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Wear Behaviour and Surface Analysis of Hybrid Al 6061 Composites Reinforced with Tungsten Carbide and Fly Ash

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Abstract

The experimental investigation explores the tribological behaviour of Al 6061 reinforced with a hybrid composition of Tungsten carbide and Fly ash. Al 6061's attributes, such as cost effectiveness and lightweight, are determined to be suitable in most applications. Tungsten carbide reinforcement enhances the strength and hardness of the material, while Fly acts as a lubricant and enhances the wear resistance of the material.The experimentation investigates the wear behaviour of the hybrid Al 6061 composites with varying composition of Tungsten Carbide by increasing steps of 3wt%, varying from 1wt% to 7wt% and 2 wt% constant reinforcement composition of Fly ash to form a combined reinforcement composition of 3wt%, 6wt% and 9wt% respectively. The hybrid Al 6061 composite specimens are subjected to 3-body abrasive wear behaviour with silica particles of 212µm size as abrading material. The investigation reveals that the hybrid composition with 6wt% reinforcement exhibits maximum wear resistance, and further increase in the composition leads to an increase in wear loss due to debonding of particulates as a result of an increase in brittleness in the material with the increase in the presence of higher percentages of particulate reinforcement. Henceforth, the hybrid composition of 94wt% base material, 4wt% Tungsten carbide and 2wt% fly ash is identified as the optimal combination resulting in high wear resistance. The volume loss for the optimum combination is found to be 0.075gm, 0.095gm and 0.2156gm for the loads, 11N, 53N and 102N, respectively. The SEM images reveal the presence of wear tracks, material deformation and surface morphology as a result of variation in the applied load and interaction of abrasive particles on the surface of the hybrid material.

Major Findings: *The optimal combination of 4wt% Tungsten carbide and 2wt% fly ash with Al6061 base material results in enhanced wear resistance compared to other compositions. The wear resistance increases with an increase in composition up to 6wt%.*

Keywords: *Fly Ash, Hybrid Al 6061 Composites, Tribological Behaviour, Tungsten Carbide*

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1.0 Introduction

Conventional metals often face limitations in achieving specific mechanical properties such as strength, hardness, stiffness, toughness, and wear resistance. Metal Matrix Composites (MMC) have been developed to address these issues. MMCs offer advantages such as low density, improved wear resistance, and superior specific properties. The production of lightweight composites, which are in high demand in the automotive and aerospace industries, necessitates the reduction in density in particular[1-4]. If hard particulates are reinforced with MMC, the materials get improved tribological and mechanical properties[5-7]. MMC have two phases, namely, the Matrix Material and Reinforcement Particulates. The stir casting method, a liquid-state fabrication technique, is generally used to produce these composites as this method minimises the casting defects[8].

Aluminium 6061-Graphite Nano filler composites were developed with varying percentages of Nano-Graphite using the hot extrusion method, and results showed significant improvements in tensile strength, hardness, and wear resistance with increased Nano-Graphite filler content[9,10]. The tribological performance of the developed Aluminium 6061-Graphite composites was investigated using a Pin-on-Disk wear test setup, and the wear rate was found to increase with higher sliding velocities and greater applied load[11]. The work on Aluminium as a matrix, Tungsten Carbide and Fly ash as a reinforcement with varying weight percentage is considered in this study to analyse the characteristics of MMC.

Scanning Electron Microscopy (SEM) analysis of worn-out surfaces reveals that the primary mode of failure in composite materials was due to delamination at the fibre-matrix interface. This failure occurs when the bond between the fibres and the matrix weakens, leading to separation under stress. The SEM images highlight that the poor bonding at the interface significantly reduces the material's durability. However, SEM images also demonstrate the improvement of the fibre-matrix bond, which can enhance the material's performance and resistance to wear. Stronger bonding helps prevent delamination, ensuring greater reliability in demanding applications[12,13].

In the present investigation, an experimental study has been conducted to analyse the wear loss in terms of the tribological behaviour of a hybrid composite material. The composite consists of Al 6061, a lightweight and commonly used aluminium alloy, as the base metal, reinforced with Tungsten Carbide (WC) and Fly Ash. The goal is to perform a parametric analysis to understand the effects of these reinforcements on wear performance under various conditions.

Aluminium is used as a matrix in composites because it is lightweight as compared to steel and low cost, with superior mechanical and tribological properties[14,15]. The Fly Ash (FA) was selected as the reinforcement phase to develop the materials because it increases the strengths and other Mechanical and Tribological properties[16].

The stir casting method stands out as the simplest and most economical technique for fabricating composites when compared to other production methods[17]. Stir casting is a popular technique for fabricating MMCs, with parameters that significantly impact the material's quality. Key factors include the matrix material, reinforcement type, size, and volume fraction, which influence the composite's mechanical properties. Critical process parameters include melting and pouring temperatures, stirring speed (300–700 rpm), stirring time, and stirrer design to ensure uniform particle distribution. Preheating reinforcement and moulds improves wettability and reduces thermal shock[18].

The composition of the MMC is maintained by keeping Aluminium as a base metal, keeping the Fly ash by weight percentage 2% and varying the Tungsten Carbide weight by 1%, 4% and 7% respectively. The samples were casted using stir casting method and according to the requirement for testing, the samples were prepared.

2.0 Materials and Methods

This involved a systematic approach to study the wear behaviour and characteristics of aluminium-based composites reinforced with Tungsten Carbide and Fly ash. Initially, materials were selected with aluminium serving as the base material and Tungsten Carbide and Fly ash as the reinforcement in MMC. The selected materials were then cast into specimens of desired shapes

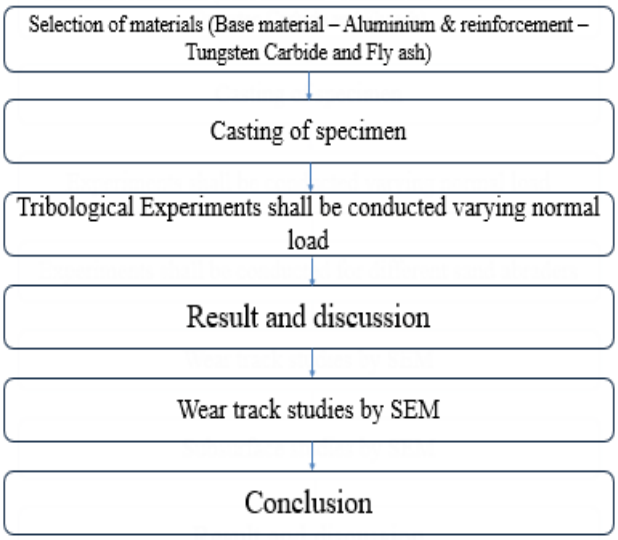


Figure 1. Flowchart of methodology.

and sizes suitable for experimental analysis. The process is explained in Figure 1.

The stir casting process was efficiently carried out using a bottom-pouring stir casting furnace, ensuring uniform reinforcement distribution in MMC. The key parameters selected for this process include the reinforcement percentage, varied at 3%, 6%, and 9%, to study its effect on composite properties. Stirring speed is adjusted at 300rpm, 350rpm, and 400rpm to optimise particle dispersion and mixing. Additionally, stirring times are set at 20 minutes, 25 minutes, and 30 minutes to achieve thorough incorporation of the reinforcement into the molten matrix. These parameters are carefully chosen to enhance the quality and uniformity of the final composite material.

Figure 2 shows the specimen information where (a) shows a sample or plate solidified after stir casting when

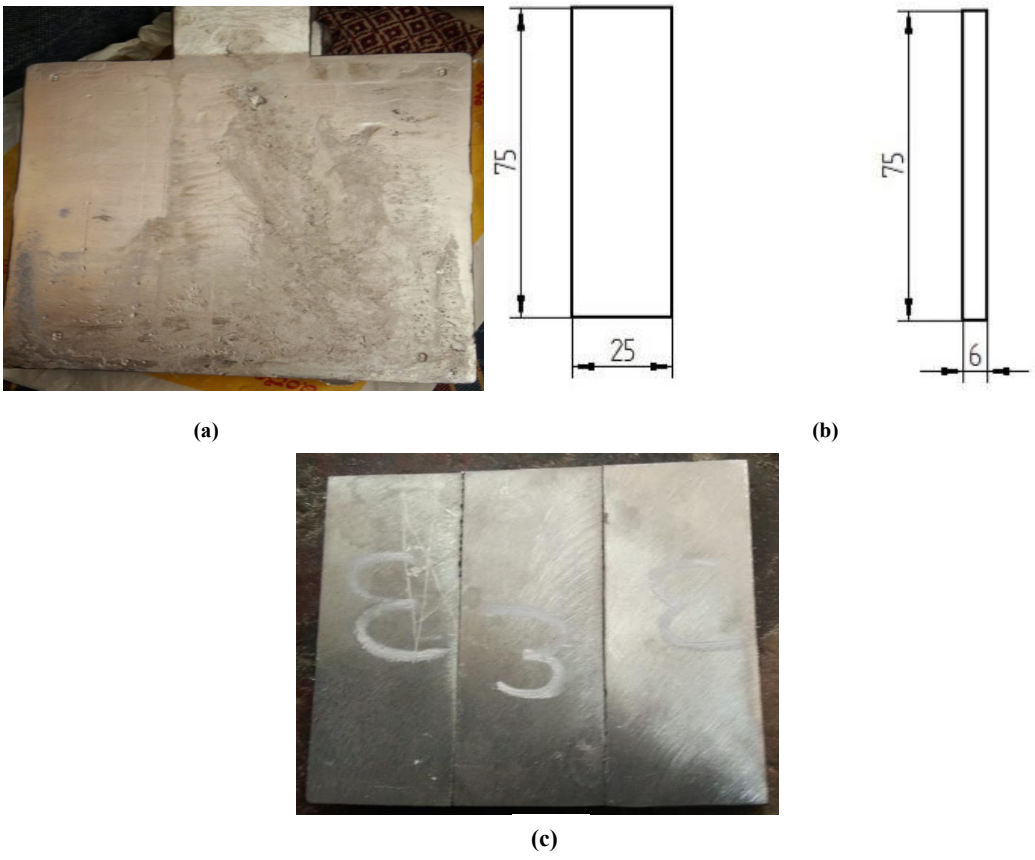


Figure 2. Details of the specimen of hybrid composites for the dry sand abrasion test. **(a)** Solidified sample after Stir Casting. **(b)** Dimension of specimen preparation as per the ASTM standards. **(c)** Sample prepared as per the ASTM standards.



(a) (b) (c)

Figure 3. Specimens of hybrid Al 6061 with **(a)** 3 wt%, **(b)** 6 wt%, and **(c)** 9 wt% reinforcement.

poured into a mould, (b) represents dimensions for preparing test samples from the solidified sample plate as per the ASTM standards (c) represents an image of the final fabricated sample cut as per the standards.

To investigate the effect of load variations on wear behaviour, experiments are carried out with various normal loads on different compositions of materials formed by varying the Tungsten Carbide and Fly ash as reinforcement, as represented in Table 1 with the hardness number for each composition.

Table 1. Hybrid composition of Al 6061 for tribological wear analysis

Sl. No.	Specimen Composition	Brinell Hardness Number
1	Base Aluminium 6061	42.63
2	Tungsten Carbide 1wt% + Fly ash 2wt%	46.834
3	Tungsten Carbide 4wt% + Fly ash 2wt%	49.714
4	Tungsten Carbide 7wt% + Fly ash 2wt%	58.645

Figure 3 depicts the compositions of the reinforcement substantiating the hybrid composition of Al 6061 metal matrix composites.

The sample is positioned against a rotating rubber wheel, and a controlled stream of dry silica sand is introduced between the sample and the wheel. The wheel spins at a designated speed and under a specified force, causing the sand to wear down the surface of the sample. After a predetermined number of rotations, the sample is taken out and weighed again. The weight change (mass loss) indicates the material's resistance to abrasion. This mass loss is often converted to a volume loss for more precise comparisons between different materials. The volume loss is then documented as an indicator of the material's abrasion resistance.



Figure 4. Dry sand abrasion test rig.

The tribological wear analysis of hybrid Al 6061 reinforced with varying composition of tungsten carbide and fixed composition of fly ash is conducted, as per ASTM G65, by using the 3–body Abrasion test rig as shown in Figure 4. The abrasive used for the wear test is composed of commercially available silica with a size of 212μm.

The test is conducted for 3 different loads, i.e., 11.77N, 53.22N, 102.4N, at a constant speed of 200rpm. The wear losses obtained for different loads and different compositions are subjected to wear analysis, and surface morphology and wear mechanisms are analysed using SEM images.

3.0 Results and Discussion

The experimentation investigates wear loss as a parametric analysis of tribological behaviour of a hybrid composition of Al 6061 base metal reinforced with Tungsten Carbide and Fly Ash.

It is evident from Table 1 that the presence of Tungsten Carbide as reinforcement has enhanced the hardness of the material with an increase in the addition of the particulates. The hybrid composition consists of Fly ash with constant addition of 2%wt, as the increase in addition of Fly ash will lead to brittleness in the composite and pave the way for crack initiation upon loading. However, the lubrication property of Fly ash will help in resistance to wear, enhancing the wear strength of the hybrid composites.

3.1 Tribological Wear Analysis

The hybrid composition of Al 6061 base metal with varying Tungsten Carbide and Fly ash reinforcements is subjected to 3-body wear analysis by conducting wear at 3 different loads. Commercially available silica with a grain size of 212µm is used as the abrading material.

Table 2 represents the abrasive wear behaviour of 3wt% hybrid Al 6061 composites comprising 1 wt% Tungsten Carbide and 2 wt% Fly ash. It is evident from Figure 5 that the increase in wear loss occurs with an increase in load. However, it is also observed that the wear loss is not linear with respect to preceding loads. Instead, a greater difference in wear loss can be observed for higher loads compared to lower loads.

The wear behaviour of 6wt% Al 6061 Hybrid Composites formed by 4 wt% Tungsten Carbide and 2 wt% Fly ash is represented in Table 3. It is observed same trend of wear behaviour is observed in this composition compared to 3wt% Al 6061 Hybrid Composites. However, it is evident from Figure 6 that the weight loss of material is slightly lower compared to 3wt% Al 6061 Hybrid Composites, as tungsten carbide provides strength while Fly ash acts as a lubricant.

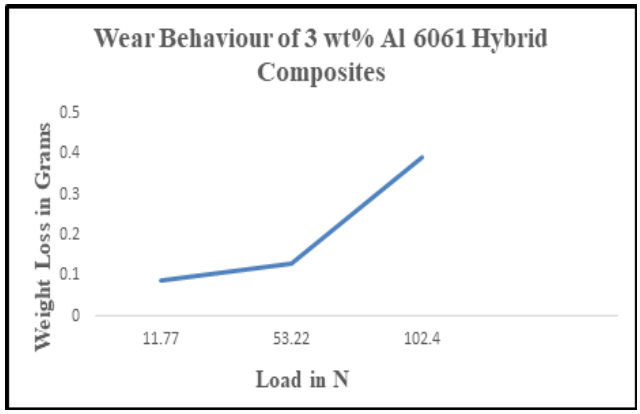


Figure 5. Wear behaviour of 3 wt% Al 6061 hybrid composites.

In the Dry Sand Abrasion Test, the wear loss of materials is typically influenced by the reinforcement content in composites. Generally, as the percentage of reinforcement in a composite increase, wear resistance improves, leading to a reduction in wear loss. This is because reinforcements, such as ceramic particles or fibres, enhance the hardness and strength of the material, effectively distributing and resisting the abrasive forces. However, an excessive amount of reinforcement can sometimes lead to agglomeration, reducing uniformity and potentially increasing wear loss. Thus, achieving an optimal balance in reinforcement percentage is crucial for minimising wear loss in abrasive conditions.

Table 2. Hybrid composition of Al 6061 with 1 wt% tungsten carbide and 2 wt% fly ash subjected to tribological wear analysis

Specimen No.	Load (N)	Size of Abrader (µm)	Initial Weight (gram)	Final Weight (gram)	Weight Loss (gram)
1	11.77	Commercially Available Silica 212µm	26.3024	26.2134	0.089
2	53.22		26.1654	26.0356	0.1298
3	102.4		26.8459	26.4551	0.3908

Table 3. Hybrid composition of Al 6061 with 4 wt% tungsten carbide and 2 wt% fly ash subjected to tribological wear analysis

Specimen No.	Load (N)	Size of abrader (µm)	Initial weight (gram)	Final weight (gram)	VolumeLoss (gram)
1	11.77	Commercially Available Silica 212µm	26.5625	26.4875	0.075
2	53.22		26.2623	26.1673	0.095
3	102.4		26.8574	26.6418	0.2156

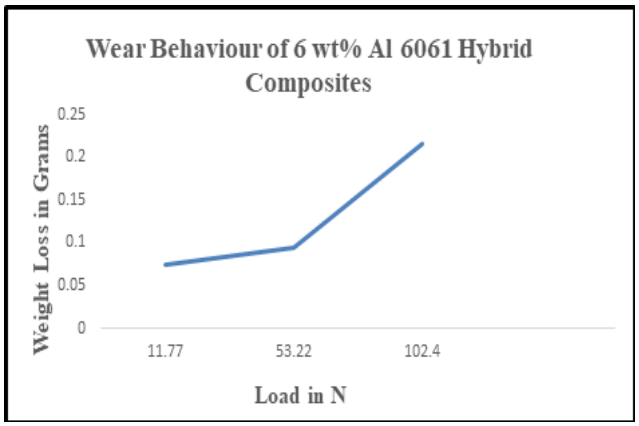


Figure 6. Wear behaviour of 6 wt% Al 6061 hybrid composites.

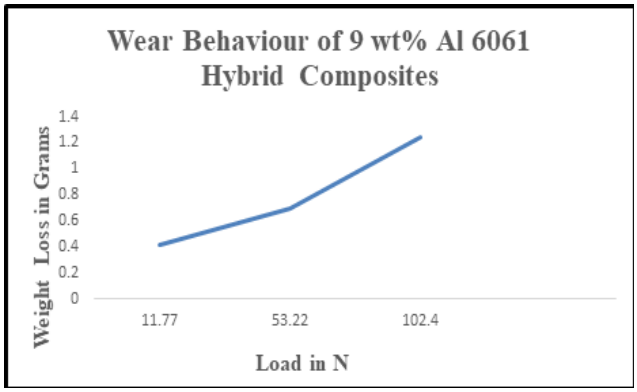


Figure 7. Wear behaviour of 9 wt% Al 6061 hybrid composites.

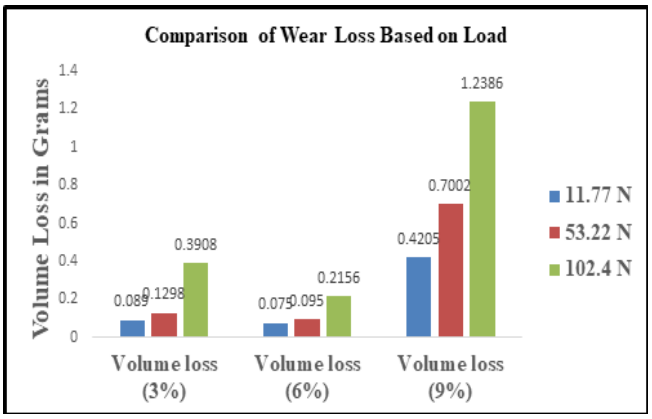


Figure 8. Wear analysis of Al 6061 hybrid composites.

Table 4 depicts the wear behaviour of 9 wt% Al 6061 Hybrid Composites formed by 7 wt% Tungsten Carbide and 2 wt% Fly ash. Figure 7 represents the wear loss of 9wt% Al 6061 Hybrid composites subjected to 3 different loads. The trend remains identical for wear behaviour. However, the high percentage of reinforcement, i.e., in Al 6061 hybrid composites, leads to brittleness in the structure of the material, leading to maximum wear loss.

Figure 8 represents the extensive analysis of the wear behaviour of Al 6061 Hybrid composites comprising varying Tungsten Carbide and Fly ash particulates. It is evident from the graphical representation that

Table 4. Hybrid composition of Al 6061 with 7 wt% tungsten carbide and 2 wt% fly ash subjected to tribological wear analysis

Specimen No.	Load (N)	Size of Abrader (µm)	Initial Weight (gram)	Final Weight (gram)	Volume Loss (gram)
1	11.77	Commercially Available Silica	27.8459	27.4254	0.4205
2	53.22		27.9545	27.2543	0.7002
3	102.4		26.7512	25.5126	1.2386

the wear resistance of the material increases with an increase in wt% inclusion of particulate materials up to a total wt% inclusion of 6wt% particulate materials. Thereafter significant increase in wear loss is observed with an increase in wt% of particulate materials due to detachment of the reinforced particulates from the base metal by the abrasion of the silica abrasive particles, which is substantiated by the SEM analysis of wear behaviour of Al 6061 Hybrid composites. It is also observed that the increase in load increases wear loss, and the difference in wear loss is highly considerable for 102.4N compared to the other two loads.

3.2 SEM Morphology Analysis

In the SEM analysis of samples after a Dry Sand Abrasion Test, the wear mechanisms can be characterised by distinct surface features. Abrasive wear is often evident through parallel grooves or scratches caused by hard particles sliding over the surface. Delamination wear appears as flaking or peeling of surface layers, often due to subsurface cracks propagating under repeated stress. Micro-cutting and ploughing marks indicate severe abrasive actions, while material transfer layers or smearing can suggest adhesive wear. Additionally, the presence of cracks, voids, or pull-out zones may indicate fatigue wear or brittle fracture. These features collectively help identify the dominant wear mechanisms and their interaction with the material properties.

Figure 9 depicts the Scanning Electron Microscopy (SEM) of 6wt% particulate reinforced Al 6061 surface morphology subjected to a wear load of 53.22N, and morphology of the particular combination is considered due to its maximum contribution towards wear resistance compared to other compositions. It is evident from the

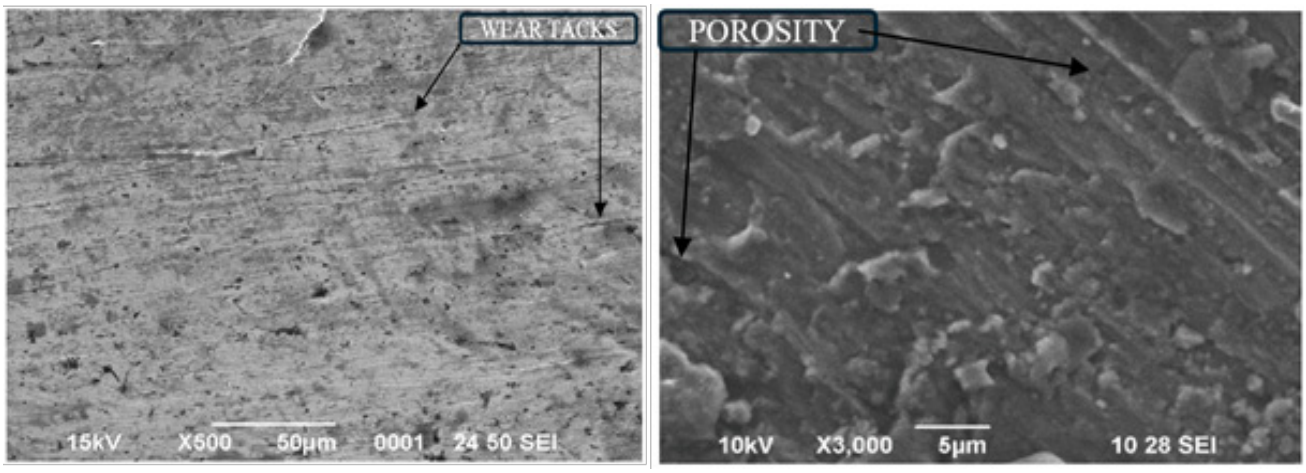


Figure 9. SEM images of 6wt% particulate reinforced Al 6061 subjected to a 53.22N wear load.

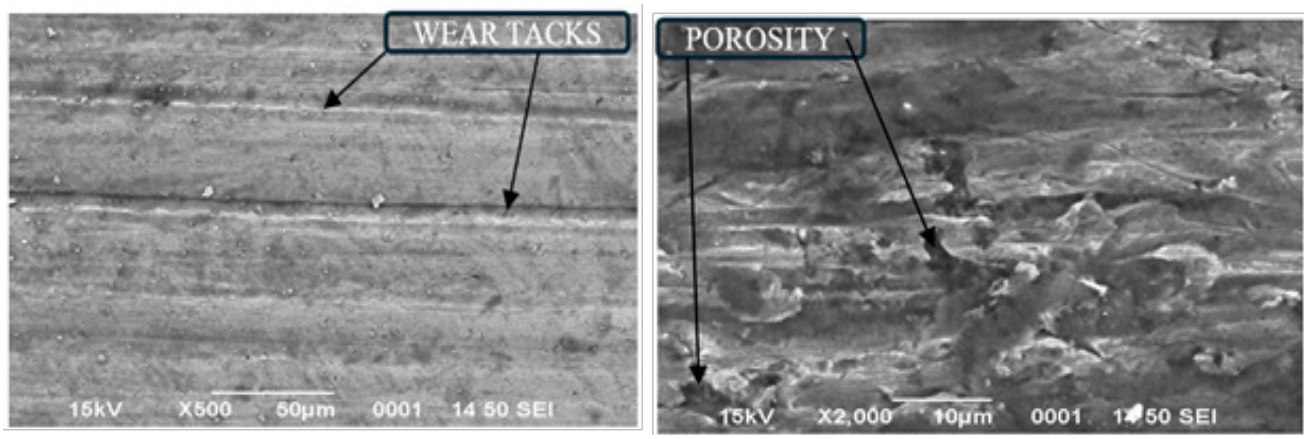


Figure 10. SEM images of 9wt% particulate reinforced Al 6061 subjected to 102.4N wear load.

SEM image that wear tracks are identified on the surface, characterised by parallel grooves, which substantiates the abrasive wear mechanism. Additionally, it is identified that during sliding contact, the interaction with the counter face has resulted in material removal of hard reinforcement particles of Tungsten carbide, resulting in detachment of particles from the surface. The presence of Fly ash has exhibited load-bearing capacity and thereby contributes towards less adhesive wear. Additionally, localised features such as pits, cracks, or debris may suggest secondary wear mechanisms, including delamination or fatigue-induced material failure. The observed surface roughness and plastic deformation patterns, such as smeared layers or ploughing effects, provide evidence of adhesive wear and surface interactions during the tribological process.

The Scanning Electron Microscopy (SEM) of 9wt% particulate reinforced Al 6061 surface morphology subjected to a wear load of 102.4N is represented by Figure 10. The morphology illustrates the presence of particulate reinforcement with Al 6061 base materials. The wear track is found to be very distinctive compared to the other compositions, exhibiting maximum wear loss at a higher percentage of reinforcement. It is evident from the pictorial representation that the delamination of particulates is found to be in excess due to improper bonding as a result of the higher composition of particulate reinforcement in the base material. A higher percentage of Tungsten carbide results in an increase in the brittle nature of the material, thereby leading to a reduction in load-bearing capacity at higher wear loads. The presence of microcracks, pits, and debris substantiates the increase in brittleness of the material due to a higher percentage of reinforcement, thereby not recommending a higher percentage of particulate reinforcement. The presence of grooves, wear tracks exhibits the wear mechanism at higher loads. Thus, it can be justified from the analysis of surface morphology that the presence of Tungsten carbide and fly ash helps to achieve wear resistance. However, optimal results can be achieved with up to 6wt% particulate reinforcement and thereafter increase in the wear loss is achieved for an increase in reinforcement beyond 6wt%.

4.0 Conclusion

The study on the wear behaviour of the hybrid Al 6061 composites provides valuable insights into the experimental results. Hybridisation in the composition is obtained by varying the wt% composition of Tungsten carbide and the addition of a constant wt% of Fly ash particulates. The fabrication of the hybrid Al 6061 composites reinforced with particulates with minimal defects is validated by the SEM images. The wear tests on the hybrid Al 6061 composites revealed that the composition with 6wt% reinforcement exhibited excellent wear resistance characteristics, compared to other compositions of the hybrid composites, as a result of the better contribution of Tungsten carbide in terms of strength and the presence of Fly ash particulates, which exhibited lubricant characteristics. The optimal combination of 94wt% base material, 4wt% Tungsten carbide, and 2wt% fly ash for high wear resistance is identified, resulting in volume loss of 0.075gm, 0.095gm, and 0.2156gm for the loads, 11N, 53N and 102N, respectively.

Experimental investigation ascertains that the increase in particulate reinforcement beyond 6wt% is not judicial as the brittleness in the material increases, leading to susceptibility of material detachment when subjected to higher loads. At high reinforcement levels like 9 wt% (7 wt% WC + 2 wt% Fly Ash), the composite becomes significantly more brittle. The excessive quantity of hard, rigid Tungsten Carbide particles restricts the plastic deformation of the Al 6061 matrix, leading to a rigid structure that is prone to crack initiation, propagation, and particle debonding under mechanical stresses during wear. This brittleness facilitates the breaking away of reinforcement particles and matrix fragments, causing maximum wear loss. Furthermore, the wear mechanisms were thoroughly analysed through SEM imaging, providing a detailed understanding of surface morphology and subsurface deformation caused by abrasive interactions.

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