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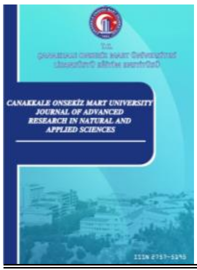


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# Production of $B_4C$ Reinforced Composite Materials and Investigation of Their Bending Strength

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***Research Article***

**Abstract-** In this study, AA2024 aluminum alloy was selected as the matrix material, while $B_4C$ was selected as the reinforcement material, and particle-reinforced Al-matrix composite materials were produced using the powder metallurgy method. Examinations were made to determine the effects of different reinforcement particle ratios and sintering temperatures on the mechanical properties of the AA2024 matrix composite materials that were produced. The powders were compressed in a metal mold at room temperature and a pressure of 525 MPa under a uniaxial press. The raw specimens that were obtained were sintered for 45 minutes at different temperatures. The produced composite materials were subjected to three-point bending tests and hardness measurements. Optical microscopy analysis was carried out for characterization. The results allowed us to draw a conclusion on how the reinforcement material in the produced specimens affected Al-matrix composite properties. It was determined that the $B_4C$ reinforcement added to the matrix increased the hardness values of the composites at all sintering temperatures, the highest bending strength was obtained in the composite with 10% $B_4C$ particle reinforcement, and in general, the $B_4C$ reinforcement was homogeneously dispersed in the matrix. Increased $B_4C$ reinforcement ratios resulted in higher hardness values in the composite materials.

***Keywords***- *Aluminum alloys, composite materials, powder metallurgy, reinforcement particle ratio, sintering.*

## 1. Introduction

Light material applications utilize high abrasion resistance (Rahmani, Majzoobı, Zadeh & Kashfı, 2021) The properties of metal-matrix composite materials (MMCs), made these materials preferable due to their high mechanical values. ( Karakoc, Ovalı, Dündar & Itak, 2019). The inadequacy of metals and alloys in providing both strength and hardness to a material has led to the development of MMCs (Topcu, Güllüoğlu, Bilici & Gülsoy, 2020). In MMCs, matrix materials such as Ti, Al, and Mg are used (Karakoc et. al., 2019). Aluminum, which is in the class of light metal materials, is used in several fields of the industry with the advancements in technology and its technical properties (Güven & Delikanlı, 2012). Aluminum alloys are the most commonly used metal engineering materials after steel in the industry today (Gökçe, Fındık & Kurt,.2017). High strength aluminum alloys are commonly used in aerospace because of their good machinability (Altıparmak, Yardley, Shi & Lin, 2021). Aluminum-based composite materials, which are produced by combining an aluminum alloy matrix and various reinforcement materials on a macro scale, have much more advantageous properties than unreinforced aluminum alloys. Although it is light, its high strength and high specific strength, low thermal expansion coefficient and high wear resistance can be counted as its main advantages (Karabulut, Karacif & Türkmen, 2021). Aluminum MMCs are scientifically engineered components with greater potential to increase strength in the defense, aerospace, and automotive industries (Radhika, Sasikumar, Sylesh & Kishore, 2020).

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Aluminum composites have become important materials for cylinders, pistons, piston rods, piston rings, and many other automotive applications (Aherwar, Patnaik & Pruncu, 2020). Aluminum alloy is used in aero-space industries (Merisalu et. al., 2021). Aluminum AA2024, which is strengthened by precipitation, is highly prevalently used in the structural components of aircraft thanks to its good mechanical, fatigue properties and high corrosion resistance (Mohammadi, Vanhove, Bael & Duflou, 2012). While some ceramic-based reinforcements like $Al_2O_3$ and SiC are used frequently in aluminum MMCs, there is a limited number of studies conducted on aluminum MMCs reinforced with $B_4C$, which is a hard ceramic (Radhika et. al, 2020). It is known that combining $B_4C$ with a metal can alleviate problems associated with brittleness. The most popular metal that is used for this purpose in combination with $B_4C$ is aluminum (Çolak & Turhan, 2019). $B_4C$ is a carbide-based reinforcement material that has a high level of hardening capacity at high temperatures, high hardness, low density, and excellent chemical and thermal stability (Radhika et. al, 2020). $B_4C$ is a superhard material. The hardness of $B_4C$ is second only to diamonds and cubic boron nitride in nature (Wang et. al., 2020). $B_4C$ is an important engineering material because of its high abrasion resistance ($\sim 2 \times$ 10-14$m^2N^{-1}$) (Lyu et. al., 2020). In composite material production, particle size and the distribution of particles inside the matrix structure are determining parameters on the properties of mechanical of the composite material that is produced (Arık, Kırmızı & Özçatalbaş et al, 2017). The fabrication of MMCs is achieved by both how and cold fabrication methods such as powder metallurgy, die casting, vacuum and pressure infiltration, and hot extrusion. Among these methods, powder metallurgy has gained great momentum in recent years. The powder metallurgy method is a fabrication method that is carried out by shaping metal powders that are mixed by compacting in a mold with a suitable shape and dimensions for the part to be produced at room temperature or high temperatures, followed by sintering them at a certain temperature (Pul & Baydaroğlu, 2020). The most important reason for the preference of the powder metallurgy method is the homogeneous distribution of particles. In this method, the desired part can be successfully produced by compacting in a mold based on the desired part shapes and dimensions (Okay & Islak, 2021).

In this study, $B_4C$ particle-reinforced metal composites of Al2024-matrix were produced at reinforcement ratios of 7% $B_4C$, 10% $B_4C$, 15% $B_4C$, and 20% $B_4C$ by the powder metallurgy, and the effects of the reinforcement materials on the mechanical and microstructural analyzes of composites were investigated. In the production of the composites, the parameters included a compacting pressure of 525 MPa, a sintering time of 45 minutes, and sintering temperatures of 550 °C, 575 °C, and 595 °C. Three-point bending and hardness tests were conducted on the samples, and the values that were obtained were analyzed along with microstructure scenes.

## 2. Material and Methods

In this experimental study, Al2024 with particle sizes of 100-150 μm was used as the matrix material, while the reinforcement material was selected as $B_4C$ powder with a particle size of 10 μm. According to methods reported in previous studies in the literature, 5 different reinforcement ratios were determined and Table 1 presents.

Table 1
Mix ratios of composite specimens

| Sample code | Mixing ratios by weight AA2024 | $B_4C$ |
|---|---|---|
| N1 | 100 | - |
| N2 | 93 | 7 |
| N3 | 90 | 10 |
| N4 | 85 | 15 |
| N5 | 80 | 20 |

Powder mixtures were obtained by weighing the powders that were used in the study using a RADWAG PS 1000/C/2 precision scale with a readability value of 0.001 g. Since the powders could not be well compacted during compression, polyethylene glycol (1% by weight) was added to the powder mixtures as a binder in order to increase the compressibility of the powders. The powders that were prepared by weighing at the desired ratios and mixed were compressed in a 10x10x55 mm mold using a Hidrokar Hidrolik (100-ton) brand uniaxial press and fabricated. During fabrication, the surface where the inside of the mold contacted the part and the punch surface contacting the mold were wiped with a lubricant (stearic acid+ethanol) solution after each compaction process. This way, the parts and the punch were prevented from getting stuck in the mold. While removing the specimens from the mold, a force that corresponded to approximately 10% of the compacting pressure was applied. During the compaction and removal of the specimens, care was taken to avoid the application of impact forces.

The AA2024-matrix and $B_4C$-reinforced composite materials that were produced were cut at the dimensions of 10x10x10 mm to conduct the hardness tests and metallurgical examinations, and they were hot-mounted using a Struers Citopress-1 hot mounting press. The hot-mounted specimens were polished by using 180, 320-, 600-, 800-, 1000-, and 1200-grid round sandpapers with a Metkon Forcipol 1v brand polishing machine. After the sanding and polishing steps of the specimens were completed, fine polishing steps were carried out by putting a diamond paste suspension at a particle size of 3 μm on a round polishing pad placed on the disc. To obtain information on the microstructures of the sanded, polished, and then acid-etched(Keller's reagent) specimens and characterize the composites, a NIKON ECLIPSE ME600D brand optical microscope was used. The hardness measurements of the composite materials were made using a Brinell hardness device (Load: 15.625 kg., Indenter Diameter: 2.5 mm, Time: 10 s). Each hardness value was taken as the average of the hardness values obtained from 5 different zones of the tested specimen. Three point bending tests of the samples were made using Autograph (AG-1/100Kn 346-52111-11) brand device and were calculated with the equation given below in ASTM B 528-16 (ASTM B 528-16. 2008) standard.

$$ÇKD = \frac{3.P.L}{2.t^2.W} \text{ (Mpa)} \qquad (2.1)$$

P: The load at the time the test specimen is broken(N), L: Length between supports(46 ±0,3mm), t: Thickness of the test sample(10±0,13mm) , W: Width of test sample(10±0,13mm), ÇKD: Cross fracture strength(MPa)

## 3. Results and Discussion

The effects of the 10-μm $B_4C$ added to the AA2024 matrix on hardness are shown in Figure 1. As seen in Figure 1, at all temperatures, as the ratio of the added reinforcement increased, the hardness values of the specimens also increased. The main reason for this was the fact that the hardness of the reinforcement phase $B_4C$ added to the matrix was higher than the hardness of the matrix.

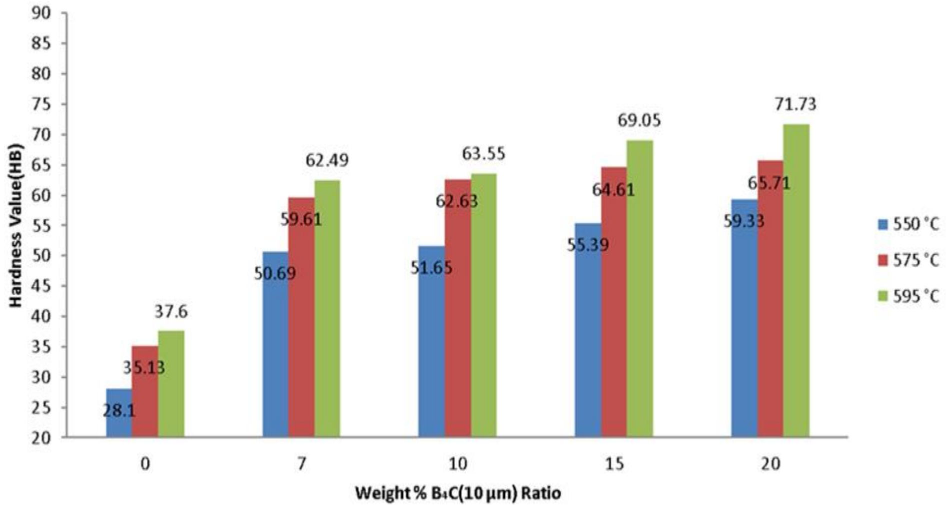
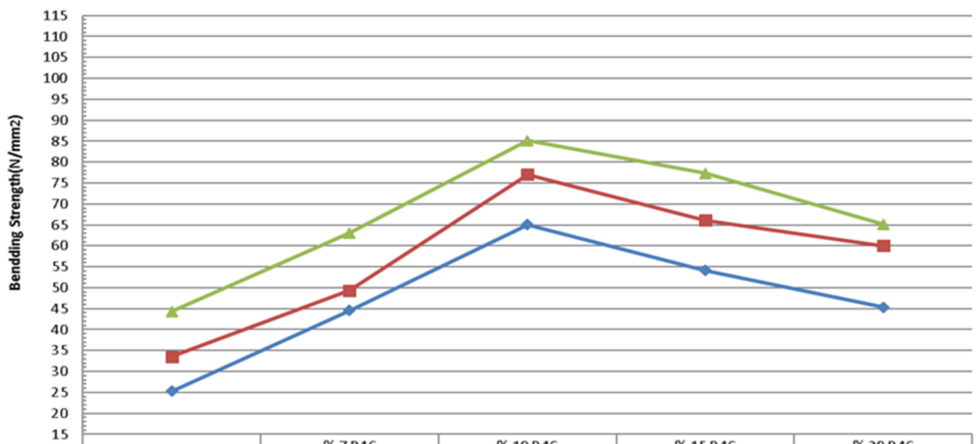



Figure 1. Changes in the hardness values of the AA2024 + 10 μm $B_4C$ specimens based on temperature and reinforcement ratio changes

Similarly, in the study conducted by Şenel M. C. (Şenel, 2020), composites of Al-$B_4C$ and Al-$Al_2O_3$ were produced by the powder metallurgy by adding $Al_2O_3$ or $B_4C$ at different ratios (0, 1, 3, 6, 9, 12, 15, 30% by weight) to pure aluminum, the effects of reinforcement ratio of composites on hardness, compressive strength and microstructure were investigated. Compressive strength and the highest hardness values were found in the Al-30% $B_4C$ specimen (hardness: 75 HV, compressive strength: 178 MPa), the $Al_2O_3$ specimen of Al-30% (hardness: 52 HV, compressive strength: 162 MPa). In comparison to the pure aluminum specimen, the hardness of the $Al_2O_3$ with Al-30% composite increased by 73.3%, its compressive strength increased by 80%, whereas the hardness of the Al-30% $B_4C$ composite increased by 150%, and its compressive strength increased by 98%. Consequently, the author reported that the ceramic reinforcement materials added to the aluminum matrix resulted in increased mechanical properties such as hardness and compressive strength. Likewise, Çolak and Turhan (Çolak & Turhan, 2016) produced an Al-Si/$B_4C$ MMC material using powder metallurgy. Into an Al-7% Si powder mixture, they added $B_4C$ at ratios of 5, 10, 15, and 20% by weight, subjected the resulting powder mixtures to cold compaction under 450 MPa pressure, sintered them by keeping them under an argon atmosphere at 590 °C for 60 minutes. Then, the mechanical properties of the composite samples were determined by making hardness measurements. The highest hardness value depending on the ratio of $B_4C$ added to the aluminum matrix was found as 71.3 HV in the N5 specimen containing 20% $B_4C$. They measured the lowest hardness value as 38.4 HV in the N1 specimen that was hot compacted without adding particle reinforcement and reported that the hardness values increased in general based on increased reinforcement ratios. Hasırcı and Gül (Hasırcı & Gül, 2010) produced $B_4C$ particle-reinforced Al-matrix composite materials using powder metallurgy and prepared 4 different specimens, pure Al, Al with 5% $B_4C$, Al with 10% $B_4C$, and Al with 20% $B_4C$. They reported that in all hardness measurements, as the reinforcement ratio and the hardness values continuously increased. Çelik et al. (Çelik, Kılıçkap & Yenigün et al, 2018) investigated the hardness and microstructure values of $B_4C$-reinforced Al-matrix composites produced with the powder metallurgy method depending on different compaction pressure values and reinforcement ratios. As a result of their experiments, the researchers determined higher hardness values as the compaction pressure and reinforcement ratio values increased. Şahin and Öksüz (Şahin & Öksüz, 2016) also produced copper-matrix with 10% $Al_2O_3$ and $B_4C$ composite materials containing by volume using the powder metallurgy and examined the mechanical properties of the composites. As a result of their experiments, they found that the composites mechanical properties were developed by the reinforcement phases added to the matrix, the hardness and wear resistance values of the $B_4C$ particle-reinforced composites were significantly superior to those of the $Al_2O_3$ particle-reinforced composites.




| | % 100 AA2024 | % 7 B4C (22-59 µm) | % 10 B4C (22-59 µm) | % 15 B4C (22-59 µm) | % 20 B4C (22-59 µm) |
|---|---|---|---|---|---|
| 550 °C | 25.29 | 44.55 | 65.09 | 54.13 | 45.29 |
| 575 °C | 33.49 | 49.35 | 77.03 | 66.09 | 60.03 |
| 595 °C | 44.33 | 63.01 | 85.09 | 77.30 | 65.13 |

Figure 2. Changes in the strength of three-point bending of the AA2024 + 10 µm $B_4C$ specimens based on temperature and reinforcement ratio changes

While the strength of three-point bending of the AA2024 + 10 µm $B_4C$ specimens increased up to the addition of $B_4C$ at 10% by weight, it decreased at higher reinforcement ratios. The main reason for this was that due to the increased reinforcement particle ratio inside the matrix, the compactness of the composite decreased, and its porosity increased. Against the force that was applied, the matrix lost its ability to absorb these pores inside it, and accordingly, the strength of three-point bending of the composite dropped as the ratio of the added reinforcement increased. This situation is demonstrated in Figure 2.

In the study conducted by Arık et al. (Arık, Kırmızı & Özçatalbaş, 2017), $B_4C$-reinforced MMCs with an Alumix-13 matrix were produced hot compaction, and their mechanical properties were examined. The powder mixtures containing 5, 10, and 15% $B_4C$ by weight were compacted under a pressure of 50 MPa at 610 °C for an hour, solution-annealed at 530 °C for 3 hours, and artificially aged at 160 °C for 13 hours. They conducted hardness measurements and three-point bending strength tests on the aged and non-aged composite materials. The authors observed that an increase in the ratio of the reinforcement material and the thermal aging procedure increased the hardness and three-point bending strength values of the composites. Among the powder-metallurgical parts they obtained, while the hardness value of the neat Alumix-13 was 63.97 HB, the composite containing 15% $B_4C$ had a hardness value of 99.59 HB, which was 55.6% higher than that of the neat Alumix-13. Considering the values, the researchers obtained as a result of their three-point bending tests, the $B_4C$ reinforcement material provided a significant increase in the three-point bending strength of the powder-metallurgical composite materials, but there was a decrease in the three-point bending strength of the composites containing 10% $B_4C$. As a reason for this result, they suggested that the increased tendency of fracture formation with the increased $B_4C$ ratio restricted the deformation during the three-point bending test and probably showed a tendency towards a cleavage fracture, which may have led to the lower three-point bending strength values at increased reinforcement ratios. Moreover, Arık H. (Arık, 2019) produced SiC-reinforced composite materials using the powder metallurgy method and investigated the hardness and fracture strength of these materials that were compacted under a pressure of 500 MPa and sintered for 2 hours at 650 °C. Compared to the neat matrix structure, the composite structure was more resistant to three-point bending, and while the flexural deformation in the neat specimen was 2.37 mm, this value was 1.83 mm for the composite material, and the author reported that the 10% SiC reinforcement added to the matrix provided a substantial improvement in the mechanical properties of the composite material. In other studies, in the literature, as in our study, it has been concluded that ceramic reinforcement materials added to the metal matrix improve the mechanical properties of the matrix.

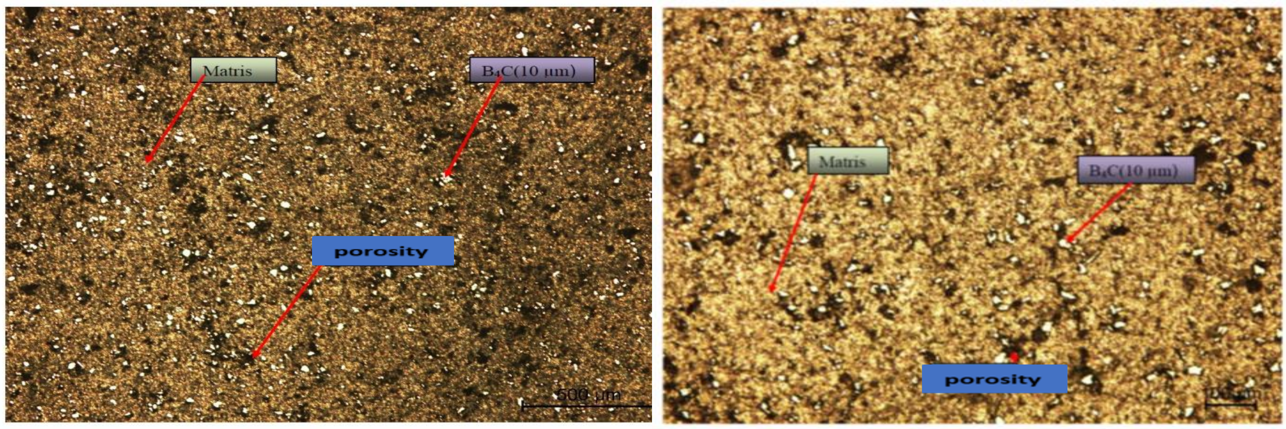



Figure 3 Optical microscopic image of 90% AA2024+10% B4C (10 µm) sintered at 575 °C

To examine the particle distributions of the obtained specimens, microstructure photographs were taken using an optical microscope. Figure 3 shows the microstructure images of the 90% AA2024+10% $B_4C$ (10 µm) composite material that was sintered at 575 °C. The images of the composite specimens revealed that a homogeneous $B_4C$ (10 µm) particle distribution occurred in the matrix. In these images, it was also seen that there were pores around some $B_4C$ particles. It is believed that these pores were caused by the inadequacy of the compaction pressure that was applied. As the grain size decreased, the ceramic particles were observed to gather usually at grain boundaries. Furthermore, it was seen that the grain sizes of the $B_4C$ particles were not uniform, and they included both large and more ground particles. While this may have been caused by the pressure that was applied, it may also be a consequence of contact among the particles.

## 4. Conclusion

In this study, upon the examination of AA2024-based MMCs that contained 7% $B_4C$, 10% $B_4C$, 15% $B_4C$, and 20% $B_4C$ reinforcement materials by volume, it was observed that the hardness and three-point bending strength values of the composites varied based on their reinforcement particle ratios and sintering temperatures. The optical microscopy examinations revealed that the $B_4C$ particles were homogeneously distributed in the matrix. According to the comparisons of the unreinforced AA2024 material and the $B_4C$ particle-reinforced composite, the hardness of the composite was significantly higher, and the reason for this was that a sufficient interface connection was achieved between the reinforcement particles and the matrix as a result of the addition of $B_4C$ powder particles which had much smaller particle sizes compared to the matrix. Moreover, the three-point bending strength of the matrix was also increased by the addition of $B_4C$, but there was a decrease in the three-point bending strength of the composite when $B_4C$ was added to the matrix at higher ratios than 10%. The main reason for this was that the density of the composite decreased, and its porosity increased with the increase in the ratio of the reinforcement particles in the matrix. In turn, the pores inside the matrix lost their absorbance capacity against the load that was applied, and the three-point bending strength of the composite decreased along with increasing reinforcement ratios.

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## Author Contributions

Halit Doğan: He planned, designed and performed the analysis.

Yılmaz Mutlu: He designed the study, made the statistical analyzes and wrote the article.

## Conflict of Interest

The authors do not have any conflict of interest to declare.

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