EFFECT OF REINFORCEMENT CONTENT AND CONSOLIDATION PROCEDURES ON PROPERTIES OF ALUMINUM–BORON CARBIDE NANO- COMPOSITES

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Gas atomized Al (6061) powder particles were used to synthesize nano-structured Al based composite powders reinforced with 2 and 5wt.% of nano and micro sized boron carbide particles by mechanical alloying. These composite powders as well as the un-reinforced Al powders were compacted by cold uniaxial pressing. In order to investigate the effect of consolidation procedures on the properties of the resultant Al-B₄C composites, a number of the samples were subjected to sintering at 620 °C for 2h while the others were hot extruded at 520 °C with the extrusion ratio of 8:1. The effect of percentage and size of B₄C on the density, hardness and mechanical properties (such as yield strength, compression strength) of the composites were evaluated and compared with those of the un-reinforced alloy. The fractured surfaces of the samples were studied by scanning electron microscopy (SEM). The results of the present study revealed a higher hardness for the extruded samples as compared with their sintered counterparts attributable to their increased density and decreased matrix grain size. It was also shown that addition of 2 and 5wt.% of B₄C nano-particles increased yield strength of the extruded samples by 3 and 4 times respectively as compared with the un-reinforced aluminum.

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1. Introduction

Metal matrix nanocomposites (MMNCs), are a class of materials that combine a metal matrix with a nano reinforcement to improve the properties of the metal. Most researches are done on MMNC consisting of light metals with a deliberate addition of ceramic particles like oxides, carbides and nitrides. Several different reinforcements can be combined with aluminum such as Al_2O_3 [1, 2], SiC [3, 4], AlN [5], TiB_2 [6], graphite [7]. Among these reinforcements, B_4C offers a good combination of properties. It is third hardest material after diamond and cubic boron nitride. It has a low density of 2.52 g/cm^3 which is close to that of aluminum [8]. Due to its high hardness it is an excellent choice to impart wear resistance to the composite. It has a melting point of 2445°C which is useful in improving the thermal properties of the composite. It offers good resistance against several chemicals and due to its ability to absorb neutrons it finds its utility in nuclear reactors [9].

In case of Al- B_4C composite, liquid phase approach is usually disadvantageous because aluminum does not wet B_4C at low temperatures. The melting temperatures of the two materials are widely apart (660°C for Al compared to 2445°C for B_4C) and therefore, at low temperature no reaction or interaction takes place between the two phases. For complete wetting of B_4C by aluminum a temperature of around 1100°C is required [10]. Apart from difficulty in processing of aluminum at such a high temperature, it also leads to several undesirable phases, such as aluminum carbide (Al_4C_3), which result in lower mechanical properties. In contrast, powder metallurgy eliminates undesirable reactions such as formation of Al_4C_3 phase and processing is relatively easy among other benefits such as low processing cost and homogenization of the reinforcement in the matrix material. Based on authors knowledge, there are limited reports on the preparation of Al- B_4C composites and nanocomposites by powder metallurgy.

In this study mechanical alloying which is a capable method for producing metal matrix nanocomposite was used for synthesizing Al- B_4C nanocomposite. The main objective of the present study is systematic investigation on the effect of some processing parameters such as B_4C size and its content on mechanical properties (microhardness, yield and compression strength) of this composite.

2. Experimental Procedures

Pre-alloyed Al-6061 powder, manufactured by gas atomization was used in the present research. The alloy powder was spherical in shape and the average particle size was $71\mu\text{m}$. Nano Boron carbide used in this research was manufactured in our laboratory and its details have been reported elsewhere [11]. Aluminum powder and B_4C particle with different size (90, 700, 1200nm) and content were milled in a high energy ball mill in argon atmosphere. Scanning electron microscopy (CamScan MV2300) and transmission electron microscopy (Leo 912-AB) was used for studying powder morphology changes during milling. Cylindrical nanocomposites and microcomposite samples were prepared

by two method 1) cold pressing at 350 MPa and hot extrusion in 520°C 2) Cold pressing at 450 MPa and sintering in a tube furnace in 620°C for 2h. The densities of samples were measured by Archimedes method. Microhardness test was conducted on sintered and extruded samples. The mechanical properties of extruded nanocomposites were evaluated by compression test and their yield and compression strength was measured. The samples were designated by Al_xC_y (Z %) in which X, Y and Z indicate aluminum particle size (μm), B_4C particle size (nm) and B_4C percent (wt. %) respectively.

3. Results and Discussion

3.1. Morphology of Al- B_4C milled powder

Figures. 1-a and b show scanning electron micrograph of as-received aluminum and TEM micrograph of B_4C powders respectively. Fig. 2 shows the SEM micrographs of Al- B_4C nanocomposite powders milled for different milling times. It can be seen that the as-received aluminum powders are rather spherical (Fig. 1-a) but by milling Al- B_4C mixture for 2h plate like particles are formed (Fig.2-a). After 4 and 8h milling the flattened aluminum particles are cold welded to each other. In the final stages of milling a balance between cold welding and fracturing has occurred and equiaxed particles are formed after 16h milling (Fig. 2-d).

Fig. 1. (a), SEM micrograph of as-received Al_{71} and TEM micrograph of B_4C nanoparticles.

3.2. Density

The relative densities of different extruded and sintered samples are presented in Fig. 3-a and b. It can be seen from these figures that the relative density of nanocomposite is lower than microcomposite. In addition, the extruded samples have higher density in comparison with the sintered samples. The average of relative density of extruded

samples is 0.98 whereas the average density of sintered samples is 0.96. From these results it can be concluded that extrusion method is more effective for consolidation of micro and nano composite in comparison to sintering method

3.3. Micro hardness

Homogenous dispersion of nanoparticles in matrix is an essential factor for achieving desirable mechanical properties for metal matrix nanocomposite. Microhardness measurement from different section of a sample could be an index for indication of quality of nanoparticles dispersion in matrix. Fig. 4 shows the microhardness results of different sections of the samples for Al-B₄C composite. This figure reveals that the microhardness values of different section of the samples don't differ from each other significantly and it is attributed to uniform dispersion of B₄C nanoparticle in aluminum matrix.

The effect of B₄C content on microhardness of samples could be seen in Fig. 5. For comparison, the microhardness of heat treated samples are shown in this figure. It can be seen that by increasing B₄C content the hardness of micro and nanocomposite increases as well. For examples, the microhardness of Al₇₁C₉₀(7%) nanocomposite is 5 times higher than monolithic aluminum.

Fig. 2. SEM micrographs of Al₇₁ powders milled for (a) 2h, (b) 4h, (c) 8h and (d) 16h.

Fig. 3. The relative density of (a) extruded samples (b) sintered samples

Fig.4. Microhardness measurement from different section of samples

Moreover, adding 2Wt. % of B_4C nanoparticles to aluminum matrix results in equal hardness with $Al_{71}C_{700}(7\%)$. From this figure it can be concluded that the microhardness of aged samples is higher than unheat-treated samples. Fig. 6 shows the effect of B_4C size on microhardness for nano and micro composite before and after heat treatment. It can be seen that by decreasing B_4C particle size, microhardness increased significantly and the slope of increasing rate promoted when the size of B_4C particle size reached smaller than 700nm.

Fig 5. Effect of B_4C content on microhardness.

Figure 6. Effect of B_4C size on microhardness : Dash line : Before heat treatment Filled line: After heat treatment

The effect of B_4C content on microhardness of sintered and extruded samples have been shown in Fig. 6. This figure reveals that similar to extruded samples, the microhardness of sintered samples intensified by increasing B_4C content. However, the microhardness of extruded sample is higher than sintered samples. These results are attributed to following cases:

- The density of extruded samples is higher than sintered sample which results in higher microhardness.
- Work hardening during extruding procedure results in finer grain size which leads to higher hardness according to Hall-Pitch relation.

3.4. Compression test

Fig. 7 shows a typical compressive tests for the $\text{Al}_{71}\text{C}_{700}(5\%)$ sample. The yield and compression strength and fracture strain of different sample was measured from stress-strain curves and listed in Table.1. From Table1 it can be concluded that by adding B_4C nanoparticles the yield and compression strength increased considerably rather than monolithic aluminum. For example Table 1 shows that the yield strength of Al- 2wt.% nano B_4C is 3.7 times higher than monolithic aluminum. In addition, the yield strength for $\text{Al}_{71}\text{C}_{90}(5\%)$, $\text{Al}_{71}\text{C}_{700}(5\%)$, $\text{Al}_{71}\text{C}_{1200}(5\%)$ are 590MPa , 360 MPa and

Fig. 6. Effect B_4C content on microhardenes of extruded and sintered samples

Fig. 7. Compression stress-strain curve for $\text{Al}_{71}\text{C}_{700}(5\%)$ composite.

320MPa respectively which indicates the effect B₄C size on yield strength. These results show that by increasing B₄C content from 2% up to 5% the yield strength increased 31%. Also this table shows that increasing B₄C content and reducing its size results in smaller strain. Fig. 7 shows SEM micrograph of fracture surface for Al₇₁C₇₀₀(5%) and Al₇₁C₉₀(2%).

Table 1. Result of compression test on different samples.

Sampels	Yield Strength (MPa)	Compression Strength (MPa)	Strain
Al-Casting	120	----	>0/3
Al ₇₁ C ₁₂₀₀ (5%)	320	450	>0/23
Al ₇₁ C ₇₀₀ (5%)	360	600	>0/27
Al ₇₁ C ₉₀ (2%)	450	670	>0/22
Al ₇₁ C ₉₀ (5%)	590	690	>0/13

Fig. 8. SEM micrograph of fracture surface (a) Al₇₁C₇₀₀(5%) (b) Al₇₁C₉₀(2%)

4. Conclusion

- Mechanical alloying of a mixture of aluminum 6061 powder particles and B₄C particles resulted in the morphological changes of Al powders during milling.
- Addition of B₄C particles to the Al matrix resulted in increased microhardnes and this effect was intensified for nanocomposite.
- The compression test results revealed that by increasing B₄C content and decreasing its size, the yield and compression strength incecreaseds significantly.
- The decreased strain was observed for nano and micro composite in comparison to monolithic aluminum

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