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Fabrication of High Strength Al Nanocomposites with Populous TiB_2 Nanoparticles

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Abstract

High performance lightweight metals offer tremendous potential to improve energy efficiency and system performance for numerous applications. Traditional manufacturing processes such as thermomechanical processing and deformation have reached their limits in further improving the properties of metals. Thus, a new approach is necessary to develop high performance lightweight metals which can offer promising properties. Metal matrix nanocomposite (MMNC) is an excellent approach to produce lightweight metals with improved properties that cannot be achieved by traditional manufacturing. Effective incorporation of a suitable nanoparticles system in a metallic matrix such as aluminum (Al) can improve the performance of the matrix. However, due to the high chemical reactivity and poor wettability of Al with nanoparticles, achieving high volume fraction of nanoparticles incorporation is of a great challenge. Here we show a novel approach to incorporate high volume fraction of titanium diboride (TiB_2) nanoparticles in Al matrix. Al-TiB_2 nanocomposite microparticles were initially produced via flux assisted solidification processes. Al-TiB_2 nanocomposites were produced by cold compaction followed by melting. Scanning electron microscopic (SEM) images revealed that the TiB_2 nanoparticles are unfirmly dispersed and distributed in Al matrix. Al-TiB_2 nanocomposites with as high as 485.9±16.9 Vickers hardness were successfully produced. Furthermore, the effect of melting time was studied on the hardness of the Al-TiB_2 nanocomposites.

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Keywords: Al metal matrix nanocomposites; TiB_2 nanoparticle reinforced aluminum; high strength aluminum matrix nanocomposits.

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1. Introduction

Metals have been widely used for diverse range of application serving broad industries, including but not limited to, automotive [1], aerospace [2, 3], mining, railroad, navy, and biomedical [4]. However, the demand for new applications in recent century requires metallic systems with significantly improved properties and energy efficiency performance. Hence, metal matrix nanocomposite (MMNCs) can be a promising approach to produce novel metals to fulfill such demands. MMNCs are class of hybrid materials consist of a metal (as matrix) and nanoscale elements (as reinforcement). Nanoscale elements are synthesized in various shapes and geometries with sizes less than 100 nm. Nanoparticles and nanofibers are common nanoscale elements that have been widely used as reinforcement for various metals [5, 6]. MMNCs can offer mechanical, thermal and chemical properties superior to those of matrix [7, 8]. To achieve such properties, a uniform dispersion and distribution of the nanoscale element is required [8].

In metals family, lightweight metals are more attractive candidates to be reinforced with nanoscale elements due to their widespread structural and functional applications [7, 9]. Among lightweight metals, Al is one of the most abundant metals in Earth and is applied in various industries such as aerospace, automobile, and military. However, Al with a low strength and a high ductility is less attractive for certain applications where high strength is required. On the other hand, conventional strengthening approaches such as alloying Al with different elements such as Ti [10] and Mg [11] have reached their limitations.

Al metal matrix nanocomposites (AMNCs) can be a viable alternative approach to produced high performance Al with improved properties. AMNCs can offer excellent strength, if high volume percent of nanoparticles are unfirmly dispersed within the Al matrix. Many researchers strived to reinforce Al with nanoscale elements such as boron carbide (B_4C) and magnesium boride (MgB_2) [12, 13] to obtain significant property enhancement. However, limited success has been reported to produce AMNCs with high volume percent of nanoscale elements.

2. Experimental Procedure

2.1. Material and Methods

In our study, we used Al microparticles (Sigma Aldrich, 99.98%) with average size of 40 μm as matrix and in-house synthesized TiB_2 nanoparticles with average size of 10 nm as nanoscale reinforcements. TiB_2 nanoparticles were synthesized via magnesio-reduction of titanium dioxide and boron trioxide in LiCl/KCl eutectic salts. Figure 1 shows the schematic of the experimental set up. Flux assisted liquid state processing technique was employed to successfully incorporate the TiB_2 nanoparticles into Al microparticles. Al microparticles (28 g), TiB_2 nanoparticles (20 g), Sodium chloride (NaCl) powder (47 g), and potassium chloride (KCl) powder (37 g) were mechanically mixed at room temperature for 10 hours (Al/TiB_2: NaCl/KCl volume ratio is 1:10). The chloride flux can promote the incorporation efficiency of the TiB_2 nanoparticles in Al matrix. The mixture was put in a graphite crucible and was placed inside an electrical resistance furnace. The graphite crucible was heated to 820 ºC and a mechanical mixing blade was then inserted to stir the molten liquid for 30 min at 200 rpm.

The final product consists of chloride salts and Al-TiB_2 nanocomposite microparticles. The final products were washed with deionized water and centrifuged (4000 rpm for 3 min) to completely remove the chloride salts from the Al-TiB_2 nanocomposite microparticles.

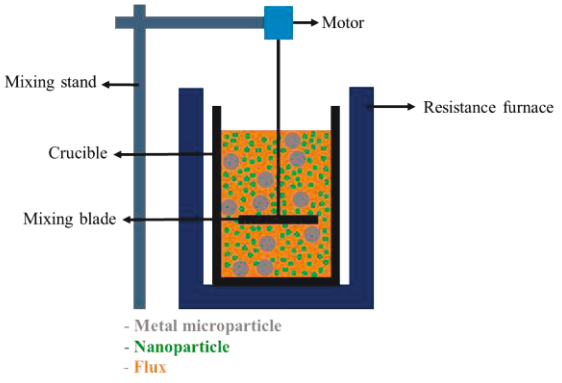

Figure 1: The schematic of the experimental set up to produce Al-TiB_2 nanocomposite microparticles.

The Al-30 vol. % TiB_2 nanocomposite microparticles was then added to a cylindrical stainless steel mold (with diameter of 10 mm and height of 40

mm). A stainless steel ram was used to compact the nanocomposite microparticles. About 200 MPa stress was applied for 5 min at room temperature to form the pellets. The pellets were placed inside an induction furnace for melting step (900 ºC). Three melting time of 20, 40, and 60 minutes were used in this step. Figure 2a and 2b shows the cold compacted pellet fabricated from Al-30 vol.% TiB_2 nanocomposite microparticles before and after melting, respectively.

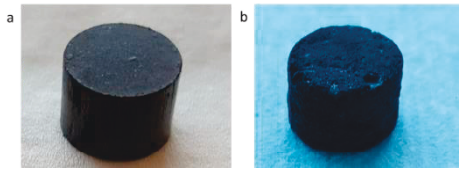

Figure 3: Image of the Al-30 vol. % TiB_2 nanocomposite pellet (a) before and (b) after melting.

2.2. Characterization

Scanning electron microscope (SEM) images were acquired using a ZEISS Supra 40VP field emission microscope operating at 10 kV and Energy-dispersive spectroscopy (EDS) mapping was performed in the same SEM field emission microscope. Microhardness machine (LM 800AT) was used to test the hardness of the Al-30 vol. % TiB_2 nanocomposite samples (after melting).

3. Results and Discussions

Figure 3 shows SEM images obtain from the Al-30 vol. % TiB_2 nanocomposite (after melting). Figure 3a shows after melting, there exist micron size porosity on the surface of the samples. This can be associate to the compaction step. In fact, the applied stress at compaction step was not sufficient to eliminate the gaps between Al nanocomposite microparticles. The gaps remained unchanged after melting. Figure 3b shows higher magnification SEM images obtain from the same sample. Figure 3c shows that the TiB_2 nanoparticle are densely packed into the Al matrix.

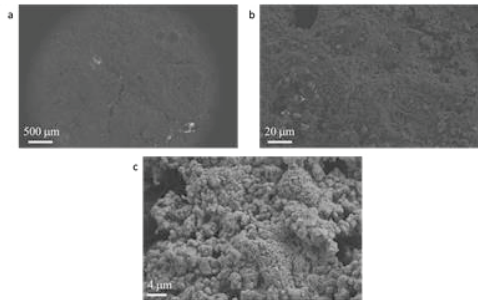

Figure 2: (a) SEM images of Al-30 vol. % TiB_2 nanocomposite after melting, (b) and (c) high magnification SEM images showing TiB_2 nanoparticles uniform dispersion and distribution.

To further confirm the presence of the designated elements in the Al-30 vol. % TiB_2 nanocomposites (after melting), EDS mapping study was carried out. Figure 4 shows the EDS mapping images obtained from the Al-30 vol. % TiB_2 nanocomposite (after melting). Figure 4a shows a typical SEM image obtained from Al-30 vol. % TiB_2 nanocomposite after melting. Figure 4b and 4c shows EDS mapping of titanium (Ti) and oxygen (O) elements, respectively.

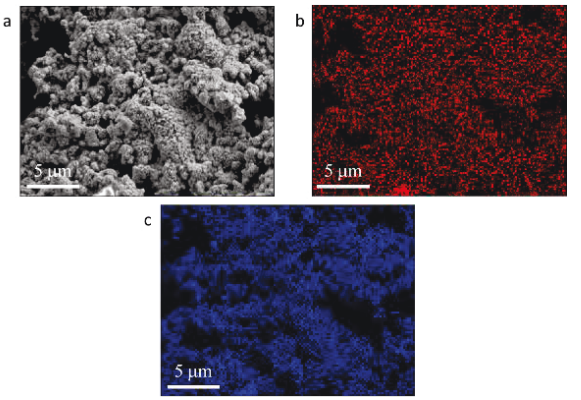

Figure 4: (a) A typical SEM images of the Al- 30 vol. % TiB_2 nanocomposite after melting, (b) and (c) EDS mapping images showing the Ti and O elements.

Figure 5 shows the Vickers hardness test results on Al-30 vol. % TiB_2 nanocomposite samples. Al NC-1, Al NC-2, and Al NC-3 are corresponding to 20, 40, and 60 min melting time, respectively. As the melting time of the pellet increases, the hardness value decreases. This can be associate to the oxidation of the Al matrix.

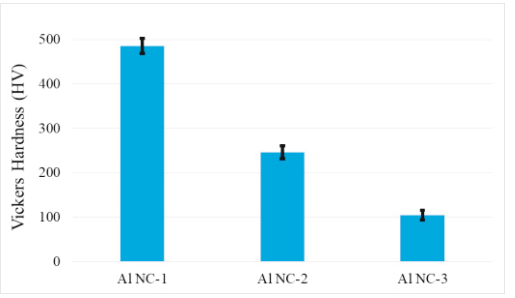

Figure 5: Vickers hardness test results on three different Al-30 vol. % TiB_2 nanocomposites. Al NC-1: Al-30 vol. % TiB_2 (with 20 min melting time), Al NC-2: Al-30 vol. % TiB_2 (with 40 min melting time), and Al NC-3: Al-30 vol. % TiB_2 (with 60 min melting time).

4. Conclusions

This work introduces a novel approach to fabricate Al-TiB_2 nanocomposites with significantly high volume fraction of the nanoparticles. TiB_2 nanoparticles were first effectively incorporated in Al microparticles via flux assisted liquid state processing. The environmentally friendly flux was removed from the Al nanocomposite microparticles. Al-30 vol. % TiB_2 nanocomposite with 485.9±16.9 Vickers hardness was produced (when 20 min melting was chosen). It was further shown that as the melting time increases, the Vickers hardness decreases.

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