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Fabrication and characteristic of Al-based hybrid nanocomposite reinforced with WO_3 and SiC by accumulative roll bonding process

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ABSTRACT

In this study, Al/WO_3/SiC hybrid nanocomposite was produced using Al 1050 sheets and WO_3 and SiC nanoparticles through accumulative roll bonding (ARB) process. Uniaxial tensile test and hardness measurement were carried out on ARBed specimens. Scanning electron microscopy (SEM) equipped with energy dispersive spectroscopy (EDS) and electron backscatter diffraction (EBSD) was used for microstructural observation. The results revealed that by increasing the number of ARB cycles, a better distribution of WO_3 and SiC nanoparticles was obtained in the Al matrix. So, after the 9th cycle, the hybrid nanocomposite showed an excellent distribution of the nanoparticles with strong bonding between the nanoparticles and the aluminum matrix. It has been shown that after 9 cycles, the microstructure exhibits a uniform of ultrafine grains elongated in rolling direction with an average grain size of approximate 400 nm. Furthermore, the tensile strengths of the hybrid nanocomposite enhanced by increasing the number of ARB cycle and reached to a maximum value of 204.5Mpa at the end of 9th cycle, which was 4.02 higher than that of the starting material. Also, the microhardness results suggested that with increasing the number of cycles, hardness increased rapidly at first stages and then dwindled at the last stages.

1. Introduction

Metal matrix composites (MMCs) with their improved mechanical properties in comparison to their non-reinforced monolithic metal counterparts offer a wide range of structure application opportunities. The composite product can be adapted more exactly to the property requirements by adding the selected reinforcements, such as particles into the matrix alloys [1,2]. Currently, there is an increasing trend in the automotive and aerospace industries to use these materials for various components, due to their enhanced properties, such as increased stiffness, tensile strength, wear resistance, low density, high elastic modulus, low thermal shock and low coefficient of thermal expansion, as compared to the conventional metals and alloys [3,4]. In the meantime, hybrid composites possess better properties compared with single reinforced composites as they combine the advantages of their constituent reinforcements [5]. Hybrid metal matrix composites (HMMCs) are second-generation composites where more than one type, shape, and sizes of reinforcements are used to obtain better properties [6]. There are several methods used to manufacture particle-reinforced MMCs, such as powder metallurgy (PM) [7,8], Squeeze casting [9,10], pressure less infiltration [11], and spray forming [12]. In these methods, reinforcements are incorporated or added into the matrix using ex situ methods. Homogeneous reinforcement and strong bonding of reinforcements with the matrix can certainly improve mechanical properties. However, these methods show non-uniform distribution, poor wettability of reinforcement, porosity, and poor economic efficiency [13]. Accumulative roll bonding (ARB) [14] is a new method that can overcome the above problems. In recent years, ARB has been successfully used for producing metal matrix composite, including Al/W [15], Al/WC [16], Al/Al_2O_3/SiC [17], Al/Al_2O_3/B_4C [18], Al/Al_2O_3/TiC [19]. Based on a literature survey, no studies have yet evaluated the feasibility of the ARB process to fabricate hybrid composite reinforced by tungsten trioxide (WO_3) and silicon carbide (SiC) particles. The aim of the present work is to fabricate Al/1vol.% WO_3/SiC hybrid nanocomposite via ARB process and investigate the effect of number of ARB cycle on the microstructure and mechanical properties.

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2. Experimental procedure

The materials used in this study were annealed at 643 k for 2 h strip of commercial purity aluminum alloy (AA1050) (specifications are given in Table 1) and WO_3 and SiC nanoparticles with size of 50 nm. Four strips of 120 mm × 50 mm × 0.5 mm with a total thickness of 2 mm were degree ased in acetone and scratch brushed with 90 mm diameter stainless steel circumferential brush with 0.26 mm wire diameter. For fabrication of Al-based nanocamposite after surface preparation, 0.5vol.% WO_3 and 0.5vol.% SiC nanoparticles were uniformly dispersed between the four strips which were then stacked over each after and fastened at both ends by steel wires. This specimen preheated for 3 min at 200 °C and then was roll-bonded with a draft percentage of 50% reduction (von Mises equivalent strain of 0.8) per cycle (First Step). To achieve a uniform distribution of reinforcement nanoparticles in matrix, the above procedure was repeated up to 9 cycles without adding WO_3 and SiC powder (Second Step). The schematic illustration of ARB process for fabrication of the Al/WO_3/SiC HMMC is shown in Fig. 1.

The microstructural characterization of the specimens was carried out by electron backscattering diffraction (EBSD) measurements using a scanning electron microscope equipped with a field-emission type gun (FE-SEM). For the EBSD measurements, longitudinal sections perpendicular to the transverse direction (TD) of the sheet were polished with sandpapers and then electropolished in a 30% HNO_3 + 70% CH_3OH solution at the voltage of 15V at −30 °C. The EBSD measurements were carried out by the use of FE-SEM equipped with TSL-OIM EBSD system at the accelerated voltage of 15 KV. The step size used in the EBSD measurements was 50 nm. The EBSD data were analyzed by orientation imaging microscopy (OIM) software. Scanning electron microscopy TESCAN equipped with energy dispersive spectroscopy (EDS) was also used to determine particles type and investigate on how well the WO_3 and SiC nanoparticles were distributed in the produced samples at different ARB cycles.

The tensile samples were machined from the ARB processed strips, according to the ASTM: E8M tensile sample, oriented along the rolling direction. The gauge width and length of the tensile test samples were 6 and 25 mm, respectively. The tensile tests were conducted at room temperature on a HounsField H50ks testing machine at on initial strain rate of $1.67 \times 10^{-4}\ s^{-1}$. Total elongation of the samples was measured from the difference between the gauge lengths before and after testing.

Vickers microhardness test was done using Akashi apparatus under the load of 50 g and the time of 25s on rolling direction – transverse direction (RD – TD) plane. Microhardness test was performed on all samples in more than seven randomly selected points and the average number was reported.

3. Result and discussion

3.1. Microstructural investigations

3.1.1. SEM analysis

Fig. 2a shows SEM micrograph of the particles used as reinforcements in the aluminum matrix composite. In addition, results from EDS analysis, illustrated by some points in Fig. 2a, have been represented in Fig. 2b and c. In this figure, the points 1 and 2 are WO_3 and SiC nanoparticles, respectively. It should be noted that tungsten trioxide particles are completely bright, silicon carbide particles are darker than WO_3. Due to the use of nonoparticle in this research, there are some agglomerations of nono particles which are carried out as observed in Fig. 2, and it seems that the size of nano particle is more than 50 nm. Researchers have used different kinds of reinforcement particles to fabricate the aluminum composites utilizing various fabrication routes for achieving the required properties [20]. With increasing use of various radiation (such as X-ray) in industry, medicine, agriculture and national defense research, it has now become necessary to study new materials with good radiation shielding effectiveness, low density and high mechanical properties. The research of radiation shielding materials, which has an important significance to national defense and civilian use, has been attached importance by the developed countries [21–23]. So hybrid composites reinforced with WO_3 and SiC particles, which will combine the properties of SiC and WO_3 particles, will have good mechanical properties and good radiation shielding properties. It is also one of the most important advantages of WO_3 compared to W and WC is its low density [16]. The benefits of using SiC as reinforcement improved stiffness, strength, thermal conductivity, wear resistance, fatigue resistance, and reduced thermal expansion. Additionally, SiC reinforcements are typically low-cost and are relatively low-density [24].

The microstructure of Al/1 vol.% WO_3/SiC hybrid nanocomposite, produced by ARB process in the 1st, 5th, and 9th cycles, has been shown in Fig. 3. After the 1 cycle, aluminum sheet (with 1 mm thickness) contains three layers of WO_3 and SiC nanoparticles. Given the Figure, in this case agglomeration of nanoparticles in the aluminum matrix is possible. In fact, after the first cycle, the matrix-reinforcement bond is still weak and the distribution of reinforcing nanoparticles in the aluminum matrix is non-uniform. By increasing the number of cycles to 5 (Fig. 3c), agglomeration decreases, but distribution of reinforcing nanoparticles in the aluminum matrix is still non-uniform. According to the figure, WO_3 and SiC particles are still clustering. Usually, after each ARB cycle, some reinforcing nanoparticles are separated from their interface and move to Al-matrix as seen in Fig. 3b. Occurrence of this phenomenon is increased when the number of ARB cycles increased [25]. Finally, after 9 cycles, the cluster of the agglomerated nanoparticles is broken and the particles are separated from each other (Fig. 3d). In other words, increase number of ARB cycles improves the uniformity of WO_3 and SiC reinforcing particles in the aluminum matrix. Since aluminum contains 12 active slip systems, it is highly capable of plastic deformation, making agglomeration break early and nanoparticles move away from each other during the rolling process. This improves uniformity in all parts of the aluminum matrix. It is worth noting that the separation and fracture of WO_3 and SiC nanoparticles increase during rolling process, as in each rolling stage the length of sample increases twice, due to 50% thickness reduction. In general, increased ARB cycles increases the number of aluminum layers and reinforcement nanoparticles [16,26]. In this process, after N cycles of ARB process, $m \times 2^N$ layers are produced. Also, the number of bonded boundaries (in which there are reinforcement nanoparticles) becomes $m \times 2^N - 1$, containing m primary composite layers and N cycles. It means that after the first cycle, the number of aluminum and reinforcement layers is 4 and 3, respectively. Finally, after 9 cycles, nanocomposite would contain 2048 aluminum layers and 1760 layers of reinforcement nanoparticles. According to Fig. 3d, given the redundancy of aluminum and reinforcement nanoparticles layers, bonding interfaces cannot be identified. In other words, increased number of cycles decreases the gap between aluminum layers (bonded interfaces). Thus, due to atomic penetration, the adhesion between the layers of aluminum and reinforcement nanoparticles

Table 1
Chemical composition of the used AA1050 aluminum strip.

Element	Al	Si	Fe	Mn	Cu	Mg	Zn	Ti	Other
Wt.%	99.50	0.20	0.22	0.02	0.01	0.01	0.01	0.01	0.02