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3D entangled wire reinforced metallic composites

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ABSTRACT

3D entangled stainless steel wire reinforced aluminum composites have been fabricated by squeezing casting. Monofilaments with a diameter of 100 μm are used to prepare the 3D wire preforms and their volume fraction in the composites varies from 17.7 to 35.4%. The interface between the reinforcements and the aluminum matrix shows perfect cohesion without any micro-pores or other defects. The introduction of 3D entangled wire structure increases the strength of A356 alloy from 164 to 318 MPa. Noticeably, the yield strength of the composites reinforced by the 3D structure with small volume fraction is reasonably low, which appears below the Voigt upper bound. But it increases significantly as the volume fraction of the reinforcements increases. For the composites with the entangled wire structure larger than 26.5 vol.%, the yield strength is beyond the upper bound. This phenomenon can be attributed to the structure-strengthening of the 3D entangled wire preforms.

1. Introduction

Aluminum-based metal-matrix composites (MMCs) show interesting physical and mechanical properties such as thermal conductivity, thermal expansion, stiffness, strength, friction, and wear resistance [1–4], which can be tailored by controlling volume fraction, size, shape and spatial distribution of reinforcements [5,6]. Various kinds of reinforcements such as particles [7,8], whiskers or fibers [9–11], the hybrid of particles and fibers [12,13], and carbon nanotube [14] have been widely used to reinforce the aluminum matrix. These reinforcements in the composites are not always continuous, leading to their unplanned orientations or non-uniform distributions and then to the difficulty in controlling the microstructure of MMCs. Ceramic-metal composites [15–19] with interpenetrating networks have been extensively studied in recent years. The network structure of preforms not only provides a controlled and stable dispersion of reinforcements, but also offers new architectures and increases the structural integrity and more effective load transfer [20,21]. Compared with the reinforcements such as particles, whiskers or short fibers for the same volume fraction, this kind of network structure will be desired to perform more efficiently in reinforcing the metal matrix. However, the aforementioned 3D interconnected structure is almost prepared by ceramic network. MMCs reinforced with ceramic phase always present low fracture toughness, which restricts their applications. Fortunately, the metallic fibers [11,22–24] have been introduced into MMCs in order to improve the ductile and fracture toughness of the MMCs. The control over the interface reactions [22] between aluminium matrix and stainless steel metallic fibers has revealed the validity of this kind of metallic wire preform/fabric as reinforcements in the aluminum-based MMCs.

Recently mono-filament entangled materials [25–29] with through-connected open pores and interconnected structure have been developed in our lab. An improved entangled wire structure (so-called ‘quasi-ordered’ structure [25]) has shown superelasticity and good toughness. If such entangled wire structure is used as reinforcements in the alloy, it is possible to fabricate MMCs with both high strength and good ductility/toughness. In the present work, entangled materials of stainless steel wires are prepared and used as preforms to reinforce aluminum alloy. Such aluminium-based matrix composites are investigated in terms of deformation behaviors and mechanical properties under compressive load.

2. Experimental procedures

A mono-filament annealed 304 stainless steel wire with 100 μm in diameter was used to prepare the entangled wire preforms. The nominal chemical constituents and mechanical properties of 304 stainless steel wires are listed in Table 1. The as-prepared cylindrical preforms with porosities of 60–80%, which are 10 mm in diameter and 20 mm in length, were fabricated by special procedures. The fabrication method and the 3D structure have been described in detail elsewhere [25]. The relationship between volume fraction (x) of wires and porosity (p) follows $x = 1 - p$.

A356 alloy was used as the matrix alloy, and its nominal chemical compositions are listed in Table 2. The composites reinforced

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Table 1
Nominal chemical constituents (wt.%) and mechanical properties of 304 stainless steel wires.

Cr	Ni	Mn	Si	C	S	P	Fe
17.0–19.0	8.0–11.0	≤2.0	≤1.0	≤0.07	≤0.03	≤0.035	Bal.

Yielding Strength (MPa)	Tensile Strength (MPa)	Elongation (%)	Young's Modulus (GPa)
~486	~1230	>10	193

Table 2
Nominal chemical compositions (wt.%) of A356 matrix alloy.

Si	Fe	Cu	Mg	Sn	Zn	Ti	Mn	Zr	Pb	Al
6.50–7.50	0.20	0.10	0.25–0.45	0.01	0.10	0.08–0.20	0.10	0.20	0.03	Bal.

with the entangled wire preforms were prepared by squeezing casting, which was carried out under the following conditions:

- Casting temperature: 740 °C for A356 alloy;
- Die temperature: 400 °C, and punch temperature: 25 °C;
- Mass of liquid metal cast in the die: 700 g;
- Pressure of squeezing casting: 35 MPa.

Before squeezing casting, the as-prepared entangled wire preforms were placed in a steel die with 10.5 mm in inner diameter and 20.5 mm in length in order to prevent the movement and deformation of the preforms during the fabrication process. The assembly for squeezing casting and the as-prepared preforms and composites are illustrated in Fig. 1. The as-prepared composite specimens were then ground by aluminum oxide cloth carefully. The difference between inner diameter of the die and outer diameter of the preforms resulted in the volume expansion of as-prepared composites. The volume fractions (x') of wires in the composites have to be re-calculated according to $x' = \left(v/v'\right) x$, where v' is the as-prepared composite volume calculated by the die. Then the calibrated volume fractions of the wires in the composites are 17.7 vol.%, 26.5 vol.%, and 35.4 vol.%, corresponding to the porosities of 80%, 70%, and 60% in the entangled wire preforms, respectively.

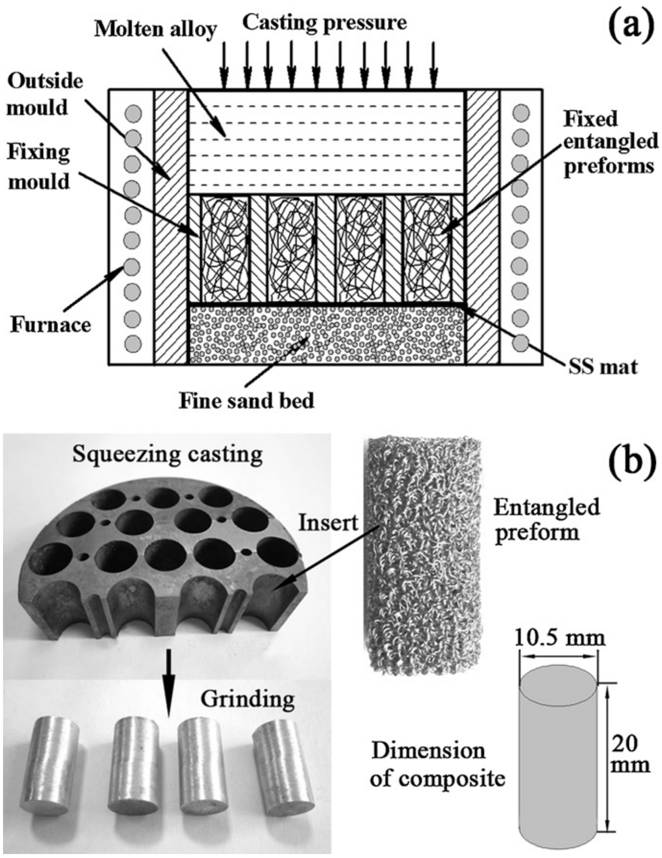

Fig. 1. Schematic diagram of assembly during squeezing casting (a), and as-prepared preform and composites (b).

The density of the composites with different volume fraction of wires was measured by Archimedes method. The specimens were etched by 15% NaOH solution and the microstructures of the cross-section and longitudinal-section were observed by Optical Microscopy (OM) and Office Scanner (OS). The distribution of wire-segments on the sections was statistically evaluated by using image analysis software.

The uniaxial compressive behaviors were studied by using Zwick T1-FR020.A50 testing machine with 2 kN load cell for the entangled preforms, and SANS5105 testing machine with 100 kN load cell for the composites. Samples with a length-diameter ratio of 2.0 are to avoid failure by buckling. Both ends of the specimens were polished to make them parallel to each other and no lubricant was applied between the specimens and the cross-heads during compression tests. The tests were conducted under displacement control with a cross-head speed of $0.5 \times 10^{-3}\ \mathrm{s}^{-1}$. The yield strength of the entangled preforms and the composites were decided by the intersection points [25], which were formed by extending the elastic zone and the pseudo-platform zone of the recorded nominal stress-strain curves.

3. Results

3.1. Microstructures of the composites reinforced with entangled wires

Fig. 2 shows the microstructures of A356 matrix alloy and the composites reinforced by entangled wires. A356 matrix consists of dendritic *fcc* Al solid solution and boundary eutectic phase as shown in Fig. 2a. The composite contains wire segments (light zones, see Fig. 2b) with various morphologies which dispersed in the matrix homogeneously. The size of the dendritic phase of the matrix in the composite is comparable to that in the A356 alloy, which is much smaller than the wire diameter. It indicates that the introduction of wires seems to have little influence on the microstructures of the matrix, which are mainly determined by the squeezing casting process. The cohesion of the matrix and wires is very well and no obvious traces of interface reaction are observed (see Fig. 2b), which is accordance with the observations by other investigators [11,22]. This phenomenon can be attributed to the oxide barrier layer on the metallic wire that prevents the reaction between the matrix and the metallic wire.

A schematic diagram of the distribution of the wires for the composite reinforced with entangled wire preforms is constructed by the acquired images on both longitudinal-section and cross-section