

# Dry sliding wear performance of AA7075/MoS<sub>2</sub> composite materials

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**Submitted** : 27/08/2020

**Revised** : 26/08/2021

**Accepted** : 06/09/2021

## ABSTRACT

This article aims at exploring the dry sliding wear performances on the aluminum (AA7075) metal matrix composites reinforced with molybdenum disulfide, which is a solid lubricant using response surface methodology (RSM). Specific Wear Rate (SWR) for the AA7075 pure alloy, AA7075+2wt% molybdenum disulfide, and AA7075+4wt% molybdenum disulfide were measured according to ASTM G99 standards in pin-on-disc apparatus. Design of experiments was selected with changed parameters like the varying percentage of molybdenum disulfide (%), applied load (N), and sliding velocity (m/s) based on Central Composite Design in response surface methodology, considering them as continuous factors. Experiments for the specific wear rate of pure alloy and the composites were conducted. The volume loss was measured using the pin-on-disc apparatus from which the specific wear rate value was calculated. The obtained results are analyzed, and a mathematical model was formulated using the response surface methodology. The optimum level parameters for the specific wear rate have been identified, and the results of the experiment specify that the sliding velocity and molybdenum disulfide percentage have a substantial role in controlling the wear behavior of composites when compared with the other parameter. The optimum condition for the specific wear rate was identified and experimented with for studying the result.

**Keywords:** AA7075; Dry sliding wear; Molybdenum disulphide; Response surface methodology; Specific wear rate.

## INTRODUCTION

A composite material is a combination of materials engineered with the intent of gaining the finest characteristic of the respective material. The options for achieving a composite microstructure by self-reinforcement are largely limited. Generally, in a metal matrix composite material, ceramic reinforcements are considerably used compared with continuous fiber reinforcement. Metal matrices include pure as well as alloys of aluminum, magnesium, nickel, titanium, copper, and other metals. The powders used as the reinforcement were typically equiaxed (roughly spherical), like a grain of sand, and between 0.5 and 40  $\mu\text{m}$  in diameter (Evans *et al.*, 2003)

The most common type of reinforcement is usually the silicon carbide or alumina, which serves as a traditional way of reinforcing the MMCs. But the unconventional way of producing an MMC depends upon the reinforcement used. One such way of producing an MMC is using a solid lubricant, like molybdenum disulfide (MoS<sub>2</sub>). The

lubricating properties of MoS<sub>2</sub> have paved the way for utilizing them in the reinforcements of metal matrix composite materials. The MoS<sub>2</sub> particles show better results in improving the wear resistance of the composite material compared to the as-cast alloy (Alidokht et al., 2013; Somasundara Vinoth et al., 2012). The improvement in the wear resistance in the composite material was due to the formation of a rich film layer on the wear surface due to the dry sliding behavior, which restricts the plastic deformation of the material (Alidokht et al., 2013; Somasundara Vinoth et al., 2012; Hemendra Patle et al., 2019).

A tribo-layer was formed in these composites, and the formation of the layer is owing to the presence of MoS<sub>2</sub>; the layer which forms over the pin avoids the direct contact of the aluminum to the disc (Anish Rajan and Shanmugasundram 2019). Also, the minimum wear rate is obtained due to the formation of strain fields around the reinforcement (Anish Rajan and Shanmugasundram 2019). The fine dispersion of the reinforcement in the matrix is vital for improving the tribological properties and also the hardness of the composite as the homogeneous dispersion of the reinforcement in the matrix gives an obstacle to the dislocations that occur in the material structure (Alidokht et al., 2013; Somasundara Vinoth et al., 2012; Siddesh Kumar et al., 2014; Anish and Ananth Kumar, 2018; Jojith and Radhika, 2019). Even though the hardness increases due to the fine dispersion of the reinforcement in the matrix, it does not favor the improvement of tensile or yield strength of the composite, as the reinforcement causes a mixed-mode, which is in Ductile-Brittle regions (Somasundara Vinoth et al., 2012). Sometimes, as an individual factor, the reinforcement improves the yield and tensile strength but does not favor the elongation properties (Jojith and Radhika, 2019; Bhargavi Rebba and Ramanaiah, 2014; Subba Rao and Ramanaiah, 2017). As a whole, the density of the composite increases as the density of the molybdenum disulfide reinforcement is high compared to aluminum alloy and other reinforcements in hybrid conditions (Alidokht et al., 2013; Somasundara Vinoth et al., 2012).

The reinforcement particles in the composites, which obstruct the motion of the atoms, offer great resistance to the plastic deformation and also increase the grain boundary strength, which increases the hardness of the composites. Wear rate was very low at the condition of lower loads as the surface interaction pressure is less. Load increment increases the wear rate due to the stresses building up and results in more material removal (Jojith and Radhika, 2019).

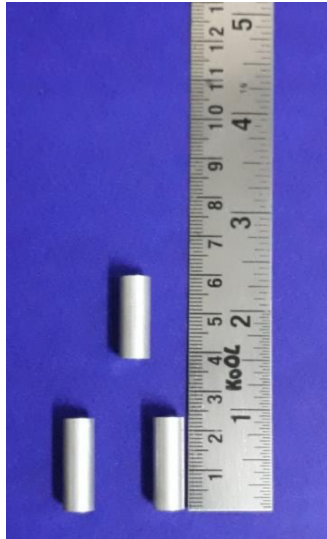
The factors like applied load, sliding velocity, and weight percentage of the reinforcement influence the wear resistance of the composite. The specific wear rate (SWR) and Coefficient of Friction (COF) are the responses of these factors where the most noteworthy influence is due to the percentage of MoS<sub>2</sub> followed by sliding velocity and applied load for SWR, and in the case of COF, the applied load contributes more, followed by the percentage of MoS<sub>2</sub> and sliding velocity. The percentage of MoS<sub>2</sub> influences the topmost priority for both SWR and COF, followed by sliding velocity and applied load (Dharmalingam et al., 2011).

Based on the major studies in the metal matrix composites, it was found that the study on the mechanical and tribological characteristics of AA7075 aluminum alloy with Molybdenum disulfide as the reinforcement is not much endeavored. Hence, an attempt was made to synthesize AA7075/MoS<sub>2</sub> MMC, and the wear behavior of the composites under dry sliding conditions was analyzed through RSM to attain an optimum wear condition.

## MATERIALS AND METHODS

The 7xxx series of aluminum alloys are generally termed as ‘hard’ alloys among the other alloys of aluminum. Aluminum alloy 7075 has zinc-magnesium-copper as the following alloying constituents next to aluminum. Aluminum alloy 7075 of series 7xxx was taken as the matrix material, and the solid lubricant Molybdenum disulfide (MoS<sub>2</sub>) was taken as the reinforcement.

The chemical composition of the AA7075 alloy used is shown in Table 1. A stir casting technique was implemented for producing the composites. Molybdenum disulfide in varying amounts ranging between 0 wt.%, 2 wt.%, and 4 wt.% was reinforced with aluminum 7075 alloy, and the weight percentages of the reinforcement were not chosen beyond 4 wt.% because the mechanical and tribological properties of the composites were not favorable beyond the considered percentages (Bhargavi Rebba and Ramanaiah, 2014).



**Figure 1.** Photograph of composite pins of dimensions Ø8 mm×24 mm for the wear test.

The cast composite pins for performing the dry sliding wear test were machined to the dimension of Ø8 mm×24 mm (Figure 1), and it was performed on the Magnum Engineers pin-on-disc apparatus system. The pin-on-disc wear and friction testing machine linked to a data collection system are shown in Figure 2.



**Figure 2.** Photograph of pin-on-disc apparatus.

The apparatus consists of a stationary pin sliding on a rotating disc driven by an electric motor. The disc material was EN32 steel. The pins are polished; their weights are measured with an electronic balance of 0.0001g precision. Wear tests were carried out at normal room temperature ( $30\pm 3$  °C) under the dry sliding condition as per the ASTM G99 standard. Before the commencement of the test, all the contacting surfaces were polished to a metallurgical finish, cleaned, and dried. The sliding distance of 1000 m was taken as a fixed parameter. The wear loss of the specimens was measured by the weight loss method. The difference between the weights measured before and after the test provides the wear loss of the composites in terms of weight loss, and it was converted into the volume loss by dividing with the theoretical density of the composite. Specific wear rate ( $W_s$ ) was calculated using equation (1), where  $\Delta V$  terms the volume loss.

$$W_s = \frac{\Delta V}{LOAD \times SLIDING DISTANCE} \text{ mm}^3 / Nm \quad (1)$$

**Table 1.** Chemical Composition of AA7075 (wt%).

Si	Fe	Cu	Mn	Mg	Zn	Pb	Ni	Ti	Al
0.45	0.19	1.55	0.043	1.62	4.98	0.004	0.008	0.05	90.91

DoE was employed in formulation using the three variable factors like weight percentage of MoS<sub>2</sub>, applied load, and sliding speed for a constant sliding distance of 1000 m as shown in Table 2. A three-level Central Composite design was adapted, which is represented in Table 2.

The upper limit of the process variable was coded as '+1' and the lower limit as '-1'. In the present study, three parameters, namely, sliding velocity (SV), applied load (L), and weight percentage of MoS<sub>2</sub> (M), were chosen as the variables. Dry sliding wear tests were conducted for 20 different conditions obtained using Central Composite Design as shown in Table 3.

**Table 2.** Experimental factors and their levels based on DoE.

Factor	Notation		Unit	Factor Level		
	Natural	Coded		-1	0	1
Weight percentage of MoS <sub>2</sub>	% MoS <sub>2</sub>	X <sub>1</sub>	%	0	2	4
Load applied	Load	X <sub>2</sub>	N	10	20	30
Sliding Velocity	SV	X <sub>3</sub>	m/s	1	2	3

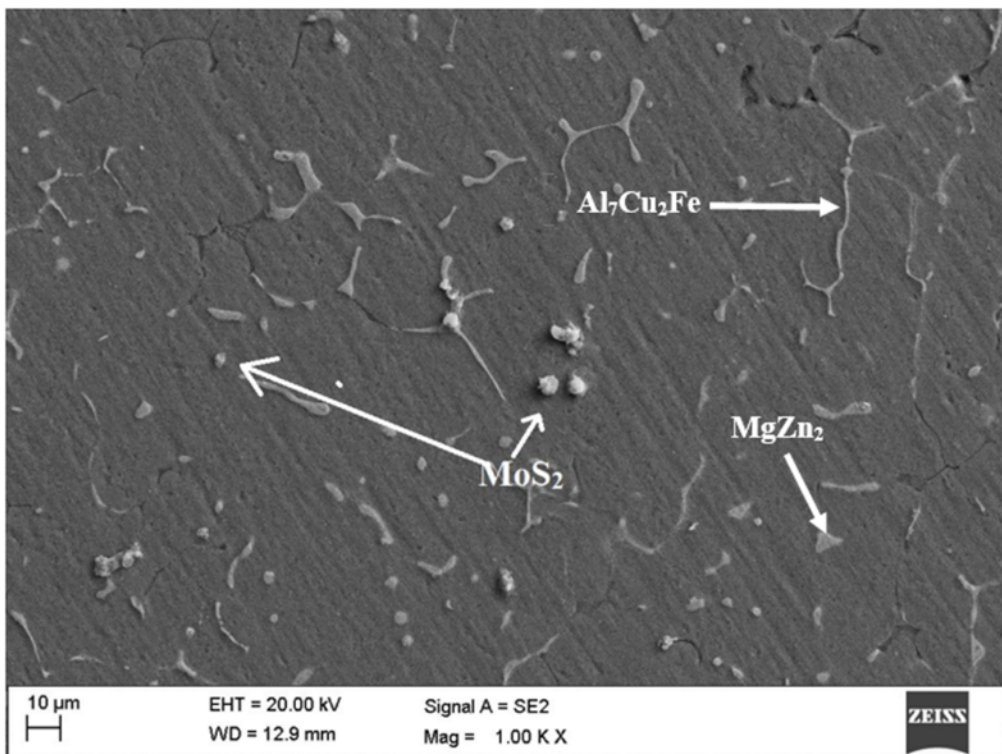
**Table 3.** Central Composite Design of experiment matrix for a wear test of AA7075/MoS<sub>2</sub> composite material.

Exp. No	Coded			Natural			Specific Wear Rate
	X <sub>1</sub>	X <sub>2</sub>	X <sub>3</sub>	% MoS <sub>2</sub>	LOAD	SV	
				(%)	(N)	(m/s)	×10 <sup>-3</sup> (m <sup>3</sup> /Nm)
1	-1	-1	-1	0	10	1	0.2929
2	-1	-1	1	0	10	3	1.3214
3	-1	0	0	0	20	2	0.8679
4	-1	1	-1	0	30	1	0.2655
5	-1	1	1	0	30	3	1.1762
6	0	-1	0	2	10	2	0.0496
7	0	0	-1	2	20	1	0.0567
8	0	0	0	2	20	2	0.0142
9	0	0	0	2	20	2	0.0832
10	0	0	0	2	20	2	0.0832
11	0	0	0	2	20	2	0.0832
12	0	0	0	2	20	2	0.0832
13	0	0	0	2	20	2	0.0832
14	0	0	1	2	20	3	0.5065
15	0	1	0	2	30	2	0.0449
16	1	-1	-1	4	10	1	0.1791
17	1	-1	1	4	10	3	0.3126
18	1	0	0	4	20	2	0.3688
19	1	1	-1	4	30	1	0.1264
20	1	1	1	4	30	3	0.3395

## RESULTS AND DISCUSSION

The microstructure of the composite materials, as well as that of the pure alloy, was studied through an SEM microimage acquired from the Field Emission Scanning Electron Microscope (FE-SEM) SIGMA HV–Carl Zeiss with Bruker Quantax 200–Z10 EDS Detector. The Energy-Dispersive X-ray Spectroscopy (EDS) analysis was also carried out to find the chemical characterization of the composites in the same machine. The results of the SEM microimage of AA7075+2wt.% MoS<sub>2</sub> and AA7075+4wt.% MoS<sub>2</sub> (Figure 3 and Figure 4) reveal the presence of the reinforced MoS<sub>2</sub>, which is disturbed uniformly in AA7075+2wt.% MoS<sub>2</sub> as well as AA7075+4wt.% MoS<sub>2</sub> composite materials. Also, the SEM microimage reveals the presence of Al<sub>7</sub>Cu<sub>2</sub>Fe, which is like a dendritic arm formation.

Furthermore, the presence of the MgZn<sub>2</sub> compound can also be traced. Uniform dispersion of the reinforcement in the matrix phase has reduced the reinforcement's cluster formation and micro porosities, which in turn enhance the mechanical properties; similar results were observed in the previous works of Jojith and Radhika (2019). The Energy-Dispersive X-ray Spectroscopy (EDS) analysis (Figure 5 and Figure 6) reveals the traces of the molybdenum disulfide reinforcement at moderate peak level, which confirms the particle reinforcement's presence in the metal matrix. The EDS also reveals the presence of Zn-Mg in high peaks, confirming the 7XXX series of the aluminum alloy.



**Figure 3.** FESEM microimage of the microstructure of AA7075+2wt.% MoS<sub>2</sub>.

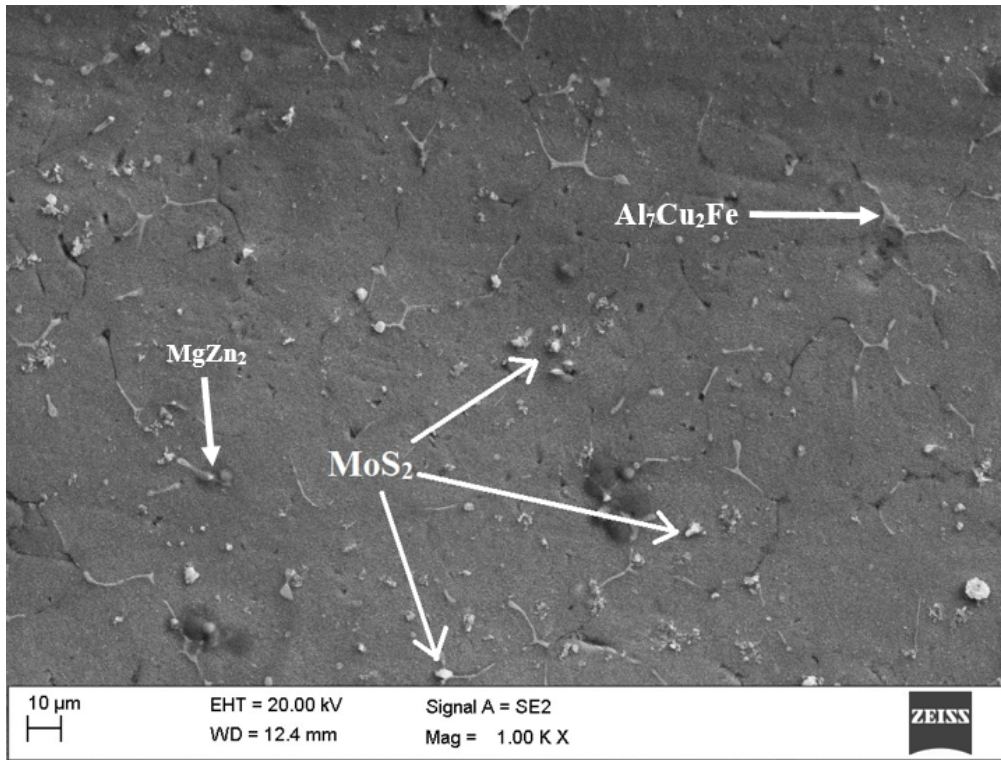


Figure 4. FESEM microimage of the microstructure of AA7075+4wt.%MoS<sub>2</sub>.

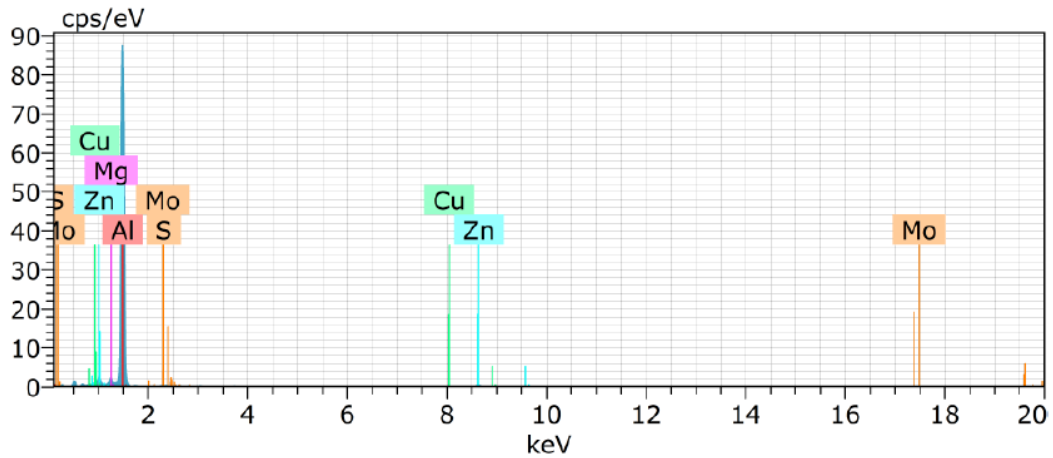
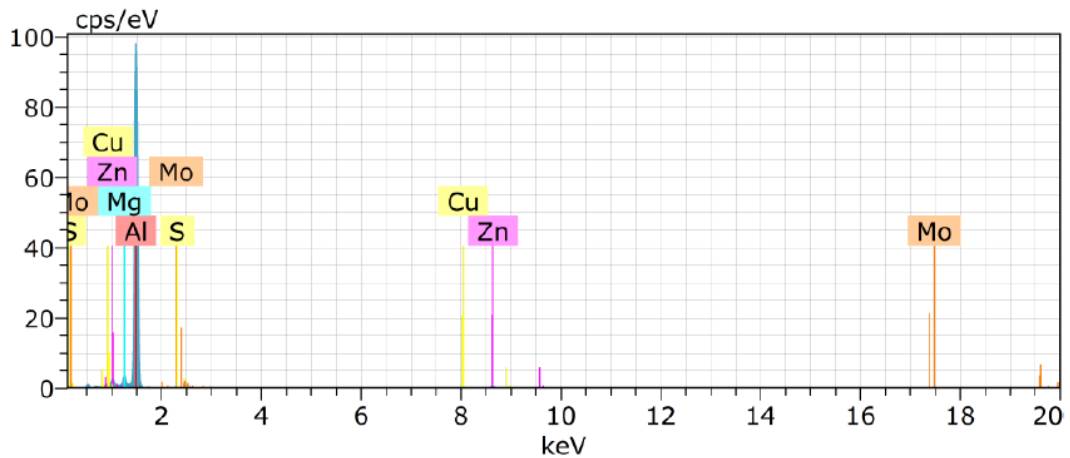


Figure 5. EDS graph for AA7075+2wt.%MoS<sub>2</sub>.



**Figure 6.** EDS graph for AA7075+4wt.%MoS<sub>2</sub>.

From Table 4, it is shown that the percentage of the MoS<sub>2</sub> is contributing to a maximum of about 24.75% in linear terms, and MoS<sub>2</sub> contributes to another 19.24% as square terms summing to a total of 44%. It can be seen from Figure 7 that the specific wear rate decreases and then slightly increases with the content of reinforcement, which increments from 0 wt.% to 4 wt.%.

The decrease of SWR at 2 wt.% of MoS<sub>2</sub> in the aluminum matrix is due to the formation of a tribo-layer by the solid lubricant in the surface of the composite, which acts as a key factor in averting the wear of the composites. A similar effect has been found in preceding works (Kanathavel *et al.*, 2016; Monikandan *et al.*, 2017; David Joseph *et al.*, 2018), but the condition changes with the further increase in the % of MoS<sub>2</sub>, and the SWR slightly increases at 4 wt.% similar to Kanathavel *et al.* (2016), which might be due to particle nature of MoS<sub>2</sub>, which is a soft particle reinforcement.

The effect of the sliding velocity factor contributes to 27.45% (Table 4) on specific wear rate, as in the linear term. This reveals that sliding velocity plays a major role in affecting the specific wear rate of the composite, which was mentioned by Dharmalingam *et al.* (2010) in their study. From Figure 7, it was observed that the specific wear rate rises slowly with an increase in sliding velocity. With an increase in sliding velocity from 1 m/s to 3 m/s, the specific wear rate increases because of the friction creating a temperature rise between the surfaces causing the composite material to soften and undergo severe plastic deformation and also the increase in SWR might be due to the crushing of the MoS<sub>2</sub> at higher sliding velocity as observed by Jojith and Radhika (2019).

The interaction mean plot (Figure 8) shows that the model is having a two-way interaction between MoS<sub>2</sub> and sliding velocity alone and the interaction between MoS<sub>2</sub> with sliding velocity factors contributing to 11.63% respectively, which in turn reveals that the major contribution to the specific wear rate is sliding velocity followed by the percentage of the reinforcement, and the equivalent results were witnessed by Dharmalingam *et al.* (2010). It may be observed that the combined effect of MoS<sub>2</sub>-sliding velocity decreases the SWR considerably. This may be due to linear terms % of MoS<sub>2</sub> and sliding velocity, which contributes to the maximum effect and because of the less significance, the applied load in the model does not have interactions with either MoS<sub>2</sub> or Sliding velocity, so the interaction between MoS<sub>2</sub>-load and sliding velocity-load was not observed (Figure 8).

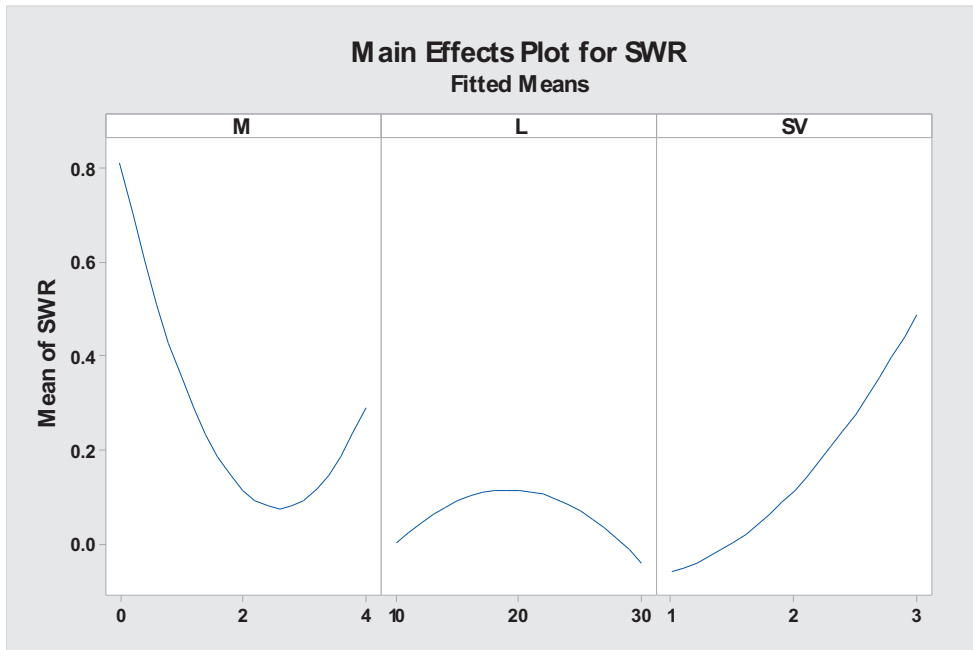
SWR is not considerably affected by the applied load. It is observed from Figure 7 that SWR increases and then decreases gradually on an increased applied load. It is also indicated in ANOVA that the applied load variable is not



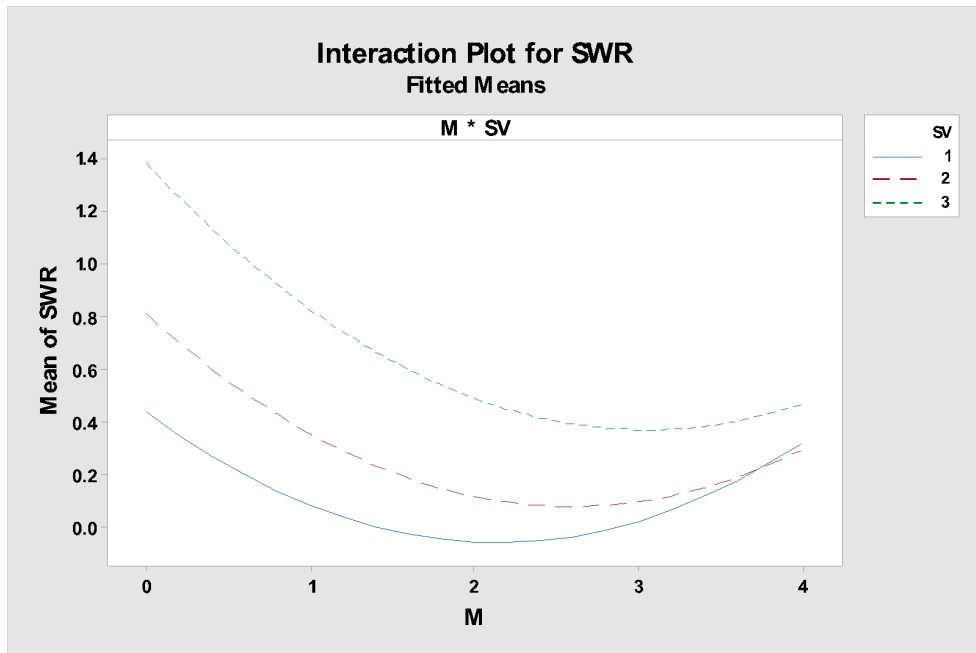
significant in terms of specific wear rate from Table 4, as the P-value for the load factor is  $>0.05$ , but the square terms of load seem to be significant but contribute to a very small percentage, and hence, the load factor is not significantly considered, and this may be due to condition that the reinforcement MoS<sub>2</sub> added to the aluminum matrix can bear the applied load.

**Table 4.** Analysis of variance for specific wear rate  $\times 10^{-3}$  (m<sup>3</sup>/Nm).

Source	Adj SS	Adj MS	F-Value	P-Value	% Contribution
M	0.67469	0.674688	138.4	0.000	24.75
L	0.00412	0.004125	0.85	0.376	0.15
SV	0.74834	0.748344	153.51	0.000	27.45
M*M	0.52464	0.524639	107.62	0.000	19.24
L*L	0.0496	0.049601	10.17	0.008	1.82
SV*SV	0.02752	0.027522	5.65	0.035	1.01
M*SV	0.31712	0.317117	65.05	0.000	11.63
Error	0.0585	0.004875	-	-	-
Lack-of-Fit	0.05453	0.007789	9.8	0.012	-
Pure Error	0.00397	0.000795	-	-	-
Total	2.72649	-	-	-	-

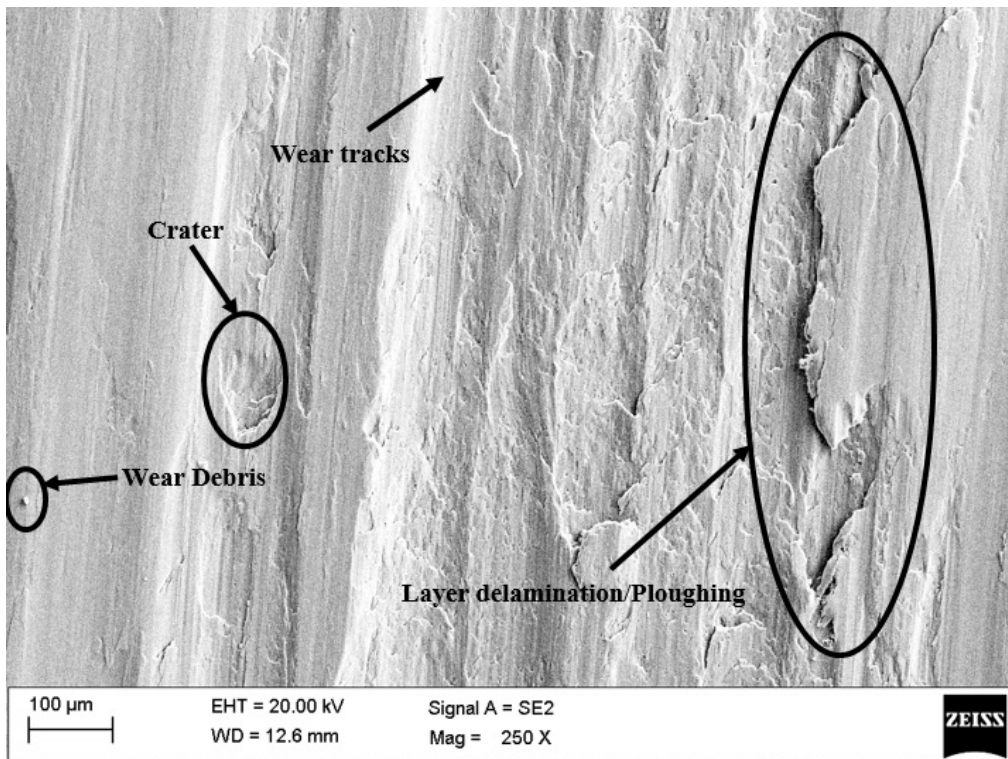


**Figure 7.** Main effect plot of specific wear rate for AA7075+MoS<sub>2</sub> composites.



**Figure 8.** Interaction plot of specific wear rate for AA7075+MoS<sub>2</sub> composites.

Comparing the SEM microimages of AA7075, AA7075+2wt.% MoS<sub>2</sub>, and AA7075+4wt.% MoS<sub>2</sub> at the applied condition 20 N and 2 m/s, Figure 9 shows the unreinforced aluminum alloy has experienced layer ploughing and delamination with crater, which indicates that the wear mechanism is adhesive wear, and similar results were perceived by Mohammad Rouhi *et al.* (2019). The reinforced aluminum alloy with 2wt.% of MoS<sub>2</sub> has shown a mild wear regime and ploughing. The wear track found can be identified as abrasive wear tracks. Figure 10 shows a film layer of MoS<sub>2</sub> that can also be detected on the surface of the composite, which acts as a key factor in preventing the wear at increasing velocity, and comparable results were observed in the previous works (Jojith and Radhika, 2019; David Joseph *et al.*, 2018). 4wt.% of MoS<sub>2</sub> reinforced aluminum alloy reveals severe ploughing and crater formation on the surface. Figure 11 shows that severe delamination is also seen as evidence of abrasive wear mechanism, which was comparable to Jojith and Radhika (2019). The wear mechanism of the composites and the unreinforced aluminum alloy is like a mixed mechanism of the adhesive and abrasive wear mechanism, which could be concluded from the delamination and ploughing in the unreinforced alloy and composites (Figures 9, 10, and 11). Oxidative wear was not formed on any of the composite, and wear debris can be found in the unreinforced aluminum alloy and AA7075+2wt.% MoS<sub>2</sub>, which indicates the breakdown of the particles, and similar observations were made by Mohammad Rouhi *et al.* (2019).



**Figure 9.** FESEM micrograph of wear surface at 20 N and 2 m/s of AA7075.

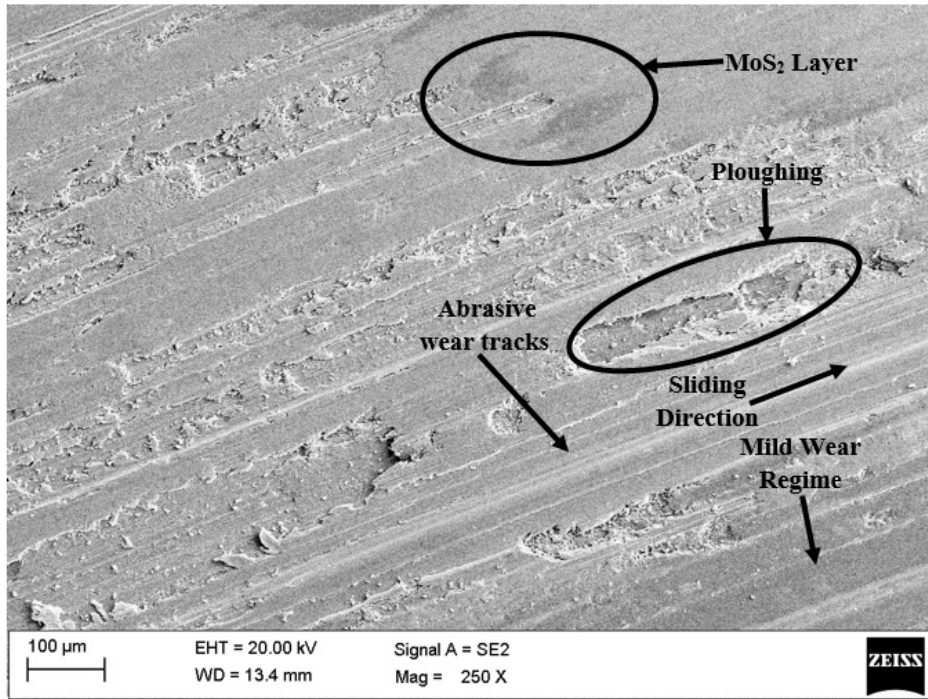


Figure 10. FESEM micrograph of wear surface at 20 N and 2 m/s of AA7075+2wt% MoS<sub>2</sub>.

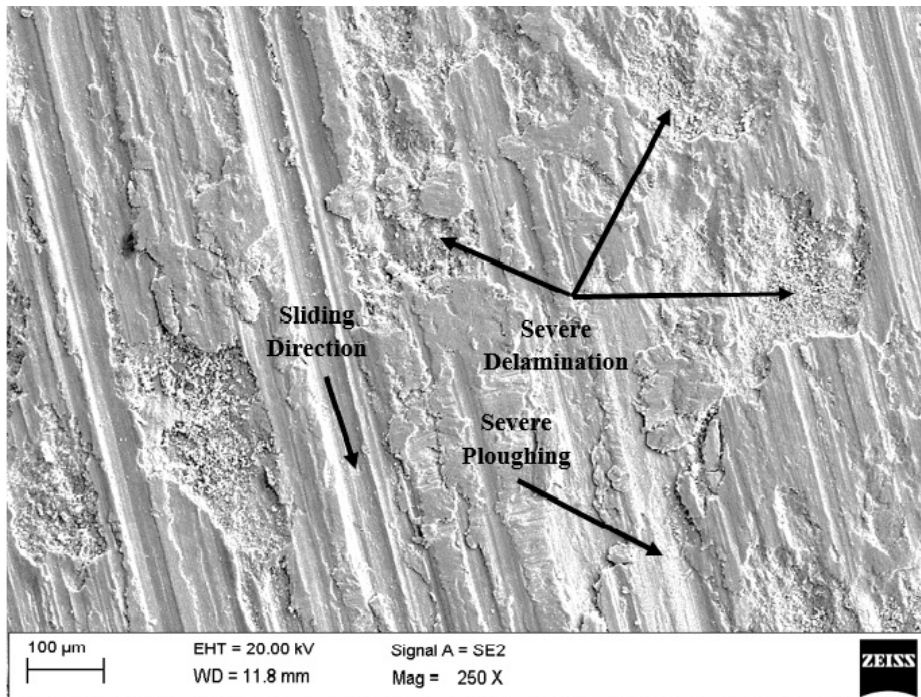


Figure 11. FESEM Micrograph of Wear Surface at 20 N and 2 m/s of AA7075+4wt% MoS<sub>2</sub>.

The mathematical relationship for correlating the output response (SWR) with the input parameters (namely, percentage of MoS<sub>2</sub>, sliding velocity, and applied load) is calculated using the regression equation that was obtained. The empirical relation was obtained for the coded terms of the weight percentage of MoS<sub>2</sub>, sliding velocity, and applied load. It is given as

$$SWR = -0.230 - 0.3676 X1 + 0.0517 X2 + 0.072 X3 + 0.1092 X1*X1 - 0.001343 X2*X2 + 0.1000 X3*X3 - 0.0995 X1*X3 \tag{2}$$

where X1 is the Weight Percentage of MoS<sub>2</sub>

X2 is the applied load.

X3 is the sliding velocity.

The model summary is shown in Table 5. R<sup>2</sup> is the percentage of variation in the response that is explained in the model used to determine the wellness of the model that fits the data. Since R<sup>2</sup> is 97.85%, the model is good. The predicted R<sup>2</sup> (92.80%) is less than the R<sup>2</sup> term (97.85%), which states that the model is overfitting.

**Table 5.** Model Summary.

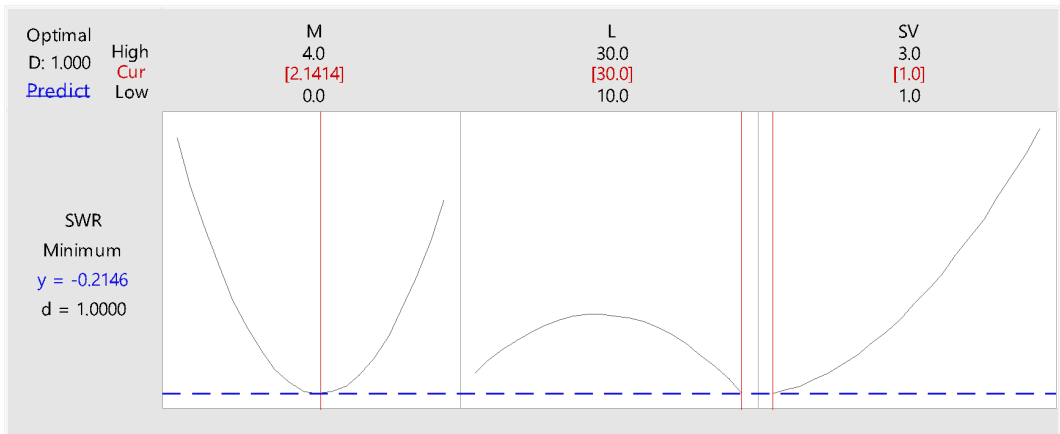
S	R-Sq.	R-Sq. (Adj)	R-Sq. (Pred)
0.0698215	97.85%	96.60%	92.80%

The response optimization was taken into consideration to obtain the minimum condition for the specific wear rate. From Table 6, the optimized result of SWR for minimized condition yields the solution of 2.14 wt% for MoS<sub>2</sub>, the applied load is optimum for 30 N, and the sliding velocity is 1 m/s.

**Table 6.** Solution for Response Optimization.

Solution	M	L	SV
1	2.14141	30	1

From the solution, we can conclude that the predicted optimum combinations yield low specific wear rate, and the optimum condition for SWR for AA7075+MoS<sub>2</sub> composites is represented graphically in Figure 12.

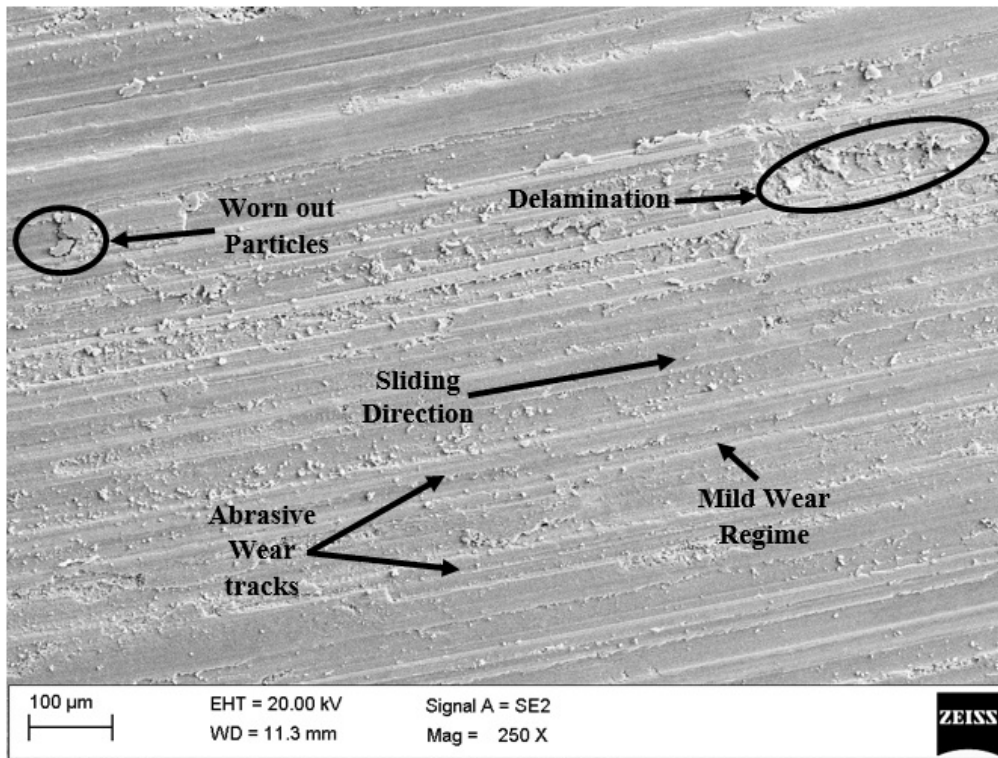


**Figure 12.** Optimum condition for SWR for AA7075+MoS2 composites.

The confirmation test using the optimum combinations of 2.14 wt% (approx. 2 wt%) of MoS<sub>2</sub>, 30 N of applied load, and 1 m/s of sliding velocity obtained from Table 6 was conducted. The optimized SWR was obtained as 0.037716×10<sup>-3</sup> (m<sup>3</sup>/Nm) through an experiment for the combination of the values in uncoded form for sliding speed, load, and weight percentage of reinforcement. The predicted and experimental values are stated in Table 7. The SEM microimage of wear surface for the optimum condition of applied load 30 N and sliding velocity 1 m/s shows mild wear and mild delamination on the surface of the composite (Figure 13). Worn-out particles can also be seen as a result of the particle breakdown in the composite, and the wear tracks can be identified as an abrasive wear track as Mohammad Rouhi et al. (2019).

**Table 7.** Result of confirmation test for specific wear rate.

Parameter	wt % of MoS <sub>2</sub>	Load	Sliding Velocity	SWR Value	
				×10 <sup>-3</sup> (m <sup>3</sup> /Nm)	
	(%)	(N)	(m/s)	Predicted	Experimental
Optimum conditions	2.14	30	1	0.03143	0.037716



**Figure 13.** FESEM micrograph of wear surface for optimum condition 30 N and 1 m/s of AA7075+2wt% MoS<sub>2</sub>.

## CONCLUSION

This article presents the dry sliding wear investigations of AA7075/MoS<sub>2</sub>, which are summarized as follows:

- I. The SEM microimage of the AA7075+2wt.% MoS<sub>2</sub> and AA7075+4wt.% MoS<sub>2</sub> shows the presence of the reinforcement, MoS<sub>2</sub> is distributed homogeneously, and the EDS confirms the traces of the particle reinforcement.
- II. The dry sliding wear characteristics are mainly influenced by the presence of MoS<sub>2</sub> reinforcement. It is evident that the specific wear rate of the composite decreases with the addition as well as the increment of the MoS<sub>2</sub> reinforcement, and only sliding velocity affects the specific wear rate, while the applied load is less significant over the SWR.
- III. Based on the ANOVA table, sliding velocity (27.45%), followed by molybdenum disulfide percentage (24.75%), employs a noteworthy influence on the specific wear rate of the composites.
- IV. The optimum combination for the specific wear rate (SWR) is obtained at the condition 30 N applied load, 1 m/s sliding speed, and 2.14 wt.% molybdenum disulfide percentage.
- V. The SEM microimage for the wear surface of AA7075+2wt.% MoS<sub>2</sub> and AA7075+4wt.% MoS<sub>2</sub> shows a mixed mechanism of adhesive wear and abrasive wear, which is commonly studied in aluminum 7075 alloys. For the optimum condition of the composite, mild wear and mild delamination is observed.

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