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Enhancing thermal and mechanical response of aluminum using nanolength scale TiC ceramic reinforcement

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ABSTRACT

In the present work, nano-sized titanium carbide (0.5, 1.0 and 1.5 vol%) reinforced aluminum (Al) metal matrix composites were synthesized by powder metallurgy incorporating microwave sintering and hot extrusion. Microstructural, mechanical and thermal properties of hot extruded unreinforced aluminum and titanium carbide (TiC) reinforced aluminum composites are presented in this paper. X-ray diffraction (XRD) patterns and scanning electron microcopy (SEM) images show the homogeneous distribution of TiC nanoparticles in the Al matrix. The tensile and compressive strengths of Al composites increased with the increase in TiC content, while the ductility decreased. The CTE of Al composite decreased with the progressive addition of hard TiC nanoparticles. Overall, hot extruded Al 1.5 vol% TiC nanocomposite exhibited the best combination of tensile, compressive, hardness and Young's modulus of 186 ± 3 MPa, 416 ± 4 MPa, 9.75 ± 0.5 GPa and ~103 GPa, respectively. High tensile strength and good thermal stability exhibited by Al-TiC nanocomposites developed in this study show the potential for a variety of weight-critical engineering applications.

1. Introduction

Increasing demand for light weighting drives the interest in development of novel high-performance lightweight metal-ceramic matrix composites (MMCs) for use in structural components in the automotive and aerospace sectors. MMCs exhibit an excellent combination of properties such as toughness, ductility, high modulus, corrosion resistance and high strength [1]. Amongst MMCs, Al MMCs containing ceramic particles attract greater attention from the ground transportation, defense, sports, and aerospace industries owing primarily to low density, high stiffness, high conductivity, high toughness, and high strength to weight ratio [2–6].

Aluminum is relatively soft and light weight metal. So far, very few types of hard ceramic particles such as TiC, WC, SiC, B_4C, Al_2O_3 and Si_3N_4 have been added to aluminum, as reinforcement particles, to enhance its mechanical properties [2,5,7–10]. Among the ceramic reinforcements, titanium carbide (TiC) has been recognized as a potential additive into the metal matrix composite materials due to its superior mechanical and thermal properties, such as low density, high elastic modulus, high hardness, good wear resistance and high thermal conductivity [11]. TiC particulate reinforced Al matrix nanocomposites posses some interesting properties because TiC nanoparticles are thermodynamically stable, can enhance the hardness and lightness of the composite which makes it potential for a variety of weight-critical engineering applications. The use of only small volume fraction of nano sized reinforcements ($<$ 2%) can help in improving the properties of Al without adversely affecting on the ductility compared to that of micron sized (typically $\gg$10%) reinforcements [12]. However, further addition of nano sized reinforcement can cause a reduction in strength that can be attributed to possible agglomeration, clustering and micropores in the nanocomposites which will result in the degradation of composites properties.

In the quest of achieving enhanced structural properties coupled with maximum possible reduction in weight, the development of novel MMCs using efficient synthesis methodologies has become so critical. Several techniques have been used to fabricate Al-TiC composites, such as hot consolidation [11], powder metallurgy [13], casting routes [13–17], in situ synthesis [18,19] and reactive synthesis [20]. Each fabrication technique has its own advantages and disadvantages. For example, though low-cost processing is a unique advantage offered by casting techniques, but the non-uniform dispersion of the reinforcements and unwanted interfacial reactions result in degradation of

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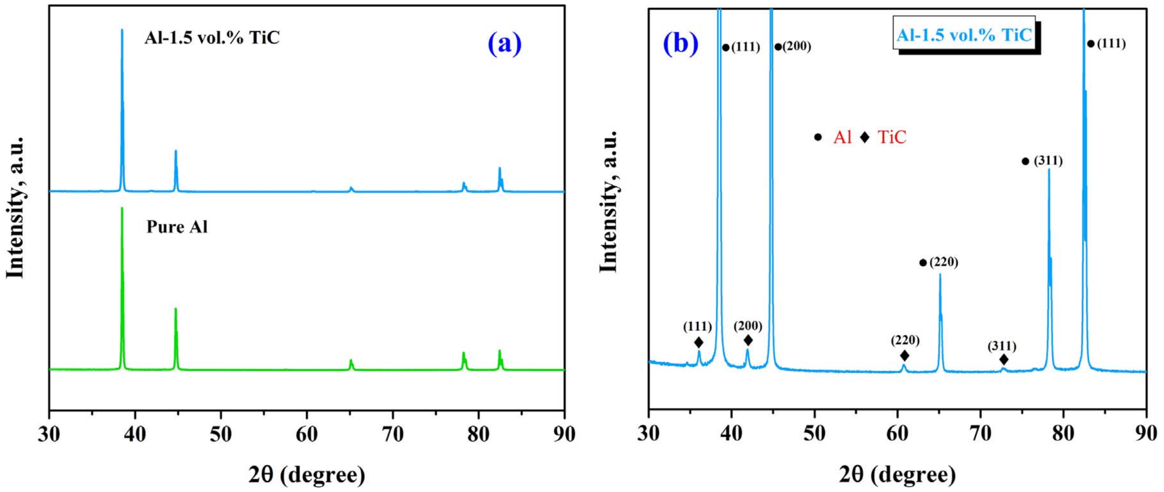

Fig. 1. (a) XRD patterns of extruded pure Al and Al-1.5 vol% TiC nanocomposite. (b) The enlarged XRD patterns of Al-1.5 vol% TiC nanocomposite.

mechanical properties [21,22].

Nowadays, there is an increasing demand from the powder metallurgy technique to develop new, efficient and enhanced sintering procedures to attain better microstructures and improved mechanical properties compared to casting methods at lower energy and operating costs. Not only the sintering properties; suitable blending and compacting parameters also have an intense effect on the final properties of the product [23]. New sintering routes, for example, laser, spark plasma, and microwave sintering (MWS) offer more benefits in terms of time and energy conserving when compared to techniques such as conventional heating. Among different sintering methods, MWS offers higher heating rate, shorter processing time, homogeneous microstructure, improved quality of the product, improved mechanical properties, and environmental friendliness over conventional sintering processes [24]. The composites obtained through MWS technique can be subjected to secondary processing such as forging, rolling and extrusion. These secondary treatments reduce porosity, enhance particle distribution and improve the mechanical properties [25].

According to the author's best knowledge, no articles and reports have yet been published on the synthesis of Al–TiC nanocomposites through powder metallurgy technique involving microwave sintering process and hot extrusion. Therefore, in the present study, attempts are carried out to fabricate the Al–TiC (0, 0.5, 1.0 and 1.5 vol%) nanocomposites by high energy ball milling, microwave sintering process followed by hot extrusion in order to produce high strength composite materials. The effect of TiC content on the microstructure, mechanical and thermal properties of Al-TiC nanocomposites were investigated in detail.

2. Experimental

The pure Al (99.7%, average size ~45 µm, Alfa Aesar, USA) and TiC powder (99.9%, regular size ~50 nm nanostructured and the amorphous materials, Houston, TX, USA), were used as starting materials. Details of fabrication process and characterizations can be found in reference [26]. Firstly, nano-sized TiC powder (0.5, 1.0 and 1.5 vol%) were added to pure Al. The blending of the powder mixtures was carried out at room temperature using a Retsch PM400 planetary ball mill for a period of 2 h, with a milling speed equals to 200 rpm to obtain a uniform distribution of particles. Blending of powders was done without using any balls. Compaction of the blended powders was carried out using a uniaxial hydraulic pump powdered compaction machine at a pressure up to 97 bar (50 t). Circular mild steel die was used to obtain cylindrical billets of having dimensions of 40 mm length and 35 mm diameter. The sintering of the compressed cylinder-shaped billets was done using an innovative hybrid microwave to achieve a temperature of 550 °C, just below the melting temperature of Al. Prior to hot extrusion; the microwave sintered billets were soaked in a resistance furnace at a temperature at 400 °C for 1 h, followed by hot extrusion at 350 °C plus 500 MPa. The ratio of extrusion was ~ 20.25:1 to yield an extruded rod with 8 mm diameter. Colloidal graphite was used as lubricant. The obtained extruded rods were further used for additional characterization studies.

The X-Ray Diffraction was employed to study the microstructural properties of Al-TiC nanocomposite samples using PANalytical X′pert Pro Cu (K_α) with a scanning angle range $30^\circ \leq 2\theta \leq 90^\circ$ and scanning rate 2°/min.

The morphological characteristics of the developed Al-TiC nanocomposites were evaluated with field emission scanning electron microscopy (JEOL JSM-6010 and Hitachi FESEM-S4300) equipped with an energy dispersive X-ray spectroscopy (EDX). The atomic force microscope (AFM) was used to investigate the surface morphology of the nanocomposites.

Vickers microhardness (HV) measurement, as per the ASTM standard E384-08, was made on the cross sections of specimens along 5 different radial directions by a hardness tester using a load of 100 gf and a dwell time of 15 s. Tensile/compressive stress-strain testing was conducted at room temperature using a universal testing machine (Lloyd) in accordance with the ASTM E8/E8M-15a (tensile) and ASTM E9–89a (compression) under an engineering strain rate of 8.3×10^{-4} s^{-1}. The representative data for each condition was obtained by averaging three values of the test results. SEM (Hitachi FESEM-S4300) was used to analyze the fractured surfaces of the selected tensile specimens were examined by scanning electron microscope. Nanoindentation analysis was carried out at room temperature using a MFP-3D NanoIndenter system.

An INSEIS TMA PT 1000LT thermo-mechanical analyzer was used to calculate the coefficient of thermal expansion (CTE) of Al-TiC nanocomposites.

3. Results and discussion

3.1. Phase identification of Al-TiC nanocomposites

XRD technique was used for phase analysis in the monolithic and nanocomposite samples. XRD analysis of the pure Al and Al-1.5 vol% TiC nanocomposites are shown in Fig. 1(a), while Fig. 1(b) shows the enlarged pattern for the Al-1.5 vol% TiC nanocomposite. Fig. 1(b) clearly shows the presence of TiC phase in the Al matrix. Regardless of the TiC content, the distinct peaks detected in the Al-TiC