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AN EXPERIMENTAL STUDY OF THE MECHANICAL AND TRIBOLOGICAL BEHAVIOUR OF Al6061/MWCNTs METAL MATRIX COMPOSITES

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ABSTRACT
The present work aims to study the mechanical and tribological behavior of the metallic matrix nanocomposites of Al6061 alloy reinforced with various weight fractions (wt.%) of 0, 0.5, 1, and 1.5 multi-walled carbon nanotubes (MWCNTs) to be applied in automotive industries. All the present nanocomposites were produced using a hot-compaction powder metallurgy technique at temperatures of 420, 460, and 500 °C and a pressure of 700 MPa.

After that, theoretical, actual, and relative densities were determined. The microstructure was also examined using a scanning electron microscope (SEM) to confirm the distribution of the MWCNTs within Al6061 alloy. Moreover, mechanical characteristics of the produced nanocomposites were examined by Vickers microhardness and compression tests. The tribological characteristics were also examined by wear and friction tests using pin-on-disk test rig. Then, the worn surfaces were examined using SEM to study the occurred wear mechanism.

According to the experimental results, the optimum compaction temperature was 460 °C. Consequently, the relative density improved and reached the highest value (97 %) at a MWCNTs content of 1.5 wt. %. Examination of the microstructure also demonstrated the good distribution of 1 wt. % MWCNTs within the Al6061 alloy. All mechanical and tribological properties including Vickers hardness number (VHN), ultimate compressive strength, wear rate, and the friction coefficient of the Al6061 alloy were improved and reached their best values at a content of 1.5 wt. % MWCNTs. Finally, the worn surface of the Al6061/1.5 wt. % MWCNTs nanocomposites contains less wear marks than that of pure Al6061 and other nanocomposites.

KEYWORDS
Wear rate, friction coefficient, Vickers hardness number, metal matrix composites, ultimate compressive strength.

INTRODUCTION

Metal matrix composites (MMCs) have a great role in a wide variety of applications because of their excellent properties. They have a high strength to weight ratio, and good mechanical properties, which helps to use in many applications such as civils, automotives, vehicles, and others, [1]. These properties lead to saving cost and energy. Moreover, MMCs have been widely used in communication, aerospace sectors, and automobile applications [2, 3]. Recently, it was found that addition of reinforcement micro- or nanoparticles increases the tensile strength and hardness of MMCs, [4]. Interestingly, MMCs reinforced with high-strength particles are widely used in the automotive and aerospace industries due to their light weight and high strength, [4, 5].

Aluminum metal matrix composites (Al MMCs) are a great addition to form high performance tribological composites. Al MMCs normally fabricated, by spray co-deposition, diffusion bonding, powder metallurgy, spark plasma sintering, or liquid casting techniques, [6- 8], which fabricate a reinforced Al form with improved mechanical properties compared to the pure Al alloy, [9, 10]. Although particulates are homogenously distributed over liquid metal at the liquid casting technique, this method is cost effective, [8, 11- 14]. On the other hand, powder metallurgy route is preferred to fabricate Al MMCs, whereas the ball milling is used to blend the matrix with reinforcement materials. Then, powders are compacted in a heated die to fabricate Al MMCs, [15].

Al6061 alloy has been a common matrix material, because of its high strength and corrosion resistance. So, this matrix could be used in various industrial applications. The various properties of these alloys can be further enhanced by addition of reinforcement materials. There is a need to produce low cost, portable, high quality, economical, simple, and improved abrasion and wear resistance, [3]. Hence, these matrices could be modified by adding reinforcement materials such as silicon carbide (SiC), alumina (Al_2O_3), and carbon nanotubes (CNTs), which led to fabrication of highly strong MMC materials for specific applications.

Among these reinforcements, CNTs has been the most widely investigated, [15 - 17]. CNTs have the form of a tubular structure made of carbon atoms, its diameter is a nanometer, and its length exceeds several microns. The development of CNTs composite materials gained much attention due to their unique advantages, such as their higher strength and lower density compared to conventional materials, [18, 19]. CNTs have two main types that are single walled carbon nano tube (SWCNT), which consists of single graphite sheets wrapped in cylindrical tubes, and MWCNTs, which comprises an array of nanotube that is concentrically nested, [20].

Previous works studied CNTs to be used at many applications because of their properties. Wu et al. prepared Al6061/CNT composites by semi-solid powder processing. They found that Al6061/CNT composites were harder and stronger than that of pure Al6061, [21]. Also, George et al. have studied CNT/Al composite to indicate the strengthening mechanism. They showed that Young's modulus was increased, [22]. Moreover, MWCNT/Al6061 was fabricated using a stir casting

method as studied by Kumar and Raghavendra. They concluded that compression strength increased, and wear loss decreased with increasing CNT content. Their results proved that hardness of CNT/Al 6061 nanocomposites increased with the increase of CNT wt. % in the composite, [23].

Also, Sivananthan et al. proved that addition of MWCNTs in the Al matrix using ball milling procedure enhanced the relative density and hardness of the composite as well as enhancing the physical properties of Al, [24]. Kwon et al. achieved an increasing in the tensile strength without degradation in the Al–CNT composite, which was fabricated by spark plasma sintering followed by hot-extrusion processes, [25].

As reported in previous works, CNTs were prepared with Al-alloy using different techniques. Furthermore, the mechanical properties of that composite were examined. On the other hand, there are no papers used a hot-compaction powder metallurgy technique to prepare Al-CNTs composites. Hence, we surmised that fabrication of Al/CNTs composites can enhance the mechanical and tribological properties of the composite. Therefore, the main aim of the present work is to introduce a new metallic matrix nanocomposite of Al6061/MWCNTs manufactured by a hot-compaction powder metallurgy technique for automotive engines industry purposes.

MATERIALS AND EXPERIMINTS

Materials

Al6061 alloy, which used as a matrix material, was supplied from Alumisr Corporation, Egypt. Al6061 alloy was converted into a powder shape, which has an average size of 400 nm, using atomization technique in the Central Metallurgical Research & Development Institute (CMRDI), Helwan, Egypt. The reinforcement material composed of MWCNTs, which supplied from Nanotech Company, Egypt. The chemical composition of as received Al6061 and characteristics of MWCNTs were introduced in Tables 1 and 2, respectively.

Table 1. Chemical composition of as received Al6061 alloy.

Elements	Mg	Cu	Fe	Si	Zn	Mn	Cr	Ti
Composition%	0.85	0.35	0.60	0.75	0.15	0.20	0.025	0.065

Table 2. Characteristics of as received MWCNTs.

Properties	Diameter	Length	Purity	Density
Values	10-12nm	1-20µm	99.9%	1~2 g/cm^3

Nanocomposites Preparation

In this part, the present nanocomposites were prepared according to the flowchart that indicated in Fig. 1. Initially, the Al6061 alloy, as a powder, was mixed with various contents of MWCNTs at 0, 0.5, 1, and 1.5 wt. %. The mixing process of Al6061/MWCNTs was carried out using a ball milling machine for an hour at a

rotation speed of 120 rpm. The ratio of the weight of the balls to the weight of the powder was 10:1. After mixing step, the Al6061/MWCNTs nanocomposites were placed inside a hot-pressing die with a diameter of 10 mm. Then, Al6061/MWCNTs nanocomposites were heated at 420, 460, and 500 ºC and pressed into at a pressure of 600 and 700 MPa to obtain the nanocomposites final shape with a length of 10 mm and a diameter of 10 mm.

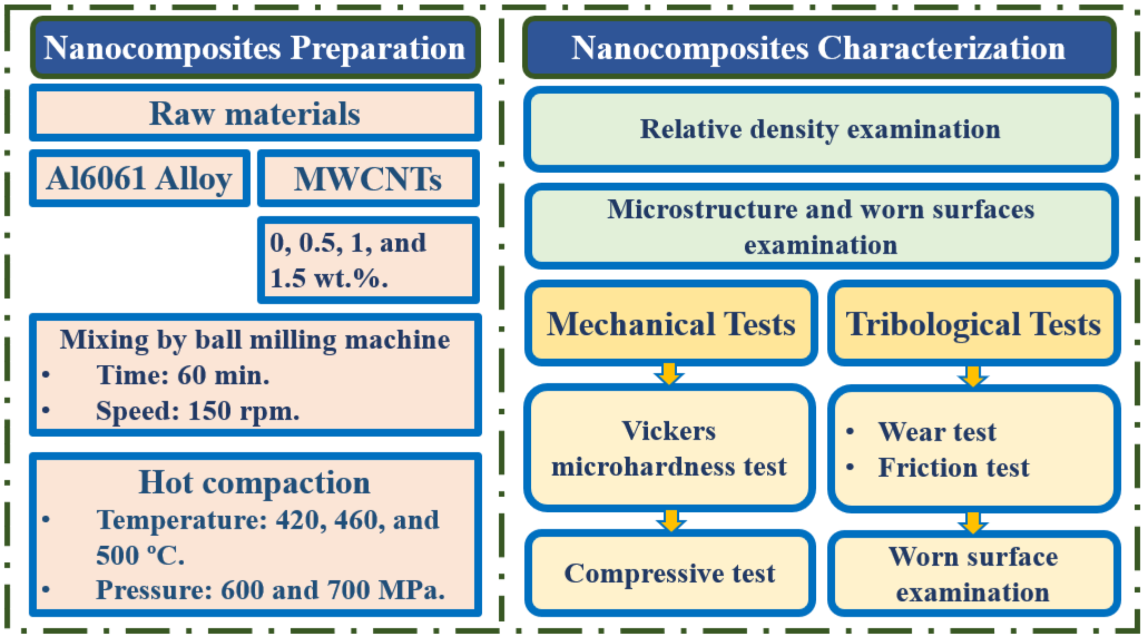

Fig. 1 Flowchart for nanocomposites preparation and characterization.

Nanocomposites Characterization

The present nanocomposites were characterized in several tests, as shown in Fig. 1. The actual density of the composites was measured by Archimedes' principle. The theoretical density was also calculated using the rule of mixture. By dividing the actual density by the theoretical density, the relative density of the specimens was estimated. To study the microstructure of the nanocomposites and the distribution of MWCNTs within the Al6061 alloy, the specimens were imaged and characterized by SEM.

Mechanical tests such as Vickers microhardness and compression tests were performed on the specimens to study the mechanical behavior of the present nanocomposites. Vickers microhardness test was performed under applied load of 2 kg for dwell time of 30 seconds according to ASTM E384-99. The specimen surface subjected to the test was polished with alumina suspension to easily see the indentation on the surface with a microscope. VHN was estimated as follows:

$$VHN = 1.8544 \left(\frac{P}{d^2}\right) \quad (1)$$

Where, P is the applied load, kgf, and d is the indentation mean diagonal length, mm. To reach accurate results, the test was repeated at least five times for each sample and the average readings were taken.

Also, the compression test was performed at room temperature according to ASTM D-695 standard. The compression test specimen had dimensions of 10 mm in diameter and 10 mm in length, and crosshead speed was kept at 2 mm/min. After that, the ultimate compressive strength of the present nanocomposites was determined.

Tribological tests such as wear, and friction tests were performed on the specimens to study the tribological behavior of the present nanocomposites. Wear test was conducted by a pin-on-disk test reg in accordance with ASTM G 99 standard under a constant applied normal load of 30 N, [25 - 27]. Also, the sliding distance and sliding speed were fixed at 377 m and 75 m/min, respectively. To perform the wear test, the specimen was weighed before and after the test using a digital electronic balance with a sensitivity of $1x10^{-5}$ g. The difference between the specimen weights before and after the wear test divided by the sliding distance expresses the wear rate that occurred in the specimen.

It is worth noting that the friction test was performed during the wear test. The friction force of the specimen on disk was measured by a 40 kg load cell. Friction force readings were recorded every one millisecond by a data logger connected to a computer. Then, the coefficient of friction was calculated by dividing the friction force by the applied normal load. Each sample was tested at least three times in the tribological tests, and the readings were averaged to obtain accurate results. After wear and friction tests, the test surfaces were imaged using SEM to study the worn surfaces microstructure and wear mechanisms that occurred in the nanocomposites.

RESULTS AND DISCUSSION

Relative Density and Microstructure of Al6061/MWCNTs nanocomposites.

Figure 2 shows the effect of adding MWCNTs on the relative density of Al6061/MWCNTs nanocomposites compacted at 420, 460, and 500 ºC. The relative density of the present nanocomposites, as shown in Fig. 2, was the best at the compaction temperature of 460 ºC compared to 420 and 500 ºC. The relative density of the Al6061/MWCNTs nanocomposites improved by 97 % with increasing MWCNTs content up to 1.5 wt. %. This may be due to the good distribution of MWCNTs at the nanoscale within the composites, which leads to less entrapment of voids within them, as indicated in Fig. 3. These results are consistent with Kumar et al, [28]. Moreover, the compaction pressure, at 700 MPa, has an effective role in improving the relative density of the present nanocomposites.

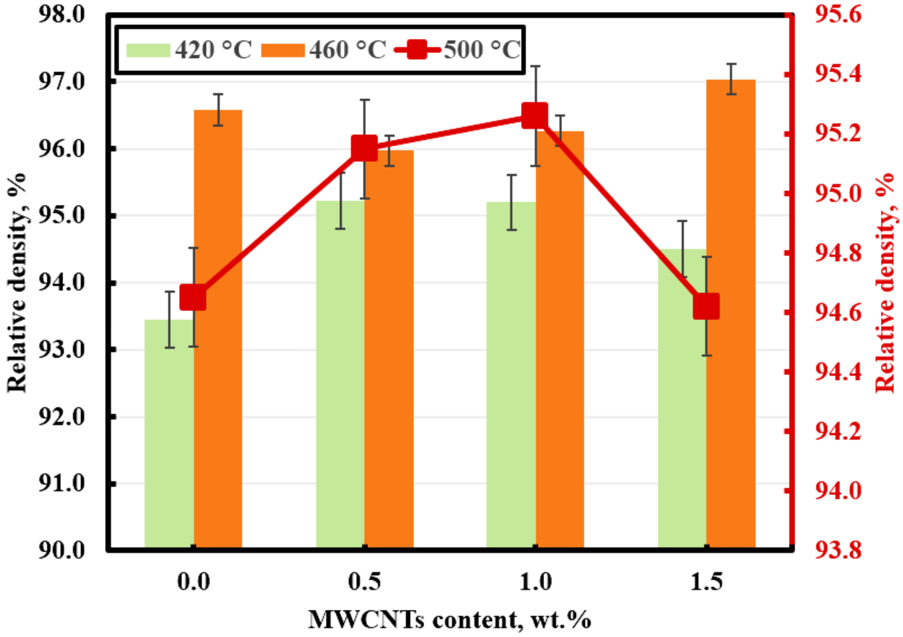

Fig. 2 Relative density of the present Al6061/MWCNTs nanocomposites compacted at 700 MPa.

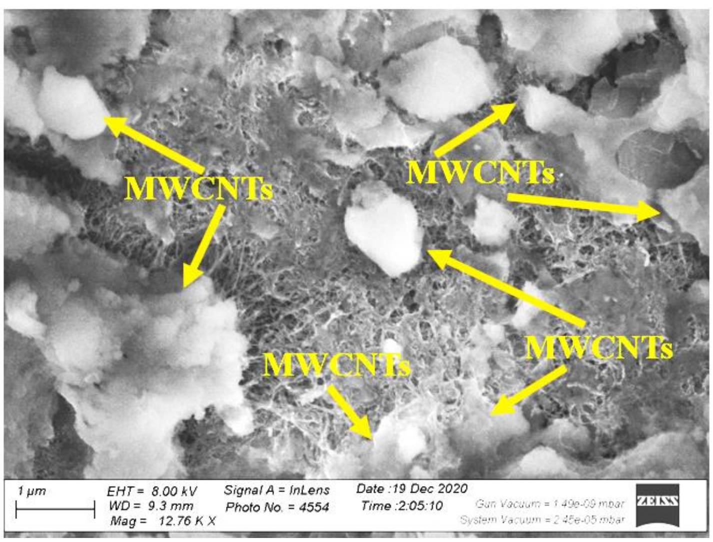

Fig. 3 Microstructure of Al6061/1 wt. % MWCNTs compacted at 700 MPa.

Mechanical behavior of Al6061/MWCNTs nanocomposites

It is important to study the mechanical behavior of Al6061/MWCNTs nanocomposites at different contents of MWCNTs that compacted at temperatures of 420, 460, and 500 ºC. Therefore, Fig. 4 shows the relationship between the VHN and the MWCNTs contents at different compaction temperatures.

As shown in Fig. 4, the VHN recorded the highest value at the compaction temperature of 460 ºC compared to those at 420 and 500 ºC. This may confirm that the optimum temperature of Al6061/MWCNTs nanocomposites that were produced

by hot-compaction powder metallurgy technique was 460 °C, which is approximately two-thirds the melting point of Al6061 alloy.

Moreover, MWCNTs increased the VHN of pure Al6061 alloy by 6.69, 13.23, and 26.87 % at 0.5, 1, and 1.5 wt. % loadings, respectively. This may be due to the good incorporation and distribution of the MWCNTs within the Al6061 alloy, which resulted in improved surface resistance and hardness of the present nanocomposites. Also, these observations in the present study were consistent with Ram et al, [29].

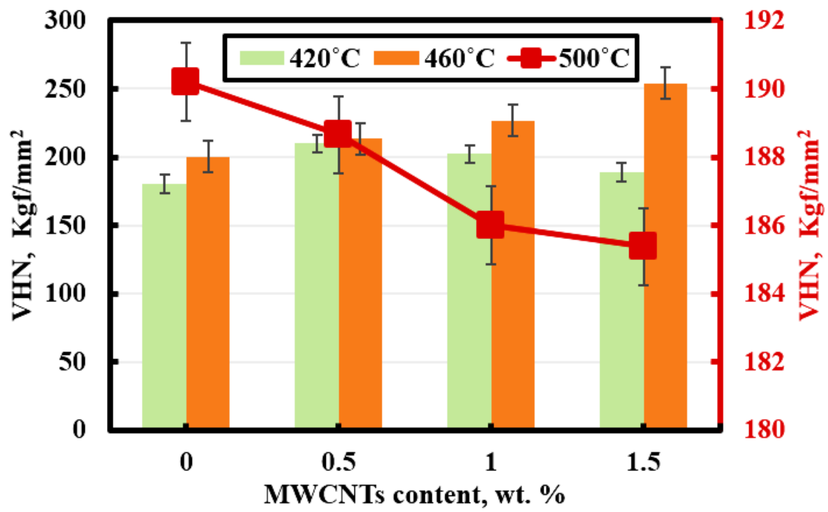

Fig. 4 VHN of the present Al6061/MWCNTs nanocomposites compacted at 700 MPa.

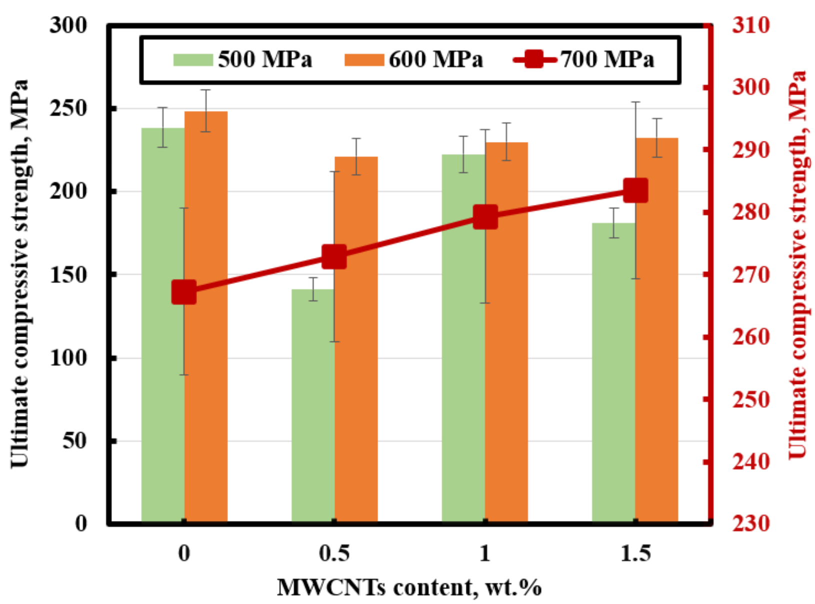

Fig. 5 Ultimate compressive strength of the present Al6061/MWCNTs nanocomposites compacted at 460 ºC.

Figure 5 represents the ultimate compressive strength results of the present nanocomposites versus MWCNTs contents. It is clear that the ultimate compressive strength of the Al6061/MWCNTs nanocomposites was higher than that of the pure Al6061 alloy at compaction temperature and compaction pressure of 460 ºC and 700 MPa, respectively.

Also, MWCNTs increased the ultimate compressive strength of pure Al6061 alloy by 2.08, 4.5, and 6.09 % at 0.5, 1, and 1.5 wt. % loadings, respectively. According to the mixture rule, the ultimate compressive strength of the composites is expected to increase with increasing MWCNTs content. It is due to MWCNTs possessing high mechanical properties and high specific surface area resulting in applied stresses being transferred from Al6061 alloy to MWCNTs easily as well as improving the ultimate compressive strength of the present nanocomposites. In addition, MWCNTs acts as a strengthening material for Al6061, which contributes to improving the ability to bear loads on the Al6061 matrix material alloy.

Tribological behavior of Al6061/MWCNTs nanocomposites.

The tribological behavior of the present nanocomposites is concerned with studying their wear rate and friction coefficient. The wear rate and friction coefficient testing of pure Al6061 alloy, and its nanocomposites were conducted under dry sliding conditions on the pin-on-disk test rig. Wear rate results as a function of MWCNTs content were introduced in Fig. 6. It is noted that the wear rate of the Al6061/MWCNTs nanocomposites recorded a significant improvement compared to the pure matrix material alloy at all compaction temperatures, [28].

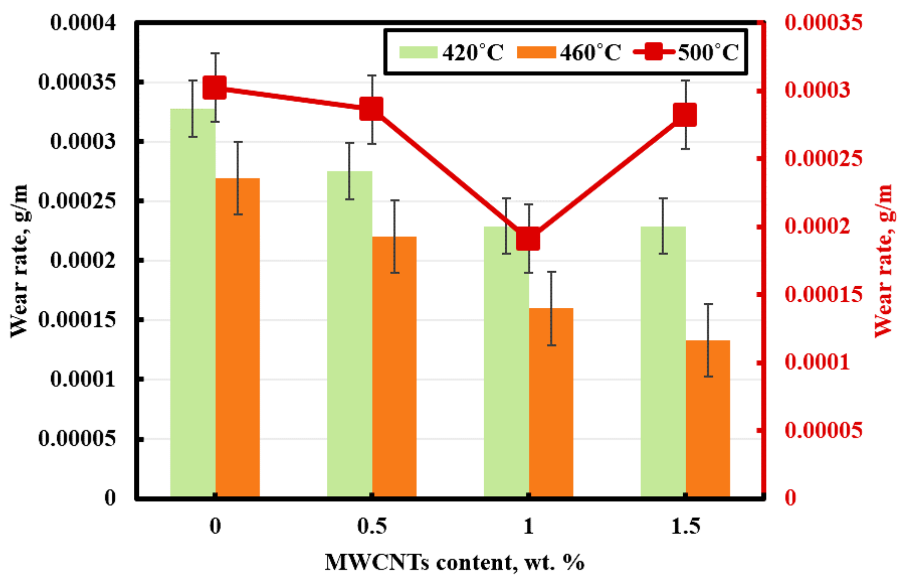

Fig. 6 Wear rate of the present Al6061/MWCNTs nanocomposites compacted at 700 MPa.

The compaction temperature has a clear effect on the wear rate results of the present nanocomposites. As indicated in Fig. 6, wear rate of the Al6061/MWCNTs nanocomposites compacted at 460 °C decreased compared to those compacted at 420 and 500 °C. Therefore, the compaction temperature of 460 °C is considered the best

among other compaction temperatures. Moreover, MWCNTs decreased the wear rate of pure Al6061 alloy by 18.3, 40.74, and 50.68 % at 0.5, 1, and 1.5 wt. % loadings, respectively. The high strength and thermal conductivity of MWCNTs may be a reason for improving the wear resistance of the present nanocomposites. It should be noted that there is a reverse relation between hardness and wear rate results of the nanocomposites, [25]. Therefore, the nanocomposites of Al6061/1.5 wt. % MWCNTs with the highest hardness have the highest resistance to wear.

The coefficient of friction readings for the present nanocomposites were recorded every one millisecond during the wear test under the same conditions and recorded on the computer through the data logger. The friction coefficient results were then represented as a function of MWCNTs contents at the compaction temperatures of 420, 460, and 500 °C, as shown in Fig. 7.

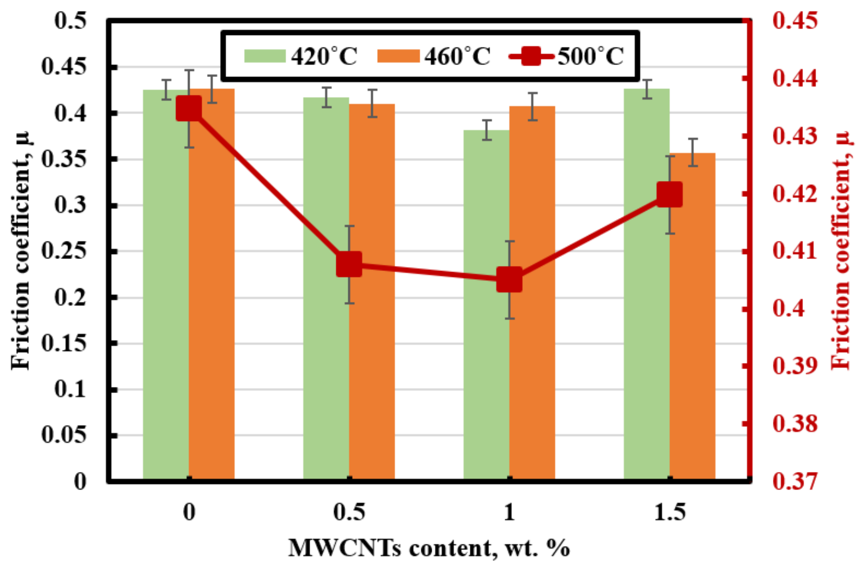

Fig. 7 Friction coefficient of the present Al6061/MWCNTs nanocomposites compacted at 700 MPa.

As shown in Fig. 7, the friction coefficient improved with increasing MWCNTs content up to 1 wt. % at the compaction temperatures of 420 and 500 °C. After increasing the MWCNTs content up to 1.5 wt.%, the friction coefficient began to gradually increase significantly. This may be due to MWCNTs agglomerates inside the base material of Al6061, which led to the poor wettability of MWCNTs with Al6061 alloy and thus higher values of the friction coefficient.

The lowest friction coefficient results recorded at compaction temperature of 460 °C, as shown in Fig. 7. As a result, MWCNTs reduced the friction coefficient of the base material Al6061 alloy by 3.7, 4.41, and 16.2 % at 0.5, 1, and 1.5, respectively. The significant improvement in the friction coefficient results may be attributed to the ability of MWCNTs to self-lubricate for the nanocomposites during testing, which led to a reduction in the friction coefficient for these nanocomposites.

It is important to study the transfer film formation when studying the improvement of the tribological behavior of nanocomposites filled with carbonaceous materials. These films released from the specimen surface exposed to contact with the steel disk during the wear test, where they protected the surface from excessive wear and thus reduced the friction coefficient.

After studying the tribological behavior of the nanocomposites, it should be considered to study the worn surface micrographs of these nanocomposites after the wear test to confirm the wear mechanism occurrence. Figure 8 compares the worn surfaces of the produced nanocomposites that compacted at temperature and pressure of 460 °C and 700 MPa. Worn surfaces after wear testing of pure Al6061 alloy, Al6061/1 wt. % MWCNTs, and Al6061/1.5 wt. % MWCNTs nanocomposites were examined by SEM images, as shown in Fig. 8a, b, and c, respectively. As shown in Fig. 8 a, the worn surface of the pure Al6061 alloy contains more wear and plowing marks.

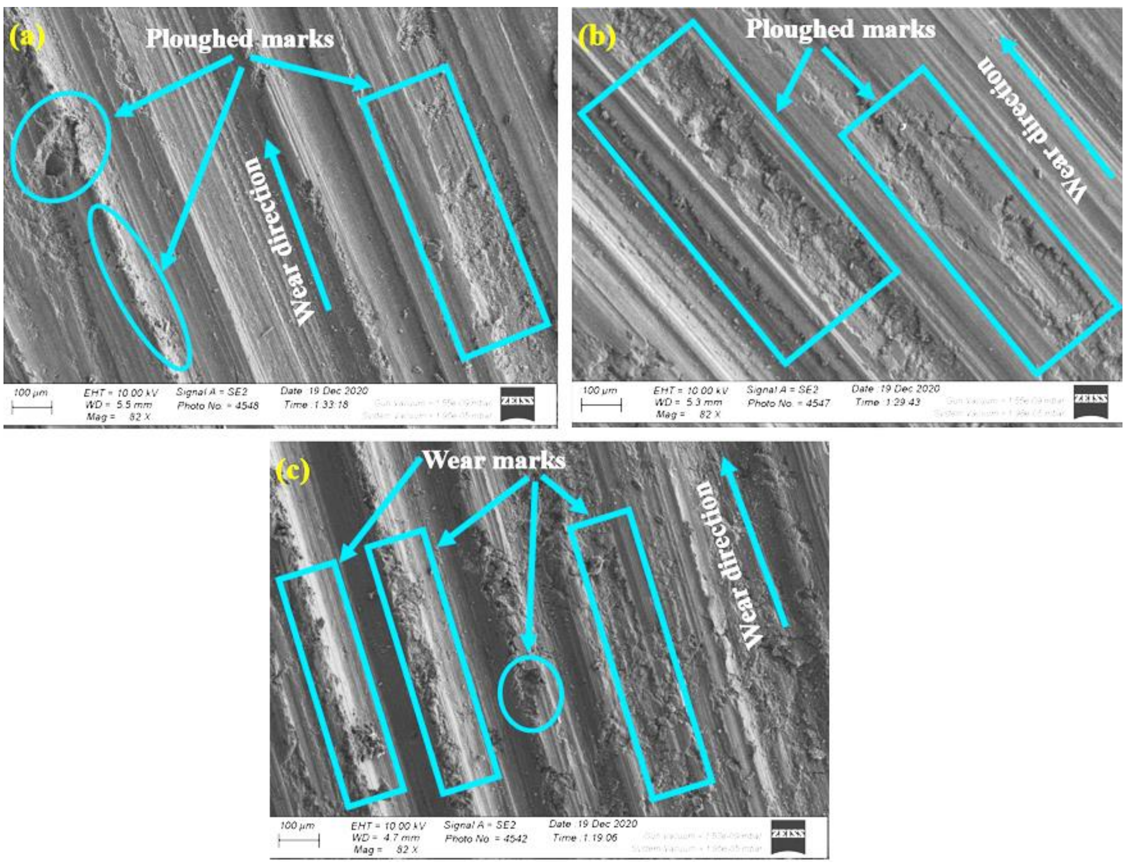

Fig. 8 SEM micrographs: (a) worn surface of pure Al6061 alloy, (b) worn surface of Al6061/1 wt. % MWCNTs, and (c) worn surface of Al6061/1.5 wt. % MWCNTs compacted at 460 °C and 700 MPa.

It may be due to the absence of MWCNTs into the Al6061 alloy, which acts as a reinforcing material, it leads to excessive wear of the Al6061 alloy surface. After adding 1 wt. % MWCNTs to Al6061 alloy, the worn surface shown contains wear marks less than that of pure Al6061 alloy, as shown in Fig. 8b. Therefore, the wear

rate and friction coefficient were the lowest at content of 1 wt. % MWCNTs compared to Al6061 alloy. A significant enhancement was observed in the worn surface of Al6061 alloy after adding content of 1.5 wt. % MWCNTs compared to Al6061/1 wt. % MWCNTs nanocomposites and unfilled Al6061 alloy, as shown in Fig. 8c. This confirms that the optimum results for the wear rate and friction coefficient were achieved at the nanocomposites, which compacted at a temperature of 460 °C, as mentioned and shown in the previous Figs 6 and 7, respectively.

Also, the surface mechanical strength plays an effective role in preventing the penetration of deep grooves into nanocomposites surface, thus improving the wear rate and friction coefficient of these nanocomposites. Moreover, the MWCNTs released during the transfer film formation also has an important effect in protecting the nanocomposites surface from excessive wear and thus increasing the friction coefficient. These results were consistent with Chang et al, [30].

CONCLUSIONS

This work is summarized in studying the mechanical and tribological behavior of Al6061/MWCNTs nanocomposites produced by a hot-compaction powder metallurgy technique. MWCNTs were added in different contents of 0, 0.5, 1, and 1.5 wt.%. All nanocomposites compacted at pressure of 700 MPa and temperature of 420, 460, and 500 °C. Also, the relative density, microstructure, and mechanical and tribological properties of the produced nanocomposites were examined. After manufacturing the present Al6061/MWCNTs nanocomposites and analyzing the mechanical and tribological tests results, the current study could be summarized in the following points:

1. **The relative density of Al6061/MWCNTs nanocomposites increased with increasing MWCNTs content up to 1.5 wt. % when the nanocomposites were compacted at a temperature of 500 °C and pressure of 750 MPa.**
2. **Microstructure of Al6061/1 wt. % MWCNTs nanocomposites compacted at 700 MPa showed the homogeneous distribution of MWCNTs within the Al6061 alloy.**
3. **VHN of Al6061/MWCNTs nanocomposites increased with increasing MWCNTs content up to 1.5 wt. % when the nanocomposites were compacted at a temperature of 460 °C and pressure of 750 MPa. While the VHN decreased at temperatures 420 and 500 °C when the MWCNTs content increased.**
4. **Ultimate compressive strength of the Al6061/1.5 wt. % MWCNTs nanocomposites that compacted at 460 ºC was observed to be higher compared to those compacted at temperatures of 420 and 500 °C.**
5. **The wear rate of Al6061 alloy improved by increasing the MWCNTs content up to 1.5 wt. % for the nanocomposites compacted at 460 °C and 700 MPa. The same observation was also achieved at 420 °C and 700 MPa.**
6. **The best friction coefficient of Al6061 alloy was achieved by increasing the MWCNTs content up to 1.5 wt. % for the nanocomposites compacted at 460 °C and 700 MPa.**
7. **After tribological tests, worn surfaces of the pure Al6061 alloy, Al6061/1 wt. % MWCNTs nanocomposites, and Al6061/1.5 wt. % MWCNTs nanocomposites compacted at 460 °C and 700 MPa were examined by SEM to study the occurred wear mechanism.**
8. **Worn surfaces of the pure Al6061 alloy contain more wear and plowed marks.**

9. After addition of 1 and 1.5 wt. % MWCNTs, the worn surfaces contain wear marks less than that of pure Al6061 alloy.
10. SEM images of the worn surfaces confirmed the wear rate and friction coefficient as well as the wear mechanism that occurred.

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