Tribological Behaviour of MoS$_2$ and Graphite Reinforced Aluminium Matrix Composites

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Abstract. Tribological behaviour of MoS$_2$ and graphite reinforced aluminium matrix composites were investigated in this research. In the current scenario, applications in which either metal based alloys or composites are used, requires lubrication to avoid friction. In such cases, self-lubricating materials based aluminium composites can be fabricated to exhibit better tribological properties. These materials can be fabricated by reinforcing self-lubricating materials like graphite (Gr), molybdenum disulphide (MoS$_2$) and so on within the aluminium matrix. In this tribological study, two different solid lubricants (Gr and MoS$_2$) were taken at equal proportions to fabricate aluminium matrix composites individually through stir casting method. Pin on Disc apparatus was utilized to record the rate of wear of the composite specimen by considering the process parameters like sliding distance, load and counter-face disc hardness. Experiments were designed by Taguchi’s approach and analyzed by means of response values and analysis of variance (ANOVA). Results depicted that graphite based aluminium alloy composites possessed better wear resistance than MoS$_2$ reinforced aluminium alloy composites.

Keywords: Tribology, MoS$_2$, Graphite, Aluminium matrix composites, Taguchi Method

1. Introduction

Aluminium metal matrix composites (AMMC) are the class of materials that indicate enormous uniqueness that enumerate the requirements of applications of AMMC in some notable areas like transportation, sports and aviation [1, 2]. Utilization of AMMCs in nuclear, aerospace and automobile fields steadily have increased owing to their admirable physical, mechanical and thermal characteristics [3]. On account of several better properties like less density, high modulus value, high corrosion resistance, good thermal properties and high ductility of aluminium based alloys possibly uphold their capability as the materials resisting friction [4, 5]. Aluminium alloys has to work under severe conditions like intense temperature, vacuum environment and in many cases these materials has to undergo sliding contact with another metallic surface. During extreme conditions of sliding and Metal to metal contacts, application of liquid lubrication is ineffective or difficult [6]. Further liquid lubricants are non-biodegradable which may release harmful materials into the atmosphere upon disintegration. Under those conditions, aluminium alloy materials can be made to resist friction by means of inherently present materials which are characterized by low coefficient of friction and rate of wear and these materials are termed as solid self-lubricating materials [7]. Incorporation of such solid lubricants into
aluminium alloys may open avenues to many other areas such as green tribology and pave way in developing sustainable and reliable materials.

Few authors stated that self-lubricating materials arise either by reinforcing solid lubricants into the matrix of a base metal or by coating the substrate material with the self-lubricating material. Many-a-times, reinforcing the solid lubricants into aluminium alloys to obtain AMMCs render greater resistance towards fatigue cycles, excellent resistance towards corrosion and incredible tribological characteristics when compared with the materials prepared through coating method. Increasing percentage of self-lubricating materials like Gr and MoS₂ in matrix material increases the wear resistance because of the development of a solid lubricant tribo-layer amidst the contact sliding surfaces [8-10]. Several studies reported the influence of MoS₂ and Gr particles on the wear behavior of AMMCs as hybrid reinforcements. Tribological properties of Al-Al₂O₃-MoS₂ hybrid composite were examined and it was noted that the inclusion of MoS₂ particles reduced the rate of wear and friction coefficient [11]. Few authors observed the tribological behaviour of AMMCs reinforced with graphite and results showed that addition of Gr particles was a significant parameter that influenced the decrease in wear rate [12, 13].

Researchers investigated the wear behaviour of AMMCs reinforced with silicon carbide and Gr and observed that the addition of Gr, applied load, sliding speed and distance influenced the wear rate. Further statistically analyzed the friction characteristics of Al-SiC-Gr hybrid composites and observed that the friction coefficient is influenced by solid lubricants [14, 15]. Experimenters carried out tribological study on Al-Al₂O₃-Gr composites with the help of Taguchi method and concluded that graphite particles influencing the wear properties and reducing the wear loss considerably [16-18].

Tribological studies were conducted on AA2219/Gr matrix composites by varying percentage of Gr particles, rotational speed and applied load. Results revealed that tribological properties influenced by solid particles percentage in matrix material [19]. AA2219/MoS₂ matrix composites were fabricated by reinforcing of MoS₂ with different percentage with stir casting as the processing route. Tribological behaviour of the AA2219/MoS₂ AMMCs was examined both in dry and lubricated wear conditions. Taguchi DOE technique was utilized to conduct and analyse the experiment results and noted that the wear behaviour of the AA2219/MoS₂ composites under lubricated condition was superior with the inclusion of MoS₂ [20-22]. Literature review shows that the tribological test parameters and the consideration of solid lubricant particles greatly influence the tribological performance of the hybrid Aluminium matrix composites. The tribological characteristic studies of composites reinforced with solid particles as a first reinforcement are limited. Mechanical properties of Al 2024-MoS₂ composites were evaluated by varying weight percentage of MoS₂ and found that 4 wt. % MoS₂ reinforced aluminium composites shows better mechanical properties compared to other weight percent of MoS₂ particles [23-26]. For this reason, in the current study, the tribological characteristics of AA2029-4 wt. % Gr composite and the AA2029-4wt.% MoS₂ composite is analyzed through Taguchi method to understand the significance of MoS₂ and Gr particles adding together on the wear resistance.

2. EXPERIMENTAL DATA

AA2219 material was procured as billets and was further processed to make composite. Solid lubricating particles Gr and MoS₂ utilized in the form of powder with average particle size of 40 µm. MoS₂ and Gr were reinforced with AA2219 at constant weight percentage of 4 for getting better tribological properties [18].

2.1. Composite fabrication

AA2219/Gr and MoS₂ fabricated by means of conventional stir casting technique in two steps: AA2219 was melted at a temperature of 780 °C in a crucible and Gr & MoS₂ particles were preheated to 200 °C by using an electrical furnace for about 20 minutes. The preheated solid lubricants were added as reinforcements into the molten matrix material [19]. A mechanical stirring action at a rate of 525 rpm was imposed to the molten matrix and reinforcement mixture in order to obtain a homogeneously dispersed solid solution for a time period of 8 minutes. The molten metal was then poured into mould which is preheated around 100 °C. Both samples AA2219 / 4 wt. % Gr and AA2219 / 4 wt. % MoS₂ were independently fabricated and cooled at atmospheric temperature.

2.2. Conduct of Experiment
Dry wear test was performed in a CONMAT pin-on-disc tribometer at room temperature with the specimens of dimensions φ 10 × 30 mm. Experiments were conducted following ASTM G99 standards. Contact face of the composite specimen was polished with a 10 grit size emery paper to obtain smooth surface finish. Sliding distance, applied load, counter-facing disc hardness and two different solid lubricants are considered as the process parameters to obtain the wear results. Table 1 shows the levels and factors of Taguchi’s L18 (2^1 x 3^7) mixed type orthogonal array (OA). L18 OA was chosen above other arrays in order to have an accurate optimization of factors. The main purpose this study is to observe the less wear and hence the objective function for the response was chosen as ‘smaller the better’ and the values of signal to noise ratio (S/N) values was inferred corresponding to the objective function. Table 2 shows the combination of levels as per Taguchi DOE and results obtained from the experiments of wear.

Table 1. Wear test Factors and levels

| Level | Solid lubricant (A) | Load (B) in N | Sliding distance (C) in m | Disc hardness (D) in HRC |
|-------|---------------------|--------------|--------------------------|-------------------------|
| I     | Gr                  | 19.62        | 1000                     | 56                      |
| II    | MoS₂                | 29.43        | 2000                     | 62                      |
| III   |                     | 39.24        | 3000                     | 68                      |

Table 2. Response values for L18 orthogonal array

| Exp.No | Solid Lubricant (A) | Load (B) | Sliding distance (C) | Hardness (D) | Wear (µm) | S/N ratio |
|--------|---------------------|----------|----------------------|--------------|-----------|-----------|
| 1      | Gr                  | 2        | 1000                 | 56           | 212       | -46.53    |
| 2      | Gr                  | 2        | 2000                 | 62           | 246       | -47.82    |
| 3      | Gr                  | 2        | 3000                 | 68           | 274       | -48.76    |
| 4      | Gr                  | 3        | 1000                 | 56           | 237       | -47.49    |
| 5      | Gr                  | 3        | 2000                 | 62           | 271       | -48.66    |
| 6      | Gr                  | 3        | 3000                 | 68           | 302       | -49.60    |
| 7      | Gr                  | 4        | 1000                 | 62           | 285       | -49.10    |
| 8      | Gr                  | 4        | 2000                 | 68           | 326       | -50.26    |
| 9      | Gr                  | 4        | 3000                 | 56           | 294       | -49.37    |
| 10     | MoS₂                | 2        | 1000                 | 68           | 251       | -47.99    |
| 11     | MoS₂                | 2        | 2000                 | 56           | 283       | -49.04    |
| 12     | MoS₂                | 2        | 3000                 | 62           | 316       | -49.99    |
| 13     | MoS₂                | 3        | 1000                 | 62           | 292       | -49.31    |
| 14     | MoS₂                | 3        | 2000                 | 68           | 323       | -50.18    |
| 15     | MoS₂                | 3        | 3000                 | 56           | 355       | -51.00    |
| 16     | MoS₂                | 4        | 1000                 | 68           | 377       | -51.53    |
| 17     | MoS₂                | 4        | 2000                 | 56           | 353       | -50.96    |
| 18     | MoS₂                | 4        | 3000                 | 62           | 366       | -51.27    |
3. RESULTS AND DISCUSSION

Results obtained in pin on disc are tabulated and shown in table 2. These observed wear results are analyzed with MINITAB software through S/N ratio values, Main effect plot, Response table and ANOVA.

3.1. Main effects plot and response table

Previous studies revealed that, Taguchi technique is a well-known method to obtain the optimal process parameters. L18 orthogonal array is meant for understanding the effect of four independent variables having mixed factor (2^1 X 3^3) level values. Objective function from which the S/N ratio is inferred is classified into three categories: lower the better, nominal the better, and higher the better. In Wear test, the less wear rate could be attributed to the good tribological behaviour of the material. Hence the objective function, for attaining optimum tribological characteristics, was chosen as “Lower the Better” and based on this S/N ratio calculated for each test [19]. Table 2 lists the calculated S/N ratios for each experiment based corresponding response value of wear which indicates the maximum and minimum values of variance.

![Main Effect Plot for SN ratios](image)

Figure 1 Main effect plot for wear

Figure 1 illustrates the main effects plot for S/N ratios and the effect of load, distance, hardness and solid lubricants on the rate of wear. This plot results revealed that wear reduced with decreasing in sliding distance, applied load and low disc hardness. Further it is observed that less wear achieved in graphite based material compared to MoS2 particles. From this plot, it was clearly found that maximum value of S/N ratio gives optimal value of the better wear characteristics. The observed optimal values are 19.62 N load, 1000 m distance and 56 HRC hardness of disc with graphite solid lubricate to achieve the better wear characteristics.

| Level | Solid Lubricants (A) | Load (B) | Sliding Distance (C) | Hardness (D) |
|-------|----------------------|----------|----------------------|-------------|
| 1     | -48.62               | -48.35   | -48.66               | -49.06      |
| 2     | -50.14               | -49.38   | -49.49               | -49.36      |
| 3     | -50.41               | -50.00   | -49.72               |             |
| Delta | 1.52                 | 2.06     | 1.34                 | 0.66        |
| Rank  | 2                    | 1        | 3                    | 4           |

Table 3. Response table
The effect of wear parameters on tribological characteristic has been presented using response table. Response tables are utilized to analyze the observed data in a simple manner. The complete response table for the experimental design is shown in Table 3 with significance of the factor by appropriate ranking. The values in table 3 depicts the significant responses when the level of process parameters move to higher levels from lower level. Ranking of parameters indicates that effect of parameter on the response of wear loss which reveals that applied load is the most influencing factor when it changes form one level to other level followed by solid lubricant, sliding distance and disc hardness.

3.2. Analysis of variance for wear

Analysis of variance (ANOVA) was utilized for determining the process parameter’s significance which were given as input to measure the wear rate [27]. ANOVA was performed to find out the optimum values for obtaining less wear rate and relative significance of wear parameters affecting wear of all the compositions.

| Source                  | Degree of Freedom | Sequential Sum of Square | Adjusted Mean Square | F-value | P value | Percentage contribution |
|-------------------------|-------------------|--------------------------|----------------------|---------|---------|-------------------------|
| Solid Lubricants (A)    | 1                 | 10.409                   | 10.409               | 43.37   | 0.000   | 32.2%                   |
| Load (B)                | 2                 | 12.724                   | 6.362                | 26.51   | 0.000   | 39.4%                   |
| Sliding Distance (C)    | 2                 | 5.492                    | 2.746                | 11.44   | 0.003   | 17.0%                   |
| Disc hardness (D)       | 2                 | 1.298                    | 0.649                | 2.7     | 0.115   | 4.0%                    |
| Residual Error          | 10                | 2.4                      | 0.24                 |         |         | 7.4%                    |
| Total                   | 17                | 32.323                   |                      |         |         |                         |

It was also carried out to verify the factors which are statistically significant at 95% confidence level with the help of the P-value. The values of P which are less than or equal to 0.05 indicates higher level of significance. According P-value, except disc hardness all other remaining factors are less than 0.05 which shows that those are significant parameters on wear. Disc hardness shown not much significant in this wear test, it may be due to utilization of fixed weight percentage of reinforcement. The last column of the ANOVA table shown in table 4 indicates the percentage of contribution (Pc) in which Applied Load has the highest level of contribution (39.4%) followed by solid lubricants (32.2%), sliding distance (17%) and Disc hardness (4.0%).

3.3. Influence of Solid lubricants on wear

In wear analysis AA2219 / 4 wt. % Gr and AA2219 / 4 wt. % MoS₂ samples were used and results are tabulated in Table 2. It revealed that AA2219 / 4 wt. % Gr specimens exhibited better tribological characteristics compared to AA2219 / 4 wt. % MoS₂ samples. Further it was illustrated from the figure 2 and 3 that Gr based specimens had undergone less wear when compared with MoS₂ specimens almost for all levels the applied load (Figure 3 a) and sliding distance (Figure 3 b).
Many literatures revealed that graphite acts as an efficient lubrication when ample amount of vapour pressure of water was available while MoS$_2$ suits better for the vacuum atmospheres [23, 24]. Many experimental results also revealed that the wear rate and friction of the materials with MoS$_2$ as a reinforcement increased with the humidity in the working environment while the phenomenon was vice-versa when the materials was reinforced with Gr. MoS$_2$ samples showcased excessive wear than graphite samples which could be due to accelerated oxidation at normal environment by the small particles of MoS$_2$ [20].

Further, Graphite is structurally hexagonal in orientations that are arranged together with planes of polycyclic carbon atoms. The distance between planes and carbon atoms are lengthy and due to this bonding between atom and plane becomes weaker. The energy available with the water vapor atmosphere would be enough to reduce the available energy of graphite within the hexagonal plane bonding to a level that is lesser than that of Gr adhesion energy with the matrix material [21]. These reasons are attributed to better tribological performance of graphite samples than MoS$_2$ samples at normal atmospheric conditions.

3.4. Confirmation tests
A confirmation tests were conducted at the optimal level of wear parameters [22]. The S/N ratio for the optimal level of parameters can be attained from the equation 1,

$$\gamma' = \gamma_m + \sum (\gamma_i - \gamma_m)$$

Where, $\gamma_m$ - total mean S/N ratio, $\gamma_i$ - mean S/N ratio of the optimum value.

In order to confirm the calculated values from the optimal levels, a confirmation test was carried out. Table 5 shows the error difference between the predicted and experimental responses. The optimal level of wear parameters obtained for minimum wear rate was at lowest applied load (19.62N) load, sliding distance (1000 m) and 56 HRC hardness of disc with graphite reinforced AA2219 sample.

### Table 5 Confirmation tests

| Optimum parameters | Experimental | Predicted |
|--------------------|--------------|-----------|
| Wear (µm)          | 212          | 207       |
| S/N ratio          | -46.53       | -46.55    |

### 4. CONCLUSION

AA2219 reinforced with 4 wt. % of Gr and MoS$_2$ were fabricated by stir casting technique and were subjected to wear tests. Optimization of wear rate was carried out by Taguchi’s method and the following conclusions were arrived.

- Addition of Gr solid lubricants shown better wear characteristics than MoS$_2$ particles based composite for the selected parameters at normal environment.
- Applied load and solid lubricants are the main factors, which is affecting the wear properties in all samples for all experimental conditions.
- Wear rate increases with the increase in applied load and sliding distance in all experimental conditions. It was observed that disc hardness less significant on wear compared to applied load and sliding distance.
- The lowest wear are recorded at the lowest applied load (19.62N) load, sliding distance (1000 m) and 56 HRC hardness of disc with graphite reinforced AA2219 sample.

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