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Effect of B_4C Reinforcement Ratio and Sintering Temperature on the Mechanical Behavior in Al-B_4C Composites

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Abstract:
In this study, powders of Al 1070 and B_4C were prepared by volume in three different reinforcement ratios 4 % B_4C, 8 % B_4C and 16 % B_4C compacted under the pressure of 500 MPa with cold pressing method then sintered under the temperatures of 500, 550 and 600 ℃. Then the hardness was measured and wear test was performed using pin-on-disk method. In the results of tests, the compression pressure of 500 MPa was not sufficient for composite structure to achieve the required density. The highest hardness values were achieved at sintering temperature of 550 ℃ and in 8 % B_4C reinforced composite. The highest wear rate was measured in 4% B_4C reinforced composite specimen sintered at 600 ℃. It is determined that a sintering temperature above 550 ℃ had adverse effects on the mechanical properties.
Keywords : *Metal matrix composite; B_4C, Sintering; Mechanical behavior.*

1. Introduction

In the rapidly developing technological age, the materials science and accordingly composite materials are developing and improving. Composite materials are increasingly used in industrial areas such as railways, automotive, navigation, aviation, medicine, astronautics, and sports as composite materials have perfect strength properties against low density, can be produced in different compositions and geometries, and have higher strength to fatigue, toughness, high temperatures, oxidization and wear. One of the type of composites is the metal matrix composites (MMCs), which is mostly produced in the recent years with a variety of methods and used widely.

Such property of composite materials has been further improved through reinforcing material in order to enhance high tensile strength, melting temperature, thermal stability, and easy manufacturability. Different reinforcing materials, e.g., SiC, Al_2O_3, C, SiO_2 and MgO, are used to produce aluminum matrix composites. Aluminum matrix is reinforced with short fibers (whiskers), long (continuous) fibers and particles to be used for production of composites. MMCs are produced many methods of production by applying solid and liquid state processes. The solid state processes are powder metallurgy, hot rolling and diffusion bonding, and liquid state processes are infiltration, pressure casting, compression molding, stir casting and spraying precipitation. Works on production of metal matrix composites using powder metallurgy method are indicated on literature [1-3]. One of the most important

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processes in the method of powder metallurgy is sintering. There are many studies about the effect of sintering parameters in the literature [4-7].

Studies performed on wear behavior of metal matrix composites used different matrix materials and reinforcing materials, and there are many research on distribution of reinforcing material in the composite, effect on the microstructure, porosity, and effect on mechanical properties such as hardness, wear behavior and tensile strength, and effect of stirring time and speed [8-17]. Wear performance of MMC material varies depending on characteristics of matrix and reinforcing material [18]. Many researchers studied on friction and wear behavior of Al metal matrix composites. Finally, they determined that hard particle-reinforced composites had a very high resistance to wear as compared to matrix alloy [19].

When reviewing the studies in the literature in general and studies on the production of composite materials, the solid-state methods, e.g., PM, among production methods for MMCs appear to be used widely. The reinforcing material in the composite structure seems to increase hardness and reduce the rupture strength in general. In this study, B_4C particle-reinforced aluminum composites were produced in different reinforcement-volume ratio using powder metallurgy method. The microstructure of produced MMC specimens was examined, and then mechanical properties of these specimens such as hardness and wear behavior were identified and assessed.

2. Materials and Methods

To produce specimens of Al-B_4C composite with powder metallurgy, the powder of Al 1070 in the size of 88 μm and powder of B_4C in the size of 37 μm were used, for which chemical composition is provided in Tab. I .

Tab. I. Chemical composition of Al 1070 matrix material and B_4C reinforcing material

Al	Cu%	Fe%	Si%	Zn%	Mg%	Mn%	Ti%	Density
Residual	0.04	0.25	0.20	0.04	0.03	0.03	0.03	2.70 gr/cm^3

B%	C%	O% max	Si% max	Fe% max	Density
77-79	18-21	0.1	0.1	0.05-0.15	2.52 gr/cm^3

The powder of Al 1070 and B_4C was prepared in three different reinforcement-volume ratios, 4 % B_4C, 8 % B_4C and 16 % B_4C, and mixed in the *Turbula* device for around 2 hours to achieve a homogenous mixture. Then, prepared Al 1070/B_4C powder mixture was compressed by cold pressing method under a pressure of 500 MPa. After pressing process, composite specimens were sintered at temperatures of 500, 550 and 600°C. The production phase of composite specimens was completed after sintering process and specimens of 9 different characteristics were obtained. Upon completion of production process of composites, microstructure images were taken by scanning electron microscope (SEM) in order to identify structural characteristics of composite specimens. Next, their hardness was measured in accordance with EN ISO 6506-1 standard using Brinell hardness measurement method in order to identify mechanical characteristics.

Upon completion of hardness measurement of composite specimens, wear test was performed using pin-on-disk method in order to identify wear behavior. The wear test was performed under dry and unlubricated sliding conditions at room temperature. The wear test was performed at constant sliding speed of 0.6 m s^{-1}, in 150 mesh particle size, using Al_2O_3 abrasive paper and under test loads of 10 N, 30 N and 50 N. The Al_2O_3 abrasive paper was replaced with new one for each wear test. The composite specimens covered approximately 20 m on the abrasive paper in each test. 27 wear tests were performed for composite specimens of 9 different characteristics. Before and after each test, the composite specimens were weighed on the electronic balance with a measuring precision of 0.1 mg to document wearing amount.

3. Results and Discussion
3.1. Assessment of microstructures

Fig. 1 shows overall scanning electron microscope (SEM) images of 4 % B_4C, 8 % B_4C and 16 % B_4C reinforced composite specimens sintered at temperatures of 500, 550 and 600°C at 400× magnification.

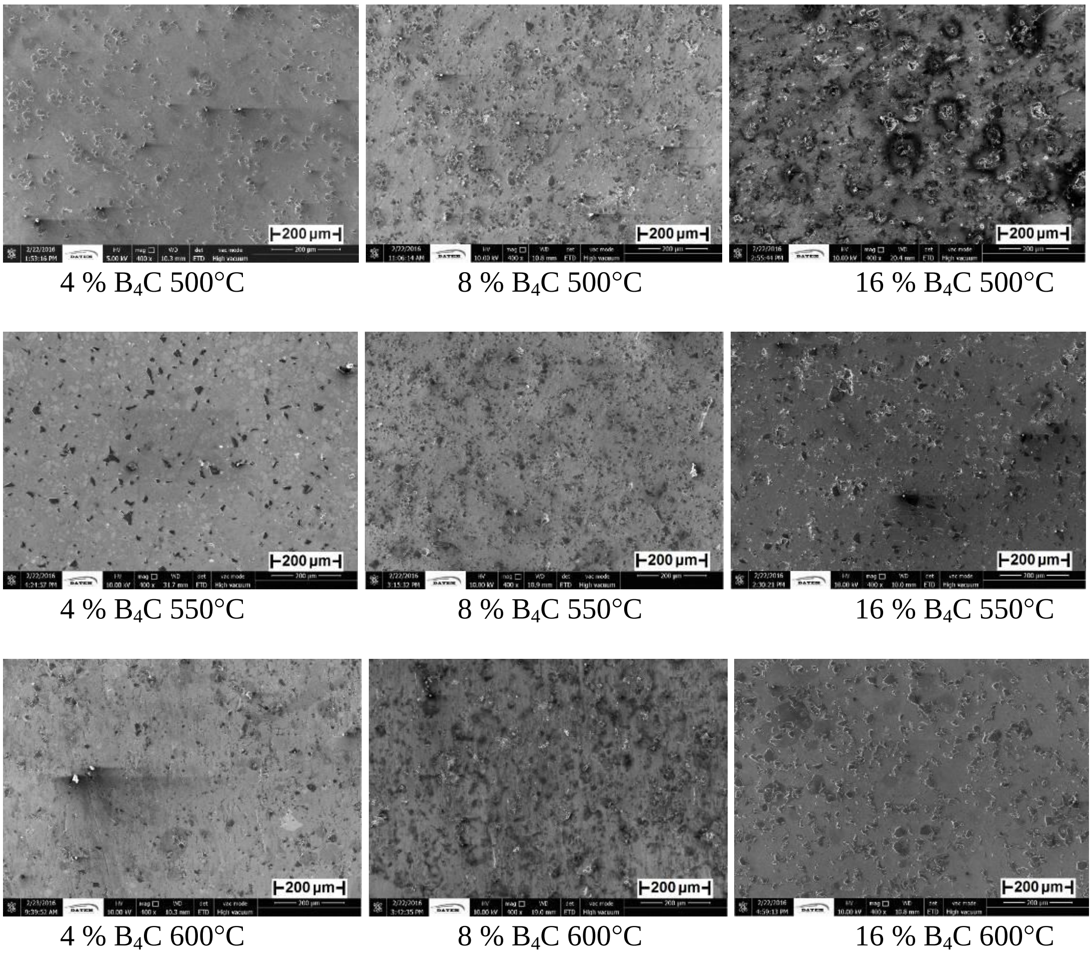
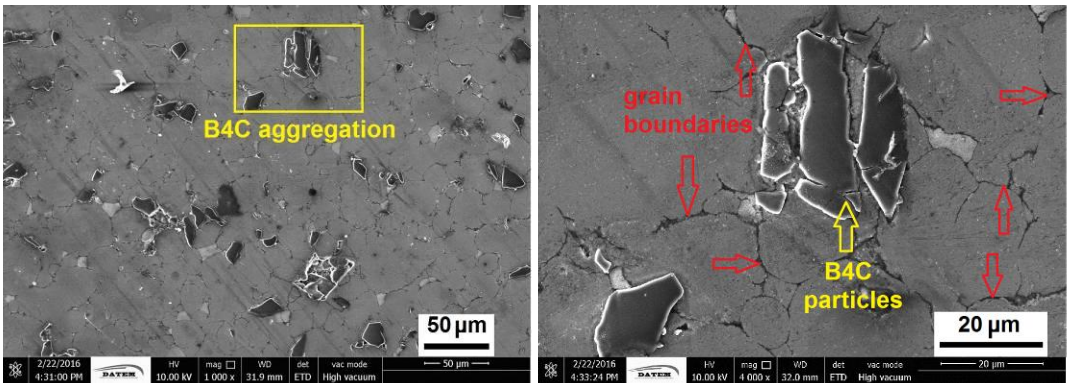


Fig. 1. SEM images of composite specimens.

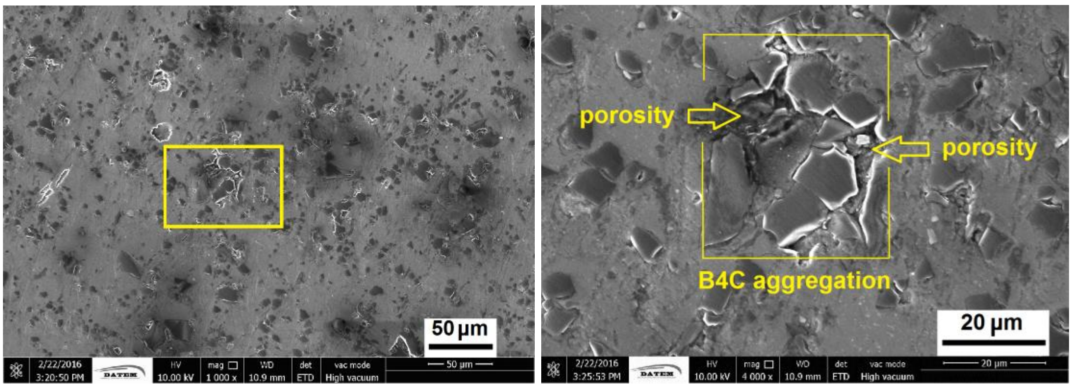
In overall review of images in Fig. 1, the homogeneity of B_4C particle distribution appears to increase a little with increased B_4C reinforcement-volume ratio. A better homogenous distribution than expected was achieved even in the composite specimen of 4% with the lowest B_4C reinforcement-volume ratio. Thus, the time of 2 hours for mixing powder seems sufficient prior to pressing. However, the reinforcement was dragged, resulting in adverse effects on the microstructure because B_4C reinforcement particles in the size of - 37 μm did not have an equal size and shape. The reinforcing material used for production of such composites should be chosen in equal particle size and shape as much as possible. SEM images at 1000× and 4000× magnification were reviewed in order to examine in detail the microstructure of produced composites. For this, Fig.s 2, 3 and 4 shows SEM images of 4 %, 8 % and 16 % B_4C reinforced specimens at 550°C which is a medium temperature for sintering.



1000× 4000×

Fig. 2. 4 % B_4C reinforced composite specimen.

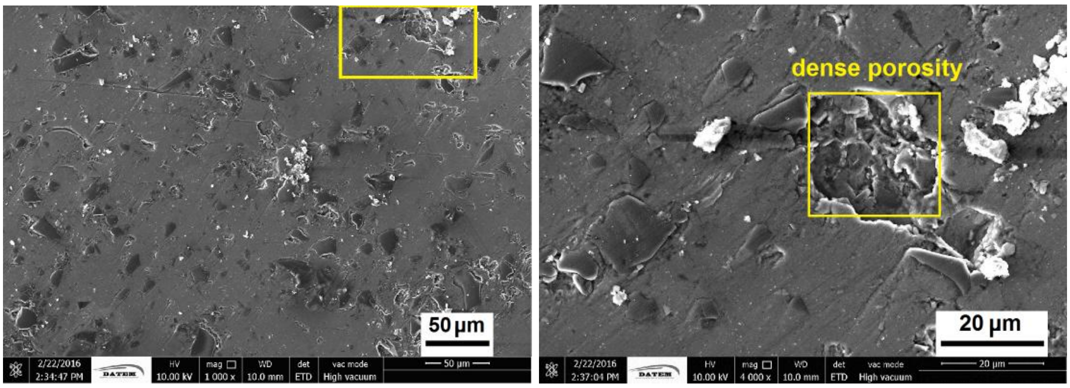
In Fig. 2, first irregularity of B_4C particles attracts the attention. This irregularity applies both to particle size and shape. Furthermore, it appears that reinforcing material was aggregated a little, and accordingly pores were generated. It is known that porosity rate of materials produced by powder metallurgy has a substantial effect on the mechanical characteristics. It is also known that pores generated create notch effect and have adverse effect on the fracture strength. Another remarkable issue is that the powder of Al fails to produce a contract of required density after pressing. The grain boundaries of Al powder are clearly seen on the SEM image at 4000× magnification. In this case, a compression pressure of 500 MPa is not sufficient.



1000× 4000×

Fig. 3. 8 % B_4C reinforced composite specimen.

In review of SEM images in Fig. 3, the particles appear irregular as with the 4 % B_4C reinforced composite. In addition, aggregation and porous structure in the composite structure were slightly increased when reinforcement ratio was increased to 8 %. Particularly, aggregation and porosity can be seen on the SEM image at 4000× magnification in Fig. 4. Furthermore, B_4C particle distribution in the structure seems more homogenous than that of 4 % when reinforcement ratio was increased to 8 %.



1000× 4000×

Fig. 4. 16 % B_4C reinforced composite specimen.

In Fig. 4, the porous structure was further increased when B_4C reinforcement ratio was increased to 16 %. Increases of 4 %, 8 % and 16 % in the reinforcement ratio appears in direct proportion to the increased aggregation of reinforcing material and porous structure.

3.2. Assessment of hardness measurement results

Values of Brinell hardness measurements made according to EN ISO 6506-1 standard in Fig. 5 shows the graphic.

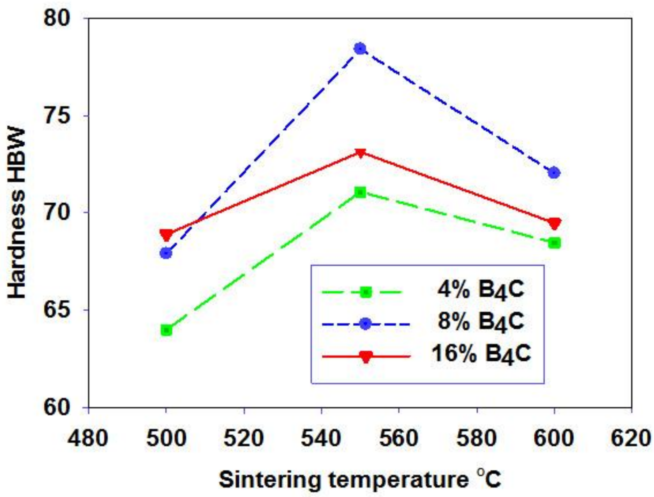


Fig. 5. Brinell hardness values in respect to sintering temperatures and reinforcement-volume ratio.

In review of graphic in Fig. 5, the highest hardness values were obtained at 550°C from all three reinforcement ratios. High hardness values can be considered favorable for such composites designed as shielding material in general or to create a surface resistant to wear. The lowest hardness values were obtained at sintering temperature of 500°C in all three reinforcement-volume ratios. The sintering temperature of 500°C was insufficient, and the hardness value was reduced a little with increased sintering temperature at 600°C. Reduction in hardness value at 600°C could be caused by approximation to melting temperature Al 1070 matrix material with increased temperature. Thus, it can be stated that a sintering temperature of 550°C is more appropriate compared to temperatures of 500°C and 600°C for such composites produced.

When reviewing the hardness values in terms of B_4C reinforcement ratio, the highest hardness values were obtained from 8 % B_4C reinforced composites. Among all measurements, the highest hardness value was obtained from 8 % B_4C reinforced composite sintered with 78.40 HBW at 550°C. In such composites reinforced with particles, the hardness of the structure is expected to increase with increased ratio of reinforcing material in very hard phase. However, depending on the size and shape of reinforcing material used and the production method for composites, hardness measurements made on composite materials may vary due to aggregation of reinforcing material and pores in the structure. Since 16 % B_4C reinforced composite produced for this study had the highest porous structure, its hardness value was lower than that of 8 %. Although 4 % B_4C reinforced composite had the lowest porous structure, the hardness value was lower than that of 8 % B_4C reinforced composite due to very low reinforcement ration in the hard phase. A study performed by Yilmaz and Buytoz, indicated that porosity had effects on the hardness and wear resistance, the hardness of the surface was reduced and wear was increased with increased porosity [17]. In evaluation of sintering temperatures and reinforcement ratios together, optimum and preferable design values were achieved with 8 % B_4C reinforced composite at 550°C.

3.3. Assessment of wear testing results

Fig. 6 shows the graphics of results of abrasive wear testing performed by Al_2O_3 sander in 150 mesh particle size using pin-on-disc method for 4 % B_4C, 8 % B_4C and 16 % B_4C reinforced composite specimens sintered at temperatures of 500°C, 550°C and 600°C.

In review of graphics in Fig. 6, the wear rate was increased with increased load applied in the specimens having all three reinforcement-volume ratios. The highest wear rate measured was 0.225 gr in the 4 % B_4C reinforced composite specimen sintered under the load of 50 N and at 600°C. The lowest wear rate measured was 0.029 gr in the 16 % B_4C reinforced composite specimen sintered at under the load of 10 N and again at 600°C. This is consistent with the literature. Similar results were obtained by Pul et al. [20]. The reason why the lowest wear rate was achieved in 16 % B_4C reinforced composite specimens at all three sintering temperatures and testing loads could be the increased hard reinforcement phase in the structure. Contrary to such approach, the lowest wear rate was observed in 4 % B_4C reinforced composite specimen. The wear rate of 8 % B_4C reinforced composite specimen was very similar to the wear rate of 4 % B_4C reinforced composite specimen at sintering temperature of 550°C. In general, it can be suggested that differences in sintering temperatures for composite specimens did not cause significant changes in the abrasion loss.

The literature suggests that abrasive loss is often increased with increased reinforcement ratio in such ceramic-reinforced composites. The reason put forth for this is that hard reinforcement phase found in the composite structure to a large extent breaks off and scratches the surface, resulting in increased abrasive wear. In addition, it is expressed that reinforcement particles, which break away in the structure during abrasion test, are increased with increased reinforcement ratio, which causes an increase in the abrasive loss. However, this is the opposite case for the present study, and the lowest abrasive values were obtained from the 16 % which was the highest B_4C reinforcement ratio. The reason why pores in the composite structure were smeared and filled with aluminum of soft phase during abrasion tests is considered that it holds B_4C reinforcement particles located around such pores and relatively prevents breaking away from inside the structure. In addition, this results can be construed that preferable values were achieved in the production method used and selected production parameters. To examine worn surfaces, Fig. 7 shows images of optical microscope at 750× magnification for surfaces obtained from abrasion tests performed for 4 % B_4C, 8 %

B_4C and 16 % B_4C reinforced composite specimens sintered at temperatures of 500, 550 and 600°C under the load of 30 N.

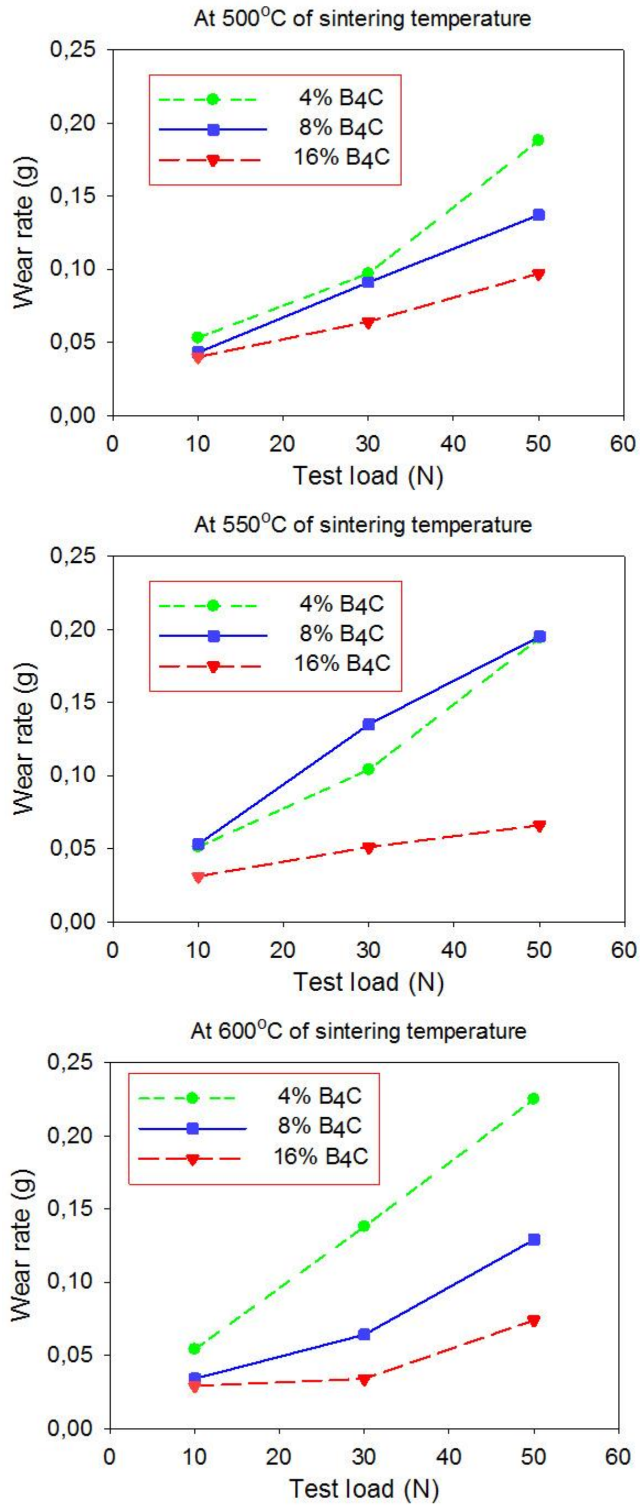


Fig. 6. Abrasion loss for 4 % B_4C, 8 % B_4C and 16 % B_4C reinforced composite specimens under the loads of 10 N, 30 N and 50 N depending on the sintering temperatures.

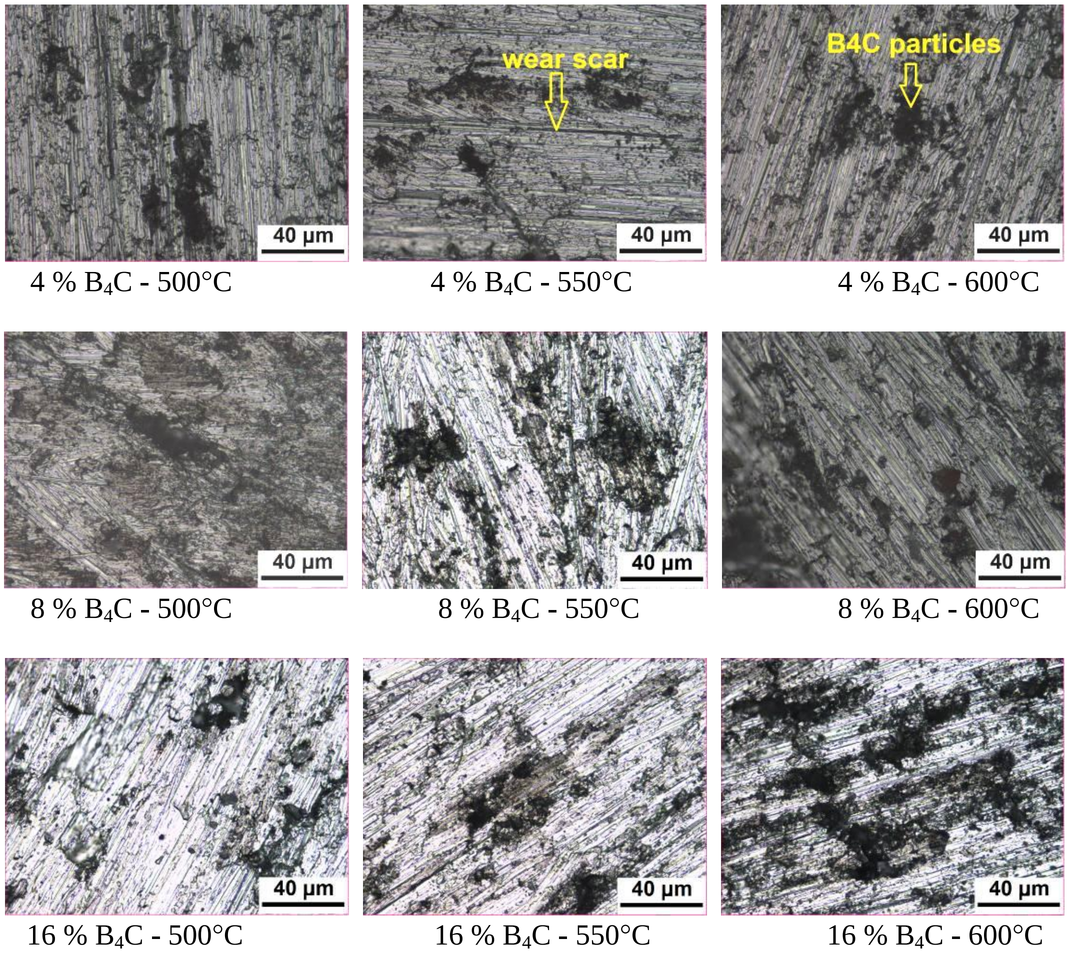
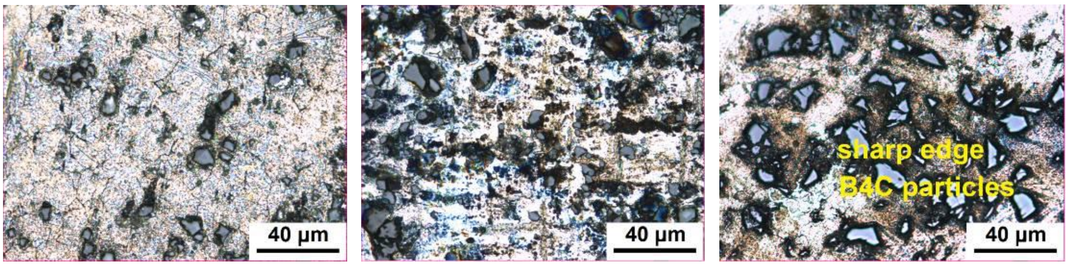


Fig. 7. Images of 4 % B_4C, 8 % B_4C and 16 % B_4C reinforced composite specimens at 750× magnification sintered at temperatures of 500, 550 and 600°C.

The abrasive process starts with deformation occurred on the material to be abraded as a result of forcing material contacting the abrasive surface to scratch (abrasion) due to load applied and advancing (movement) force [21]. When reviewed images in Fig. 8, the wear scars are clearly seen on the surface due to effect of abrasive wear mechanism. The reinforcing material partly broke off and pores of broken off reinforcing material are seen. In addition, broken off B_4C particles were dragged and caused abrasive effect just as Al_2O_3 sander particles, and abrasion lines were formed on the Al matrix. These lines and pores can be explained by irregular scars and pores generated by random movement of B_4C reinforcing material and sander particles of Al_2O_3 when they were dragged away from the surface. The most important reason for breaking off of B_4C reinforcing material is considered that composite specimens have relatively a porous structure, and such particles having a hard structure cause cavities on the surface of specimens. Furthermore, aluminum having a soft structure was smeared on the scratches and pores generated on the worn surface and partly filled these pores.

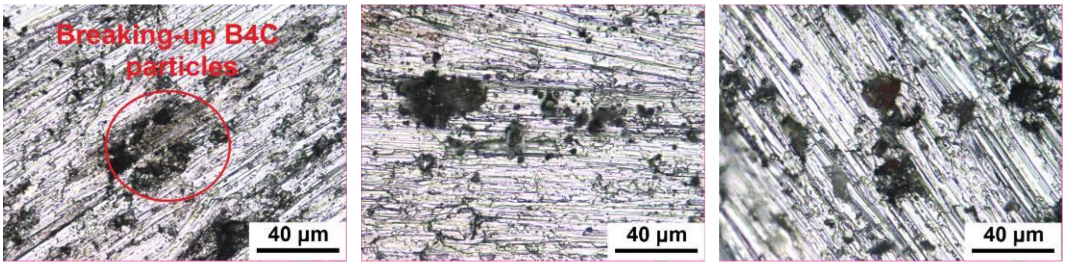
The wear scars were partly increased with increased B_4C reinforcement ratio, but this increase appears negligible. The particles of B_4C reinforcing material were partly broken up, spread and smeared on the surface of aluminum matrix at sintering temperatures in three different B_4C reinforcement ratios. To more clearly see that B_4C reinforcing material was broken up and smeared on the surface during abrasion test, Fig. 8 provides optical microscope images taken from surfaces of 4 % B_4C, 8 % B_4C and 16 % B_4C reinforced composite specimens sintered at 600°C prior to abrasion testing.



4% B_4C 8% B_4C 16% B_4C

Fig. 8. Images at 750× magnification of 4 % B_4C, 8 % B_4C and 16 % B_4C reinforced composite specimens sintered at 600°C prior to abrasion testing.

In the images of Fig. 8, it is clearly seen that particles of B_4C reinforcing material in the composite structure had sharp edges and did not break up within. As indicated before, B_4C particles were broken into smaller particles and spread in the aluminum matrix and smeared on the surface during abrasion testing due to friction of Al_2O_3 particles in the abrasive sander and effect of the testing loads applied. To examine the effect of sintering temperatures on the abrasion surfaces, images of 16 % B_4C reinforced composite specimens sintered at 500, 550 and 600°C were taken at 1000× magnification.



500°C 550°C 600°C

Fig. 9. 16 % B_4C reinforced composite specimens sintered at 500, 550 and 600°C.

In the images of Fig. 9, breaking up of B_4C particles and spread on the surface was reduced with increased sintering temperature, and the particles were held well in the aluminum matrix. However, initial particle formed with sharp edges was disrupted in the specimens sintered at all three temperatures. It is considered that penetration of B_4C particles into the aluminum is increased when sintering temperature is increased and approximated to the melting temperature of aluminum, and it resists more to breakup during abrasion test. Furthermore, it can be construed that pores, which were initially observed around the particles of B_4C reinforcing material, were filled by smear of soft aluminum during abrasion tests.

4. Conclusions

- Mixing of B_4C powder with Al 1070 powder for two hours was sufficient for homogeneous distribution in the composite structure. The homogeneous distribution was improved in the structure with increased B_4C particle reinforcement ratio.
- The compression pressure of 500 MPa was not sufficient for composite structure to achieve required density.

- When evaluating sintering temperatures and reinforcement ratios together, the highest hardness value was achieved with 8 % B_4C reinforced composite sintered at 550°C with 78.40 HBW, and the lowest hardness value was achieved with 4 % B_4C reinforced composite sintered at 500°C with 64.00 HBW.
- The hardness value was reduced at sintering temperature of 600°C. It is considered that this reduction in hardness value was caused by approximation of Al 1070 matrix material to the melting temperature.
- Aggregation of reinforcing material and porosity were increased with increased B_4C reinforcement ratio. The hardness values were reduced with increased porosity in the composite structure.
- The highest wear rate was measured in the 4 % B_4C reinforced composite specimen sintered at 600°C under the load of 50 N, and the lowest wear rate was measured in the 16 % B_4C reinforced composite specimen was measured in the 16 % B_4C reinforced composite specimen sintered at 600°C under the load of 10 N.
- The lowest wear rate was achieved with 16 % B_4C reinforced composite specimens at all three sintering temperatures and testing loads. During abrasion tests, the aluminum of soft phase was smeared and filled into the pores in the composite structure, which is considered to hold particles of B_4C reinforcement located around these pores and relatively prevent breaking away from the structure. Thus, the abrasion loss was less in the 16 % B_4C reinforced composites that includes the highest porous structure.
- It is considered that the most important reason for breakup of B_4C reinforcing material is that composite specimens relatively had porous structure, and these particles having a hard construct caused cavities on the surface of specimens.
- The particles of B_4C reinforcing material that initially had sharp edges were partly broken up, spread and smeared over the aluminum matrix, but this was relatively reduced as the sintering temperature was increased.
- Differences in sintering temperatures for composite specimens did not cause significant changes in the abrasion loss.

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Садржај: *У овом раду припремљени су прахови Al 1070 и B_4C са три различита односа, 4 % B_4C, 8 % B_4C и 16 % B_4C који су компактирани под притиском од 500 MPa и синтеровани на температурама од 500, 550 и 600℃. Затим су мерене чврстоћа и хабање. Резултати су показали да притисак од 500 MPa није био довољан за постизање потребне густине узорака. Највише вредности чврстоће добијене су на температури синтеровања од 550℃ за узорак са 8 % B_4C. Највише вредности теста за хабање постигнуте су за композит са 4 % B_4C синтерованог на 600℃. Установљено је да температура синтеровања изнад 550℃ има негативан утицај на механичка својства.*
Кључне речи: *метал матрикс композит, B_4C, синтеровање, механичка својства.*