Identify the effect of Fe$_2$O$_3$ nanoparticles on mechanical and microstructural characteristics of aluminum matrix composite produced by powder metallurgy technique

Abstract: Aluminum is a highly valuable structural metal utilized in various industrial sectors; particularly, it is utilized in considerable quantities in the nautical, aeronautical, and automotive industries. Aluminum is additionally utilized in small amounts in several other industrial sectors. The composite materials are now extensively utilized in various applications after their introduction. In this research, they prepared composite samples of aluminum with adding hematite nanoparticles with different ratio (2, 4, 6, and 8) wt% by powder metallurgy technology, and the sample preparation conditions was (mixing time reach to 2 h for every sample; the compaction loads is 6 tons and sintering temperature equal to 600°C). The tests conducted were XRD, SEM, EDS, green density, green porosity, micro-hardness, compression, and wear. The results illustrate that the hardness and wear values increase when increasing the hematite percentage.

Keywords: hematite, nanoparticles, aluminum, composite materials microhardness

1 Introduction

Aluminum and aluminum alloys are generally utilized in different industries, including aerospace, building, cooking utensils, packaging, and electrical wiring [1,2]. Unfortunately, there are limited sources for primary aluminum, which has been mined from ores. As a result, it is essential to recycle aluminum effectively. Thus, the researchers are focusing their efforts on developing aluminum recycling processes that are very effective [3,4]. Aluminum composites are recognized as sophisticated materials because they outperform conventional technical materials in their mechanical, electrical [5], and thermal characteristics [6] while being more cost-effective [7–11]. Because of their strong mechanical qualities, aluminum matrix composites [12–14], often known as AMCs, have become more important in various sectors. Aluminum–metallic matrix composites are the material of choice in many industries and applications involving marine, automotive, military, aerospace, and other domestic uses. Enhanced mechanical characteristics are the consequence of combining a variety of reinforcements with aluminum metal matrix composites utilizing powder metallurgy technology. These improvements involve increased wear rate, hardness, compressive strength, and ultimate tensile strength. AMCs are made up of nonmetallic reinforcement (SiC, B$_4$C, Si$_3$N$_4$, AlN, TiC, TiB$_2$, and TiO$_2$) inserted into an aluminum matrix. This combination offers improved qualities compared to alloys made of base metal (Al). Reinforcement in AMCs may be present in the form of discontinuous or continuous fibers, whiskers, or particles in volume fractions ranging from a few percent to 70%. AMCs are examples of sophisticated technical materials, and compared to other standard aluminum alloys, their qualities surpass those of AMCs [15–22].

Powder metallurgy, often known as PM, is an important part of many different sectors since it allows for producing high-strength materials at a lower price, and PM
alloys have superior mechanical qualities. Powder metallurgy is the manufacturing and usage of powder metallurgy, and powders have been specified as particles that are typically smaller than 1,000 nm in size. The term “powder” refers to these particles. In addition, a powder metallurgy alloy with an aluminum basis has enhanced characteristics like excellent stress resistance for corrosion cracking and high transverse yield strength [23,24]. Utilizing PM is beneficial for several reasons, the most important of which are economic, distinctiveness, and captive application. The powder metallurgical technique offers the additional benefit of manufacturing near-net-shape components while eliminating the need for completed machining procedures. Compared to other metal casting methods, the PM has been illustrated to improve product quality and significantly reduce the number of raw materials utilized [25,26].

Utilizing the powder metallurgy method, there are a few different approaches to manufacturing metal foams based on aluminum [27]. The density, weight, or compaction pressure of the reinforcing and the kind of reinforcement are some of the powder metallurgy process factors that significantly impact the recycling and foaming of aluminum [3]. A significant amount of development and research work was done in AMCs utilizing various reinforcing materials to obtain a material with the needed qualities by strategically utilizing various reinforcing elements inside the aluminum matrix.

Mohammad et al. [28] researched whether adding materials involving aluminum boron carbide and manganese may increase the strength of aluminum composites – the application of powdered metallurgy to accomplish enhanced mechanical functionality. The obtained results show that the alloy is improved at less addition of boron and manganese. This lead to enhance casting capacity and mechanical performance of the alloy and the composites with superior mechanical characteristics. Rojas et al. [29] researched the recyclability of aluminum as waste called chips and typically is not ideal for melting. Sawing procedures combined with powder metallurgy are utilized to obtain the aluminum powder. The grinding process utilized various grinding times and a 55 revolutions/minute rotating speed. A pressure of 800 MPa was utilized while compacting the material. The cylindrical specimens were sintered by argon at a temp of 620°C for 1 h. Based on the findings, it is clear that aluminum chips have reached the optimum state to be processed throughout the powder metallurgy process. Zamani et al. [30] researched mixed metals (MCCs) strengthened with Al + Gr + Al2O3 particles to attain better wear and mechanical characteristics. Powder metallurgy was the approach that was utilized to explore the mechanical characteristics, wear characteristics, and purity of Al + Gr. The results show that the mixed impact of Al2O3 and graphite reinforcing particles leads to improving the mixed mechanical and wear characteristics of the hybrid MMC. Also, the mechanical characteristics have improved while the wear rate and friction decreased significantly.

Zhangab et al. [31] utilized the powder metallurgy process to investigate the effect of SiC-graphene nanosheets (GNSs) and SiC-graphite on the microstructures and characteristics of particulate-reinforced metal matrix composites. The ceramic nanoparticle dispersion is necessary for mixing with aluminum matrix composites [32]. The results show that the thin GNSs enhance the aluminum particle deformation and are distributed more evenly within the composite than graphite. Yu et al. [33] utilized graphene nanoplatelets (GNPs) because of their good mechanical characteristics and excellent electrical and thermal characteristics. The process was undertaken with the powder metallurgy by adding 0.5 wt% (GNPs) and pure Al.

In most cases, the microstructure will influence the material’s physical and mechanical characteristics. The GNPs were distributed uniformly throughout the Al matrix, and the tensile yield strength hardness and composite fracture were measured at 73 HV and 248 MPa, respectively. Charan et al. [34] utilized four composite alloy specimens, each consisting of aluminum powder mixed with silicone carbide at 2 and 7 volts and alumina at 3 and 8 volts [35]. The specimens were charged to varying voltages. According to the findings, increased Al/SiC volume reduced the material’s hardness, density, and compressive strength. The physical and mechanical characteristics of the pipeline’s powder metallurgy process have dramatically improved compared to commercial aluminum ones. Albert et al. [36] involve three different volume fractionation to improve the mechanical characteristics of aluminum carbide (TiC) in metal aluminum metal composites. The synthesis of mechanically alloyed by powder metallurgy processes of 0, 5, and 10% TiC. The results suggest that adding TiC increases the composite’s hardness significantly.

Analysis of nanocomposites (MMNCs) made of aluminum–aluminum oxide (Al-Al2O3) by Amierah et al. [37] with varying volumes of reinforcement made of aluminum oxide. Three different kinds of Al-Al2O3 nanocomposite have been generated utilizing a typically pumped metal–lurgy (PM) approach, with 10, 15, and 20% volume fractions of Al2O3, respectively. The optical micrographs revealed that the nanoparticles were closely connected to the matrix and the Al2O3 reinforcement. Also, when the quantity of reinforcing rises, the mechanical qualities of the reinforcement, involving its compressive power, tensile resistance, and hardness, would increase. Venkatesh et al. [38] enhanced the mechanical behavior of the kaolin-fortified aluminum matrix
that was created utilizing the technique of powder metallurgy. The composite samples were produced utilizing powder metallurgy and reinforced with 5, 10, 15, and 20% kaolin. It was demonstrated that A-Kaoline stiffness increases from 77 VHN to 187 VHN when aluminum is reinforced by 20%. Still, the rigidity of aluminum without reinforcement is only 20% higher, involving high-strength ceramic particles into the kaoline reinforcement phase, such as Al₂O₃ and SiO₂, resulting in a tensile and compression strength improvement of the composition ranging from 0 to 20%.

The current work aims to produce composite material from aluminum-added hematite (iron oxide) with 2, 4, 6, 8 wt% and studied the effect of added on mechanical characteristics involving (compression, wear, and hardness tests) physical tests such as apparent density, porosity in addition to investigating the microstructure of aluminum substrate before and after adding iron oxide utilizing X-ray diffraction (XRD), scanning electron microscope (SEM), and energy-dispersive spectroscope (EDS).

2 Experimental part

In this part, we will discuss the tools and resources utilized throughout this project and the order in which operations and assessments have been carried out.

The materials utilized in this work are aluminum and hematite powders of high purity (99.9 wt%). The elemental powders (i.e., Al and Fe₂O₃) utilized in this research with an average particle size are as follows: for Al = 33 µm and Fe₂O₃ = 25 nm.

2.1 Plan of work

The following is one possible explanation for the plane of work:
1. Preparation of several nanocomposite materials as indicated with nano Fe₂O₃ added as 0, 2, 4, 6, and 8 wt% to the aluminum matrix.
2. Wet-mixing the powders for 2 h.
3. The addition of powders to the die cavity in a step-by-step, precisely regulated way.
4. Pressing powders at a pressure of six tons.
5. Sintering of all prepared specimens in a vacuum oven with Argon inert gas at 350°C for 1 h, then increasing the sintering temp to 600°C for the next 3 h.

After the sintering process, go to the samples tested.

3 Tests

3.1 X-Ray diffraction analysis

The X-ray diffraction examination was done on specimens containing 6 and 8 weight percent of Fe₂O₃ aluminum composite to detect the already present phases. Lab XRD-6000 from Shimadzu was utilized as the X-ray diffraction instrument. It had a single wavelength of Cu-Kα ~ 1.54 A° and a nickel filter.

3.2 Physical tests

Many physical tests were performed on sintered specimens, green compacts, and elemental powders. The following are possible components of these examinations:

3.2.1 The apparent density of powders and blended powders

The measure of the weight of a single unit volume of a metal powder in a noncompacted state, expressed in grams per cubic centimeter, is referred to as the apparent density. The determination of apparent density is a crucial characteristic of powdered substances. The volumetric property of loose powder is a crucial factor that influences various process parameters, such as the design of compacting machinery and the extent of press movements required to achieve compaction and densification of the powder.

Pouring powder into standard-graded cubes with a max capacity of 10 ml into the appropriate grade is how apparent density measurements are produced. During the leveling process, extreme caution is required to prevent the powder in the cup from becoming physically denser. A microbalance is utilized to determine, with an accuracy of within ±0.0001 g), the cup's weight both with and without the powder. The following calculation is then utilized to estimate the material’s apparent density in grams/cubic centimeter.

\[ \rho_a = \frac{m_2 - m_1}{V_p}, \]

where \( \rho_a \) is the apparent powder's density (g cm⁻³), \( m_1 \) is the cup weight without powder empty cup (g), \( m_2 \) is the cup weight with powder (g), and \( V_p \) is the powder volume in cup (cm³).

3.2.2 Green density and porosity

The green density of the compact may be represented as the weight of a unit volume of compressed mixed powder...
in grams/cubic centimeter. The following formula is utilized to determine it based on the assessment of the dimensions and the weight of the compact specimen:

$$\rho_g = \frac{m_g}{V_g}$$

where \(\rho_g\) is the green density (g cm\(^{-3}\)), \(m_g\) is the green compact mass (g), and \(V_g\) is the compacted volume (cm\(^3\)).

The understanding of the theoretical density of mixed powders (mixed), computed by the percent by weight of elements powder multiplied by its theoretical density, is utilized to measure green porosity. The formula for this calculation is as described in the following:

$$\rho_{ib} = \sum_{i=1}^{n} W_t \cdot \rho_{i} + \sum_{i=1}^{n} W_{t2} \cdot \rho_{i2} + \sum_{i=1}^{n} W_{t3} \cdot \rho_{i3} + \ldots + W_{tn} \cdot \rho_{in},$$

where \(\rho_{ib}\) is the theoretical mixed powder’s density (g cm\(^{-3}\)), \(n\) is the element’s powder number, \(W_t\) is the weight percent (%), and \(\rho_{i1,2,3,\ldots,n}\) is the element’s powders density (g cm\(^{-3}\)).

The formula may then be utilized to determine the porosity of the green material:

$$p_g = \left(1 - \frac{\rho_g}{\rho_{ib}}\right) \times 100\%,$$

where \(p_g\) is the green porosity (%), \(\rho_g\) is green density (g cm\(^{-3}\)), and \(\rho_{ib}\) is theoretical mixed powder’s density mix (g cm\(^{-3}\)).

### 3.3 Scanning electron microscope examination

These specimens, which had a diameter of 10 millimeters, were flattened utilizing SiC grinding papers of varying roughness (400, 600, 800, and 1,000 grit size). Samples had a diameter of 10 mm. Throughout the grinding procedure, the water served as a coolant, preventing an increase in temp that the friction between the specimen and the grinding sheets would have otherwise caused. After that, a mirror-like surface that is flat, scratch-free, and reflective was produced by polishing the samples utilizing diamond paste. The grinding and polishing processes were carried out with the help of model polishing equipment (MP-2B grinder polisher). After the samples had been etched utilizing a solution of 0.5% hydrofluoric acid and 99.5% distilled water for fifteen seconds at room temperature [15], they were washed with distilled water and then dried utilizing an electrical drier [39] to determine the microstructure of each sample.

### 3.4 Microhardness measurements

Microhardness type of the Vickers tester (Digital Display microhardness Tester model Hv-1000). Utilizing a standard 136° Vickers diamond pyramid indenter and optical microscopy to evaluate the diagonal length of Vicker’s impression, this apparatus was utilized to determine the hardness of the specimen by applying a load of 100 g and holding it in place for 20 s on the specimen’s outermost layer. The following is a specification of the microhardness (H.V.) of the Vicker [31]:

$$HV = \frac{1.854P}{d^2},$$

where \(P\) = applied to the load and \(d\) = mean diagonal length \(\mu m\).

Each specimen has its unique sequence of the three measurements.

### 3.5 Test of compression

The following are the dimensions of the cylindrical specimens subjected to the compressive load: 1 cm diameter and 2 cm height. In this instance, samples were created by the ASTM standard [34]. The compression tests were conducted at room temp utilizing a computerized conventional test machine (Gunt/Hamburg, China) with a loading proportion of 0.1 mm min\(^{-1}\).

### 3.6 Wear test

By ASTM (G99-04) [40] specimens with a diameter of 1.3 cm and a height of 0.5 cm were created for each composite sample. To prepare the samples for testing, a surface roughness of 0.8 \(\mu m\) on the mean was achieved by grinding them with SiC sheets. After that, the samples were weighed utilizing a sensitive electric balance model (M254A) with an accuracy of +0.0001. The pin-on-disk idea was utilized in the research of dry wear with several types of wear tester devices (MT-4003, version 10.0). The samples put through the test were pinned vs. a standard disk made of steel with a hardness of (850 HV).

\(F\) is the normal force on the pin = 10 N, \(d\) is the pin diameter = 1 cm, Disk diameter = 3 cm, \(R\) is the radius of wear track = 0.5 cm, and \(\omega\) is the rotating disk speed = 250 rpm.

The sample was weighed after 5, 10, 15, and 30 min to calculate how much weight had been lost. The following formula was utilized to translate the total loss in weight to an equivalent loss in volume:
Volume loss (mm³) = \frac{\text{Weight loss (g)}}{\text{Density (g mm}^{-3}\text{)}}. \quad (6)

where weight loss = weight before the test – weight after the test.

Furtherance of observing the deterioration of the surface's microstructure utilizing an optical microscope, the rate of wear was calculated utilizing the results of this test. The experiment was conducted at room temperature and with no lubrication present.

4 Results and discussion

The findings of X-ray diffraction experiments and the microhardness of composite specimens produced of Fe₂O₃ and aluminum are examined in depth. In addition, the findings of the wear test and the green density of compact specimens are involved in the discussion.

4.1 X-ray diffraction pattern of compacts

X-ray diffraction examinations of all samples were conducted to determine which nanocomposite samples were employed in this investigation. The results of these analyses are displayed in Figure 1. An X-ray diffraction test was conducted on the samples 0, 6, and 8 wt% of Fe₂O₃ nanopowders implanted in the aluminum matrix to ascertain the phases already present in each sample. The diffraction angle (2θ°) ranges from 30° to 90°, and the phases produced by this range are discussed further down. When compared the XRD results can noted Fe₂O₃ shifted aluminum peaks.

*Figure 1: Demonstrates X-ray diffraction findings for specimens.*
4.2 The green density of compacts

Figure 2 illustrates the correlation between compacting pressure and the green density of compacted specimens. The green density will grow as more pressing tension is applied to any compact. This increase will take place from 4 to 7 MPa. According to what is illustrated in Figure 2, the compacting pressure is the foundation for all subsequent investigations of other factors involving the loading rate, the time during which the load is at its most significant, and all other parameters involved in the sintering process [41, 42].

Another factor that plays a role in determining density is the ratio of the compact to the amount of pressure given to the contact area between the die-side walls and powder. Where there is the most wall friction, which results in the most significant amount of relative motion between particles, the tip of the outside circle has the highest density. The circumference density drops quickly from top to bottom, with the most compact density toward the bottom. Since there is less friction between the powder and die wall, there is less of an impact on the density distribution along the centerline of the compact. This results in a more consistent density distribution.

4.3 Scanning electron microscope and energy-dispersive spectroscope

The FESEM images captured at a magnification of 50 µm or 70,000× are depicted in Figure 3. The nanocomposite microstructure incorporating varying weight percentages (2, 4, 6, and 8) of Fe₂O₃ is depicted in the presented images, which demonstrate the existence of Fe₂O₃ and uniform dispersion within the Al-matrix. The presence of Fe₂O₃ within the boundaries of grains of aluminum particles can be attributed to the high energy levels of these boundaries, which serve as attractive sites for foreign particles. The gray light signifies the aluminum matrix. Examining nanocomposite microstructure indicates a homogeneous dispersion of the hybrid nanomaterials and reduced porosity at the interfaces between grains. The Fe₂O₃ nanoceramic exhibits a white coloration as shown in Figure 3, whereas the Al matrix displays a darker hue [43, 44].

The energy dispersion spectrum (EDS) analysis was employed to ascertain the composition of the nanocomposite. The outcome commonly derived from the data presented in Figure 3a is depicted in Figure 3b. Due to the relatively larger identification area of the EDS beam in comparison to the mean size of Fe₂O₃ nanoparticles, the resulting EDS peaks for said nanoparticles will unavoidably contain compositional data about the Al matrix near the particles. Based on the compositional analysis of the matrix, it is apparent that the composition of the nanoparticles is solely responsible for the presence of O and a portion of the Fe peak. The data indicate that the values of Fe and O increase as the percentage of Fe₂O₃ added increases [45].

4.4 Microhardness measurement

For determining the microhardness of the samples that were created utilizing a powder metallurgy technique (compaction and sintering), the tests were carried out by taking the average of three readings taken at each position. The graphical representation of the obtained findings may be seen in Figure 4.

The determined hardness magnitude for the nanocomposite specimens is illustrated in Figure 4. Since it is common knowledge that Fe₂O₃ has a higher hardness and a higher level of brittleness compared to Al, and since Al has a lower level of strength and a higher level of softness in this system, [20] and since the specimens consist of both Fe₂O₃ and Al, it can be deduced (based on the hardness magnitudes) that when the amount of Fe₂O₃ increases, the level of hardness also increases. Because of this, a phase composed entirely of Fe₂O₃ would have a greater value for its hardness (which is said to have greater strength than the other). The flexibility of the aluminum matrix is anticipated to be maintained, although the strength of aluminum that ceramic nanoparticles have strengthened is anticipated to be significantly increased [46–48].

The mechanical [48] properties evaluation reveals an improvement in hardness and tensile strength with the fiber addition without significant loss in ductility. Ultimate
Figure 3: SEM and EDS patterns for different Fe$_2$O$_3$ ratios.
tensile strength increased by 65.51 with 6% reinforcement of short basalt fibers. Here, continuous fiber, continuous fiber, and random distribution were compared up to 6% volume distribution only. The effect of the further addition of fibers was not discussed. The microstructure shows a uniform distribution of fibers. Uniform distribution and enhanced mechanical properties were found in a study [47] with 5% rice husk ash where experimental data was compared with simulations.

**4.5 Compressive strength test**

The compressive strength test findings are illustrated in Figure 4, which involves a list of the magnitudes. Figure 5 also illustrates how the percentage of hematite particles in the aluminum matrix affects the material’s compressive strength.

Because of these findings, it is simple to demonstrate that increasing the proportion of hematite in the aluminum base increased the compressive strength. The increase in compressive strength may be attributed to the function that micro iron oxide particles play in the material. These particles acted as impediments that hampered the migration of dislocations, which resulted in the matrix being reinforced. The sample with Al + 8% Fe₂O₃ showed the most significant increase in compressive strength, 129% compared to the control.

The increases in the compressive resistances of nanocomposites are associated with the introduction of the hard ceramic materials of Fe₂O₃. However, the increase in Fe₂O₃ can increase brittleness and decrease compressive strength, and it can then inhibit elastic deformation and prevent failure at the rimmed area on the surface. Nanoparticles of hematite-AMCs impedes dislocation motion and that will cause dislocation rotate around the hematite particles [49].
4.6 Wear tests

They are utilizing the density of every specimen to do a conversion from the loss in weight to a reduction in volume. The outcomes of this test are illustrated in Figure 6 and were carried out under the same settings as those described earlier ($F = 10$ N; $n = 300$ rpm; $t = (5, 10, 15, 20, 25, \text{ and } 30)$ min).

The data indicate a positive correlation between the applied load and volume loss, with the highest volume loss observed at a load of 10 N and the lowest at lower loads. The maximum volume reduction was observed at a force of 10 N, while the opposite was true for the minimum volume loss. The anticipated outcome was the manifestation of this phenomenon, whereby the augmentation of the load results in a concomitant rise in the level of friction between the surface of the specimen and the rotating disk. In addition, the volume loss was illustrated to grow with time since an increase in the amount of specimen particles lost with increasing friction duration. In addition, these data demonstrate the impact of adding iron oxide particles on wear rates in various situations. The volume loss experienced by the composite fell dramatically as the percentage of iron oxide in the composite increased. It reached its lowest value in the composite, involving the highest amount of iron oxide (8%). This may be due to the function that iron oxide particles play in inhibiting the mobility of dislocations; as a result,

![Figure 6: The volume loss of specimens.](image)

![Figure 7: Microstructure for aluminum and aluminum reinforced by 8% Fe$_2$O$_3$ alloys by use light optical microscope with magnification 100× after wear test under 10 N load and 30 min. (a) Al; (b) Al-8% Fe$_2$O$_3$.](image)
material's hardness was raised, and its resistance to wear was also improved. According to the data presented earlier, the wear rate in the Al specimen is at its peak at 10 N. However, this rate is reduced by 66% in aluminum reinforced with 8% Fe₂O₃.

The wear volume and wear factors have decreased as the percentage of reinforcement increased. It is due to the fact that hematite is a harder material, and it imparts the hardness property to the composite [50]. The damaged surface has been studied due to the adhesion wear for aluminum and aluminum reinforced by 8% Fe₂O₃ alloys, and images have been taken by the light microscope as shown in the following figures:

Figure 7a and b shows the light optical microscope for aluminum and aluminum reinforced by 8% Fe₂O₃ alloys after wear test. These figures illustrated the effect of wear process on the surface of the samples and the grooves are found in the direction of rotation of disk. Due to friction, the increase in temperature is observed.

Where the grooves were clearer and deeper in aluminum alloy compared to samples aluminum reinforced by 8% Fe₂O₃ alloy due to the presence of iron oxide, which increases the hardness and gives relatively high wear resistance (Table 1).

### 5 Conclusion

The following are some possible inferences to make after looking at the findings:

1. The powder metallurgy (PM) technique is theoretically viable, energetically efficient, and economically cost-effective successfully to fabricate composite samples of aluminum reinforced by Fe₂O₃ particles.

2. The experimental results showed that (Fe₂O₃ + Al₂O₃) Al composites could be helpful for automotive and aeronautic applications, which can be fabricated without difficulty utilizing the powder technology route.

3. All the specimens compacted at 6 tons and sintered at (600°C ± 5) for (3 h) of prepared specimens are effective in satisfying sintering completely Al and Fe₂O₃ into a structure that gained.

4. Almost all the prepared samples resulted in a two-phase structure (i.e., Al and Fe₂O₃) at room temperature.

5. The microstructure analysis reveals that the hybrid nanomaterials Fe₂O₃ exhibit a homogeneous distribution within the pure aluminum matrix, reducing porosity. This particular factor results in a noteworthy improvement in both tribological and mechanical characteristics.

6. The Al-Fe₂O₃ prepared increased the hardness, compression strength, and wear resistance relatively with increasing Fe₂O₃.

7. The wear test was conducted utilizing produced nano-composite cylindrical pins in contact with a steel disc, with a constant load of 10 N and a sliding speed of 300 rpm. The findings indicate that the incorporation of nano Fe₂O₃ resulted in a decrease in wear rate, weight loss, and coefficient of friction (COF). Notably, the highest reduction in wear was found by adding 8% Fe₂O₃ wt% as compared to the base metal, with a decrease of 66%.

### Acknowledgments

The Ministry of Higher Education, University of Babylon, and Al-Mustaqbal University are gratefully acknowledged (Grant number: MUC-E-0122). This research was carried out in the laboratory at the University of Babylon.

### Conflict of interest

The authors state no conflict of interest.

### Data availability statement

Most datasets generated and analyzed in this study are in this submitted manuscript. The other datasets are available on reasonable request from the corresponding author with the attached information.
References


