

Article

Microstructural Analysis and Mechanical Properties of a Hybrid Al/Fe₂O₃/Ag Nano-Composite

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Abstract: This work aims to define the microstructure and to study the mechanical properties of an Al matrix incorporated with various amounts of Fe₂O₃ (3, 6, 9, 12 and 15 wt.%) with a constant amount of Ag at 1 wt.%. Al/Fe₂O₃ + Ag hybrid nano-composite samples are manufactured using powder metallurgy. An aluminum matrix is considered an important alloy, owing to its properties such as being lightweight, strong and corrosion and wear resistant, which enable it to be used in many applications, such as electronics, aerospace and automotive purposes. Various examinations have been performed for the samples of this work, such as Field Emission Scanning Electron Microscopy (FESEM) and X-ray Diffraction (XRD) analysis to estimate the microstructure and phases of manufactured nano-composites. Mechanical testing is also carried out, such as micro-hardness testing, compressive testing and wear testing, to estimate the mechanical properties of the hybrid nano-composites. The results of FESEM and XRD demonstrate that Fe₂O₃ and Ag nanoparticles are uniformly distributed and dispersed into the Al matrix, whereas the mechanical tests show that enhancement in micro-hardness, compressive strength of 12 wt.% Fe₂O₃ + 1Ag and wear rate decrease to a minimum value of 12 wt.% of Fe₂O₃ + 1Ag.

Keywords: hybrid nano-composites; powder metallurgy; Fe₂O₃; Ag; microstructure; mechanical properties; wear



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1. Introduction

Aluminum matrix nano-composites (AMNCs) are materials reinforced with metal or ceramic materials used to obtain nano-composite materials for different industrial applications. Al alloys are characterized as having a high strength/light weight, having resistance to the environment and having strong mechanical characteristics. These characteristics make them convenient for use in metal matrix composites (MMCs) [1]. Various reinforcement materials are utilized to enhance their mechanical and physical features. Improvements of these properties have been made in their manufacturing (AMNCs), which are utilized for high-technique engineering components, such as for aerospace, automotive purposes, and engineering shipbuilding. They are quite attractive for this purpose, as reinforced aluminum matrix composites with nano iron oxide (Fe₂O₃) are used in many aeronautical, automotive, etc., purposes due to their excellent efficiency and ratios of strength/weight and stiffness/weight [2].

AMNCs exhibit strong physical properties (electrical and magnetic properties) which enable them to be as lightweight as a multi-functional alloy. However, they do not have high wear resistance [3]. Mechanical properties of aluminum matrix composites, such as hardness, strength, modulus of elasticity and wear resistance, may be improved when the dispersed particles are nano-sized. Improvements in mechanical properties by using nanoparticles incorporated in aluminum matrices have been interesting in recent years [4].

However, the mechanical properties of AMNCs are affected by the manufacturing method used to synthesize nano-composites. Many different processing techniques have been used to manufacture composite and nano-composite materials involving melting casting and powder metallurgy [5]. However, the powder metallurgy technique appears to be the preferred method, owing to its ability to produce a homogeneous dispersion of additive materials into an aluminum matrix. In addition, the powder metallurgy technique gives better mechanical and physical properties. There are many advantages of powder metallurgy techniques, such as good bindings between the additive materials and the matrix, simple technique, easy control of the matrix's microstructure, near-net dimensions and shapes of the product and low cost. It is worth noting that products of powder metallurgy are affected by the particle size of additive materials (nano or micro) and their weight percentages.

Various reinforcing materials may be used to produce aluminum composites or nano-composites for many applications, such as in aircrafts and electrical motors. Many investigations have been conducted in the same fields to obtain composites and nano-composites with unique properties, which are related to the size of the reinforcing materials, their dispersion into the matrix and the grain size of the matrix particles [6–8]. AA7068 alloy is used in different industrial engineering applications, including medical equipment, automobile parts and aerospace. The powder metallurgy technique is utilized to produce AA7068/MgO composites. Additive particles are mixed carefully to obtain a homogeneous dispersion into the matrix. The additive of MgO particles increases the mechanical properties of the product of composite materials, and, as a reinforcing material into the AA7068 alloy, it extensively increases wear resistance [9,10]. In present times, there are many additive materials that are used to improve mechanical properties, such as Al_2O_3 , ZrO_2 and TiC , or electrical and magnetic properties, such as Fe_2O_3 , Fe_3O_4 , Ag and Co. In addition, other additive materials, such as Fe_2O_3 , ZnO , TiO_2 , WO_3 and BiVO_4 , which are known as semiconductor photo anode materials [11], are used to improve the efficiency of solar cells. Fe_2O_3 and Fe_3O_4 have received great attention, owing to their unique properties, such as being easy to fabricate, having a low cost, being non-toxic and being thermodynamically stable. Fe_2O_3 exhibits various crystal phases (α , β , γ and ϵ) which enable it to be used in many applications, such as in photocatalysts, adsorbents and biological and medical applications [12], solar cells. There have been many investigations dealing with hybrid nano-composites with aluminum matrices. Marcu D.F. et al. (2018) studied the mechanical and physical properties of a hybrid nano-composite ($\text{Al}/\text{Al}_2\text{O}_3/\text{Gr}$) prepared by powder metallurgy. Al_2O_3 was added by 10, 15 and 20 wt.%, whereas Gr was added by 1, 2 and 3 wt.%. The microstructure analysis was defined using FESEM, XRD and EDS. The results of FESEM, XRD and EDS show that the additive nanomaterials (Al_2O_3 and Gr) dispersed homogeneously into the Al matrix, and they created a fine grain structure at 295 nm–1.63 μm . Moreover, improvements in physical properties reveal that the densities of the sintered samples were higher than those of the compacted samples. Finally, the results of a hardness test show that hardness increases with increasing weight percentages of the additive nano-materials [13].

L.F.P. Ferreira et al. (2017) [14] studied the mechanical properties of hybrid nano-composites $\text{Al}/\text{Fe}_3\text{O}_4/\text{TiO}_2$ manufactured by powder metallurgy. TiO_2 was added by 2.5 wt.%, 5 wt.%, 75 wt.% and 10 wt.%, whereas Fe_3O_4 was added by 10 wt.% into the aluminum matrix. The microstructures of the samples were analyzed by scanning electron microscope (SEM), and the mechanical properties were defined by micro-hardness and wear tests. The results of this work show that a homogeneous dispersion of TiO_2 and Fe_3O_4 into the Al matrix also improve mechanical properties, such as the micro-hardness, strength and wear resistance of the samples, with increasing weight percentages of TiO_2 . In addition, the experimental density of green compacts increases with increasing weight percentages of TiO_2 depending on the applied load, and then they improve the sintered densities of the samples.

Negin Ashrafi et al. (2020) [15] synthesized a hybrid nano-composite of $\text{Al}/\text{Fe}_3\text{O}_4/\text{SiC}$ using the powder metallurgy technique for Fe_3O_4 with varied weight percentages of 10,

20, 30 and 40 wt.% and with a constant weight percentage of SiC (20 wt.%). The objective of this research is to investigate the impacts of nanomaterials (Fe_3O_4 and SiC) on the microstructures and on the mechanical properties, such as corrosion resistance and wear behavior, of the products. The results of this study show a homogeneous dispersion of the additive nanoparticles (Fe_3O_4 and SiC) into the Al matrix, which also improves micro-hardness and wear resistance. The preferred sintered density and micro-hardness were obtained for Al/30 Fe_3O_4 /20 SiC as 2.69 g/cm³ and 91 HV, respectively, and the friction coefficient for the applied load 10 N decreased from 0.601 to 0.412 for the sample of Al/30 Fe_3O_4 /20 SiC. The results of the corrosion test show that the corrosion resistance for Al/30 Fe_3O_4 /20 SiC is about 99.83%, and the corrosion resistance for Al/30 Fe_3O_4 is about 88.07%.

Recently, the challenge of developing a hybrid nano-composite with great performance is addressing its limitations. There are many problems and difficulties in manufacturing a hybrid nano-composite, including the type of the matrix alloy as well as the additive materials and manufacturing conditions.

Generally, good interfacial bindings between the matrix and additive materials are difficult. Moreover, the aggregation of additive nanomaterials leads to creating many imperfections, which in turn minimize the physical and mechanical properties. Many processes have been used to improve the dispersion problem of additive materials into the matrix. Therefore, powder metallurgy can be used to overcome this problem and then to improve the mechanical properties.

The aim of the proposed study is to examine the influence of Fe_2O_3 and Ag nanoparticles on the microstructures and mechanical properties of Al matrices during manufacturing by the powder metallurgy technique.

2. Experimental Section

2.1. Raw Substrates

In this work, aluminum powder was used with a grain size of 40 μm and a purity of 99.9%, reinforced with nano iron oxide powder (Fe_2O_3) at a grain size of 31 nm and a purity of 99.8% and with silver (Ag) nanoparticles at a grain size of 25 nm and a purity of 99.9%. The varied weight percentages of Fe_2O_3 powders were 3, 6, 9, 12 and 15 wt.%, and Ag was added as a constant with 1 wt.%.

2.2. Preparing Hybrid Nano-Composites

All samples of hybrid nano-composites were prepared by the PM technique, and the powders were mixed using planetary ball milling (QM-ISPO4). The powder mixture consisted of Al powder as a matrix, iron oxide (Fe_2O_3) powder with different weight percentages (3, 6, 9, 12 and 15 wt.%) and constant Ag (1 wt.%) powder as a reinforcing material. The mixing process was performed at a speed of 450 rpm for 0.5 h at room temperature without lubricant materials due to high ductility for the Al matrix to obtain a homogeneous distribution and a dispersion of additive materials into Al matrix. After the mixing process, the powder mixture was compacted by uniaxial pressure at 4 tons to obtain green compacts in the cylindrical samples of 12.65 mm in diameter. The green compacts were sintered at 500 °C for 1.5 h in an electrical furnace under an argon atmosphere to prevent oxidation.

2.3. Microstructural Examination

Microstructural examination was conducted by field emission scanning electron microscopy (FESEM) (model cam scan MV-2300) for the received samples and for after incorporating the iron oxide (Fe_2O_3) at different weight percentages and the silver at a constant wt.% into the aluminum matrix. Before the examination, the samples were ground by using emery paper with a grit size of 1000 μm , and then the samples were polished using polishing cloth. This examination was carried out to define the dispersion of the additive

materials, the pressure influences and sintering temperature on the microstructures of the prepared samples.

2.4. Examination by X-ray Diffraction (XRD)

An examination by X-ray diffraction was implemented using XRD-6000 equipment (SHIMADZU model) for all the samples to determine the phases of the prepared nano-composites. This examination studied the effects of Fe₂O₃ at different wt.% and at constant wt.% of Ag on the resultant phases of the prepared samples of AMNCs.

2.5. Mechanical Properties Definitions

Here, the mechanical properties of the samples involved micro-hardness, wear testing and compressive testing.

2.5.1. Micro-Hardness Testing

Vickers micro-hardness testing according to the ASTM (E384-99) standard was carried out to determine the micro-hardness of the prepared samples for pure Al and Al/Fe₂O₃ + Ag of hybrid nano-composites. The values of the Vickers micro-hardness for the samples (Al/Fe₂O₃ + Ag) were measured before the sintering samples were ground by grinding papers at a grit size of 500 µm, and then they were polished by polishing cloth. Afterwards, the samples were tested by Vickers micro-hardness apparatus (HVS 1000) digital micro-hardness testing for 15 s. A minimum of four measurements for each sample was obtained, and then the average value of micro-hardness was calculated.

2.5.2. Wear Testing

Wear testing was conducted by the pin-on-disc technique according to the ASTM (G99-95) standard to calculate the wear rate of pure Al and Al/Fe₂O₃ + Ag hybrid nano-composite. The samples used for wear testing were fabricated at 1.2 cm in diameter and 2 cm in length. The samples for wear testing were fixed against the hardened disc, which was rotating at 400 rpm for 5 min. Wear testing was carried out by changing the applied loads at values of 2, 4, 6, 8 and 10 N. The wear rate for the samples was determined by the following equations [16]:

$$\text{Wear rate} = \Delta w / 2\pi r \cdot n \cdot t \text{ (g/cm)} \quad (1)$$

$$\Delta w = w_1 - w_2 \quad (2)$$

where:

Δw : the difference in weight of the samples (g);

w_1, w_2 : weight of the sample before and after wear testing (g);

r : rotating disc radius(cm);

n : revolutions per min (rpm);

t : sliding time (min).

2.5.3. Compressive Testing

Compressive testing was conducted by a universal testing machine for the samples, which were the neat Al and Al/Fe₂O₃ + Ag hybrid nano-composites according to ASTM (G1-90).

2.6. FTIR Examination

Fourier-Transform Infrared Spectroscopy (FTIR) examination was carried out using an FTIR apparatus to give information on the molecules which constituted the prepared nano-composites and on the vibrational reaction of (IR) radiation of the molecules. This was performed at wave numbers of about 4000–400 cm^{−1}, and they registered with an electro-magnetic sample absorption. The radiations of the band were absorbed in the spectrum at a specific frequency, which excited a certain binding or many bindings in the molecules

that made the atoms vibrate with each other. The peaks of infrared spectra were obtained from the changes in the frequencies of binding mode and binding stretching depending on the strength of binding and on the atom mass attached to the binding. To understand the interactions between reinforcing nanoparticles and the Al matrix, the surface chemistry and chemical properties for each sample of Al/Fe₂O₃ + Ag nano-composite were analyzed through an FTIR apparatus (SHIMADZU IRA affinity-1) at a range of about 4000–400 cm^{−1} (made in Japan).

3. Results

3.1. Results of FESEM Examination

Figure 1 depicts the photomicrographs of FESEM examination of the Al/Fe₂O₃ + Ag hybrid nano-composites with different weight percentages of Fe₂O₃ and with a constant weight percentage of Ag. The reinforcement materials can be seen to be homogeneously distributed, have low porosity and no cracks. The reinforcing materials Fe₂O₃ and Ag are diffused at the interfaces between Fe₂O₃ and Ag with the Al matrix. The role of Ag metal is to create new phases with the Al matrix and then to be diffused at the grain boundaries between Al grains and Ag. Moreover, the dispersion of Ag is to minimize porosity and then to improve the mechanical properties.

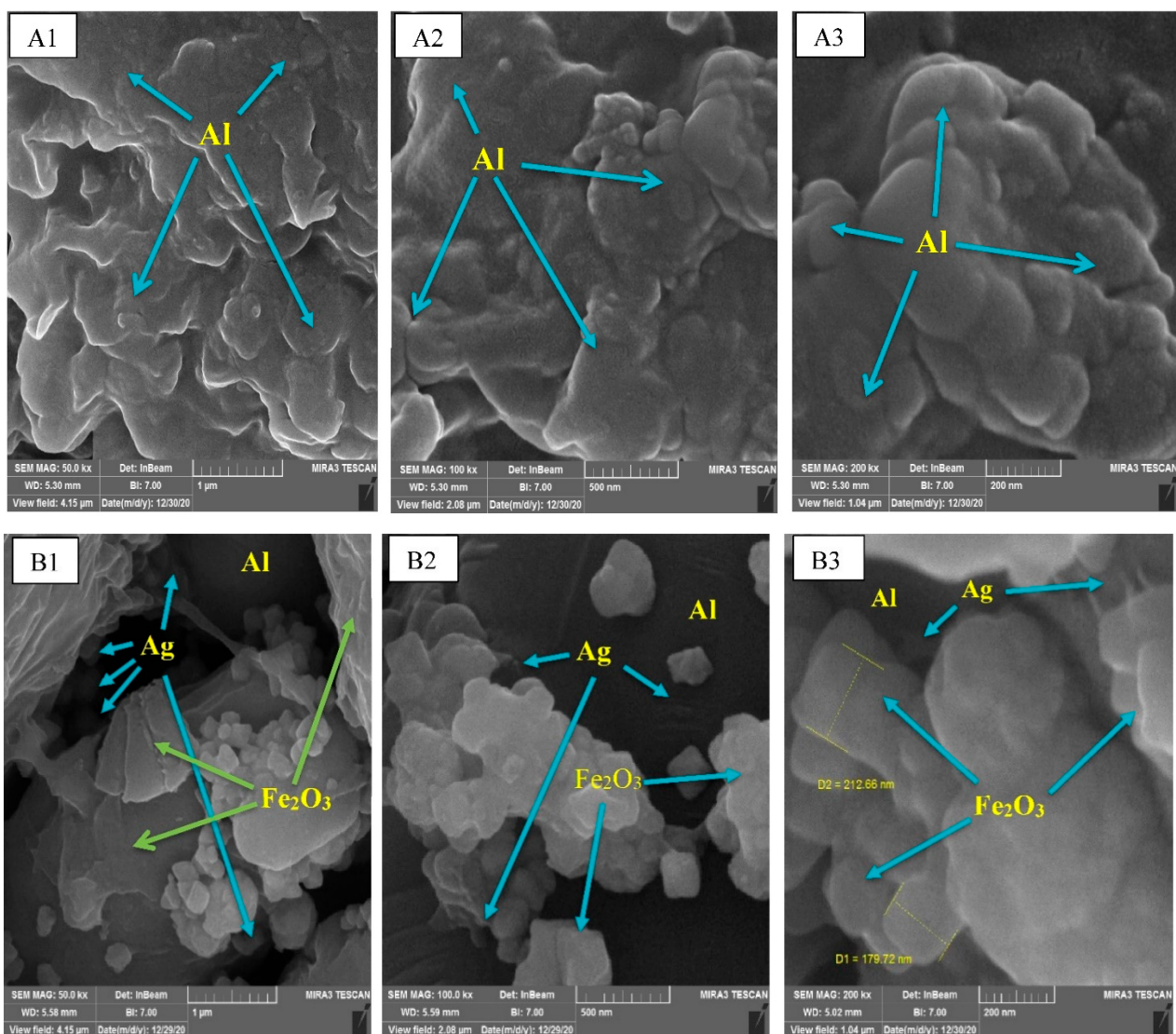


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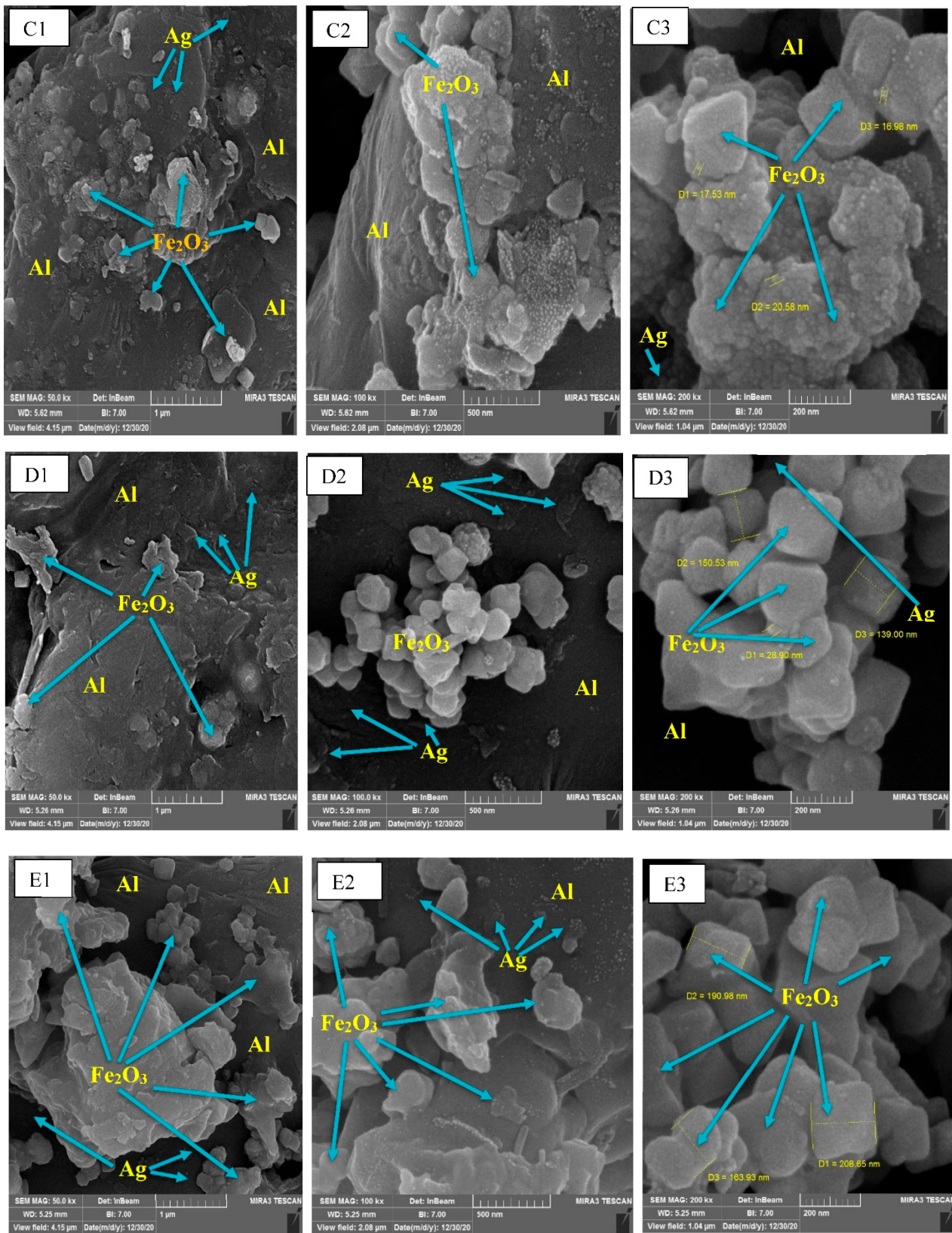


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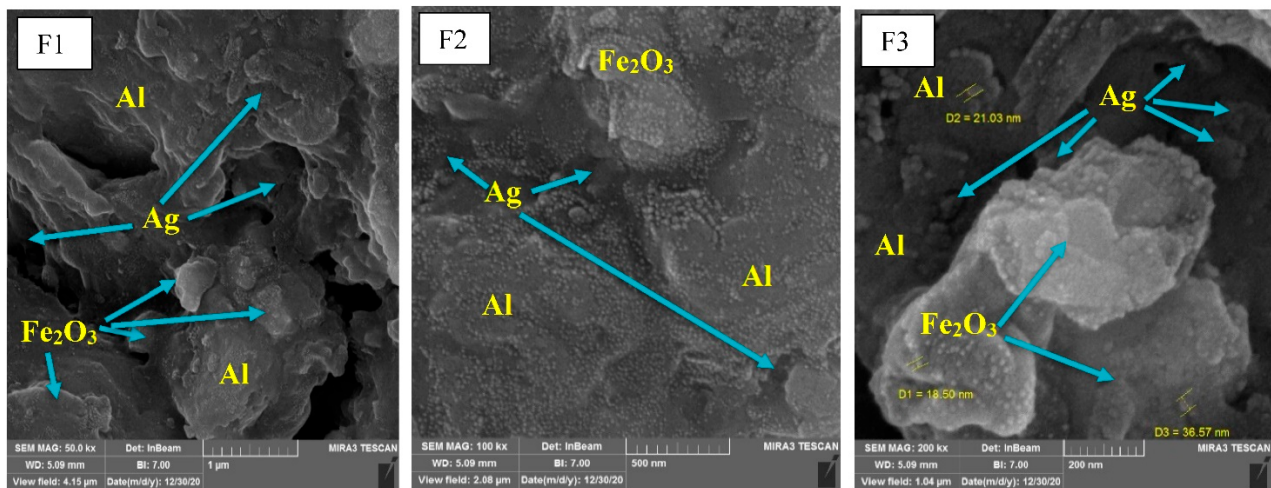


Figure 1. FESEM images of the samples with different percentages of Fe₂O₃ and 1% Ag: (A1–A3) pure Al; (B1–B3) Al/3 wt.% Fe₂O₃ + 1 wt.% Ag; (C1–C3) Al/6 wt.% Fe₂O₃ + 1 wt.% Ag; (D1–D3) Al/9 wt.% Fe₂O₃ + 1 wt.% Ag; (E1–E3) Al/12 wt.% Fe₂O₃ + 1 wt.% Ag; and (F1–F3) Al/15 wt.% Fe₂O₃ + 1 wt.% Ag.

3.2. Results of X-ray Diffraction

Figure 2 shows X-ray diffraction (XRD) peaks for the samples before and after adding Fe₂O₃ + Ag. The results of XRD analysis for the samples of Al reinforced by Fe₂O₃ depict that increasing the wt.% of Fe₂O₃ with a constant wt.% of Ag leads to an increase in the peaks of Fe₂O₃ phase and Ag phase. In fact, the results of the XRD examination reveal that the increase in the wt.% of the reinforcement materials leads to an increase in the intensity of diffraction peaks. Moreover, there are no other possible intermetallic inclusions, most likely created between Al and Fe₂O₃ + Ag in a thermo-dynamically steady state [17].

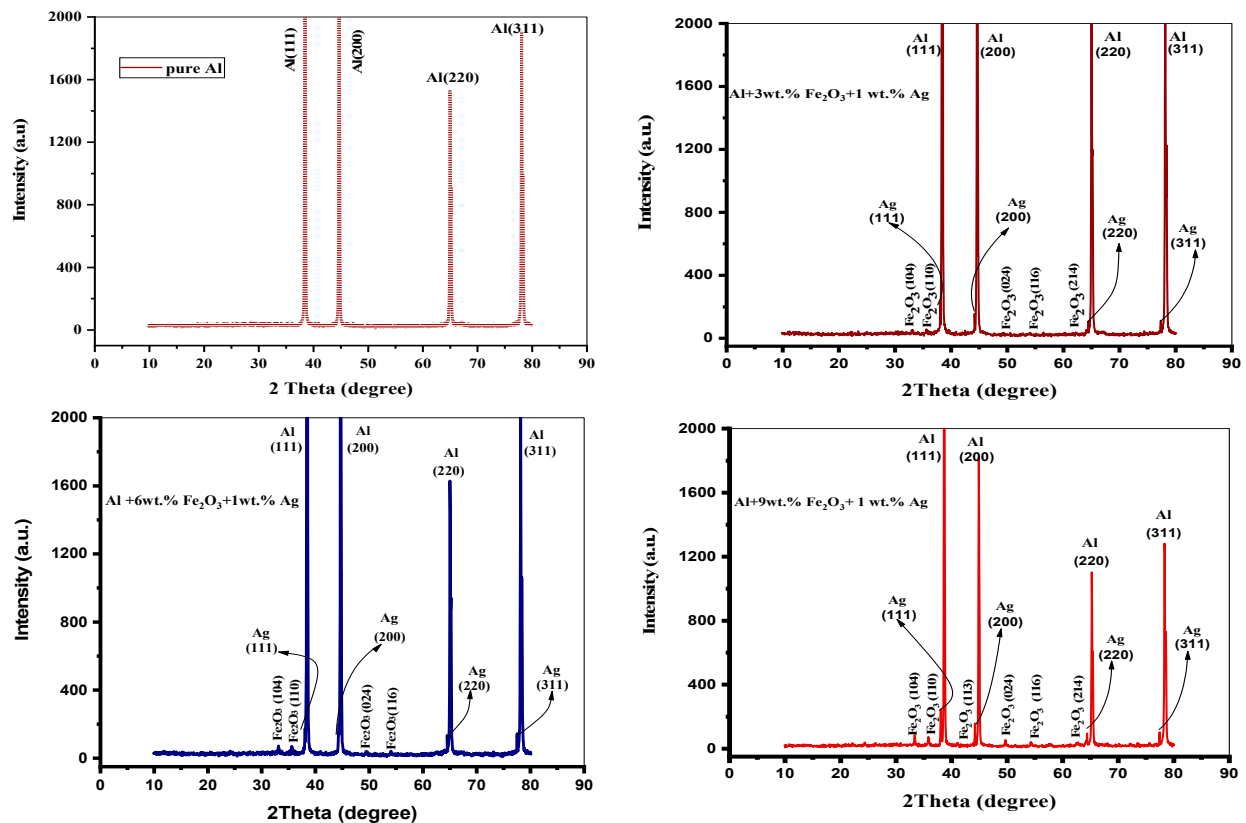


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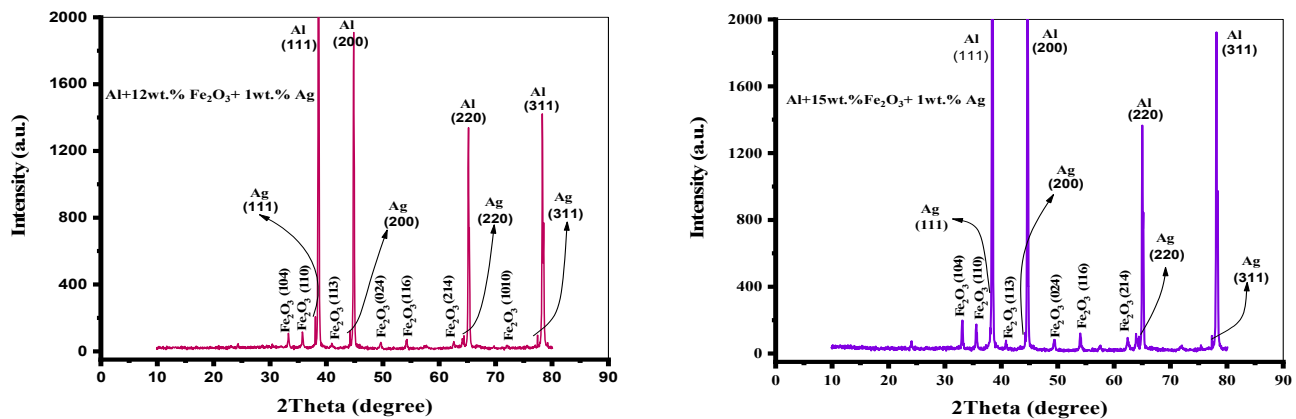


Figure 2. X-ray diffraction spectra of pure Al and Al/Fe₂O₃ + Ag hybrid nano-composites.

As shown in Figure 2, for the XRD data for the pure Al sample, the Al phase formed at 2θ (38.485°, 44.735°, 65.135° and 78.285°) for the planes at hkl (111, 200, 220 and 311), respectively. For the XRD data for the Al/3Fe₂O₃ + 1Ag sample, in addition to the Al phase, the Ag phase formed at 2θ (38.035°, 44.185°, 64.385° and 77.435°) for the planes at hkl (111, 200, 200 and 311), and the Fe₂O₃ phase was created at 2θ (33.185°, 35.585°, 49.485°, 54.085° and 62.485°) for the planes at hkl (104, 110, 024, 116 and 214), respectively. For the XRD data for the Al/6Fe₂O₃ + 1Ag sample, in addition to the Al and Ag phases, the Fe₂O₃ phase formed at 2θ (33.185°, 35.585°, 49.485° and 54.085°) for the planes at hkl (104, 110, 024 and 116), respectively. For the Al/9Fe₂O₃ + 1Ag sample, in addition to the Al and Ag phases, the Fe₂O₃ phase formed at 2θ (33.185°, 35.585°, 40.885°, 49.485°, 54.085° and 62.485°) for the planes at hkl (104, 110, 113, 024, 116 and 214), respectively. In addition, the XRD data for the Al/12Fe₂O₃ + 1Ag sample show that, in addition to Al and Ag phases, the Fe₂O₃ phase was created at 2θ (33.185°, 35.585°, 40.885°, 49.485°, 54.085°, 62.485° and 71.935°) for the planes at hkl (104, 110, 113, 024, 116, 214 and hkl 1010), respectively. Finally, for the XRD data for the Al/15Fe₂O₃ + 1Ag sample, in addition to the Al and Ag phases, the Fe₂O₃ phase was created at 2θ (33.185°, 35.585°, 40.885°, 49.485°, 54.085° and 62.485°) for the planes at hkl (104, 110, 113, 024, 116 and 214), respectively.

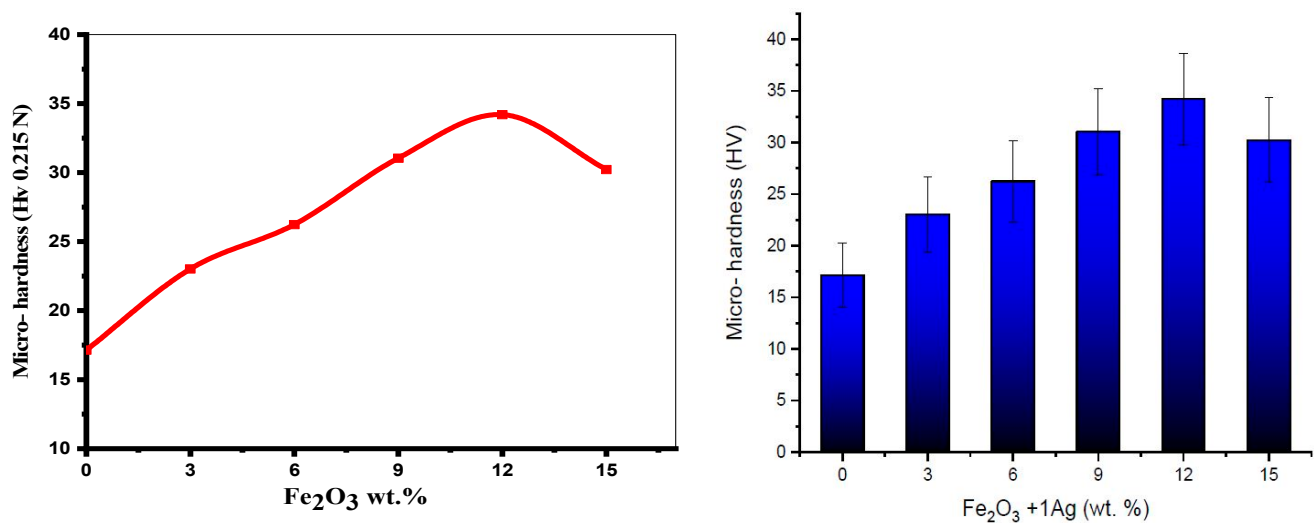
3.3. Results of Mechanical Testing

3.3.1. Results of Micro-Hardness Testing

Micro-hardness values of the prepared Al/Fe₂O₃ + Ag hybrid nano-composites are extremely dependent on the compacting pressure, sintering temperature and weight percentages of the reinforcing nano-materials. Table 1 shows the Vickers micro-hardness results for the specimens of Al/Fe₂O₃ + 1 wt.%Ag. The results of micro-hardness increase with increasing wt.% of Fe₂O₃ + Ag until reaching 12 wt.% Fe₂O₃ + 1Ag, and then it drops down. This is because the hardness of Fe₂O₃ is higher than that of the Al matrix. The increase in the weight fraction wt.% of Fe₂O₃ and the steady wt.% of Ag leads to decreases in the porosity of nano-composites by filling the pores and then virtually affecting micro-hardness, as illustrated in Figure 3.

Table 1. Micro-hardness values of the samples of Al/Fe₂O₃ + 1 wt.%Ag.

Sample No.	Fe ₂ O ₃ + 1Ag (wt.%)	Micro-Hardness (HV)	STD Error Bars
1	0	17.13	3.14
2	3	23.01	3.61
3	6	26.23	3.95
4	9	31.04	4.17
5	12	34.19	4.47
6	15	30.22	4.10

**Figure 3.** The variation of micro-hardness with different wt.% of Fe₂O₃.

Finally, micro-hardness testing is considered an important tool to define the microstructures and mechanical properties of nano-composites [18].

As shown in Figure 3, the maximum micro-hardness of Al/12Fe₂O₃ + 1Ag is most likely a result of the phase created especially for the Fe₂O₃ phase created at 2θ (71.935°) for the hexagonal plane at hkl (1010), which in turn increases the micro-hardness for this sample.

3.3.2. Results of Wear Testing

Figure 4 shows the results of wear rate with varied weight percentages of Fe₂O₃ and with a constant weight percentage of Ag for Al/Fe₂O₃ + Ag hybrid nano-composites by changing loads by 2, 4, 6, 8 and 10N with a constant sliding velocity of 750 rpm. Wear rate minimizes with increases in the weight percentage of Fe₂O₃ nanoparticles, and the improving of the wear resistance of Al/Fe₂O₃ + Ag nano-composites is a result of good chemical bonding at the interfaces between Fe₂O₃ ceramic nanoparticles and Ag with the Al matrix. Moreover, strain fields are formed around Fe₂O₃ because of the difference in the thermal expansion coefficient of Fe₂O₃ and Al. These strain fields make networks of dislocations at the interfaces between the Fe₂O₃ and Al matrix, which in turn constrains the propagation of cracks. The uniform dispersion of Fe₂O₃ and Ag nanoparticles into the Al matrix improves the Orwan strengthening of the product [19]. Therefore, the wear resistance of Al/Fe₂O₃ + Ag nano-composites is improved and, in turn, enhances the tribological characteristics between the pin (Al/Fe₂O₃ + Ag nano-composites) and the hardened steel disc, which reduces shear stresses between them. The preferred low wear rate for Al/12Fe₂O₃ + 1Ag is a result of the same reasons mentioned for the micro-hardness and compressive tests. This is agreed with in [20].

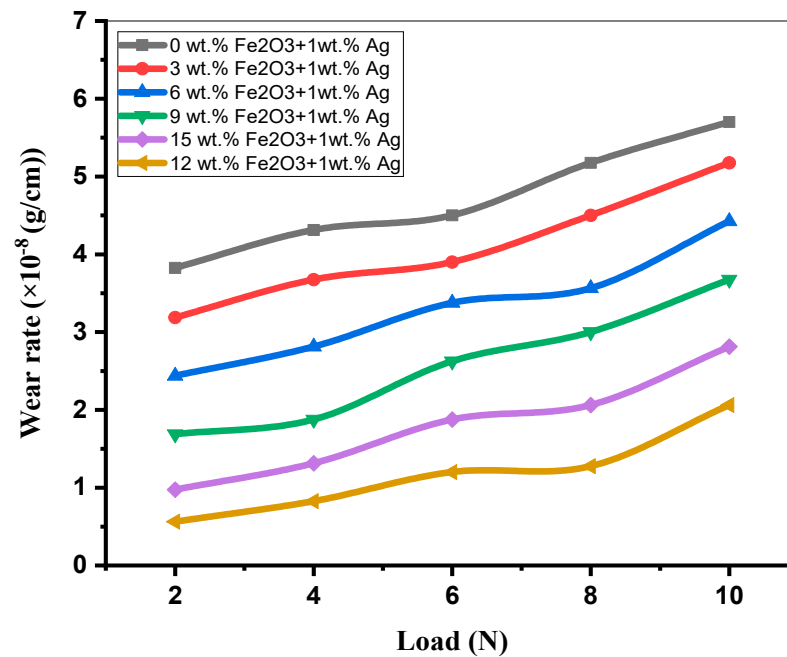


Figure 4. The variation of wear rate as a function of normal loads for pure Al and Al/Fe₂O₃ + Ag hybrid nano-composites.

3.3.3. Results of Compressive Testing

Figure 5 demonstrates the stress–strain curves of compression testing for Al and Al/Fe₂O₃ + Ag hybrid nano-composites with different percentages of Fe₂O₃ and with a constant weight percentage of Ag. The figure shows that the introduction of Fe₂O₃ and Ag nanoparticles increases compressive strength until reaching 12 wt.% Fe₂O₃ + 1 wt.% Ag at about 84 MPa. This is a result of decreases in ductility with increasing amounts of Fe₂O₃ nanoparticles. The highest value of compressive strength is attributed to the strong interfacial bindings between Fe₂O₃, Ag nanoparticles and the Al matrix [21].

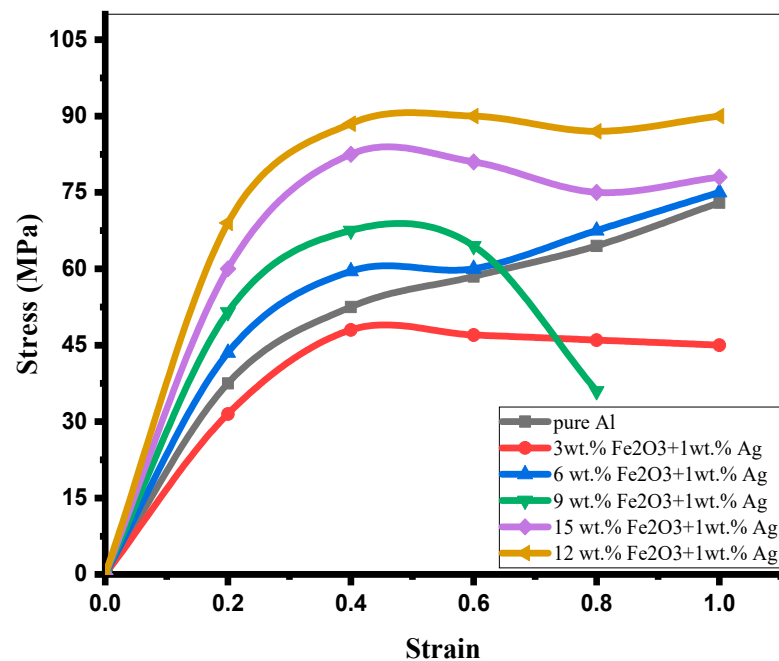


Figure 5. The stress–strain diagrams of pure Al and Al/Fe₂O₃ + Ag hybrid nano-composites.

The increases in the compressive resistances of nano-composites are associated with the introduction of the hard ceramic materials of Fe_2O_3 . However, the increase in Fe_2O_3 of more than 12 wt.% can increase brittleness and decrease compressive strength, and it can then inhibit elastic deformation and prevent failure at the rimmed area on the surface.

3.3.4. Results of FTIR Examination

The FTIR spectra of pure Al and Al/ Fe_2O_3 + Ag hybrid nano-composites is shown in Figure 6. There are similar features in FTIR spectra between pure Al and Al/ Fe_2O_3 + Ag hybrid nano-composites. The peak at 3700 cm^{-1} is compatible with the oscillations of hydroxyl (OH) groups, indicating that OH structures exist on the face of the nanoparticles. The OH groups can be seen on the nanoparticles, as OH groups attach to absorbed water molecules. The strong and broad absorption bands in the range of 2955 cm^{-1} – 2840 cm^{-1} correspond to C-H stretching vibration modes. The peaks that appear in the range of 1750 cm^{-1} – 1535 cm^{-1} in nano-composites correspond to carbonyl group stretching vibrations C=O. The absorption bands in the range of about 1500 cm^{-1} – 1250 cm^{-1} are related to C-O stretching vibrations. When the spectra are at 1020 cm^{-1} , new bindings form for the Al-O stretching mode. The absorption bands for the hybrid nano-composites that are seen in the range of about 900 cm^{-1} – 450 cm^{-1} are attributed to the formation of new bindings for the Fe-O stretching mode. Finally, absorption bands at 1000 cm^{-1} – 500 cm^{-1} correspond to C-N vibration modes [22].

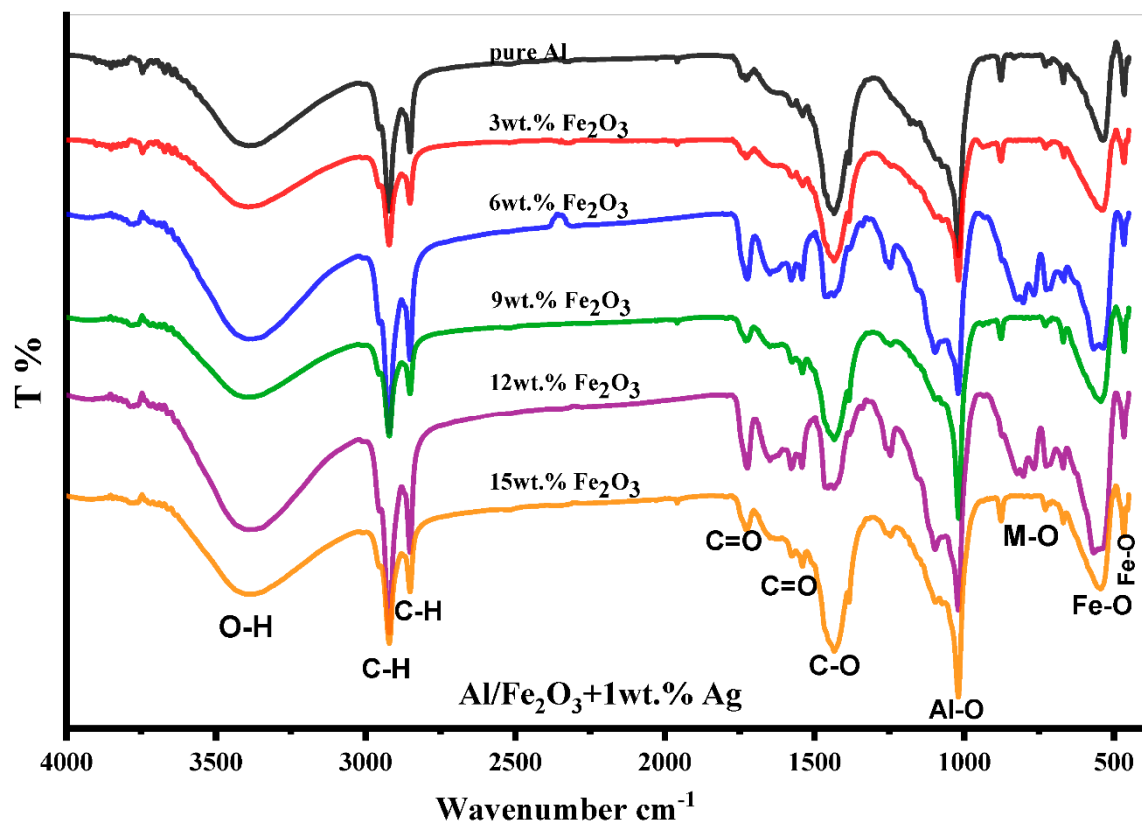


Figure 6. FTIR spectra of pure Al and Al/ Fe_2O_3 + Ag hybrid nano-composites.

4. Conclusions

In this investigation, a hybrid nano-composite (Al/ Fe_2O_3 + Ag) was composed of an Al matrix reinforced by different wt.% of (Fe_2O_3) and a constant wt.% of (Ag). Al/ Fe_2O_3 + Ag hybrid nano-composites were successfully synthesized by powder metallurgy, and the microstructure was depicted by (FESEM) and (XRD) examinations. The mechanical properties were calculated by micro-hardness testing, compressive testing and wear testing. The results of FESEM and XRD examinations reveal good dispersion and distribution of rein-

forcing additives, Fe₂O₃ and Ag nanoparticles, into the aluminum matrix. The results of this work show enhancements in mechanical properties. The values of mechanical testing increased with increases in weight percentages of the reinforcing nanoparticles until reaching 12 wt.% Fe₂O₃. For Al/12 wt.% Fe₂O₃ + 1 wt.% Ag hybrid nano-composites, the micro-hardness was about 34.19 HV, the compressive strength was 89.9 MPa and the decreasing wear rate was the same weight percentage as that of Al/12 wt.% Fe₂O₃ + 1 wt.% Ag of about 1.8×10^{-8} g/cm compared with pure Al. This is a result of Aluminum matrix. The results of this work show enhancements in mechanical properties. The values of mechanical testing increased with the increases in weight percentages of the reinforcing nanoparticles until reaching 12 wt.% Fe₂O₃. For Al/12Fe₂O₃ + 1Ag hybrid nano-composites, the micro-hardness increased with increases in wt.% of Fe₂O₃ compared with pure Al, and the wear rate decreased with increases in the weight percentages of Fe₂O₃. The introduction of Fe₂O₃ and Ag nanoparticles increased the compressive strength to 12 wt.% Fe₂O₃ + 1 wt.% Ag compared with the pure Al. This was a result of decreases in ductility with increases in the weight percentages of nanoparticles. Generally, the highest compressive strength is attributed to strong interfacial bindings between Fe₂O₃, Ag nanoparticles and the Al matrix.

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