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Liquid rolling of woven carbon fibers reinforced Al5083-matrix composites

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ABSTRACT

A liquid rolling method was successfully developed for the fabrication of woven carbon fibers reinforced Al5083-matrix composites. The woven fibers were coated with Ni/P to facilitate wetting of the fibers by the molten matrix. It was found that the composite fabricated in this way had a good microstructure with few defects, which was most likely due to the occurrences of pressure infiltration, rapid solidification, and hot-deformation strengthening on the materials. Finite-element simulation was conducted to analyze the temperature field and solidification process during the liquid rolling. A wide semi-solid region was observed in the simulation, and it would effectively avoid the fiber damages. The results of three-point bending measurements implied that the application of liquid rolling and the addition of reinforcements could both offer obvious improvements to the materials. The liquid rolling method could increase the matrix bending strength by 43% than the casting method. Furthermore, when the liquid rolling was used, the addition of woven fibers could offer an improvement of 22% to the matrix.

1. Introduction

Al-matrix composites have prospectively wide applications in the aerospace and automotive industries due to their low density, good mechanical properties, and ease of processing [1,2]. One of the best reinforcements for the Al-matrix is the carbon fiber, which could increase the specific strength and the wear resistance significantly [3–5]. Because of its unmatched benefits, considerable attention has been paid towards the synthesis and characterization of the carbon fiber reinforced Al-matrix composites (CFRAC) [6,7]. However, manufacturing problems, such as poor wettability and chemical reactions between the fibers and molten Al, are the key hindrances to synthesizing these high performance materials and making use of their full potential [8,9]. The wettability are improved only when the temperature of the Al-matrix is above 1273 K, while the carbon fibers would start to react with the molten Al at 773 K [10]. Such undesirable interfacial reaction product is the Al_4C_3, which is known to severely damage the fibers and deteriorate the mechanical properties of the composites [11].

One solution to overcome these problems is coating the fibers. Ni or Cu elements are the most commonly used coating materials because these metal coatings are easily obtained through the method of electroless plating [12,13]. The refractory ceramic materials, such as Al_2O_3 and SiC, are also widely used because of their inertness towards both the matrix and the reinforcements [14–16]. In recent years, an increasing number of experts in the CFRAC field have focused on the advancement of fabrication processes. The squeeze casting method was successfully adopted by Hajjari, et al. [17], who discovered that the appropriate applied pressure for preparing the composite was approximately 30 MPa. Daoud [6] fabricated an Al2014 alloy with 30 vol% carbon fiber composite through a gas pressure infiltration method. His results showed that the application of appropriate pressure could effectively increase the interface bonding degree of the composites. A continuous M40J carbon fiber reinforced Al–Mg matrix composite wire was developed by Matsunaga, et al. [18,19] using an ultrasonic infiltration method. The ease of infiltration was proved to be proportional to the maximum intensity of the acoustic cavitation, and the addition of surfactant elements significantly improved the infiltrating behavior. In addition to the above fabrication processes, other methods, such as spark plasma sintering (SPS) [20], centrifugal infiltration [21], and others, have also been successfully adopted.

All the fabrication methods mentioned above could offer an applied pressure to facilitate the matrix infiltrating into the fiber bundles, in which case the size of the composite samples are strictly limited by the production equipment. The industrial preparation of larger samples and the efficient continuous production are still difficult; therefore, the development of a convenient fabrication method is valuable. In this study, rolling pressure was introduced to improve the infiltrating ability of the Al5083-matrix through a liquid rolling method. Woven carbon fibers were selected as the reinforcement. Due to the mutual restriction between longitudinal and latitudinal direction fibers, the woven form could ensure a more stable fiber distribution in the matrix and completely eliminates fiber clustering. Furthermore, the woven form is capable of bearing a two-dimensional load, and is more suitable for

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enhancing plate materials. The interface microstructure, element distribution and mechanical property of the composites were systematically investigated. Finite-element simulation was also conducted for analyzing the temperature field and solidification process during the rolling process.

2. Experimental procedures

2.1. Materials and pre-treatment

Commercially available Al5083 alloy was used as the matrix alloy; its composition is provided in Table 1. Plain weave polyacrylonitrile-based carbon fibers produced by the Institute of Coal Chemistry at the Chinese Academy of Sciences were selected as the reinforcement material. There were approximately 3000 fibers per bundle, with a nominal longitudinal strength of more than 3.5 GPa. Each individual fiber had a mean diameter of 7–8 μm.

The epoxy resin glue on the as-received fibers was removed by heating the woven carbon fibers in a furnace at 773 K for 45 min. After the original fiber surfaces were fully exposed [22], an electroless plating process was performed, the details of which was previously reported [23]. The obtained coating had a thickness of 0.5 μm and a P content of 10.2 wt.%, which would provide an improved wetting behavior during further fabrication processes [1].

2.2. Composite fabrication

A rolling process was adopted to prepare the composite samples, the schematic diagram is provided in Fig. 1(a). After soaked for 60 s in the molten Al5083 (two different temperatures were used in this study, 953 K and 1003 K), the coated woven fibers (120 mm × 60 mm) was placed in the middle of the solid Al5083 back-sheet (150 mm × 80 mm × 2 mm, 623 K). The molten Al5083 was poured from the tundish to completely cover the fibers, meanwhile the rolling process was carried out. Two baffles were used to prevent the spreading laterally of the molten matrix. The roller spacing was 4 mm, the rolling speed was 3 rad/min, and the diameter of the roll wheel was 250 mm. The Al5083 matrix samples without reinforcements were also prepared under the same conditions. In order to investigate the element distributions and to compare the performances, this study also used an electromagnetic casting method, which had a pulsed magnetic field (PMF) with a frequency of 5 Hz and a voltage of 700 V. The casting temperature was 993 K, and the solidification times were controlled by the cooling environment.

2.3. Microstructures and mechanical properties

To investigate the infiltration results of different processes, the composite samples were sectioned, and the transverse section microstructures were observed using a Zeiss Supra 55 scanning electron microscope (SEM). Micro-compositional analyses of the interfaces were carried out using an energy dispersive spectroscopy (EDS), and the surface scanning was employed to investigate the element segregation. The mechanical properties of the composites were evaluated through a three-point bending measurement, which was conducted with a span length of 20 mm and a crosshead speed of 1.2 mm min^{-1}. The experimental samples, measuring 50 mm × 10 mm × 3.5 mm, were cut from the composites, as well as from the matrix fabricated without reinforcements. Three samples were respectively tested under per condition, the results were similar to each other.

Table 1
Chemical composition of Al5083.

Elements	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	Al
Percentage	0.38	0.29	0.03	0.51	4.42	0.08	0.01	0.02	Balance

2.4. Finite-element simulation

Finite-element simulation was conducted to analyze the temperature field and solidification process of the liquid rolling process using the commercial finite-element analysis package ANSYS Workbench. The commercial modeling software of UG NX was used to produce a 2-D model, the size of which was consistent with the experiment in Section 2.2. The corresponding meshed finite-element model of the processing region under the roll wheel (obtained by Gambit software) is shown in Fig. 1(b), and the boundary conditions are described as following:

2.4.1. Inlet boundary

The velocity and temperature boundary conditions were used in this region. The value of velocity was calculated based on the rolling velocity, and the temperature value was the casting temperature.

2.4.2. Outlet boundary

The velocity boundary condition was used as the outlet boundary. The value of velocity was calculated based on the rolling velocity together with the length of the inlet and outlet.

2.4.3. Boundary conditions of the part that came into contact with the roller wheel

The velocity and thermal convection boundary conditions were used in this region. The value of velocity was calculated based on the rolling velocity, and the value of heat transfer coefficient between 5083 and the wheel was determined by an inverse method.

2.4.4. Boundary conditions of the remaining parts

The velocity and thermal convection boundary conditions were used for the remaining parts. The value of velocity was calculated based on the rolling velocity, and the value of heat transfer coefficient was the convection exchange coefficient of air.

3. Results and discussion

3.1. Electromagnetic casting

Since the presence of element Si could offer a better wetting behavior during the solidification process, it is a common addition element to Al matrixes [8,21,24]. The experimental matrix in this study, Al5083, also has a large content of Si element. Therefore, the distribution of Si in the CFRAC was firstly investigated using a hypoeutectic composition of Al–Si (96–4 wt.%) as the matrix material. Fig. 2(a) shows the microstructure of the composite obtained by the electromagnetic casting which has a solidification time of 300–400 s. The smooth interfaces between the matrix and the carbon fibers are easily observed, which means that the magnetic pressure generated in the pulsed magnetic field could force the liquid matrix to infiltrate into the woven carbon fibers and attach tightly to the fibers. The Ni/P coatings could not be observed after solidification, and no obvious segregation occurs. Rams et al. [15] thought the Ni atoms coming from the Ni/P coatings could improve the composites by increasing their hardness and strength at elevated temperatures and by reducing the coefficient of expansion. An obvious interlayer appears between the matrix and carbon fibers, as shown in Fig. 2(a). This light-colored region closely covers the fiber reinforcements and combines tightly with the metal matrix. It exists in the form of continuous and uniform segregation, which is characterized by EDS as a Si-rich phase (70.5 at.%). In addition to Si, there are also large amounts of Al (22.8 at.%) and P (6.7 at.%).

For further research, surface scanning was conducted to investigate element distribution, the results of which are shown in Fig. 2(b). Most