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Effect of ball milling on microstructural evolution during partial remelting of 6061 aluminum alloy prepared by cold-pressing of alloy powders

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Abstract: The effect of ball milling on the microstructural evolution was investigated during partial remelting of 6061 aluminum alloy prepared by cold-pressing of atomized alloy powders. The results indicate that the microstructural evolution of 6061 aluminum alloy can be divided into three stages, the dissolution of eutectic phases and the coarsening and growth behavior of the resulting grains, structural separation and spheroidization of primary particles, and the final coarsening behavior of the particles. Compared with the alloy without ball milling, ball milling accelerates the first stage of microstructural evolution due to the energy stored in the powders, but the latter two stages are slowed down because of the formation of large-sized powders. Moreover, the finer the as-cold-pressed microstructure is, the smaller and more spherical the primary particles in the final semisolid microstructure are. Furthermore, properly elevating the heating temperature is beneficial for obtaining small and spheroidal particles.
Key words: 6061 aluminum alloy; ball milling; powder thixoforming; partial remelting; microstructural evolution

1 Introduction

Particle-reinforced aluminum matrix composites (AMCs) have been widely used in aerospace and automotive fields because of their attractive properties such as low cost, low density, high stiffness and high strength [1−4]. Many methods have been developed to fabricate AMCs, such as squeeze-cast [5], stir casting [6], friction stir welding [7] and powder metallurgy (PM) [8]. It is known that PM process is popularly used because of the uniform distribution of reinforcements and the flexible design of constituents [1]. But the resultant composites generally have many voids besides high cost [8]. In addition, it is difficult to obtain large-sized components with complex shape [9]. However, thixoforming is not only a relatively simple process, but also can significantly decrease or eliminate voids. In addition, this technology is also suitable to fabricate large-sized parts with complex shape [10,11]. For PM technology, atomization technology has been widely used for preparing small and spheroidal alloy powders. The bulk alloy prepared by pressing of the atomized powders can be used as the feedstock of thixoforming [11]. Therefore, a novel technology named powder thixoforming which combines the advantages of powder metallurgy and thixoforming has been proposed. The blending and pressing steps of PM are applied to preparing the ingots with uniform distribution of reinforcing particles in the matrix, then the ingots are partially remelted and thixoformed. It can be expected that composite components with uniform distribution of reinforcing particles and low or without voids can be obtained by using this technology. Simultaneously, the process is simpler and thus the cost is lower compared with the PM technology.

Similar to the traditional thixoforming, the microstructural evolution during partial remelting of the feedstock is also a crucial topic for the powder thixoforming because this process has great influence on the resultant semisolid microstructure. And the resultant semisolid microstructure plays a decisive role in the mechanical properties of a component. In order to further study the microstructural evolution of composite during

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partial remelting, the microstructural evolution of the matrix alloy should be first clarified. The heat-treatable 6061 alloy has taken as the most commonly used matrix alloy of the AMCs [12,13]. And the author's previous investigation indicated that the 6061 alloy prepared by cold-pressing of the atomized alloy powders can be taken as the start ingots of thixoforming [13,14]. Furthermore, for preparing AMCs, high energy ball milling must be used to disperse the reinforcement particles to uniformly distribute in the matrix alloy powders [14−16]. Thus, a problem is then arising, how does the ball milling affect the semisolid microstructure? Unfortunately, most of the existing investigations focus on the effects of reinforcement size, morphology, distribution and volume fraction [17−19], and there is no investigation to involve this problem.

Therefore, in order to further study the microstructural evolution of the AMCs, the effect of ball milling on the microstructural evolution during partial remelting of 6061 aluminum alloy prepared by cold-pressing of alloy powder was studied in this work.

2 Experimental

The used 6061 aluminum alloy powder was produced by atomization and the average powder particle size was 18.376 μm. The nominal chemical composition (mass fraction) of 6061 alloy is as follows: 0.8%−1.2% Mg, 0.4%−0.8% Si, 0.7% Fe, 0.15%−0.40% Cu, 0.04%−0.35% Cr, 0.15% Mn, 0.25% Zn, 0.15% Ti and balance Al. The solidus and liquidus temperatures of this alloy were 610.2 and 674.6 °C, respectively, measured by a pyris diamond TG/DTA differential thermal analyzer (DTA). The powders were ball-milled using a planetary ball milling machine. The employed mass ratio of ball to powder, milling speed and milling time were 5:1, 100 r/min and 40 min, respectively. The diameter of balls was 9.5 mm. The ball milling parameters are the same as those which achieved homogenous distribution of SiC particles in the matrix powders. After being ball-milled, the average powder particle size was 16.282 μm, which was a little smaller than that of the un-milled powder.

The milled powders were cold-pressed into some specimens with dimensions of *d*22 mm × 5 mm using a pressure of 145 MPa on a jack. Some of them were heated at a semisolid temperature of 660 °C for different durations, ranging from 0 to 60 min, to study the microstructural evolution during partial remelting. The other specimens were heated for 20 min at various semisolid temperatures, 650, 655, and 665 °C, to investigate the effect of reheating temperature on semisolid microstructure.

All of the heated specimens were quickly quenched in a Bi-based low melting point alloy at about 50 °C. One cross-section of each specimen was ground and polished, followed by etching using NaOH aqueous solution. Subsequently, the metallographic microstructure was observed on an optical microscope (OM) and a scanning electron microscope (SEM). The compositions of the primary α(Al) phase of the specimens were examined by energy disperse spectroscopy (EDS). For comparison, the compositions of the specimens without milling were also examined.

3 Results and discussion

3.1 As-cold-pressed microstructure

In order to further study the microstructural evolution during partial remelting, it is necessary to first clarify the as-cold-pressed microstructure. It can be seen that after being cold pressed, both the ball-milled powders and un-milled ones are mechanically consolidated (Fig. 1). Furthermore, as shown by Fig. 1(a), the microstructure of the milled alloy can be divided into two regions: the first is the region of small-sized powers, and the second is the region of large powders surrounded by the long flat-shaped powders. But the microstructure of the un-milled one is regarded as large powders surrounded by small and nearly globular powders.

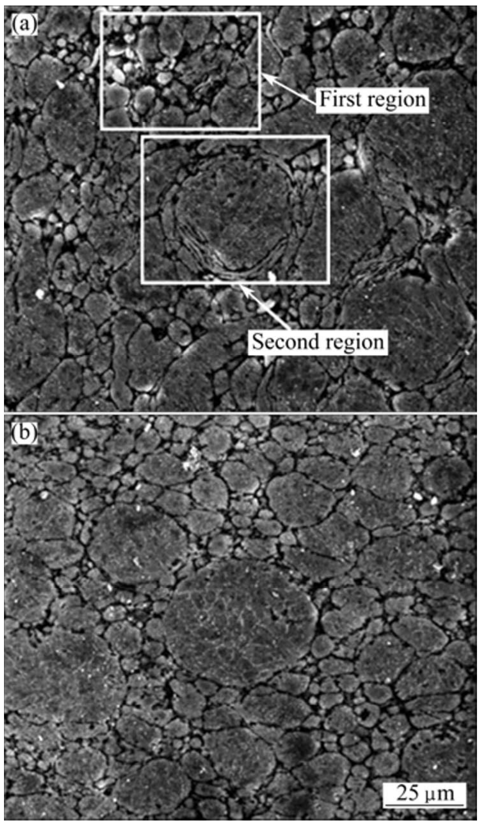

Fig. 1 SEM micrographs of 6061 alloy prepared by cold-pressing of ball-milled powders (a) and un-milled powders (b)

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