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# A Fractional Factorial Design Study of Reciprocating Wear Behavior of Al-Si-SiC$_p$ Composites at Lubricated Contacts

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**The lubricated reciprocating wear behavior of two composites A319/15%SiC$_p$ and A390/15%SiC$_p$ produced by the liquid metallurgy route was investigated by means of an indigenously developed reciprocating friction wear test rig using a fractional factorial-design approach. The main purpose was to study the influence of wear and friction test parameters such as applied load, sliding distance, reciprocating velocity, counter surface temperature and silicon content in composites, as well as their interactions on the wear and friction characteristics of these composites. Two output responses (wear loss and coefficient of friction) were measured. The input parameter levels were fixed through pilot experiment conducted in the newly developed reciprocating friction and wear test rig. The counter surface material used for the wear study was cast iron having Vickers hardness of 244 HVN. It had been demonstrated through established equations that A390/15%SiC$_p$ composite is subjected to low wear compared to the A319/15%SiC$_p$ composite. The experimental results indicate that the proposed mathematical models suggested could adequately describe the performance indicators within the limits of the factors that are being investigated. The applied load, sliding distance, reciprocating velocity, counter surface temperature, and silicon content in composite are the five important factors controlling the friction and wear characteristics of the composite in lubricated condition. Moreover, the two factor interactions have a strong effect on the wear of composites. The results give a comprehensive insight into the wear of the composites.**

**Keywords** composite, lubrication, mathematical model, reciprocating wear, wear resistance

## 1. Introduction

Aluminum matrix composites (AMCs) reinforced with hard ceramic particles have emerged as a potential material especially for wear-resistant and weight critical applications such as brake drums, cylinder liners, pistons, cylinder blocks, connecting rods, etc. (Ref 1-4). These components are subjected to sliding wear with the counter bodies. The fact that wear behavior is quite sensitive to a number of material characteristics and experimental/operating variables makes it important to look into possible reasons and factors that become responsible for controlling the wear response (Ref 5). Lubricated tribology of AMCs sliding against gray cast iron is of problematic interest to automotive (Ref 6) and metal-forming industries (Ref 7). Application of lubricant oil to the contact eliminates the wear significantly (Ref 7), even in boundary lubrication regime. This lowers the friction coefficient generally to about the 0.1 level. In view of this, several attempts were made to examine the sliding wear related to these composites during the last decade. Almost all of them were performed using either pin-on-disk or block-on-ring testing machines where the composite material experienced only unidirectional sliding wear (Ref 2-7). Rohatgi et al. (Ref 3, 4) have investigated tribological properties of aluminum MMC modified with graphite particles focusing on the influence of solid lubricant in the composite owing to the presence of graphite. An extensive review on dry sliding wear characteristics of aluminum alloy-based composites was undertaken by Sannino and Rack (Ref 8), and the one on abrasive wear behavior undertaken by Deuis et al. (Ref 9) summarizes the effect of reinforcement volume fraction, reinforcement size, sliding distance, applied load, sliding speed, hardness of the counter face, and properties of the reinforcement phase on the dry sliding wear behavior of AMCs. However, very few of these tests were reported under lubricated sliding conditions (Ref 10). Higher wear rate has been reported under reciprocating condition compared with unidirectional sliding (Ref 11-15). It is, therefore, important to understand the lubricated reciprocal sliding wear behavior of these composites considering the fact that a number of industrial applications, such as engine cylinders, pistons etc., involve reciprocal sliding wear. Studies on wear performance under the lubricated reciprocating condition is, therefore, of practical significance, and not enough investigations concerning the influence of combined effect of wear and friction test parameters on the reciprocating wear of AMCs have been reported in the literature.

Further, research into the wear of composites has usually investigated the effect of a single factor, such as sliding distance, sliding speed, or contact pressure, on the wear performance. However, attempt to predict wear loss of composites in terms of applied load, sliding distance, reciprocating velocity, counter

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surface temperature, and silicon content in composites is lacking. It is possible to assess quantitatively the influence of each of the above variables separately on the wear loss and coefficient of friction (COF) of composites through deriving some empirical equations involving statistical analysis of the recorded data through design of experiments. However, such an approach has not been adopted to examine the combined effect of wear and friction test parameters on the lubricated wear response of aluminum alloy composites.

## 2. Experimental Details

### 2.1 Materials

The Al-Si alloys used for manufacturing of AMCs were based on A319 and A390. These alloys provide excellent combination of strength, low coefficient of thermal expansion at elevated temperature, and excellent wear resistance (Ref 16). The SiC particles used to fabricate the composite had an average particle size of 32 μm, and average density of 3.2 g/cm$^3$. The SiC particle reinforcement was fixed at 15 wt.%. The nominal chemical composition (wt.%) of the matrix alloys are given in Table 1.

### 2.2 Preparation of the Composites

The liquid metallurgy technique was used to prepare composite specimens (Ref 17). In this process, matrix alloy was molten at 800 °C, and then the temperature was lowered gradually below the liquidus temperature at 610 °C to keep the matrix alloy in the semisolid state. Magnesium (2 wt.%) was added to the melt for increasing the wettability of SiC particles with the aluminum alloy prior to the addition of preheated SiC particles (Ref 18). The preheated SiC particles at 720 °C were introduced into the slurry, and mixed. The composite slurry temperature was increased to molten state, and then stirring was continued for 5 min at an average stirring speed of 325 rpm. The melt was then superheated above liquidus temperature and finally poured into mould of cast iron of size 40 × 40 × 250 mm$^3$. The castings were solution heat treated at 500 °C for 6 h, water quenched at room temperature, and precipitation hardened at 190 °C for 12 h. The optical microstructures of A319/15%SiC$_p$ and A390/15%SiC$_p$ heat-treated composite with uniformly distributed SiC particle in alloy matrix is evident from micrograph shown in Fig. 1. The measured density and Vickers hardness of the heat-treated composites are shown in Table 2.

**Table 1 Composition of aluminum alloys (wt.%)**

| | Si | Fe | Cu | Mn | Mg | Ni | Zn | Ti | Al |
|---|---|---|---|---|---|---|---|---|---|
| A319 | 6 | 1 | 4 | 0.5 | 0.1 | 0.35 | 3 | 0.25 | Balance |
| A390 | 18 | 0.5 | 5 | 0.1 | 0.45 | … | 0.1 | 0.20 | Balance |

### 2.3 Experimental Setup and Procedures

A reciprocating wear test rig (Fig. 2) utilized to investigate the wet wear characteristic of the composite was fabricated as

**Table 2 Density and hardness of the heat-treated composites**

| Composite | Density, g/cm$^3$ | Hardness, VHN |
|---|---|---|
| A319/15 wt.%SiC$_p$ | 2.67 | 148.3 |
| A390/15 wt.%SiC$_p$ | 2.42 | 240.2 |

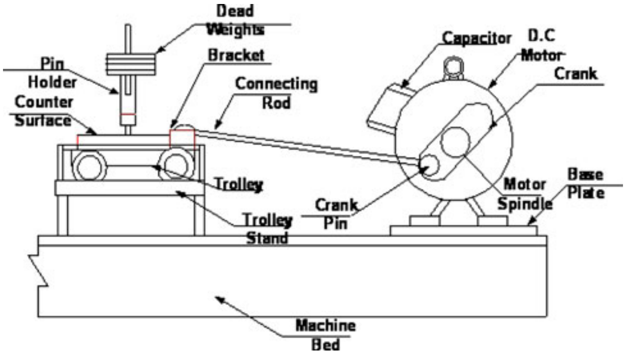

**Fig. 2** Schematic diagram showing the front view of reciprocating wear test rig

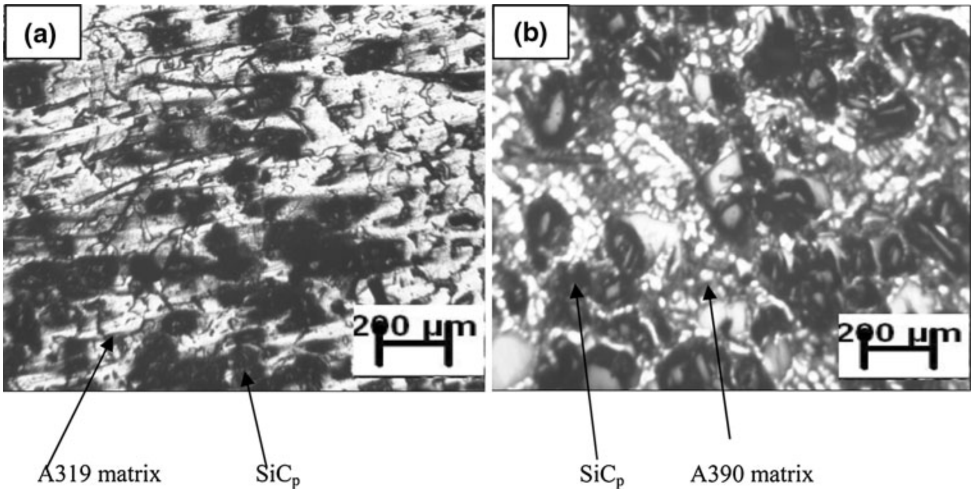

**Fig. 1** Optical microstructure of heat-treated (a) A319/15%SiC$_p$, (b) A390/15%SiC$_p$ composites with magnification 25× and 50×, respectively

per ASTM G 133-05 standards (Ref 19). The wear specimen (composite pin) of 6-mm diameter and 30-mm length was cut from the heat-treated samples. The initial weight of the specimen was measured in a single pan electronic weighing machine with least count of 0.0001 g. During the test, the composite pin was pressed against the counter surface by applying the dead load. The counter surface is a reciprocating plate made of cast iron having a CLA roughness value of 0.27 μm and hardness 244 VHN. One end of the composite pin was polished flat up to 0.35 μm ($R_a$) and then ultrasonically cleaned in a hot alcohol bath prior to the friction tests. $R_a$, the parameter of surface roughness, was used to measure the roughness. Counter surface was heated using a press fit element with a temperature controller for studying the effect of temperature on the wear of the composites. The common engine oil SAE 10W30 was used as the lubricant. The oil has a viscosity of 3500 centipoise at 20 °C and a viscosity between 9.3 and 12.5 centistokes at 100 °C. During the start up of experiments, running in was observed. After running through a fixed sliding distance, the specimens were removed, cleaned with acetone, dried, and weighed to determine the weight loss due to wear. The difference in the weight measured before and after test gave the sliding wear of the composite specimen using electronic balance by SHIMADZU with a least count of 0.1 mg. During the wear testing, the relative humidity of the laboratory atmosphere was measured to vary between 60 and 65%. The frictional force was measured using four strain gauges mounted on a metallic ring of thickness 2 mm and diameter 100 mm as per Wheatstone bridge circuit. The four leads of the circuit were attached to a digital strain gauge indicator to get the strain in the form of digital output. The ring was calibrated using known weights up to 50 N, and the calibration curve was plotted as shown in Fig. 3; the same was used to convert the digital output to the corresponding tangential friction force ($F_p$). Knowing the normal force $F_n$ (applied force), the COF between the two materials tested was computed using the following formula:

$$\text{COF} = F_p/F_n$$

### 2.4 Plan of Experiments

The experiments were conducted as per the fractional factorial design (FFD). The resolution of the design used was 'resolution V' with five wear and friction test parameters and two responses. Table 3 shows the levels of five experimental parameters. The experimental plan is generated using the stipulated conditions based on the FFD and involves 16 runs as shown in Table 4. The experimental parameters chosen for the experiments were (1) applied load ($L$), (2) sliding distance

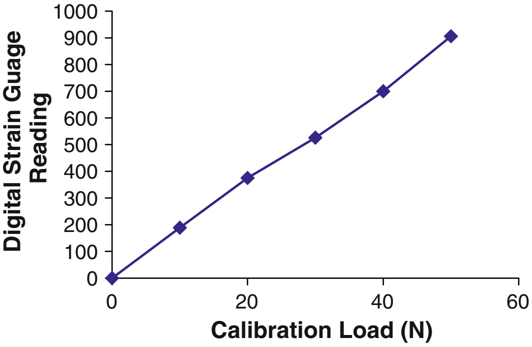

**Fig. 3** Calibration curve for coefficient of friction measurement

**Table 3 Design scheme of experimental parameters and their levels**

| | | Levels | |
|---|---|---|---|
| **Experimental parameters** | **Unit** | **Low (−1)** | **High (+1)** |
| Applied load ($L$) | N | 15 | 45 |
| Sliding distance ($D$) | m | 500 | 1500 |
| Reciprocating velocity ($V$) | m/s | 0.2 | 0.4 |
| Counter surface temperature ($T$) | °C | 60 | 120 |
| Silicon content in composite ($S$) | wt.% | 6 | 18 |

**Table 4 Design of experimental matrix and experimental results**

| | | Design parameters | | | | | Experimental results | |
|---|---|---|---|---|---|---|---|---|
| **Sl No.** | **Run** | **Applied load, N** | **Sliding distance, m** | **Reciprocating velocity, m/s** | **Counter surface temperature, °C** | **Silicon content in composites, wt.%** | **Wear loss, mg** | **Coefficient of friction** |
| 1 | 13 | 15 | 500 | 0.2 | 60 | 18 | 0.5 | 0.0512 |
| 2 | 7 | 45 | 500 | 0.2 | 60 | 6 | 1.3 | 0.0323 |
| 3 | 11 | 15 | 1500 | 0.2 | 60 | 6 | 1.3 | 0.0798 |
| 4 | 2 | 45 | 1500 | 0.2 | 60 | 18 | 1.6 | 0.0399 |
| 5 | 4 | 15 | 500 | 0.4 | 60 | 6 | 0.4 | 0.0578 |
| 6 | 15 | 45 | 500 | 0.4 | 60 | 18 | 0.4 | 0.0469 |
| 7 | 3 | 15 | 1500 | 0.4 | 60 | 18 | 0.3 | 0.0519 |
| 8 | 5 | 45 | 1500 | 0.4 | 60 | 6 | 0.9 | 0.0498 |
| 9 | 12 | 15 | 500 | 0.2 | 120 | 6 | 0.6 | 0.0789 |
| 10 | 14 | 45 | 500 | 0.2 | 120 | 18 | 0.8 | 0.0459 |
| 11 | 6 | 15 | 1500 | 0.2 | 120 | 18 | 1.3 | 0.0568 |
| 12 | 8 | 45 | 1500 | 0.2 | 120 | 6 | 1.6 | 0.0516 |
| 13 | 16 | 15 | 500 | 0.4 | 120 | 18 | 0.7 | 0.0486 |
| 14 | 1 | 45 | 500 | 0.4 | 120 | 6 | 0.9 | 0.0475 |
| 15 | 9 | 15 | 1500 | 0.4 | 120 | 6 | 1.4 | 0.0851 |
| 16 | 10 | 45 | 1500 | 0.4 | 120 | 18 | 1.1 | 0.0451 |

(*D*), (3) reciprocating velocity (*V*), (4) counter surface temperature (*T*), and (5) silicon content in composite (*S*). In this study, these experimental parameters are chosen as the independent input variables. The study of reciprocating wear behavior of the composites, and its significance lies in direct industrial applications such as in reciprocating machineries and passenger cars where the wear-intensive region of the liner represents the upper section (top) against the cast iron cylinder. The combustion pressure acting radially on the piston ring is converted into normal force, and it generally lies between 30 and 100 N (Ref 20). Hence, applied load in this study was taken as the first wear and friction test parameter with the low and high levels, which were fixed as 15 and 45 N, respectively. Nesarikar et al. (Ref 15) have reported that the wear of the cast iron sliding against composite plate started to increase after a sliding distance of approximately 220 m for $Al_2O_3$-particle-reinforced aluminum alloy composites. Hence, the low and high ranges of sliding distance in this case study were kept at 500 and 1500 m, respectively. The typical cases for passenger car engines and reciprocating pumps are subjected to an average sliding velocity of approximately 0.3 m/s (Ref 20). Hence the low and high levels of average reciprocating velocity in this research were kept as 0.2 and 0.4 m/s, respectively. Temperature had a significant influence on the wear rate of lubricated rubbing pairs. As the lubricant temperature changes, not only the viscosity and property of the lubricant but also the mechanical property of the rubbing pair will be altered. Hence, in this study, the high level temperature of the counter surface containing lubricant was fixed at 120 °C, while the low level temperature was fixed at 60 °C. It has been observed that addition of silicon in aluminum increases its wear resistance, increases fluidity, and results in low shrinkage of the Al-Si alloys (Ref 21). Si can be made to dissolve into Al to form a solid solution. However, there is a saturation point that limits how much Si can be dissolved into Al to form a solid solution. When Si is added above this particular saturation point, it will precipitate out in the form of hard, small Si particles. For an Al-Si system, this saturation point is nearly 12%Si. Therefore Al alloys with less than 12%Si are referred to as hypoeutectic, those with close to 12%Si as eutectic and those with greater than 12%Si as hypereutectic. Also, it has been observed that eutectic and hypereutectic compositions of Al-Si alloys exhibit the highest wear resistance (Ref 21). Hence, the upper level of composition of the alloy is considered as 18%Si (by wt.), and the low level of alloy composition is fixed at 6%Si (by wt.).

Table 3 indicates the experimental parameters and their levels. The investigated response variables are the wear loss and COF. The experiment consists of 16 tests (each row in the $2^{5\text{-}1}$ design arrays), and the columns were assigned with parameters as shown in Table 4 along with abbreviations.

## 3. Results and Discussion

The results of the wear performance of the composites as per the experimental plan are tabulated in Table 4. In order to ensure the goodness of fit of the polynomial model obtained in this study, the test for significance of the regression model, the test for significance on individual model coefficients, and the test for lack-of fit need to be performed (Ref 22, 23). The analysis of ANOVA is usually applied to summarize the above tests performed.

### 3.1 ANOVA Analysis

The results of model for the wear loss in the form of ANOVA are presented in Table 5. The value of "Prob $> F$" in Table 5 for this model is less than 0.05 (i.e., $\alpha = 0.05$, or 95% confidence) indicates that the model is considered to be statistically significant. This is desirable as it demonstrates that the terms in the model have a significant effect on the response. In the same manner, the main effect of factor *L* (applied load), factor *D* (sliding distance), factor *V* (reciprocating velocity), factor *T* (counter surface temperature), factor *S* (silicon content in composites), and the interaction effect of factor *L* (applied load) with factor *V* (reciprocating velocity), factor *L* (applied load) with factor *T* (counter surface temperature), and factor *V* (reciprocating velocity) with factor *T* (counter surface temperature) are significant model terms

**Table 5 ANOVA table for wear loss of composites**

| Source | Sum of squares | Degrees of freedom | Mean square | *f*-Value | Prob. > *F* | *p* Contribution percentage |
|---|---|---|---|---|---|---|
| Model | 2.84 | 10 | 0.28 | 37.26 | 0.0005 | Significant |
| *L* | 0.28 | 1 | 0.28 | 36.15 | 0.0018 | 9.57 |
| *D* | 0.95 | 1 | 0.95 | 124.7 | 0.0001 | 33.01 |
| *V* | 0.53 | 1 | 0.53 | 68.93 | 0.0004 | 18.25 |
| *T* | 0.18 | 1 | 0.18 | 23.69 | 0.0046 | 6.27 |
| *S* | 0.18 | 1 | 0.18 | 23.69 | 0.0046 | 6.27 |
| *LV* | 0.076 | 1 | 0.076 | 9.92 | 0.0254 | 2.63 |
| *LT* | 0.11 | 1 | 0.11 | 13.85 | 0.0137 | 3.67 |
| *DV* | 0.11 | 1 | 0.11 | 13.85 | 0.0137 | 3.67 |
| *DT* | 0.051 | 1 | 0.051 | 6.64 | 0.0496 | 1.76 |
| *VT* | 0.39 | 1 | 0.39 | 51.23 | 0.0008 | 13.57 |
| Residual | 0.038 | 5 | 0.007625 | | | 1.33 |
| Corr. total | 2.88 | 15 | | | | |

Standard deviation = 0.087, Mean = 0.94, Coefficient of variation = 9.25, Predicted residual error of sum of squares (PRESS) = 0.39, $R^2 = 0.9868$, $R^2$ adjusted = 0.9603, Predicted $R^2 = 0.8644$, Adequate precision = 18.30

**Table 6 ANOVA table for coefficient of friction (COF) of composites**

| Source | Sum of squares | Degrees of freedom | Mean square | *f*-Value | Prob. > *F* | *p* Contribution percentage |
|---|---|---|---|---|---|---|
| Model | 0.003213 | 10 | 0.0003213 | 48.73 | 0.0002 | Significant |
| *L* | 0.001427 | 1 | 0.001427 | 216.45 | 0.0001 | 43.97 |
| *D* | 0.0001619 | 1 | 0.0001619 | 24.56 | 0.0043 | 4.99 |
| *V* | 0.0000008556 | 1 | 0.0000008556 | 0.13 | 0.7334 | 0.026 |
| *T* | 0.0001556 | 1 | 0.0001556 | 23.61 | 0.0046 | 4.80 |
| *S* | 0.0005820 | 1 | 0.0005820 | 88.28 | 0.0002 | 17.93 |
| *LD* | 0.00003393 | 1 | 0.00003393 | 5.15 | 0.0726 | 1.05 |
| *LV* | 0.000150 | 1 | 0.000150 | 17.45 | 0.0087 | 3.54 |
| *LS* | 0.0005029 | 1 | 0.0005029 | 76.28 | 0.0003 | 15.49 |
| *DS* | 0.0001482 | 1 | 0.0001482 | 22.48 | 0.0051 | 4.57 |
| *TS* | 0.00008510 | 1 | 0.00008510 | 12.91 | 0.0157 | 2.62 |
| Residual | 0.00003296 | 5 | 0.000006593 |  |  | 1.014 |
| Corr. total | 0.003246 | 15 |  |  |  |  |

Standard deviation = 0.002568, Mean = 0.054, Coefficient of variation = 4.73, Predicted residual error of sum of squares (PRESS) = 0.0003375, $R^2$ = 0.9898, $R^2$ adjusted = 0.9695, Predicted $R^2$ = 0.8960, Adequate precision = 24.866

influencing the lubricated sliding wear of composites. The column 7 of the ANOVA analysis of wear results of composites (Table 5) indicates the percentage contribution (*p*) of each factor on the total variation indicating their degree of influence on the wear. It can be observed from Table 5 that the sliding distance (*p* 33.01%), reciprocating velocity (*p* 18.25%), load (*p* 9.57%), silicon content in composites (*p* 6.27%), and temperature (*p* 6.27%) are the controlling factors on the wear of the composites. These results indicate the sliding distance, load, reciprocating velocity, counter surface temperature, and silicon content in composites are the predominant factors greatly influencing the wear of the composites in lubricated condition within the range of investigation. Interaction between reciprocating velocity and counter surface temperature (*p* 13.57%), that between load and counter surface temperature (*p* 3.67%), and that between sliding distance and reciprocating velocity (*p* 3.67%) are the significant interaction model terms. The other interactions between sliding distance and counter surface temperature (*p* 1.76%) and that between load and reciprocating velocity (*p* 2.63%) are not predominant. The error contribution is 1.33%.

The other important coefficient $R^2$ in the resulting ANOVA table is defined as the ratio of the explained variation to the total variation. It is a measure of the degree of fit. When $R^2$ approaches unity, the better response model fits the actual data. The value of $R^2$ calculated in Table 5 for this reduced model is over 0.98, i.e., reasonably close to unity, and thus it is acceptable. It demonstrates that about 98% of the variability in the data is explained by this model. It also confirms that this model provides reasonably good explanation of the relationship between the independent factors and the response (wear loss).

Furthermore, the value of adequate precision in this model, which compares the range of the predicted value at the design point to the average prediction error, is well above 4. The value of the ratio is greater than 4, and then it represents the adequate model.

The same procedure is applied to deal with the other response i.e., the COF, and the resulting ANOVA for the reduced model is shown in Table 6. The significant model terms include the main effect of factor *L* (applied load), factor *D* (sliding distance), factor *T* (counter surface temperature), factor *S* (silicon content in composites) and the interaction effect of factor *L* (applied load) with factor *V* (reciprocating velocity), factor *L* (applied load) with factor *S* (silicon content in composites), factor *D* (sliding distance) with factor *S* (silicon content in composites), and factor *T* (counter surface temperature) with factor *S* (silicon content in composites). The $R^2$ value calculated in Table 6 is 0.9898 close to 1. The adequate precision value of this reduced model is still well above 4. The column 7 of the ANOVA analysis of friction results of composites (Table 6) indicates the percentage contribution (*p*) of each factor on the total variation indicating their degree of influence on the friction behavior of the composites. It can be observed from Table 6 that the load (*p* 43.97%), sliding distance (*p* 4.99%), counter surface temperature (*p* 4.80%), and silicon content in composite (*p* 17.93%) are the controlling factors on the friction of composites, whereas the effect of reciprocating velocity (*p* 0.026%) on the friction of the composites is marginal. These results indicate that the load, silicon content in composites, counter surface temperature, and sliding distance are the predominant factors greatly influencing the friction of the composites. Interaction between load and reciprocating velocity (*p* 3.54%), load and silicon content in composite (*p* 15.49%), sliding distance and silicon content in composite (*p* 4.57%) are significant interaction model terms. The other interactions between load and sliding distance (*p* 1.05%) and that between counter surface temperature and silicon content in composite (*p* 2.62%) are not predominant. The error contribution is 1.014%.

Through the backward elimination process, with α to exit = 0.05 used to arrive the final models of response, equations in terms of coded factors are presented as follows:

$$\begin{aligned}\text{Wear loss } (W) = 0.94 &+ 0.13L + 0.24D - 0.18V + 0.11T\\ &- 0.11S - 0.069LV - 0.081LT - 0.081DV\\ &+ 0.056DT + 0.16VT \pm \varepsilon \qquad \text{(Eq 1)}\end{aligned}$$

$$\begin{aligned}&\text{Coefficient of friction } (\mu)\\ &\quad = 0.054 - 0.009444L + 0.003181D - 0.0002312V\\ &\qquad + 0.003119T - 0.00603S - 0.001456LD + 0.00268LV\\ &\qquad + 0.005606LS - 0.003044DS - 0.002306TS \pm \varepsilon \qquad \text{(Eq 2)}\end{aligned}$$

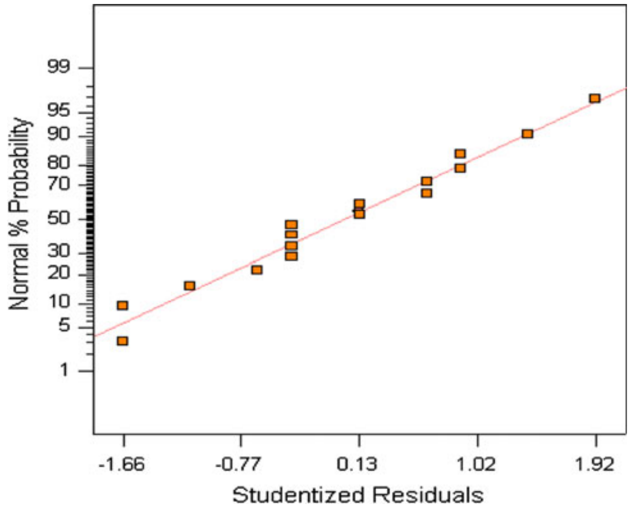

**Fig. 4** Normal probability plot residuals for the wear loss

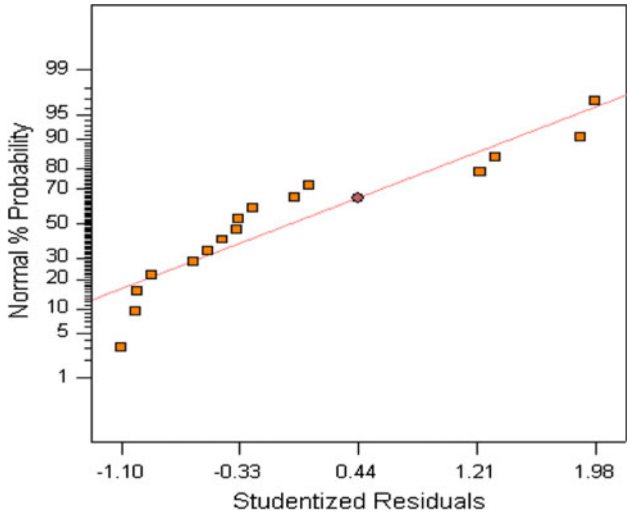

**Fig. 5** Normal probability plot residuals for the coefficient of friction

In terms of actual factors, the final models of response equations are as follows:

$$\begin{aligned}\text{Wear loss } (W) = {} & 0.98750 + 0.03875L + 0.0006375D - 3.5V \\ & - 0.010417T - 0.017708S - 0.045833LV \\ & - 0.000180556LT - 0.001625DV \\ & + 0.00000375DT + 0.052083VT \pm \varepsilon\end{aligned} \quad \text{(Eq 3)}$$

$$\begin{aligned}& \text{Coefficient of friction } (\mu) \\ & = 0.076919 - 0.00171917L + 0.0000243629D \\ & \quad - 0.055937V + 0.000257708T - 0.00070625S \\ & \quad - 0.000000194167LD + 0.0017875LV \\ & \quad + 0.000062291LS - 0.00000101458DS \\ & \quad - 0.0000128125TS \pm \varepsilon\end{aligned} \quad \text{(Eq 4)}$$

The above models can be used to predict the values of wear loss and COF within the limits of the factors studied. Normal probability plots of the residuals for both the wear loss and COF are shown in Fig. 4 and 5. It can be observed that the residuals generally fall on a straight line implying that the errors are normally distributed. Further, it adequately supports the least-square fit.

### 3.2 Effect of Experimental Parameters on Wear Loss and COF of Composites

The effect of the factors on the wear loss and COF is presented in Fig. 6 and 7. It can be observed that wear increases with increase of applied load and sliding distance, Fig. 6(a) and (b). Increase in load increases the metallic intimacy (adhesion), and their related wear also increases. As the silicon carbide particles are fractured at higher loads, the wear is increased by abrasive wear of the fractured silicon carbide fragments (Ref 24). With an increase in sliding distance, prolonged interaction between asperity and asperity contacts takes place, and the adhesion between the pin and slider increases (Ref 10). This increases the wear of composite. Increase in reciprocating velocity decreases wear (Fig. 6c) and is attributed to the increase in the hershey parameter with increase in reciprocating velocity which in turn shift the boundary lubrication regime to mixed lubrication regime and decreases the wear (Ref 25). There is an increase in the wear of composite for increase in counter surface temperature (Fig. 6d). When the SAE10W30 lubricant temperature was increased several changes occurred. These include (1) the viscosity of the lubricant decreased, (2) the quality of the lubricant degraded, and (3) the rate of oxidation and corrosion increased. All these influenced the wear behavior of the composites. The decrease in the bearing strength of the SAE10W30 lubricant has resulted in an increase in the direct contact area of rubbing pair surfaces which in turn has caused adhesive wear. The shear mixed layer was broken down due to the adhesive wear, resulting in the generation of wear debris and is attributed to the increased wear with increase in counter surface temperature (Ref 26). Increase in silicon content decreases the wear of composite (Fig. 6e). Increase in silicon content in composite increases the resistance to thermal softening and ability to support the surface oxide film owing to higher hardness. The primary silicon particles that act as load supporting elements greatly affect the wear property of the composite. Silicon and SiC particles resist against destructive action of abrasive caused by wear debris and protect the surface (Ref 27).

Figure 7(a) presents the effect of applied load on the COF. It was observed that an increase in applied load decreased COF. Reduction in COF values during lubricated tests as applied load is increased could be attributed to physically or chemically adsorbed as well as chemically reacted boundary layers formed in the contacting surfaces due to the reaction of the additives in the lubricant with the contacting surfaces. Tribo chemical substances, commercially classified as anti-wear (AW) and anti-scuff, or extreme pressure additives like chlorine, sulphur, phosphorous containing organic compounds, adsorb and react with the contacting surfaces and form boundary layers with a reduction in friction even under high contacting load (Ref 26). Increase in sliding distance increases the COF (Fig. 7b). Increasing COF with sliding distance could be due to a greater extent of predominant abrasive action of the fragmented hard mass entrapped in between the contacting surfaces (Ref 10). Figure 7(c) presents the effect of

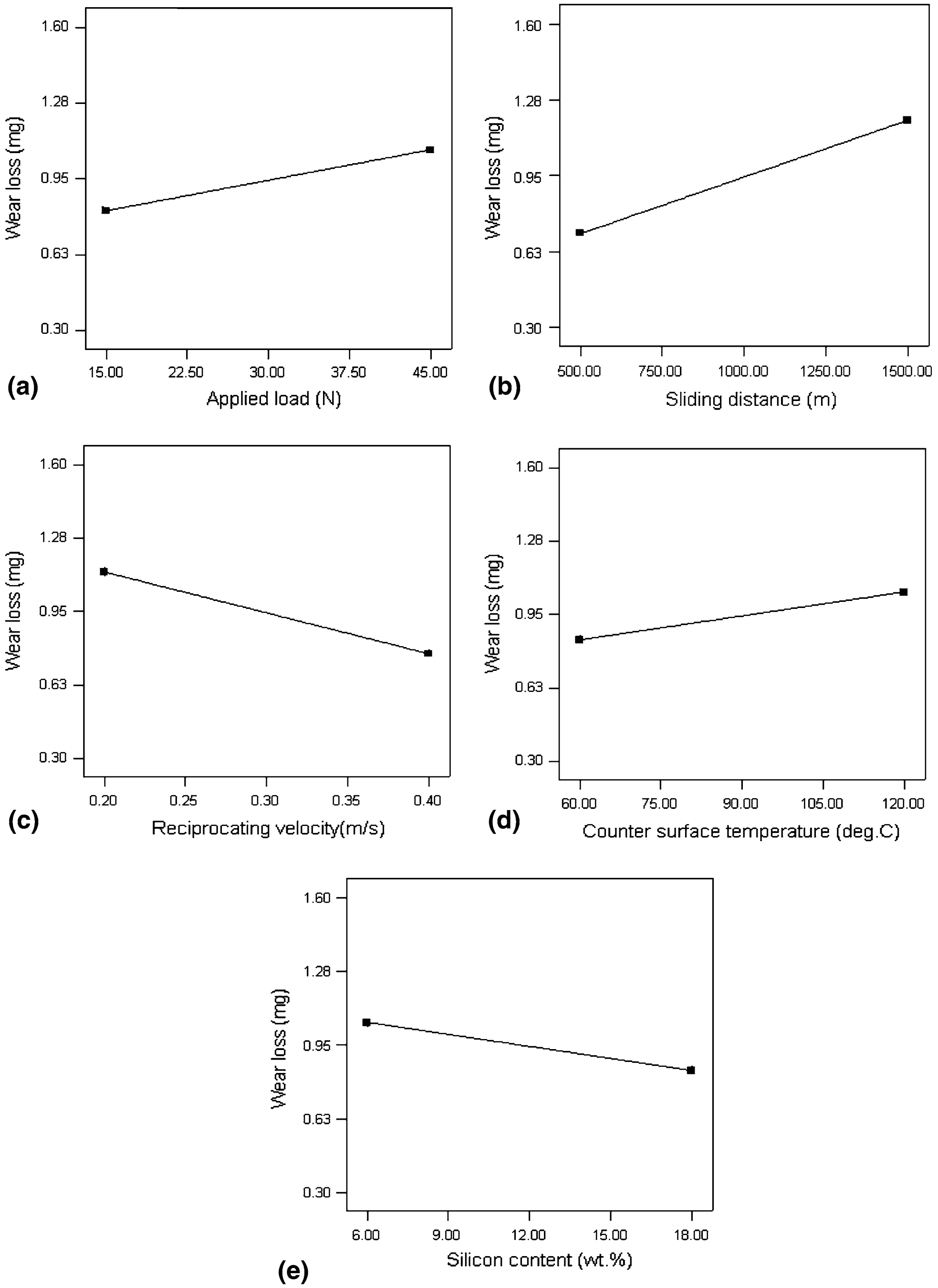

**Fig. 6** Effect of (a) applied load, (b) sliding distance, (c) reciprocating velocity, (d) counter surface temperature, and (e) silicon content on the wear of composite

reciprocating velocity on the COF. It can be observed that increase in reciprocating velocity slightly decreases COF and is attributed to the increase in the hershey parameter with increase in reciprocating velocity, which shifts the boundary lubrication regime to mixed lubrication regime and decreases COF (Ref 25). Effects of counter surface temperature on the COF are presented in Fig. 7(d). Results are directly proportional to each other i.e., COF increased as counter surface temperature increases because increase in counter surface temperature reduces the bearing strength of the lubricant which in turn would increase the adhesion and, therefore, increases the COF (Ref 28). Results of silicon content in composite with respect to COF are presented in Fig. 7(e). Inverse proportionality was observed between the silicon content in composite and COF because increase in silicon content in composite increases the resistance to thermal softening and ability to support the surface oxide film owing to higher hardness. The primary silicon particles act as load supporting elements greatly affect the wear and friction property of the composite. Silicon and SiC particles resist against destructive action of abrasive caused by wear debris and protect the surface (Ref 27).

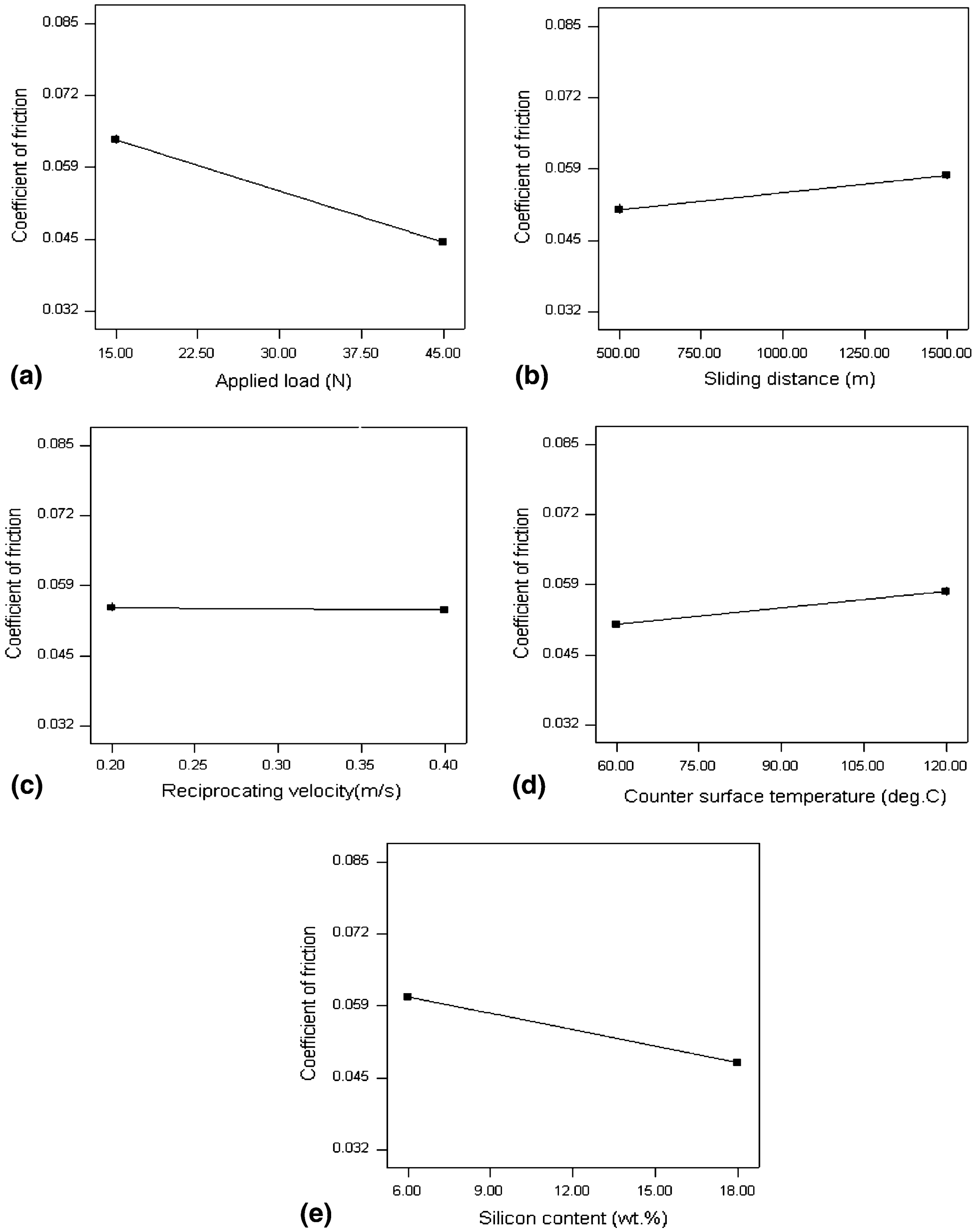

**Fig. 7** Effect of (a) applied load, (b) sliding distance, (c) reciprocating velocity, (d) counter surface temperature, and (e) silicon content on coefficient of friction of composite

## 4. Conclusions

Mathematical models of the wear loss and COF have been developed to correlate the dominant experimental parameters of the reciprocating wear behavior of aluminum alloy composites. The effect of various experimental on wear loss and COF was studied independently by using the mathematical model developed and experimental results. The conclusions of this study are as follows:

1. The results of ANOVA show that the polynomial models of the wear loss and COF are fairly well fitted with the experimental values. The influences of all the wear parameters on the wear characteristics of wear loss and COF have been analysed by the obtained mathematical models.
2. ANOVA reveals that the most significant variables affecting the lubricated reciprocating wear of composites in terms of individual percentage contribution are the main effect of sliding distance (33.01%), reciprocating velocity (18.25%), applied load (9.57%), counter surface temperature (6.27%), and silicon content in composite (6.27%) together with the interaction effect of reciprocating velocity with counter surface temperature (13.57%) within the selected range of investigation. They account for 86.94% of the experimental variance.
3. ANOVA reveals that the most significant variables affecting the lubricated reciprocating friction behavior of composites in terms of individual percentage contribution are the main effects of applied load (43.97%), silicon content in composite (17.93%), sliding distance (4.99%), counter surface temperature (4.80%), and together with

the interaction effect of applied load and silicon content in composite (15.49%), sliding distance, and silicon content in composite (4.57%), and applied load and reciprocating velocity (3.54%) within the selected range of investigation. They account for 95.29% of the experimental variance.

4. The A319/15%Si$C_p$ composite exhibited higher COF than A390/15%Si$C_p$.
5. Wear of A319/15%Si$C_p$ and A390/15%Si$C_p$ composite/Cast iron tribo pairs were decided by the silicon percent content in the composites, and the wear of the composites decreased with the increased content of silicon in it. Statistical analysis of the wear data of the composites revealed that A390/15%Si$C_p$ composite offer better wear resistance than A319/15%Si$C_p$ composites.

As an extension of this study, multiresponse optimization of wear loss and COF of composites and sensitivity analysis for friction and wear test parameters in wear of composites should be carried out.

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