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Original Research

Enhanced performance of nano-sized SiC reinforced Al metal matrix nanocomposites synthesized through microwave sintering and hot extrusion techniques☆

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ABSTRACT

In the present study, nano-sized SiC (0, 0.3, 0.5, 1.0 and 1.5 vol%) reinforced aluminum (Al) metal matrix composites were fabricated by microwave sintering and hot extrusion techniques. The structural (XRD, SEM), mechanical (nanoindentation, compression, tensile) and thermal properties (co-efficient of thermal expansion-CTE) of the developed Al-SiC nanocomposites were studied. The SEM/EDS mapping images show a homogeneous distribution of SiC nanoparticles into the Al matrix. A significant increase in the strength (compressive and tensile) of the Al-SiC nanocomposites with the addition of SiC content is observed. However, it is noticed that the ductility of Al-SiC nanocomposites decreases with increasing volume fraction of SiC. The thermal analysis indicates that CTE of Al-SiC nanocomposites decreases with the progressive addition of hard SiC nanoparticles. Overall, hot extruded Al 1.5 vol% SiC nanocomposites exhibited the best mechanical and thermal performance as compared to the other developed Al-SiC nanocomposites.

1. Introduction

The development of metal-ceramic matrix composites (MMCs) is of great interest in automobile and aerospace applications due to their potential to exhibit excellent combination of properties such as toughness, ductility, high modulus, corrosion resistance and high strength [1,2]. In MMCs, aluminum based metal matrix composites are being increasingly used in automobiles, aerospace, defense and military industries due to their low density, high specific modulus, high strength to weight ratio and toughness [3–6].

Aluminum is used in a variety of applications due to its high strength to weight ratio but the major drawback is its poor wear resistance. This has been rectified by the addition of hard SiC [7] particles as reinforcement. Addition of SiC ceramic nanoparticles in aluminum, an addition, also leads to improvements in strength, hardness and corrosion resistance. The major advantage of using nanoreinforcements is that the superior properties can be attained at lower volume fractions ($<2\%$), whereas for micron-scale particles reinforced MMCs higher volume fractions ($\gg 10\%$) are required [8].

Aluminum-silicon carbide (Al-SiC) composites have been considered as promising materials for lightweight structural applications due to their unique combination of low density and high strength. However, in order to produce sound nanocomposites with enhanced mechanical properties, good dispersion of the nanoreinforcement phase within the matrix is necessary, which is in turn strongly governed by the selection of a suitable production process [9–11]. Several processing methods have been developed to prepare Al-SiC composites such as powder metallurgy [12], conventional casting [13], spark plasma sintering [14] and conventional hot extrusion [15].

Generally, powder metallurgy (PM) process is well known to be one of excellent metal synthesis techniques for producing near net shape products. In addition, the undesirable levels of interaction between matrix and reinforcements can be avoided because of lower processing temperatures usually associated with PM methods [3]. New sintering routes such as laser, spark plasma, and microwave sintering (MWS) could offer more advantages in terms of time and energy saving when compared to conventional heating [16]. Among different sintering methods, MWS offers high heating rate, shorter processing time, homogeneous microstructure, improved quality of the product, im-

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proved mechanical properties, and environmental friendliness over conventional sintering processes [17].

Processing of fine-grained metal matrix composites via microwave sintering was emphasized also, because the consolidation can be achieved at much lower temperatures. The composites obtained through MWS technique can be subjected to secondary processing such as forging, rolling and extrusion. These secondary treatments reduce the porosity, enhance the particle distribution and improve the mechanical properties [18–20].

Microwave processing of powder metallurgy metal composites is a novel integrated manufacturing method that is very rarely seen in recent research works. This research work has done to check the feasibility of synthesis and characterization of the composites by using this novel sintering process [17]. The present work attempts to synthesis Al-SiC nanocomposites via high energy ball milling and microwave sintering process followed by hot extrusion in order to produce high strength composite materials. The structure, microstructure, thermal and mechanical behavior; including the compression strength, tensile strength, ductility and hardness, of the extruded Al-SiC nanocomposites are critically investigated and interrelated.

2. Materials and methods

2.1. Materials

In the present study, pure aluminum powder of the size range ~ 7–15 µm and 99% purity was procured from Alfa Aesar, USA and SiC powder with an average size of ~ 15 nm and purity > 99 +% supplied by nanostructured and amorphous materials, Inc. (Houston, TX, USA), was used as the reinforcement phase for the synthesis of Al-SiC nanocomposites.

2.2. Fabrication of Al-SiC nanocomposites

2.2.1. Primary processing

To produce Al-SiC nanocomposites, nano-sized SiC powder (0.3, 0.5, 1.0 and 1.5 vol%) was added to pure Al. The mixture of powders was blended at room temperature using a Retsch PM400 planetary ball mill for 2 h with the milling speed of 200 rpm in order to get a homogeneous particle distribution. No balls were used in this stage. The blended powder mixture was compacted at a pressure of 97 bar (50 t) into billets of size 35 mm in diameter and 40 mm in length. The consolidated composite specimens are shown in Fig. 1. The compacted cylindrical billets were sintered using an innovative hybrid microwave assisted two-directional sintering technique [21] to achieve a temperature of 550 °C, just below the melting temperature of Al.

2.2.2. Secondary processing

Prior to hot extrusion, the microwave sintered billets were soaked in a resistance furnace at a temperature of 400 °C for 1 h, and then hot extruded at 350 °C under 500 MPa. The extrusion ratio was ~ 20.25:1 to produce an extruded rod with 8 mm diameter (Fig. 1). Colloidal graphite was used as lubricant. These extruded rods were subsequently used for characterization studies.

2.3. Materials characterization

The phase identification of the extruded samples was carried out using X-ray powder diffractometer (PANalytical X′pert Pro) based on Cu-K_{α} radiation (1.541 Å) over the 2θ range 30–90° at scan rate of 0.2°/min. Individual phases were identified by matching the characteristic XRD peaks against JCPDS data. Field emission scanning electron microscopy (JEOL JSM-6010 and Hitachi FESEM-S4300) equipped with energy dispersion spectroscopy (EDS) was used to identify the reinforcement phase and microstructure of the extruded composite samples.

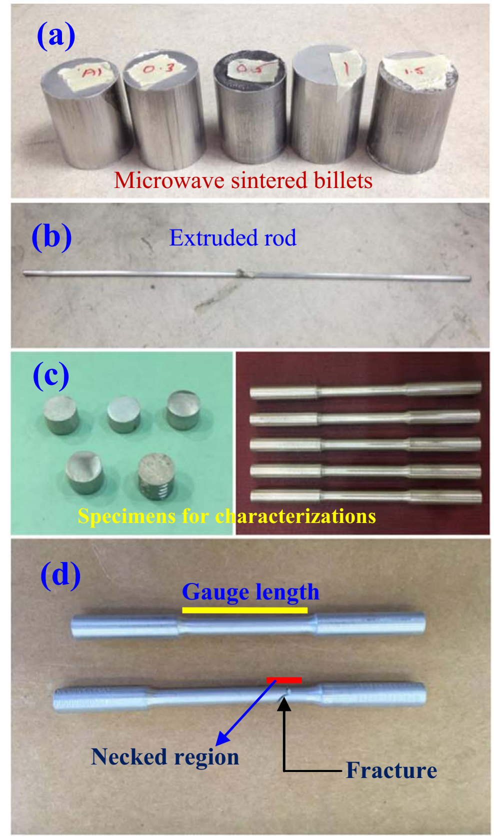

Fig. 1. Samples of Al-SiC nanocomposites: (a) microwave sintered billets, (b) hot extruded rod, (c) machined samples for characterization and (d) failed specimen under tensile loading.

The hardness of the pure Al and composite samples was determined using Vicker's microhardness tester (FM-ARS9000, USA) with applied load of 100 gf for 15 s as per the ASTM standard E384-08. Compressive testing of the cylindrical specimens was performed at room temperature in accordance with the procedures outlined in ASTM standard E9-89a using Universal testing machine-Lloyd. The test specimens with a length to diameter (l/d) ratio ~ 1 were subjected to a compression load at a constant strain rate of $8.3 \times 10^{-4}\ s^{-1}$. From the load-displacement curves, 0.2% offset compressive yield strength (CYS), ultimate compression strength (UCS) and failure strain were determined. Tensile properties of the extruded samples were determined using an universal testing machine-Lloyd in accordance with the ASTM E8/E8M-15a standard at room temperature under the strain rate of $8.3 \times 10^{-4}\ s^{-1}$. The tensile test specimens were smooth round specimens of 5 mm gauge diameter and 25 mm gauge length using a fully automated servo-hydraulic mechanical testing machine, MTS-810. For each composition, three samples were tested to ensure repeatable values. From the stress-strain curves, 0.2% tensile yield strength (TYS), ultimate tensile strength (UTS) and percentage elongation (ductility) were determined. The fracture surfaces of the selected compression and tensile specimens were examined by scanning electron microscope (Hitachi FESEM-S4300). Nanoindentation analysis was performed using a MFP-3D NanoIndenter (head connected to AFM equipment) system equipped with standard Berkovich diamond indenter tip. The testing was performed at room temperature. The hardness (H) and young's modulus (E) in nanoindentation test are directly obtained. The indentation was made to a maximum load of about 100 mN and under loading and unloading rate of 200 µN/s and dwell time at maximum load: 5 s. In order to take the repeatability into account, the test results were acquired from the average of 6 indentations.

Coefficient of thermal expansion of Al-SiC nanocomposites was determined using a INSEIS TMA PT 1000LT thermo-mechanical