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Influence of a new kind of Al–Ti–C master alloy on the microstructure and mechanical properties of Al–5Cu alloy

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ABSTRACT

The microstructure and mechanical properties of Al–5Cu alloy refined by a new kind of Al–5Ti–0.75C master alloy were investigated. The results show that the master alloy has an excellent grain refining performance on Al–5Cu alloy, and the average grain size of α-Al is reduced from about 1000 μm to 50 μm when 0.2 wt.% of the master alloy was added. It also indicates that the addition of Al–5Ti–0.75C considerably increases the quantity of θ' precipitates and decreases their sizes during heat treatment process. In addition, the tensile property, hardness and wear resistance of the Al–5Cu alloy are improved markedly after grain refinement. The improved mechanical properties are attributed to a fine equiaxed grain structure of the alloy, a dispersed distribution of second phases and a large number of fine θ' precipitates.

1. Introduction

Al–Cu, one of the most important Al-based alloys, is becoming increasingly important as lightweight metal structural materials because of excellent castability and good mechanical properties [1–3]. It has been used in many industries, such as aircraft construction, military field and automobile manufacturing [4,5]. However, Al–Cu alloys are very prone to hot tearing, thus, decreasing mechanical properties of the alloys and limiting their applications [6]. It has been reported that grain refinement is an effective way to avoid hot tears in Al–Cu alloys [7]. Moreover, grain refinement can also bring other benefits, such as high yield strength, high toughness and good workability of products [8–10].

There are many methods to refine grains, whereas the addition of master alloys is the most economical one [11]. Al–Ti–C master alloys, containing TiC particles, have been proven to be effective grain refiners for aluminum alloys [12]. Most recently, some investigations have made an attempt to study the influence of Al–Ti–C on the microstructure of Al–Cu alloys. Sato and Flemings [13] observed that Al–24Ti–6C master alloy shows an excellent grain refining performance on Al–4.5Cu alloy and the TiC particles are very stable in the aluminum melt. Yu et al. [14] studied the Al–5Cu alloy refined by Al–5Ti–0.4C master alloy and found that Ti(Al, Cu)$_2$ can be formed due to the reaction between $TiAl_3$ and Al_2Cu, resulting in the refinement fading. However, many researches concentrate on studying the microstructure of Al–Cu alloys after grain refinement. The reports about mechanical properties of the Al–Cu alloys with addition of grain refiners are rare to find.

The present paper aims to study the effect of Al–Ti–C master alloy on the microstructure and mechanical properties of Al–5Cu alloy. In this paper, a new Al–5Ti–0.75C master alloy with uniform microstructure was successfully prepared. The microstructure, hardness, wear resistance and tensile properties of Al–5Cu alloy refined by the master alloy were also studied.

2. Experimental procedures

The Al–5Ti–0.75C master alloy was prepared by pure Ti (99.8%, all compositions quoted in this work are in wt.% unless otherwise stated), commercial pure Al (99.7%) and Al–5C alloy using a melt reaction method in a medium frequency furnace. The conventional Al–5Ti–1B and Al–5Ti–0.3C master alloys (Provided by Shandong Al&Mg Melt Technology Co. Ltd.) were used in this experiment for comparison.

At first, Al–5Cu alloy was melted in an electrical resistance furnace at about 720 °C. Then 0.2% of Al–5Ti–0.75C, Al–5Ti–0.3C and Al–5Ti–1B master alloys were added into the melt respectively, to achieve a level of 0.01 wt.% Ti in the alloy melt. Degassing was conducted by submerging dry C_2Cl_6 tablets (0.3% of the melt). After stirring the melt with a graphite rod and cleaning off the dross, the melt was poured into an iron mold (pre-heated to 200 °C). The macrostructure photos were taken from each sample by a high scope video microscope (HSVM, KH-2200). The average grain sizes were calculated using the linear intercept method, and each value is an average of 30 measurements. To further test the mechanical properties, the samples were solution-treated at 515 °C for 15 h, quenched in hot water, and then aged naturally.

The hardness of specimens was measured in a Rockwell hardness tester with a load of 60 kg. Each value was an average of at least ten separate measurements taken at random places on the surface of specimens. The tensile test was carried out on 'dog-bone' type specimens (as shown in Fig. 1) using a universal material test machine at ambient temperature. The tensile test specimens were made according

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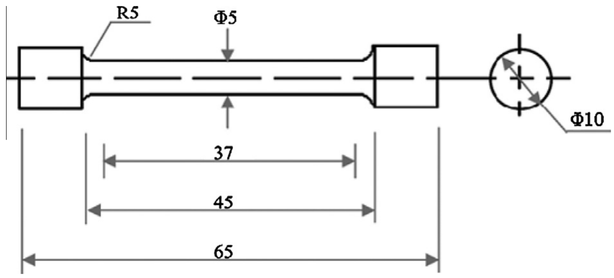

Fig. 1. Schematic drawing of tensile test specimen.

to the GB/T228-2002 standard [15]. In each case, four specimens were tested and the averages of results have been reported. The wear test was conducted by a MM-200 model ring-on-block test ring. The wear specimens with 10 mm × 10 mm in cross-section and 50 mm in length were cut from the samples. The schematic diagram of wear testing is show in Fig. 2. The test was performed at a sliding speed of 200 r/min with a load of 100 N. Wear tests were interrupted at certain intervals (10, 20, 30 and 40 min) to weigh mass loss of the specimens.

The specimens were cut from the center of each sample, then mechanically ground and polished. For optical investigation, specimens of Al–5Cu alloy were etched with Keller's reagent. The microstructures were analyzed by X-ray diffraction (XRD), high scope video microscope (HSVM), field emission scanning electron microscope (FESEM) equipped with an energy-dispersive spectroscopy detector (EDS) and transmission electron microscope (TEM).

3. Results and discussion

3.1. Microstructure and microanalysis of the Al–5Ti–0.75C master alloy

The Al–5Ti–0.75C master alloy mainly contains three kinds of phases: α-Al, $TiAl_3$ and TiC, as shown in the XRD result (Fig. 3). The microstructure of the master alloy shows that the second phase particles are dispersed in the Al matrix homogeneously (Fig. 4a). EDS microanalysis suggests that the fine particles are TiC, while the plate-like particles are $TiAl_3$. As shown in the magnified microstructure (Fig. 4b), the TiC particles with size of 0.2–1.0 μm are disconnected from each other. It has been reported that the more the particles are dispersed in the matrix, the better their grain refining effect [16–18]. From this point of view, it can be considered that the Al–5Ti–0.75C master alloy may possess an excellent grain refining ability.

3.2. Influence of the Al–5Ti–0.75C on the microstructure of Al–5Cu alloy

The effect of three different master alloys on the grain size of as-cast Al–5Cu alloy is shown in Fig. 5. It can be seen that the structure of unrefined Al–5Cu alloy consists of columnar dendrites with an average grain size of approximate 1000 μm (Fig. 5a). These coarse grains are obviously refined to small equiaxed ones by adding the master alloys. However, compared to the

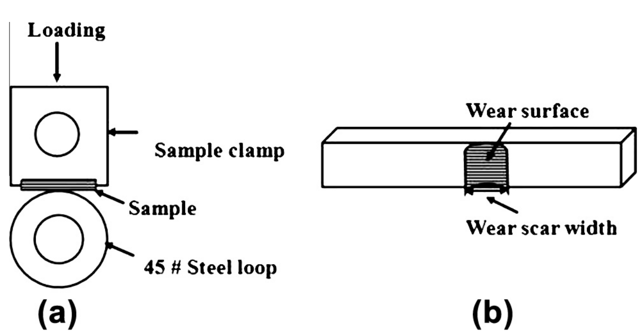

Fig. 2. Schematic diagram of wear testing: (a) schematic of ring-on-block configuration; (b) wearing specimen.

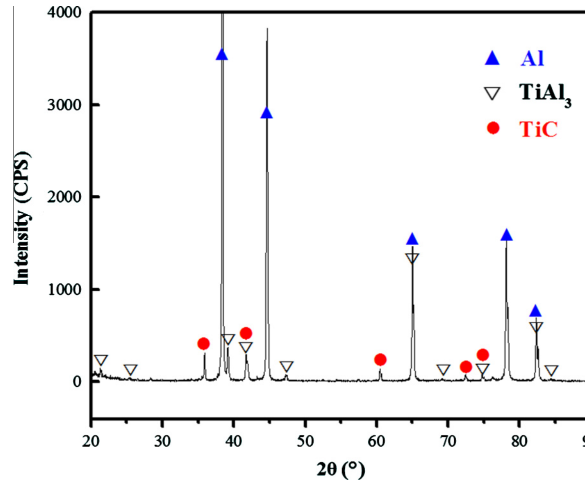

Fig. 3. XRD result of the Al–5Ti–0.75C master alloy.

grains refined by the conventional Al–5Ti–0.3C and Al–5Ti–1B, those refined by the Al–5Ti–0.75C master alloy are much finer. As shown in Fig. 5, after addition of 0.2 wt.% of the three kinds of master alloys, the average grain sizes of the Al–5Cu alloys are refined to about 113, 108 and 50 μm, respectively. Furthermore, the microstructure of Al–5Cu alloy shows a more pronounced equiaxed grain structure after the addition of Al–5Ti–0.75C. From these results, it can be concluded that the Al–5Ti–0.75C master alloy has a much better grain refining effect than that of Al–5Ti–0.3C and Al–5Ti–1B on Al–5Cu alloy. Based on the published literature [19,20], the high grain refining efficiency is mainly because of uniform distribution of TiC nucleating particles in the Al–5Ti–0.75C master alloy.

As mentioned above, the grain size of Al–Cu alloy refined by master alloys has been studied by many researchers. On the other hand, it is well known that the strength of Al–Cu alloy can be improved through the formation of θ' precipitate during heat treatment. Thus, our interest is to further study the influence of Al–5Ti–0.75C on the precipitation behavior of the θ' precipitate. For this purpose, the microstructures of heat treated Al–5Cu alloys (i.e. unrefined or refined by Al–5Ti–0.75C) were observed by a transmission electron microscope. Fig. 6 shows the TEM micrographs of the unrefined and refined alloys. It is clear that there are only a few plate-like θ' precipitates with the average length of 50 nm in the unrefined alloy (Fig. 6a), while, there are a large number of needle-like θ' precipitates with the average length of 30 nm in the refined alloy (Fig. 6b). Besides, the distribution of the needle-like θ' precipitate in the refined alloy is regular and homogeneous. These results indicate that the addition of Al–5Ti–0.75C can facilitate the formation of the θ' precipitates and decrease their size.

Many researches [21,22] pointed out that excess vacancies play an important role in the formation of θ' precipitate, and the vacancy clusters in Al–Cu alloy are considered to be the nucleation sites for the θ' precipitate and accelerate the formation of fine θ' precipitate. It means that the density of vacancy determines the number of θ' precipitate to a certain extent.

Wierszyłłowski et al. [23] considered that grain size can influence the precipitation kinetics and grain boundaries are preferential places for precipitate nucleation. Miki et al. [24] suggested that vacancies existing in the matrix at the solution-treatment temperature migrate to grain boundaries during quenching. Therefore, it is indicated that the vacancy concentration improves greatly with the increment of grain boundary. As shown in Fig. 5d, the volume fraction of grain boundaries of Al–5Cu alloy increases markedly when refined by Al–5Ti–0.75C master alloy, indicating that the