Fabrication and Modelling of Tribological Performance of Al-Si/12Al2O3/2MoS2 Composite using Taguchi Technique

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ABSTRACT – This paper investigates the effect of mechanical, microstructural and dry sliding wear behaviour of Al-Si/2wt%MoS2, Al-Si/12wt%Al2O3, and Al-Si/12wt%Al2O3/2wt%MoS2 composites that prepared using the stir-casting route. To avoid friction and wear at the interfaces of materials, an attempt has been made by adding solid lubricant MoS2 to build such a self-lubricating composite with Al-matrix. The tribological analysis has been described based on the Taguchi orthogonal array (L27). Three variables combination such as sliding velocity, sliding distance and contact pressure are used for this study to determine the tribological responses, i.e. wear rate and coefficient of friction. The properties of composites were improved by increasing the weight % of MoS2 and Al2O3. The tensile strength of Al-Si/2MoS2, Al-Si/12Al2O3, and Al-Si/12Al2O3/2MoS2 composites is 6.02%, 12.46%, and 2.44% compared to the base matrix. The addition of MoS2 helps the hybrid composite to attain better tribological properties with a slightly lower specific strength. Analysis of variance showed that the composites such as Al-Si/2 MoS2 and Al-Si/12Al2O3/2MoS2 were strongly influenced by the pressure in wear rate. Similarly, sliding velocity affects the coefficient of friction for Al-Si/2MoS2. Wear tracks formed during the dry slide process were analysed using optical and SEM with an EDS. It was discovered that pressure plays a vital effect in the wear mechanism. The hybrid composite (Al-Si/12 Al2O3/2MoS2) material can be utilised in place of conventional materials in tribological demanding automotive applications.

INTRODUCTION

In recent times, technologists constantly develop novel materials, having lightweight and good reliability parts, much like in the vehicle sector, to meet the ever-increasing demands and complexity of the new technologies. It is difficult to obtain all of those previously established qualities using traditional materials. A number of economic benefits have been associated with aluminium matrix composites, being good modulus of elasticity, wear resistance, low cost, high strength, and thermal conductivity, along with use in aircraft, space, defence, and automobiles [1–3].

Mostly when talking about wear resistance, lubrication is important to mitigate. That is usually difficult to do but can be done while interfaces are wearing components. Self-lubricated components purged completely during wear. Graphite and MoS2 are common lubricants for high load and temperature. Few lubricants do not need a liquid medium to have low friction. While they are in the solid state to decomposition at high temperature, it is difficult to stay the liquid lubricant for some time, and then solid lubricants are used to meet the specific requirements[4–8].

The MoS2 has a number of other noteworthy properties, such as lubricity at high loads, fret safety, anti-slip effect, wear resistance, and anti-corrosion. Lubricant particle size has an effect on friction. The larger particles work well at slow speeds, while the finer particles are best on rougher surfaces. These particles may be used to improve their properties also in liquid lubricants[9–12]. More related compounds include polytetrafluoroethylene (PTU), calcium fluoride (CaF2), and cerium tungsten disulfide (CeW12), have the same effect [13]. The interface of MoS2 appears to be linear with lamella directed in the direction of motion, serving as a pathway for relative motion but hindering interaction through different sliding components under varying strain [14]. Using lubricants is useful to keep materials from adhering to each other, due to a weak bond with the surface. These layers glide proportionally with a minimal force and thus achieve low drag characteristics. For this function, MoS2 has been utilized in industrial conditions.

The mechanical and tribologically efficient preparation of Al/MoS2 (3 and 10% wt) composites using a hot press process has been researched by Chen and others [8]. Results show that the hardness and compression strength of 3% MoS2 composite is somewhat higher than that of 0% MoS2 composite, while the strength of composites with 10% MoS2 content was dramatically reduced. The wear rate of the composite with 10% MoS2 increased rapidly at 50 N load and 0.69 m/s sliding speed, while the composites at 30 N load and 0.69 m/s sliding speed had low and stable wear rates, with MML present shape across the wear track. Rajesh et al. [6] studied on AA2219/xMoS2 (x = 1.5, 3 and 4.5) composites, which were subjected to lubricated wear with tyre oil. The study was analysed using a 2D plot and analysis of variance (ANOVA). In this analysis, the process variables such as load, velocity, %MoS2 and hardness of disc were considered.

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The author concluded from these findings that the wear rate increases proportionally with applied force and disc hardness but reduced with the weight % of MoS2.

Harpreet et al. [13] studied the tribological effect of composites during lubrication environments such as MoS2 molybdenum disulphide, boric acid (H3BO3) and multi-concentrational carbon nanotubes (MWCNT) in paraffin SN500 oiled. The composites were Al-SiC, Al-B4C and Al-SiC-B4C. In contrast to MoS2, which exhibits moderate frictional improvement in performance, the compounds H3BO3 and MWCNT exhibit significant friction and wear improvement. Kanthavel et al.[15] examined the tribological properties of Al/5% Al2O3 (5-10%) MoS2 composites produced by powder metallurgy. At constant sliding speeds of 0.5 m/s and distances of 1000 m, Al/5% Al2O3/5% MoS2 exhibits the least amount of wear and coefficient of friction. The study shows that adding 10% MoS2 to the composite may not enhance tribological properties. Moharami [16] investigated the influence of the interdependence among the sliding distance and the wear rate on the dry sliding wear behaviour of as-cast (Al-30Mg2Si) and friction stir process (FSP) samples at ambient and elevated temperatures. The author demonstrated that FSP-induced microstructural change significantly increased the wear resistance of an Al-30Mg2Si alloy at ambient conditions. Decreased wear rate (at 1000 m) and average COF (compared to as-cast) were also achieved by increasing pass number. This was caused by small Mg2Si particles in the FSP substratum which likely hindered the development of grain at a higher temperature and transformed the serious adhesive mechanisms.

Ali [17] investigated the influence of several tool pin topologies on the combining capability of AA6061-T6 and Al-20%Mg2Si with FSW. This study was conducted using a flow rate of 80 mm/min and a rotation speed of 1000 rpm. They demonstrated that the triangle tapered (TT) tool reduced the average grain size of the AA6061 alloy from 18.4 mm to 4.6 mm and the Mg2Si particles from 115 mm to 7.5 mm, due to intense dynamic recrystallisation and particle-induced pinning effects. Low solubility in alloys of AA6061-T6 and Al-Mg2Si is thought to have aided the development of Fe rich intermetallic compounds. Frictions of the joints AA6061/Al-Mg2Si is greatly reduced within the TT joints because of the steady increase of the hard Mg2Si particles in the nuggets [18]. The average diameters of the naturally existing Mg2Si phase also influenced the corrosion attack on the AA6061/Al-Mg2Si junction. The sample made with a TT tool had the least corrosion attack in NaCl solution due to the finer average Mg2Si phase diameters and shorter interparticle (Mg2Si) distances. They determined that a triangular pin tool is recommended for the different Al/composite welding because of the favourable flow of material, diffusion, and fragmentation caused by the tool. Vinoth et al. [19] studied the impact of Al-Si-10Mg, Al-Si-10Mg/MoS2 composites in mechanical and tribological aspects. They found that adding MoS2 particles reduced composite properties but improved wear resistance. The 2MoS2 and 4MoS2 composites demonstrate a reduced wear rate by 46% and 62%, respectively, compared to the basic alloy.

Patle and colleagues used friction stir processing (FSP) to make an AA7075-B4C/MoS2 hybrid composite [20]. Typically, a 12-h heat treatment solution treatment at room temperature of 50 °C, followed by artificial quenching and a 0.5-h solution treatment time, which are both conducted for an additional 24-h duration, will result in soft leather hardening desired. The composites hardness improved from 156 to 160HV. The B4C and MoS2 seem to diminish the adhesive mechanisms.

According to the aforementioned literature, it was determined that the mechanical and tribological properties of Al-Si alloys reinforced by Al2O3 and MoS2 were still not completely examined. As a result, an attempt was undertaken to synthesize a hybrid Al-Si/Al2O3/MoS2 composite in producing superior mechanical and dry wear resistance qualities. Taguchi OA has been adopted to determine the wear behaviour of composite materials during dry sliding in order to determine the optimal wear setting.

**METHODOLOGY**

**Composites Fabrication using Stir Casting Route**

In this study, the stir casting route was adopted for the fabrication of composites. The matrix in Table 1 was chopped into pieces and filled in a graphite crucible, and melted in a bottom-pouring furnace (Model: ENV120T, Naskar) beyond its thermal stability of 750 °C. The crucible holds the melted aluminium. On the other side, in order to cleanse and remove the artificial hydrox coating and adsorbed gases on the Al2O3 and MoS2 particles, they were preheated in a hot oven for 2 hours at 600 °C. The melting permitted to cool in between its liquid and solids stages but also kept in a halved form. If the metal is totally melted and the temperature is placed well above the liquid, the melting rate is halved. To improve wettability, magnesium ribbon is incorporated into the molten metal prior to reinforcement. The estimated reinforcement volume is applied to molten metal 3-4 times rather than only added at once in the whirlpool. The mixture was stirred for 10 minutes and refined into a liquid form with a furnace apprehended at 750 ± 5°C. After the process, the melt is poured into a preheated graphite mould and then allowed to cool at room temperatures. The mould is taken out after 15 minutes and allowed to cool further before the cooling process is complete.
into the preheated mild steel mould. All the composites (i.e., Al-Si/2wt%MoS2, Al-Si/12wt%Al2O3, and Al-Si/12wt%Al2O3/2wt%MoS2) adopted the same methodology in preparation.

Table 1. Elemental composition of Al-Si matrix.

| Element | Si   | Fe  | Cr  | Cu  | Mn  | Zn  | Mg  | Remain |
|---------|------|-----|-----|-----|-----|-----|-----|--------|
| Content (%) | 0.80 | - 1.2 | ≤ 0.20 | ≤ 0.10 | ≤ 0.050 | ≤ 0.050 | ≤ 0.010 | Al |

Materials Testing and Methods

The fundamental objective of this work is to establish and characterize the feasibility of wear-resistant and friction properties of developed hybrid matrix composites materials. In this study, the AMCs are prepared using MoS2 and Al2O3 as reinforcements. The MoS2 particulates were supplied by Intelligent Materials Private Limited, Punjab and Al2O3 particulates are obtained from Sajan overseas private limited, Ahmadabad. The particulate size of MoS2 and Al2O3 having average size of 45 µm. The shape of the reinforced materials is shown in Figure 1.

Figure 1. Reinforced particulates: (a) MoS2 (b) Al2O3.

Hardness testing (Model: MRB HM-RB/187), tensile strength testing (Model: ETM-ER3), metallurgical analysis for surface by ASTM E-7-17, adopting SEM (Model: JEOL JSM-5600LV), density measurement, and pin-on-disc wear tester (Model: TE-165-SPOD) are among the characterization methods used. The Archimedes theory was taken to calculate the densities of a stir cast hybrid reinforced AMCs, which provides an accurate and quicker process to determine the density of certain irregular solid particles. The metals structure was examined at different scales using an optical microscope (Model: METZ-797) to provide descriptive and analytical characterization. The form, scale, and scattering of structure oxide fillers were investigated using a metallurgical microscope in this study. The samples were polished with fine grit and then swabbed with a Keller test solution for 20-40 seconds to study the structure of composites.

According to the ASTM G99-95a standard, a pin-on-disc tester (Model: TE-165-SPOD) was used to determine the tribological performances, and the test was performed at room temperature [23]. The counter disc is made of steel material that has approximately 62 HRC (EN-31A) hardness. The disc had a diameter of up to 80 mm with a thickness of 8 mm. The dimension of the pin sample is 35 mm long and 8 mm in diameter. The pin specimens are polished with fine sandpaper in grades 600 to 1200 prior to carrying out the tribological test. The pin and disc were cleaned with acetone before and after wear. The wear rate determines the quantity of wear loss/volume loss or linear dimension change per unit of normal force per sliding distance applied—the wear rate measured in mm³/m [2,24]. The COF of the specimens has been recorded automatically throughout the test. Further, all investigations were repeated three times with the average values stated in each situation to confirm the reliability of the results.

Experimental Design with Taguchi Approach (L27)

Doing a single experiment is too difficult with precise factorial design as doing a single experiment with more control factors. The Taguchi procedure provides a well-designed orthogonal structure to overcome the issue and helps to test the whole parameter with the exception of minimal experiments. Taguchi’s method is an interpretive paradigm to learn about the performance of a process. ANOVA was used to evaluate the results [25–27]. ANOVA is a method for determining the most important factor and quantifying the variation into distinguishable causes of deviation. The F-test is a reference deviation factor. If variance analysis was performed on a set of statistics, the adjusted square sums were assigned to the quality factors. By comparing this value to the total sum of squares, the percentage of contribution in each variable can be determined. P-value (meaning probability) is determined by the meaning of F. The P-value is a variable typically ≤ 0.05 (with 95% confidence); therefore, the presence of data-point interactions is significant.

In this study, three variables are used at three levels. The variables applied were pressure (P), sliding distance (SD) and sliding velocity (SV), which were employed to measure tribological quantities, i.e. wear rate (WR) and coefficient of friction (CF). The chosen variables are shown in Table 2, while Table 3 shows the 27 tests that make up the evaluation plan. The variables are reserved in a column of one, two, and five; the other columns specified in interactions, under the assumption that flexibility degree would be essentially equivalent to a number of certain response variables upon factor analysis. The overall degree of freedom required for the overall experiment is related to the number of factors, levels, and
associated interactions. The tribological quantities and their signal to noise (SN) values of cast materials are shown in Table 4 and Table 5.

**Table 2.** Variables with selection levels.

| Variables          | Units/ Levels | Level 1 | Level 2 | Level 3 |
|--------------------|---------------|---------|---------|---------|
| Sliding Velocity (SV) | m/s           | 1       | 1.5     | 2       |
| Sliding Distance (SD) | m             | 600     | 900     | 1200    |
| Pressure (P)       | Kg·f/cm²      | 2.04    | 3.06    | 4.08    |

**Table 3.** Experimental layout of Taguchi orthogonal array (L27).

| Run | SV  | SD   | P    | Run | SV  | SD   | P    |
|-----|-----|------|------|-----|-----|------|------|
| 1   | 1   | 600  | 2.04 | 15  | 1.5 | 900  | 4.08 |
| 2   | 1   | 600  | 3.06 | 16  | 1.5 | 1200 | 2.04 |
| 3   | 1   | 600  | 4.08 | 17  | 1.5 | 1200 | 3.06 |
| 4   | 1   | 900  | 2.04 | 18  | 1.5 | 1200 | 4.08 |
| 5   | 1   | 900  | 3.06 | 19  | 2   | 600  | 2.04 |
| 6   | 1   | 900  | 4.08 | 20  | 2   | 600  | 3.06 |
| 7   | 1   | 1200 | 2.04 | 21  | 2   | 600  | 4.08 |
| 8   | 1   | 1200 | 3.06 | 22  | 2   | 900  | 2.04 |
| 9   | 1   | 1200 | 4.08 | 23  | 2   | 900  | 3.06 |
| 10  | 1.5 | 600  | 2.04 | 24  | 2   | 900  | 4.08 |
| 11  | 1.5 | 600  | 3.06 | 25  | 2   | 1200 | 2.04 |
| 12  | 1.5 | 600  | 4.08 | 26  | 2   | 1200 | 3.06 |
| 13  | 1.5 | 900  | 2.04 | 27  | 2   | 1200 | 4.08 |
| 14  | 1.5 | 900  | 3.06 |      |     |      |      |

**Table 4.** Responses of WR of composites with SN ratios.

| Run | Al-Si | Al-Si/2MoS<sub>2</sub> | Al-Si/12Al<sub>2</sub>O<sub>3</sub> | Al-Si/1212Al<sub>2</sub>O<sub>3</sub>/2MoS<sub>2</sub> |
|-----|-------|------------------------|---------------------------------|---------------------------------|
|     | WR SNRA | WR SNRA | WR SNRA | WR SNRA |
| 1   | 2.383 | -7.542 | 1.940 | -5.757 | 1.787 | -5.044 | 1.039 | -0.329 |
| 2   | 2.678 | -8.558 | 2.161 | -6.693 | 2.033 | -6.162 | 1.259 | -2.003 |
| 3   | 2.974 | -9.467 | 2.382 | -7.538 | 2.279 | -7.153 | 1.480 | -3.406 |
| 4   | 2.461 | -7.822 | 1.980 | -5.931 | 1.795 | -5.081 | 1.078 | -0.652 |
| 5   | 2.725 | -8.707 | 2.200 | -6.850 | 2.059 | -6.273 | 1.299 | -2.270 |
| 6   | 2.989 | -9.511 | 2.421 | -7.680 | 2.323 | -7.321 | 1.519 | -3.634 |
| 7   | 2.422 | -7.683 | 2.019 | -6.102 | 1.791 | -5.063 | 1.117 | -0.964 |
| 8   | 2.702 | -8.633 | 2.240 | -7.003 | 2.046 | -6.218 | 1.338 | -2.530 |
| 9   | 2.981 | -9.489 | 2.460 | -7.820 | 2.301 | -7.238 | 1.559 | -3.856 |
| 10  | 2.054 | -6.254 | 1.735 | -4.785 | 1.541 | -3.755 | 0.835 | 1.584 |
| 11  | 2.350 | -7.421 | 1.956 | -5.825 | 1.786 | -5.040 | 1.054 | -0.457 |
| 12  | 2.645 | -8.450 | 2.176 | -6.754 | 2.032 | -6.159 | 1.275 | -2.109 |
| 13  | 2.028 | -6.141 | 1.774 | -4.980 | 1.362 | -2.684 | 0.873 | 1.183 |
| 14  | 2.272 | -7.128 | 1.995 | -5.998 | 1.606 | -4.115 | 1.095 | -0.775 |
| 15  | 2.516 | -8.014 | 2.216 | -6.910 | 1.850 | -5.343 | 1.314 | -2.373 |
| 16  | 2.041 | -6.198 | 1.814 | -5.170 | 1.451 | -3.236 | 0.912 | 0.800 |
| 17  | 2.311 | -7.276 | 2.034 | -6.168 | 1.696 | -4.590 | 1.135 | -1.082 |
| 18  | 2.581 | -8.235 | 2.255 | -7.063 | 1.941 | -5.761 | 1.355 | -3.269 |
| 19  | 1.890 | -5.530 | 1.632 | -4.255 | 1.418 | -3.031 | 0.731 | 2.726 |
| 20  | 2.186 | -6.791 | 1.853 | -5.357 | 1.663 | -4.419 | 0.951 | 0.433 |
| 21  | 2.481 | -7.893 | 2.074 | -6.335 | 1.909 | -5.616 | 1.172 | -1.379 |
| 22  | 1.663 | -4.418 | 1.672 | -4.462 | 0.997 | 0.026 | 0.770 | 2.271 |
| 23  | 1.887 | -5.515 | 1.892 | -5.539 | 1.221 | -1.734 | 0.991 | 0.081 |
| 24  | 2.111 | -6.490 | 2.113 | -6.498 | 1.445 | -3.197 | 1.211 | -1.666 |
| 25  | 1.777 | -4.992 | 1.711 | -4.646 | 1.207 | -1.636 | 0.809 | 1.838 |
| 26  | 2.036 | -6.177 | 1.932 | -5.718 | 1.442 | -3.180 | 1.030 | -0.257 |
| 27  | 2.296 | -7.220 | 2.152 | -6.658 | 1.677 | -4.490 | 1.251 | -1.943 |
The tensile strength (UTS) of Al-Si/2% MoS₂ decreased by 6.41% to Al-Si alloy, as shown in Figure 2(a). Also, the strength of Al-Si/12Al₂O₃ and hybrid composites (Al-Si/2MoS₂/12Al₂O₃) increased by 11.08% and 2.38%, respectively. The improvement of UTS may be caused to the strong Al₂O₃ reinforcement particles lead to the homogenous dispersion in the materials and acts as a load barrier. The composite Al-Si/12Al₂O₃ exhibited better UTS than other materials. However, the decreased UTS in the hybrid and MoS₂ composites can be attributable to low ultimate MoS₂ (tolerance of 70 MPa) tensile strength compared with the Al-Si matrix (at 162 MPa) resulting in a decrease in UTS of MoS₂ composites. Similarly, the composite elongation in Figure 2(a) revealed that the Al₂O₃ and MoS₂ addition decreased the ductility of the composite slightly than the Al-Si alloy. The addition of 2 wt.% of MoS₂, 12% of Al₂O₃ and 2% of MoS₂ and 12% of Al₂O₃ led to a decline of elongation by 18.67%, 26.51% and 22.59%, which caused to increases the composite hardness.

The Al₂O₃ density (3.95 g/cm³) is higher than in Al-Si (2.71 g/cm³), such that the Al₂O₃ volume enhances the composite density, as in the Al-Si matrix. As the particle density of MoS₂ (5.03 g/cm³) is significantly greater than the Al-Si density, increasing the reinforcing weight fraction (such as Al₂O₃ and MoS₂) could increase the characteristics of the hybrid composites. Figure 2(b) shows that the density of mono (Al-Si/2% MoS₂ and Al-Si/12% Al₂O₃) increased by 1.12% and 1.48%, respectively, compared to Al-Si. Similarly, hybrid composites (Al-Si/2MoS₂/12Al₂O₃) have a 2.82% improvement in density compared to Al-Si alloy. With the increased content of MoS₂ and Al₂O₃ reinforcement, the composite slightly than the Al-Si alloy. The addition of 2 wt.% of MoS₂, 12% of Al₂O₃ and 2% of MoS₂ and 12% of Al₂O₃ led to a decline of elongation by 18.67%, 26.51% and 22.59%, which caused to increases the composite hardness.

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### Metallographic Analysis of Composites

Figure 3 illustrates grain refinement in composites as a result of proper stirring and the use of necessary control performance, which aids in dispersing particles (Al₂O₃, MoS₂) inside the matrix. Figure 3(a) illustrates the microstructure of the Al-Si matrix. The images indicate that the matrix is free of cracks and agglomeration. The morphology of the composites (Al-Si/2MoS₂) is becoming progressively refined. The heterogeneous nucleation induced by the MoS₂ is responsible for this structural refinement. Because of the larger Al₂O₃ quality, the Al-Si/12Al₂O₃ composite has the finest
crystalline structure. The pinning action of dispersoids at grain boundaries caused the hybrid composites in Figure 3(d) to diminish in certain grain borders during solidification. The Orowan Mechanism elucidates the relationship between the fineness of composite grain and strength [28–30].

Figure 2. Properties of composites: (a) UTS and elongation, (b) density and hardness.

Figure 3. Metallographic images of (a) Al-Si (b) Al-Si/2MoS₂ (c) Al-Si -12 Al₂O₃ (d) Al-Si /2MoS₂/12Al₂O₃ composites.

Fine granules increase the strength and toughness of the cast composite because of the increased heterogeneous nucleation rate caused by incoherent particles in the material. Cast composite grains are often significantly finer than Al-Si alloy, see Figure 3(a). The volume percent was also determined using an image processing analyzer and is shown in Figure 4.

Tribological Examination of Cast Composites using Surface Plots

The main objective of the current work is to found the optimum process parameters to obtain minimum wear rate (WR) and coefficient of friction (CF). The model responses were analysed by plotting 3D-response surface plots. Surface
plots were drawn for a combination of the process variables such as sliding velocity (SV) and sliding distance (SD) for Al-Si and all cast composites such as Al-Si/2MoS2, Al-Si/12Al2O3, and Al-Si/12Al2O3/2MoS2.

Figure 4. The volumetric proportion of reinforced particles and their dispersion in Al-Si/12Al2O3 composite.

Figure 5. Combined effect of wear rate on composites (a) Al-Si (b) Al-Si/2MoS2 (c) Al-Si/12Al2O3 (d) Al-Si/2MoS2/12Al2O3.

The combined effect on the wear rate of cast materials was carried at a constant pressure of 3.06 kg-f/cm² with varying SD and SV, shown in Figure 5(a) to 5(d). Figure 5(a) and 5(c) show that as the sliding distance increases, the wear rate decreases until it exceeds 750 m, after which it rises due to the loss of the intrinsic strength of AMCs and also may be
owing to friction offered by counterface (steel disc). While the sliding distance affects the wear rate, it reduces when coupled with the sliding velocity since the sliding distance dominates the load [31,32]. Hard phase particles (Al2O3) are not able to support a matrix against a higher sliding distance; thus, a mildly brittle fracture will occur and causing increase in wear rate.

However, when sliding velocity (SV) increases, the rate of wear decreases. Wear loss decreased slightly when sliding velocity (SV) increases owing to the development of a rich layer amid the pair’s contact area. The addition of MoS2 particles act as a lubricant and reduce friction between the tribo surfaces. Unreinforced composite in Figure 5(a) shows a maximum wear rate because of direct contact surfaces compared to reinforced composites.

The main effect plot observed in Figure 6(a) and Figure 6(b) for the combined effect of SD and SV revealed a decrease in coefficient of friction (CF). The reduction in friction due to the formation of the MoS2 layer lay in between the tribo surfaces, act as a lubricant. MoS2 particles fill the asperities of the worn surface of the pin and stick on the disc, to prevent direct contact between the pin, and the disc is the main cause of reducing the coefficient of friction. Pressure and sliding velocity have an insignificant factor in the coefficient of friction because a thin layer of MoS2 is almost maintained stably in between the contact surfaces. The wt. % of Al2O3 and MoS2 is the main significant factor that affects the hybrid composite due to their high inclination, as shown in Figure 6(d). The coefficient of friction decreases with the addition of MoS2 and due to hard phase oxide particles as well form oxide layer between the tribo surfaces. The coefficient of friction is found higher in the base matrix; the high degree of contact between surfaces increases the plastic deformation [8,33]. Similarly, the hard particles (Al2O3) is abrasive in nature and lies in between the contact surfaces and surface eroded while pressure increased to cause a high coefficient of friction.

![Figure 6](image_url)

**Figure 6.** Combined effect of wear rate on composites (a) Al-Si (b) Al-Si/2MoS2 (c) Al-Si /12Al2O3 (d) Al-Si /2MoS2/12Al2O3.

**Regression Analysis of Cast Materials**

The main purpose of the present study was to investigate optimal operating conditions in order to achieve minimal wear and friction coefficients. The following sections represent individual analysis as well optimal conditions of Al-Si, Al-Si/2MoS2, Al-Si/12 Al2O3, and Al-Si/2MoS2/12Al2O3. The analysis was using Minitab-16 software.
Regression Statistical Analysis for Al-Si Matrix

ANOVA was used to demonstrate the importance of variables and their intervention correlations. According to ANOVA in Table 6, the most important controlling parameter for wear rate is sliding velocity, followed by pressure. Similarly for COF, the highest controlling parameter is pressure followed by sliding velocity. In Table 7, the insignificant parameter is the sliding distance, where found by measuring the p-value. It is also worth noting that R² and adjusted R² are almost identical, with a confidence interval of 0.084. From Table 7, using the multiple linear regression method, the wear-rate statistical governing equations were established from coefficient of variables as shown in Eq. (1). The positive sign indicates a synergistic impact, whereas the negative signal indicates a contradictory effect.

\[
WR (Al-Si) = 2.62103 - 0.66543 \times SV - 9.2E-05 \times SD + 0.264454 \times P
\]  
(1)

### Table 6. ANOVA of Al-Si.

| Source  | WL | DF | Adj MS | % Cont. | WL | DF | Adj MS | % Cont. |
|---------|----|----|--------|---------|----|----|--------|---------|
| SV      | 27.932 | 2 | 13.966 | 56.92   | 0.247 | 2 | 0.124 | 17.67   |
| SD      | 0.961 | 2 | 0.48   | 1.96    | 0.139 | 2 | 0.069 | 9.91    |
| P       | 18.397 | 2 | 9.198  | 37.49   | 1.014 | 2 | 0.507 | 72.44   |
| SV*SD   | 1.59 | 4 | 0.398  | 3.24    | 0.001 | 4 | 0 | 0.07   |
| SV*P    | 0.13 | 4 | 0.033  | 0.27    | 0.001 | 4 | 0 | 0.07   |
| SD*P    | 0.061 | 4 | 0.015  | 0.12    | 0.002 | 4 | 0.001 | 0.14   |
| Error   | 0.001 | 8 | 0.003  | 8       | 1.399 | 26 |
| Total   | 49.072 | 26 | 1.399  | 26      |

### Table 7. Regression analysis of Al-Si.

| WR | CF |
|----|----|
|     |     |
|     |     |
|     |     |

- Table 7 has no trivial parameters that can be found using p-value estimation. It is also worth noting that R² and adjusted R² are almost identical, with a standard error of 0.000653. Table 7 uses multiple linear regression method and the statistical formula for CF; developed by means of factors coefficients and Eq. (2) as follows.

\[
CF (Al-Si) = 0.2854 - 0.0077 \times SV - 9.7E-06 \times SD + 0.0077 \times P
\]  
(2)

Figure 7(a) and 7(b) illustrate S/N ratio graphs for various degrees of WR and CF. The optimal parametric option for minimal WR is SV3SD2P1, as with CF is SV3SD3P1, which is 2 m/s of SV, 1200 m of SD, and 2.04 kg-f/cm² of P.
 Regression Statistical Analysis for Al-Si / 2MoS2 Composite

As shown in ANOVA from Table 8, pressure is among the most important variables impacting wear rate. Similar to CF, showed that pressure (at 72.43%) is the most important factor, followed by SV (at 17.62%). Table 9 indicates the importance of including all input variables. It should also be noted that R² and Adjusted R² are essentially equal, with a typical 0.026222 of error. Table 9 uses linear regression analysis and the WR empirical controlling equation is shown in Eq. (3). Table 9 has no trivial parameters that can be found using p-value estimation. It is quite worth remembering that R² and adjusted R² are almost identical, with a standard error of 0.000653. Table 9 is employing correlation methods, and the empirical mathematical formulation of coefficient of friction formed with factors coefficients is in the following Eq. (4).

\[
CF(Al − Si / 2MoS2) = 0.162157 − 0.00767 \times SV - 9.7E−06 \times SD + 0.007734 \times P
\]  

(4)

\[
WR (Al − Si / 2M\text{oS}2) = 1.710982 − 0.30803 \times SV + 0.000131 \times SD + 0.000131 \times P
\]  

(3)

Table 8. ANOVA of Al-Si/ 2MoS2.

| Source   | SS   | DF  | Adj MS | % Cont. | SS   | DF  | Adj MS | % Cont. |
|----------|------|-----|--------|---------|------|-----|--------|---------|
| SV       | 8.083| 2   | 4.042  | 32.3    | 0.752| 2   | 0.376  | 17.62   |
| SD       | 0.523| 2   | 0.261  | 2.09    | 0.423| 2   | 0.212  | 9.91    |
| P        | 16.352| 2   | 8.176  | 65.33   | 3.092| 2   | 1.546  | 72.43   |
| SV*SD    | 0.002| 4   | 0.001  | 0.01    | 0    | 4   | 0      | 0       |
| SV*P     | 0.064| 4   | 0.016  | 0.25    | 0.001| 4   | 0      | 0.03    |
| SD*P     | 0.004| 4   | 0.001  | 0.02    | 0.001| 4   | 0      | 0.01    |
| Error    | 0.001| 8   |        |         |      |     | 0.001  | 8       |
| Total    | 25.028| 26 |        |         |      |     | 4.269  | 26      |

Table 9. Regression analysis of Al-Si/ 2MoS2.

| WR    | Coeff. | Error | t Stat | P-value | p<0.05 | Coeff. | Error | t Stat | P-value | p<0.05 |
|-------|--------|-------|--------|---------|--------|--------|-------|--------|---------|--------|--------|
| Intercept | 1.7E+00 | 3.3E-02 | 5.3E+01 | 1.8E-25 | Sig.   | 1.6E-01 | 8.1E-04 | 2.0E+02 | 8.5E-39 | Sig.   |
| SV    | -3.1E-01 | 1.2E-02 | -2.5E+01 | 3.8E-18 | Sig.   | -7.7E-03 | 3.1E-04 | -2.5E+01 | 3.8E-18 | Sig.   |
| SD    | 1.3E-04 | 2.1E-05 | 6.4E+00 | 1.7E-06 | Sig.   | -9.7E-06 | 5.1E-07 | -1.9E+01 | 1.5E-15 | Sig.   |
| P     | 2.2E-01 | 6.1E-03 | 3.6E+01 | 1.2E-21 | Sig.   | 7.7E-03 | 1.5E-04 | 5.1E+01 | 3.2E-25 | Sig.   |
| R²    | 0.988 |       |        |         |        | 0.994 |       |        |         |        |
| Adjusted R² | 0.987 |       |        |         |        | 0.993 |       |        |         |        |
| Standard error | 0.026 |       |        |         |        | 0.0007 |       |        |         |        |

S/N ratio graphs for specific control factors of WR and CF are shown in Figure 8(a) and Figure 8(b). It was discovered that the optimal parameter configuration for obtaining the lowest wear rate (WR) values is sliding velocity(SV), sliding distance (SD), and pressure (P) at level 3, level 1, and level 1 respectively, represented as SV3SD1P1. Similarly, for the coefficient of friction (CF) the optimal values are sliding velocity (SV) at level 3, sliding distance (SD) at level 3, and pressure (P) at level 1 and denoted as SV3SD1P1.
ANNOVA in Table 10 illustrated the significant parameter on wear rate is sliding velocity (51.52%) then pressure (33.46%). Likewise, ANNOVA of CF shows that pressure (84.27%) is the most influential factor. Table 11 revealed $R^2$ and Adjusted $R^2$ are almost similar with 0.12 in error. A regression equation formed with coefficients of wear rate as given in Eq. (5)

$$WR(Al - Si/12Al_2O_3) = 2.0485 - 0.6038 \times SV - 0.00017 \times SD + 0.24002 \times P$$ (5)

Table 11 does not include an irrelevant parameter by calculating p-value. It can also found that $R^2$ and corrected $R^2$ are closer and have a 0.002701 defect. The mathematical model equation for a friction coefficient developed using correlation approaches in Table 11 using the coefficients of the variables as in Eq. (6)

$$CF(Al - Si/12Al_2O_3) = 0.117209 - 0.00406 \times SV + 1.58E - 05 \times SD + 0.013611 \times P$$ (6)

![Figure 8. Covariates effect of Al-Si/2MoS2 on (a) WR and (b) CF.](image)

### Table 90. ANOVA of Al-Si/12Al_2O_3.

| Source    | SS  | DF | Adj MS | % Cont. | SS  | DF | Adj MS | % Cont. |
|-----------|-----|----|--------|---------|-----|----|--------|---------|
| SV        | 44.452 | 2 | 22.226 | 51.52 | 0.46 | 2 | 0.23 | 4.12 |
| SD        | 6.319 | 2 | 3.16 | 7.32 | 1.141 | 2 | 0.57 | 10.21 |
| P         | 28.869 | 2 | 14.434 | 33.46 | 9.417 | 2 | 4.708 | 84.27 |
| SV*SD     | 6.138 | 4 | 1.535 | 7.11 | 0.089 | 4 | 0.022 | 0.8 |
| SV*P      | 0.384 | 4 | 0.096 | 0.44 | 0.031 | 4 | 0.008 | 0.27 |
| SD*P      | 0.089 | 4 | 0.022 | 0.1 | 0.036 | 4 | 0.009 | 0.32 |
| Error     | 0.036 | 8 |     |     | 0.001 | 8 |     |     |
| Total     | 86.287 | 26 |     |     | 11.174 | 26 |     |     |
Table 101. Regression analysis of Al-Si/12Al2O3.

|       | WR       | CF         |
|-------|----------|------------|
|       | Coeff.   | Error      | t Stat  | P-value | Coeff.   | Error      | t Stat  | P-value  |
| Intercept | 2.0E+00  | 1.4E-01    | 1.4E+01 | 7.9E-13 | Sig.     | 1.2E-01    | 3.3E-03 | 3.5E+01 | 1.9E-21 |
| SV      | -6.0E-01 | 5.5E-02    | -1.1E+01| 1.3E-10 | Sig.     | -4.1E-03  | 1.3E-03 | -3.2E+00| 4.1E-03 |
| SD      | -1.7E-04 | 9.2E-05    | -1.8E+00| 8.4E-02 | Sig.     | 1.6E-05   | 2.1E-06 | 7.5E+00 | 1.4E-07 |
| P       | 2.4E-01  | 2.7E-02    | 8.9E+00 | 6.8E-09 | Sig.     | 1.4E-02   | 6.2E-04 | 2.2E+01| 7.3E-17 |

R² Adjusted R² Standard error R² Adjusted R² Standard error
0.898 0.885 0.120 0.959 0.954 0.003

S/N ratio graphs for different factor levels of WR and CF are shown in Figure 9(a) and Figure 9(b). The conclusion is that the optimum variable set for WR is sliding velocity (SV) at level 3, sliding distance (SD) at level 2, and pressure (P) at level 1. Similarly, for coefficient of friction (CF) the optimal values are sliding velocity (SV) at level 2, sliding distance (SD) at level 1, and pressure (P) at level 1, is denoted as SV2SD1P1.

Figure 9. Covariates effect of Al-Si/12Al2O3 on (a) WR and (b) CF.

Regression Statistical Analysis for Al-Si/12Al2O3 / 2MoS2 Composite

According to the ANOVA in Table 12, the most controlling parameter for WR and CF is pressure. Table 12 shows that all input variables are important, but Table 13 shows that sliding velocity is negligible. It is indeed worth noting that the expected R² agrees reasonably well with the R²adj, with standard errors of 0.026 and 0.005 for WR and CF, respectively. To use a correlation model, the empirical governing Eq. (7) and (8) for WR and CF are written in the following form:

\[ WR(Al - Si/12Al2O3 / 2MoS2) = 0.809437 - 0.30803 \times SV + 0.000131 \times SD + 0.216403 \times P \]  
\[ CF(Al - Si/12Al2O3 / 2MoS2) = 0.07226 - 0.00046 \times SV + 4.14E - 05 \times SD + 0.019488 \times P \]
Table 112. ANOVA of Al-Si/12 Al₂O₃/2MoS₂.

| Source | WR     | DF | Adj MS  | % Cont. | CF     | DF | Adj MS  | % Cont. |
|--------|--------|----|---------|---------|--------|----|---------|---------|
| SV     | 26,904 | 2  | 13.452  | 31.79   | 0.800  | 2  | 0.400   | 2.79    |
| SD     | 1.794  | 2  | 0.897   | 2.12    | 7.834  | 2  | 3.917   | 27.28   |
| P      | 55.141 | 2  | 27.570  | 65.16   | 19.257 | 2  | 9.629   | 67.07   |
| SV*SD  | 0.024  | 4  | 0.006   | 0.03    | 0.384  | 4  | 0.096   | 1.34    |
| SV*P   | 0.706  | 4  | 0.177   | 0.83    | 0.170  | 4  | 0.043   | 0.59    |
| SD*P   | 0.050  | 4  | 0.013   | 0.06    | 0.259  | 4  | 0.065   | 0.90    |
| Error  | 0.003  | 8  | 0.007   | 8       |        |    |         |         |
| Total  | 84.621 | 26 |         |         | 28.712 | 26 |         |         |

Table 13. Regression analysis of Al-Si/12 Al₂O₃/2MoS₂.

|        | WR     |       |       | CF     |       |       |       |
|--------|--------|-------|-------|--------|-------|-------|-------|
|        | Coeff. | Error | t Stat | p<0.05 | Coeff. | Error | t Stat | p<0.05 |
| Intercept | 8.1E-01 | 3.3E-02 | 2.5E+01 | 3.9E-18 | Sig. | 7.2E-02 | 6.1E-03 | 1.2E+01 | 2.8E-11 | Sig. |
| SV      | -3.1E-01 | 1.2E-02 | -2.5E+01 | 3.8E-18 | Sig. | -4.6E-04 | 2.3E-03 | -2.0E-01 | 8.4E-01 | Sig. |
| SD      | 1.3E-04 | 2.1E-05 | 6.4E+00 | 1.7E-06 | Sig. | 4.1E-05 | 3.9E-06 | 1.1E+01 | 2.0E-10 | Sig. |
| P       | 2.2E-01 | 6.1E-03 | 3.6E+01 | 1.2E-21 | Sig. | 1.9E-02 | 1.1E-03 | 1.7E+01 | 1.3E-14 | Sig. |
| R²      | 0.988  | 0.987 | 0.026 |         |       |       |       |
| Adjusted R² |       |       |       | 0.947  | 0.940 | 0.005 |

Figure 10(a) and 10(b) shows S/N ratio diagram for various parameter levels for WR and CF. It revealed that, the optimal parametric setting is sliding velocity (SV) at level 3, sliding distance (SD) at level 1 and pressure (P) at level 1, (SV3SD1P1), whereas sliding velocity (SV) at level 2, sliding distance (SD) at level 1 and pressure (P) at level 1, is denoted as SV2SD1P1, for WR and CF.

![Figure 10](image-url)
Linear Regression Analysis of Composites Using Normal Probability of Residuals

The normal probability of residuals plot of wear rate has shown in Figure 11, it revealed that the residuals of composites are scattered randomly about straight lines. It shows that this plot is not consistent, missing phrases, outlines or significant points. From linear regressions, it is clear that while increasing the weight % of MoS$_2$ and Al$_2$O$_3$, wear rate decreased and was clearly defined with slope equations. The composites with MoS$_2$ having a significant effect on wear resistance and confirmation via R$^2$ values.

Figure 11. Normal probability of residuals of wear rate.

Similarly, the normal probability distribution of residuals for CF is shown in Figure 12. It cleared that; coefficient of friction for composites exhibited better than base alloy, owing to hard phase reinforced particulates. The linear regression of cast materials exhibited significant responses and having R$^2$ values greater than 95%.

Figure 12. Normal probability distribution of residuals for coefficient of friction.

Surface Morphology Examination

Figure 13 displays the surface morphology of base alloy and cast composites tested at 3.06 kg-f/cm$^2$(P), 900 m (SD), and 1.5 m/s (SV). The surface of base material in Figure 13(a) simply proves that dislocation density has led to increasing wear rates due to the deep cutting, the existence of large debris on the worn surface. Figure 13(b) shows the worn-out image of the Al-Si /2MoS$_2$ composite. It can be observed on the surface, uniform pattern of wear, fine residue and burring...
at the substrate edge. The MoS₂ establishes an adherent film between the tribo surfaces, which reduces the delamination effect. A sharp layer on the worn surface is described, separating the tribo pair, thus reducing the wear rate [12, 34]. Figure 13(c) depicts the tribo surface of an Al-Si/12Al₂O₃ composite. The pin surface material has been worn even though oxide particles have plugged and broken down. The worn surface indicates that the substance has been degraded and the surface has been abraded. A significant fracture occurs as a result of pair contact, a decrease in hardness, and ductile behaviour [35]. As compared to other composites, the Al-Si alloy exhibits a considerable amount of extreme plastic deformation.

Along with the Al₂O₃ and MoS₂ lubricant reinforcement, the worn surface of a hybrid Al₉Si/2MoS₂/12Al₂O₃ composite in Figure 13(d) varies. The composite substrate was flawless, with small grooves and fine debris evident. By analysing the supplied wear tracks, adhesion is visible as adhesion craters inside the wear track, surrounding by parallel grooves indicating abrasion. Adhesion pits vary in shape and size, owing mostly to the material structure in the surface and deeper layers. EDS investigation in Figure 14 reported the presence of elements, which helps to the reduction of friction between tribo surfaces. EDS of hybrid composite referring to SEM image shows adhesion pits and wear tracks confirmed the existence of Fe originating from the steel disc. These results indicate the formation of an oxide layer during dry sliding. Both contact materials respond to atmospheric oxygen. As sliding speed increases, contact temperature rises, promoting oxidation and thickening the oxide layer on both sides. This occurs as a result of direct interaction with oxidized MML.

![Figure 13](image1.png)

**Figure 13.** Surface morphological examination of worn-out samples (a) Al-Si (b) Al-Si /2MoS₂ (c) Al-Si /12% Al₂O₃ (d) Al-Si /2MoS₂/ 12% Al₂O₃.

![Figure 14](image2.png)

**Figure 14.** SEM and EDX analysis of worn-out surface of Al-Si/2MoS₂ /12Al₂O₃ composite.
Figure 15 depicts the fluctuation in work hardness with regard to sliding distance. The material gets toughened more quickly after 900 m of sliding distance — work hardening results in increased material hardness, which reduces the rate of wear. The degree of work hardening, on the other hand, increases as that the exerted pressure increases. In this case, the recrystallisation happens due to the Al-excellent alloy’s heat conductivity. This reduces hardness in this location, thereby increasing the wear rate [36, 37].

Figure 15 Working effects of composites at specified SV of 1.5 m/s and 3.06 kgf/cm² with varied sliding distance.

After wear testing, the worn surfaces of the counterface (steel discs) were also examined with an optical microscope. Figure 16 illustrates the wear track created owing to Al-Si/12Al₂O₃ composite sliding at various applied pressures at counterface. The size of the wear scars is determined by the rate at which the specimens were worn. Figure 16(b) shows abrasion patterns and the narrowest wear scar upon steel disc at low pressure. Abrasion is a predominant mechanism for all pressures due to softening reinforcing material (Al₂O₃ and powder debris) which caused distortion of the wear scars. Figure 16(c) shows the importance of iron oxide debris in the wear track for reducing friction. Deep ploughing marks and delamination as well as excessive plastic deformation with an increase in the applied pressure, are proven to be wear of adhesion [24]. As illustrated in Figure 16(d), deep grooves were detected on the worn surface as a result of strong asperities penetrating the material. The MML creation rate on the tribal surface is quite low, which shows that the oxide layer removal rate is severely reduced in comparison with its production. This could be due to the matrix becoming softer as a result of higher warmth caused by friction. This produces the material’s insufficient hardness and strength that worsens the composite wear rate. The MML presence of Al-Si/12Al₂O₃ in the longitudinal area is illustrated in Figure 17. As a result of cracks propagating along the interface between the MML and the pin contact surface, this layer was not completely bonded to the composites. Under the MML, a shattered Al₂O₃ may be seen. Figure 17 show that the MML has an average thickness of 0.812 m.
CONCLUSION

The aim of this study is to develop Al-Si/2MoS2, Al-Si/12Al2O3 and Al-Si/2MoS2/12Al2O3 composites successfully via liquid metallurgical route and also determined optimal tribological performance using Taguchi method. The following are the findings from the survey.

i. As the weight fractions of MoS2 and Al2O3 grew, the density of composites increased. As compared to Al-Si alloy, the density of Al-Si/2MoS2, Al-Si/12Al2O3, and hybrid composites (Al-Si/2MoS2/12Al2O3) raised about 1.15%, 1.84 %, and 2.18%, due to higher density of MoS2 and Al2O3.

ii. Al-Si/12Al2O3 composite exhibited better tensile strength as compared to hybrid (Al-Si/2MoS2/12Al2O3) composite and strength has enhanced by 11.08% and 2.38% respectively compared to Al-Si matrix, this happens due to MoS2 in a soft form and has lamellar structure.

iii. Sliding velocity (56.92 %) has the greatest influence on Al-Si of wear rate (WR), while pressure (72.44 %) has the major effect on CF.

iv. The best setting for Al-Si for wear rate is SV3SD2P1, and COF is SV3SD3P1. Pressure (72.43 %) has the strongest impact on Al-Si/2MoS2 of wear rate (WR), while sliding velocity (51.52 %) has the major effect on the coefficient of friction (CF).

v. The optimum condition of Al-Si/2MoS2 composite for wear rate (WR) is SV3SD1P1.

vi. Sliding velocity (51.52 %) has the greatest effect on Al-Si/12Al2O3 wear rate, while pressure (84.27 %) has the greatest effect on CF. The best parametric option for Al-Si/12Al2O3 composite on WR is SV3SD2P1, while for CF is SV2SD1P1.

vii. The most favourable condition of wear rate for Al-Si/12Al2O3/2MoS2 composite is SV3SD1P1 and for COF is SV2SD1P1.

viii. Taguchi technique is useful in evaluating the tribological responses from the regression equation.

ix. The worn-out surfaces of pin and counter faces were used to study composite wear behaviour.

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