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Research article

Comparative study of mechanical performance between Al–Graphite and Cu–Graphite self-lubricating composites reinforced by nano-Ag particles

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Abstract: Copper and aluminum metals are classified relatively as softer materials that possess comparatively poor mechanical and wear characteristics; accordingly, this study has aimed an attempt to improve their properties and compare between them. At the present work, both copper and aluminum metals were used separately as a matrix composite for a comparative study. They reinforced with a fixed content of 4 vol% graphite as a solid lubricant and various content of 0, 1, 2, 3, and 4 vol% silver nanoparticles. The pure metals and the hybrid nanocomposites were manufactured by utilizing the powder metallurgy technique. Mechanical properties such as hardness, diametral compressive strength, and tensile strength were studied. Moreover, a dry wear test was performed by applying various loads of 5, 10, 15, and 20 N with constant sliding distance and speed of 1810 m and 1.5 m/s, respectively. In order to interpret the results and prove the preparation goodness, Field Emission Scanning Electron Microscope (FESEM) and Energy-Dispersive X-ray (EDX) analysis were employed to characterize the as-received composite powders, worn surface, and wear debris morphology. The results were revealed that the microhardness, diametral compressive strength, tensile strength, friction coefficient, and wear resistance were improved significantly by increasing silver nanoparticle content up to 2 vol% and 3 vol% in aluminum and copper matrix composites, respectively, and then deteriorated gradually as compared with pure metals. Convergence was observed in the wear rate results between the copper and aluminum matrix composites in the silver content of 2 vol%. Besides that, the increment in applied loads was associated negatively with the wear resistance. Lastly, the impact of improving silver nanoparticles content on strengthening the copper matrix composite is higher than aluminum matrix composite.

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

1. Introduction

Metal matrix composite (MMC) is a featured type of composite material composed of metal or alloys as the matrix phase, and the other component is embedded in this metal matrix and works typically as reinforcement. The main advantages of MMCs are the ability to dominate the physical and mechanical properties by a suitable choice of matrix and reinforcement volume fractions. Composites production is a low-cost process concerning their excellent performance [1–3]. The term of metal matrix nano composite (MMNC) is defined as a class of MMC in which the size of matrix or reinforcements is in the nanoscale. MMNC, with the reinforcement size down to the nanoscale, displays properties that are more exceptional over MMCs and are expected to overcome the weakness of MMCs like low fracture toughness, poor ductility, and low machinability [4,5]. The central benefits of MMNC are to incorporated excellent mechanical properties, high toughness, functional strength, low creep rate, and excellent wear resistance. The significant central problem in producing MMNC is the even and proper distribution of nanoparticles in the matrix material [6,7]. Wherefore there are several technical methods to the uniform distribution of nanoparticles in the composite matrix, such as high-energy mechanical activation mills, ultrasonic treatment, and other high-energy impacts [8,9]. The selection of method influence on the composite powders is determined by its mechanical and physical properties, granulometric structure, and phase [1,10]. Powder Metallurgy Technique (PMT) is the most promising methods for the manufacture of MMNC that present improving properties, homogeneous microstructures, and cost-effective one compared to those obtained utilizing the casting and other manufacturing processes [5,6]. PMT is used widely because complex forms with perfect shapes and sizes can be fabricated at a high production rate in a cost-effective method. PMT offers a suitable processing technique to avoid these challenges [4,11,12]. Silver is one of the most active metals in modern industries due to possessing unique properties that make it a particularly precious and useful metal. It has unique thermal, electrical, and optical properties and is being consolidated into products that extend from chemical and biological sensors to photovoltaics. Silver particles are frequently utilized in typical applications for antimicrobial coatings, wound dressings, keyboards, and biomedical devices presently include silver nanoparticles that continuously release a low level of silver ions to protect against bacteria [13,14]. Graphite particles are the essential additives to the copper and aluminum matrix composites because of its superior lubrication influence. Therefore, the graphite addition is beneficial in reducing the wear rate and friction coefficient of the composites by creating a lubricant transfer layer of graphite on the counterpart surface because of its lamellar structure [15,16]. When incorporation, the copper or aluminum metals with graphite particles will produce composites with favourable properties such as high electrical and thermal conductivity of metals with the low coefficient of thermal expansion and excellent lubricating properties of graphite [3,17,18].

Freshly, many researchers successfully studied the manufactured of Al and Cu metal matrix composites reinforced by graphite as well as other materials by using various techniques. Zamani et al. [19] studied the tribological and mechanical characteristics of aluminum—0, 3, 5, and 7 wt% graphite composite prepared by PMT to reveal the optimum reinforcement composition. Their results achieved that the aluminum—3 wt% graphite (approx. 4 vol%) composite showed optimum mechanical and tribological properties while compared to other compositions. The influence of sintering techniques and milling time of Cu-graphite composite on mechanical properties has been investigated by Samal et al. [20]. The sintering process of both traditional and spark plasma (SP) was used in order to sinter the composite samples through the PMT. They found that the maximum of both compressive strength and transverse rupture strength was achieved at 5 vol% graphite content. Gohar et al. [21] manufactured hybrid composites of Cu–10 wt% Al–0, 2, 2.5, 3, 4, 5, 5.5, and 6.0 wt% Ag through the PMT and studied the microstructural, mechanical and thermal properties. Their results display that the addition of Ag in Cu−Al alloy revealed maximum hardness at 3% Ag while the better compressive strength at 2% Ag. Also, both thermal diffusivity and thermal conductivity improved with the addition of Ag particles. Pitchayyapillai et al. [13] investigated the influence of 1 and 2 wt% Ag nanoparticles on microstructure, tribological, and mechanical behaviour of Al6061 alloy prepared by stir casting method. It was inferred that all of the elongation, ultimate tensile strength, compressive strength, and wear resistance was improved with increasing of Ag content. Besides, the results revealed that the Al6061 reinforced with Ag nanoparticle offers the most suitable combination of microhardness can replace classical material for better behaviour and longer life.

To the best of our knowledge, from the literature review, no prior studies have examined the influence of nano-Silver content on both Al-Graphite and Cu–Graphite self-lubricating composites manufactured by PMT despite these hybrid composites are very suitable for enhancing the mechanical and wear performance of advanced applications. Therefore, this work focuses on the comparative study of mechanical and wear properties between the Al–Graphite and Cu–Graphite self-lubricating composite reinforced with various content on the nano-Ag particle prepared by PMT. Self-lubricating composites such as copper–graphite and aluminum–graphite were widely used in many electrical applications, especially in conductors like the electrical brushes and electrical circuits breakers due to possessing high electrical conductivity and good wear resistance. In this study, an attempt to improve these composites by adding nano silver particles that possess excellent electrical conductivity higher than both the copper and aluminum metals. Besides, nano silver particles have a better bonding with the copper and aluminum metals. On the other hand, nano silver has limitations in use such as expensive and toxic.

2. Materials and methods

2.1. Hybrid composites manufacture

PMT fabricated two types of hybrid nanocomposites in order to obtain a comparative study between them. Graphite particles with a constant volume fraction of 4% were used as a first reinforcement material. Nano-sized silver particles were utilized as a second reinforcement material with various content of 0, 1, 2, 3, and 4 vol%. Matrix material for the two types of hybrid nanocomposites was employed Aluminum and Copper powders, respectively. Table 1 gives the details of the as-received raw materials utilized in the current study. Figure 1 shows the FESEM images and EDX spectrums of the morphology and the purity, respectively, of the as-received raw powders. Graphite particles were dried for three hours at 250 ^{o}C to cleanup from the moisture and different volatile materials [3,8]. By using a sensitive electronic balance with 0.1 mg accuracy, the nanocomposite powders weighed based on the required volume fractions. In the beginning, the hybrid nanocomposite powders were blended within a high-energy ball mill for 5 h to prevent particle agglomeration and clustering, especially with the presence of nanoparticles. The steel ball diameter, the ratio of steel balls to powder, and rotational speed are 12 mm, 10:1, and 300 rpm, respectively. After that, the mixture powder was pressed uniaxially in an air atmosphere for 2 min at 500 MPa in a steel mould by utilizing the Universal Testing Machine (UTM) in order to form green samples with 10 mm diameter and 6 mm high. Subsequently, the two types of hybrid nanocomposites were sintered separately inside the electric furnace for 2 h in the argon gas atmosphere. The copper matrix composite was sintered at 900 ^{o}C while the aluminum matrix composite at 600 ^{o}C. Then, the samples were left to be cooled to room temperature into the furnace after the completion of the sintering period.

Table 1. The details of the as-received raw material powders.

Composite materials	Elements	Purity (%)	Shape	Average particles
First matrix	Copper	99.8	Dendritic	25 µm
Second matrix	Aluminum	99.9	Spherical	48 µm
First reinforcement	Graphite	99.8	Flake	63 µm
Second reinforcement	Silver	99.9	Spherical	50 nm

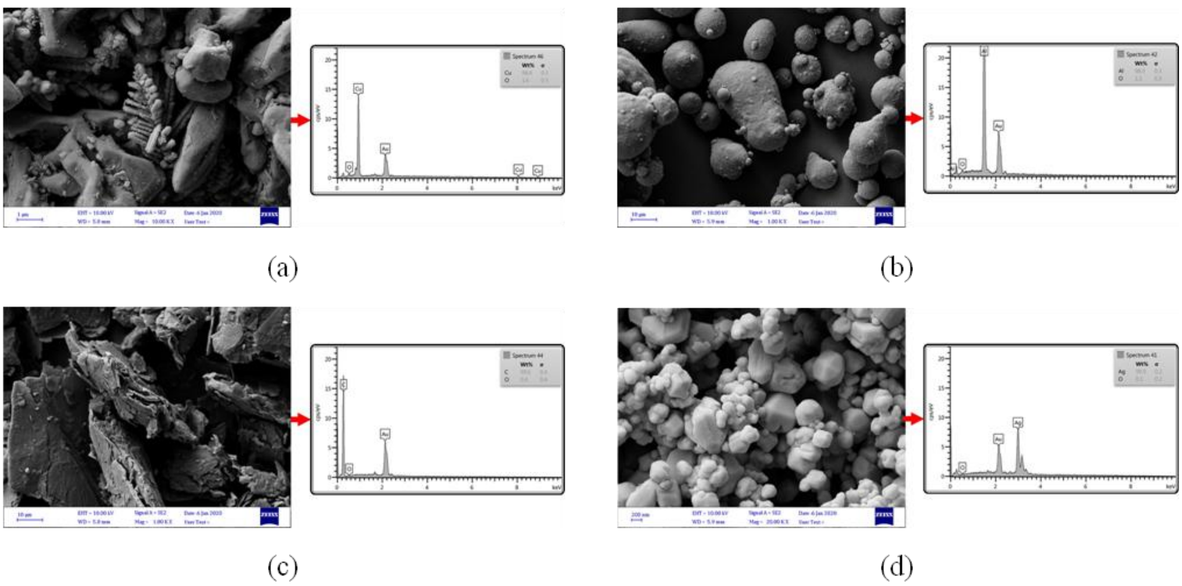

Figure 1. The FESEM images and EDX spectrums of the as-received raw powders: (a) Copper, (b) Aluminum, (c) Graphite, and (d) Silver.

2.2. Characterization and testing

In this study, numerous mechanical properties were studied. The micro-Vickers hardness of all the hybrid nanocomposites was measured by employing the microhardness device with loaded 10 N for 15 s [22]. At least, an average of five values was recorded for each sample at suitable positions. According to mean hardness values results, both the yield and tensile strengths were determined by utilizing the Eqs 1 and 2 that offered and suggested by Cahoon et al. [23], and which has been used by each of Adebiyi et al. [24] and Ujah et al. [25,26]:

$$Ys = (H/3) \times (0.1)^{n} \quad (1)$$

$$Ts = (H/2.9) \times (n/0.217)^n \quad (2)$$

where Ys, Ts, H, and n are the yield strength (MPa), the tensile strength (MPa), microhardness (MPa), and the strain-hardening coefficient, respectively. For this study, n was chosen and recorded from Callister and William [27].

The maximum stress of the material subjected under radial load is defined as Diametral Compressive Strength (DCS). DCS is a critical mechanical property of the hybrid nanocomposite samples as it reveals the capacity of the material to resist the radial loads. UTM was used to apply the loads radially between two flat jaws. DCS was determined by using the Eq 3 [4,5,9,14]:

$$DCS = 2N/\pi KL \quad (3)$$

where N, K, and L are the radial force (N), the sample thickness (mm), and the sample diameter (mm), respectively. Based on ASTM G99-95 [28], the dry sliding wear test was performed at room temperature by employing a pin-on-disc tribometer model (ED-201, Ducom). The samples with 10 mm diameter and 6 mm high were installed in the holder against steel disc with 62 HRC hardness. Both the sample and the counter steel disc was washed by acetone before and after each period of the dry wear test. The test parameters, such as sliding distance, sliding velocity, time, and different applied loads, are 1810 m, 1.5 m/s, 20 min, and 5, 10, 15, and 20 N, respectively. The applied loads were connected vertically and directly to the longitudinal direction of the samples by the device design. After each test, the counter steel disc was left to cool to the room temperature, then cleaned with the organic solvents in order to remove the wear debris that stuck over the disc surface. Before and after each test, the samples were weighted in order to determine and calculate the loss of the wear. The wear rate was determined by dividing the wear loss over the sliding distance, whereas the coefficient of friction was calculated by dividing the friction force over the applied load [3,8,9,14]. Three samples for each composition of the hybrid nanocomposites were tested to determine the average value of wear rate. After that, the morphology of the wear tracking and worn surfaces was investigated by FESEM and EDX. Figure 2 displays the flowchart of the procedure sequence of the experimental part to manufacture the hybrid composites.

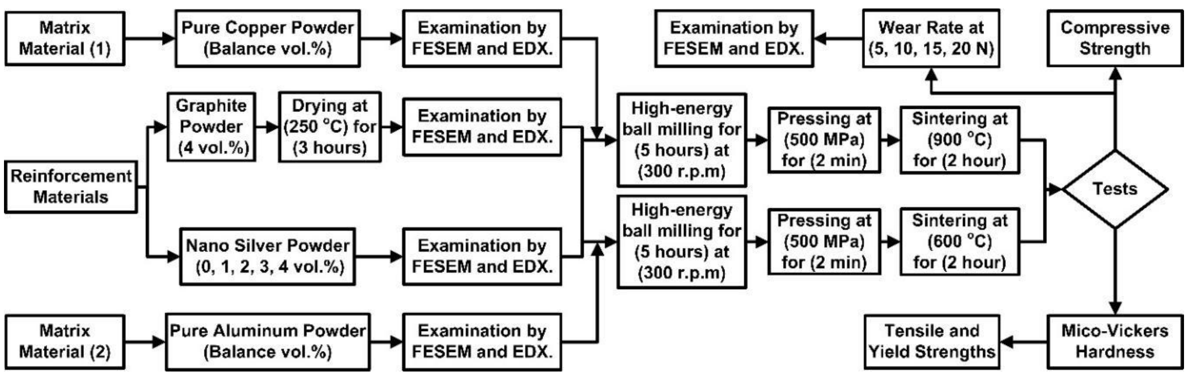

Figure 2. The flowchart of the procedure sequence of the experimental part.

3. Results and discussion

3.1. Mechanical properties

Figures 3 and 4 demonstrated the relation between the content of Ag nanoparticles with both the microhardness values and diametral compressive strength, respectively, for the copper and aluminum matrix nanocomposites. As can be observed, both the hardness and compressive strength results improved significantly with increasing the Ag nanoparticles content until 3 vol% of the copper matrix composite, whereas in the aluminum matrix composite, increasing until 2 vol% and then decline suddenly for all the composites. Moreover, the microhardness and compressive strength of the copper-based nanocomposite is higher than aluminum-based nanocomposite. In addition, the two types of matrix composites at 0% Ag content have lower strength when compared with the other reinforcement contents and pure metals. The minimum strength of the composites at 0% Ag nanoparticles content due to the presence graphite particle that possesses soft nature, it is well-accepted and known that existence soft particles should result in a reduction of the composite strength. Moreover, during the milling period, graphite particles will cover the matrix metals, which prevent complete incorporation between adjacent matrix particles on the sintering process [3]. Thereafter, it is clearly shown that the hardness and compressive strength values improved drastically with an increase in Ag nanoparticles content. This behaviour can be ascribed to the presence of Ag nanoparticles that have relatively hardness and strength more than the matrix material, and based on the mixture law; any improvement in reinforcement content should increase the strength. Also, the proper and well distribution of the Ag nanoparticles in the base of the composite must produce improvement in the strength of the hybrid nanocomposite because of the increase in the contact area between the matrix material and the nanoparticles. On the other hand, in accordance with the strengthening mechanisms of the Hall–Petch and Orowan [29,30], which suggested that the presence of nanoparticles usually results in an improvement in strength. Furthermore, existent nanoparticles in the hybrid matrix composites prevent the motion of dislocations and migration of grain boundaries, and that will cause enhancement of the nanocomposite strength. Similar behaviours have been published in the literature [13,14,21].

The strength improvement can be summarized with increasing the Nano-sized silver content to:

1. The reinforcement phase has a higher strength.
2. Semi-homogeneous distribution of the nanoparticles is in the matrix.
3. The structure of the nanocomposites.
4. The proper incorporation between the nanoparticles and the matrix, greatly influenced by the densification method utilized.

Subsequently, the reduction behaviour in strength after 3% and 2% Ag content of the copper and aluminum matrix nanocomposites, respectively, can be associated with clustering and agglomeration of the reinforcing nanoparticles, according to the fact that the nanoparticles possess a great tendency to agglomerate and cluster, especially at high content. As compared between the two types of hybrid nanocomposites, it can be observed that the copper-based nanocomposite possesses the strength higher than aluminum-based nanocomposite. This behaviour can be attributed to the fact that the copper metal has a density and strength more than aluminum metal.

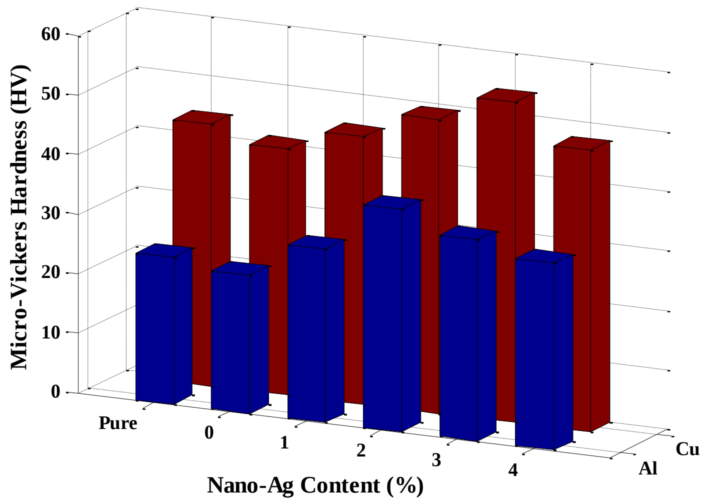

Figure 3. Relationship between micro-Vickers hardness with nano-Ag content.

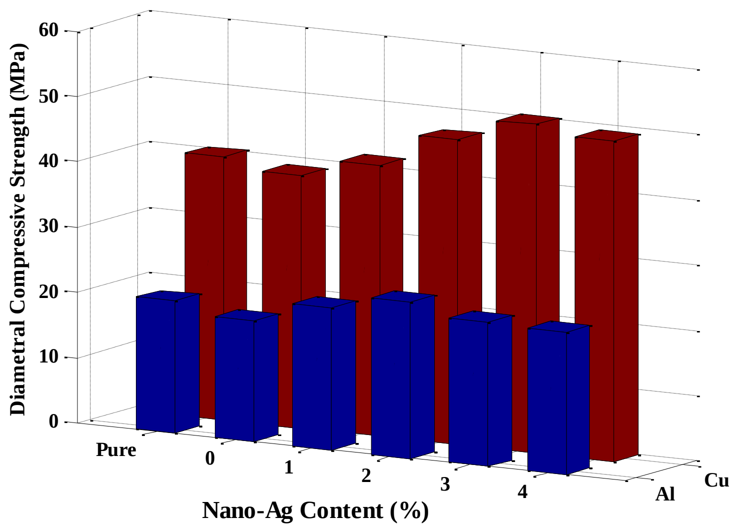

Figure 4. Relationship between the diametral compressive strength with nano-Ag content.

Figure 5 illustrates the correlation between both the tensile and yield strengths with Ag nanoparticles content of the hybrid nanocomposites. These strengths were directly determined from microhardness values by using Cahoon's equation [23,25,26]. The tensile tests were not performed experimentally due to the physical limitations of specimens generated from the PMT, especially the difficulty in manufacturing the mould for producing tensile specimen and applying the pressure through the pressing process. Therefore, the tensile and yield strengths were calculated by the utilization of Eqs 1 and 2 and employing the suitable coefficient strain hardening of the material. It can be observed that poor strengths achieved at 0% Ag content at all the hybrid nanocomposites. After that, both the strengths improved considerably till 3 vol% and 2 vol% for the copper-based and aluminum-based hybrid nanocomposites, respectively, and next declined suddenly. The enhancement behaviour in strengths can be correlated with the same factors mentioned above about the improvement in both the microhardness and compressive strength. Foremost, among the proper and uniform distribution of the nanoparticles which is in the matrix as well as the good incorporation of the Ag particles in the matrix material. These factors could contribute to the improve strength accomplished. Similar effects were recorded in the literature [13]. Poor strengths relatively of 0% Ag nanoparticles content as compare with pure metal and other reinforcement content can be attributed with the presence of only graphite particles that have soft nature and lower strength [3,15].

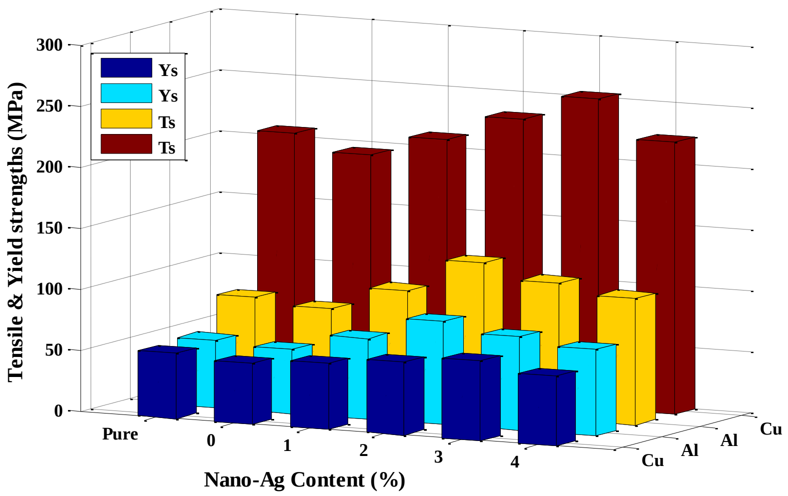

Figure 5. Relationship between both the tensile and yield strengths with nano-Ag content.

3.2. Dry sliding wear test

The influence of different volume fraction of Ag nanoparticles on the wear rate and friction coefficient of both the copper and aluminum matrix composites at various applied loads are demonstrated in Figures 6–11. Pin on disc method was used to find the wear rate for the hybrid nanocomposites at room temperature with a constant sliding distance and velocity of 1810 m and 1.5 m/s, respectively. The rate of wear was measured based on the amount of dislocated the debris from the nanocomposite. The wear rate is proportional inversely with the wear resistance. At the start of the wear test, the sample surface is directly adhesion with the disc surface without any separations. Then, the shear force is developed by the hard counter disc and will be caused deformation of the sample surface as well as dislocate the particles from the sample and composed the wear debris. The presence of wear debris between the tribosurfaces during the sliding is acted as an abrasive medium and change the wear mechanism from a two-body wear mechanism toward a three-body wear mechanism. It can be observed in Figure 6 in copper matrix composites that the wear rate remarkable decline with an increase in reinforcement content, especially in 5 N and 10 N applied loads, but at 15 N and 20 N the wear rate was decreasing up to 3 vol% Ag content and then increased slightly. Whereas in Figure 7 in aluminum matrix composites, the wear rate considerably declines with improving in reinforcement content up to 2 vol% Ag content, then the wear rate significantly increases for all the applied loads. The severe and drastic wear rate has primarily been seen in pure metals of both copper and aluminum in all the applied loads. Besides, the wear rate significantly increases with an increment in applied loads. On the other hand, Figures 9–11 reveal that the coefficient of friction positively associated with the wear rate at various applied loads. Besides, the friction coefficient declines with increasing the applied loads.

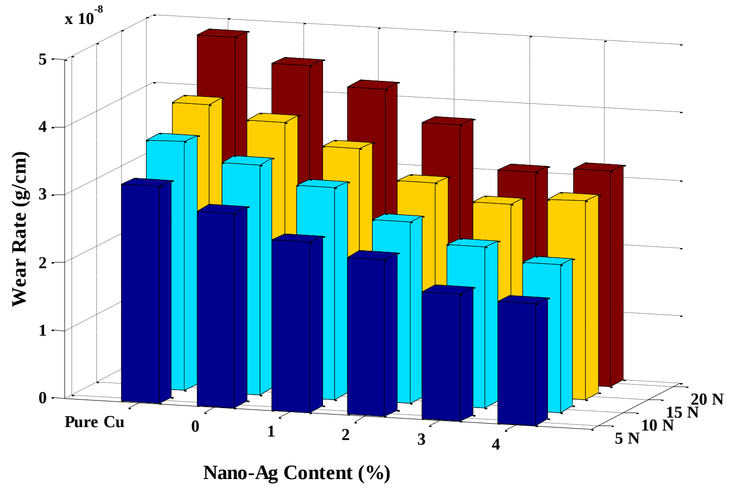

Figure 6. Relationship between the wear rate of the copper matrix with nano-Ag content at different applied loads.

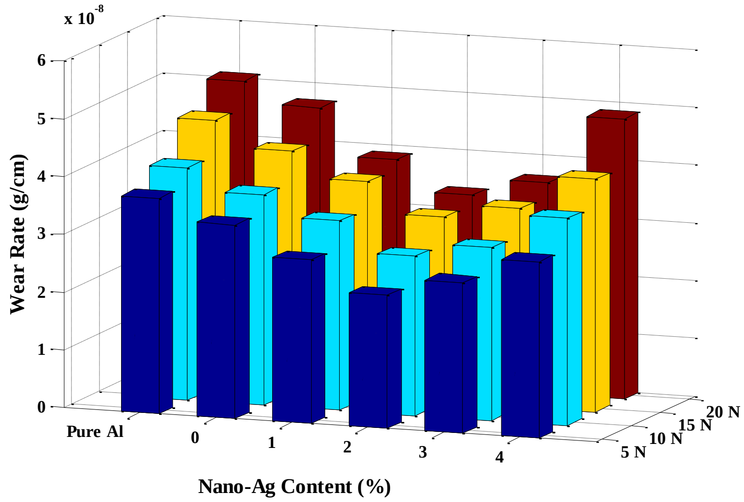

Figure 7. Relationship between the wear rate of the aluminum matrix with nano-Ag content at different applied loads.

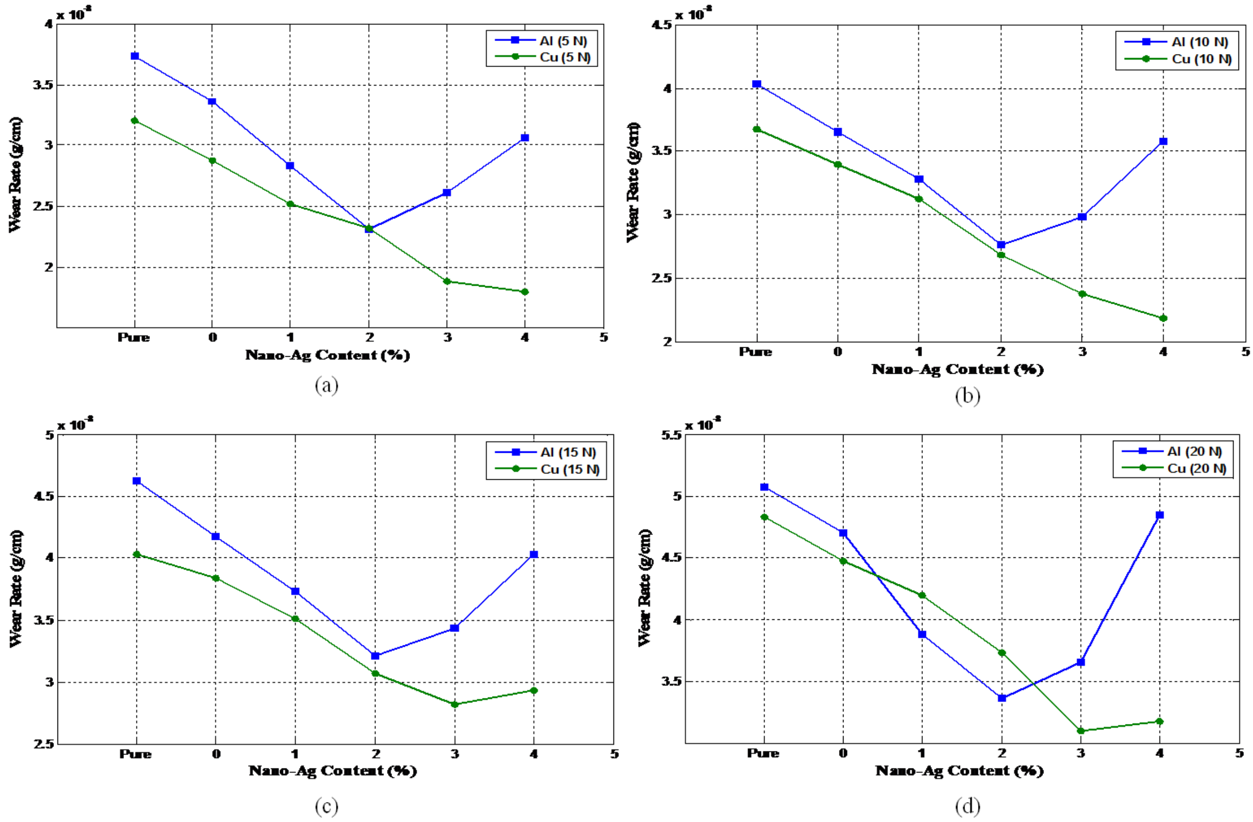

Figure 8. Relationship between the wear rate with nano-Ag content of both copper and aluminum matrix composites at (a) 5 N, (b) 10 N, (c) 15 N, and (d) 20 N.

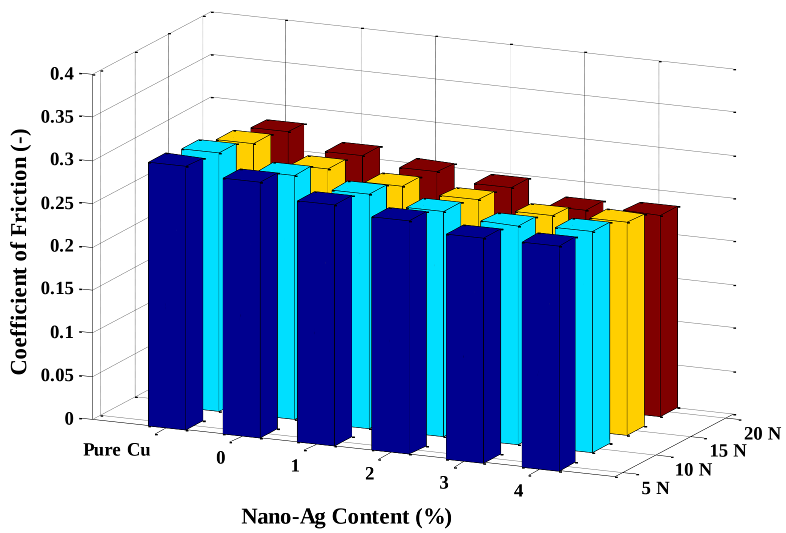

Figure 9. Relationship between the friction coefficient of the copper matrix with nano-Ag content at different applied loads.

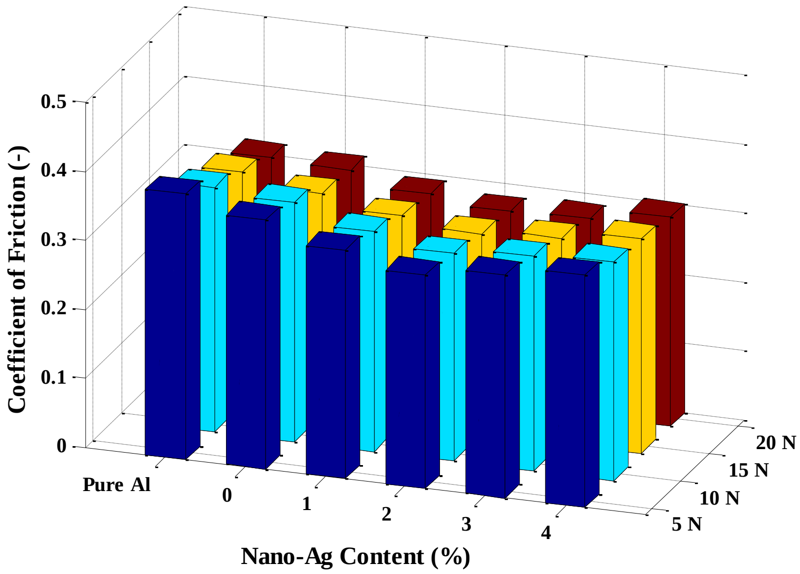

Figure 10. Relationship between the friction coefficient of the aluminum matrix with nano-Ag content at different applied loads.

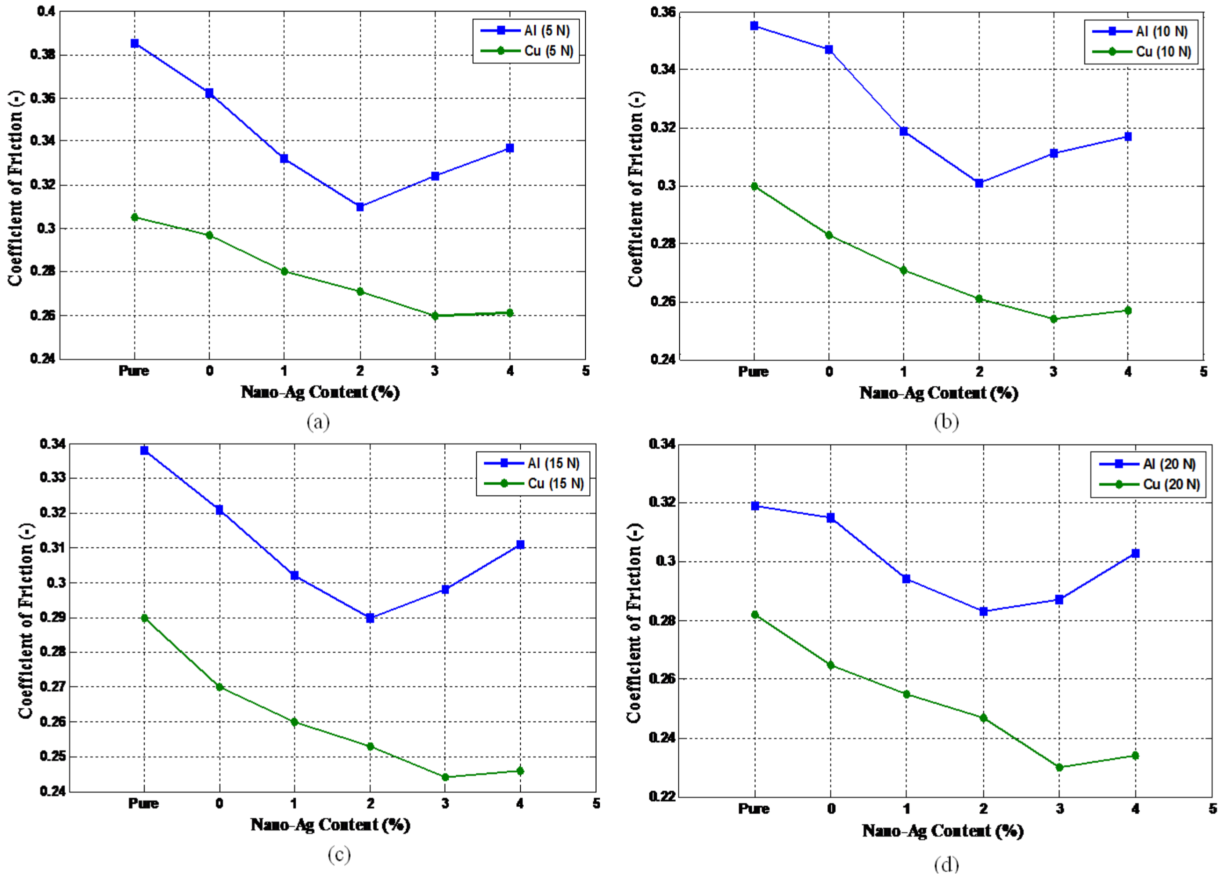

Figure 11. Relationship between the friction coefficient with nano-Ag content of both copper and aluminum matrix composites at (a) 5 N, (b), 10 N, (c) 15 N, and (d) 20 N.

These behaviours in wear resistance and coefficient of friction with and without the addition of Ag nanoparticles compared with pure metals can be correlated with several factors:

1. The pure metals have a high wear rate as compared with the other composites. This phenomenon can be attributed to two main reasons. Firstly, pure metals possess a higher friction coefficient, as shown in Figures 9–11, due to the sliding of the same material over the hard disc, have the coefficient of friction higher than various material, and this drives to more rate of wear. Secondly, the more wear debris will affect adhesion into the steel disc, and this leads to the further actual area of the harder material surface (increasing micro-cutting material) and producing more loss of wear.
2. The wear behaviour at 4 vol% graphite (0% Ag content) is extensively attributed to the presence of graphite particles as a solid lubricating material, which forms a tinny thin film between the tribosurfaces. This lubricating film will change the contact surfaces nature from metal to metal to the tribosurfaces separated by the thin lubricating film that must be resulted in decreasing the wear rate from the composites [3,8].
3. The evident improvement in wear resistance with the addition of Ag nanoparticles can be attributed to the enhancement in the nanocomposites hardness, as shown in Figure 3, it can be observed the similarity behaviour between the hardness and the wear resistance. According to Archard's law, any increment in the hardness will cause improving the wear resistance. This law related to the fact that improving the hardness means increasing the contact force between the particles that prevent severe contact between the tribosurfaces. Uniform and proper distribution of Ag nanoparticles and well incorporated in the nanocomposites will reduce the plastic flow during the wear test and resulting in reduction wear loss. Comparable results were noted in the literature [13,14].
4. The slight decline in wear resistance after 3% for the Cu matrix and 2% for the Al matrix is expected behaviour due to a gradual decrease in composite hardness. As mentioned above from Archard's law, wear resistance positively associated with the composite hardness. In addition, at high reinforcement content, the nanoparticles have a considerable tendency to the agglomeration and clustering, which prevents the right consolidation between the composite compounds and produces separated debris. Related behaviour has been recorded in the literature [14].
5. The increment in applied loads resulted in deteriorated the wear resistance for both types of nanocomposites. This severe behaviour is expected due to increasing the friction and contact forces between the tribosurfaces with increasing the applied loads, which produce accelerated the deformation from the composites. Furthermore, Archard's law [5,9,31] proved that the wear loss associated positively with the applied loads according to the fact that was increasing the compressive and friction forces by rising loads. Besides, the increment in applied loads is proportional directly to the frictional heat quantity, which generated between the tribosurfaces. This rising in frictional heat decreases the resistance of the matrix composite against the deformation, shear force, and detach the reinforcement particles from the composite surface. Similar behaviour has been published in the literature [5,9,31].
6. As compared with pure metal, the improvement in reinforcement content drives to a lower coefficient of friction for all the applied loads. The friction coefficient can be described as a function of composite characteristics like density, hardness, shear strength, modulus of elasticity, yield, and tensile strength. The improvement in strength and hardness causes reduce the fracture event, and surface deformation, as well as decreasing the actual contact area between the

tribosurfaces. Hence, the reduction behaviour in the friction coefficient by increasing the reinforcement volume fractions can be associated with improving the strength and hardness, as shown in Figures 3–5. Furthermore, for the same reason mentioned above, it can be considered as an explanation for the reduction in the friction coefficient of the copper matrix composite as compared with an aluminum matrix composite, as shown in Figure 11.

7. The decline behaviour in the coefficient of friction with increment in applied loads is attributed to numerous factors. When increasing the loads over the sample surface, the temperature generated between the contact surfaces increases, which leads to the formation skinny molten layer at the sample surface that reducing the shear strength and assists in declining the friction coefficient [32]. Additionally, the increase in temperature helps to create a dense oxide layer that may drive to low adhesion and decreased friction coefficient. The EDX spectrum evidently reveals the formation of the oxide layer at the worn surface of the sample. Another reason, at high applied loads, a sufficient quantity of wear debris entrapment between the tribosurfaces leads to decrease friction coefficient. Whereas at lower applied loads, the apparent area of the sample surface is more significant than the actual surface area that effecting by the pressure. Due to this, only a small area will be affected by high pressure. At the low loads, the generated temperature between the contact surfaces is also low and so that there is no formation of oxidation. Accordingly, the adhesion and abrasion mode will control the wear test causing a high coefficient of friction due to the contact area is still clean comparatively.

Figure 8 demonstrates a comparative study in wear rate between the copper and aluminum matrix composites with increasing in reinforcement content under various applied loads. As can be seen, the wear rate of the aluminum matrix composite is higher than the copper matrix composite in all the applied loads. In addition, it was observed a convergence in wear rate results between copper and aluminum matrix composites at 2 vol% silver nanoparticles content. The following several recommended reasons can describe this behaviour:

1. Copper matrix composite possesses density, strength, and hardness more than the aluminum matrix composite. Therefore, per Archard's law, the wear resistance of copper matrix composite is higher.
2. The friction coefficient of the aluminum matrix composite is higher than the copper matrix composite, as shown in Figure 11. Accordingly, the wear resistance of aluminum matrix composite must be lower.
3. The convergence in melting temperatures between copper and silver will facilitate the formation of a solid solution and intermetallic compounds in the composite during the sintering process, which results in high resistance against the wear loss in contrast with the aluminum matrix composite.

3.2.1. Worn surface characteristics

The worn surfaces of both the copper and aluminum matrix composites are displayed by utilizing FESEM images and EDX spectrum in Figures 12 and 13. The wear rate drastically effects on the surface morphology of the tested sample and also the type and size of wear debris. At the beginning of the sliding period, the counter steel disc will deform and dug the relatively softer composite material and detach the particles from it because of sliding the surface of softer material over the hard material (steel disc), and the debris will fill the wear valleys, as shown in Figures 12a,c and 13d. These detached particles (wear debris) will be stuck into both the surfaces of disc and sample and convert the friction mode from adhesion to the abrasion, which causing machining the sample surface. As can be seen from Figures 12b,d and 13a,c,d, with increment in applied loads, the composites are gradually deteriorated because of increment and development of the shear stress by the hard surface that generates more ditches and debris loss. At high applied loads, the pits and ditches intensities will be higher, as well as when compared with low applied loads, and it can also be seen the plastic deformation of the ditches boundary material due to generate more frictional heat between the contact surfaces. With more time continuity of high-applied loads, because of delamination, cracking and shear forces on the sample surface, the digs will be developed and advanced to the ditches edges, as shown in Figures 12d and 13d. Besides, the softer matrix material is digging by the harder counter steel disc that leads to form the cracks that spread and distributed into lateral directions and axial as well as deform the subsurface of the sample. Additionally, generation the digs, ditches and appearance texture along the matrix material surface are proper and uniform in all worn surfaces, as shown in Figures 12a and 13a. Also, it can show the distribution of the materials lumps throughout the worn surfaces because of the high ductility properties of a material matrix, at the visualization of the worn surface, shown clearly that the loss of the wear is due to the micro-cutting and delamination (abrasion wear).

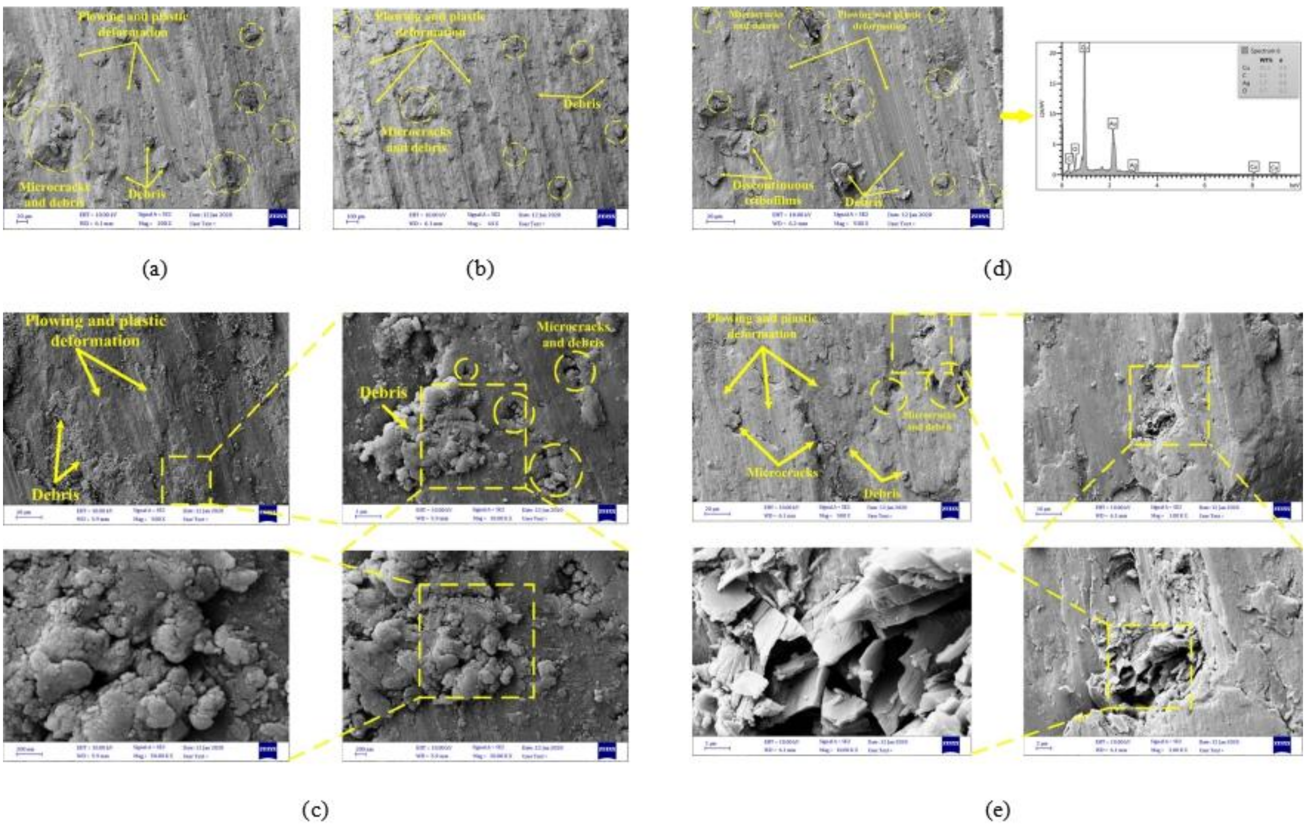

Figure 12. FESEM images of the worn surface of copper matrix composites: (a: pure copper at 15 N), (b: 3% Ag at 15 N), (c: 0% Ag at 10 N), (d: 1% Ag at 20 N), (e: 2% Ag at 10 N).

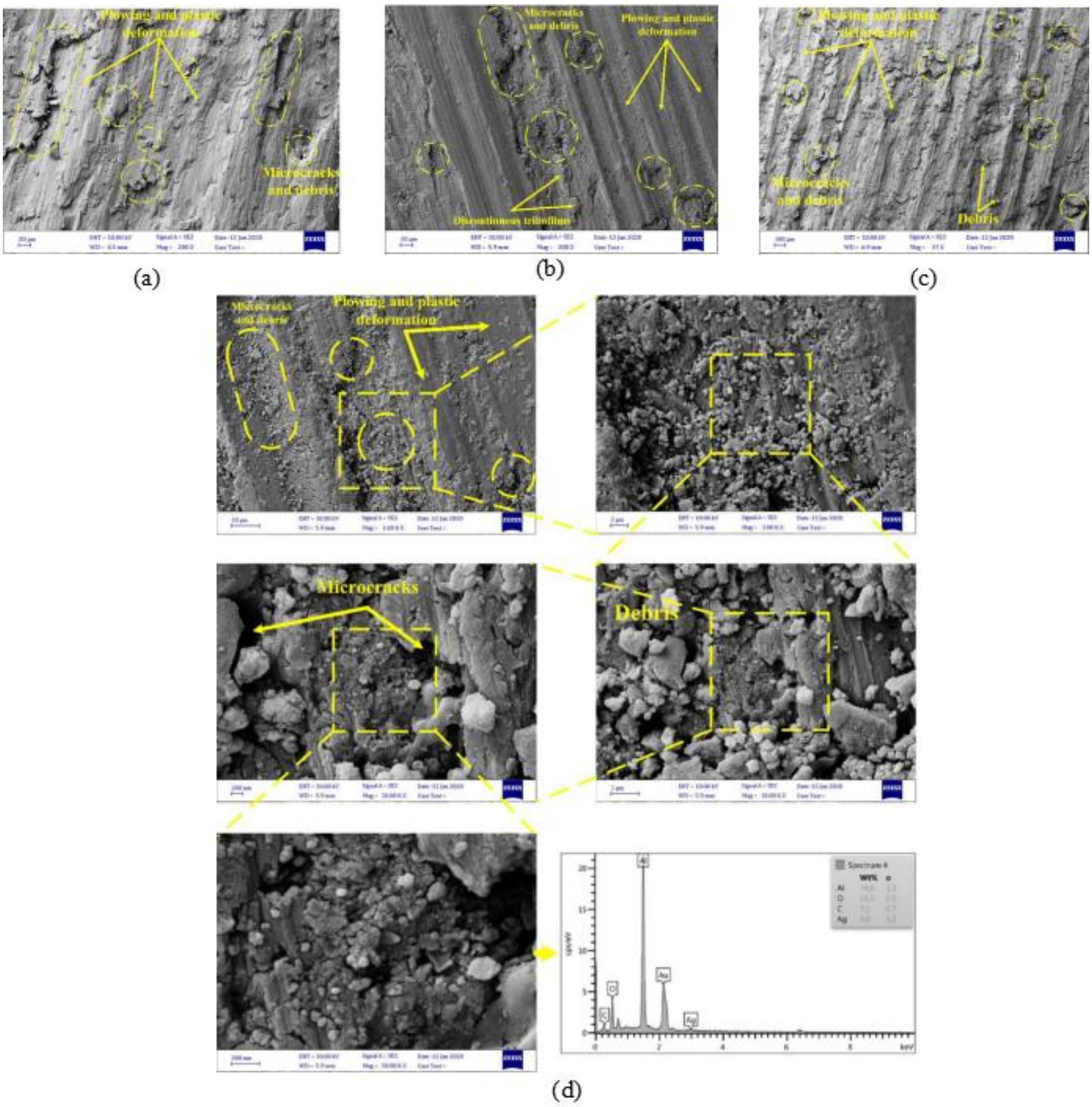

Figure 13. FESEM images of the worn surface of aluminum matrix composites: (a: pure Aluminum at 15 N), (b: 0% Ag at 10 N), (c: 2% Ag at 15 N), (d: 4% Ag at 20 N).

The other main parameter that affected drastically by the applied loads is the size and shape of wear debris. Firstly, when the applied loads are low, the debris colour will be shiny and less bright as well as the debris size will be small and more uniformed in shape as compared with the generated debris at high-applied loads. In addition, the colour and shape of the debris generated from the composites are grey and irregular. Secondly, when applied high loads, the wear rate will be severe and produced large size of debris as well as generated the debris with a texture similar to the sample tested, as shown in Figures 12d and 13d. The debris texture that produced from the composite is various from the generated debris of matrix material. The region of dark oxidation is distributed intermittently along the worn composite surface.

4. Conclusions

In the current study, by employing the classical powder metallurgy technique, both copper and aluminum metals separately were reinforced successfully by graphite and nano-silver particles in order to manufacture hybrid nanocomposites. Hence, mechanical and wear properties of both types of hybrid nanocomposites were investigated experimentally to compare between them. The main conclusions are summarized below:

1. Copper and aluminum metals were recorded minimum mechanical properties and wear resistance as compared with the hybrid nanocomposites. In addition, pure copper was showed mechanical properties and wear resistance higher than pure aluminum.
2. Microhardness, diametral compressive strength, and tensile strength were improved drastically with increasing the volume fraction of silver nanoparticles until 2 vol% and 3 vol% in aluminum and copper matrix composites, respectively, and after that, suddenly declined.
3. Enhance the content of silver nanoparticles up to 2 vol% in aluminum matrix composites led to a considerable decline in the wear rate and then increased gradually for all the applied loads. Whereas in copper matrix composites, the wear rate was significantly reduced with improving the reinforcement content at 5 N and 10 N applied loads, but at 15 N and 20 N, the wear rate was declining up to 3 vol% Ag content and then rising slightly.
4. The coefficient of friction was associated positively with the wear rate of both the hybrid nanocomposites at all applied loads.
5. Convergence was observed in the wear rate results for all the applied loads between the copper and aluminum matrix composites in 2 vol% silver nanoparticles content.
6. Comparatively, the improvement and strengthening effects on copper matrix composites were higher than on aluminum matrix composites by increasing the silver nanoparticles volume fraction.

Conflict of interests

The authors declare no conflict of interest.

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