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Improvement of grain refining efficiency for Mg–Al alloy modified by the combination of carbon and calcium

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ABSTRACT

The effects of carbon and/or Ca on the grain refinement of the Mg–3Al alloy have been investigated in the present study. The grain size of the Mg–3Al alloy decreased steeply with increasing the Ca content when it was lower than 0.2%. And then, the grain size decreased slightly when the Ca content was increased to 0.5%. A remarkable grain refining efficiency could be obtained for the Mg–3Al alloy treated with only carbon. Further high grain refining efficiency could be obtained by the combination of 0.2%C and the optimal content (0.2%) of Ca. Therefore, Ca is an effective element to improve the grain refining efficiency for the Mg–Al alloys refined by carbon. The Al—C—O particles were observed in the samples refined whether by only 0.2%C or by the combination of 0.2%C and a little (less than 0.2%) Ca addition. These Al—C—O particles should be the potent nuclei for the Mg grains. However, the Al—C—O—Ca intermetallic particles were observed when Ca content was increased to 0.5%. Peculiar particles with duplex phases were found in this sample in such a state that Al—C—O coating film was formed on the surface of Al–Ca compounds. These particles should also be the potent nuclei for the Mg grains.

1. Introduction

Recently, the demand for magnesium alloys has been increased rapidly owing to adopting more and more light materials by the automobile industry, in order to reduce fuel consumption and lower waster gas emission [1]. Among the broad range of magnesium alloys, aluminum bearing magnesium alloys (Mg–Al alloys) take a dominating position of consumption. The wider applications could be envisaged for Mg alloys, if their low absolute strength and poor formability were improved. To improve the mechanical properties, it is well known that grain refinement is one of the very effective routes for the cast metal products.

There are many researches on grain refinement for the Mg–Al alloys since 1930s [2,3]. The main grain refining methods for this group alloys are superheating [4,5], $FeCl_3$ inoculation [6], carbon inoculation [7–15] and addition of solute elements [16–21]. Among them, the carbon inoculation has the advantages in the low cost, the low operating temperature and the less fading. For the carbon inoculation, the most possible refining mechanism proposed by Emley in his book [3] is that Al_4C_3 particles formed in the Mg–Al melt act as nuclei for the Mg grains during solidification. This hypothesis has been widely appreciated by other researchers [7–12]. In the studies performed by Tamura et al. [7,8], it was found that Al—C—O particles acted as nuclei for the Mg grains in Mg–Al alloys, in which O was suggested to be from contamination during sample preparation. Moreover, Haitani et al. [14] concluded that Fe and Mn were inhibiting elements for grain refinement, since they poisoned the potency of the Al—C—O nucleants by transforming Al—C—O into Al—C—O—Fe(Mn). However, Pan et al. [15] insisted that Fe played an important role in the formation of the nucleating particle rather than an inhibiting element. In our previous study, further grain refining efficiency could be obtained for the Mg–3Al alloy modified by the combination of carbon and Fe [22]. It is very difficult to understand clearly why contradictory conclusions were made for the same phenomenon. From the above researches, it is known that the alloying elements play an important role in the grain refinement for the Mg–Al melt refined by the carbon inoculation.

As for the Mg–Al alloys, the addition of solute elements (*e.g.* Ca, Sr, RE) is another important grain refining method. For example, small amount of addition of Ca was found to be very effective in refining the microstructures of Mg–Al alloys [16,17]. However, the brittleness would increase if Ca content is higher than 0.2%

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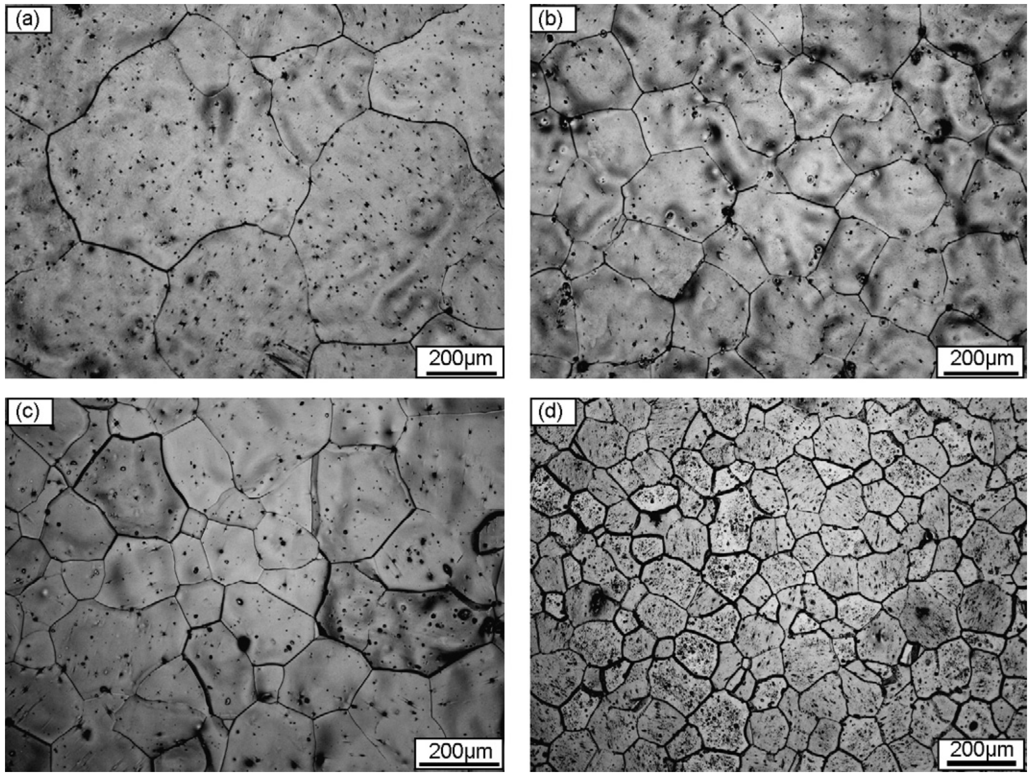

Fig. 1. Grain morphologies of the Mg–3Al alloy (a) without any treatment, (b) with treatment by 0.2%C, (c) with treatment by 0.2%Ca, (d) with the combined treatment by 0.2%C and 0.2%Ca.

[17,21]. In fact, the main purpose of the addition of Ca in the Mg–Al alloys is to improve their creep resistance due to the formation of thermally stable Al_2Ca phase, which can effectively inhibit grain boundary sliding at a high temperature [18,19]. The significant grain refinement potential of Ca is associated with higher constitutional undercooling at the advancing solid/liquid (S/L) interface during solidification due to the strong segregating power of Ca in the magnesium melt [2,16]. This refining mechanism is completely different from that of the carbon inoculation.

According to the classical solidification theory, the grain size of a casting can be refined by increasing the number of potent nuclei in the melt and constitutional undercooling at the advancing S/L interface during solidification [16]. Therefore, it is promising that a higher grain refining efficiency could be obtained for the Mg–Al alloys if they were modified by the combination of carbon and Ca due to the synergistic action of more potent nuclei and higher constitutional undercooling. Unfortunately, few studies on the grain refinement of Mg–Al alloys by the combination of carbon and Ca have been conducted.

In the present study, the relatively high purity raw materials were used and the following research works have been carried out to clarify (1) whether Ca is an effective element to improve the grain refining efficiency for the Mg–Al alloys refined by carbon; (2) how grain size changes after addition of Ca in the Mg–Al alloys melt which have been refined by carbon; The ultimate purpose is to take advantage of the grain refining power of both carbon and Ca, and to provide an important data to develop a suitable grain refiner, *i.e.* reliable and easy to be applied for the Mg–Al alloys.

2. Experimental procedure

The raw materials used in the present study included relatively high purity magnesium (99.95%Mg, 0.002%Fe, 0.002%Mn), high purity aluminium (99.99%Al), Al–15%Ca master alloy, carbon powder (45 μm in average diameter and purity of higher than 99%), magnesium powder (200–400 μm in size and purity of higher than 99%) and aluminum powder (70–150 μm in size and purity of higher than 99.5%).

To ensure the carbon powder can be dispersed into the melt slowly and uniformly, the cylindrical pellets containing carbon powder were prepared in advance, having about 3 mm in diameter and about 5–10 mm in height. The mixtures comprising carbon powder, magnesium powder and aluminum powder were blended at a mass ratio of 1:5:4 firstly, then the pellets were formed by using a cold isostatic press (CIP) under a pressure of 150 MPa for 1 h.

The alloy used in the present study was the system of Mg–3Al, which is the basic composition widely used in industries as wrought magnesium alloy. The Mg–Al melt was alloyed with Ca in the form of Al–15%Ca master alloy. The addition of carbon is 0.2% of the melt. To exactly control the Al content in the Mg–3Al melt, the amounts of Al in the pellets and Al–15%Ca master alloy were carefully taken into consideration.

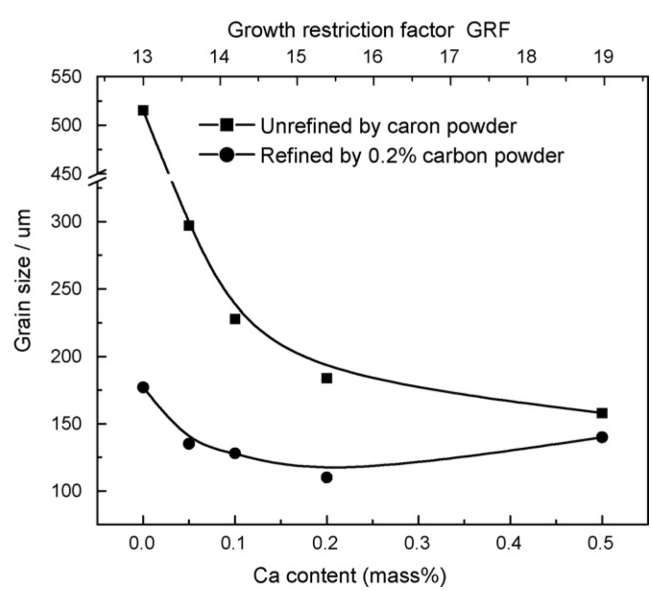

Fig. 2. Effects of Ca content and GRF value on the grain size of the Mg–3Al alloy unrefined and refined by 0.2%C.