Dry Reciprocating Wear Characteristics of A356/20% SiC_p Functionally Graded Composite

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Abstract. In this paper, centrifugally cast A356/20 wt.% SiCp functionally graded metal matrix composite (FGMMC) pins were subjected to wear test against EN31 steel plate in reciprocating contacts under dry sliding conditions. The influence of temperature, load, sliding velocity, wt.% of SiC and sliding distance on wear loss was studied using fractional factorial design. The most important factors affecting wear loss were observed to be load and sliding distance with percentage contributions of 34.68 and 34.27 respectively. While temperature, sliding velocity and wt.% of SiC only had minor influence on wear loss. Among two factor interactions, interaction of sliding velocity and wt.% of SiC was found to have significant influence with 13.14 percentage contribution followed by that of temperature and wt.% of SiC with 6.53 %.

Keywords: Functionally graded composites; fractional factorial design; wear; high temperature.

1 Introduction

Functionally graded materials (FGMs) are a class of composite materials that have a gradual variation in composition and properties across their volume. This approach allows for the design and fabrication of advanced materials with tailor-made properties, such as high toughness, wear resistance, and thermal stability. FGMs were first implemented to develop thermal barrier materials in Japan in1984 [1]. FGMs are used in applications such as aerospace structures, nuclear reactors, or dental implants [2]. Various methods for processing FGMs exist; including centrifugal casting, chemical vapour deposition, powder metallurgy, thermal spraying [2]. Functionally graded aluminium metal matrix composites (AMMC), have applications in aerospace, automotive, and biomedical engineering [2]. Aluminium metal matrix composites (AMMC) are materials that combine aluminium with another metal or ceramic to enhance its properties. AMMCs have advantages such as high strength to weight ratio, stiffness, wear resistance, and corrosion resistance.

Dry sliding wear characteristics of AMMC's has been studied widely [3]. Statistical studies on characteristics of AMMC's have also been performed with various reinforcements [4] [5] [6]. When it comes to behaviour of AMMC's at elevated temperatures, unidirectional wear studies are also available [7] [8] [9]. However, there are few investigations on the reciprocating wear characteristics of AMMCs.

In the present study, the high temperature wear characteristics of A356/20wt.% SiCp functionally graded composite is evaluated using fraction factorial design.

2 Materials and Methods

2.1 Materials

The material used for the study is A356/20wt% SiCp functionally graded metal matrix composite (FGMMC) ring with an outer diameter of 240mm processed by vertical centrifugal casting. The composition of A356 alloy is given in Table1.

Table1: Composition of A356 alloy.

Chemical composition								
Element	Si	Mg	Fe	Cu	Mn	Zn	Ti	Al
Percentage	7.00	0.40	0.11	0.02	0.0014	0.04	0.18	Balance

Based on microstructure evaluation the FGMMC ring, five regions of differing composition were identified; chill, particle rich, transition, matrix and porous/agglomeration regions.

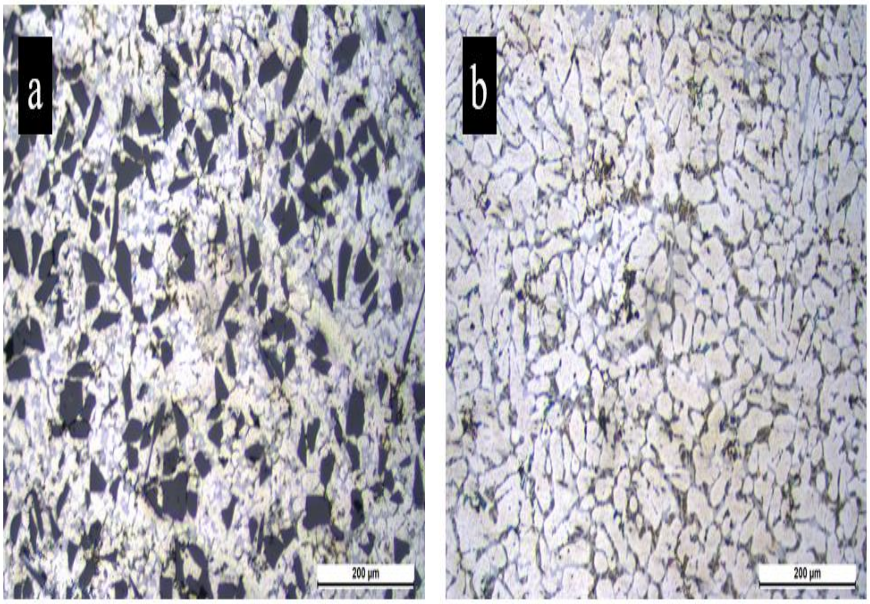

Fig.1: Microstructure of FGMMC ring; a) particle rich region and b) matrix region

Figure 1 shows the microstructure of the FGMMC ring from particle rich region and matrix region. Using image analysis, it was observed that the maximum concentration of SiC particles occurred at particle rich region, with 34% weight fraction. Pin samples of 6mm diameter were cut radially from particle rich and matrix regions of the FGMMC ring using electrical discharge machining (EDM) as shown in Figure 2. The pins were heat treated at T6 condition. The heat-treated specimens had a maximum hardness of 107 BHN at particle rich region, while at matrix region it was 69 BHN

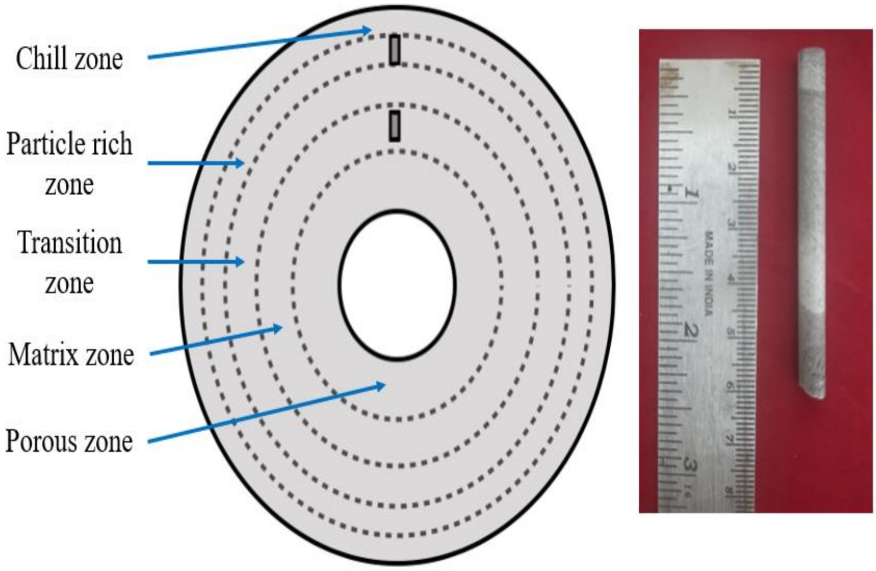

Fig.2: Pins for wear study cut from different locations of FGMMC ring.

2.2 Design of experiment

Wear behaviour was analysed by fractional factorial experimental design. Fractional factorial design or 2^(5−1) design was chosen for the study. The experiments were conducted by varying countersurface temperature, load, sliding velocity, wt.% of SiC and sliding distance. Two levels were selected for each factor The levels selected are given in Table 2. Design of experiment was carried out using Design Expert software. The levels were selected based on prior studies and pilot experiments. For wt.% of SiC, pins were taken from matrix region (0% SiC) and from particle rich region (34% SiC). The upper level for load was set at 60N, since severe wear was observed from pilot experiments for pins taken from matrix region (0% SiC) at higher loads. The upper level for sliding velocity was set at 0.8m/s to avoid severe wear, since mild to severe wear transition occurs at 1 m/s for Al/SiC composites [10].

Table 2: Factors and their levels selected for fractional factorial design

Level	A: Temperature (℃)	B: Load (N)	C: Sliding velocity (m/s)	D: SiC (% wt.)	E: Sliding distance (m)
-1	30	15	0.2	0	250
+1	250	60	0.8	34	500

Wear loss was selected as the response parameter. The confidence interval for the statistical study was set at 95% and only two-factor interactions were considered.

The influence of each parameter and interactions were calculated by the formula:

$$Percentage\ contribution = \frac{SS_F}{SS_T} \times 100$$

Where, SSF is the sum of squares for each term and SST is the total sum of squares.

3. Experimental Procedure

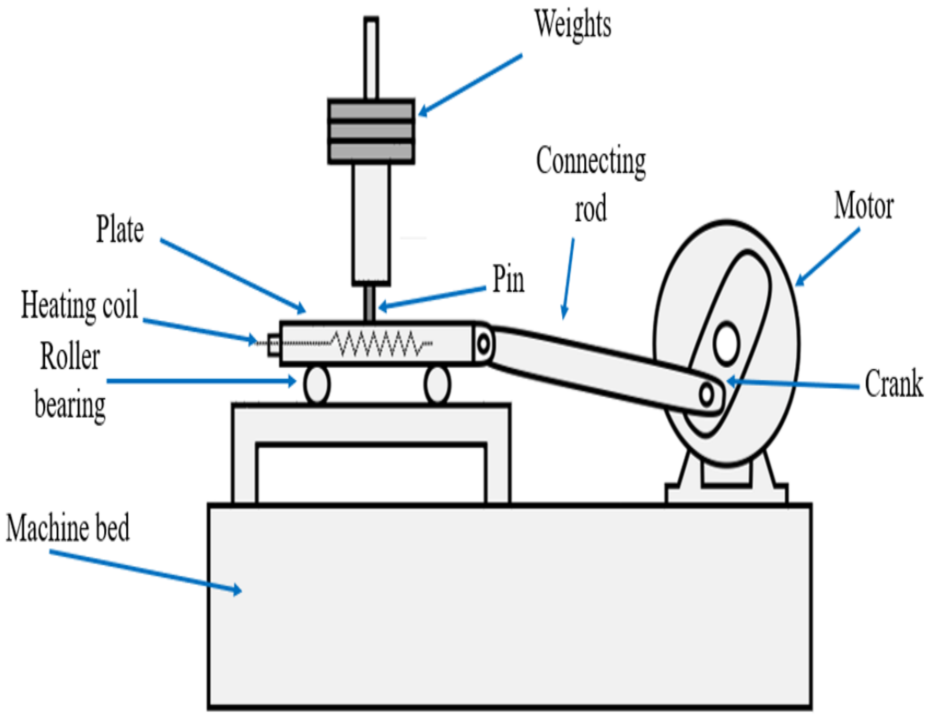

Fig.1: Schematic diagram of pin-on reciprocating plate test rig.

The experiments were carried out utilizing a pin on reciprocating plate tribometer that complies with ASTM 133-05 standards. Heat-treated FGMMC pins were tested in reciprocating contact with an EN-31 steel counter surface plate. A temperature control unit and heating coils were installed to the produce desired temperatures in the counter surface plate. A stroke length of 100mm was chosen. The schematic diagram of the experiment setup is given in the Figure 3.
For each experiment, the surfaces of the pins and counter plate were polished with emery paper (800 grit SiC) and were cleaned with acetone. The surfaces had an average surface roughness (Ra) of 0.3µm. By comparing the specimen's weight before and after the test, sliding wear loss was calculated.

4. Results and discussion

The responses from the experiments along with the plan is given in the Table 3. Wear loss values were between 0.00063g and 0. 01402g were observed. The coefficient of friction values observed were in the range of 0.16 to 0.35.

Table3: Experimental plan with results

		Factor 1	Factor 2	Factor 3	Factor 4	Factor 5	Response 1
Std	Run	A:Temperature (°C)	B:Load (N)	C:Sliding velocity (m/s)	D:Wt.. % SiC	E:Sliding distance (m)	Wear loss (g)
12	1	250	60	0.2	34	250	0.00403
15	2	30	60	0.8	34	250	0.00171
7	3	30	60	0.8	0	500	0.01402
6	4	250	15	0.8	0	500	0.0031
4	5	250	60	0.2	0	500	0.00607
9	6	30	15	0.2	34	250	0.00126
16	7	250	60	0.8	34	500	0.00573
13	8	30	15	0.8	34	500	0.00136
14	9	250	15	0.8	34	250	0.00068
2	10	250	15	0.2	0	250	0.00063
10	11	250	15	0.2	34	500	0.00399
1	12	30	15	0.2	0	500	0.00597
11	13	30	60	0.2	34	500	0.00937
3	14	30	60	0.2	0	250	0.00336
5	15	30	15	0.8	0	250	0.00272
8	16	250	60	0.8	0	250	0.00444

3.1 Analysis of Wear Loss.

The Table.4 gives the analysis of variance (ANOVA) for wear loss values. From analysis, it was observed that the factors with highest influence on wear loss were load (B) and sliding distance (E) with a percentage contribution of 34.68 and 34.27 % respectively. The factors, weight percentage of SiC (D), temperature (A) and sliding velocity (C) also had statistically significant, but minor influence on wear loss, with percentage contributions of 5.30, 1.83 and 0.67 respectively. When it comes to interactions, AB (Temperature * load), AD (Temperature*wt. %of SiC), CD (Sliding velocity * wt. % of SiC) and CE (Sliding velocity*Sliding distance) were found to be having significant influence, with percentage contributions of 1.14, 6.53, 13.14 and 1.46 respectively. Figure 4 shows percentage contribution of each single factors and their interactions.

Figure 5 gives the single factor effect plots for wear loss. From the plots, it can be observed that wear loss increases significantly with increase in either load or sliding distance. With the other factors, i.e., temperature, sliding velocity and wt.% of SiC, wear loss is inversely related.

Table 4: ANOVA table for wear loss.

Source	Sum of Squares	df	Mean Square	F-value	p-value		% Con-tribution
Model	11.61	9	1.29	66.99	< 0.0001	signifi-cant	
A-Tempera-ture	0.2142	1	0.2142	11.12	0.0157		1.83
B-Load	4.07	1	4.07	211.14	< 0.0001		34.68
C-Sliding velocity	0.0783	1	0.0783	4.06	0.0904		0.67
D-Wt.. % SiC	0.6213	1	0.6213	32.26	0.0013		5.30
E-Sliding distance	4.02	1	4.02	208.69	< 0.0001		34.27
AB	0.1342	1	0.1342	6.97	0.0385		1.14
AD	0.7663	1	0.7663	39.78	0.0007		6.53
CD	1.54	1	1.54	80.00	0.0001		13.14
CE	0.1709	1	0.1709	8.87	0.0247		1.46
Residual	0.1156	6	0.0193				
Cor Total	11.73	15					

As a result of more work being done, wear loss increases as load increases. This is in line with the well-known Archard's law [11] and also in accordance with literature [12]. The length of time that each surface is in contact rises as the sliding distance increases. This results in more asperity-to-asperity contact which leads to more wear debris and hence increased wear loss [11]. Wear declines as SiC weight % rises. This is explained by the rise in hardness that occurs with increasing SiC content. The negative relationship between wear and hardness is also supported by literature [13] and Archard's law [11].

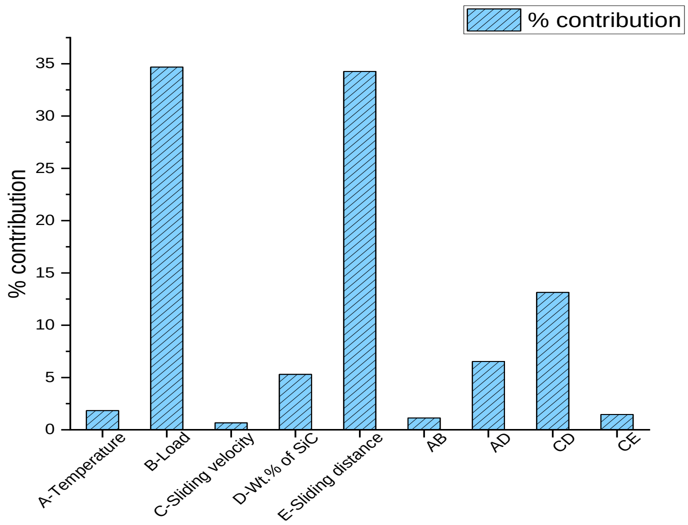

Fig.4: Percentage contribution of wear test parameters and their interactions

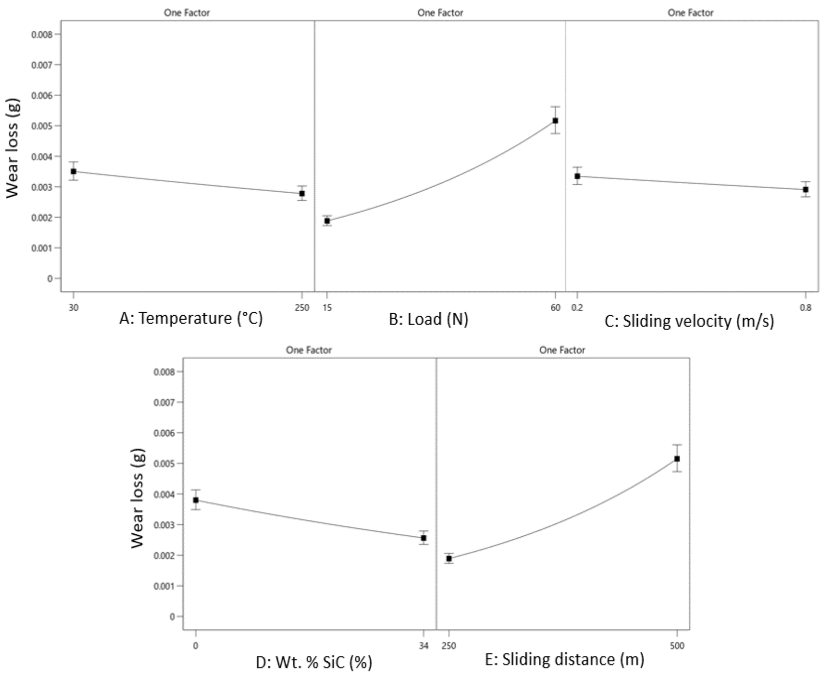

Fig.5 Single factor effect plots for wear loss.

Increase in temperature caused slight decrease in wear loss. The production of a glaze layer at higher temperatures, which can be observed from the Figure 6-R16, can be used to explain why an increase in temperature results in a decrease in wear loss. Glaze layer is a smooth and hard layer that forms due to sintering of fine oxide wear debris at conditions of high temperature and pressure [14], [7]. This layer prevents sliding layers from direct contact, thus reducing wear loss.

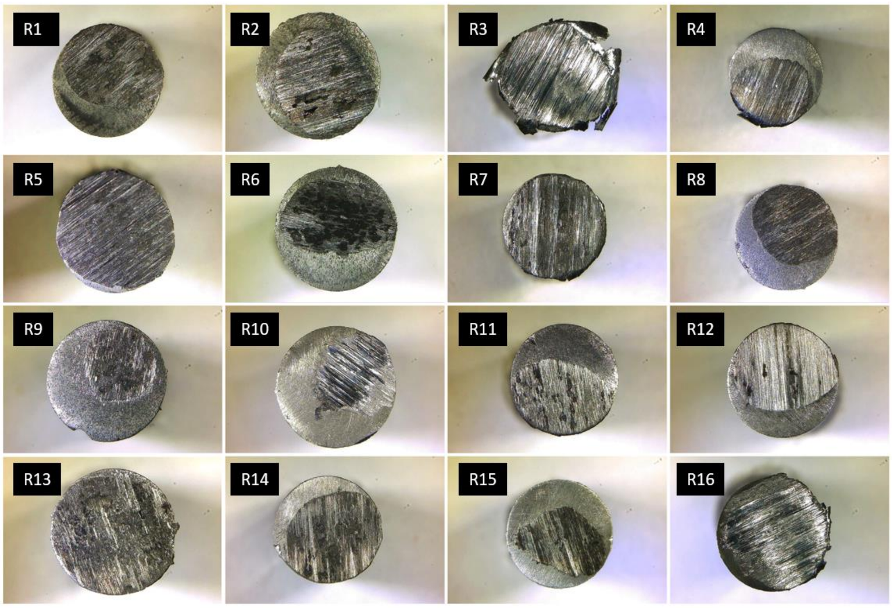

Fig.6: Stereo images of worn surfaces of FGMMC pins.

3D surface plots of two factor interactions for wear loss are shown in Figure 7. the most significant two factor interaction is CD i.e., between sliding velocity and wt.% of SiC (Figure 7-c). For matrix region (0wt.% SiC), as the sliding velocity increases wear increases marginally. However, for particle rich region (34 wt.% SiC), the inverse is true. Other than CD, AD i.e., Interaction between temperature and wt.% of SiC also has significant influence.

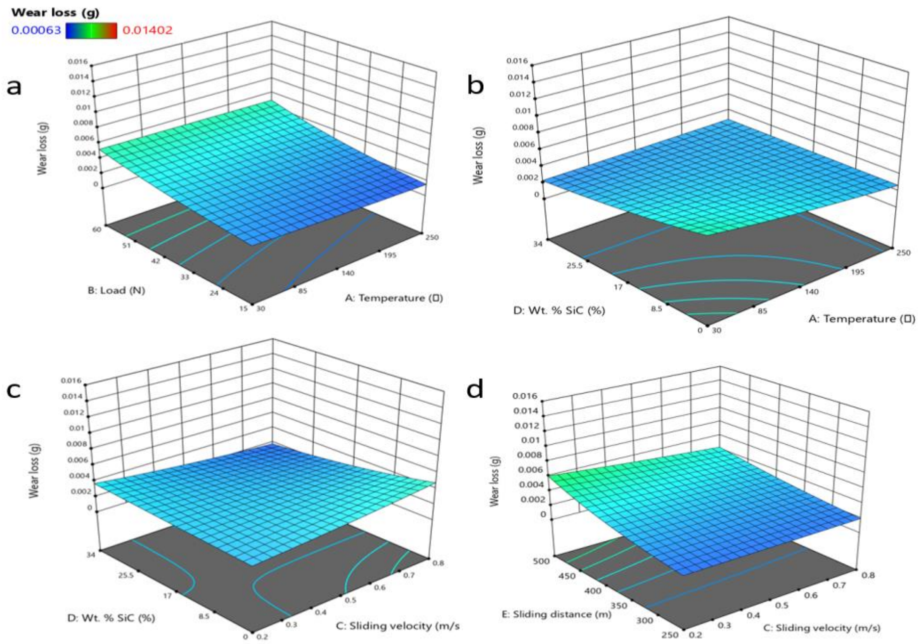

Fig.7 3D surface plots of two factor interactions for wear loss; a) AB, b) AD, c) CD and d) CE.

3.2 Model equation

Using Design Expert 13, a multiple linear regression model was made to analyse how the wear test parameters (temperature, load, sliding velocity, weight percentage of SiC, and sliding distance) impact dry sliding wear loss. The model only contained the main factors and statistically significant interactions. The models' equation is as follows

$$ln(wear\ loss) = -8.22362 - 0.004429 * A + 0.017226 * B + 1.83485 * C + 0.002379 * D + 0.005388 * E + 0.000037 * A * B + 0.000114 * A * D - 0.059111 * C * D - 0.002756 * C * E$$

Where, wear loss is in grams and the other terms are as follows

A- Temperature (30 to 250°C)
B- Load (15 to 60N)
C- Sliding velocity (0.2 to 0.8 m/s)
D- Wt.% of SiC (0 to 34%)
E- Sliding distance (250 to 500m)

4. Conclusion

Pins from centrifugally cast A356-20% SiCp functionally graded composite were subjected to dry wear test against EN31 steel plate in reciprocating contacts. To determine the effects of temperature, load, sliding velocity, SiC (weight percentage), and sliding distance, a statistical investigation was carried out. The following conclusions can be drawn from these findings

- With percentage contributions of 34.68, 34.27, and 5.30, respectively, the load, sliding distance, and SiC (% weight) were discovered to be the most significant components for wear loss from the statistical analysis.
- Wear loss increased with higher loads and longer sliding distances, whereas it decreased with higher weight percentages of SiC.
- Sliding velocity*wt% SiC was the most significant two-factor interaction, followed by temperature*wt% SiC, with 13.14 and 6.53 percentage contributions, respectively.
- Increase in temperature results in a modest reduction in wear loss, which could be due to the production of glaze layers at high temperatures.

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