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Influence of the Load, Sliding Speed, and Weight Fractions on Wear of a Hybrid Aluminium Metal Matrix Composite

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Abstract

The vital focus of the research is intended in examining the aspect that impact the rate of wear for a hybrid aluminium metal matrix composite. The percentages of two reinforcements that are employed, the weight, and the sliding speed are the variables taken. The procedure entails employing the vortex-stir casting process to produce the hybrid composite. Utilizing a pin-on-disc apparatus, the fabricated composite materials are evaluated in compliance with the ASTM G99 standard. The test settings embrace varying weights and sliding speeds ranging from of 10 N to 30 N and 1 m/s to 3 m/s via Response Surface Method. The acquired rate of wear findings of the composites was examined for the utmost significant parameter, which was observed as sliding speed, followed by the load. The load factor was the solitary factor that had an impact in both the linear and square terms, whereas the weight fractions of the cenosphere and molybdenum disulphide had the minimum bearing effects. The wear percentage is primarily influenced by the combinative influence of the weight fraction of cenosphere – weight fraction of molybdenum disulphide, load – weight fraction of molybdenum disulphide, weight fraction of molybdenum disulphide – sliding speed and load – sliding speed. Despite their relatively small percentage contributions, cenosphere and MoS2 have been discovered to have a significant outcome on the wear rate of composite materials. The rate of wear also tends to decrease as cenosphere, and molybdenum disulphide weight percentages raise.

Keywords: HAMMCs, AA7075, Cenosphere, Molybdenum Disulphide, Wear Rate, Response Surface Methodology

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INTRODUCTION

Engineering materials termed as composite materials are specifically developed for a particular application by combining two or more physically different materials. In general, continuous fiber reinforcement is frequently related to the behaviour of ceramic reinforcements in metal matrix composites, furthermore, it is impossible to imagine any limitations on obtaining composite microstructure by self-reinforcement. Owing to their low density, enhanced corrosion resistance, excellent resistance to abrasion and wear, high specific modulus, and thermal conductivity properties, aluminum and its alloys are frequently used as the matrix metal in metal matrix composites. All such properties make them suitable for use in a range of industries, including the automotive, marine, and aerospace sectors. Typical metal matrix composites often use reinforcement powders that are broadly spherical (equiaxed) and range in diameter from 0.5 to 40 [µm], similar to sand grains [1].

Traditionally, ceramic particle reinforcement like as silicon carbides, aluminium oxides, graphite, or boron carbides have been employed to reinforce MMCs. The inclusion of reinforcements, such as fly ash/cenosphere, moreover as a solitary reinforcement or as a component of reinforcement in hybrid composite, to the metal matrix composite, is sometimes essential for the unconventional method of producing an MMC. Comparing the Fly-ash/Cenosphere reinforcement to the alloys of aluminum employed in the matrix phase of composites, the former has a lower molecular density [2]. The density of the composites is minimized by the less dense reinforcement, which is an outstanding benefit in a composite [3]. The fly-ash/cenosphere reinforcement helps in retaining the composite's fine grain structure in place by minimizing matrix dislocation movement [4].

The limitation of matrix dislocation enhances the composite material's hardness [5]. The composite becomes harder as the cenosphere percentage increases [6]. The composite material's improved hardness is favorable towards the composite's wear resistance [7]. When the composites' wear resistance improved as their hardness increased, this was enticing [8]. The composite's resistance to seizures improves as the fly-ash/cenosphere reinforcement proportion increases [9]. The fly-ash/cenosphere reinforcement is increased, which further increases seizure resistance [10].

In certain studies, solid lubricants like MoS_2, often referred as metal dichalcogenide and a part of the chalcogenide family, have been employed. The resistance to wear of Molybdenum Disulphide was greatly aided by the development of tribo-film over the exterior layer of the composites during non-lubricated wear behavior [11]. The MoS_2 reinforcement creates a Tribo-film layer that limits the plastic distortion of the composites [12]. The Tribo-layer that forms over the pin prevents a connection between the aluminum and the disc [13]. In composite materials, the wear rate is reduced by strain fields forming around the reinforcement [14]. Because of the homogenous placement of the reinforcements in the matrix, a dislocation barrier in the material structure is formed and the matrix contains finely dispersed MoS_2 reinforcement, which is essential for improving the tribo properties of the composites [15]. The composite's stiffness and wear opposition also are enhanced by the MoS_2 reinforcement [16].

According to the leading observations in metal matrix composites, the research carried over the tribo-properties of aluminum/cenosphere composites and aluminum/Molybdenum Disulphide composites was up to a finite extent by many researchers, while the cenosphere and Molybdenum Disulphide reinforcement combinations in aluminum matrix were not looked into. In order to accomplish the ideal condition of non-lubricated gliding wear, an endeavor was made to creäte AA7075/cenosphere/molybdenum disulphide MMCs. The efficacy of every process variable as well as the wear performance of the composites under non-lubricated gliding wear circumstances were investigated using RSM.

EXPERIMENTAL WORK

Composite Specimens Development by Stir-Casting

The 7075 alloy of aluminum was elected as the matrix material due to the reason as it is one of the strongest alloys of aluminum that is conventionally available and is equally effective with or comparable to the majority of steel alloys in terms of strength qualities, making it ideal for use in high-stress circumstances. In alloys of aluminum 7075, zinc occurs second as an alloying component after aluminum, and is then followed by copper, magnesium, and other components. The elements that are involved in making AA7075 are listed in Table 1.

Molybdenum disulphide and cenosphere were used as reinforcements in this work. Cenosphere reinforcements are inert, hollow spheres that are lightweight. They are typically composed of oxides of silicon and aluminium, a natural remnant source of the combusted coal from thermal plants. Also, it works better as a binding material and, due to its lower density, makes an excellent filler reinforcement for use in composite manufacturing, among other things. Molybdenum disulphide (MoS_2), a solid lubricant, was utilized in the creation of this material as a secondary reinforcement. The composite wear pins were fabricated by employing vortex-stir casting technique, which were then machined to the Ø8 mm × 22 mm dimensions depicted in Figure 1.

Non-Lubricated Wear Test

Magnum Engineers' pin-on-disc equipment system, paired with a data collection system, was used to conduct the experiment. The apparatus consists of a configuration for supporting a static pin that slides on an EN32 steel disc under the control of an electric motor. Before being weighed with an automated weighing scale with an accuracy of 1×10^{-4} g, the pins are polished, cleaned, and dried. Wet sliding, as required by the ASTM G99 standard, was used for the wear studies, which were conducted at room temperature (28°C) [17]. Along with the different parameters, a fixed condition of sliding distance 1000 m was set. The specimens' weight-loss was utilized to quantify the wear loss. By dividing the experiential weight loss by the composite's theoretic density, the wear of the composites was calculated in terms of volume loss. For calculating the rate of wear (WR) of the composites Equation (1) was used, where V g/cm^3 stands for volume loss.

$$\text{Wear Rate} = \frac{\Delta V}{\text{Sliding Distance}}\left[{mm^3}/{m}\right] \tag{1}$$

Response Surface Methodology

Response Surface Methodology, an approach of DOE, was used in evaluating the effect of the variables of AA7075/cenosphere/Molybdenum Disulphide. Apart from the load and sliding speed factors, the weight fractions of the cenosphere and molybdenum disulphide were taken in the varying ranges of 0%, 2%, and 4%. The reinforcement percentages were limited to 4% in weight of the aluminum matrix because composites with reinforcement more than 4% by weight have inappropriate tribological characteristics [18]. Additionally, the load within extent of 10 N, 20 N, and 30 N as well as the sliding speed within order of 1 m/s, 2 m/s, and 3 m/s are considered. Table 2 displays the level and factors of each component and Table 3 shows the outcomes of non-lubricated wear testing for a total of 31 different scenarios produced by Central Composite Design (CCD).

Table 1. Element Structure of AA7075 (weight %).

Aluminum	**Zinc**	**Magnesium**	**Copper**	**Silicon**
90.90	4.94	1.61	1.45	0.55
Iron	Titanium	Manganese	Nickel	Lead
0.20	0.07	0.04	0.009	0.003

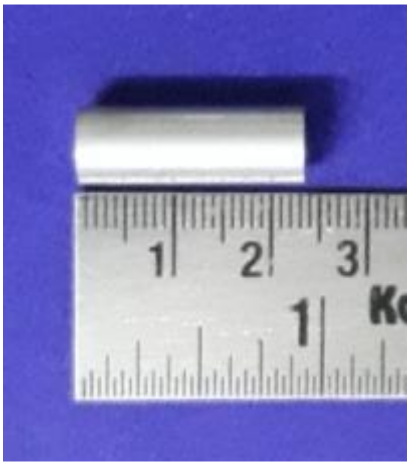

Figure 1. Composite Wear pins of appropriate proportions Ø8 × 22 mm.

Table 2. Chemical Composition of AA7075 (wt.%).

Factors	Symbolization	Unit	Factor Levels		
Weight fraction of cenosphere	C	%	0	2	4
Weight fraction of MoS_2	M	%	0	2	4
Load applied	L	N	10	20	30
Sliding Velocity	SV	m/s	1	2	3

Table 3. Central Composite Design for the AA7075/Cenosphere/MoS_2 composite material's wear test.

Trail	C [%]	M [%]	L [N]	SV [m/s]	Wear Rate $\times10^{-3}$ [mm^3/m]
1	0	0	10	1	2.9290
2	0	0	10	3	13.2140
3	0	0	30	1	7.9650
4	0	0	30	3	35.2860
5	0	2	20	2	1.6640
6	0	4	10	1	1.7910
7	0	4	10	3	3.1260
8	0	4	30	1	3.7920
9	0	4	30	3	10.1850
10	2	0	20	2	5.8700
11	2	2	10	2	4.3970
12	2	2	20	1	1.0700
13	2	2	20	2	4.0636
14	2	2	20	2	4.0636
15	2	2	20	2	4.0636
16	2	2	20	2	4.0636
17	2	2	20	2	4.0636
18	2	2	20	2	4.0636
19	2	2	20	2	4.0636
20	2	2	20	3	9.7620
21	2	2	30	2	13.3950
22	2	4	20	2	2.2800
23	4	0	10	1	0.4090
24	4	0	10	3	2.5320
25	4	0	30	1	0.8150
26	4	0	30	3	22.1880
27	4	2	20	2	2.2080
28	4	4	10	1	5.4970
29	4	4	10	3	5.5040
30	4	4	30	1	4.1910
31	4	4	30	3	18.0490

Using Minitab 19 software, in the non-lubricated wear scenario, the most significant linear, squared, and also interaction components that affected the output response were found. The significance of the coefficients was also tested, along with the model's fit.

RESULTS AND DISCUSSION

The three major elements that influences the wear performance of the composite are the weight fraction of cenosphere (C) and Molybdenum Disulphide (M), load (L), and sliding speed (SV). The Response Surface Methodology (RSM) technique for variance analysis provides details on the mutable factor's contribution in terms of its linear, squared, and also interaction effects. In Table 4, the outcomes of the analysis of variance (ANOVA) are presented while taking the significant terms alone into account.

Effect of Distinctive Factors on Non-Lubricated Wear

The performance of various parameters on the hybrid composite material's wear rate is shown in the analysis of variance table. It was evident from Table 4 that the sliding speed is the primary aspect affecting wear rate, contributing the highest percentage up to 28.85% as in linear term while providing no contribution in the square term. Since the P-value for the sliding speed factor remained less than 0.05, its degree of implication was good, and in Figure 2, main effect graph illustrates how the rate of wear grows as the sliding speed steadily rises.

Load applied was the second factor to be conditional, as it has a significant P-value of less than 0.05. Additionally, the applied load's contribution percentage was 10.3% in square terms and 20.2% in linear terms, demonstrating that the composite’s wear is encouragingly influenced by the applied load. It also exemplifies how the constituent elements influence the composite’s wear performance in linear term alone which is shown in the ANOVA table and the applied load was the only condition where the square term could be revealed, suggesting that it possibly will be the most crucial element affecting the composite's wear rate. The main effect plot (Figure 2) shows that it marginally decreases between 10 N and 20 N before increasing between 20 N and 30 N.

The cenosphere and MoS_2 weight fractions were the linear term variables that had the least influence on the outcomes having a minor impact on the P-value. The weight fractions of cenosphere and molybdenum disulphide each contributes 1.2% and 4.7% respectively. The wear rate has no square term influence in the case of the weight ratio of cenosphere and molybdenum disulphide.

The main effects graph (Figure 2) demonstrates that weight fractions of cenosphere and molybdenum disulphide increasingly experience lower wear rates from 0 wt. % to 4 wt. %, indicating that the weight fractions of cenosphere and molybdenum disulphide can be advantageous characteristics which are essential for the composites in controlling the wear rate.

Effect of Multiple Factor Interactions on Non-Lubricated Wear

The interaction graph (Figure 3) demonstrated the interaction between the weight fraction of the cenosphere and MoS_2, load-sliding speed, and the weight fraction of the MoS_2 - load. Sliding speed-load interaction term contributed the most to the composite's wear rate (11.8%), as seen in the ANOVA table (Table 4) for each interaction component. With a contribution of 8.9%, the load - sliding speed interactions is the most significant interaction component, followed by the weight fraction of cenosphere-weight fraction of MoS_2 interaction term. The weight fraction of the MoS_2 - sliding speed interaction term provides 6.1%, tailed by the weight fraction of the MoS_2 - load interaction, which contributes to 2.8%, in addition to the aforementioned two interaction components. Because the P-value was less than 0.05, all interaction terms were significant at the same level of significance.

Domination of the Sliding Velocity in the Wear Rate of the Composites

The trend in Figure 2 shows that the sliding speed parameter has an overall advantage over the other variables when it comes to the composites' rate of wear. The AA7075/cenosphere/MoS_2 composites had an up to 83% increase in rate of wear when the sliding speed parameter was augmented from 1 m/s to 3 m/s.

Domination of the Load in the Wear Rate of the Composites

The load parameter, another factor that affects how quickly composite materials wear out, originally showed a decreasing trend up to 20 N before beginning to increase, as revealed in Figure 2. The rate of wear for the composites made of AA7075/cenosphere/MoS_2 has increased by up to 83% as a result of the applied load parameter.

Table 4. Analysis of Variance (ANOVA) for wear rate ×10^{-3} [mm^3/m].

Source	Adj SS	Adj MS	F-Value	P-Value	Contribution in %
C	19.1	19.1	4.8	0.04	1.20%
M	75.2	75.2	18.9	0.00	4.70%
L	324.8	324.8	81.6	0.00	20.20%
SV	463.9	463.9	116.6	0.00	28.80%
L*L	165.3	165.3	41.5	0.00	10.30%
C*M	142.7	142.7	35.8	0.00	8.90%
M*L	45.1	45.1	11.3	0.00	2.80%
M*SV	97.5	97.5	24.5	0.00	6.10%
L*SV	190.4	190.4	47.8	0.00	11.80%
Error	83.5	3.9	-	-	-
Lack-of-Fit	83.5	5.5	-	-	-
Pure Error	0.0	0.0	-	-	-
Total	1607.9	-	-	-	-

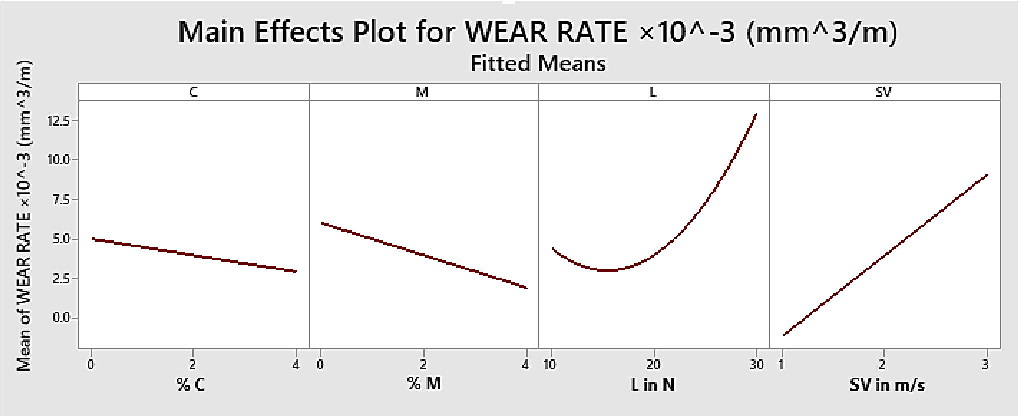

Figure 2. Main Effects graph wear rate for composites.

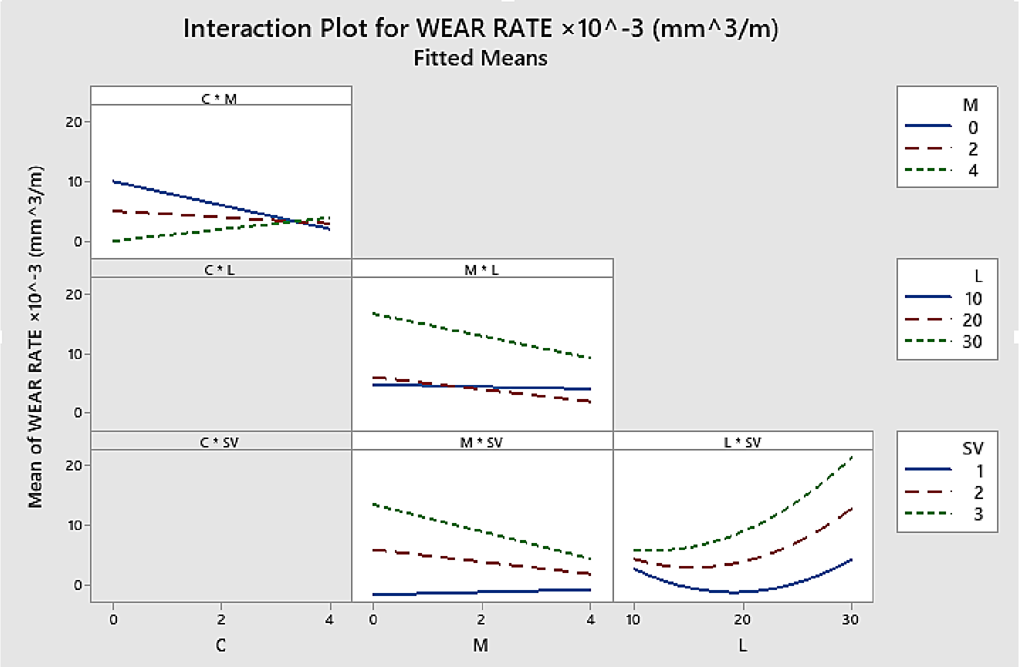

Figure 3. Interaction graph for wear of composites.

Domination of the Reinforcements in the Wear Rate of the Composites

The delamination mechanism in the AA7075+2C composites were observed in SEM images (Figure 4), together with a mild wear regime and abrasive wear track. In Figure 5, AA7075+2M composites reveals mild wear along with ploughing, and the wear tracks in the composite are identified as abrasive wear tracks. As with Al-Si10Mg/MoS_2 composites, a tribo-film layer of MoS_2 formation was also found to form on the exterior layer of the composites, and this layer was vital in the ability of the composites to resist wear at increasing speed [13].

The delamination that was mostly mild in the composite was the wear mechanism that can be investigated from the wear SEM images of the AA7075+2C+2M, AA7075+2C+4M, and AA7075+4C+2M (Figures 6, 7, and 8). The presence of MoS_2 reinforcements was a prominent factor in the occurrence of delamination in the composite surfaces. Due to its hard particle nature, cenosphere favours the ploughing action on the surface of the composites, and MoS_2 reinforcement increases the delamination mechanism's favorability. The presence of cenosphere reinforcement contributed to the surfaces' pitting as well [4].

Confirmation Experiment and the Reliability of Wear Model

The summary of the model is shown in Table 5, and R^2, which represents the proportion of response variation that the model explains, is used to assess how the model is appropriately fit. The R^2 score is almost 94.80%, which specifies that the model is competent. The model is overfitting (94.80%) since the projected R^2 (80.12%) is lower than the R^2 term.

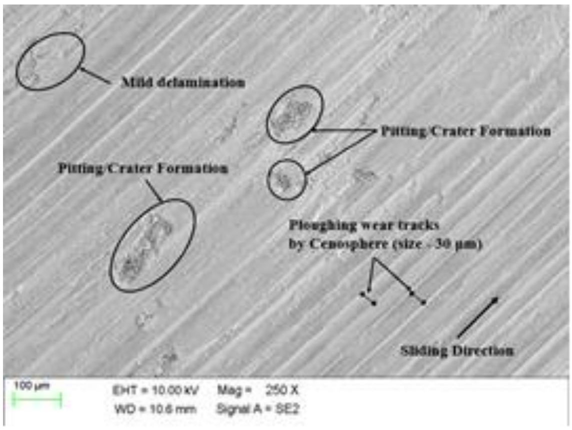

Figure 4. Microimage of worn-out surface for AA7075+2C composite at 20 N and 2 m/s.

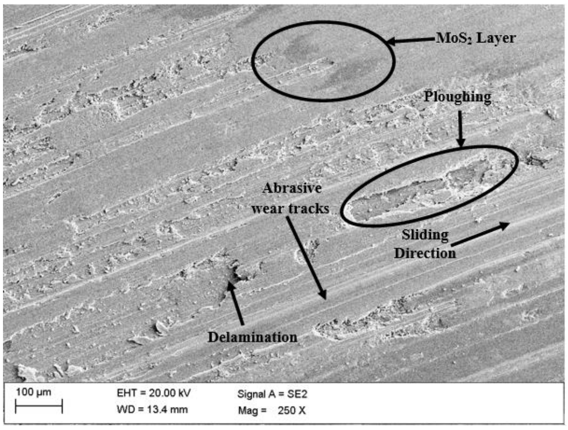

Figure 5. Microimage of worn-out surface for AA7075+2M composite at 20 N and 2 m/s.

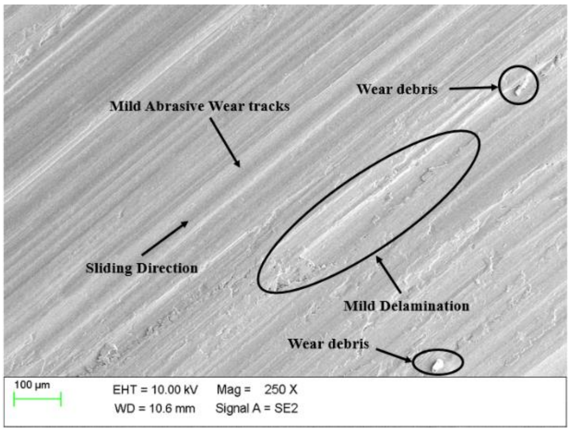

Figure 6. Microimage of worn-out surface for AA7075+2C+2M composite at 20 N and 2 m/s.

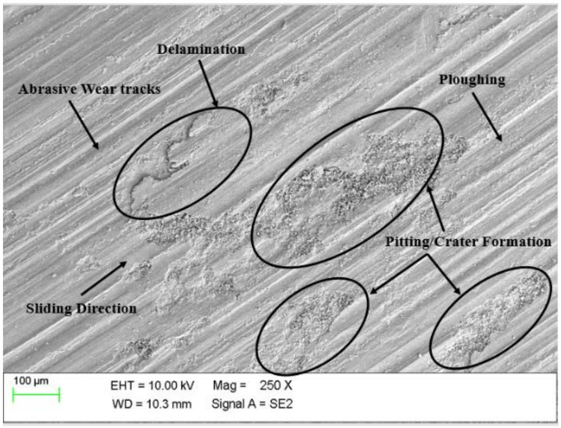

Figure 7. Microimage of worn-out surface for AA7075+2C+4M composite at 20 N and 2 m/s.

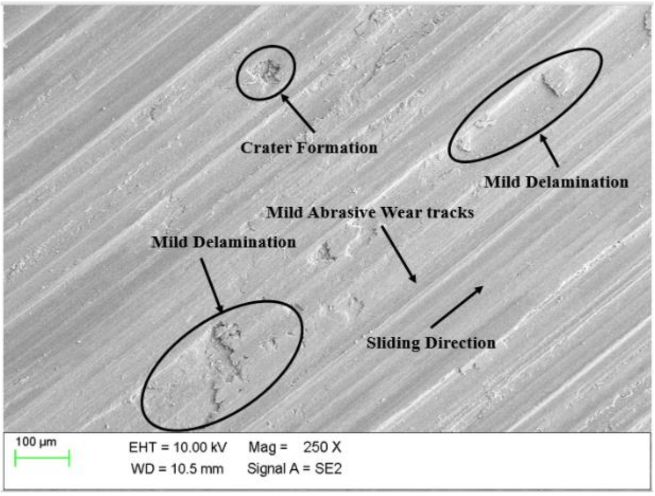

Figure 8. Microimage of worn-out surface for AA7075+4C+2M composite at 20 N and 2 m/s.

Table 5. Summary of Model.

S	R^2	R^2 (Adj)	R^2 (Pred)
1.994	94.8%	92.5%	80.1%

Table 6. Response Optimization Solution.

C (%)	M (%)	L (N)	SV (m/s)
4	0	17.27	1

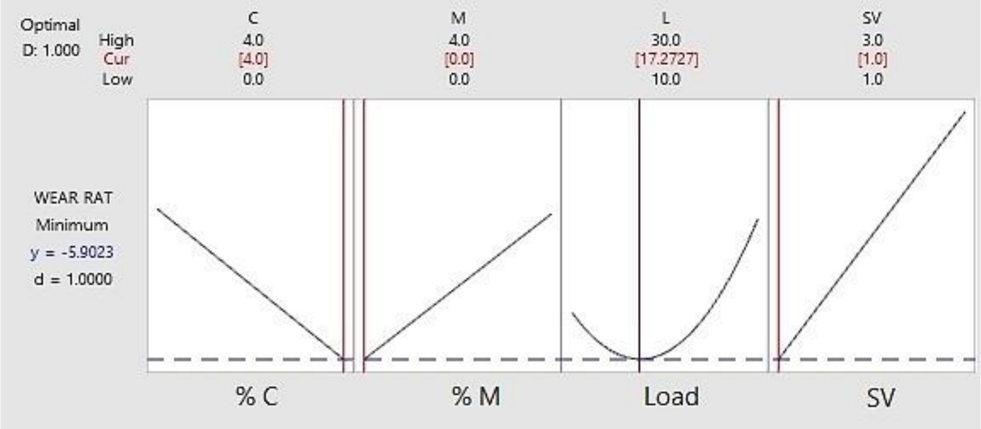

Figure 9. Optimal Combinations for Wear Rate of the hybrid composites.

The optimum conditions of the acquired response were treated in order to determine the wear rate's marginal condition via response optimization. The ideal conditions for the wear rate minimization are displayed in Table 6, which were 4 weight % cenosphere and 0 weight % MoS_2. The ideal sliding speed is 1 m/s, and the ideal applied load is 17.27 N.

Table 6 shows the projected optimal conditions for the composites have low wear rates, and Figure 9 shows a graphic representation of the ideal conditions for the wear rate of AA7075/cenosphere/MoS_2 composites.

In a follow-up experiment, from Table 6, the ideal combinations of 4 weight % for the cenosphere, 20 N approximation of 17.27 N for load, and 1 m/s for sliding speed were determined. The experiment's results showed that the ideal wear was 0.3680×10^{-3} mm^3/m when the weight fraction of reinforcements, sliding speed, and load were combined. The expected and trial values are listed in Table 7.

Table 7. Validation test results for wear rate $\times 10^{-3}$ [mm^3/m].

Parameter	C [%]	M [%]	L [N]	SV [$m.s^{-1}$]	Value of Wear Rate $\times 10^{-3}$ [mm^3/m]	
					Predicted	***Trial***
Optimum conditions	4	0	20	1	0.3560	0.3680

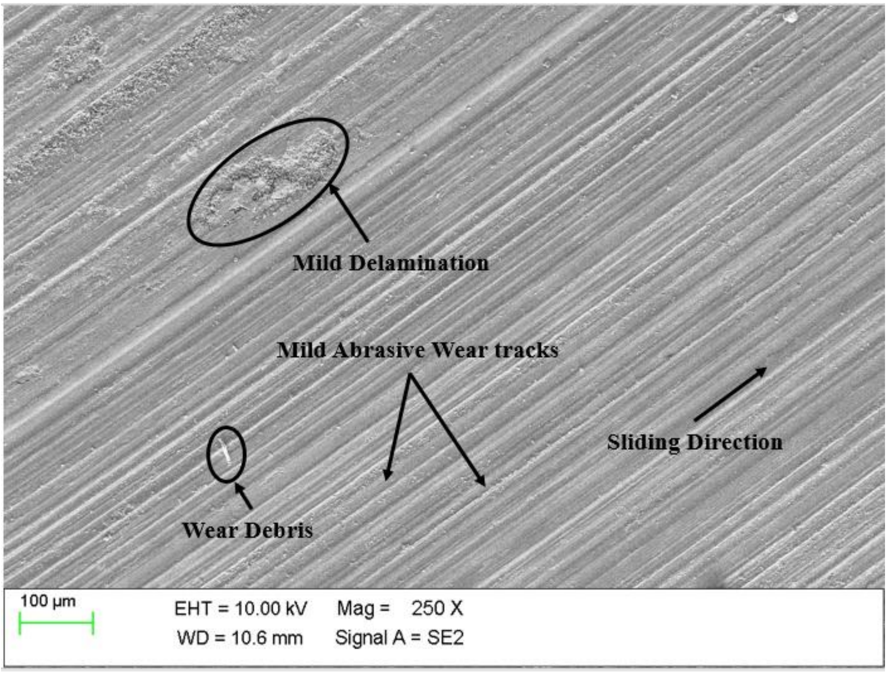

Figure 10. Microimage of worn-out surface of AA7075/cenosphere/MoS_2 composite at 20 N and 1 m/s

The wear of the composite reveals a minimally abrasive state combined with wear debris on the exterior layer of the composites in the microimage of the worn-out surface (Figure 10) under the ideal conditions of 4 wt. % cenosphere, 20 N of load, and 1 m/s of sliding speed.

CONCLUSIONS

The vortex-stir casting technique was successfully engaged to produce the AA7075/cenosphere/MoS_2 composites, and the following findings were reached from this experiment:

1. The sliding speed has a momentous impact on the wear characteristics of non-lubricated sliding. It was clear that as sliding speed rose, so did the rate at which composite materials wore out.
2. Though if increasing, the sliding speed and load aids the wear rate of the composites whereas the weight fraction of cenosphere and MoS_2 affects the wear rate of the hybrid composites.
3. According to the analysis of variance (ANOVA) table, the linear, square, and interaction significant levels for the variables weight fractions of cenosphere, weight fractions of MoS_2, load, and sliding speed are good.
4. 20.2% by load, 1.2% by the weight fractions of cenosphere and 4.7% by the weight fractions of MoS_2 which all had a sizable linear impact on the wear of the hybrid composites, but with the sliding speed accounting for 28.85% on the wear rate.
5. Wear was also influenced by the applied load (10.3%) in square terms.
6. The wear of the hybrid composites was significantly influenced by the interaction between load and sliding speed, which contributes nearly 11.8%, cenosphere-weight percentage of MoS_2 (which contributes 8.9%), sliding speed-weight percentage of MoS_2 (which contributes 6.1%), and applied load (which contributes 2.8%).
7. At 1 m/s sliding speed, 17.27 N load and 4 wt. % cenosphere percentage, the wear rate of the optimum composites reached its lowest value of wear.

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