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Impact of heat treatment on the mechanical performance of hot extruded Al6061-BN reinforced metal matrix composites

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Abstract. Boron nitride (BN) reinforced Al6061 aluminum-based composites are synthesized by conventional stir casting method followed by exposure to hot extrusion. The optical images confirmed the distribution of BN nanoparticles in the aluminum alloy matrix. The concentration of BN is varied from (0.5, 1.5, 3, 4.5, 6, 7.5, and 9 wt%) in the composites and its effect on the tensile strength was investigated. The results revealed that both extruded and heat-treated composites specimens showed enhanced toughness an tensile strength by increasing BN nanoparticle concentration. The heat-treated composite samples showed lower flexibility of up to 40%, and further, it exhibited 37% greater hardness and 32% enhancement in tensile strength over the extruded sample. The tensile properties of Al6061-BN composites were evaluated by temperature-dependent internal friction (TDIF) analysis and the results showed that the as-prepared composite's strength increased with temperature..

Key words: Al6061; metal matrix composites; boron nitride; heat treatment; hot extrusion.

1. Introduction

In the present-day significance, composite materials play a very vital role, and their constant exploration and improvement made them attractive in different applications such as automobile, aerospace, biomaterials, defense, and sports. It is expected that the application of composite materials will cover many emerging research fields in the future and dominate many applications for a longer period [1–3]. Over the last 30 years metal matrix composites (MMC's), with aluminum as the base metal, have emerged as an important class of materials for aircraft, aerospace, automobiles and various other fields [4, 5]. In addition, BN which is used as target reinforcement material has gained enormous attention because of its properties like excellent thermal conductivity, higher melting point, and good electrical resistivity [6, 7]. So, coupling MMC's with BN often presents remarkable improvement in MMC's strength, stiffness, conductivity, etc. Hence, various researchers have tried out many synthesis approaches such as semi-solid powder metallurgy, mechanical alloying technique, squeezed casting, stir casting to fabricate aluminum-based ceramic BN reinforced metal matrix composites.

Recently, BN reinforced composite specimens have shown exceptional ability to enhance the mechanical strength of materials. For instance, Chunguang *et al*. synthesized Al6061-BN composite by adopting the liquid-solid powder metallurgy technique and reported that mechanical properties of as-prepared composite material could be enhanced by reducing their particulate size [8]. Chawla *et al*. developed particulate reinforced composites by mechanical alloying technique and demonstrated that the hardness of developed compounds is significantly affected by milling time during the alloying process [9]. Lotfy *et al*. adopted the squeeze casting method to fabricate aluminum-based composites and had demonstrated that the composites developed by squeeze casting exhibit uniformity in reinforcement distribution in the matrix alloy [10]. Besides, the composites prepared by stir casting technique consume less time and are more economical for mass production [11]. By refining their microstructure, the mechanical properties could be enhanced and thus it could be used in automobile and space applications [12, 13]. Aluminum alloy reinforced with TiB_2 particles shows drastic enhancement in toughness and flexible strength in comparison with aluminum alloy [14]. The rate of wear is inversely proportional to reinforcement concentration and hot extrusion of metal matrix composites thus, increase the composite's mechanical properties [15, 16]. The work of Berndt *et al*. showed that extrusion and heat treatment of aluminum alloys leads to enhancement in mechanical properties [17]. Firestein *et al*. have witnessed the strength and ductility in aluminum alloy compos-

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ite and described that hot extrusion of composites improved the mechanical behavior [18]. Gangil *et al*. reported that in stir cast and hot extruded SiC reinforced aluminum 6061 composites the metal particle was rearranged in the extrusion direction [19]. However, some issues, such as weak interfacial bonding between alumna matrix and BN, and the effect of poor dispersion within alumina composites, need to be timely addressed. Therefore, to resolve this issue, compositing Al 6061 metal with suitable hard material is required to significantly enhance the mechanical properties by varying matrix phase, volume fraction, and processing parameters. Hence, it is desirable to develop a new synthesis strategy that is economical and reliable.

In this study, we report the fabrication of Al6061-BN based metal matrix composites by conventional stir casting method followed by exposure to hot extrusion. Compared to Al6061 bulk alumina metal, the as-fabricated Al6061–BN metal composites showed enhanced mechanical behavior over extruded and heat-treated reinforced metal matrix composites.

2. Methodology

2.1. Casting process. In a typical experimental process, 2 kg of commercial casting grade Al 6061 alloy (99.5% pure procured from PMC Corporation, Bangalore, India) was melted and degassed in an electric furnace using commercially available tablets (hexachloroethane). Centrifugal stirrer having 3 blades inclined at 45° and placed 120°C apart was used to agitate the molten metal. Vertex was formed by the rotation of the stirrer at the speed of 400 rpm. The approximate depth of the immersed impeller was $1/3^{rd}$ of the height from the bottom of the crucible having molten metal. The analytical grade BN (procured from RASAYANA, Bengaluru, India) in the hexagonal powder phase having a particle size of 2 μm was slowly added into molten aluminum and stirred continuously for 15 min. The BN percentage was varied from 0.5–9% for each of 1.5 wt%. The melted composite was maintained at 700°C and transferred to treated metallic molds for further use.

2.2. Extrusion process. The extrusion sample measuring 40 mm in length with a cross-section diameter of 35 mm, was subjected to the extrusion process (Mechatronic Control Systems, India). Initially, the test samples were heated to 550°C and later transferred into preheated extrusion die, in the 450−500°C range, which was followed by ageing to increase the mechanical properties of as-prepared composites. The inner surface of the extrusion die was lubricated by grease and graphite powder mixture. Progressive application of load was carried out to extrude Al6061-BN composites with BN percentage such as 3, 6, and 9 wt% with 332 KN load and 10 mm/min feeding speed. The hot extrusion of composites was employed to achieve homogeneity in particle distribution leading to an enhanced mechanical property.

2.3. Heat treatment. An Al6061-BN reinforced composite was heat treated by annealing process to further increase the composite's mechanical properties. Initially, the composite samples were heated till 530°C and maintained for 2 hrs, and then the samples were subjected to ice quenching followed by ageing for 2, 4, 6, and 8 hrs.

2.4. Characterization. The morphology of the as-prepared Al6061-BN composites was studied using an optical microscope (Meiji, Singapore) connected CCD color video camera (Samsung) which can reach a magnification range of 500x. Besides, scanned electron microscopy (JEOLJSM-6500F) was used to study morphology and microstructure. The hardness and ductility measurement were performed using UTM (Mechatronic Control Systems, India) and Vickers hardness tester (ROCKWELL, India).

3. Results and discussion

3.1. Microstructural studies. The optical microstructure of Al6061 with 9 wt% BN extruded, and extruded plus heat-treated samples are shown in Fig. 1. It is evident from the micrographs that reinforcement is homogeneously distributed and there exists a robust interfacial bonding between the alloy matrix and reinforcement. Besides, as per the optical images, there is no indication of holes in the crystalline structure of the matrix and particle clustering. It can be observed that heat-treated samples constitute Mg_2Si intermetallic components which are evident in stress relief established during hot extrusion which acts as a barrier leading to an increase in mechanical properties [20].

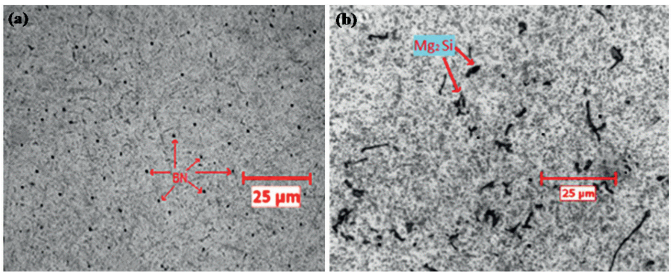

Fig. 1. Optical microphotographs of (a) extruded and (b) extruded + heat treatment specimens

3.2. Micro-hardness

3.2.1. Effect of reinforcement. It is well-known that the effect of composite reinforcement is closely related to its mechanical strength. Figure 2 shows the change in micro-hardness variation of extruded and heat-treated composites with several BN reinforcements. It could be observed that increasing the wt% of BN in both extruded and heat-treated composites might drastically enhance the micro-hardness. When compared with extruded alloy matrix an optimum of 37% rise in toughness is observed in extruded Al6061 – 9 wt% BN composite specimens. Improvement in hardness with varying wt% of BN concentration can be justified as follows:

- In general, the BN reinforcement increases the resistance of the aluminum matrix composite hardness [21].

- Increasing the content of reinforcement results in improved dislocation densities in matrix alloy on solidification of thermal divergence between Al6061 alloy and BN particles and thus slowdown of plastic deformation [22].
- In composite material, the indenter load is partially accommodated by much harder BN particles, and thus by increasing the amount of BN concentration the hardness increases.

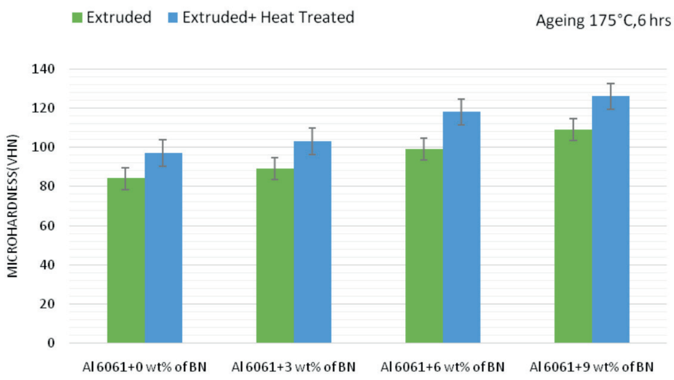

Fig. 2. Variation of micro-hardness of hot extruded and heat treated Al6061-BN composites with wt%of reinforcement

The heat-treated Al6016 – 9 wt% BN particles showed about 37% increase in micro-hardness related to extruded matrix alloys. This clearly illustrates that heat-treated material forms intermetallic precipitates like Mg_2Si which improves the hardness of the metal matrix composite.

3.3. Effect of ageing duration. The variation in micro-hardness of hot extruded Al6061-BN composites with ageing duration is shown in Fig. 3. It is observed that, by increasing the duration of ageing, the micro-hardness of MMC's was increased. Interestingly, after ageing for 6 hrs, a maximum of about 51% increase in hardness was observed in Al6061 – 9 wt% of BN composite sample. The above result is due to an increase in the formation of intermetallic fine state precipitated dispersion. A slight decrease in micro-hardness has been observed in both composites and its matrix alloy at 8 hrs ageing. This variation in results might be owing to long-duration ageing of intermetallic precipitates which could develop coarser materials resulting in a reduction in hardness [23].

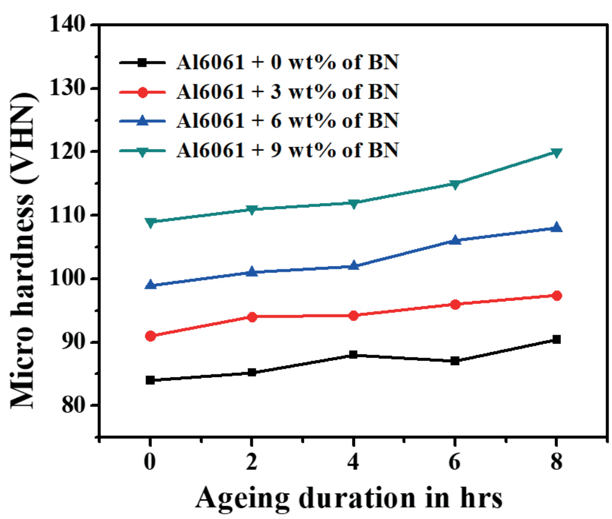

Fig. 3. Effect of ageing duration over micro harness of Al6061-BN composites

3.4. Ultimate tensile strength (UTS)

3.4.1. Effect of reinforcement. The changes in UTS of hot extruded and heat treated Al6061-BN composites are shown in Fig. 4. It is clear from the figure that the final strength of heat-treated composites (3, 6, and 9 wt%) shows drastic improvement in comparison with extruded ones. It is observed that the strength of the composites is associated with reinforcement concentration. However, the reinforced samples showed lower elastic deformation in contrast with unreinforced specimens. A maximum improvement of 32% is observed in extruded Al6061 – 9 wt% of BN composites with 6 hrs ageing. The improved strength of extruded composites could be credited to the decreased porosity and refinement of grain structure during extrusion. The extrusion process results in higher compressive forces on material leading to a reduction in reinforcement. The higher stress during the extrusion process results in a large degree of reduction in BN particle size. The smaller the size of the reinforced particles, the higher its homogeneity in its distribution within the matrix alloy, with significant enhancement of strength of the composites was observed. Such kind of behavior was also observed and reported by other researchers [24].

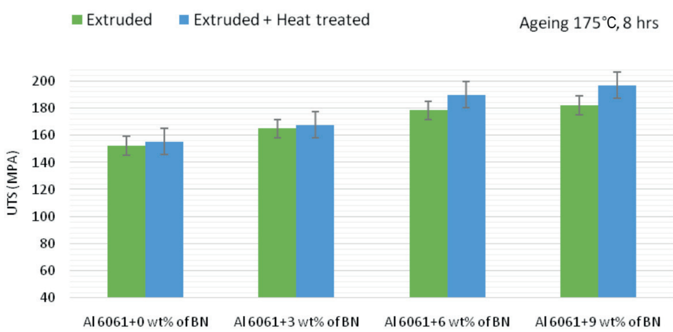

Fig. 4. Variation of UTS of hot extruded and heat-treated Al6061-BN composites

3.4.2. Effect of reinforcement. The tensile test performance of hot extruded Al6061 alloy by varying wt% of BN composites with different ageing duration is shown in Fig. 5. From the plot, it could be observed that the strength of composites improves with ageing duration, and an improvement of 40% rise in heat-treated composites was observed in comparison to extruded specimens. It is apparent to observe that 6 hrs heat-treated samples showed improved tensile strength for the entire BN wt% samples. Further, it is examined from the data that the tensile strength of alumina alloys and composites declines after 6 hrs of ageing.

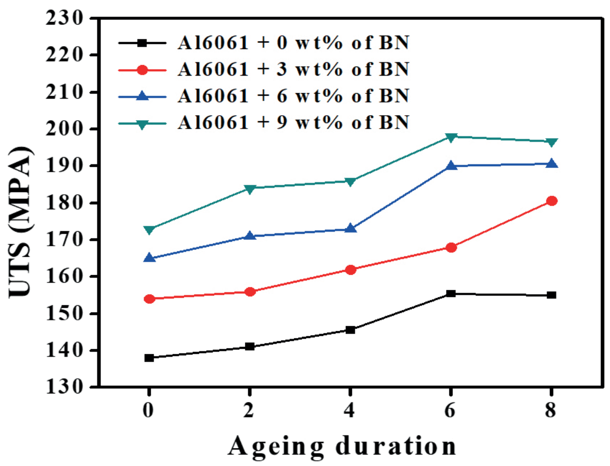

Fig. 5. Ageing duration effect on tensile- strength of Al6061-BN composites

3.5. Ductility

3.5.1. Effect of reinforcement. The difference in ductility of hot extruded Al6061-BN composite samples is shown in Fig. 6. A reduction in ductility is noticed with the increase in BN concentration. An increase in BN concentration leads to closer packing of reinforcement in matrix alloy leading to a decrease in ductility. An upsurge in reinforcement percentage reduces space between the particles, leading to localized stresses and a reduction in ductility. The ductility reduction in composites is due to the stress concentration effect caused due to the addition of reinforcement [25]. The presence of intermetallic reinforcement phases acts as potential spots for primary crack nucleation leading to a decrease in ductility under static loading [26].

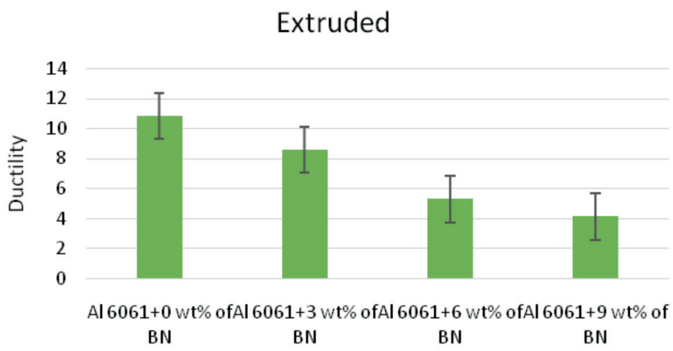

Fig. 6. Ductility variations of hot extruded Al6061 alloy and Al6061-BN composites

3.6. Effect of ageing duration. The response of Al6061-BN composites in terms of ductility for a rise in the content of reinforcement under varying conditions such as extrusion and heat treatment are shown in Fig. 7. Interestingly, it could be observed that heat treatment leads to a further decrease in the ductility of extruded composites. A reduction in an area up to 52.3% is observed for heat-treated Al6061 – 9 wt% BN composites in contrast with extruded alumina alloy. This might be the reason for Al6061 alloy and composites to exhibit higher hardness and tensile strength on heat treatment. The higher the value of strength and hardness, the ductility will be lower. For instance, Ramesh *et al.* have shown that the impact of Sic_p particle reinforcement on the ductility of aluminum alloys in both peak and age conditions. From their results, it could be observed that ductility drops with the ageing of the matrix [27].

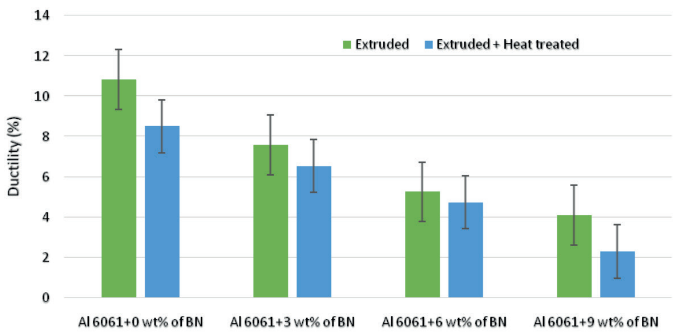

Fig. 7. Variation in ductility of hot extruded and extruded with heat-treated Al6061-BN composites

3.7. Fractography. The fractured surface fractography of extruded Al6061-BN composites and heat-treated Al6061-BN reinforced composites are shown in Fig. 8(a)–(d). The cracked exterior of Al6061 alloy showed small size voids that are distributed consistently, specifying ductile failure. While the Al6061-BN composites show finer sized voids in grain boundaries suggesting a fragile type failure on macroscopic view and ductile type failure on microscopic view. Fractured surface morphology of composites shows several cracks in matrix morphology due to interfacial stress developed on load application, as suggested by other researchers [28, 29]. There is no evidence of particle pullout from morphology indicating the existence of a tough bonding between strengthening particles and the matrix phase. Further smaller depressions are formed nearer to

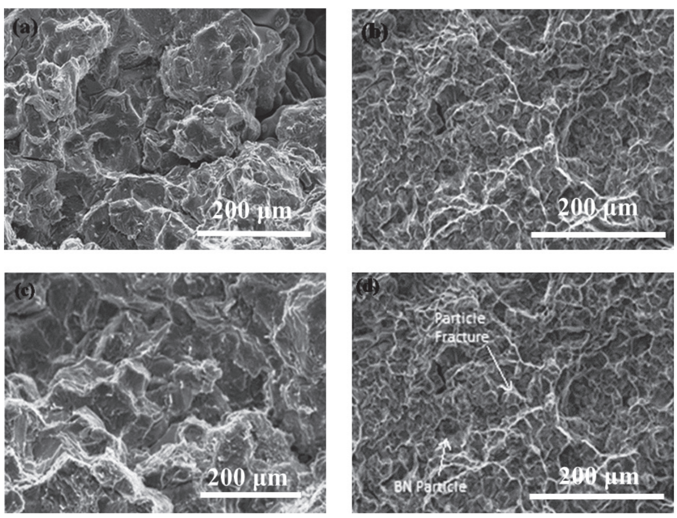

Fig. 8. The microstructure of fractured surface of extruded: a) Al6061 + 6 wt% of BN and (c) Al6061 + 9 wt% of BN. extruded + heat treated: (b) Al6061 + 6 wt% of BN and (d) Al6061 + 9 wt% of BN

strengthening particles caused through the presentation of tensile load due to the mobility of reinforcement particles. Initially, the applied tensile load is occupied by larger-sized particles, on exceeding of tensile load more cohesive strength between the matrix and reinforcement is applied. The larger size particles cracks transfer the load on to smaller size particles resulting in void formation.

4. Conclusions

Alumina 6061-BN composites were processed by stir casting route and exposed to hot extrusion, followed by heat treatment. The microstructure studies confirmed consistency in the dissemination of boron nitride in the alumina alloy matrix. Both extruded and heat-treated composite test samples exhibited an enhancement in toughness and tensile strength with increased content of BN in the matrix. The ductility of extruded specimen samples decreased with an increase in the BN reinforcement composition in the matrix alloy. However, the heat-treated composite samples reveal lower ductility in contrast with the cast counterparts. Heat-treated composites display enhancement in the hardness of up to 37% and tensile strength up to 32% with a reduction in ductility up to 40% in comparison with extruded ones. Besides, the as-prepared Al6061-BN composite tends to decrease its tensile strength with an increase in temperature. This study can also offer new insight into the proposal and development of other metal matrix composites by a low-cost fabrication method for higher mechanical properties.

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