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Improvement of aluminum properties by adding tungsten carbide using powder metallurgy

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Powder metallurgy is a usable technique with multiple industrial applications. The first reinforcement material (Al_2O_3) was used at a constant rate 10wt.%, while the second reinforcement material (tungsten carbide (WC) was used at different rates (0,5,10,15,20wt.%), and the base material is (Al). The three powders were ground together for two hours, and then they were poured into the mold. The compaction process was done with a hydraulic press at (5) tons for one minute. The resulting samples had green density, requiring a thermal sintering process in order to increase their durability and hardness. The sintering process was performed at 560°C for only two hours. Then, structural examinations (scanning electron microscope (SEM) and mechanical examinations (Brinell hardness, compressive strength, and wear) were performed on the sintered samples. The results showed that the best reinforcement rate was 20%, and after thermal sintering, the best Brinell hardness was 146.72 HB, with the highest compressive strength of 45.33MPa, while the lowest wear rate was 1.18×10^{-8}g/cm.
Keywords: compressive strength, hardness, Material, Composite, Wear Rate.

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Introduction

Powder metallurgy is a technology used for the preparation of metals through which different parts are produced from metal powders [1]. Hence, powders are pressed to obtain the required shapes and then the resulting parts are heated at sintering process in order to bind particles and obtain a rigid mass [2,3]. The compaction process is performed at certain pressure levels using a compaction machine [4] with tools designed and manufactured for this purpose [5], namely mold and piston [6,7]. The subsequent sintering process is performed at a temperature below the melting point of the matrix [8,9]. This method is used either because it is difficult to produce these alloys by casting because their components are not mixed in liquid condition or because they are difficult to melt [10,11]. The great industrial development has forced researchers in materials technology to find alternatives to materials involved in important industries with impact strength [12,13], corrosion resistance [14], cost effective [15], and have other qualities that make them the basis for achieving the desired development [16,17]. Therefore, the importance of composite materials with distinctive properties has emerged [18,19]. Composites represent a mixture of two materials [20,21], namely matrix and reinforcement [22]. Matrix is called the continuous phase and reinforcement is called the reinforcement phase [23,24], while the area surrounding the matrix of the reinforcement material is called interphase [25]. Attention to and knowledge of the type of both matrix and reinforced materials, their specifications and their characteristics enable us to determine the type of material to be produced and the area in which they can be used. For example, in the field of space, composite materials are developed with low density that withstand high temperatures; while in the field of medicine [26,27], for the purpose of compensating for body parts, composite materials are manufactured with high specifications and techniques resistant to corrosion and fracture [28]. Composite materials are a mixture of two or more materials that are closely related to each other based on which the material acts as a single mass with intermediate properties of its components properties [29,30]. In other words, composite material consists of two phases, the first is the matrix phase and the second is the reinforcement phase. The phases used are either metal [31], ceramic or polymeric materials and the reinforcement phase is either particles, fibers, whiskers or laminates [32-34]. Aluminum matrix composites have been extensively studied since decades ago and are still evolving [35]. Due to their expanding uses and being involved in industry, they are currently used in sports equipment such as golf stick, electronics packaging, the manufacture of parts of motor vehicles, the manufacture of many parts of airplane engines and structures, and satellite structures and the electronic industries [36]. They are usually reinforced by alumina (Al_2O_3), silicon carbide (SiC), tungsten carbide (WC) or carbon (C) and a number of other carbides [37]. The current research aims to illustrate the extent to which tungsten carbide affects aluminum in terms of structural and mechanical properties, which enable us to select useful materials by manufacturing many different engineering materials.

I. Practical Part

1.1. Materials Used

Aluminum matrix (Al) with a granular size ≤ 53 µm and purity (99wt.%) of German origin from Riedel-de Haën Company was used. A constant rate of alumina (Al_2O_3) with a granular size ≤ 63 µm and purity 99wt.% of German origin from Fluka Company was used. In addition to tungsten carbide (WC) with a granular size 75 µm and purity 99.8wt.% manufactured by the Chinese Changsha Santech Materials Co.

1.2. Preparation Method

Powders were dried at a temperature of 200℃ for two hours to remove moisture and other volatile materials. The mixture weights of each component were then prepared by following the weight ratios so that the ratio of (Al_2O_3) was constant (10wt.%) for all mixtures, while the rates of (WC) were different (0, 5, 10, 15, 20wt.%). The weight was calculated using a Japanese-origin sensitive electric balance (Sartorius) with an accuracy of 0.0001 g and calibrated by the Central Agency for Standardization and Quality Control. After the grinding and mixing processes and obtaining a coherent powder, the samples were formed through uniaxial compaction in a solid steel mold with hardness (60HRC). The mixture was placed inside the compaction mold carefully and cautiously to prevent any movement of its parts. Then, 5 Ton pressure was applied for one minute to avoid the possibility of elastic strain. For this purpose, a Turkish-made hydraulic press (HALIM USTA) with a capacity of 20 Ton, calibrated by the Central Agency for Standardization and Quality Control was used to obtain cylindrical samples with a diameter of (10) mm and height (6) mm. After the compaction process, the samples were not well prepared for testing and had weak resistance, i.e., green resistance, requiring care when transporting and handling until performing the sintering process. Sintering was performed using a German-origin CARBOLITE oven at a temperature 560℃ for only two hours.

II. Practical Examinations and Measurements

2.1. Scanning Electron Microscope (SEM)

Scanning electron microscope (SEM) consists of an electron generator that produces the electrons required for the microscope to work, two converging lenses and an objective lens such as those found in the optical microscope used to obtain a clear and detailed image. The only difference is that these lenses are not glass, as they are designed from a magnetic material capable of changing the path of electrons and thereby controlling them [38]. All this is in a vacuum chamber to avoid the effect of air particles on electrons. On the other hand, there is the sample chamber, which is where the sample is placed to be examined and is isolated from vibrations, because the microscope is very sensitive to movement; therefore, it is often located in the ground floor of the laboratory [39]. Inside this chamber, there are two sensors; one reveals how electrons and samples interact, while the other sensor records the movement of secondary electrons emitted from the surface of the sample [40]. In addition, there are X-ray sensors that allow researchers to obtain information about the composition of elements called (Eds) that gives the microscope a 3D image of the sample with the smallest details. Dealing with this device is relatively easy and data and topography of the surface can be collected within a short time of no more than five minutes [41].

2.2. Brinell Hardness

Hardness is defined as metal resistance to indentation or surface abrasion. Hardness can be measured using several ways, including Brinell Hardness, Vickers Hardness, Rockwell Hardness, and Meyer Hardness… etc. [42]. In this study, Brinell hardness was adopted. Brinell hardness is used to measure the hardness of metals that contain relatively high porosity because it gives more space than that of the body whose hardness is to be measured compared to other methods. Brinell device consists of a cylinder with a cone to which a stainless steel ball (Brinell ball) in different diameters (1, 2, 5, 10 mm) is attached [43]. As a result of the effect of the standard load on the ball, it indents the body to be measured, leaving a semi-spherical indentation whose diameter (d_h) can be measured. By defining the diameter of ball used in the measurement (D) with the load applied (F), the hardness value can be obtained using the following equation [44]:

$$HB = \frac{2F}{\pi * D(D - \sqrt{D^2 + {d_b}^2}} \quad (1)$$

2.3. Compressive Strength Test

Compressive strength is the maximum load that the material can withstand before failure. It represents a crucial factor when manufacturing composite materials. Most studies and research have shown that failure to resist compression depends on the way the load is applied [45], as the height of the sample must be equal to its diameter at most when testing compressive strength according to the international specifications adopted. Therefore, the cylindrical composite materials are tested by applying continuous loads on the sample diameter until it fails. The value of compressive strength (σ) can be found using the following equation [46]:

$$\sigma = 2 * F/\pi \cdot h \cdot d_s \quad (2)$$

Where d_s is the sample diameter (mm), h is the sample height (mm), and F is the maximum load applied (N).

2.4. Wear Rate

Wear rate test was carried out using a Chinese-origin Pin-on-Disc device. A vertical load was applied through a pin through a holder attached and held the sample on a disc. Reading was recorded through an upper sensor attached vertically to the holder of sample and the reading then moved to a digital scale fixed at the front of the device, and the required loads were fixed at the top of the device as required. Wear rate was calculated using the weight method, which included calculating the amount of weight loss per sample by weighing the sample before attaching it to the device and after stopping the device (for 20 minutes) using a digital balance and the following equation [47,48]:

$$W = \frac{\Delta W}{\mathrm{SD}} \text{ (gm/cm)}. \quad (3)$$

Where W is wear rate (gm/cm), ΔW is the lost weight (gm) and represents the difference in weight of the sample before and after operation, and SD represents the slip distance (cm) and is equal to:

$$\mathrm{SD} = \pi \mathrm{D} \mathrm{n} \mathrm{t}. \quad (4)$$

Where D represents the disc diameter (cm), n represents the rotational speed of the disk (rpm), and t is the test time (min).

III. Results and Discussion

3.1. Analysis of SEM Results

Figure 1 shows the image of SEM and X-ray spectroscopy at different reinforcement rates of WC before sintering, while figure 2 shows this image after sintering at 560°C for two hours. The samples were examined at a depth of (1μm) for all images and forms with different reinforcement rates of WC. All forms reveal the homogeneity and distribution of WC grains within composites for different cases of increasing rates of the reinforcement material after sintering, explaining the increase in the values of hardness. Several previous studies reached the same effect of adding carbide and alumina separately (as reinforcement materials) to the matrix (aluminum) on hardness. In addition, images of the X-ray spectroscopy show the presence of aluminum, oxygen and carbide. The grinding process changed both the shape and volumes of particles. The two figures of all rates reveal a relative homogeneity between the components because of the susceptibility of the reinforcement material to homogenize with the aluminum matrix. Therefore, before sintering, there was a great heterogeneity with the presence of gaps, while after sintering there was a homogeneity and a great integration between compounds with approximately complete disappearance of gaps. This improvement will affect the structural and mechanical properties. Sintering at 650℃ and increasing the reinforcement rate has a clear effect of the distribution of WC with a clear disappearance of pores and lack of surface defects, i.e., recrystallization of reinforcement grains, as there was a significant homogeneity between grains. The WC particles were distributed into aluminum consistently and distinctively [49, 50].

3.2. The Effect of WC Rates on Composites Hardness before and after Sintering

The relationship between Brinell hardness of composites (Al-10wt.%Al_2O_3–wt.%WC) and the change in the reinforcement rates of WC is shown in figure 3. The increase in the WC content 0-20wt.% increased the values of hardness from (78.4 to 132.61) HB before sintering and from (88.72 to 146.78) HB after sintering. This increase can be attributed to several reasons including WC has a high hardness, thus its grains act as barriers to the deformation of matrix due to its high hardness, which will therefore further obstruct the movement of dislocation when increasing its content in composites. In this case, the stress should be significant in order for the dislocation to pass through the grains, requiring an increase in the values of the load applied, which indicates the increase in the hardness values. Lack of porosity also explains the increase in hardness values. Several previous studies found the same effect in an aluminum-based matrix [51]. The high values of hardness can also be due to the formation of high hardness phases after sintering process resulting from the interaction between the reinforcement material and the matrix as shown in the X-ray. Such phases include (WO_3) phases, which has high hardness reaching 7.5 Mohs according to (Mohs) scale [52] with the presence of the alumina phase, which also has high hardness. This result is consistent with that found in [53,54] for aluminum-based matrix.

3.3. The Effect of WC Rates on Compressive Strength of Composites before and after Sintering

Compressive strength values increased from 15.46 MPa to 31.01 MPa) before sintering and from 22.35 MPa to 45.33 MPa after sintering with the increase in the WC content from 0 wt.% to 20 wt.%, as shown in figure 4. This increase can be attributed to several reasons, primarily the decrease in porosity by increasing the WC content, as porosity is the core of weakness and failure of composites through weakening the bonding between grains. While the second reason is the increase in composite hardness by increasing the WC content, as well as compressive strength of WC. In addition, the phases

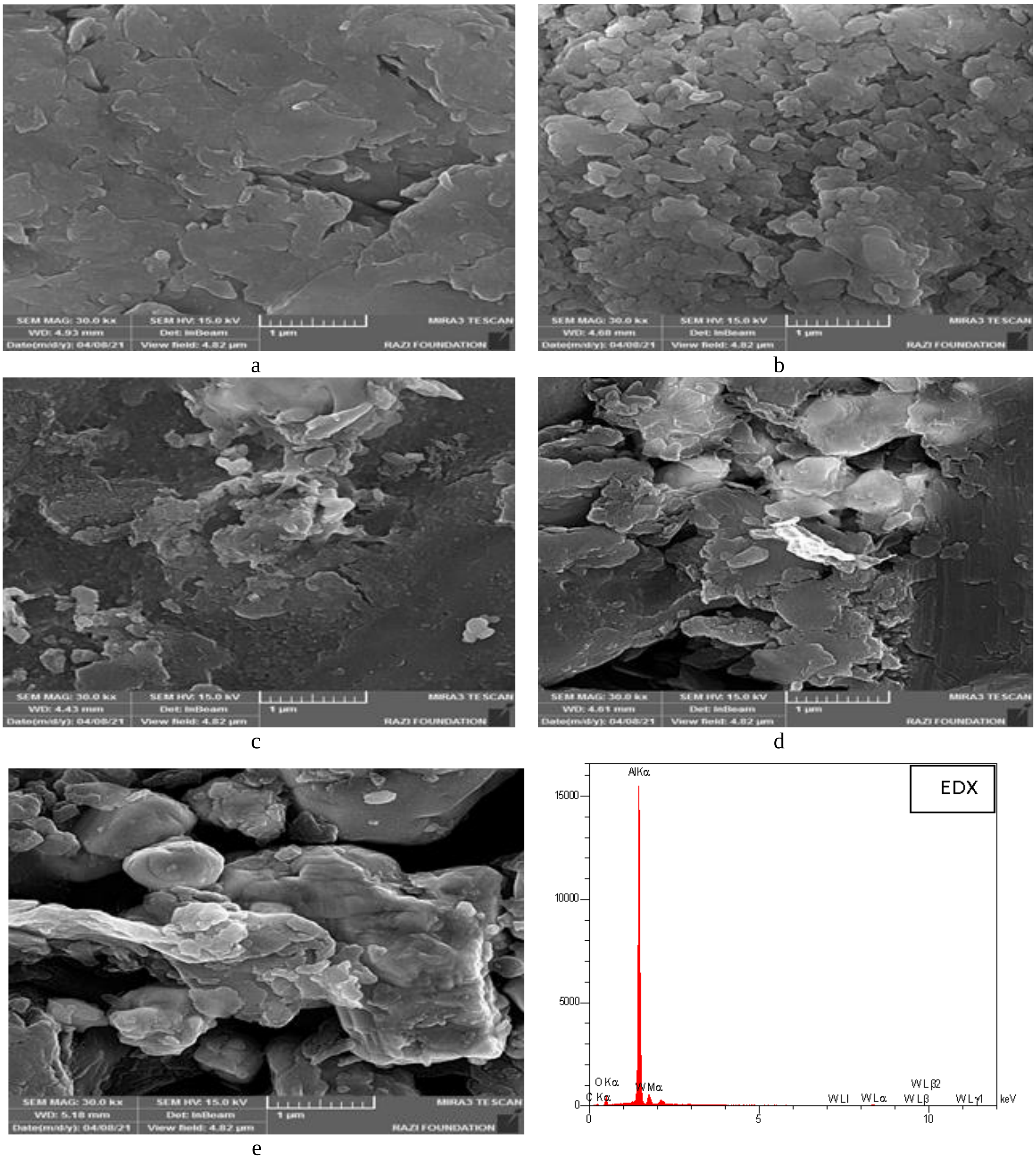

Fig. 1. Images of SEM and X-ray spectroscopy of the (Al-Al_2O_3-WC) system at different reinforcement rates of WC before sintering.

formed after sintering played an important role in increasing the bonding power between the grains of composite components. All of these reasons contributed to increasing compressive strength values of composites. This result is consistent with that found in for aluminum-based matrix composites [55].

3.4. The Effect of WC Rates on Wear Rate of Composites before and after Sintering

Figure 5 presents the relationship between wear rate and the WC content before and after sintering. It is observed that wear rate decreased from 4.57×10^{-8} g/cm to 2.75×10^{-8} g/cm before sintering and from 3.37×10^{-8} g/cm to 1.18×10^{-8} g/cm after sintering at (0-20) wt.% of WC content. Wear rate of non-sintered samples was higher than the that of the reinforced and thermally sintered samples. Wear occurred due to the deformation between the sample surface and the disc, which led to the increase in density of cracks and defects. The value of the load applied had a direct effect on the plastic deformation that occurred at the peaks of projections and the area near the surface. Therefore, the holes and grooves increase as a result of the effect of particles resulting from the fracture of the surface coating. Small cracks combine, resulting in the removal of surface layers, creating wear in the form of thin laminates. The reason for low wear rate is that aluminum-based composites are harder when reinforced by ceramic particles, which in turn obstruct the progress of dislocations, as weight loss is low as a result of reinforcing

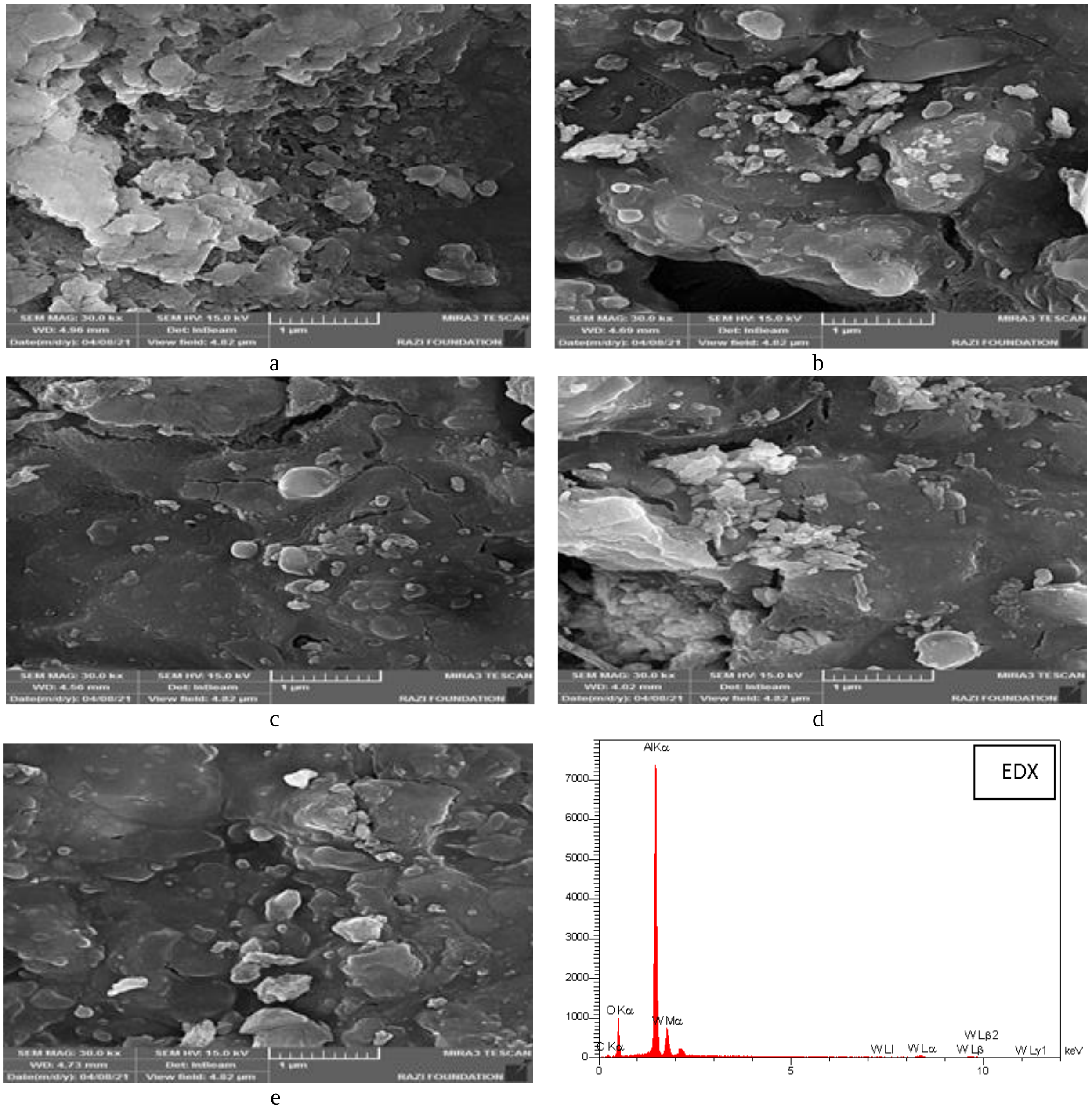

Fig. 2. Images of SEM and X-ray spectroscopy of the ($Al-Al_2O_3-WC$) system at different reinforcement rates of WC after sintering.

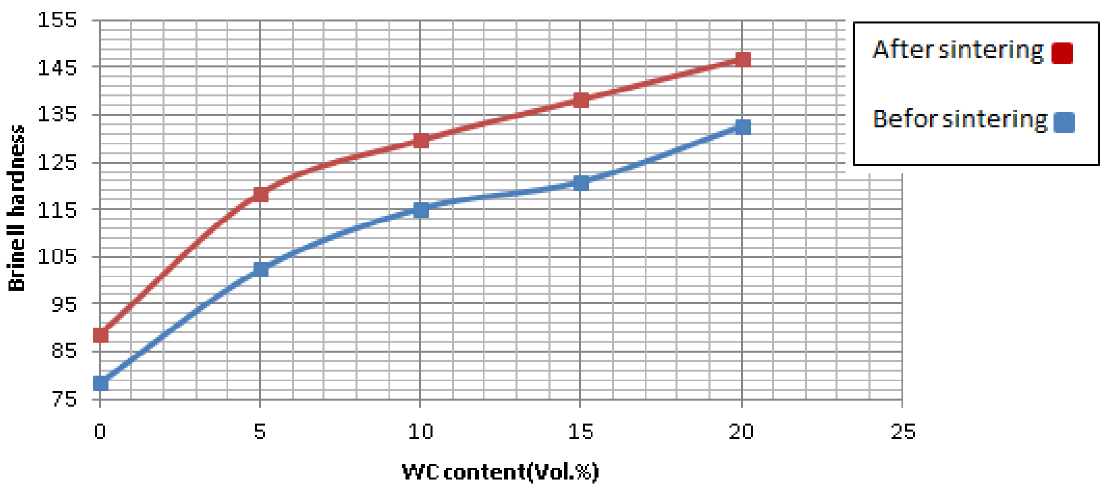

Fig. 3. The effect of different WC rates on hardness before and after sintering.

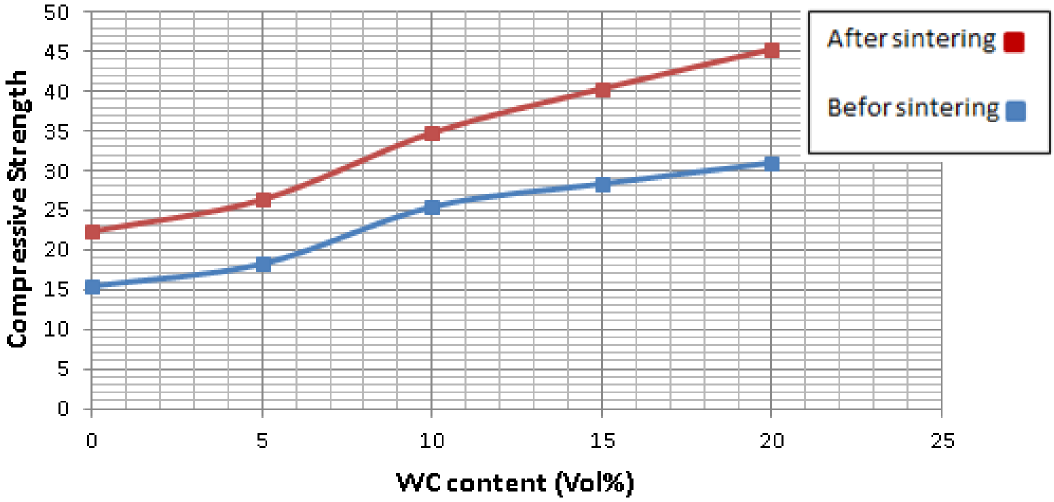

Fig. 4. The effect of different WC rates on compressive strength before and after sintering.

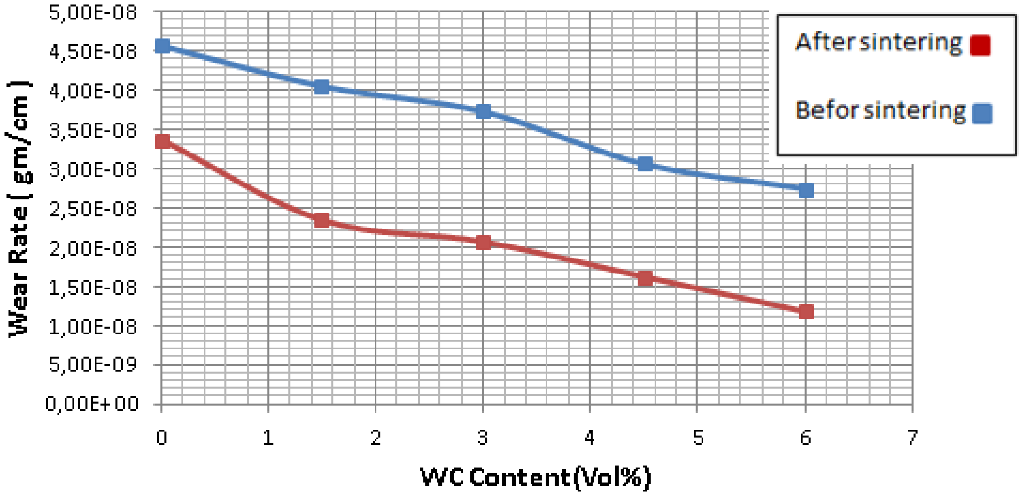

Fig. 5. The effect of different WC rates on wear rate before and after sintering.

the matrix with these particles. In addition, the difference in the coefficient of thermal expansion increases hardness by increasing the content of reinforcement materials. Hard particles, such as WC and Al_2O_3 resist the stresses generated and thus generate a dislocation density. Because of the high hardness of reinforcement particles, these particles will be inserted into the disk of wear test device, leading to abrasion [56]. As a result, the surface of compacted sample will need large friction forces to slip on the surface of the disc of wear test. Therefore, most of the energy will be consumed on friction between reinforcement particles and the disc of the test device when the reinforcement content increases [57]. Consequently, the metal matrix will move away from the test disc and wear rate will decrease. By adding reinforcement particles that cause an increase in hardness, wear rate decreases, as it is inversely proportional to hardness. This result is consistent with that found by K.Yildizli and colleagues, who concluded that wear rate decreases with the increase in volumetric fraction of reinforcement particles [58].

Conclusion

The important conclusion of the current research is the possibility of homogenizing the three compounds in aluminum matrix using compaction method. Moreover, the addition of tungsten carbide has improved some mechanical and structural properties of the system, as the best reinforcement rate of WC is 20% at thermal sintering of 560°C for only two hours. This rate results in almost distinctive properties in terms of hardness, compressive strength and wear.

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Покращення властивостей алюмінію шляхом додавання карбіду вольфраму методом порошкової металургії

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Порошкова металургія має значну кількість промислових застосувань. Перший армуючий матеріал (Al_2O_3) використовувавли з постійним вмістом 10 мас.%, тоді як другий армуючий матеріал (карбід вольфраму (WC) використовували з різними вмістами (0, 5, 10, 15, 20 мас.%) та базовим матеріалом (Al). Три порошки подрібнювали разом протягом двох годин, а потім їх виливали у форму. Процес ущільнення проводили за допомогою гідравлічного пресу при 5 тонн навантаження протягом однієї хвилини. Отримані зразки мали зелений колір, достатню щільність, яку вимагає процес термічного спікання, щоб підвищити їх довговічність і твердість. Для досягнення цього використовувалася піч англійського виробництва. Процес спікання проводили при 560°C протягом двох годин. Потім проводили структурні дослідження (скануючий електронний мікроскоп - SEM) та механічні дослідження (твердість за Брінеллем, міцність на стиск і зношування) на спечених зразках. Результати показали, що найкращий коефіцієнт зміцнення становив 20%, а після термічного спікання найкраща твердість за Брінеллем становила 146,72 HB із найвищою міцністю на стиск 45,33 МПа, тоді як найменша швидкість зносу становила $1{,}18 \times 10^{-8}$ г/см.

Ключові слова: міцність на стиск, твердість, матеріал, композит, швидкість зношування.