

Article

Effects of $\text{Nd}_2\text{Fe}_{14}\text{B}$ Powder Particle Size and Content on Microstructure and Properties of $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ Composites

Tao Qin ^{1,*}, Qin Yang ², Jincheng Yu ¹, Bowen Fan ¹ , Ping Guo ¹ and Chenglong Ding ¹¹ School of Mechanical Engineering, Wuxi University of Technology, Wuxi 214121, China² Wuxi Vision Pro Ltd., Wuxi 214121, China

* Correspondence: qint@wxit.edu.cn; Tel.: +86-15852842341

Abstract

In this article, a $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ composite was prepared using high-energy ball milling, magnetic field cold isostatic pressing, and microwave sintering. The influence of powder particle size on microstructure and mechanical properties was discussed. The experimental results demonstrated that a ball milling duration of 10 h yielded powders with an average particle size of 5 μm , resulting in a refined and homogeneous microstructure, with a hardness value of 115 HV. Additionally, the densification process of the microwave-sintered sample was analyzed. When the sintering temperature was 490 $^\circ\text{C}$, in-depth analysis was conducted on the effect of $\text{Nd}_2\text{Fe}_{14}\text{B}$ addition on the microstructure and properties of the composite. The results showed that when the addition of $\text{Nd}_2\text{Fe}_{14}\text{B}$ was 15 wt.%, the microstructure of the composite was uniform with fewer pores, and the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase was evenly distributed on the matrix. At the same time, the compactness, microhardness, yield strength, and compressive strength of the composite also reached their optimal values, which were 94.3%, 136 HV, 190.5 MPa, and 248.9 MPa, respectively. When the addition of $\text{Nd}_2\text{Fe}_{14}\text{B}$ reached 20 wt.%, the magnetic properties of the composite were slightly better than those of 15 wt.% $\text{Nd}_2\text{Fe}_{14}\text{B}$ addition. However, based on the goal of preparing a high-magnetic and high-performance aluminum-based composite, considering the microstructure, mechanical properties, and magnetic properties comprehensively, it is believed that 15 wt.% is the optimal addition amount of $\text{Nd}_2\text{Fe}_{14}\text{B}$.



Academic Editor: Tomasz Sadowski

Received: 21 September 2025

Revised: 10 October 2025

Accepted: 11 October 2025

Published: 13 October 2025

Citation: Qin, T.; Yang, Q.; Yu, J.; Fan, B.; Guo, P.; Ding, C. Effects of $\text{Nd}_2\text{Fe}_{14}\text{B}$ Powder Particle Size and Content on Microstructure and Properties of $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ Composites. *Crystals* **2025**, *15*, 882. <https://doi.org/10.3390/cryst15100882>

Copyright: © 2025 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

Keywords: composite; $\text{Nd}_2\text{Fe}_{14}\text{B}$; microstructure; properties

1. Introduction

As the “power heart” and “information nerve” of modern industry, innovations in the performance of magnetic materials profoundly influence the development landscape of key fields such as energy conversion, information storage, and transportation. Conventional rare-earth permanent magnet materials, typified by neodymium iron boron ($\text{Nd}_2\text{Fe}_{14}\text{B}$), have maintained a dominant position in applications due to their superior magnetic energy product ($(\text{BH})_{\text{max}}$), high remanence (B_r), and coercivity (H_c), providing a powerful magnetic source for devices such as electric motors, loudspeakers, and sensors. However, as the requirements for comprehensive material performance in cutting-edge technology fields increase exponentially, such traditional magnetic materials, which are mainly iron-based, are increasingly revealing their inherent physical and chemical limitations: high density (generally higher than 7.6 g/cm^3) leads to bulky systems; the chemical activity of iron elements makes them highly susceptible to oxidation and failure in humid, hot, and corrosive environments; and more prominently, their intrinsic hard and brittle nature

(with fracture toughness generally less than 5 MPa/m²) makes them unable to withstand complex stress environments, resulting in processing difficulties and safety hazards [1,2]. These shortcomings severely restrict their application in emerging scenarios that pursue ultimate performance and reliability [3]. With the rapid development of industries such as new energy vehicles and rail transportation, new requirements have been placed on magnetic materials, such as light weight, miniaturization, and high strength and toughness, in order to achieve safety, energy efficiency, and ease of processing for magnetic devices like magnetic bearings, motors, and relays [4–6].

As early as 1978, the Laboratory of the Department of Production Engineering at a Japanese university first attempted to prepare magnetic aluminum alloys by adding ferrite composite powder to aluminum melt [7]. However, due to the excessively high temperature of the aluminum melt, the magnetic powder reacted rapidly upon contact with aluminum, and metal compounds were formed at the interface, which greatly reduced the magnetism. Eventually, only low-magnetic aluminum materials were obtained. In 1987, the Kobe Steel Research Institute in Japan, utilizing its advanced technologies such as magnetic material manufacturing, aluminum alloy powder production, and powder mixing and solidification molding, successfully prepared finished magnetic aluminum alloy products. Nevertheless, these products had poor stability, low magnetic properties, and their reliability could not be guaranteed. In 2012, Indian researcher Chandan [8] prepared a composite with cobalt ferrite magnetic nanoparticles dispersed in the aluminum matrix, which had a magnetization of 17.07 emu/g and a coercivity of 0.058 T, both lower than the performance levels achieved in previous studies. Analyzing the reasons, this may be attributed to the insufficient magnetic properties of the magnetically reinforcing particles, as well as the conventional sintering process which resulted in insufficiently dense microstructure and poor uniformity of particle dispersion. In 2015, Egyptian scholar Fathy and his colleagues [9] conducted an experimental study on the role of Fe element in the microstructure, mechanical properties, and magnetic properties of aluminum matrix composites synthesized by powder metallurgy. The experimental results showed that the magnetization of the sample with 5%Fe added was 0.3816 emu/g, while that of the sample containing 10 wt.% Fe increased to 0.6597 emu/g. However, this was still much lower than the 33.06 emu/g obtained in previous experiments. Moreover, due to the excessively high iron content, a large number of iron-containing brittle phases were formed, resulting in the low strength and toughness of the material.

In the preliminary research of our research group, we attempted to add neodymium iron boron (Nd₂Fe₁₄B) in the form of fine particles to aluminum melt. However, due to the high melting temperature of aluminum melt, the Nd₂Fe₁₄B particles reacted with the aluminum matrix to form complex intermetallic compounds, resulting in a decrease in the magnetic properties of Nd₂Fe₁₄B. Subsequently, powder metallurgy methods (such as sintering) were used to prepare Nd₂Fe₁₄B_p/aluminum composites and high-entropy alloys (HEA) [10–12]. Among all the existing sintering methods, microwave sintering is considered the best choice due to its advantages, such as obtaining better microstructure and mechanical properties [13,14], fast heating speed, selective sintering, and activation sintering effect [15–17].

In this study, the 2024Al was used as the matrix and the Nd₂Fe₁₄B particles were used as the reinforcing phase. Nd₂Fe₁₄B_p/2024Al composite was prepared through high-energy ball milling, magnetic field cold isostatic pressing, and microwave sintering. The influence of Nd₂Fe₁₄B powder size and addition on the microstructure and properties of the composite was studied in depth, and the optimal addition amount was determined.

2. Experimental Setup

2.1. Materials and Methods

In the present study, 2024Al powder with a purity of 99.99% (average particle size of 10 μm , Changsha Tijo Metal Materials Co., Ltd., Changsha, China) and $\text{Nd}_2\text{Fe}_{14}\text{B}$ powder with a purity of 99% (average particle size of $\text{Nd}_2\text{Fe}_{14}\text{B}$ powder is about 45 μm , Guangdong Xinnuode Transmission Parts Co., Ltd., Guangzhou, China) were used as the main raw materials, as shown in Figure 1a. First, the 2024Al powder and $\text{Nd}_2\text{Fe}_{14}\text{B}$ powder were placed in the planetary ball mill for high-speed ball milling to further refine them into fine and uniform powders. Ball milling was performed using zirconia grinding media with diameter ratios of 15 mm/10 mm/5 mm at 1:2:4 (mass ratio). Anhydrous ethanol was employed as the process control agent. The ball milling was conducted at a rotation speed of 200 r/min for 12 h. After ball milling, the powder was filtered and then placed in a vacuum drying oven, where it was dried at 72 $^{\circ}\text{C}$ for 48 h. The purpose of this process was to obtain submicron-sized 2024Al and $\text{Nd}_2\text{Fe}_{14}\text{B}$ powders. Then, the two powders were mixed and ball-milled together. The prepared mixed powder was placed in a drying oven for drying and then subjected to cold isostatic pressing in the magnetic field atmosphere. During the sintering process, based on the previously optimized sintering process, the pressed samples were first heated to 200 $^{\circ}\text{C}$ and held for 5 min. Then, the temperature was increased at a rate of 10 $^{\circ}\text{C}/\text{min}$ until 490 $^{\circ}\text{C}$, and was held for 30 min [18]. The preparation process of the samples is shown in Figure 1b, and the dimensions of the samples are illustrated in Figure 1c. To achieve the magnetic properties of the composite, the sintered samples were placed in a magnetizing device for magnetization.

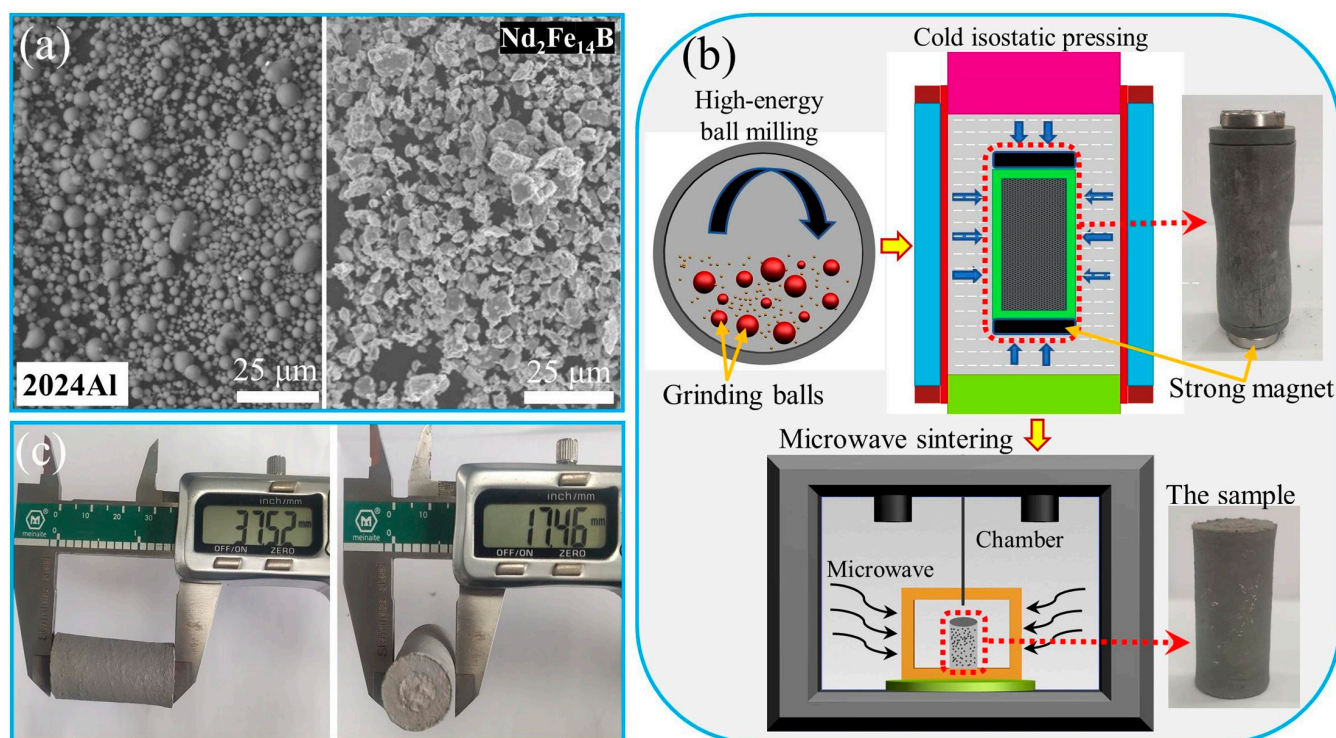


Figure 1. (a) The SEM morphology of 2024Al powder and $\text{Nd}_2\text{Fe}_{14}\text{B}$ particles; (b) schematic diagram of the composite preparation process; (c) the dimensions of one of the prepared samples.

2.2. Testing and Characterization

The particle size of the mixed powder was measured by a laser particle size analyzer (model: Masterizer-2000, Malvern, UK). The particle size testing range was 0.02–2000 μm , and the scanning speed was 1000 times per second.

Microstructure observations of the samples were carried out using an optical microscope (model: BA310MET, Motic, Xiamen, China) and an SEM (model: Nova NanoSEM450, FEI, Portland, OR, USA). The samples were cut into a uniform size of $\Phi 8 \text{ mm} \times 12 \text{ mm}$ through wire cutting, and the etching agent used was Kohler reagent. The backscattered images of the sample were collected on the surface for microstructure analysis, and the accelerating voltage was 5.00 kV.

X-ray diffraction (XRD, Bruker, D8 Advance, Karlsruhe, Germany) was used to perform phase analysis on the prepared samples, and the anode target material was Cu target. Prior to testing, the samples were cut into cylindrical shapes of $\Phi 8 \text{ mm} \times 12 \text{ mm}$, and the surface to be tested was polished flat and shiny.

Microhardness testing was performed with a DYDUV-1000 microhardness tester. The testing process is as follows: 7 points were uniformly dispersed on a flat and smooth sample surface for hardness testing, and the data were processed: the extreme values were removed, and the middle 5 effective values were selected to calculate the average value.

The compactness of the samples was measured using the Archimedes drainage method [19]. Firstly, the composite sample was placed in an ultrasonic cleaning device for cleaning. After complete drying, we weighed the mass of the sample in the air as m_1 . Then we placed the sample in distilled water and weighed it as m_2 . The actual density of the composite can be calculated by Formula (1).

$$\rho = \frac{m_1}{m_1 - m_2} \rho_1 \quad (1)$$

In the formula, ρ_1 is the density of distilled water at room temperature.

According to the mixing law, the theoretical density of composite samples can be obtained from Formula (2).

$$\rho_0 = \sum \rho_i X_i \quad (2)$$

In the formula, ρ_i is the theoretical density of element i , and X_i is the corresponding atomic fraction of this element. From this, it can be concluded that the comprehensive compactness I of the composite material is obtained by Formula (3).

$$I = \frac{\rho}{\rho_0} \quad (3)$$

The compressive performance was tested by a DDL-100 electronic testing machine. The size of the compression test sample is $\Phi 8 \text{ mm} \times 12 \text{ mm}$, and both ends need to be polished smooth and flat. The downward pressure speed during testing is 0.5 mm/min.

The magnetic properties were measured using a vibrating sample magnetometer (model: LakeShore7407, Columbus, OH, USA). The maximum external magnetic field range of the equipment was (−4 T, 4 T). The sample was cut into small pieces of $3 \text{ mm} \times 3 \text{ mm} \times 3 \text{ mm}$, and the hysteresis loop of the composite was measured from this. Then, the residual magnetism B_r , coercive force H_{cj} , and maximum magnetic energy product $(BH)_{\max}$ were obtained through the hysteresis loop.

3. Results and Discussion

3.1. Influence of Powder Particle Size on Microstructure and Mechanical Properties

Figure 2a–c show a particle size distribution diagram of the composite mixed powder prepared under different ball milling times. The ball diameter ratio is 1:2:4, the ball-to-powder ratio is 5:1, and the ball milling times are 6 h, 8 h, and 10 h. The average particle sizes of the prepared composite powders are 25 μm , 10 μm , and 5 μm , respectively. When the ball milling time is 6 h, the mixed powder undergoes a relatively short duration, resulting in insufficient mechanical alloying. The coarse particles are not fully impacted

and crushed, leading to a larger average particle size of the powder. According to the action principle of microwave sintering on metal particles, powder with such a particle size is not suitable for microwave sintering materials [20]. With the increase in ball milling time, the average particle size of the mixed powder decreases significantly. When the ball milling time is 10 h, the average particle size of the powder drops to about 5 μm . It is found that sufficient ball milling time can significantly increase the number of collisions between grinding balls and the ball mill tank, as well as between grinding balls themselves. At the same time, it increases the system energy inside the ball mill tank, enabling the powder to be fully impacted and crushed, thus effectively improving the mechanical alloying effect of ball milling.

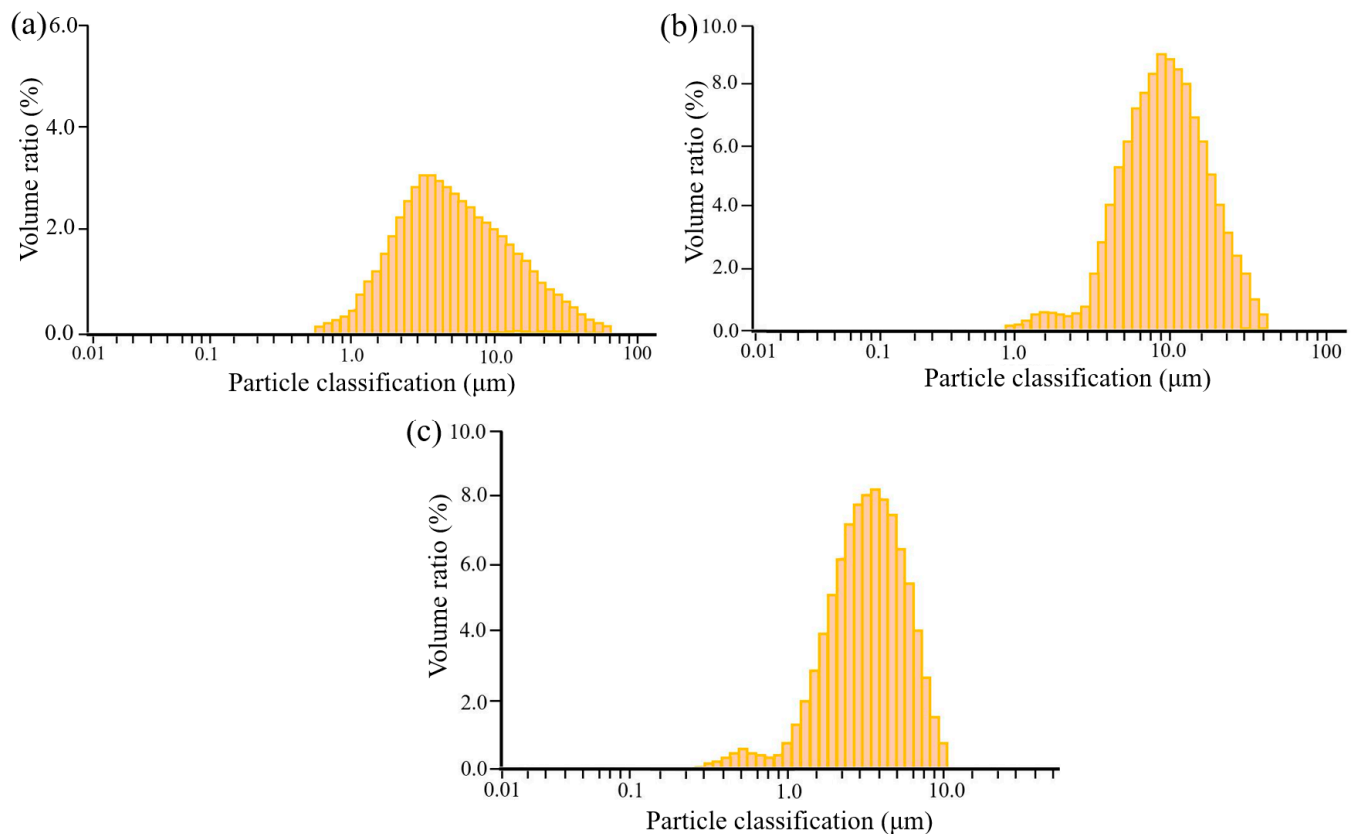


Figure 2. Effect of ball milling time on particle size distribution of composite powder: (a) ball milling time is 6 h; (b) ball milling time is 8 h; (c) ball milling time is 10 h.

Figure 3a–c show the optical metallographic structure diagrams of $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ composites with different powder particle sizes (25 μm , 10 μm , 5 μm) prepared by microwave sintering, where the addition amount of $\text{Nd}_2\text{Fe}_{14}\text{B}$ powder is 15% and the sintering temperature is 490 $^\circ\text{C}$. It can be seen that the particle size of the mixed powder has a significant impact on the microstructure of the composite. When the powder particle size is 25 μm , the grain size of the composite sample is relatively coarse and uneven, with the grain size in some local areas reaching 43 μm (as marked in Figure 3a). Most of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phases in the composite present sharp acute angles, which can easily split the matrix and destroy the continuity of it, and are not conducive to the exertion of the mechanical properties of the composite. When the powder particle size is 10 μm , the grain size of the composite is optimized, the average grain size is reduced to about 20 μm , the interface between the matrix and the particle phase is well bonded, and the morphology of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase is improved with relatively uniform distribution. As the powder particle size is 5 μm , the grain size of the 2024Al matrix in the composite is significantly reduced, with an

average grain size of about 10 μm (as shown in Figure 3c). The surface morphology of the matrix is uniform and flat, and the distribution uniformity of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ particle phase is significantly improved, showing a characteristic of dispersed distribution. It is found that during microwave sintering, a smaller particle size is helpful for microwaves to fully penetrate into the core of metal particles. The overall heating mode of powder particles from the surface to the interior, where microwave energy is converted into heat energy, achieves higher heating efficiency, and gives full play to the advantage of “low-temperature and fast sintering” of microwave sintering. Under higher superheat, it promotes phase transformation nucleation during the sintering process, the number of crystal nuclei is greatly increased, and the grains are refined [21].

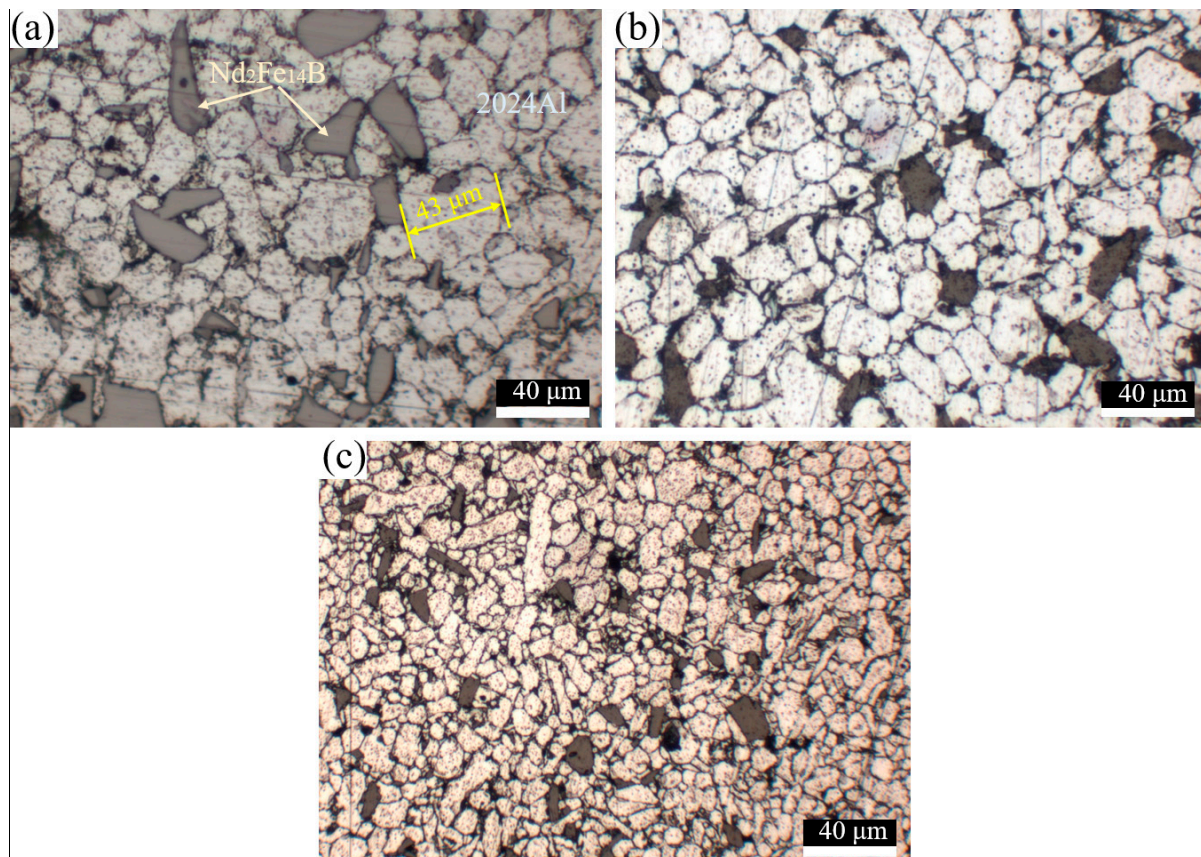


Figure 3. OM morphologies of 15 wt.% $\text{Nd}_2\text{Fe}_{14}\text{B}_p$ /2024Al composites with different powder sizes: (a) 25 μm ; (b) 10 μm ; (c) 5 μm .

As depicted in Figure 4, the microhardness of the composites increased monotonically with decreasing powder composites and increased monotonically with decreasing powder particle size, peaking at 115 HV for the 5 μm sample. When the powder particle size is large, the $\text{Nd}_2\text{Fe}_{14}\text{B}$ particle phase is coarse and distributed in the matrix in an irregular shape with sharp corners (as shown in Figure 3a), which is not conducive to the interface bonding between the reinforcing phase and the matrix. When the average particle size of the powder is 5 μm , the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase is mainly in a nearly spherical shape and distributed relatively uniformly in the matrix, thus making the composite show a higher overall hardness.

Analysis indicates that the factors influencing the hardness of the composite mainly include compactness, the morphology and quantity of reinforcing phase particles, and their distribution state in the 2024Al matrix. During the sintering process, the densification of the green compact is mainly achieved through the diffusion and rearrangement of atoms. When the particle size of the composite powder is small, the grains of the composite synthesized

by microwave sintering are also small, and its mechanical properties such as strength and toughness are better. In this experiment, a small powder particle size may be closer to the skin depth δ of the microwave used, and the proportion of the particle depth that microwaves can penetrate is larger. Therefore, the composite powder with a small particle size can better absorb microwave energy and convert it into heat energy, reaching the preset sintering temperature in a shorter time, which is conducive to the rapid densification of the material. From a thermodynamic perspective, metal powders with small particle sizes have a larger specific surface area, thus higher surface energy and greater activity, which further promotes the densification process during sintering.

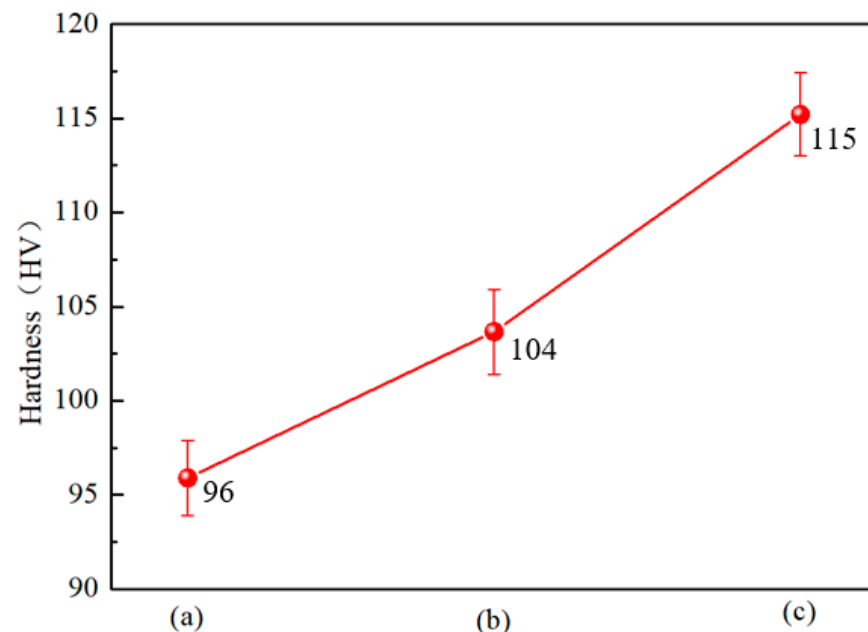


Figure 4. Hardness of 15 wt.%Nd₂Fe₁₄B_p/2024Al composites fabricated with different powder sizes: (a) 25 μm ; (b) 10 μm ; (c) 5 μm .

Figure 5 is a schematic diagram showing the densification process of the sample compact during microwave sintering. Figure 5a presents the state of particles inside the compact before the start of sintering, that is, the state after cold isostatic pressing. During the cold isostatic pressing process, migration and deformation occur between particles, leading to an increase in the number of internal defects in the particles. The increase in defects will promote the diffusion of atoms during microwave sintering. Meanwhile, under the high-strength load of cold isostatic pressing, tight bonds are formed between powder particles, which helps to promote the formation of sintering necks between particles during sintering. Figure 5b shows the formation of sintering necks during the sintering process.

When the compact is sintered, under the action of the microwave field, material migration first occurs on the surface layer of the compact. Among them, the migration phenomenon is most significant in adjacent particles or areas with small gaps between them, and the material migration mainly proceeds through volume diffusion. The result of material migration is the formation of “bubbles” on the surface of powder particles due to the aggregation of atoms, as shown in Figure 5a. With the continuous aggregation of atoms during the heating process, the “bubbles” continue to grow and connect with the surfaces of adjacent particles or between “bubbles”, realizing the connection between powder particles and forming sintering necks (as shown in Figure 5b).

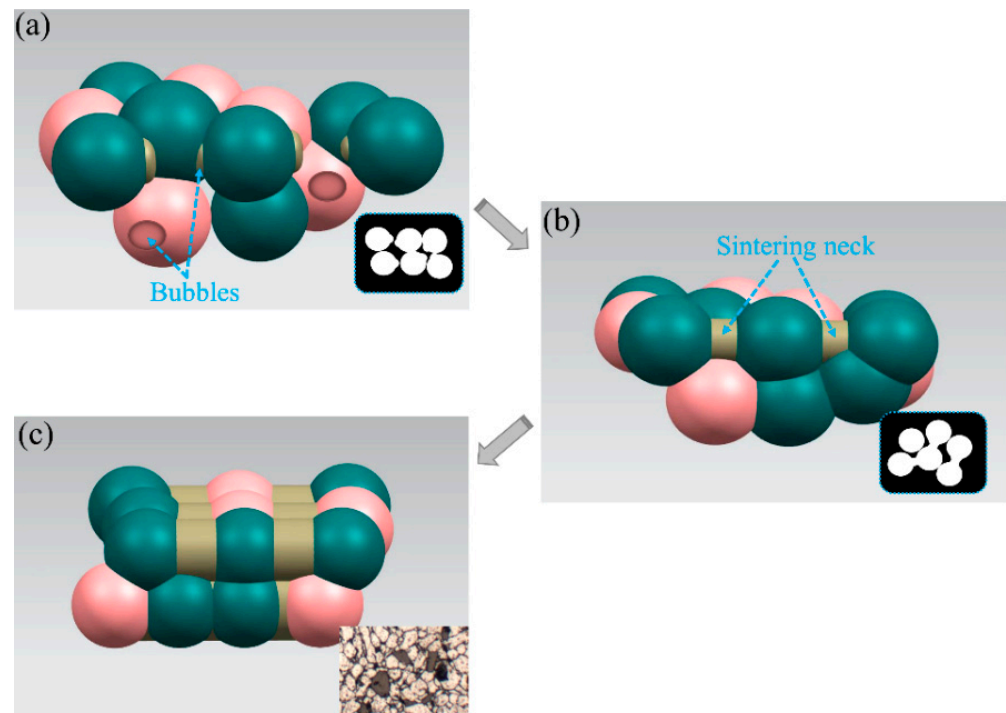


Figure 5. Schematic diagram of metal powder densification principle during microwave sintering process: (a) the interior of the metal compact at the initial stage of microwave sintering; (b) formation of particle sintering neck within the compaction; (c) consolidation process of composite materials.

Table 1 shows the compactness of bulk composites calculated from the theoretical density and actual density for the three samples. As the particle size of the composite powder decreases, the measured density of the samples gradually increases, and the corresponding density gradually increases. When the average particle size is 5 μm , the compactness is 94.3%. It can be known that the same metal powder has the same penetration depth in the microwave field of the same frequency [22]. For compacts with the same mass and volume, the finer the original powder, the more particles it contains. Therefore, combined with the microwave sintering densification principle, when the microwave penetration depth is constant, the finer the original powder particles in the compact, the larger the volume ratio penetrated by microwaves, the more sufficient the microwave absorption, and the higher the quality of microwave sintering. On the other hand, the finer the powder particles, the higher their surface energy and surface activity [23], and the lower the activation energy required in the microwave sintering process, which is conducive to achieving a high densification process of the composite at a lower temperature in a short time. This is also in line with the “low-temperature and fast sintering” characteristics of microwave sintering.

Table 1. Compactness of 15 wt.% $\text{Nd}_2\text{Fe}_{14}\text{B}_p$ /2024Al composites fabricated with different powder sizes.

Particle Size of Powder (μm)	Theoretical Density (g/cm^3)	Actual Density (g/cm^3)	Compactness (%)
25	3.71	3.23	93.2
10	3.71	3.30	93.8
5	3.71	3.33	94.3

3.2. Influence of $\text{Nd}_2\text{Fe}_{14}\text{B}$ Addition Amount on the Microstructure

Figure 6a–d show the SEM morphology of $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ composites with different amounts of $\text{Nd}_2\text{Fe}_{14}\text{B}$ added. When the addition is 5 wt.%, the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase is relatively sporadically distributed on the matrix. At this time, the grain size of the matrix is relatively coarse and has poor uniformity, and some pores can be observed in the matrix, as shown in the marked area of Figure 6a. When the addition of $\text{Nd}_2\text{Fe}_{14}\text{B}$ reaches 10 wt.% (Figure 6b), the grain size of the 2024Al matrix decreases, and the pores between the grains reduce compared to Figure 6a. The distribution of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase on the matrix is relatively uniform, but the morphology tends to exhibit irregular and sharp angular shapes. When the addition is 15 wt.% (Figure 6c), compared to Figure 6b, the number of grains with sharp angular morphology has notably decreased, and the distribution in the matrix is relatively uniform, with no obvious aggregation observed. Additionally, the number of visible pores in the matrix has also decreased. When the addition of $\text{Nd}_2\text{Fe}_{14}\text{B}$ reaches 20 wt.% (as shown in Figure 6d), the packing density of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ particle phase on the matrix is higher, and nearby particles tend to stick together and aggregate [24]. Meanwhile, it is evident that a larger number of pores are formed at the interface between the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase and the 2024Al matrix, as indicated by the green dashed lines in Figure 6d. Therefore, from the perspective of the microstructure, when the addition of $\text{Nd}_2\text{Fe}_{14}\text{B}$ is 15 wt.%, the microstructure of the $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ composites is more ideal.

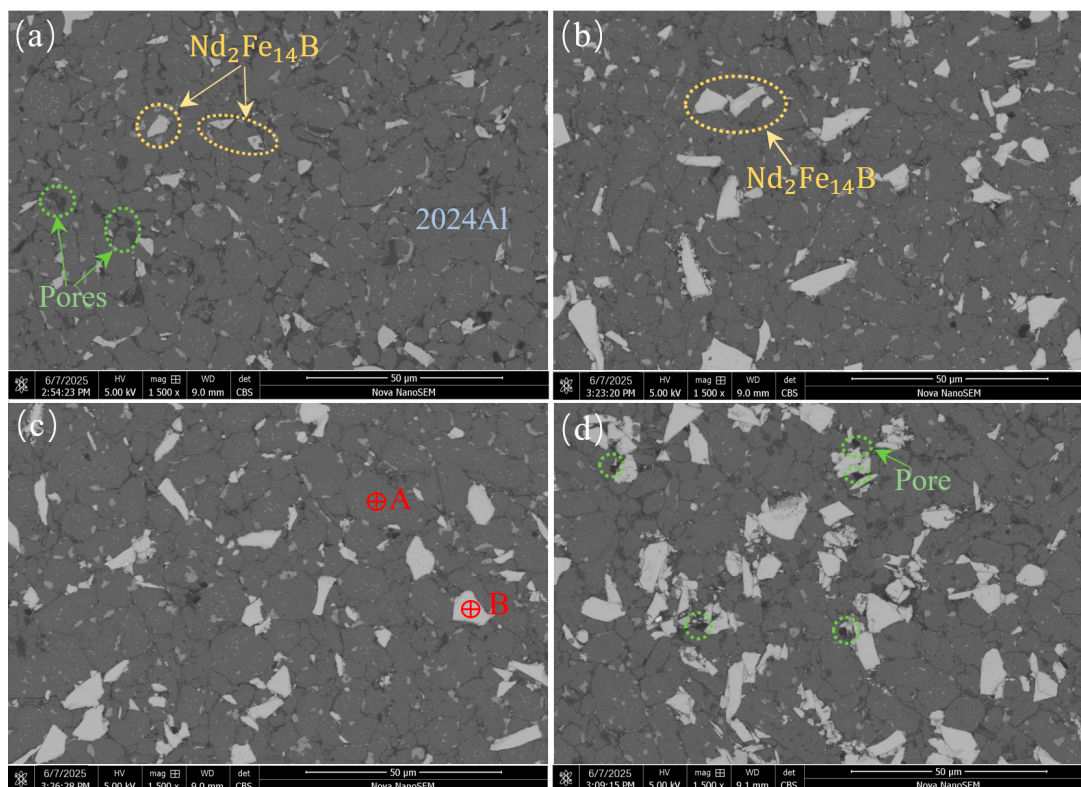


Figure 6. (a–d) The SEM morphologies of $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ composite with different $\text{Nd}_2\text{Fe}_{14}\text{B}$ content.

For particle-reinforced aluminum matrix composites prepared by powder metallurgy, there is a limit to the addition amount of reinforcing phase particles. When the volume fraction of the reinforcing phase exceeds this limit, agglomeration occurs. The influencing factors of this limit value mainly include the particle morphology of the matrix and reinforcing phase, the size ratio of matrix particles to reinforcing phase particles, and the preparation process of the composite. At present, the calculation method for the maximum volume fraction of enhanced phase particles is mostly based on the mathematical model ob-

tained from the mixing ratio, while research on the influence trend of ball mill preparation parameters on particle distribution is relatively rare. For the calculation of the limit value of the volume ratio of reinforcing phase particles, the model proposed by Slipenyuk et al. is commonly used [25], as shown in Formula (4).

$$W_{\text{crit}} = \delta \left[1 - \left(1 + \left(\frac{d}{D} \right)^3 + \left(\frac{2}{\sqrt{\lambda}} + \lambda \right) \left(\frac{d}{D} \right)^2 + \left(\frac{1}{\lambda} + 2\sqrt{\lambda} \right) \frac{d}{D} \right)^{-1} \right] \quad (4)$$

In the formula, W_{crit} represents the maximum volume ratio at which the particle reinforcing phase in the composite can be uniformly distributed in the matrix; δ is a constant whose value is based on parameters such as the particle size distribution and morphology of the actual powder particles, and the commonly used value is 0.18; d is the actual diameter of the reinforcing phase particles; D is the actual diameter of the matrix phase particles; λ is the extrusion ratio. In this experiment, the limit value of the particle volume ratio of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase calculated by using this model formula is 13.1%. However, as shown in Figure 6, when the addition amount of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase reaches 15%, it is still uniformly distributed in the composite matrix. This indicates that the previous high-energy ball milling has promoted the uniform distribution of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase.

Figure 7a shows the XRD patterns of the composite before and after sintering. It can be seen that no new phases were generated after sintering, as the sintering temperature was 490 °C, which is far below the melting point of $\text{Nd}_2\text{Fe}_{14}\text{B}$ (1150 °C) and 2024Al (655 °C). Moreover, the XRD peaks of $\text{Nd}_2\text{Fe}_{14}\text{B}$ are consistent with each other, showing no changes or shifts. This indicates that the structure of $\text{Nd}_2\text{Fe}_{14}\text{B}$ remains stable during the sintering process, thereby ensuring the magnetic properties of $\text{Nd}_2\text{Fe}_{14}\text{B}$. Meanwhile, no other new phases or oxides are formed in the composite, as the sintering process is carried out under the protection of an argon atmosphere, which effectively inhibits the oxidation of the composite. The EDS spectroscopy (Figure 7b) analysis was conducted on points A and B in Figure 6c, indicating that the compositions are 2024Al matrix and $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase, respectively.

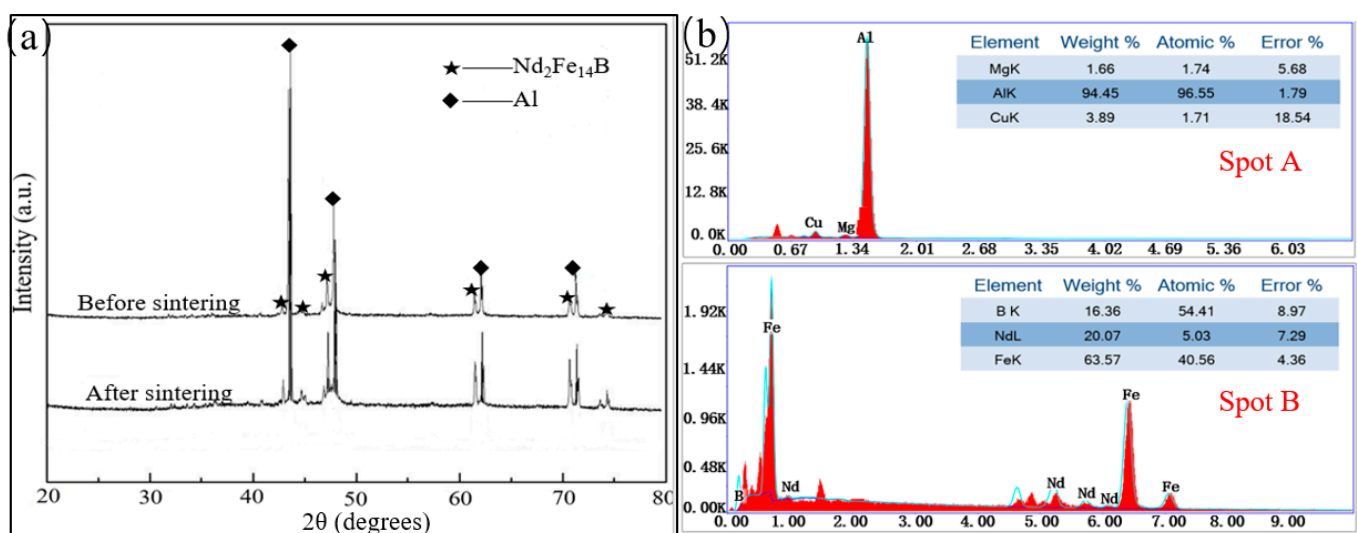


Figure 7. (a) The XRD patterns of the composite before and after sintering; (b) the element composition at spot A and spot B in Figure 6c.

3.3. Mechanical Characterization

Figure 8a shows the trend of the compactness of the composite as the content of $\text{Nd}_2\text{Fe}_{14}\text{B}$ changes. When $\text{Nd}_2\text{Fe}_{14}\text{B}$ is not added, the compactness of the 2024Al alloy is approximately 95.5%. However, after adding different amounts of $\text{Nd}_2\text{Fe}_{14}\text{B}$ powder,

the compactness of the composite first decreases and then increases. As the addition varies at 5 wt.%, 10 wt.%, and 15 wt.%, the compactness of the composite gradually increases, reaching the highest value at the addition of 15 wt.% $\text{Nd}_2\text{Fe}_{14}\text{B}$. As the amount of $\text{Nd}_2\text{Fe}_{14}\text{B}$ increases, the thermal effect of the reinforcing phase in the composite during the microwave sintering process becomes more significant, contributing increasingly to the absorption and conversion of microwave energy in the overall heating, and resulting in a more uniform microstructure and refined grains, thus increasing the compactness. However, when the addition of $\text{Nd}_2\text{Fe}_{14}\text{B}$ reached 20 wt.%, the mobility of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ particles was weakened during the cold isostatic pressure process, leading to aggregation and an increase in the number of gaps between particles [26], which subsequently decreases the compactness of the composite.

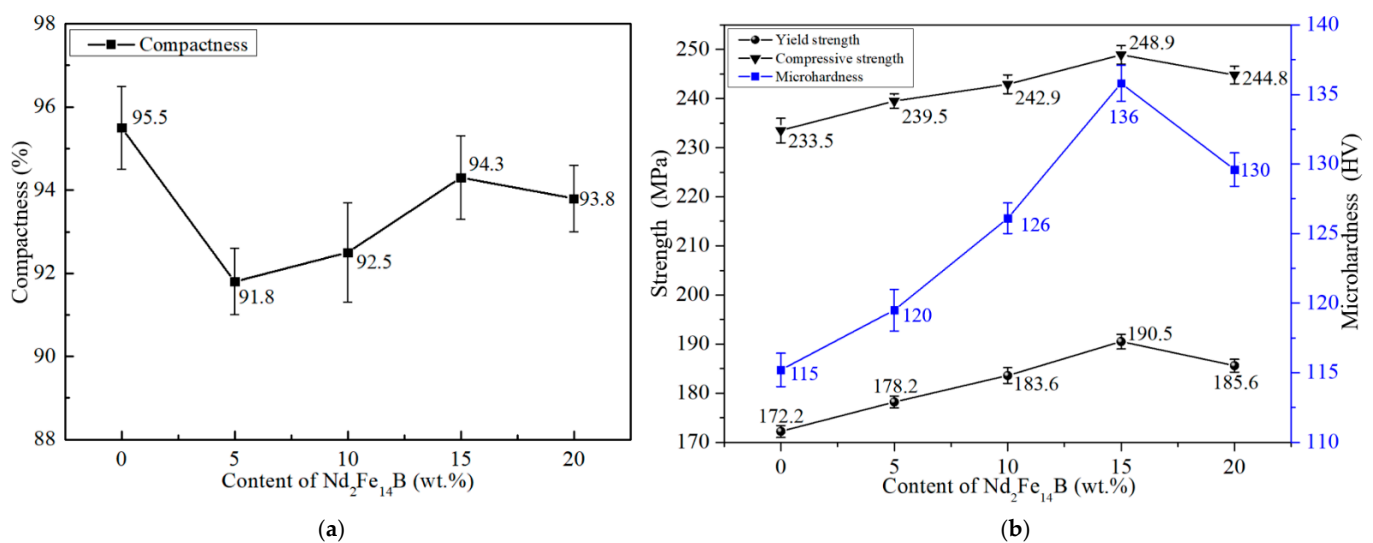


Figure 8. (a) The compactness of $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ composite with different $\text{Nd}_2\text{Fe}_{14}\text{B}$ content; (b) the microhardness and compressive properties of $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ composite with different $\text{Nd}_2\text{Fe}_{14}\text{B}$ content.

Figure 8b shows the trend of the mechanical properties of the composite with different $\text{Nd}_2\text{Fe}_{14}\text{B}$ content. As the amount of $\text{Nd}_2\text{Fe}_{14}\text{B}$ increases, the microhardness, yield strength, and compressive strength first increase and then decrease, reaching the peak when the $\text{Nd}_2\text{Fe}_{14}\text{B}$ content is 15 wt.%, at 136 HV, 190.5 MPa, and 248.9 MPa, respectively. Compared to the control sample, these values are increased by 17.9%, 10.6%, and 6.6%, respectively. As the content of $\text{Nd}_2\text{Fe}_{14}\text{B}$ increases to 20 wt.%, the microhardness, yield strength, and compressive strength of the composite slightly decrease. The $\text{Nd}_2\text{Fe}_{14}\text{B}$ phases have extremely high hardness, they are distributed in the 2024Al matrix as the reinforcing phases. With the increase in the addition amount, the surface area of $\text{Nd}_2\text{Fe}_{14}\text{B}$ particles on the matrix is expanded, the effective load-bearing capacity of the composite is improved, the ability of the composite to bear deformation is enhanced, and the deformation resistance of the micro-regions of the material is increased. In other words, the dispersively distributed $\text{Nd}_2\text{Fe}_{14}\text{B}$ particles restrict the deformation of the matrix grains in local regions, thus improving the macroscopic hardness of the composite. However, when the addition amount of $\text{Nd}_2\text{Fe}_{14}\text{B}$ particles reaches 20 wt.%, the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phases agglomerate to a certain extent, as can be seen from Figure 6d. This is not conducive to the improvement of the effective load-bearing capacity of the composite; on the contrary, it may even reduce it [27]. Moreover, it will cause uneven deformation resistance in various regions of the material surface, so the mechanical property decreases.

3.4. Characterization of Magnetic Properties

Figure 9a–d show the VSM (vibrating sample magnetometer) curves of composites with different $\text{Nd}_2\text{Fe}_{14}\text{B}$ content, which were measured and characterized using an oscillating sample magnetometer to assess the magnetic properties of the materials. The magnetic properties' parameters of the composite, such as remanence (B_r), coercivity (H_{cj}), and maximum magnetic energy product ($(BH)_{\max}$), can be calculated through the VSM curve, as shown in Figure 9e.

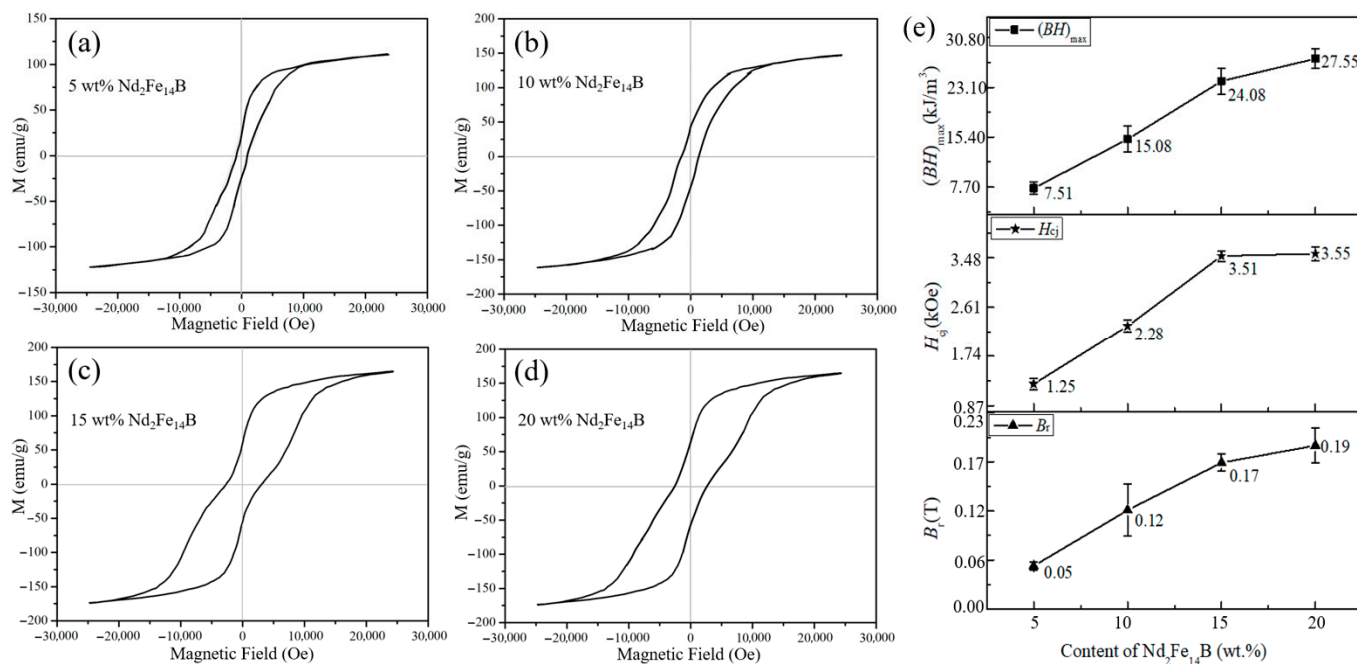


Figure 9. (a–d) The VSM curves of the $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ composites with different $\text{Nd}_2\text{Fe}_{14}\text{B}$ content; (e) magnetic properties of the composite with different $\text{Nd}_2\text{Fe}_{14}\text{B}$ content.

From Figure 7a,b in Section 3.2, it can be seen that no new phases were generated during the sintering process. Therefore, the magnetic properties of composite are closely related to the amount of $\text{Nd}_2\text{Fe}_{14}\text{B}$ added. It is generally believed that the magnetic properties of composite increase with the increase in $\text{Nd}_2\text{Fe}_{14}\text{B}$ content, and the experimental results have also verified this. At the same time, we also noticed that when the $\text{Nd}_2\text{Fe}_{14}\text{B}$ content increased from 15 wt.% to 20 wt.%, the increasing trend of the magnetic performance parameters of the composite slowed down, with only an increase of 14.4%, 1.1%, and 11.8%, all significantly lower than the previous growth level.

The magnetic properties of the composite are influenced by both the amount of $\text{Nd}_2\text{Fe}_{14}\text{B}$ added and the microstructure and compactness. The pores inside the composite and the sharp corners of irregularly shaped particles have low energy barriers. When magnetized, these defects are prone to form uneven and dispersed reverse magnetic fields, leading to the occurrence of the demagnetization phenomenon (as shown in Figure 10) and reducing the magnetic properties of the material [28]. When the addition amount is 20 wt.%, the $\text{Nd}_2\text{Fe}_{14}\text{B}$ particles agglomerate and there are more pores in the microstructure (Figure 6d). These areas can form more reverse magnetic fields during the magnetization process, affecting the exchange coupling between $\text{Nd}_2\text{Fe}_{14}\text{B}$ magnetic particles and resulting in a decrease in the overall magnetic properties of the composite.

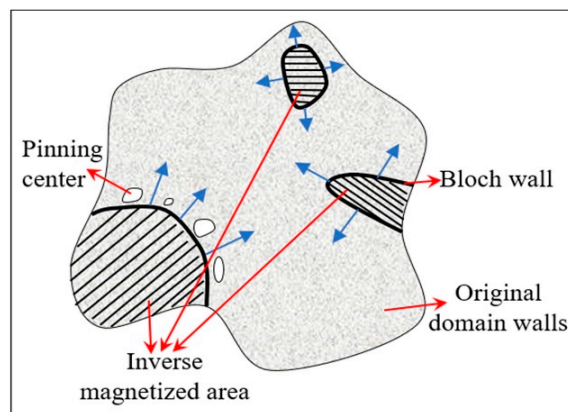


Figure 10. Schematic diagram of magnetization and inverse magnetization.

Based on the comprehensive effect of $\text{Nd}_2\text{Fe}_{14}\text{B}$ addition on the compactness, mechanical properties, and magnetic properties of the composite, from the perspective of preparing high-magnetic and high-performance aluminum-based composite, it is believed that the optimal value for $\text{Nd}_2\text{Fe}_{14}\text{B}$ addition is 15 wt. %

4. Conclusions

In the present work, the influence of $\text{Nd}_2\text{Fe}_{14}\text{B}$ powder size and addition on the microstructure, mechanical properties, and magnetic properties of the $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ composite were discussed, and the following conclusions were drawn:

(1) When the ball milling time was 10 h, the average particle size of the obtained powder was 5 μm , and the microstructure of the sample was fine and uniform, with a hardness value of 115 HV.

(2) Sintering was carried out at 490 $^{\circ}\text{C}$, and no new phases were generated in the $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ composite, ensuring the magnetic properties of the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase. When the addition of $\text{Nd}_2\text{Fe}_{14}\text{B}$ is 15 wt. %, the microstructure of the $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ composite is uniform, and the $\text{Nd}_2\text{Fe}_{14}\text{B}$ phase is smooth and evenly distributed on the matrix. At this point, the compactness, mechanical properties, and magnetic properties of the composite have all reached their optimal values.

(3) The magnetic properties of the 20 wt. % $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ composite are slightly higher than those of the 15 wt. % $\text{Nd}_2\text{Fe}_{14}\text{B}_p/2024\text{Al}$ composite. However, a comprehensive evaluation of the microstructure, mechanical properties, and magnetic performance indicates that 15 wt. % $\text{Nd}_2\text{Fe}_{14}\text{B}$ represents the optimal composition for achieving balanced performance in the composite.

Author Contributions: Conceptualization, T.Q. and B.F.; methodology, T.Q.; software, C.D. and P.G.; formal analysis, J.Y.; investigation, Q.Y.; resources, J.Y.; writing—original draft preparation, T.Q.; writing—review and editing, B.F.; supervision, J.Y.; funding acquisition, T.Q. All authors have read and agreed to the published version of the manuscript.

Funding: This research was funded by “Jiangsu Province Vocational College Teachers Enterprise Practice Training Project (2024QYSJ038)”.

Data Availability Statement: The original contributions presented in this study are included in the article. Further inquiries can be directed to the corresponding author.

Conflicts of Interest: Author Qin Yang was employed by the company Wuxi Vision Pro Ltd. The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Wang, X.; Zhu, K.; Li, W.; Xu, J.; Ali, Z.; Hou, Y. Nd₂Fe₁₄B hard magnetic powders: Chemical synthesis and mechanism of coercivity. *J. Magn. Magn. Mater.* **2021**, *518*, 167384. [\[CrossRef\]](#)
- Wang, L.; Zhang, M. Study on synthesis and magnetic properties of Nd₂Fe₁₄B nanoparticles prepared by hydrothermal method. *J. Magn. Magn. Mater.* **2020**, *507*, 166841. [\[CrossRef\]](#)
- Dong, S.; Li, X.; Lu, Q.; Liu, W.; Wu, Y.; Yue, M. Study on mechanical properties of recycled sintered Nd-Fe-B magnets. *J. Alloys Compd.* **2023**, *962*, 171156. [\[CrossRef\]](#)
- Kumari, S.; Pradhan, D.K.; Pradhan, N.R.; Rack, P.D. Recent developments on 2D magnetic materials: Challenges and opportunities. *Emergent Mater.* **2021**, *4*, 827–846. [\[CrossRef\]](#)
- Brown, D.; Ma, B.-M.; Chen, Z. Developments in the processing and properties of NdFeB-type permanent magnets. *ChemInform* **2003**, *248*, 432–440. [\[CrossRef\]](#)
- Solomon, D.G.; Greco, A.; Masselli, C.; Gundabattini, E.; Rassiah, R.S.; Kuppan, R. A Review on Methods to Reduce Weight and to Increase Efficiency of Electric Motors Using Lightweight Materials, Novel Manufacturing Processes, Magnetic Materials and Cooling Methods. *Ann. Chim. Sci. Mater.* **2020**, *44*, 1–14. [\[CrossRef\]](#)
- Li, G.; Chen, J.; Zhang, D.; Wang, H.; Liu, M.; Tang, F.; Yan, Y.; Wen, H.; Ren, W.; Wang, C. Microstructure and properties of the Nd₂Fe₁₄B_p/Al-Co composites fabricated via microwave sintering. *J. Mater. Res. Technol.* **2021**, *10*, 34–50. [\[CrossRef\]](#)
- Chandan, B.; Kaustubh, A. A new aluminum-based metal matrix composite reinforced with cobalt ferrite magnetic nanoparticle. *J. Mater. Sci.* **2013**, *48*, 162–171.
- Fathy, A.; El-Kady, O.; Mohammed, M. Effect of iron addition on microstructure, mechanical and magnetic properties of Al-matrix composite produced by powder metallurgy route. *Trans. Nonferrous Met. Soc. China* **2015**, *25*, 46–53. [\[CrossRef\]](#)
- Li, G.-R.; Xie, M.-L.; Wang, H.-M.; Xu, T.; Liu, M. Microstructure and properties of Nd₂Fe₁₄B particles reinforced aluminum matrix composites synthesized by microwave sintering. *Mater. Res. Express* **2019**, *6*, 026538. [\[CrossRef\]](#)
- Wang, S.; Sun, J.-B.; Xiao, Z.-X.; Yang, M.-X.; Shi, W.-D. Effect of doping Al-Cu-Fe alloy on the microstructure and magnetic properties of annealed Nd-Fe-Co-B ribbons. *Phys. B Condens. Matter* **2022**, *646*, 41433. [\[CrossRef\]](#)
- Gao, L.; Li, G.; Wang, H.; Yan, Y. Interfacial structure and properties of microwave sintered FeCoNi_{1.5}CrCu/Al composites. *Mater. Charact.* **2022**, *189*, 111993. [\[CrossRef\]](#)
- Venkatesh, V.S.S. Microstructure and mechanical properties comparison between spark plasma sintered and microwave sintered Al-(SiC + B₄C) composite. *Mater. Lett.* **2024**, *366*, 136496. [\[CrossRef\]](#)
- Chintada, S.; Dora, S.P.; Kare, D. Mechanical Behavior and Metallographic Characterization of Microwave Sintered Al/SiC Composite Materials—An Experimental Approach. *Silicon* **2022**, *14*, 7341–7352. [\[CrossRef\]](#)
- Ghasali, E.; Yazdani-Rad, R.; Asadian, K.; Ebadzadeh, T. Production of Al-SiC-TiC hybrid composites using pure and 1056 aluminum powders prepared through microwave and conventional heating methods. *J. Alloys Compd.* **2017**, *690*, 512–518. [\[CrossRef\]](#)
- Raynova, S.; Imam, M.; Yang, F.; Bolzoni, L. Hybrid microwave sintering of blended elemental Ti alloys. *J. Manuf. Process.* **2019**, *39*, 52–57. [\[CrossRef\]](#)
- Saravanan, B.A.; Balavignesh, M.; Goutham, S.; Gowthaman, S.; Jagadeesh, M. Characteristics study on aluminium graphene composite for different sintering approaches. *AIP Conf. Proc.* **2020**, *2327*, 1–8.
- Qin, T.; Fan, B.; Song, J.; Xu, G. The Effect of Sintering Temperature on the Microstructure and Properties of 15wt.%Nd₂Fe₁₄B_p/2024Al Composite. *Mater. Lett.* **2024**, *377*, 137485. [\[CrossRef\]](#)
- Xiu, M.; Hu, C.; Liu, J.; Ye, Q. Effect of Y₂O₃ and ZnO co-doping on the densification and properties of magnesium aluminum spinel. *Ceram. Int.* **2023**, *49*, 31598–31606. [\[CrossRef\]](#)
- Venkatesh, V.; Deoghare, A.B. Effect of microwave sintering on the mechanical characteristics of Al/kaoline/SiC hybrid composite fabricated through powder metallurgy techniques. *Mater. Chem. Phys.* **2022**, *287*, 126276. [\[CrossRef\]](#)
- Croquesel, J.; Bouvard, D.; Chaix, J.-M.; Carry, C.P.; Saunier, S.; Marinel, S. Direct microwave sintering of pure alumina in a single mode cavity: Grain size and phase transformation effects. *Acta Mater.* **2016**, *116*, 53–62. [\[CrossRef\]](#)
- Qin, T.; Li, G.R.; Wang, H.M.; Su, W.; Dong, C.; Yu, J. Microstructure and Properties of Microwave-Sintered Nd₂Fe₁₄B_p/2024 Aluminum-Alloy-Co Composites. *Crystals* **2022**, *12*, 1493. [\[CrossRef\]](#)
- Malkin, A.I.; Fomkin, A.A.; Zalavutdinov, R.K.; Klueva, V.A.; Loznetsova, N.N.; Popova, D.A.; Toropova, Y.P.; Shkolin, V.A. Changes in the Surface Properties of Powder Titanium under Mechanoactivation. *Prot. Met. Phys. Chem. Surf.* **2022**, *58*, 1028–1035. [\[CrossRef\]](#)
- Wu, C.; Ma, K.; Wu, J.; Fang, P.; Luo, G.; Chen, F.; Shen, Q.; Zhang, L.; Schoenung, J.M.; Lavernia, E.J. Influence of particle size and spatial distribution of B₄C reinforcement on the microstructure and mechanical behavior of precipitation strengthened Al alloy matrix composites. *Mater. Sci. Eng. A* **2016**, *675*, 421–430. [\[CrossRef\]](#)

25. Slipenyuk, A.; Kuprin, V.; Milman, Y.; Goncharuk, V.; Eckert, J. Properties of P/M processed particle reinforced metal matrix composites specified by reinforcement concentration and matrix-to-reinforcement particle size ratio. *Acta Mater.* **2006**, *54*, 157–166. [[CrossRef](#)]
26. Luo, J.; Shi, F.; An, J.; Mu, X.; Xu, L.; Guo, S. The influence of fine powder content on the properties of FeNi50 soft magnetic composites. *J. Mater. Sci. Mater. Electron.* **2024**, *35*, 783. [[CrossRef](#)]
27. Luo, K.; Liu, S.; Xiong, H.; Zhang, Y.; Kong, C.; Yu, H. Mechanical Properties and Strengthening Mechanism of Aluminum Matrix Composites Reinforced by High-entropy Alloy Particles. *Met. Mater. Int.* **2022**, *28*, 2811–2821. [[CrossRef](#)]
28. Filder, J.; Schrefl, T. Overview of Nd-Fe-B magnets and coercivity (invited). *J. Appl. Phys.* **1996**, *79*, 5029–5034.

Disclaimer/Publisher’s Note: The statements, opinions and data contained in all publications are solely those of the individual author(s) and contributor(s) and not of MDPI and/or the editor(s). MDPI and/or the editor(s) disclaim responsibility for any injury to people or property resulting from any ideas, methods, instructions or products referred to in the content.