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Technical Note

Influence of Nanoparticles Reinforcements on the Mechanical Performance and Tribological Properties of Aluminum 6082 Alloys

Anwer J. AL-OBAIDI*, Abdalameer TARIQ, Hussein DALFI

University of Wasit, College of Engineering, Mechanical Department
Al Kūt, Wasit, Iraq

*Corresponding Author e-mail: aalobaidi@uowasit.edu.iq

This research investigates the effect of using hard ceramic SiC particles on the mechanical and tribological properties of Al6082 alloy. This investigation is performed by mixing various contents of SiC as weight percentages of 0, 1, 2, 3, and 4% with Al6082. Mechanical tests, such as tensile strength and hardness tests, are adopted for this composite (Al6082/SiC) at various contents of the filler (SiC). Besides, the wear test is conducted for the Al6082/SiC composite at various normal loads (10, 15, 20, 25, and 30 N) and sliding distances (200, 400, 600, 800, and 1000 m). Taguchi's approach is used to create the experimental runs' matrix. The findings reveal that the mechanical properties improved with increasing the percentage of SiC reinforcement. The tensile strength and Rockwell hardness of Al6082 increased by about 24.6 and 14%, respectively, using 4% of SiC particles. Regarding the tribological behavior, the average wear of Al6082 alloy decreased with increasing the percentage of SiC reinforcement due to higher hardness of reinforcement in Al6082/SiC composite. At the same time, an increase in the normal load and sliding distance led to a decrease in wear due to increasing plastic deformation at elevated loadings and larger area contacts.

Keywords: Al6082 alloy; SiC nanoparticles; tensile strength; wear resistance; metal matrix composite.

1. Introduction

In the present era, the replacement of conventional materials has become a central issue for various applications, such as military weapons, aerospace, and automotive industries. Recently, researchers have shown an increased interest in metal matrix composites (MMCs) reinforced with ceramic [1] and [2]. MMCs quickly become key instruments in replacing conventional materials due to their improved mechanical and physical properties [3]. These composites display their isotropic properties through their three directions combined with low cost and the possibility to prepare easily [4]. Various metals have been used in MMCs, such as aluminum and magnesium, because of their appropriateness when used in the casting processes. To enhance their properties, different reinforcements can be used in MMCs, such as SiC, graphite, Al_2O_3, MgO, and eggshell [5] and [6]. The machinability of Al2024 strengthened by Al_2O_3 and B_4C was investigated in [7]. The stir casting method was adopted to produce this composite and was characterized through microhardness analysis.

The failure of SiC fiber-reinforced glass composites was discussed in [8]. The tests that were performed on the composite samples were tensile and bending tests. The results showed that the composite component's strength strongly depend on the geometry and loading. A composite of Al7075 reinforced with various nanoparticle sizes was studied in [9]. It was found that the compressibility decreased with decreasing the filler particle size. However, the sinterability increased with decreasing the size of fillers because of easy filling up the pores.

The effect of nanoparticle size on the fatigue life of A7075-T651 was studied in [10]. The various weight percentages of SiC were used, and it was observed that the fatigue life increased when the weight percentage increased around 12% more than the base metal at 10 wt% of SiC.

In addition, studying the tribological behavior of lightweight materials, such as aluminim alloys is very important due to using these alloys in various applications, such as pistons, cylinder bores, and engine brakes. The wear test of AZ91 alloy was examined versus a counterface ring made of AISI 52100 type bearing steel [11]. Limited investigations were conducted on the tribological behavior of magnesium-based MMCs. The study in [12] found that the wear rates of Mg alloy reinforced by feldspar particles decreased with increasing the reinforcement percentage. The wear rate was transferred from mild to severe due to variation in the applied load. In [13], the effect of the addition of SiC particles on the tribological properties of the Mg alloy during the wear test was investigated. The results found a significant influence of SiC on the properties of Mg alloy. The wear rate and coefficient of friction of aluminum alloy (Al2024) were analyzed by Zawawi *et al.* [14]. This analysis was performed at a constant load of 10 kg and at various speeds. The results found that the coefficient of friction and the wear rate decreased when the composite nano lubricant (SiO_2/PAG) was used.

The dry sliding behavior of another aluminum alloy (Al6061) was investigated by Naveed and Khan [15]. Two types of fillers were used (SiC with content at 7% and graphite with content at 4%). Based on the findings, the wear resistance increased with the presence of SiC particles and this increase was continuous with adding Gr up to 4 wt%. Furthermore, it was found that ice quenching is the best in improving wear resistance. The mechanical and tribological properties of Al7075 reinforced by B_4C were studied by Baradeswawaran and Perumal [16]. The authors used the stir casting method to synthesize the composite and observed that the hardness increased with increasing hard B_4C. Moreover, the wear rate and coefficient of friction of the alloy decreased when the content of the B_4C was increased.

Given all that has been mentioned so far, one may suppose that strengthening aluminum alloys is very important and necessary to enhance the mechanical and tribological properties due to their important applications in, for example, the aerospace and transportation industries. Therefore, the current research aims to study the effect of using nano SiC particles on the mechanical and tribological properties of Al6081. Besides, Taguchi's approach was conducted to design the experimental runs of the wear test using five levels of each SiC reinforcement, normal load, and sliding distance.

2. Materials and experimental tests

2.1. Materials

Aluminum alloy (Al6082) exhibits excellent corrosion resistance, medium strength, and good mechanical properties. It contains a large amount of manganese in the grain structure, which results in a strong alloy. Therefore, this alloy is used in various applications, such as aeroplanes, vehicles, and engineering applications [17] and [18]. Table 1 presents the compositions of aluminum 6082 alloy.

Table 1. The composition of Al6082 alloy.

Elements	Weight [%]
Manganese (Mn)	0.40–1.00
Ferrous (Fe)	0.00–0.50
Magnesium (Mg)	0.60–1.20
Silicon (Si)	0.70–1.30
Copper (Cu)	0.00–0.10
Zinc (Zn)	0.00–0.20
Titanium (Ti)	0.00–0.10
Chromium (Cr)	0.00–0.25
Aluminum (Al)	Balance

Silicon carbide (SiC) can also be called carborundum, a combination of silicon and carbon. This combination occurs in nature as extremely rare mineral moissanite or silicon carbide grains can be bonded using sintering. This compound is a very hard ceramic widely used in different applications that require high endurance, such as car brakes and antibullet vests. Besides, it exhibits good erosion and abrasive resistance [19]. Table 2 shows the composition of the silicon carbide nanoparticles used in this study.

Table 2. Composition of silicon carbide nanoparticles (SiC).

Silicon	Carbon	Particle size [nm]
70	30	20 ± 5

2.2. Fabrication process

The stir casting process produces composite materials through the liquid state, in which the molten matrix metal is mixed with fillers, such as ceramic particles and short fibers, using stirring. The benefits of this approach are flexibility, applicability, and simplicity for production in large volumes. Al6082 was selected for its good properties, and the SiC nanomaterial was also chosen due to its good properties. The sample is designed by melting Al6082 inside a melting pot using an electric oven at a temperature of 850°C for 20 minutes. After that, the nano SiC composite was preheated to 200°C. Then, nanopowder of SiC was added into the melt of aluminum alloy by the percentage (1, 2, 3, and 4) wt% at stirring speed 450 rpm for 5 min using an electric mixer. This is to obtain good homogeneity in a protected atmosphere (argon gas to avoid oxidation). Figure 1a illustrates the flowchart of the fabrication of Al6082/SiC alloy and Fig. 1b – Al6082/SiC alloy. In addition, Fig. 2 presents the microstructures of pure Al6082 and nanocomposite Al6082/SiC.

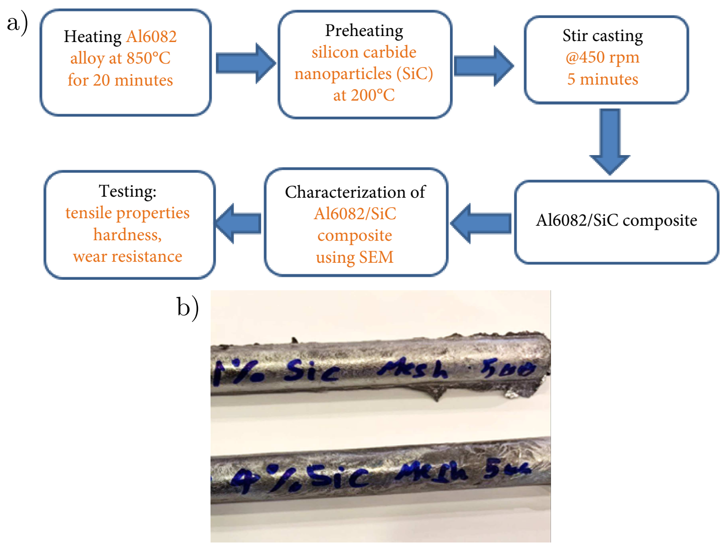

FIG. 1. Flowchart of fabrication of: a) Al6082/SiC alloy; b) Al6082/SiC alloy.

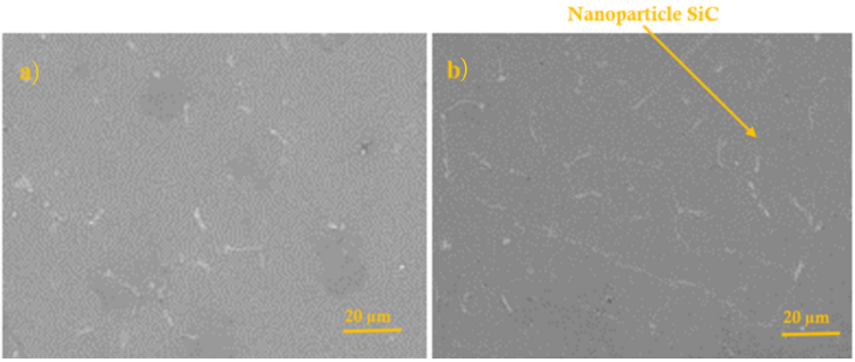

FIG. 2. SEM images of: a) Al6082 alloy; b) Al6082 +4 wt% SiC.

2.3. *Experimental tests*

2.3.1. Tensile strength test. The tensile test was conducted to study the influence of SiC reinforcement on the tensile strength of Al6082 alloy. At ambient temperature, the tensile test followed the ASTM E8-04 standard [20]. Universal Testing Machine (Model UE34300) was used to carry out the tensile test of the samples. The dimensions of the samples are shown in Fig. 3.

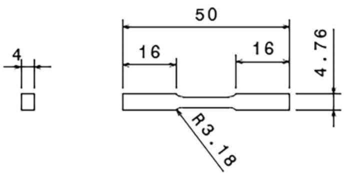

FIG. 3. Dimensions of the tensile test samples [mm].

2.3.2. Hardness test. Hardness is a necessary property to be improved in materials and enables them to resist plastic deformation through penetration. Therefore, the Rockwell hardness test (HRB) was used to investigate the effect of adding SiC to Al6082 alloy. The hardness test was conducted according to ASTM E18-15 [21]. The hardness test was carried out using the universal hardness tester HBRVS-187.5. The test was repeated three times for each weight percentage of SiC particles.

2.3.3. Wear resistance test. The effect of SiC reinforcement on the tribological behavior of Al6082 was investigated using a dry wear test. A pin-on-disk wear test was performed following ASTM G99-04 standard [22]. Such an apparatus disc is made of EN31 steel with a surface roughness of 0.1. The wear weight loss is calculated by measuring the weight of the pins before and after the test. The surface of the samples was cleaned and polished using abrasive papers. A DUCOM TR-20M-106 machine was used to carry out the wear test. This test was conducted with various weight percentages of SiC reinforcements under different normal loads and sliding distances, while the sliding speed was constant at 500 rpm.

3. Results and discussion

3.1. Mechanical properties

3.1.1. Tensile test. The tensile test was conducted to study the influence of SiC reinforcement on the tensile strength of Al6082 alloy. The tensile test followed the ASTM E8-04 standard [20]. Three samples were prepared for this test for each composition of Al6082/SiC. An Instron device was used for this test. Table 3 presents the results obtained from the tensile test of Al6082/SiC samples.

Table 3. Tensile test results.

Al6082 wt%	SiC wt%	Average ultimate strength [MPa]
100	0	143
99	1	151
98	2	175
97	3	180
96	4	187

It can be seen in Fig. 4 that the average ultimate strength of the composite Al6082/SiC was increased to reach about 24.6% when the weight percentage of SiC was 4% compared with no addition of SiC particles. The observed increase in

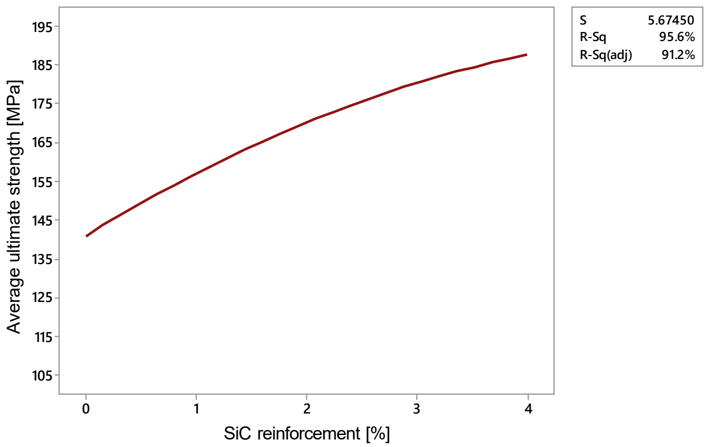

Fig. 4. The effect of SiC reinforcement [%] on the ultimate strength.

tensile strength might be explained by an increase in the load-bearing capacity of Al6082/SiC through the load transferred to the SiC particles from the Al6082 matrix. The addition of hard ceramic SiC reinforcements leads to achieving the strengthening of the Al6082/SiC composite that enhances the grain boundaries of the Al6082 matrix and then results in higher strength. This is because the hard ceramic SiC reinforcement resists the plastic flow of Al6082/SiC when exposed to strain [23].

3.1.2. Rockwell hardness test. Hardness is an essential property to be improved in materials. It enables to resist plastic deformation through penetration. Therefore, the Rockwell hardness test (HRB) is used to investigate the effect of adding SiC on Al6082 alloy. The hardness test is conducted according to ASTM E18-15 [21]. The test is repeated three times for each weight percentage of SiC particles. Table 4 provides the results obtained from the Rockwell hardness test of Al6082/SiC.

Table 4. Rockwell hardness test of Al6082/SiC.

Al6082 wt%	SiC wt%	Average Rockwell hardness (HRB)
100	0	43
99	1	45
98	2	46
97	3	48
96	4	49

From the trend in Fig. 5, it is apparent that increasing SiC reinforcement addition leads to an increase in the HRB of the Al6082 matrix. These find-

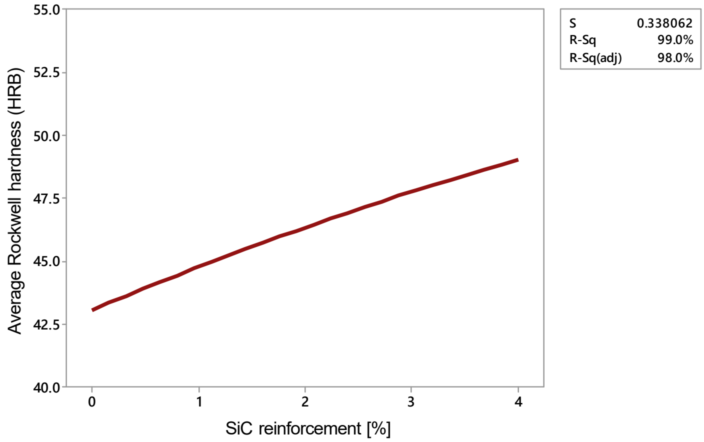

Fig. 5. The effect of SiC reinforcement [%] on the Rockwell hardness.

ings reveal the importance of adding SiC, which enhances the hard and brittle phase of Al6082 and then increases the density at the Al6082/SiC interface. Further, because of this addition, the grain recrystallization and internal residual stress relief increase the hardness of the composite. Moreover, the hard ceramic SiC decreases the ductility and gives high plastic deformation resistance that enhances the hardness of Al6082/SiC. According to the obtained results, an increase in HRB reached about 14% compared with no addition when SiC was added by 4 wt%.

3.2. Tribological properties

The tribological behavior has been investigated for the influence of adding SiC on the Al6082 alloy using a dry wear test. After conducting the test, the calculation of wear depends on measuring the weight of pins before and after the test. Each sample should prepare before testing which includes cleaning and polished using abrasive papers. The variable factors of this test are weight percentages of SiC reinforcements, normal load, and sliding distances, while the sliding speed was constant at 500 rpm. Table 5 illustrates the factors and their levels used.

Table 5. Wear test factors and their levels.

SiC reinforcement [%]	Normal load [N]	Sliding distance [m]
0	10	200
1	15	400
2	20	600
3	25	800
4	30	1000

According to Table 5, massive experimental runs can be generated using a full factorial experimental design. Based on it, it is very difficult to study the combined influences of the selected factors. Therefore, the design of the experiment, which is a statistical method, is necessary to tackle this challenge [24]. One of these designs of experiments is the Taguchi methodology.

3.2.1. Taguchi methodology. Taguchi methodology is an experimental design used to reduce the number of runs and estimate the average values of the response. Therefore, this method saves time and cost due to using a fewer number of runs. This approach depends on calculating the signal-to-noise ratio (Eq. (3.1)) type to find the optimum values of the used factors [24]:

$$\frac{S}{N} = -10 \log \left[\frac{1}{n} \sum \frac{1}{y^2} \right], \tag{3.1}$$

where n and y represent the number of replications and observations of each level, respectively. According to the Taguchi approach (orthogonal array L25) and Table 5, the experimental runs for the wear test are created using the Minitab 17 statistical software. Each experimental run was repeated three times to check reliability. Table 6 illustrates the results of the wear test. While the relationship between the wear average and the factors is shown in Fig. 6.

Table 6. Wear test results.

SiC reinforcement [%]	Normal load [N]	Sliding distance [m]	Average wear [g]
0	10	200	0.01130
0	15	400	0.02210
0	20	600	0.04710
0	25	800	0.06510
0	30	1000	0.07740
1	10	400	0.01310
1	15	600	0.02010
1	20	800	0.03100
1	25	1000	0.04910
1	30	200	0.03410
2	10	600	0.01100
2	15	800	0.02090
2	20	1000	0.02900
2	25	200	0.01670
2	30	400	0.02710
3	10	800	0.01130
3	15	1000	0.02821
3	20	200	0.01765
3	25	400	0.01982
3	30	600	0.02610
4	10	1000	0.01120
4	15	200	0.00721
4	20	400	0.00841
4	25	600	0.01030
4	30	800	0.01410

Further, the analysis of variance (ANOVA) is performed to evaluate the findings statistically and reveal the importance and significance of the factors and

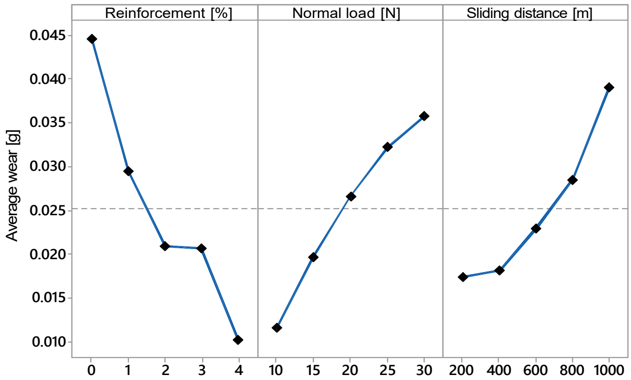

FIG. 6. Relationship between average wear and SiC reinforcement, normal load, and sliding distance.

their levels. Table 7 shows the ANOVA results of the wear test for Al6082/SiC samples.

Table 7. ANOVA results of the wear test.

Source	DF	Adj SS	Adj MS	F-value	p-value
SiC reinforcement [%]	4	0.003288	0.000822	11.79	0.000
Normal load [N]	4	0.001892	0.000473	6.78	0.004
Sliding distance [m]	4	0.001586	0.000396	5.69	0.008
Error	12	0.000837	0.000070		
Total	24	0.007602			

From the data in Fig. 6 and Table 7, it is interesting to note that all three parameters of this study have a significant effect on the wear of Al6082 depending on the p-value, which is considered significant if its value is less than 0.05. Moreover, Taguchi's approach predicts the wear model in terms of its factors through the regression as follows:

$$\begin{aligned} \text{Wear [g]} &= 0.02518 + 0.01942\ \text{Reinforcement\%\_0} \\ &+ 0.00430\ \text{Reinforcement\%\_1} - 0.00424\ \text{Reinforcement\%\_2} \\ &- 0.00456\ \text{Reinforcement\%\_3} - 0.01493\ \text{Reinforcement\%\_4} \\ &- 0.01360\ \text{Normal load [N]\_10} - 0.00547\ \text{Normal load [N]\_15} \\ &+ 0.00146\ \text{Normal load [N]\_20} + 0.00703\ \text{Normal load [N]\_25} \\ &+ 0.01058\ \text{Normal load [N]\_30} - 0.00778\ \text{Sliding distance [m]\_200} \\ &- 0.00707\ \text{Sliding distance [m]\_400} - 0.00226\ \text{Sliding distance [m]\_600} \\ &+ 0.00330\ \text{Sliding distance [m]\_800} + 0.01381\ \text{Sliding distance [m]\_1000}. \end{aligned} \tag{3.2}$$

All terms in Eq. (3.2), such as reinforcement, normal load, and sliding distance, were mentioned previously in Table 5.

3.2.2. Effect of the individual factor on the wear. The influence of each factor on the wear of Al6082 is shown in Fig. 7. The wear decreased when the reinforcement percentage of SiC was increased. However, an increase in normal load and sliding distance leads to an increase in the wear of the alloy. The wearing weight or wear volume can be estimated using Archard's law [25]. Based on this law, the wear is directly proportional to normal load and sliding distance, but the relationship becomes reverse to the hardness of the material, as follows:

$$V = \frac{K_1 N l}{3H}, \tag{3.3}$$

where V, N, l, and H are volume loss in wear, normal load, sliding distance, and the hardness of the material, respectively. In addition, K is the wear constant that depends on elastic and plastic contacts.

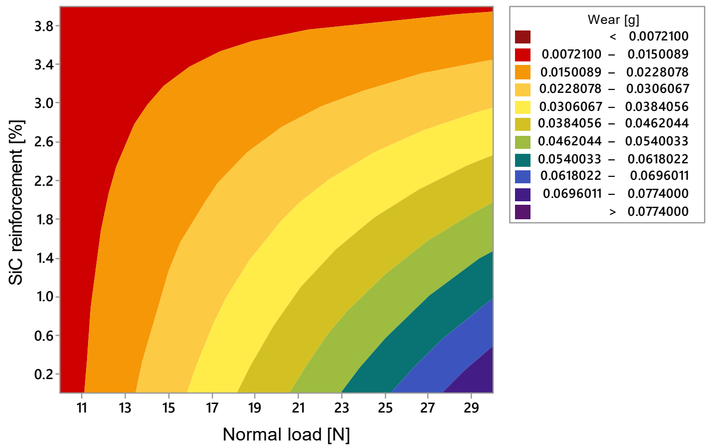

FIG. 7. Interaction effect of SiC reinforcement and normal load on the wear.

The wear resistance of Al6082 is improved using SiC particles. The decrease in wear is due to adding hard SiC reinforcement into the Al6082 alloy, which results in dry lubrication between the hard disk and soft pin. Hence, when the SiC particles are present, the friction coefficient reduces while the temperature rises. This leads to plastic deformation at the surface of Al6082 alloy, while the surface remains relatively smooth at the Al6082/SiC composite due to the protection by the reinforcement. Therefore, the wear weight loss decreased by increasing the amount of hard SiC. This phenomenon was observed in previous studies [26, 27].

In Fig. 7, there is a clear trend of increasing the wear with increasing the applied load. At increasing the applied load, the surface of the composite was "plowed" deeply by the grits. Therefore, using large particles might be better than using fine particles in the wear test at high loads due to moving the fine particles away together with the matrix. Although the increase of reinforcement percentage produces the highest wear resistance, Al6082/SiC offered a moderate improvement with increasing loads, as shown in Fig. 6. The most likely cause of this behavior is the brittle interface formed between SiC particles and the Al6082 matrix that is unable to resist the action of the wear under elevated pressures [27].

Figure 8 reveals that there is a steady increase in the average wear by increasing the sliding distance. This increase in the wear may be due to increasing the contact area with increasing contact time, which in turn increases the wear. Furthermore, the increase of sliding distance with the presence and increase of normal load leads to an increase in the wear rate (see Fig. 6) because of increasing the temperature at the contact surface, which causes a deeply plowed composite [28, 29].

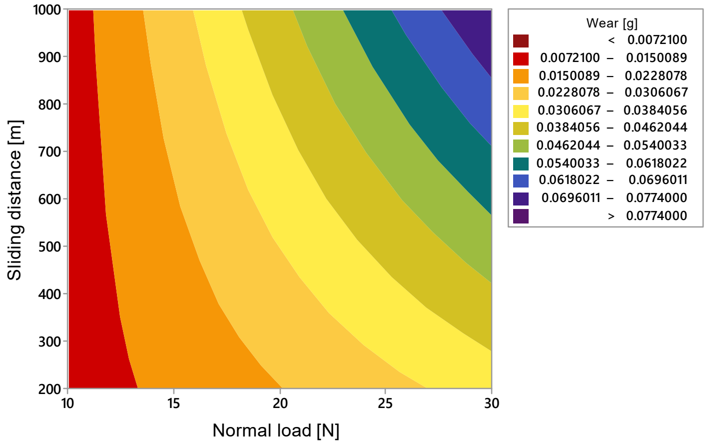

FIG. 8. Interaction effect of sliding distance and normal load on the wear.

4. Conclusions

This investigation's aim was to assess the mechanical and tribological properties of the Al6082/SiC composite. One of the more significant findings of this study is that the presence of hard reinforcement SiC enhances the mechanical and tribological properties of Al6082 alloy. The findings of this investigation complement those of earlier studies and make several contributions to the existing literature. According to the mechanical properties of Al6082 alloy, tensile strength and hardness increased by around 24.6% and 14%, respectively, when the weight percentage of SiC particles was 4% because of the presence of a hard reinforcement in a soft alloy.

Regarding the tribological properties, the average wear of Al6082/SiC composites decreased with increasing the percentage of SiC reinforcement due to higher hardness in reinforcement in Al6082/SiC. However, the wear increased with an increase in the normal load and sliding distance due to increased plastic deformation at elevated loadings and larger area contacts. Moreover, Taguchi's approach was conducted to design the experimental runs of the wear test using three factors and each factor had five levels. The statistical findings concluded that all used factors have a significant impact on the wear.

Based on this study, it can be concluded that the addition of nano ceramic SiC in the Al6082 alloy can improve the mechanical and tribological behavior of the Al6082 alloy and is suitable for various applications, for example, in the transportation industries. Therefore, the hybrid composite of Al6082/SiC is expected to be considered a light hybrid composite that offers some advantages in its applications.

Declaration of conflicting interests

The authors declare no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

References

1. Al-Alkawi H.J., Aziez S.A., Idan D.A., Microstructure and electrical onductivity of 7075Al alloy/SiC nano composites, *Engineering and Technology Journal*, **36**(10A): 1034–1038, 2018, doi: 10.30684/etj.36.10A.3.

2. Nadim A., Taghiabadi R., Razaghian A., Noghani M.T., Ghoncheh M.H., Effect of Fe-impurity on tribological properties of Al-15Mg_2Si composite, *Transactions of Nonferrous Metals Society of China (English Edition)*, **28**(6): 1084–1093, 2018, doi: 10.1016/S1003-6326(18)64744-2.

3. Madhankumar S., Rajesh S., Vignesh T., Harikrishnan M., Fabrication of Al 6082, SiC and boron glass powder composites and evaluation of mechanical properties, *International Journal of Innovative Research in Science, Engineering and Technology,* **7**(1), 2018, doi: 10.15680/IJIRSET.2017.0701003.

4. Kumar D., Suman K, Sasanka C., Ravindra K., Poddar P., Venkata S., Microstructure, mechanical response and fractography of AZ91E/Al_2O_3 (p) nano composite fabricated by semi solid stir casting method, *Journal of Magnesium and Alloys*, **5**(1): 48–55, 2017, doi: 10.1016/j.jma.2016.11.006.

5. Khajuria A., Influence of ceramic Al_2O_3 particulates on performance measures and surface characteristics during sinker EDM of stir cast AMMCs, *World Journal of Engineering*, **16**(4): 526–538, 2019, doi: 10.1108/WJE-01-2019-0015.

6. Parande G., Manakari V., Kopparthy S., Gupta M., A study on the effect of low-cost eggshell reinforcement on the immersion, damping and mechanical properties of magnesium–zinc alloy, *Composites Part B: Engineering*, **182**(1): 1–37, 2020, doi: 10.1016/j.compositesb.2019.107650.

7. Najem S., Machinability of Al-2024 reinforced with Al_2O_3 and or B_4C, *Journal of University of Babylon for Engineering Sciences*, **21**(1): 1–13, 2013.

8. Jansson S., Leckie F., The mechanics of failure of silicon carbide fiber-reinforced glass-matrix composites, *Acta Metallurgica et Materialia*, **40**(11): 2967–2978, 1992, doi: 10.1016/0956-7151(92)90461-M.

9. Karunanithi R., Ghosh D., Bera S., Influence of particle size of the dispersoid on compressibility and sinterability of TiO_2 dispersed Al 7075 alloy composites prepared by mechanical milling, *Advanced Powder Technology*, **25**(5): 1500–1509, 2014.

10. Divagar S., Vigneshwar M., Selvamani S., Impacts of nano particles on fatigue strength of aluminum based metal matrix composites for aerospace, *Materials Today: Proceedings*, **3**(10): 3734–3739, 2016, doi: 10.1016/j.matpr.2016.11.021.

11. Chen H., Alpas A.T., Sliding wear map for the magnesium alloy Mg-9Al-0.9 Zn (AZ91), *Wear Journal*, **246**(1–2): 106–116, 2000, 10.1016/S0043-1648(00)00495-6.

12. Sharma S.C, Anand B., Krishna M., Evaluation of sliding wear behaviour of feldspar particle-reinforced magnesium alloy composites, *Wear Journal*, **241**(1): 33–40, 2000, 10.1016/S0043-1648(00)00349-5.

13. Thakur S.K., Dhindaw B.K., The influence of interfacial characteristics between SiC_p and Mg/Al metal matrix on wear, coefficient of friction and microhardness, *Wear*, **247**(2): 191–201, 2001, 10.1016/S0043-1648(00)00536-6.

14. Zawawi N.N.M., Azmi W.H., Redhwan A.A.M., Sharif M.Z., Coefficient of friction and wear rate effects of different composite nanolubricant concentrations on Aluminium 2024 plate, *IOP Conference Series: Materials Science and Engineering*, **257**(1): 012065, 2017, doi: 10.1088/1757-899X/257/1/012065.

15. Naveed M., Khan A.R.A., Dry sliding wear of heat treated hybrid metal matrix composites, *IOP Conference Series: Materials Science and Engineering*, **149**: 012084, 2016, doi: 10.1088/1757-899X/149/1/012084.

16. Baradeswaran A., Perumal A.E., Influence of B_4C on the tribological and mechanical properties of Al 7075–B_4C composites, *Composites Part B: Engineering*, **54**: 146–152, 2013, doi: 10.1016/j.compositesb.2013.05.012.

17. Moridi A., *Powder Consolidation Using Cold Spray*, Cham: Springer International Publishing, 2017, doi: 10.1007/978-3-319-29962-4.

18. Rana S.R., Pattnaik A.B., Patnaik S.C., Comparison of wear behaviour and mechanical properties of as-cast Al6082 and Al6082-T6 using statistical analysis, *IOP Conference Series: Materials Science and Engineering*, **338**: 012050, 2018, doi: 10.1088/1757-899X/338/1/012050.

19. Srikanth D.V., Desu V.S., Investigation of drilling time v/s depth of cut & kerf using abrasive jet machining, *IOSR Journal of Mechanical and Civil Engineering*, **12**(6): 54–61, 2020, doi: 10.9790/1684-12625461.

20. ASTM E8-04 Standard Test Methods for Tension Testing of Metallic Materials, ASTM International, 2010.

21. ASTM E18-15 Standard Test Methods for Rockwell Hardness of Metallic Materials, ASTM International, 2019.

22. ASTM G99-04 Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus, ASTM International, 2010.

23. Nie J., Fan J., Zhang S., Wei S., Zuo T., Ma Z., Xiang Z., Tensile and fracture properties of 15 vol% SiC_p/2009Al composites fabricated by hot isostatic pressing and hot extrusion processes, *Acta Metallurgica Sinica (English Letters)*, **27**(5): 875–884, 2014, doi: 10.1007/s40195-014-0127-2.

24. Al-Obaidi A.J., *Ultrasonic Joining of Metal-Polymer Surfaces*, Ph.D. Thesis, The University of Sheffield, UK, 2017.

25. Archard J., Wear theory and mechanisms, [in:] Peterson M.B., Winer W.O. [Eds.], *Wear Control Handbook*, pp. 35–80, American Society of Mechanical Engineers, New York, 1980.

26. Smith A.V., Chung D.D.L., Titanium diboride particle-reinforced aluminium with high wear resistance, *Journal of Materials Science*, **31**(1): 5961–5973, 1996, doi: 10.1007/BF01152146.

27. Yang J., Chung D.D.L., Wear of bauxite-particle-reinforced aluminum alloys, *Wear*, **135**(1): 53–65, 1989, doi: 10.1016/0043-1648(89)90095-1.

28. Kumar M., Murugan M.A., Baskaran V., Ramji K.S.H., Effect of sliding distance on dry sliding tribological behaviour of Aluminium Hybrid Metal Matrix Composite (AlHMMC): An alternate for automobile brake rotor – A Grey Relational approach, *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, **230**(4): 402–415, 2016, doi: 10.1177/1350650115602724.

29. Tahir N.A.M., Abdollah M.F.B., Hasan R., Amiruddin H., The effect of sliding distance at different temperatures on the tribological properties of a palm kernel activated carbon-epoxy composite, *Tribology International*, **94**(1): 352–359, 2016, doi: 10.1016/j.triboint.2015.10.001.

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