental work and process for determining the ideal circumstances for the better performance of composites like Al5059/SiC/MoS_2 were both well described by Daniel et al. [15-17]. The current study adopts a number of the specified control parameters, including the sliding speed, alloying weight percentage (wt. %), and load. According to the research, the load, SiC weight percentage, and sliding velocity affect the composites' ability to resist wear.

After an extensive review of various methodologies, Joseph et al. [18] advocated for stir casting as the most efficient and cost-effective means of crafting composites. To enhance the performance of composites formed with Al7075 as the foundational metal and varying weight percentages of SiC and TiB2 as reinforcement particles, the investigation centered on determining the optimal process parameters. Lawate et al. [19] delved into the impact of stir-casting process variables on the behavior of aluminum alloys fortified with Al_2O_3. Meanwhile, Mohan et al. [20] scrutinized several mechanical characteristics of the Al6061/B4C/Gr composite, maintaining a consistent volume ratio for the constituent elements. Their study elucidated the augmentation of hardness and toughness with the addition of B4C and the concurrent increase in tensile strength with elevated graphite weight percentage, delineating the properties of the aluminum alloy, carbide, and graphite employed. James et al. [21] explored the hardness, tensile strength, and tribological characteristics of an Al6061/ZrO_2/Al_2O_3 composite, employing the stir-casting procedure. Their findings indicated an augmented distribution of particle elements, correlating with increased tensile strength, hardness, and wear resistance[22].Suraya et al. [23] emphasized the influence of altering the weight percentage of reinforcing particles in aluminum alloys on composite materials. The study revealed that the qualities of the aluminum alloy composite steadily improved when the weight percentage of TiC ranged from 0 to 10, but crucial features of the alloy diminished with higher TiC weight percentages. Investigations into Metal Matrix Composites (MMCs) showcased diverse manufacturing technologies and analytical approaches, offering optimized parameters to enhance the qualities of various base metals for application across different engineering domains [24]. Additionally, researchers [25–28] explored composites based on titanium.

The quantity of reinforcing particles in the manufactured composite plays a pivotal role in enhancing the physical, mechanical, and tribological characteristics of different aluminum alloys. In alignment with existing literature, the present work assesses the tensile strength, hardness, and wear resistance of hybrid MMCs. Aluminum oxide contributes to the improvement of tensile strength and hardness, while boron carbide enhances erosion resistance. The primary objective of this endeavor is to develop hybrid MMCs that bolster their mechanical attributes and resilience to dry slide wear. The study evaluates the influence of wear factors, including sliding speed, load, and reinforcement content (SiC and Al_2O_3). SEM analysis of the cracked and wear-tested MMC provides insights into the bonds between particles and matrix material. The results suggest that the produced composites offer a novel approach to enhancing the characteristics of composites for industrial applications.

2. Material and research methods

Fabrication of composite

Composite ware produced through the utilization of a stir-casting process. The composite specimen was fabricated by employing Al-5052 as the base metal matrix, complemented by the addition of ceramic components, namely Al_2O_3 and SiC, as reinforcing particles. Compositions of Al-5052 is detailed in Table 1.It is worth noting that prior research has demonstrated that when the proportion of reinforcing particles in a composite material remains below 20%, there is a noticeable enhancement in the physical and mechanical properties of the material [24]. However, this comes at the expense of certain attributes, such as ductility, rendering the composite less suitable for various manufacturing processes, including forming. Consequently, in order to ensure that the composites remain adaptable to a wide range of manufacturing techniques, the maximum weight percentage (wt.%) of reinforcing material applied in this study was set at 6%. The weight percentages of reinforcing particles incorporated into the three distinct manufactured composites were 2%, 4%, and 6%, as detailed in this investigation. The High-Pressure Die Casting (HPDC) manufacturing technique employed in this study is well-documented in existing literature [24, 29, 30]. The results of this process, yielding three distinct specimens by varying the weight percentages of ceramic particles and the metal matrix, are comprehensively tabulated and depicted in Tables 2 and 3, respectively. Figure 1 provides a visual representation of the resulting composite specimen samples.

Table 1.Properties of Al5052

Name	**Specification**
Magnesium	2.2%-2.8% by wt
Chromium	0.15% -0.35% (maximum)
Copper	0.1% (maximum)
Iron	0.4% (maximum)
Manganese	0.1% (maximum)
Silicon	0.25% maximum
Zinc	0.1% (maximum)
Al	96.7%-95.9%

Table 2 Properties of Al_2O_3

Name	**Specification**
Chemical formulation	Al_2O_3
Molar mass	101.960 g·mol−1
Density	3.987 g/cm^3
Melting point	2,345 K
Boiling point	3,250 K

Table 3 Properties of Al_2O_3

Name	**Specification**
Chemical formulation	CSi
Molar mass	40.096 g·mol−1
Density	3.16 g/cm^3 (hex.)

Table 4 Composite designations and descriptions of sample

Sample Number	**Composition**
SM1	Al 5052
SM2	Al5052/SiC 2%wt
SM3	Al5052/SiC 4%wt
SM4	Al5052/SiC 6%wt
SM5	Al5052/Al_2O_3 2%wt
SM6	Al5052/Al_2O_3 4%wt
SM7	Al5052/Al_2O_3 6%wt
SM8	Al5052/Al_2O_3 2%wt /SiC 2%wt
SM9	Al5052/Al_2O_3 4%wt /SiC 4%wt
SM10	Al5056/Al_2O_3 6%wt /SiC 6%wt

The mechanical parameters of three distinct kinds of manufactured HMMC specimens were determined using hardness and tensiletests. The methodologies used to conduct these mechanical tests are detailed below.

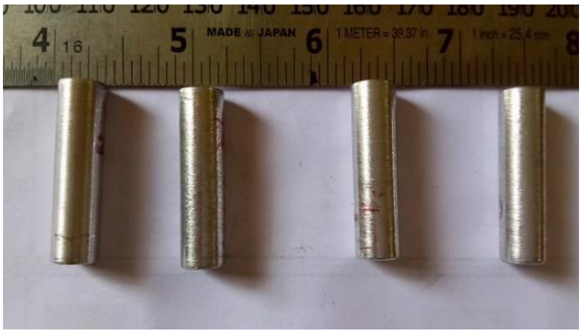

Fig1. Wear test samples: (a) 0% reinforcement, (b) 2% reinforcement, (c) 4% reinforcement, and (d) 6% reinforcement.

Fig2. Pin-on-Disc wear testing apparatus (Courtesy: R & D Centre, BIT, Bangalore)

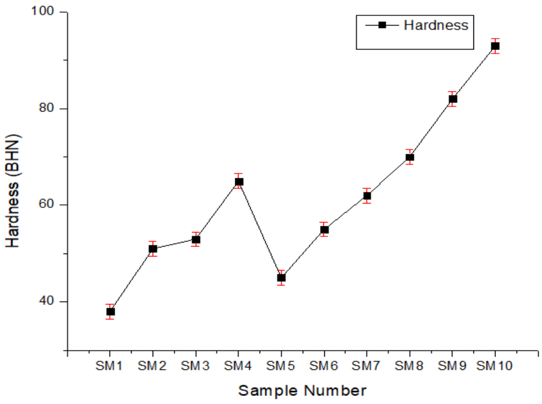

Fig 3. Hardness value of sample with different wt.% of SiC and Al_2O_3

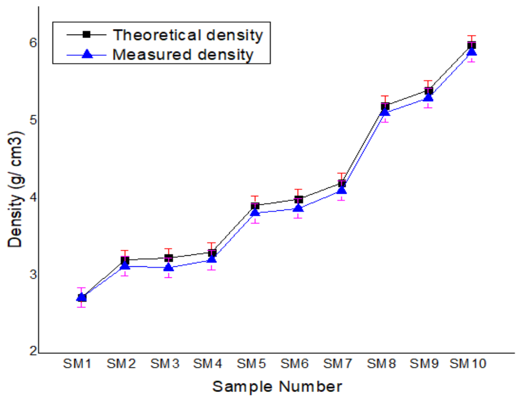

Fig 4 The Theoretical and measured density values of the composites

Wear Test

The wear test methodology utilized in this study has been comprehensively documented in the existing literature [24]. The wear tests were conducted using a DuCom Pin-on-Disc tribometer, as illustrated in Figure 2. To ensure standardized testing conditions, the wear tests in this research adhered to the ASTM G99 standards [33]. The counter-face consisted of an EN-32 steel disk with a track diameter of 60 mm. Three separate specimens were assessed, each varying in load and sliding speed. The load was incrementally increased from 10 N to 30 N in 10 N increments, while the sliding speed ranged from 500 rpm to 700 rpm, increasing in 100 rpm intervals. The specific wear rate (SWR) was computed using Equation (1).

$$SWR = \Delta W / \rho \times Fn \times Sd \qquad (1)$$

Where ΔW is the weight loss, ρ is the density of the specimen, Fn is the normal load and Sd is the sliding distance

XRD Test

Figure 6 displays the X-ray diffraction (XRD) pattern for the Al5052/SiC/Al_2O_3 composite developed in this study. XRD analysis was conducted using CuK α radiation with a wavelength (λ) of 1.54056 Å, covering a diffraction angle range from 0^o to 100^o. The XRD data of the Al5052/SiC/Al_2O_3 sample was subjected to analysis using MAUD 2.8 software, in conjunction with the Crystallography Open Database (COD). This analysis revealed that the diffraction profiles of the Al, SiC, and Al_2O_3 constituents match with the XRD profiles, confirming the presence of SiC and Al_2O_3 within the developed composite. Detailed information regarding the sample type and designation can be found in Table 4. Furthermore, theoretical and measured densities, as well as the percentage of voids, are presented in Figure 4 and Figure 5, respectively.

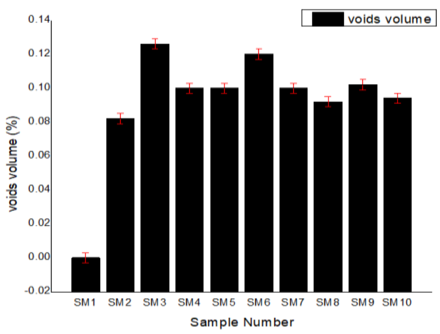

Fig 5 Void Volume % of sample composites

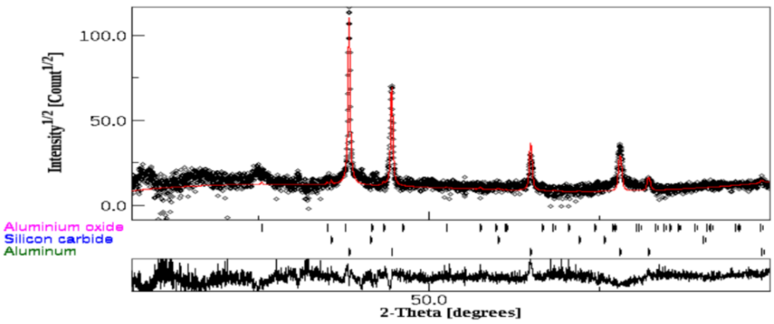

Fig.6 X-ray diffraction pattern of Al5052/SiC/Al_2O_3 Sample

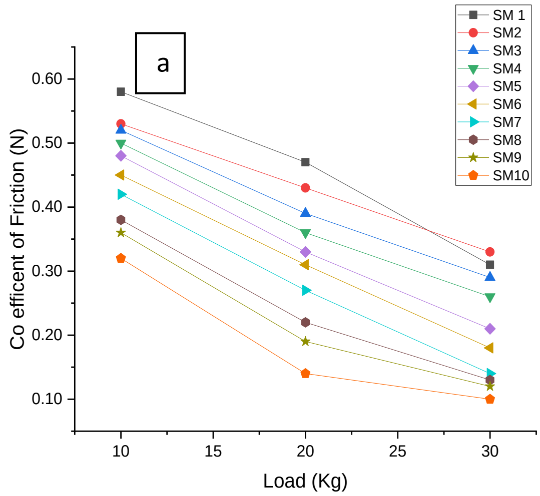

Fig 7 Coefficient of friction Vs Load

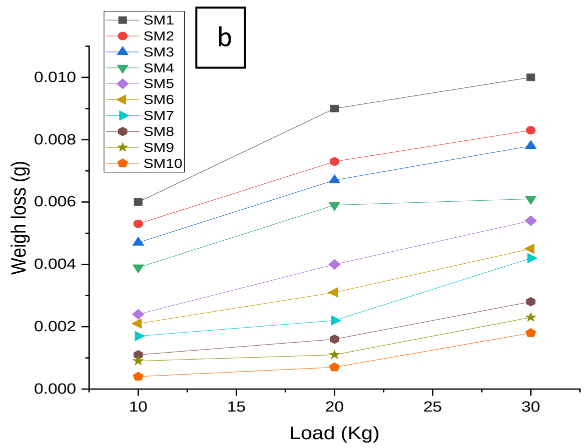

Fig 8 Weight loss vs load.

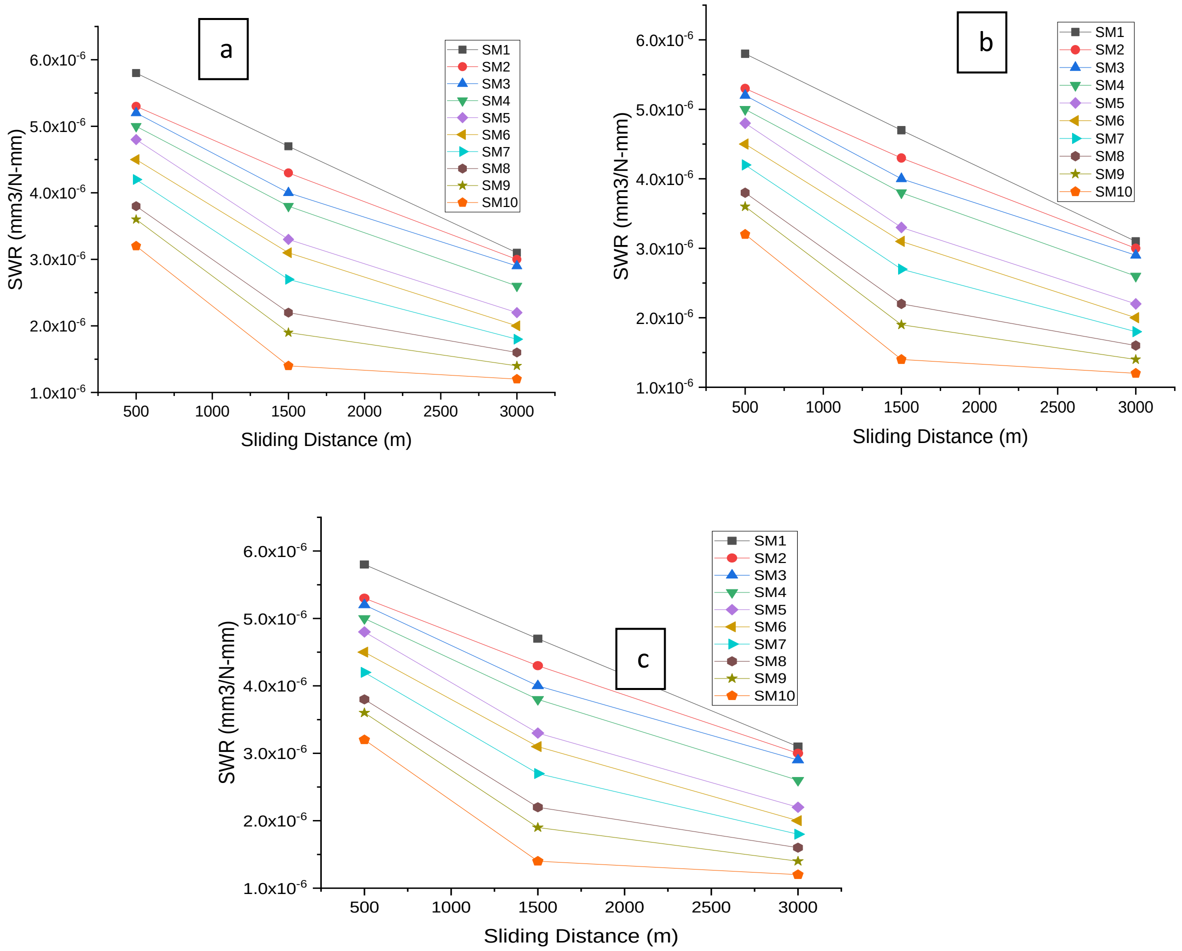

Fig. SWR vs. sliding distance (a) 10N load (b) 20N load, (c) 30N load, respectively.

Density and Porosity

It is evident, as depicted in Figure 4, that both the measured and theoretical densities exhibit an increasing trend with the incorporation of SiC and Al_2O_3 particulates into the Al5052 matrix. This observed phenomenon can be attributed to the inherently higher densities of SiC and Al_2O_3 in comparison to that of the Al5052 matrix.

Furthermore, as illustrated in Figure 5, it can be inferred that the measured and theoretical densities of the casted compositions are congruent, signifying the compatibility of the stir casting method.

Notably, the measured density of the AM10 sample surpasses that of the unreinforced Al5052 matrix by an impressive 46%. This is consistent with previous research findings [18, 21, 24, and 33], all of whom reported a similar elevation in density with the introduction of SiC particulates into Al alloys.

Figure 5 also provides insight into the percentage of porosity present in both the as-cast Al5052 and AA5052/SiC/Al_2O_3 specimens. The discernible difference between measured and theoretical density implies the existence of porosity within the casted compositions, which has the potential to influence their overall performance.

It is worth noting that, as depicted in Figure 5, the level of porosity observed in the as-cast Al5052 and Al5052/SiC/Al_2O_3 samples is minimal, measuring less than 0.5%. This can be attributed to the effectiveness of the casting process employed, which contributes to the high quality of the resulting components.

3 Microscopic wear behaviors

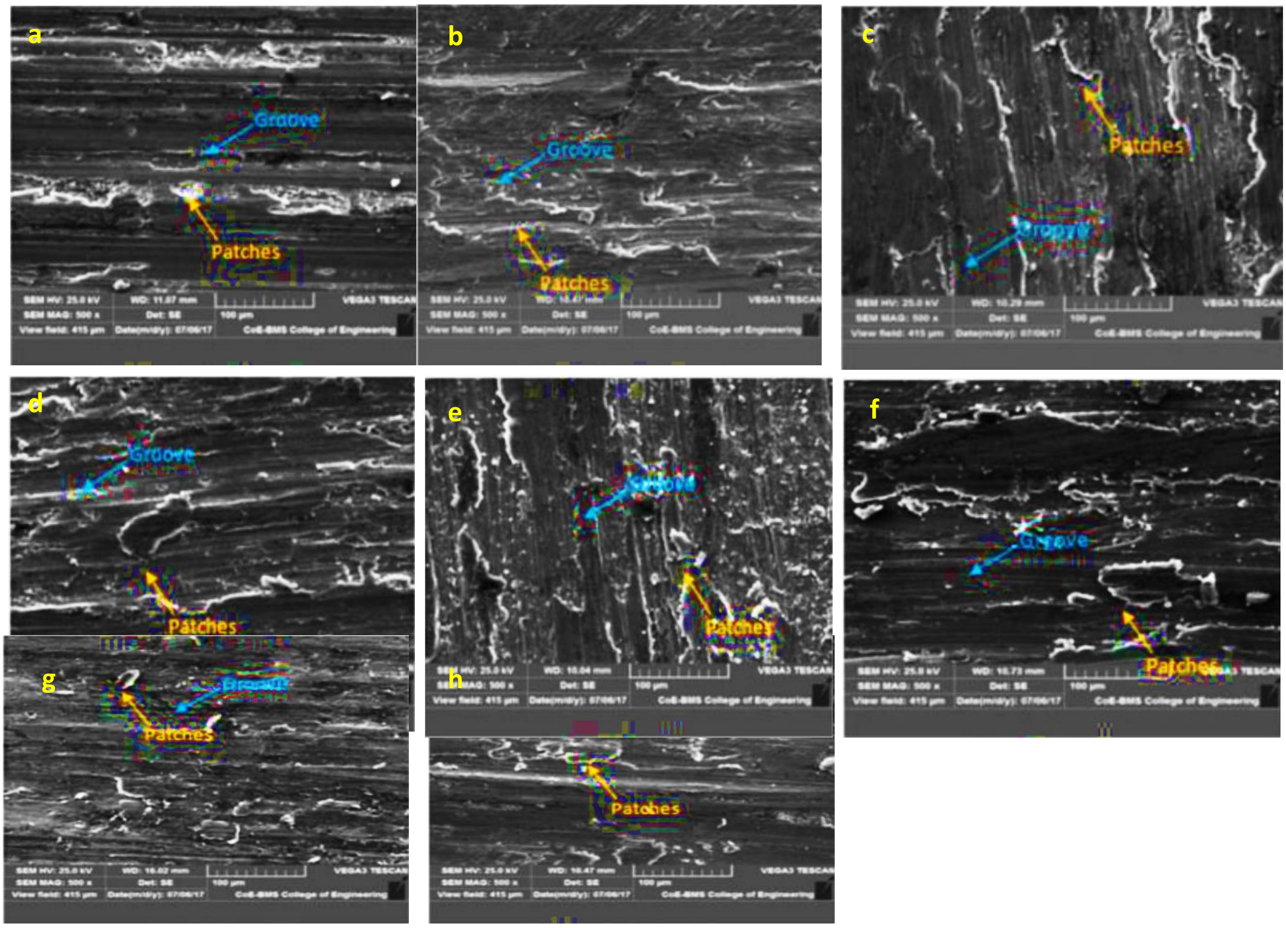

Fig7. SEM of worn surface of composites. (a) as-cast-Al5052; (b) as-cast- Al5052/SiC2%wt/Al_2O_3 2%wt; (c)as-cast-Al5052/SiC4%wt/Al_2O_3 4%wt; (d)as-cast- Al5052/SiC6%wt/Al_2O_3 6%wt; (e) as-cast-Al5052; (f) as-cast-Al5052/SiC 2%wt /Al_2O_3 2%wt; (g)) as-cast-Al5052/SiC 4%wt /Al_2O_3 4%wt (h)) as-cast-Al5052/SiC 6%wt /Al_2O_3 6%wt

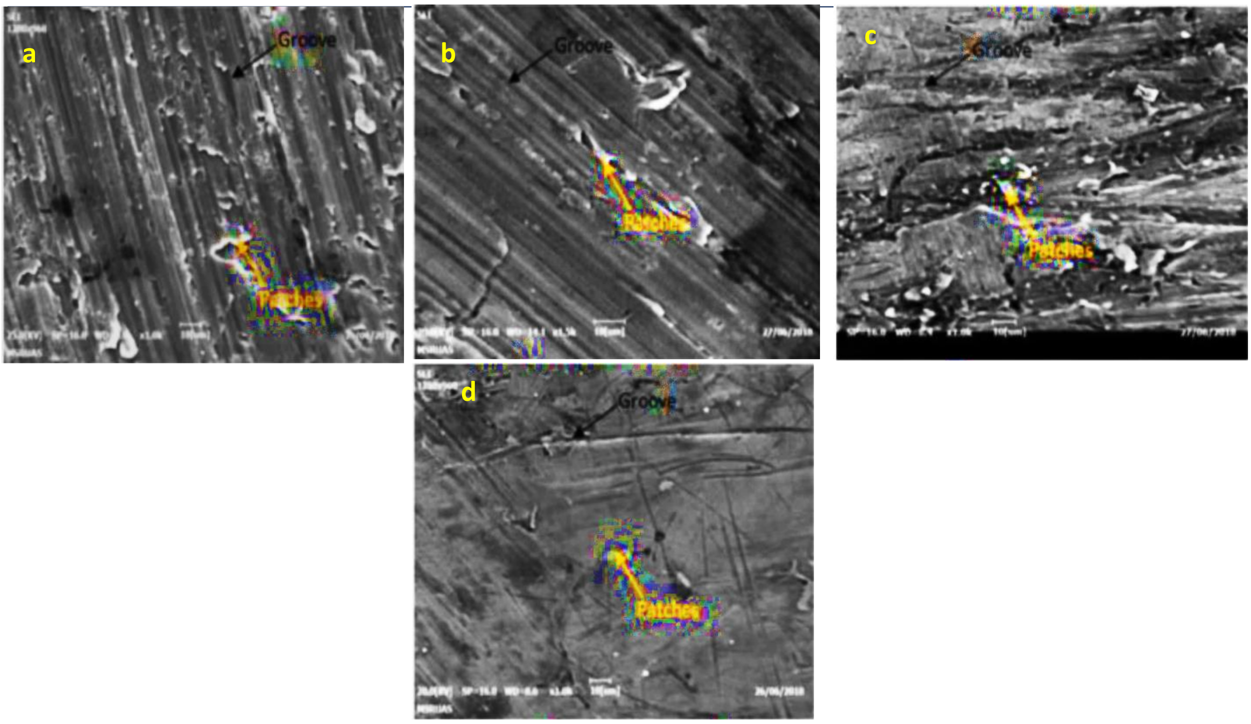

Fig 8. Worn surface (a) Al5052, (b) Al5052/2%wt SiC (c) Al5052/4%wt SiC, and (d) Al5052/6%wt SiC.

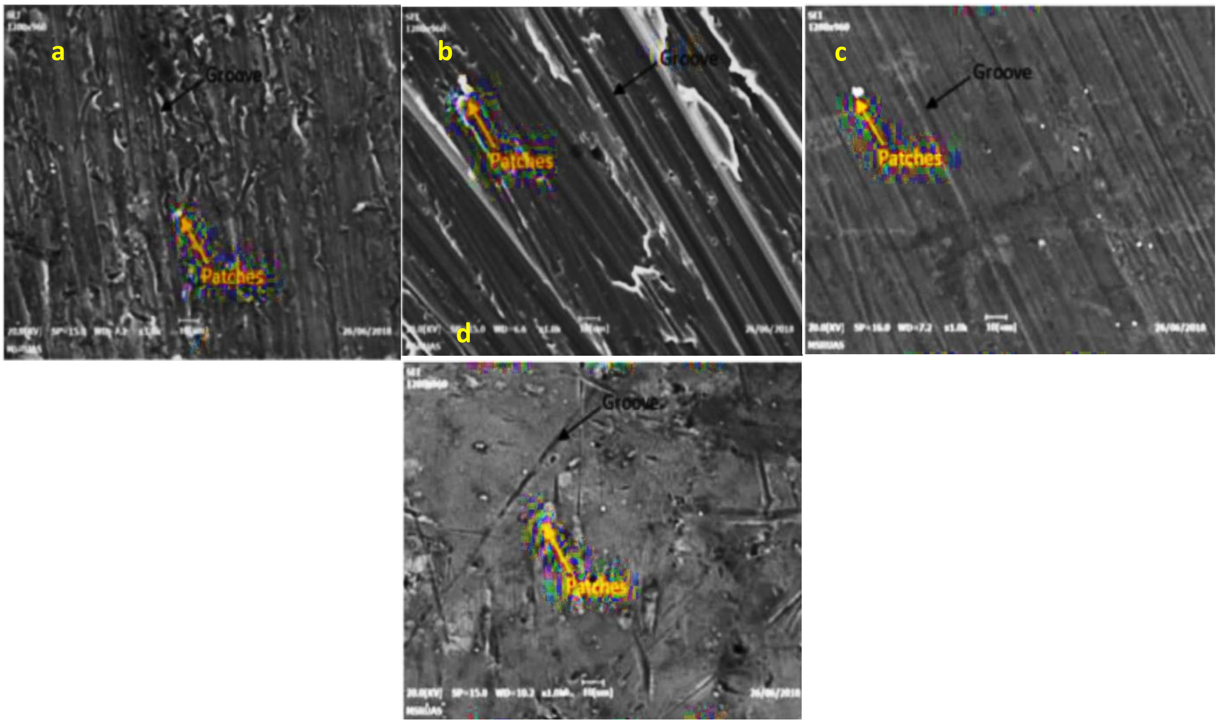

Fig 9. Worn surface (a) Al5052, (b) Al5052/2%wt Al2O3 (c) Al5052/4%wt Al2O3, and (d) Al5052/6%wt Al2O3.

Hardness measurements were conducted at three distinct points within the developed compositions, and the average hardness values for each composition are depicted in Figure 3. Notably, it is evident that the hardness of the developed composites surpasses that of the unreinforced Al5052 alloy.The introduction of 6% hard SiC particulates results in a substantial increase in composite hardness, marking a 58.46% enhancement compared to unreinforced Al5052. Similarly, the inclusion of 6% Al_2O_3 particulates leads to a hardness increase of 61.29% compared to unreinforced Al5052. Impressively, when 6% SiC and 6% Al_2O_3 are combined in the composite, a remarkable 69.89% increment in hardness is observed compared to the 6% SiC-reinforced composite, and a 66.67% increment compared to the 6% Al2O3-reinforced composite. Furthermore, the combined presence of 6% SiC and 6% Al_2O_3 results in a substantial 40.86% hardness increase compared to unreinforced Al5052.This trend aligns with the findings of Dolatkhah et al. [25], who reported that the addition of SiC to Al 5052 led to a hardness increase of up to 55%. Specifically, the incorporation of hard SiC particulates into the Al5052 matrix leads to an impressive 39.72% improvement in hardness.

Microscopic analysis reveals smooth surfaces with minor ploughing grooves. Similar wear behavior was observed in the testing of Al6061-Al_2O3 and Al7075-SiC composites by other researchers, with a comparable tendency towards hardness improvement. In contrast, the as-cast matrix alloy surfaces exhibit coarse grooves and plastic deformation, highlighting the significance of solidification conditions and microstructures in achieving desired material properties, especially when compared to the extruded matrix alloy. Composite strength is influenced by factors such as secondary dendritic arm spacing and grain size, emphasizing the importance of studying microstructural behavior for a comprehensive understanding of material performance. Notably, the fractured surfaces exhibit brittle failure characteristics, with deep dimples present across all experimental composites, in contrast to the shallow dimples observed.Figure 7 provides a visual representation of the surface morphology of an aluminum alloy composite subjected to an evaluation under room temperature conditions, with variations in load and speed. The prominent features characterizing the abrasive wear are the discernible wear scars.Upon closer examination, it has been observed that fine grooves appear on the worn surface of the aluminum alloy pin. Analysis of micrographs, as presented in Figures 3 and 4, reveals the presence of cracks propagating in various directions. This observation may be attributed to the strain hardening effect experienced by Al-based Metal Matrix Composites (MMCs) under load, as a result of the dislodging of hard-phase particles.The enhanced wear resistance exhibited by the composite under lower loads can be attributed to the presence of reinforcements interspersed between the composite material and the contacting surface of the counterface, creating a protective thin layer.

The morphological characteristics of the worn surfaces of the base alloy, as well as both the composites in their as-cast state after undergoing wear testing with applied loads of 10 N and 20 N, were examined using scanning electron microscopy (SEM). Figure 7 illustrates the SEM images of the as-cast samples, highlighting the presence of severe plastic deformation, manifested as white patches, which correlate with increased wear.

Within Figure 7, the SEM images associated with the 4 wt.% SiC/4% Al2O3-reinforced samples depict a reduced degree of grooving, indicative of decreased plastic deformation.Furthermore, Figure 7(b, c, d) and Figure 7(e, f, g, h) offer SEM images of 6 wt.% SiC/6% Al_2O_3-reinforced samples, showcasing a further reduction in the number of grooves and plastic deformation. Similar microscopic behavior was observed for the as-cast samples throughout the evaluation process. SEM micrographs of Al5052/SiC samples are shown in Figure 8. The samples show a uniform distribution of SiC particles. To generate a composite with standardized mechanical characteristics, the reinforcements must circulate uniformly throughout the matrix. Theparticle aggregation is modest. The samples' worn surfaces result in the creation of iron-rich layers. Figure 8 depicts a worn surface with white areas of iron oxide and exposed particles on the contact surface of samples. The development of FeO_2 was less pronounced at medium levels than at lower loads. The presence of SiC was discovered at the morphological surface. The heat influence on the appearance of the specimen was greater at a medium wear rate than at a lower wear rate.Figure 9 illustrates the scanning electron microscopy (SEM) images of the worn surfaces of Al5052/Al_2O_3 composite samples under varying loads. Notably, as the applied loads increase, the Al_2O_3 film on the surface becomes thicker and continuous, effectively covering the entire surface.At a critical velocity, this Al_2O_3 layer takes on the role of a sliding surface, causing the thin films to separate and leading to a reduction in the wear rate. When the thick film reaches a point where it becomes plastically distorted and nearly molten, it allows particles to flow upward into the matrix without bearing an initial weight. These particles then ascend and accumulate, creating a substantial barrier that prevents further movement.Consequently, the composite acquires a denser and, consequently, harder surface, resulting in an elevated transition in hardness. It's important to note that due to surface asperities between the contacting surfaces, all the composites exhibit an increased coefficient of friction. However, once a steady-state condition is achieved, the coefficient of friction diminishes. Additionally, coatings of Al_2O_3 and iron oxide are applied to the sliding surface as part of the observed wear behavior.

4 Conclusions

The additions SiC partial in Al5052 matrix make composite hard and brittle, however it is observed that the addition of Al_2O_3 with same wt percent in the al 50552 matrix makes the composite soft it is proved by the test results. Distribution of the particles in the matrix also holds key role in characterization of the hybrid composite, wear SEM shows the mix behavior of Adhesive and Abrasive wear where as more abrasive wear due to shear failure work Hardened layer which breaks along the grain boundary. The failed particles form the debris and causes the abrasive wear this is due to the SiC inclusion. Whereas Al_2O_3 show the adhesive wear because of its softness.

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