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Tribological behavior of a newly developed AA2014/waste eggshell/SiC hybrid green metal matrix composite at optimum parameters

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Abstract: The effect of waste carbonized eggshell and silicon carbide (SiC) wt.% on the dry sliding wear behavior of AA2014 alloy green composites produced by electromagnetic stir casting method was investigated. The percentage of waste carbonized eggshell particles and SiC particles varied from 2.5% to 12.5%. The tribological behavior of AA2014/waste carbonized eggshell/SiC hybrid green metal matrix composites (MMCs) was investigated on a pin-on-disc apparatus. The weight percentages of waste carbonized eggshell and of SiC, normal load, and sliding speed and distance were taken as input process parameters, and wear rate was taken as a response. Response surface methodology was used to plan and analyze the experiment. Minimum wear rate was found to be 8.89×10^{-5} mm^3/m with desirability one at optimum parameters of 1.75 m/s (sliding velocity), 6.5 (carbonized eggshell wt.%), 34.24 N (normal load), 1219.63 m (sliding distance), and 11 wt.% (SiC wt.%). In the confirmation experiment, the experimental wear rate of the hybrid green MMC at optimum parameters was found to be 9.5×10^{-5}. Results showed that the experimental wear rate and density of the hybrid green MMC were reduced by about 36.66% and 0.35%, respectively, compared with the matrix.

Keywords: normal load; sliding distance; sliding velocity; waste eggshell; wear.

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1 Introduction

Nowadays, automobile manufacturing companies are interested in developing a low-weight, enhanced tribological property-based braking system [1]. Such a system should have very good wear resistance. Aluminum metal matrix composites (MMCs) have a wide range of applications for their superior qualities, such as high mechanical properties, high corrosion resistance, and low density [2]. At present, there is a need to increase R&D efforts in developing light-weight and low-cost MMCs according to engineering applications [3].

A significant amount of environmental pollution is due to the waste of industries/societies, thus encouraging researchers to utilize these waste products in many research areas. More recent advancements involve the use of waste or recycled materials like fly-ash, red mud, rice-hull ash, bagasse ash, basalt fiber, breadfruit seed hull ash, maize stalk waste, and eggshell waste particles. These waste materials create more opportunities because their composites can be produced at lower costs [4].

Chicken eggshell waste is an industrial byproduct, and its disposal constitutes a serious environmental hazard. Fortunately, chicken eggshell can be used in commercial products to produce new materials, and it has been highlighted in recent investigations for its renovation prospects. There have been several attempts to use chicken eggshell components for a variety of applications, and their chemical composition and accessibility make them a probable source of biofiller-reinforced composites, resulting in additional or improved thermal and mechanical properties [5]. The other advantages of using chicken eggshell are its availability in bulk quantity, its light weight, and the fact that it is economical and environmentally friendly [6].

For further enhancing the wear properties of aluminum alloys, ceramic particles can be used as reinforcements. Various ceramic particles, such as SiC, B_4C, Al_2O_3, TiO_2, and TiB_2, have been used as reinforcements in aluminum-based MMCs [7], which showed better mechanical and tribological properties than the non-reinforced ceramic particles. Silicon carbide (SiC) has been reported to be a promising ceramic reinforcement material due to various advantage, such as good wear resistance and wettability [8].

In the previous study [5], the mechanical properties of the AA2014/eggshell/SiC hybrid green MMC have been investigated [6]. Based on the literature, few researchers have fabricated hybrid green MMCs using carbonized eggshell and SiC as reinforcement materials and developed the mathematical model for five parameters (including eggshell and SiC wt.%) to reduce the wear rate of green hybrid MMCs. The aim of this study is to investigate the effects of the waste carbonized eggshell and SiC wt.%, sliding velocity and distance, normal load, and their interactions on the wear behavior of the AA2014/waste carbonized eggshell/SiC hybrid green MMC by using the Box-Behnken Design method (RSM).

2 Materials and methods

2.1 Matrix material

In the present investigation, AA2014 aluminum alloy was selected as a matrix material. AA2014 aluminum alloy is typically used in the aviation industry [5]. The hardness of this alloy is very high compared with other existing aluminum alloys [6], but its resistance against rust is poor. The chemical composition of AA2014 is shown in Table 1. Meanwhile, the wear rate of AA2014 alloy is 15×10^{-5} mm^3/m at optimum parameters of 1.75 m/s (sliding velocity), 34.24 N (normal load), and 1219.63 m (sliding distance). The hardness of AA2014 alloy is 60 BHN.

2.2 Primary reinforcement material

In the present investigation, carbonized eggshell powder, which contained ceramic materials, was selected as a primary reinforcement material, as shown in Figure 1A. The compounds of the eggshell (by weight) are given below.

- Calcium carbonates (94%)
- Magnesium carbonates (1%)
- Calcium phosphate (1%)
- Organic matter (4%)

To remove the upper cover of the eggshells, these were cleaned and dried in sunlight [6]. The dried eggshells were ball-milled to obtain eggshell powder, as shown in Figure 1B. The powder was then carbonized to 500°C for 3 h to remove the carbonaceous materials, as shown in Figure 1C.

2.3 Secondary reinforcement material

SiC was selected as a secondary reinforcement material to further improve the mechanical and wear properties of the composites. A previous study reported that the mechanical properties of the MMCs increased when SiC is used as a reinforcement in an aluminum matrix [9]. SiC also increased the modulus elasticity and resistance against dust, and can work at higher temperatures [10]. The density of the SiC is 3.2 g/cm^3, which are very close to the density of aluminum alloy AA2014. SiC also works against acids, alkalis, or molten salts of up to 800°C [11]. For these reasons, SiC is considered one of the best reinforced materials in aluminum-based MMCs [12]. Furthermore, SiC is easily available and its wettability with aluminum alloys is good [13].

Table 1: Chemical composition of AA2014 alloy (wt.%).

Si	Fe	Cu	Mn	Mg	Zn	Ti	Ni	Cr	Al
0.5–0.9	0.5	3.9–5.0	0.4–1.2	0.2–0.8	0.25	0.2	0.1	0.1	Balance

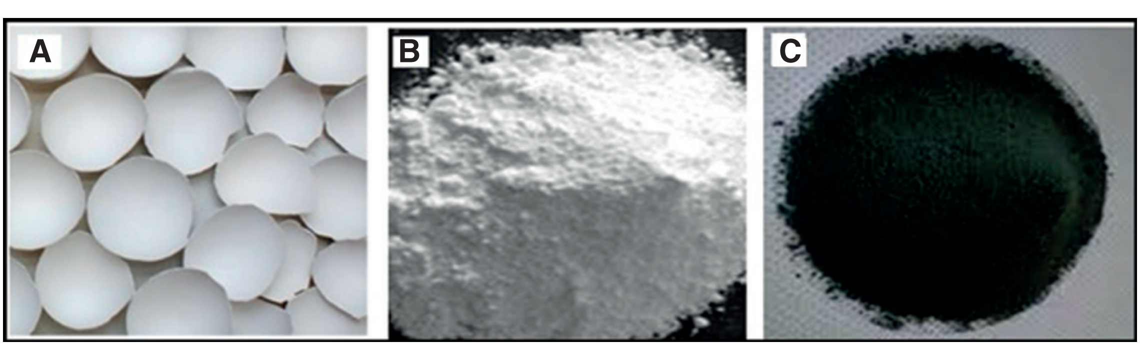

Figure 1: Photographs of: (A) eggshells, (B) eggshell powder, (C) carbonized eggshell powder.

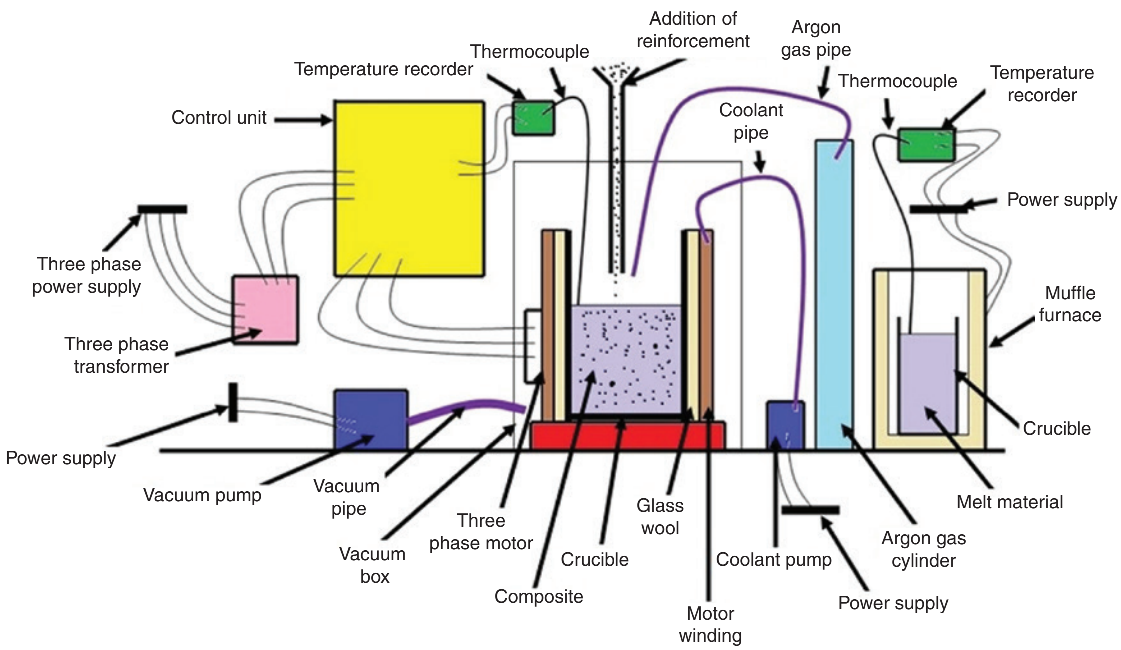

Figure 2: Schematic diagram of the electromagnetic stir casting setup [5].

2.4 Fabrication of hybrid MMCs

The AA2014/carbonized eggshells/SiC hybrid green MMC used in this study was fabricated by electromagnetic stir casting technique at parameters of 12 A (stirring current), 200 RPM (stirring speed), 180s (stirring time), and 700°C (matrix pouring temperature), and then immediately extruded on a UTM machine at 60 MPa, using a cylindrical H13 tool steel die coated with graphite [5].

The matrix material was heated above its liquidus temperature in a muffle furnace. Carbonized eggshell and SiC particles were also preheated to about 300°C and 500°C, respectively, to avoid the wettability problem. The liquid AA2014 aluminum alloy with a temperature of 700°C was poured into a graphite crucible. After pouring the matrix material, preheated reinforcement particles were mixed with melted aluminum alloy, as shown in Figure 2. A thermocouple was inserted into the graphite crucible for the temperature measurement of the composite during stirring.

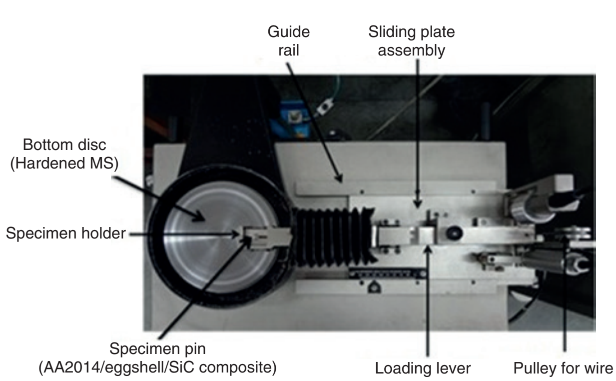

Figure 3: Experimental set up of the pin-on-disc machine with specimen pin (AA2014/eggshell/SiC composite).

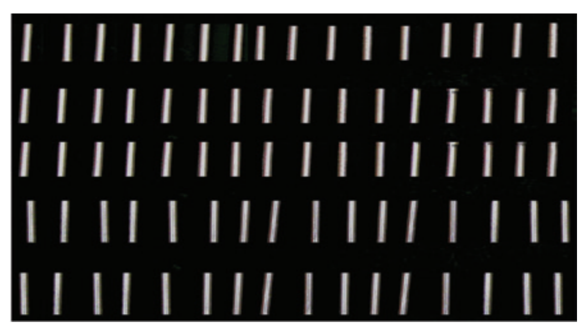

Figure 4: Specimen pins (AA2014/eggshell/SiC hybrid green metal matrix composite) used in the wear test.

The size of each reinforcement particle was set at 25 µm. Although it was not easy to obtain the exact particle size (25 µm) of all reinforcement particles (SiC, carbonized eggshell powder), the particle size with deviation 2 µm (25 µm ± 2 µm) was selected. SiC particles were directly purchased from the market and had an average particle

Table 2: Process parameters with their ranges.

S. No.	Input parameters	Range
1	A: Sliding velocity (m/s)	1.5–7.5
2	B: Carbonized eggshell (wt.%)	2.5–12.5
3	C: Normal load (N)	15–45
4	D: Sliding distance (m)	1000–2500
5	E: SiC (wt.%)	2.5–12.5

Table 3: Design matrix for wear rate.

Run	A: Sliding velocity (m/s)	B: Carbonized eggshell (wt.%)	C: Normal load (N)	D: Sliding distance (m)	E: SiC (wt.%)	Response: Wear rate ×10^{-5} (mm^3/m)
1	4.50	7.50	45.00	1750.00	2.50	9.25
2	7.50	12.50	30.00	1750.00	7.50	9.3
3	1.50	12.50	30.00	1750.00	7.50	9.35
4	7.50	7.50	15.00	1750.00	7.50	9.3
5	4.50	7.50	45.00	1000.00	7.50	9.17
6	1.50	7.50	15.00	1750.00	7.50	9.3
7	4.50	7.50	30.00	1000.00	2.50	9.1
8	1.50	7.50	30.00	1000.00	7.50	8.9
9	4.50	7.50	30.00	1750.00	7.50	9.55
10	4.50	2.50	30.00	1750.00	2.50	9.4
11	7.50	7.50	45.00	1750.00	7.50	9.4
12	4.50	12.50	30.00	2500.00	7.50	9.3
13	4.50	12.50	15.00	1750.00	7.50	9.45
14	4.50	7.50	30.00	1750.00	7.50	9.57
15	7.50	7.50	30.00	1000.00	7.50	9.1
16	7.50	7.50	30.00	2500.00	7.50	9.11
17	1.50	7.50	45.00	1750.00	7.50	9.1
18	4.50	12.50	30.00	1000.00	7.50	9.16
19	4.50	7.50	30.00	1000.00	12.50	9
20	4.50	7.50	30.00	2500.00	2.50	9.01
21	7.50	7.50	30.00	1750.00	2.50	9.1
22	4.50	7.50	30.00	1750.00	7.50	9.54
23	4.50	2.50	30.00	1750.00	12.50	9.4
24	4.50	2.50	30.00	1000.00	7.50	9.23
25	4.50	12.50	45.00	1750.00	7.50	9.5
26	1.50	7.50	30.00	1750.00	12.50	9
27	4.50	7.50	30.00	1750.00	7.50	9.56
28	4.50	2.50	15.00	1750.00	7.50	9.5
29	1.50	2.50	30.00	1750.00	7.50	9.2
30	4.50	7.50	30.00	1750.00	7.50	9.54
31	1.50	7.50	30.00	2500.00	7.50	9.04
32	7.50	2.50	30.00	1750.00	7.50	9.55
33	4.50	7.50	30.00	2500.00	12.50	9.25
34	4.50	7.50	15.00	1750.00	2.50	9.3
35	4.50	7.50	15.00	1000.00	7.50	9.17
36	4.50	7.50	30.00	1750.00	7.50	9.54
37	4.50	12.50	30.00	1750.00	2.50	9.27
38	4.50	2.50	30.00	2500.00	7.50	9.25
39	4.50	7.50	15.00	2500.00	7.50	9.25
40	4.50	7.50	15.00	1750.00	12.50	9.36
41	4.50	12.50	30.00	1750.00	12.50	9.44
42	4.50	2.50	45.00	1750.00	7.50	9.4
43	4.50	7.50	45.00	1750.00	12.50	9.35
44	4.50	7.50	45.00	2500.00	7.50	9.2
45	7.50	7.50	30.00	1750.00	12.50	9.4
46	1.50	7.50	30.00	1750.00	2.50	9.2

size of 25 ± 2 µm. Carbonized eggshell particles were ball-milled to obtain a uniform particle size (25 µm ± 2 µm).

2.5 Pin-on-disc apparatus and its parameters

The wear test of the AA2014/carbonized eggshell/SiC hybrid green MMC was carried out on a pin-on-disc apparatus. A hardened mild steel (MS) circular plate was used as a bottom disc, whereas the AA2014/carbonized eggshell/SiC hybrid green MMC was selected as a specimen pin, as shown in Figure 3. Specimen pins used in the wear test are shown in Figure 4. Different process parameters of pin-on-disc machine affect the wear rate and coefficient of friction. A pilot experiment was carried out using a single factor (carbonized eggshell and SiC wt.%, normal load, and sliding velocity and distance) to determine the optimum level of factors in the pin-on-disc machine. Their ranges are given in Table 2.

Table 4: ANOVA table for wear rate.

Source	Sum of square	DF	Mean square	F-value	Prob. >F	
Model	1.39	20	0.070	195.17	<0.0001	Significant
A	0.086	1	0.086	239.77	<0.0001	
B	1.6×10^{-3}	1	1.6×10^{-3}	4.48	0.0443	
C	4.26×10^{-3}	1	4.23×10^{-3}	11.84	0.0020	
D	0.021	1	0.021	58.92	<0.0001	
E	0.020	1	0.020	56.91	<0.0001	
AB	0.040	1	0.040	112.10	<0.0001	
AC	0.023	1	0.023	63.05	<0.0001	
AD	4.26×10^{-3}	1	4.26×10^{-3}	11.84	0.0020	
AE	0.063	1	0.063	175.15	<0.0001	
BC	5.63×10^{-3}	1	5.63×10^{-3}	15.76	0.0005	
BD	3.60×10^{-3}	1	3.6×10^{-3}	10.09	0.0039	
BE	7.23×10^{-3}	1	7.23×10^{-3}	20.25	0.0001	
DE	0.029	1	0.029	80.99	<0.0001	
A^2	0.37	1	0.37	1032.01	<0.0001	
C^2	0.040	1	0.040	112.81	<0.0001	
D^2	0.77	1	0.77	2170.71	<0.0001	
E^2	0.24	1	0.24	669.22	<0.0001	
B^2	8.02×10^{-4}	1	8.02×10^{-4}	2.25	0.1465	
CD	6.25×10^{-4}	1	6.25×10^{-4}	1.75	0.1977	
CE	4.0×10^{-4}	1	4.0×10^{-4}	1.12	0.2998	
Residual	8.92×10^{-3}	25	3.57×10^{-4}			
Lack of Fit	8.12×10^{-3}	20	4.06×10^{-4}	2.54	0.1530	Not significant
Pure error	8.0×10^{-4}	5	1.60×10^{-4}			
Cor total	1.40	45				
Std. dev.			0.019	R-Square		0.9936
Mean			9.29×10^{-5}	Adj-R squared		0.9885
C.V.			0.20	Pred R–squared		0.9760
PRESS			0.034	Adeq precision		50.552

2.6 Planning of the experiment

Response surface methodology (RSM) refers to the set of statistical and mathematical techniques that are used to develop, improve, or optimize a product or process. RSM is helpful for the modeling and analysis of programs [5]. The experimental work is carried out as per the Box-Behnken Design, using response surface methodology. Based on the experimental design given in Table 3, 46 experiments were performed to test the wear rate of the AA2014/eggshell/SiC hybrid green MMCs. The measured wear rates are shown in Table 3.

3 Results and discussion

3.1 Mathematical modelling

In the present study, ANOVA Table (Table 4) was used to analyze the results for the regression model test, the test for the significance of individual models (sliding velocity and distance, carbonized eggshell and SiC wt.%, and normal load), and test for lack-of-fit.

The Model F-value shown in 195.17 indicates that the model is very important. It is diffcult to say that the large "Model F-Value" is obtained because of noise. Values of "Prob > F" but not more than 0.0500 shows the importance of model terms. Here A, B, C, D, E, A^2, C^2, D^2, E^2, AB, AC, AD, AE, BC, BD, BE, and DE are all significant model

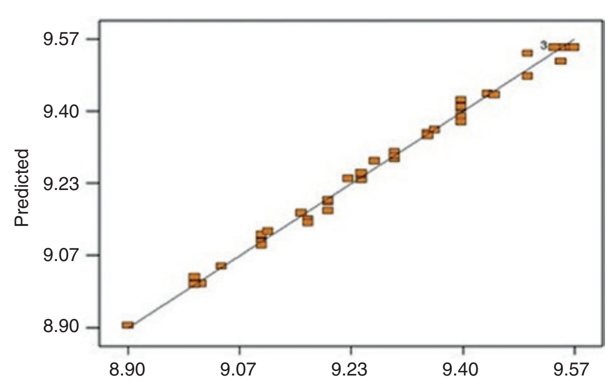

Figure 5: Correlation between the predicted and actual values.

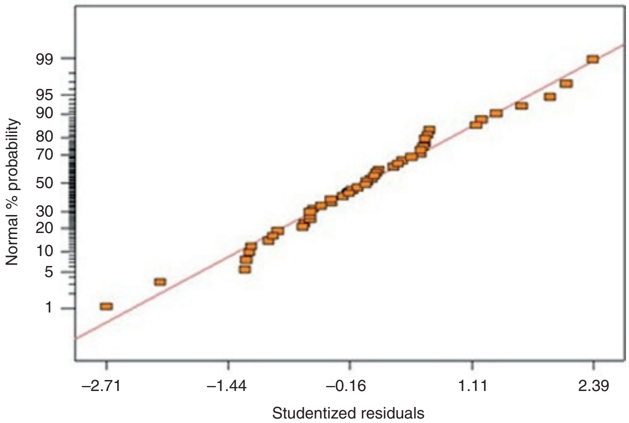

Figure 6: Normal probabilities of residuals.

terms. When the value is more than 0.100, this indicates that the model terms are not significant.

When the "Lack of Fit F-value" approaches 2.54, this means this value is not very important. When "Lack of Fit F-value" is large, this may be attributed to noise. Non-important lack of fit is fine. "Pred R-Squared" is 0.9760, which is in good agreement with the "Adj R-Squared." The "Adj R-Squared" is 0.9885. Meanwhile, the "Adeq Precision" determines the signal to noise ratio, which should be more than four.

Figure 5 shows the relationships between the wear rate of predicted value and that of actual value. The model adequacy is obtained, keeping in mind that the basic statement of regression concept has not been violated. The graph of the residual and normal percentage probabilities is shown in Figure 6, which indicates a straight line. Actual value, predicted value, and residuals (difference between actual and predicted) are shown in Table 5. Residual vs. run and residual vs. predicted graph are shown in Figures 7 and 8, respectively. Both graphs show that the experiment was conducted randomly and that no similar patterns were observed.

The regression coefficients of the second order equation (Equation 1) for wear rate were developed by using the experimental data (Table 3) given below.

$$\begin{aligned}\text{Wear rate} = {} & +7.35 + 0.19\times A - 8.0\times10^{-3}\times B + 6.72\times10^{-3} \\ & \times C + 1.77\times10^{-3}\times D + 0.01\times E - 0.02\times A^2 - 3.83\times10^{-4} \\ & \times B^2 - 3.02\times10^{-4}\times C^2 - 5.30\times10^{-7}\times D^2 - 6.62\times10^{-3} \\ & \times E2 - 6.67\times10^{-3}\times A\times B + 1.67\times10^{-3}\times A\times C - 1.44 \\ & \times10^{-5}\times A\times D + 8.33\times10^{-3}\times A\times E + 5.0\times10^{-4}\times B\times C \\ & + 8.0\times10^{-6}\times B\times D + 1.70\times10^{-3}\times B\times E - 1.11\times10^{-6} \\ & \times C\times D + 1.33\times10^{-4}\times C\times E + 2.27\times10^{-5}\times D\times E\end{aligned}$$

Table 5: Diagnostics case statistics.

Standard order	Actual value ($\times10^{-5}$)	Predicted value ($\times10^{-5}$)	Residuals ($\times10^{-5}$)
1	9.20	9.17	0.028
2	9.55	9.52	0.032
3	9.35	9.35	-1.875×10^{-3}
4	9.30	9.30	1.875×10^{-3}
5	9.17	9.15	0.018
6	9.17	9.14	0.026
7	9.25	9.25	8.333×10^{-4}
8	9.20	9.19	8.333×10^{-3}
9	9.40	9.39	8.125×10^{-3}
10	9.27	9.29	−0.017
11	9.40	9.38	0.022
12	9.44	9.44	-3.125×10^{-3}
13	9.30	9.29	5.208×10^{-3}
14	9.30	9.29	8.958×10^{-3}
15	9.10	9.11	−0.012
16	9.40	9.41	-8.542×10^{-3}
17	9.10	9.10	2.083×10^{-4}
18	9.01	9.00	7.708×10^{-3}
19	9.00	9.00	-1.042×10^{-3}
20	9.25	9.24	6.458×10^{-3}
21	9.50	9.54	−0.036
22	9.45	9.44	8.750×10^{-3}
23	9.40	9.43	−0.029
24	9.50	9.48	0.016
25	8.90	8.90	-4.792×10^{-3}
26	9.10	9.12	−0.016
27	9.04	9.04	-2.292×10^{-3}
28	9.11	9.12	−0.014
29	9.30	9.31	-7.292×10^{-3}
30	9.25	9.25	-4.792×10^{-3}
31	9.36	9.36	1.458×10^{-3}
32	9.35	9.35	3.958×10^{-3}
33	9.20	9.20	4.583×10^{-3}
34	9.10	9.09	8.333×10^{-3}
35	9.00	9.02	−0.017
36	9.40	9.41	−0.013
37	9.23	9.25	−0.016
38	9.16	9.17	-6.250×10^{-3}
39	9.25	9.26	-8.750×10^{-3}
40	9.30	9.30	1.250×10^{-3}
41	9.54	9.55	−0.010
42	9.56	9.55	1.000×10^{-2}
43	9.54	9.55	−0.010
44	9.55	9.55	0.000
45	9.57	9.55	0.020
46	9.54	9.55	−0.010

3.2 Effects of parameters on wear rate

In this study, the effects of sliding velocity and distance, carbonized eggshell and SiC wt.%, and normal load on the wear rate of the AA2014/eggshells particulate/SiC hybrid

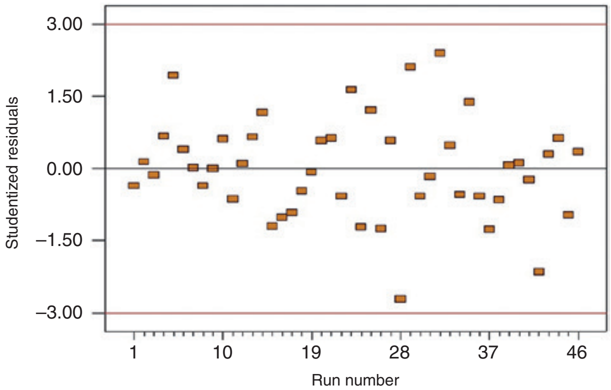

Figure 7: Residual vs. run.

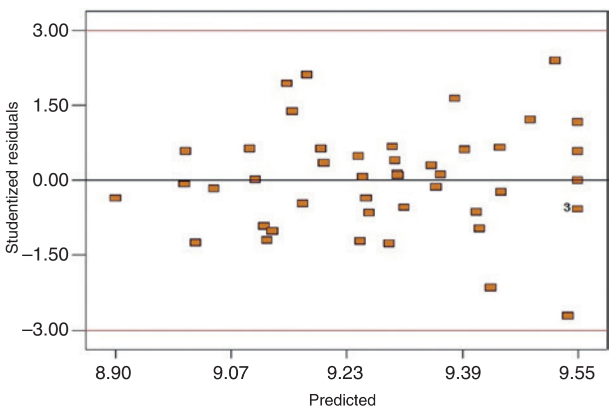

Figure 8: Residual vs. predicted.

green MMC were studied. Figure 9 shows the individual parameters' effects on wear rate. Figures 10 (a–d) show the interactions of parameter A with parameters B, C, D, and E, respectively, to reduce the wear rate of composite. Figures 11 (a and b) display the interaction of parameter C with parameters D and E, respectively, to reduce wear rate. Figures 12 (a–c) present the interactions of parameter B with parameters C, D, and E, respectively, to reduce wear rate. Figure 13 shows the interaction of parameter D with parameter E to reduce wear rate.

3.2.1 Effects of sliding velocity on wear rate

The dependence of wear rate on sliding velocity is shown in Figures 10 (a–d). As can be seen, there is an increase of wear rate with the increase of sliding velocity. This happens due to the high strain rate subsurface deformation. The contact area by fracture and fragmentation of asperities increases with the increase in the rate of subsurface deformation. The increase of wear rate can also be justified by the increase in sliding velocities due to the rising temperatures between the contact surfaces; moreover, the thermal softening of the AA2014/carbonized eggshell/SiC hybrid green MMC has led to greater wear rates. From Figure 9A, it can be observed that when the sliding speed further increases beyond the center value (about 5 m/s), wear rate decreases for the AA2014/carbonized eggshell/SiC hybrid green MMC.

3.2.2 Effects of carbonized eggshell weight percentage on wear rate

As shown in Figures 12 (a–c), the addition of carbonized eggshell particles of up to the weight fraction of about 6.5% in AA2014/SiC composites resulted in minimal wear rates of the hybrid green MMC. Further, the wear rate slightly increased when the weight fraction of carbonized eggshell particles in AA2014/SiC composite also increased. The presence of 94% $CaCO_3$ in carbonized eggshell reduces [5] the wear rate of the AA2014/carbonized eggshell/SiC hybrid green MMCs. However, it increases at a higher weight fraction of carbonized eggshell (more than 6.5% in AA2014/SiC composite). This phenomenon may be due to the clustering of carbonized eggshell particles in AA2014/SiC composite.

3.2.3 Effects of normal load on wear rate

The wear rate of the AA2014/carbonized eggshell/SiC hybrid green MMC increases with the increase in normal load from the minimum to maximum limit up to the center value. With the increase in normal load, the wear rate increases because at higher loads, there is a tendency of plastic deformation which can lead to higher wear rate. The higher the amount of plastic deformation, the greater the probability of substance cracking, which results in larger material removal. From Figure 11, it can be observed that when the normal load further increases beyond the center value, the wear rate decreases for the AA2014/carbonized eggshell/SiC hybrid green MMC.

3.2.4 Effects of sliding distance on wear rate

Figure 13 shows the dependence of wear rate on sliding distance under the testing condition of the hybrid green

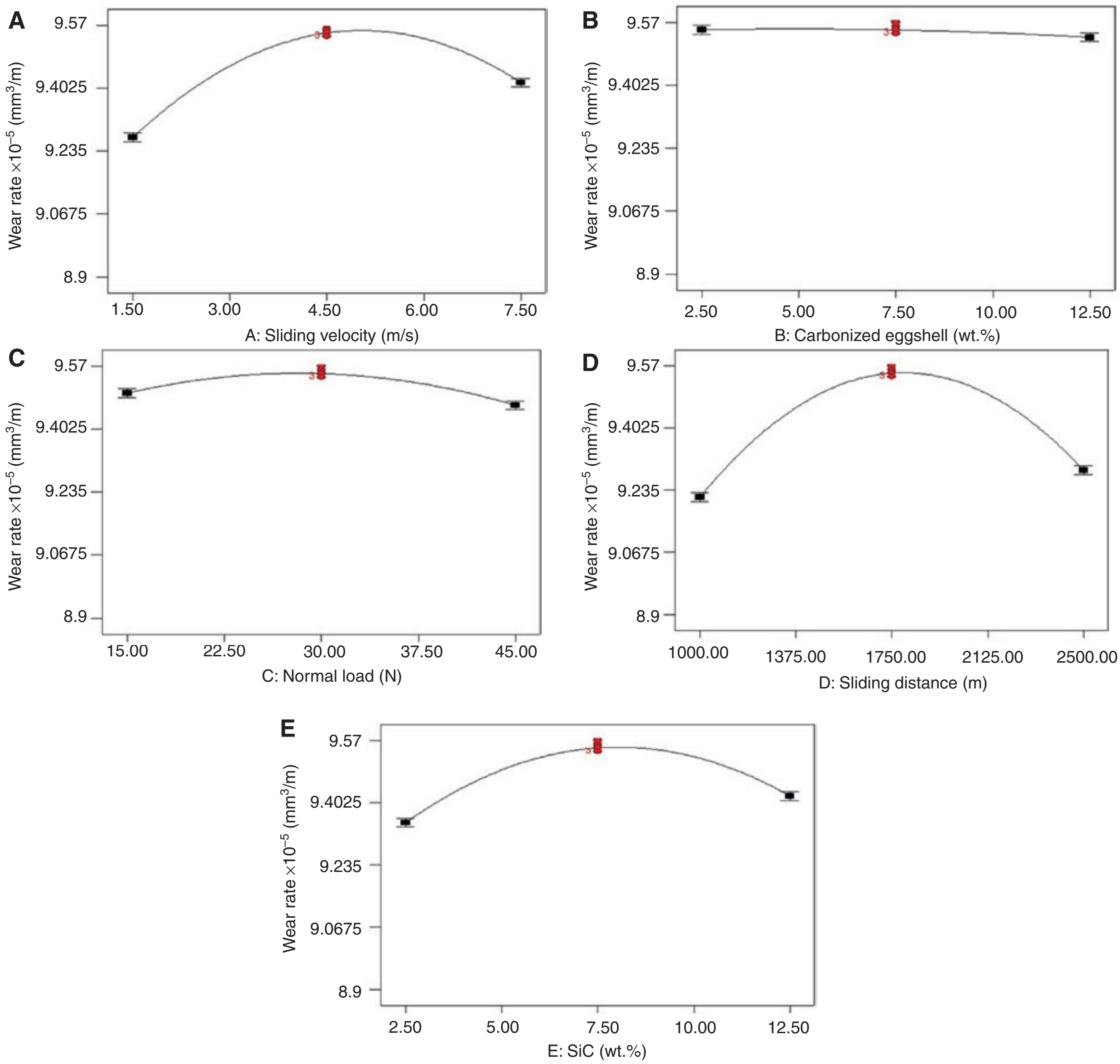

Figure 9: Single factor effects on wear of hybrid composite.
(A) sliding velocity, (B) carbonized eggshell wt.%, (C) normal load, (D) sliding distance, (E) SiC wt.%.

MMC. The wear rate increases with the increase in both sliding distance and time.

3.2.5 Effects of SiC weight percent on wear rate

Figure 13 shows the relation between SiC wt.% and wear rate of AA2014/carbonized eggshell particulate/SiC hybrid green MMC. As can be seen from Figure 9 (e), by increasing the weight fraction of SiC particles in AA2014/carbonized eggshell composite, the wear rate consistently decreases at the lowest point of about 11% weight fraction. Previous studies have reported that the presence of SiC phase reduces the wear rate of a composite.

3.2.6 Three-dimensional interaction effects on wear rate

Figures 10–13 show the 3D interactions of sliding velocity, carbonized eggshell wt.%, normal load, sliding distance, and SiC wt.% vs. the wear rate of the hybrid green MMC. As shown in Figure 12, the wear rate of the hybrid green MMC increases with increasing sliding distance and SiC wt.% of up to the center limit. Beyond the center value of

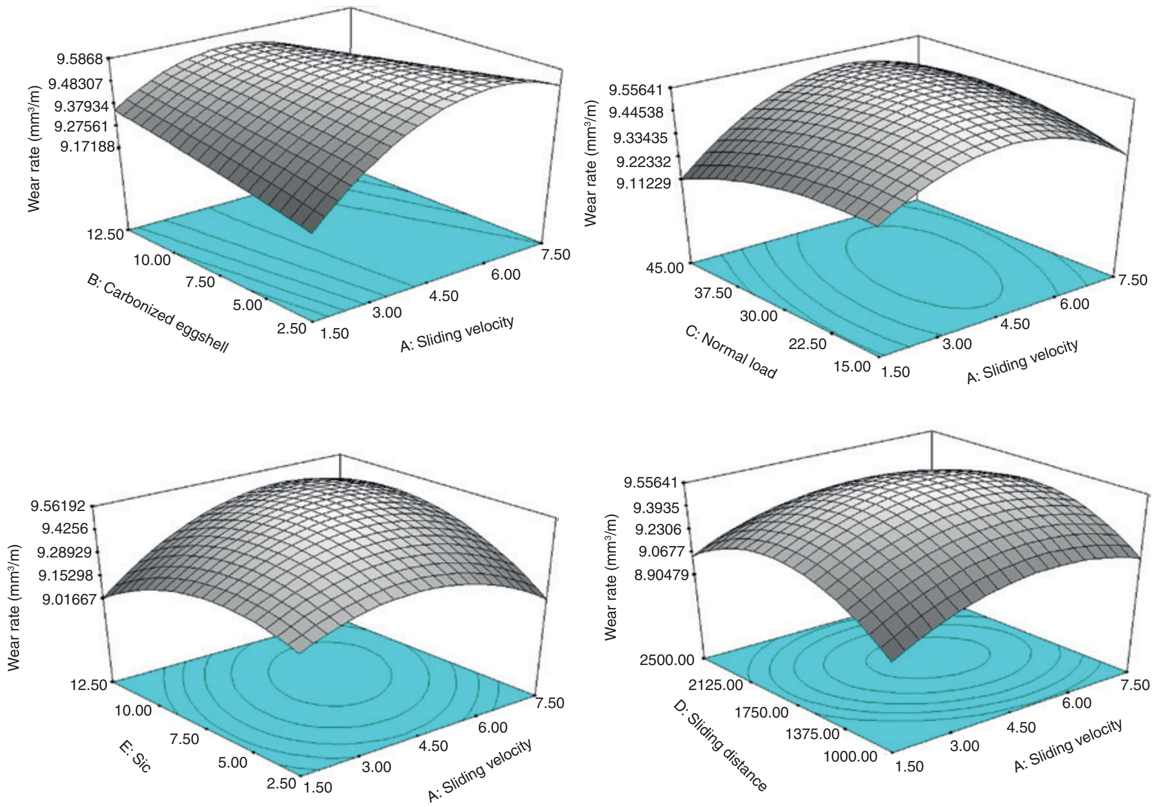

Figure 10: Interactions of sliding velocity with carbonized eggshell wt.%, normal load, sliding distance, and SiC wt.% to reduce wear rate.

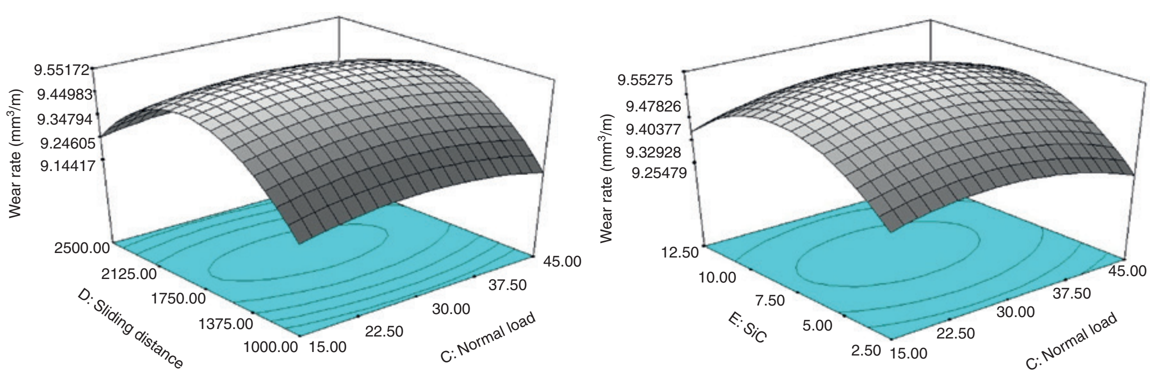

Figure 11: Interactions of normal load with sliding distance and SiC wt.% to reduce wear rate.

sliding distance and SiC wt.%, the wear rate of the hybrid green MMC is reduced. Other interaction effects can be discussed in the same way.

3.3 Optimum parameters with desirability one

From the ramp function graph (Figure 14), it can be observed that when sliding velocity, carbonized eggshell wt.%, normal load, sliding distance and SiC wt.% are 1.75 m/s, 6.5%, 34.24 N, 1219.63 m, and 11 wt.% respectively, then the optimum value of the wear rate of the AA2014/carbonized eggshell/SiC hybrid green MMC is 8.89×10^{-5} mm^3/m. ANOVA results in Table 4 show that all the selected parameters (sliding velocity, carbonized eggshell wt.%, normal load, sliding distance, and SiC wt.%) are significant with respect to wear rate. The importance of the process parameters can be ranked based on

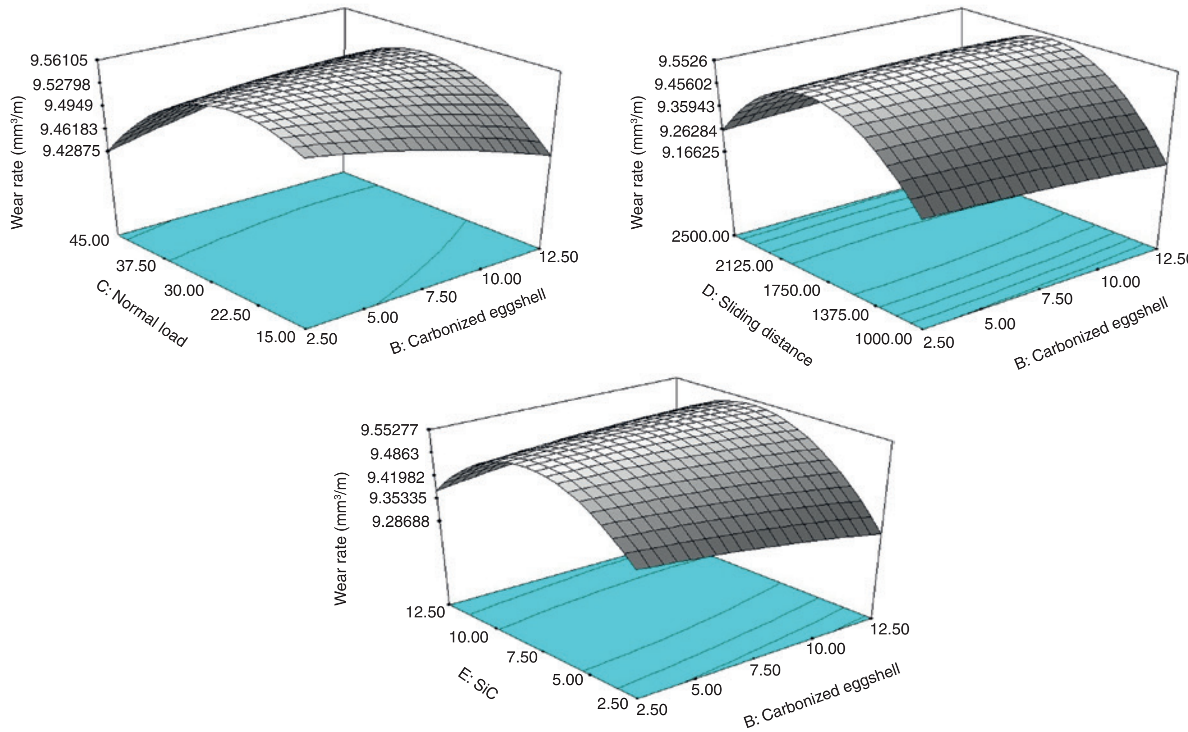

Figure 12: Interactions of carbonized eggshell wt.% with normal load, sliding distance, and SiC wt.% to reduce wear rate.

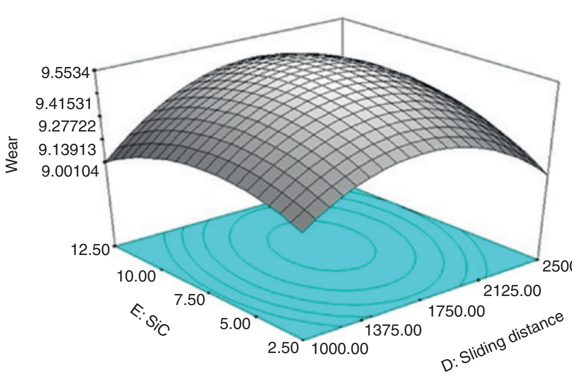

Figure 13: Interaction of sliding distance with SiC wt.% to reduce wear rate.

their F ratios, as shown in Table 4. It can be concluded that sliding velocity contributes most, followed by sliding distance, SiC wt.%, normal load, and carbonized eggshell wt.% in reducing the wear rate of the AA2014/6.5% carbonized eggshell/11% SiC hybrid green MMC.

3.4 Confirmation experiment

Three samples of the AA2014/6.5% carbonized eggshell/11% SiC hybrid green MMC were fabricated by electromagnetic stir casting process, followed by hot extrusion for the confirmation test. Figure 15A and B show

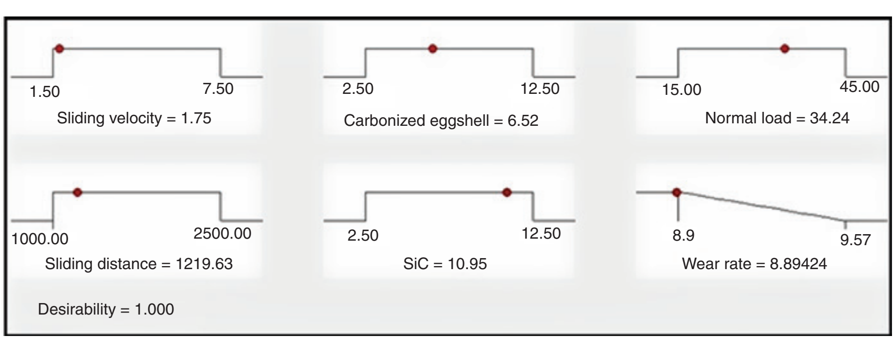

Figure 14: Ramp function graph for the minimum wear rate with desirability one.

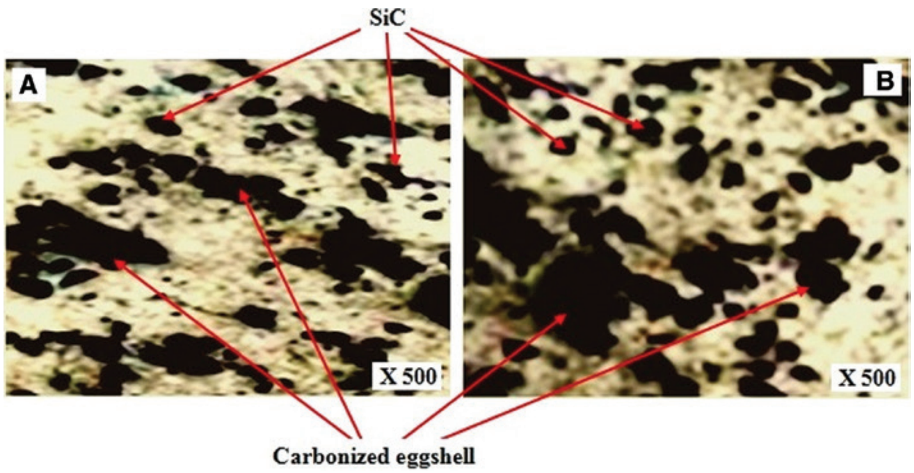

Figure 15: Microstructure of AA2014/6.5% carbonized eggshell/11% SiC hybrid green metal matrix composite.

the typical microstructures of AA2014/6.5% carbonized eggshell/11% SiC hybrid green MMC. The microstructure images show the uniform distribution of 6.5 wt.% eggshell and 11 wt.% SiC in the AA2014 matrix alloy. From the fabricated hybrid composite samples, three specimen pins were prepared for the wear test. The experimental wear rate (average for three test samples) corresponding to these parameter values (sliding velocity of 1.75 m/s, carbonized eggshell wt.% of 6.5%, normal load of 34.24 N, sliding distance of 1219.63 m and SiC wt.% of 11%) was found to be 9.5×10^{-5} mm^3/m. The average achievable wear rate with desirability one was 8.89×10^{-5} mm^3/m. There was only a 6.42% error rate in the experimental and modeled results. Hence, the developed model can be effectively used in the stated process parameter range.

Meanwhile, the experimental wear rate of the AA2014/6.5% carbonized eggshell/11% SiC hybrid green MMC at optimum parameters was found to be 9.5×10^{-5} mm^3/m. The wear rate of the AA2014 matrix alloy was 15×10^{-5}. Results showed that the wear rate of the hybrid green MMC was reduced by about 36.66% compared with the matrix alloy (Table 6). Figure 16A shows the SEM

Table 6: Confirmation experimental table for wear rate and coefficient of friction.

Wear rate of AA2014 (mm^3/m)	Wear rate of AA2014/6.5% carbonized eggshell/11% SiC hybrid composite (mm^3/m)	Reduced wear rate (%)	Corresponding coefficient of friction of AA2014/6.5% carbonized eggshell/11% SiC hybrid composite
15×10^{-5}	9.5×10^{-5}	36.66%	0.20

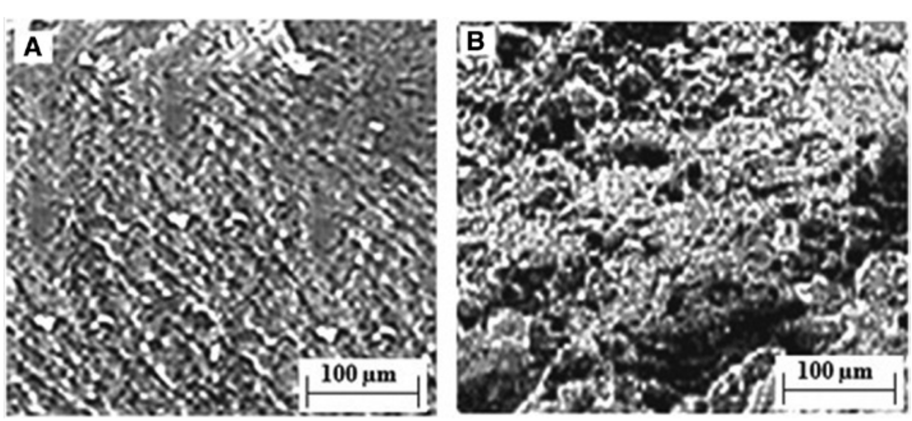

Figure 16: SEM photographs of: (A) AA2014 matrix alloy, (B) AA2014/6.5% carbonized eggshell/11% SiC hybrid composite composites.

photographs of the AA2014 matrix alloy, and Figure 16B shows the SEM photographs of the AA2014/6.5% carbonized eggshell/11% SiC hybrid green MMC. The experimental coefficient of friction (average for three test samples) corresponding to these parameter values (sliding velocity of 1.75 m/s, carbonized eggshell wt.% of 6.5%, normal load of 34.24 N, sliding distance of 1219.63 m, and SiC wt.% of 11%) was found to be 0.20. This value is considered acceptable.

3.5 Density analysis

To determine the density of the alloy AA 2014, 6.5% by weight carbonized eggshells and 11% by weight SiC hybrid green MMC, three samples were prepared in the laboratory. It was observed that 6.5% by weight carbonized eggshells was lighter than the AA 2014 matrix and SiC hybrid green MMC. The densities of the above three materials were 2.80, 2.0, and 3.21 g/cm^3, respectively. These indicate that when the percentage of the carbonized eggshells increases in AA2014, the density of the composite material decreases. Initially, the eggshell is added as a primary reinforcement material, to which SiC is then added to increase the resistance to wear.

4 Conclusions

The following conclusions can be drawn from the analysis:

1. Carbonized eggshell and SiC particles can be adapted favorably as reinforcement materials for the fabrication of AA2014/eggshells particulate/SiC hybrid green MMCs.
2. Minimum wear rate was found to be 8.89×10^{-5} mm^3/m with optimum parameters of 1.75 m/s (sliding velocity), 6.5 (carbonized eggshell wt.%), 34.24 N (normal load), 1219.63 m (sliding distance), and 11 wt.% (SiC wt.%).
3. The ANOVA results show that sliding velocity contributes the most, followed by sliding distance, SiC wt.%, normal load, and carbonized eggshell wt.% in reducing the wear rate of the AA2014/carbonized eggshell/SiC hybrid green MMC.
4. The experimental wear rate of the AA2014/6.5% carbonized eggshell/11% SiC hybrid green MMC at optimum parameters was found to be 9.5×10^{-5} mm^3/m.
5. Experimental wear rate and density of hybrid green metal matrix were reduced by about 36.66% and 0.35%, respectively, at a corresponding coefficient of friction of 0.20 compared with the matrix alloy. This coefficient is considered acceptable.

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Bionotes

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