

Performance studies on hybrid nano-metal matrix composites for wear and surface quality

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Aluminium-based hybrid nano-metal matrix composites are right materials, finding application in the aerospace and automotive industry. The present research focused on the effects of sliding load, sliding velocity, and temperature on wear behaviour of a novel hybrid metal matrix nano-composite. Stir-squeeze casting setup is used to produce the composites. The base metal is scrap aluminium alloy wheel (SAAW) reinforced with 1, 2, wt.% and 5.5, 7 wt.% of micro-sized alumina (Al_2O_3)_m and nano-sized alumina (Al_2O_3)_n particle respectively. An orthogonal array L₉ (OA) has been used for designing the experiments. Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is applied to find the optimal condition for Coefficient of Friction (COF), wear, surface roughness. Analysis of Variance (ANOVA) results show that the reinforcement contributes 19.40% and most influencing factor is sliding load with 62.33%. The samples tested were examined and analyzed using a Field Emission Scanning Electron Microscope (FESEM) and an energy-dispersive X-ray spectrometry (EDX). Additionally, a profilometer was used to measure the surface roughness of the worn-out specimen.

Keywords: *Scrap aluminium alloy wheel, applied load, temperature, sliding speed, abrasive wear*

1. Introduction

Aluminium (Al) is second largest metal finding application in engineering application and the secondary route for production of Al is recycling of Al scrap. The recycling of waste saves the resources, reduces the necessity for landfill space and, in the case of non-renewable resources, namely metals, extend the essential time to deplete them. Scrap aluminium alloy wheels (SAAWs) are considered as a potential resource for production of metal matrix composites (MMCs) and suitable addition of reinforcement to SAAWs envisage the possible application in engineering fields. In this research SAAW based hybrid composites is fabricated and considered for the study. Hybrid composites are a select group of composites, highly favoured among the fastest-growing family of new materials exhibiting many potential properties. Due to their better mechanical and tribological prop-

erties, there is a continuous demand and use of Al-based hybrid composites in automotive applications such as brake rotors, engine parts, cylinder liners, etc. Hence, fabricating and evaluating their tribological properties becomes a point of attraction for researchers. Jebin et al. used the pin - on - disk device with various parameters to test the wear behaviour of Al alloy (AA 6063) with Aluminium oxide (Al_2O_3). It is found that the wear rate has decreased as the Al_2O_3 percentage increased by weight [1, 2]. Harish et al. 2022 have fabricated the Al7075- Al_2O_3 -E-glass hybrid composites and studied the wear characteristics and reported that the increase in percentage of reinforcements reduce the rate of deterioration. Vignesh kumaret al. has studied the wear behaviour of AA7075 alloy reinforced with boron carbide and boron nitride. They evaluated the hardness and tensile behaviour of the hybrid composites and found that AA7075/6boron carbide/3boron nitride had good hardness, tensile and wear properties. The dry sliding type of behaviour of the AA6061/Silicon Car-

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bide (SiC)/Al₂O₃ hybrid metal matrix composite was examined by Umanath et al. with load ranges of 3–5 kgf, sliding distance of 1413 m and sliding speed at 1.57 m/s. It is evident from the study that at ambient temperature, the wear of the composites reduces and increases with loading and sliding distance [5]. Radhika and others analyzed the wear rate of the AlSi10Mg alloy reinforced with 3 wt.% graphite and 9 wt.% alumina. The considered various parameters on the wear rate and studied the performance with L₉ orthogonal array (OA) experimental plan. Analysis of Variance (ANOVA) results shows that the load had the highest wear rate contribution followed by temperature and sliding speed [6]. The selection of input parameters in our study aimed to simulate and investigate the tribological behavior of the hybrid nano-metal matrix composites under controlled laboratory conditions. Ponugoti et al. (2018) developed nonlinear mathematical model using response surface for the friction–wear characteristics of as cast and heat-treated AMC (Al6061/9%Gr/WC). The effect of factors such as percentage of reinforcement (WC), load, sliding distance and velocity on wear loss (WL) and coefficient of friction (COF) were studied. A result shows that, the wear loss decreases with increase in percentage of WC. Using fuzzy grey relational analysis (GRA), the parameter combination of 3%WC–10N–100m–1m/s is found to be the optimal combination for the wear test. Natrayan and Kumar (2020) explored the tribological performance of SiC reinforced AA2024 composite. The factors such as SiC wt%, sliding distance, sliding velocity, and applied load were varied using L₁₆OA. ANOVA study shows that the reinforcement percentage (SiC 3 wt.%) is the most significant factor in dry sliding wear. Viswanatha et al. studied the wear behaviour of A356 aluminium alloy reinforced with as-cast and heat-treated SiC and graphite (Gr) particles for a specific load, velocity and sliding distance conditions [9]. Altinkok and others performed dry sliding wear experiments on AMC reinforced by Al/Al₂O₃/SiC particles. They found that hybrid and bimodal particle addition increases the hardness and prevents the gouging of tiny alumina particles during the wear process [10]. Many researchers have evaluated the tribological

characteristics of Al-based hybrid metal matrix composites. In this research, a new Al–Al₂O₃ hybrid metal matrix casted from waste/scraped aluminium alloy wheel (SAAW) reinforced with nano-sized alumina (Al₂O₃)_n and micro-sized alumina (Al₂O₃)_m are analyzed for tribological characteristics. Moreover in this research input factors are optimised by TOPSIS method and Analysis of Variance (ANOVA) study is performed to obtain the significant factor. The novelty of our research lies in the investigation of hybrid nano-metal matrix composites for wear and surface quality applications. Specifically, we focused on the effects of sliding load, sliding velocity, and temperature on the wear behavior of a novel composite material fabricated from scrap aluminum alloy wheels reinforced with micro-sized and nano-sized alumina particles. Our study not only optimized the compositions and experimental conditions using advanced techniques like TOPSIS and ANOVA but also provided comprehensive insights into the tribological performance and surface characteristics of these composites. The combination of hybrid reinforcement, the use of scrap aluminum alloy wheels, and the application of statistical analysis techniques adds to the novelty of our research, contributing to the development and potential applications of these composites in the aerospace and automotive industry.

2. Materials and methods

2.1. Materials

Aluminium-alumina hybrid metal matrix composite (AHMCs) was produced by the stir-squeeze casting method. The stir casting process was chosen because of its lower cost, better particle matrix bonding and many controllable processing parameters [11]. The SAAW was the matrix material and was reinforced with varying combinations of reinforcement i.e., 1, 2, wt.% and 5.5, 7 wt.% of micro-sized alumina (Al₂O₃)_m and nano-sized alumina (Al₂O₃)_n particle respectively.

Table 1. Details of wear studies

Parameters	Details
Wear test standard	ASTM-G99
Pin material	Hybrid AMMC (SAAW with nano and micro Al_2O_3) Size: diameter: 10 mm, length: 30 mm
Disc material	Hard bearing steel EN31 Size: Dia: 100, Thickness: 8 mm; Initial roughness, Ra: 0.20–0.25 μm
Load applied	20, 40, & 60 N
Sliding velocity	1–3 m/s
Test Duration	1500 s
Sliding distance	50–120mm
Temperature	30, 150 & 300°C
Sliding condition	Dry

Table 2. Control factors and their levels

Factors	Level 1	Level 2	Level 3
Composite identification (Alumina wt.%)	E8 (C1) (1%: Nano Al_2O_3 + 5.5%: Micro Al_2O_3)	E9 (C2) (2%: Nano Al_2O_3 + 7%: Micro Al_2O_3)	E2 (C3) (2%: Nano Al_2O_3 + 5.5%: Micro Al_2O_3)
Sliding load (N)	20	40	60
Sliding velocity (m/s)	1	2	3
Temperature (C)	30	150	300

2.2. Wear test

According to ASTM G99, wear samples of AMMCs were prepared with dimensions of 10mm diameter and 30mm height. Before loading the specimen into the wear test apparatus, surface preparation was done by using fine disc sandpaper (320 grit) and thoroughly cleaned using alcohol. The pin-on-disc test experiments were performed in DUCOM make, TR201LE model capable of friction and wear measurements along with data acquisition system. A disc material of EN31 with a hardness of 63HRC was used. Table 1 presents the testing parameters for wear, including material specifications. The composites after the wear tests were analyzed using a Field Emission Scanning Electron Microscope (FESEM) of Shimadzu make and model: UV-1700 with Energy Dispersive Spectroscopy (EDS). The tribological tests were conducted in triplicate for each experimental condition. This was done to ensure the reliability and repeatability of the results. The repeated tests helped to minimize any experimental variations and provide a more robust analysis of the tribological be-

havior of the hybrid nano-metal matrix composites. The pins were made of EN31 hardened bearing steel with a specified hardness of 63 HRC (Rockwell hardness scale). Regarding the surface roughness of the pins, they were initially prepared with a smooth surface finish, with a roughness value (Ra) within the range of 0.20–0.25 μm . The contact between the pin and the disc surface was ensured by applying a sufficient normal load during the wear tests. The normal load exerted on the pin creates contact pressure, allowing for contact between the entire pin surface and the disc surface. The applied normal load ensures adequate contact and facilitates the initiation of wear between the pin and the disc.

2.3. Experimental design

Many researchers have used the Taguchi process effectively for the DOE approach in wear analysis of composite materials [12]. In the current studies, an L_9 OA was chosen based on degrees of freedom. Table 2 presents the control factors and their levels. In the present investiga-

Table 3. L₉ OA

Exp. Numbers	Composite identification	Parameters				
		Reinforcement (wt.%)	Sliding load (N)	Sliding velocity (m/s)	Temperature (°C)	
1	C1	1%: Nano Al ₂ O ₃ 5.5%: Micro Al ₂ O ₃	20	1	30	
2	C1		40	2	150	
3	C1		60	3	300	
4	C2	2%: Nano Al ₂ O ₃ 7%: Micro Al ₂ O ₃	20	2	300	
5	C2		40	3	30	
6	C2		60	1	150	
7	C3	2%: Nano Al ₂ O ₃ 5.5%: Micro Al ₂ O ₃	20	3	150	
8	C3		40	1	30	
9	C3		60	2	300	

tion, reinforcement composition, the influence of sliding load, sliding velocity and temperature on AMMCs has been studied and evaluated. Table 3 displays the experimental parameter detail for the wear tests. The composite samples selected in this study are based on our recent publication [11], where again, an L₉ OA was used but to optimize the stir-squeeze parameters that can produce composites with lower porosity and better mechanical and wear properties.

2.4. Basics of TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method

A multi-criteria method of decision analysis for evaluating a set of alternatives by identifying weights for each criterion and standardizing scores for each criterion is considered for this study. A multi-criteria-based decision-making system called Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) was developed in the 1980s. TOPSIS selects the alternative with the largest distance from the negative ideal solution and the lowest Euclidean distance from the ideal solution. In this approach, a set of alternatives are compared by specifying weights for each criterion and standardizing the scores for each criterion [13, 14].

The normalization of the decision matrix, weight normalization, positive ideal solution negative ideal solution, variance of each alternative and closest relative are evaluated using the equation (1)

to (7)

$$a_{ij} = \frac{p_{ij}}{\sqrt{\sum_{i=1}^b p_{2ij}}}, \quad i = 1, 2 \dots b, j = 1, 2 \dots a \quad (1)$$

$$D_{ij} = \omega_j \times a_{ij} \quad (2)$$

$$E^+ = \{D_1^+, D_2^+, \dots, D_i\} \quad (3)$$

$$= \left\{ \left(\frac{\left(\frac{\max_{i \in I} D_{ij}'}{j} \right)}{j}, \frac{\left(\frac{\min_{i \in I} D_{ij}''}{j} \right)}{j} \right) \right\}$$

$$E^- = \{D_1^-, D_2^-, \dots, \bar{D}_i\} \quad (4)$$

$$= \left\{ \left(\frac{\left(\frac{\min_{i \in I} D_{ij}'}{j} \right)}{j}, \frac{\left(\frac{\max_{i \in I} D_{ij}''}{j} \right)}{j} \right) \right\}$$

where benefit and cost criteria indicated with I' and I'' respectively

$$S_j^+ = \sum_{i=1}^n (v_{ij} - v^*), \quad j = 1, 2 \dots b \quad (5)$$

$$S_j^- = \sum_{i=1}^n (v_{ij} - v^*)^2, \quad j = 1, 2 \dots b \quad (6)$$

$$F_j = \frac{G_j^+}{G_j^+ - G_j^-} \quad j = 1, 2 \dots b \quad (7)$$

where F_j 's index value is 0 to 1.

Ranking must be done according to F_j 's descending values; larger values mean higher ratings and better alternative. Table 4 shows the summary of test results (wear loss, COF, surface roughness) and TOPSIS ranking.

Table 4. Test results of output performance

Expt No	Composite identification	COF	Wear (gms)	Surface roughness Ra (μm)	STDEV of COF	STDEV of Wear (gms)
1	C1	0.424	0.02063	0.910	0.0071	0.0003
2	C1	0.51	0.02197	1.852	0.0141	0.0007
3	C1	0.586	0.03795	3.279	0.0184	0.0014
4	C2	0.382	0.00402	0.322	0.0141	0.0007
5	C2	0.409	0.02665	2.944	0.0049	0.0017
6	C2	0.562	0.02274	4.863	0.0141	0.0007
7	C3	0.509	0.00804	0.405	0.0064	0.0007
8	C3	0.408	0.0174	0.604	0.0071	0.0000
9	C3	0.697	0.65243	2.098	0.0028	0.0356

Table 5. Normalised values of output performance

Normalized data			Positive Matrix			Negative Matrix		
0.2781	0.0315	0.0635	0.1524	0.0020	0.0212	0.0835	0.0020	0.2182
0.3346	0.0335	0.2493	0.1524	0.0020	0.0212	0.0835	0.0020	0.2182
0.3844	0.0579	0.4414	0.1524	0.0020	0.0212	0.0835	0.0020	0.2182
0.2506	0.0061	0.2212	0.1524	0.0020	0.0212	0.0835	0.0020	0.2182
0.2683	0.0407	0.3963	0.1524	0.0020	0.0212	0.0835	0.0020	0.2182
0.3687	0.0347	0.6547	0.1524	0.0020	0.0212	0.0835	0.0020	0.2182
0.3339	0.0123	0.1123	0.1524	0.0020	0.0212	0.0835	0.0020	0.2182
0.2677	0.0265	0.1092	0.1524	0.0020	0.0212	0.0835	0.0020	0.2182
0.4572	0.9954	0.2824	0.1524	0.0020	0.0212	0.0835	0.0020	0.2182

Table 6. TOPSIS ranking

Si +	Si –	Pi (Pref.value)	TOPSIS Ranking
0.0603	0.1975	0.6490	4
0.0748	0.1383	0.6251	5
0.1295	0.0857	0.3982	8
0.0867	0.1445	0.8052	1
0.1281	0.0871	0.4047	7
0.1995	0.0405	0.1687	9
0.0443	0.1829	0.7661	2
0.0654	0.1820	0.7358	3
0.3377	0.3590	0.5153	6

3. Results and discussion

The tabulated values (Table 5) are evaluated based on the equations (1) to (7). Table 6 shows the top ranked experiment and based on the evaluation the composite (2% nano Al_2O_3 + 7% micro Al_2O_3) is best composites shows good wear resistance, COF and surface quality. The experiment run 4 is best solution and followed by experiment runs

7 and 8. Based on ANOVA Table 7 the reinforcement contributes 19.40% and most influencing factor is sliding load with 62.33% which affects the COF, wear and surface roughness.

3.1. Effect of reinforcement (wt.%)

Figure 1 shows the mean effect plot for the factors, levels and preference values. It is evident that the composition of reinforcement wt.% shows the significant influence on the output performance namely COF, wear and surface roughness. The 2% nano Al_2O_3 + 7% micro Al_2O_3 composite shows low COF, wear and surface roughness. The incorporation Al_2O_3 in the matrix (aluminium), improves the hardness, and subsequently reduces the COF and wear resistance of the composites. The results are in line with the findings in which Al alloy composite reinforced with more amount of Al_2O_3 demonstrated greater wear resistance [15]. At 2% nano Al_2O_3 + 5.5% micro Al_2O_3 the composite shows high COF, wear and surface roughness. The lesser (5.5%) Al_2O_3 increase the plastic deforma-

Table 7. ANOVA table

Symbol	Factors	df	SS	MS	F	% contribution
A	Reinforcement (wt. %)	2	0.0681	0.0341	0.1065	19.4063
B	Sliding load (N)	2	0.2188	0.1094	0.3421	62.3338
C	Sliding velocity (m/s)	2	0.0329	0.0164	0.0514	9.3644
D	Temperature (deg.C)	2	0.0312	0.0156	0.0488	8.8955
E	Error	1	0.3198	0.3198		0.0000
	Total	9	0.6708	0.0745		100

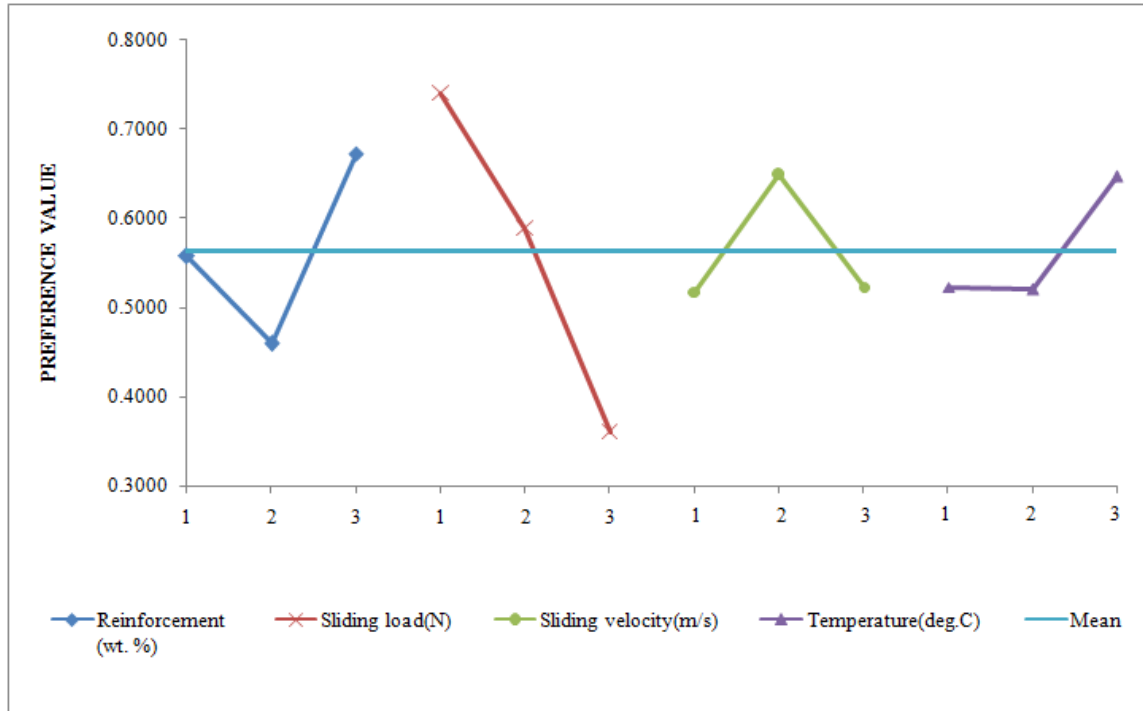


Fig. 1. Mean effect plot

tion of the matrix attributing for higher COF, wear and surface roughness.

3.2. Effect of the sliding load

An increase in sliding load leads to higher COF, wear, and surface roughness values. The presence of 2% nano Al_2O_3 in composites resist the plastic deformation of the matrix and takes up the forces created during sliding between the Al_2O_3 reinforcement. The COF of A206/silica sand containing composites is lower than the matrix alloy, as reported by Rohatgi et al. [16]. Figure 2(a)-(d) shows the composite surface with wear tracks and craters. The modification of applied load match to the pen-

etration of the counter surface's. Hard projections into the softer pin surface, attributes for increase in deformation and fracturing of the soft surface asperities. The material is removed from the worn pin surface in the form of platelet-shaped particles that result in the formation of a shallow crater. Sliding grooves are also observed around the surface of the shallow crater, as shown in figure. The propagation of cracks through the surface of the worn pins is witnessed. When loads are low, worn surfaces of composite specimens normally have wear marks and shallow craters in all cases [17]. The detailed wear inspection revealed that the wear debris was loose and scattered over the surface. A detailed investigation of the worn surfaces and subsurface

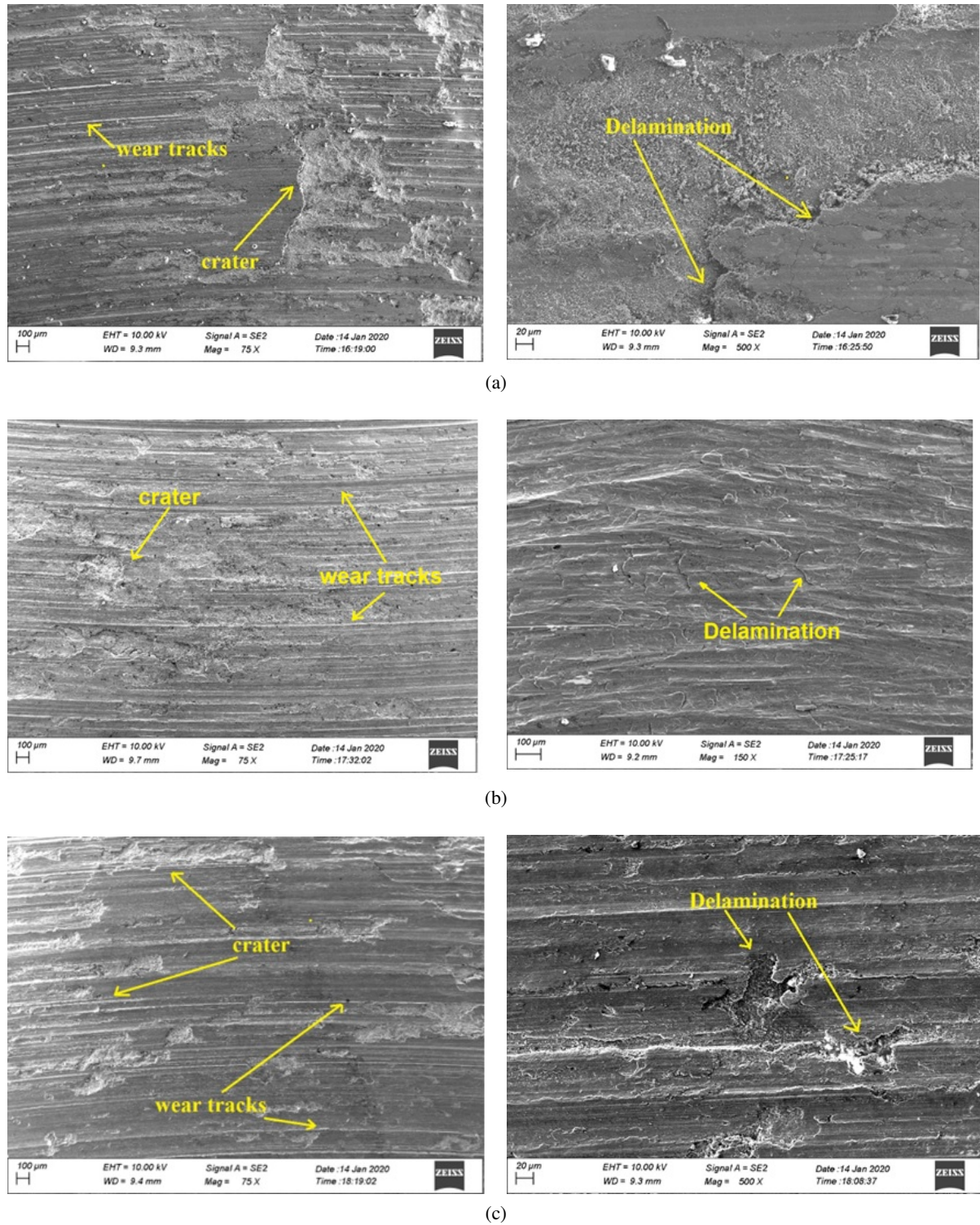


Fig. 2. (a-d) SEM images wear tracks and delamination of top four TOPSIS ranking composites

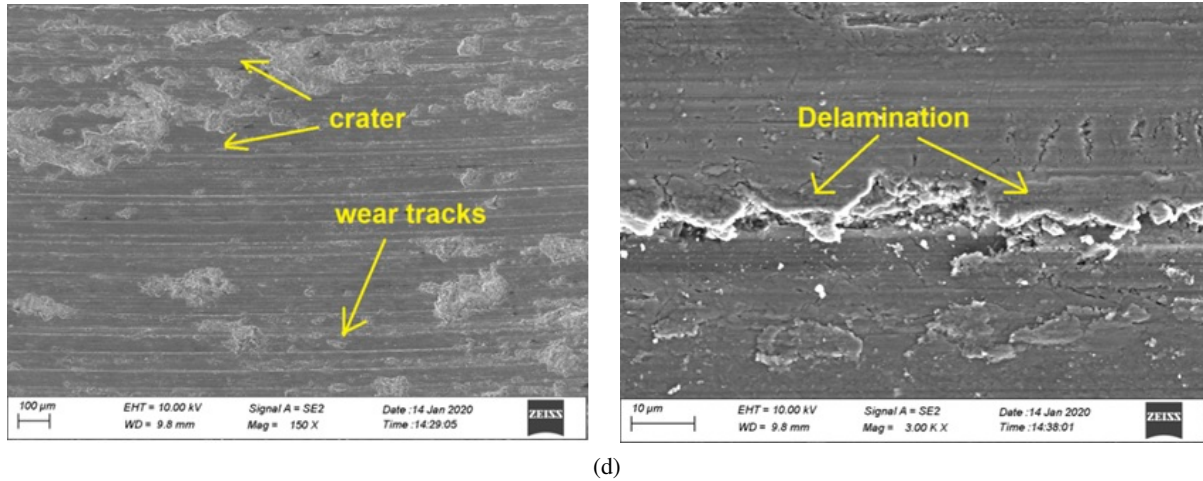


Fig. 2. ...continued

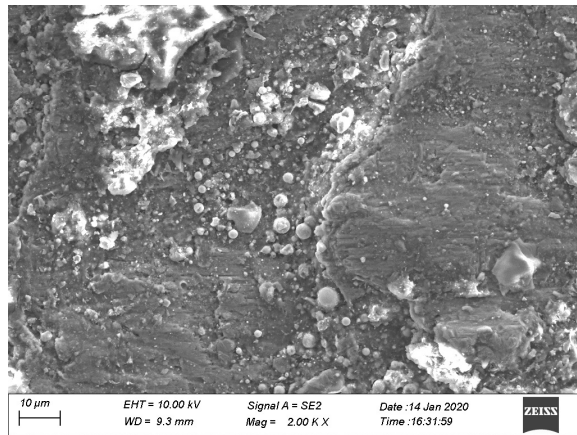
expose that tribo-layers emerge under a variety of loads and temperatures, and it never disappears until severe wear arises [17]. The tribo-layer is a mechanically mixed layer (MML) consisting of tribo-oxides, wearing alloy fragments, and Fe transferred from the counter-face. MML thickness increases slowly with increase in temperature and load. Figure 2(b) shows the layer of material moved by the shear force due to the sliding effect. Abrasive reinforcing particles erode the steel surface and cause iron transfer and MML production. The MML does not only consist of matrix alloy and spent composite reinforcements, it also shows the transfer of iron from the face of the steel disk. The formation of the MML is attributed to the turbulent plastic flow due to the onset of shear instability at a critical depth below the worn surface [18]. Figure 3(a) and (c) depicts the FESEM image of the worn-out surface of the experiment run 4 and experiment run 7. Figure 3(b) and (d) indicates the spot/area where EDS was performed. The EDS spectrum in Figure 3(e) and (f) exhibited iron-oxygen rich MMLs. It is evident that the transfer of alumina and iron particles took place during sliding action.

Figure 3(e) and (f) furthermore corroborate the presence of an oxide layer. Most metals naturally oxidize in the air, forming an oxide film within minutes which plays a dominant role in the attribute of friction. At regular loading, the oxide films separate the two metals, and COF is low because of

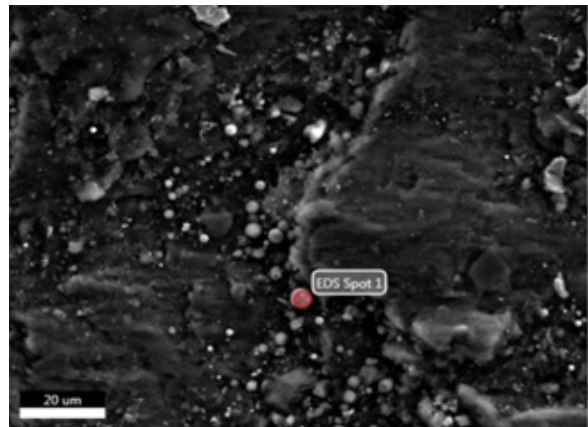
the low shearing strength and ductility. The presence of an oxide layer minimizes the risk of immediate metal contact. However, at higher loads, surface films distort and fracture, causing a metallic contact, leading to a deformation of the surface which is avoided by the presence of Al_2O_3 .

3.3. Effect of sliding velocity

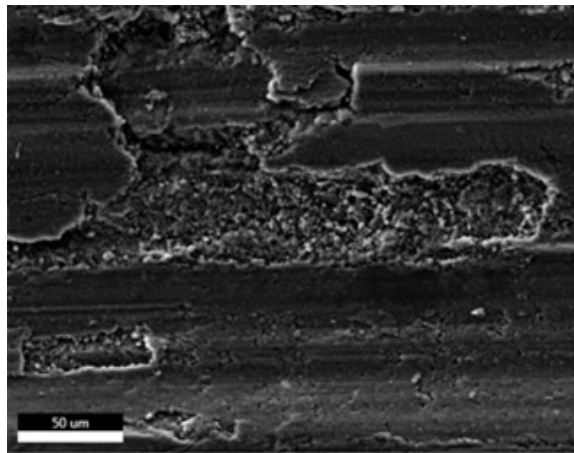
It is inferred from Figure 1 that the COF, wear and surface roughness increases with sliding velocity and then decreases with increase in sliding velocity. Strong lubrication offered by the alumina for the sliding rate ranging from 1-2 m/s credits for less COF. The normal load determines the actual contact area, which individually regards the impact of normal and tangential loads [19]. The wear rate is increased due to delamination, at the sliding speed range of 1-2 m/s. The platelet-shaped delaminated wear debris attributes rigorous damage of the worn surface of the pin and increasing friction. The development of MML reduces COF for the mono composite above the sliding speed of 2 m/s. For sliding velocity of 1 to 2 m/s the increase in COF is witnessed due to friction created by the delaminated debris trapped between the contact surfaces of the tribo-couple. To shear over this area of contact, a tangential force is needed, and if normal load increases, then the real contact area with tangential force increases, contributing to an increase in COF. Increasing of COF with load contributes to



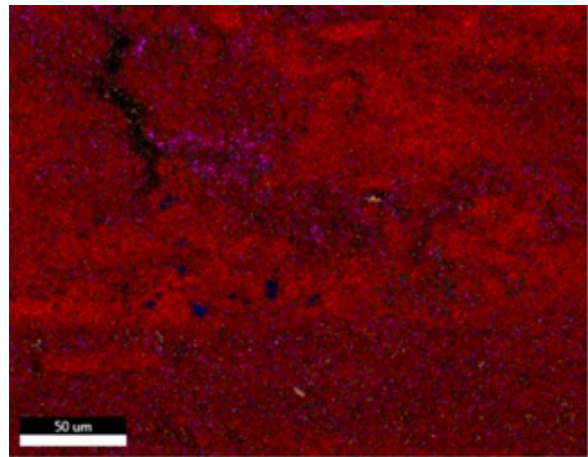
(a)



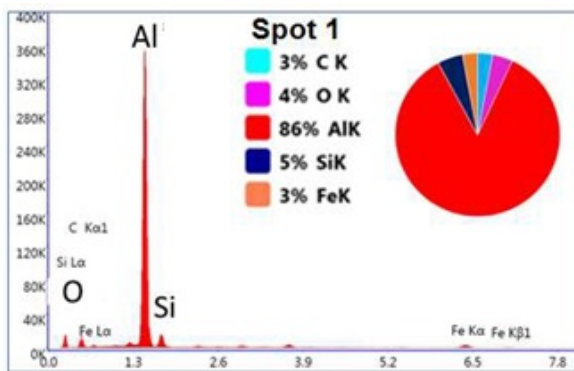
(b)



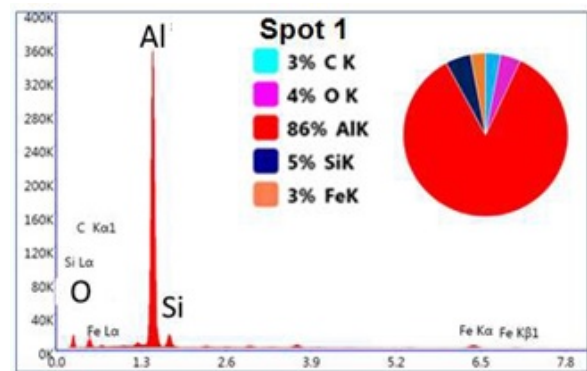
(c)



(d)

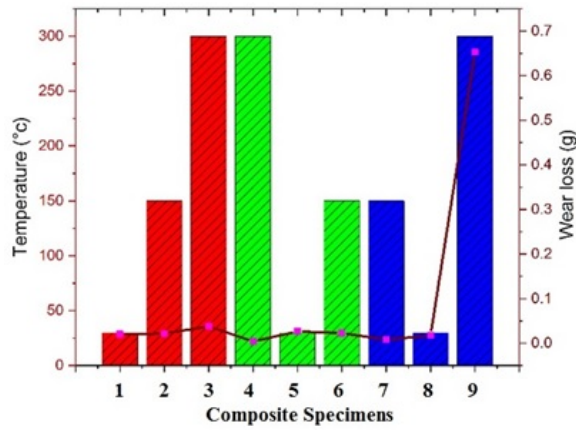


(e)

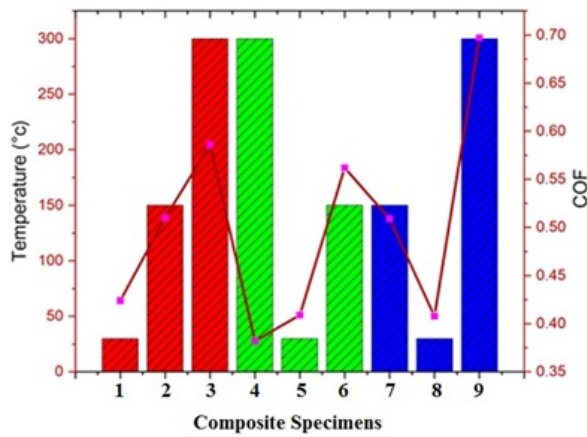


(f)

Fig. 3. (a-f) FESEM, EDAX and EDS analysis images of top-ranking composite



(a)



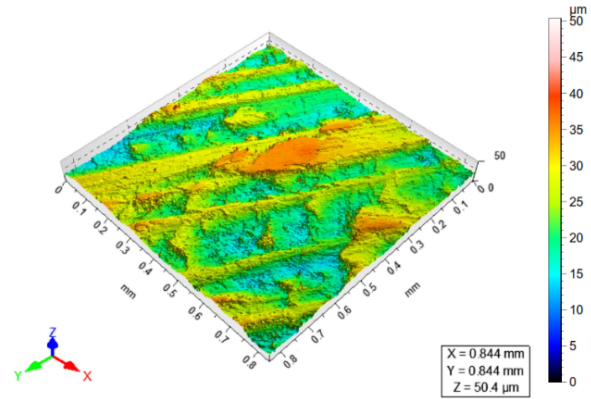
(b)

Fig. 4. Relationship between: a) temperature and wear loss and b) temperature and COF for all the specimens

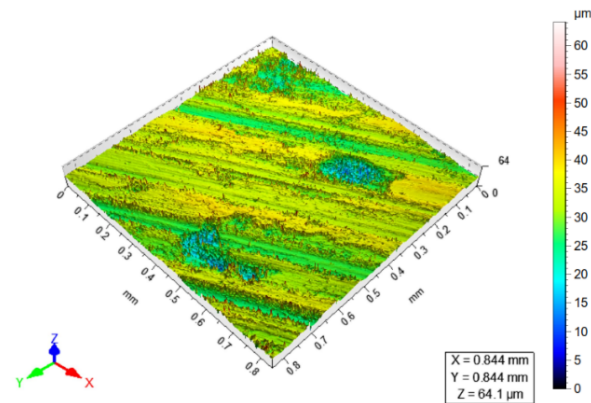
the plowing effect and micro-cutting at the time of wear leads to elevated frictional forces.

3.4. Effect of temperature

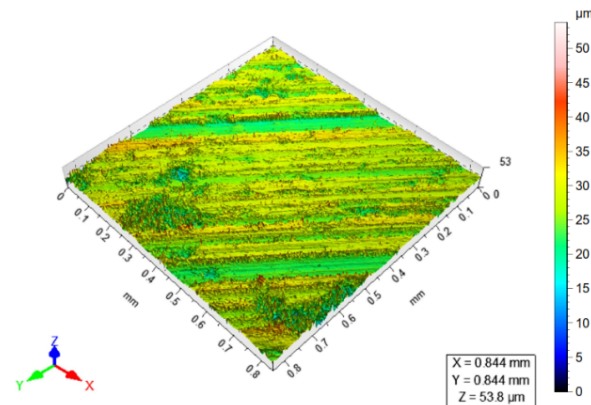
Figure 1 shows that increase in temperature increases the COF, wear and surface roughness. Figure 4(a&b) shows the correlation of temperature related wear loss and COF for all the nine specimens. As the temperature of the pin increases, it becomes softer, and wear resistance is liable to decrease, which attributes for more material removal from the contact surface [20].



(a)



(b)



(c)

Fig. 5. (a-c) 3D surface profile of the worn-out surface of first three TOPSIS ranked composites

3.5. Surface roughness and depth profile

The optical profilometer is used to obtain the surface roughness of worn-out samples of the AMMCs and is presented in Table 5. A Zygo

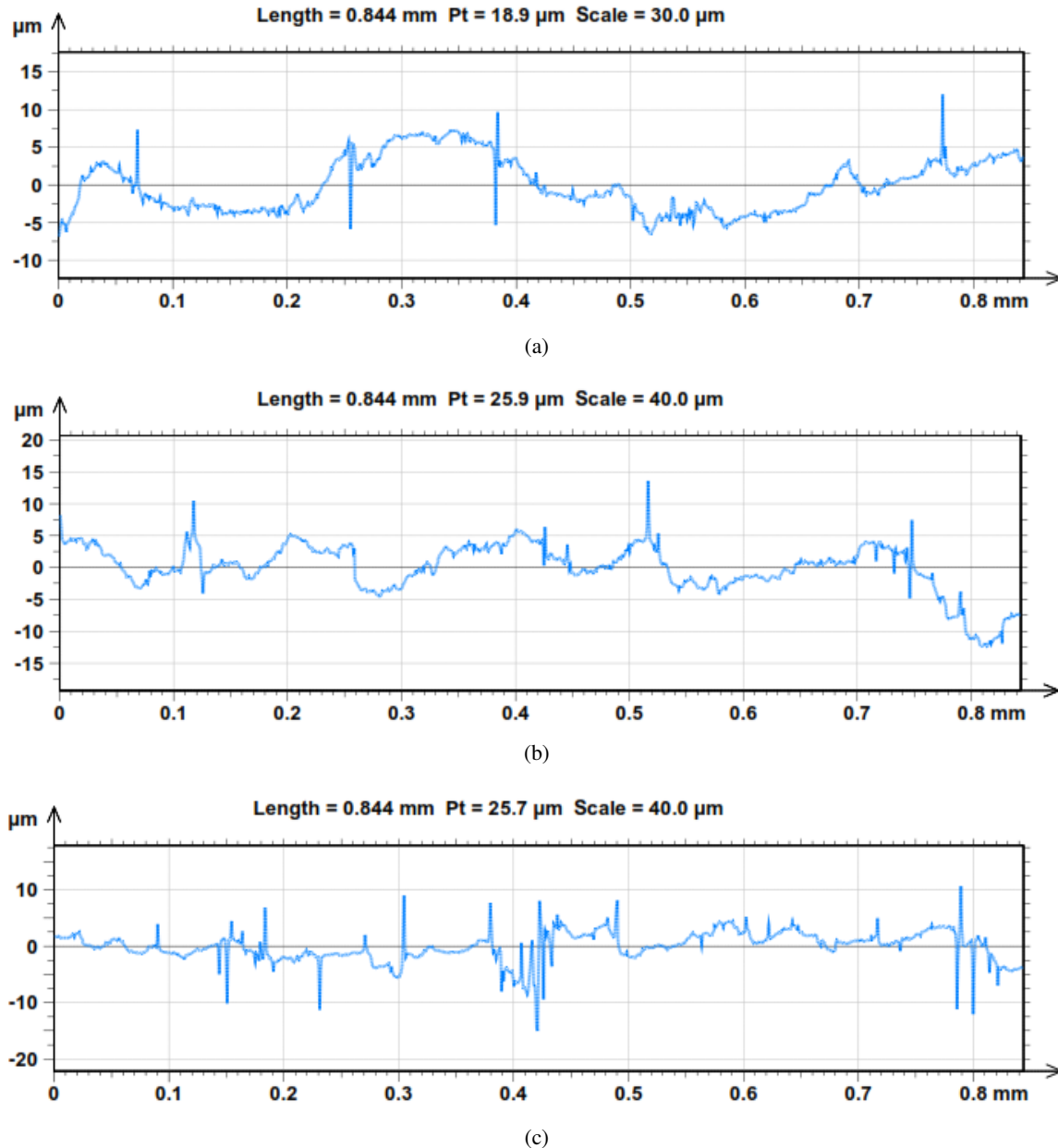


Fig. 6. (a-c) Depth profile of worn-out surface of first three TOPSIS ranked composites

New View optical profilometer was used for surface roughness measurements. The average surface roughness (R_a) values of the first three TOPSIS ranked composites are 0.322 μm , 0.405 μm , and 0.604 μm , respectively. The surface roughness of worn-out AMMCs depends on a surface features—such as pore size and density, pores (deep or shallow), micro-cracks and pinholes which is formed during the solidification and wear testing process.

The 3D surface profiles of the top ranked composites are shown in Figure 5(a-c). Among the 3D surface profiles of composites, 2% nano Al_2O_3 7% micro Al_2O_3 shows a smooth surface, which is also evident from the depth profile shown in Figure 6(a). The depth profiles of first three TOPSIS ranked composites are shown in Figure 6(a-c).

4. Conclusions

In summary, based on the design of experiments, the tribological characteristics of AMMCs was conducted, estimated, and contrasted under dry conditions through the pin-on-disc test. The wear analysis of the developed Al-Al₂O₃ hybrid composite have contributed in identifying the potential applications such as for discs of brake/rotating parts, piston, liners to meet the most required wear properties like high wear resistance and low COF. The following outcomes are summarized below.

- The composite (2% nano Al₂O₃ + 7% micro Al₂O₃) is best composites shows good wear resistance, COF and surface quality.
- The nano size 2% Al₂O₃ with 7% and 5.5% Al₂O₃ are best hybrid composites composition. The 2% nano Al₂O₃ has significant impact on COF, wear and surface roughness. Based on ANOVA, the reinforcement contributes 19.40% and most influencing factor is sliding load with 62.33%.
- The nano size 2% Al₂O₃ with 7% micro Al₂O₃ along with 20N sliding load, 2m/s sliding velocity and 300°C temperature is top ranked combination as per TOPSIS and next best combination is 2% Al₂O₃ with 5.5 % micro Al₂O₃ with 20N, 3m/s and 150°C respectively.
- An increase in sliding load leads to higher COF, wear, and surface roughness values at the same time increase in temperature increases the COF, wear and surface roughness.
- Surface roughness is purely dependent on the applied load, temperature, and texture formed on the worn-out surface.

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Conflict of interest

On behalf of all authors, the corresponding author states that there is no conflict of interest.

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