Düzce University
Journal of Science & Technology

Research Article

Fabrication and Mechanical Behavior of Aluminum Matrix Composites Reinforced with Nano Alumina Particles

Mahmut Can ŞENEL, Mevlüt GÜRBÜZ*

Mechanical Engineering Department, Faculty of Engineering, Ondokuz Mayıs University, Samsun, TURKEY
** Corresponding author: mgurbuz@omu.edu.tr*
DOI : 10.29130/dubited.518527

ABSTRACT

In the present work, nano alumina (Al_2O_3) reinforced aluminum (Al) matrix composites with various alumina content (0-2.5wt.%) were fabricated by powder metallurgy method. This method consists of mixing, ultrasonic dispersion, filtering, drying, pressing, and sintering processes. The effects of nano alumina amount on the Vickers hardness, apparent density, compressive strength, and microstructure of nano alumina reinforced aluminum matrix composites were investigated. The maximum apparent density (2.66 g/cm3), Vickers hardness (43±1 HV), and compressive strength (130±3 MPa) were determined at Al-2wt.%Al_2O_3 composite. After 2wt.% nano alumina content, the agglomeration was detected by a scanning electron microscope (SEM). This agglomeration deteriorated the mechanical properties of nano alumina reinforced aluminum matrix composites.

Keywords: *Aluminum, Alumina, Hardness, Density, Strength, Microstructure*

Nano Alümina Parçacıkları ile Takviyelendirilmiş Alüminyum Matrisli Kompozitlerin Üretimi ve Mekanik Davranışı

ÖZET

Bu çalışmada nano alümina (Al_2O_3) takviyeli alüminyum (Al) matrisli kompozitler (ağ. % 0-2.5) toz metalurjisi yöntemiyle üretilmiştir. Bu yöntem karıştırma, ultrasonik dağıtma, filtreleme, kurutma, presleme ve sinterleme işlemlerinden oluşmaktadır. Nano alümina miktarının Vickers sertliği, yoğunluk, basma dayanımı ve kompozitlerin mikroyapıları üzerindeki etkileri incelenmiştir. Maksimum yoğunluk (2.66 g/cm^3), Vickers sertliği (43±1 HV) ve basma dayanımı (130±3 MPa), ağırlıkça %2 Al_2O_3 takviyeli Al kompozit yapıda elde edilmiştir. Ağırlıkça %2 nano alümina katkısından sonra, topaklanma oluşumu taramalı elektron mikroskobu (SEM) ile tespit edilmiştir. Bu topaklanmalar nano alümina takviyeli alüminyum matrisli kompozitlerin mekanik özelliklerini olumsuz etkilemiştir.

Anahtar Kelimeler: *Alüminyum, Alümina, Sertlik, Yoğunluk, Dayanım, Mikroyapı*

Received: 28/01/2019, Revised: 15/04/2019, Accepted: 29/04/2019

I. INTRODUCTION

In industrial applications, various methods such as injection molding, thermoforming, and powder metallurgy (PM) method can be used to fabricate the composite material [1]. PM method has many advantages such as high production rate, controlled porosity, and production with little scrap. Also, final near net shape can be obtained without any extra process by this method [2, 3].

Metal matrix composites have some desirable properties such as low thermal expansion, better high-temperature performance, high specific strength, and high stiffness [4-6]. Among MMCs, aluminum matrix composites remain the most explored materials. This is primarily due to the broad spectrum of properties offered by aluminum matrix composites at the low processing cost [6]. Aluminum matrix composites can be used in solar panel substrates, aerospace technology, electronic heat sinks, defense, automotive drive shaft fins, explosion engine components, antenna reflectors, and sports equipment among others [6, 7].

Various materials such as Al_2O_3, SiC, B_4C, TiB_2, TiC, SiO_2, MgO, and graphene can be used as a reinforcement material to fabricate aluminum matrix composites [8, 9]. Among these reinforcement materials, the most preferred material is known as alumina (Al2O3). Alumina particles have superior properties such as high corrosion resistance, high strength, high purity, high density, and good biocompatibility. For this reason, alumina is frequently used in cutting tools, spark plugs, refractors, hip prostheses, dental implants, etc. [10].

In the literature survey, most papers were focused on the mechanical properties of nano Al_2O_3 reinforced Al-based composites [11-14]. Ezatpour et al. [11] researched the effects of nano alumina content (0.4, 0.8, 1.2 wt.%) on the mechanical properties and microstructures of nano alumina reinforced Al7075 composites. The highest strength value was obtained at Al7075-0.4wt.% nano alumina composite. After this alumina content, the mechanical properties of aluminum matrix composites were decreased due to the agglomeration of nano Al_2O_3 particles. Srivastava and Chaudhari [12] investigated the mechanical properties and microstructure of nano alumina reinforced Al6061 composites with various weight percentages (1, 2, 3 wt.%). The Vickers hardness (+76%) and yield strength (+81%) of Al6061-2wt.%Al_2O_3 composite improved when compared to the Al6061 alloy. The mechanical properties of aluminum matrix composites reduced because of the formation of microcracks over 2wt.% nano alumina content. Kok [13] studied on the mechanical properties of alumina reinforced Al2024 matrix composites with various alumina particle sizes (16, 32, 66 μm) and weight percentages (10, 20, 30wt.%). The tensile strength and Vickers hardness of Al2024-Al_2O_3 composites increased with decreasing the particle size and increasing the weight fraction of particles.

In this work, nano alumina reinforced aluminum matrix composites with various alumina content (0-2.5wt.%) were fabricated by the powder metallurgy (PM) method. This works aims to investigate the effect of nano alumina amount on Vickers hardness, apparent density, microstructure, and compressive strength of aluminum matrix composites.

II. Materials And Method

A. MATERIALS

In the present work, pure Al powders (99% purity, 8-15 µm particle size) were used as a matrix material. Also, nano alumina powders (98% purity and 100 nm particle size) were preferred as a reinforcement material in order to fabricate Al-Al_2O_3 composite. Aluminum and alumina powders were supplied by Alfa Aesar Inc. (United Kingdom) and Panadyne Inc. (United State of America), respectively. The theoretical density of Al and Al_2O_3 were determined as 2.7 and 3.97 g/cm^3.

B. METHOD

Fabrication scheme of pure Al and Al-Al_2O_3 composites via powder metallurgy (PM) method is given in Figure 1. In the method, Al powders were mixed in ethanol solution for 1 hour. At the same time, nano alumina powders were dispersed in ethanol solution by the ultrasonic homogenizer. Then, the aluminum solution was added to the alumina solution drop by drop. The Al-Al_2O_3-ethanol solution was mixed and filtered. After filtering, Al-Al_2O_3 mixture was dried under vacuum during the overnight. Afterward, the mixture was compacted under 600 MPa to obtain green samples. The samples were sintered under vacuum at the certain sintering time (t_S=180 min) and sintering temperature (T_S=630 °C). The phase analyses of powders and composites were performed by X-ray diffraction (XRD) device (Rigaku Smartlab). The microstructure and morphology of powders and composites were examined by scanning electron microscope (Jeol JSM-7001F). The Vickers hardness of samples was detected by micro-Vickers hardness tester under 200 g load for 15 s. The measurement was carried out at least six times from the surface of the sample and then, they were averaged. The apparent density and compressive strength of composites were performed by Archimedes' density meter and universal test machine (Mares Tst_10t), respectively [15-17].

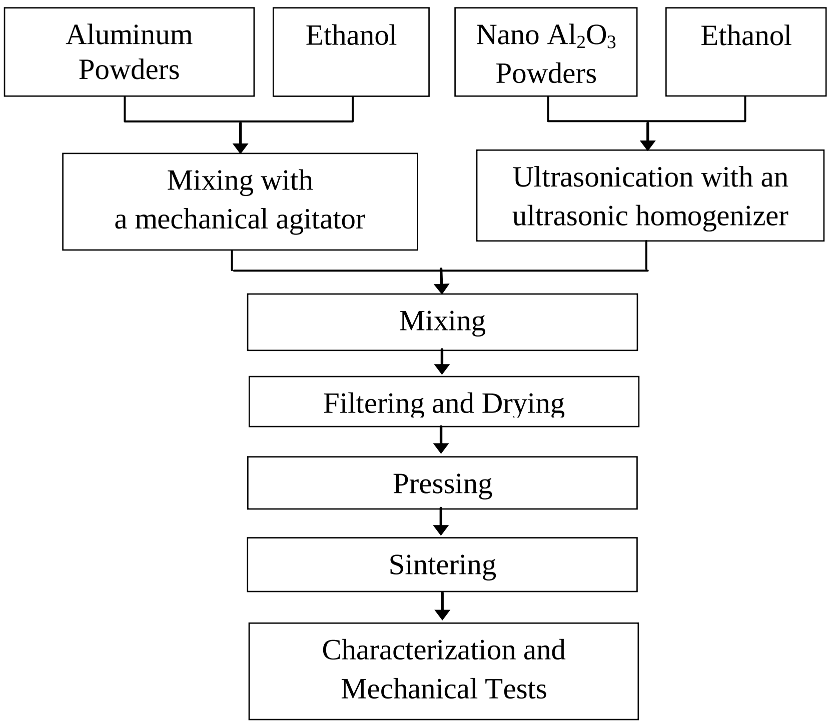

Figure 1. *Fabrication schemes of Al-Al_2O_3 composites by powder metallurgy method [15]*

III. Results And Discussion

A. CHARACTERIZATION OF POWDERS

Figure 2 illustrates the secondary electron microscope (SEM) images of pure aluminum (Al) and nano alumina (Al_2O_3) powders. As seen from the figures, Al and nano Al_2O_3 powders have an irregular morphology. Also, the particle sizes of pure Al and nano Al_2O_3 powders are approximately measured as 10 µm and 100 nm, respectively.

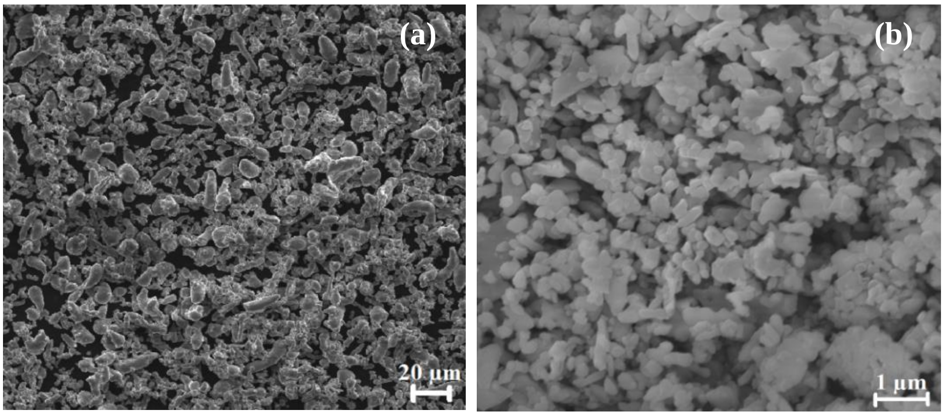

Figure 2. *SEM images of pure Al (a) and nano alumina (Al_2O_3) powders (b)*

SEM-EDX (Energy Dispersive X-ray) analyses of Al-2%Al_2O_3 mixed powders were given in Figure 3. As shown in the figure, the distributions of aluminum (Al) and nano alumina (Al_2O_3) powders were shown at green and blue color, respectively. Alumina particles in Al-2%Al_2O_3 mixed powders were distributed uniformly. This uniform distribution affected the mechanical properties of Al-2%Al_2O_3 composite positively.

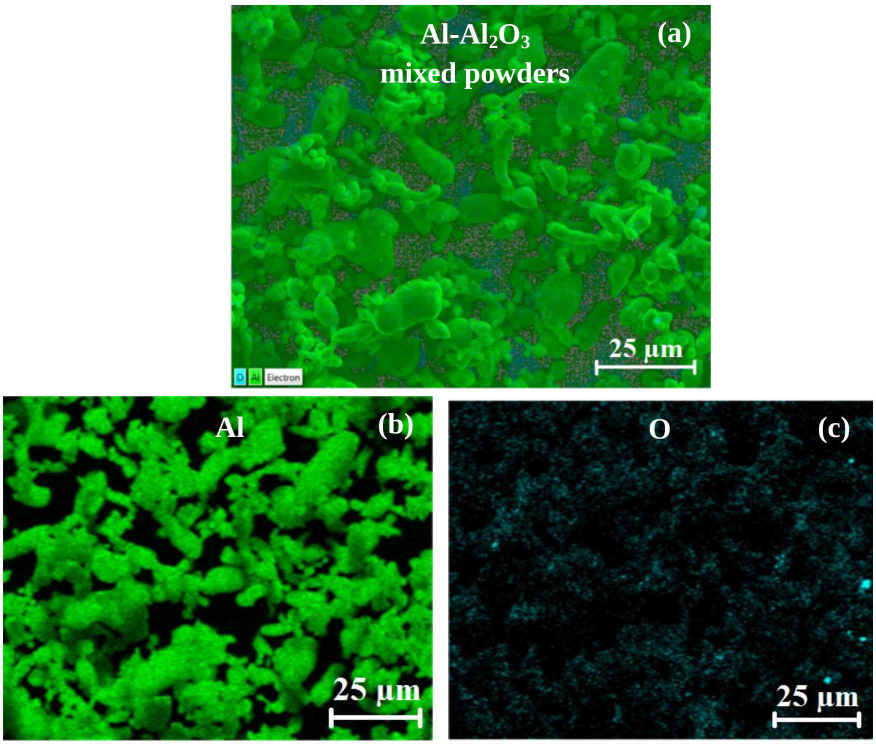

Figure 3. *SEM-EDX images of Al-2%Al_2O_3 mixed powders (a), Al (b) and O (c) distribution in mixed powders*

B. DENSITY AND HARDNESS MEASUREMENT OF COMPOSITES

The densities of sintered and unsintered samples were detected by Archimedes density meter kit. The highest density was determined at sintered Al-2%Al_2O_3 composite (2.66 g/cm^3). After 2%Al_2O_3 content, the apparent density of the composite decreased because of the agglomeration tendency of nano Al_2O_3 particles. It was clearly seen that the sintering effect increased the apparent density of Al-Al_2O_3 composite (Figure 4).

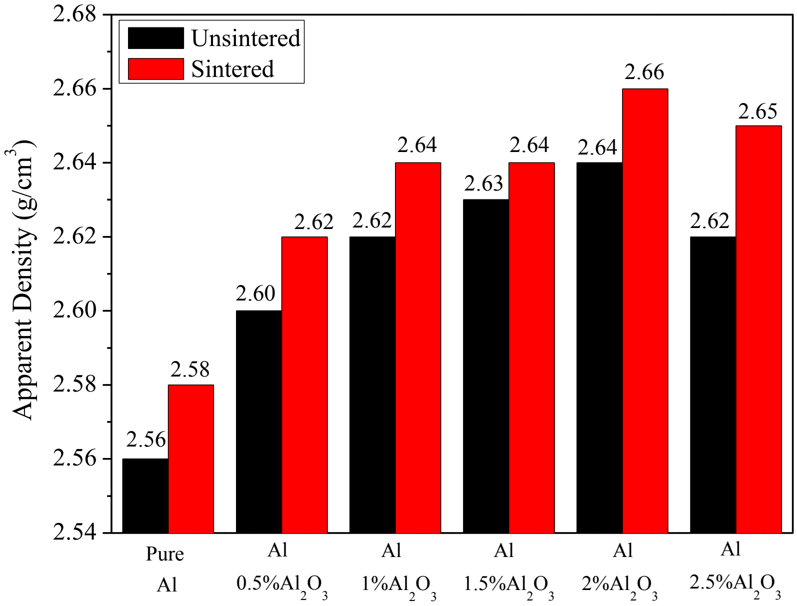

Figure 4. *The apparent density variation for Al-Al_2O_3 composites and pure Al*

The Vickers hardness variation for sintered Al-Al_2O_3 composites and pure Al were shown in Figure 5. The highest Vickers hardness value (43±1 HV) was obtained at Al-2%Al_2O_3 composite. The Vickers hardness of Al-2%Al_2O_3 increased nearly the rate of 43% compared to pure aluminum. After 2%wt. nano alumina amount, the Vickers hardness decreased because of the agglomeration of nano Al_2O_3 particles.

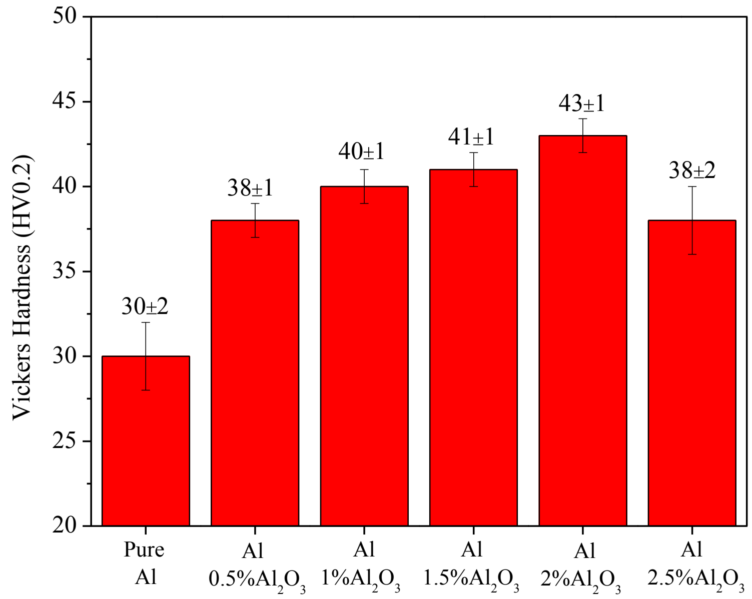

Figure 5. *The Vickers hardness variation for sintered Al-Al_2O_3 composites and pure Al*

C. COMPRESSIVE STRENGTH OF COMPOSITES

Figure 6 illustrated the compressive strength variation for sintered Al-Al_2O_3 composites and pure Al. The compressive strength of pure aluminum was determined as 82±2 MPa. By adding to 2wt.%Al_2O_3 to Al matrix, the compressive strength of Al-2%Al_2O_3 improved up to 130±3 MPa. After 2wt.% nano alumina content, the Vickers hardness of Al-2.5wt.%Al_2O_3 composite decreased to 120±2 MPa due to the agglomeration of Al_2O_3 particles.

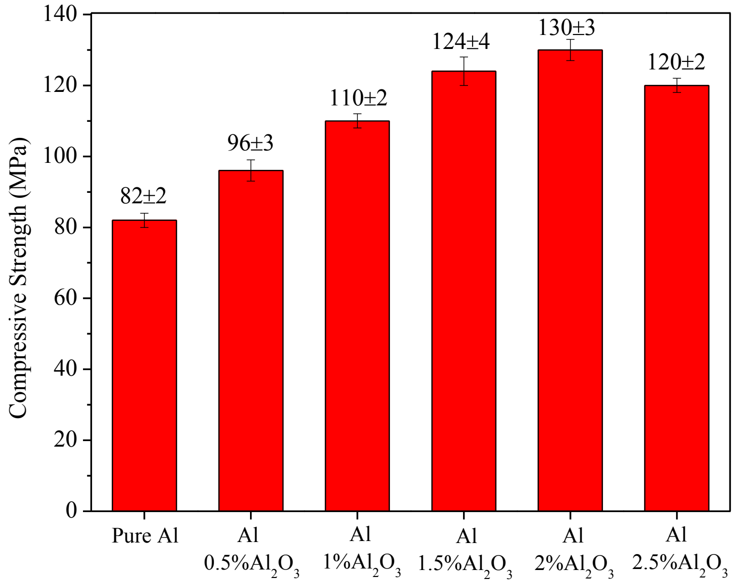

Figure 6. *The compressive strength variation for sintered Al-Al_2O_3 composites and pure Al*

D. CHARACTERIZATION OF COMPOSITES

X-ray diffraction (XRD) graphs of sintered Al-Al_2O_3 composites and pure Al were presented in Figure 7. From the figure, the peak angles (2θ=~25°, 35°, 38°, 43°, 53°, 58°, 61°, 67°, 68°, 77°) of Al_2O_3 confirmed the existence of Al_2O_3 in Al-Al_2O_3 composites. Also, the intensity of alumina peaks in aluminum composites increased with increasing alumina content. From the XRD analysis, the undesired in-situ phase formation was not detected in any Al-Al_2O_3 composition.

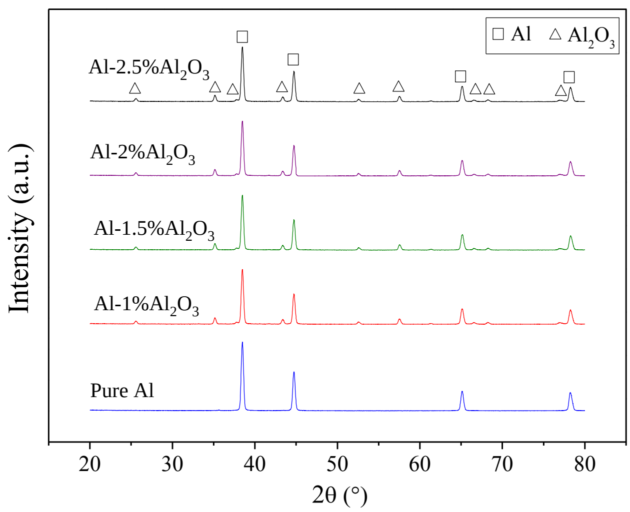

Figure 7. *XRD plots of sintered Al-Al_2O_3 composites and pure Al*

SEM images of 1%, 1.5%, 2%, and 2.5% nano Al_2O_3 reinforced Al composites were illustrated in Figure 8. As shown in the figure, nano alumina particles were distributed homogeneously in Al-x%Al_2O_3 (x=1, 1.5, 2) composites. On the other hand, the agglomeration was observed in Al-2.5%Al_2O_3 composite. This agglomeration was deteriorated the mechanical properties of nano alumina reinforced aluminum matrix composite.

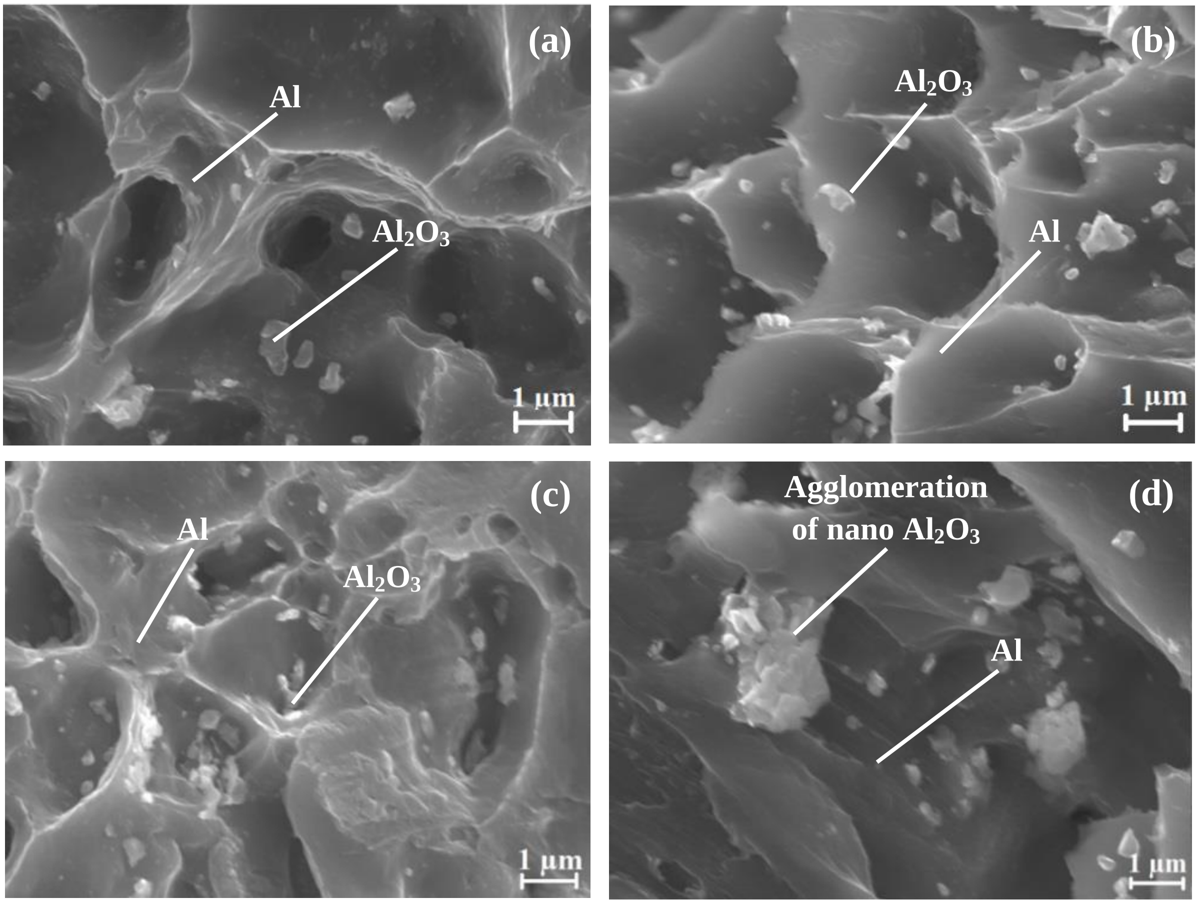

Figure 8. *SEM images of 1% (a) ,1.5% (b), 2% (c), and 2.5% (d) Al_2O_3 reinforced Al composites*

Figure 9 gave the SEM-EDX mapping images and elemental distribution of Al-2%Al_2O_3 composites. In this composite structure, aluminum and nano alumina distributions were shown in green and red color, respectively. Nano-alumina particles were uniformly distributed in Al-2%Al_2O_3 composite. The maximum Vickers hardness, compressive strength, and apparent density were obtained at Al-2%Al_2O_3 composite. Hence, the microstructure analyses confirmed the density, compressive strength, and Vickers hardness measurement of the composites.

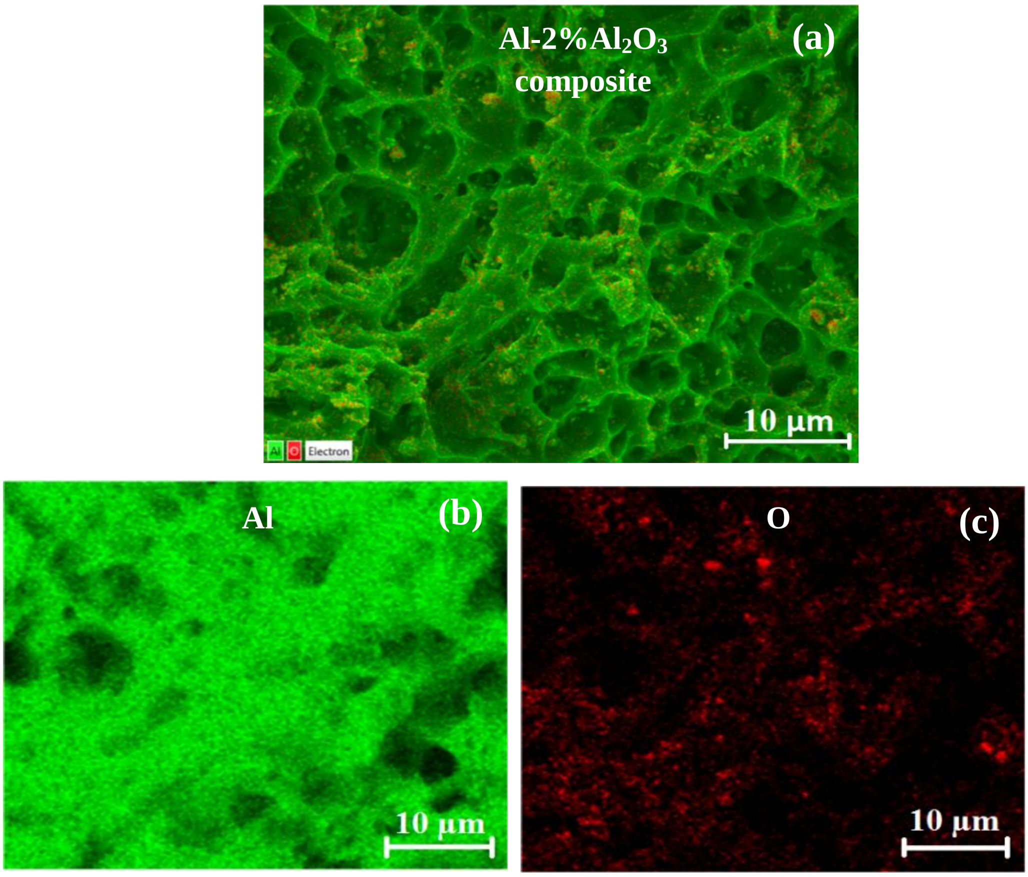

Figure 9. *SEM-EDX mapping images of Al-2%Al_2O_3 (a) and Al (b) and O (c) distribution in Al-2%Al_2O_3 composite*

The fractured surface microstructure images of Al-2.5wt.%Al_2O_3 composite with low and high magnification were illustrated in Figure 10. By using SEM device, the microstructure image with x10000 magnification was obtained from Figure 10a. The agglomerations of nano alumina particles were observed into Al-2.5wt.%Al_2O_3 composite. To detect the grain growth after sintering, SEM image with x22000 magnification was given in Figure 10b. From this image, the grain size of alumina particles was measured as nearly 100 nm. It is clear that the size of alumina grain is equal to the size of alumina powders. Hence, any grain growth in alumina particles were not detected from the SEM micrograph images which negatively affected the mechanical properties.

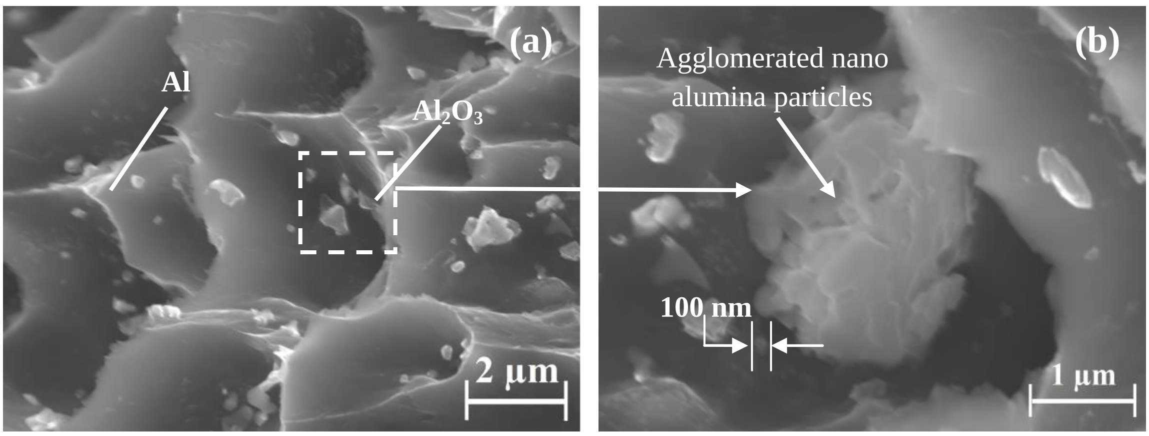

Figure 10. *The microstructure images of Al-2.5%Al_2O_3 composite with low (a) and high magnification (b)*

IV. CONCLUSIONS

In this study, pure aluminum and nano alumina (Al_2O_3) reinforced aluminum (Al) matrix composites with various alumina content (0-2.5wt.%) were produced by the powder metallurgy method. The effects of nano alumina amount on Vickers hardness, apparent density, compressive strength, and microstructure of the fabricated composites were summarized as given below.

- Among Al-Al_2O_3 composites, the best apparent density (2.66 g/cm^3), Vickers hardness (43±1 HV), and compressive strength (130±3 MPa) were obtained at Al-2wt.%Al_2O_3 composite.

- From the SEM analyses, a good neck formation and bonding between the particles were detected in all compositions. The uniform distribution was detected in Al-x%Al_2O_3 (x=1, 1.5, 2) composite. On the other hand, the agglomeration was observed in Al-2.5wt.%Al_2O_3 composite. These agglomerations led to the higher porosity and lower mechanical properties.

- The fractured surface SEM images of Al-2.5wt.%Al_2O_3 composite shows that any grain growth was not detected which negatively affected the mechanical properties. On the other hand, agglomerations of alumina particles were detected from the fracture surfaced microstructure image with high magnification. These agglomerations deteriorated the mechanical properties of Al-2.5%Al_2O_3 composites.

- From XRD analysis, the peak angles (2θ=~25°, 35°, 38°, 43°, 53°, 58°, 61°, 67°, 68°, 77°) of nano alumina confirmed the presence of alumina in Al-Al_2O_3 composites. Also, undesired secondary phase formation was not detected in any composition.

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