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Research Article

The Influence of Hot Extrusion on The Mechanical and Wear Properties of an Al6063 Metal Matrix Composite Reinforced With Silicon Carbide Particulates

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Lightweight composite materials have gained extensive importance over other categories of materials and alloys in industrial and structural applications due to their tailorability to design and engineering for specific requirements. This article addresses the mechanical and wear behaviour study of aluminium 6063 alloy reinforced with different weight fractions of silicon carbide for 'as-cast' and 'hot extruded' conditions. The composite systems were developed using the stir casting technique, and a set of samples was further subjected to hot extrusion at 500 degrees Celsius with an extrusion ratio of 9.0. Both cast and hot extruded samples were investigated for mechanical and adhesive wear studies. The addition of reinforcement improved the mechanical properties and wear resistance, and a significant improvement in mechanical and wear resistance was observed when the samples were subjected to secondary processing through hot extrusion.

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1. Introduction

The alloys are the main constituents for the development of metal matrix composites. Aluminium is the most efficient and commonly used alloy due to its high strength-to-weight ratio, high corrosion resistance, and ease of availability. Aluminium alloys have become popular in the automobile, aerospace, recreational, and construction industries. Base aluminium alloys provide good mechanical,

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physical, and chemical properties, but reinforcing aluminium alloy with ceramic particles will improve its mechanical as well as tribological properties [1]. Composites can be fabricated by liquid metallurgy or solid metallurgy; many researchers prefer liquid metallurgy over solid metallurgy because it is inexpensive and more cost-effective for mass production. Stir casting is the simplest and least expensive method of processing [2]. Non-uniform dispersion of particulates due to poor wettability and gravity-regulated segregation is a common problem with the stir casting technique. It is critical to avoid the reinforced material forming an intermetallic compound with the matrix element [3][4]. To improve their physical and mechanical properties, aluminium alloys are reinforced with ceramic particles such as SiC, CeO_2, TiO_2, and others. Several aluminium alloy series have been used in industries; the most popular are the Al 6000 and Al 7000 series due to their ease of fabrication, low cost, and machinability. A.M. Xavior et. al [5] developed composites considering aluminium alloys from the 2xxx series as the matrix and SiC and Al_2O_3 as reinforcements by the powder metallurgy route. The composite had 1.5 times the compressive strength of the peak-aged aluminium alloy 6061. The molten metal and ceramic foam only slightly reacted. Microwave sintering was used to process the aluminium reinforced with silicon carbide at 5 vol% at a sintering temperature of 770 °C and a pressure of 250 MPa [6]. Many researchers have attempted to develop metal matrix composites with widely available reinforcements such as graphite, silicon carbide, titanium carbide, tungsten, boron, Al_2O_3, Al-Mg, ZA27, and TiB2[7][8][9][10].

The wear coefficient is a more precise measure of material wear behavior. Kalyan et al. [11] investigated the effects of composite wear life under various normal loads and sliding speeds. When a composite is composed of a base aluminium matrix alloy in a dry lubricated condition, the coefficient of friction was significantly reduced. In dry sliding wear conditions, titanium di-boride (TiB_2) demonstrated improved wear performance and a decrease in the coefficient of friction [12]. The challenge with primary processed metal matrix composites is the non-uniform reinforcement distribution caused by poor wettability, which leads to porosity. To address this issue, researchers are exploring secondary processing techniques such as forging, rolling, and extrusion. In the light of the forgoing, this study aims to characterize aluminum 6063 matrix composites reinforced with ceramic particulate of silicon carbide, SiC stands out for its lightweight nature, high strength, and ability to enhance wear resistance. The weight fractions of SiC used in the composites range from 0 to 8wt%. The composites were developed using the liquid metallurgy route through the stir casting technique. Following casting, the composites underwent secondary processing through hot extrusion to investigate the effects of extrusion and comprehensively understand the impact of varying SiC content on the mechanical and wear properties of the resulting composites.

2. Experimental work

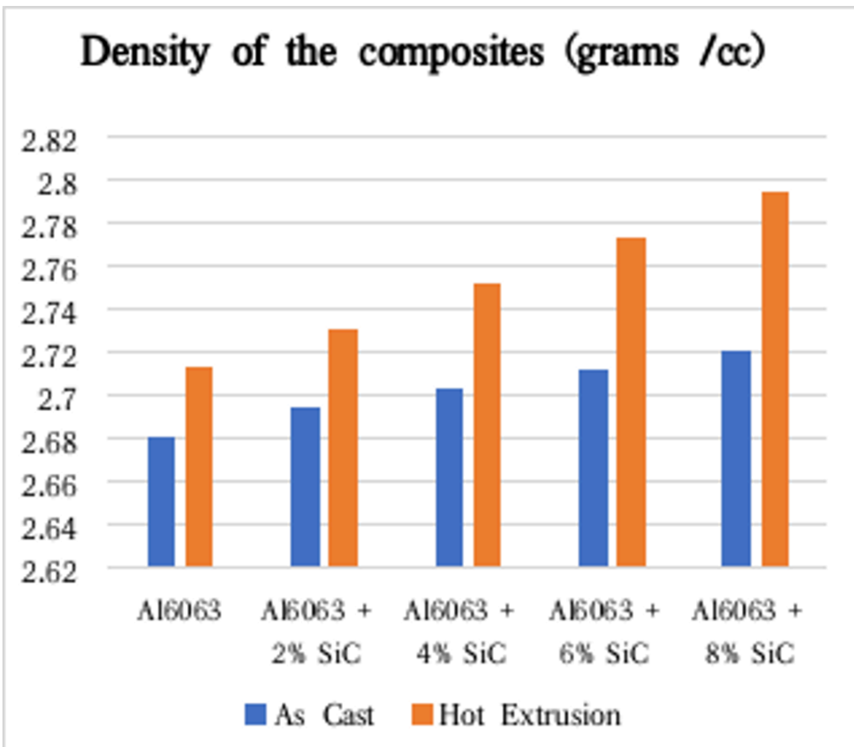
2.1. Fabrication of the composite

Al6063-SiC composites were fabricated using a liquid metallurgy route (stir-casting). Locally procured aluminium ingots were melted in an electric resistance furnace till they reaches to molten state. Silicon carbide is preheated to 400°C to remove moisture and trapped gases. The pre-heated silicon carbide were then introduced into molten aluminium at a predefined weight percentage. To ensure thorough mixing and uniform distribution of reinforcement within the aluminum matrix, continuous stirring was performed using a mechanical stirrer. The molten melt temperature was maintained at 720°C, and the stirring process was continued for 10 minutes at a speed range of 300-400rpm. The developed molten melt is then poured into permanent moulds that are pre-heated to 200°C to drive out moisture. The stirring speed, duration, and temperature, which are crucial parameters, were meticulously considered [13]. Subsequent hot extrusion processing was performed on the cast composite to enhance its mechanical properties. The hot extrusion operation was conducted using a 500-ton extrusion press at a temperature of 550°C. An extrusion ratio of 9.0 was maintained to ensure significant deformation and consolidation of the composite material. The ram speed during the extrusion process was set to 2 millimeters per second, providing a controlled and consistent flow of the material through the die. For mechanical and wear testing, all developed composite specimens were machined following ASTM and IS standards. Each test consisted of a set of three samples, and the average readings were calculated. This approach ensured consistency and reliability in the test results, providing a representative understanding of the material's properties. Tensile tests were conducted according to ASTM B557M standards, while compression tests followed ASTM E9 standards. This ensured that the specimens met the required specifications for accurate and reliable testing results. Al6063 and its developed composites systems were subjected to tensile test on FIE (Fluid Instruments and Engines) machine of 400kN capacity. Vickers microhardness tests were performed on all samples as per ISO 6507. The polished samples were subjected to microhardness tests on a Shimadzu Micro hardness tester. The microhardness was determined by applying 10 N load for 20 seconds. The specimen were prepared as per IS1757 standard for charpy impact test. The notch is located at the bottom opposite to the hammer. Adhesive wear test was performed on a standard pin on disc wear test rig as per ASTM G99 standard, wear test samples for various loads ranging from 10 N to 60 N in step of 10N at a constant speed of 100 rpm and constant track radius of 0.2 m were used to study the wear rate of both the matrix alloy and its composite system.

3. Results and Discussion

3.1. Density and porosity

The density test was conducted on all prepared composite systems, for both the as-cast and hot extruded conditions,



Graph 1. Density of composites with different reinforcement percentages in as-cast and hot extruded conditions.

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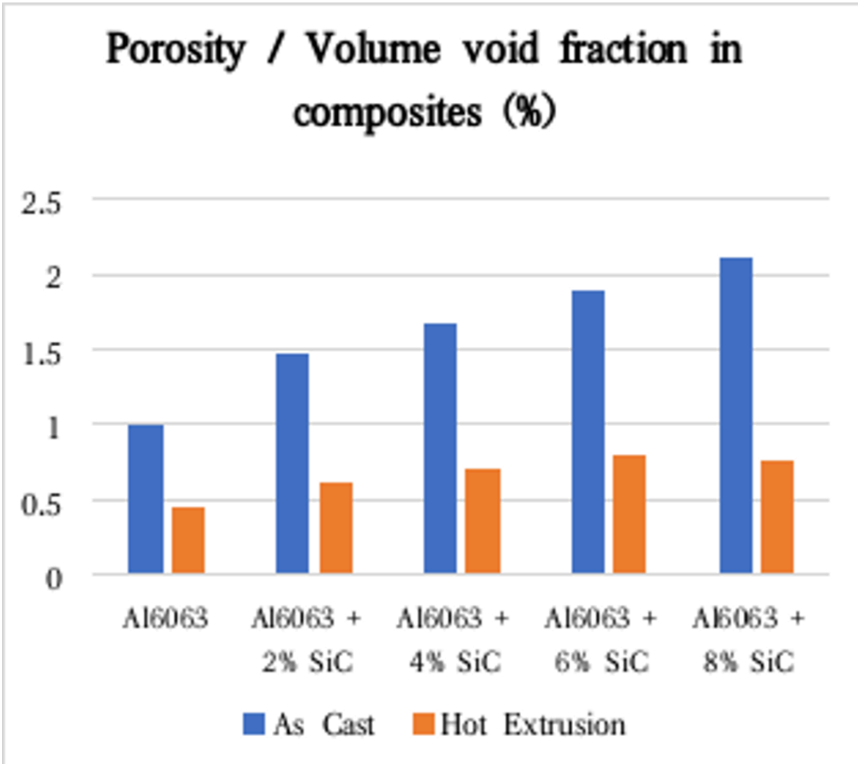

Graph 2. Porosity of composites with different reinforcement percentages in as-cast and hot extruded conditions.

Graphs 1 and 2 show the density and porosity of the developed composite systems with varying weight percentages in the as-cast and hot extruded conditions.

The results reveal that the density continued to increase with increasing weight fractions of reinforcement in composites. Due to differences in the density and mechanical structure of crystals and the atomic arrangement in ceramic reinforcements, density exhibits a relative enhancement with the increasing weight fraction of reinforcement. This is consistent with the findings of other researchers such as Hima et al[14]. Density improves further in postcast processing by 1.2%. This is due to strain hardening and the atomic compacting of composites, which results in optimal interstitialcy and atomic substitutions at elevated temperatures (generally in a higher state of temperature), a similar observation found with other researchers [15][16].

It was noticed that the porosity of the composite is mainly influenced by the particle size of ceramic reinforcements; thus, as the volume fraction of reinforcement is increased, porosity is also increased due to the inhomogeneity of the alloy and the reinforcing element at the atomic level and the

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particulate nature of reinforcements. Mohanakumar et al. [17] reported that the porosity percentage was significantly reduced in the secondary processing extrusion when compared with the cast composite.

3.2. Tensile test results

Tensile tests were performed under controlled conditions on composites containing varying weight fractions of SiC reinforcements of 2%, 4%, 6%, and 8%, as shown in Fig. 1.

Fig. 1. Tensile tested specimen

The test results were compared to those of the unreinforced Al6063 alloy. The ASTM E-8 standard was followed in the test, and testing standards were carefully studied. Three specimens were tested for each sample to statistically optimize the test data. The mechanical testing data were used to calculate the tensile properties and the strength of the composites, resulting in tensile strength and elasticity modulus. The elongation of the material is observed to decrease with the incorporation of ceramic reinforcements. A similar observation was made by another researcher [18]

The elasticity modulus of composites with SiC reinforcement had a significant effect on tensile strength. Tensile strength was improved by 78% with an increased reinforcement quantity in composites. Furthermore, with post-cast conditions of hot extrusion, tensile strength was improved as observed in graph 3. The Young's modulus of the composites was improved at a maximum reinforcement of 8%, as seen in graph 4.

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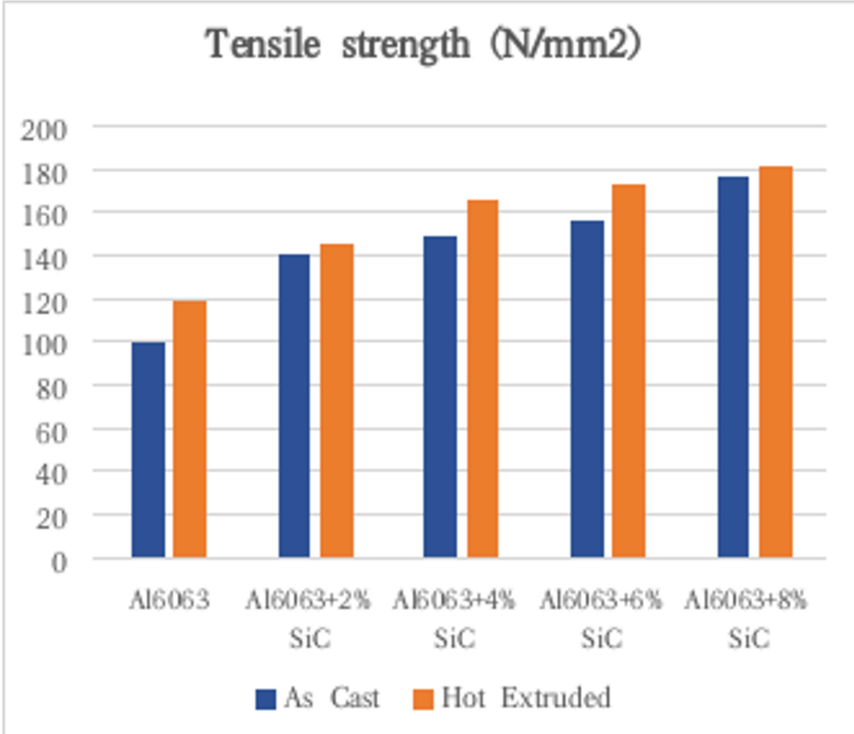

Graph 3. Tensile strength effect on the progressive integration of SiC reinforcement from 0% to 8% in as-cast and hot extruded conditions.

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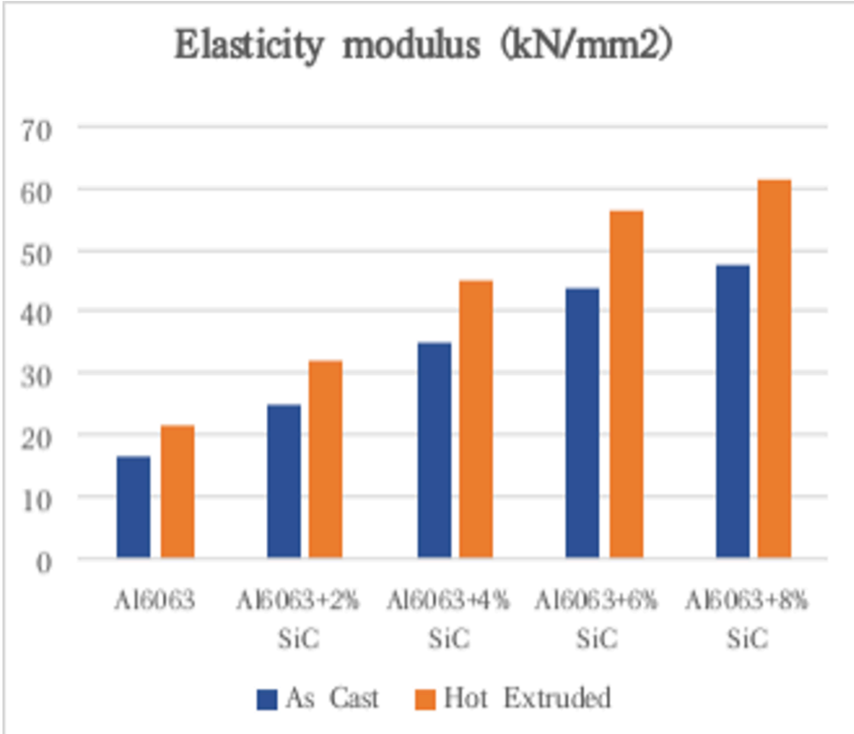
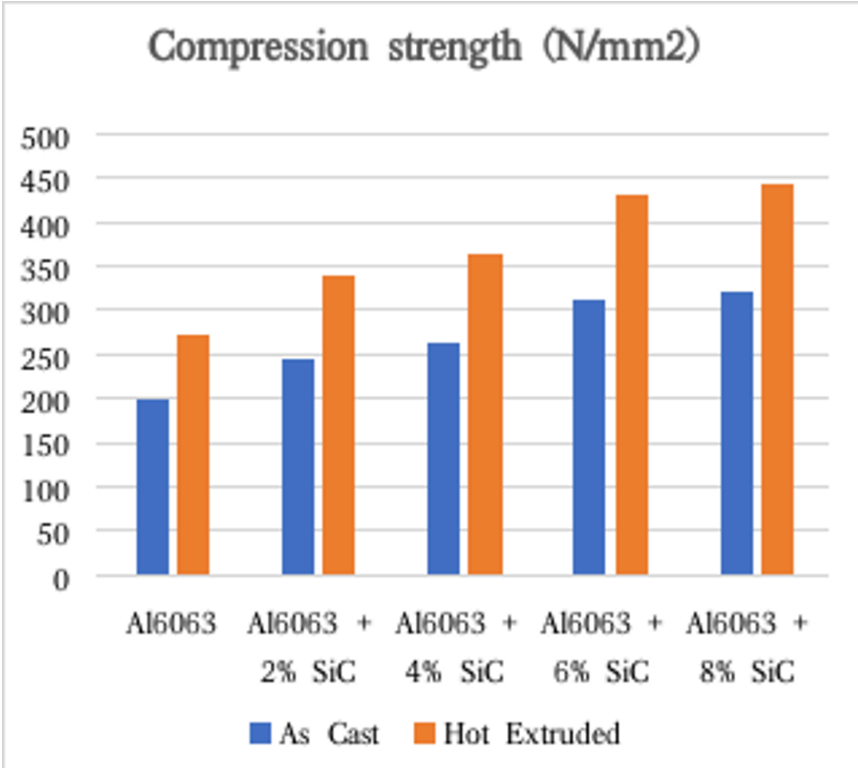


Graph 4. Young's modulus effect on the progressive integration of SiC reinforcement from 0% to 8% in as-cast and hot extruded conditions.

3.3. Compression test

Fig. 2. Samples of the compression test specimen



Graph 5. Compression strength for the effect of the progressive integration of reinforcement under cast and hot extruded conditions.

The crushing of SiC-reinforced composites was observed to be steady due to the optimal mixture of SiC into the aluminium alloy. Compression strength was increased by 62% for a maximum SiC reinforcement of 8%, as seen in graph 5. The fracture behaviour of silicon carbide-reinforced composites was found to be identical to that of the as-cast condition, with progressive integration of SiC reinforcement resulting in a harder and stronger material under compression.

3.4. Vickers hardness test

The investigation revealed that reinforcement has a significant impact on hardness. The hardness of the material increased as the quantity of reinforcement increased, and it demonstrated linear improvement with systematic doping of particulate reinforcement. For a maximum weight fraction of 8%, silicon carbide has the highest hardness. Hot-extruded aluminum-based composites have influenced hardness because the pressurized and hot work of the material has evidently resulted in the compacting of crystals under mechanical and thermal loads, resulting in a greater atomic packing factor in the material and thus increased atomic density, which has improved hardness. This is coherent with the observations of other researchers. [19][20]

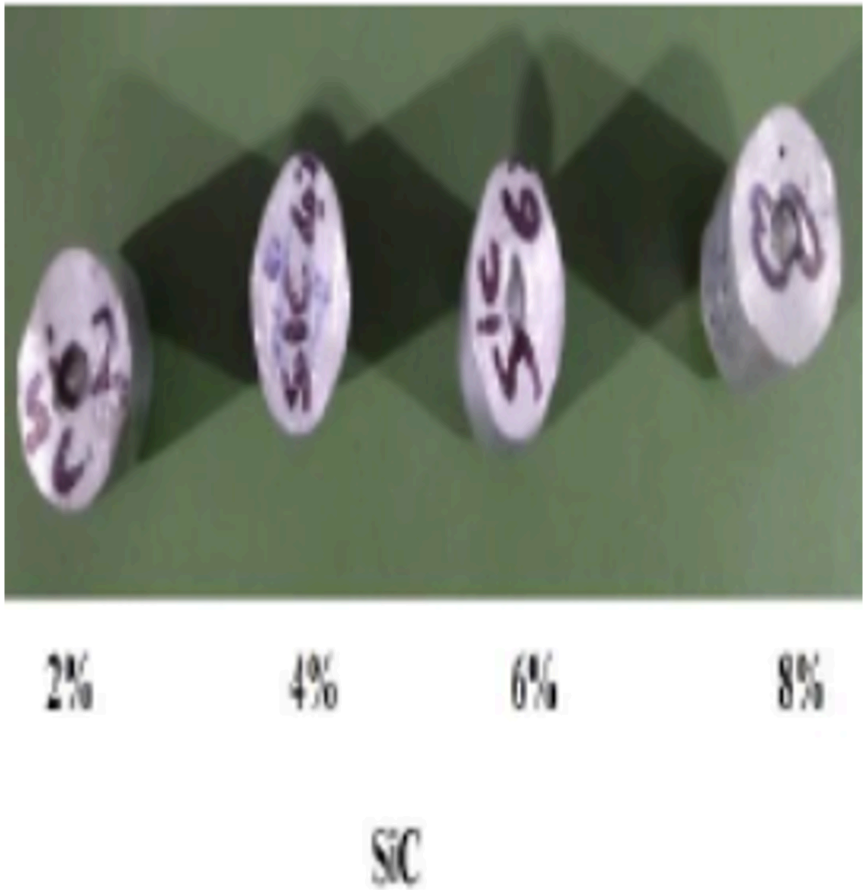


Fig. 3. Specimens tested for hardness using a Vickers hardness tester

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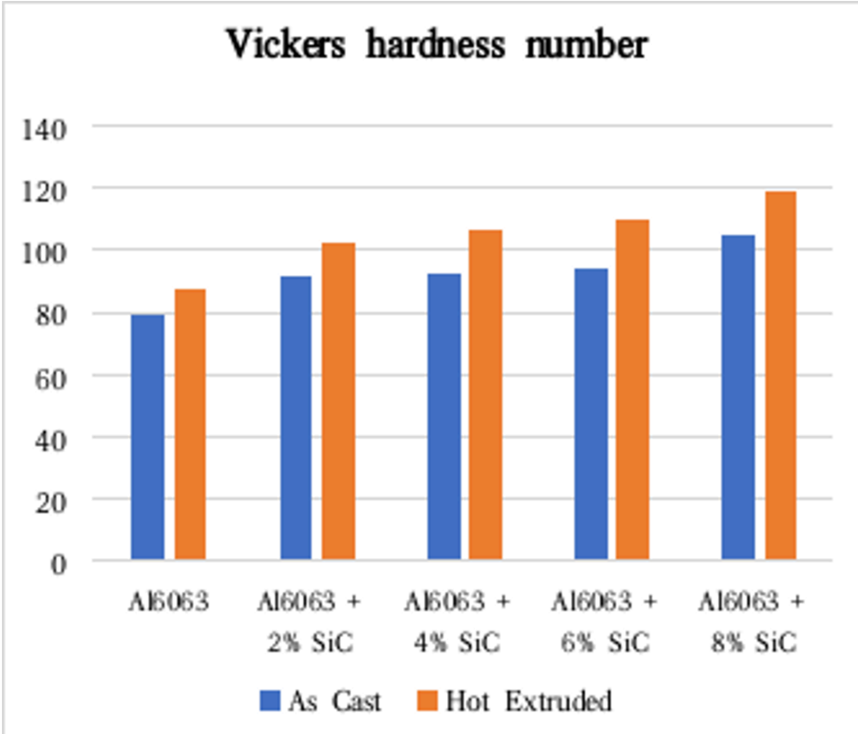

Graph 6. Hardness of composites by varying the percentage of reinforcement in the as-cast and hot extruded conditions

3.5. Impact test

Graph 7 shows that the impact strength of the material has an adverse effect on composition and showed depleting impact strength as the reinforcement quantity increased. This is due to the fact that densification of the material increased hardness, which increased brittleness and thus resulted in crack propagation by intergranular augmentation, and thus the material failed due to embrittlement of the material due to the intense doping of ceramic reinforcements causing over-interstitialcy and a reduction in the ductile nature of the material, as observed in other research findings[21][22]. Due to its high-temperature working environment, the hot extrusion process has significantly reduced the distortion of impact strength, and recrystallization of the material has aided in the effective doping and arrangement of atoms in their orientation, which has resulted in atomic bonding, allowing it to withstand impact loads, in agreement with similar findings from other researchers [23]

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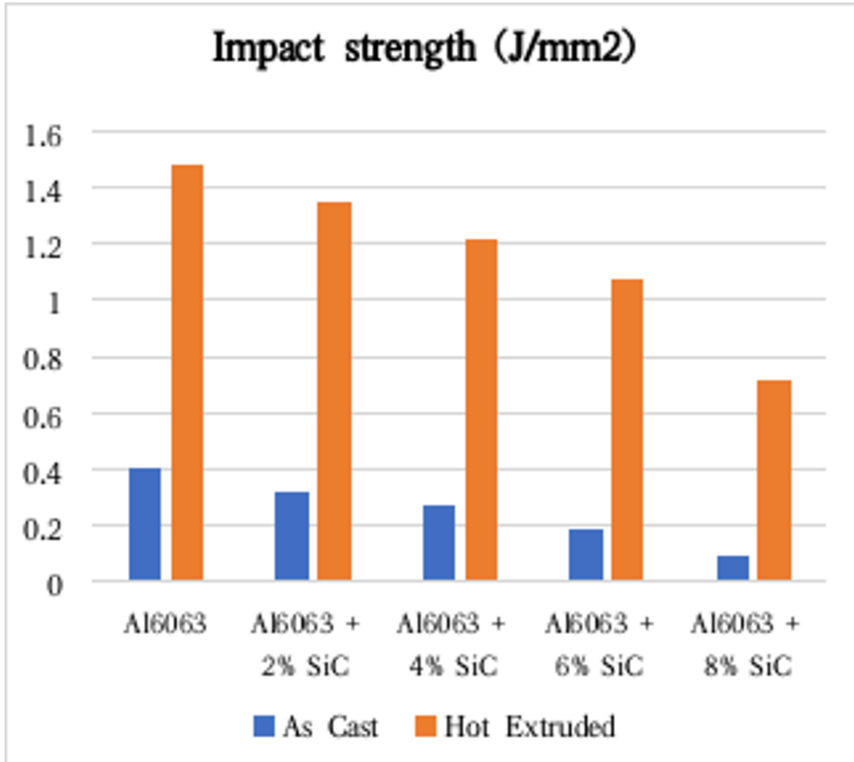
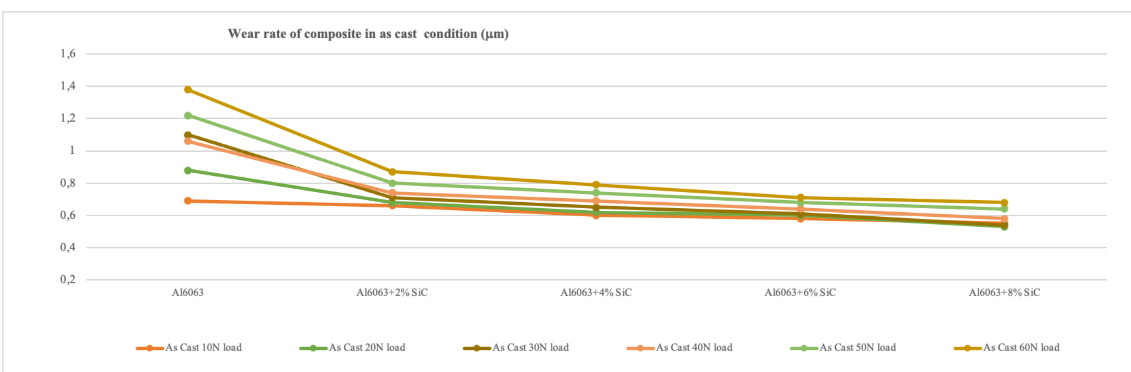
SiC

Fig. 4. Specimens tested under Charpy impact



Graph 7. Impact strength of composites with varying percentages of reinforcement in the as-cast and hot extruded conditions

3.6. Adhesive wear test



Graph 8. Wear rate of composites in the as-cast condition under different loads, reinforced with a silicon carbide reinforcement.

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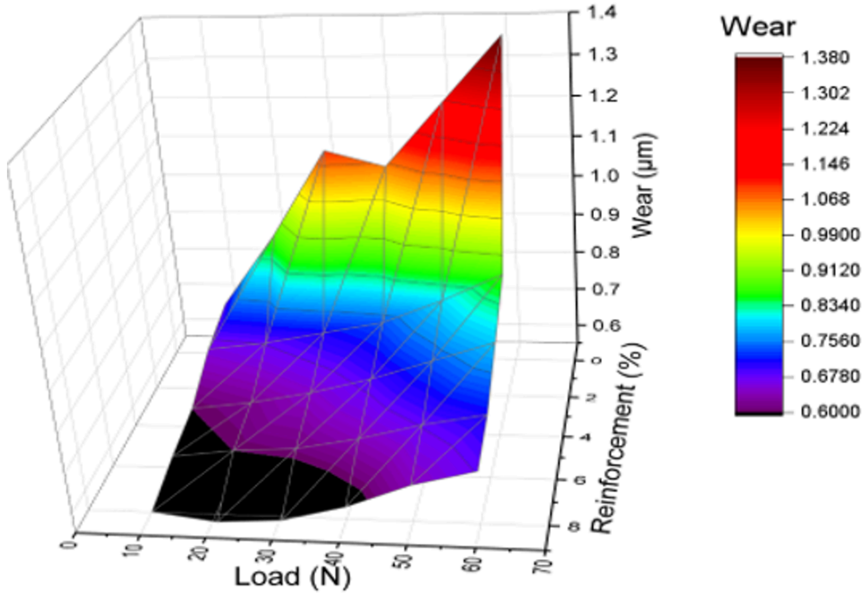

Graph 9. Effect of load and reinforcement on the wear rate of SiC-reinforced composites in the as-cast condition.

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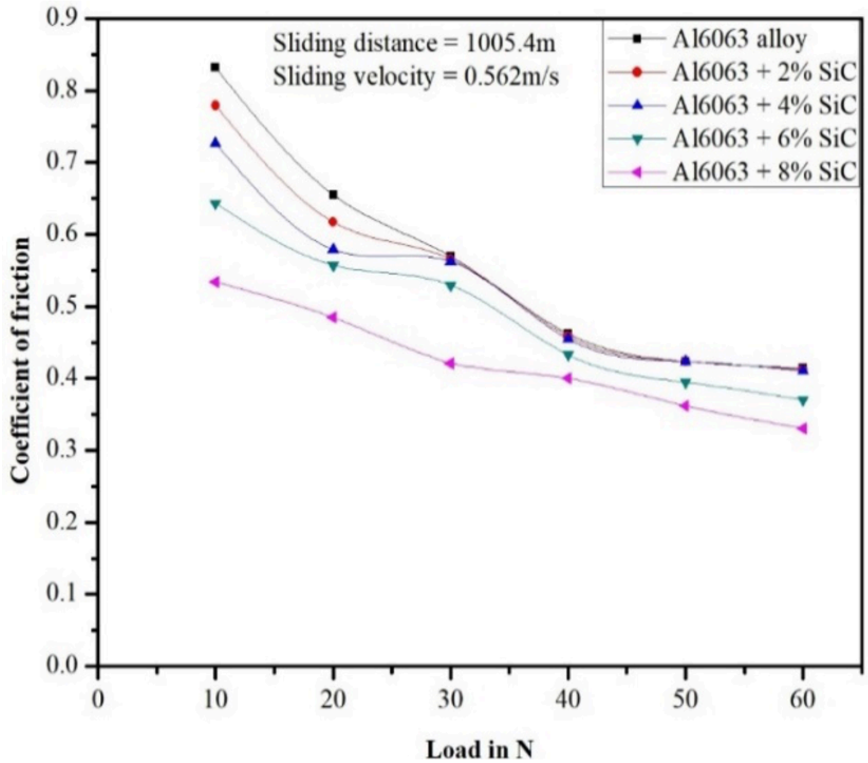
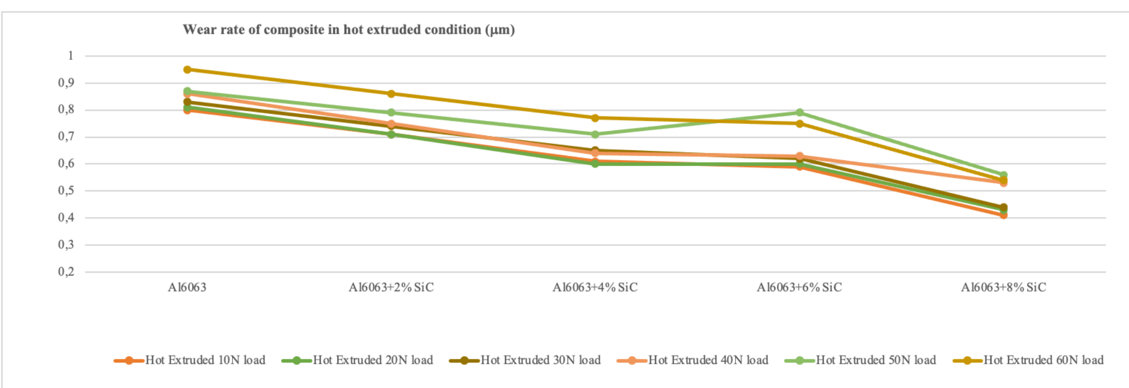


Graph 10. Coefficient of friction of composites by varying the weight of SiC reinforcement at different loads in 'as cast' condition.

Graphs 8-10 show the wear rate and coefficient of friction for various loads for a composite reinforced with SiC with various weight fractions under 'as cast' conditions.. Similar observations have been made by other studies [24][25]



Graph 11. Wear rate of composites in the hot extruded condition under different loads, reinforced with Silicon carbide.

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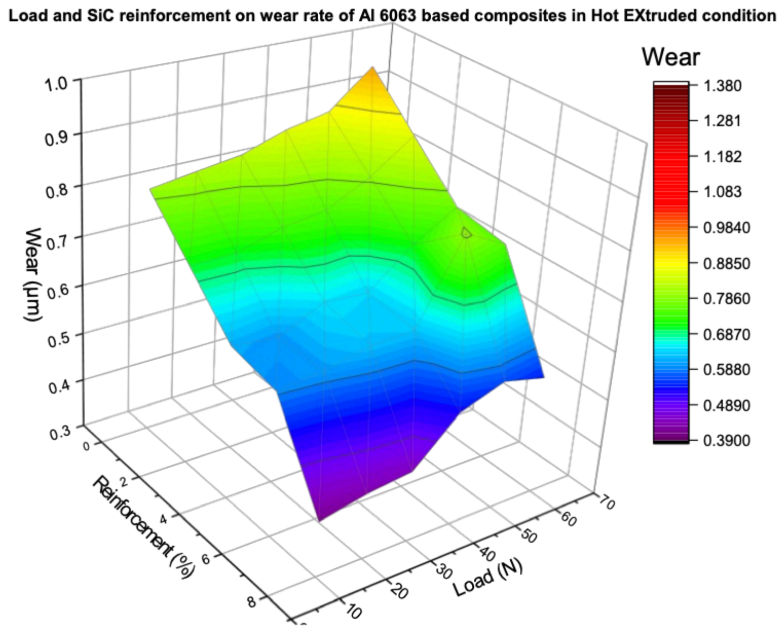
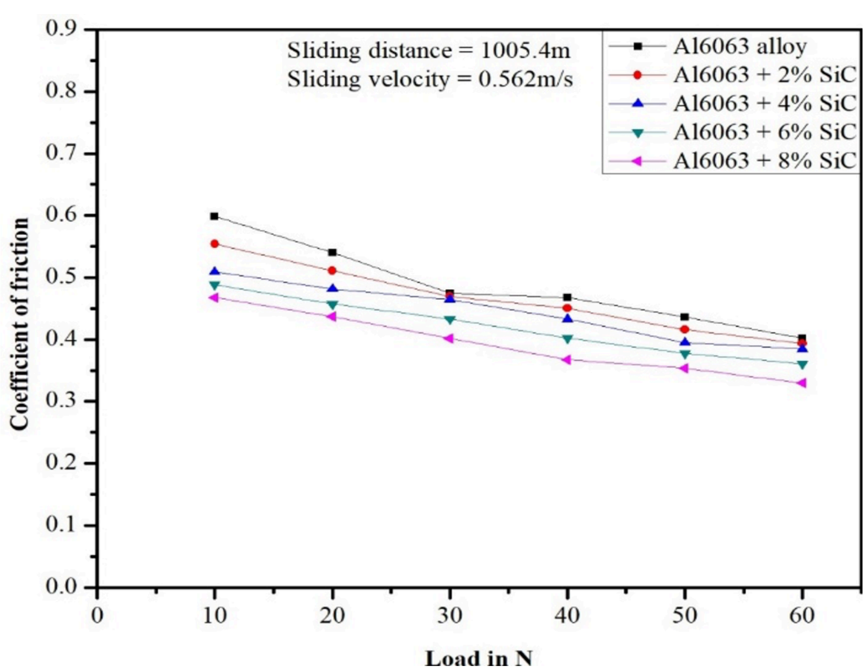


Graph 12. Effect of load and reinforcement on the wear rate of SiC reinforced composites in the hot extruded condition.



Graph 13. Coefficient of friction of composites by varying the weight of SiC reinforcement at different loads in the hot extruded condition.

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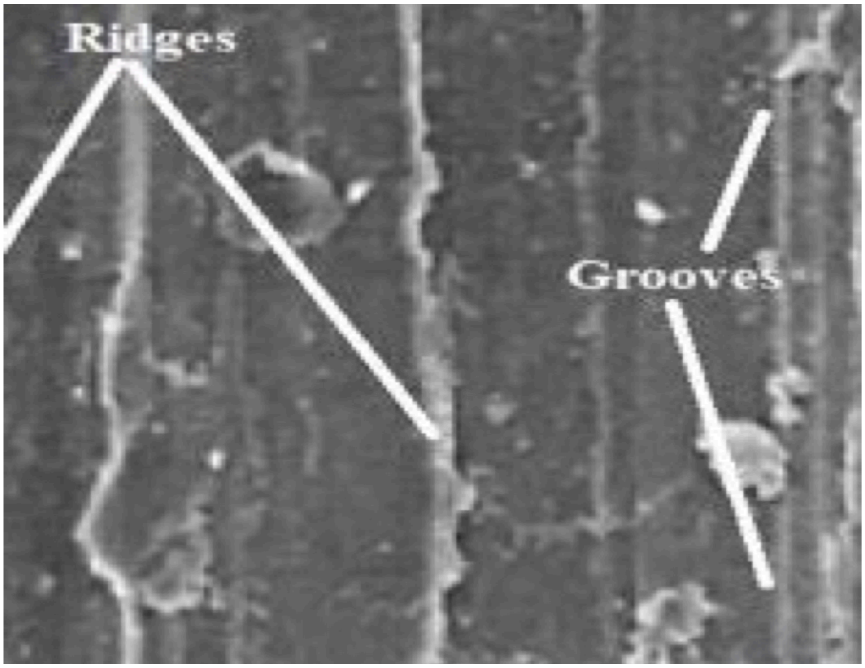
Graphs 11-13 show the wear rate and coefficient of friction for various loads for a composite reinforced with SiC with various weight fractions under 'as cast' conditions.

From the above graph 8-13 the wear rate studies for the developed composite system, under both as-cast and hot-extruded conditions. The graphs indicate that as the applied load increases, the wear rate of the composite also increases. This is attributed to higher contact force and increased adhesive forces. Notably, the wear rate shows an almost linear relationship with the applied load. Furthermore, the wear rate decreases linearly with an increase in the percentage of reinforcement. This suggests that higher reinforcement content improves the composite's resistance to wear. The hot-extruded composite, in particular, shows a significant improvement in wear performance compared to the as-cast condition. This improvement is likely due to the higher density and better distribution of reinforcement achieved through the hot extrusion process. This reduction indicates a more stable wear surface and less material adhesion. The coefficient of friction is higher in the as-cast condition, whereas it is relatively lower in the hot-extruded composites. This lower coefficient of friction in hot-extruded composites reflects a dominance of adhesive wear mechanisms over abrasive interactions. The high compactness of the composites developed under high pressure and temperature during hot extrusion contributes to this behavior. The wear tracks in hot-extruded composites are smoother, with some evidence of material transfer and plowing. This smoother wear pattern is indicative of the improved structural integrity and uniform reinforcement distribution achieved through the hot extrusion process. Consequently, the hot extrusion process significantly enhances the wear resistance and overall performance of the developed composite system.

3.7. Surface micrograph study of wear

The wear track morphology changes significantly with varying loads, as shown in Graphs 14-17. These graphs indicate that different wear mechanisms dominate at different load levels, a phenomenon also observed in other studies [24][25][26][27][28]. In the micrographs it is seen that material was removed due to adhesion and abrasion in sliding wear mechanism. Graph 14 represents the micrograph of worn surface of Al 6063 alloy, in which it is seen that alloy formed ridges, grooves, flash and wedges due to the soft nature of material. SiC reinforced composite has shown resistance and hence not much debris or flashes are seen but it formed ridges and grooves, due to the residual wear track. This in accordance with other researcher [29]



Graph 14. SEM micrographs of the wear surface of reinforced composites in the as-cast condition: Al6063 without reinforcement

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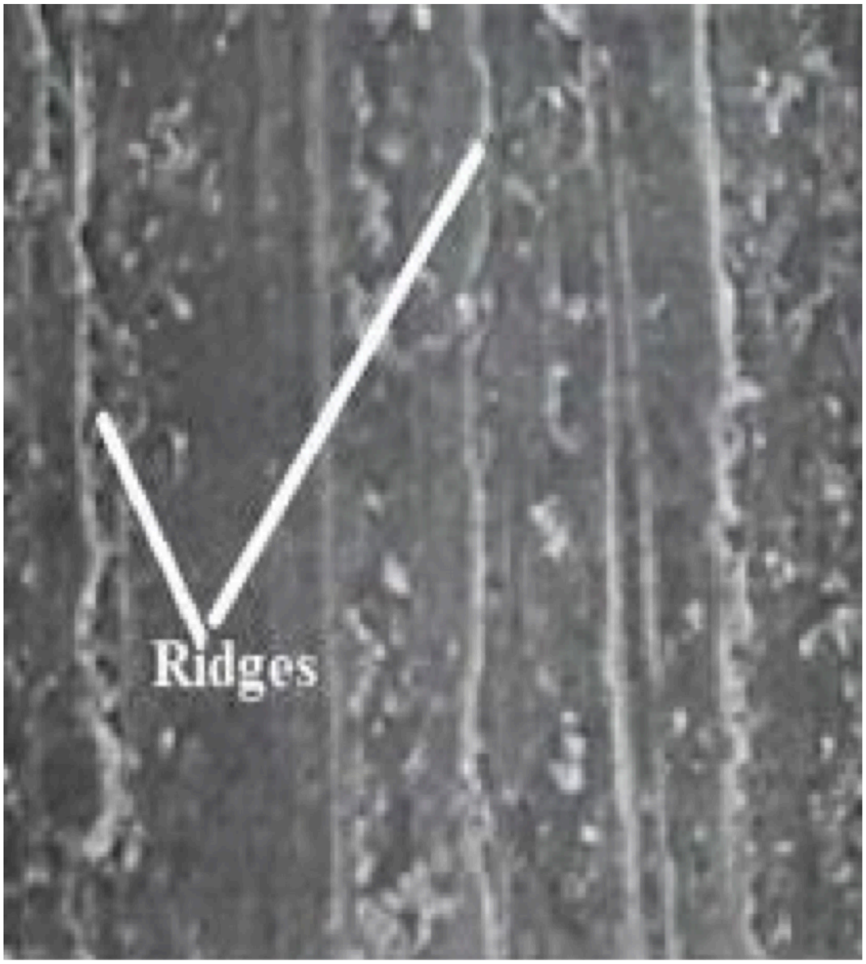

Graph 15. SEM micrographs of the wear surface of reinforced composites in the as-cast condition with 8wt.% SiC

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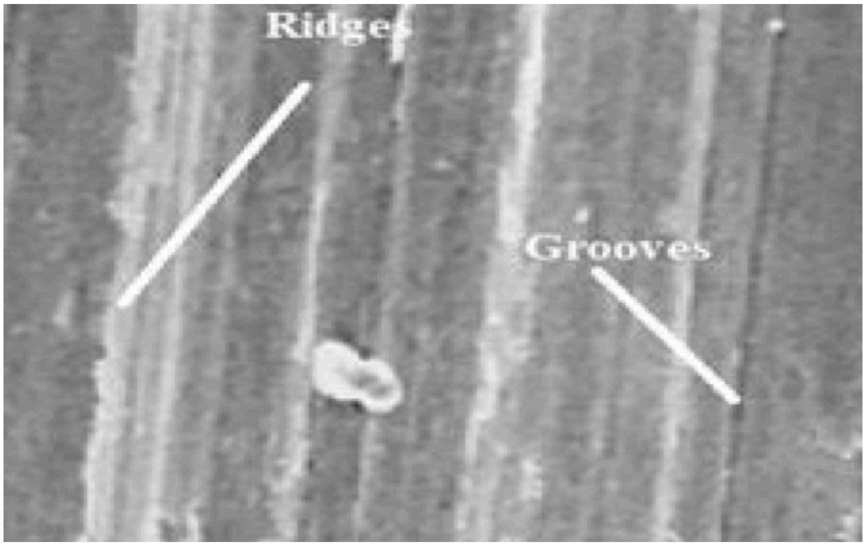
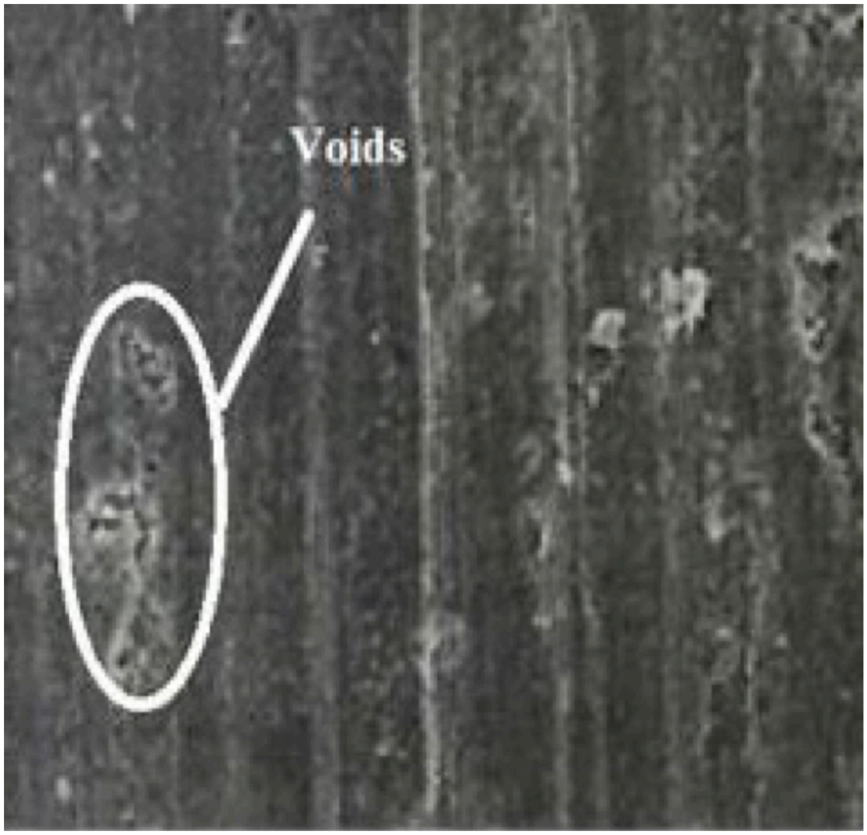


Graph 16. SEM micrographs of the wear surface of reinforced composites in the hot extruded condition, Al6063 without reinforcement



Graph 17: SEM micrographs of the wear surface of reinforced composites in the hot extruded condition with 8wt.% SiC

Hot extrusion process significantly enhances the wear resistance of Al6063 composite systems by increasing its hardness and influencing the wear mechanisms. The increased hardness of hot extruded materials is primarily due to the refined microstructure achieved through the extrusion process. During hot extrusion, the material undergoes substantial plastic deformation, which breaks down the grain structure and distributes alloying elements more uniformly. This increased hardness directly correlates to a lower wear rate, as harder materials are more resistant to the abrasive and adhesive forces encountered during wear.

In graph 16, the presence of ridges and grooves on the surface of hot extruded Al6063 indicates the wear patterns that develop during the wear testing. These features are typical of a material that has undergone significant plastic deformation during wear. The extrusion process influences these wear patterns by aligning the material's microstructure in a way that promotes uniform wear resistance across the surface. The consistent presence of ridges and grooves suggests that the extrusion process contributes to a stable wear mechanism, reducing the overall wear rate. Wear debris analysis provides valuable insight into the wear mechanisms at play in materials such as hot extruded Al6063. The debris from this composite material predominantly consists of fine particles of aluminum and silicon carbide (SiC). This composition reflects the inherent composite nature of Al6063, highlighting the interactions between the aluminum matrix and the SiC reinforcement during the wear process. The predominance of fine particles suggests that the wear mechanisms involved are primarily micro-abrasion and micro-adhesion. Micro-abrasion occurs when hard SiC particles either dislodge from the matrix or act as abrasive agents or when they remain embedded and cause localized wear on the softer aluminum matrix. This is indicative of the significant role that SiC particles play in the wear process. Their hardness and angularity contribute to the abrasion of the aluminum matrix, generating fine debris. Furthermore, the presence of SiC particles in the wear debris underscores the mechanical interactions within the composite. These particles are not only instrumental in reinforcing the matrix but also in contributing to its wear. During sliding contact, SiC particles may become loose from the matrix due to differential wear rates or stresses at the interface. Once dislodged, these particles can exacerbate wear by acting as micro-abrasive elements that grind against the aluminum matrix.

4. Conclusion

- The density of the composites increased proportionally to the percentage of reinforcement. The highest density was observed with 8% reinforcement. In hot extruded Al 6063, the volume of voids or porosity was found to be reduced by 54%.
- The mechanical properties of the composites improve significantly with the addition of reinforcements before extrusion. The hot extrusion samples showed even more improvement.
- In the hot extruded composite, the grains were noticeably refined, and the reinforcement layers were considerably dissolved, reflecting the effective diffusion and doping of reinforcement atoms into the Al 6063 matrix.
- Wear debris analysis of hot extruded Al6063 reveals that the wear mechanisms are dominated by micro-abrasion and micro-adhesion
- The wear rate of the composites decreased as the reinforcement quantity increased, as the form and quantity of reinforcement demonstrated the tribological advantage of materials.
- Topographic analysis of the worn surfaces of sliding wear observed under SEM and the optical specimen under sliding wear revealed less wear and tear.

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