Arch. Metall. Mater. **70** (2025), 2, 601-607

DOI: https://doi.org/10.24425/amm.2025.153461

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MICROSTRUCTURE AND WEAR PROPERTIES OF ALUMINUM METAL MATRIX COMPOSITE (Al6061-B_4C) FABRICATED BY STIR CASTING PROCESS

Mechanical properties of Al6061-B_4C composites fabricated by stir casting method, even though over 120 µm B_4C reinforcement was used, was evaluated. The big reinforcement also could exert an impact on mechanical properties such as hardness and wear resistance. The presence of the harder particles dispersed in Al6061 increased hardness, which would in turn affect wear performance. The high hardness reduced the contact area between the sample and ball and thus, leaded to the reduced coefficient of friction (COF) and wear loss. The Al6061-12 wt.% B_4C composite showed the best wear resistance, resulting in the narrowest and shallowest scar. The higher hardness of the Al6061-12 wt.% B_4C composite changed wear mechanism changed from adhesive to abrasive wear so that the best wear resistance could be achieved.

Keywords: Aluminum; Metal Matrix composite; B_4C; Microstructure; Wear properties

1. Introduction

Composite materials consist of two or more constituent materials that have different properties so that combination of dissimilar properties could exhibit more advanced ones than those of conventional materials [1-3]. Among them, metal matrix composites (MMCs) could be promising structure materials due to improved specific strength which could be achieved by mixing high hardness reinforcements with lightweight metals such as aluminum and magnesium [4-6]. Reinforcements used in MMCs are commonly carbides or oxides which usually have higher hardness than metals, leading to the improved mechanical properties of MMCs [7-10]. Fabrication of MMCs involving dispersion of a reinforcement in a metal matrix could be achieved by deposition processes, solid-state processes and liquid state processes. Among these manufacturing methods, stir casting method as one of liquid-state processes has been most widely used because it is the most economical process and many metals such as aluminum, copper, titanium and magnesium could be applicable in fabricating MMCs, where mechanical agitation has to be continuously provided to obtain a well-dispersed reinforcement throughout a metal matrix [11-14].

Aluminum metal matrix composites (Al MMCs) have been intensively studied due to their excellent properties such as high specific strength, good wear and corrosion resistance, allowing them to be good structural materials for automobile and aerospace applications [15-18]. The critical parameters determining properties of Al MMCs are reinforcement types and sizes, stirring time and speed and temperature [19-22]. Reihani et al. studied size effect of the SiC reinforcement on mechanical properties of Al6061 MMC fabricated by squeeze casting [23]. The decrease in the reinforcement size from 22 µm to 16 µm resulted in the improved mechanical properties and wear resistance. Also, the nano-sized SiC reinforcement induced grain refinement due to the heterogeneous nucleation and thus, the increase in the hardness, yield and tensile strength of the stir casted A356 MMC. Sotani et al. reported that an increase in the stirring time and temperature made the reinforcement dispersion better when the Al-SiC composite was fabricated through a stir casting [24].

Among various reinforcement materials such as Al_2O_3, SiC and TiC, B_4C would gain more attraction in fabricating a lightweight material due to its density as low as 2.52 gcm^{-3}, while its hardness is about 3,770 HV, which is the third highest one

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after diamond and boron nitride [25,26]. In addition, B_4C shows good chemical compatibility with various metals, particularly when liquid -state processes such as stir casting are used [27-29]. However, high cost of the B_4C reinforcement would restrict its expansion to industrial applications, except for nuclear reactor materials and thus, limited studies have been conducted to fabricate Al-B_4C composites [30,31]. Generally, smaller reinforcements would exert greater impact on mechanical properties than coarse ones with the equal volume fraction, resulting in better strength and wear resistance. However, depending on the wear conditions such as the slower sliding speed (25 m/s) and abrasive wear condition, the coarse reinforcement could show better wear resistance. [32-34]. The bigger B_4C particles also had a good aspect in terms of dispersion because the small ones tended to be agglomerated so if work, the coarse reinforcements would be a good option for stir casting process which applied to fabricate MMCs [35,36].

In this study, B_4C particles with over 100 μm of D_{50} was used in fabricating Al6061-B_4C composites through the stir casting process and then, mechanical properties such as hardness and wear properties were investigated to find out how the big B_4C reinforcement affected mechanical properties of the composite. If over 120 μm B_4C particles could exert a good impact on mechanical properties of the Al6061-B_4C composite, it would boost the usage of coarse B_4C powders as a reinforcement because they could reduce material cost as well as process cost.

2. Experimental procedure

2.1. Metal matrix composite fabrication

Al6061 was used as a metal matrix material and its composition was shown in TABLE 1. As a reinforcement material, B_4C particle was utilized, where its size was about 124 μm of D_{50} and the amounts added were 3 wt.%, 6 wt.% and 12 wt.%. Stir casting method was applied to fabricate Al6061-B_4C composites (Al6061-3 wt.% B_4C, Al6061-6 wt.% B_4C and Al6061-12 wt.% B_4C). About 5.19 kg of Al6061 pieces were charged into a graphite crucible of a resistance heating furnace and heated up to 770°C, allowing Al6061 to be melted completely. The preheated B_4C reinforcement particles at 900°C, then were added into the Al melt with a rate of 2 g/s. At the same time, a graphite impeller with four blades, which was also preheated at 200°C was inserted into the molten mixture to generate turbulence of the molten mixture, allowing the Al melt and reinforcement to be mixed completely, where stirring was conducted at 300 rpm for 20 min. The Al6061-B_4C composite ingots were obtained by pouring the molten mixture into a mold with 150 × 150 × 100 mm size, heated at 400°C. To remove inside pores, a hot isotropic press (HIP) was applied under 580°C temperature and 1,000 bar pressure for 4hrs, followed by furnace cooling. And then, T6 heat treatment was conducted as follows; solid solution at 570°C for 2 hrs, followed by water quenching and then aging heat treatment at 170°C for 6 hrs.

TABLE 1

Chemical compositions of Al6061 used in this study

Element	Mg	Fe	Si	Cu	Mn	Zn	Cr	Ti	Al
wt.%	1.08	0.17	0.63	0.32	0.52	0.01	0.17	0.02	Bal.

2.2. Characterizations

Scanning electron microscopy (SEM, FEI company, Quanta 250) was used to characterize dispersion of the B_4C reinforcement particles of the Al6061-B_4C composite and worn surface morphology after the wear test. Before the SEM observation, the samples were grinded with 800, 1200 and 2400 grit papers, followed by polishing with 1 μm diamond paste. Density was measured based on Archimedes method. Following the ASTM E18 standard, Rockwell hardness test (KB Prüftechnik GmbH, KBW 150RCD) was carried out, where a 1/16 inch hardened steel ball indenter with the 60 kgf load was used as F scale. Wear tests (R&B Co. Ltd, RB102-PD) were conducted based on the ASTM G-99 standard, where the high carbon bearing steel (SUJ2) ball with the 6 mm diameter was used for a ball on disc mode. Condition of the wear test was 20 N load with 100 rpm rotation speed and 120 mm distance. Worn surface was characterized in terms of wear scar width and depth through optical microscope (OM, KEYENCE, VHX-5000) and profilometer (Mitutoyo, S-3000).

3. Results and discussion

3.1. Microstructure

Mechanical properties of MMCs could be improved by dispersing a high hardness reinforcement throughout a metal matrix, which could be classified into three main factors; load-bearing effect, dislocation density effect and Orowan strengthening effect as a result of dispersion strengthening [37,38]. To maximize these strengthening mechanisms, the reinforcement added into the matrix should be well-dispersed without agglomeration of the reinforcement particles. Fig. 1 showed the morphology of the B_4C reinforcement particles with the size distribution and their distribution in the Al6061 matrix. The B_4C reinforcement particles had irregular shape with sharp corner and their size distribution was revealed to be 85 μm, 124 μm and 192 μm in terms of D_{10}, D_{50} and D_{90}. After fabricated by the stir casting, the Al6061-B_4C composites showed pretty good dispersion of the reinforcements in the Al matrix even though some parts contained mild agglomeration of the B_4C particles as the preheating at 900°C improved wettability of the B4C particles. The agglomeration behavior became dominant with the increase in the reinforcement amount, indicating that higher amount of the particles would have more chances to be agglomerated. Also, clear interface between the Al matrix and reinforcement supported a good interfacial bonding was achieved. Due to the lower density of the B_4C than the Al6061 matrix, the Al6061-B_4C composite

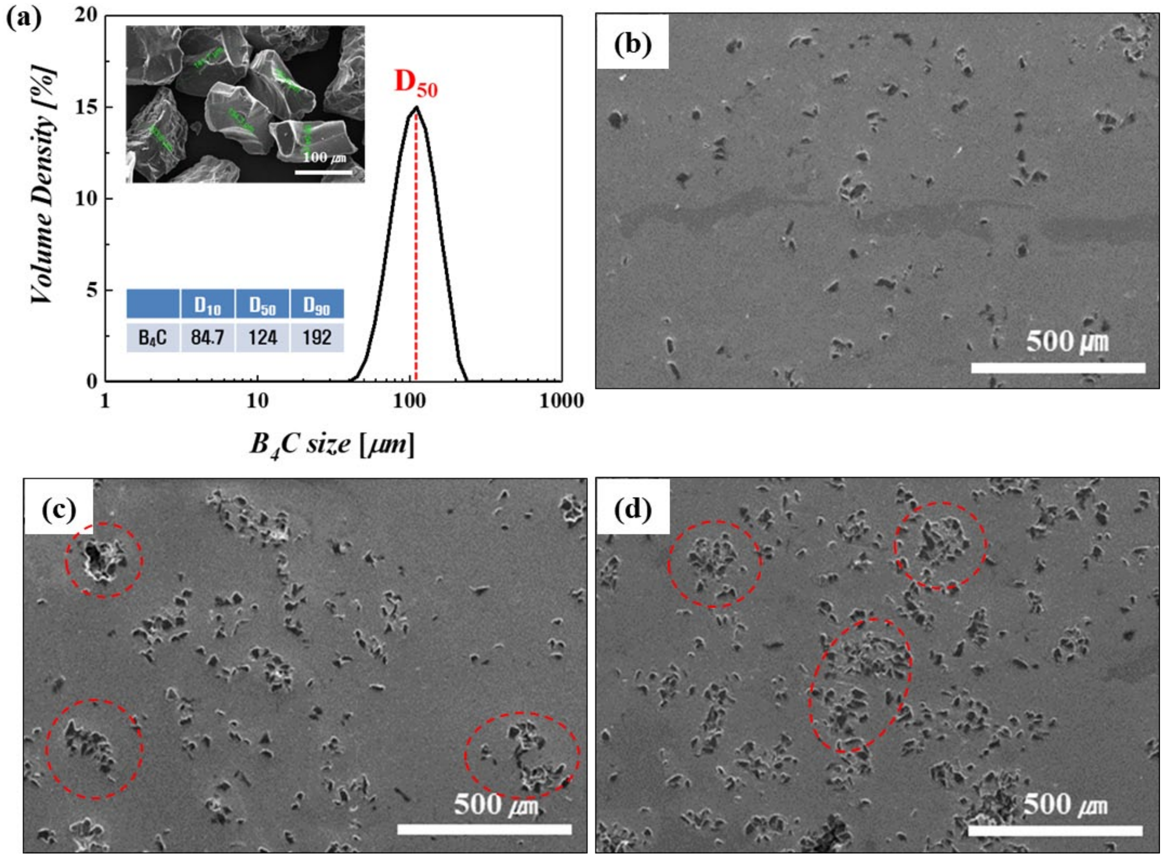

Fig. 1. Size distribution of B_4C reinforcement particles. The inset is SEM image showing morphology of B_4C particles

showed the lower density value than the original density of the Al6061 (2.7 g/cm^3) and the decrease in the density further proceeded with the reinforcement amount added, as shown in Fig. 2.

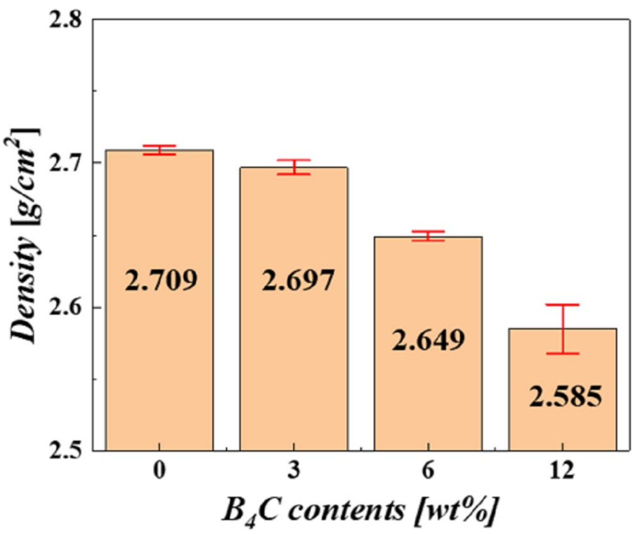

Fig. 2. Densities of the matrix material (Al6061) and composites (Al6061-3 wt.% B_4C, Al6061-6 wt.% B_4C and Al6061-12 wt.% B_4C)

3.2. Hardness and wear properties

Usually, multiple strengthening mechanisms such as load-bearing (load transfer) mechanism and Orowan strengthening mechanism works for strengthening MMCs so it is not easy to identify a prevailing mechanism in determining final mechanical properties of MMCs. All strengthening mechanisms were mainly related to the microstructure of MMCs, which however varied with process parameters such as reinforcement type, size and dispersion method. Fig. 3 showed Rockwell hardness values and their variations with the B_4C content. In comparison to the base Al6061, all composites showed the enhanced hardness value and the highest hardness value was achieved when the

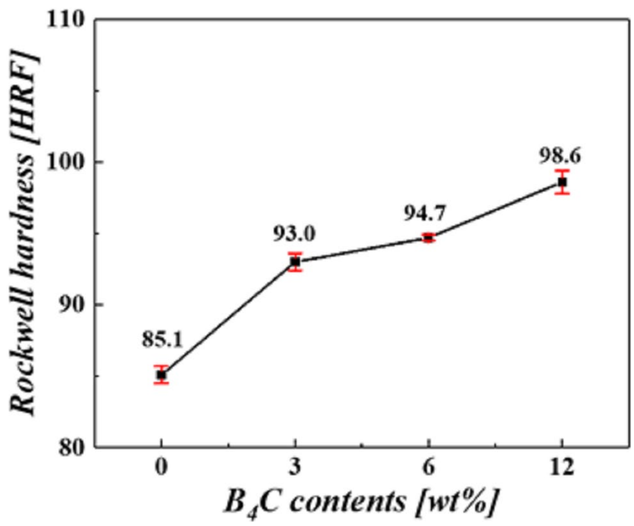

Fig. 3. Variation of Rockwell hardness with addition of B_4C reinforcement into Al6061

12 wt.% B_4C was added, which was about 15.9% improvement in the hardness value compared to the Al6061. Even though one main strengthening effect could not be suggested in this study, the increase in the hardness could simply be explained by the presence of the harder B_4C particles than the Al6061. The harder B_4C particles could withstand the load transferred from the Al6061 matrix, preventing deformation of the Al6061-B_4C composite when external load was applied. And, the increase in the hardness was directly related to the B_4C fraction based on linear mixture rule (or inverse mixture rule). The B_4C particles would further work as an obstacle for dislocation motion, however it was reported that Orowan strengthening was not critical when micro-sized reinforcements were applied due to the coarse size and wide interparticle size [38].

Wear is a kind of phenomenon that material loss gradually occurs due to the continuous relative motion between two materials in contact. Wear performance was mainly influenced by the applied load and sliding speed and characterized in terms of wear rate (wear loss) and coefficient of friction. Fig. 4 showed the wear loss after the wear test and variation of coefficient of friction (COF) with the sliding distance. The small amount of B_4C addition as low as 3 wt.% resulted in the significant reduction in the weight loss (~39.5%) compared to that of the matrix material and this reduction magnitude maintained by the 6 wt.% B_4C addition and as a result, the reduction in the wear loss reached about 89.1%. The B_4C addition up to 12 wt.% also reduced further decrease in the wear loss but in this range, the contribution of the B_4C addition to the wear loss was not remarkable compared to the former two cases. As shown in Fig. 4(b), the reduced COF with the B_4C addition would contribute to the improved wear property. With the increase in the B_4C amount, the COF was reduced gradually from 0.64 to 0.43 and its deviation for each sample was moderate with the sliding distance, ranging in a specific region. These trends were also consistent with the results of the wear scar in terms of width and depth, as shown in Fig. 5. High hardness would reduce the contact area between the sample and ball due to the restricted plastic deformation, which would lead to less wear loss in terms of worn width and

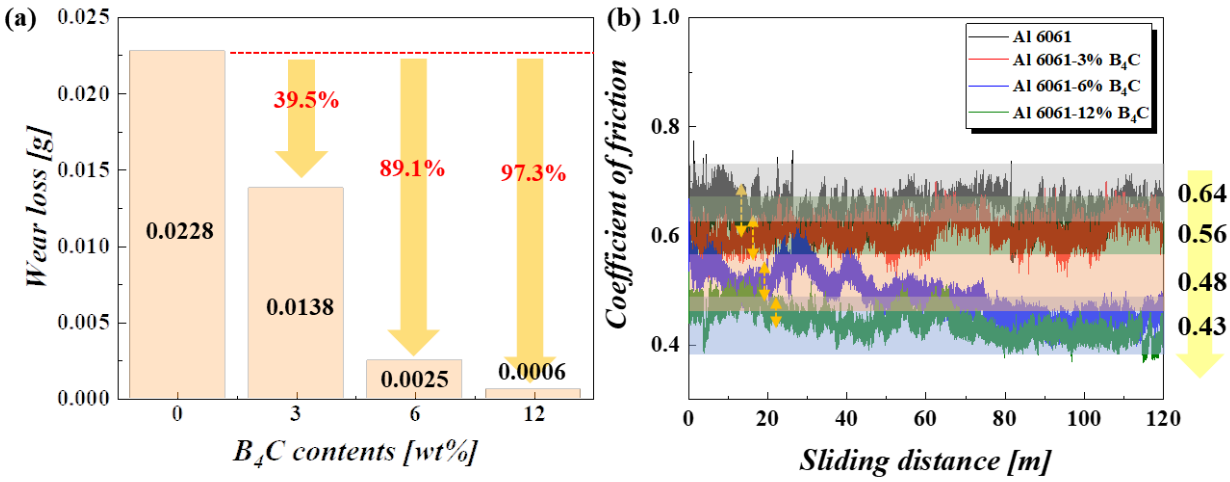

Fig. 4. (a) Calculated phase diagram of the alloys and (b) enlarged part of (a) showing variations of Ti_2Ni and β-Ti with the Ta content

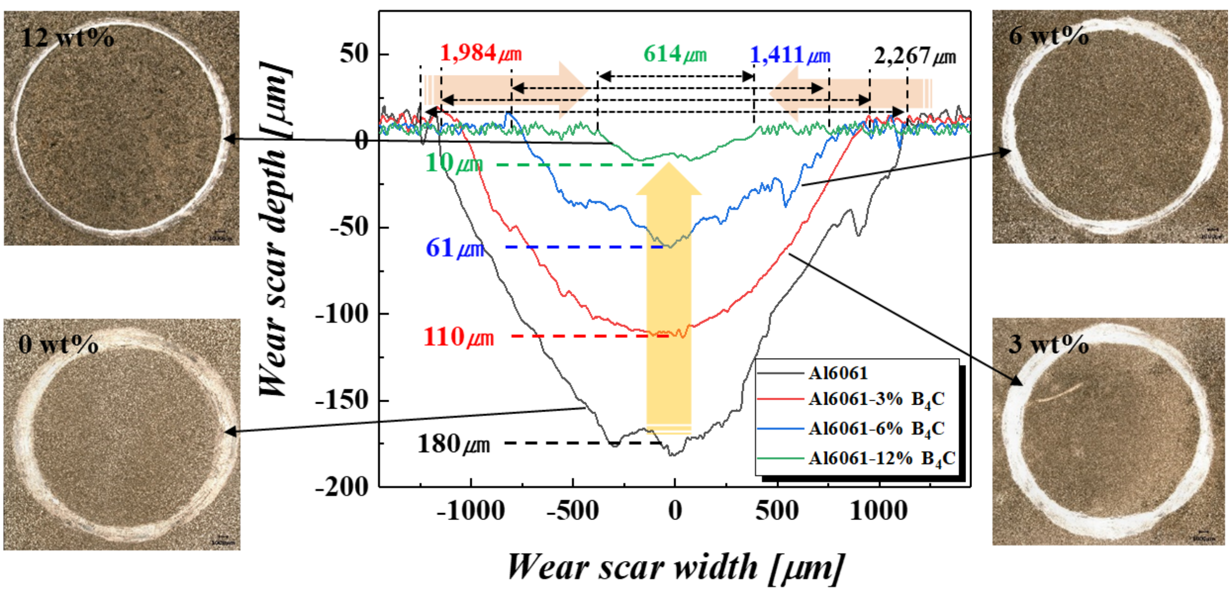

Fig. 5. Profile results on worn surfaces and corresponding OM images showing wear scar of the matrix material and composites

depth. With higher B_4C loading, worn area (scar) showed narrower width and shallower depth. The scar width was reduced from 2,267 μm to 614 μm and the scar depth was also decreased from 110 μm to 10 μm, indicating that the wear amount could be significantly reduced through the addition of the B_4C reinforcement. The high hardness would cause the reduction in the contact area, leading to the low COF and consequently, the improved wear performance.

Worn surface morphology was analyzed to find out which wear mechanisms such as delamination, adhesive and abrasive modes played a critical role in determining the wear performance, as shown in Fig. 6. The high worn, and torn morphology with smooth load-bearing patches and deep grooves along with the sliding direction were observed on the worn surface of the matrix material (Al6061), indicating that adhesive wear was dominant for the matrix material. The Al6061-3 wt.% B_4C composite also showed the similar morphology with the matrix material. Even though mechanical properties such as hardness and wear resistance were a little improved as a result of the 3 wt.% B_4C addition, this effect was not enough in shifting the wear mechanism. However, when the reinforcement was added over the 6 wt.%, the wear mechanism seemed to be changed from adhesive to abrasive wear. As shown in Fig. 5(c) and (d), the composites containing over 6 wt.% B_4C showed the clear parallel grooves, while the wear debris was significantly reduced. For the Al6061-6wt.% B_4C composite, some pits denoting the adhesive wear still remained, suggesting that the composite placed under the transition state from adhesive to abrasive wear. While, only smooth surface with the mild grooves was observed for the Al6061-12 wt.% B_4C composite, where the abrasive wear prevailed.

4. Conclusions

The addition of B_4C reinforcement particles into Al6061, even though their size was over 120 μm in terms of D_{50} gave a significant impact on mechanical properties such as hardness and wear resistance. Well-dispersed harder B_4C particles in the Al6061 matrix worked as a reinforcement and thus, resulted in the increase in Rockwell hardness. Wear performance was also enhanced in terms of wear loss and coefficient of friction (COF), by forming the Al6061-B_4C composites. The reduction in the wear loss was achieved when the B_4C particles were added and gradually proceeded up to the 12 wt.% B_4C addition, accompanying with the reduction of COF. Eventually, the Al6061-12 wt.% B_4C composite showed the narrowest and shallowest wear scar. Analysis on worn surface revealed that the dominant wear mechanism for the Al6061-12 wt.% B_4C composite was abrasive wear, while the matrix material and the Al6061- wt.% B_4C composite showed adhesive wear and the Al6061-6 wt.% B_4C did mixed characteristic of adhesive and abrasive wear.

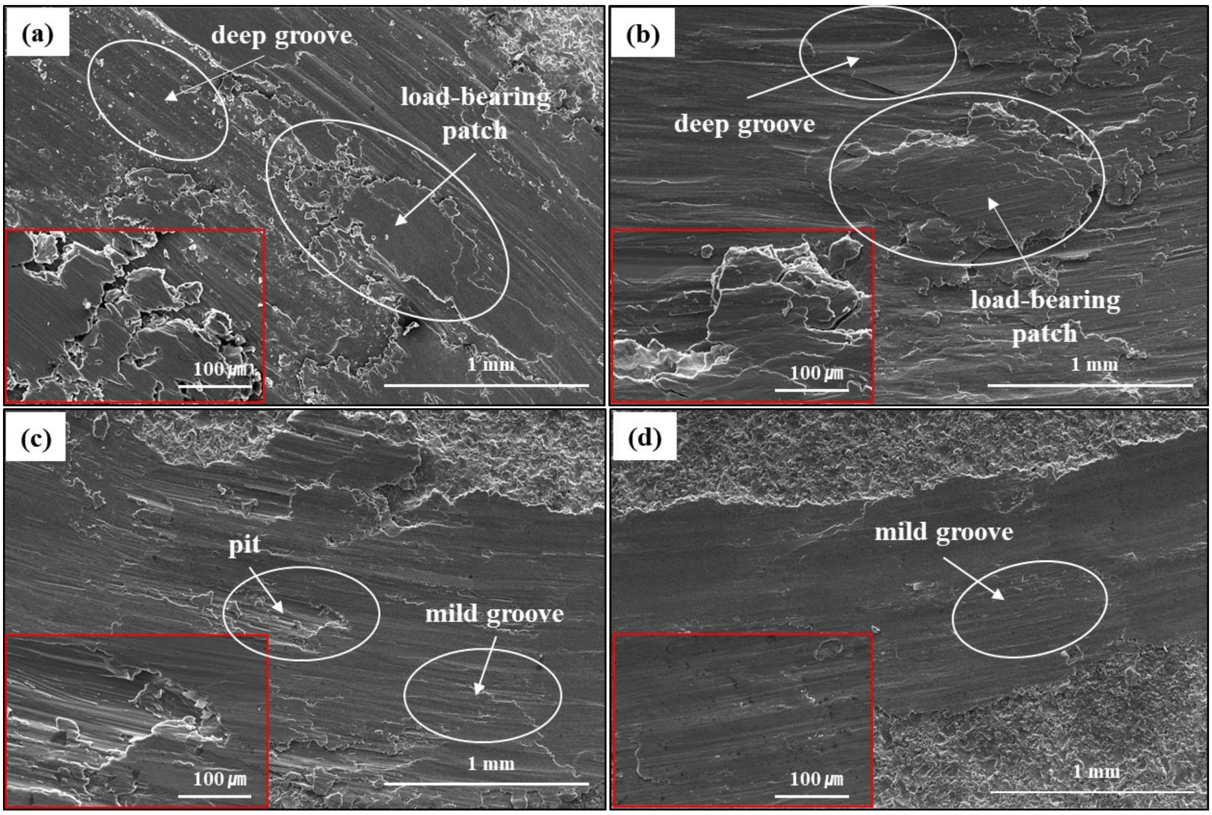

Fig. 6. SEM images showing worn surface morphology of (a) Al6061, (b) Al6061-3 wt.% B_4C, (c) Al6061-6 wt.% B_4C and (d) Al6061-12 wt.% B_4C

Acknowledgement

This work was supported by the Korea Electric Power Research Institute (KEPRI-R22DA03) and funded by the Korea Electric Power Corporation (KEPCO, Korea)

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