Wear Performance Analysis of Aluminum Matrix Composites and Optimization of Process Parameters Using Statistical Techniques

AMIR HUSSAIN IDRISI and ABDEL-HAMID ISMAIL MOURAD

This paper presents the wear behavior of gears manufactured using Al matrix composites (AMCs) reinforced with microparticles (with sizes of 40 μm and contents of 5 and 10 wt pct) and nanoparticles (with sizes of < 100 nm and contents of 1 and 2 wt pct) of SiC, fabricated using stir casting. Specially designed test rig was manufactured for determining the wear performance of these gears and investigated under different applied loads and experiment times. The composite prepared using 2 pct SiC nanoparticle reinforcements was superior to other compositions tested in terms of tribological applications. The effectiveness of nanoparticles compared to that of microparticles was analyzed statistically. Taguchi's method was used for optimizing the wear parameters. Furthermore, the influence of the experiment time, applied load, and SiC content on the wear was investigated and a regression equation was developed for AMCs reinforced with micro- and nanoparticles. The "smaller is better" characteristic was selected as the objective of this model to analyze the wear resistance. The experiment time and applied load had the most significant effect, followed by the SiC content, in the case of microparticles, whereas for nanoparticles, the applied load was the least significant factor when compared to experiment time and SiC content.

I. INTRODUCTION

AL matrix composites (AMCs) are superior quality advanced materials that combine a soft metal matrix with a hard reinforcement.[1] Al alloys (AAs) are used as a matrix material in AMCs, which are widely utilized in various applications such as in manufacturing automobiles and aerospace parts owing to their several advantageous properties such as light weight, low cost, high stiffness, and high dimensional stability, which aid in molding the material into the required shapes and sizes.

Using AAs reinforced by particulates is the most promising way to enhance the wear properties of any metal matrix composite (MMC). Reinforcing AAs using silicon carbide (SiC),[2–9] alumina (Al_2O_3),[10–12] carbon nanotubes (CNT),[13,14] and graphene nanoplatelets (GNP)[15,16] has been reported to enhance the mechanical properties of AMCs. These reinforcements have been significantly explored recently to determine the most optimal route. Fathy et al.[16] fabricated Al-Al_2O_3/GNP hybrid composites and compared them with Al-Al_2O_3 composites. Their results showed that the wear rate of Al-Al_2O_3 composite reinforced with 1.4 pct GNP decreased by 19 times compared to that the Al-Al_2O_3 composite without GNPs. Qutub et al.[17] investigated the wear behavior and friction coefficient of the Al 6061 alloy reinforced with 1 wt pct CNT. It was noted that the wear behavior and friction were significantly affected by the applied load. Furthermore, the critical load could have a negative impact on the wear resistance of the composite. The wear properties of CNT and Al_2O_3 composite were compared by Lu et al.[18] The wear performance of the Al_2O_3 composite was better that of the composite reinforced with CNT. Similarly, the wear performances of AMCs reinforced with SiC and Al_2O_3 were compared. The results demonstrated that SiC particles were more effective than Al_2O_3 particles in enhancing the wear resistance of AMCs because of their high hardness.[19] Thus, SiC should be preferably used as reinforcement.

The stir casting method has been widely used by various researchers. Sajjadi et al.[20] fabricated AA/Al_2O_3 micro- and nanocomposites using stir casting and observed improved hardness and compressive strength and increased porosity for a higher weight percentage of Al_2O_3 nanoparticles. Ezatpour et al.[21] prepared Al

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6061 nanocomposites using stir casting to investigate the effects of adding Al_2O_3 nanoparticles to the Al 6061 alloy and the effects of the extrusion process on the mechanical and microstructural properties of the composites. They found a reasonable distribution of Al_2O_3 in the matrix alloy with low agglomeration and low porosity. In addition, the strength and ductility of the extruded samples were superior to those of the as-cast samples. Abdizadeh et al.[22] used casting and powder metallurgy methods for fabricating AMCs reinforced with nano MgO to compare the microstructure and mechanical properties of the AMCs obtained using the two methods. They concluded that stir casting generated more homogeneous materials and superior mechanical properties compared to powder metallurgy.

Previously, various combinations of AA5083 and SiC have been utilized to improve the tribological properties of AMCs. Gargatte et al.[23] fabricated a AA5083/SiC metal matrix composite using the stir casting method, where different volume fractions of SiC particles (3, 5, and 7 wt pct) were used for analysis. In addition, they examined the wear behavior of AA and its composites using a pin-on-disk testing machine. It was noted that the wear rate decreased with increase in the SiC particle content. AA5083 reinforced with 3, 5, and 7 wt pct SiC showed smaller wear rates than that of pure AA5083. Similarly, Ravindra et al.[24] performed dry sliding wear tests on AA5083 composites with 10 wt pct SiC using the pin-on-disk procedure with normal loads of 10, 20, and 30 N for sliding distances of 754, 1131, 1508, and 1885 m and sliding velocities of 0.42, 0.63, 0.84, and 1.04 m/s for a constant time of 30 minutes. They found that the applied load had the highest influence on the wear rate. Furthermore, Singla et al.[25] utilized a wide range of SiC contents (5, 10, 20, and 25 wt pct) as reinforcements for fabricating composites. They reported that 20 wt pct of SiC in the composite led to the minimum wear under different applied loads. A test rig was used by Tunalioğlu and Tuç[26] for testing the internal spur gears manufactured from St50. These gears were tested under different torques and motor speeds. The wear that occurred in tooth profiles of internal gears was determined for different load cycles. They found that the maximum wear occurred in the region of the tooth tip where the internal gear begins to mesh with the pinion teeth.

Many statistical models such as regression techniques, response surface methodology (RSM), analysis of variance (ANOVA), and the Taguchi method have been developed for the analysis and optimization of machining parameters and determining the minimum wear. Sachin[27] used a linear factorial design approach for analyzing the wear performance of SiC particulate (SiCp)-reinforced AMC. Abrasive wear tests were carried out using AMC against SiC and Al_2O_3 emery papers on a steel counterface at a determined speed. The wear rate of the composite was expressed in terms of the applied load, sliding distance, and particle size. The composite showed a lower wear rate compared to that of the unreinforced alloy in both cases. Moreover, the wear rate increased with increasing applied load and abrasive size for both SiC and Al_2O_3 paper but, in the case of sliding distance, the wear rate increased for SiC and decreased for Al_2O_3 paper.

Idrisi et al.[28] fabricated AMCs reinforced with SiC nanoparticles and analyzed them under wear application. They used ANOVA analysis to examine the influence of process parameters. Similarly, Basavarajappa et al.[29] fabricated AMCs reinforced with graphite (Gr) and SiCp. They also used the L27 orthogonal array and ANOVA to investigate the influence of wear parameters such as the normal load, sliding speed, and sliding distance on the dry sliding wear of the composites. It was found that Gr particles were effective agents for increasing the dry sliding wear resistance of Al/SiCp composites.

In light of the above studies, it is evident that the effect of SiC micro- and nanoparticles in the development of AMCs for the fabrication of gears has not been studied so far. This alloy is lightweight and non-heat-treatable, which makes it suitable for gear applications. Replacing traditional steel gears with lightweight materials such as AMC can directly decrease the weight of, for instance, a vehicle's gear box and therefore reduce the vehicle's fuel consumption. Cars can then carry additional sophisticated emission control, safety, and integrated electronic systems without increasing their overall weight. The applications of these gears are not limited to automobile industries only: they can be used in many other industries such as in those involving marine and aerospace applications. Therefore, the main objective of this study was to investigate the wear properties of the fabricated composites utilizing the AA5083 alloy reinforced with SiC micro- (40 μm) and nanoparticles (< 100 nm). Moreover, a special test rig was designed and manufactured for the wear analysis of external gears. This test rig helped in determining the wear rate of the gears for a given operation time. Furthermore, the Taguchi method was used for determining the appropriate process parameter levels for the minimum wear rate and a regression model was employed for predicting the wear rate. Finally, as a confirmation test, this regression model was validated by experimental data.

II. MATERIALS AND METHODS

A. Materials

AA5000 alloys are widely utilized in automobile and marine applications owing to their predominant corrosion resistance, higher strength-to-weight ratio, and formability. However, because of the higher wear rate and low strength, the utilization of these alloys has been limited. Therefore, research and development into lightweight materials such as AA5083-based MMC is essential. In this study, AA5083 was used as a base material for the composite. The composition of AA5083 is shown in Table I.

Table I. Chemical Composition of AA5083

Element	Zn	Ti	Si	Cu	Fe	Cr	Mn	Mg	Al
Content Wt Pct	0.035	0.028	0.18	0.07	0.18	0.1	0.58	4.8	balance (pct)
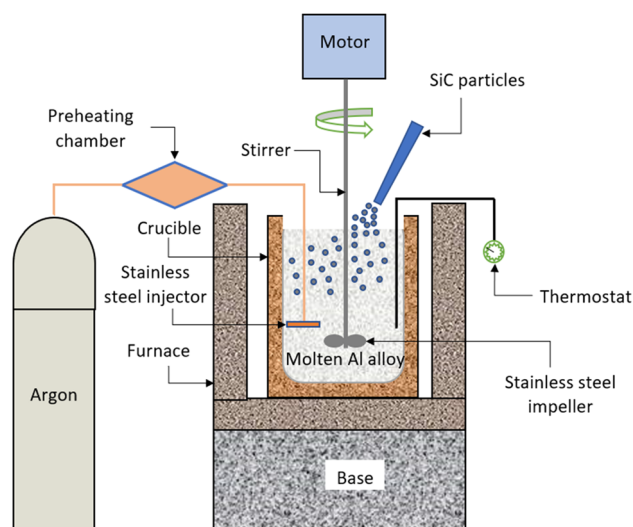
Fig. 1—Schematic of the designed equipment.

Fig. 2—Gears manufactured with developed AMCs. Pitch circle diameter: 62 mm, thickness: 15 mm, and number of teeth: 30.

B. *Fabrication of Metal Matrix Composites*

Stir casting was utilized to manufacture the particulate AMCs since it is one of the most cost-effective methods to fabricate composites particulates. A schematic of the stir casting process is shown in Figure 1. First, the matrix alloy (AA5083) was melted in a graphite crucible in an electrical furnace at 760 °C. This temperature was above the melting point of the aluminum alloy.[23] Slag powder was showered to expel the slag content. Furthermore, the slurry was degassed. During degassing, the temperature of the solute was lowered to 680 °C, which is below the liquidus temperature. The dissolved gases were removed by passing Ar gas through the melt for 5 minutes. Subsequently, the surface was cleaned again, and the temperature of the solute was increased to 780 °C.[30] The alloy was melted under stirring by a mechanical stirrer. At this temperature, different weight percentages of preheated micro/nanoparticles were added to the liquid metal to develop composite materials with varying compositions. The micro/nanoparticles were preheated to enhance the wettability of the ceramic particles and molten aluminum to avoid rejection of particles. Preheating reduced an instant drop in the local melt temperature upon particle addition, *i.e.*, it minimized the temperature difference between the melt and the reinforcement particles. Thereafter, the slurry was superheated above the liquidus temperature and the automatic stirring was continued for approximately 10 minutes at a normal stirring rate of 500 rpm. Finally, the slurry was poured into a pre-warmed mild steel circular in shape.
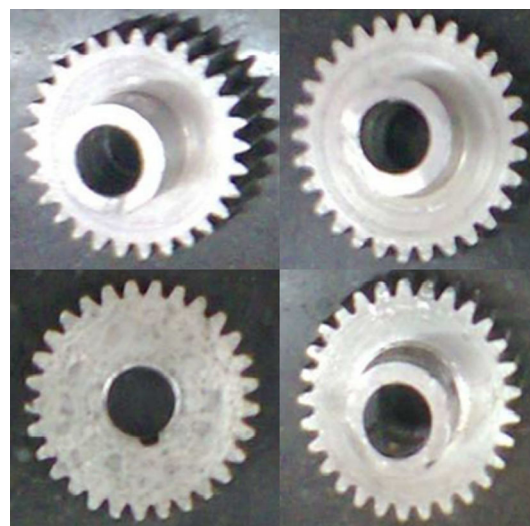
During this fabrication process, circular discs were manufactured with 0, 5, and 10 wt pct SiC microparticles and 1 and 2 wt pct SiC nanoparticles as reinforcement. Furthermore, after solidification, the cast circular discs were removed from the die and machined to achieve the required dimensions. Subsequently, teeth were created on the circular discs using a milling machine to form gears as shown in Figure 2.

C. *Plan of Experiments*

The test plan was defined considering three factors and three levels in accordance with the Taguchi method. Three parameters (applied load, time, and SiC content) were used to perform the wear analysis. Furthermore, three levels of these parameters were selected. The values of these parameters for the micro- and nanoparticles used during the experiments are presented in Table II.

An L27 (3^{13}) orthogonal array was selected for analysis. The array is used to understand the impact of three autonomous elements, each having three value levels, which encompassed 27 rows and 13 columns as shown in Table III.

A total of 27 examinations were performed, and each test depends on the combination of different level values. Based on the arrangement shown in Table III, tests were performed. The response to the model was wear (pct). In the orthogonal array, the first column was assigned to the applied load (N), the second to the experiment time (min), and the fifth to the SiC content (wt pct); the remaining columns were assigned to their interactions. A similar arrangement of interactions was used by

			SiC (Wt Pct)	
Level	Applied Load (N)	Experiment Time (Min)	Microparticles	Nanoparticles
1	10	30	0	0
2	20	60	5	1
3	30	90	10	2

Table III.   L27 Orthogonal Array (L is the Applied Load, T is the Experiment Time, and S is SiC Content)

Interaction	L	$\frac{L}{T}$	$\frac{L}{T}$	$\frac{L}{T^2}$	S	S	$\frac{L}{S^2}$	$\frac{T}{S}$	$\frac{LT}{S}$	$\frac{LT^2}{S^2}$	$\frac{T}{S^2}$	$\frac{LT^2}{S}$	$\frac{LT}{S^2}$
$L27(3^{13})$	1	2	3	4	5	6	7	8	9	10	11	12	13
1	1	1	1	1	1	1	1	1	1	1	1	1	1
2	1	1	1	1	2	2	2	2	2	2	2	2	2
3	1	1	1	1	3	3	3	3	3	3	3	3	3
4	1	2	2	2	1	1	1	2	2	2	3	3	3
5	1	2	2	2	2	2	2	3	3	3	1	1	1
6	1	2	2	2	3	3	3	1	1	1	2	2	2
7	1	3	3	3	1	1	1	3	3	3	2	2	2
8	1	3	3	3	2	2	2	1	1	1	3	3	3
9	1	3	3	3	3	3	3	2	2	2	1	1	1
10	2	1	2	3	1	2	3	1	2	3	1	2	3
11	2	1	2	3	2	3	1	2	3	1	2	3	1
12	2	1	2	3	3	1	2	3	1	2	3	1	2
13	2	2	3	1	1	2	3	2	3	1	3	1	2
14	2	2	3	1	2	3	1	3	1	2	1	2	3
15	2	2	3	1	3	1	2	1	2	3	2	3	1
16	2	3	1	2	1	2	3	3	2	1	2	3	1
17	2	3	1	2	2	3	1	1	2	3	3	1	2
18	2	3	1	2	3	1	2	2	3	1	1	2	3
19	3	1	3	2	1	3	2	1	3	2	1	3	2
20	3	1	3	2	2	1	3	2	1	3	2	1	3
21	3	1	3	2	3	2	1	3	2	1	3	2	1
22	3	2	1	3	1	3	2	2	1	3	3	2	1
23	3	2	1	3	2	1	3	3	2	1	1	3	2
24	3	2	1	3	3	2	1	1	3	2	2	1	3
25	3	3	2	1	1	3	2	3	2	1	2	1	3
26	3	3	2	1	2	1	3	1	3	2	3	2	1
27	3	3	2	1	3	2	1	2	1	3	1	3	2

Davim[31] in the optimization of cutting parameters for turning metal matrix composites.

III. EXPERIMENTAL SETUP AND PROCEDURE

In this study, a test rig was designed and manufactured for the wear test. Figure 3 shows a 3D model of the test rig used for testing the gears manufactured using the developed composite material. This test rig consisted of few major components such as a gearbox, a prime mover, and a loading device. The motor of the test rig was used as the prime mover. Moreover, 10, 20, and 30 N weights were used as applied loads during the wear test. These loads were changed using a ring connected to the load and a hook attached to the belt.

In addition, the gearbox consisted of two gears. Both gears of the gearbox had the same pitch circle diameter (62 mm), thickness (15 mm), and number of teeth (30). The gears were formed by machining 72-mm-diameter discs that were 20 mm thick. One gear was coupled with the motor in the test rig. The motor provided a constant 1450 rpm rotation to the gear for testing. The second gear was coupled to the loading device, which was similar to a band brake. The loading device consisted of a flat belt with a rectangular cross-section that passed through the cast iron pulley. One end of the belt was secured to the ground and the other was connected to the load.

The flowchart in Figure 4 shows the steps followed for calculating the wear (pct). For the wear test, we used gears manufactured from the composite discs by milling. Both gears were manufactured from the same composite
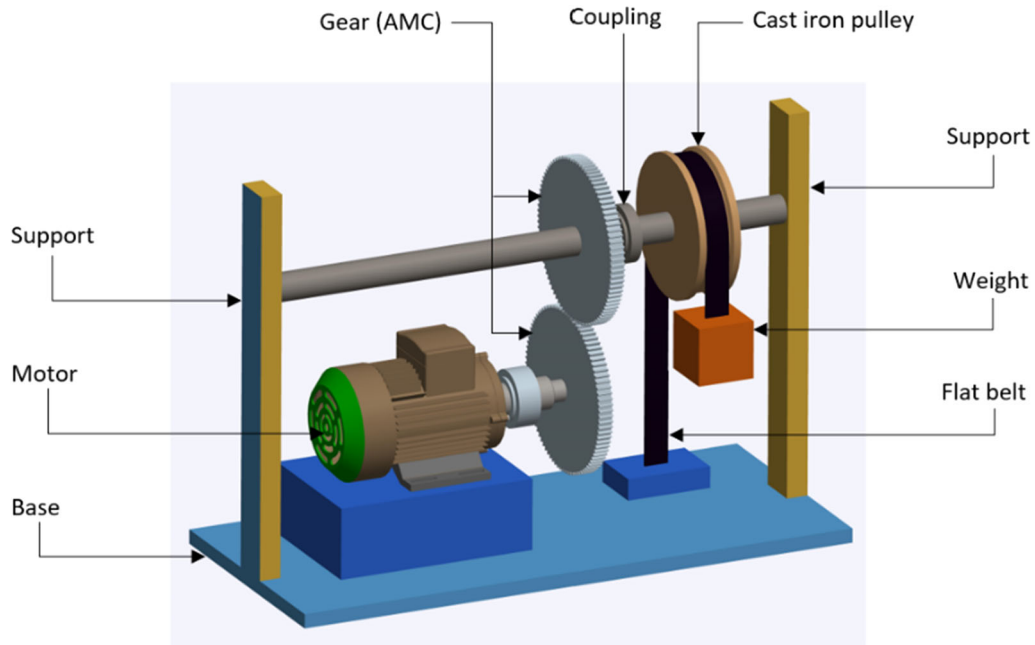
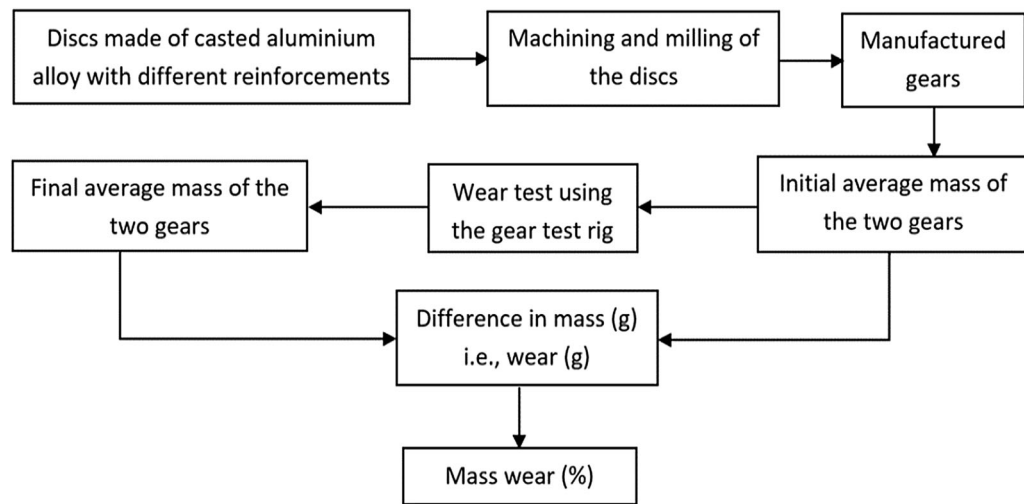Fig. 3—3D model of the gear test rig.

Fig. 4—Step-by-step procedure used to evaluate the wear (pct) of manufactured gears with different reinforcements.

material. The masses of both gears were measured before mounting them to the test rig and the average mass was considered to be the initial mass. A digital Shimadzu ATX 224 analytical balance with a 0.0001 g precision was used for measuring the masses of the gears. After mounting the gears, the test rig operated for a certain time under a certain applied load. The masses of both gears were measured after completing the test and the average value was considered to be the final mass in our calculations. To determine the wear in mass (g), the difference between the initial and final mass of the gears was used. This wear in mass (g) was converted to wear (pct) for further analysis using the following formula:

$$\text{Wear in mass (pct)} = \frac{\text{IM} - \text{FM}}{\text{IM}} \times 100 \qquad [1]$$

where IM is the initial mass and FM the final mass.

IV. RESULTS AND DISCUSSION

A. Wear Analysis

Wear tests were performed on gears fabricated from the produced AMC reinforced with different contents of SiC particles. The initial and final masses were compared to determine the wear at different times, and the
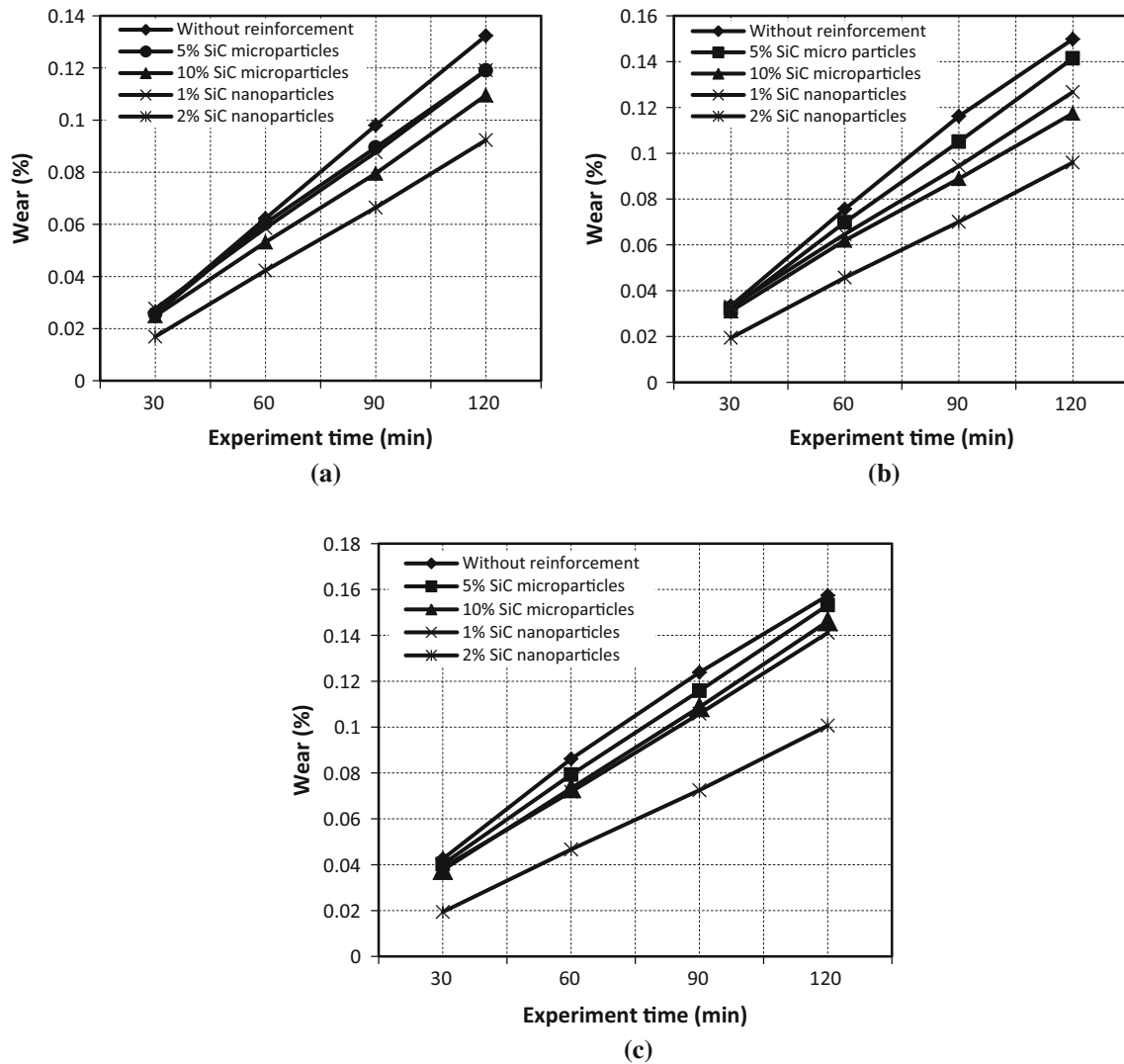
Fig. 5—Wear against time for different applied loads: (*a*) 10 N, (*b*) 20 N, and (*c*) 30 N.

results were converted to wear (pct). Figures 5(a) through (c) show the linear relationship between the wear and operation time for all applied loads for microparticle- and nanoparticle-reinforced composites. It was observed that the wear rate increased with increase in the applied load. A similar linear trend was observed by Miyajima and Iwai.[32] In addition, the wear rate of the unreinforced alloy was determined to be higher than that of the reinforced AMC when the applied load was 10, 20, and 30 N.

As can be seen in Figure 5(a), the AA containing 5 pct SiC microparticles presented the same wear resistance as the composite containing 1 pct SiC nanoparticles. The AA containing 10 pct SiC microparticles showed a higher wear resistance compared to that of the AA with 1 pct SiC nanoparticles under the applied load of 10 N. Under the applied load of 20 N, the wear resistance of the composite containing 1 pct nanoparticles was higher than that of the composite containing 5 pct SiC microparticles but smaller than that of the one containing 10 pct SiC microparticles, as shown in Figure 5(b).

Figure 5(c) illustrates the wear behavior under the 30 N applied load. This behavior indicated that the composite containing 1 pct SiC nanoparticles showed better wear resistance than the 10 pct SiC microparticle-containing composite. This reflected the effectiveness of the nanofiller at higher applied loads. It was also determined that AA reinforced with 2 wt pct SiC nanoparticles showed the maximum wear resistance under every loading value tested: these results are supported by the findings reported by Narasimman *et al.*[33] They optimized the operating conditions for produced Ni-B-SiC (particle size: 50 nm) nanocomposites with maximum wear and scratch resistance using the sediment electro-co-deposition technique (SECD) and compared the results with those obtained for Ni-SiC microcomposites (particle size: 1 nm) prepared using the same technique. They added a lower volume pct of nanoparticles compared to that of microparticles, but the nanoparticles had a higher number density, which increased the wear resistance. Garcia *et al.*[34] also found that a decrease in the particle size affected the wear resistance
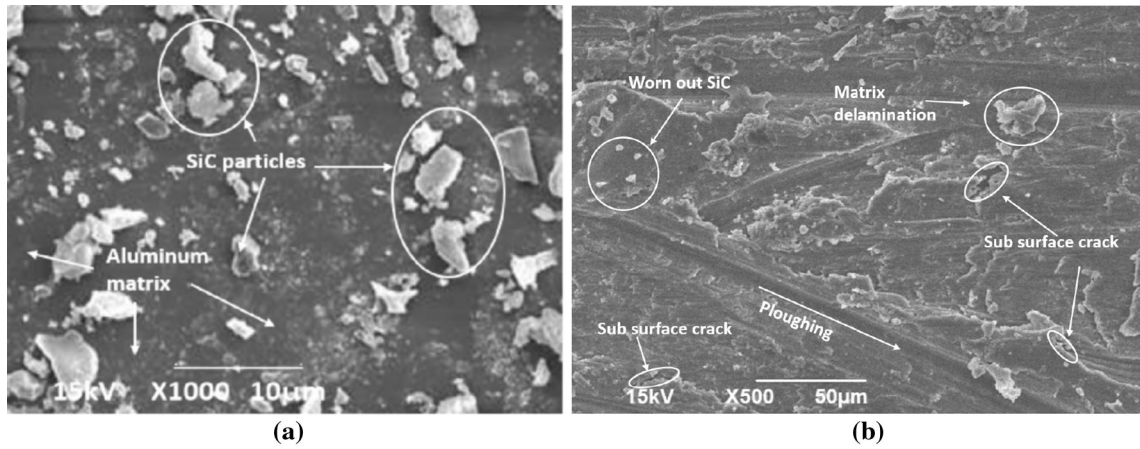
Fig. 6—Scanning electron micrograph microparticles-reinforced composite (*a*) after casting (*b*) after wear test.
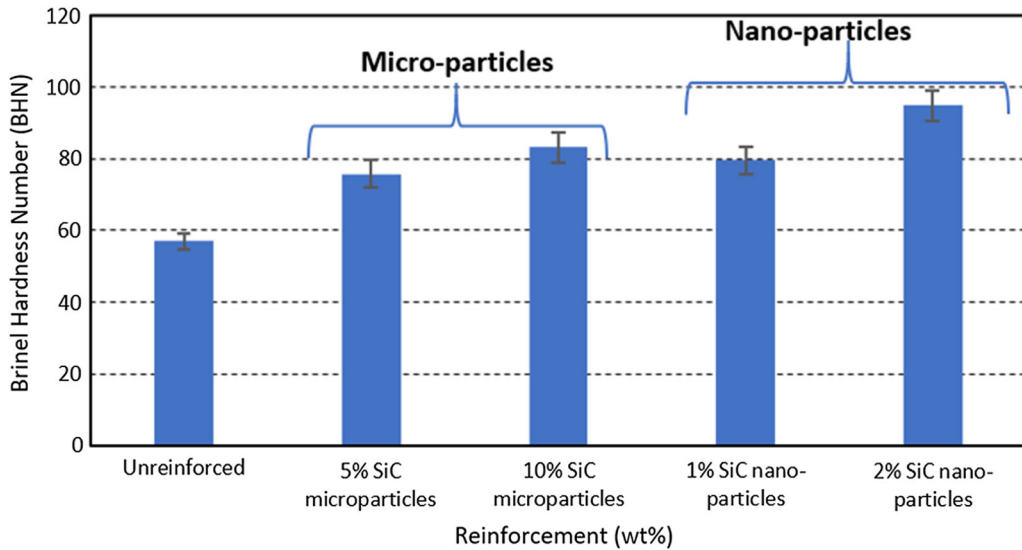

Fig. 7—Hardness of microcomposite and nanocomposite with different wt pct of reinforcement.

positively. This increase in the wear resistance of composites containing SiC nanoparticles compared to that of the microparticles was due to the increase in the number of particles per unit mass (number density) of the powder and the increase in the number density of the particles in the composites due to the decrease in particle size μ.

The representative images of the composite after fabrication and the wear test are shown in Figure 6. Figure 6(a) was obtained after the casting: it shows a uniform distribution of SiC particles in the Al alloy matrix phase. Figure 6(b) shows the worn-out surface of the microcomposite gear operated under the maximum load and for the maximum experiment time. Evidence of micro-pitting and plowing can be observed at the surface, which may be due to the sub-surface cracks developed due to fatigue stresses. During continuous loading, the sub-surface cracks initiated localized matrix delamination, resulting in micro pits on the gear surface.[35] In Figure 6(a), SiC particles are more visible

than in Figure 6(b), which demonstrates the grooving of the SiC particles and plastic deformation of the matrix material. This plastic deformation of the matrix covered the SiC particles at the surface. Garcia *et al.*[36] have also observed similar wear patterns for developed AMCs.

B. *Hardness Test*

A universal hardness testing machine (Reicherter UH 250) was used for the hardness measurements. The samples were subjected to metallographic preparation using emery papers of different grit sizes to ensure precise measurement of the hardness. For testing, a 2.5-mm-diameter indenter ball was used with a load of 187.5 kg and an 8-second dwell time. Five readings were taken at different points on the sample and average values were considered. The hardness values measured for the fabricated composites are presented in Figure 7. As seen in this figure, the hardness increased by 35 pct on adding 5 wt pct of SiC microparticles. However, the

Table IV. Results of L27 Orthogonal Array for the AA5083 Composite Reinforced with Micro- and Nanoparticles

Experiment No.	L (N)	T (Min)	SiC Content		Wear		S/N Ratio	
			S_{mc} (Wt Pct)	S_{nc} (Wt Pct)	W_{mc} (Pct)	W_{nc} (Pct)	SR_{mc}	SR_{nc}
1	10	30	0	0	0.02625	0.02625	31.61741	31.61741
2	10	30	5	1	0.02561	0.027646	31.83181	31.16735
3	10	30	10	2	0.02489	0.016896	32.0795	35.44432
4	10	60	0	0	0.06226	0.06226	24.11582	24.11582
5	10	60	5	1	0.06046	0.058586	24.37064	24.64412
6	10	60	10	2	0.05314	0.042318	25.49157	27.4695
7	10	90	0	0	0.098	0.098	20.17548	20.17548
8	10	90	5	1	0.0895	0.087653	20.96354	21.14466
9	10	90	10	2	0.07954	0.06644	21.98829	23.55141
10	20	30	0	0	0.03336	0.03336	29.53548	29.53548
11	20	30	5	1	0.03211	0.032976	29.86719	29.63604
12	20	30	10	2	0.03105	0.019393	30.15877	34.2471
13	20	60	0	0	0.07568	0.07568	22.42038	22.42038
14	20	60	5	1	0.06985	0.06464	23.11667	23.78997
15	20	60	10	2	0.06194	0.04568	24.16058	26.80548
16	20	90	0	0	0.11617	0.11617	18.69812	18.69812
17	20	90	5	1	0.10506	0.094401	19.57125	20.50047
18	20	90	10	2	0.0889	0.070042	21.02196	23.09283
19	30	30	0	0	0.0425	0.0425	27.43222	27.43222
20	30	30	5	1	0.04026	0.038774	27.90252	28.22919
21	30	30	10	2	0.03771	0.019412	28.47087	34.23859
22	30	60	0	0	0.0861	0.0861	21.29994	21.29994
23	30	60	5	1	0.07928	0.071789	22.01673	22.87884
24	30	60	10	2	0.07335	0.046681	22.692	26.6172
25	30	90	0	0	0.12383	0.12383	18.14348	18.14348
26	30	90	5	1	0.11583	0.105838	18.72358	19.50717
27	30	90	10	2	0.10871	0.072473	19.27461	22.79648

L is the applied load, T is the experiment time, and mc and nc refer to the microcomposite and nanocomposite, respectively.

rate of increase for the hardness was comparatively less on further addition of reinforcement. The hardness increased by more 10 pct on adding 10 wt pct of SiC microparticles as compared to the 5 wt pct of SiC microparticles. This may be due to the increase in particle agglomeration on increasing the weight percentage of SiC microparticles.[37] The hardness was the maximum for 2 wt pct of SiC nanoparticles, whereas it was almost the same for the composite reinforced with 5 wt pct SiC microparticles and 1 wt pct SiC nanoparticles. These results aligned with the wear performance of the gears as the composites reinforced with 5 wt pct SiC microparticles and 1 wt pct SiC nanoparticles had almost the same wear resistance under the maximum applied load. The high hardness of nanocomposites compared to that of microcomposites could be due to the high number density of nanosized particles in the matrix material. These nanoparticles could act as obstacles for the formation of any dislocation.[38]

C. Analysis of the Signal-to-Noise (S/N) Ratio

The signal-to-noise (S/N) ratio depends on the type of characteristic being evaluated. In this investigation, "smaller is better" characteristics were chosen to analyze the wear resistance. For investigating the effect of each variable on the output, the S/N ratio must be determined for the experiment conducted. The S/N ratio for wear (pct), which is the logarithmic transformation of the loss function, is given as

$$S/N_i = 10 \log \frac{\overline{y_i^2}}{s_i^2} \tag{2}$$

where
Mean value of wear (pct)

$$\bar{y} = \frac{1}{N_i} \sum_{u=1}^{N_i} y_{i,u} \tag{3}$$

and the standard deviation

$$s_i = \frac{1}{N_i - 1} \sum_{u=1}^{N_i} (y_{i,u} - \bar{y}) \tag{4}$$

where i is the experiment number, u is the trial number, and N_i is the number of trials for experiment i.

Minitab is a user-friendly software. It uses the Taguchi plan mentioned in Table III but, for the convenience of the user, it needs the value of only three main variables to initiate the analysis as the remaining ten variables are the interactions among these variables. To clarify, the level of the variable in column 1, column

Table V. Response for S/N Ratios of Microparticle- and Nanoparticle-Reinforced Composites

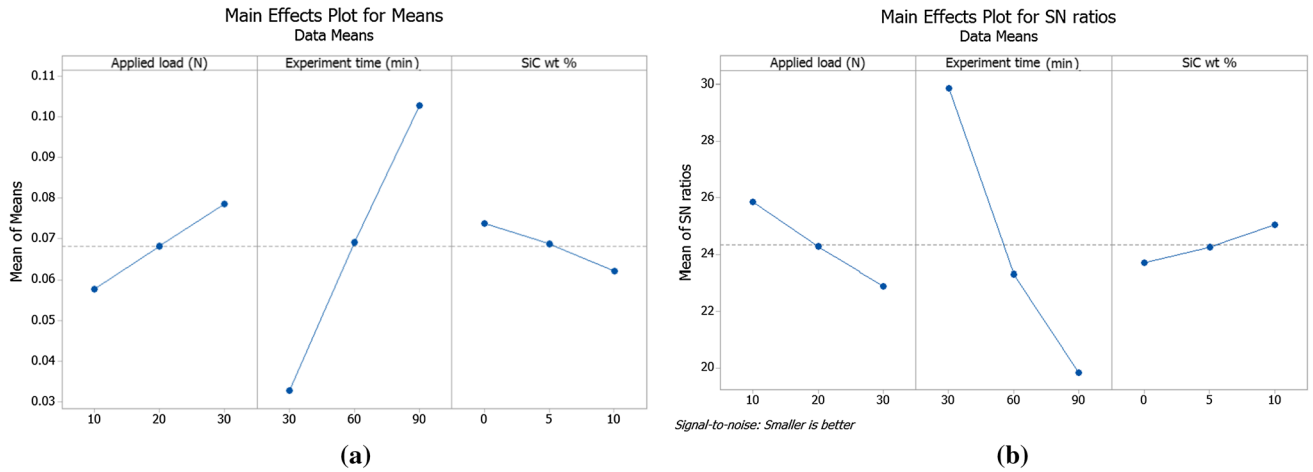| | Control Factors | | | | | |
| | S/N Ratio of Microparticle-Reinforced Composites | | | S/N Ratio of Nanoparticle-Reinforced Composites | | |
Level	L (N)	T (Min)	SiC (Wt Pct)	L (N)	T (Min)	SiC (Wt Pct)
1	25.85	29.88	23.72	26.59	31.28	23.72
2	24.28	23.3	24.26	25.41	24.45	24.61
3	22.88	19.84	25.04	24.57	20.85	28.25
Delta	2.96	10.04	1.32	2.02	10.44	4.54
Rank	2	1	3	3	1	2

Fig. 8—Main effects plots for (*a*) wear (pct) and (*b*) S/N ratios for the microparticle-reinforced composites.
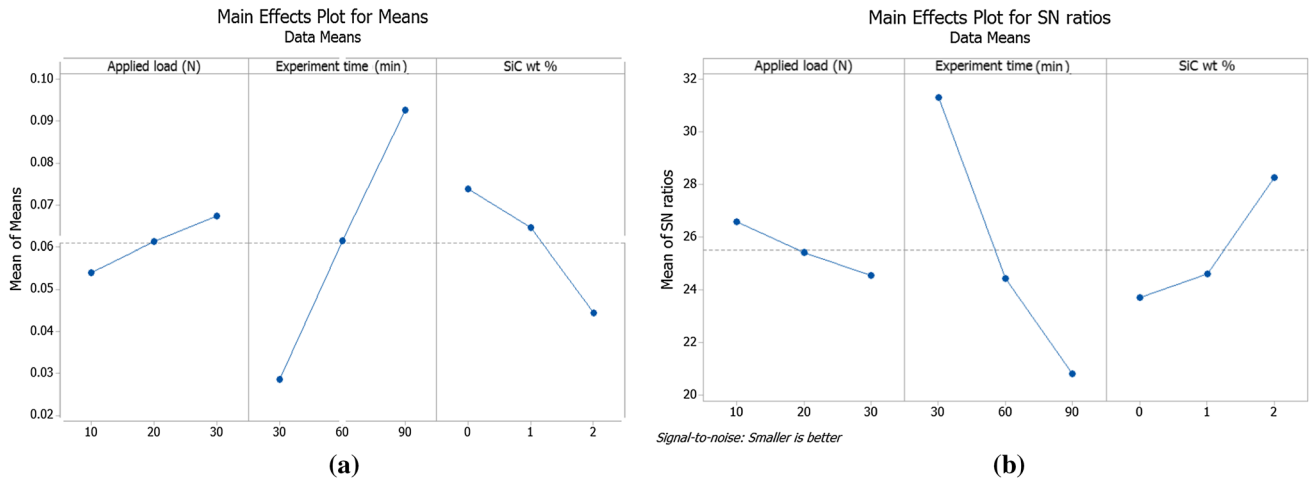

Fig. 9—Main effects for plot for (*a*) wear (pct) and (*b*) S/N ratios for the nanoparticle-reinforced composites.

2, and column 5 of Table III can be compared with the level of three variables (control factors) mentioned in Table IV. For example, row 7 in both tables represent the first level of applied load, third level of experiment time, and first level of SiC content (wt pct). The simplified plan and S/N ratio were also obtained for

various combinations of parameters using the Minitab 17 software, as shown in Table IV.

The effect of testing parameters such as the experiment time, applied load, and SiC content on the wear (pct) was investigated according to the rank of the given parameters. The rank of the testing parameters using the

S/N ratios and means obtained for different parameter levels for wear were also obtained using the Minitab software. The values are listed in Table V. The response table for the S/N ratio shows the average value of the selected features for each level of the factor. This table lists the ranks created on the delta statistics, which equate the relative values of the effects. The S/N ratio is a response that consolidates repetitions and the effect of the noise levels for one data point. The report indicates that the experiment time was more critical as it had the first rank for both types of particle reinforcements. The first rank noted for the experiment time was expected as the gear was subjected to erosive and abrasive wear on the face and flack of the gear teeth. The experiment time predominantly affected the wear (pct) compared to the other operating parameters (applied load and SiC content).[31] The impact of the applied load was more significant than that of the SiC content but was not as significant as that of the experiment time in the case of the SiC microparticles. However, for nanoparticles, the SiC content had a higher influence on the wear resistance than the applied load did. This change in rank (effectiveness) of the SiC content showed that nanoparticles were more effective in improving the wear resistance of the reinforced composites than microparticles. However, such an observation might change if the time and size of the filler were increased. This is because the wear contact surface of the filler will reduce with size. Further, if the content of the nanofiller is increased, agglomeration may take place and the wear rate will consequently increase. Nevertheless, these points require further investigation.

D. Residual Analysis

The main effect plots for the mean wear (pct) and S/N ratios for the microcomposites and nanocomposites are presented in Figures 8 and 9, respectively. As can be seen from the main effect plots for wear and S/N ratios in Figures 8(a) and (b), respectively, the experiment time was the most significant parameter while the applied load also had a significant effect when using microparticles as reinforcements. On the other hand, for nanoparticle-reinforced composites, the main effect plot for wear and S/N ratios shown in Figures 9(a) and (b), respectively, show that the experiment time was the most significant parameter while the SiC content also had a significant effect. The data were analyzed, and graphs were plotted based on the "smaller is better" condition. The goal of this analysis was to generate the plots with minimal wear. The "smaller is better" option in the Minitab program analyzes the input parameters and provides values for S/N ratios to minimize the response value. The plots shown in Figures 8 and 9 indicate that, for minimizing the wear, the experiment time and applied load should be small but the SiC content must be high.

The interaction effect plots for the process parameters are shown in Figure 10. Rana et al.[24] optimized the wear performance of AA5083/10 wt pct SiC$_p$ composites using the Taguchi technique and plotted interaction

effect plots to interpret the results. They proposed that the non-parallelism effect of the parameters plays an important role in the study of the means interaction plot. Nominal interaction occurs if the lines of an interaction plot are not parallel. In addition, the intersection of the lines indicates strong interaction between the process parameters. Figures 10(a) and (b) show strong interactions between the experiment time and SiC content, whereas a moderate interaction was noted between the experiment time and applied load and between the SiC content and applied load. Thus, based on the present analysis, it is clear that the experimental time is the most influencing parameter that determines the wear characteristic of the developed MMCs.

E. Results of ANOVA on Minitab

ANOVA was used to analyze the experimental results and determine the effect of process parameters such as the experiment time, applied load, and SiC content on the wear rate. Using this analysis, the dominant factors and the contribution of each independent variable could be calculated for wear rate. The ANOVA results shown in Table VI(a) and (b) are carried out for the 95 pct confidence level.

For the AMCs, it can be seen that the experiment time (88.15 pct) had the highest contribution to the wear rate, followed by the applied load (7.79 pct), whereas the SiC content (2.44 pct) had the lowest contribution to the wear rate for the microparticle-reinforced composites, as shown in Table V(a). For the nanoparticle-reinforced composites, the experiment time (76.23 pct) had the highest influence on the wear rate, as shown in Table V(b), but the contribution of the SiC content (16.80 pct) and applied load (3.37 pct) was dramatically different from their respective contributions for the microparticle-reinforced composites. The percentage error was very small: 0.13 and 0.09 pct for the microparticle- and nanoparticle-reinforced composites, respectively. Davim[39] analyzed the tool wear using ANOVA with the objective to analyze the influence of the cutting velocity, feed rate, and cutting time on the total variance of the results. They also found that cutting time ($P = 50$ pct) had a higher influence than the feed rate ($P = 24$ pct) and cutting velocity ($P = 9$ pct).

F. Multiple Linear Regression Models

Many researchers including Kivak[40] and Cetin et al.[41] have used regression models for modeling and analyzing wear parameters where a relationship between a dependent variable and one or more independent variables exists. During this analysis, the experiment time (min), applied load (N), and SiC content (wt pct) were the independent variables, whereas the wear (pct) was the dependent variable. To obtain the prediction equations for the wear (pct), regression analysis was used. The prediction equations were generated for two regression models: linear and quadratic. Equations (5) and (6) were obtained from the linear regression model (model-1) for micro- and nanocomposites, respectively.

Wear (pct) = − 0.01705 + 0.001044 L (N) + 0.001170 T (min) − 0.001166 SiC wt pct

R-sq	R-sq(adj)	R-sq(pred)
98.33 pct	98.12 pct	97.56 pct

[5]

Wear (pct) = − 0.00200 + 0.000674 L (N) + 0.001070 T (min) − 0.01471 SiC wt pct

R-sq	R-sq(adj)	R-sq(pred)
95.60 pct	95.02 pct	93.54 pct

[6]

The R-sq values of the equations obtained using the linear regression model of the wear (pct) for micro- and nanocomposites were found to be 98.33 and 95.60 pct, respectively.

Equations [7] and [8] were obtained from the quadratic regression model (model-2) for micro- and nanocomposites, respectively:

regression equation, three levels were used for the applied load, SiC content, and experiment time. The wear (pct) was predicted using the linear (Eqs. 5 and 6 for model-1) and quadratic (Eqs. [7] and [8] for model-2) regression equations for both the micro- and nanocom-

Wear (pct) = − 0.01725 + 0.000617 L (N) + 0.001163 T (min) + 0.001382 SiC (wt pct) + 0.000008 L (N) × T (min) − 0.000040 L (N) × SiC wt pct − 0.000040 T (min) × SiC wt pct + 0.000001 L (N) × T (min) × SiC wt pct

[7]

R-sq	R-sq(adj)	R-sq(pred)
99.74 pct	99.64 pct	99.33 pct

Wear (pct) = −0.01486 + 0.000628 L (N) + 0.001137 T (min) + 0.00486 SiC (wt pct) + 0.000008 L (N) × T (min) − 0.000290 L (N) × SiC wt pct − 0.000179 T (min) × SiC wt pct − 0.000003 L (N) × T (min) × SiC wt pct

[8]

R-sq	R-sq(adj)	R-sq(pred)
99.07 pct	98.71 pct	97.49 pct

The R-sq values of the equations obtained using the quadratic regression model of the wear (pct) for the micro- and nanocomposites were found to be 99.74 and 99.07 pct, respectively, which were more than those resulting from the linear equation. Hence, more intensive predicted values can be obtained using the quadratic regression model compared to those given by the linear regression model. As a result, the quadratic regression model was more successful in estimating the wear (pct) in the developed MMCs.

G. Confirmation Test

A confirmation test was the final step in the experimental process. The wear test on gears was conducted using a predefined set of parameters. To develop the

posites, as shown in Table VII(a) and (b), and the predicted values were compared with the experimental values to validate and determine the accuracy of the model and the respective errors. The following equation was used to calculate the error (pct):

$$\text{Error (pct)} = \frac{\text{experimental wear (pct)} - \text{predicted wear (pct)}}{\text{experimental wear (pct)}} \times 100$$

The fourth level of experimental time (120 minutes) was used to confirm that the regression can predict other values that have not been used in the Taguchi and regression models. Tables VIII(a) and (b) show the predicted and experimental values for the micro- and nanocomposites, respectively.
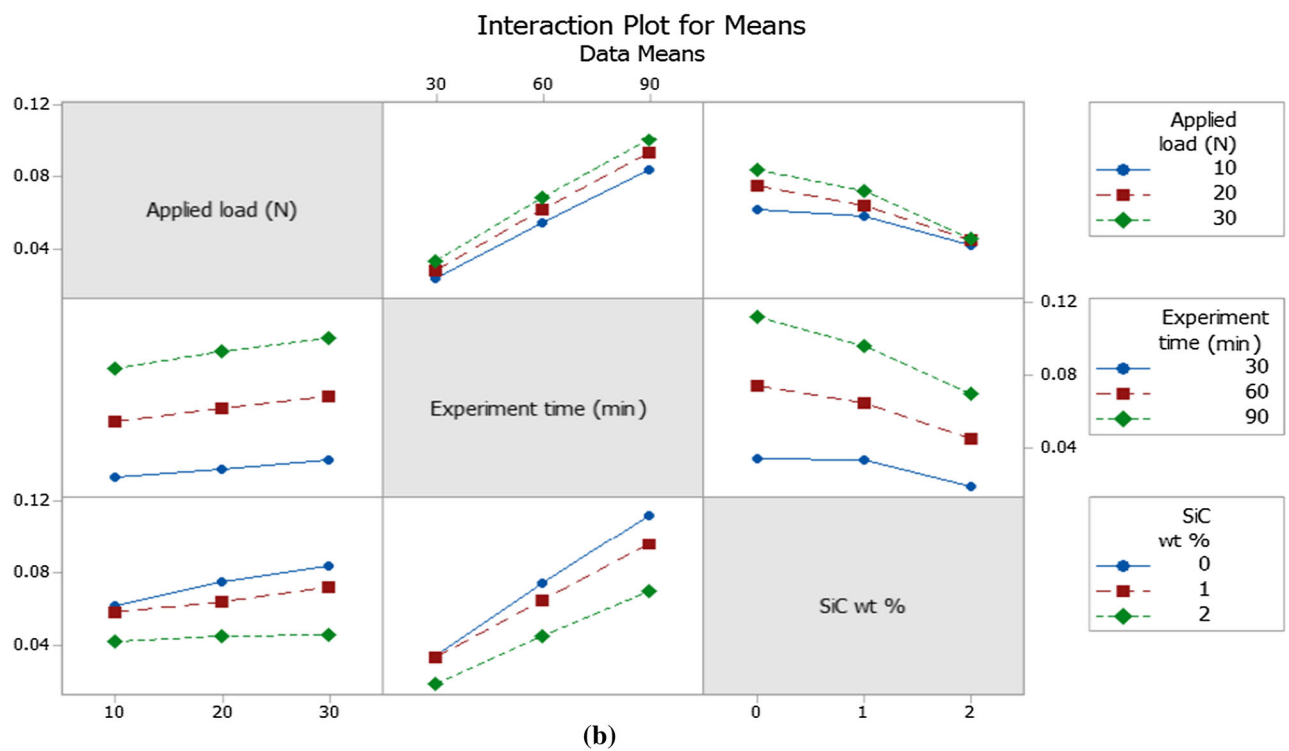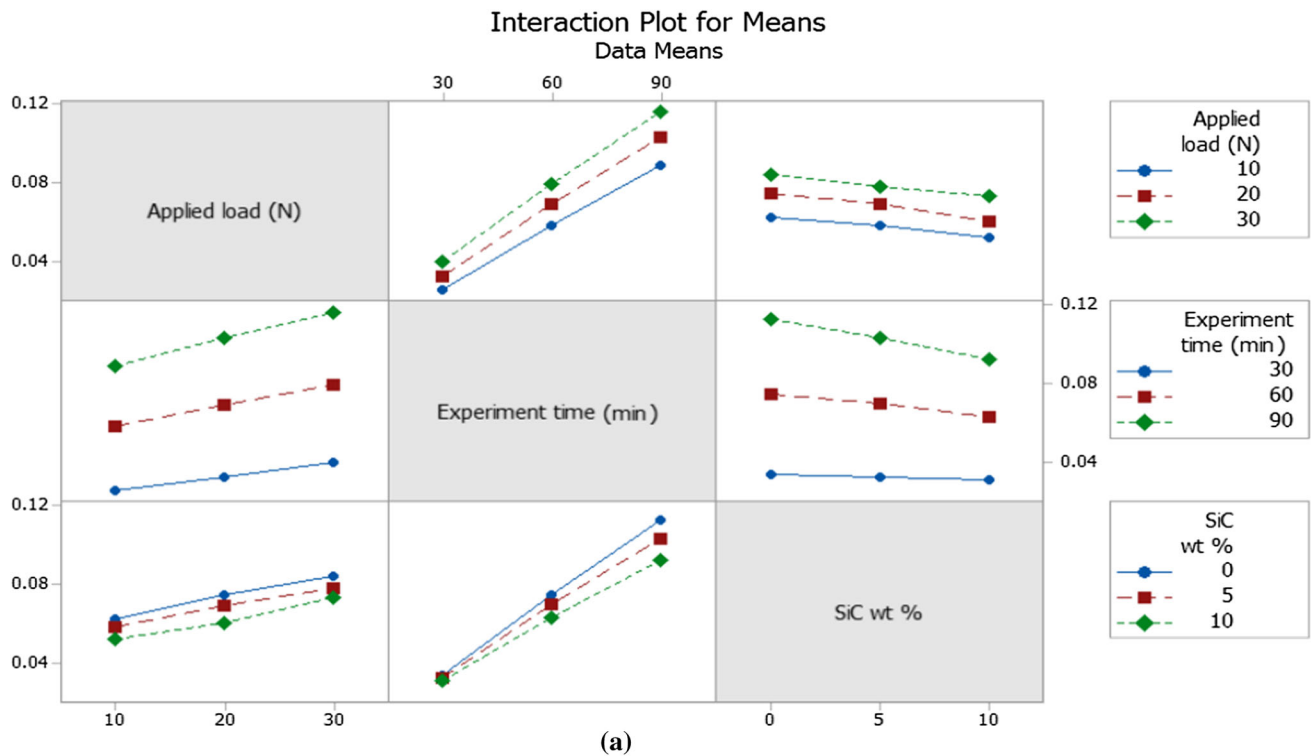
Fig. 10—Interaction effects plots of process parameters on wear for (*a*) microparticle-reinforced composite and (*b*) nanoparticle-reinforced composite.

Table VI. ANOVA for Microparticle-Reinforced Composites

Source	df	Seq SS	Contribution (Pct)	Adj SS	Adj MS	F Value
(a)						
L (N)	2	0.001962	7.79	0.001962	0.000981	233.17
T (Min)	2	0.022188	88.15	0.022188	0.011094	2636.99
SiC Wt Pct	2	0.000614	2.44	0.000614	0.000307	73.03
L (N) $\times$ T (Min)	4	0.00012	0.48	0.00012	0.00003	7.14
L (N) $\times$ SiC Wt Pct	4	0.000021	0.08	0.000021	0.000005	1.26
T (Min) $\times$ SiC Wt Pct	4	0.00023	0.91	0.00023	0.000058	13.68
Error	8	0.000034	0.13	0.000034	0.000004	
Total	26	0.025169	100.00			
(b)						
L (N)	2	0.00082	3.37	0.00082	0.00041	152.49
T (Min)	2	0.018542	76.23	0.018542	0.009271	3446.4
SiC Wt Pct	2	0.004085	16.80	0.004085	0.002043	759.35
L (N) $\times$ T (Min)	4	0.000035	0.15	0.000035	0.000009	3.3
L (N) $\times$ SiC Wt Pct	4	0.000244	1.00	0.000244	0.000061	22.71
T (Min) $\times$ SiC Wt Pct	4	0.000574	2.36	0.000574	0.000143	53.34
Error	8	0.000022	0.09	0.000022	0.000003	
Total	26	0.024323	100.00			

Table VII. Comparison of Predicted and Experimental Wear of Microcomposites (with Three Levels of Experiment Time)

Sr. No.	L (N)	T (Min)	SiC (Wt Pct)	Experimental Wear (Pct)	Predicted Wear (Pct)		Error (Pct)	
					Model 1	Model 2	Model 1	Model 2
(a)								
1	10	30	0	0.02625	0.02849	0.02621	8.53	0.15
2	10	60	5	0.06046	0.05776	0.05941	4.47	1.74
3	10	90	10	0.07954	0.08703	0.08361	9.42	5.12
4	20	60	5	0.06985	0.0682	0.07138	2.36	2.19
5	30	60	5	0.07928	0.07864	0.08335	0.81	5.13
(b)								
1	10	60	0	0.06226	0.06894	0.06444	10.73	3.50
2	10	60	1	0.058586	0.05423	0.05386	7.44	8.07
3	20	60	0	0.07568	0.07568	0.07552	0.00	0.21
4	20	60	2	0.04568	0.04626	0.04496	1.27	1.58
5	30	90	0	0.12383	0.11452	0.12791	7.52	3.29

Table VIII. Comparison of Predicted and Experimental Wear of Microcomposites (with Fourth Level of Experiment Time)

Sr. No.	L (N)	T (Min)	SiC (Wt Pct)	Experimental Wear (Pct)	Predicted Wear (Pct)		Error (Pct)	
					Model 1	Model 2	Model 1	Model 2
(a)								
20	10	120	0	0.13233	0.13379	0.13808	1.10	4.35
21	20	120	0	0.14982	0.14423	0.15385	3.73	2.69
22	20	120	5	0.14142	0.1384	0.14476	2.14	2.36
24	30	120	5	0.15322	0.14884	0.16453	2.86	7.38
25	30	120	10	0.14615	0.14301	0.15944	2.15	9.09
(b)								
19	10	120	0	0.13233	0.13314	0.13746	0.61	3.88
21	10	120	2	0.09232	0.10372	0.09122	12.35	1.19
22	20	120	0	0.14982	0.13988	0.15334	6.63	2.35
23	20	120	1	0.12673	0.12517	0.12372	1.23	2.37
25	30	120	1	0.14108	0.13191	0.1331	6.50	5.66

The results show that the experimental and predicted values were not significantly different. Cetin et al.[41] conducted confirmation experiments for Taguchi's optimal random points and regression equations. They suggested that, for reliable statistical analysis, errors must be smaller than 20 pct. In their work, the maximum calculated error was 18.03 and 17.92 pct for cutting and feed forces, respectively, for the higher levels. The maximum calculated errors in this work were found to be 9.09 pct, which is much smaller than the acceptable limit. Therefore, the confirmation test demonstrated the successful optimization and generation of the prediction model.

V. CONCLUSIONS

AMCs have been successfully developed by reinforcing the AA5083 alloy with SiC micro- and nanoparticles *via* stir casting. The composites were used to fabricate a gear that was tested for wear using a specially designed test rig. The following conclusions were drawn by studying the results of the wear test of the gear using statistical techniques:

1. Nanoparticle reinforcement is more effective in improving wear resistance compared to microparticle reinforcement.
2. The AMC reinforced with 2 wt pct of nanoparticles showed a lower wear rate than that of composites with all other micro- and nanoparticle compositions investigated.
3. The experiment time and applied load had the highest influence on the wear rate, followed by the SiC content, in the case of the AA5083 composite reinforced with SiC microparticles.
4. The experiment time and SiC content had the highest influence on the wear rate, followed by the applied load, in the case of the AA5083 composite reinforced with SiC nanoparticles.
5. The regression equation generated for MMCs exhibited reasonable accuracy in predicting the wear of the composites for intermediate conditions.
6. A confirmation test was successfully performed by comparing the experimental results with the predicted values with reasonable error. Thus, designing the experiments using the Taguchi method could successfully predict the tribological behavior of the composites.

ELECTRONIC SUPPLEMENTARY MATERIAL

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