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Fabrication of Al–Si–Mg functionally graded materials tube reinforced with in situ Si/Mg_2Si particles by centrifugal casting

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ABSTRACT

The influences of various process parameters on the particle segregation ratio and the particle distributions involving the particle size and volume fraction of in situ primary Si/Mg_2Si particles in tubes of Al–Si–Mg functionally graded materials (FGMs) fabricated by centrifugal casting were systematically investigated. The properties of hardness, wear resistance and thermal expansion of the tubes were examined. The results show that, (1) the FGMs tubes consisted of a reinforcement layer and an un-reinforcement layer; (2) the particle segregation ratio varied with various process parameters; (3) the volume fractions and sizes of primary Si/Mg_2Si particles presented a graded distribution in the reinforcement layer; and (4) the FGMs had an advantage over the conventional motorcycle/automobile cylinder liners and the conventional materials Al–12Si–1Cu–1 Mg–1Ni alloy in the wear resistance and the thermal expansion property, respectively.

1. Introduction

In recent years, in order to apply lightweight materials for automobile parts, aluminum based composites have been researched to produce industry components, such as aluminum cylinder liners of engines, which are used as substitutes for iron liners. Perrot and Mazodier [1] invented a hollow cylindrical block, such as an internal combustion engine sleeve, produced by powder extrusion of Al–Si alloys with silicon content between 15% and 20%, and the friction and wear properties of the liners were obviously improved. Rückert et al. [2] invented a new kind of cylinder liners of hypereutectic aluminum–silicon alloy fabricated using the spray compaction method for use in a crankcase. Ha et al. [3] have produced a 180 mm diameter billet of an Al–25Si alloy by spray forming, and the billet was a promising material to form cylinder liners. Uozato et al. [4] have studied the corrosion and wear behaviors of ferrous powder thermal spray coatings on aluminum alloy in order to improve the wear-resistance of the inner surface of the aluminum cylinder block without cast iron liner.

However, these processes present inherent complexity and high cost. With the advent of FGMs, the centrifugal method, proposed by Fukui [5], was provided to make FGMs with in situ reinforcement phase occurring during the solidification of the melt. Several kinds of alloys, such as Al–Ti, Al–Ni–Ti, Al–Cu, Al–Cu–Fe, Al–Mg–B, Al–Ni and Al–Zr, have been used to fabricate FGMs [6–12]. The reinforcement phase in the matrix can remarkably improve the mechanical properties of materials; thus, FGMs are considered to be applicable as structural and functional materials to make components, such as aluminum cylinder liners. Zhai et al. [13] have fabricated the Al–Si–Mg FGMs by centrifugal casting, and it was found that the Si and Mg_2Si primary crystal particles formed in the alloys were abundantly segregated and enriched in the inner layer of castings in the centrifugal field due to their smaller densities ($\rho_{Si} = 2.33\ g/cm^3$, $\rho_{Mg_2Si} = 1.99\ g/cm^3$) than that of Al melt ($\rho_{Al} = 2.37\ g/cm^3$). In contrast to the traditional smoothly varying gradient composites, this kind of FGMs shows *a sudden change* of particle distributions across the section and the section appearance is obviously divided into two layers, the reinforcement layer with plenty of particles and the un-reinforcement layer with few particles. The segregation of primary Si and Mg_2Si particles in the reinforcement layer imparts a superior wear resistance to these castings. Lin et al. [14] have investigated the influences of Si and Mg contents on the microstructures of the Al–Si–Mg FGMs fabricated by centrifugal casting. The results showed that Si and Mg contents had a great effect on the particle segregation, and proper contents of Si and Mg in the alloy were provided. However, effects of different process parameters on particle distribution characteristics and properties of Al–Si–Mg FGMs fabricated by centrifugal casting were not reported and are not yet clear.

It is well known that the particle distributions in particle-reinforced composites play an important role in attaining superior mechanical properties. Some work has been done by Watanabe et al. [15,16] on the particle distribution characteristics of FGMs fabricated by centrifugal casting. In this research, the Al–Si–Mg FGMs tubes were fabricated by centrifugal casing, and an

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aluminum cylinder liner was obtained. The distributions of the particle size, volume fraction and the segregation ratio of the primary Si/Mg_2Si particles in the FGMs tubes fabricated with different process parameters were investigated. The hardness of the tubes was measured to confirm those microstructural distribution characteristics. The wear resistance and thermal expansion property of the reinforcement layer of FGMs tubes were investigated as well to give a comparison to the conventional materials.

2. Experimental

2.1. Material preparation and process parameters

Raw materials smelted to prepare the composites in this experiment were commercial alloys of Al–18 mass%Si–1.2 mass%Mg and pure Si and Mg metals. The raw materials were melted with an electrical resistance furnace to prepare the Al–Si–Mg suspension.

To investigate the influences of various process parameters on the particle segregation ratio, *k*, and the particle distributions involving the particle size and volume fraction, three groups of process parameters were designed in this experiment according to the different pouring temperatures, mold temperatures and *G* numbers ($G = \omega^2 R/g$, where R is the radius of the cast tube (m), ω is the mold rotation rate (in radians s^{-1}) and g is the acceleration due to gravity). Two factors of the three mentioned above were kept constant as the other was varied. Thus, 14 combinations of process parameters were arranged. The casting conditions applied in the present study and notations of the specimens are summarized in Table 1.

2.2. Casting preparation

After modification at 740 °C, the Al–Si–Mg suspension was poured at different temperatures into a hot mold with different temperatures in a horizontal centrifugal machine. Tubes were formed under the centrifugal force of different *G* numbers. The dimensions of the formed FGMs tubes are as follows: the outer diameter is 94 mm, the length is 176 mm, and the thickness is 15 mm, as shown in Fig. 1a. There were two notable layers with different colors on the cross section, as shown in Fig. 1b. Between the two layers, an interface appeared.

A FGMs tube was cut in the middle part and a ring was obtained. The cross section of the ring was polished, and it was found that the section was divided into two different zones, which were the reinforcement layer (inner layer) and the un-reinforcement layer (outer layer), radically from the inner-to-outer surface. The inner layer of the particle segregation area was divided into ten zones of equal width along the radial direction for the evaluation of the microstructural characteristics as a function of position normalized with the radial thickness of the ring. Hereafter, they are referred to as the normalized position, and 0.0 and 1.0 of the normalized position are the inner wall of the tube and the interface between the two layers, respectively, as shown in Fig. 1b. The microstructures of the 14 specimens were observed with an optical microscope (OM). The volume fractions of primary Si and Mg_2Si particles of the FGMs were measured directly from micrographs using the image processing software Image PRO Plus.

Table 1
Process parameters and notations of the specimens.

	Pouring temperature (°C)	Mold temperature (°C)	*G* number
Specimen P1	690	90	110
Specimen P2	720	90	110
Specimen P3	750	90	110
Specimen P4	780	90	110
Specimen P5	810	90	110
Specimen M1	720	40	110
Specimen M2(P2)	720	90	110
Specimen M3	720	145	110
Specimen M4	720	205	110
Specimen M5	720	255	110
Specimen R1	720	90	40
Specimen R2	720	90	60
Specimen R3	720	90	90
Specimen R4	720	90	130
Specimen R5	720	90	180

2.3. Sample preparation and tests

2.3.1. Test of hardness

Hardness test samples were cut from the middle part of tubes by Electron Discharge Machining (EDM). All the test samples were solution treated at 510 °C for 8 h. Hardness was measured using a model HR–150A Rockwell hardness tester at seven zones at increasing radial distance on the reinforcement layer of the rings (see Fig. 2). The hardness of the un-reinforcement layer (matrix region) of the rings was also examined.

2.3.2. Test of wear resistance

Samples for wear test were cut by EDM from the middle part of the rings. The size of the samples was 19.05 mm in length, 12.32 mm in width and 8.32 mm in thickness (see Fig. 2). The sampling location was 3 mm distance from the inner wall of the ring to ensure that there was no inclusion in samples. Samples were solution treated at 510 °C for 8 h and aged at 180 °C for 12 h.

The wear tests were performed on the surface of the reinforcement layer of the samples with a diamond grinding head that was 8 mm in diameter, different loads of 100–400 N, a rotation speed of 280 rpm, and a period of 10 min. Tests were carried out under the conditions of as-cast, solution treated and aged conditions of samples, respectively.

2.3.3. Test of thermal expansion property

The samples used for thermal expansion test were cut by EDM in the reinforcement layer at the location which was 3 mm distance from the inner wall (see Fig. 2). The size of the sample was 4 mm in diameter and 20 mm in length. A model NETZSCH–DIL402C thermal expansion testing machine was used to measure the coefficient of thermal expansion (CTE) of the samples. The temperature ascending rate and the maximum temperature were 1 °C/min and 350 °C, respectively.

2.4. Evaluation of particles

2.4.1. Evaluation of the particle segregation ratio, k

To describe the ratio of the particle segregation area in terms of the whole cross section of the tubes, the following formula was adopted:

$$k = a/L \tag{1}$$

where a is the width of the reinforcement layer, and L is the thickness of the whole cross section from the inner wall to the outer wall along the radial direction, as shown in Fig. 2. The ratio k represents the proportion of the width of the reinforcement layer to the thickness of the whole cross section of the specimens. The wider the reinforcement layer is, the greater the value of k is.

2.4.2. Evaluation of particle size

The sizes of primary Si/Mg_2Si particles located in different zones from the inner wall to the interface were measured. The particle diameter d_p of a particle was calculated from its area, S_p, using the following equation: