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ORIGINAL STUDY

Effect of Adding Nano Carbon on Density, Porosity, and Water Absorption of Nickel by Powder Metallurgy

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Abstract

Powder metallurgy is used to obtain high strength and good toughness pistons as an application in aviation, space, and parts. Carbon nanotube CNTs were used with reinforcement ratios of (0,5,10,15,20) wt. % to nickel base, and the device used for piston is a hydraulic piston. The process was carried out at 5 tons for 3 min, and the pistons were processed at variable temperatures of (900,950,1000,1050 °C) for 2 h. XRD of the composites was examined and it was found that the dominant phase of nickel at Miller parameters (111), and of carbon nanotube at (002) with crystalline stability with different sintering temperatures. As for the physical properties, the optimal reinforcement content was found to be 20 wt. % at a sintering temperature of 1050 °C, as it yielded the highest density and lowest porosity, Archimedes' method was used to calculate porosity and density. Which included the apparent density at (8.6 g/cm^3), the true density (8.75 g/cm^3), the apparent porosity (10.5 %), the true porosity (15.5 %), and the water absorption (0.972 %). This shows that the percentage of adding nano-carbon has a role in improving the structural and physical properties.

Keywords: Apparent density, Sintering, True porosity, XRD

1. Introduction

Powder technology is one of the leading technologies in materials science due to its ease of manufacturing and complex shapes of parts and others. This method became famous at the beginning of the new century due to the need for it compared to the simple methods known from casting, because the casting method produces samples that require subsequent processes of cutting, machining and polishing to reach the required samples. Also, complex shapes cannot be produced as is the case in powder metallurgy [1]. The powder method has been able to combine materials with different specifications in terms of strength, flexibility, hardness and density [2]. For example, this technology can be used to combine metals as base materials and ceramics as reinforcement materials or vice versa. The technology has developed to include the processes of producing nanopowders in the laboratory and then pressing them in this way, which gives lower costs and higher durability to the final products [3]. Many metal alloys suffer from poor physical and mechanical properties in terms of hardness and high flexibility, so they must be reinforced with ceramic or carbide materials, and even materials mixed with both ceramic and carbide powders, whether micro or nano in size [4].

Powder metallurgy is used to benefit from several things, the most important of which is the possibility of pressing different materials, not losing materials significantly compared to the casting method, obtaining complex shapes, and getting rid of potential impurities during pressing [5]. The need for powder metallurgy lies in its industrial application in a large number of devices and equipment, including the manufacture of aircraft bodies, internal combustion engines, the manufacture of car bodies, a number of medical and industrial parts, military missile launch bases and other various

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manufacturing processes [6]. All of the aforementioned applications require high strength in shock resistance, high hardness and light weight, especially in space applications. As a result, other techniques cannot be used that contradict the required properties in addition to the beauty of the final shape that this technology gives. The main thing on which the use of this technology is based is economic feasibility, as the cost of the powders used, especially the micro powders, are low and easily available in the markets, in addition to the possibility of producing large quantities of compressed materials according to the application and the mold used [7]. Adding carbon nanotubes to a metal base improves properties such as structural, physical and mechanical properties. Nano carbon also has strength, hardness and durability that prevent nickel from having new, distinctive properties.

The methods of reinforcing metal materials have become famous to include different metal powders, ceramics or carbides. However, the most important reinforcing materials used were nanomaterials, which are of great importance in terms of improving the properties in general, as they are characterized by increasing the hardness and resistance of the final presses by stabilizing the metal grains and making the final surface smooth and cohesive [8]. In addition, the nanoparticles have the ability to reduce pores and homogeneity at high speed with the metal base, and give a surface that has the ability to withstand different loading pressures, and resistance to corrosion and friction represented by wear [9]. The nanomaterials supported by metals helped in the possibility of distributing crystal stresses during pressing, which helps to get rid of irregular or random distribution, which contributes to the distribution of energy across the surface and improves the thermal sintering processes of the presses. Metal materials have developed to include the possibility of reinforcing them with nanomaterials with medical biocompatibility to be used as a substitute for bones or sharp medical cutting tools that are widely used medically [10]. Therefore, the use of nano-reinforced materials gives pistons that contribute to improving their physical properties and chemical stability and eliminating the need to change materials frequently [11].

The work in the article aims to improve the structural properties in terms of the internal and external structure of nickel or develop the mechanical resistance through different nano additions of carbon tubes CNTs, which have promising applications in advanced engineering applications. In addition to knowing the change of physical properties through sintering processes and at variable temperatures for presses.

2. Raw materials

Nickel(Ni) was used as the matrix material of American origin with a particle size of 45 μm, purity of 99.8 %, and density of 8.90 g/cm^3. While the reinforcement material was carbon nanotubes(CNTs) of German origin with a particle size of (30 nm), purity of 99 %, and density was between (1.3–1.4) g/cm^3.

3. Experimental side

The pressing process was carried out for nickel-based metal powders reinforced with carbon nanotubes (CNTs) at ratios of (0.5, 10, 15, 20) wt. %. The materials were initially dried to get rid of moisture in the laboratory, and the nanopowders were mixed on a nickel substrate using a mechanical mixing method using a locally made micro mill containing small steel balls to help increase the grinding and mixing of the two materials. A pressing mold with a diameter of 10 mm was used, where the specified ratios were placed inside the mold and a pressing pressure of 5 tons was applied for 3 min, noting that the hydraulic press used is of the (SHOP PRESS) type, which has safety standards, and is of Chinese origin. The samples resulting from the piston have a rather weak resistance and therefore need to be strengthened by heat that should not exceed the melting point of the base material. As a result, the pistons were sintered by placing them inside ceramic lids and completely covered with fine sand, and the mouth of the lids was covered with refractory clay in order to reduce oxidation as much as possible, the sand used during sintering is regular sand after it has been filtered and purified from impurities. The pistons are placed inside a Korean-made thermal oven of the Muffle type available in the laboratory, and the oven timer is set at 900 °C so that the temperature begins to rise gradually until reaching the required temperature and is left for 2 h at this temperature, then the pistons are turned off and extracted the next morning. The sintering processes were repeated for other temperatures, which are (950, 1000, 1050) ℃ at the same time for 2 h. Different temperatures were used, but they should not reach the melting point of nickel, which is 1455 °C. That is, 70–90 % of the melting point of the base material was taken. The pistons resulting from the sintering processes need modification in the external structure in terms of cleaning and polishing in a simple way to prepare them for various structural and mechanical tests. Fig. (1) shows the initial

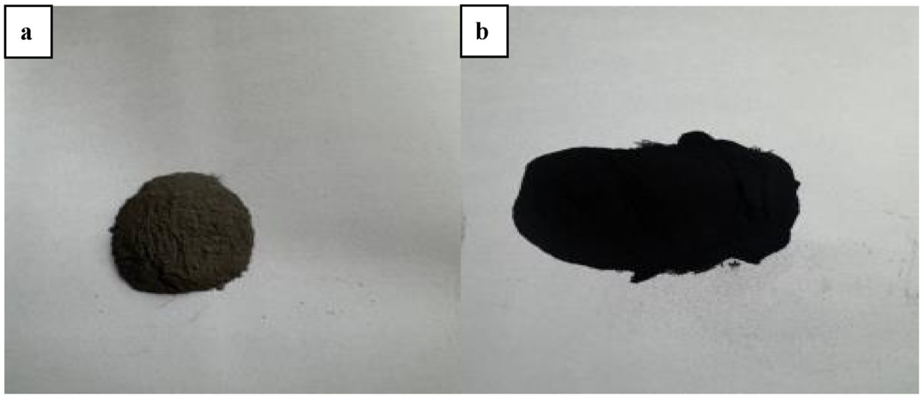

Fig. 1. Raw powders used (a-Ni, b-CNTs).

powders before mixing for both nickel and CNTs. Fig. (2) shows the pressed samples of both the base and reinforcement materials.

4. Theoritical side

4.1. XRD tests

X-ray diffraction was used to obtain information about the materials used in the compressed materials, namely the type of materials, their crystal system, and their phase structure. A Philips PW1730 device made in the Netherlands was used. Miller coefficients were determined by matching the international card of each material.

4.2. Physical properties tests

Physical properties are one of the basic features of the presses, through which the best ratios can be determined that can be used as a suitable application for devices and equipment manufactured by powder metallurgy. The true density represents a measure for calculating the ratio between the mass of the presses to the volumes of the open and closed spaces, unlike the apparent density, which represents the mass of those presses divided by their volume, which represents the closed spaces only [12]. As for the true porosity, it included dividing the total volume of the presses into the volume of the open and closed pores, unlike the apparent porosity, which represents the volume of the open pores only. As for the water absorbency, it is the division of the volume of any open pores within a single press to the volume of the material as a whole. The process of extracting the results of the physical properties was carried out through the famous Archimedes test, through which the presses can be weighed while they are dry, so that the first weight represents X_1, and after immersing those presses in water free of impurities for a full day and then weighing them the next day to represent the second weight X_2, and then suspending the dry sample in distilled water and weighing it while suspended in water to represent the third weight X_3. All physical variables were calculated using the relationships below [13–17].

Fig. 2. Compressors made of nickel base and carbon nanotubes (CNTs) reinforcement.

$$D_A = \frac{X_1}{X_1 - X_3} \times D_W \tag{1}$$

$$D_T = \frac{X_1}{X_2 - X_3} \times D_W \tag{2}$$

$$P_A = \frac{X_2 - X_1}{X_2 - X_3} \times 100\ \% \tag{3}$$

$$P_T = \frac{t_d - t_b}{t_d} \times 100\ \% \tag{4}$$

$$A_W = \frac{X_2 - X_1}{X_1} \times 100\ \% \tag{5}$$

Where: D_A: apparent density (g/cm3), D_W: water density (g/cm3), D_T: true density (g/cm3), P_A: apparent porosity (%), P_T: true porosity (%), t_d: theoretical density (g/cm3), t_b: practical density (g/cm3), A_W: water absorption (%).

5. Results and discussion at variable sintering

5.1. X-ray diffraction results of compressed

Fig. (3) shows the results of X-ray diffraction of (Ni-%CNTs) composites at different thermal sintering temperatures. We find that there is a high intensity of the curves for nickel powder with carbon nano-powder, which indicates the possibility of thermal sintering to improve the composites. We find that at the angle ($2\theta \approx 26.1^\circ$) CNTs material appears with Miller coefficients (002), which is a structure with a hexagonal crystal system, and as it appeared at the angle ($2\theta \approx 42^\circ$) carbon with partial crystallization, i.e. incomplete arrangement, and at Miller coefficients (110) [18]. As for the angle ($2\theta \approx 44^\circ$), the highest peak for the basic nickel appears with Miller coefficients (111), which is at the FCC phase, followed by the rest of the crystal curves that represent nickel and indicate complete crystallization of the grains at these peaks with a gradual increase in temperature. We note from the results that at temperatures between 900 °C and 950 °C, carbon nanotubes appear with the highest peak of nickel (111) but the rest of the crystalline peaks of nickel do not appear due to not reaching high crystallization degrees, i.e. higher temperatures are needed to reach crystalline stability [19]. As for temperatures 1000 °C and 1050 °C, the peaks gradually increase in height, indicating an improvement in the crystalline system and a clear increase in crystallization [20]. Nickel also appears at peak (311) at a sintering temperature of 1000 °C, which shows the completion of the crystallization process and the appearance of all nickel phases more precisely after that. This is attributed to the fact that at high temperatures we obtain high crystal homogeneity with an increase in the sharpness of the crystalline peaks, which in turn indicates a complete improvement in the physical properties, whether structural or mechanical [21,22].

5.2. Apparent density, true density, apparent porosity, true porosity, and water absorption tests

Figs. (4–8) dealt with the apparent density, true density, apparent porosity, apparent porosity, and

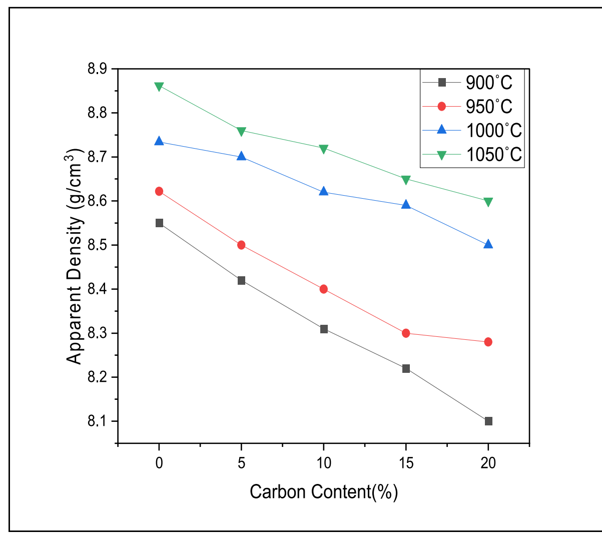

Fig. 4. The relationship between the nano carbon content and the apparent density at different sintering degrees.

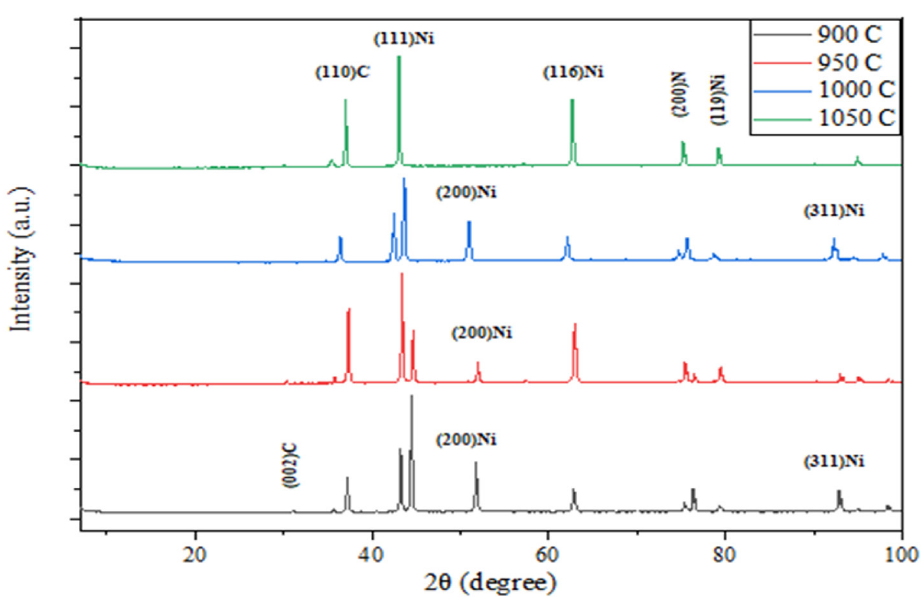

Fig. 3. XRD results of Ni- % CNTs composites upon variable sintering.

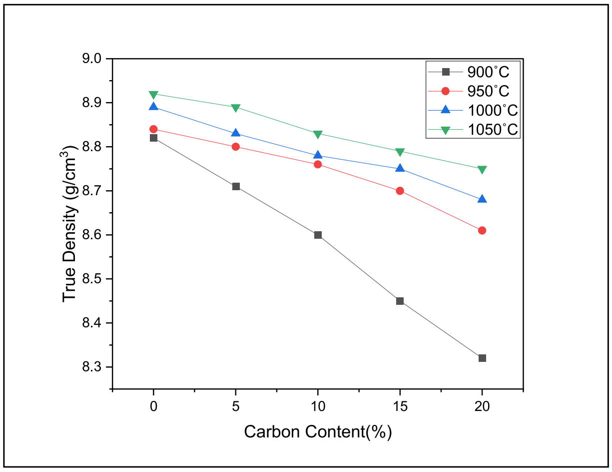

Fig. 5. The relationship between the nano carbon content and the true density at different sintering degrees.

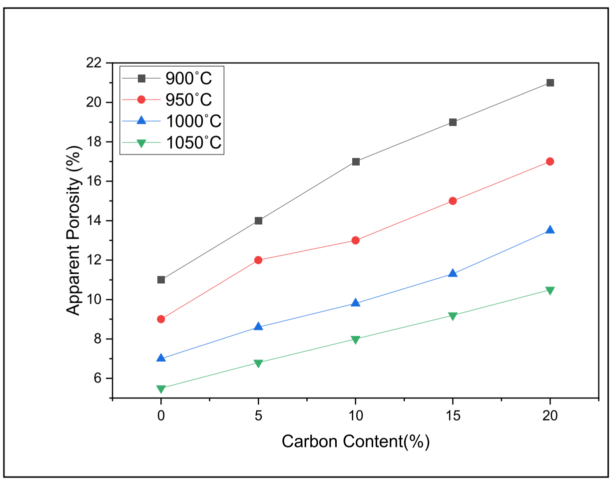

Fig. 6. The relationship between the nano carbon content and apparent porosity at different sintering degrees.

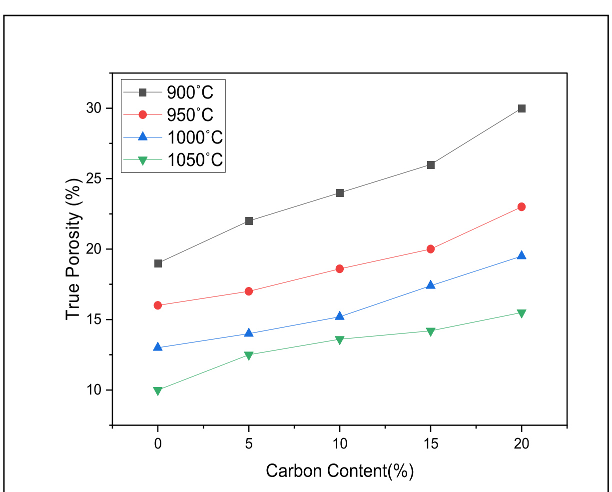

Fig. 7. The relationship between the nano carbon content and true porosity at different sintering degrees.

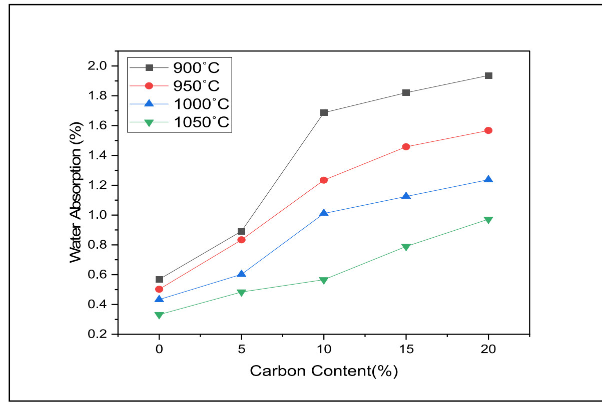

Fig. 8. The relationship between the nano carbon content and water absorption at different sintering degrees.

water absorption of (Ni-%CNTs) pistons after thermal sintering at variable temperatures (900, 950, 1000, 1050 °C). We find from Fig. (4) that the addition of nano carbon increases the porosity percentage and thus works to decrease the apparent density, and this is attributed to the formation of carbide phases that affect the pistons and increase the interstitial spaces, which results in low densities [23]. As for Fig. (5), the true density behaves in a similar form to what was obtained in the apparent density due to its complete reliance on the sizes of the open and closed voids and pores, and the dissolution of carbon atoms within the nickel matrix leads to a continuous expansion in the total lattice of the pistons, which leads to a decrease in the true density. Thermal sintering also helped homogenize the compressed materials and prevented a further decrease in density through the cohesion of the grains of the base material and reinforcement [24]. As for Fig. (6), we find that the apparent porosity increases significantly. This is due to the interaction of carbon atoms with each addition with oxygen, which leads to the disappearance of the real carbon atoms, which leave a void or pores within the material, and the apparent porosity increases continuously [25]. As for Fig. (7), we find that the real porosity follows the same increase that was shown in the apparent porosity, and the reason is attributed to the partial burning of carbon atoms within the alloy, thus leaving pores and gaps that increase the total closed and open pores. Also, the increase in pores affects the obstruction of the cohesion and growth of the crystalline grains, but thermal sintering contributed to the increase in pores by the carbon atoms losing their original positions significantly and leaving gaps that enhance the increase in pores within the alloy [26]. While we find in Fig. (8) we find an increase in water absorption with each addition of nano-carbon based on the height of pores and gaps, but the water absorption remains less than 1 %, which gives composites with a vitrified crystalline structure because the percentage obtained at 20 % was (0.972 %) by thermal sintering at 1050 °C, which is an encouraging result for obtaining composites with a crystalline structure that possess good physical and mechanical properties. Thermal sintering played an important role in enhancing the granular cohesion between the materials, and the higher the temperature, the more carbon spreads through the composites and leads to convergence with the nickel grains, which gives an alloy with distinctive properties. If it were not for thermal sintering, the number of pores and gaps would be large, which reduces the properties of the resulting alloy based on nickel [27,28]. Nanocarbon has a high capacity to form pores within the alloy. This is due to its low carbon density of 1.3 g/cm^3, which is negligible compared to the nickel density of 8.90 g/cm^3. Consequently, the carbon will evaporate through the matrix, leaving behind large pores and voids that increase composite defects. However, the high sintering temperature helps minimize the pores.

6. Conclusions

The successful compression process of nickel-based metallic materials using carbon nanotube nanomaterials provides encouraging results that enable these composites to be used in suitable applications. We found that the addition of carbon nanotubes significantly improves some structural and physical properties, and the optimal addition ratio is 20 % carbon nanotubes with thermal sintering at 1050 °C for 2 h. Under these conditions, an improvement in the outer surface of the composites was observed, resulting in a smooth, cohesive structure. The physical properties of density, porosity, and water absorption showed similar behavior at the same optimal ratio of high porosity to density, which enables these composites to be used in filters or a number of components. Other testing methods, such as hardness, radial compressive strength, and frictional wear, can also be used to more accurately characterize composites.

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Conflict of Interest

No conflicts of interest.

Ethical Approval

Not applicable.

Data Availability

The data supporting the findings of this study are available upon request from the corresponding author.

Author Contributions

Writing—original draft preparation, [Hadeel J. Aziz]; Writing—review and editing, [Ibrahim K. Salman]. All authors have read and approved the final manuscript.

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