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Research article

Mechanical and wear properties of hybrid aluminum matrix composite reinforced with graphite and nano MgO particles prepared by powder metallurgy technique

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Abstract: In the present study, aluminum–5 wt% graphite self-lubricating composites with 0, 1.5, 2.5, 3.5, and 4.5 wt% of MgO nanoparticles were prepared by utilizing powder metallurgy route to achieve high mechanical and wear properties. The hybrid composites were characterized by using a scanning electron microscope (SEM) and X-ray Diffractometer (XRD). The dry sliding wear test was performed under various loads of 5, 10, 15 and 20 N at a constant sliding distance of 1810 m. It was found that increasing nano–MgO content results in a decrease in density and an increase in porosity. By increasing the weight fraction of MgO nanoparticles improved both the micro-hardness and diametral compressive strength, until an optimum value up to 2.5 wt% and then, the severe reduction was observed. The wear rate reduced with improving the amount of nano–MgO particles up to 2.5 wt% then increased for all applied loads and also the wear rate is still lower when the MgO content is 1.5 and 3.5 wt% compared with that without MgO nanoparticles. Additionally, the wear rate for all hybrid composites positively correlated with the applied loads. Lastly, the results revealed that the hybrid composites with 2.5 wt% MgO nanoparticles showed better mechanical and wear properties.

Keywords: microhardness; MgO nanoparticles; mechanical properties; powder metallurgy; wear test

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1. Introduction

Nowadays, metal matrix composites (MMCs) have been used widely in modern engineering applications due to its superior mechanical properties such as specific stiffness to weight ratio, fracture toughness, high creep and impact resistance as well as high corrosion and oxidation resistance compared to the conventional material. MMCs with different matrix metals; like Aluminum, Copper, Iron, and Nickel; are reinforced with various ceramics particles such as; MgO, SiC, Al_2O_3 and TiC; to increase strength through multiple strengthening mechanisms at room temperature that include the refinement grains to the matrix microstructure and thermal dislocations fabrication because of mismatch between thermal expansion coefficients of the composite. Moreover, in the elevated temperature, these mechanisms might not describe the resulting deformation, where thermally activated mechanisms such as across interlayer boundaries of cross slip and climb of dislocation may happen [1–5]. Mechanism of Orowan strengthening contributed strength improvement in the matrix material according to the small hard particle resistance against the dislocations motion and concluded that this mechanism is effective only when the added particle size is below 1 μm. At both elevated and room temperatures, the Orowan mechanism term is essential, with little variation between its high-temperature and room forms. Whereas the thermal activation facilitates improved climb of dislocation and cross slip across interlayer boundaries, while the work hardening is considerably strong at room temperature [5,6].

Aluminum matrix composite reinforced with nano–ceramic particles is a growing demand. Currently, it is used in many applications such as the automobile industry and aerospace because it has an excellent combination of properties, i.e., low density, high stiffness, controlled thermal expansion coefficient, reasonable wear, and corrosion resistance. In many application sectors, several parts are used in tribological systems that require improved wear and friction performance of these composites, so the addition of graphite particulates is necessary to enhance the wear and machinability resistance [7–10]. There are many techniques in manufacturing MMCs such as stir casting, squeeze casting, liquid metal infiltration, spray decomposition, powder metallurgy, and mechanical alloying [9,11].

Powder metallurgy (PM) process is a highly advanced technique that used a method of fabrication for producing MMCs widely. Where in this process, it is achieved the homogeneity of both microstructure and composition of the composite with more control over the reinforcement distribution. This technology involves three significant steps: mixing the metal with a reinforcement, cold compaction, or pressing and sintering by the controlled furnace to create bonds between the powder elements. At hot pressing, the last two steps are often combined [12–16].

Many researchers have introduced studies on the synthesis of aluminum matrix composite reinforced with graphite and MgO particles by using the powder metallurgy technique. Baghchesara et al. [17,18] studied the mechanical properties and microstructure of AA365.1 MMCs reinforced with 1.0, 1.5, and 5.0 vol% nano–MgO particles that were prepared by the powder metallurgy route. They sintered the samples at 575, 600, and 625 ^oC for 1 h. The results showed improvement in the hardness and compressive strength by increasing reinforcement content as well as the maximum compressive strength observed at 2.5 vol% nano–MgO with sintering temperature 625 ^oC. Statistical analysis of dry sliding wear behavior of graphite particles reinforced aluminum MMCs was investigated by Rajesh et al. [19]. It was inferred that the optimum conditions of wear loss and friction coefficient were observed at 5 wt% graphite content and 0.4 MPa contact stress of MMCs tested because of the self-lubricating effect of graphite. Comparative mechanical properties of Al6061 alloy with Al6061–MgO composite was studied by Balaji et al. [20] manufactured by powder metallurgy technique with 1.0, 1.5, 2.0, and 2.5 wt% MgO content. The results showed that the presence of MgO particles increased the wear resistance, mechanical strength, and it doubled the microhardness. Also, the results revealed that the MMCs containing 2 wt% MgO particles have improved mechanical properties compared to other studied cases. Joshua et al. [21] investigated the microstructure and mechanical behavior of AA7068 MMCs reinforced with 0, 1.0, 2.0, and 5.0 wt% MgO particles prepared by powder metallurgy route. It was concluded that the maximum microhardness was obtained by adding 5 wt% MgO and the wear resistance has been improved by increasing MgO content in MMCs.

This study aims and focuses on the effect of MgO nanoparticles content on the mechanical properties of Al–Gr self-lubricating composite produced by the powder metallurgy technique. As well as investigates the influence of various applied loads on the wear properties of the hybrid composites in order to reach the best mechanical and wear properties of the hybrid composites, which can be used in advanced engineering applications.

2. Materials and methods

2.1. Composite preparation

Aluminum metal matrix composites were prepared by powder metallurgy technique. The pure aluminum powder used as a matrix reinforced with a constant content of graphite 5 wt% and various content of nano-sized MgO powder 0, 1.5, 2.5, 3.5, and 4.5 wt%. Table 1 provides details about the powder's hybrid composite. Aluminum and graphite powders were purchased from Riedel-De Haen AG Company, Germany, while nano–MgO powder was purchased from Nanjing High Technology Nano Material Co., Ltd. (HTNano)–Nanjing, Jiangsu, China. Graphite powder was dried at 250 °C for 2 h to get rid of moisture and other volatile substances. Reinforcement powders were mixed with aluminum powder to fabricate the hybrid composite by using a planetary mechanical mixer with steel balls of 12 mm diameter for 6 h. The rotational speed and steel ball to powder ratio (weight ratio) was 300 rpm and 5:1, respectively. The mixing of powders with steel balls reduces clustering and agglomeration of the hybrid composite particles. Then, the mixture was pressed in a uniaxial cold press at 500 MPa for 1 min in a cylindrical mold by using the universal testing machine type (HOYTOM) in order to form green compacts with 10 mm in height and diameter. The electrical furnace sintered the green compacts at 625 °C for 1 h at an argon atmosphere to avoid any contamination and then followed by furnace cooling to room temperature.

Table 1. Details of powders hybrid composite.

Powder	Particle size	Purity (%)	Shape	Density (g/cm^3)
Al	≤48 µm	99.9	Spherical	2.71
Gr	≤63 µm	99.8	Flake	2.09–2.23
MgO	30–40 nm	99.9	Irregular	3.58

2.2. Characterization and testing

Theoretical density was calculated through the rule of the mixture, while the experimental density and porosity of the sintered samples were carried out according to Archimede's principle accordance with ASTM B962-8 [22–24]. The ends of the samples were polished sequentially with an emery paper of grades 600, 800, and 1000. The microstructure analysis of the samples was obtained by Scanning Electron Microscope (SEM, Tescan Vega3 LMU). The hardness of the composites was evaluated by Micro–Vickers hardness tester and recorded the mean of five measurements at various regions of the polished samples. The Diametral compressive strength σ was found for the composite by using the universal testing machine and calculated from the following equation [3,11,12]:

$$\sigma = 2K/\pi LC \tag{1}$$

where K, L, and C are the applied load (N), the diameter (mm) and thickness (mm) of the samples, respectively. Five samples were at least tested for each composition.

Dry sliding wear tests were performed according to ASTM G99 [25] test standards by using a pin-on-disc tribometer type (Ducom, model: Wear and Friction Monitor ED-201, Bangalore, India). The sintered samples with 10 mm in diameter and height represent the cylindrical pins that are mounted on the specimen holder against a hardened steel disk SAE 1045 with 10 cm diameter, 0.8 cm thick, and 62 HRC hardness. Before and after each test, the samples and counterface disk were cleaned with acetone and organic solvents to remove the traces of the composite. The sliding distance and speed were maintained constant at 1810 m and 1.5 m/s, respectively. All samples of different compositions were performed for various applied loads of 5, 10, 15, and 20 N. The loads were directly applied and installed in a longitudinal direction of the specimens as the design of the tribometer. During the wear test, the wear debris was stuck into the surface of the counter steel disk. Therefore, the organic solvents were used to remove this debris. The steel disc was left to cool to the room temperature after each test in order to symmetry the test condition for all the specimens. The samples were weighed before and after each test by a sensitive balance with 0.1 mg accuracy to determine the wear loss amount. The average results were taken after repeating the test five times. The wear rate WR was calculated from the following equation [23]:

$$WR = (D_1 - D_2)/SD \tag{2}$$

where D_1 and D_2 are the weight of the tested sample (g) before and after the test, and SD is the sliding distance.

3. Results and discussion

3.1. XRD analysis

Figure 1 shows the X-ray diffraction pattern of the prepared composites with various content of MgO nanoparticles. It can be recorded from the X-ray diffraction pattern the peaks of the aluminum matrix, graphite, and MgO materials. By improving the weight fraction of MgO nanoparticles, the peaks intensity enhanced. It was showed the absence of MgO peaks at 0 wt%; after that, it observed appearing and improving the peaks of MgO particles. Moreover, Al matrix peaks in 4.5 wt% content were higher than reinforcement materials; this indicates that the MgO and Gr particles were in steady-state thermodynamically that means the interface between the reinforcement materials and the Al matrix tends to be free. As seen from the X-ray diffraction pattern, there are no peaks found of any other possible intermetallic compounds, probably that the reaction between the composite compounds was complete, but the intermetallic compound amount is entirely invisible to be recognized by XRD.

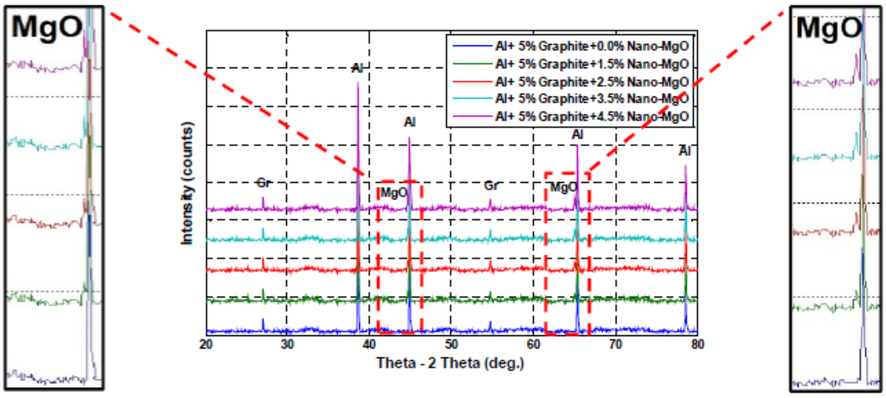

Figure 1. X-ray diffraction pattern of the hybrid composite with different contents of nano–MgO.

3.2. Microstructure analysis

Figures 2 and 3 show the microstructure of fracture surfaces to the composites with 2.5 and 4.5 wt% nano–MgO content, respectively. It can be noticed the high contrast of the micrographs due to the difference between the aluminum and MgO densities. Therefore, we can observe bright particles of nano–MgO, dark grey aluminum matrix, and black regions of porosities. Arrows on the figures indicate these phases. We can infer some points from the microstructure analysis, which are:

1. The aluminum particles were well bonded by the compacting and sintering process.
2. The nano-sized MgO particles were distributed evenly and well bonded with aluminum matrix and just a partial agglomeration and clustering in composites with high MgO content. This behavior causes a decrease in the homogeneity, and uniformity of the specimens can be detected in Figures 2c–d and 3c–d. Baghchesara et al. [17] noticed similar results.
3. The black regions (porosities) increased by increasing the weight fraction of nano–MgO particles in Figure 3 by comparing it with Figure 2.

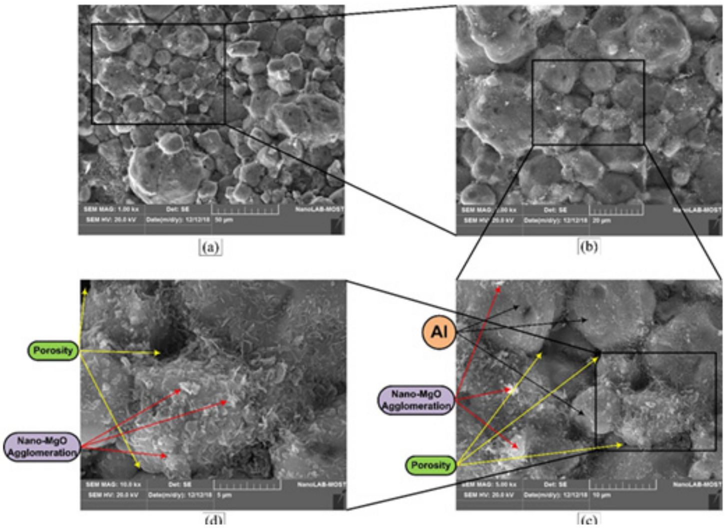

Figure 2. SEM micrographs of the hybrid composite with 2.5 wt% nano–MgO.

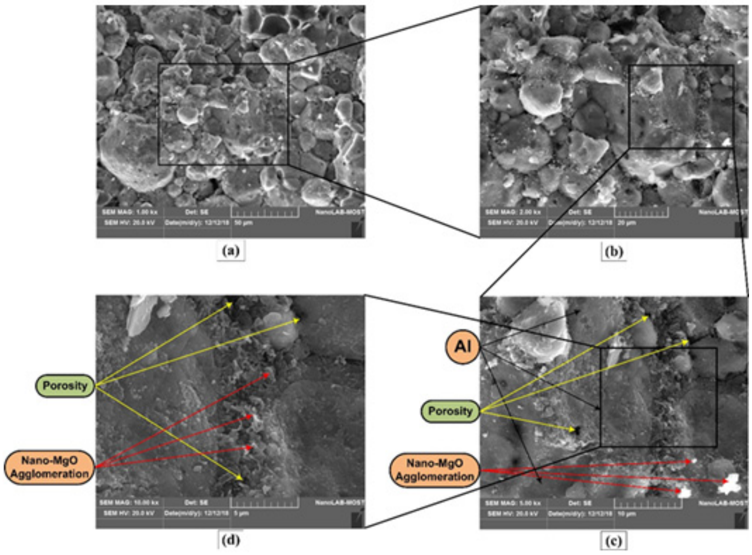

Figure 3. SEM micrographs of the hybrid composite with 4.5 wt% nano–MgO.

3.3. Density and porosity

The effect of nano–MgO content on the density and porosity of Al MMCs are shown in Figures 4 and 5. As can be seen, there was increasing in the content of nano–MgO particles that decreased the experimental density and increased the porosity of the composites. However, the adding of nano–MgO up to 1.5 wt% had a little effect on the density and porosity while increasing nano–MgO content between 1.5 to 4.5 wt% resulted in a rapid reduction in the density and increase in porosity. This behavior can be attributed to the following three factors:

1. The porosity of composite increases with enhance in the nano–MgO content, as shown in the microstructure analysis of Figures 2 and 3 during the powder metallurgy technique.
2. In the sintering process, MgO nanoparticles were rigid quietly and had strong lattice formation, which prevented sample compaction. Due to the high melting point of magnesium oxide, i.e., prevented their complete consolidation and reduced the ability of the compact to the densification, plastic deformation, and volume shrinkage during sintering, which in turn produced a composite with low density and high porosity content.
3. By increasing the content of reinforcement, the sintering of MgO nanoparticles by the Al matrix decreased. On the other hand, the agglomeration of the particles was expected, and the incidence of the created porosities caused density reduction. Furthermore, the reduction trends of the composite density in Figure 4 are due to the clustering and agglomeration of nano–MgO particles during the sintering process. The MgO nanoparticles dense totally and can be expected that particles make a dense network with distributing randomly, which prevents the samples from being dense due to the high melting point of MgO particles and expects that in the temperature of sintering. As a result, during sintering, the closed porosity will remain in their positions and will increase the porosity and decrease the experimental density.

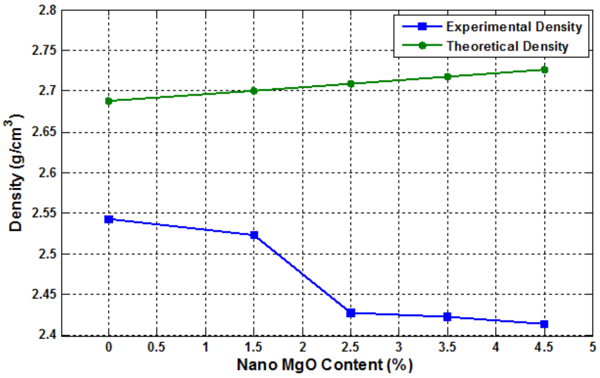

Figure 4. The relationship between the density and nano–MgO content.

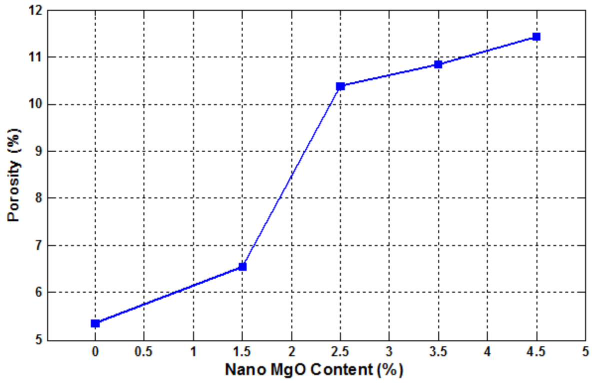

Figure 5. The relationship between total porosity and nano–MgO content.

3.4. Hardness and compressive strength tests

The relationship between the weight fraction of nano–MgO and both microhardness and compressive strength is represented in Figures 6 and 7. The figures show that adding nano–MgO up to 2.5 wt% resulted in enhancement of hardness and compressive strength by 16.3% and 13.5%, respectively, and reaches higher values. While increasing the content of nano–MgO between 2.5 to 4.5 wt%, cause rapidly decreased in the hardness and compressive strength. The enhancement behavior can be attributed to:

1. The hardness value of nano–MgO was higher than the Al matrix. According to the mixture law, by increasing the nano–MgO particles in aluminum, the hardness of composite should be increased.
2. The increase in nano–MgO content in Al matrix composite impeded the dislocation motion and migration of grain boundaries, which prevent grain growth, causing an enhancement of the strength of material and hardness.
3. Nano-sized reinforcement particles are working to enhance the hardness values due to Nanoparticles possess high penetration ability into the matrix materials and lead to improving the interdependence among them, which caused increasing the contact area between the composite.

4. The enhancement of material strength related to the effects of elastic properties of ceramic particles prevents the plastic deformation of the metal matrix. Because a ceramic particle can only deform elastically while metal matrix can deform plastically, therefore, the nano–MgO particles prevented the plastic deformation of the Al matrix if assuming boundary is firm. All of this will lead to a higher work-hardening rate.
5. High-density dislocation and stress concentrations were caused by the difference between the thermal expansion coefficients of the ceramic and metal matrix. Therefore, the strength of the Al matrix will increase accordingly, which confirms the apparent effect of nano–MgO particles reinforced the composite.
6. By increasing the nano–MgO content in the constant particle size of the Al matrix, the distance between particles decreased and resulted in improving the density of dislocation and clustering behind the MgO particles. Therefore, in order to move dislocations, we need higher stress and which affects strength increment. To explain this effect better by using the following equation [18]:

$$\tau = GB/\lambda \tag{3}$$

where τ, G, B, and λ are shear stress to a single crystal, shear module, Burger's vector for crystal, and the distance between reinforcement particles, respectively. According to Eq 3, it can be inferred that decreasing the distance between particles will cause increasing the stress for shearing of dislocations, so more stress is needed.

The results mentioned above, similar findings can be observed in the literature [18,20,21,26]. The reduction behavior between 2.5 to 4.5 wt% nano–MgO content is attributed to:

1. As shown in Figures 4 and 5, by increasing the reinforcement particles, the density decreased, and the porosity increased. For this reason, the mechanical properties will reduce severely because the opened and closed porosities will be central locations for stress concentration.
2. The homogeneity distribution of nano–MgO particles in the Al matrix phase will be decreased by increasing the reinforcement content due to forming the agglomeration and clustering in some areas, and during the sintering process, these regions will be remained constant causing no binding agent between them. These regions could be found near every boundary in the higher percentage of nano–MgO content, and the weak binding between boundaries will be noted because of the direct contact of nano–MgO regions. Thus, the mechanical properties must be deterioration, as was found by previous studies [18,20].

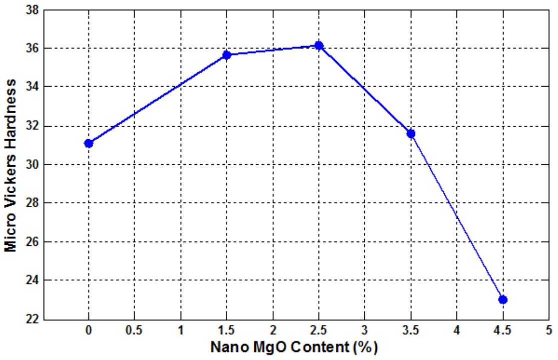

Figure 6. The relationship between micro Vickers hardness and nano–MgO content.

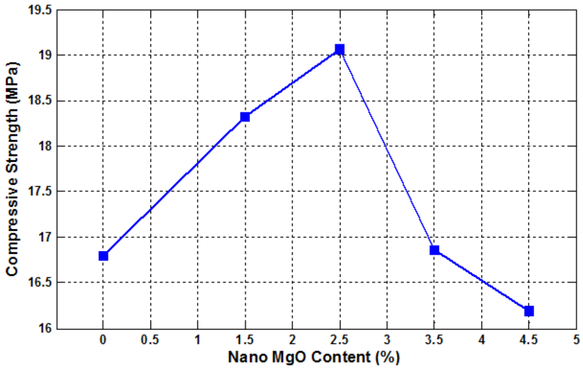

Figure 7. The relationship between compressive strength and nano–MgO content.

3.5. Dry sliding wear test

3.5.1. Effect of nano–MgO content on wear rate

Figure 8 demonstrates the relationship between the weight fraction of nano–MgO particles and the wear rate at different applied loads. It can be noticed that the wear rate decreased by increasing the reinforcement content up to 2.5 wt% and then increased for all applied loads.

The reduction in the wear rate was caused by increasing the composite hardness, as shown in Figure 6. The higher hardness of nano–MgO particles and the bonding force between them and the Al matrix give the composite more resistance to wear rate. This behavior can be indicated by Archard's law [12,27]:

$$W = K(N.S/C.H) \tag{4}$$

where W, N, K, S, C, and H are the wear loss, the normal applied load, the wear constant, the distance of sliding, the geometrical factor of the microstructure, and the hardness of the composites, respectively. The presence of graphite particles, solid lubricant, in the compound of composite also contributes in reducing the wear rate due to forming the lubricating graphite-rich thin film between the steel disc and composite pin, sliding surfaces, which changes the contact nature from metal to metal to the two surfaces separated by lubricating graphite film. The graphite particles improve the tribological properties between the tribosurfaces, which caused reducing the shear stress and enhancement of the wear resistance. Similar results were specified by the literature [21,28,29].

The reduction in wear resistance after 2.5 wt% MgO content for all applied loads is generally expected. Form Archard's law; this reduction happened due to the decrease in the composite hardness after 2.5 wt% MgO content, as shown in Figure 6. The considerable increase in porosity and a significant decrease in the density, as shown in Figures 5 and 4, respectively, increased the wear rate because they caused a weak bonding between the composite particles that made it easy to dislocate out during their sliding motion. Moreover, the wear debris increasing was rich in nano–MgO dislocated particles, which stacked on the steel disc and accelerated the removal of composite particles because it acted as stress concentrators. Balaji et al. can observe similar findings [20].

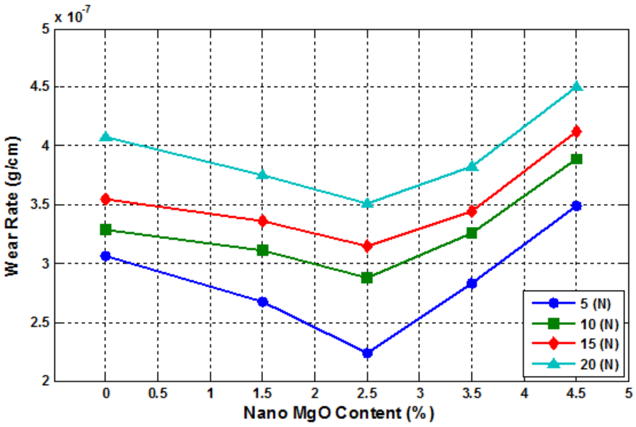

Figure 8. The relationship between the wear rate and nano–MgO content at various applied loads.

3.5.2. Effect of applied loads on wear rate

The wear rate variation of the hybrid composites with different applied loads for all nano–MgO content is shown in Figure 9. It can be observed that the wear resistance decreased with increasing the applied loads. According to Archard's law, the wear rate must be increased by increasing the loads because the contact and friction between the tribosurfaces increased and working to rapid deformation of the hybrid composites due to compressive and frictional forces that dominated in dry sliding, as was found by previous works [10,21,28,30].

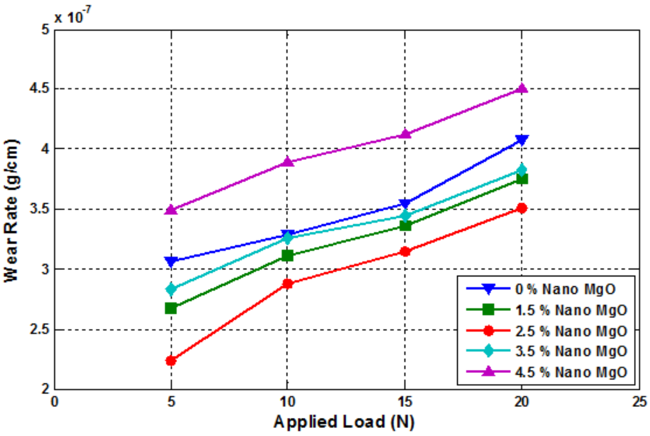

Figure 9. The relationship between the wear rate and applied loads at various nano–MgO content.

4. Conclusions

The following conclusions were made throughout this work:

1. Aluminum–5 wt% graphite composite successfully reinforced with various content of MgO nanoparticles through conventional powder metallurgy technique.
2. X-ray diffraction pattern of the prepared composites shows the peaks of the aluminum matrix, graphite, and MgO materials, as well as no intermetallic compounds, were found.

3. SEM micrographs of the hybrid composite indicate that nano–MgO particles distributed homogeneously in the composite matrix with partial clustering and agglomeration were observed in the high content of nano–MgO.
4. By increasing the nano–MgO content of the hybrid composites, the experimental density decreased while the porosity was increased.
5. Microhardness and compressive strength improved by 16.3% and 13.5%, respectively, with increases in the nano–MgO content up to 2.5 wt% and then decreased rapidly.
6. A considerable reduction in wear rate for all applied loads was resulted from increasing the nano–MgO content up to 2.5 wt% then increased as well as the wear rate is still lower when the MgO content is 1.5 and 3.5 wt% compared with that without MgO nanoparticles. Also, a significant increase in wear rate was observed by increasing the applied loads for all reinforcement content.
7. Lastly, through the conclusions as mentioned above, it was proved that aluminum–5 wt% graphite–2.5 wt% nano–MgO hybrid composite possesses relatively optimum mechanical and wear properties.

Conflict of interests

The authors declare no conflict of interest.

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