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Effects of grain refinement and boron treatment on electrical conductivity and mechanical properties of AA1070 aluminum

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ABSTRACT

Aluminum has been used as an alternative to copper for the production of electrical grade conductors. However, good electrical conductivity with excellent mechanical properties is hard to realize. Grain refinement can improve plastic deformation and mechanical properties. Boron treatment is advantageous to the improvement of electrical conductivity. So it is promising to achieve good mechanical properties and electrical conductivity by the interaction of grain refinement and boron treatment. In our work, the effect of grain refinement and boron treatment on electrical conductivity and mechanical properties of AA1070 aluminum was studied. The ideal grain refiner is Al–5Ti–0.8B–0.2C master alloy and with 0.2% addition, the electrical conductivity keeps at 60.7% IACS. Besides, the effect of different boron additions on electrical conductivity of AA1070 aluminum was studied. With 1%Al–6B addition, its electrical conductivity can reach 64% IACS, improved by 5.3%. With 0.2%Al–6B and 0.5%Al–5Ti–0.8B–0.2C additions, the electrical conductivity can reach 63.2% IACS, ultimate tensile strength at room temperature ($UTS_{25\ °C}$) is 85 MPa, and elongation (ε) is 58%. Compared with AA1070 aluminum without addition, the ultimate tensile strength and elongation have been improved by 26.9% and 9.4% separately.

1. Introduction

Aluminum has been used as an alternative to copper for the production of electrical grade conductors. Owing to its excellent electrical conductivity, commercial pure aluminum is one of the most important industrial conductive materials. As we all know, the conductivity of aluminum is affected by its purity obviously. As reported, the reject ratio can reach more than 70% because the conductivity is unqualified causing by the unqualified composition [1–3]. The factors, such as chemical composition, crystalline states, and processing craft, influencing the electrical conductivity is complex. Chemical composition is a basic influencing factor and the amount of transition metal (TM) elements can influence the conductivity significantly [2–4]. 1000 series alloys have a narrow specification range of dissolved impurities especially transition metals (TM) (V, Ti, Zr and Cr <0.03 wt.%). The influencing mechanisms of TM elements on electrical conductivity can come down to two reasons: one reason is that the TM elements prefer to dissolve into Al matrix causing lattice distortion. The lattice distortion can hinder the electronic transmission which can damage electrical conductivity. Grandfield et al. reported the impact of dissolved impurities, especially V and Ni, on downstream products and highlighted potential improvement strategies [5]. The other reason is that the TM elements, such as Ti, V, Cr, Zr are active in Al melts and they easily react with Al forming TM–Al compounds reducing the number of free electrons in the process of electronic transmission. Thus it is important and necessary to control the content of TM elements. For cond aluminum, boron treatment is a necessary process to improve the electrical conductivity. Now, boron treatment is widely used to remove the TM impurities from the Al melts [6–12]. The addition of boron can react with TM elements forming borides and then the compounds easily sink down at the bottom of the Al melts. The detailed mechanism of borides formation has been reported [2,8]. The effects of V and Ti on electrical resistivity are summarized in Table 1. It is worth noting that the effect of V and Ti on electrical resistivity (which is reciprocal to conductivity) of aluminum is about 12 times and 24 times higher when it is in solution form compared with the form of a solid second phase, such as borides [9]. The addition of boron makes the TM impurities from solid solution state into precipitation state, thus it can maximum limit the damage to electrical conductivity.

Aluminum alloy wire, aluminum alloy cable conductor, and aluminum alloy rail must be performed proper extrusion deformation before they can be applied. As we all know, small grain size is helpful to deformation. So grain-refinement treatment is important and necessary for aluminum alloy conductor. Grain refinement by inoculation is considered to be an essential technique to notably improve the mechanical properties of aluminum alloys [13–19]. It is an effective way to achieve a fine equiaxed grain structure and improve the comprehensive mechanical properties of aluminum products [18,20]. In industrial applications, Al–5Ti–1B master alloy is widely used in the grain-refinement treatment of aluminum alloy conductor. However, Al–5Ti–1B master alloy refines the alloys with sacrificing the electrical conductivity. So

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Table 1
Transition metals solubility and their effects on the electrical resistivity of aluminum [8].

Element	Max. solubility in Al (Wt.%)	Avg. increase in resistivity (or decrease in conductivity) (μΩ cm per wt.%)	
		In solution	Out of solution
Vanadium	0.50	3.58	0.28
Titanium	1.00	2.88	0.12

Al–5Ti–1B master alloy is not the ideal grain refiner for aluminum alloy conductor. There is no technological guidance about the grain refiners during the production of conductive aluminum alloys. So it is necessary to look for an ideal grain refiner for aluminum alloy conductor which not only refines α-Al but also keeps good electrical conductivity to some extent. It is promising that grain refinement combined with boron treatment can achieve good electrical conductivity with excellent mechanical properties. Up to now, the work about grain-refinement treatment of aluminum alloy conductor lacks systematic study, let alone the studies about the interaction between boron treatment and grain-refinement treatment. Moreover in foundry practice is present method of grain refinement of aluminum by use of electromagnetic stirring as reported Wróbel et al. in paper [21]. This method does not adversely affect on the electrical conductivity of aluminum but is used practically only in continuous casting process and is more difficult to apply in traditional casting process with use of permanent mold than inoculation by introducing to metal bath a master alloy.

In our study, five master alloys were selected to refine AA1070 aluminum (99.7%, all compositions quoted in this work are in wt.% unless otherwise stated) and the ideal grain refiner for the aluminum alloy conductor was chosen. Then, the influence of different boron additions on electrical conductivity was also studied. At last, the interaction between boron treatment and grain-refinement treatment to electrical conductivity and mechanical properties was studied. The optimum pre-treatment conditions for AA1070 aluminum were established.

2. Experimental process

AA1070 aluminum which mainly contains 99.7% Al has been chosen for the research. Five master alloys, namely Al–5Ti–1B, Al–5Ti–3B, Al–5Ti–0.25C, Al–5Ti–0.3B–0.2C and Al–5Ti–0.8B–0.2C, were used to refine AA1070 aluminum. The five master alloys are provided by Shandong Al&Mg Melt Technology Co. Ltd.

For grain refinement experiment, firstly, the AA1070 aluminum was melted in a medium frequency furnace at 750 ± 10 °C and the slag-removing and degassing were carried out by adding 0.5% C_2Cl_6. Then the Al melts were moved to electric resistance furnace cooled to 720 °C. Secondly, five master alloys were added into the melts separately, keeping for 15 min and the addition was 0.2%. At last, the Al melts were poured into a pre-heated (200 °C) iron mold.

For boron treatment experiment, Al–6B master alloy was selected as the boron source. To find out an optimal level to the improvement of electrical conductivity of AA1070 aluminum, 0.2%, 0.5%, 1%, 2%, 4% and 8% additions were carried out. Firstly, the AA1070 aluminum was melted in a medium frequency furnace at 750 ± 10 °C and then Al–6B master alloy was added into Al melts. After that, the melts were cooled to 720 °C holding for 30 min before poured into a pre-heated (200 °C) standard iron mold for electrical conductivity test.

For the different adding orders of Al–5Ti–0.8B–0.2C and Al–6B master alloys experiment, in addition to the adding order is different, the main process is similar with the above experimental process. Considered to keep a good grain refinement performance, the addition of Al–5Ti–0.8B–0.2C master alloy in this part is 0.5%. For boron treatment, Al–6B additions are 0.1%, 0.2%, 0.5% and 1.0% separately. Considering good effect, the melts were cooled to 720 °C holding for 15 min before poured into a pre-heated (200 °C) standard iron mold for electrical conductivity test.

Specimens for metallographic micro-structure observations were cut from the AA1070 aluminums with different treatment. Metallographic samples were mechanically grounded and polished through standard routines. The micro-structures were observed by using field emission scanning electron microscope (FESEM, SU-70). The average grain sizes were determined using a linear intercept method. The electrical conductivity property test bars were machined to rod type specimens (10 mm in diameter and 150 mm in length), and examined by a RS.03-DX200H electrical resistivity meter according to the ASTM B193 standard. The tensile test bars were machined to 'dog-bone' type specimens and then tested by electronic all-purpose test machine (CMT4204) at room temperature. Each performance test data is an average of three specimens for accuracy.

3. Results and discussion

3.1. Influence of grain refinement on electrical conductivity of AA1070 aluminum

In order to find an ideal grain refiner for commercial purity Al conductor alloy, the grain refining effects of Al–5Ti–1B, Al–5Ti–3B, Al–5Ti–0.25C, Al–5Ti–0.8B–0.2C, Al–5Ti–0.3B–0.2C and Al–6B master alloys on AA1070 aluminums were studied. Fig. 1a shows the grain sizes of AA1070 aluminums by adding 0.2% master alloys and the detail grain sizes of AA1070 aluminums are listed in Table 2. At the same time, after grain refinement, the electrical conductivities of AA1070 aluminums were also tested, as shown in Fig. 1b. It is found that the addition of 0.2% Al–5Ti–0.25C, Al–5Ti–1B and Al–5Ti–0.3B–0.2C master alloys (2#, 3# and 5#) can induce very effective grain refinement of AA1070 aluminum. The average grain size of α-Al can be reduced to 250 μm, 253 μm, and 220 μm from about 5000 μm, separately. The three master alloys show excellent grain refinement efficiency. However, the corresponding electrical conductivities of the three AA1070 aluminums are

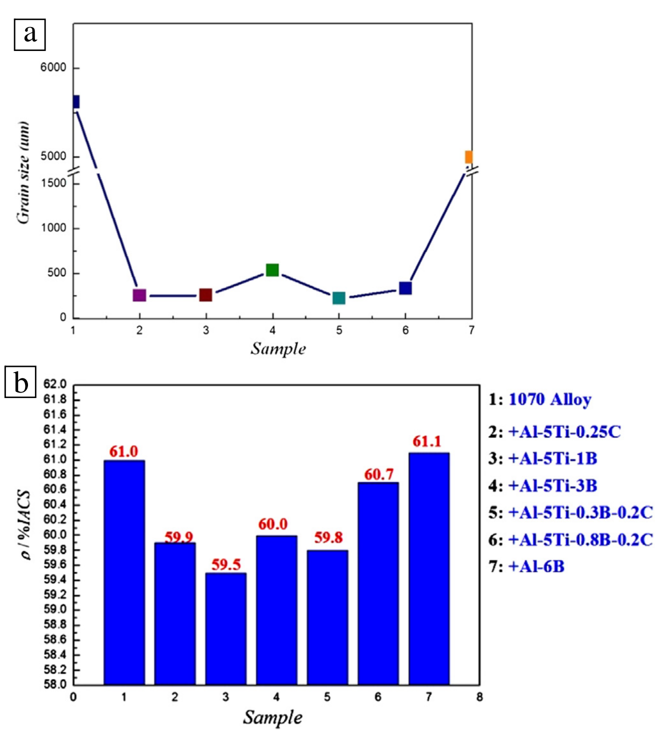

Fig. 1. (a) Grain size and (b) electrical conductivity of the AA1070 aluminums.