Silicon (2021) 13:2369–2379
https://doi.org/10.1007/s12633-020-00854-y

ORIGINAL PAPER

Investigation of Mechanical and Wear Behaviour of Al7075/SiC Composites Using Response Surface Methodology

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Received: 21 September 2020 / Accepted: 19 November 2020 /

Abstract

This work studies the effect of reinforcement weight percentage (Wt.%SiC) on wear and mechanical behaviour of the aluminium 7075 composites produced by the powder metallurgy technique. The three different reinforcements weight percentage used in this study are to 5,10 and 15. The hardness and toughness values reveals that with an increment in weight percentage of reinforcement, the mechanical properties decreases because of the development of large and more number of pores and agglomerations. The composites wear behaviour is examined by the wear testing equipment. The selected tribological parameters for the study are reinforcement weight percentage, applied load and sliding distance at three levels. The Design of Experiments, Box-Behnken method is used to design the number of experiments. ANOVA is used to find the effect of input parameters on output responses. The response surface methodology confirms that sliding distance and reinforcement weight percentage are two parameters which mostly affects wear loss.

Keywords Al7075 composite, mechanical property · Wear · RSM

1 Introduction

Aluminium 7075 alloy owns unique features like high strength-to-weight ratio, good resistance to corrosion, low density excellent ductility and better thermal conductivity made it applicable for wide variety of applications in numerous sectors like automotive, defence and structural applications [1, 2]. With the inclusion of several ceramic particles to the aluminium matrix, its characteristics are altered and used in a wide range of industrial applications [3]. Many investigators are working on Al_2O_3, B_4C, TiC and SiC composites because of its enhanced mechanical and wear properties. SiC reinforced composites display better resistance to wear [4–7]. Selection of fabrication technique plays a crucial role in metal matrix composites. To fabricate the composites, a broad range of fabrication techniques like centrifugal casting, powder metallurgy, hot pressing, thermal spraying and chemical vapour deposition are available [8–10]. Among all the methods available, powder metallurgy is one of the easiest and cost-effective technique because of its ability to control composition, density and produce the composites near to a net shape [11–13]. The mechanical properties of composites mainly depend on its microstructure, type and size of reinforcement and its interfacial bonding [14]. The wear loss of composite hugely depends on reinforcement weight percentage, normal load, sliding distance and sliding velocity, type of lubricant, type of counter disc material. Among all these parameters, particle size is one factor which highly influences properties of the composites [15, 16]. This research aims to develop a material selection method. The material selection method is demonstrated by selecting optimum material for the application of the brake disc system with an emphasis on the substitution of cast iron by any other lightweight material. The analysis led to an aluminum metal matrix composite as the most appropriate material for the brake disc system. In the current investigation, aluminium 7075 and (5,10&15) silicon carbide reinforced composites are produced using traditional powder metallurgy technique. These composites are subjected to different tests to examine their physical, mechanical and wear properties. Response surface methodology is used to

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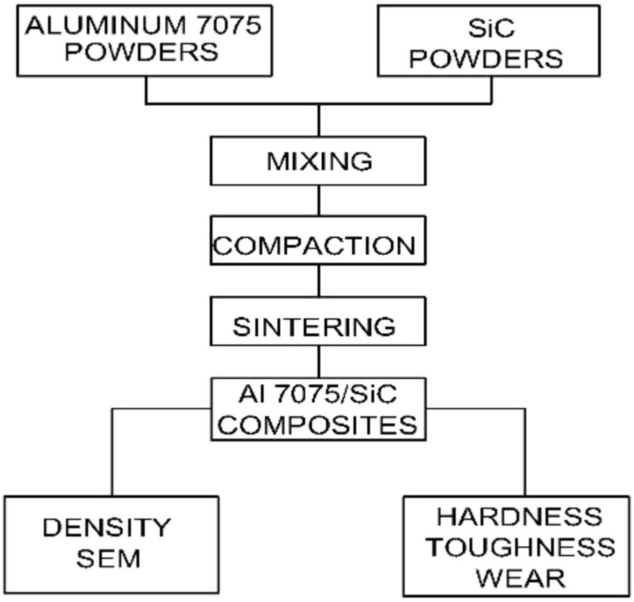

Fig. 1 Methodology of the work

analyze the effect of reinforcement weight percentage, load and sliding distance on wear behaviour of the composites.

2 Experimentation

2.1 Matrix and Reinforcement Materials

Figure 1 shows the step by step methodology of the work carried. Figure 2 shows the SEM images of aluminium 7075 (30 µm) and Silicon Carbide(SiC) (20 µm), which are used matrix and reinforcement in this study. Table 1 shows the various chemical constituents present in aluminium 7075.

2.2 Specimen Preparation

Table 2 shows the composition of aluminium and silicon carbide powders used to produce three different composites, for examining wear and mechanical properties. These powders are weighed and poured into the ball milling cups to mix them evenly with 10: 1 ball to powder proportion. The die and punch walls are lubricated with zinc stearate every time before performing compaction. The milled powders are placed inside a die and pressed at a pressure of 300 MPa for 5 min of constant loading using compaction machine to produce different composites of 25 mm height and 10 mm diameter for wear test and 55X10X10 mm for hardness and toughness tests. These green specimens lack strength. These specimens are sintered at 530 °C in a protected atmosphere furnace(argon) as to attain high strength. Figure 3 shows the sintering cycle curve which has used in the current investigation. Figures 4 and 5 shows the Rockwell hardness testing and wear testing equipment's. Figures 6 and 7 shows the images of composites after sintering for wear and mechanical tests.

Table 1 Al7075 Chemical composition

Al-7075 Constituents	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Percentage	0.4	0.5	1.6	0.3	2.5	0.15	5.5	0.2	Bal

2.3 Wear Test

The wear examination on the composite is conducted using computer-aided wear testing instrument (Pin on disc) as per ASTM G99 standards [17]. En31 steel is employed as the counter disk material [15]. Acetone is used to clean both pin and En31 steel disc after conducting every test to remove wear debris. The wear height loss of the pin in microns was recorded during each wear test using a linear variable differential transducer (LVDT) of least count 1.0 mm. On wearing the pin surface during rubbing with the counter disc, the pin continuously moves down to re-establish the contact with the disc surface. This linear downward movement of the pin is a

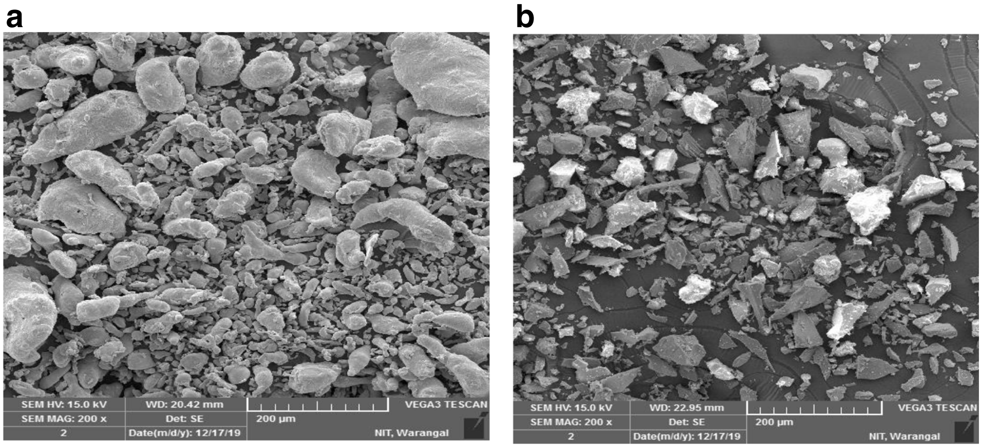

Fig. 2. SEM pictures of **a**) Aluminium and **b**) SiC powders.

Table 2 Three composite powders Wt.%

S. No	Wt.% Al-7075	Wt.% SiC
1	95	5
2	90	10
3	85	15

measurement of the wear height loss and is recorded by the LVDT [18]. In the current work, Wt.% reinforcement, load and sliding distance at three different levels are considered to study the wear behaviour of composites. The number of experiments is planned using design of experiments, Box-Behnken method using Minitab-17 software. Table 3 displays various input parameters and levels considered for wear examination.

3 Results and Discussion

3.1 Microstructure Examination

The microstructural examination is used to study the dispersion of aluminium and silicon carbide particles in the composite, which has a massive impact on mechanical and tribological properties. Figure 8(a-c) displays the microstructure of 5,10& 15 weight percentage reinforced composites respectively. Figure 8a shows the even distribution of SiC in 5 Wt.% SiC composite with very fewer agglomerations and pores. From Fig. 8b, it is understood that SiC is dispersed homogeneously with small agglomerations, which is the primary reason for a slight reduction in mechanical and tribological properties of 10 Wt.% SiC composite. From Fig. 8c it is understood that SiC is dispersed unevenly in the composite and excess presence of SiC is the primary reason for the formation of more pores and large agglomerations, which are the major causes for the more reduction in mechanical and tribological properties of 15 Wt.%SiC composite.

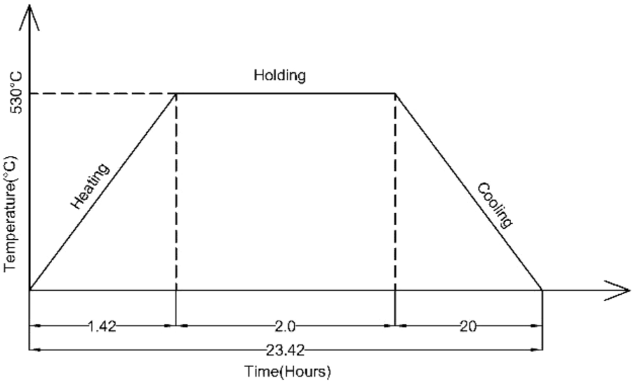

Fig. 3 Sintering cycle curve

Fig. 4 Rockwell hardness tester

3.2 Density

The measured and the theoretical densities of (5,10 & 15) Wt.%SiC composites are measured and calculated using Archimedes and rule of mixtures methods. Table 4 shows the experimental values density, hardness and impact of composites. From Fig. 9, it is observed that theoretical density is high when compared with measured density. Theoretical density increases with an increase in Wt.% reinforcement while experimental density decreases with an increase in SiC weight percentage due to the presence of large and more number of pores.

3.3 Hardness

Rockwell test is performed as per ASTM E18–15 standard to compute the hardness of (5,10 &15) Wt.%

Fig. 5 Wear testing equipment

Fig. 6 Wear examination composites

Fig. 7 Composites for Mechanical Examination

Reinforcement composites. Figure 10 shows the average hardness of composites. From Fig. 10, it is clear that with an increment in reinforcement Wt.% a noticeable diminish in the hardness of the composites is observed. The cause for the reduction in hardness is due to the presence of excess percentage of SiC. The 5Wt.%SiC composite exhibited higher hardness than the other composites because of the uniform distribution of reinforcement in the matrix, which resulted in strong bonding. The 10 Wt.%SiC composite exhibited less hardness than 5Wt.% and more than 15 Wt.% reinforcements because of less porosity and small SiC agglomerations. The 15Wt.%SiC composite exhibited less hardness than others because of the formation of a high and large number of SiC agglomerations.

Table 3 Input parameters for wear examination

S. No	Wt.% Reinforcement	Load(N)	Sliding Distance(m)
1	5	10	500
2	10	15	1000
3	15	20	1500

3.4 Toughness

As per the ASTM E23 the toughness of the composites is measured using the Charpy impact test. Figure 11 shows the average toughness comparison of (5, 10 &15) Wt.% reinforcement composites. The 5 Wt.%SiC

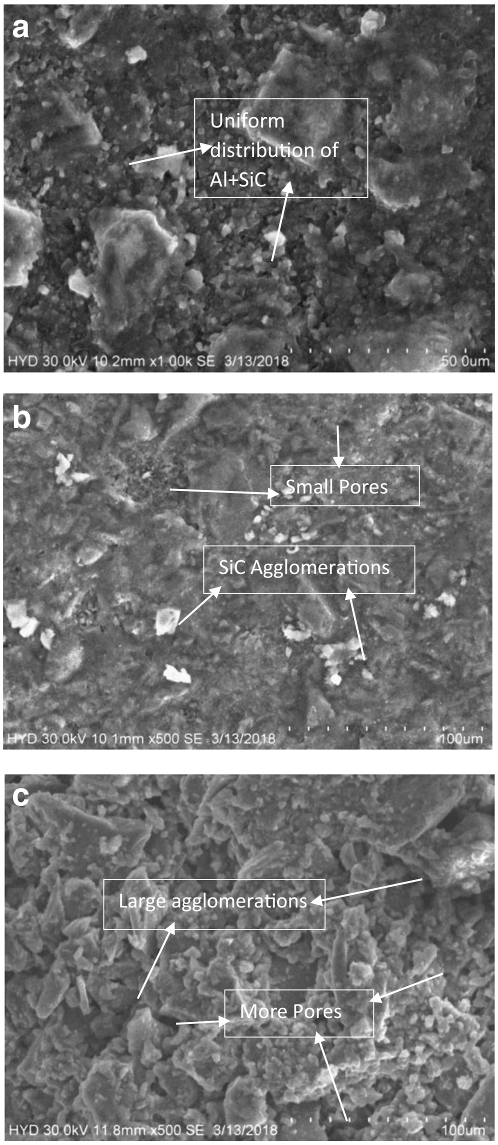

Fig. 8 **a** SEM images of 5Wt.% SiC Composite **b**. SEM images of 10Wt.% SiC Composite ***C***. *SEM* images of 15Wt.% SiC Composite

Table 4 Properties of Composites

Composites	Experimental Density(g/cc)	Hardness (HRB)	Impact Toughness(J)
5 Wt.%SiC	2.71	70	5
10 Wt.%SiC	2.68	67	4.5
15Wt.%SiC	2.61	64	3.8

composite exhibited high toughness than others because of high ductility. The even dispersion of SiC particles in the matrix and strong interfacial bonding is the reason for high ductility. The existence of more SiC made the composite more brittle and less ductile.

4 Wear Behaviour

The possible wear mechanisms which are commonly witnessed in different Wt.% SiC composites when subjected to different loads and sliding distance and sliding speeds are Adhesive, abrasive, delamination and abrasion [19]. Metallurgical, environmental circumstances and type of counter disc material are the superior reason for multiple types of wear mechanism. [20]. Table 4 shows the number of experiments conducted and each experiments actual and predicted wear values.

Figure 12(a-b) show 15 Wt.% reinforcement composites wear surface and wear debris SEM images. From Fig. 12a, it is observed that delamination and abrasion governing wear mechanism in 15 Wt.% reinforcement composites [2, 21, 23]. From Fig. 12b it observed that presence of deep cavities and breakage of oxide layers in Al-15Wt.%SiC composite, are the results of increased wear and the formation of more wear debris.

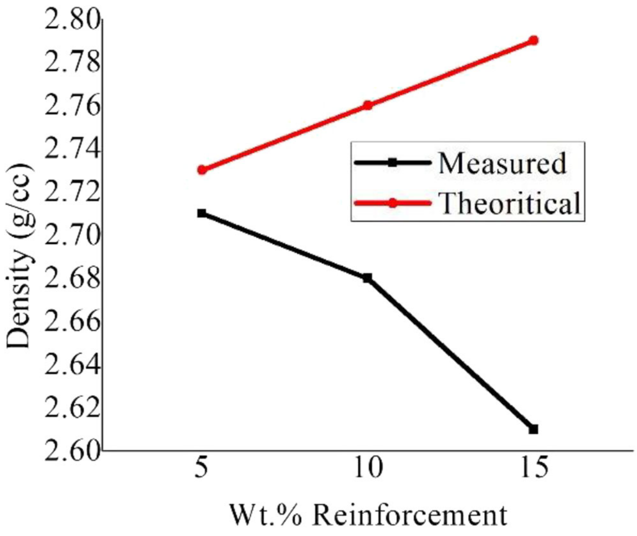

Fig. 9 Measured and Theoretical density of composites

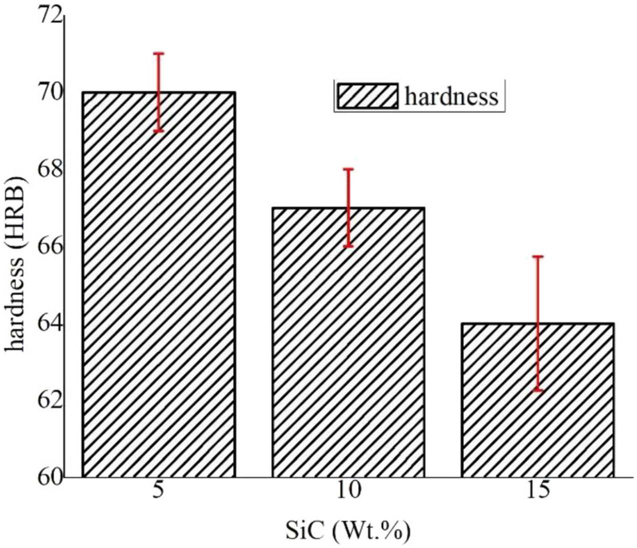

Fig. 10 Hardness of composites

Figure 13(a-b) show 10Wt.% reinforcement composites wear surface and wear debris SEM images. From Fig. 13a, it is evident that most abrasive and partly adhesion and plastic deformation are the predominant wear mechanism [8, 21, 22]. The presence of parallel grooves and crater in the direction of sliding in wear surfaces is an indication of abrasive wear. Figure 13b shows the

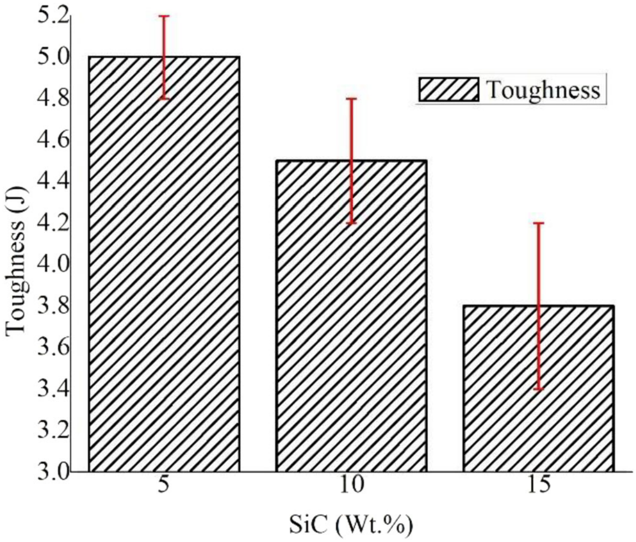

Fig. 11 Toughness of composites

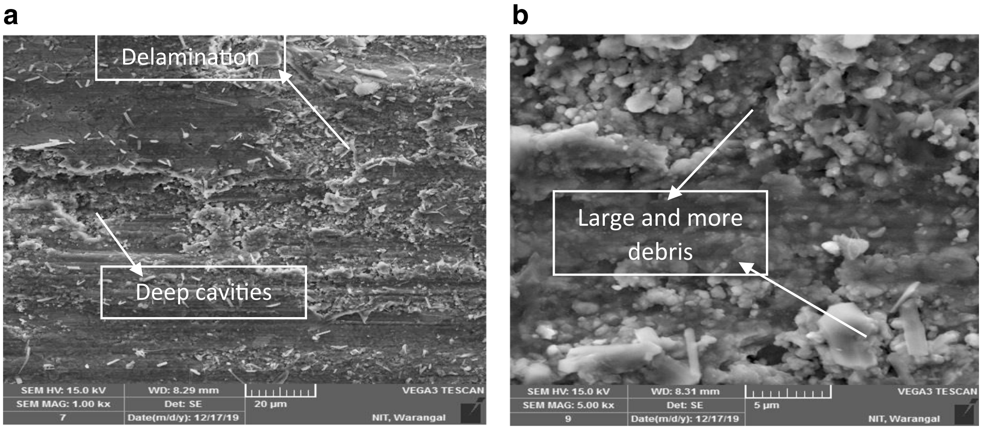

Fig. 12 (**a**) Wear surface and (**b**) Wear debris SEM images of 15%SiC composites

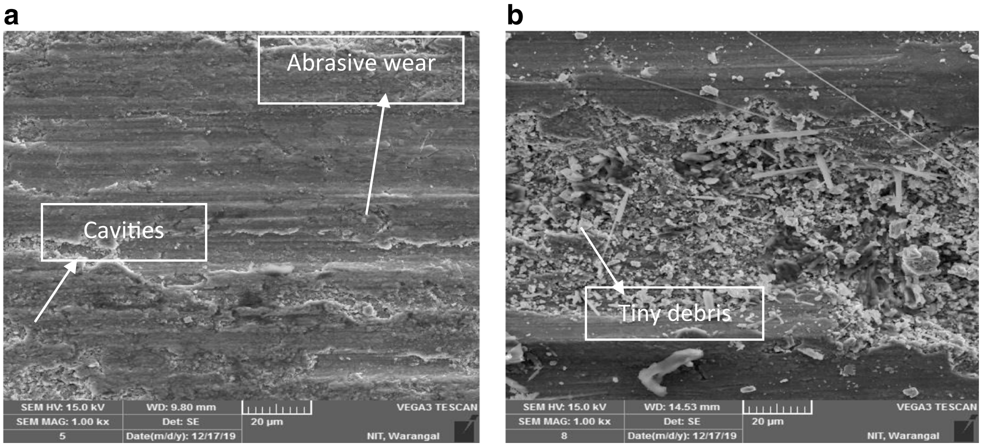

Fig. 13 (**a**) Wear surface and (**b**) Wear debris SEM images of 10%SiC composites

appearance of small cavities and fracture of oxide layers in Al-10%SiC composite due to adhesive wear which resulted in wear and formation of tiny wear debris.

Figure 14(a-b) show 5Wt.% reinforcement composites wear surface and wear debris SEM images. From Fig. 14a, it is evident that the wear mechanisms witnessed in Al-5Wt.%SiC composites are oxidation and adhesion [23]. Figure 14b reveals the appearance of small craters in Al-5%SiC composites which resulted in little wear and the formation of tiny debris. When compared with the other two

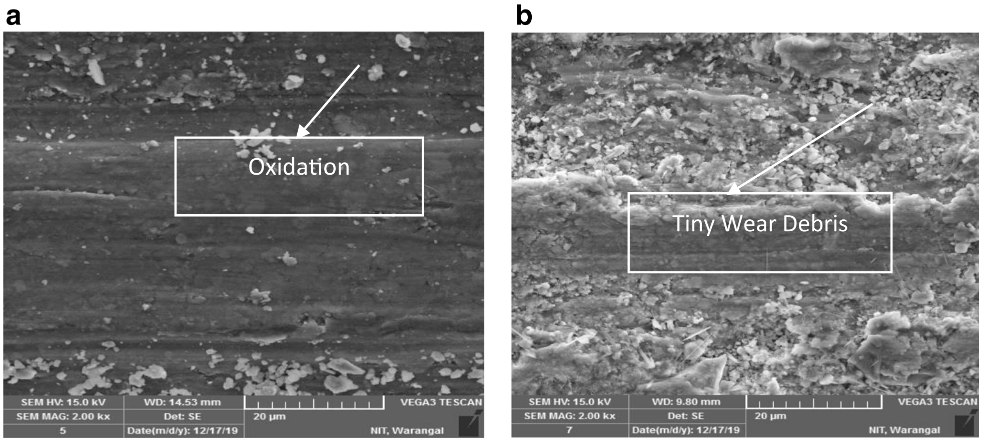

Fig. 14 (**a**) Worn surface and (**b**) Wear debris SEM images of 5%SiC composites

Table 5 Experimental design using L_{15} orthogonal array

Parameters	Wt.% Reinforcement	Load(N)	Sliding Distance(m)	Actual wear(mm^3)	S/N ratio [dB]
1	15	15	1500	0.135	17.3933
2	10	15	1000	0.101	18.4651
3	5	15	500	0.065	23.7417
4	15	20	1000	0.141	17.0156
5	15	10	1000	0.131	17.6546
6	10	20	500	0.087	21.2096
7	10	10	500	0.086	21.3100
8	10	10	1500	0.134	17.4579
9	10	15	1000	0.126	18.4651
10	15	15	500	0.096	20.3546
11	10	15	1000	0.129	18.4651
12	5	10	1000	0.121	18.3443
13	10	20	1500	0.132	17.5885
14	5	15	1500	0.112	19.0156
15	5	20	1000	0.096	20.3546

Table 6 Response Table for Signal to Noise Ratios Smaller is better

Level	Wt.% Reinforcement	Load(N)	Sliding Distance(m)
1	20.36	18.69	21.65
2	19.21	19.79	18.37
3	18.10	19.04	17.86
Delta	2.26	1.10	3.79
Rank	2	3	1

composites, a mechanically mixed layer (MML) is formed on the 5 Wt.% SiC composite, which serves as a protective layer and solid lubricant resulted in the reduction of wear [24].

4.1 Analysis of Variance

Experimental wear rate results and their transformations into S/N ratio are shown in Table 5. The analysis based on Taguchi methods was conducted in the program MINITAB 17 to determine the primary factor affecting the wear rate to analyze the variables (ANOVA) and determine optimal conditions.

Based on the S/N ratio results it can be determined which control factor has the greatest impact on the wear rate (Table 6). Optimal wear rate parameters of these controlled factors can be determined on the base of S/N ratios as shown in Table 6 and Fig. 15.

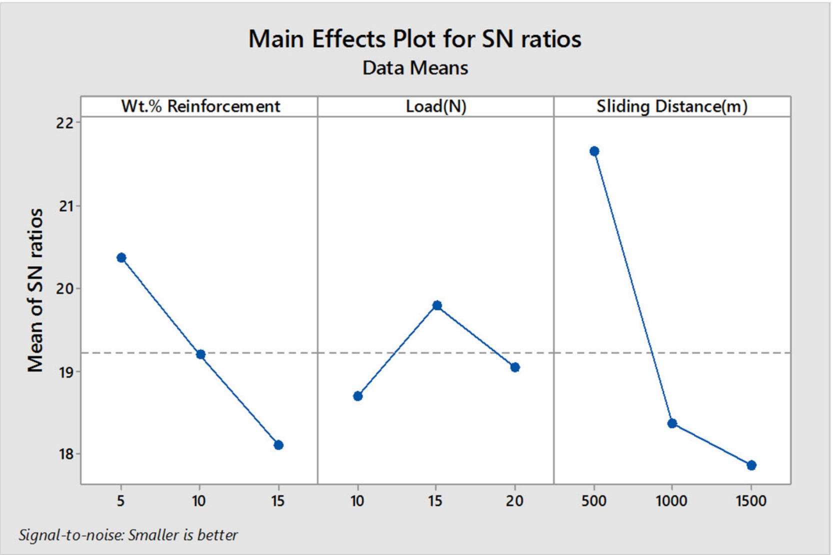

Fig. 15 Main effects for wear

Table 7 Analysis of variance for wear

Source	DF	Adj SS	Adj MS	F-Value	*P* Value	% Cont.
Wt.% Reinforcement	1	0.001485	0.001485	14.75	0.012	26.87
Load(N)	1	0.000032	0.000032	0.32	0.597	0.58
Sliding Distance(m)	1	0.004005	0.004005	39.78	0.001	72.47
Error	5	0.000503	0.000101			
Lack-of-Fit	3	0.000031	0.000010	0.04	0.985	0.07
Pure Error	2	0.000473	0.000236			
Total	14	0.007314				100
Model Summery						
	R-sq	R-sq (adj)	R-sq (pred)			
0.0100341	93.12%	80.73%	78.73%			

Table 8 Equation of regression coefficients

Term	Coef	SE Coef	T-value	P value
Constant	0.0468	0.0189	2.48	0.031
Wt.% Reinforcement	0.002725	0.000903	3.02	0.012
Load(N)	−0.000400	0.000903	−0.44	0.666
Sliding Distance(m)	0.000045	0.000009	4.96	0.000

S = 0.0127641 R-sq = 75.50% R-sq(adj) = 68.82

The objective of the analysis of variance (ANOVA) is to analyze, which input process parameters significantly affects the wear. The developed model analysis considered for the level of confidence is 95%. The statistical importance of the suggested model is represented with the help of F-value. Larger values of F confirm the influence of the factor over the response, and $p < .0001$ gives the 95% of confidence levels of significance. The developed model for wear rate responses were found significant at a 95% confidence level. Tables 7 and 8 shows the ANOVA analysis, which is used to estimate the percentage contribution of each parameter on the output response. The factor which is having the highest and low percentages will have more and less influence on the wear. From Tables 7 and 8 it is analyzed that sliding distance has the highest (72.27%) effect on the wear followed by Wt.% Reinforcement (26.87%) and load (0.5%). Small changes in sliding distance and Wt.% reinforcement has huge impact on wear.

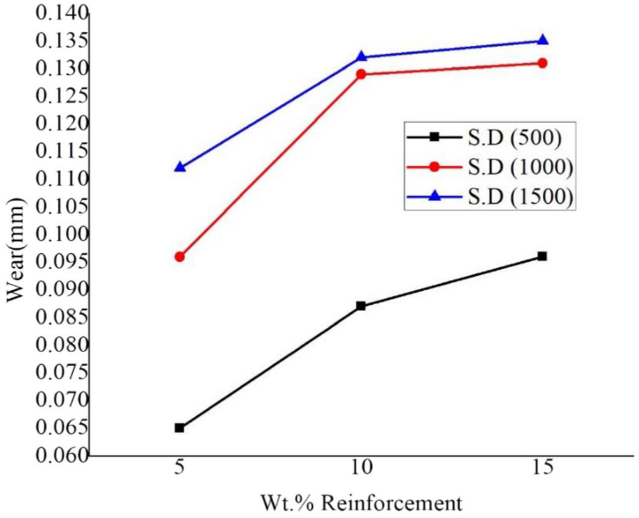

Fig. 16 Effect of Wt.% Reinforcement and Sliding Distance on Wear rate

From Fig. 16, it is clear that with an increase in Wt.% reinforcement and sliding distance the wear rate increases. With an increase in Wt.% reinforcement, there is a high chance of formation of agglomeration and porosity, which weakens the composite and increases the wear rate, as the sliding distance increases the rubbing time of composite and counter disc increases which leads to increased wear rate.

4.2 Response Surface Analysis

Figure 17 shows the normal probability plots for wear rate. From these plots, it is clear that all plots display no sign of the

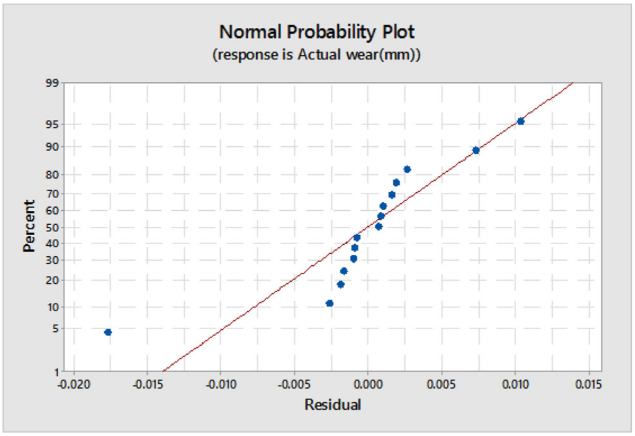

Fig. 17 Normal Probability Plots for wear

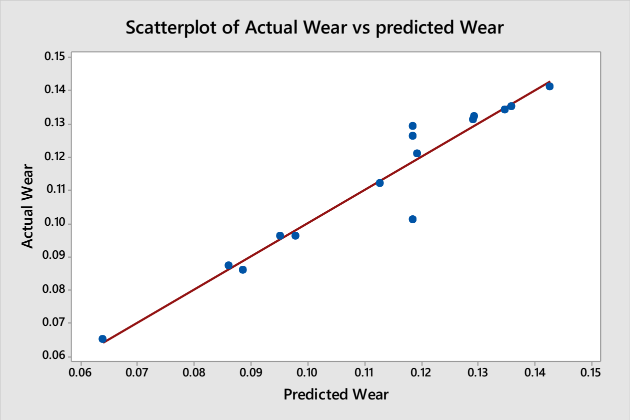

Fig. 18 Actual vs Predicted values for wear

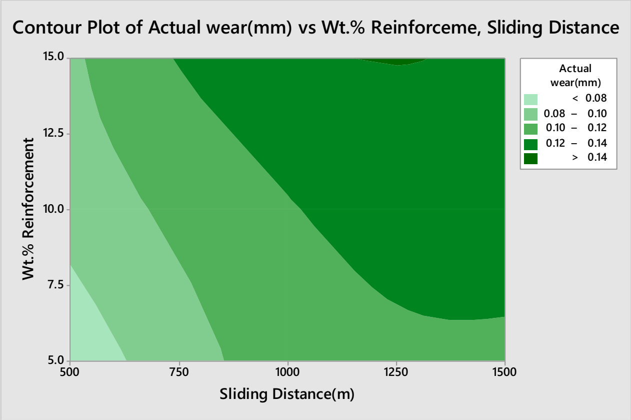

Fig. 20 Counter plots for sliding distance and Wt.% reinforcement on wear

violation since each point on the plot follows a straight-line pattern indicating that the errors are distributed normally. Figure 18 shows the relationship between actual and predicted responses of wear rate. It is confirmed that the generated model is more than enough as the predicted values are in good agreement with actual ones. The coexistence of points with the fitted line authenticates that the model is valid with the smallest errors.

In this investigation, the Wear rate output response is assigned smaller the best criterion. From Tables 7 and 8, it is clear that sliding distance has the most significant influence on wear rate, followed by Wt.% reinforcement and load. A small variation in sliding distance can have the most significant deviation in wear loss. Similarly, considerable variation in load has the least effect on wear loss.

Since the sliding distance and Wt.% reinforcement have the most significant impact. Figures 19 and 20 shows the counter plots and surface plots of the dependency of the sliding distance and the Wt.% reinforcement on the wear rate, respectively. The slight interaction between the sliding distance and the Wt.% reinforcement lines in the diagram (Fig. 20) are slightly curved. The lowest wear rate is observed when the sliding distance is at 500 m and the wt.% reinforcement is 5. whereas the highest value is observed when sliding distance is at 1500 m and the wt.% reinforcement is 15.

4.3 Linear Regression Model

The model of linear regression was obtained through statistic software MINITAB 17. Linear regression model was developed to establish a correlation between significant terms (Terms) achieved by ANOVA analysis and those are the applied load, the sliding speed and the sliding distance [25]. The coefficients of the equation of regression are shown in Tables 7 and 8. The equation of regression for the wear rate is as follows:

$$\begin{aligned}\mathrm{Wear(mm)} &= 0.0468 + 0.002725\ \mathrm{Wt.\%Reinforcement} - 0.000400\ \mathrm{Load(N)} \\ &\quad + 0.000045\ \mathrm{Sliding\ Distance(m)}\end{aligned} \tag{1}$$

4.4 Conformation Test

The optimal parameters obtained from the RSM analysis for least wear loss are validated with the experimental test to

Fig. 19 Effect of variation of Wt.% reinforcement and sliding distance on wear

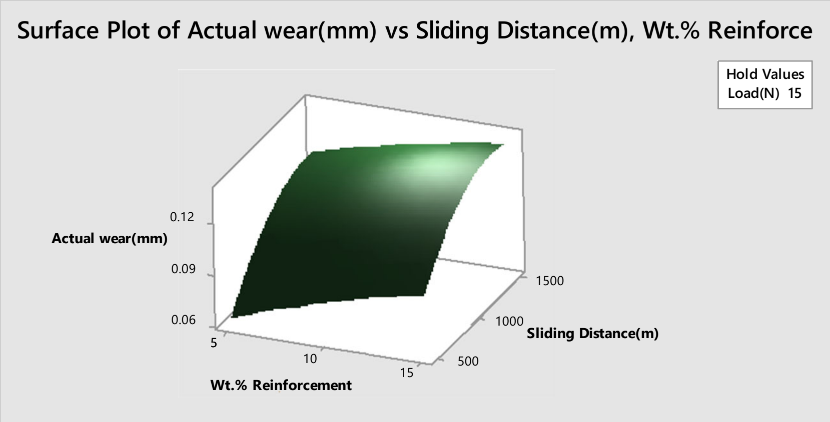

Table 9 Parameters for minimum wear loss

Parameter	Wt.% Reinforcement	Load(N)	Sliding Distance(m)	(Actual)
Wear(mm^3)	5	15	500	0.067

authenticate the effectiveness of the model. The optimal combination for minimum wear is 5Wt.%reinforcement, sliding distance 500 m, load 15 N. The optimal parameters combation is done in the L_{15} experiments. No need to conduct conformation test. Table 9 shows the optimal parameters for minimum wear loss.

5 Conclusions

In the current work, (5, 10 and 15) Wt.% SiC-Al7075 composites are produced successfully through powder metallurgy route. The influence of SiC weight percentage on wear and mechanical behaviour of the composites are examined. The microstructural and mechanical characteristics of Al7075 composites diminished with an increment in Wt.% reinforcement. The wear loss of composites enhanced with an increment in Wt.% reinforcement.

Delamination and abrasion wear mechanism was observed in 15Wt.%SiC composites with deep grooves and large debris on wear surfaces. Oxidation and adhesion wear mechanism was noted on the 5Wt.%SiC composites with small groves and tiny debris found on the wear surface. A mechanically mixed layer (MML) is developed on 5 Wt.% SiC composite, which acts as a lubricant and decreases the wear loss.

The ANOVA results conclude that the favorably influencing wear loss parameters are sliding distance (72.47) and Wt.% reinforcement (26.87). The load (0.58) has the least influence on the wear loss. A small variation in the sliding distance can significantly impact wear loss.

The response surface methodology results conclude that the optimal combination for minimum wear loss is 5Wt.%reinforcement(level-1), sliding distance 500 m (level-1) and load 15 N(level-2).

6 Future Scope

Further, the Al7075/SiC composites are produced by varying reinforcement particle type, volume fraction and size in each composite and their effect of physical, mechanical and tribological properties can be investigated.

Author Contributions All authors contributed to the study conception and design. Material preparation, data collection and analysis were performed by [Mulugundam Siva Surya], [G. Prasanthi] and [S.K.Gugulothu]. The first draft of the manuscript was written by [Mulugundam Siva Surya] and all authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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The authors have no affiliation with any organization with a direct or indirect financial interest in the subject matter discussed in the manuscript.

This manuscript has not been submitted to, nor is under review at, another journal or other publishing venue.

Funding The authors have no relevant financial or non-financial interests to disclose.

The authors have no financial or proprietary interests in any material discussed in this article.

No funds, grants, or other support was received.

Compliance with Ethical Standards

Conflict of Interest The authors declare that they have no conflict of interest.

The authors have no conflicts of interest to declare that are relevant to the content of this article.

Human Participants or Animals No human participants or animals are involved in carrying out this research work.

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