Wear and mechanical properties of Al6061/SiC/B4C hybrid composites produced with powder metallurgy

Article in Journal of Materials Research and Technology · September 2019
DOI: 10.1016/j.jmrt.2019.09.002

CITATIONS
11

READS
162

4 authors, including:

Halil Karakoç
Hacettepe University
28 PUBLICATIONS 128 CITATIONS

Dündar Sibel
Gazi University
1 PUBLICATION 11 CITATIONS

Ramazan Cıtak
Gazi University
47 PUBLICATIONS 159 CITATIONS

Some of the authors of this publication are also working on these related projects:

Innovative design applications View project

Eğitimde Artıklı Sergelik Uygulamalarının Kullanımı-Eğiticiyin Uzmanlaşması Eğitim View project
Original Article

Wear and mechanical properties of Al6061/SiC/B₄C hybrid composites produced with powder metallurgy

Halil Karakoç a,*, İsmail Ovalı b, Sibel Dündar c, Ramazan Çitak c

a Department of Mechanical Program, Hacettepe University, 06935 Ankara, Turkey
b Department of Manufacturing Engineering, Pamukkale University, 20160 Denizli, Turkey
c Department of Metallurgy and Materials Engineering, Gazi University, 06500 Ankara, Turkey

ABSTRACT

This study investigates the production of various reinforced and non-reinforced composite materials using powder metallurgy (PM). It presents the new approach into optimize the mechanical properties of hybrid composites (Al-SiC-B₄C) produced with powder extrusion process. Al6061 powders are used as the matrix material and B₄C and SiC powders are used as the reinforcement materials. Matrix and reinforcement materials are mixed in a three-dimensional mixer. The mixtures are then subjected to cold pressing to form metal block samples. Block samples are subjected to hot extrusion in an extrusion mold after being subjected to a sintering process. This produces samples with a cross-sectional area of 25 × 30 mm². These extruded samples were subjected to T6 heat treatment. The composite materials produced are examined in terms of density, hardness, transverse rupture strength, tensile strength, and wear resistance. Furthermore, optical microscopy, scanning electron microscopy, energy-dispersive X-ray spectroscopy and XRD are performed to examine the microstructure, surface fractures, and surface abrasion. In this study, high density Al6061/B₄C/SiC hybrid composite materials were successfully produced. After extrusion, some micro particles were found to crack. The highest hardness occurred in 12%B₄C reinforced composites. The lowest hardness was obtained in Al6061 alloy without reinforcement. The highest tensile strength occurred in 12%SiC particle reinforced composite material. The highest wear resistance was obtained for 9%B₄C+3%SiC samples due to the hardness of B₄C and the good adhesion properties of the matrix and SiC.

© 2019 The Authors. Published by Elsevier B.V. This is an open access article under the CC BY-NC-ND license (http://creativecommons.org/licenses/by-nc-nd/4.0/).

1. Introduction

Superior properties of metal matrix composites (MMC), such as their high strength, low density, and high modulus of elasticity, make these materials indispensable [1]. Different matrix materials, such as Al, Mg, and Ti, are used in MMCs [2]. Among these, Al is one of the most preferred matrix materials because
of its light weight, good effective heat and electrical conductivity, and high corrosion resistance [3]. Many Al alloys (eg 2xxx, 5xxx, 6xxx and 7xxx) are used industrially [4]. 6xxx series of aluminum alloys have good machinability and extrudability [5]. By adding hard ceramic particles into these alloys, abrasion resistance and mechanical properties can be improved [6]. Particles of boron carbide (B₄C) and silicon carbide (SiC), the most favored reinforcement materials among aluminum matrix composites (AMC) materials, strengthen the matrix structure and provide high resistance, good wear resistance, and high thermal stability [7,8]. Today, two different types of ceramic particles are incorporated into the Al matrix to produce hybrid composite materials [9]. Dual reinforcement elements used in hybrid composite materials can improve mechanical properties and cost of composites can be reduced [10,11]. In addition, the weight of the composite formed due to the reinforcing elements used can be reduced [12]. The aluminum hybrid composite devices also show that it can be used in place of conventional materials in advanced applications [13]. Many different techniques such as PM and casting are used in the production of MMC materials [14]. When we compare the casting technique with the PM technique, some advantages of PM come to the forefront. In the production of PM, no chemical reaction occurs between the matrix phase and the reinforcing element, since production occurs at low temperatures. In addition, high amounts of ceramic particles can be added into the matrix phase [15,16].

The main aim of this study is to produce hybrid composite materials which have improved wear and mechanical properties by adding B₄C and SiC particles to Al6061 alloy, which has good machinability and extrudability and also has good corrosion resistance. In this study, non-reinforced (Al6061 alloy), conventional reinforced (Al6061 / B₄C - Al6061 / SiC) and double reinforced (Al6061 / B₄C / Al6061 / SiC) composite materials were produced by using extrusion process in PM. The mechanical properties, such as hardness, bending strength, and elongation, were investigated and compared by evaluating fracture surfaces and microstructures. Microstructural analyses were carried out using scanning electron microscopy (SEM).

2. Experimental procedures

2.1. Materials and methods

The powder size of the 6061 series aluminum was taken to be smaller than 100 µm (suppliers: Beijing Xing Rong Yuan Technology Company, China). The chemical composition of Al6061 is shown in Table 1. The AMC materials were reinforced with 3 wt.% B₄C and 9 wt.% SiC; 6 wt.% B₄C and 6 wt.% SiC, 9 wt.% B₄C and 3 wt.% SiC, and 12 wt.% B₄C (<10 µm) and 12 wt.% SiC (<8 µm). SiC and B₄C ceramic powders which were used as reinforcing elements were obtained from Tural Technology Company in Turkey. The properties of metal and ceramic powders used in the production of composite materials are given in Table 2. A flowchart of the process is shown in Fig. 1. First, the mixture ratios of the Al6061 and B₄C powders were determined and separately mixed for 30 min in a Turbula three-dimensional mixer. Next, Al6061 and SiC powders were prepared with the same parameters. All of the volume fractions are shown in Table 3. During the experimental work, the reinforcement particles were added slowly for a homogeneous distribution. The mixed compositions were pressed at 300 MPa and sintered at 550 °C for 1 h. Finally, the composite materials were extruded at the same temperature using a pre-heated hydraulic extrusion mold and taking the form of shaped metal blocks (Fig. 2a and b). The composite materials obtained after extrusion were subjected to T6 aging heat treatment. The composite materials were subjected to 1 h dissolution at 530 °C and then immediately cooled in water. The cooled samples are then artificially aged for 8 h by heating at 175 °C with a heating speed of 10 °C/min.

2.2. Analysis of microstructure and mechanical properties

In this study, Al6061 was used as a metal matrix and B₄C and SiC powders as reinforcement materials. Fig. 3 shows SEM images and particulate size distributions of the powders used in the study. The analyses show that the Al6061 matrix powders had irregular spherical forms with a grain size of below 100 µm on average. The B₄C powders, on the other hand, were found to have a complex and cornered form with grain sizes varying between 1 and 10 µm. The SiC powders had a complex form with sizes varying between 1 and 8 µm. For the metallurgical examination, three samples of each powder at sizes of 24 × 18 × 5 mm were cut using a diamond cutter in the direction of vertical extrusion. After they were cut, the samples were subjected to cold mounting (molding by epoxy resin). Then, using decoupage, the samples were sanded with emery papers of 400, 600, 800, 1000, and 1200 grits, respectively. After sanding, the samples were polished by means of diamond suspension with felts of 6, 3, and 1 µm, respectively. This polishing procedure minimized the surface roughness.
The samples were then seared for 15 s using a 1-ml HF + 200-ml H₂O searing solution.

A Leica DM4000 M optical microscope was used to perform a microstructural examination of the composite materials. A JEOL JSM 6060LV scanning electron microscope was used to investigate the interfacial connection cohesion between the reinforcement materials (B₄C, SiC) and main material (Al6061). In the composites produced, and energy-dispersive X-ray spectroscopy (EDS) analyses were also performed on the same SEM microscope. A Sartorius scale of 0.1 mg sensitivity was used to perform density measurements of the Al6061/B₄C/SiC composite materials produced using the Archimedes method. The Brinell method for hardness measurement was used to investigate the hardness of the composite materials that were produced using the PM method and subjected to the T6 ageing process. Hardness measurements were performed using an EMCO-TEST DuraVision 200 hardness measurement device using 2.5 mm ball end and a 31.25 kgf load. Three samples of each type of composite material produced were selected for mechanical tests of tensile and transverse rupture strength. A
Johnford T35 CNC lathe workbench and a Johnford VMC550 CNC planer with three axes (manufactured in the Manufacturing Engineering Department of Gazi University) were used to prepare the samples for the mechanical test. Samples were prepared to ASTM E8M standards in the direction of extrusion using the composite materials obtained after the extrusion process. Tensile tests were performed using an Instron 3369 universal testing device with 50 kN tensile and compression capacity at 1 mm/min at room temperature. Tensile strengths and percentage elongation values were produced and recorded on a computer connected to the tensile testing device. Samples with sizes of 31.7 × 12.7 × 6.35 mm were prepared for the transverse rupture tests in compliance with “MPFI–411998” standards. The transverse rupture tests were performed with a transverse rupture apparatus specially prepared with the Instron 3369 universal test device with 50 kN tensile and compression capacity. The tests were conducted at room temperature and at a speed of 1 mm/min. X-ray diffraction (XRD) of composite materials was performed on Bruker brand D8 Discover model XRD. Cu Kα radiation (Kα = 1.54056) was used for measurements.

XRD results were analyzed for microstructural characterization of composite materials. The average crystallite size was calculated from the full width at half maximum (FWHM) of the XRD peak by using Scherer’s Eq. (1) [17,18].

\[ D_p = \frac{(\lambda \cos \theta)}{B \sin \theta} \]  

(1)

Where:
- \( D_p \) = Average crystallite size,
- \( \lambda \) = X – Ray wavelength,
- \( B \) = FWHM of the diffraction peak,
- \( \theta \) = Angle of diffraction,
- \( K \) = Scherer’s constant of the order of about unity (0.94) for usual crystals.

### 2.3. Analysis of wear properties

The wear tests were carried out using a pin-on-disk wear-testing device according to ASTM G132-96. Sample surfaces were ground with 80 SiC paper for removing rough surface, then the AMC test pin, with a diameter of 10 mm, was fixed and a counter face abrasive disk (abrasive paper of 200 grit) was used during the test. The wear tests were performed at distances of 100, 200, and 300 m, at a speed of 1.2 m/s and with imposed loads of 5, 10, and 15 N. The coefficient of friction between the pin specimen and the disk was determined with a load cell. Prior to measurement, the samples were cleaned with acetone to remove surface contaminants, dried, and then weighed using an electronic balance with a resolution of 0.001 mg.

A pin-on-ball wear test was applied to examine the abrasion behavior of the AMC materials. This test was carried out with a velocity of 2.8 m/s and load conditions of 5, 10, and 15 N.

### 3. Experimental results

#### 3.1. Microstructure, density and mechanical characterization

Optical microscope was used to acquisition images that revealed the particle distribution of the composite materials after vertical extrusion (Fig. 4). In the image of Al6061, no pores are observed in the microstructure (Fig. 4a). This resulted from the high density of the material that occurred in parallel with the plastic deformation during the extrusion process. For the microstructures of the composites reinforced with B4C and SiC, this study found that B4C/SiC particles in 3%B4C+9%SiC composites generally exhibited a homogenous distribution in the matrix. In 6%B4C+6%SiC and 9%B4C+3%SiC composites, on the other hand, it was observed that the formation of agglomerations increased in parallel with the increase in B4C content.
While 12%B₄C composites exhibited a higher level of agglomeration, low numbers of pores is formed in the microstructure. It was observed that micro cracks are formed in some particles, as a result of friction between particles during the extrusion process. The study also demonstrated that SiC particles in 12%SiC composites displayed a homogenous distribution in the matrix structure.

In Fig. 5, XRD peaks of Al6061 alloy and B₄C, SiC particle reinforced composite materials are given. The Al, B₄C and SiC peaks in the figure were found by looking at the literature [20-22]. When the XRD peaks are examined, it is seen that Al (111) and Al (200) peaks are more extensive and distinct than other peaks. B₄C and SiC peaks are less prominent. The average crystal sizes of the composite materials were calculated according to Scherer equation and compared with each other. In literature studies, it is known that micro stresses increase with decreasing crystal size [23,24]. Increased micro tension increases the strength of the material. Consequently, the highest value was observed in Al6061 alloy with 45.8 nm. The lowest value was found in 12SiC composite material with 33.1 nm. This explains why the 12SiC composite material exhibits superior strength properties than Al6061 material. The 12B₄C reinforced composite material was found to be larger than the 12SiC particle reinforced composite material having an average crystal size of less than Al6061. In hybrid composite materials, average crystal size increased with increasing B₄C ratio.

Composite materials with an Al6061 matrix and reinforced with B₄C and SiC particles in different proportions were produced by means of a PM technique. Zheng et al. investigated composite materials reinforced with AA2024/20%B₄C, which they produced via mechanical milling, hot pressing, and hot extrusion, with respect to mechanical properties and microstructure. The samples subjected to hot pressing under 823 K and 400 MPa were also subjected to hot extrusion at the same temperature, which produced composites with maximum density. They observed that after the hot extrusion the B₄C particles exhibited a regular distribution in the AA2024 matrix and the pores formed during the sintering process disappeared [19].

Low density reduces the mechanical properties of composites. For this reason, in the present study, the samples were subjected to hot extrusion and then were sintered after cold pressing in order to produce high-density samples.

Fig. 6a shows theoretical and experimental density relationships versus reinforcement rates for the composite materials produced. As Fig. 6a shows, the average densities of all the powder metal blocks subjected to cold pressing are over 89%. In the cold-pressed samples, Al6061 had the highest density (91.03%) and 12%B₄C-reinforced composites had the lowest density (89.55%). While the densities of Al6061 and 12%SiC are close to each other, the densities decrease in parallel with the increase in B₄C ratio. The average densities in all the samples subjected to extrusion were observed to be 99%. This situation resulted from the high plastic deformation of the composites during the extrusion process. While the highest density was observed in the Al6061 alloy (99.74%), composite materials reinforced with 12%B₄C had the lowest density (99.02%).

Fig. 6 shows the hardness, transverse rupture resistance, and tensile resistance values of the composite materials produced. The reinforced composites had higher hardness values compared with the reinforced Al6061 alloy (Fig. 6b). While Al6061 had an average hardness value of 50 HB, the 12%B₄C composite displayed the highest value of hardness with 76 HB. It is known that in an Al matrix the hardness values of composites generally increase in parallel with the increase in B₄C ratio [25]. The average hardness value in 12%SiC composites was calculated to be 54 HB. In composites reinforced with B₄C and SiC, the hardness values displayed an increase in parallel with the increase in B₄C ratio. It was observed that ceramic particles in reinforced composite materials played a role in
the increase in hardness by forming a strain in the matrix structure. Mechanical properties of aluminum alloys can be improved by the addition of ceramic particles, silicon carbide, alumina, barium chloride etc. With the addition of reinforcements to aluminum alloy, the hardness value of the material increases while ductile value decreases [26].

The transverse rupture strength was found to be 402.5 MPa in composites reinforced with 12%SiC (Fig. 6c). The composite 12%B4C, which displayed the highest hardness value, showed the lowest transverse rupture strength with 358 MPa. Transverse rupture strength decreased in parallel with the increase in B4C ratio in the B4C and SiC composites. The transverse rupture strengths of 3%B4C+9%SiC, 6%B4C+6%SiC, and 9%B4C+3%SiC composites were calculated to be 378, 367, and 362 MPa, respectively.

In the optical microscope images, it can be seen that B4C reinforcement elements form an agglomeration in the matrix structure. It can also be observed in the mixed composites that agglomerations increased in parallel with the increase in B4C content.

The tensile strength values of the composite materials that were subjected to tensile tests in the same environment are shown in Fig. 6d. While the Al6061 material displayed the lowest tensile resistance with 174 MPa, the 12%SiC composite had the highest value at 185.1 MPa. This study thus demonstrated that in B4C/SiC composites, tensile resistance values tend to decline with increasing B4C reinforcement ratio. As is the case with the transverse rupture values, agglomerations in the matrix structure also had an effect on the tensile strength. Harichandran and Selvakumar reported that particles displayed an agglomeration when the B4C ratio was over 6% with respect to weight and that this formation caused the strength and ductility of the composite materials to decline [27].

After the extrusion, SEM images were taken and EDS analyses were performed of Al6061 material that was not reinforced.
in the direction of vertical extrusion and of the composite material reinforced with 6%B4C+6%SiC. Examining the SEM image of the Al6061 material, we observed that there was scarcely any porosity in the structure (Fig. 4). In addition, alloy composition rates in the structure were also calculated by means of elemental analysis. SEM images and EDS results obtained from 6%B4C+6%SiC composite material are shown in Fig. 7.

Elementary (EDS) analyzes were performed from certain regions of the composite material. In Fig. 7a, in the EDS analysis taken from zone 1, the high boron content and carbon ratio indicate the presence of B4C particles. In the EDS results obtained from zone 2, it is understood that this particle is SiC because of high silicon and carbon content. Examining the SEM image in Fig. 7d, we observed that cavities are formed around the B4C particles. These result from the weak wettability between the B4C particles and the matrix phase. It is known that there is a problem of wettability between aluminum and B4C reinforcement in literature researches [28].

In Fig. 8, it is seen that some hard particles are cracked or broken. It is thought that micro-cracks or fractures occur in the hard brittle ceramic particles that move into the mold cavity with the matrix material due to high deformation and friction during extrusion. In a similar study, it was stated that macro or micro cracks occur in B4C particles extruded with aluminum matrix [29].

3.2. Fractography of tensile specimens

Three tensile tests were performed for each of the Al6061 composite materials, which contained 12% ceramic particles with respect to weight. After the tensile tests, fracture surface tests were conducted to characterize the fracture behaviors and the interface bonds between the matrix and reinforcement materials. To investigate the microstructures of the broken surfaces, samples were taken from full sections of the fractured surfaces and placed in the SEM device. SEM images at different magnifications were taken from the broken surfaces of non-reinforced Al6061, 6%B4C, 6%SiC, 12%B4C, and 12%SiC composite materials (Fig. 9).

The excessive ductility preferred in the production of composite materials caused micro-poring on all the surfaces of the broken materials, owing to the Al6061 matrix. A higher level of dimple formation was observed on the broken surface, owing to the structure of the non-reinforced Al6061 material, which has a behavior that is more ductile compared with reinforced composites. Comparing the particle-reinforced composites, it was observed that dimple formation on the broken surfaces decreased in parallel with the increase in B4C ratio. This resulted from the trend of the B4C ratio, which increases brittleness in composite materials. Comparing the broken surfaces of 12%B4C and 12%SiC, we observed that 12%SiC caused the formation of more dimples. As a result, the 12%SiC composite material, which was more ductile in the tensile test, displayed greater strength.

It was observed that B4C particles on the broken surfaces are debonded from the matrix. Due to the weak bonding between the matrix phase and B4C particles in B4C-reinforced composite materials, that is, due to insufficient wetting, B4C particles are easily debonded from the matrix at the moment of breakage and remained on both sides of the broken surfaces. In SiC-reinforced composites, on the other hand, it was
observed that, thanks to good bonding at the interface, the SiC particles remained embedded in the matrix phase at the moment of traction.

3.3. Effect of sliding distance and load on volume loss

The variation in volume loss of the HMMCs and unreinforced composite Al6061 as a function of load and sliding distance are shown in Fig. 10. The volume loss increased with the increase in applied load and wear distance in all samples. Canakci investigated microstructure and abrasive wear behavior of B4C particle reinforced 2014 Al matrix composites. The experimental results showed that sliding time (distance) affects the average wear volume loss of the composites. The volume loss also increases with increasing sliding time (distance) and with decreasing particle content of B4C. His results show the good agreement with the present study [30]. Hard reinforcing particles increase the wear performance of Al MMCs [31].

As can be seen from Fig. 10, the volume loss of Al6061 was lower compared to that in the HMMCs. While the minimum volume loss was found to be 0.07 mm³ from the 12%B4C hybrid composite for a 5 N load and a 100 m sliding distance, the maximum volume loss was found to be 3 mm³ for the 12%SiC hybrid composite for a 15 N load and a 300 m sliding distance. As evident from Fig. 10, weight loss decreased with the increase in weight percent of B4C in the HMMCs. The B4C reinforcement decreased the volume loss more than the SiC reinforcement and had effects that are more beneficial. The 9%B4C+3%SiC samples exhibited a lower weight loss than the 12%B4C samples. The 9%B4C+3%SiC samples show the highest wear resistance.

3.4. Effects of sliding distance and load on the wear rate

To investigate the relationship between reinforcement content of HMMCs, sliding distance, and load, the wear rates were calculated. The wear rates of the unreinforced and HMMC samples are given as a function of sliding distance in Fig. 10. As can be clearly seen from the figures, the wear rate decreases linearly with the increase in sliding distance. Uthayakumar et al. Investigated wear performance of Al–SiC–B4C hybrid composites under dry sliding conditions. They defined that, as a result of large scale plastic deformation, wear rate increase within crease in the loads applied [32]. The results show the good agreement with the present study. Tang et al. [33] also defined that Al–B4C composites showed higher wear rate at higher loads (65 N).

Al6061 samples exhibit greater wear rates compared to those of HMMC samples. The 9%B4C+3%SiC hybrid compos-
This created The 3.5.

Fig. 10 – Variation in the volume losses and wear rate of (a) Al6061 (b)12SiC, (c) 3B4C9SiC, (d) 6B4C6SiC, (e) 9B4C3SiC and (f) 12B4C wt.% Hybrid composite as a function of the sliding distance at different applied loads.

ite exhibits the lowest wear rate. As evident from Fig. 3, B4C particles have more beneficial effects on the wear rate than SiC particles. These results can be attributed to the greater hardness of the B4C particles.

As can be seen from Fig. 10, the maximum wear rate was found to be $6.6 \times 10^{-13}$ mm$^3$/m for the 12%SiC hybrid composite for a 15 N load and 300 m sliding distance, while the minimum wear rate was found to be $1.4 \times 10^{-13}$ mm$^3$/m for the 9%B4C+3%SiC hybrid composite for a 5 N load and 100 m sliding distance. Uthayakumar et al. [32] reported that B4C easily created a boron oxide (B$_2$O$_3$) layer on the surface of a sample. This layer reduces the wear rate significantly.

3.5. Effects of sliding distance and load on the friction coefficient

The coefficient of friction of the unreinforced samples and HMMCs samples were measured in order to determine the wear behavior. As illustrated in Fig. 11, the coefficient of friction decreased with the increase in load but also fluctuated during sliding. All samples displayed similar trends for the coefficient of friction during sliding. Previous studies [34], showed that a localized abrasive zone formed by a higher load increased the coefficient of friction. Ghosh at al. studied the tribological characteristics of Al-SiC MMC. They observed that friction coefficient of composite materials decreased with increasing in applied loads [35].

As can be seen from Fig. 11, the coefficient of friction varied depending on the B$_4$C reinforcement content. The 12%B$_4$C samples showed the lowest coefficient of friction of the hybrid composites. The coefficients of friction for Al6061, 12%SiC, 3%B$_4$C+9%SiC, 6%B$_4$C+6%SiC, 9%B$_4$C+3%SiC, and 12%B$_4$C were found to be 0.63, 0.51, 0.42, 0.35, 0.23, and 0.29, respectively, for a 15 N load and 300 m sliding distance. As can be observed from Fig. 11, the coefficient of friction decreases with the increase in content of SiC and B$_4$C particles. The effects of B$_4$C on the coefficient of friction can be attributed to a boron oxide (B$_2$O$_3$) layer forming at the contact zone. The B$_4$C particles are easily pulled out and react with the environment, thus creating the B$_2$O$_3$ oxide layer.

3.6. Characterization of wear mechanisms by analysis of worn surfaces

The optimum wear resistance was achieved with the 9%B$_4$C+3%SiC HMMCs samples. Therefore, the worn surfaces of the 9%B$_4$C+3%SiC samples were analyzed through SEM in order to define the wear mechanisms and it was clear that the wear mechanisms change with the wear conditions (i.e., load and sliding distance). The wear mechanisms that can occur in Al MMCs include adhesives, abrasives, delamination and abrasion wear [31]. Abrasion wear appears on the worn surface for 5 N at sliding distances of 100 m and 300 m (Fig. 12). Deeper grooves appear for longer sliding distances than for shorter slid-
Fig. 11 – Variation in the friction coefficient of (a) Al6061 (b) 12SiC, (c) 3B4C9SiC, (d) 6B4C6SiC, (e) 9B4C3SiC and (f) 12B4C wt.% Hybrid composite as a function of the sliding distance at different applied loads.

It can be determined from this that the wear contact interface temperature increased with increasing sliding distance [36]. Wear cracks also appear in the worn surface for lower loads (Fig. 12). As can be seen from Fig. 12, numerous grooves on the worn surface are aligned parallel to the sliding direction.

Deformation and delamination wear mechanisms are formed for 10 N at sliding distances of 100 m and 300 m. The delamination wear mechanisms can be explained as being due to a removal of material, because cracks occur where delamination occurs [37]. Work hardening is caused by deformation of the matrix. A higher load increases work hardening, and as a result cracks are formed in the matrix and reinforcement interface. The cracks cause the delamination wear. As can be seen from Fig. 12, the degree of delamination wear on the worn surface increases with the increase in load. Deformation (plastic) wear is also shown in Fig. 12. Larger deformation zones are seen for higher loads and sliding distances (Fig. 12). Fig. 12 shows that several wear mechanisms occurred on the worn surface for 10 N at sliding distances of 100 m and 300 m.

EDS results of worn surfaces for 150 N at a sliding distances of 100 and 300 m are given in Fig. 13 in order to reveal the
effects of SiC and B₄C on the worn surfaces. All peaks of the aluminum alloy and SiC and B₄C reinforcement particles are observed. This characterization of the worn surfaces reveals that SiC particles have a better interface between the matrix and particles compared to B₄C particles. SiC particles are broken during the wearing process, while B₄C particles are pulled out. The higher wear resistance of 9%B₄C+3%SiC compared to 12%B₄C can be attributed to this behavior. SiC particles also displayed good bonding and are not pulled out from the matrix. Uthayakumar et al. found that SiC can become trapped between the sliding surfaces or embedded into the soft aluminum matrix and thus increases the wear resistance [33].
3.7. **Volume loss map**

Fig. 14 shows a volume loss map for the 9%B₄C+3%SiC HMMCs samples under various wear conditions. Each contour on Fig.14 marks the volume loss for different sliding distances and loads. The contour volume loss map was drawn using ORIGIN software for volume loss data. Fig. 14 gives a detailed illustration of how volume loss changes with different wear conditions. The volume loss is the lowest at a lower load and shorter sliding distance and the highest at a higher load and longer sliding distance.

3.8. **Map of wear mechanisms**

A map of the wear mechanisms of the 9%B₄C+3%SiC HMMCs samples are given in Fig.15 for different wear conditions. As can be clearly seen, the wear conditions directly influence the wear mechanisms. Which wear mechanisms dominate at the defined wear conditions can be characterized using the wear mechanisms map. The wear map can also be used for forecasting wear mechanisms at different wear conditions. Alpas and Zhang used the wear maps to define the transition between wear mechanisms [38]. As illustrated in Fig.15, the wear mechanisms on the worn surfaces of the 9%B₄C+3%SiC HMMCs samples transition from mild wear to ultra-severe wear with the increase in sliding distance and load.

Mild, severe, and ultra-severe wear regimes are defined for the 9%B₄C+3%SiC HMMCs samples for different wear conditions (Fig.15). Abrasion wear mechanisms are dominant for the mild and severe regimes, while delamination wear mechanisms play an important role in the severe wear regime and the deformation wear mechanism mostly occurs in the ultra-severe wear regime.

4. **Summary and conclusions**

In this study, a non-reinforced Al6061 alloy and B₄C/SiC-reinforced composite materials were produced successfully using a hot extrusion technique. The properties of the produced materials, such as the density, hardness, transverse rupture strength, tensile strength, and wear, were examined. The study yielded the following findings:

1. It is produced with high density materials by hot extrusion technique. The average densities of cold pressed and extruded composites respectively were 89 and 99%, respectively. While the highest density was observed in the extruded Al6061 alloy (99.74%), composite materials reinforced with extruded 12%B₄C had the lowest density (99.02%).

---

**Fig. 14 – Volume loss map of 9B₄C3SiC samples.**

**Fig. 15 – Wear mechanisms map of wear mechanisms of 9B₄C3SiC samples.**
2. Investigating the microstructure of Al6061 with a hot extrusion technique, we observed that the microstructure had no pores. Examining the microstructures of the B₄C/SiC-reinforced composites, the study found that B₄C/SiC particles in 3%B₄C+9%SiC composites generally had a homogenous distribution in the matrix. In 6%B₄C+6%SiC and 9%B₄C+3%SiC composites, agglomerations increased in parallel with the increase in B₄C content. While the 12%B₄C composites displayed a higher level of agglomeration compared with the other composites, low numbers of micro-pores were observed in the microstructure.

3. It was observed that micro cracks formed in some particles as a result of friction between particles during the extrusion process.

4. Determining the hardness values of the composites produced, the study found that reinforced Al6061 alloy had an average hardness value of 50 HB, the 12%B₄C composite displayed the highest hardness of 76 HB.

5. Investigating the transverse rupture strength values, we found that while 12%SiC-reinforced composites showed the highest transverse rupture strength with 402 MPa, the 12%B₄C composite, which had the highest hardness value, had the lowest transverse rupture strength with 358 MPa. In the B₄C and SiC composites, on the other hand, the transverse strength values displayed a decrease in parallel with the increase in B₄C ratio.

6. Al6061 alloy has a lower tensile strength (174 MPa) than those of the composites. The highest tensile strength was achieved in 12% SiC reinforced composites (185.1 MPa). In B₄C / SiC composites, some decrease in tensile strength was observed due to B₄C ratio.

7. The minimum volume loss was found to be 0.07 mm³ for the 12%B₄C hybrid composite for a 5 N load and 100 m sliding distance, while the maximum volume loss was found to be 3 mm³ for the 12%SiC hybrid composite for a 15 N load and 300 m sliding distance.

8. Abrasion, deformation, and delamination wear mechanisms occurred on the surfaces depending on the wear conditions. The wear mechanisms can be determined by controlling the wear conditions for HMMCs.

9. The highest wear resistance was obtained for the 9%B₄C+3%SiC samples because of the hardness of B₄C and the good adherence properties of the matrix and SiC.

10. The coefficient of friction varies with the reinforcement type and content. The lowest coefficient of friction was obtained for the 12%B₄C samples.

Acknowledgments

This work was financially supported by the Gazi University Scientific Research Projects Coordination Unit (07/2016-03). The author wish to thank the Hacettepe University Technology Transfer Center Unit.

REFERENCES

[18] Rao JB, Kush D, Bhargava N. Production and characterization of nano structured silicon carbide by high energy ball


