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The influence of MoS_2 and SiC reinforcement on enhancing the tribological and hardness of aluminium matrix (Al6061-T6) hybrid composites using Taguchi's method

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ABSTRACT

The current study has examined the dry sliding wear behaviour of MoS_2 and SiC reinforced aluminium composites. An aluminium matrix reinforced with SiC and MoS_2 was used for this investigation. Silicon carbide (SiC) and molybdenum disulphide (MoS_2) particles are employed as reinforcements, and the matrix is made of the aluminium alloy series Al6061. Three weight steps were used to adjust the SiC and MoS_2 reinforcements in the Al6061 matrix from 3% to 5%. Dry sliding wear behaviour is examined using a pin-on-disc apparatus. Additionally, the test was further validated using a suitable set of parameters that confirmed Taguchi's findings. The Brinnell hardness test is used to determine the composite material's hardness. When the percentage of reinforcement reaches 3% SiC and 5% MoS_2, wear is less compared to a combination of 5% SiC and 3% MoS_2. By increasing the MoS_2 percentage of reinforcement, wear was consequently decreased. The microstructure of AL6061/SiC/MoS_2 composites is evident from the scanning electron microscopy images, where the silicon carbide (SiC) phase and the molybdenum disulfide (MoS_2) phase are evenly distributed throughout the matrix.

Keywords: Silicon Carbide; Molybdenum disulphide; wear behaviour; stir casting method.

1. INTRODUCTION

Since composite materials have been around since the beginning of time, they weren't commercially viable until after World War II. In order to create new materials and improved properties over the base matrix materials, a composite material combines multiple unique physical combinations [1]. The fabrication process affects the fabricated composite material's properties. SAMAL *et al*. [2] concluded that producing aluminium metal matrix composites (AMMC) using powder metallurgy is a viable option. AMMC is gaining popularity as a material for engineering applications such as cars, aircraft, and other applications. The need for strong, light-weight, and high-performing components is continually met by AMMCs. AMMCs have exceptional electrical conductivity, low thermal expansion, superior strength, and wear resistance. It aids in the replacement of traditional aluminium alloys. The last two to three decades have seen a notable upsurge in AMMC research. Metal matrix composites (MMCs) are frequently made using Al and Mg because of their exceptional qualities and accessibility. MAHESH and VENKATESH [3] have noted that Al-Si-Mg composites exhibit significantly enhanced corrosion resistance when reinforced with zircon and alumina particles. PAI *et al*. [4]. Simply stated, the dispersoid's surface energy is increased by the presence of magnesium in AMMCs when the dispersoid's surface is separated from the oxygen during composite fabrication. However, its use in the automotive industry is restricted by its low ductility, poor fracture resistance, and highly reactive environment. Because AMMCs have poor wetting, very little research has been done on them when reinforced with MoS_2. In contrast, MoS_2 exhibits low density, high hardness, and thermal stability. It is also used in the construction of armour tanks, bulletproof jackets, and other armoured vehicles. When MoS_2 was added to AA6061 AMMC reinforced with it, SUBBA and RAMANAIAH [5] observed a progressive increase in the composites' hardness and tensile strength. SENTHIL KUMAR *et al*.'s study [6] of the material's porosity, microhardness, and compressive strength revealed that these properties increase as the weight percentage of MoS_2 increases. The study "Investigation of bonded molybdenum disulphide self lubricant coating rotational fretting wear on medium carbon steel" was conducted in 2011 by J.F. Zheng and J.L. Mo. The rotational fretting dry wear behaviours of the bonded molybdenum disulphide firm lubricant coating and its substrate steel were compared under varying applied load, angular displacement

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amplitudes, and rotational disc speed. Utilising optical microscopes, surface profilometers, EDX, XPS, SEM, and other microscopes, dynamic analysis was carried out in conjunction with microscopic investigation. The experimental findings demonstrated that MoS_2 altered the substrate's fretting running regimes. MoS_2's friction coefficients were less than the substrate's. In the partial slip regime, MoS_2 suffered very little damage. The primary causes of coating damage in the slip 12 regime were tribo-oxidation, delamination, and abrasive wear [7]. "Investigations on dry sliding wear behaviour of in situ casted AA7075–TiC metal matrix composites by using Taguchi technique" was the title of a 2014 study by BASKARAN *et al*. [8] using the reactive in situ casting technique, high strength 7075 aluminium matrix composites with 4 and 8 weight percent of TiC particle reinforcement were created. The use of both scanning electron microscopy and X-ray diffraction analysis, it was determined that TiC particles were present and uniformly distributed throughout the aluminium matrix. In order to determine the importance of reinforcement quantity, load, and sliding, the dry sliding wear behaviour of the as-cast composites was studied using an experimental design based on the Taguchi L27 orthogonal array. Slide distance and velocity in relation to wear rate. Using the main effect plot, the best blend for the lowest wear rate was found to be 4 weight percent TiC, 9.81 N load, 3 m/s sliding velocity, and 1500 m sliding distance. Using ANOVA analysis, the conclusion was made that the sliding velocity and applied load were highly significant factors that contributed to the dry sliding wear rate [9]. Study of the literature indicates that at a given temperature, liquid lubricants evaporate. The material ages rapidly in the lack of lubricant. Hence, molybdenum disulphide, or MoS_2, can be used as a self-lubricating substance. MoS_2 is used in a variety of application areas, including grease, fluid lubricants, and solid film (dry) lubricants. Its physical and chemical properties are also included, along with the impact of temperature. MoS_2 will be used to reduce wear [10].

2. MATERIALS AND METHODS

2.1. Materials

Al6061 aluminium alloy was chosen as the matrix material in the present study, and silicon carbide and molybdenum disulphide, or MoS_2 particles were taken as reinforcement particles [11]. The nominal chemical compositions of the Al6061 alloy obtained using spectrometer is (wt.%): 97.57 aluminium, 0.63 Silicon, 0.89 Magnesium, 0.24 Copper, 0.16 Iron, 0.48 Mn, 0.014 Ti, 0.007 Zn, and 0.003 Cr. The average size of reinforcement particles are 75 microns.

2.2. Fabrication of composites

The liquid metallurgy method was used to create the aluminium hybrid composite. The alloy Al6061 was melted at 1073 K in an electric furnace. Once the metal attained a molten state, a motor-driven stirrer was added, causing a vortex to form on the top surface. Following efficient degassing, a preheated silicon carbide and graphite particle was added to the molten alloy's vortex. Using a graphite impeller, the molten alloy was mechanically stirred for ten minutes. 400 rpm of stirring speed was kept up. Next, a cast iron mould that had been heated up was filled with the composite slurry. The casting was then taken out of the mould after it had solidified [12]. The machined state of the cast composites is indicated in Table 1 and Figure 1.

2.3. Conducting the experiments

This experimental investigation's hybrid composite was made via the stir casting method. The wear testing machine used for the experiments is a pin-on-disc device. A rendering of the Ducom Wear and Friction Monitor, a pin-on-disc wear testing device, is displayed alongside a schematic representation of the same device [13]. To prevent systematic errors, the wear tests are conducted randomly and in accordance with the conditions specified by the design matrix [14]. Table 2 lists test combinations in detail, along with the corresponding experimental results and coded and actual factor values.

Table 1: Fabrication of composites sample.

FACTORS		LEVELS		
		–1	0	1
Reinforcement (%)	A	3% SiC, 5% MoS_2	4% SiC, 4% MoS_2	3% SiC, 5% MoS_2
Load (N)	B	20	30	40
Sliding speed (rpm)	C	200	400	600
Sliding distance (m)	D	600	900	1200

Figure 1: Fabricated materials by stir casting method.

Table 2: Details of experimental results.

S.NO	A	B	C	D	VOLUME FRACTION (%)A	LOAD (N) B	SPEED (rpm) C	DISTANCE (m) D	EXPT. VOLUME LOSS (mm^3)	PREDICTED VOLUME LOSS (mm^3)
1	–1	–1	–1	–1	3	20	200	600	68.035	67.888
2	–1	0	0	0	3	30	400	900	134.082	133.892
3	–1	1	1	1	3	40	600	1200	144.67	144.456
4	0	–1	0	1	4	20	400	1200	83.242	83.028
5	0	0	1	–1	4	30	600	600	171.202	170.954
6	0	1	–1	0	4	40	200	900	202.321	202.186
7	1	–1	1	0	5	20	600	900	74.863	74.59
8	1	0	–1	1	5	30	200	1200	141.577	141.43
9	1	1	0	–1	5	40	400	600	160.54	160.36

2.4. Hardness test

The Brinnell hardness testing machine is used to examine the hardness of composite materials. The hardness of the aluminium hybrid composites is rising as the proportion of silicon carbide (SiC) particles rises. Sample's hardness and worn surface are displayed in Figures 2 and 3. The samples made of hybrid metal matrix composite had been polished with standard grit (400–1000) rough sheets [15–17]. A Brinell hardness tester has been utilised to determine the hardness of samples made of single and hybrid metal matrix composites. As indicated in Figure 5, a test force of 500 kg was used with a carbide ball indenter over a duration of 15 s at five distinct locations on the samples' surface in accordance with 'ASTM E10-18' [18]. Results of the Brinell Hardness Test are displayed in Figure 4, as-cast composites with varying reinforcement content. Due to the thermal mismatch during the solidification of the molten metal, the hardness values of Al6061 alloy composites increase with the addition of SiC particles. The increased dislocation density is due to the differing thermal expansion of the Al6061 alloy and the silicon carbide particles. As dislocation density increases, dislocation movement is blocked, leading to an increase in hardness values. The presence of hard silicon carbide particles also resists dislocation motion, increasing the composite's hardness.

2.5. Analysis of variance results for wear test

The study employed Analysis of Variance (ANOVA) to examine the impact of four wear parameters: volume fraction, applied load, sliding speed, and sliding distance. These parameters were found to have a significant effect on the performance measures[18, 19]. It is possible to determine which independent factor predominates over the others and what percentage of that specific independent variable is contributed by using analysis of variance. The wear rate of Al6061 metal matrix composites reinforced with 5wt% SiC and 5wt% MoS_2 was examined using ANOVA, with four factors and their interactions being varied. When a factor is not significant, it is pooled. Regretfully, the significance test can only be carried out in cases where the error term has a non-zero DOF. Starting with the least influential factor, pooling is done. Sliding speed is pooled as indicated in Table 3 because it has the least impact in this analysis. At a significance level of $\alpha = 0.05$, or a 95% confidence level, this

Figure 2: Hardness values of tested samples.

Figure 3: Wornout surface wear tested samples.

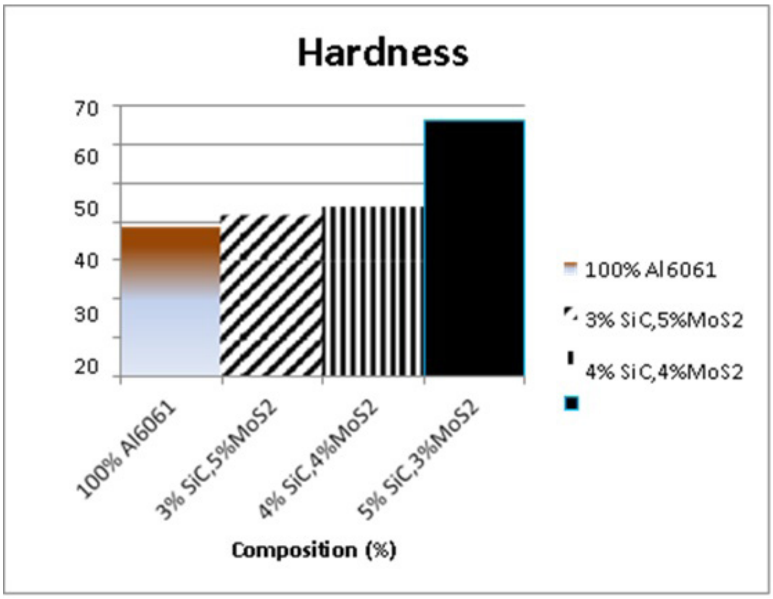

Figure 4: Composition (%) vs. hardness (BHN).

Table 3: Analysis of variance for wear rate.

SOURCE	DOF	SEQ SS	ADJ SS	ADJ MS	F-VALUE	P-VALUE
Volume fraction	2	2152.5	2152.5	1076.56	10.91	0.084
Applied load	2	14619.9	14619.9	7309.97	74.10	0.013
Sliding distance	2	310.5	310.5	155.26	1.57	0.389
Error	2	197.3	197.3	98.65		
Total	8	17280.3	17280.3			

Figure 5: Main effect plot for means.

analysis is performed. Sources were deemed to have contributed statistically significantly to the performance measures if their P-value was less than 0.05. The pooled ANOVA table makes it clear that sliding speed—which influences the wear reasoning volume fraction by 10.91%—is the most important factor. Sliding distance and applied load—which contribute 1.57 percent and 74.10%, respectively—follow sliding speed. Better results are obtained when the ANOVA's "S" value is 9.93231 and its R2 value is 98.86%.

Figures 5 and 6 illustrates how wear is less than reinforcement of 5% SiC& 3% MoS_2 when the percentage of reinforcement is at the level of 3% SiC and 5% MoS_2. Wear was thereby reduced by raising the MoS_2 percentage of reinforcement and lower wear rate result from applying a load of 20 N. As a result, wear increases as load increases. According to Figure 7, the wear rate is significantly influenced by the sliding speed. When the sliding speed is 400 rpm, the wear rate is at its lowest [19, 20]. Wear would increase if we accelerated the sliding speed. Once the sliding distance and speed reach approximately 1200 m and 600 rpm, the rate of wear starts to decrease.

According to Figure 8, It is discovered that the residuals, or errors, in the dry sliding rate of wear normal probability plot have a normal distribution together the line that is straight. According to Figure 8, wear is increasing in the area of 40 N applied load, 4% MoS_2, and 4% SiC. As the applied load and reinforcement percentage increased, the wear effect grew. The relationship between sliding distance and wear is shown in Figure 9. Wear will decrease as the sliding distance increases when the percentage of MoS_2 reinforcement is increased.

2.6. Microstructure study using scanning electron microscope

A few informative method for examining a sample's surface structure is scanning electron microscopy, or SEM. Scanning electron microscopy is an early microscopic method used in crystal monitoring, mostly utilised in the 1980s. In the past, SEM has been used to clearly visualise the microstructure of the underlying surface [21]. The JSM-6610 scanning electron microscope instrument is used to capture the SEM images.

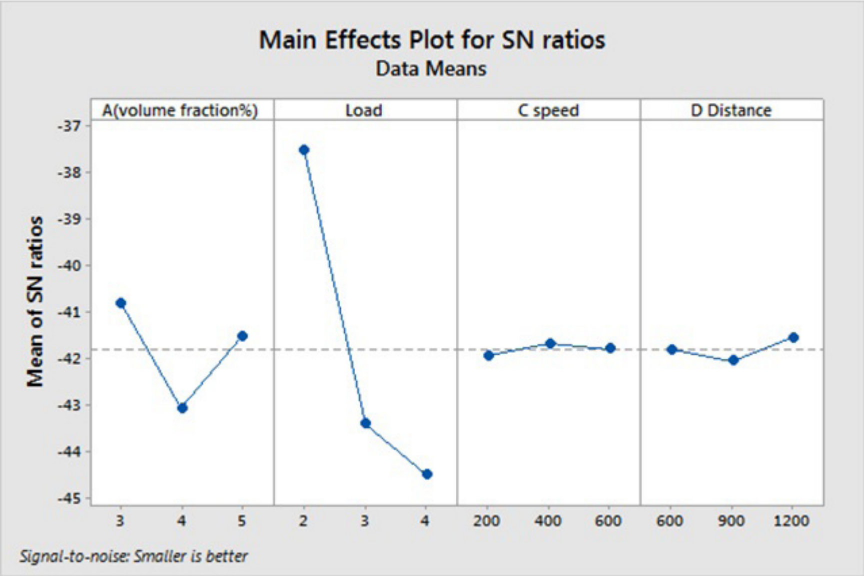

Figure 6: Main effect plot for SN ratio.

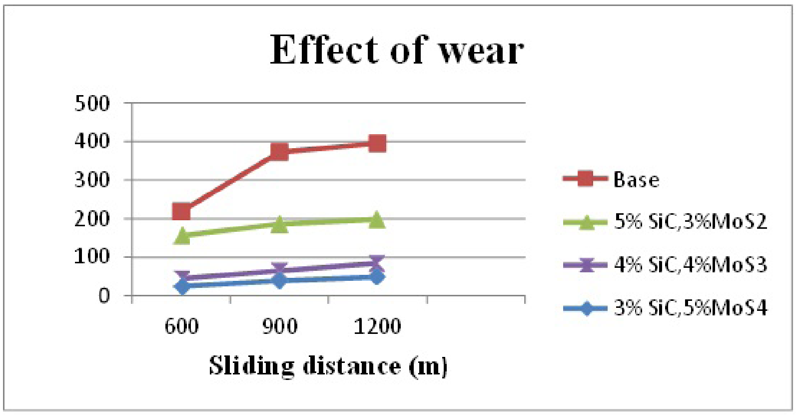

Figure 7: Sliding distance (m) vs. wear in microns.

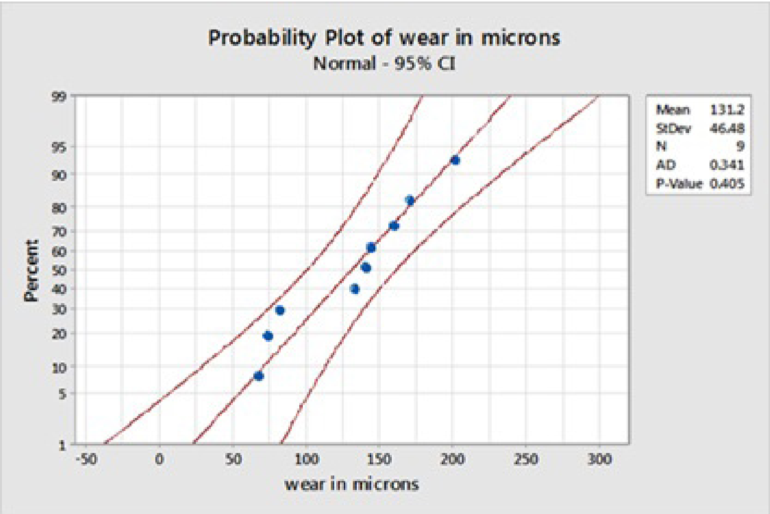

Figure 8: Probability plot of wear.

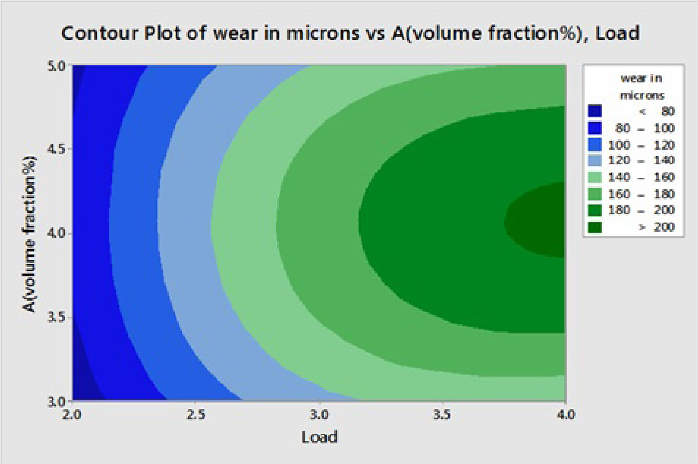

Figure 9: Contour plot of wear vs. volume fraction (%), load.

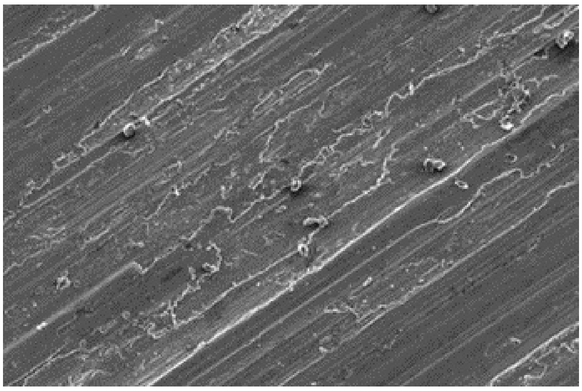

Figure 10: 100% Al6061, 40 N, 400 m.

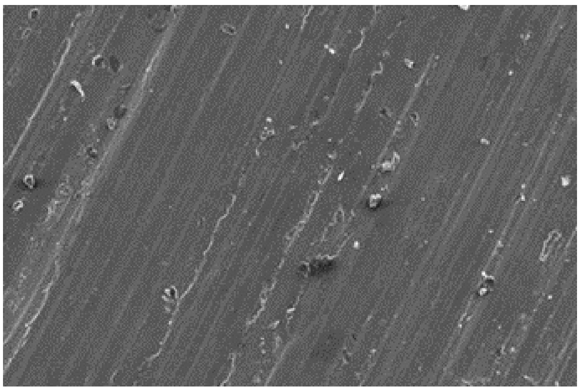

Figure 11: 5%SiC, 3% MoS_2, 40 N, 400 m.

The SiC and MoS_2 phases were evenly distributed throughout the matrix in the schematic diagram of the tribological layer formation process of Al6061/SiC/MoS_2 composites (Figure 10a). Plastic deformation was the initial result of metal-to-metal wear or adhesion (Figure 11). Wear debris, including metal, SiC, and MoS_2 particles, was generated in this state (Figure 12). As those wear particles slid against the counter face surface over and over, they were crushed [22]. An oxidative wear mechanism produced the compacted layer of wear particles (Figure 13). The friction reduction and wear resistance of Al6061/SiC/MoS_2 composites were found to be improved by the synergistic effect of SiC and MoS_2 addition [23].

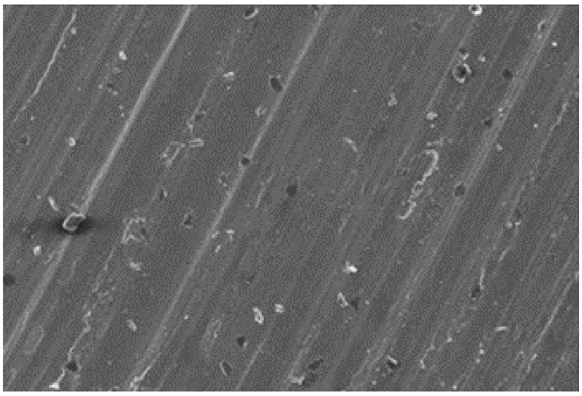

Figure 12: 4%SiC, 4% MoS_2, 40 N, 400 m.

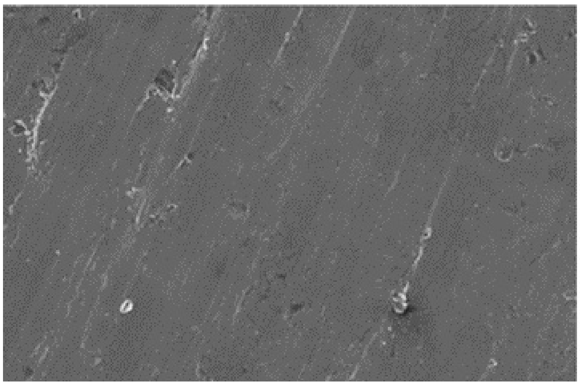

Figure 13: 3%SiC, 5% MoS_2, 40 N, 400 m.

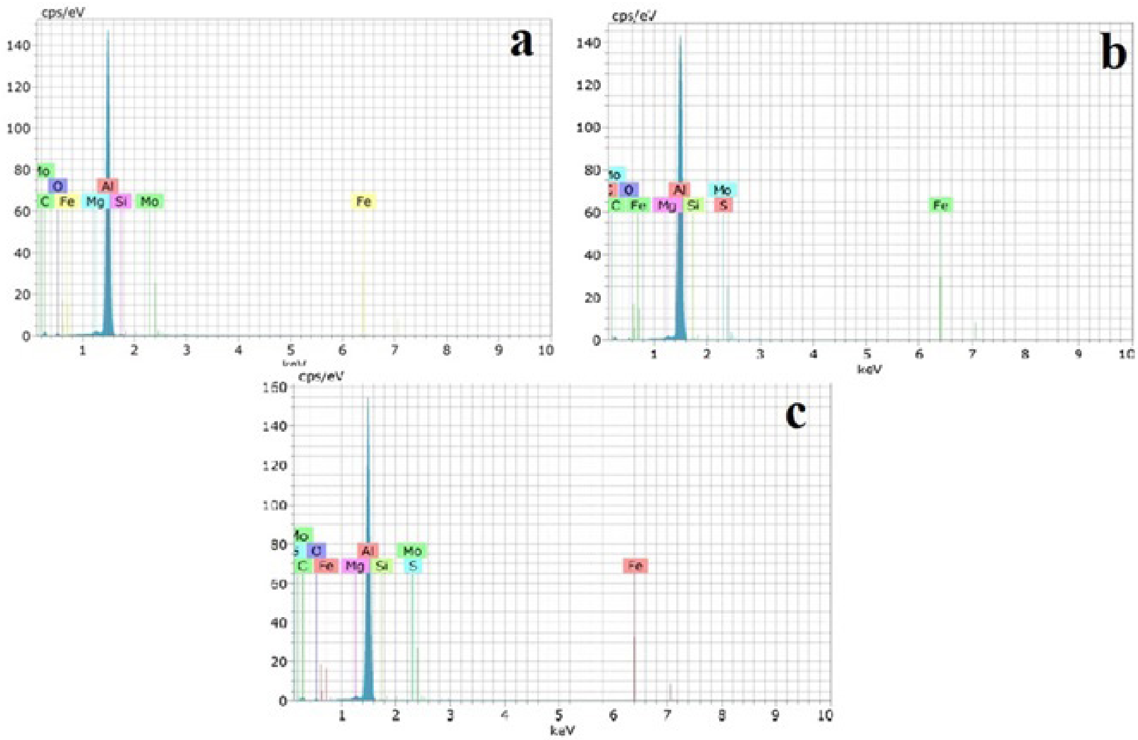

Figure 14: (a–c) EDS image of the AlMg1SiCu/silicon carbide/molybdenum disulphide composite.

The surface EDS of the AlMg1SiCu/silicon carbide/molybdenum disulphide composite samples are shown in Figure 14(a–c). Silicon carbide (SiC) and molybdenum disulfide (MoS_2) reinforcing components are clearly visible on the aluminium hybrid composites' surfaces. These elements are present in the composites with varying percentages of matrix materials. Additionally, the addition of copper, sulfur, silicon, magnesium, molybdenum, and other alloying elements reveals up.

3. CONCLUSION

Pin-on-disc apparatus is used to conduct experiments on Al-SiC-MoS_2 hybrid composites with combined reinforcement up to 8% Al-MoS_2 and Al-SiC. These are the investigation's conclusions. Using a Brinnell hardness testing machine, the hardness of composite materials is examined. Aluminium hybrid composites are becoming harder as a result of an increase in the percentage of silicon carbide (SiC) particles. The sliding speed is by far the most important factor that influences wear, as shown by the pooled ANOVA table. Volume fraction by 10.91%, applied load by 74.10%, and sliding distance by 1.57% are the next three figures. Better results are obtained when the ANOVA's "S" value is 9.93231 and its R2 value is 98.86%. When the percentage of reinforcement reaches 3% SiC and 5% MoS_2, wear is less compared to a combination of 5% SiC and 3% MoS_2. By increasing the MoS_2 percentage of reinforcement, wear was consequently decreased. The microstructure of Al6061/SiC/ MoS_2 composites is evident from the scanning electron microscopy images, where the silicon carbide (SiC) phase and the molybdenum disulfide (MoS_2) phase are evenly distributed throughout the matrix.

4. BIBLIOGRAPHY

[1] GARG, P., JAMWAL, A., KUMAR, D., *et al*., "Advance research progresses in aluminium matrix composites: manufacturing & applications", *Journal of Materials Research and Technology*, v. 8, n. 5, pp. 4924–4939, 2019. doi: http://dx.doi.org/10.1016/j.jmrt.2019.06.028.

[2] SAMAL, P., VUNDAVILLI, P.R., MEHER, A., *et al*., "Recent progress in aluminum metal matrix composites: a review on processing, mechanical and wear properties", *Journal of Manufacturing Processes*, v. 59, pp. 131–152, 2020. doi: http://dx.doi.org/10.1016/j.jmapro.2020.09.010.

[3] MAHESH, K.V., VENKATESH, C.V., "A comprehensive review on material selection, processing, characterization and applications of aluminium metal matrix composites", *Materials Research Express*, v. 6, n. 7, pp. 072001, 2019. doi: http://dx.doi.org/10.1088/2053-1591/ab0ee3.

[4] PAI, B.C., RAMANI, G., PILLAI, R.M., *et al*., "Role of magnesium in cast aluminium alloy matrix composites", *Journal of Materials Science*, v. 30, n. 8, pp. 1903–1911, 1995. doi: http://dx.doi.org/10.1007/BF00353012.

[5] SUBBA, R.E., RAMANAIAH, N., "Experimental study on mechanical properties of aluminium metal matrix composites (AA6061 Reinforced with MOS_2)", *International Journal of Material Science*, v. 6, n. 2, pp. 91–99, 2016. doi: http://dx.doi.org/10.12783/ijmsci.2016.0602.03.

[6] KUMAR, S.S., PANDIAN, R.S., PITCHIPOO, P., *et al*., "Investigation of Al-Mg based composite incorporated with MoS2 through powder metallurgy", *Proceedings of the Institution of Mechanical Engineers. Part E, Journal of Process Mechanical Engineering*, v. 235, n. 4, pp. 986–996, 2021. doi: http://dx.doi.org/10.1177/0954408920985761.

[7] LUO, J., ZHU, M., WANG, Y., *et al*., "Study on rotational fretting wear of bonded MoS2 solid lubricant coating prepared on medium carbon steel", *Tribology International*, v. 44, n. 11, pp. 1565–1570, 2011. doi: http://dx.doi.org/10.1016/j.triboint.2010.10.011.

[8] SEL, B., VEERAMANI, A., DURAISELVAM, M., "Investigations on dry sliding wear behavior of in situ casted AA7075–TiC metal matrix composites by using Taguchi technique", *Materials & Design*, v. 60, pp. 184–192, 2014. doi: http://dx.doi.org/10.1016/j.matdes.2014.03.074.

[9] RAMADOSS, N., PAZHANIVEL, K., GANESHKUMAR, A., *et al*., "Effect of SiC and MoS2 Co-reinforcement on enhancing the tribological and anti-corrosive performance of aluminum matrix (Al6063-T6)", *Nanocomposites Silicon*, v. 14, n. 10, pp. 5471–5479, 2022. doi: http://dx.doi.org/10.1007/s12633-021-01334-7.

[10] GONFA, B.K., SINHA, D., VATES, U.K., *et al*., "Investigation of mechanical and tribological behaviors of aluminum based hybrid metal matrix composite and multi-objective optimization", *Materials (Basel)*, v. 15, n. 16, pp. 5607, Aug. 2022. doi: http://dx.doi.org/10.3390/ma15165607. PubMed PMID: 36013744.

[11] RAGUPATHY, K., VELMURUGAN, C., EBENEZER JACOB DHAS, D.S., *et al*., "Prediction of dry sliding wear response of AlMg1SiCu/silicon carbide/molybdenum disulphide hybrid composites using Adaptive Neuro-Fuzzy Inference System (ANFIS) and Response Surface Methodology (RSM)", *Arabian*

Journal for Science and Engineering, v. 46, n. 12, pp. 12045–12063, 2021. doi: http://dx.doi.org/10.1007/s13369-021-05820-3.

[12] VELMURUGAN, C., MUTHUKUMARAN, V., RAGUPATHY, K., *et al*., "Modelling volume loss of heat treated Al6061 composites using ANN", *Procedia Materials Science*, v. 5, pp. 31–40, 2014. doi: http://dx.doi.org/10.1016/j.mspro.2014.07.239.

[13] GAJALAKSHMI, K., SENTHILKUMAR, N., PRABU, B., "Multi-response optimization of dry sliding wear parameters of AA6026 using hybrid gray relational analysis coupled with response surface method", *Measurement and Control*, v. 52, n. 5-6, pp. 540–553, 2019. doi: http://dx.doi.org/10.1177/0020294019842603.

[14] HAMIDREZA, G., MOHD, H.I., NORHAYATI, A., *et al*., "Microstructure development mechanical and tribological properties of a semisolid A356/xSiCp composite", *Journal of Applied Research and Technology*, v. 15, n. 6, pp. 533–544, 2017. doi: http://dx.doi.org/10.1016/j.jart.2017.06.002.

[15] MANJUNATH-PATEL, G.C., SHETTIGAR, A.K., MAHESH-PARAPPAGOUDAR, B., "A systematic approach to model and optimize wear behaviour of castings produced by squeeze casting process", *Journal of Manufacturing Processes*, v. 32, pp. 199–212, 2018. doi: http://dx.doi.org/10.1016/j.jmapro.2018.02.004.

[16] VIJAYAKUMAR, S., KARUNAMOORTHY, L., "Modelling wear behaviour of Al–SiC metal matrix composites: soft computing technique", Tribology - Materials, Surfaces & Interfaces v. 6, n. 1, pp. 25–30, 2013. doi: http://dx.doi.org/10.1179/1751584X12Y.0000000002.

[17] KUMAR, S., BALASUBRAMANIAN, V., "Effect of reinforcement size and volume fraction on the abrasive wear behaviour of AA7075 Al/SiCpP/M composites—a statistical analysis", *Tribology International*, v. 43, n. 1-2, pp. 414–422, 2010. doi: http://dx.doi.org/10.1016/j.triboint.2009.07.003.

[18] BARADESHWARAN, A., VETTIVEL, S.C., ELAYAPERMAL, A., *et al*., "Experimental investigation on mechanical behavior, modelling and optimization of wear parameters of B4C and graphite reinforced aluminium hybrid composites", *Materials & Design*, v. 63, pp. 620–632, 2014. doi: http://dx.doi.org/10.1016/j.matdes.2014.06.054.

[19] VINOTH, K.S., SUBRAMANIAN, R., DHARMALINGAM, S., *et al*., "Mechanical and tribological characteristics of stir-cast Al–Si10Mg and self-lubricating Al–Si10Mg/MoS2 composites", *Materials Technology*, v. 46, n. 5, pp. 497–501, 2012.

[20] SHARMA, V.K., KUMAR, V., JOSHI, R.S., "Effect of RE addition on wear behavior of an Al-6061 based hybrid composite", *Wear*, v. 426–427, pp. 961–974, 2019. doi: http://dx.doi.org/10.1016/j.wear.2019.01.044.

[21] SHARMA, V.K., RAVINDER, V.K., JOSHI, S., "Experimental investigation on effect of RE oxides addition on tribological and mechanical properties of Al-6063 based hybrid composites", *Materials Research Express*, v. 6, n. 8, pp. 0865d7, 2019. doi: http://dx.doi.org/10.1088/2053-1591/ab2504.

[22] SHOROWORDI, K.M., LAOUI, T., HASEEB, A.S.M.A., *et al*., "Microstructure and interface characteristics of B4C, SiC and Al2O3 reinforced Al matrix composites: a comparative study", *Journal of Materials Processing Technology*, v. 142, n. 3, pp. 738–743, 2003. doi: http://dx.doi.org/10.1016/S0924-0136(03)00815-X.

[23] OMRANI, E., MOGHADAM, A.D., MENEZES, P.L., *et al*., "Influences of graphite reinforcement on the tribological properties of self-lubricating aluminum matrix composites for green tribology, sustainability, and energy efficiency—a review", *International Journal of Advanced Manufacturing Technology*, v. 83, n. 1–4, pp. 325–346, 2016. doi: http://dx.doi.org/10.1007/s00170-015-7528-x.