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Fabrication and characterization of squeeze cast A413-C_{SF} composites

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ABSTRACT

A413 aluminum matrix composites reinforced with short carbon fibers (C_{SF}s) were produced using a combination of vortex and squeeze casting processes and the effects of reinforcement volume fraction and reinforcement coating on density, porosity, reinforcement distribution and mechanical properties of the produced composites were studied. The results showed that increasing the volume fraction of C_{SF}s led to decreased density and increased porosity of the cast composites. Distribution of uncoated C_{SF}s in the matrix of the reinforced samples was poor and most of the fibers were in agglomerated bundle form. Utilization of coated C_{SF}s resulted in a rather uniform distribution of the reinforcement in the matrix. Mechanical properties of squeeze cast composites fabricated using uncoated C_{SF}s improved by increasing the reinforcement volume fraction up to 2% and decreased beyond it. Mechanical properties of the squeeze cast composites fabricated using coated C_{SF}s improved steadily by increasing the reinforcement volume fraction up to 3%. Ultimate tensile strength and hardness values of the composites reinforced with 3 vol% coated C_{SF}s increased by more than 100% and 60%, respectively, in comparison with those of the monolithic cast sample.

1. Introduction

Carbon fibers (C_Fs) are valuable reinforcements for aluminum and its alloys in fabrication of advanced composite materials. C_Fs have been used as reinforcement in aluminum matrix composites because of the fact that they can improve the strength, stiffness and electrical/thermal conductivities of aluminum alloys while reducing their density and friction coefficient [1]. That is why Al-C_F composites are increasingly used in various automotive and aerospace applications. However, poor wettability of C_F with molten aluminum at typical casting temperatures and detrimental reactions between C_F and molten aluminum are the most challenging issues in production of such advanced materials [2]. An efficient method to overcome these problems is coating of C_F with a material that is inert towards both the molten metal and the C_F reinforcement [3]. Among metallic coatings, nickel coating has been taken into consideration in different studies [4,5].

Different techniques such as vortex method, squeeze casting, metal spray and metal infiltration have been developed to fabricate Al-C_F composites [6]. Use of squeeze casting method for fabrication of metal matrix composites includes solidifying a slurry of a melt and some reinforcing materials under pressure [7,8]. Applying pressure on liquid metal during its solidification leads to higher cooling rate and, therefore, thermal modification of the as cast microstructure. The most important features of squeeze casting process includes reduction of shrinkage and gas porosities, near-net shape casting, high mechanical properties close to work hardened alloys, high production rate, high yield due to elimination of running and risering systems, close dimensional tolerance and ability to cast metals and alloys with poor castability [9,10]. On the other hand, application of high pressure on a composite slurry during squeeze casting process leads to better wettability and shorter contact time between the reinforcement and the melt. The latter will restrict the interfacial reactions [11].

Investigations on squeeze casting of aluminum matrix composites reinforced with C_Fs have been mostly based on infiltration of preforms made of continuous C_Fs [12,13] or discontinuous C_{SF}s [14,15]. However, as the fabrication of preforms to produce complex cast parts is difficult and costly, therefore, squeeze casting of composite slurries prepared by vortex method seems to be a reasonable alternative.

In this study, A413 (LM6) aluminum matrix composites reinforced with C_{SF}s were produced using a combination of vortex and squeeze casting processes. Excellent castability, dimensional stability, pressure tightness and corrosion resistance as well as good weld ability and specific strength are among the main

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characteristics of A413 alloy. As a result, the alloy is largely used in automotive and marine sectors where large thin walled parts with cast in letterings and high definition details as well as good corrosion resistance and pressure tightness are required [16]. The alloys has been the subject of many investigations in recent years in its monolithic or composites forms. Bolzoni et al. [16], for example, studied the effect of addition of Nb-based grain refiner on the microstructural features and mechanical properties of A413 alloy and found out that formation of Nb-based compounds (i.e., NbB_2 and Al_3Nb) lead to significant refinement of the microstructural features and improvement of the mechanical properties. Srinivasulu Reddy et al. [17] reinforced the A413 alloy with carbon nanotubes (CNTs) and showed that the presence of CNTs in the alloys resulted in significant improvement in mechanical properties and thermal stability of the alloy.

This study reports the effects of volume fraction of C_{SF}s and fiber coating on density, porosity, reinforcement distribution and mechanical properties of A413-C_{SF} composites produced using a combination of vortex and squeeze casting processes.

2. Experimental procedure

2.1. Materials

A413 aluminum alloy was selected as the matrix alloy for fabrication of the composites. Table 1 shows the chemical composition of the alloy obtained by spark emission spectrometry. C_{SF}s used in this study were chopped from commercially available ex-PAN (polyacrylonitril-based) carbon fibers (T300, Toray Co. Ltd., Japan). Some properties of T300 fibers are listed in Table 2 [18].

2.2. Preparation and coating of C_{SF}s

First, the sizing of the C_Fs was removed by heat cleaning the fibers at 550 °C for 10 min. C_Fs were then rinsed with distilled water and dried in an oven at 100 °C for an hour. Some of the C_Fs were chopped to 3–5 mm short fibers at this stage to be used for fabrication of the control samples. Some of the C_{SF}s were coated using Ni-P electroless coating technique. Details of the optimized electroless coating process used have been reported elsewhere [19]. Here the coating procedure is briefly described.

In order to improve the interfacial adhesion between the Ni-P coating and the rinsed and dried C_Fs, they were immersed in nitric acid for 4 h and washed thoroughly with distilled water. Then the continuous fibers were cut to 3–5 mm short fibers. Electroless Ni-P plating was carried out in electroless acid plating bath containing different proportions of a commercial electroless plating solution of nickel sulfate, as the source of nickel, and sodium hypophosphite, as the reducing agent (Slotonip 70A series, Schloetter Co., Germany). SEM micrographs of uncoated and Ni-P coated carbon short fibers used are shown in Fig. 1.

2.3. Casting of A413- C_{SF} composites

First, A413 aluminum alloy was heated to 680 °C in an alumina crucible in an electrical resistance furnace. A refractory coated stainless steel mechanical stirrer with three blades was then introduced in to the melt and melt stirring was started at 500 rpm.

Table 1
Chemical composition of A413 aluminum alloy.

	Si	Fe	Cu	Mg	Zn	Ni	Pb	Al
Wt%	12.6	0.53	0.49	0.17	0.39	0.12	0.22	Bal.

Table 2
Some properties of T300 fibers [18].

Diameter (μm)	7.0
Tensile strength (MPa)	3530
Tensile modulus (GPa)	230
Number of filament in each bundle	6000
Elongation (%)	1.5
Mass per length (10^{-3} g m^{-1})	396

In order to fabricate A413-C_{SF} composites, the desired volume fraction of coated or uncoated C_{SF}s was gradually added to the melt and stirring continued for 5 min. Fig. 2a schematically shows the set up used for preparation of the composite slurry.

The crucible was subsequently removed and the slurry was poured in to a cup-shaped squeeze casting die placed on the bed of a 200 tones hydraulic press and was immediately squeezed at 80 MPa pressure. The die was made of heat treated H13 steel and was preheated to about 250 °C before casting. Fig. 2b schematically shows the design and dimensions of the squeeze casting die. The applied pressure was removed approximately after 30 s, when the solidification was completed and the casting was removed from the die. A picture and the schematic of an as cast sample as well as the schematic of the casting after sectioning are shown in Fig. 3.

Casting conditions of different samples are shown in Table 3. As shown in the table, one monolithic A413 reference sample (C0), three A413-C_{SF} composites reinforced with 1–3 vol% of uncoated C_{SF}s (C1 to C3) and three A413-C_{SF} composites reinforced with 1–3 vol% of electroless Ni-P coated C_{SF}s (CE1 to CE3) were cast. It is worth noting that the melt preparation and casting sequence for all the castings was similar. Even for the monolithic sample (C0), the melt was squeeze cast after 5 min melt stirring of the same amount of unreinforced A413 aluminum alloy as was used for the composite samples.

2.4. Porosity and density measurements

Before sectioning the samples, their density and internal volume defects were determined by Archimedes method. Apparent density of the samples (ρ_{app}) were measured using Eq. (1), where ρ_w, w and w' are density of water (roughly 1 g/cm^3) and sample weights in dry and immersed states, respectively.

$$\rho_{app} = \frac{W \times \rho_w}{W - W'} \tag{1}$$

Volume fraction of the porosity (P) was estimated using Eq. (2), where ρ_P and ρ_m are theoretical densities of the reinforcement and the matrix alloy, respectively, and V_P is the volume fraction of the reinforcement.

$$P = \left(1 - \frac{\rho_{app}}{\rho_m(1 - V_p) + \rho_p V_p}\right) \times 100 \tag{2}$$

2.5. Microstructural analyses and mechanical tests

In order to examine the distribution of C_{SF}s in the matrix and evaluate the mechanical properties of the castings, all the samples were sectioned as shown in Fig. 3b and metallographic and mechanical test samples were prepared from the samples walls. Microstructural evaluations in terms of reinforcement distribution were performed on polished and non-etched surfaces of the samples using a Nikon Epiphoto300 microscope equipped with a image recording system. Microstructures as well as fracture surfaces of