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Achieving ultrafine grained and homogeneous AA1050/ZnO nanocomposite with well-developed high angle grain boundaries through accumulative press bonding

Sajjad Amirkhanlou [a,*], Mostafa Ketabchi [b], Nader Parvin [b], Masoomeh Askarian [b], Fernando Carreño [c]

[a] Young Researchers and Elite Club, Najafabad Branch, Islamic Azad University, Najafabad, Iran
[b] Department of Mining and Metallurgical Engineering, Amirkabir University of Technology, Tehran, Iran
[c] Department of Physical Metallurgy, CENIM-CSIC, Av. Gregorio del Amo 8, 28040 Madrid, Spain

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ABSTRACT

Aluminum matrix nanocomposites with 2 vol% ZnO nanoparticles were produced using accumulative press bonding (APB) as a very effective and novel severe plastic deformation process. Microstructural evaluation and mechanical properties of specimens were characterized by field-emission scanning electron microscopy (FE-SEM), scanning transmission electron microscopy (STEM), electron backscatter diffraction (EBSD) and tensile test. Microstructure of AA1050/ZnO nanocomposite showed a uniform distribution of ZnO nanoparticles throughout the aluminum matrix. STEM and EBSD observations revealed that ultrafine-grained Al/ZnO nanocomposite with the average grain size of <500 nm and well-developed high angle grain boundaries (80% high angle boundaries and 37° average misorientation angle) was successfully obtained by performing 14 cycles of the APB process. When the number of APB cycles increased the tensile strength of Al/ZnO nanocomposite improved and reached 228 MPa after 14 cycles, which was 2.6 and 1.3 times greater than the obtained values for annealed (raw material, 88 MPa) and monolithic aluminum (180 MPa), respectively.

1. Introduction

Metal matrix composites (MMCs) particularly aluminum-based MMCs are widely used in aerospace and automobile industries due to their excellent properties such as low density, high specific modulus and strength [1]. From many different types of MMCs, particulate composites strengthened by nano-size particles are at the center of attention due to superior mechanical properties in comparison with micro-size particles [2]. The production methods of MMCs can be divided into three types: (a) solid state methods such as mechanical milling and powder metallurgy; (b) liquid state methods such as ultrasonic casting and stir casting; and (c) semi solid state methods such as compocasting [3,4]. Each of these processes has its own advantages and disadvantages [5–7]. The main problems in these methods are high production cost, high energy consumption and formation of defects such as porosity, particle agglomeration and particle free zones (PFZs) [8–10]. In order to eliminate these problems, the present authors recently invented a new manufacturing process, namely accumulative press bonding (APB) [11]. Accumulative press bonding has been developed as an effective approach to fabricate ultrafine-grained metal matrix nanocomposite. This method has two important independent strengthening mechanisms; (1) formation of nano/ultrafine structure by severe plastic deformation and (2) reinforcing metal matrix by ceramic nanoparticles [11]. The APB process was established on the principle of accumulative roll bonding (ARB) process, but the APB process can be used to produce sheet material and thick billet, while the ARB process can only be used to produce sheet materials. The equipment of the APB process is very simple and only a conventional pressing machine equipped with a simple-channel die is all that is required. This study aims to investigate the probability of fabricating Al/ZnO nanocomposite by the APB process. In addition, the effect of number of APB cycles on the microstructure and mechanical properties of monolithic aluminum and Al/ZnO nanocomposite were examined.

2. Experimental procedure

2.1. Materials

The materials used in this study were fully annealed strips of AA1050 aluminum alloy at 623k for 1 h and ZnO nanopowder with

* Corresponding author. Tel.: +98 911 1511024; fax: +98 21 66405846.
E-mail addresses: s.amirkhanlou@aut.ac.ir, s.amirkhanlou@ma.iut.ac.ir, s.amirkhanlou@gmail.com (S. Amirkhanlou).

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average particle size of about 60 nm. Synthesis of the used ZnO nanoparticles has been reported elsewhere [12]. A micrograph of the used ZnO nanoparticles is shown in Fig. 1. Initial dimension of the aluminum specimen was 100 mm in length and 50 mm in width with a thickness of 1.5 mm. The chemical composition of the aluminum strips is given in Table 1.

2.2. Surface preparation

Two sides of each strip were degreased with acetone and scratch brushed by a steel circumferential brush with 0.4 mm wire diameter and peripheral speed of 2800 rpm in order to remove the contaminated layer and also produce a rough surface. To avoid contamination and thick alumina layers formation, the press bonding process was performed immediately after degreasing and scratch brushing. For dispersing the nanopowder, an acetone-base suspension was prepared and put under ultrasonic waves with frequency of 48 KHz for 30 min. The nanoparticles were deposited, and acetone was evaporated in air so that the brushed surface of one strip was uniformly covered with ZnO powder.

2.3. Accumulative press bonding (APB) process

The schematic illustration of the APB process is shown in Fig. 2. The cold press bonding process was performed on the stacked strips with no lubrication, using a laboratory hydraulic press machine (Toni Technik Baustoffprüf systeme GmbH), with a loading capacity of 200 t. The specific reduction in thickness was equal to 50%. The deformation process was performed in a simple channel-die, resulting in no lateral/width spreading (only a reduction in thickness and increase in length occurred). The two layers of material were bonded together by pressing in ambient temperature and then the length of the obtained material was cut into halves. The APB process for manufacturing Al/ZnO nanocomposite can be divided into two stages. The aim of first stage was adding ZnO nanoparticles between two layers of aluminum strips, and this process was repeated up to five cycles. The second stage was designed to reach a uniform distribution of ZnO nanoparticles and minimize the porosity in the interfaces of the layers. The procedure used in the second stage was repeated without adding ZnO particles up to 14 cycles. The same process was employed for the production of the monolithic aluminum, for which the aluminum strips were manufactured without adding ZnO powder in any stage of the APB process. Table 2 shows specifications of the APB process.

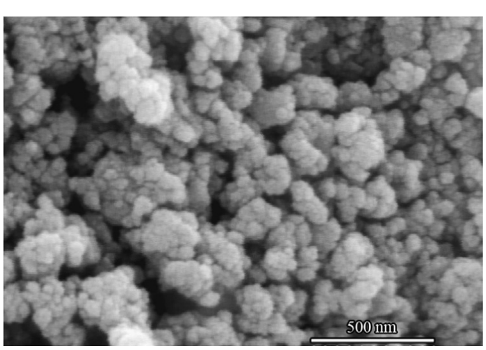

Fig. 1. FE-SEM micrograph of the used ZnO nanopowder.

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

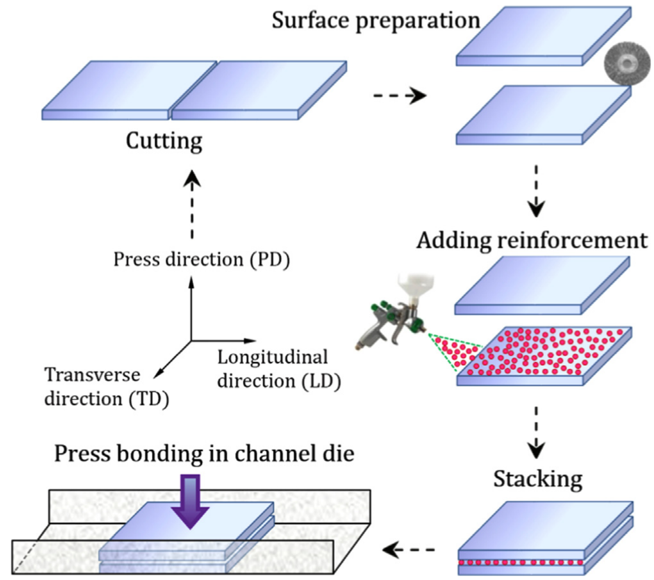

Fig. 2. Schematic illustration of the accumulative press bonding (APB) process.

Table 2
Specifications of the accumulative press bonding (APB) process.

Number of APB cycles	Number of aluminum layers	Number of interfaces	Reduction in each cycle (%)	The thickness of aluminum layers (nm)	Total reduction (%)
0	1	0	0	1,500,000	0
1	2	1	50	750,000	50
2	4	3	50	375,000	75
3	8	7	50	187,500	87.5
4	16	15	50	93,750	93.75
5	32	31	50	46,875	96.875
6	64	63	50	23,437.5	98.4375
7	128	127	50	11,718.75	99.21875
8	256	255	50	5859.375	99.60938
9	512	511	50	2929.688	99.80469
10	1024	1023	50	1464.844	99.90234
11	2048	2047	50	732.4219	99.95117
12	4096	4095	50	366.2109	99.97559
13	8192	8191	50	183.1055	99.98779
14	16,384	16,383	50	91.55273	99.9939
n	2^n	2^n-1	50	$1,500,000/2^n$	$(1-(1/2^n))$ 100

2.4. Microstructural and mechanical evaluation

To examine the distribution of ZnO particles through the different stages of the APB process, field-emission scanning electron microscopy (FE-SEM, HITACHI S-4160, Japan) was used. The electron backscatter diffraction (EBSD) mapping of the aluminum specimens and Al/ZnO nanocomposite were conducted in a JEOL JSM 6500F field emission gun scanning electron microscope (FE-SEM) operating at 20 kV with a working distance of 15 mm and tilt angle of 70°. The microstructures of the specimens were also characterized by field-emission scanning transmission electron microscopy (FE-STEM, HITACHI S-4800) operating at 30 kV. For EBSD and STEM investigations, 3 mm diameter disks were prepared from the specimens and were thinned using a twin-jet electro-polishing tool and a 30% nitric acid and 70% methanol solution at 11 V and −28 °C. In order to clarify the failure mode,