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INVESTIGATION ON MECHANICAL PROPERTIES AND MICROSTRUCTURE OF BORON NITRIDE NANOPARTICLE REINFORCED ALUMINUM-BASED COMPOSITES

ABSTRACT

In the current work, nano boron nitride (BN) reinforced aluminum (Al) matrix composites with different BN amounts (0.5-2wt.%) were produced by the powder metallurgy(PM) route. This fabrication method consists of dispersing, filtering, mixing, drying, compaction, and sintering processes. The density, compressive strength, micro Vickers hardness, microstructure, and phase structures of Al-BN composites and pure Al were examined. The obtained results indicated that minimum porosity (3.2%), highest density (~2.61g/cm^3), Vickers hardness (~50HV), and compressive strength (~168MPa) were obtained at 1%BN reinforced aluminum matrix composite. A tremendous enhancement in Vickers hardness and compressive strength of %1BN reinforced Al matrix composite was achieved as ~61% and ~110% compared to pure Al. Consequently, the mechanical strength of BN reinforced Al-based composites enhanced up to 1% nano boron nitride amount. Due to the clumping of BN nanoparticles, the mechanical strength decreased after this content.

Keywords: Composite, Powder Metallurgy, Aluminum, Boron Nitride, Microstructure

1. INTRODUCTION

Aluminum-based composites are considered for advanced aerospace and automotive applications since they can be processed using some basic techniques such as rolling, forging, extrusion, or powder metallurgy (PM). PM is an unusual method because of its ability to giving a more uniform dispersion. PM method is applicable for a wide variety of alloy systems, the fabrication of complex-shaped parts, self-lubrication bearings, and filters. Also, it minimizes scrap losses by using more than 96% of the raw material in the fabricated component. These components may be fabricated cost-effectively at a high volume production rate by this method [1, 2, 3, 4 and 5]. In metal matrix composites, copper, magnesium, titanium, aluminum may be utilized as the main element. Among these materials, aluminum is the most preferred metallic material owing to its lightweight, high strength, good machinability, high thermal and electrical properties. The tensile strength, elasticity modulus, and density of pure aluminum change between 70-90MPa, 65-70GPa, and 2.65-2.7g/cm^3, respectively. Thanks to all these mechanical properties, aluminum and its alloys are utilized in various industrial areas such as aviation and automotive applications [6, 7 and 8].

Some ceramic materials (boron carbide (B_4C), silicon dioxide (SiO_2), titanium carbide (TiC), boron nitride (BN), titanium boride (TiB_2), and silicon nitride (Si_3N_4)) may be used as a reinforcing

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material in the aluminum matrix. Among these, boron nitride is an excellent reinforcing material for corrosion-resistant coatings, thermal conductivity enhancement, insulating coatings, hydrogen storage, electrical and oxidation circuits, water treatment, and mechanical strength enhancement. Boron nitride nanostructures also have outstanding mechanical properties. Elasticity modulus, tensile strength, and density of hexagonal boron nitride vary up to 0.8-1.3TPa, 20-33GPa, and 2.15-2.25g/cm^3, respectively. Thus, Al-based composites reinforced with boron nitride may be used in various industrial fields like cosmetics, lubricants for paints, cement for dental, and pencil lead applications [9, 10 and 11].

Some researchers published many studies [9, 10, 11, 12, 13, 14, 15 and 16] related to the determination of the mechanical strength of BN reinforced aluminum matrix composites. One paper [12] examined the influences of Cu, BN contents, and Al powder's particle sizes (2, 12, 35µm) on the microstructures and mechanical strength of aluminum alloy composites. The maximum compressive strength (~763MPa) and Brinell hardness (~128HB) were determined at 3%BN and 5.3%Cu reinforced Al matrix composite (the particle size of aluminum: 2µm). An increase in the nano boron nitride content and a decrease in the aluminum's particle size enhanced the mechanical properties of the fabricated composite. The other study [9] researched the thermal properties, compressive, and tensile strength of Al-BN composites (BN contents: 0.5, 2, 1.5vol.%). An incredible enhancement in thermal expansion coefficient (-17.6%), ultimate tensile strength (~32.8%), ultimate compressive strength (~48.7%), and hardness (~83%) was obtained at Al-1.5vol.% compared to pure Al. Another study [11] investigated the wear and mechanical strength of Al6061-Al_2O_3-BN-graphite composites. An increase in impact strength (~12J), hardness (~63HV), and compressive strength (~187MPa) of Al6061-10Al_2O_3-30BN-5graphite were detected. The wear rate declined with an increase in Al_2O_3 and BN content. The paper [10] focused on the mechanical strength of BN reinforced Al-based nanocomposites (nano BN contents: 1, 2, 4wt%). A significant enhancement in the tensile strength (~55%) and hardness (~90%) of Al-4BN composite was achieved compared to pure aluminum. A rise in BN content improved the hardness and the strength of the Al-BN nanocomposites.

2. RESEARCH SIGNIFICANCE

In this work, Al-BN composites were fabricated with various boron nitride contents (0.5, 1, 1.5, 2wt.%) by the powder metallurgy route. This paper aimed to examine the influence of nano boron nitride contents on the microstructure, hardness, compressive strength, density, and porosity of nano BN reinforced Al matrix composites.

3. EXPERIMENTAL STUDY

3.1. Materials

In the present work, pure Al powders with 10µm mean particle size, 2.70g/cm^3 theoretical density, and 99% purity were used as the main element. Besides, boron nitride with a mean particle size of ~60 nm, a theoretical density of ~2.30g/cm^3, and a purity of ~98% was selected as the reinforcement element. Hexagonal BN and pure Al powders were purchased from Alfa Aesar Company.

3.2. Method

The fabrication scheme of Al-BN composites was presented in Figure 1. First of all, BN nanoparticles were dispersed in ethanol for 60 min. Simultaneously, Al powders were mixed in ethanol. Then, BN-ethanol solution was inserted into the Al-ethanol solution little by little, and the solution was mixed by the mechanic mixer. Afterward, the filtering process was performed to remove the ethanol by filtering equipment. Al-BN mixed powders were dried at 45°C. The powders were compacted with a uniaxial press under a pressure of 600 MPa. Then, the green specimens were sintered with a sintering time of 180 min and a temperature of 630°C via a tube furnace. The samples were ground with abrasive papers of #300 and #1200, respectively. Afterward, the samples were polished using a diamond solution. Hence, the specimens were prepared for the microstructure investigations, phase analyses, the measurements of Vickers hardness, density, and compressive strength [17, 18, 19, 20 and 21].

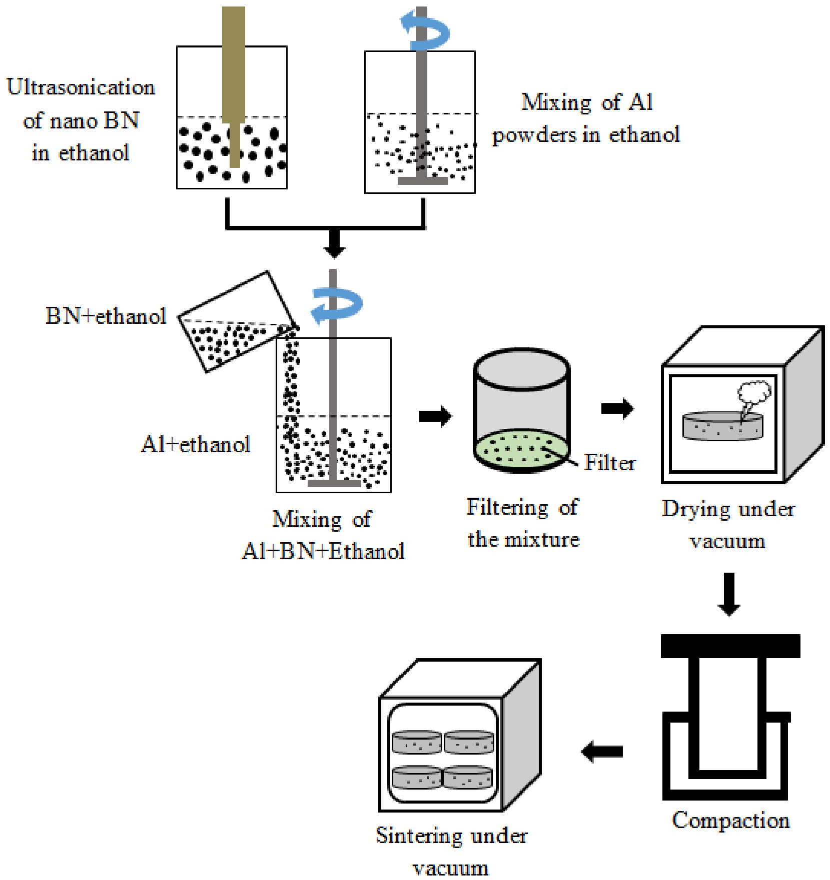

Figure 1. Production procedure of Al-BN composites via PM method

To evaluate the microstructure and phase investigations of Al-BN composites, SEM and XRD analyses were performed. XRD analyses were employed to examine the powders and specimens by an XRD device (Rigaku Smartlab) with a scanning angle of 20°≤2θ≤80°. SEM images were achieved to examine the specimens' microstructure by a SEM device (Jeol JSM-7001F).

The densities of the samples were detected by Archimedes' density meter with the precision of ±0.0001. The apparent densities may be measured as given below [22]:

$$\rho_D = [m_K/(m_D - m_A)].\rho_W \quad (1)$$

where m_K, m_A, and m_D are the mass of the specimen in air, the mass of the submerged specimen in water, the mass of the water-saturated specimen, respectively. Also, ρ_W is defined as the water's density.

The theoretical densities (ρ_T) of Al-BN composites may be indicated in Equation 2 [22]:

$$\rho_T = (m_{BN}\% \times \rho_{BN}) + (m_{Al}\% \times \rho_{Al}) \quad (2)$$

In this equation, m_{Al}% and m_{BN}% are expressed as the mass fraction of pure Al and BN. In this equation, ρ_{BN} (2.3g/cm^3) and ρ_{Al} (2.7g/cm^3) are defined as the theoretical density of boron nitride and pure aluminum. The percentage of the porosity for Al-BN composites may be determined by Equation 3 [22].

$$P\% = (1 - \rho_D/\rho_T) \times 100 \quad (3)$$

Using a Vickers hardness test device (HV-1000B) with a dwelling time of 15 s under a load of 200 g, the measurements of Vickers hardness for the samples were employed. The hardness value was detected by averaging five measures on the top surface. The compressive strength of the composite was analyzed by a Mares tst-10t compression test device.

4. FINDINGS AND DISCUSSIONS

4.1. Characterization of the Powders

Scanning electron microscope images of nano boron nitride and pure aluminum powders were presented in Figure 2. Hexagonal boron nitride nanoparticles were preferred as a reinforcing element with an irregular shape and an average particle size of 60nm (Figure 2a). Also, Al powders were selected as the matrix element with a 10µm mean particle size.

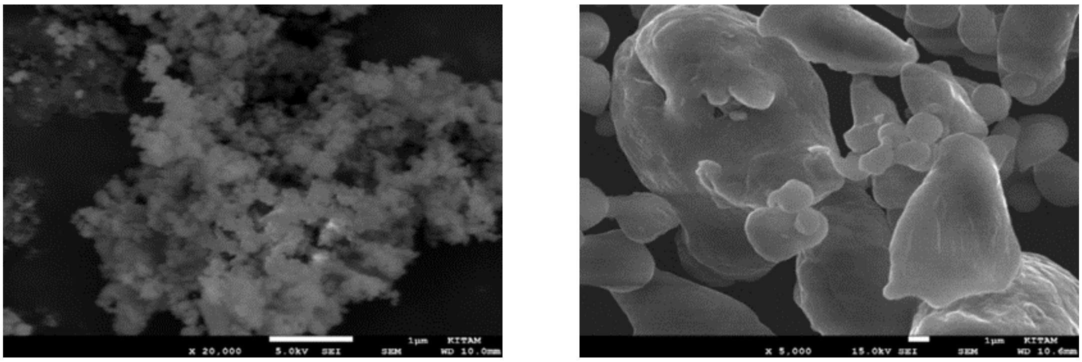

Figure 2. SEM images of nano boron nitride and pure aluminum powders

X-ray diffraction (XRD) analyses of hexagonal nano boron nitride and pure aluminum powders were illustrated in Figure 3. The high-intensity peaks (2θ=~28°, 42°, 44°, 50°, 55°, 76°) of boron nitride (JCPDS card number: 85-1068) corresponding (002), (100), (101), (102), (004), (110) planes may be clearly observed (Figure 3a). As given in Figure 3b, XRD peaks from pure Al (JCPDS card number: 89-4037) was expected at 2θ=~78°, 65°, 45°, 38° corresponding (311), (220), (200), (111) planes. The XRD analyses are an excellent source to examine the phases in the samples. Besides, undesired secondary phases (Al_4C_3 and AlN) after heat-treatment may be confirmed by this XRD analysis.

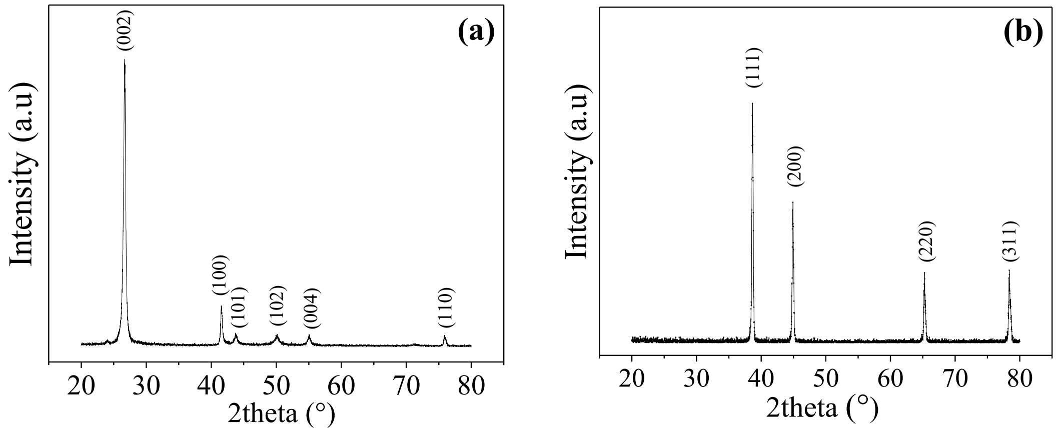

Figure 3. XRD plots of boron nitride (a) and pure Al (b)

4.2. Mechanical Test Results

The porosity and density variations of Al-BN composites were illustrated in Figure 4. As shown in Figure 4a, the maximum green density (2.59±0.01g/cm^3), apparent density (2.59±0.01g/cm^3), and minimum porosity (3.2%) were determined at %1BN reinforced Al matrix composite. The green density developed from 2.50±0.01g/cm^3 (for pure Al) to 2.59±0.01g/cm^3 (for Al-1BN) with increasing BN content. It was seen that the apparent density of BN reinforced Al matrix composites is higher than the green density of Al-BN composites due to the sintering effect. The density was increased up to 1wt.%BN content. After this content, the density was decreased due to the clustered BN nanoparticles. The porosity percentage variation of Al-BN composites was given in Figure 4b. The minimum porosity value (3.2%) was determined at the Al-1%BN composite. It was due to the fact that boron nitride nanoparticles filled the pores in the microstructure up to 1wt.%BN content. Over 1wt.%BN nanoparticles, the porosity percentage increased due to the clustered BN nanoparticles. These agglomerations negatively affected the density of the samples.

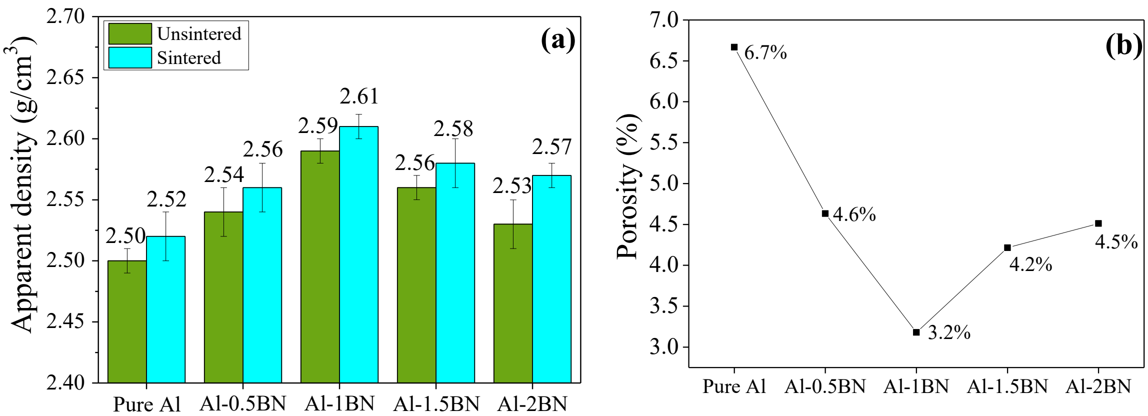

Figure 4. The apparent density (a) and porosity (b) values of the specimens

Figure 5 demonstrates the Vickers hardness values of BN reinforced aluminum matrix composites. From this figure, the hardness enhanced from 31±1 (pure Al) to 50±1 (Al-1BN) with an increase of boron nitride amount. The higher hardness value is due to the excellent dispersion of BN nanoparticles up to 1wt.%BN content. After 1wt.%BN content, the composites' hardness deteriorated due to the accumulation of BN. This accumulation was occurred due to the nanostructure of BN particles. It causes easy sliding among the agglomerated BN nanoparticles during deformation. Hence, SEM analyses were carried out to show the clustered nanoparticles.

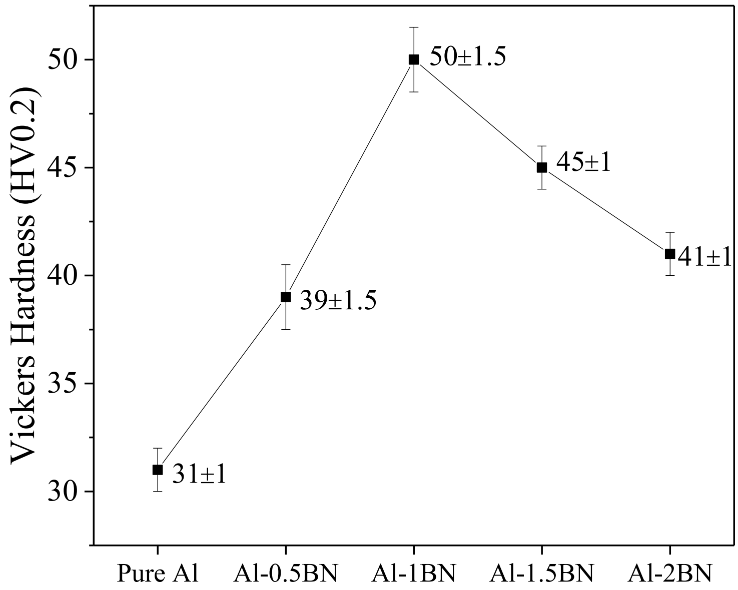

Figure 5. The Vickers hardness values of the specimens

According to the mixtures' rule, Equation 4 implies the hardness of the composites (H_C) [22 and 23].

$$H_c = f_r H_r + f_m H_m \quad (4)$$

where H_m and H_r are the hardness of the main and reinforcing material, f_m and f_r are the volume fraction of the main and reinforcing material, respectively.

An improvement in the Vickers hardness with the BN addition for boron nitride reinforced Al matrix composites can be explained by Equation 5 [22 and 23].

$$H = Gb\alpha\sqrt{\rho} + h\sqrt{tD} \quad (5)$$

where b is Burger's vector, G, α, and h are material's constant. The strengthening of the dislocation may be expressed as the dislocation density mechanism. It controls the Vickers hardness of the composites. The boron nitride addition increased the dislocation density (ρ) because of the nano-sized grains of BN. Therefore, an increment in the dislocation density causes an improvement in Al-BN composites [22 and 23].

The compressive strength variation of BN reinforced Al matrix composites and pure Al was shown in Figure 6. The compressive strength was detected as 80MPa (pure Al), 168MPa (Al-1BN), and 149MPa (Al-1.5BN). Compared to pure aluminum, an enhancement in the compressive strength of Al-1BN was achieved as 110%. A significant increase in strength may be attributed to boron nitride nanoparticles as a reinforcement element. Due to the having preference for nanosize particles, 1wt.%BN content is incredibly effective for enhancing the mechanical strength of Al-BN composites due to the preferred BN nanoparticles.

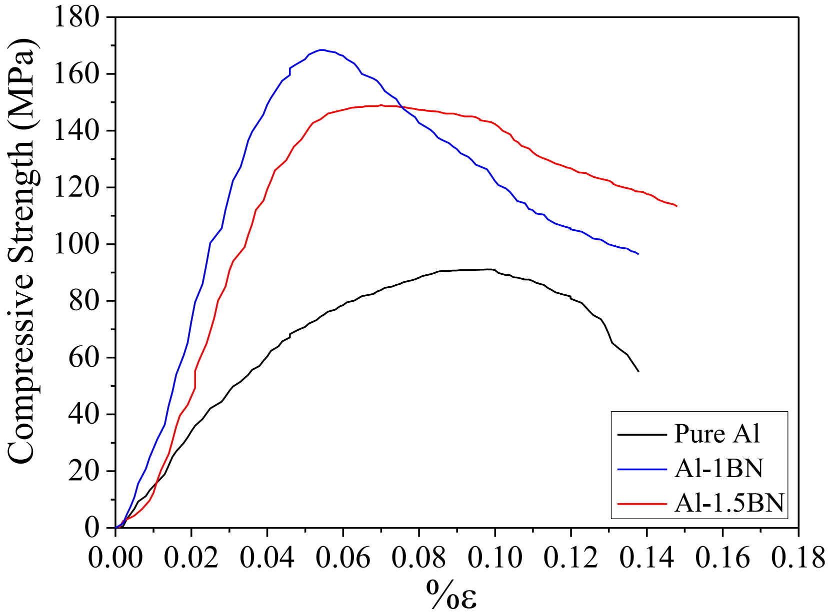

Figure 6. The compressive strength plots of the specimens

The distance among particles (λ) declines with rising the volume fraction of boron nitride (f_r) as follows [22]:

$$\lambda = [4r(1-f_r)]/(3f_r) \quad (6)$$

In this equation, r is expressed as the radius of the boron nitride nanoparticles.

The shear stress (τ_0) can be stated with a shear modulus (G), burger vector (b), and distance among particles (λ) given as below [22]:

$$\tau_0 = bG/\lambda \quad (7)$$

By investigating Equations 6 and 7, the decrease in the distance between particles raises the strength of the composite. BN nanoparticles act as a block near the grain boundary of aluminum, and it obstructs the dislocation motion. Thus, Al-based composites' strength was enhanced.

Equation 8 may be explained the strength of the composites (σ_c) as follows [24, 25, 26 and 27]:

$$\sigma_c = f_r\,\sigma_r + f_m\,\sigma_m \quad (8)$$

where f_r is the reinforcement material's volume fraction, f_m is the reinforcement material's volume fraction, σ_m is the main material's strength, σ_r is the reinforcement material's strength. Up to 1wt.% BN content, good bonding, and low pores occur between the aluminum and boron nitride nanoparticles. These occurrences enhance the strength of the composite. After 1wt.%BN content, the poor interfaces among Al and BN were formed due to the clustered boron nitride nanoparticles. These clustered nanoparticles led to lower compressive strength and higher porosity.

4.3. Characterization of the Specimens

X-ray diffraction plots of Al-1BN, Al-2BN composites, and pure aluminum were shown in Figure 7. From this figure, boron nitride peaks were illustrated at 2θ=~27.5°, 41.7°, 44.8°, 49.6°, 54.5°, 76.2° for BN reinforced Al-based composites. The boron nitride peaks verified the existence of boron nitride in BN reinforced Al-based composites. The presence of boron nitride in the Al-BN composite positively affected the mechanical strength of the composite. The undesired secondary phase structure such as AlN was not observed in any boron nitride reinforced Al-based composites. The occurrence of AlN may negatively affect the mechanical strength of boron nitride nanoparticle reinforced Al-based composites.

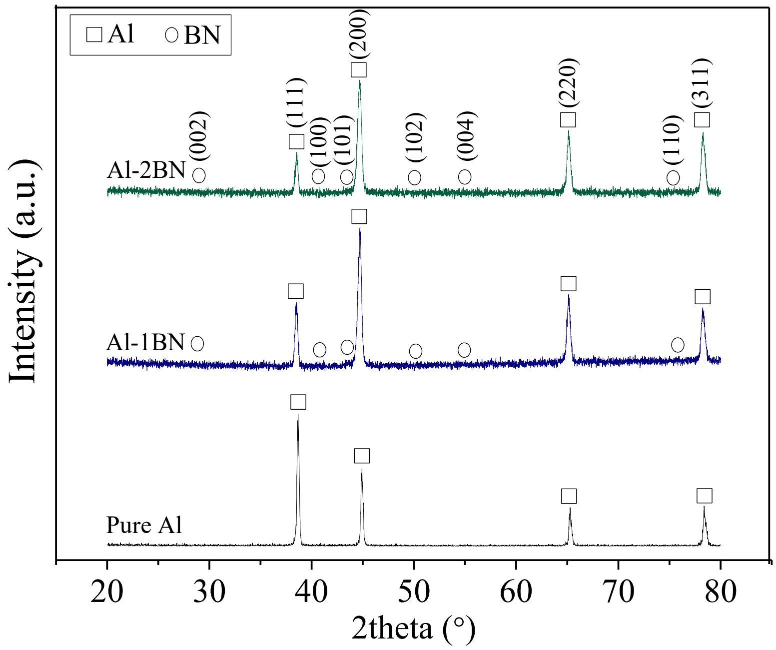

Figure 7. XRD plots of the specimens

SEM micrographs of pure aluminum and Al-BN composites were shown in Figure 8. As given in the samples' fracture surface analyses, an excellent neck formation and well bonding were detected in the samples' microstructures (Figure 8a and Figure 8d). It was clear that boron nitride was homogeneously distributed at the 1%BN reinforced Al matrix composite (Figure 8b). In contrast, agglomerated boron nitride nanoparticles were observed at 1.5%BN and 2%BN reinforced Al matrix composites (Figure 8c and Figure 8d). Also, the porosity in the microstructure of Al-1.5%BN and Al-2%BN composites is higher than the Al-1%BN composite. It is attributed to no uniform dispersion of BN nanoparticles. Similarly, the highest hardness, density, and compressive strength were detected at 1%BN reinforced Al-based composite. Thus, the microstructure analyses were verified with the results of the mechanical tests. Also, BN nanoparticles located at the grain boundaries of aluminum occurred a barrier, and hence, the composite's properties improved.

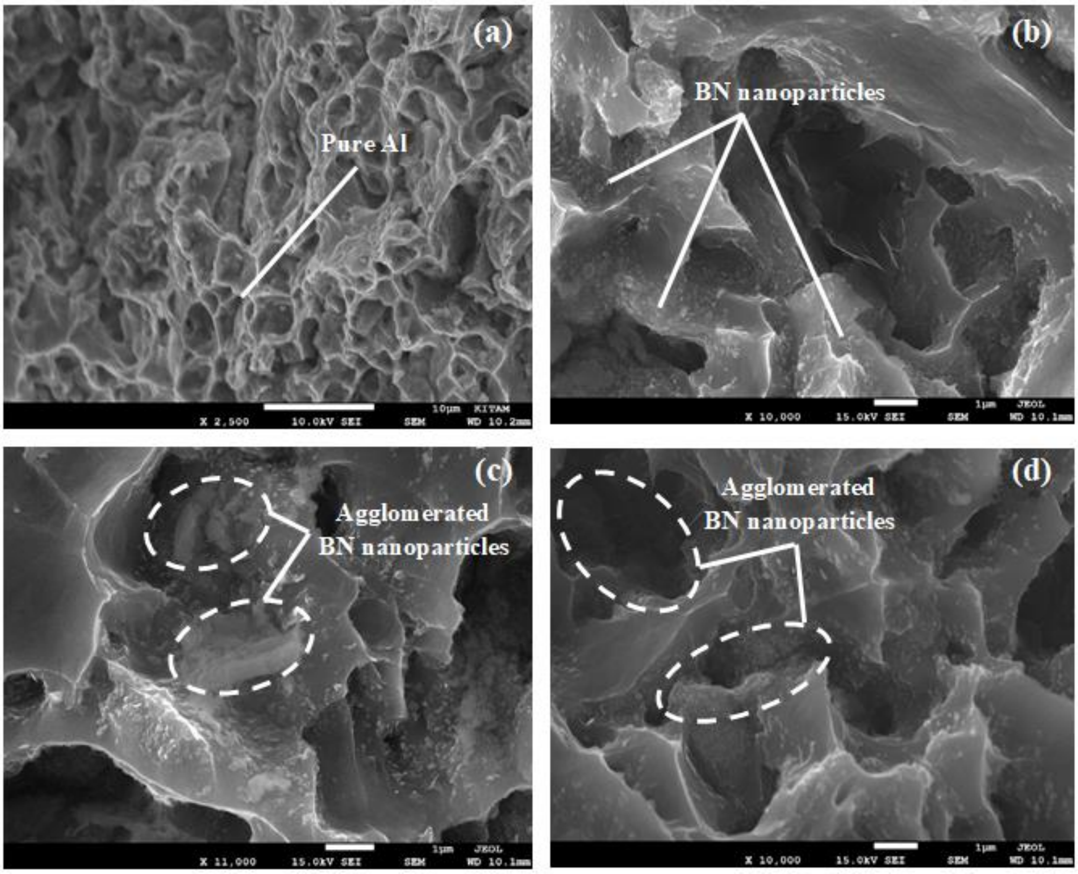

Figure 8. SEM images of pure Al (a), Al-1BN (b), Al-1.5BN (c), and Al-2BN (d) composites

5. CONCLUSIONS

In this current work, pure aluminum and BN reinforced Al matrix composites (BN: 0.5, 1, 1.5, 2wt.%) were produced via the PM route. The effect of BN content on the hardness, microstructure, porosity, density, and compressive strength of the specimens was examined. According to the mechanical test results, maximum Vickers hardness (50±1 HV), minimum porosity ratio (3.2%), maximum compressive strength (168 MPa), and experimental density (2.61±0.01g/cm^3) were observed at A-1%BN composite. After %1 BN content, the composites' strength decreased due to the clustered nanoparticles. These clustered structures were detected at SEM analyses of Al-1.5BN and Al-2BN composites. According to the SEM images, the existence of boron nitride nanoparticles was observed in all BN reinforced Al matrix composites. In the Al-1%BN composite structure, well-dispersed BN nanoparticles were observed. These particles create an obstacle at the grain boundaries. It prevents grain growth during sintering, and hence, the mechanical strength of 1%BN reinforced aluminum matrix composite improves. This study showed the skill of Al-BN composites in terms of the mechanical strength of Al-BN composites. These composites might be used as structural and functional materials in weight-critical aerospace and automotive sectors.

CONFLICT OF INTEREST

The authors declared no conflict of interest.

FINANCIAL DISCLOSURE

The authors declare that this study has received no financial support.

DECLARATION OF ETHICAL STANDARDS

The authors of this article declare that the materials and methods used in this study do not require ethical committee permission and/or legal-special permission.

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