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Research Article

A Study on the Effect of Coke Particle Size and Applied Compacting Pressure on the Physical Properties of Electrographite Brushes

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ABSTRACT

In this study, electrographite brushes were produced from petroleum coke and coal tar pitch via the powder metallurgy method, and the effect of petroleum coke particle size and applied compacting pressure were investigated on the green density, hardness and, the graphitization process. The results showed that an increase in the density of the raw sample and the hardness of the final product occurred due to a decrease in particle size by increasing the milling time up to 4 h. Additionally, an increase in both density and hardness of the sample was observed as the applied compacting pressure was increased up to 150 MPa, where no alteration in the obtained values was observed with a further increase in the applied pressure. As a result of increasing the milling time and applying the optimum pressure, the density of the raw sample increased to 1.41 g/cm³ and the hardness increased to 81 Shore C. The results also proved that the average particle size of the used petroleum coke and the applied compacting pressure do not have an influence on the graphitization process.

1. Introduction

An electrographite brush is a type of electrical contact that is used in electrical machines, such as motors and generators to transfer electrical current between rotating and stationary parts [1]. The brush is made of a block of electrographite [2], which is a highly conductive and durable form of graphite [2, 3]. Electrographite brushes (Fig. 1) are commonly used in high-performance electrical machines because of their excellent electrical conductivity, thermal stability, and resistance to wear and tear [4]. They are able to operate at high speeds and temperatures without degrading or losing their electrical properties [5]. Electrographite brushes are typically used in applications where high current densities and high speeds are required, such as in electric vehicles, industrial motors, and wind turbines. They are also used in aerospace applications, such as satellite positioning systems and radar equipment [6].

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Fig. 1. An image of electrographite, which is commonly used in industry [6].

The hardness and density of electrographite brushes are important properties that determine their performance and suitability for use in high-performance electrical machines [7]. The hardness of electrographite brushes is typically in the range of 40 to 80 on the Shore C scale, which indicates a high level of resistance to wear and deformation [6, 7]. This high hardness is due to the unique microstructure of electrographite, which is characterized by highly oriented crystalline grains that are densely packed together [8]. The density of electrographite brushes can vary depending on the specific grade and manufacturing process used, but in general, it ranges from 1.6 to 1.8 g/cm³ [9]. Also, the density of electrographite parts in their raw state is typically between 1.2 and 1.5 g/cm³ prior to the baking process [10]. This high density gives electrographite brushes their exceptional strength and durability, as well as their excellent electrical conductivity and thermal stability [11].

The density of electrographite is considered as a critical factor in its development and use in electrical applications. Higher density electrographite is generally more durable, which has better wear resistance and exhibits better electrical conductivity [2, 4, 12]. Over the years, there have been several developments and innovations that have led to an increase in the density of electrographite [13]. One key development was the use of higher quality raw materials, such as petroleum coke and coal tar pitch in the production of electrographite [14, 15]. These materials have a higher carbon content and fewer impurities, leading to a purer and denser final product [12]. The development of new processing techniques, such as high-temperature graphitization, has also contributed to the increased density of electrographite. Another innovation that has led to increased density is the use of additives during the production process. For example, the addition of high-temperature binders or fillers can help to increase the density of the final product. The use of pressure during the production process as in the hot-pressing technique, can also help to increase the density of electrographite [16]. In recent years, advancements in nanotechnology have also led to new approaches to increase the density of electrographite. For example, the addition of graphene or other carbon nanomaterials to the production process can help to increase the density of electrographite while maintaining its electrical conductivity [17]. Overall, increasing the density of electrographite has been driven by a combination of advancements in raw materials, processing techniques, and the use of additives and nanomaterials. These developments have enabled the production of electrographite with increasingly higher densities, leading to improved performance and durability in a wide range of electrical applications [18].

In addition to density, the hardness of electrographite has been a critical factor in its development and use in a variety of applications, including electrical contacts, brushes, and current collectors [1]. The hardness of electrographite is influenced by several factors, including the quality of raw materials, processing techniques, and the use of additives [19]. In the early days of electrographite production, the hardness of the material was limited by the quality of the raw materials used, as well as the processing techniques available [4]. Early electrographite was relatively soft and had a lower density in comparison to modern electrographite. During the time, advancements in raw materials and processing techniques led to an increase in the hardness of electrographite. For example, the use of higher-quality raw materials, such as petroleum coke and coal tar pitch led to a more consistent and purer final product with higher hardness [6, 20]. The development of new processing techniques, such as high-temperature graphitization and hot pressing, also contributed to increased hardness [21]. In addition to improvements in

raw materials and processing techniques, the use of additives has also played a role in increasing the hardness of electrographite. For example, the addition of silicon carbide or other hard particles during the production process can help to increase the hardness and wear resistance of electrographite [19].

The combination of high hardness and density makes electrographite brushes well-suited for use in high-performance electrical machines that require high speeds, high current densities, and resistance to wear and deformation [18]. These properties also make electrographite brushes ideal for use in harsh operating environments, such as those found in aerospace, industrial, and automotive applications [12]. The particle size of electrographite can have a significant impact on its properties and performance. Smaller particles can also lead to a smoother surface finish, which can reduce friction and improve electrical conductivity [5, 20]. However, increasing the particle size can also have benefits. Larger particle sizes can increase the porosity of the material, which can improve its ability to absorb and release lubricants or other fluids. This can be beneficial for applications that require good lubrication or that operate in high-temperature environments, where fluids can evaporate quickly [15]. In some cases, the particle size of electrographite may also affect its electrical conductivity. Smaller particles may have a higher surface area, which can lead to more contact points between particles and better electrical conductivity. However, in some cases, larger particles may be more conductive due to a more open structure that allows for better electron transport [19, 22].

Totally, the effect of particle size on electrographite will depend on the specific application and the desired properties of the material. Engineers and designers must carefully consider the particle size and other material properties when selecting electrographite for a particular application [23].

It is important to note that the optimal approach for improving the density and hardness of electrographite will depend on the specific application requirements. Therefore, it is critical to carefully consider the physical and mechanical properties required for a given application and to work with experts in the field to choose the most appropriate materials and processing techniques [24].

There is a lack of research on the production process parameters of electrographites, leading to limited information on how to obtain even better properties for this material. In the present work, electrographite samples are produced through powder metallurgy route and efforts have been made to investigate the effects of various process parameters, such as coke particle size and applied compacting pressure, on the green density and hardness of the fabricated electrographite are investigated.

2. Experimental

2.1. Materials and methods

In this study, the powder metallurgy technique was employed to fabricate an electrographite brush, which is a commonly used component in electrical machinery. By using this technique, a more uniform and consistent product with enhanced mechanical properties, such as improved hardness and wear resistance, was aimed to be produced. The use of petroleum coke powder and coal tar pitch as raw materials for producing electrographite was investigated. These materials were selected for their high carbon content and low impurities, which are important factors in producing high-quality electrographite. Commercially available pet coke powder was used as the raw material for the study, with an average particle size of 0.75 mm with an irregular shape. The chemical composition is presented in Table 1, while the morphology of the pet coke powder is illustrated in Fig. 2. In addition, the density of the powder is measured and found to be 1100 kg/m^3. These details are important for understanding the properties and behavior of the pet coke powder during the production of electrographite.

Table 1. Chemical composition of the pet coke powder

C	Humidity	Sulfur	Ash	Volatile substances
95%	1%	2%	1%	1%

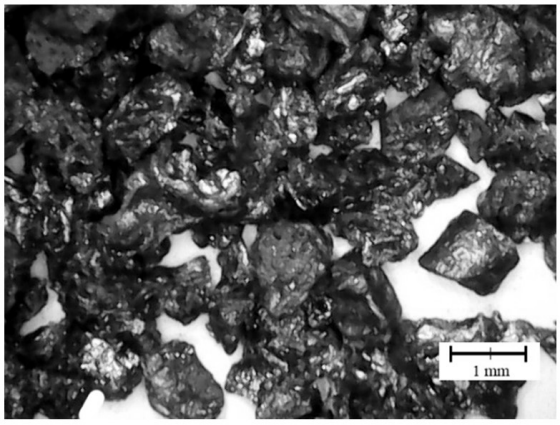

Fig. 2. Optical microscope (OM) image of the used commercial pet coke powder.

Fig. 3 summarizes the fabrication stages of the electrographite brushes used in the present research study. The construction stages involved: grinding, sieving, mixing, shaping, baking, and graphitization, followed by terminal processes such as polishing.

The first step of the process involves grinding coke powder using an attrition mill and varying the grinding time in the range of 1 to 4 h to produce coke powders with different average particle sizes. The next step involves mixing the ground coke powder with coal tar pitch at a temperature that softens the pitch, typically around 150-200°C, to ensure a homogeneous mixture. At this temperature, the coke powder is fully incorporated into the coal tar pitch. The mixture is then stirred to further promote mixing and ensure uniform distribution of the coke powder throughout the coal tar pitch.

The green specimens were formed using a uniaxial hot-pressing technique, where different pressures in the range of 50-250 MPa were applied to the powder mixture. The die setup shown in Fig. 4 was used to carry out the hot-pressing compaction process at a temperature around 250°C for 2 min. Using this setup, it was possible to apply the desired pressure, as well as controlling the temperature and heating rate during the process.

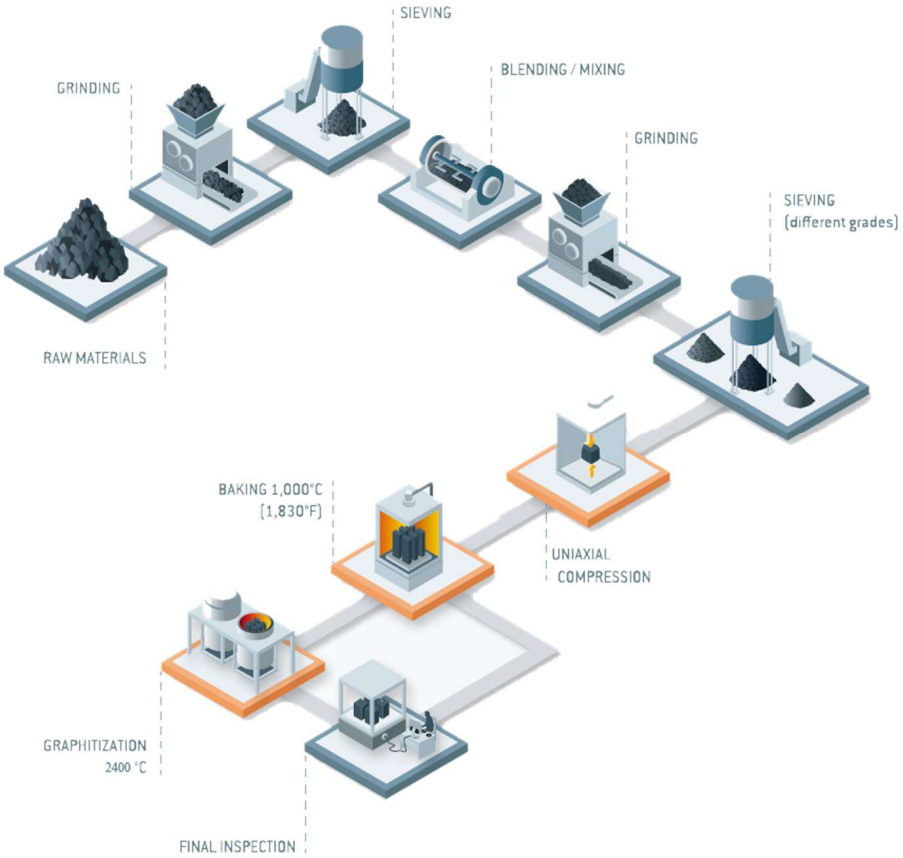

Fig. 3. Schematic of the fabrication stages of the electrographite brushes [6].

Fig. 4. Hot-pressing and die setup.

The characteristics of green samples manufactured by applying different ranges of pressure and using coke powders that were attrition milled for varying durations between 1 to 4 h resulting in different particle sizes are presented in Table 2.

In order to prepare the electrographite, the green compact was first baked at a temperature of 1000°C to remove any remaining volatile components and ensure that the sample was fully carbonized, which is essential for the subsequent graphitization process. The baking process was typically carried out for several hours (~5 h) in a controlled atmosphere to prevent oxidation and at an extremely slow heating rate (~30 °C/h) to prevent cracking and ensure uniform heating.

Table 1. Characterization of samples produced with varying applied pressure and particle size

Sample	Attrition time (h)	Applied pressure (MPa)	Mass (g)	Thickness (mm)	Diameter (mm)
EG-1	1	50	2.9672	7.26	19.85
EG-2	1	100	2.9658	7.25	19.92
EG-3	1	150	2.9588	7.3	19.93
EG-4	1	200	2.9693	7.33	19.92
EG-5	1	250	2.9587	7.5	19.9
EG-6	2	50	2.962	7.28	19.85
EG-7	2	100	2.9647	7.21	19.92
EG-8	2	150	2.9631	7.22	19.93
EG-9	2	200	2.9751	7.24	19.92
EG-10	2	250	2.9537	7.39	19.93
EG-11	3	50	2.9713	7.1	19.85
EG-12	3	100	2.9608	7.17	19.88
EG-13	3	150	2.9536	7.1	19.87
EG-14	3	200	2.9745	7.1	19.89
EG-15	3	250	2.9543	6.99	19.89
EG-16	4	50	2.9579	6.9	19.84
EG-17	4	100	2.9624	6.88	19.87
EG-18	4	150	2.9466	6.91	19.86
EG-19	4	200	2.9751	6.88	19.85
EG-20	4	250	2.9537	7.26	19.85

Once the baking process was completed, the graphitization process was performed to convert the amorphous carbon into crystalline graphite. The graphitization process typically involves heating the sample to a high temperature, usually around 2400-3000°C. The resulting graphite has a highly ordered crystal structure and exhibits desirable properties such as high electrical conductivity and thermal stability. In the present work, graphitization process was carried out at 2400°C for 2 h.

2.2. Characterization

X-ray diffraction method (Panalytical X'Pert Pro) was used to evaluate graphitization process and optical and scanning electron microscope were used for determining shape and estimating size of the coke particles in the as-received and attrition milled conditions. The primary pet coke powder's particle size was initially checked using an optical microscope. After grinding the primary coke powders, the obtained particle size was evaluated by using a Tescan Vega3 scanning electron microscope (SEM). To determine the density of the fabricated electrographites, standard techniques specified by IEC 60413 standard and a Sartorius machine were used [25]. The weight and volume of each sample were measured using the Archimedes principle, which involved submerging the sample in water and measuring the displacement of the water. To evaluate the hardness of the electrographites, a test using the Santam SHB-512 machine was performed, which is designed to measure the indentation hardness of materials. The hardness test was conducted in accordance with IEC 60413 standard, which specifies the testing conditions and procedures for determining the indentation hardness of electrical insulating materials [25]. The weight of 2.2 kg was used in the Shore hardness test, and the force was applied for a duration of 6 s. To evaluate the impact of different production conditions on the properties of electrographite, three samples with the highest density and hardness were selected and subjected to X-ray testing.

3. Results and Discussion

As it has been mentioned, the effect of milling time on the average size of the coke particles is determined by using a scanning electron microscope. As depicted in Fig. 5, an inverse relationship was observed between attrition milling time and particle size, where longer milling times resulted in smaller particle sizes.

The characteristics of green samples were fabricated by applying different applied pressure and by using coke powders with different particles sizes produced by attrition milled in different times in the range of 1 to 4 h is provided in Table 2.

Based on the information provided in Table 2 and the shape of the samples shown in Fig. 6, variations in height and diameter that were attributed to differences in the fabrication process parameters such as variations in particle size and pressure is clear. These variations in sample size and shape were likely due to differences in the manufacturing conditions and lead to different green densities.

Density changes of the green samples, as a result of increasing milling time at constant pressures, are depicted in Fig. 7(a). As it can be seen, minimal changes in density are observed with increasing milling time up to 3 h, at low applied pressures of 50 and 100 MPa. However, a significant increase in density is observed for the 4-hour milled coke powder due to significant reduction in particle size. At high pressures (150, 200, 250 MPa), increasing the milling time up to 2 h resulted in an initial increase in density, followed by little change upon further milling up to 3 h. This indicates that a suitable particle size distribution was achieved by milling up to 2 h, while milling beyond 3 h resulted in smaller particles, but did not improve the particle size distribution, does not lead to a substantial increase in

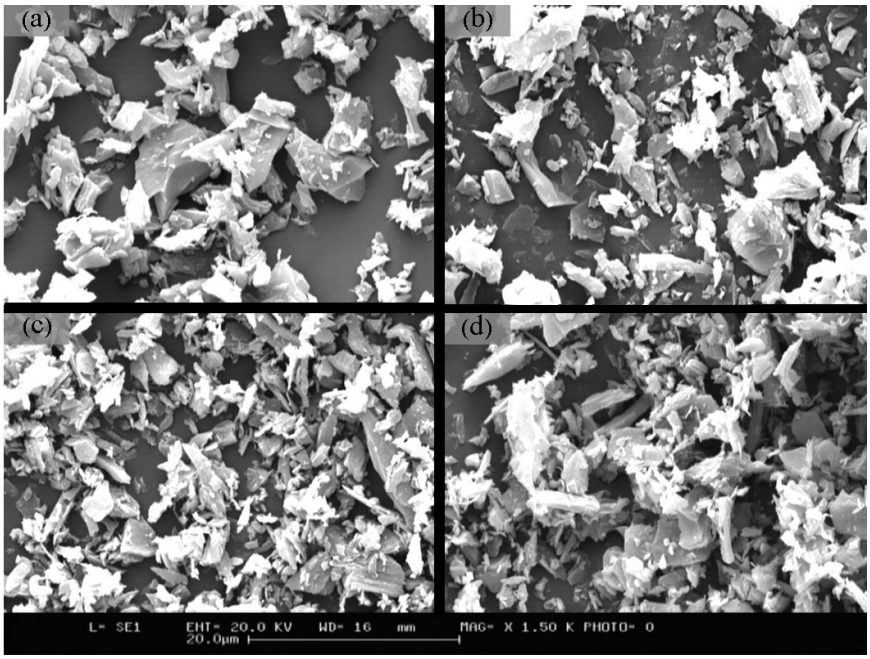

Fig. 5. SEM images of pet coke particles after being ball-milled for: (a) 1 h, (b) 2 h, (c) 3 h, and (d) 4 h.

Fig. 6. Samples produced with varying particle size and applied pressure.

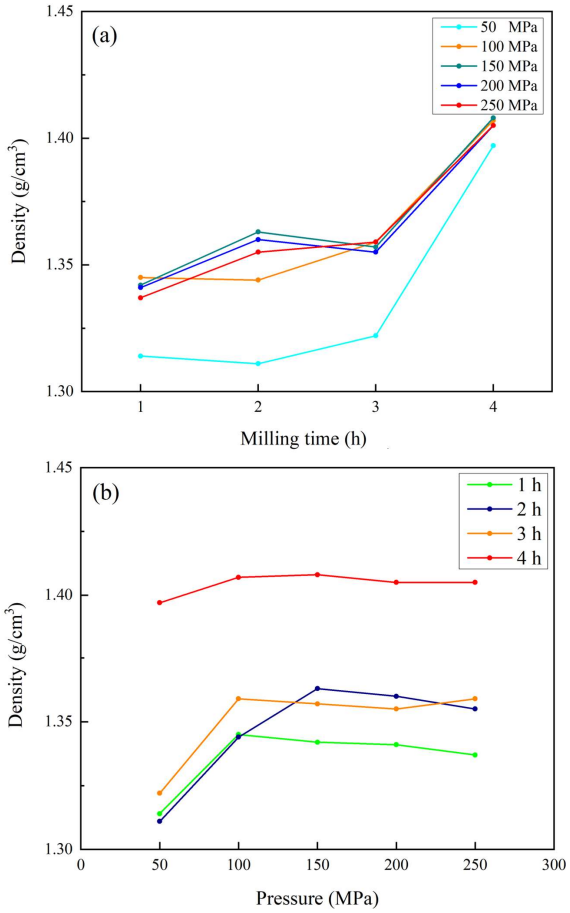

Fig. 7. Changes in density (a) as a function of milling time for green samples, (b) as a function of pressure for green samples.

density. At both high and low pressures, a significant increase in density was observed upon increasing the milling time up to 4 h. The lack of significant increase in density during milling at 2 and 3 h under low pressures may be explained by the fact that increasing the milling time results in finer particles and higher friction between them. This requires higher pressure to achieve a further increase in density. In any case, Fig. 7(a) indicates that higher densities can be attained by increasing the milling time up to 4 h. This is likely due to the finer particle size and improved particle distribution achieved through longer milling times.

Fig. 7(b) shows the changes in density as a function of applied pressure, where it can be observed that increasing the applied pressure also affects the density of the samples. A clear visual representation of the relationship between pressure and density demonstrates how the density of the samples are affected by changes in pressure. It can be observed from Fig. 7(b) that an increase in pressure resulted in a corresponding increase in density for all samples including coke powders with different average particle size and size distribution, reaching a maximum density by applying a pressure around 100-150 MPa. Beyond this pressure range, the effect of further increase in pressure on the density is minimal. It is interesting to note that the same trend in density changes by pressure was observed for all the samples regardless of the size of the coke powder used.

Regarding the experimental results presented in Figs. 7(a) and 7(b), it can be concluded that the dominant factor affecting the density of the samples is mainly the size and size distribution of the coke powder used, while the applied pressure plays a secondary role.

For hardness evaluation, two sets of samples were selected; one produced by using coke powders milled in the time range of 1 to 4 h and by applying constant pressure of 100 MPa, and another produced from coke powder ground for 4 h and by applying different pressures in the range of 50 to 250 MPa. The same baking and graphitization processes were performed on each set of samples to prepare them for hardness testing. The samples were then subjected to the Shore C method of hardness measurement, which involves the application of a known load to the surface of the sample, followed by the measurement of the resulting indentation depth. This method is commonly used to evaluate the hardness of materials, particularly those with high strength and low ductility. The results of the hardness testing provide valuable information about the mechanical properties of the samples, such as their resistance to wear. These findings can be used to optimize the production process and improve the performance of the samples in various applications.

As it can be seen in Fig. 8(a), increasing the green shaping pressure generally leads to an increase in hardness, where the greatest increase observed between 50 and 100 MPa. However, beyond 100 MPa, the rate of

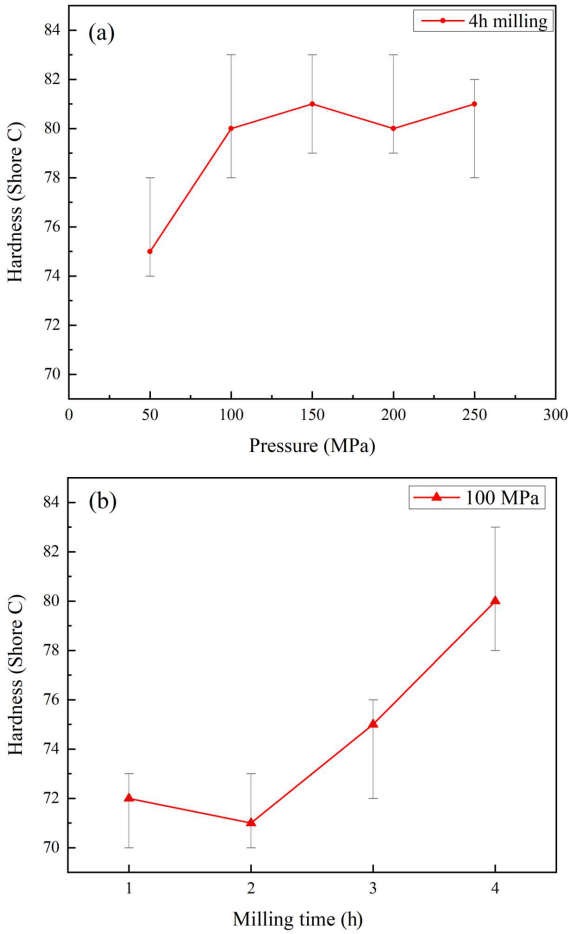

Fig. 8. The relationship between (a) hardness and pressure for samples produced from particles that were milled for 4 h. (b) hardness and milling time for samples produced at a pressure of 100 MPa.

the increase in hardness begins to slow down, with little change observed beyond 150 MPa. These trends suggest that there is an optimal pressure range for achieving maximum hardness for these samples, and that exceeding this range may not result in further improvements in hardness.

Additional insights into the relationship between hardness and milling time for the sample produced by applying a constant pressure of 100 MPa are provided by Fig. 8(b). The hardness of the sample is shown to change as a function of increasing milling hours. It is generally observed that longer milling times result in higher hardness values, with the greatest increase being observed for the samples includes coke powders prepared by milling for 3 and 4 h.

Regarding the data presented in Figs. 8(a) and 8(b), it can be concluded that by controlling the milling time and applied compacting pressure, it may be possible to achieve a desired level of hardness, which can be tailored to specific applications.

Graphitization is a process which involves the conversion of carbon materials into graphite, and it is influenced by various factors, including temperature, pressure, and particle size. By evaluating the effect of particle size and applied compacting pressure on the degree of graphitization, the study can provide insights into how these parameters can be adjusted to optimize the properties of the final product for specific applications. Moreover, the investigation of the effect of particle size and applied compacting pressure on graphitization can contribute to a better understanding of the fundamental mechanisms underlying the synthesis and properties of graphitic materials. The results for the X-ray characterization of the fired samples produced by using coke powders with different average particle sizes and different applied compacting pressure are presented in Fig. 9. Regarding this figure it can be concluded that, altering the applied compacting pressure and particle size does not appear to have a significant effect on the graphitization process. This implies that other factors, such as temperature or the presence of certain catalysts may have a greater impact on this process. This result is in line with the result reported by other researchers [26].

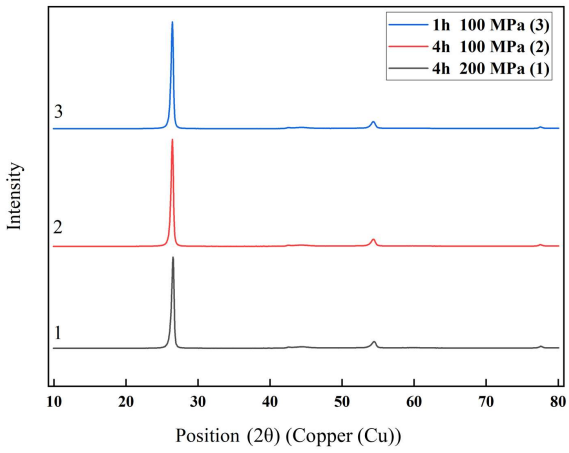

Fig. 9. X-ray diffraction patterns of samples produced in different conditions.

4. Conclusion

This study aimed to investigate the effects of varying levels of applied compacting pressure and coke powder particle sizes on the production of electrographite using the powder metallurgy route. The results of this study showed that the applied pressure and coke powder particle size had a significant impact on the final product's hardness and the green body density. The findings suggest that optimizing the applied pressure and selecting the appropriate coke powder particle size are critical factors in the production of electrographite via powder metallurgy. Specifically, an increase in the applied pressure and the use of smaller coke powder particle sizes led to a significant increase in the hardness of the final product. Additionally, the green body density is observed to increase as the applied pressure increased and the coke powder particle size decreased. The results demonstrated that increasing the milling time up to 4 h improved the particle size distribution and homogeneity of the powder mixture, leading to a more uniform green body and denser final product. Moreover, the study found that increasing the applied pressure up to 150 MPa, in combination with the optimal milling time, resulted in a significant increase in the density and hardness of the final product. However, further increases in applied pressure beyond this point did not lead to any significant improvement in the properties of the final product. The study suggests that controlling the milling time and applied pressure within certain ranges can lead to the fabrication of electrographite with desirable properties. The results also proved that selected electrographite production parameters (coke particle size and applied compacting pressure) do not have significant effect on graphitization process and all the samples completely graphitized by a heat treatment at 2400°C for 2 h.

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Conflict of Interests

The authors declare no conflict of interest.

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