Wear behaviour of aluminium alloy 5083/SiC/fly ash inoculants based functional composites – optimization studies

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Keywords: Fly Ash, SiC, inoculation, AA5083, wear rate, ANOVA

Abstract
The wear characteristics of Aluminium AA 5083/SiC/Fly Ash functional composites under different load conditions are an important aspect to assess the inoculation of Fly Ash for enhancing the functionality of the aluminium composites with respect to its tribological behaviour and its influence on wear properties. The present work is majorly aimed at the development of AA 5083/SiC functional composites inoculated with Fly Ash using stir casting method for different blends of the reinforcements (2.5, 5 & 7.5 wt%). The novelty of this research is majorly attributed to the incorporation of functional inoculants in the form of Fly Ash, which along with the SiC is bound to influence the tribological characteristics of the composites. The wear characteristics of these fabricated composites have been investigated considering various process parameters viz., the load, sliding distance, sliding velocity, wt% of SiC and wt% of Fly Ash, based on the operational requirements of the composites in real time considered from the earlier research studies and the influence of each parameter on the wear rate is discussed. Based on the different wear regimes obtained after characterization of the samples at different load conditions, Analysis of Variance (ANOVA) is carried out for each blend of the samples to statistically validate the experimental outcomes. The results have given sufficient substantiation to the fact that wear rate decreases with the inoculation. The wear rate and coefficient of friction (COF) is minimum viz., 0.00095 mm³/m, and 0.301 respectively for L9 experimental trial, i.e., for the composite specimens synthesized by reinforcing 7.5 wt% SiC, and 7.5 wt% Fly Ash for a load of 20 N, sliding velocity of 6 m s⁻¹, and a sliding distance of 3000 m. The results have conferred that micro segregation (coring) of SiC and uniform dispersion of Fly Ash in the matrix enhances its tribological characteristics.

1. Introduction

The composites reinforced with inoculants have wide potential for use in wear resistant applications and the requirement of functional composites has led to the development of various process methodologies to engineer them for wide potentialities [1]. With the development of lightweight materials with high specific strength and rigidity, a wide range of metal matrix composites (MMCs) have been developed as alternatives to conventional engineering alloys and research on ceramic reinforced MMCs have increased significantly. While composites exhibit superior properties in comparison with the base metals, the high strength to low weight ratio make them
ideal futuristic materials for a variety of applications in automotive, construction, electronic packaging, aerospace, and critical defence oriented areas [2]. Particle reinforced MMCs are of particular interest because they are easy to manufacture, economical, and highly isotropic. The size and volume fraction of the strengthening phase and the properties of the matrix strengthening interface control the properties of these composites in practice. Also, thermally stable ceramic particles dispersed in a metal matrix tend to provide an optimal set of mechanical properties. Majority of the research on MMC is pointed on Al based composites to improve mechanical properties by incorporating hard ceramic particles into the metal matrix. However, the use of carbides in the Al metal matrix have resulted in agglomeration of Al-C compounds as Al reacted with carbides above 720 °C. Hence, there is a need for inoculants which avoids the agglomeration and enhance their strength. Further, it is noticed that the Al–SiC composites have embrittlement concerns and have serious corrosion problems. To overcome these shortcomings, several other reinforcements that do not react with Al have been studied, among which Fly Ash has high lubricity, excellent stability at high temperatures, excellent electrical and optical characteristics [3, 4]. To date, Fly Ash has been most commonly used as the enhanced Nano phase in the metal matrix. Most of the MMCs are manufactured by conventional stir casting technique, however the vacuum environment during the process reduces the entrapment of gases and the inclusion of inoculants result in strong bonding [5]. Fly Ash is one such inoculant and the reinforcement-metal mixture must be vigorously stirred during the first mixing step. Various stirrer designs have been considered by researchers to achieve sufficient densification. Kanth et al [6] investigated Al-Zn/Fly Ash/SiC based composites, which were fabricated by vortex method using stir casting procedure. Their studies revealed that incorporation of Fly Ash particles enhanced the hardness and the addition of SiC particles in the matrix enhanced the ultimate tensile and yield strengths of the composites. Rajesh et al [7] studied the behaviour of Al 7075/Fly Ash/SiC composite using stir casting technique. The inclusion of Fly Ash enhanced the hardness of the composites and improved the tensile characteristics, such as ultimate and yield tensile strength, through the incorporation of SiC grains. Devaraju et al [8] prepared metal matrix composites with Cu (95%) + SiC (5%) and Cu (90%) + SiC (5%) + Fly Ash (5%) combinations using powder metallurgy route. Investigators have ensured the uniform distribution of reinforcement particulates in the copper matrix phase, and enhancement in their properties owing to the addition of Fly Ash particles as inoculants. Naher et al [9] have reported the influence of the stir casting process parameters on the fabrication of Al–SiC composites. They have stir cast the composites at varying stirring speed ranging from 200 to 500 rpm for different time duration. The castings obtained have shown a uniform distribution of the reinforcements in the matrix phase due to the homogenization brought about by the stirring action in the molten metal. In the past, researchers have concentrated on the optimization of the process parameters influencing wear rate with respect to various MMCs, and have considered the composition of reinforcements and the stirring speed as the critical issue for the enhancement of the properties [10–12]. Prasath et al [13] studied the wear properties of AA6061–SiC–B4C–Fly Ash composites fabricated by stir casting. The levels of experimental factors like load, sliding speed and sliding distance are sequenced and designed by response surface methodology. The increase in the SiC and B4C content up to certain range reduces the wear loss, it’s about 28.03% at optimum operating conditions and it falls with further increase in the reinforcement’s content beyond threshold limit. Ajay Prakash Pasupulla et al [14] prepared metal matrix composites of AA 5083/SiC/Fly Ash with varying proportion of reinforcements. Wear characteristics of prepared composites were evaluated for different process parameters (sliding velocity, load, and wt% of SiC–Fly Ash powders). The results revealed that sliding velocity and wt% reinforcements incrementally reduce the wear rate of the composites and the results were validated with the statistical analysis. Khan et al [15] studied the erosive wear response of ADC 12/10 wt% SiC and ADC 12/Fly Ash fabricated through liquid metallurgy route. Erosion wear was conducted by varying the sand concentration of slurry (0%–60%) keeping the rotational speed constant. In comparison with the ADC12-Fly Ash composite, ADC12–SiC composite exhibited better wear resistance in both the media irrespective of the sand content. Both the combination of the composites have exhibited better wear resistance than the matrix alloy in the mining environment. Rana et al [16] have carried out extensive work on the friction properties of Al–SiC composites and have reported that the ceramic reinforcements have significant influence on the wear of the composites owing to the hardness imparted by the strong coherent bonding actuated by the ceramic particles. Shyam Lal et al [17] have fabricated and characterized hybrid metal matrix composites (Al-2014/SiC/Fly Ash). The results revealed a fairly uniform distribution of reinforcement particulates in the matrix material. The hybrid MMC exhibited an improvement in the tensile strength by 31% and an improvement in the hardness by 32%. The impact strength being 30.5% and 58.12% higher in comparison to it’s as cast and as heat treated conditions. Sachinkumar et al [18] stated that the inclusion of Fly Ash particles in to the matrix enhanced the micro hardness and ultimate tensile strength of the composites, owing to inoculation and formation of ceramic surface layer on the composite specimen leading to the enhanced wear resistance. The need for optimizing the experimental factors for wear tests have triggered the interests of several researchers and hence optimization studies are conducted by using various optimization models and statistical methods, which are considered for baseline models [19, 20]. However, the information on the
statistical analysis of wear studies for functional composites incorporating Fly Ash inoculants is still in its incipient stage and has necessitated the need for further studies aimed at optimizing the process parameters. In this view, the purpose of this study is to investigate the wear behaviour of AA 5083/SiC/Fly Ash composites and infer the influence of Fly Ash inoculants on the composites.

The outcomes of the present research are found to suffice the requirements of developing a high performance hybrid aluminium composite, which can offer higher wear resistance and provide better performance capabilities. The research framework adopted in the present work based on the detailed review of the literature and the scientific study of the identified problem possess inherent novelties as follows.

- The inclusion of Fly Ash inoculants for bringing homogeneity in the distribution of the reinforcements in the matrix is a novel approach.
- The methodology adopted is a novel study encompassing the use of vacuum assisted stir casting to avoid the entrapment of oxygen.
- The use of statistical approach to validate the results and the Taguchi’s optimization technique adopted for optimizing the factors of wear test is unique. Also the Analysis of Variance (ANOVA) and regression analysis carried out to develop a statistical model to predict the wear rate and coefficient of friction is a novel methodology for optimization studies aimed at minimizing the effects of wear on the composite developed.

### 2. Materials and methodology

#### 2.1. Materials

Aluminium alloy AA 5083 is chosen as matrix, received from S. P. Metals Inc., Bengaluru, India, it exhibits better strength, corrosion resistance and good castability. These alloys can be effectively utilized for stir casting with Fly Ash and SiC reinforcements. Particulates of SiC of size 45 to 70 μ, procured from 3M India Ltd, Bengaluru and C-type Fly Ash of size 40 to 105 μ were used. The mixing proportions of the reinforcements with matrix were decided based on the available literature; it is described in the table 1.

#### 2.2. Composites fabrication

Composites were fabricated by stir casting method. It consists of three processes namely; melting, stirring and casting, and the entire process was carried out in inert atmosphere in accordance with the procedures [21]. The reinforcements of SiC and Fly Ash flakes are preheated to 150 °C, and the die sets are preheated to 150 °C in a hot air oven (Make: Biooction India Ltd). The matrix material (AA 5083) billets are cut into pieces and charged into the stir casting setup. The billet pieces are melted at a temperature of 670 °C, until it reaches the liquid slurry state, subsequently followed by degassing by Nitrals tablets and sonication process. The weighed set of preheated reinforcements along with 1g of Mg is wrapped in an aluminium foil and plunged into the molten metal in an inert (argon) atmosphere and stirred at a speed of 600 rpm for duration of 10 min using a paddle type mild steel stirrer. The stirred mixture is then superheated to 740 °C and the stir casting chamber is evacuated to remove the entrapped gases by a vacuum pump. The molten metal with the dispersions is then poured into the die sets through the bottom pouring arrangement, and allowed to solidify in an inert environment to obtain the composite castings. The schematic outlay of the stir casting procedures followed in the present work is given in figure 1. Figure 2 shows the stir casting apparatus & its specifications.

#### 2.3. Wear characterization

Wear test is carried out on a calibrated Pin on Disc wear testing machine (make: Ducom Instruments Pvt. Ltd model: ED 201) for different load and speed conditions, in accordance with ASTM G99 Standards. The Pin on Disc wear test apparatus and specimen details are shown in figure 3. Table 2 describes the wear parameters and their levels defined in the study.

| Table 1. Composition of the composites prepared. |
|-----------------------------------------------|
| Composite | SiC (wt%) | Fly Ash (wt%) | Al |
| AS2.5F2.5 | 2.5       | 2.5            | remaining |
| AS5F5     | 5         | 5              | remaining |
| AS7.5F7.5 | 7.5       | 7.5            | remaining |
The wear parameters viz., the load, sliding distance, and sliding velocity are considered based on the research works of Ravichandran et al. They have reported that the composites can be used in real time conditions, provided the wear rate of the composites are minimized for varying loads, sliding distances, and sliding velocities by effectively reinforcing the composites with suitable reinforcements and filler materials.

In the dry sliding wear test, the wear loss and the friction force are noted and the wear rate, Coefficient of Friction (COF) are calculated using the equations (1) and (2), while the morphology of wear track and wear debris are studied from the micrographs using scanning electron microscope (make: JEOL JSM, model: 6490 LV).

\[
\text{Wear Rate} = \frac{\text{Wear Volume Loss (V_{loss}) in mm}^3}{\text{Sliding Distance in m}}
\]  

(1)
Where, wear volume loss is given by

\[ V_{\text{Loss}} = \frac{\pi \times d^2}{4} \times \text{Wear loss in mm} \]

Similarly the Coefficient of Friction, COF (\(\mu\)) is given by [12]

\[ \text{COF} (\mu) = \frac{F}{N} \]  \hspace{1cm} (2)

Where, F is the Frictional force N is the Normal force.

### 2.4. Statistical analysis

Statistical analysis of the wear samples is carried out in conjunction with values obtained in each trial to statistically validate the data obtained. Statistical analysis is done for Analysis of Variance, normality and 'P'
value in Minitab software. Initially Gage R & R analysis is done in order to determine the repeatability and reproducibility among the values obtained. The process parameters selected for optimization of the wear are shown in Table 3.

The experiments are developed based on L27 orthogonal array as shown in Table 4. These factors are distinct and intrinsic feature of the wear process that influence and determine the performance of composites.

Taguchi’s factorial design majorly recommends analyzing the S/N ratio and obtaining a response table that help identify the critical factors which have its implications on the wear behaviour of the composite materials developed.

### 3. Results and discussion

From a tribological perspective, wear rate and friction factors are complex parameters resulting in gradual loss of one or both materials. Wear rate and friction factors are functional variables that play a pivotal role in determining the loss of material due to wear and tear under different operating loads. The wear results at three different loads, speed and sliding distance for different samples obtained by varying blended composition of Fly Ash and SiC are discussed in this section.
3.1 Wear characteristics

3.1.1 Wear rate

Wear rate was evaluated from the volume loss considering various process parameters such as normal load (19.62, 39.24, 58.86 N), sliding distance (1000 m, 2000 m and 3000 m) and sliding velocity (2, 4 and 6 m s$^{-1}$) and are statistically validated in Minitab software using Taguchi and ANOVA techniques. Table 5 describes the actual and predicted wear rate for all experimental trials. Figure 4 shows the calculated wear rate for L27 trials.

The outcomes of the experiment depicts a decrease in the wear with the increase in the wt% of reinforcements. This anti-wear mechanism is majorly attributed to the formation of the hard ceramic surface on the composite due to the formation of strong bonds between Al and SiO$_2$ and SiC compounds as observed by Santhosh et al [23] in their research work on the influence of Fly Ash inoculants and heat treatment on the characteristics of the Aluminium/SiCp/Fly Ash composites. Tables 6 and 7 presents response table for signal to noise ratio and means respectively.

Figure 5 gives the main effects plot for SN ratios, while the figure 6 gives the main effects plot for Means. The main effects plot for SN ratios and the means clearly indicate that the control factors can be optimally discerned with the level 3 of load (A3), level 1 of sliding velocity (B1), level 2 of sliding distance (C2), level 2 of wt% of SiC (D2), Level 1 of wt% of Fly Ash (E1). Thus, the S/N ratio analysis suggests that the A3, B1, C2, D2 and E1 are the optimum levels for minimum wear rate for AA 5083/SiCp/Fly Ash composites.

Analysis of Variance (ANOVA) is carried out to determine the impact of control factors on the output characteristics. Table 8 depicts the % contribution of each factor on the total variance, along with the degrees of freedom (DF), adjusted sum of squares (SS), adjusted mean squares (MS) values, F significance, and P values. From table 8, it is evident that the load is having major contribution for optimization of output characteristics with 58.33%, while the speed is the second major contributor on the output with 16.67% contribution, followed by wt% of Fly Ash with 12.5% contribution, sliding distance with 4.166% contribution, and wt% of SiC with 4.166% contribution on the total variance. These data suggest that the load and speed have a high significance on the variance, followed by wt% of Fly Ash, sliding distance and wt% of SiC. The regression table suggests that the R-sq. value is more than 90% and the regression equation yields predicted wear rate that is within $+/- 10\%$ band, except for L9 experimental trial with an erratic deviation of 24.516%. Table 9 represents regression table.

Table 5. Actual and predicted wear rate for different experimental trials.

| Trial no. | Wear loss in mm | Actual wear rate $(mm^3 m^{-1})$ | Predicted wear rate $(mm^3 m^{-1})$ | % Error |
|-----------|-----------------|---------------------------------|-----------------------------------|---------|
| L1        | 0.0365          | 0.00284                         | 0.00313                           | 10.275  |
| L2        | 0.0341          | 0.00272                         | 0.00265                           | 2.507   |
| L3        | 0.0493          | 0.00248                         | 0.00226                           | 9.008   |
| L4        | 0.1190          | 0.00299                         | 0.00297                           | 0.649   |
| L5        | 0.1018          | 0.00256                         | 0.00249                           | 2.711   |
| L6        | 0.0800          | 0.00201                         | 0.00210                           | 4.249   |
| L7        | 0.1289          | 0.00216                         | 0.00206                           | 4.722   |
| L8        | 0.1020          | 0.00171                         | 0.00158                           | 7.713   |
| L9        | 0.0567          | 0.00095                         | 0.00118                           | 24.516  |
| L10       | 0.1949          | 0.0049                          | 0.00465                           | 5.147   |
| L11       | 0.1591          | 0.04                             | 0.00417                           | 4.198   |
| L12       | 0.1468          | 0.00369                         | 0.00377                           | 2.241   |
| L13       | 0.1904          | 0.00319                         | 0.00337                           | 5.677   |
| L14       | 0.1748          | 0.00293                         | 0.00289                           | 1.328   |
| L15       | 0.1569          | 0.00263                         | 0.00250                           | 5.099   |
| L16       | 0.0660          | 0.00332                         | 0.00342                           | 3.123   |
| L17       | 0.0593          | 0.00298                         | 0.00294                           | 1.218   |
| L18       | 0.0519          | 0.00261                         | 0.00255                           | 2.356   |
| L19       | 0.0307          | 0.00516                         | 0.00486                           | 5.723   |
| L20       | 0.2447          | 0.0041                          | 0.00438                           | 6.946   |
| L21       | 0.2375          | 0.00398                         | 0.00399                           | 0.239   |
| L22       | 0.0861          | 0.00433                         | 0.00431                           | 0.436   |
| L23       | 0.0784          | 0.00394                         | 0.00385                           | 2.764   |
| L24       | 0.0658          | 0.00331                         | 0.00344                           | 3.804   |
| L25       | 0.1667          | 0.00419                         | 0.00430                           | 2.589   |
| L26       | 0.1516          | 0.00381                         | 0.00382                           | 0.226   |
| L27       | 0.1412          | 0.00355                         | 0.00342                           | 3.566   |
The residual plot for wear rate is depicted in figure 7. The normal probability plot is more or less a straight line, since the residuals have a normal distribution. This is also ascertained by the plot of residuals versus the fitted values. The histogram of the residuals is more or less a bell-shaped curve with a slight skew towards the negative residual. Further, the residual versus observation order predicts if the data is in order of collection, with

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\[ \text{Wear rate (mm}^3\text{/m)} = 0.003401 + 0.000044 \times \text{Load (kN)} - 0.000239 \times \text{Sliding Velocity (m/s)} - 0.000001 \times \text{Sliding Distance (m)} + 0.000014 \times \text{wt\% of SiC} - 0.000175 \times \text{wt\% of FA} \]  

Figure 4. Experimental wear rate for defined trials.

Table 6. Response table for signal to noise ratios for wear rate (mm\(^3\)/m\(^{-1}\)) smaller is better.

| Level | Load (kN) | Sliding velocity (m s\(^{-1}\)) | Sliding distance (m) | SiC (wt\%) | FA (wt\%) |
|-------|-----------|---------------------------------|----------------------|------------|-----------|
| 1     | 53.30     | 48.74                           | 50.12                | 50.16      | 49.00     |
| 2     | 49.64     | 50.38                           | 49.34                | 49.95      | 50.20     |
| 3     | 47.94     | 51.76                           | 51.42                | 50.76      | 51.67     |
| Delta | 5.37      | 3.01                            | 2.08                 | 0.82       | 2.67      |
| Rank  | 1         | 2                               | 4                    | 5          | 3         |

Table 7. Response table for means for wear rate (mm\(^3\)/m\(^{-1}\)).

| Level | Load (kN) | Sliding velocity (m s\(^{-1}\)) | Sliding distance (m) | SiC (wt\%) | FA (wt\%) |
|-------|-----------|---------------------------------|----------------------|------------|-----------|
| 1     | 0.002268  | 0.003763                        | 0.003170             | 0.003149   | 0.003675  |
| 2     | 0.003362  | 0.003099                        | 0.003521             | 0.003301   | 0.003195  |
| 3     | 0.004040  | 0.002808                        | 0.002980             | 0.003221   | 0.002800  |
| Delta | 0.001771  | 0.000955                        | 0.000541             | 0.000153   | 0.000875  |
| Rank  | 1         | 2                               | 4                    | 5          | 3         |
Figure 5. Main effects plot for SN ratios for wear rate.

Figure 6. Main effects plot for mean of means for wear rate.

Table 8. ANOVA table for wear rate (mm$^3$ m$^{-1}$).

| Source            | DF  | Adj SS       | Adj MS       | F-Value  | P-Value | % Contribution |
|-------------------|-----|--------------|--------------|----------|---------|----------------|
| Load (kN)         | 2   | 0.000014     | 0.000007     | 184.65   | 0.000   | 58.33          |
| Speed (m/s)$^{-1}$| 2   | 0.000004     | 0.000002     | 55.35    | 0.000   | 16.67          |
| Sliding Distance (m) | 2   | 0.000001     | 0.0000005    | 17.40    | 0.000   | 4.1667         |
| Wt% of SiC        | 2   | 0.000001     | 0.0000005    | 1.35     | 0.288   | 4.1667         |
| Wt% of FA         | 2   | 0.000003     | 0.000002     | 44.40    | 0.000   | 12.5           |
| Error             | 16  | 0.000001     | 0.000000     | 4.1666   | 0.000   | 12.5           |
| Total             | 26  | 0.000024     |              | 100      |         | 100            |
the plots of residuals versus the order of the data ascertaining the fact that residual versus order is in line with the trend of observation order.

Figures 8 and 9 depicts the contour and 3D surface plots for wear rate (mm$^3$ m$^{-1}$) for varying wt% of Fly Ash and SiC in the Aluminium composites. It is herewith evident from the plots that, the wear rate decreases with the increase in the wt% of the SiC and Fly Ash reinforcements. This is majorly due to the micro-coring and segregation that will enhance the bonding between the matrix and reinforcements and improve the wear resistance of the composites.

3.1.2. Coefficient of friction (COF)
The Coefficient of Friction (COF) is a major attribute depicting the ratio of the Frictional Force (F) and Normal Force (N). The response table for SN ratios and means for COF are evaluated and results revealed that the load is having a major influence on the COF, then subsequently followed by the sliding velocity, wt% of Fly Ash, sliding distance and wt% of SiC. Further, the response table for means gives an overview of the means for the combination of the control factors influencing the co-efficient of friction. Figure 10 shows the variation of COF for all trials. Table 10 shows COF for different experiments trials.

Figures 11 and 12 shows the main effects plot for SN ratios and Means for COF respectively. The main effects plot for SN ratios clearly indicate that the control factors can be optimally discerned with the level 3 of load (A3), level 1 of sliding velocity (B1), level 3 of sliding distance (C3), level 2 of wt% of SiC (D2), Level 1 of wt% of Fly Ash (E1). Thus, the S/N ratio analysis suggests that the A3, B1, C3, D2 and E1 are the optimum levels for minimum COF for the AA 5083/SiCp/Fly Ash composites. Tables 11 and 12 presents the response table for signal to noise ratio and means of COF.

Table 13 depicts the % contribution of each factor on the total variance, along with the degrees of freedom (DF), adjusted sum of squares (SS), adjusted mean squares (MS) values, F significance, and P values. It is confirmed that the load is major contributing parameter for optimization of COF with 56.07%, while the sliding velocity is the second major contributor on the output with 26.95% contribution, followed by wt% of Fly Ash.
with 11.84% contribution, sliding distance with 1.18% contribution and wt% of SiC with 0.76% contribution on the total variance of COF. These data suggest that the load and sliding velocity have a high significance on the variance of COF, followed by wt% of Fly Ash, sliding distance and wt% of SiC. The regression table suggests that the R-sq. value is more than 88% and the regression equation yields predicted wear rate that is within $\pm 6\%$ band. Table 14 Regression table for COF.

The residual plot for wear rate is depicted in figure 13. The normal probability plot is more or less a straight line, since the residuals have a normal distribution. This is also ascertained by the plot of residuals versus the fitted values. The histogram of the residuals is more or less a bell-shaped curve with a slight skew towards the right side (positive residual). Further, the residual versus observation order predicts if the data is in order of collection, with the plots of residuals versus the order of the data ascertaining the fact that residual versus order is in line with the trend of observation order.

The surface plot (figure 14) and 3D contour plot (figure 15) demonstrates that there is a drastic decrease in COF with increase in the percentage of Fly Ash, since the addition of Fly Ash will result in intricate entanglement and agglomeration leading to morphological changes that result in increased wear resistance and offers opposition to ploughing of the specimens by hardened steel disc. Wear rate and the friction factors for various specimens decreases with increase in Fly Ash attributing to the fact of micro coring or segregation that has taken place leading to increased hardness with precipitation of dendrite growth x-ray recurring all along the periphery of the reinforcement in the specimen. Similar work reported by Joakim Schon [24], revealed that the COF decreases with the increase in the carbon fibre, which brings about inoculation in the composite and thereby enhances the wear resistance and reduces the friction due to the sliding contact between the two surfaces.

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\[
\text{COF} = 0.3403 + 0.001239 \times \text{load (kN)}
- 0.00889 \times \text{Sliding velocity (m/s)}
+ 0.000002 \times \text{Sliding Distance (m)}
+ 0.00087 \times \text{wt% of SiC}
- 0.00480 \times \text{wt% of FA}
\] (4)
Figure 9. 3D Surface plots for wear rate (mm$^3$ m$^{-1}$).

Figure 10. COF for defined trial runs.
3.2. Worn out surface morphology

Figure 16(a) shows the worn surface of the Aluminium matrix reinforced with 2.5% SiC and 2.5% Fly Ash, exhibits the presence of deep permanent grooves and fracture of the oxide layer, which may have caused the increase of wear loss. However, the worn surfaces exhibit finer grooves and slight plastic deformation at the edges of the grooves. The surface also appears to be smooth because of the Fly Ash reinforcement content. The formation of friction film on the surface, even though not very distinctive, also it can be noted that flaking phenomena is observed in the middle of the worn surface. Figure 16(b) depicts the SEM image of the worn surface of AS5F5 specimen, shows the formation of Al-Si-C film that significantly resists the wear of the surface.

Table 10. COF for different experimental trials.

| Trial no. | Friction force N | Actual COF | Predicted COF | % Error |
|-----------|-----------------|------------|--------------|---------|
| L1        | 7.02            | 0.351      | 0.347        | 1.161   |
| L2        | 6.72            | 0.336      | 0.334        | 0.551   |
| L3        | 6.34            | 0.317      | 0.323        | 1.869   |
| L4        | 6.5             | 0.325      | 0.325        | 0.125   |
| L5        | 6.14            | 0.307      | 0.312        | 1.568   |
| L6        | 6.1             | 0.305      | 0.301        | 1.445   |
| L7        | 6.32            | 0.316      | 0.319        | 0.926   |
| L8        | 6.06            | 0.303      | 0.306        | 1.039   |
| L9        | 6.02            | 0.301      | 0.295        | 2.018   |
| L10       | 14.52           | 0.363      | 0.357        | 1.581   |
| L11       | 13.8            | 0.345      | 0.344        | 0.150   |
| L12       | 13.08           | 0.327      | 0.333        | 1.914   |
| L13       | 13.64           | 0.341      | 0.337        | 1.292   |
| L14       | 12.92           | 0.323      | 0.324        | 0.252   |
| L15       | 12.36           | 0.309      | 0.313        | 1.163   |
| L16       | 13.08           | 0.327      | 0.328        | 0.181   |
| L17       | 12.24           | 0.306      | 0.315        | 2.881   |
| L18       | 12.52           | 0.313      | 0.304        | 3.006   |
| L19       | 24.36           | 0.406      | 0.406        | 0.100   |
| L20       | 23.94           | 0.399      | 0.393        | 1.350   |
| L21       | 22.5            | 0.375      | 0.382        | 1.738   |
| L22       | 22.38           | 0.373      | 0.377        | 1.055   |
| L23       | 22.32           | 0.372      | 0.364        | 2.111   |
| L24       | 20.94           | 0.349      | 0.353        | 1.125   |
| L25       | 20.94           | 0.349      | 0.357        | 2.176   |
| L26       | 20.7            | 0.345      | 0.344        | 0.344   |
| L27       | 20.34           | 0.339      | 0.333        | 1.890   |

Table 11. Response table for Signal to Noise ratios for COF smaller is better.

| Level | Load (kN) | Sliding velocity (m s$^{-1}$) | Sliding distance (m) | SiC (wt%) | FA (wt%) |
|-------|-----------|-------------------------------|----------------------|-----------|----------|
| 1     | 9.965     | 8.959                         | 9.436                | 9.521     | 9.140    |
| 2     | 9.689     | 9.555                         | 9.541                | 9.416     | 9.473    |
| 3     | 8.712     | 9.853                         | 9.389                | 9.429     | 9.753    |
| Delta | 1.253     | 0.894                         | 0.153                | 0.105     | 0.614    |
| Rank  | 1         | 2                             | 4                    | 5         | 3        |

Table 12. Response table for means for COF.

| Level | Load (k N) | Sliding velocity (m s$^{-1}$) | Sliding distance (m) | SiC (wt%) | FA (wt%) |
|-------|------------|-------------------------------|----------------------|-----------|----------|
| 1     | 0.3179     | 0.3577                        | 0.3382               | 0.3344    | 0.3501   |
| 2     | 0.3282     | 0.3338                        | 0.3339               | 0.3403    | 0.3373   |
| 3     | 0.3674     | 0.3221                        | 0.3414               | 0.3388    | 0.3261   |
| Delta | 0.0496     | 0.0356                        | 0.0076               | 0.0059    | 0.0240   |
| Rank  | 1          | 2                             | 4                    | 5         | 3        |
These SEM micrographs of AS5F5 exhibit the formation of friction film and worn debris accumulate together on the worn surfaces, as the reinforcement of Fly Ash in the specimen increases and SiC particulate content surpasses certain limit, the bonding strength between the Fly Ash and the matrix increases and offers resistance to wear, henceforth wear rate and COF decreases. Figure 16(c) demonstrates a very thick friction film formed all along its surface due to interfacial bonding between the Fly Ash and matrix and coring of SiC Particulates with
the aluminium matrix, it essentially increases the wear resistance of the sample. There are facets of Fly Ash bonded in aluminium matrix phase along with traces of micro agglomerates of SiC. The accumulation of agglomerates, and the distinct separation between the SiC particles and Fly Ash, and the excellent contrast between the particles and the matrix facilitated accurate image analysis which demonstrated decrease in wear rate and COF. Debris were collected during the study, micrographs were presented in figure 16 (d).

Further, the x-ray Diffraction (XRD) and Energy Dispersive Spectroscopy (EDS) of are carried out to understand the phase, elemental dispersion and epitaxy of the wear debris and to infer the influence of Fly Ash on the wear mechanisms of the composite specimens. The XRD studies are carried out for wear debris collected for L9 Experimental trial (Optimum set of parameters considered from Taguchi Analysis) using a Malvern Panalytical make X’Pert machine (Courtesy: BMSCE, Bangalore). The XRD pattern in figure 17, reveal a set of peaks corresponding to the Al phase, \( \alpha \)-Al phase and the aluminium-magnesium-silicates. The XRD pattern gives distinct peaks corresponding to the Al (1 1 1) phase formed at a diffraction angle of 38.968\(^\circ\); SiO\(_2\) (2 1 1) phase lines formed at a diffraction angle of 41.360\(^\circ\), SiC (1 1 1) phase lines formed at a diffraction angle of 43.952\(^\circ\), \( \alpha \)-Al (2 2 0) phase lines formed at a diffraction angle of 66.624\(^\circ\), \( \alpha \)-Al (2 2 2) phase lines formed at a diffraction angle of 79.112\(^\circ\), AlMgSiO\(_2\) (1 1 0) phase lines formed at a diffraction angle of 82.272\(^\circ\). The XRD peaks give substantial information related to the phase and ‘h k l’ planes of the elements present in the wear debris. The XRD pattern have ascertained the effect of smaller particulate sizes of Fly Ash particles in forming the \( \alpha \)-solid solution of aluminum and the \( \beta \)-solid solution of AlMgSiO\(_2\), which are known to increase the hardness of the composite materials due to the formation of ridges of oxides and carbides that resist the dry sliding wear of the composites.

Table 13. ANOVA table for COF.

| Source         | DF | Adj SS | Adj MS | F-Value | P-Value | % Contribution |
|----------------|----|--------|--------|---------|---------|----------------|
| Load (kN)      | 2  | 0.012303 | 0.006151 | 140.66 | 0.000 | 56.07 |
| Sliding velocity (m s\(^{-1}\)) | 2  | 0.005913 | 0.002956 | 67.61 | 0.000 | 26.95 |
| Sliding Distance (m) | 2  | 0.000259 | 0.000129 | 2.96 | 0.081 | 1.18 |
| Wt% of SiC     | 2  | 0.000168 | 0.000084 | 1.92 | 0.179 | 0.76 |
| Wt% of FA      | 2  | 0.002596 | 0.001298 | 29.68 | 0.000 | 11.84 |
| Error          | 16 | 0.000700 | 0.000044 | 3.20 |        | 3.20 |
| Total          | 26 | 0.021939 |        | 100     |        | 100  |
The EDS for the wear debris collected during the L-9 experimental trial is given in figure 18. The Elemental Dispersive Spectroscopy (EDS) of the wear debris have clearly revealed the presence of Si and C elements alongside the Al base material. The presence of Si and C in the wear debris have substantiated the inclusion of Fly Ash particles which have brought about the inoculation that has led to the formation of ceramic layer on the top surface of composite, thereby enhancing the wear resistance characteristics of the composites.

From the SEM, XRD and EDS of the wear debris, it is herewith noted that the Fly Ash particles catalyze the formation of AlMgSiO$_2$, Al-SiO$_2$ and Al-SiC bonds that eventually form a ceramic layer on the top surface of the composite, thereby reducing the wear.

4. Conclusions

In the present investigation, AA 5083-SiC-Fly Ash Inoculants based Functional Composites were prepared successfully by using stir casting method, then they were subjected to wear studies. Results of experimental and statistical data were recorded and discussed. Based on the results the following conclusions were drawn:

1. The reinforcement of aluminium by SiC and Fly Ash, and increasing the percentage of Fly Ash inoculants from 2.5% to 7.5% leads to significant improvement in wear resistance.

2. The maximal wear resistance in regime of wearing is observed for samples with 7.5% Fly Ash. This is ascertained by the ANOVA, wherein the interactions of control factors on wear are analyzed and the influence of load, sliding velocity, sliding distance and wt% of reinforcements are evaluated based on their % of contribution for variance of wear rate and COF.
Figure 15. 3D surface plots for coefficient of friction.

Figure 16. SEM image of the worn surface of (a) AS2.5F2.5 (b) AS5F5 (c) AS7.5F7.5 composites (d) debris micrograph.
3. The experimental outcomes and the statistical predictions are in line with each other and the error between them is within a band of $\pm 5$ to 10%, thereby validating the regression equation and optimization models evolved for predicting the wear model of functional aluminium composite with Fly Ash as inoculants.

4. Critical evaluation of relationship expresses a linear proportionality of wear rate, i.e., with the increase in the percentage of Fly Ash, the wear decreases by about 1.6 times. This clearly exhibits the influence of Fly Ash on the amount of wear of the samples.

5. The SEM, XRD and EDS of the wear debris have revealed the presence of ceramic particulates in the form of silicates, carbides and oxides that reduce the dry sliding wear of the aluminium composites fabricated in the present work.

**Data availability statement**

All data that support the findings of this study are included within the article (and any supplementary files).
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