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Tribological Properties Evaluation Of Hybrid Composites (Al6061-Tungsten Carbide-Fly Ash)

Dr. Anand S N[1*], Amar Gandge Subash[2], Prashant[3]

[1*]Head, Department of Aeronautical Engineering, MITE Moodbidri.
[2,3]Assistant Professor, Department of Aeronautical Engineering, MITE, Moodbidri.
*Corresponding Author: Dr. Anand S N
*Head, Department of Aeronautical Engineering, MITE Moodbidri

Abstract:
Particulate-reinforced Metal Matrix Composites (MMCs) are highly attractive due to their excellent specific properties and compatibility with conventional metalworking techniques. These composites are widely used in the automotive and aerospace sectors and have well-established applications in the space industry. The improved mechanical and tribological properties of MMCs make them ideal for lightweight components. Hybrid Metal Matrix Composites (HMMCs) are a specialized category of MMCs that utilize multiple reinforcement materials to achieve enhanced properties, particularly in tribology.
This study focuses on the fabrication and evaluation of the tribological properties of Al6061 alloy reinforced with tungsten carbide and fly ash particles. The composites are prepared using the liquid metallurgy (stir casting) technique with varying reinforcement percentages. The results demonstrate significant improvement in tribological properties, including wear resistance, due to the synergistic effects of the dual reinforcements.

Keywords: *Tungsten Carbide, Fly Ash, Hybrid, MMCs, Tribology*

I. INTRODUCTION:

The development of advanced materials with superior mechanical, thermal, and tribological properties is pivotal in addressing the growing demands of the automotive, aerospace, and space industries. Metal Matrix Composites (MMCs), particularly aluminum-based composites, have emerged as promising candidates due to their high strength-to-weight ratio, enhanced wear resistance, and excellent thermal conductivity. These attributes make MMCs highly suitable for applications requiring lightweight and durable materials, as highlighted in the works of Das et al. and Röttger et al. [1][2]. Among MMCs, hybrid composites, reinforced with multiple secondary phases, offer further optimization of properties by leveraging the synergistic effects of different reinforcements. The incorporation of ceramic particles like silicon carbide (SiC), tungsten carbide (WC), and industrial by-products such as fly ash has proven effective in achieving significant improvements in wear resistance and mechanical strength [3][4]. Techniques like stir casting have been extensively used for their cost-effectiveness and ability to distribute reinforcements, as demonstrated by Chong et al. uniformly and Miao et al. [5][6]. Recent studies have explored the potential of hybrid aluminum composites in tribological applications. For instance, Ramanan et al.
[7] examined the influence of fly ash on wear properties, while Daoud et al. [9] focused on tungsten carbide reinforcements. These efforts emphasize the importance of tailoring reinforcement combinations to enhance performance under demanding operational conditions.
This research investigates the tribological properties of Al6061 alloy hybrid composites reinforced with tungsten carbide and fly ash particles, fabricated using the stir casting method. By varying reinforcement compositions, this study aims to evaluate their effects on wear resistance and microstructural behavior, contributing valuable insights into the optimization of hybrid MMCs for industrial applications.

I. LITERATURE SURVEY:

The increasing demand for lightweight, durable, and high-performance materials in the automotive and aerospace sectors has led to extensive research on aluminum-based metal matrix composites (Al-MMCs). Researchers have explored various reinforcement materials, fabrication techniques, and their effects on the mechanical and tribological properties of Al- MMCs.Das et al. [1] provided an in-depth review of aluminum MMC applications in the automotive industry, emphasizing their potential to replace conventional materials due to their superior strength-to-weight ratio. They highlighted the role of reinforcements such as silicon carbide (SiC) in enhancing mechanical and wear properties. Similarly, Röttger et al. [2] investigated the mechanical properties of Al-SiC composites, revealing significant improvements in hardness and wear resistance.

Miao et al. [3] discussed advancements in material processing techniques for Al-MMCs, emphasizing the effectiveness of stir casting in achieving uniform dispersion of reinforcements. Jayaprada et al. [4] further validated this by studying Al-SiC composites prepared using stir casting, reporting enhancements in tribological properties, including reduced wear rates.

The incorporation of industrial by-products such as fly ash has garnered attention for its dual benefits of cost reduction and environmental sustainability. Chong et al. [5] demonstrated the positive impact of fly ash on the tribological properties of Al-MMCs, highlighting its potential as a reinforcement material. Ramanan and Raja Dhas [7] also evaluated Al6061 composites reinforced with activated fly ash, noting improvements in wear resistance and hardness.

Studies have also explored hybrid reinforcements to achieve a balanced combination of properties. For instance, Daoud et al. [9] examined the tribological properties of Al composites reinforced with tungsten carbide (WC) and fly ash, showing that hybrid reinforcements could synergistically enhance performance. Similarly, Barath et al. [10] demonstrated the efficacy of WC and fly ash in improving the wear resistance of Al-MMCs, attributing the enhancements to the combined effects of hard ceramic particles and lightweight fly ash.

Furthermore, researchers have investigated the impact of microstructural factors such as porosity and particle distribution on composite properties. Aqida et al. [8] reviewed the role of porosity in influencing the tribological behavior of MMCs, emphasizing the need for optimized fabrication techniques to minimize defects. Sivasri et al. [6] performed a microstructural analysis of Al alloys reinforced with NbC and SiC, correlating improved tribological properties with uniform particle distribution.

This literature review highlights the significant advancements in Al-MMCs, focusing on the effects of various reinforcements and processing methods. The insights gained from previous studies form the basis for the current research, which aims to investigate the tribological properties of hybrid Al6061 composites reinforced with tungsten carbide and fly ash, fabricated via stir casting. This study seeks to contribute to the growing body of knowledge by providing a comprehensive understanding of the effects of hybrid reinforcements on wear behavior and microstructural characteristics.

II. OBJECTIVES OF PRESENT WORK:

The following are the objectives of the present study:

1. Fabricate Al6061-based MMCs reinforced with WC and fly ash particulates using the stir casting method.
2. Analyze the microstructure for uniform distribution, bonding, and porosity in the composites.
3. Investigate tribological properties, including wear resistance and frictional behavior.

III. EXPERIMENTAL WORK

The experimental work carried out to achieve the objectives outlined in this study is presented in this section. It includes the selection of materials, type of reinforcements, processing techniques, and the testing methods employed. The following subsections provide detailed explanations of these aspects.

Fig 4.1 Al6061 Matrix Material This presents a work of Al-6061

The performance and characteristics of the developed composites are influenced by the selection of both the matrix and reinforcement materials, with particular attention to their physical, chemical, and mechanical properties. It is essential to choose materials that facilitate easy fabrication and offer good machinability. In this study, Al-6061 alloy was chosen as the base matrix material. The raw Al-6061 alloy billets (depicted in Fig 4.1) were sourced from a trusted supplier in the market.
alloy is used as a base matrix material. The raw Al-6061 alloys in billet form (Fig 4.1) were procured from one of the suppliers in the market. In the present study, tungsten carbide (WC) is utilized as one of the reinforcing materials. Tungsten carbide particulates of 2-3μm size were sourced from M/s ACE Rasayan, Bangalore.

Fig 4.2 Tungsten Carbide

Fig 4.3 Fly Ash

The raw tungsten carbide particulates are shown in Fig. 4.2 Fly ash is also employed as a reinforcing material in conjunction with tungsten carbide particulates. The fly ash used is filtered and procured from the market The raw fly ash material is shown in Fig. 4.3.
In this study, tungsten carbide (WC) is selected as one of the reinforcing materials. Tungsten carbide particulates, with a size range of 2-3μm, were sourced from M/s ACE Rasayan, Bangalore. The raw tungsten carbide particulates are depicted in Fig. 4.2.
Fly ash is used as an additional reinforcing material alongside tungsten carbide particulates. The fly ash, which has been filtered, was procured from the market. The raw fly ash material is shown in Fig. 4.3.

- **Fabrication of composites:**

In the present study, the fabrication of Al-6061 Metal Matrix Composites (MMCs) reinforced with tungsten carbide (WC) particulates and fly ash was carried out using the stir casting method, which is a liquid state fabrication technique.
Tungsten carbide (WC) particulates were added in varying proportions of 1%, 2%, and 3%, while fly ash was added in proportions of 2%, 4%, and 6% by mass fraction to the molten Al-6061 alloy. The different combinations of tungsten carbide and fly ash content in weight percentages were used to fabricate MMCs in the form of solid rods. The dimensions of the casted rods were 22mm in diameter and 220mm in length.

Fig. 4.4 Electrical resistance furnace with stirrer setup

Fig 4.5 Metallic die

Fig. 4.6 Casted Al-6061, WC, and fly ash composite rods.

The process of casting Metal Matrix Composites (MMCs) follows these steps:

1. The furnace is preheated to 900°C, and Al-6061 ingots are placed into a crucible, which is then positioned inside the furnace.
2. The metallic die is cleaned, dried, and coated with silica powder. To eliminate moisture and prevent excessive chilling, the die is heated to a temperature of 300°C.
3. Simultaneously, the reinforcing materials (tungsten carbide and fly ash) are preheated to remove any moisture content.
4. Once the molten metal reaches the desired temperature, degassing is performed by adding solid dry hexachloroethane ($C2Cl6$) as a degasser. Additionally, scum powder is introduced to remove the slag from the melt.
5. The stirring setup is placed near the furnace, and the coated stirrer is lowered into the crucible to a depth of one-quarter of the crucible's length. The stirrer speed is set to 300 rpm.
6. After initiating the stirring, the preheated tungsten carbide (WC) and fly ash particulates are gradually introduced into the melt in precise quantities, with stirring continuing for 8 to 10 minutes at a constant speed of 300 rpm.
7. Upon completion of the stirring process, the molten mixture is poured into the preheated die. The molten metal is allowed to cool and solidify, after which the solidified casting is carefully extracted from the die.

Specimen preparation:

Fig 4.7 Wear Testing Pin

The dry sliding pin-on-disc wear test specimens were prepared in accordance with the ASTM G99 standard, as illustrated in Figure 4.7.

- **Wear Test:**

The wear test is conducted to evaluate the wear loss, measured as the mass or volume reduction resulting from friction, and to predict the product's lifespan. It assesses the material's resistance to friction. For this study, the dry sliding wear test was performed using the Ducom pin-on- disc apparatus. Wear tests were carried out under suitable parameters to analyze the wear behavior of the composites. The composite pins were fabricated and tested according to ASTM G99 standards. The pins had a diameter of 6 mm and a length that was one-third of the diameter. The surface in contact with the disc was finely polished. A steel disc of EN31 material, with a hardness of 60 HRC, was used. The track diameter was set to 70 mm, the disc rotational speed was 273 rpm, the test duration was 15 minutes, and loads of 500 kg, 1000 kg, and 1500 kg were applied.

- **Wear Test Procedure for Composites in Pin-on-Disc:**

Fig 4.8 Pin on Disc Apparatus

The disc is first cleaned with acetone to remove rust, dust, and debris, and its track diameter is adjusted to 70 mm by repositioning the arm; the pin specimen is then secured and pressed firmly against the rotating steel disc using the load application arm, which is locked in place; after unlocking the arm, a specified load of 500 kg is applied, and the micrometer is set to zero for balance; the rotational speed is adjusted to 273 rpm with a duration of 15 minutes using the electronic digital gauge; the machine is then started, allowing the pin to slide over the rotating disc, causing friction-induced material loss, which is recorded in micrometers by the electronic digital gauge and plotted against sliding or rotational time using Winducom software; the procedure is repeated with new contact surfaces for applied loads of 1000 kg and 1500 kg, and the Ducom pin-on-disc wear testing machine is shown in Figure 4.8.

IV. RESULTS & DISCUSSIONS:

The processed materials are subjected to testing to assess their tribological properties, and a detailed explanation of the obtained results is presented in this section.

5.1 Tribological Test

A dry sliding wear test was performed to evaluate the wear resistance of the composites. Table 5.1 presents the wear test results for various compositions of Al-6061 composites reinforced with tungsten carbide (WC) and fly ash particulates.

Table 5.1 Wear Test Results

Serial No.	Reinforcement content (%)	Normal Load					
		4.91N		9.81N		14.71N	
		Wear (mm)	Volume loss (mm^3)	Wear (mm)	Volume loss (mm^3)	Wear (mm)	Volume loss (mm^3)
1	WC-0% and flyash-0%	88	2.4881	140	3.9584	169	4.7783
2	WC-1% and flyash-2%	77	2.1771	114	3.2233	149	4.2129
3	WC-1% and flyash-4%	73	2.0640	112	3.1667	147	4.1563
4	WC-1% and flyash-6%	70	1.9792	110	3.1102	146	4.1281
5	WC-2% and flyash-2%	62	1.7530	106	2.9971	145	4.0998
6	WC-2% and flyash-4%	60	1.6965	104	2.9405	143	4.0432
7	WC-2% and flyash-6%	55	1.5551	91	2.5730	140	3.9584
8	WC-3% and flyash-2%	51	1.4420	87	2.4599	96	2.7143
9	WC-3% and flyash-4%	48	1.3572	81	2.2902	86	2.4316
10	WC-3% and flyash-6%	42	1.1875	48	1.3572	58	1.6399

Notably, the unreinforced Al-6061 exhibits the highest wear volume loss (mm^3) under all load conditions. However, among the various compositions, the Al-6061 composite containing 3 wt.% WC and 6 wt.% fly ash demonstrate the minimum wear volume loss (mm^3) across all applied loads. The wear test results are further analyzed through the plotted graphs, as shown below.

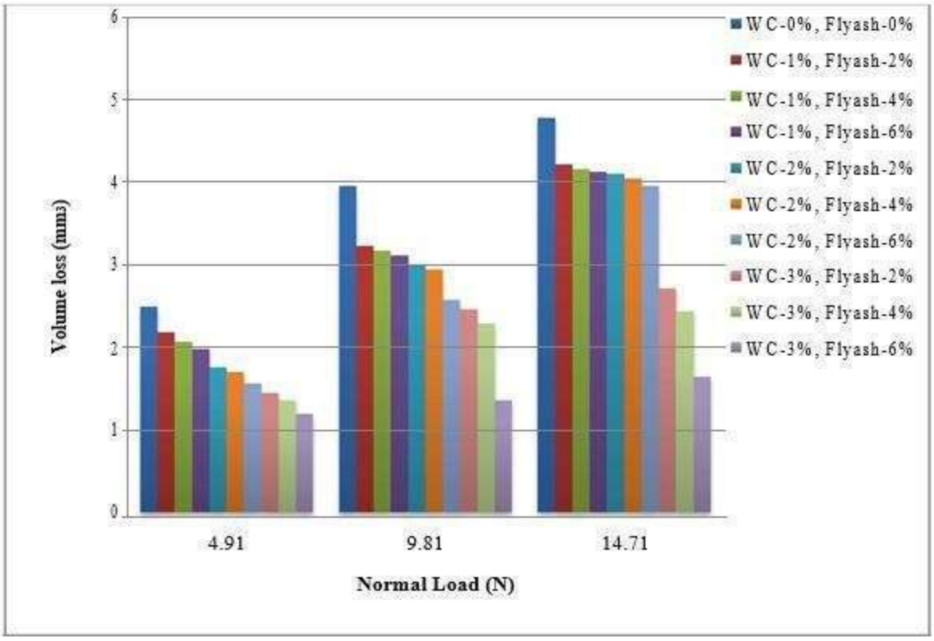

Fig. 5.1 Graph of Volume loss (mm^3) v/s Normal load (N)

graph illustrating the relationship between volume loss due to wear (mm^3) and normal load (N) for various compositions of Al-6061 composites reinforced with WC and fly ash is shown in Fig. 5.1. The results reveal that as the reinforcement content increases, the wear volume loss decreases consistently across all normal loads (4.91 N, 9.81 N, and 15.71 N). The unreinforced Al-6061 alloy exhibits the highest wear volume loss, while the addition of reinforcements leads to a linear reduction in wear volume loss.

This trend indicates that wear resistance improves with an increase in the weight percentage of tungsten carbide and fly ash in the matrix. Specifically, the unreinforced Al-6061 alloy shows the least wear resistance, whereas the composite with 3 wt.% WC and 6 wt.% fly ash demonstrate the highest wear resistance. This improvement is attributed to the reinforcement particles enhancing the load-carrying capacity of the matrix.

Additionally, as the normal load increases, the volume loss due to wear rises for all compositions. Graphs depicting the relationship between volume loss and reinforcement content at specific normal loads are shown in Figs. 5.2, 5.3, and 5.4.

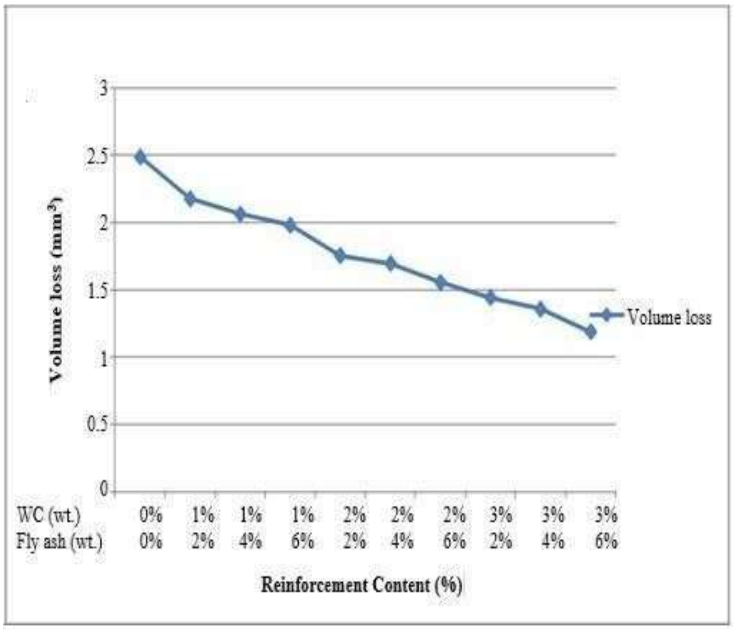

Fig. 5.2 Graph of volume loss (mm^3) v/s reinforcement content (wt. %) at 4.91N load.

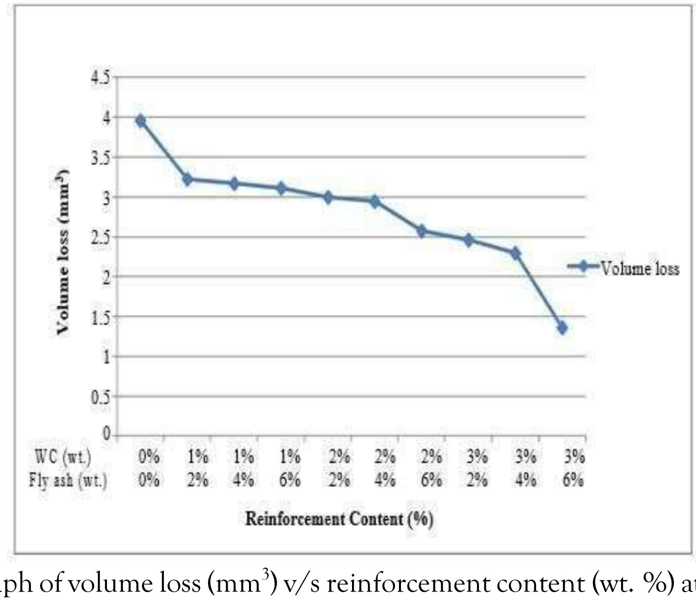

Fig. 5.3 Graph of volume loss (mm^3) v/s reinforcement content (wt. %) at 9.81N load.

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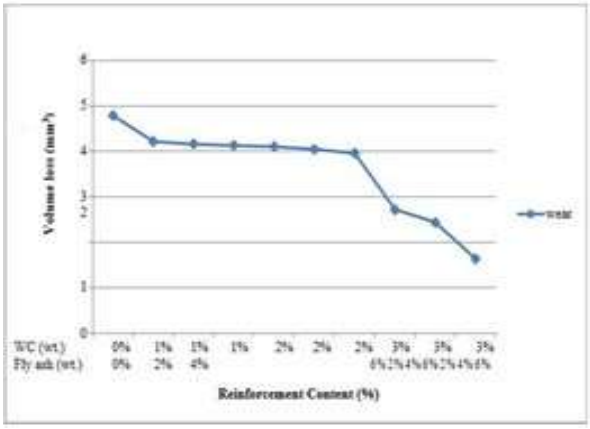

Fig. 5.4 Graph of volume loss (mm^3) v/s reinforcement content (wt. %) at 14.71N load

Figure 5.2 presents the graph of wear volume loss (mm³) versus reinforcement content (wt.%) under a load of 4.91 N, showing a linear decrease in wear volume loss as the reinforcement content increases. Similarly, Figures 5.3 and 5.4 illustrate the same relationship for loads of 9.81 N and 14.71 N, respectively. In all cases, it is observed that an increase in the percentage of reinforcement results in reduced wear volume loss.

From Figures 5.2 to 5.4, it can be concluded that enhancing the reinforcement content in the matrix improves wear resistance. This improvement is attributed to the tungsten carbide (WC) and fly ash particles, which enhance the load-carrying capacity of the composites.

Additionally, graphs showing the relationship between wear volume loss (mm³) and tungsten carbide (WC) content (wt.%) with varying fly ash content at specific normal loads are plotted in Figures 5.5, 5.7, and 5.9. These graphs further reinforce the observed trend of increased wear resistance with higher reinforcement content.

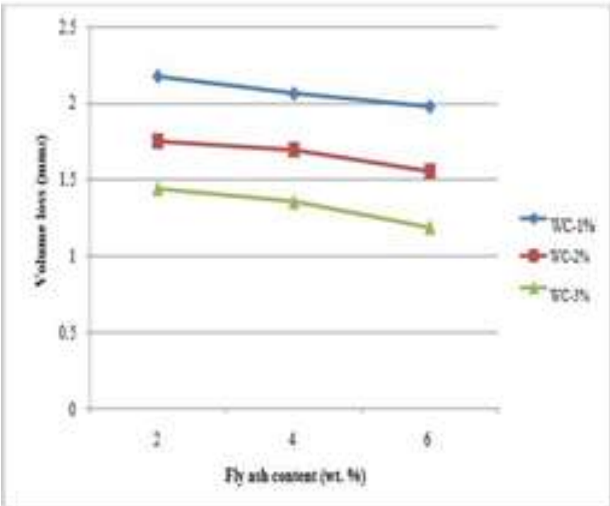

Fig. 5.6 Graph of volume loss (mm^3) v/s fly ash content (wt. %) with varying WC content (wt. %) at 4.91N load.

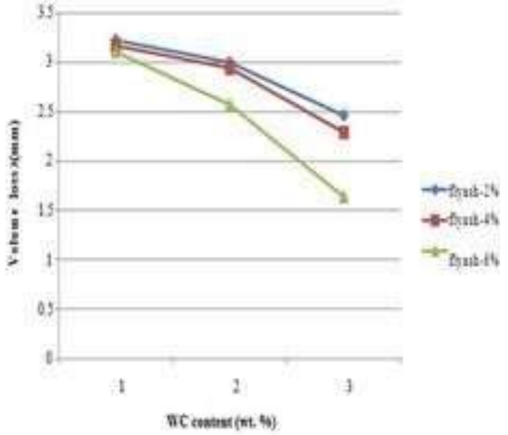

Fig. 5.7 Graph of volume loss (mm^3) v/s WC content (wt. %) with varying fly ash content (wt. %) at 9.81N load.

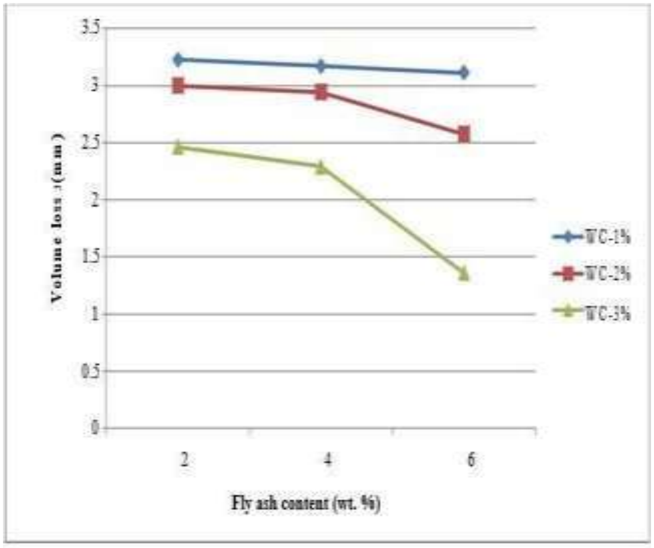

Fig. 5.8 Graph of volume loss (mm^3) v/s fly ash content (wt. %) with varying WC content (wt. %) at 9.81N load.

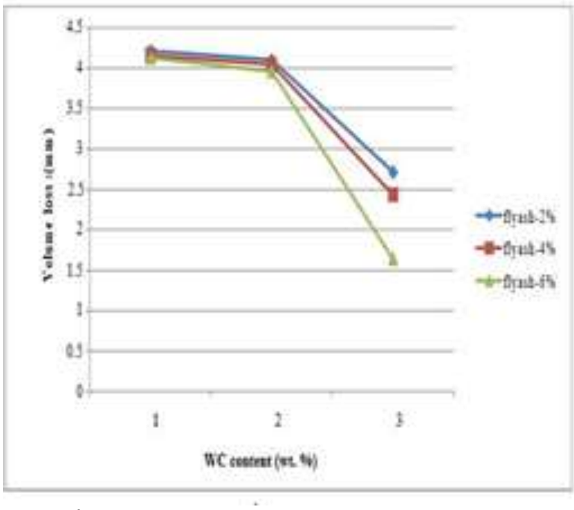

Fig. 5.9 Graph of volume loss (mm^3) v/s WC content (wt. %) with varying fly ash content (wt. %) at 14.71N load.

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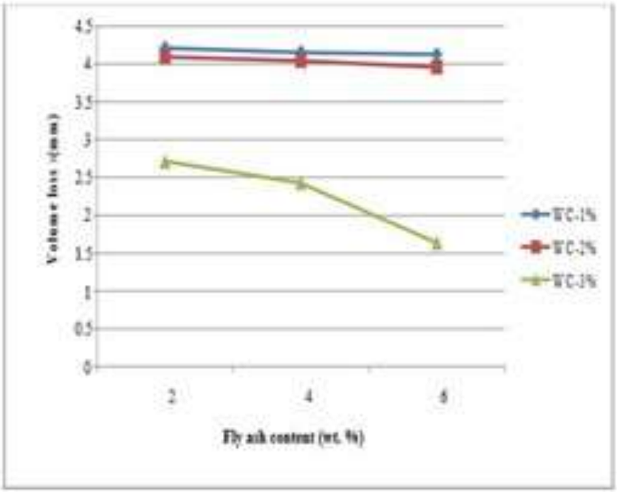

Fig. 5.10 Graph of volume loss (mm^3) v/s fly ash content (wt. %) with varying WC content (wt. %) at 14.71N load

The graphs depicting wear volume loss (mm³) under varying reinforcement compositions are detailed as follows:
Figures 5.5 to 5.10 illustrate the relationship between wear volume loss (mm³) and varying content of tungsten carbide (WC) and fly ash under different normal loads, where in Figures 5.5 and 5.7, a decrease in wear volume loss is observed as fly ash and WC content increase at loads of 4.91 N and 9.81 N, respectively, with a similar trend in Figures 5.6 and 5.8 showing reduced wear volume loss as WC content increases alongside fly ash; Figures 5.9 and 5.10 further confirm this trend at a 14.71 N load, and overall, the analysis indicates that the enhancement in wear resistance is more significant with WC compared to fly ash.

- **Microstructure Studies:**

The SEM micrographs of the worn surfaces for different composite compositions are presented in Figures 5.11 to 5.13.
Figures 5.11 to 5.13 present SEM micrographs of the worn surface of the Al-6061 + 2 wt.% WC

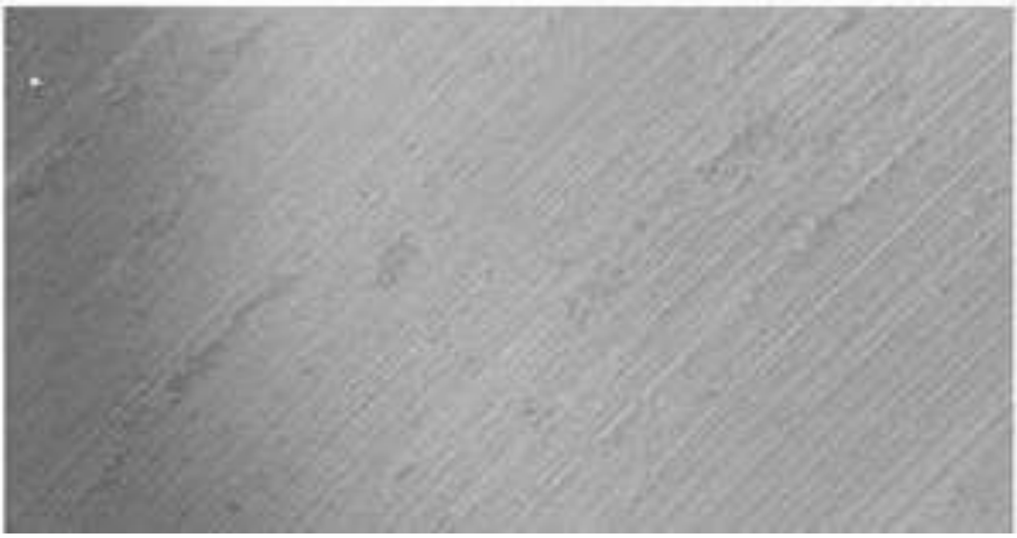

Fig. 5.11 SEM micrograph of worn surface of Al6061+WC-2%+fly ash-6% at 4.91N normal load and sliding velocity 1m/s.

+ 6 wt.% fly ash composite under various normal loads and a sliding velocity of 1 m/s, showing smooth surfaces indicative of adhesive wear, with Figure 5.11 under a 4.91 N load revealing fine and smoother scratches due to reduced friction, Figure 5.12 under a 9.81 N load showing a relatively smooth surface, and Figure 5.13 under a higher load of 14.71 N demonstrating adhesive wear with no significant particle removal, while localized micro-cracks observed in the magnified views are likely due to fatigue wear associated with adhesive contact.

Fig. 5.12 SEM micrograph worn surface of Al6061+WC-2%+fly ash-6% at 9.81N normal load and sliding velocity 1m/s.

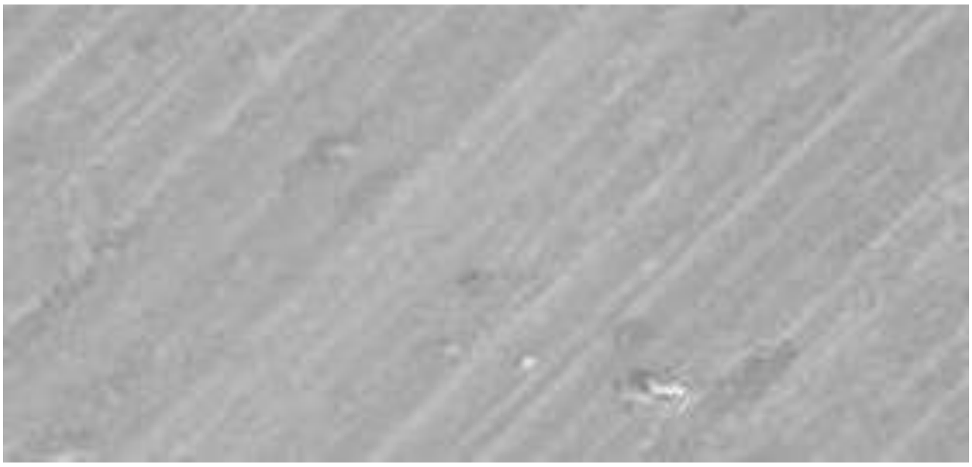

Fig. 5.13 SEM micrograph of worn surface of Al6061+WC-2%+fly ash-6% at 14.71N normal load and sliding velocity 1m/s.

V. CONCLUSIONS:

The key conclusions derived from the present investigation indicate that the wear resistance of the composites improves with higher weight fractions of tungsten carbide (WC) and fly ash under varying normal loading conditions. Tungsten carbide reinforcement shows a more significant enhancement in tensile strength, wear resistance, and hardness compared to fly ash reinforcement. The sliding wear surfaces are observed to be smoother, with no significant particle removal, suggesting controlled wear mechanisms. Additionally, as the reinforcement weight fractions increase, the worn surfaces transition gradually from visible fine scratches to distinct microgrooves, highlighting a progressive wear pattern.

VI. FUTURE SCOPE:

The present study paves the way for further research into the optimization of hybrid metal matrix composites (HMMCs) with advanced reinforcement materials for a range of applications. Future work could explore the influence of different combinations of reinforcements, such as nano-sized particles or ceramic reinforcements,

to further enhance the mechanical and tribological properties of Al6061-based composites. Additionally, the effect of processing parameters, such as temperature, stirring speed, and reinforcement distribution, on the final properties could be investigated to optimize fabrication techniques for industrial scalability.
Long-term wear testing under varying environmental conditions, such as elevated temperatures or corrosive environments, will be valuable in determining the reliability and performance of these composites in real-world applications, particularly in aerospace and automotive sectors. Furthermore, the development of computational models to predict the behavior of MMCs under different loading and wear conditions could expedite the design of next-generation composites. The potential of recycling fly ash and other sustainable materials as reinforcements could also be explored to enhance the environmental sustainability of these advanced composites.

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