Materials and Design 111 (2016) 263–270

Contents lists available at ScienceDirect

Materials and Design

journal homepage: www.elsevier.com/locate/matdes

Fabrication of manganese-aluminum bronze as a shape memory alloy by accumulative roll bonding process

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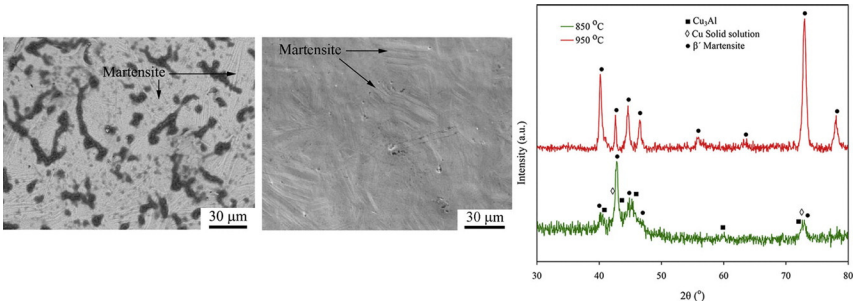
HIGHLIGHTS

- ARB followed by the annealing is a feasible process to produce Cu/Al/Mn alloy.
- The heat treatment had a major effect on the microstructure and phase formation.
- The corrosion resistance of the Cu/Al/Mn alloy is more than that of the composite.

GRAPHICAL ABSTRACT



ARTICLE INFO

Article history:
Received 2 July 2016
Received in revised form 10 August 2016
Accepted 26 August 2016
Available online 29 August 2016

Keywords:
Multilayered composite
Shape memory alloy
Heat treatment
Microstructure

ABSTRACT

Cu/Al/Mn nanocomposites were produced from copper and aluminum strips and manganese powder using Accumulative Roll Bonding (ARB) and then solid solution treatment was performed to produce shape memory alloy. Two solid solution treatment temperatures (850 and 950 °C) were employed to evaluate the phase formation. Scanning electron microscopy, optical microscopy and X-ray diffraction were used for the microstructural and structural studies of the samples. The composition of the produced sample after solid solution treatment at 950 °C was also evaluated by energy dispersive X-ray spectroscopy. The results showed that manganese-aluminum bronze, 83Cu-12Al-5Mn (wt.%), was successfully produced by the ARB process followed by heat treatment. The microstructure of the composite annealed at 950 °C consisted of a fully martensitic phase after ice-water quenching. In addition, the electrochemical corrosion behavior of the produced nanocomposite and bronze was investigated in a 3.5 wt.% NaCl solution by a potentiostat-galvanostat device. It was found that the corrosion resistance of the bronze alloy is higher than that of the composite due to having a single phase microstructure.

1. Introduction

Shape memory alloys (SMAs) have unique properties which make them a multifunctional material for different applications [1]. Among shape memory alloys, NiTi compounds are widely used in medical and engineering applications, due to their shape memory effect (SME), superelasticity and biocompatibility [2,3]. However, the low transformation temperature and excessive production cost of NiTi alloys reduce their applications, particularly for high-temperature uses [1,4]. Inexpensive Cu-based SMAs have been investigated and developed because of advantages in electrical and thermal conductivities and deformability compared with Ti-Ni-based SMAs [4–7]. The most applicable Cu-based SMAs are in the Cu-Zn and Cu-Al systems. The application of Cu-Al SMAs is limited due to large elastic anisotropy and large grain size [1,8,9]. Therefore, many researchers have tried to improve the properties of Cu-based SMAs by the addition of alloying elements (e.g. Ni, Mn, Ti, Be, and so on) [1,5,10–12]. Among the alloying elements,

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http://dx.doi.org/10.1016/j.matdes.2016.08.074
0264-1275/

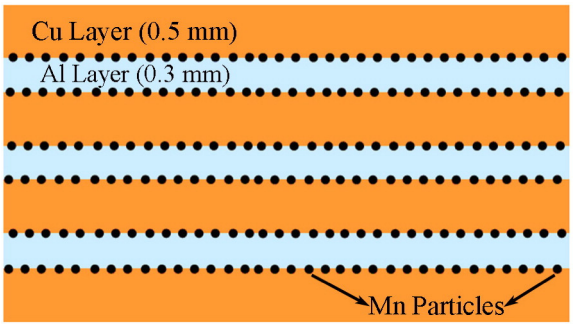

Fig. 1. Schematic of the strip stacking sequence for the 7-layers specimens subjected to ARB.

manganese is often added to improve the alloy ductility [10,11]. For instance, it has been reported that Cu–Al–Mn SMAs exhibit more ductility than Cu–Zn–Al and Cu–Al–Ni alloys [5,8,13–15].

The SME in Cu-Al-Mn alloys is based on the thermoelastic martensitic transformation that occurs between a β phase (with DO3 or L2, order structures) and a martensitic phase (identified as 3R, 9R, 18R, or 2H structures) [6,10]. The β phase in the binary Cu-A1 alloy system undergoes eutectoid decomposition at about 350 °C into α and γ [16]. However, if it is quenched from the β phase region to ambient temperature, it transforms martensitically [4]. It is known that ordering reactions, β → β2 (CuAl: B2) → β1 (Cu_3Al: DO3) [4,5,16], occur at low temperatures during quenching, according to Cu-A1pahse diagram.

Cu-based SMAs are usually produced by melting processes [5,6,10,17,18]. A solid-state method which can be used to produce Cu-based SMAs is accumulative roll bonding (ARB) followed by solid solution treatment. The ARB process which is a severe plastic deformation method consists of roll-bonding of prepared sheets by 50% thickness reduction [19,20]. In this process due to repeating roll-bonding procedure, very high strains are introduced into the materials, and structural refinement is achieved [21,22]. In this process at first, a multilayered composite is produced and then by using a suitable heat treatment it changed to a SMA.

Many researches have been focused on multilayered composites produced by the ARB process [23,24]. But, aluminum bronze alloy fabricated by ARBed multilayered composites and subsequent solid solution treatment is not reported. In the present work, for the first time, ARB accompanied by heat treatment was used to fabricate an aluminum bronze (Cu-12Al-5Mn) as shape memory alloy. Then, the structural characteristics as well as corrosion behavior of the composites were investigated.

2. Experimental procedure

In this research, commercially pure copper and aluminum strips and also manganese powder with the purity levels of 99.9, 99, and 99%, respectively, were used as the primary materials. In order to achieve a nominal composition of 83Cu–12Al–5Mn (wt.%), four Cu and three Al strips with the dimensions of 150 × 30 × 0.5 and 150 × 30 × 0.3 mm^3, respectively, were employed. Prior to stacking the strips, their surfaces were cleaned by acetone and scratch-brushed with a steel wire brush. Wire brushing removes oxide layers and makes a hard layer on the surface, providing the best condition for bonding [23]. After the surface preparation, three Al strips were placed among four Cu strips, as depicted in Fig. 1, while the Mn powders with an average particle size of 40 μm were dispersed between every two of the layers. This sequence of the stacked layers was used for producing initial sandwiches with a thickness of 2.9 mm and previously-mentioned chemical composition.

The produced sandwich was roll-bonded to about 66% thickness reduction under an un-lubricant condition, using a laboratory rolling mill with a loading capacity of 20 tons at room temperature. Then, the length of the sample obtained from this stage was sectioned into two halves. After surface preparation, they were stacked again and rolled to 50% thickness reduction. It was named the one cycle and repeated until 9 cycles, as referred as accumulative roll bonding (ARB).

For the structural investigations of the produced composites after different ARB cycles, XRD measurements were carried out on the rolling direction-normal direction (RD–ND) plane of the ARB processed composites. The XRD experiments were performed by an X-ray diffractometer (XRD, Bruker) using Cu $K\alpha_1$ radiation (λ = 0.15406 nm). The step size and scan rate was selected 0.03° and 6 s, respectively. In the present work, the Williamson–Hall formula was used to quantify the XRD data.

The composites produced by 9 ARB cycles were subjected to heat treatment inside a furnace at the environment atmosphere. The heat treatment consisted of solid solution treatment followed by ice water quenching. The composite samples were annealed at two temperatures of 850 and 950 °C for 30 min. The heat-treated composite samples were cut transverse to the rolling direction and after mounting and polishing, were prepared for structural and microstructural studies. Microstructural and compositional studies were performed on the RD–ND plane by a scanning electron microscope (SEM) (EVO-MA25) equipped with energy dispersive spectroscopy (EDS). SEM images were taken by either backscattered electron or secondary electron modes.

The corrosion performance of the produced composites was carried out by a three-electrode cells assembly. The ARBed samples with an area of 0.5 cm^2 was exposed as a working electrode. A platinum plate and an Ag/AgCl were used as auxiliary and reference electrode, respectively. The measurements were conducted in a 3.5% NaCl solution at room temperature. Electrochemical polarization measurements were carried out using a potentiostat/galvanostat device (Vertex, Ivium). The corrosion potential and corrosion current density of the produced composites were determined from Tafel curves.

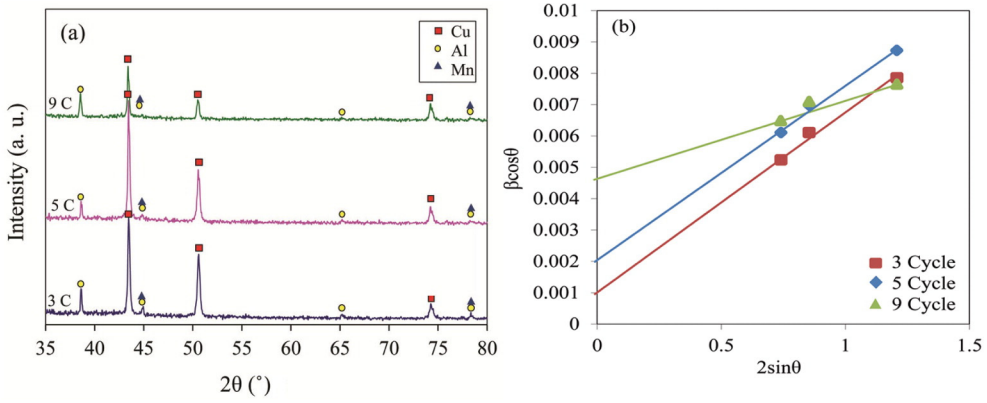

Fig. 2. XRD pattern (a) and Williamson-Hall plot (b) of the composites processed by 3, 5 and 9 ARB cycles.