Friction and sliding wear studies on functionally graded Al LM25/WC composite

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Abstract. Functionally graded LM25/15 wt.% Tungsten carbide composite of dimension Øout 150 mm x Øin 110 mm x 100 mm and thickness 20 mm was studied to understand the influence of process parameters (applied load, sliding velocity, sliding distance) on the dry sliding wear rate and co-efficient of friction. A 5-level 3 parameter central composite design was developed using response surface methodology considering applied load (10-50N), sliding velocity (1-3 m/s) and sliding distance (500-2500 m) as input parameters. Dry sliding experiments were performed on pin-on-disk tribometer at ambient conditions. Significance tests, Analysis of Variance and confirmation experiments were done to check the accuracy of generated regression model. Generated surface plots revealed wear rate to be increasing as applied load and sliding distance increases and decrease as sliding velocity increases. Worn surface analysis performed revealed formation of deep grooves at high load, MML formation at high velocities and heavy delamination and particle pull-out at high sliding distances.

1. Introduction
The demand for using aluminium alloys widely in various applications can be credited to their excellent properties such as tensile and ultimate strength, thermal properties and mainly, its low strength to weight ratio. Hence it is widely used in various applications like brake rotors, cylinder liners, piston rings etc. [1]. Due to its poor tribological characteristics under machine conditions, there arose a necessity to introduce metal matrix composites (MMC), having improved wear characteristics [2]. Even then, some automotive components like piston rings, cylinder liners, gears and bearings require improved performance at specific locations, which cannot be provided by MMCs. Hence, an advanced class of composites called functionally graded (FG) composites are developed, which has gradient properties along its radial direction [3]. Although various fabrication techniques are available for FG composites, centrifugal casting is chosen as all other techniques require high-cost fabrication techniques and equipment while centrifugal casting is an economical method through which bulk quantity production can be easily achieved [4]. The effect of various centrifugal casting parameters on the adhesive wear rate of FG Al-10Si-4.5Cu-2Mg/ silicon carbide (SiC) composite are studied and it is concluded that low centrifugal speed promoted smooth gradient distribution of reinforcement particles while high centrifugal speed promoted sharp gradient distribution of particles [5]. Certain studies reported that increasing concentration of reinforcement particles enhances wear resistance [6,7] and superior wear behaviour over homogenous alloy, mainly due to the reinforcement particles behaving as load-bearers...
Analysis of titanium carbide (TiC) reinforced 7075 Al matrix composites and boron carbide (B₄C) reinforced Al5083 composites concluded that increasing reinforcement content enhances the wear resistance of the composite, irrespective of the fabrication method [9, 10]. It is also reported that neither particle size nor volume fraction of the reinforcement affects the friction co-efficient of the fabricated composite under dry sliding conditions [11]. It should also be noted that the particle type has an impact on the co-efficient of friction (CF), with hard reinforcement particles such as SiC exhibiting higher values of friction as compared to soft particles such as graphite (Gr) [12]. Studies on hybrid Al-SiC-Gr composite revealed varying CF with sliding speed and applied load while the % reinforcement and sliding distance did not have an influence on the CF [13]. Mathematical modelling methods, one of which is Response Surface Methodology (RSM), is used to develop a suitable parametric relation between process parameters (input) and response (output) and to optimize the response characteristics [14]. Decrease in wear rate and friction co-efficient are observed with increasing reinforcement particle addition on analysis while the mathematical models generated, predicted high accuracy with minimal error [15]. An analysis of wear trends observed for Al-7075/SiC/Gr composite revealed wear rate to be increasing with increasing applied load and sliding distance, while a decreasing trend is observed with increasing sliding velocity up to 4 m/s beyond which the wear rate increases. RSM analysis confirmed applied load to be the most prominent factor affecting wear rate while other parameters are deemed secondary [16].

Although many studies focus on the MMCs and hybrid MMCs, it is noted that wear and friction studies of FG composites reinforced with tungsten carbide (WC) are not fully explored. Hence, this article focuses mainly on the dry sliding wear characteristics and the corresponding frictional co-efficient values. Statistical analysis methods such as Analysis of Variance (ANOVA) and RSM are used to explore and identify the interdependence of the process parameters i.e. applied load, sliding velocity and sliding distance on the response (wear rate, co-efficient of friction). Worn surface analysis is performed to identify the wear mechanisms and also to confirm the validity of the model.

2. Experiments
This section deals with the selection of material, fabrication of the composite, preparation of specimen for wear test and the dry sliding experimental details.

2.1. Fabrication of composite
LM 25 aluminium alloy (Al-7Si-0.5Mg) of density 2.7 g/cm³ is chosen as base metal matrix and 15 wt.% tungsten carbide (WC) having a particle size of 10 µm and density 15.6 g/cm³ is chosen as reinforcement particle, is shown in Figure 1. These are chosen mainly due to their superior properties which can be utilized to enhance the wear resistance, hardness, elevated temperature strength and resistance to corrosion. Fabrication process is done in two steps, initially stir casting followed by centrifugal casting. The alloy pieces are taken in a graphite crucible placed inside an electric furnace and heated to 760°C, which is above its liquidus temperature, to achieve the molten state. WC reinforcement particles are preheated to 350°C, to remove the presence of any moisture content, to improve wettability characteristics and to avoid excess cooling of molten alloy during mixing. A motor driven stirrer performs the stirring action for a duration of 5 minutes, which creates the vortex, to which the reinforcement particles are added through a hopper provided atop the furnace. A steel centrifugal die of dimension Øout 150 mm x 100 mm is preheated at 400°C and rotated at 1500 rpm so as to avoid any thermal gradation. After molten state of the metal is achieved at 760°C, it is then poured into the die and is allowed to air cool and solidify to a final casting of dimension Øout 150 mm x Øin 110 mm x 100 mm, as shown in Figure 2.
2.2. Wear test specimen preparation
The cast specimen as shown in Figure 2, is laser-cut into smaller sections to be machined and milled for wear test. Specimens are prepared by machining 12 mm x 12 mm square cross-section from the outer layers of the composite as WC reinforcement particles segregate towards the outer layers in high concentration, owing to the superior density of tungsten carbide over aluminium and high centrifugal speed of the die. The pins are prepared in such a way that the outer layer forms the surface to be tested. To increase the height of pin to 35 mm, a hollow cylindrical steel pipe is fitted on the specimen counterface through cold-setting. Square cross-section is preferred over cylinder section mainly due to the reason of scatter in wear and friction data and also due to the difficulty in obtaining circular cross-section specimen [17, 18]. The pin surfaces are thoroughly cleaned before and after each experiment using acetone solution.

2.3. Dry sliding wear test
The frictional and dry sliding wear characteristics of LM 25/15 wt.% WC are studied using a pin-on-disk tribometer (DUCOM TR-20LE-PHM 200) based on ASTM G99-05 standards. Before conducting each experiment, the EN31 stainless steel disk (hardness 65 HRC) is cleaned using emery sheets of grades ranging from 400 to 800 to remove any stuck wear debris. The pin to be tested is loaded on the pin-holder and is pressed on the sliding disk which acts as a counter-face. It is ensured that specimen weight before and after each experiment, is measured using an electronic balance of 0.01 mg accuracy. Tests were conducted based on the following parameters chosen, applied load varying from 10 to 50 N, sliding velocity varying from 1 to 3 m/s and sliding distance varying from 500 to 2500 m. The parameters are chosen, considering the limitations of the experimental setup. No lubrication is used during the tests. The tests are performed at ambient conditions i.e. a relative humidity of 65% and a temperature of 27ºC. The frictional co-efficient is calculated based on the frictional force measured using a stress sensor during the wear test. The wear rate can be calculated using equation 1.

\[
W = \frac{M}{\rho D}
\]

where ‘W’ is the dry sliding wear rate in mm³/m, ‘M’ represents the mass loss in grams while ‘ρ’ and ‘D’ represents density in g/mm³ and sliding distance in m respectively.

2.4. Response surface methodology
The relation connecting input process parameters (applied load, sliding velocity and sliding distance) and the output response (wear rate, co-efficient of friction) is studied using a mathematical and statistical method called Response surface methodology (RSM), which utilizes regression model for predicting the relationship [16]. The number of experiments to be performed and the levels of processing...
parameters are generated using MINITAB 18 statistical software which utilized central composite design (CCD) for determining how process parameters affected the dry sliding wear rate and frictional co-efficient of the fabricated composite. The number of experimental runs to be conducted are generated based on the number of process parameters and levels. Here, three process parameters are decided and 20 experimental runs are generated, varying each parameter with five levels. Table 1 represents the process parameters and their five levels.

Table 1. Process Parameters and their levels.

| Factors          | Levels |
|------------------|--------|
| Load (N)         | 10     | 20   | 30   | 40   | 50   |
| Velocity (ms⁻¹)  | 1      | 1.5  | 2    | 2.5  | 3    |
| Distance (m)     | 500    | 1000 | 1500 | 2000 | 2500 |

3. Analysis of results

Table 2 represents the generated process parameter combinations and their corresponding experimental wear rate (WR) and CF values. The ANOVA results of WR and CF values of the fabricated composite are given in Table 3 and 4 respectively. From the results, it is understood that as the p-value of lack-of-fit is greater than 0.05, it is significant and the conclusion reached is that the generated model fits the system very well. The surface plots generated for WR and CF for all wear experiments are shown in Figures 3 – 5. The effect of each process parameter on the CF and WR are explained to discuss how they influence the wear trend in the upcoming sections. It is observed from the figures 3 -5 that the WR trend increases with increase in applied load (L), decreases with increasing sliding velocity (V), and increases with increasing sliding distance (D). Similarly, same trend is observed for CF also, supporting the WR behaviour at various process parameter conditions.

Table 2. Generated experiments and the corresponding wear rate and co-efficient of friction.

| Applied Load (N) | Sliding Velocity (m/s) | Sliding Distance (m) | Wear Rate (mm³/m) | Co-efficient of Friction |
|------------------|------------------------|----------------------|-------------------|------------------------|
| 10               | 2.0                    | 1500                 | 0.0027            | 0.012                  |
| 20               | 1.5                    | 2000                 | 0.0055            | 0.040                  |
| 20               | 2.5                    | 2000                 | 0.0042            | 0.027                  |
| 20               | 2.5                    | 1000                 | 0.0032            | 0.017                  |
| 20               | 1.5                    | 1000                 | 0.0044            | 0.029                  |
| 30               | 2.0                    | 1500                 | 0.0058            | 0.043                  |
| 30               | 3.0                    | 1500                 | 0.0035            | 0.020                  |
| 30               | 2.0                    | 1500                 | 0.0058            | 0.043                  |
| 30               | 2.0                    | 1500                 | 0.0058            | 0.040                  |
| 30               | 2.0                    | 500                  | 0.0048            | 0.033                  |
| 30               | 2.0                    | 1500                 | 0.0067            | 0.048                  |
| 30               | 2.0                    | 2500                 | 0.0057            | 0.042                  |
| 30               | 1.0                    | 1500                 | 0.0082            | 0.059                  |
| 30               | 2.0                    | 1500                 | 0.0044            | 0.029                  |
| 40               | 2.5                    | 2000                 | 0.0073            | 0.052                  |
| 40               | 2.5                    | 1000                 | 0.0060            | 0.044                  |
| 40               | 1.5                    | 2000                 | 0.0074            | 0.054                  |
| 40               | 1.5                    | 1000                 | 0.0070            | 0.051                  |
| 50               | 2.0                    | 1500                 | 0.0089            | 0.062                  |
Table 3. ANOVA results of wear rate of LM25/WC FG composite.

| Source     | DF | Adj SS  | Adj MS  | F-Value | P-Value |
|------------|----|---------|---------|---------|---------|
| Model      | 9  | 0.003215| 0.000357| 10.04   | 0.001   |
| Linear     | 3  | 0.000147| 0.000049| 1.37    | 0.307   |
| L          | 1  | 0.000030| 0.000030| 0.86    | 0.377   |
| V          | 1  | 0.000039| 0.000039| 1.08    | 0.323   |
| D          | 1  | 0.000016| 0.000016| 0.44    | 0.523   |
| Square     | 3  | 0.000019| 0.000006| 0.18    | 0.909   |
| L*L        | 1  | 0.000013| 0.000013| 0.37    | 0.555   |
| V*V        | 1  | 0.000000| 0.000000| 0.01    | 0.933   |
| D*D        | 1  | 0.000009| 0.000009| 0.26    | 0.624   |
| 2-Way Interaction | 3 | 0.000047| 0.000016| 0.44    | 0.732   |
| L*V        | 1  | 0.000032| 0.000032| 0.90    | 0.365   |
| L*D        | 1  | 0.000012| 0.000012| 0.35    | 0.567   |
| V*D        | 1  | 0.000002| 0.000002| 0.06    | 0.817   |
| Error      | 10 | 0.000356| 0.000036|         |         |
| Lack-of-Fit| 5  | 0.000149| 0.000030| 0.72    | 0.636   |
| Pure Error | 5  | 0.000207| 0.000041|         |         |
| Total      | 19 | 0.003571|         |         |         |
| Model      | 9  | 0.003215| 0.000357| 10.04   | 0.001   |

Table 4. ANOVA results of CF of LM25/WC FG composite.

| Source     | DF | Adj SS  | Adj MS  | F-Value | P-Value |
|------------|----|---------|---------|---------|---------|
| Model      | 9  | 0.003215| 0.000357| 10.04   | 0.001   |
| Linear     | 3  | 0.000147| 0.000049| 1.37    | 0.307   |
| L          | 1  | 0.000030| 0.000030| 0.86    | 0.377   |
| V          | 1  | 0.000039| 0.000039| 1.08    | 0.323   |
| D          | 1  | 0.000016| 0.000016| 0.44    | 0.523   |
| Square     | 3  | 0.000019| 0.000006| 0.18    | 0.909   |
| L*L        | 1  | 0.000013| 0.000013| 0.37    | 0.555   |
| V*V        | 1  | 0.000000| 0.000000| 0.01    | 0.933   |
| D*D        | 1  | 0.000009| 0.000009| 0.26    | 0.624   |
| 2-Way Interaction | 3 | 0.000047| 0.000016| 0.44    | 0.732   |
| L*V        | 1  | 0.000032| 0.000032| 0.90    | 0.365   |
| L*D        | 1  | 0.000012| 0.000012| 0.35    | 0.567   |
| V*D        | 1  | 0.000002| 0.000002| 0.06    | 0.817   |
| Error      | 10 | 0.000356| 0.000036|         |         |
| Lack-of-Fit| 5  | 0.000149| 0.000030| 0.72    | 0.636   |
| Pure Error | 5  | 0.000207| 0.000041|         |         |
| Total      | 19 | 0.003571|         |         |         |
| Model      | 9  | 0.003215| 0.000357| 10.04   | 0.001   |
Figure 3. RSM plot of (a) wear rate (b) co-efficient of friction vs load, velocity at a constant sliding distance of 1500m

Figure 4. RSM plot of (a) wear rate (b) co-efficient of friction vs velocity, distance at a constant applied load of 30 N

Figure 5. RSM plot of (a) wear rate (b) co-efficient of friction vs load , distance at a constant sliding velocity (V) of 1500m

Tables 5 and 6 provides the coded co-efficient for the model generated for wear rate (WR) and co-efficient of friction (CF) respectively.
The $R^2$ and $R^2$ (adjusted) values for WR as obtained from the analytical experiment are 89.31% and 79.69% respectively while for co-efficient of friction, the $R^2$ and $R^2$ (adjusted) values are 90.04% and 81.07% respectively, which are close to each other. This concludes that the regression model developed successfully predicts the relationship between the responses (wear rate characteristics and co-efficient of friction) and the process parameters generated (applied load, sliding velocity and sliding distance). The generated regression equations for dry sliding wear rate (WR) and co-efficient of friction (CF) is denoted as equation 2 and equation 3 respectively.

\[
WR = 0.00648 + 0.000068L - 0.00398V + 0.000001D + 0.000177V^2 + 0.000035LV
\]

(2)

\[
CF = 0.0288 + 0.00119L - 0.0274V + 0.000017D - 0.000007L^2 - 0.000041V^2 + 0.000040L^2 + 0.000002V^2D
\]

(3)

4. Discussion

Analysing the effect of applied load, it is observed from figures 3 and 5 that WR and CF increases with increasing load which is supported by the positive regression coefficient observed for applied load in both regression equations (1) and (2). At low load condition, i.e. 10 N, low WR is observed owing to the mild wear mechanism. Here, the hard reinforcement particle remains intact as low contact stresses are generated between the pin and the counter face, and act as load bearing elements. With increasing applied load, the contact stresses build up at the interface, exceeding the fracture strength of the reinforcement particle, leading to its fracture. These particles act as minute agents degrading the surface
of the soft aluminium matrix, increasing the material removal in the form of wear debris. Simultaneously, as there’s a temperature rise at the interface, an oxide layer called Mechanically Mixed Layer (MML) is formed which is unstable under high loads due to the inability of the fractured reinforcement particles. Hence, these layers are easily removed. Also, the sharp asperities present plough into the pin at heavy loads, thus removing material in the form of fragments. Hence, increased WR and CF is observed at high loads i.e. 50 N. Similar wear characteristics were observed on analysis of stir-cast and functionally graded aluminium composites, highlighting applied load to be an important factor affecting the wear rate and frictional co-efficient [19-21].

Analysing the worn surface morphological images obtained at low load (10 N) and high load (50 N) conditions at constant velocity and distance of 1.5 m/s and 1500 m respectively, it is observed that shallow grooves and fine scratches are predominantly present on the pin surface at low load (Fig 6a), owing to the abrasive action of WC particles acting as load bearers. This resulted in minimal wear at low load applications. At high load i.e. 50 N (Figure 6b), it is observed that heavy delamination accompanied by continuous grooves are present on the pin surface, due to the high temperature and increased contact stresses forcing material removal from the pin surface. Due to this, an increase in the cutting and ploughing action is the primary wear mechanism, which leads to high wear rate [22].

Figure 6. Worn Surface at different loads (a) L=10N, V=2m/s, D=1500m (b) L=50N, V=2m/s, D=1500 m.

Analysing the effect of sliding velocity, it is observed from figures 4 and 5 that WR and CF decreased with increasing sliding velocity. Also, the negative coefficients associated with sliding velocity in equations (1) and (2) denote that WR and CF decrease as sliding velocity increases, which is in accordance with another study which focussed on aluminium A356 MMC reinforced with silicon carbide (SiC) particle [23]. It should be noted that as sliding velocity increases, temperature increases at the interface between pin and the counter face which simultaneously increases the rate of aluminium alloy oxidation which aids in the tribolayer formation i.e. MML [24]. This layer contains various metal oxides of aluminium, iron etc. along with fractured particles which behave as solid lubricant, thus reducing the material removal rate and co-efficient of friction. Hence at high velocities, a transition from abrasive wear mode to oxidative wear mode is observed [25].

Analysing the worn surface morphological images obtained at low velocity (1 m/s) and high velocity (3 m/s) conditions at a constant applied load of 20N and sliding distance of 1000 m, it is observed that at low velocity conditions i.e. 1 m/s (Figure 7a), heavy delamination is observed characterized by the heavy removal of pin material due to the increased duration of contact between the sliding pin and the disk counter face, which results in high wear rate. At high sliding velocity i.e. 3 m/s (Figure 7b), the formation of MML is observed due to the increased oxide layer formation. High velocity application increases the temperature at the interface which plastically softens the specimen and thereby increases the oxide layer formation rate, which then acts as a lubricant layer over the surface, thus reducing the WR [25].
Analysing the effect of sliding distance on the WR and CF, it is observed from equations (1) and (2) that the regression co-efficient associated with sliding distance is positive, which infers that as sliding distance increases, an increase in WR and CF is observed, which aids in increased material loss. Initially, the pin surface containing sharp asperities is in contact with the counterface, thus abrasive mode of wear is observed [26]. With increasing sliding distance, more and more reinforcement particles are exposed, which leads to the particle fracture which entraps itself between the pin and sliding counter face. These behave as sharp asperities and aids in material removal from the plastically deformed aluminium matrix surface, enhancing the wear loss. As sliding distance increases, this leads to increased duration of contact between the asperity and the pin, thus leading to continuous material removal as wear debris and thus the trend observed [27, 28].

Analysing the worn surface morphological images obtained at low sliding distance (500 m) and high sliding distance (2500 m) conditions at a constant applied load of 40 N and sliding velocity of 1 m/s, it is observed that at low sliding distance conditions i.e. 500 m (Figure 8a), small fissures, grooves and slight delamination are present on the pin surface, which is mainly due to the reinforcement particles acting as load bearing elements, withstanding the heavy deformation forces. Hence the minimum wear rate at low sliding distances. At high sliding distance i.e. 2500 m (Figure 8b), heavy material removal is observed as heavy delamination and particle pull-out on the pin surface. This can be attributed to the rise in magnitude of contact forces and contact time.

The regression model generated is validated using confirmation experiments, where the generated regression co-efficients are checked using new process parameter combination selected from the range of experimental values which vary from the CCD generated parametric values. The model results obtained are then compared to the experimental values generated for the parameter combination. The
The error percentage is calculated by comparing the experimental wear rate to the regression model wear rate, and as all error percentage values are less than 5%, it can be concluded that the regression model generated for mathematically predicting the dry sliding wear rate and co-efficient of friction for the fabricated composite, exhibited high accuracy. It should also be noted that model generated displayed high accuracy for the range of parameters selected for the particular study as well as the range of wear rate and friction co-efficient values. Therefore, the generated model can be considered highly efficient within this range and will retain its high accuracy when large range of parameters are considered.

RSM optimization technique identifies the optimum process parameter combination at which minimum WR and CF is achieved. This is done by analysing the relationship between the process conditions i.e. applied load, sliding velocity, sliding distance and the response i.e. dry sliding wear rate, co-efficient of friction. The optimization is done by focussing on minimizing the response, by setting a target and upper bound as inputs. Here the target for wear rate is set as 0.0027 mm$^3$/m while upper bound is set as 0.0089 mm$^3$/m. For co-efficient of friction, 0.012 and 0.062 are set as target and upper bound respectively. On analysis, the optimum parameter combination is set as applied load of 10 N, sliding velocity of 3 m/s and sliding distance of 500 m, as observed in figure 9.

![Optimum Parameters for Minimal WR and CF](image)
5. Conclusion

Functionally graded aluminium LM25/15 wt.% WC composite was successfully fabricated through centrifugal casting and the dry sliding characteristics and frictional co-efficient was studied. Statistical analysis was performed using RSM and the developed regression model was found to behave exceptionally in predicting the dry sliding wear behaviour and friction co-efficient of the composite with high accuracy. Validation experiments revealed the developed model to be highly accurate with low error percentage. The surface plots revealed increasing WR and CF as applied load and sliding distance increases, decreasing as sliding velocity increases. Optimal conditions for obtaining minimal wear rate and co-efficient of friction were applied load of 10 N, sliding velocity of 3 m/s and sliding distance of 500 m. Worn surface analysis performed on pin surface revealed formation of deep grooves at high load suggesting a transition from mild to severe wear, formation of MML at high velocities which implied the transition of wear from abrasive wear to oxidative wear and heavy delamination and particle pull-out at high sliding distances, due to heavy plastic deformation. The composite having high wear resistance and low co-efficient of friction values can be employed as a material to fabricate automotive parts like piston rings, bearings and liners where these properties can be utilized to a great effect.

6. References

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