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TRIBOLOGICAL PERFORMANCE OF HEAT-TREATED Al6061 HYBRID METAL-MATRIX COMPOSITES

TRIBOLOŠKE LASTNOSTI TOPLOTNO OBDELANIH HIBRIDNIH KOMPOZITOV S KOVINSKO MATRICO NA OSNOVI ZLITINE Al6061

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We investigate the tribological performance of a heat-treated Al6061 alloy and its hybrid composites under dry-sliding conditions. Hybrid aluminium metal-matrix composites reinforced with graphite, nano-tungsten carbide and red mud were fabricated using the stir-casting technique. The as-cast alloy and composites were subjected to a T6 age-hardening treatment to examine the effect of microstructural modification on the wear behaviour. Dry-sliding wear tests were carried out using a pin-on-disc tribometer under varying loads, sliding velocities and sliding distances based on a Taguchi L9 design. The specific wear rate and coefficient of friction were measured, and worn surfaces were analysed using FESEM and EDS. The results show that hybrid composites exhibit superior wear resistance compared to the base alloy after heat treatment. Tungsten carbide improved the hardness and load-bearing capacity, reducing material removal, while graphite contributed to the friction reduction through tribo-layer formation. The combined addition of tungsten carbide and graphite resulted in the lowest wear rate and stable friction behaviour. Red mud enhanced the wear resistance under moderate conditions by promoting oxide-layer formation but caused brittleness under severe sliding. Heat treatment further improved the performance by refining the microstructure and strengthening matrix–reinforcement bonding. Overall, hybrid reinforcement combined with heat treatment enhances the tribological performance.

Keywords: hybrid metal-matrix composites, heat treatment, dry-sliding wear, tungsten carbide nanoparticle

V članku avtorji opisujejo raziskavo tribološke učinkovitosti toplotno obdelane zlitine Al6061 in njenih hibridnih kompozitov v pogojih suhega drsenja. Hibridni kompoziti s kovinsko Al6061 matrice, ojačani z grafitom, nano-volframovim karbidom in rdečim blatom, so bili izdelani s tehniko vrtilno-mešalnega litja. Ulita zlitina in kompoziti so bili po litju v kokile in ohlajanju toplotno obdelani s standardiziranim postopkom umetnega staranja tipa T6, da bi preučili vpliv mikrostrukturne modifikacije na obnašanje med obrabo. Preskuse obrabe pri suhem drsenju so avtorji izvedli z uporabo tribometra s čepom na vrtečem se disku (angl.: pin-on-disc) pri različnih obremenitvah, drsnih hitrostih in drsnih razdaljah na podlagi postavitve matrike Taguchi L9. Izmerili so specifično stopnjo obrabe in koeficient trenja, obrabljene površine pa so analizirali z elektronskim vrstičnim mikroskopom FESEM in prigrajenim EDS analizatorjem. Rezultati analiz so pokazali, da imajo hibridni kompoziti po toplotni obdelavi boljšo odpornost proti obrabi v primerjavi z osnovno zlitino. Volframov karbid je izboljšal trdoto in nosilnost, kar je zmanjšalo odstranjevanje materiala, grafit pa je prispeval k zmanjšanju trenja zaradi nastanka tribološke plasti. Kombinirani dodatek volframovega karbida in grafita je imel najnižjo stopnjo obrabe in stabilno trenje. Rdeče blato je izboljšalo odpornost proti obrabi v zmernih pogojih s spodbujanjem nastajanja oksidne plasti, vendar je to povzročilo krhkost pri močnem drsenju. Toplotna obdelava je dodatno izboljšala delovanje zaradi izboljšanja mikrostrukture kompozitov in krepitve vezi med kovinsko matrico in ojačitvijo. Avtorji v zaključkih ugotavljajo, da hibridna ojačitev na splošno v kombinaciji s toplotno obdelavo znatno izboljša tribološko obnašanje izbranih kompozitov.

Ključne besede: hibridni kompoziti s kovinsko matrico iz Al zlitine, toplotna obdelava, suha drsna obraba, nanodelci volframovega karbida

1 INTRODUCTION

Heat-treatable aluminium alloys and their composites have attracted attention in advanced engineering applications where light weight, high specific strength and superior surface durability are demanded simultaneously. Among these, Aluminium 6061 (Al6061) stands out due to its excellent formability, corrosion resistance and widespread use in automotive, aerospace and structural components, many of which operate under repeated sliding/rolling contact. While the reinforcement of Al6061 with ceramic and solid-lubricant particulates is well known to enhance the hardness and load-bearing capacity, the tribological performance (wear rate, friction coefficient and surface damage mechanisms) remains strongly dependent on the matrix microstructure and interfacial stability. In particular, heat treatment plays a decisive role in controlling the precipitation behaviour,

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grain refinement and dislocation density in Al6061, thereby influencing the surface hardness and the formation and retention of tribo-films during sliding. Hence, investigating the tribological behaviour of heat-treated Al6061-based composites is essential for establishing correlations among the structures, property and performance and for optimizing processing parameters to meet the growing demand for wear-resistant and energy-efficient materials in modern mechanical systems.

Aluminium matrix composites (AMCs) and hybrid metal-matrix composites (HMMCs) have received interest due to their enhanced specific strength, stiffness and wear resistance compared with monolithic aluminium alloys. A wide range of reinforcements such as Si_3N_4, SiC, B_4C, Al_2O_3, graphite and TiC are used to strengthen aluminium alloys through load transfer, grain refinement and increased dislocation density.[1–3] Among ceramic reinforcements, tungsten carbide (WC) is notable for its high hardness, elastic modulus and thermal shock resistance, contributing to improved hardness, tensile strength and wear resistance; however, its high density and tendency to reduce ductility at higher fractions demand optimization.[4,5] Recent researches focus on sustainable, renewable and waste-based reinforcement materials like fly ash, quarry dust, red mud, cowpat ash, and coconut-shell ash, which are being explored as alternatives for synthetic ceramic reinforcements.[6–8] Hybrid composites combining hard ceramics with sustainable particulates, which improve performance while supporting resource utilization, have been shown to improve the strength and hardness without severely compromising ductility when reinforcement levels are controlled.[9]

Heat treatment plays a decisive role in determining the final performance of Al6061 composites since microstructural evolution through precipitation hardening directly influences the hardness, fatigue resistance and wear behaviour. Heat-treated Al6061–Al_2O_3 composites show improved fatigue strength and fracture toughness due to an enhanced crack resistance and a more uniform reinforcement distribution, though excessive heat treatment can lead to grain coarsening and reduced ductility.[10] Similar enhancement in strength, hardness and wear resistance is reported for heat-treated Al6061–BN composites due to a refined microstructure, improved distribution and stronger interfacial bonding, but ductility decreases with an increased reinforcement fraction.[11] Heat treatment combined with quenching and ageing has also been shown to promote precipitation strengthening and improve hardness in Al6061-based composites such as Al6061–AlB_2.[12] Thermomechanical processing routes like stir casting followed by hot forging and heat treatment enable an improved dispersion of nanoparticles and an improvement in mechanical properties up to an optimum reinforcement content, beyond which clustering deteriorates the properties.[13]

The tribological behaviour of Al6061 composites is strongly influenced by reinforcement type, particle scale, dispersion quality and heat-treatment conditions. Hybrid reinforcements such as SiC+WC improve the hardness and wear resistance, but an increasing ceramic fraction typically reduces ductility, indicating a strength–ductility trade-off.[14] The addition of solid lubricants such as graphite improves the seizure resistance and reduces the friction by forming protective tribo-films; it is preferred over some transition dichalcogenides due to thermal stability concerns in aluminium processing.[15–17] Heat-treated graphite-reinforced alloys have shown superior wear resistance with reduced crack formation, and friction coefficient reduction up to 50 % due to tribo-layer formation.[18] Studies also underscore the need for optimum reinforcement limits, for instance Al6061 with 3 *w*/% WC shows a peak hardness/strength, beyond which it shows reduced properties. Graphite addition improves the ductility, but lowers the hardness and wear resistance, if used at higher concentrations.[19] Sustainable hybrid composites reinforced with quarry dust+B_4C+ graphite and WC+coconut shell ash reported improved wear resistance and property balance respectively, reinforcing the need for hybrid reinforcement combinations of hard ceramics and waste-based reinforcements.[6,8] Recent work on powder-metallurgy composite fabrication and microstructural control indicates that tailoring WC particle size and morphology improves strength-ductility synergy and offers future directions for advanced hybrid composites.[20,21]

The combined influence of reinforcement type, reinforcement scale (micro vs nano), dispersion quality, and heat-treatment conditions dictate the tribological behaviour in Al6061-based composites. Developing durable, high-performance, and sustainable Al6061 composites can be achieved by maintaining an optimal balance between improvements in hardness, retention of ductility, tribo-film stability and microstructural integrity.

2 EXPERIMENTAL PART

2.1 Fabrication of Hybrid Metal-Matrix Composites

The aluminium alloy Al6061 was selected as the matrix material, while tungsten carbide (WC) nanoparticles with an average particle size of 30 nm, graphite and red-mud particles with an average particle size of 160 nm were used as reinforcements. Using the stir-casting technique, five different material compositions, including re-melted and as-cast Al6061 and hybrid composite variants with reinforcement weight fractions as listed below were fabricated.

Specimen 1: Al6061 – 100 *w*/% Al6061
Specimen 2: Al6061+Gr – 98 *w*/% Al6061 + 2 *w*/% Gr
Specimen 3: Al6061+WC – 98.5 *w*/% Al6061 + 1.5 *w*/% WC
Specimen 4: Al-HMMC – 96.5 *w*/% Al6061 + 2 *w*/% Gr + 1.5 *w*/% WC
Specimen 5: RM-HMMC – 91.5 *w*/% Al6061 + 2 *w*/% Gr + 1.5 *w*/% WC + 5 *w*/% RM

During fabrication, a corresponding weight percentage of Al6061 was melted and the preheated reinforcement particles were added to the molten matrix. Mechanical stirring was carried out at 400 rpm for 6 minutes, after the addition of the reinforcement using a stirrer positioned at a depth of approximately two-thirds from the melt surface to ensure an effective vortex formation and the homogeneous dispersion of reinforcements.[22,23] To enhance the wettability and minimize any gas entrapment, 1 *w*/% magnesium and 1 *w*/% degassing powder respectively were added to the melt.[24] The molten metal was subsequently transferred to a circular mould of 25-mm diameter through a bottom-pouring mechanism. After the solidification, the cast specimens were machined to near-net dimensions as per ASTM G99-05 standards.

2.2 Heat Treatment

The cast specimens were subjected to the T6 heat treatment to understand the tribological performance of the composites. The T6 treatment was carried out using an electrical muffle furnace. Proper specimen placement was ensured by arranging the samples horizontally with adequate spacing and the avoidance of direct stacking to facilitate a uniform heat distribution and prevent localized overheating.

The heat treatment consisted of solution heat treatment, quenching, and artificial ageing. The solution heat treatment was performed at 530 °C for 8 h. Immediately after solutionizing, the specimens were quenched in water at room temperature to retain the supersaturated solid solution. Artificial ageing was conducted at 165 °C for 6 h, followed by air cooling to ambient temperature.[11,24]

2.3 Dry-Sliding Wear Test

The dry-sliding wear and friction behaviour of the composites were evaluated using a pin-on-disc tribometer (DUCOM Instruments, Bengaluru, India) as per ASTM G99-05 standards. Wear-test pins of 10-mm diameter and 30-mm height were machined from the cast composite samples. Two-body dry-sliding tests were conducted by holding the pin stationary against a rotating EN-32 steel disc (165-mm diameter, 8-mm thickness), having a hardness of 63 HRC and a surface roughness of approximately 0.5 µm.

Prior to each run, the pin surface was polished using different grades of emery paper to maintain the surface roughness in the range 0.2–0.5 µm and cleaned using acetone to remove any surface contaminants. All the experiments were conducted at room temperature under dry-sliding conditions. The tribological behaviour was examined by varying input parameters such as the applied load, sliding velocity, and sliding distance.

The specific wear rate and coefficient of friction were measured as responses. Wear loss is calculated by measuring the mass of the specimen before and after each test using an electronic balance with 0.0001 g precision. The specific wear rate was calculated based on volumetric wear loss and applied load according to Archard's wear relationship (SWR = volume loss / product of normal force and sliding distance).[25] Coefficient of friction (CoF) was computed using the ratio of the frictional force to the normal force, where the frictional force during sliding was measured continuously using an LVDT sensor and recorded using a data-acquisition system (DAQ).

2.4 Design of Experiments

A statistical Design of Experiments approach (DoE) was adopted to study the combined effect of wear parameters on the tribological response. The Taguchi method was employed using an L9 orthogonal array, which is well suited for experiments involving three control factors at three levels each. This method reduces the number of experiments from 27 (full factorial design) to 9 while ensuring a balanced representation of factors and orthogonality in the design matrix. [22,23,26]

The tests were performed under varying applied loads (20 N, 30 N and 40) N, sliding velocities (1.05, 2.09 and 3.14) m/s, and sliding distances (1000, 2000 and 3000) m. The factor levels and experimental trial combinations used for conducting the dry-sliding wear tests are presented in **Table 1**.

Table 1: L9 orthogonal array experiment design

Exp. No.	Applied Load (N)	Sliding distance (m)	Sliding Velocity (m/s)
1	20	1000	1.05
2	20	2000	2.09
3	20	3000	3.14
4	30	2000	1.05
5	30	3000	2.09
6	30	1000	3.14
7	40	3000	1.05
8	40	1000	2.09
9	40	2000	3.14

3 RESULTS AND DISCUSSION

Dry-sliding wear experiments were conducted to evaluate the wear performance of the Al6061 alloy and its composites reinforced with graphite (Gr), tungsten carbide (WC), hybrid metal matrix composite (Al-HMMC), and red mud reinforced HMMC (RM-HMMC) are examined under unlubricated conditions. Based on earlier investigations, heat treatment was found to influence the mechanical performance of Al6061 and its composites; therefore, this study focused on the tribological behaviour of heat-treated specimens.[27] The specific wear rate (SWR) and CoF values obtained from the experiments conducted as per the L9 orthogonal array is given in **Table 2**.

Table 2: Consolidated wear-test results (SWR, CoF) for all heat-treated specimen combinations

	Specific Wear Rate (mm^3/Nm)					Coefficient of Friction				
Exp. No.	Al6061	Al6061 +Gr	Al6061 +WC	Al-HMMC	RM-HMMC	Al6061	Al6061 +Gr	Al6061 +WC	Al-HMMC	RM-HMMC
1	0.000041	0.000043	0.000026	0.000014	0.000024	0.34	0.37	0.28	0.46	0.49
2	0.000052	0.000016	0.000038	0.000036	0.000031	0.16	0.24	0.3	0.36	0.27
3	0.000043	0.000069	0.000018	0.000031	0.000028	0.15	0.11	0.37	0.14	0.22
4	0.000043	0.000020	0.000010	0.000017	0.000017	0.48	0.28	0.42	0.39	0.41
5	0.000067	0.000040	0.000016	0.000018	0.000033	0.13	0.13	0.27	0.45	0.32
6	0.000032	0.000017	0.000010	0.000030	0.000021	0.14	0.27	0.29	0.11	0.06
7	0.000044	0.000020	0.000025	0.000034	0.000026	0.48	0.29	0.36	0.26	0.29
8	0.000034	0.000025	0.000015	0.000062	0.000017	0.11	0.14	0.15	0.07	0.12
9	0.000035	0.000035	0.000032	0.000025	0.000034	0.12	0.11	0.08	0.08	0.15

3.1 Specific Wear Rate

The SWR results reveal a clear improvement in wear resistance with the addition of reinforcements to the Al6061 matrix. The base alloy consistently recorded the highest wear due to severe plastic deformation and material removal under sliding conditions. The Al6061 alloy has no other hard particles to reduce the wear loss except secondary phases (formed in the T6 heat treatment), so a higher wear loss is observed. Whereas the graphite-reinforced composite had a reduced wear as compared to Al6061, this is primarily due to the formation of a lubricating tribo-layer that minimized the direct asperity contact. And the incorporation of WC particles in the Al6061 matrix also reduced the wear by enhancing the hardness and the load-bearing capacity, thereby limiting groove formation and surface damage.

The hybrid metal-matrix composite (Al-HMMC) demonstrates the lowest SWR across the maximum test conditions. This confirmed that there is a synergistic interaction between the hard WC particles and lubricating graphite. The addition of 5 *w*/% red mud further influenced the wear behaviour by contributing to tribo-oxide layer formation.[28] However, slight variations in SWR suggest that excessive red mud can induce localized brittleness and oxidative wear under severe sliding conditions. Overall, the results indicate that hybridization provides the most stable and effective wear resistance by simultaneously resisting abrasion and reducing adhesion.

3.2 Coefficient of Friction

Figure 1b shows the CoF results that correlate strongly with the wear results and the reinforcement mechanisms. The Al6061 alloy experiences higher and zig-zag unstable friction values because of adhesive wear at the sliding interface. And in the graphite reinforcement to the Al6061 alloy effectively reduced the friction by forming a solid lubricating film, though deviations were observed when the tribo-layer detached under different loads and speeds. Al6061, when reinforced with WC particles, resulted in moderate friction values, as increased hardness reduces adhesion, but may increase micro-ploughing due to hard reinforcements.

Al-HMMC exhibited a balanced and relatively stable friction response due to the combined presence of WC, which maintains the surface integrity and graphite, that reduces the shear resistance at the contact interface. The RM-HMMC composite also exhibited a relatively low friction in several test conditions, indicating the formation of stable oxide-rich tribo-layers.[29] However, at a higher red-mud content and severe sliding conditions, oxidative film breakdown causes temporary friction variations. These observations confirm that the hybrid and

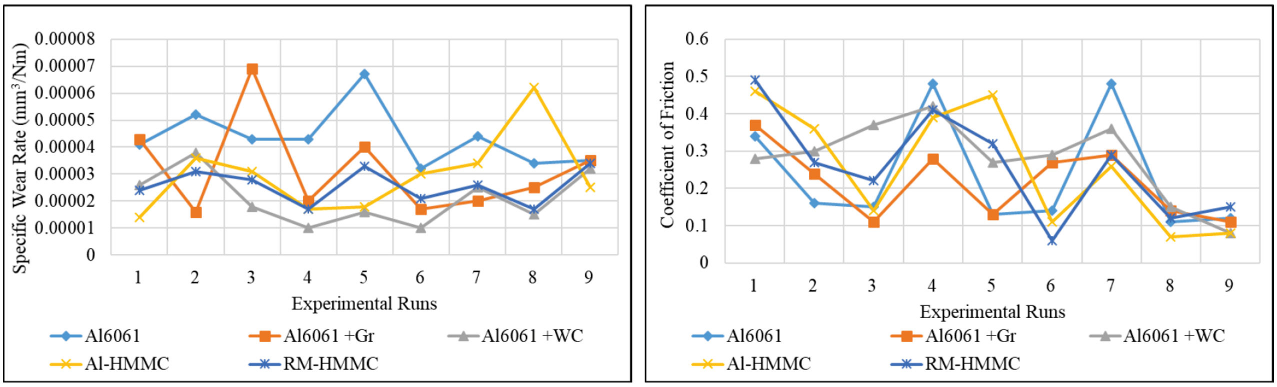

Figure 1: Variation of: a) specific wear rate and b) coefficient of friction against experimental runs for composites fabricated

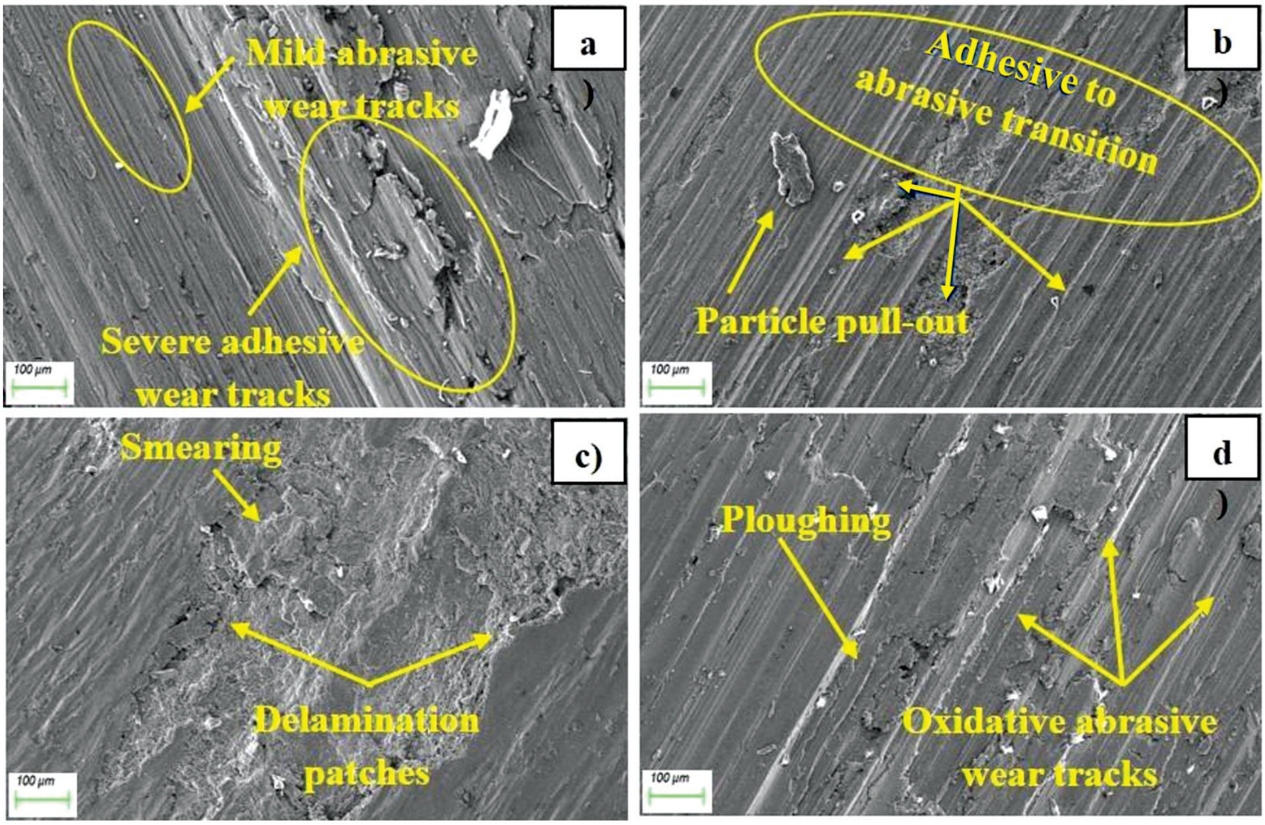

Figure 2: FESEM micrographs of 40 N Load, 2000 m Sliding Distance, 3.14 m/s Sliding Velocity for: a) Al6061 b) Al6061+WC c) Al-HMMC d) RM-HMMC

red-mud reinforcements not only improve the wear resistance but also help regulate the friction behaviour.

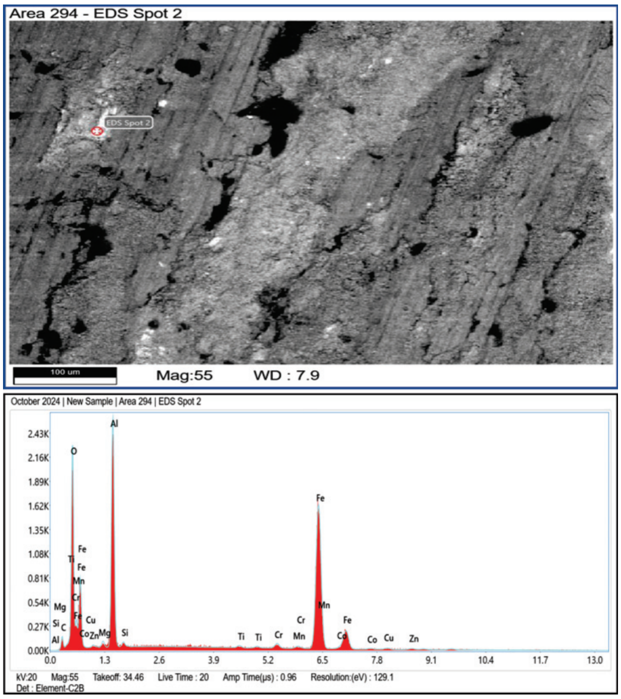

Figure 3: FESEM worn surface morphology with EDS of 40 N Load, 2000 m Sliding Distance, 3.14 m/s Sliding Velocity for RM-HMMC

3.3 Microscopic Analysis of Worn Surfaces

FESEM and EDS analyses provide microstructural evidence supporting the wear and friction results. FESEM micrographs of wear specimens subjected to 40N Load, 2000m Sliding Distance, 3.14 m/s Sliding Velocity are analysed for all compositions and shown in **Figure 2**. The worn surface of Al6061 shows severe plastic deformation, and adhesive wear tracks, confirming its high SWR and friction values (**Figure 2a**). Whereas wear surfaces of the FESEM Micrograph of Al6061+WC composite in **Figure 2b** exhibits shallower grooves and reduced surface deformation, indicating a transition from severe adhesive wear to mild abrasive wear. The uniform dispersion of WC particles distributes the applied load, minimizing localized stress concentrations and forms a protective layer that resists material removal.

Al-HMMC possesses the most uniform worn-surface morphology, having a stable tribo-layer and well-dispersed reinforcements, ensuring its superior wear-resistance performance. The graphite reinforcement helps with tribo-layer formation, supporting its reduced friction behaviour. However, FESEM images **Figure 2c** reveal occasional film detachment, explaining fluctuations in wear and friction. **Figure 3** displays FE-SEM images with EDS analyses of the worn surface morphology of the RM-HMMC composite. EDS results (**Figure 3**) clearly show the oxygen-rich regions associated with oxide layer formation. But the incorporation of a medium amount RM exhibits the better wear resistance, but a higher amount leads to brittle-fracture features and oxidative abrasive wear, which is observed in **Figure 2d**. These microstructural transitions clearly explain the trends observed in SWR and CoF.

The strong agreement between the table results and the micrographic evidence demonstrates that hybrid reinforcement effectively shifts the wear mechanism from severe adhesive wear to controlled abrasive and oxidative wear, resulting in enhanced durability and stable friction characteristics.

5 CONCLUSIONS

The Al6061 alloy and its hybrid composites were successfully fabricated using the stir-casting process, followed by T6 age-hardening treatment. The tribological behaviour of the heat-treated materials was evaluated under dry-sliding conditions, leading to the following conclusions:

The incorporation of reinforcements reduced the specific wear rate. The base Al6061 alloy exhibited higher wear values, whereas the Al-HMMC showed a reduced SWR, indicating improved wear resistance due to the combined effect of hard particle strengthening and lubrication.

The addition of graphite contributed to more stable CoF values, while tungsten carbide enhanced the surface hardness and load-bearing capacity. This synergistic effect helped maintain consistent friction behaviour under varying sliding conditions.

FESEM analyses of the worn surfaces revealed smoother wear tracks and reduced surface damage in reinforced composites compared to the base alloy. This indicates a transition from severe adhesive wear in the Al6061 to controlled abrasive and oxidative wear in the composites. The formation of protective tribo-layers minimized the direct metal-to-metal contact, thereby enhancing the wear resistance.

Overall, the combined effect of reinforcements and heat treatment improves the tribological performance of Al6061 composites, making them suitable for demanding wear applications.

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