The effect of cold and hot pressing on mechanical properties and tribological behavior of Mg-Al$_2$O$_3$ nanocomposites

Kaveh Rahmani$^1$, Ali Sadooghi$^2$ and Seyed Jalal Hashemi$^3$

$^1$ Mechanical Engineering Department, Bu-Ali Sina University, Hamedan, Iran
$^2$ Department of Mechanical Engineering, Shahid Rajaee Teacher Training University (SRTTU), Tehran, Iran
$^3$ Department of Mechanical Engineering, Faculty of Enghelab Eslami, Tehran Branch, Technical and Vocational University (TVU), Tehran, Iran

E-mail: a.sadooghi@sru.ac.ir

Keywords: Powder metallurgy; nanocomposite, wear properties, magnesium

Abstract

In this research, pure powder of Mg was mixed with 0, 1.5, 3, 5% vol. of Aluminium oxide in a planetary mill. Next, the powder mixture was poured in a mold and pressed in two diverse conditions of (1) hot pressing at 600 MPa pressure and 450 °C temperature for 25 min and (2) cold pressing at 600 MPa pressure in the room temperature and samples sintered in a furnace under Argon gas at 450 °C temperature for 2 h. Density and mechanical properties, e.g., microhardness, and wear properties of the produced samples were assessed. Also, metallographic photography and SEM analysis were done on the samples to investigate their microstructure properties and analyze their worn surfaces. The results revealed that with an increase in the volume of the reinforcement particles, the experimental density and microhardness soared, on the contrary, the relative density showed a decreasing trend. Moreover, the results of the microhardness analysis for the produced samples via hot pressing method were achieved better than those of cold pressing, as the highest hardness 81HV was achieved for 9.5 vol. Al$_2$O$_3$ containing samples produced through the hot pressing method, which was about 198 more than that of the 95 vol. Al$_2$O$_3$ containing samples produced via the cold pressing method and was about 985 more than of the pure Mg samples produced via the hot pressing method. The results of the samples’ wear properties also signified the improvement of wear resistance and decrease of mass loss with an increase in the volume fraction of the reinforcement particles. The lowest mass loss of 2.5 g was obtained for the sample containing 95 vol. of the reinforcement particle which was produced via the hot pressing method. This value was less about 9640 and 980 compared to pure Mg samples produced via hot and cold pressing methods, respectively.

1. Introduction

Due to the lightness, Magnesium is one of the most applied metals in the automotive and aerospace industries. Mechanical and wear properties of Mg and its alloys can be enhanced through the addition of reinforcement materials. Nanocomposites are composite materials formed of two phases. The first phase is called the ‘base’ or the ‘matrix’ and can be polymeric, metallic, or ceramic. The second phase is comprised of nanoparticles which are added to the first phase as ‘reinforcement’ to improve the strength, wear resistance, electrical conductivity, etc of the composite. Mg is one of the most applied and lightest metals which is used as the base material in the production of nanocomposites. Till now, many researches have been done in the field of production of Mg-based nanocomposites with ceramic particles, such as B$_4$C, TiN, Al$_2$O$_3$, and SiC as the reinforcement, to improve the mechanical properties. The role of reinforcement depends on the structure of the base material. In reinforced metal-based nanocomposites by nanoparticles, the base material is the main part to endure the applied load, and the role of the reinforcement is to enhance the strength and hardness to avoid plastic deformation of the sample [1]. Metal-based nanocomposites have drawn attention to engineering applications.
owing to their lightness, strength, high resistance against fatigue and corrosion, and dimensional stability [2]. There are various methods for the production of Mg reinforced by nanoparticles, such as powder metallurgy [3, 4], dynamic compaction [5, 6], and cold pressing along with normal sintering [7]. Production of nanocomposites through the powder metallurgy process possesses many advantages as compared to the other methods, and this has led to its wide use relative to the other methods [8]. The wear phenomenon is one of the problems that the industry has faced for a long time. Wear is about erosion or mechanical decay of material from the surface of a subject through its connection with a surface or another subject. Despite the mechanical nature of the erosion mechanism, this phenomenon is sometimes followed by a chemical reaction which leads to corrosion [9]. Different kinds of wear in the industry are as follows: (1) abrasive wear, whose one of signs is the presence of parallel grooves on the wear surface, (2) adhesive wear, which normally occurs at low speed and high pressure between the surfaces which are in slip contact, and its dominant mechanism is based on the removal of the particles from the surface followed by plastic cut [10], (3) layered wear, which, at low slip speeds, includes germination and subsurface cracks and their growth in parallel to the surface [3], and (4) fatigue wear, which occurs when one surface is stagnant and the other surface is moving [9]. The effective factors on wear are metallurgies, operational, and environmental variables, the amount of applied force, and the slip distance. Also, for nanocomposites, there are other parameters, e.g., type, shape, size, the volume fraction of reinforcing particles, and type of thermal operations which have a profound influence on their wear properties [11]. There are different reports on the impact of volume fraction and size of the reinforcement on mechanical properties and wear resistance of metal-based nanocomposites. Jiang, Q, et al [12] investigated the advantages of production Mg-based nanocomposites via the powder metallurgy method. They developed an affordable, simple method based! on powder metallurgy. The researchers compared the experimental results of mechanical and microstructure analysis to find the best percentage of the nanoparticle. One of the most important parameters involved in the production of materials via powder metallurgy method is the working temperature of the production process [13]. Rahmani, K, et al [14, 15] and Majzoobi, G, et al [16, 17] investigated the impact of temperature on the production of Mg-based nanocomposites. Francis, E, et al [18] assessed the effect of sintering in the production process of Mg-based nanocomposites with Al2O3 reinforcing nanoparticles. They performed mechanical experiments on the produced samples and realized that by adding nanoparticles, the mechanical properties improved dramatically. Thakur, S K, et al [19] investigated the weight ratio of ceramic reinforcing particles in an Mg base. Also, diverse research has been done on the impact of Al2O3 nanoparticles; for instance, Prasad, Y, et al [8] appraised the effect of the nanoparticles on mechanical properties of Mg/Al2O3 nanocomposite which they produced via powder metallurgy and extrusion. Leong Eugene, et al [20] produced Mg-based nanocomposites with Cu, Al2O3, and SiC reinforcing nanoparticles via the method of mixing, pressing, and sintering by microwave. They investigated the impact of particle size and mechanical properties of the reinforcing particles on Mg and reported the improvement of mechanical properties. Hassan, S, et al [21] appraised the mechanical properties of Mg/Al2O3 nanocomposites via the mechanical alloy method. In this research, they experienced improvement of nanocomposites’ mechanical properties with an increase in the percentage of the reinforcement, and the most improved mechanical properties were finally obtained in the Mg/1.1Al2O3 sample. Also, Lu, D [22] and Umeda, J [23] reported the production of hybrid nanocomposites reinforced by CNTs and SiO2 nanoparticles via the FSP method, and the result was an increase of wear resistance and decrease of the coefficient of friction. Finally, they reported the lowest wear rate of the Mg/Al2O3 sample relative to the Mg/CNTs sample, and they were lower than those of both nanocomposites in hybrid form.

It should be noted that until now, only a few studies have been performed on comparing mechanical and wear properties of nanocomposites by the hot press (HP) and cold press (CP). The main objective of this study is to experimental investigation of HP and CP effect on the mechanical and wear properties of Mg reinforcement by Al2O3 nanoparticles. In this research, Mg base nanocomposite samples reinforced by Al2O3 nanoparticles were produced. The reinforcing nanoparticles were added to the Mg base material in different fraction volume (0, 1.5, 3, and 5%). The samples were produced via two methods. One method included hot pressing followed by simultaneous applying of pressure and temperature, and another method included cold pressing and sintering in a furnace. The applied pressure and temperature values were the same in both methods. Theoretical and experimental density, relative density, and the porosity of the produced samples were calculated. Also, microhardness and mass loss tests were done on the produced samples. Finally, to assess the microstructure properties and the worn surfaces of the samples, metallographic photography and SEM analysis were carried out.

2. Materials and devices

In this research, the pure powder of Mg with a mean particle size of 40micron, an irregular spherical morphology and purity of %99 was used as the base material, and Al2O3 nanoparticles with the purity of %99 and the size less
than 100 nm with spherical morphology were used as the reinforcing material. Figures 1 and 2 show the scanning electron microscope (SEM) images of Mg and Al₂O₃ at two different magnifications.

To produce the nanocomposite materials, at first, different fraction volume (0, 1.5, 3, 5% vol.) of the Al₂O₃ reinforcing powder were mixed with Mg powder in a planetary mill with a ball to powder weight ratio of 12:1 and rotation speed of 200 rpm for 1 h. To avoid agglomeration of the particles as well as the formation of MgO composition, stearic acid (0.5% vol.) was used, and Argon gas was applied to the mill to impede the oxidation of the powders. The mixture of the powders was pressed in a mold encompassing the upper mold, cap, mandrel, and two hot-working steel discs (figure 3). The samples were fabricated via two diverse methods. The first method included hot pressing at 600 MPa pressure and 450 °C temperature for 25 min [24], and the second method included cold pressing followed by pressing the powders at room temperature at 600 MPa pressure and sintering them in a furnace under Argon gas at 450 °C temperature for 2 h. Measuring the samples’ density was done by the Archimedes method based on the standard ASTM B962 [25]. Relative density and porosity percentage of each sample were obtained separately. The microstructural examination was done using a VEGA Field Emission Scanning Electron Microscope (FESEM). X-ray diffraction (XRD) analysis was performed under Cu K radiation of wavelength \( \lambda = 1.54056 \) Å with a scan speed of 2/minute. The Vickers hardness of the samples was done based on the standard ISO-6507 with the force of 10 N at 10 s [26]. To investigate the wear resistance of the samples, the pin on disc test was performed based on the standard ASTM-G99 [27]. The erosive pin was made of AISI 52100 steel with a diameter of 1.5 mm, and the disc was made of nanocomposite samples with a diameter of 2 cm. The pin was moving at the speed of 0.09 m s⁻¹ and force of 20 N in a 200 m distance to apply wear on the samples. To assess the morphology of the powders, the microstructure of the samples, and the worn surfaces, optic microscope and scattering electron microscope (SEM) were used.
3. Results and discussion

3.1. Density

Theoretical densities of the samples were calculated according to the rule of mixture law via equation (1) which are shown in Table 1. Based on the equation (1), the total density, $\rho_{tot}$, of each material is multiplied by the value of fraction volume, in which $V_m$, $V_r$, $\rho_m$, and $\rho_r$ are fraction volumes of Mg and Al$_2$O$_3$ and density of Mg and Al$_2$O$_3$, respectively, and their summation results in the value of theoretical density. The resulted number was the same for an equal fraction volume of every reinforcing nanoparticle and was not dependent on the process of the production samples. The experimental density, $\rho_{Exp}$, and relative density, $\rho_{relative}$, were also calculated based on the Archimedes method and equation (2), respectively, and the results are shown in Table 1. Moreover, the porosity percentage of the samples was calculated according to equation (3) in terms of theoretical density, $\rho_{The}$, and relative densities. In this research, from now on, the samples produced via hot pressing are referred to as ‘HP’, the samples pressed via cold pressing and then sintered in the furnace are referred to as ‘CP’, and the percentage of the reinforcement is written along with them. Figure 4 shows the produced Mg nanocomposite samples. It should be noticed that the diameter and height of the produced green sample are equal to 15 mm and 12 mm, respectively.

$$\rho_{tot} = V_m \rho_m + V_r \rho_r$$  \hspace{1cm} (1)

$$\rho_{relative} = \rho_{Exp}/\rho_{The}$$  \hspace{1cm} (2)

$$\%\text{Porosity} = \left(\rho_{The} - \rho_{Exp}\right)/\rho_{The} \times 100$$  \hspace{1cm} (3)

Table 1. The density of nanocomposites.

| Sample    | Theoric Density (g cm$^{-3}$) | Experimental Density (g cm$^{-3}$) | Relative Density | Porosity, % |
|-----------|-------------------------------|-----------------------------------|------------------|-------------|
| CP—%0 vol. | 1.73                          | 1.62                              | 0.94             | 6.35        |
| CP—%1.5 vol. | 1.76                         | 1.63                              | 0.93             | 7.38        |
| CP—%3 vol. | 1.78                          | 1.64                              | 0.92             | 7.86        |
| CP—%5 vol. | 1.83                          | 1.65                              | 0.90             | 9.83        |
| CP—%10 vol. | 1.73                         | 1.65                              | 0.95             | 4.62        |
| CP—%15 vol. | 1.76                         | 1.66                              | 0.94             | 5.68        |
| CP—%20 vol. | 1.78                         | 1.67                              | 0.94             | 6.17        |
| HP—%0 vol. | 1.83                          | 1.68                              | 0.92             | 8.19        |
| HP—%1.5 vol. | 1.76                         | 1.66                              | 0.94             | 5.68        |
| HP—%3 vol. | 1.78                          | 1.67                              | 0.94             | 6.17        |
| HP—%5 vol. | 1.83                          | 1.68                              | 0.92             | 8.19        |

Figure 3. The used die for pressuring powders.

Figure 5 shows the diagrams of the experimental density and theoretical density of the nanocomposites produced via two methods of the production samples As seen, with the percentage of the nanoparticles increased, theoretical density showed an increasing trend, while the experimental density showed an increasing trend which revealed that addition of Al$_2$O$_3$ nanoparticles gave rise to abatement of density owing to the hardness and agglomeration rendered among Mg particles, so the number of pores augmented in the samples. Also, it can be seen that for the entire fraction volume of the reinforcing nanoparticles, the experimental density of the samples produced via hot pressing method was more than that of those produced via the cold
pressing method. This was because of simultaneous applying of pressure and temperature during the sintering process which led to better bonding between the nanoparticles and the base material [29]. The highest density equal to 1.68 g cm$^{-3}$ was obtained for HP-%5 vol. sample, which was respectively %5 and %1 more than those of two CP-%0 vol. and HP-%0 vol. samples, respectively.

### 3.2. XRD analysis

The XRD analysis was done on the produced specimens to find and realize the structure of the composition after and while milling [30]. Figure 6 illustrates the XRD patterns of Mg and Al$_2$O$_3$ powders after 1 h ball milling at a different percentage of reinforcement. Since the time of mixing was short, no new phases were recognized. On the other hand, MgO has not been produced because of mixing time and using stearate acid as well as Argon gas. Also, figures 7 and 8 illustrate the XRD patterns of produced Mg–Al$_2$O$_3$ nanocomposites samples via HP and CP methods, respectively. No new phases were identified after the compaction and sintering process. It can be considered that temperature effects on grain growth under uncontrolled thermal conditions [31]. In this regard, W–H approach [32] was employed to decrease the crystallite size of the Mg matrix due to the changing peaks’ intensity and as a result of thermo–mechanical deformation of Mg in the vicinity of Al$_2$O$_3$ nanoparticles. Rashad et al [33] also reached the grain size reduction of Mg matrix after hot extrusion as a result of recrystallization phenomena in their investigation. Similar reports and results can be found in [34].

### 3.3. Microstructural analysis

To investigate and validate density results, metallographic photography was done for the entire samples. This photography test is useful to assess the grain boundaries, bonds, and pores among the particles which all have an impact on density results. As seen in SEM images, the more the percentage of the reinforcing particles, the more the number of the pores and the more the discontinuity among the particles. Also, it can be seen that due to
simultaneous applying of pressure and temperature, the bond between the particles noticeably improved for the samples fabricated via hot pressing method relative to those fabricated via the cold pressing method [35]. Figure 9 shows the produced samples via the cold pressing method, and the periphery of the samples are marked by circles. Figure 10 exhibits the metallographic photographs of the produced sample via the hot pressing method. As seen, these samples possessed fewer pores and in discontinuity as compared to those produced via the cold pressing method.

Moreover, SEM analysis was done to have a higher resolution for investigating the microstructure of the samples’ surface and, especially, the effect of the hot pressing process on the quality and mechanical properties of the samples. SEM images showed more surface coherency and smoothness for the samples containing less amount of nanoparticles and produced through simultaneous of applying pressure and temperature in comparison with the cold pressing process. Figures 11 and 12 show the produced samples via CP and HP methods.

3.4. Microhardness
The microhardness analysis was done on three points of the produced nanocomposites. The Microhardness results have been listed in table 2, and the average microhardness results of the samples are shown in figure 13 for better investigation and evaluation.
Microhardness results revealed that with an increase in the percentage of the reinforcement, the value of hardness increased. This was due to the presence of the reinforcing nanoparticles and their proper distribution and sufficient bond with the base material, which allowed the nanocomposite samples to resist against the plastic flow\cite{36}. Upon applying the force on these samples, the nanoparticles played the main role, relative to the base material, to endure the force. Also, the obtained result of the hardness of the produced samples via the hot pressing method was better than that of those produced via the cold pressing method. This resulted from the production method and the way of applying pressure and temperature. The highest hardness equal to 81HV was achieved for the HP-%5 vol. sample, which was an improvement of about %85 relative to the pure Mg sample.
Figure 10. The metallography photo of produced samples via HP method in which the number of pores is less than produced samples via CP method and increased by a higher amount of reinforcements.

Figure 11. The SEM photo of produced samples via CP method in which the number of pores are more than produced samples via HP method and increased by a higher amount of reinforcements.
Figure 12. The SEM photo of produced samples via HP method in which the number of pores is less than produced samples via CP method and increased by a higher amount of reinforcements.

Table 2. The microhardness of nano-composites.

| Sample       | HV 1 | HV 2 | HV 3 | Average HV |
|--------------|------|------|------|------------|
| CP—%0 vol.   | 38   | 50   | 54   | 50         |
| CP—%1.5 vol. | 43   | 54   | 67   | 55         |
| CP—%3 vol.   | 54   | 78   | 80   | 78         |
| CP—%5 vol.   | 67   | 78   | 81   | 80         |
| HP—%0 vol.   | 43   | 50   | 54   | 50         |
| HP—%1.5 vol. | 62   | 78   | 80   | 78         |
| HP—%3 vol.   | 78   | 78   | 80   | 80         |
| HP—%5 vol.   | 80   | 81   | 82   | 81         |

Figure 13. Variation of Vickers average micro-hardness for fabricated samples via HP and CP.
produced via the hot pressing method. The hardness of this sample was also %18 and %87 more than that of both CP-%5 vol. and CP-%0 vol. samples, respectively.

### 3.5. Wear resistance behavior

Produced nanocomposites via different methods, based on the specified parameters in section 2, underwent the wear analysis. The weight of the samples was calculated before and after the wear test, and the mass change of each sample was separately determined. Also, the mean coefficient of friction of the samples was calculated and presented. Also, the results of the wear analysis, in terms of wear loss and coefficient of friction, have been listed in table 3 and shown in figures 14 and 15 for better investigation and comparison.

Based on figure 14, mass loss of the reinforced samples decreased with an increase in the percentage of the reinforcing nanoparticles, and the reason was the presence of Al2O3 nanoparticles and their good distribution and bonding in the base material which endured the main load upon applying the force and thus led to increasing of wear resistance and also, to the strong bonding between the nano reinforcements and Mg matrix.
that facilitates the load transfer from the matrix to the hard particles. Also, it was previously mentioned that the hardness of the samples produced via hot pressing method was more than that of those produced via the cold pressing method which could be the reason for the increase of wear resistance of the samples produced via simultaneous applying of pressure and temperature as compared to the samples produced via the cold pressing method. The highest mass loss was obtained for pure Mg sample, and the lowest was for HP-%5 vol. sample equal to 2.5 g was achieved which was %32 lower than that of CP-%5 vol. sample and %44 lower than that of CP-%0 vol. sample which had the highest mass loss.

Another parameter related to wear properties is nanocomposites’ coefficient of friction. Figure 15 shows the mean coefficient of friction versus the percentage of the reinforcing nanocomposite for the produced samples. As seen, the highest coefficient of friction was for the pure Mg sample. But through the addition of reinforcing nanoparticles, coefficient of friction curtailed. This was owing to the presence of the tough, wear-resistant particles of Al2O3. The results also revealed that the production process of hot pressing, relative to cold pressing, resulted in a decrease in the coefficient of friction. The lower coefficient of friction for produced samples by HP method can be explained due to the strong bonding between Mg and hard Al2O3 nanoparticles, and a lower tendency to adhesive friction during wear. Generally, harder surfaces lead to the smaller contact area between the pin and the sample surface, consequently, reduction of coefficient friction [5]. The highest coefficient of friction equal to 0.0248 was obtained for CP-%0 vol. sample and the lowest coefficient of friction equal to 0.021 was obtained for HP-%5 vol. sample, which signified an improvement of about %18. This sample also reached an improvement of about %9 relative to HP-%5 vol. sample. The total wear loss is proportional to the coefficient of friction. It means that the uniform distribution of Al2O3 nanoparticles is effective in improving the tribological properties of the Mg- Al2O3 nanocomposite by decreasing the coefficient friction and wear loss during sliding [5].

To validate the results of wear analysis of the samples’ worn surfaces, SEM analysis was done. Figures 16 and 17 show the worn surfaces of the produced samples in terms of the increase of reinforcing nanoparticles’ percentage in two cold and hot pressing conditions. It is obvious in the figures the reinforcing content increases, the wear track becomes smaller and the width of the grooves decreases. Given the low number and shallowness of the appeared grooves, which are marked in the obtained images, increase of wear resistance, as compared to pure Mg sample, was concluded owing to the presence of Al2O3 nanoparticles. The SEM images of the produced samples via the hot pressing method revealed that their worn surfaces were in a better surficial condition relative to the samples produced via the cold pressing method, and less plastic deformation occurred for them. Moreover, the grooves on the samples fabricated by HP method are narrower and shallower compared with CP.
method that indicates an adhesive friction mechanism [33]. Besides, the samples were produced via HP method have less plastic deformation and delaminations on their surfaces which means, these samples have more strength and hardness, as well as stronger bonding between Mg and Al2O3 particles, compare to the produced samples by CP method [5]. Actually, for the samples with lower microhardness, the counter faces between the pin and the sample surface increase, therefore more materials are detached from the sample’s surface. This detachment may be due to adhesive friction that consequently increases the mass loss. Lower mass loss in the samples produced by HP is traced back to the mild wear with abrasive wear mechanism and shows improved condition for wear behavior [37]. Higher surface hardness due to nano reinforcement or obtained by HP method reduces adhesion features and converts the wear mechanism to abrasive a comparison CP method.

In these samples, the parallel and continuous grooves were signs of abrasive wear, and the obtained mass loss value also supported this result and indicated the increase of wear resistance [38]. Moreover, the images of the samples produced via the hot pressing method indicated that an increase of the volume fraction of the Al2O3 nanoparticles led to increase in wear resistance and decrease of plastic deformation, and abrasive wear was blatantly obvious for HP-%5 vol. sample; also, the mass loss of this sample was the lowest among the entire samples. Better bond and junction during simultaneous applying of pressure and temperature allowed the produced sample to have better bonding between the base material and the reinforcing nanoparticles which increased resistance against wear. Indeed, the presence of Al2O3 nanoparticles led to an enhancement of strength and stability of the base phase and increased the resistance of the base phase against plastic deformation [39, 40]. Besides, SEM images showed the worn surfaces of the samples produced via cold pressing, so that they exhibited severe wear, and their plastic deformation was extremely high. Severe plastic deformation and the appearance of lateral cracks on the surface of the samples indicated adhesive wear. The higher mass loss of these samples, relative to that of those fabricated via the hot pressing method, supported this result.

4. Conclusion

In this research, the physical, mechanical, and wear properties of the Mg-based nanocomposite reinforced with %0, 1.5, 3, 5 of Al2O3 were investigated. The samples were produced via two methods of hot pressing and cold pressing. Summary of research results is as follows:

1. The relative density of the samples decreased with an increase in the percentage of the reinforcing nanoparticles. The relative density of the samples produced via the hot pressing method was more than that
of the samples produced via the cold pressing method. The highest obtained relative density equal to 1.68 g cm$^{-3}$ was for the sample containing %5 of Al$_2$O$_3$ produced via hot pressing, which was respectively %5 and %1 more than that of two CP-%0 vol. and HP-%0 vol. samples.

2. The hardness of the samples increased with an increase in the percentage of the reinforcing nanoparticles. The highest hardness equal to 81HV was obtained for HP-%5 vol. sample indicating an improvement of about %85 relative to the pure Mg sample produced via the hot pressing method. Also, this sample had an improvement of about %18 and %87 relative to that of CP-%5 vol. and CP-%0 vol. samples, respectively.

3. The increase of the percentage of reinforcing nanoparticles also led to increase in wear resistance and a decrease in mass loss also, the samples produced via hot pressing method had a lower mass loss relative to the samples produced via the cold pressing method. The lowest was for HP-%5 vol. sample equal to 2.5 g was achieved which was %32 lower than that of CP-%5 vol. sample and %44 lower than that of CP-%0 vol. sample which had the highest mass loss.

4. SEM analysis of the worn surface of samples revealed that by increasing of reinforcing nanoparticles’ percentage the less number and shallowness were achieved and increased wear resistance. Less plastic deformation occurred in the worn surfaces and it is a sign of abrasive wear mechanism in the samples produced via HP method compared to the adhesive wear mechanism in the samples produced by CP method.

5. Similar to mass loss, the coefficient of friction of the nanocomposites experienced a decreasing trend with the increase of reinforcing nanoparticles. The highest coefficient of friction equal to 0.0248 was obtained for CP-%0 vol. sample and the lowest coefficient of friction equal to 0.021 was obtained for HP-%5 vol. sample which reached an improvement of about %18. This sample also reached an improvement of about %9 relative to HP-%5 vol. sample.

**References**

[1] Sadooghi A et al 2020 Bending strength and notched-sample fatigue life of hBN/TiC-reinforced steel 316 L: a numerical and experimental analysis J. Compos. Mater. 54 1001–11
[2] Sadooghi A et al 2019 Experimental and numerical analysis of high-cycle fatigue behavior of steel matrix nanocomposites reinforced by TiC/hBN nanoparticles Met. Mater. Int. 23 1–13
[3] Sadooghi A and Payganeh G 2018 Effects of sintering process on wear and mechanical behavior properties of titanium carbide/hexagonal boron nitride/steel 316L base nanocomposites Mater. Res. Express 5 025038
[4] Rahmani K, Sadooghi A and Hashemi S J 2020 The effect of Al$_2$O$_3$ content on tribology and corrosion properties of Mg-Al$_2$O$_3$ nanocomposites produced by single and double-action press Mater. Chem. Phys. 14 123058
[5] Majzoobi G H, Kaveh Rahmani and Atrian A 2018 An experimental investigation into wear resistance of Mg-SiC nanocomposite produced at high rate of compaction Journal of Stress Analysis 3 35–45
[6] Rahmani K, Majzoobi G H and Atrian A 2020 Simultaneous effects of strain rate and temperature on mechanical response of fabricated Mg-SiC nanocomposite J. Compos. Mater. 54 659–68
[7] Sadooghi A and Jalal H S 2019 Investigating the influence of ZnO, CuO, Al$_2$O$_3$ reinforcing nanoparticles on strength and wearing properties of aluminum matrix nanocomposites produced by powder metallurgy process Mater. Res. Express 6 105019
[8] Prasad Y, Rao K and Gupta M 2009 Hot workability and deformation mechanisms in Mg/nano–Al$_2$O$_3$ composite Compos. Sci. Technol. 69 1070–6
[9] Matizamhuka W R 2016 Spark plasma sintering (SPS)—an advanced sintering technique for structural nanocomposite materials J. South Afr. Inst. Min. Metall. 116 171–80
[10] Babica M, Mitrovica S and Vencib A 2013 Tribological characteristics of aluminium hybrid composites reinforced with silicon carbide and graphite Journal of the Balkan Tribological Association 19 83–96
[11] Bauri R and Surappab M K 2008 Sliding wear behavior of Al–Li–SiCp composites Wear 265 1756–66
[12] Jiang Q et al 2005 Fabrication of B$_4$C particulate reinforced magnesium matrix composite by powder metallurgy J. Alloys Compd. 386 177–81
[13] Rahmani K and Majzoobi G H 2020 The effect of particle size on microstructure, relative density and indentation load of Mg–B$_4$C composites fabricated at different loading rates J. Compos. Mater. 54 2297–311
[14] Rahmani K and Majzoobi G H 2019 The effect of compaction loading rate on hardness and wear resistance of Mg–B$_4$C nanocomposite Mater. Res. Express 6 125081
[15] Rahmani K, Majzoobi G H, Sadooghi A and Kashfi M 2020 Mechanical and physical characterization of Mg–TiO$_2$ and Mg–ZrO$_2$ nanocomposites produced by hot-pressing Mater. Chem. Phys. 31 122844
[16] Majzoobi G, Hossein and Rahmani K 2020 Mechanical characterization of Mg–B$_4$C nanocomposites fabricated at different strain rates Int. J. Miner. Metall. Mater. 27 252–63
[17] Majzoobi G H, Rahmani K and Kashfi M 2020 The effect of pre-compaction on properties of Mg/SiC nanocomposites compacted at high strain rates Journal of Stress Analysis 4 19–28
[18] Francis E et al 2011 Synthesis of nano alumina reinforced magnesium-alloy composites Synthesis 27 35–44
[19] Thakur S K, Kwee G T and Gupta M 2007 Development and characterization of magnesium composites containing nano-sized silicon carbide and carbon nanotubes as hybrid reinforcements J. Mater. Sci. 42 10040–6
[20] Leong Eugene W W and Gupta M 2010 Characteristics of aluminum and magnesium based nanocomposites processed using hybrid microwave sintering J. Microwave Power Electromagn. Energy 44 14–27
[21] Hassan S and Gupta M 2005 Development of high performance magnesium nano-composites using nano-Al2O3 as reinforcement Materials Science and Engineering: A 392 163–8
[22] Lu D, Jiang Y and Zhou R 2013 Wear performance of nano-Al2O3 particles and CNTs reinforced magnesium matrix composites by friction stir processing Wear 305 286–90
[23] Umeda J, Kondoh K and Imai H 2009 Friction and wear behavior of sintered magnesium composite reinforced with CNT-Mg2Si/MgO Materials Science and Engineering: A 504 157–62
[24] Rahmani K and Majzoobi G-H 2018 An investigation on SiC volume fraction and temperature on static and dynamic behavior of Mg-SiC nanocomposite fabricated by powder metallurgy Modares Mechanical Engineering 18 361–8
[25] ASTM B962–08 2008 Standard test methods for density of compacted or sintered power metallurgy (PM) products using Archimedes’ principle
[26] Standard, A., E384 (2010e2) 2010 Standard test method for Knoop and Vickers hardness of materials. ASTM Standards (West Conshohocken, PA: ASTM International)
[27] Standard, A., G99-05 2010 Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus (West Conshohocken, PA: ASTM International)
[28] Rahmani K, Sadooghi A and Nokhberoosta M 2020 The effect of the double-action pressure on the physical, mechanical and tribology properties of Mg-WO3 nanocomposites Journal of Materials Research and Technology 9 1104–18
[29] Balasundar P et al 2018 Characterisation of ferric oxide reinforced magnesium nano-composites processed through microwave sintering/powder metallurgy Int. J. Microstruct. Mater. Prop. 13 447–53
[30] Rajkumar P R et al 2020 Study on formability and strain hardening index: influence of particle size of boron carbide (B4C) in magnesium matrix composites fabricated by powder metallurgy technique Mater. Res. Express 7 016597
[31] Singh A and Bala N 2019 Synthesis and comparative sliding wear behavior of stir cast Mg and Mg/Al2O3 metal matrix composites Mater. Res. Express 6 076512
[32] Williamson G and Hall W 1953 X-ray line broadening from filed aluminum and wolfram Acta Metall. 1 22–31
[33] Rashad M et al 2015 Improved mechanical properties of ‘magnesium based composites’ with titanium–aluminum hybrids J Magnesium Alloys 3 1–9
[34] Ahmed A et al 2010 Synthesis, tensile testing, and microstructural characterization of nanometric SiC particulate-reinforced Al7075 (United Kingdom: Springer)
[35] Eltaher M A, Wagh A, Melaihari A, Fathy A and Lubineau G 2019 Effect of Al2O3 particles on mechanical and tribological properties of Al–Mg dual-matrix nanocomposites Ceram. Int. 11 98–123
[36] Narayanasamy P, Selvakumar N and Balasundar P 2015 Effect of hybridizing MoS2 on the tribological behaviour of Mg–TiC composites Trans. Indian Inst. Met. 68 911–25
[37] Markov D and Kelly D 2000 Mechanisms of adhesion-initiated catastrophic wear: pure sliding Wear 239 189–210
[38] Selvam B, Marimuthu P, Narayanasamy R and Kamaraj M 2014 Dry sliding wear behaviour of zinc oxide reinforced magnesium matrix nano-composites Mater. Des. 58 475–81
[39] Kaviti R V P et al 2019 Improving the friction and wear characteristics of AZ31 alloy with the addition of Al2O3 nanoparticles Mater. Res. Express 6 126505
[40] J Wang 2011 P/M Lightweight Metals (United State: ASM International (Society))