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Optimizing Ultrasonic Power on Fabricating Aluminum Nanocomposites Reinforced with Boron Carbide Nanoparticles

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Abstract. In this work, sonication assisted casting technique was utilized to manufacture aluminum nanocomposites reinforced with B_4C nanoparticles with an average size of 50 nm. To examine the effect of sonication power on manufacturing the metal matrix nanocomposites (MMNCs), the MMNC samples were sonicated with a power of 1.0 kW, 1.5 kW and 2.0 kW. The dispersion of B_4C nanoparticles in Al matrix was predominantly affected by sonication power. From the microstructural analysis it was observed that the MMNC sample processed with 2.0 kW sonication power showed the uniform distribution of B_4C in the aluminum alloy melt which is the prime criteria for the good mechanical properties.

1 Introduction

In general, metal matrix composites (MMCs) contain a low-density metal, reinforced with fibers, whiskers or particulates of ceramic material. Particulate reinforced MMCs possess unique advantages over fiber or whisker reinforced MMCs because of their homogenous properties. It also has better mechanical properties like high strength-weight ratio, stiffness-weight ratio, working temperature and superior wear resistance. Apart from the above mentioned properties it is also possible to tailor the properties of MMCs for different applications. Due to their versatile properties, MMCs possess applications in aircraft, satellites, jet engines and missiles [1].

The ductility and fracture toughness of MMCs are reduced due to the incorporation of ceramic powders in micrometer dimensions. It is reported in the literature that the addition ceramic particles in nanometer scale could solve the above mentioned problems considerably. The major problem associated with nanoparticles is their non-uniform mixing nature in metal matrix. Prof. Xiochum Li and his colleagues in 2004 developed a novel nanoparticles mixing setup famously known as ultrasonic cavitation assisted casting method [2].

The various process parameters that affect the sonication (ultrasonic processing) are as follows: power, amplitude, frequency, pulse ON-time and pulse OFF-time. Ultrasonic power and amplitude are the most significant parameters which affects the dispersion of nanoparticles in metal matrix [3-6]. In this research work, aluminum alloy 6061 (AA6061-chosen due to its low weight) reinforced with boron carbide (2.0 wt.% B_4C) nanoparticles with a mean diameter of 50 nm were fabricated using different sonication power including 1.0 kW, 1.5 kW and 2.0 kW.

2 Experimental Procedures

The matrix material was chosen as Aluminium alloy 6061 with B_4C (boron carbide) nanoparticles as the reinforcements having an average size of 50 nm. The density of Al and B_4C are close to each other, hence, there won't be a segregation problem during the processing of nanocomposites. Here, the problem of increased dislocation density is caused due to the high difference in thermal expansion coefficient between Aluminium alloy and the B_4C nanoparticle. Increase in dislocation density is prerequisite for increase in strength of the material as it is the major strengthening mechanism in particle reinforced composites. The more the number of dislocations, more will be the restrictions to the movement of dislocations.

Previous experimental results showed that ultrasonic assisted casting is one of the proven methods for dispersing nanoparticles in metal matrix. The ultrasonic vibration causes the following phenomena; formation of bubbles within the melt, size growth of bubble, ultrasonic pulsation and bubble bursts in the liquid melt [7-9]. While these phenomena take place, the nanoparticles are stuck over the micro bubbles surface. During the implosive burst of bubble after continuous ultrasonic pulsation, the clustered nanoparticles break open and thus uniform distribution of nanoparticles are achieved in the liquid matrix. Photograph of ultrasonic assisted casting setup and solidified Al/B_4Cp samples are shown in figure 1a and figure 1b respectively.

To analyse the effect of ultrasonic power on fabricating the Al/B_4C MMNCs, the 2.0 wt. % B_4Cp reinforced MMNC samples were sonicated at 1.0 kW, 1.5 kW and 2.0 kW ultrasonic powers. Mechanical stirring continued for obtaining the primary dispersion of B_4C in Al melt. Then mechanical stirrer was detached and then the melt was sonicated at 680^0C by immersing the sonotrode (ultrasonic probe) into the Al melt (Fig.1-a). To understand the effect of power ultrasound, the fabricated Al/B_4Cp MMNC samples were examined for their microstructure, tensile strength and hardness. In each experiment, same processing parameters were used. Sonication was carried out through a 20 kHz indigenously developed ultrasonic system.

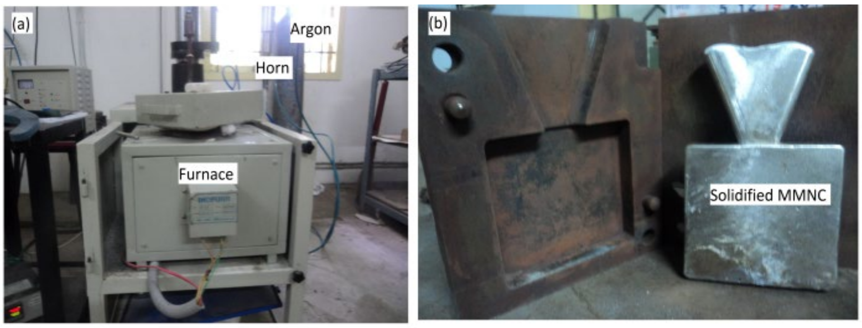

Figure 1 (a) Sonication setup (b) Soildified MMNC

3 Results and Discussion

3.1 Microstructure of Al/ B_4Cp MMNC

The scanning electron microscopy (SEM) micrographs of Al/B_4C metal matrix nanocomposites processed with different ultrasonic power are depicted in figure 2. The microstructural studies showed that the MMNC processed with 2 kW power have a more uniform distribution of B_4Cp in Al matrix than the other two MMNCs processed with 1 kW and 1.5 kW ultrasonic powers. The reasons could be explained in the following way.

It has been well-known fact that the power of ultrasonic vibration (P) is directionally proportional to the intensity of vibration (I) [10-11].

$$P \alpha I \tag{1}$$

The 1 or 1.5 kW ultrasonic power is more or less the minimum power required for the formation of small micro bubbles in the Al melt. The intensity developed due to 1 or 1.5 kW power was not sufficient to separate the liquid Al particles, to produce the required amount of cavitation in the Al melt. The microstructure of the Al/B_4C MMNC fabricated using 1 and 1.5 kW power is illustrated in figure 2a and 2b. Reasonable amount of clustering of B_4C observed in Al matrix in both the images. To reduce the formations of cluster of nano reinforcements, ultrasonic power increased to 2 kW. At 2 kW ultrasonic powers, energy required to separate the liquid Al particles is increased when compared to 1 kW and 1.5 kW power and this 2 kW power observed to be a nearly optimum value. Hence, during sonication, more amounts of cavitation bubbles are formed inside Al melt. The formation and collapse of these cavitation bubbles generates enormous amount of energy. This energy is more than sufficient to create required amount cavitation bubbles in Al melt. The bursting of these cavitation bubbles during high pressure cycle suddenly forces the B_4C in all directions randomly.

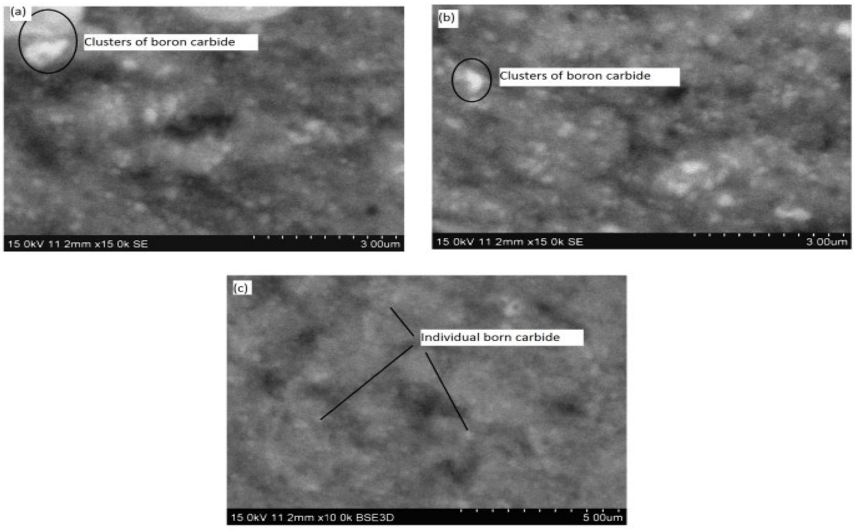

Figure 2 SEM images of Al/B_4C MMNC processed at (a) 1.0 kW (b) 1.5 kW (c) 2.0 kW power

The SEM image of MMNC sample processed with 2 kW ultrasonic powers is depicted in figure 2c. It shows a nearly uniform distribution of B_4C in Al melt. Numerous individual B_4Cp are observed which is due to the effect created by the 2 kW ultrasonic powers. The same amount of B_4C distribution is not observed in other two SEM images (HITACHI S3400N SEM Machine). Figure 3 (a) represents the transmission electron microscopy (TEM- JEOL JEM 2100 High Resolution TEM) image of Al alloy, it shown very little amount of dislocations. Significant amount of dislocations are observed in Al-B_4C MMNC sample (figure 3-b). Increased dislocations are the prime reason for the increase in strength of Al-B_4C MMNC.

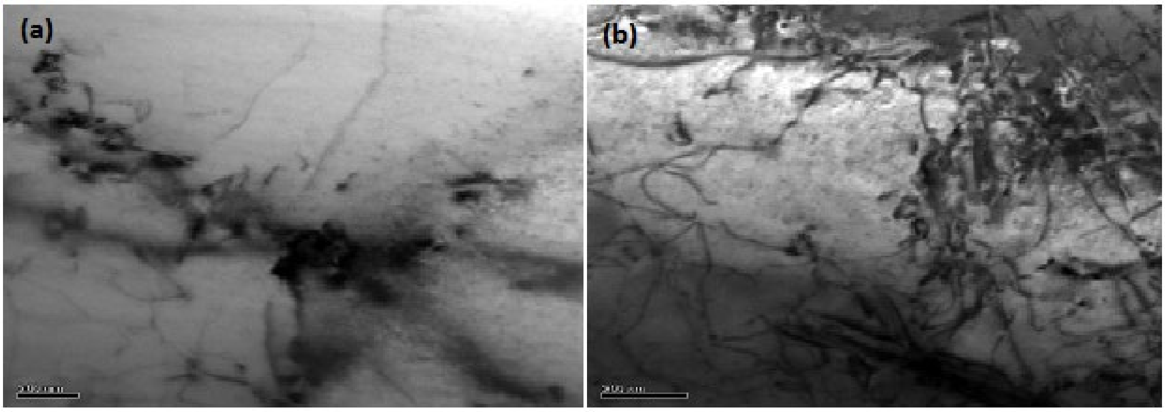

Figure 3 TEM images (a) Al alloy (b) Al-B_4C MMNC

3.2 Effect of Power Ultrasound on Tensile Strength

The tensile test and impact test samples are indicated in figure 4 (a-b). The effect of ultrasonic power on the tensile properties of the fabricated Al/2 wt. % B_4C MMNC is shown in figure 5. The figure clearly depicts that the MMNCs processed with 2 kW of ultrasonic power has maximum tensile strength compared to the other two MMNCs. The tensile strength and hardness values are also tabulated in table 1 for easy reference.

Table 1 Ultrasonic power vs tensile strength and hardness

Ultrasonic Power (kW)	Tensile Strength (MPa)	Brinell hardness number
1.0	260	100
1.5	265	105
2.0	281	120

At 1 and 1.5 kW ultrasonic power, B_4C nanoparticles were agglomerated which were observed in SEM images. During tensile loading, the tensile test specimens were failed at particles agglomerated area. The nanoparticles are loosely packed at the agglomerated areas; hence, that area becomes starting point of tensile fracture. The intensity created by the 1 and 1.5 kW ultrasonic power is not sufficient to break up the clusters of B_4C in Al melt. Also at the loosely packed areas, B_4C nanoparticles are not sufficiently bonded with themselves and with Al matrix.

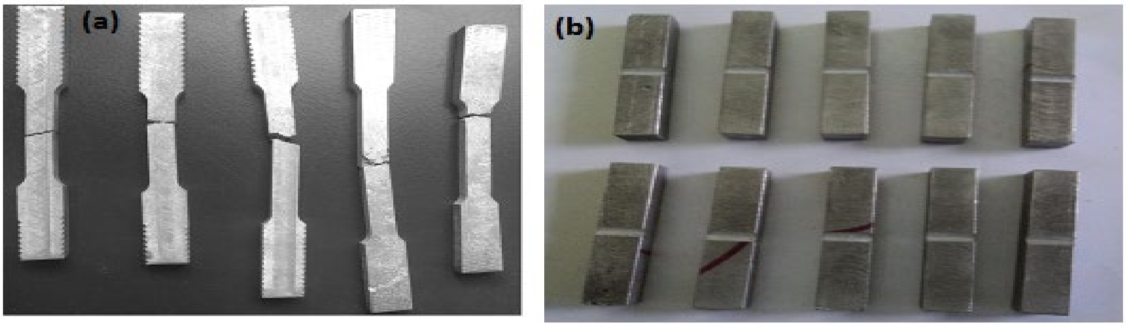

Figure 4 (a) Tensile specimens (b) Impact specimens

The maximum tensile strength obtained in this study is 281 MPa for 2 wt. % B_4C reinforced nanocomposites, which is 8% higher than 1 wt. % B_4C reinforced nanocomposites and 6% higher than 1.5 wt. % B_4C reinforced nanocomposites. At 2 kW ultrasonic power, the energy developed by the ultrasonic system is just sufficient to generate adequate amount of micro bubbles in Al melt. Uniform dispersion nanoparticles are the main reason for the increase in strength of this nanocomposite.

The major strengthening mechanisms associated with the particle reinforced composites are as follows; increased dislocations density-dislocations are increased due to the larger difference in thermal expansion coefficient and elastic modulus mismatch between Al and B_4C, Hall-Petch strengthening due to grain refinement-Grains are refined due to the addition of nano-B_4C and also due to ultrasonic cavitation effect.

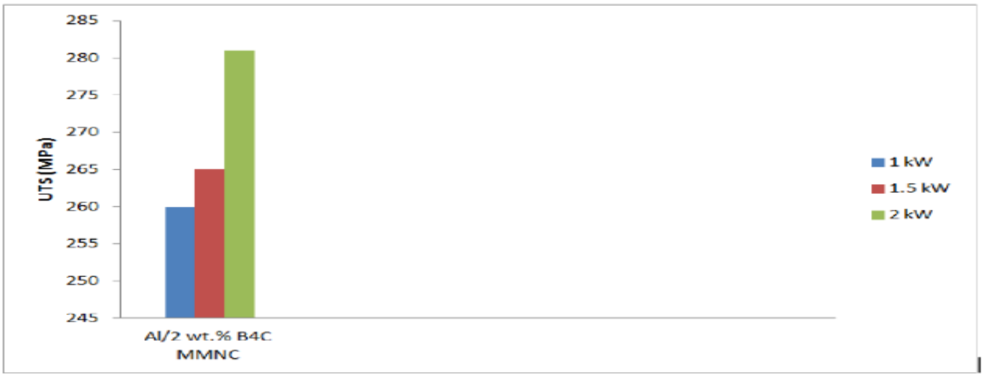

Figure 5 Tensile strength vs ultrasonic power

3.3 Effect of Power Ultrasound on Impact Strength

Figure 6 Impact strength vs ultrasonic power

The influence of ultrasonic power on the impact energy of the Al-B_4C nanocomposites is presented in figure 6. From the figure it was observed that impact energy of the MMNC sample not significantly affected by ultrasonic power.

3.4 Effect of Power Ultrasound on Hardness

The Brinell hardness (BHN) values of Al/ B_4C MMNC processed with different ultrasonic power is shown in figure 7. As same as the tension test results, the Brinell hardness of Al/ B_4C MMNC processed with 2 kW power exhibited maximum hardness compared to the other two MMNC samples. The Al/ B_4C MMNC fabricated with 2 kW of ultrasonic power showed more than 20 % BHN when compared to Al/ B_4C MMNC processed with 1 kW of ultrasonic power. Thus the better incorporation and uniform distribution of B_4C nanoparticles in the AA6061 melt at 2 kW power can be inferred.

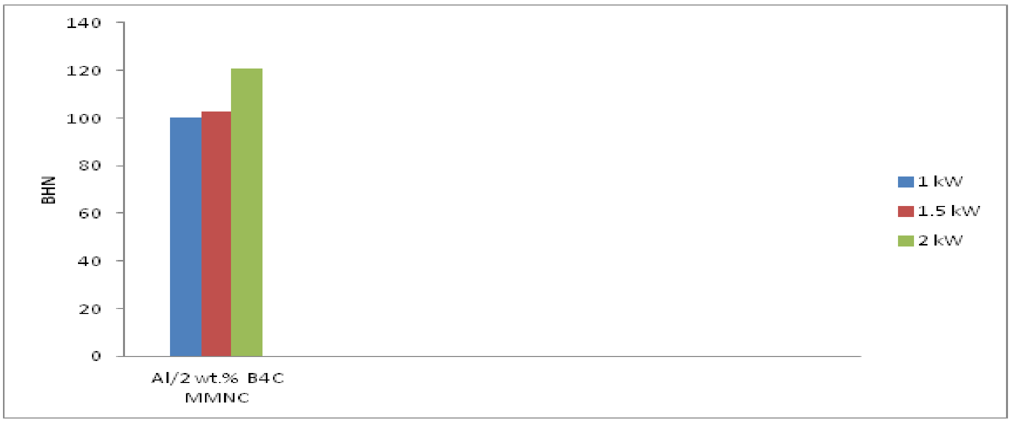

Figure 7 Hardness vs ultrasonic power

4 Conclusions

Al/2 wt. % B_4C MMNC was successfully manufactured by sonication method. Three different ultrasonic power values were used to process the nanocomposites including 1 kW, 1.5 kW and 2 kW. The results indicated that the MMNC sample processed with 2 kW power shows uniform dispersion of B_4C in the AA6061 melt compared to that of the MMNCs processed with 1 kW and 1.5 kW power. The strength and hardness of the sample processed with 2 kW power was higher than the other two nanocomposites.

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