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Study and Analysis of Silicon Carbide Particles Reinforced with Al 6061 Metal Matrix Composites of Brake Rotor using Pin-on-Disc

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Key words: Al6061, Silicon Carbide (SiC), Stir casting, pin on disc apparatus

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Abstract: Aluminium Metal matrix Composites (AMC) is being extensively used in various field of life, especially in aerospace and automotive industries, because of its good thermal stability and excellent specific strength. AMCs are well known for high strength to weight ratio and high temperature applications. In the present study, wear behaviour of SiC particles reinforced with Aluminium Matrix composites have been investigated. Al 6061 discs were made with 10, 15 and 20% SiC particles by stir casting and machined to fit as a disc in pin on disc tribometer. Using Taguchi Design of Experiments, the experiments were carried out with 4 factorials and 3 levels based on L9 orthogonal array and the results are discussed.

INTRODUCTION

The study has been carried on the use of aluminium metal matrix composite material for brake rotors which is expected to have less heat content due to high thermal dissipation of the heat generated due to braking action[1, 2]. Brake materials transform the kinetic energy of the vehicle into thermal energy by friction between the pad materials and metal disc or drum, usually cast iron[3, 4]. It has been thought that aluminium material is not suitable for parts used under extremely severe frictional conditions and it cannot withstand higher temperatures. But it is found that Al-MMC can withstand higher temperatures[5]. The most important condition is the ability of the brake rotor material to withstand high temperatures generated of the order of 300-800°C during a braking action, its resistance to abrasive wear. The performance of a braking action is affected by the rise in temperature during application in braking load which is known as brake fade. In general, wear occurs by five principal processes: adhesive, abrasive wear, corrosion, surface fatigue and erosion. Earlier study[6] for SiC particles reinforced composites showed that wear was strongly dependent on the contents of the reinforcement, sliding distance and speeds. In this study, the effects of mixture of aluminium and silicon carbide, i.e. (SiC) reinforced aluminium metal matrix composite on the wear of brake pad materials were studied and the results are discussed.

Composite materials are usually classified based on the physical or chemical nature of the matrix phase, e.g., polymer matrix, metal-matrix, and ceramic composites. Aluminium metal matrix refers to the class of lightweight high performance aluminium centric material systems. The major advantages of Aluminium metal matrix compared to unreinforced materials are a greater strength, improved stiffness, reduced weight, improved high-temperature properties, controlled thermal expansion coefficient and improved abrasion and wear resistance[7].

Table 1: Properties of Al6061 with 20% SiC

Properties	Values
Ultimate tensile strength	370 (MPa)
Compressive strength	761 (MPa)
Hardness	80 (BHN)
Elastic modulus	103 (GPa)
Ductility	2.5 (%)
Coefficient of friction	0.44
Thermal conductivity	5 (W m^{-1} K)
Specific heat capacity	0.92 (kJ kg^{-1} K)
Heat transfer coefficient	50 (W m^{-2} K)

Al6061, an alloy of aluminium, magnesium and silicon is chosen in this work because of its mechanical and thermal stability. An in-depth investigation of literature shows that 20% SiC-reinforced aluminium alloy exhibits a significant reduction in the wear compared to other volumetric fraction of SiC in the aluminium matrix. The composite material also has lower thermal expansion than the matrix material due to the presence of SiC particles[8]. The properties of Al6061 with 20% SiC is shown in Table 1.

MATERIALS AND METHODS

Material selection and procedure

Aluminium composite: The increase in weight percentage of SiC up to 25%, when added to Al 6061 matrix, increases both hardness and impact strength of the composite. Beyond this weight fraction, the hardness starts to decrease as SiC particles interact with each other leading to the clustering of particles and consequently settling down. Therefore, in the study, the SiC powder in weight percentages of 10, 15 and 20 were added to Al 6061 alloy to make wear discs to be fitted to pin on disc tribometer.

Fabrication process of the composite brake rotor

Stir casting: In stir casting, the reinforcement phase in powder form varying between 10 and 30 μm size is added to molten matrix phase and it is mixed thoroughly using stirrer blades attached to an electric motor. The stirring time can vary from a minimum of 5 min to a maximum of 3 to 4 h depending upon the volume of the melt.

In order to achieve the optimum properties of the metal matrix composite, the distribution of the reinforcement material in the matrix alloy must be uniform and the wettability or bonding between these substances should be optimized. The porosity levels need to be minimized and chemical reactions between the reinforcement materials and the matrix alloy must be avoided. SiC reinforcement in an Al alloy matrix containing <7% Si may cause the following reaction[9]:

$$4Al+3SiC \leftrightarrow Al_4C_3+3Si$$

Formation of Al_4C_3 affects the mechanical properties of the composite. In order to prevent the reaction, SiC particulates should be heated to a temperature of 700°C, so that a thin coat of 2-μm-thick SiO_2 is formed over the SiC. This barrier coating prevents the migration of Al into SiC and hence prevents the reaction. The oxide layer also improves the wettability of SiC particles by aluminium[10]. The molten Al 6061 with SiC powder thoroughly stirred was poured into the metal die made to the shape of the disc with machining allowances.

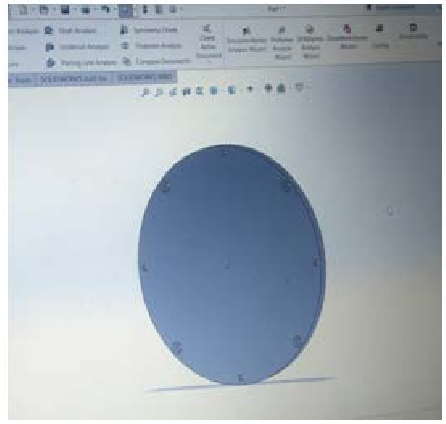

Fig. 1: CAD Model of disc

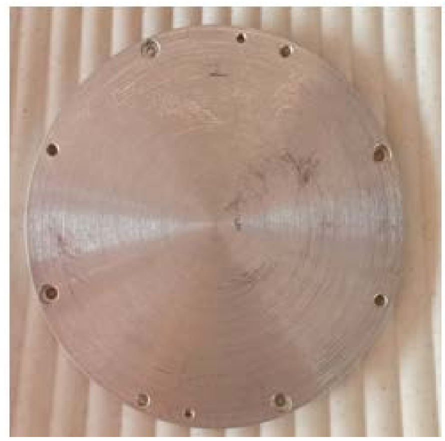

Fig. 2: Disc after machining

Specimen preparation for wear test: The disc on pin on disc apparatus has a diameter of 165 mm and thickness of 10 mm. The assembly holes and the outer profile of the disc were machined in a Vertical Machining Centre (VMC). The CAD Model of the disc for pin on disc, Disc after machining are shown in Fig. 1 and 2, respectively.

Wear test

Pin on disc apparatus: Wear test was carried out for three different compositions of SiC in Al6061 alloy. The Silicon carbide particles were mixed at 10, 15 and 20% by

Fig. 3: Pin on disc test

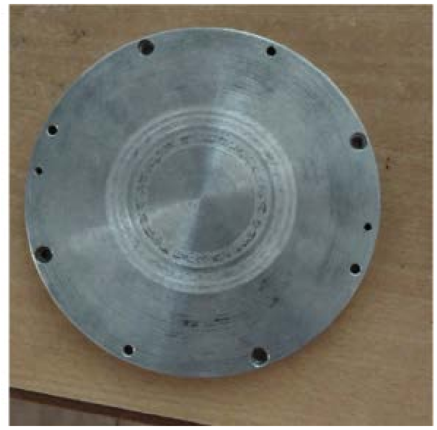

Fig. 4: Disc after wear test

Table 2: Different discs and brake pads

Disc	Al6061 with 10% SiC	Al6061 with 15% SiC	Al6061 with 20% SiC
Pad	Non asbestos	Semi metallic	Cast iron

Table 3: Combinations of changing parameter

SiC in weight (%)	Load (N)	Speed (rpm)	Time (min)
10	50	250	10
10	100	500	15
10	150	750	20
15	50	500	20
15	100	750	10
15	150	250	15
20	50	750	15
20	100	250	20
20	150	500	10

weight with the aluminium alloy. The wear test was carried out using three different brake pads which are shown in Table 2.

The disc and the pin fitted with brake pad were fitted to the apparatus as shown in Fig. 3 and the experiments were carried out according to the Taguchi design combinations and the worn mass was found.

A Taguchi based design of experiments (L9 orthogonal array) was constructed a using commercial software and the experiments were conducted according to the combinations of the changing parameters given in Table 3.

RESULTS AND DISCUSSION

Wear analysis of disc: The worn mass was found for all the three discs using an electronic balance after conducting wear tests against three different brake pads. Similarly the worn mass for the three different brake pads were weighed and tabulated as shown in Table 4-6. The worn disc is shown in Fig. 4 and the worn out portion of the disc is clearly seen as a ring. The wear track may have tribo-oxidation and acts as a protective coating and provides a better wear resistance.

Using the commercial software, the graphs were generated for analysis Al-SiC composite disc wear with semi metallic, CI and non-asbestos brake pad materials which are shown in Fig. 5a-c. It is observed that the wear loss in 20% Al-SiC disc is less in comparison with 10% and 15% Al-SiC disc for all the three brake pads tested. This is due to higher hardness attained in the case 20% SiC and the disc/components with higher hardness wear less as reported in many wear studies. Also, it is observed from Fig. 5a-c, the wear increases as the load and time increases which in line with Archard's wear model wherein wear depth is directly proportional to load and sliding distance.

Analysis of variance was carried using ANOVA considering only three factors viz. % SiC, Load and Time for all the brake pads and the results are shown hereunder. In the case of semi metallic brake pad, based on F and p-values, the order of significance is 1. Load, 2. SiC% and 3. Time. It is also observed that R^2 value is 99.15% and the results obtained for wear are in good agreement with the regression model, since, $R^2>0.8$ (Table 7-11).

In the case of CI brake pad based on F and p-values, the order of significance is 1. SiC%, 2 Load and 3. Time. It is also observed that R^2 value is 97.68% and the results obtained for wear are in good agreement with the regression model, since, $R^2>0.8$ (Table 12-15).

In the case of non asbestos brake pad based on F and p-values, the order of significance is 1. Load, 2. SiC% and 3. Time. It is also observed that R^2 value is 99.93% and the results obtained for wear are in good agreement with the regression model since $R^2>0.8$.

Frictional force and coefficient of friction (μ) values: Similarly the effect of friction coefficient of the three brake pad materials, non-asbestos, CI and semi metallic brake pads on the three discs of 10% SiC, 15% SiC and 20% SiC Al6061 composite were studied and the results

Table 4: Disc worn mass values for semi-metallic brake pad

				Weight loss (g)			
SiC (%)	Load (N)	Speed (rpm)	Time (min)	Trial 1	Trial 2	Trial 3	Average
10	50	250	10	0.0082	0.0085	0.0071	0.007933333
10	100	500	15	0.0101	0.0106	0.0095	0.010066667
10	150	750	20	0.0125	0.0132	0.0139	0.0132
15	50	500	20	0.0072	0.0076	0.0065	0.0071
15	100	750	10	0.0081	0.0095	0.0089	0.008833333
15	150	250	15	0.0093	0.0095	0.0105	0.009766667
20	50	750	15	0.0042	0.005	0.0051	0.004766667
20	100	250	20	0.0078	0.0072	0.0082	0.007733333
20	150	500	10	0.0091	0.0082	0.0081	0.008466667

Table 5: Disc worn mass values for cast iron

				Weight loss (g)			
SiC (%)	Load (N)	Speed (rpm)	Time (min)	Trial 1	Trial 2	Trial 3	Average
10	50	250	10	0.0125	0.0145	0.0152	0.014066667
10	100	500	15	0.0185	0.0187	0.0184	0.018533333
10	150	750	20	0.0215	0.0217	0.0214	0.021533333
15	50	500	20	0.0099	0.0098	0.0097	0.0098
15	100	750	10	0.0105	0.0101	0.0109	0.0105
15	150	250	15	0.0125	0.0122	0.0121	0.012266667
20	50	750	15	0.0081	0.0078	0.0079	0.007933333
20	100	250	20	0.0092	0.0089	0.009	0.009033333
20	150	500	10	0.0101	0.0099	0.0102	0.010066667

Table 6: Disc worn mass values for non- asbestos

				Weight loss (g)			
SiC (%)	Load (N)	Speed (rpm)	Time (min)	Trial 1	Trial 2	Trial 3	Average
10	50	250	10	0.0075	0.007	0.0062	0.0069
10	100	500	15	0.0102	0.0111	0.0107	0.010666667
10	150	750	20	0.0126	0.0119	0.013	0.0125
15	50	500	20	0.006	0.0052	0.0059	0.0057
15	100	750	10	0.0082	0.0076	0.0078	0.007866667
15	150	250	15	0.0099	0.0105	0.0103	0.010233333
20	50	750	15	0.005	0.0051	0.0045	0.004866667
20	100	250	20	0.0073	0.0076	0.0083	0.007733333
20	150	500	10	0.0083	0.0089	0.0095	0.0089

Table 7: Analysis of variance with semi metallic brake pad

Factors	Types	Levels	Values
SiC (%)	Fixed	3	10,15,20
Load (N)	Fixed	3	50,100,150
Time (min)	Fixed	3	10,15,20

Table 8: Analysis of variance (i)

Source	df	Adj SS	Adj MS	F-value	p-values
SiC (%)	2	0.000017	0.000009	48.14	0.020
Load (N)	2	0.000023	0.000011	62.73	0.016
Time (min)	2	0.000002	0.000001	6.13	0.140
Error	2	0.000000	0.000000		
Total	8	0.000042			

Table 9: Model summary (i)

S	R^2	R^2 (adj)	R^2 (pred)
0.0004262	99.15%	96.61%	82.84%

Table 10: Analysis of variance with CI brake pad

Factors	Types	Levels	Values
SiC (%)	Fixed	3	10,15,20
Load (N)	Fixed	3	50,100,150
Time (min)	Fixed	3	10,15,20

Table 11: Analysis of variance (ii)

Source	df	Adj SS	Adj MS	F-value	p-values
SiC (%)	2	0.000137	0.000068	37.49	0.026
Load (N)	2	0.000024	0.000012	6.660	0.131
Time (min)	2	0.000006	0.000003	1.600	0.385
Error	2	0.000004	0.000002		
Total	8	0.000171			

Table 12: Model summary (ii)

S	R^2	R^2 (adj)	R^2 (pred)
0.0013502	97.86%	91.44%	56.68%

Table 13: Analysis of variance with non-asbestos brake pad

Factors	Types	Levels	Values
SiC (%)	Fixed	3	10,15,20
Load (N)	Fixed	3	50,100,150
Time (min)	Fixed	3	10,15,20

are tabulated and are shown in Table 16-18. The experimental analysis were carried and using the commercial software the results were analysed and plotted as shown in Fig. 6a-c. In Fig. 6a-c, it is observed that there is no much variation in coefficient of friction value

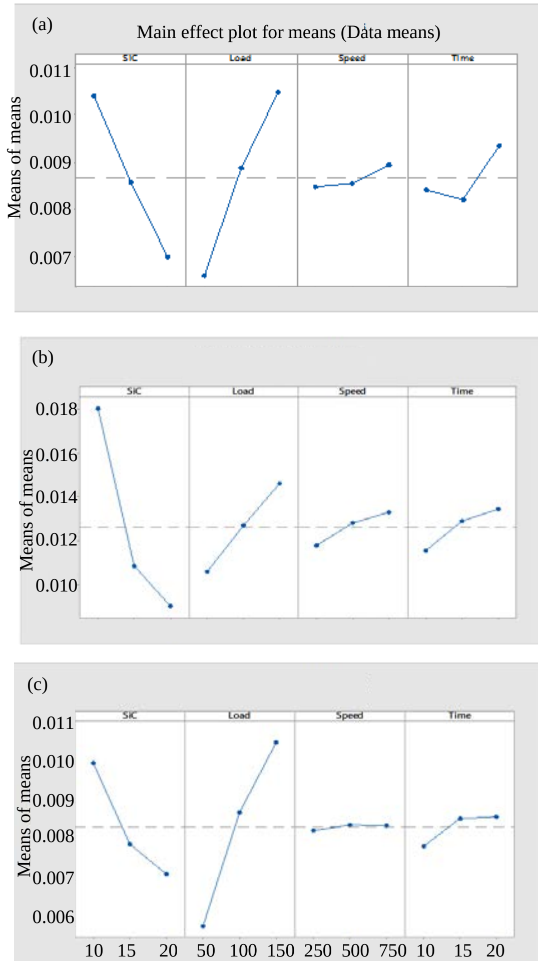

Fig. 5(a-c): (a) Disc worn mass graph for Al-SiC disc using semi metallic brake pad, (b) Disc worn mass graph for Al-SiC disc using cast iron brake pad and (c) Disc worn mass graph for Al-SiC disc using non-asbestos brake pad

Table 14: Analysis of variance (iii)

Source	df	Adj SS	Adj MS	F-value	p-values
SiC (%)	2	0.000013	0.000007	399.07	0.002
Load (N)	2	0.000034	0.000017	1038.50	0.001
Time (min)	2	0.000001	0.000001	32.40	0.030
Error	2	0.000000	0.000000		
Total	8	0.000048			

Table 15: Model summary (iii)

S	R^2	R^2 (adj)	R^2 (pred)
0.0001281	99.93%	99.73%	98.62%

for 10, 15 and 20% Al-SiC composite but it is slightly lower in the case of 15% Al-SiC for semi metallic and non-asbestos brake pad materials. However, it is interesting to note that friction coefficient is higher in the case CI brake pad for 15% Al-SiC in comparison with the other two composites 10% Al-SiC and 20% Al-SiC. It is

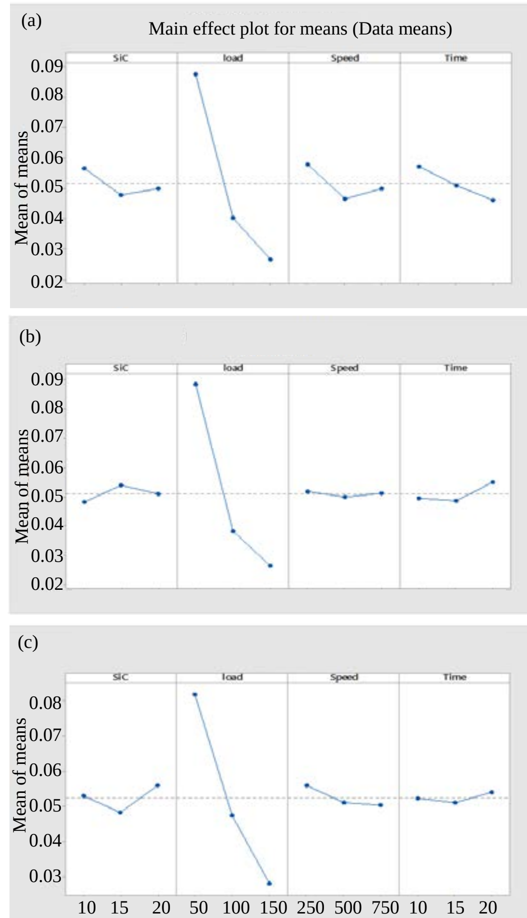

Fig. 6(a-c): (a) Coefficient of friction graph for semi metallic brake pad, (b) Coefficient of friction graph for cast iron brake pad and (c) Coefficient of friction graph for non-asbestos brake pad

observed that as the load increases the friction coefficient gets reduced probably due to the formation of oxide layer on the surface of disc. The influence of running time duration on friction coefficient is much less compared to the load applied.

Wear analysis of brake pad: The wear of brake pads were measured during experimentation and using the commercial software the results were analysed and plotted as shown in Fig. 7a-c. From Fig. 7a-c, it is clearly understood that CI pad wear is less in comparison with semi metallic and non-asbestos brake pad. This may be due to the presence of graphite flakes which acts as a lubricant thereby reducing the wear of pad (Table 19-21).

From Fig. 7a-c, it is noted that the pad wear increases with increase in percentage of SiC in Al-SiC composites. This is due to the presence of higher percentage of SiC

Table 16: Frictional force values for semi metallic brake pad

SiC	Load (N)	Speed (rpm)	Time (min)	Trial 1	Trial 2	Trial 3	Average	Average/Load (μ)
10	50	250	10	4.6	5.4	5.8	5.26	0.1052
10	100	500	15	5.2	4.5	4.5	4.73	0.0473
10	150	750	20	2.3	4.1	4.9	3.76	0.025067
15	50	500	20	4.2	4.1	2.9	3.73	0.0746
15	100	750	10	4.4	4.8	3.1	4.1	0.041
15	150	250	15	3.4	4.7	5	4.36	0.029067
20	50	750	15	4.2	3.8	4.6	4.2	0.084
20	100	250	20	3.1	4.8	4.2	4.0	0.04
20	150	500	10	4.1	3.8	3.9	3.93	0.0262

Table 17: Frictional force values for cast iron

SiC	Load (N)	Speed (rpm)	Time (min)	Trial 1	Trial 2	Trial 3	Average	Average/Load (μ)
10	50	250	10	4.2	4.7	3.9	4.266	0.08532
10	100	500	15	3.7	3.9	2.2	3.266	0.03266
10	150	750	20	4.2	3.6	4.9	4.233	0.02822
15	50	500	20	4.9	4.7	4.6	4.733	0.09466
15	100	750	10	4.5	3.7	3.8	4.0	0.04
15	150	250	15	5.1	4.2	3.7	4.33	0.028867
20	50	750	15	3.3	5.7	3.9	4.3	0.086
20	100	250	20	3.8	4.8	4.3	4.3	0.043
20	150	500	10	3.3	3.8	3.7	3.6	0.024

Table 18: Frictional force values for non asbestos

SiC	Load (N)	Speed (rpm)	Time (min)	Trial 1	Trial 2	Trial 3	Average	Average/Load (μ)
10	50	250	10	4.3	4.2	4.4	4.3	0.086
10	100	500	15	4.6	4.7	4.2	4.5	0.045
10	150	750	20	3.3	5.1	4.2	4.2	0.028
15	50	500	20	3.2	4.4	4.2	3.933	0.07866
15	100	750	10	5.1	4.2	3.2	4.166	0.04166
15	150	250	15	2.6	4.1	5.2	3.966	0.02644
20	50	750	15	4.2	4.1	4.1	4.133	0.08266
20	100	250	20	7.5	5.1	4.2	5.6	0.056
20	150	500	10	5.2	4.1	4.4	4.56	0.0304

Table 19: Brake pad worn mass values for semi metallic brake pad

SiC	Load (N)	Speed (rpm)	Time (min)	Trial 1(g)	Trial 2(g)	Trial 3(g)	Average
10	50	250	10	0.012	0.012	0.011	0.011667
10	100	500	15	0.013	0.015	0.014	0.014
10	150	750	20	0.019	0.018	0.021	0.019333
15	50	500	20	0.015	0.014	0.016	0.015
15	100	750	10	0.022	0.020	0.019	0.020333
15	150	250	15	0.025	0.029	0.024	0.026
20	50	750	15	0.023	0.026	0.024	0.024333
20	100	250	20	0.029	0.033	0.035	0.032333
20	150	500	10	0.035	0.036	0.039	0.036667

Table 20: Brake pad worn mass values for non asbestos brake pad

SiC	Load (N)	Speed (rpm)	Time (min)	Trial 1(g)	Trial 2(g)	Trial 3(g)	Average
10	50	250	10	0.011	0.018	0.016	0.015
10	100	500	15	0.013	0.016	0.018	0.015667
10	150	750	20	0.022	0.021	0.026	0.023
15	50	500	20	0.026	0.024	0.029	0.026333
15	100	750	10	0.030	0.031	0.033	0.031333
15	150	250	15	0.039	0.040	0.04	0.039667
20	50	750	15	0.035	0.032	0.039	0.035333
20	100	250	20	0.041	0.042	0.045	0.042667
20	150	500	10	0.049	0.046	0.048	0.047667

Table 21: Brake pad worn mass values for cast iron

SiC	Load (N)	Speed (rpm)	Time (min)	Trial 1(g)	Trial 2(g)	Trial 3(g)	Average
10	50	250	10	0.001	0.002	0.001	0.001333
10	100	500	15	0.002	0.002	0.003	0.002333
10	150	750	20	0.004	0.003	0.002	0.003
15	50	500	20	0.002	0.002	0.003	0.002333
15	100	750	10	0.003	0.002	0.004	0.003
15	150	250	15	0.004	0.003	0.004	0.003667
20	50	750	15	0.006	0.006	0.005	0.005667
20	100	250	20	0.007	0.006	0.007	0.006667
20	150	500	10	0.008	0.009	0.01	0.009

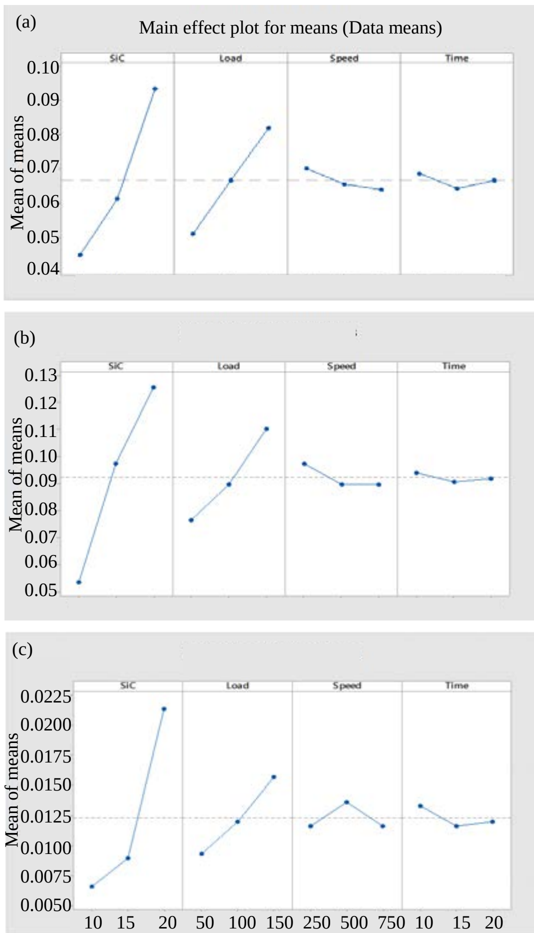

Fig. 7(a-c): (a) Brake pad worn mass values for semi metallic brake pad, (b) Brake pad worn mass values for non-asbestos brake pad and (c) Brake pad worn mass values for cast iron

abrasives in Al matrix disc. Pad wear in all the pad materials increased due to the increase in load and there is no much influence on it due to the change in time duration of testing.

Analysis of variance was carried using ANOVA considering only three factors SiC%, Load and time for all the brake pads and the results are shown hereunder. In the case of semi metallic brake pad based on F and P value, the order of significance is 1. SiC%, 2. Load and 3. Time. It is also observed that R^2 value is 98.88% and the results obtained for wear are in good agreement with the regression model, since, R^2>0.8 (Table 22-24).

In the case of non-asbestos brake pad based on F and p-value, the order of significance is 1. SiC%, 2. Load and 3. Time. It is also observed that R^2 value is 98.79% and the results obtained for wear are in good agreement with the regression model, since, R^2>0.8 (Table 25-27).

Table 22: Analysis of variance with semi metallic brake pad

Factors	Types	Levels	Values
SiC (%)	Fixed	3	10,15,20
Load (N)	Fixed	3	50,100,150
Time (min)	Fixed	3	10,15,20

Table 23: Analysis of variance (iv)

Source	df	Adj SS	Adj MS	F-values	p-values
SiC (%)	2	0.000403	0.000201	63.00	0.016
Load (N)	2	0.000160	0.000080	25.04	0.038
Time (min)	2	0.000003	0.000002	0.49	0.671
Error	2	0.000006	0.000003		
Total	8	0.000572			

Table 24: Model summary (iv)

S	R^2	R^2 (adj)	R^2 (pred)
0.0017884	98.88%	95.53%	77.38%

Table 25: Analysis of variance with non-asbestos brake pad

Factors	Types	Levels	Values
SiC (%)	Fixed	3	10,15,20
Load (N)	Fixed	3	50,100,150
Time (min)	Fixed	3	10,15,20

Table 26: Analysis of variance (v)

Source	df	Adj SS	Adj MS	F-values	p-values
SiC (%)	2	0.000877	0.000439	67.13	0.015
Load (N)	2	0.000192	0.000096	14.71	0.064
Time (min)	2	0.000002	0.000001	0.14	0.874
Error	2	0.000013	0.000007		
Total	8	0.001084			

Table 27: Model summary (v)

S	R^2	R^2 (adj)	R^2 (pred)
0.0025558	98.79%	95.18%	75.60%

Table 28: Analysis of variance with CI brake pad

Factors	Types	Levels	Values
SiC (%)	Fixed	3	10,15,20
Load (N)	Fixed	3	50,100,150
Time (min)	Fixed	3	10,15,20

Table 29: Analysis of variance (vi)

Source	df	Adj SS	Adj MS	F-values	p-values
SiC (%)	2	0.000041	0.000021	46.64	0.021
Load (N)	2	0.000007	0.000003	7.59	0.116
Time (min)	2	0.000001	0.000000	0.58	0.632
Error	2	0.000001	0.000000		
Total	8	0.000050			

Table 30: Model summary (vi)

S	R^2	R^2 (adj)	R^2 (pred)
0.0006663	98.21%	92.83%	63.72%

In the case of CI brake pad based on F and p-value, the order of significance is 1. SiC%, 2. Load and 3. Time. It is also observed that R^2 value is 98.21% and the results obtained for wear are in good agreement with the regression model, since, R^2>0.8 (Table 28-30).

The SEM images of non asbestos brake pad are shown in Fig. 8a, b. From the images; it is found that there are large quantities of Al particle embedded on the surface of the pad. Moreover, the flaking of the pad material is also seen.

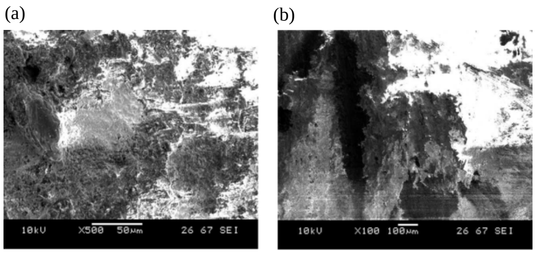

Fig. 8(a, b): SEM images of non-asbestos brake pad after wear test

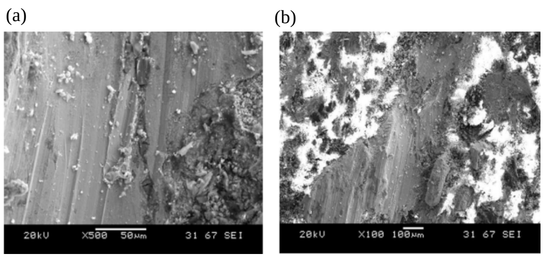

Fig. 9(a, b): SEM images of semi metallic brake pad after wear test

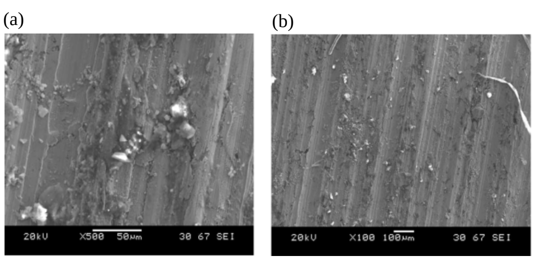

Fig. 10(a, b): SEM images of cast iron after wear test

The SEM images of semi metallic brake pad are shown in Fig 9a, b. From the images it is found that there are large quantities of Al particle embedded on the surface of the pads. Moreover, the ploughing of the surface of pads are also seen that may be due to abrasive action of SiC.

The SEM images of CI brake pad are shown in Fig. 10a, b. From the images; it is found that there are few quantity of Al particle embedded on the surface of the pads. Moreover, the ploughing of the surface of pad is also seen due to the presence of SiC abrasives in the disc.

CONCLUSION

Al-SiC with 10, 15 and 20% silicon carbide-reinforced Al 6061 metal matrix composite discs were cast using stir casting and machined to fit in the pin on disc tribometer. The disc made of 20% of the SiC particles with Al 6061 matrix worn less in comparison with the other two percentages of SiC viz. 10 and 15% discs. The wear rate varied directly with the applied normal load and the sliding speed and the load has a major effect on the wear of the Al-SiC disc in comparison with time. Of the three brake pad materials used in this study, CI brake pad has given a better wear characteristic with 20% Al-SiC disc.

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