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Effect of Boron Carbide Addition on Wear Resistance of Aluminum Matrix Composites Fabricated by Stir Casting and Hot Rolling Processes

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Abstract: In this study, to evaluate the effect of boron carbide (B_4C) addition on the wear performance of aluminum (Al), Al6061 and 5, 10, and 20 vol.% B_4C /Al6061 composites were manufactured using the stir casting and hot rolling processes. B_4C particles were randomly dispersed during the stir casting process; then, B_4C particles were arranged in the rolling direction using a hot rolling process to further improve the B_4C dispersion and wear resistance of the composites. Furthermore, a continuous interfacial layer between B_4C and the Al6061 matrix was generated by diffusion of titanium (Ti) and chromium (Cr) atoms contained in the Al6061 alloy. Wear depth and width of the composites decreased with increasing B_4C content. Furthermore, with B_4C addition, coefficient of friction (COF) improved as compared with that of Al6061. The results indicate that interface-controlled, well-aligned B_4C particles in the friction direction can effectively increase the wear properties of Al alloys and improve their hardness.

Keywords: aluminum matrix composite; boron carbide; hot rolling; stir casting; wear property

1. Introduction

Aluminum matrix composites (AMCs) have many advantages over Fe-based alloys or composites, including high specific strength, high hardness, high stiffness, and wear resistance. AMCs are desirable materials for structural applications in the aircraft, automotive, and military industries and as neutron absorber materials in the nuclear industry [1–4]. Boron carbide (B₄C) is currently considered the most promising ceramic reinforcement due to its attractive properties of high strength, low density of 2.52 g/cm³, high hardness (third hardest material after diamond and cubic boron nitride), and good chemical stability compared with other ceramic materials, such as silicon carbide and titanium boride [1,5–10]. B₄C has a high melting point and a good neutron absorbing property, so it has become a major focus in the field of nuclear shielding [11–14].

The inclusion of hard ceramic reinforcement in Al can improve the hardness and wear resistance of the soft Al matrix. Ortiz et al. reported that the lubricated sliding wear resistance of a fine-grained B_4C composite fabricated by transient liquid-phase assisted spark-plasma sintering with Ti-Al additives under smooth conditions was comparable to that of the reference monolithic B_4C ceramic [15]. It was shown that the Ti-Al- B_4C composite has an excellent sliding wear resistance that exceeds that of monolithic B_4C ceramic by one order of magnitude, and that is attributable to its greater hardness and densification. Kumar et al. manufactured an Al7075- B_4C -rice husk ash (RHA) hybrid alloy composite using high vacuum casting [16]. The mechanical wear behavior, hardness, and flexibility were analyzed, and the conclusion was drawn that RHA and B_4C particles improved the abrasion resistance of hybrid composites and reduced damage to the worn



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Copyright: © 2021 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (https:// creativecommons.org/licenses/by/ 4.0/). surface. Zhao et al. studied the wear behavior with increasing B_4C content and changing load [17]. Augmentation of B_4C content resulted in an increase in the friction coefficient and decrease in the wear mass loss. At a low load of 50 N, the dominant wear mechanisms of the $B_4C/Al5083$ composites were microcutting and abrasive wear. At a high load of 200 N, the dominant wear mechanisms were microcutting and adhesion wear associated with the formation of delamination layers that protected the composites from further wear and enhanced the wear resistance under conditions of high load. Dou et al. found that with heat-treated $B_4C/Al6061$ composites, the wear mass loss and coefficient of friction (COF) increased significantly under conditions of sliding time, applied load, and threshold of sliding speed [18]. Májlinger et al. reported that syntactic forms (hollow-sphere-reinforced Al matrix composites) would be promising materials for a moderately loaded sliding part because opened hollow inclusions during wear testing serve as lubricant reservoirs in Al composites [19].

To achieve better tribological properties, it is very important to prepare AMCs with uniform distribution of reinforcing particles. Furthermore, interfacial properties can dramatically alter the mechanical and wear properties of AMCs. In the case of AMCs fabricated by powder metallurgy, interfacial bonding with reinforcements can deteriorate due to surface oxide layers on the surfaces of Al powder. In our previous research, B₄C/Al6061 composites having in situ interfacial layers produced by the reaction of the B₄C and Al6061 matrix were successfully fabricated by the stir casting process [20]. A rolling process can also be used to fabricate AMCs with improved reinforcement dispersion. Thus, the purpose of this study was to evaluate the wear properties of low volumetric B₄C/Al composites having uniform B₄C dispersion and a controlled B₄C/Al6061 interface manufactured using the stir casting and hot rolling processes. The ball-on-disk test was performed to observe the wear behavior under applied loads of 5 and 20 N. Phase analyses of microstructures and interface were performed through scanning electron microscopy (SEM) and electron probe microanalyzer (EPMA) analysis. Wear behavior according to the applied load and volume fraction of the B₄C reinforcement was analyzed.

2. Materials and Methods

Al6061 alloy (ThyssenKrupp Materials Korea Co., Ltd., Seoul, Korea) was used as a matrix to fabricate metal matrix composites (MMCs). B₄C powders (Dunhua Zhengxing Abrasive Co., Ltd., Dunhua, China) with commercial grades of F320 (Federation of European Producers of Abrasives (FEPA)-specified size distributions, $39.0 \pm 1.5 \mu$ m) were used as reinforcements. The chemical composition of Al6061 provided by the company is shown in Table 1.

Mg Si Fe Cu Mn Cr Zn Ti Al 0.529 0.549 0.172 0.086 0.954 0.142 0.0061 0.031 97.450

Table 1. Chemical composition of Al6061 alloy (wt.%).

 B_4C -reinforced Al6061 composites were prepared using the stir casting process comprising a pitched blade turbine type of impeller, which is suitable for suspending particles by strong down pumping. The size of the impeller was set to 2/3 of the diameter of the crucible. Baffles were installed to prevent swirling and to convert the horizontal flow of molten metal into a vertical flow when the impeller was rotating in the molten Al.

Al6061 alloy was melted in a graphite crucible by induction heating at a temperature of about 750 °C for 20–30 min. Degassing of the melt was performed with argon gas. After degassing, B₄C particles preheated at 200 °C were added to the graphite crucible while continuing the stirring process. Stirring was maintained for 10 min at 800 rpm after finishing the B₄C addition. After stirring, melt was poured into the preheated steel mold at 200 °C. The fabricated composites were cut into 100 mm × 100 mm × 10 mm pieces for the hot rolling process.

For hot rolling, composites fabricated by the stir casting process were cross-rolled in atmospheric environments after preheating to 500 °C. A preheated composite plate was hot-rolled and then heat-treated again for 5 min per one pass. Twenty rolling passes were performed on each composite for fabricating a 1.6 mm thick plate from a 10 mm thick bulk composite. The fabricated hot-rolled B₄C/Al6061 composites were cut into 250 mm × 350 mm sheets.

Wear test was performed using a ball-on-disk-type device (JLTB060, J&L Tech, Ansan, Korea) at 5 and 20 N loads with a 105 mm/s test speed. A Si₃N₄ ball (Φ 6 mm) was used as the counterpart material. The size of the wear specimen was Φ 25 × 2 mm. An alpha step (DektakXT, Bruker, Billerica, MA, USA) was used to measure the wear depth and width, and a Vickers hardness tester (HM-122, Mitutoyo, Kawasaki, Japan) was used to measure the hardness of the composites. The measured load was 100 gf, and the holding time was 10 s. Each specimen was measured 5 times. The microstructures of the composites were observed with a scanning electron microscope (SEM, LEO-1450, Zeiss, Oberkochen, Germany), field emission-electron probe microanalyzer (FE-EPMA, JXA-8530F, JEOL, Akishima, Japan), and 3D X-ray tomography microscope (Zeiss, Xradia Ultra/Versa Hybrid Systems, Oberkochen, Germany).

3. Results

3.1. Microstructures of $B_4C/Al6061$ Composites Fabricated by the Stir Casting and Hot Rolling Processes

The microstructures of $B_4C/Al6061$ composites are shown in Figure 1. In the case of the $B_4C/Al6061$ composites fabricated by stir casting, most of the B_4C particles were relatively well dispersed in the Al6061 matrix, as shown in Figure 1a–c. When the $B_4C/Al6061$ composites were manufactured by stir casting, the B_4C particles were randomly arranged in three dimensions. Some B_4C particles (irregular shape) appeared like small particles because parts of them were exposed in the 2D SEM image. Figure 1d–f shows cross-sectional SEM images of hot-rolled $B_4C/Al6061$ composites. After hot rolling, the B_4C reinforcement in the Al6061 matrix was arranged according to the rolling direction. This phenomenon is more clearly observed with increasing B_4C content (Figure 1f).



Rolling direction

Figure 1. Scanning electron microscope images of stir-cast $B_4C/Al6061$ composites with (**a**) 5 vol.%, (**b**) 10 vol.%, and (**c**) 20 vol.% B_4C , and hot-rolled $B_4C/Al6061$ composites with (**d**) 5 vol.%, (**e**) 10 vol.%, and (**f**) 20 vol.% B_4C .

Figure 2 shows 3D images of 5 and 20 vol.% $B_4C/Al6061$ composites analyzed by a 3D X-ray tomography microscope. Like the 2D SEM image, it can be seen that threedimensionally arranged B_4C particles are observed in the stir-cast $B_4C/Al6061$ composites (Figure 2a,c). In the case of the 20 vol.% B_4C composite, change in B_4C dispersion after hot rolling was not observed well due to highly concentrated B_4C particles (Figure 2d). However, it was clearly observed in the 5 vol.% composite after hot rolling. After hot rolling of the stir-cast $B_4C/Al6061$ composites, B_4C particles were arranged according to the rolling direction as shown in Figure 2b. Partially agglomerated B_4C particles of the stir-cast $B_4C/Al6061$ composites were rarely observed in the 3D image of the hot-rolled $B_4C/Al6061$ composite. In addition, it was confirmed that pores generated in the stir casting process decreased after hot rolling.



Figure 2. Three-dimensional microstructures of $B_4C/Al6061$ stir-cast MMCs with (**a**) 5 vol.% and (**c**) 20 vol.% B_4C and hot-rolled MMCs with (**b**) 5 vol.% and (**d**) 20 vol.% B_4C .

3.2. Interfacial Analysis of B₄C/Al6061 Composites

EPMA was used to analyze the elemental distribution of $B_4C/Al6061$ composites. Figure 3 shows EPMA mapping images of the 5 vol.% $B_4C/Al6061$ composite fabricated by the stir casting process. Since it was manufactured by the casting process, defects were not observed at the B_4C/Al interface. In the EPMA element mapping images, large amounts of the boron (B) and carbon (C) elements can be observed in the B_4C areas, which indicates that the crystal structure of the B_4C particles was maintained in molten Al during the stir-casting process. Elemental titanium (Ti) and chromium (Cr) appeared continuously along the interface between the B_4C and Al matrix. It is known that AlB_2 and Al_3BC precipitates form in the B_4C/Al system [21]. However, these did not appear in the $B_4C/Al6061$ composite manufactured by the stir casting process due to the Ti and Cr in the Al6061 alloy. Previous research has revealed the formation of multi-interfacial layers of $Al_4C_3/(Ti,Cr)B_2$ in the $B_4C/Al6061$ composites [20]. The formation of interfacial layers can limit the decomposition of B_4C reinforcements and promote their wettability in liquid Al in the stir casting process. There was no interfacial debonding between the Al matrix and B_4C reinforcement. Therefore, $B_4C/Al6061$ composites fabricated by stir casting followed by the hot rolling process have well-aligned B_4C distribution along the rolling direction, with a continuous interfacial layer between B_4C and the Al matrix.



Figure 3. Element mapping images of the stir-cast 5 vol.% B₄C/Al6061 composite observed using an electron probe microanalyzer.

Figure 4 is a schematic diagram showing the microstructure of the $B_4C/Al6061$ composites manufactured by stir casting and hot rolling. As confirmed in the three-dimensional images, reinforcements in the composites manufactured by stir casting were randomly arranged in three dimensions. In addition, some pores existed in the Al matrix. Through the hot rolling process, the B_4C reinforcement was arranged according to the rolling direction, forming several layers, and pores were remarkably reduced. Therefore, it is expected that well-aligned B_4C particles along the wear direction, with decreased pores, could increase composite wear properties. Furthermore, the interfacial layer generated between B_4C and the Al6061 matrix is expected to contribute to increasing the wear properties of the composites.



Figure 4. Schematic diagram of the porosity and reinforcement arrangement of $B_4C/Al6061$ composites according to process.

3.3. Wear Properties of B₄C/Al6061 Composites

Figure 5 shows SEM images of the wear track after the wear test of the Al6061 matrix and 5, 10, and 20 vol.% $B_4C/Al6061$ composites tested under 5 and 20 N loads. It can be seen that the wear width decreases as the volume fraction of the B_4C reinforcement increases. A similar tendency was observed in both conditions (5 N, 20 N). B_4C reinforcement was



observed around the wear track, but pull-out B₄C from the Al matrix was net observed in the SEM images.

Figure 5. Worn surface SEM images of Al6061, 5 vol.%, 10 vol.%, and 20 vol.% B₄C/Al6061 composites after wear tests at 5 and 20 N loads.

Figure 6 shows 3D wear tracks and wear depth images obtained using alpha-step equipment. Through 3D mapping analysis, as shown in Figure 6a,b, we confirmed that there was a deviation in wear depth for each wear part. Therefore, cross-sectional analysis of the most worn parts was conducted in Figure 6c,d. At a low load of 5 N, the wear width of the Al6061 matrix was 1303 μ m; this value showed a tendency to decrease as the volume ratio of reinforcement increased. The wear width of the 20 vol.% B₄C/Al6061 composites was measured and found to be 720 μ m. The wear depth decreased with increasing B₄C content from 80 μ m (Al6061) to 23 μ m (20 vol.% B₄C/Al6061 composites). Similarly, the wear width and depth also decreased with increasing B₄C content of the composites tested at 20 N load. The 20 vol.% B₄C/Al6061 composites had the smallest wear width and depth values of 856 and 36 μ m, respectively, tested at 20 N load. These values are believed to have originated from the uniformly dispersed B₄C particles and increased interfacial bonding with the Al matrix, resulting in increased resistance to wear.



Figure 6. (**a**,**b**) 3D wear surface images of 10 vol.% $B_4C/Al6061$ composites tested at 20 N load measured using an alpha step. The wear width and maximum wear depth of Al6061 and $B_4C/Al6061$ composites were tested at (**c**) 5 N and (**d**) 20 N loads.

Figure 7 shows the coefficients of friction (COF) of the Al6061 and $B_4C/Al6061$ composites according to the 5 and 20 N loads. In the case of Al6061 and the 5 vol.% B₄C/Al6061 composites tested under 5 N load, the friction coefficients are almost identical. However, the COF of the B₄C/Al6061 composites decreases as the B₄C volume fraction increases. Table 2 shows a summary of the wear width, wear depth, COF, and hardness of the Al6061 and $B_4C/Al6061$ composites. The average COF values of Al6061 and of the 5 vol.%, 10 vol.%, and 20 vol.% composites are 0.35, 0.37, 0.28, and 0.31, respectively. Although the COF of the 5 vol.% sample was slightly higher than that of Al6061, the COF of the $B_4C/Al6061$ composites decreased with the addition of B_4C . In the case of 20 N load, the average COF values of Al6061 and of the 5 vol.%, 10 vol.%, and 20 vol.% composites are 0.39, 0.31, 0.33, and 0.38, respectively. The COF of the composites decreases with the increasing vol.% of B_4C and reaches a minimum of 0.28 at 10 vol.% B_4C . Therefore, it is difficult to say that the friction coefficient decreases as the volume ratio increases. However, the COF of the B₄C/Al6061 composites tested at 20 N also slightly decreased with the addition of B_4C . Vickers hardness of the composites increased from 116.5 to 139.9 as the B_4C volume fraction increased. Therefore, the results reveal that the wear amount and hardness of the $B_4C/Al6061$ composites are inversely proportional. When the load was increased from 5 to 20 N, the wear width of Al6061 increased from 1303 to 2101 μ m, and the wear depth increased from 80 to 156 μ m, which are 0.61 and 0.95 times increases, respectively. When the load was increased from 5 to 20, the wear width and depth of Al6061 increased 1.5 or 2 times, while that of the composite increased 0.5 times. However, when the load was increased from 5 to 20 N, the wear width of $B_4C/Al6061$ increased from 720 to 856 μ m, and the wear depth increased from 20 to 36 μ m, which are 0.18 and 0.8 times increases, respectively. As a result, the wear rate was decreased with increasing the volume fraction of B₄C. Furthermore, wear rate showed a tendency to decrease as the applied load increased. The presence of hard B_4C particles having good interfacial bonding with the Al matrix acts as an obstacle to wear of the soft Al matrix. Therefore, it is possible that the wear properties of the $B_4C/Al6061$ composite will increase even further at a higher applied load.



Figure 7. Comparison of coefficients of friction at (a) 5 N and (b) 20 N loads.

Table 2. Summarized wear width, wear depth, COF, wear rate, and hardness of Al6061 and B₄C/Al6061 composites.

B ₄ C vol.%	Width (µm)		Depth (µm)		Wear Rate (mm ³ /m)		COF(µ)		Hardness
	5 N	20 N	5 N	20 N	5 N	20 N	5 N	20 N	(Hv _{0.1})
0 5 10	$\begin{array}{c} 1303 \pm 1.21 \\ 1286 \pm 1.38 \\ 1123 \pm 2.17 \end{array}$	$\begin{array}{c} 2101 \pm 1.44 \\ 1573 \pm 1.39 \\ 1265 \pm 1.61 \end{array}$	$\begin{array}{c} 80 \pm 0.32 \\ 72 \pm 0.85 \\ 55 \pm 0.74 \end{array}$	$\begin{array}{c} 165 \pm 0.29 \\ 122 \pm 0.35 \\ 71 \pm 0.86 \end{array}$	0.0375 0.0313 0.0164	0.1315 0.0644 0.0289	$\begin{array}{c} 0.38 \pm 0.02 \\ 0.38 \pm 0.02 \\ 0.34 \pm 0.03 \end{array}$	$\begin{array}{c} 0.42 \pm 0.02 \\ 0.37 \pm 0.03 \\ 0.34 \pm 0.02 \end{array}$	$\begin{array}{c} 104.2 \pm 4.63 \\ 116.5 \pm 3.70 \\ 125.7 \pm 0.63 \end{array}$
20	720 ± 2.54	856 ± 2.21	23 ± 0.65	36 ± 0.85	0.0056	0.0092	0.31 ± 0.01	0.35 ± 0.02	139.9 ± 4.25

Figure 8 shows worn surface images of the 20 vol.% $B_4C/Al6061$ composites and Si_3N_4 ball. Large amounts of fine wear debris and grooves were identified in the $B_4C/Al6061$ composites. In the case of AMCs, the weakly bonded particles with the Al matrix are easily separated from the matrix to create a wear groove on the surface of the specimen, which accelerates surface peeling as wear progresses. However, as a result of confirming the SEM images of the worn surface, it was found that most B_4C particles are incorporated in the Al matrix. The surface of the ball had a worn trace and the $B_4C/Al6061$ composite attached to it. Although partial adhesive wear was observed, abrasive wear was suppressed by well-aligned B_4C , which had strongly bonded with the Al matrix. It is thought that due to the formation of a continuous interfacial layer between B_4C and the Al matrix, pull-out of B_4C particles hardly occurred. This is mainly because the interface was tightly bonded by a continuous (Ti,Cr)B₂-based layer, and the protruded, well-aligned particles can bear the main wear force by abrasives and protect the surrounding Al matrix from further failure as shown in the schematic diagram in Figure 8f.



Figure 8. Surface SEM images of 20 vol.% $B_4C/Al6061$ composites after wear test at (**a**,**b**) 5 N and (**c**,**d**) 20 N, (**e**) SEM images of Si₃N₄ ball after wear test, (**f**) Schematic of wear mechanism of $B_4C/Al6061$ composite.

4. Conclusions

In this research, well-aligned, interface-controlled $B_4C/Al6061$ composites were successfully fabricated by stir casting, followed by the hot rolling process. B_4C particles were well aligned in the Al6061 matrix along the hot rolling direction. As the B_4C content increased, the wear width and depth tended to decrease. Compared with that of Al6061, COF also improved via B_4C addition. The $B_4C/Al6061$ wear mechanism was mainly delamination of Al6061 and the strong interfacial bonding between B_4C and the Al matrix. The following conclusions can be drawn:

- 5, 10, and 20 vol.% of the B₄C particles were well dispersed by stir casting, and threedimensional irregular particles were arranged along the rolling direction through hot rolling. In addition, dispersion of the B₄C particles was improved through hot rolling.
- The (Ti,Cr)B₂ layer was created at the B₄C/Al interface of the stir-cast B₄C/Al6061 composites.
- The wear width and depth decreased with increasing B₄C contents of the composites tested at both 5 and 20 N loads. The 20 vol.% B₄C/Al6061 composites had the smallest wear width and depth of 856 μm and 36 μm, respectively (20 N load).
- Vickers hardness of the composites increased from 116.5 to 139.9 as the B₄C volume fraction increased.
- Wear loss amount and hardness of the B₄C/Al6061 composites are inversely proportional.
- The average COF values of the B₄C/Al6061 composites mostly decreased compared with those of Al6061 and reached a minimum value of 0.28 at 10 vol.% B₄C.
- A tightly bonded B₄C/Al6061 interface by a continuous (Ti,Cr)B₂-based layer and the protruded, well-aligned particles can bear the main wear force by abrasives and protect the surrounding Al matrix from further failure.

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References

- 1. Sharifi, M.; Karimzadeh, F.; Enayati, M.H. Fabrication and evaluation of mechanical and tribological properties of boron carbide reinforced aluminum matrix nanocomposites. *Mater. Des.* **2011**, *32*, 3263–3271. [CrossRef]
- Sun, C.; Shen, R.J.; Song, M. Effects of sintering and extrusion on the microstructures and mechanical properties of a SiC/Al-Cu composite. *J. Mater. Eng. Perform.* 2009, 267, 585–592. [CrossRef]
- Vieria, A.C.; Sequeria, P.D.; Gomes, J.R.; Gomes, L.A. Dry sliding wear of Al alloy/SiC_p functionally graded composites: Influence of processing conditions. Wear 2009, 267, 585–592. [CrossRef]
- 4. Alizadeh, M.; Paydar, M.H. High-strength nanostructured Al/B₄C composite processed by cross-roll accumulative roll bonding. *Mater. Sci. Eng. A* **2012**, *538*, 14–19. [CrossRef]
- Mohanty, R.M.; Balasubramanian, K.; Seshadri, S.K. Boron carbide-reinforced aluminum 1100 matrix composites: Fabrication and properties. *Mater. Sci. Eng. A* 2008, 498, 42–52. [CrossRef]
- Topcu, I.; Gulsoy, H.O.; Kadioglu, N.; Gulluoglu, A.N. Processing and mechanical properties of B₄C reinforced Al matrix composites. *J. Alloys Compd.* 2009, 482, 516–521. [CrossRef]

- Aizenshtein, M.; Froumin, N.; Shapiro, T.E.; Dariel, M.P.; Frage, N. Wetting and interface phenomena in the B₄C/(Cu-B-Si) system. *Scr. Mater.* 2005, 53, 1231–1235. [CrossRef]
- 8. Jung, J.; Kang, S. Advances in manufacturing boron carbide-aluminum composites. J. Am. Ceram. Soc. 2004, 87, 47–54. [CrossRef]
- 9. Zhu, X.; Dong, H.; Lu, K. Coating different thickness nickel-boron nanolayers onto boron carbide particles. *Surf. Coat. Technol.* **2008**, 202, 2927–2934. [CrossRef]
- 10. Shrestha, N.K.; Kawai, M.; Saji, T. Co-deposition of B₄C particles and nickel under the influence of a redox-active surfactant and anti-wear property of the coatings. *Surf. Coat. Technol.* **2005**, 200, 2414–2419. [CrossRef]
- 11. Lee, B.S.; Kang, S. Low-temperature processing of B₄C-Al composites via infiltration technique. *Mater. Chem. Phys.* **2001**, *67*, 249–255. [CrossRef]
- 12. Khakbiz, M.; Akhlaghi, F. Synthesis and structural characterization of Al-B₄C nano-composite powders by mechanical alloying. *J. Alloys Compd.* **2009**, *479*, 334–341. [CrossRef]
- 13. Yue, X.Y.; Wang, J.J.; Li, Y.S.; Ru, H.Q. Properties of B₄C/Al-B₄C composite with a two-layer structure. *Mater. Res. Bull.* **2013**, *48*, 1720–1724. [CrossRef]
- Lee, T.; Lee, J.; Lee, D.; Jo, I.; Lee, S.K.; Ryu, H.J. Effect of particle size and surface modification of SiC on the wear behavior of high volume fraction Al/SiC_p composites. *J. Alloys Compd.* 2020, *831*, 154647. [CrossRef]
- 15. Ortiz, A.L.; Galan, C.A.; Borrero-Lopez, O.; Guiberteau, F. High sliding-wear resistant B₄C composites fabricated by spark-plasma sintering with Ti-Al additives. *Scr. Mater.* **2020**, *177*, 91–95. [CrossRef]
- 16. Kumar, A.; Kumar, M. Mechanical and dry sliding wear behavior of B₄C and rice husk reinforced Al7075 alloy hybrid composite for armors application by using taguchi techniques. *Mater. Today Proc.* **2020**, *27*, 2617–2625. [CrossRef]
- 17. Zhao, Q.; Liang, Y.; Zhang, Z.; Li, X.; Ren, L. Microstructure and dry-sliding wear behavior of B₄C ceramic particulate reinforced Al5083 matrix composite. *Metals* **2016**, *6*, 227. [CrossRef]
- Dou, Y.; Liu, Y.; Liu, Y.; Xiong, Z.; Xia, Q. Friction and wear behaviors of B₄C/6061Al composite. *Mater. Des.* 2014, 60, 669–677.
 [CrossRef]
- 19. Májlinger, K. Wear properties of hybrid AlSi₁₂ matrix syntactic foams. Int. J. Mater. Res. 2015, 106, 11. [CrossRef]
- 20. Lee, D.; Kim, J.; Park, B.; Jo, I.; Lee, S.K.; Ki, Y.; Lee, S.B.; Cho, S. Mechanical and thermal neutron absorbing properties of B₄C/aluminum alloy composites fabricated by stir casting and hot rolling process. *Metals* **2021**, *11*, 413. [CrossRef]
- 21. Zhang, L.; Shi, G.; Kun, X.; Wu, H.; Li, Q.; Wu, J.; Wang, Z. Phase transformation and mechanical properties of B₄C/Al composites. *J. Mater. Res.* **2020**, *9*, 2116–2126. [CrossRef]