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# Dry sliding tribological behavior and mechanical properties of Al2024–5 wt.%$B_4C$ nanocomposite produced by mechanical milling and hot extrusion

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ABSTRACT

In this paper, tribological behavior and mechanical properties of nanostructured Al2024 alloy produced by mechanical milling and hot extrusion were investigated before and after adding $B_4C$ particles. Mechanical milling was used to synthesize the nanostructured Al2024 in attrition mill under argon atmosphere up to 50 h. A similar process was used to produce Al2024–5 wt.%$B_4C$ composite powder. The milled powders were formed by hot pressing and then were exposed to hot extrusion in 750 °C with extrusion ratio of 10:1. To study the microstructure of milled powders and hot extruded samples, optical microscopy, transmission electron microscopy and scanning electron microscopy (SEM) equipped with an energy dispersive X-ray spectrometer (EDS) were used. The mechanical properties of samples were also compared together using tension, compression and hardness tests. The wear properties of samples were studied using pin-on-disk apparatus under a 20 N load. The results show that mechanical milling decreases the size of aluminum matrix grains to less than 100 nm. The results of mechanical and wear tests also indicate that mechanical milling and adding $B_4C$ particles increase strength, hardness and wear resistance of Al2024 and decrease its ductility remarkably.



## 1. Introduction

Aluminum based composites are one of the most widely used metal based composites which have attracted much attention so that a large number of studies in the field of metal based composites were belong to this area [1,2]. The reason is the very good properties of these composites such as low density, high strength and stiffness, high specific modulus ($E/\rho$), very good wear resistance, low coefficient of thermal expansion, high damping capacity and excellent high temperature properties. These properties have led to numerous applications of these composites in different industries such as automotive, aerospace, military and nuclear power [3–5]. Wrought aluminum alloys have long being used as a matrix alloy in producing metal based composites. The main cause of this is the low density of aluminum [6,7]. Lillo [4], as an example, used 6061 alloy as matrix composite in his research. Al7075 alloy was also used in Sankar et al. [8] research. Li et al. [9] have used Al5083 alloy as matrix composite in their studies. Most wrought aluminum alloys are appropriate for extrusion and most discontinuously reinforced aluminum composites are produced this way. 2xxx and 7xxx series alloys, because of being heat treatable, are among the best aluminum alloys for producing aluminum based composites [7].

The reinforcement phase in aluminum based composites could be as particle, continuous fiber, short fiber or whisker; however, Particles reinforcement, due to easier manufacturing process and creating isotropic properties in the composite is the most commonly used form [10,11]. The most common ceramic particles used in producing aluminum based composites are as follows: $Al_2O_3$ [12], TiN [13], $B_4C$ [14], MgO [15], $MoSi_2$ [16], etc. These particles can be used in nano and micron scales. Among ceramic particles $B_4C$, due to high melting point (2450 °C), high modulus (445 GPa), good thermal stability, good hardness ($B_4C$ is the third hardest material after diamond and cubic boron nitride (CBN)), high wear and impact resistance, high chemical resistance and low density (2.51 g/cm$^3$), is an appropriate reinforcing material for producing aluminum based composites. Besides, because of high capacity for neutron absorption in isotope $B_{10}$, Al–$B_4C$ composites have special applications in nuclear industries [17–21]. For example, Alizadeh et al. [22] compared the mechanical properties of aluminum matrix composites reinforced with 1, 2 and 4 wt.%$B_4C$ nanoparticles fabricated via stir casting method. Their results show that with increasing amount of $B_4C$ nanoparticles,

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yield strength and tensile strength increased but elongation to fracture decreased.

Al–$B_4C$ composites are produced by three different methods: solid state methods (such as mechanical milling and powder metallurgy), molten methods (such as stir casting) and semi-solid methods [23,24]. Generally, solid state methods are usually used to produce particle composites with high mechanical properties, because these methods provide a uniform distribution of secondary phase particles in the matrix. Therefore, composites produced by these methods are isotropic. In addition, as the temperature in these methods are much less than in molten methods, undesirable interfacial interaction between the matrix and reinforcement, that usually leads to loss of mechanical properties, are avoided and the segregation of reinforcement particles becomes minimized [13,18]. For example Zhang et al. [25] observed extensive debonding during mechanical testing of a bulk Al–$B_4C$ composite fabricated with conventional powder metallurgy method attributable to a weak bonding between the reinforcement and matrix. Han et al. [26] in their research on Al5083 alloy proved that mechanical milling enhances the strength of alloy up to 713 MPa but reduces its ductility to 0.3%.

Wear behavior of aluminum matrix composites depends on strength of the interface between matrix and reinforcement particle. If the interface between the matrix and reinforcement material is not strong enough, reinforcement particles slow down and lead to considerable material losses [27]. In general, the effect of reinforcing particles size on wear behavior of composite is related to powder preparation method. In composites produced by mechanical milling, reinforcement particles are distributed well and hence with more fine particles, the wear resistance improves [28]. Alizadeh et al. [29] have studied wear behavior of nanostructured Al–Cu alloy and Al–Cu/$B_4C$ nanocomposites produced by mechanical milling and hot extrusion. Their results revealed a lower friction coefficient and a lower wear rate for the nanostructured matrix of Al in contrast to a commercial coarse grained Al matrix. The same pattern was also observed in the nanocomposite samples with respect to the base matrix.

Researchers have studied the effect of pure metals and different alloys grain size on wear properties. The results of these investigations have shown that finer grains lead to increased hardness and reduced wear rate [30–35]. In a study on the wear properties of nanostructured iron, Lv et al. [36] observed that wear rate is higher comparing to coarse grained iron. They attributed this decrease in wear resistance to a sharp decrease of flexibility in a nanostructured sample. Studies on the wear behavior and mechanical properties of the $B_4C$ particulate-reinforced MMCs with Al2024 matrices are, however, limited. This could be due to the high strength and low compressibility of this alloy [37]. Therefore, in the present research, Al2024–5 wt.%$B_4C$ nanocomposite was produced by mechanical milling and hot extrusion. We studied the effect of $B_4C$ particles on microstructure refinement of Al2024 based composite in mechanical milling process. The mechanical and wear properties of Al2024 alloy, before and after incorporation of $B_4C$ particles, were also examined.

## 2. Experimental details

In this research, Al2024 powder, atomized by Argon gas, with average particle size of 60 μm, was used as the matrix. 5 wt%$B_4C$ powder, with average particle size of 20 μm was also used as reinforcement.

An attrition mill equipped with water cooling system was used for mechanical milling process and producing Al2024–5 wt.%$B_4C$ composite powder. Ball-to-powder weight ratio and the rotational speed were defined 1:10 and 400 rpm respectively. To prevent oxidation and contamination of powders during mechanical milling, argon with 99/99% purity was used. To prevent cold welding during milling, 2 wt.% stearic acid was used as process control agent (PCA). In order to study the effect of boron carbide on microstructure, wear resistance and mechanical properties, unreinforced Al2024 aluminum alloy powder was milled for 50 h under same condition. Microstructure of powder, after 50 h being milled was studied by Transmission electron microscopy (Philips-FEGC200) to define the grain size and reinforcement particles distribution within the aluminum matrix. To study the effect of mechanical milling process on the grain size of matrix alloy and the amount of lattice strain, Williamson–Hall method was used [38,39].

After mechanical milling process, hot extrusion process was used for final forming. To that end, powders were hot-pressed in a cylindrical mold. Then, the hot pressed powders were exposed to hot extrusion in 750 °C with extrusion ratio of 10:1. It should be noted that in order to study the effect of boron carbide particles and mechanical milling on Al2024 alloy properties, a coarse-grain sample using unmilled Al2024 powder was produced through hot-pressing and then hot extrusion.

At the end of extrusion process, the microstructure of extruded samples was studied parallel and perpendicular to extrusion direction by Optical microscopy (OM) and Scanning electron microscopy (TESCAN XMU VEGA-II). To compare the mechanical properties of samples, tension, compression and hardness tests were applied. The samples of tension test were provided according to ASTM: B557 and the test was performed at room temperature at a speed of 1 mm/min. In order to determine the fracture mode of samples, the cross section fracture was examined by SEM after tension test. The compression test was also performed at room temperature at displacement rate of 1 mm/min. The samples of compression test were produced with 1/4 length-to-diameter ratio. The hardness of samples was measured by Brinell hardness test with ball diameter of 2.5 mm and 30 kg force.

The wear test in this research is performed by a pin-on-disk wear-testing apparatus. The pins used in this research were produced of extruded samples as cylinder with diameter of 1 cm and height of 2 cm. The disk used in this research was also made of steel with a hardness of 63 HRC. The wear test was performed in distance 3000 m, at speed of 0.6 m/s and with imposed load of 20 N. At the end of each stage, the surface of samples were cleaned and washed by alcohol, then weighed carefully and the weight loss is defined and recorded. In order to study the surface changes of worn samples and understand the mechanism of wear, the worn surface was examined by scanning electron microscopy with an energy dispersive X-ray spectrometer (EDS). At this stage, besides taking microscopic image of worn surface and wear particle morphology, the chemical composition of tribological layer was also determined by EDS.

## 3. Results and discussion

### 3.1. Average size of sub-grains

Fig. 1 shows a TEM image of Al2024 powder and Al2024–$B_4C$ composite powder after 50 h of mechanical milling and an EDS analysis of aluminum based and boron carbide. As it is shown, following the mechanical milling process, $B_4C$ particles are dispersed quite uniformly in aluminum based so that $B_4C$ particles have even penetrated into aluminum grains. Moreover, no clustering or agglomeration of particles is observed. The TEM image of Al2024 powder (Fig. 1b) shows sub-grains of aluminum based with average size of 35–50 nm which a little more than grain size calculated by Williamson–Hall method for Al2024 powder.