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Study on the improvement of electrical conductivity and mechanical properties of low alloying electrical aluminum alloys

Xiaoli Cui, Yuying Wu*, Guojun Zhang, Yibo Liu, Xiangfa Liu**

Key Laboratory of Liquid-Solid Structural Evolution and Processing of Materials, Ministry of Education, Shandong University, Shandong Jinan 250061, PR China

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ABSTRACT

In this paper, several low alloying conductive Al alloys Al-0.5Fe-0.2Si, Al-0.5Mg-0.35Si, Al-0.8Fe-0.2Cu were selected as the research objects. According to our study, the combination of boron treatment and grain refinement was proved to be an effective method to improve the electrical conductivity and mechanical properties of the alloys. Firstly, 0.12% was chosen as the optimal amount of boron addition and the electrical conductivity of Al-0.5Mg-0.35Si, Al-0.5Fe-0.2Si and Al-0.8Fe-0.2Cu can be improved to 55.0%IACS, 58.3%IACS and 59.8%IACS, improved by 3.8%, 10%, 6.4% respectively. Secondly, based on the former step, boron treatment combined with grain refinement, the electrical conductivities of Al-0.5Mg-0.35Si, Al-0.5Fe-0.2Si and Al-0.8Fe-0.2Cu can be further improved to 56.5%IACS, 60.4%IACS and 61.8% IACS. At the same time, the low alloying conductive Al alloys show excellent mechanical properties.

1. Introduction

Historically, copper was the unique metal transferring of electrical energy from source to consuming areas for human beings because of high conductivity and satisfaction on required mechanical properties. Copper is a kind of strategic metal and raw material source of copper in the world is limited. Therefore pricing and procuring in international markets is always under political crises and effect of speculation [1,2]. More recently, the homogeneous all-aluminum alloy conductors (AAAC) have become quite popular in the last 15–20 years [3–6]. Aluminum has been used as an alternative to copper for the production of electrical grade conductors. Aluminum is well accepted in electrical engineering field for transferring electrical energy from hydraulic, thermic, and nuclear power plants to main consuming areas [3]. Aluminum alloys employed in wire and cable industry require good conductivity, good heat resistance and corrosion resistance, as well as excellent mechanical properties. Generally, 1XXX series alloys are used as electrical grade conductors. However, with the development of electrical industry, 1XXX series alloys can not to meet the performance requirements of Al conductors. Thus owing to their good electrical conductivity and excellent properties, more and more low alloying Al alloys are used to make over head power transmission lines [4–6]. Among the low alloying Al alloys, low alloying Al-Mg-Si alloys (6xxx series) have been widely used as conductors for overhead power lines and conductor rail due to their good combination of enhanced strength and electrical conductivity compared to other Al alloys. Al-Fe-Cu and Al-Fe-Si alloys belonging to AA8xxx series electrical Al alloys, are new type of heat-resistant alloys. In general, AA8xxx series electrical Al, not only the tensile strength but the plastic is close to copper. What's more, its electrical conductivity is good. Owing to its excellent electrical performance and mechanical properties, this kind of alloy is widely used in wire and cable industry.

It is well known that mechanical strength and electrical conductivity are the most important properties for conducting metallic materials used in electrical engineering [4–7]. Generally, Al alloy wires enhance their strength at the expense of electrical conductivity, such as Al-Mg-Si, Al-Fe-Si, Al-Fe-Cu alloy wires. Electrical conductivity of these Al alloy wires is generally 50%–56% IACS, making a lot of electricity waste during the transport process. Electrical conductivity is very sensitive to the composition and microstructure of the metallic materials since it is determined by the scattering of electrons due to disturbances in the atomic crystal

* Corresponding author.
** Corresponding author.
E-mail addresses: wuyuying@sdu.edu.cn (Y. Wu), xfliu@sdu.edu.cn (X. Liu).

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structure including thermal vibrations, solutes, and crystal defects. As reported, transition metal (TM) elements in solution can reduce the electrical conductivity seriously, thus it is necessary to control the content of TM elements [9]. For AAAC, boron treatment is effective to improve its conductivity. Now, boron treatment is widely used to remove the TM impurities from Al melts [8–13]. The detailed mechanism of borides formation has been reported[14]. Khaliq A et al. studied the effect of boron treatment on electrical conductivity and studied the reaction process through the research of Al-V-B and Al-Zr-B systems [11–14]. During boron treatment process, TM elements prefer to react with boron forming doped TM borides, thus making TM elements from solid solution state to precipitation state. After holding for 30 min, most of the TM borides settle down at the bottom of Al melts. In addition, excellent mechanical properties, such as high hardness, good tensile strength and elongation, are good for their applications. Grain refinement by inoculation is considered to be an essential technique to notably improve the mechanical properties of low alloying Al alloys, such as ultimate tensile strength (UTS) and elongation. Grain refinement treatment is important and necessary for AAAC. It is an effective way to achieve a fine equiaxed grain structure and improve the comprehensive mechanical properties of Al products[15–18]. In industrial applications, there is rare technological guidance about the grain refiners during the production of conductive Al alloys. As the grain refiners include a wide range of items and there are many studies about the effect of grain refinement on Al conductors [19–25]. Generally, Al-5Ti-1B is used to refine the Al alloys but this master alloy is not suitable for all of the Al alloy conductors [20,21]. It is necessary to look for an ideal grain refiner for the low alloying Al alloys and combined with boron treatment to make the low alloying Al alloy conductors owning excellent properties. As known that, good electrical conductivity and excellent mechanical properties are hard to be improved at the same time and this limited the development of Al alloy conductors. Although many researches are about boron treatment and grain refinement, rare researches are about the interaction of boron treatment and grain refinement and their effect on electrical conductivity and mechanical properties was seldom studied. During our previous work, the interaction of boron treatment and grain refinement has been used to improve the electrical conductivity and mechanical properties of AA1070Al (the content of Al is no less than 99.7%) simultaneously and this pretreatment process has been proved to be an effective and promising method [22].

Considering the industrial application, not only electric pure Al needs to be improved but also other low alloying Al alloy conductors need to be improved. So considering the practical production requirements, three kinds of typical conductive Al alloys, namely Al-0.5Mg-0.35Si, Al-0.5Fe-0.2Si and Al-0.8Fe-0.2Cu, are selected as research objects in our study. The influence of different boron additions on the electrical conductivity was studied. Then, the ideal grain refiner for the Al alloy conductors was chosen. Based on the previous study, the interaction between boron treatment and grain-refinement treatment for the three typical Al alloys were studied in detail. At last, the electrical conductivity, ultimate tensile strength at room temperature ($UTS_{25\ ^\circ C}$) and elongation of the three alloys with the interaction of boron treatment and grain refinement have been tested. The optimum pretreatment conditions for the three kinds of alloys have been established.

2. Materials and methods

Al-0.5Mg-0.35Si, Al-0.5Fe-0.2Si and Al-0.8Fe-0.2Cu (all compositions quoted in this work are in wt.% unless otherwise stated) were chosen as the research objects based on the actual production. The commercial pure Al (99.7%), commercial pure crystalline silicon (99.9%), commercial pure crystalline iron (99.9%), commercial pure crystalline copper (99.9%) and commercial pure magnesium (99.9%) were used as raw materials to produce Al-0.5Mg-0.35Si, Al-0.5Fe-0.2Si and Al-0.8Fe-0.2Cu alloys. Pure Al was melted in an electric furnace at 750 °C and then according to the elemental composition of the three low alloying alloys, Mg\Si\Fe\Cu was added to the melts, respectively. After that, the melt was cooled to 720 °C and the slag-removing and degassing were carried out by adding 0.5% C_2Cl_6. The melt was kept at 720 °C for 10 min before poured into the pre-heated (200 °C) standard tensile testing mold and electrical conductivity testing mold.

For boron treatment, Al-3B master alloy was selected as boron source. To indicate the effect of boron on electrical conductivity of the three kinds of alloys, 0.03%, 0.06%, 0.09%, 0.12%, 0.24% boron additions were carried out in order to find out the optimal level to the improvement of electrical conductivity. When the alloy was melted in a medium frequency furnace at 750 ± 10 °C, Al-3B master alloy was added into the melts, stirring for 2 min. Then the Al melts was moved to electric resistance furnace cooled to 720 °C, holding for 30 min. Most of the TM impurity elements were settle down at the bottom and were removed in forms of borides sludge. For grain refinement experiment, firstly, the three kinds of alloys 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. Secondly, three grain refiners with 0.5% addition were added into the melts separately, keeping for 15 min and then poured into a pre-heated (200 °C) iron mold. For the interaction of boron treatment and grain refinement, firstly boron treatment and then grain refinement, the detail main process is similar with the above experimental process, as shown in Fig. 1. At last, the melts was poured into the pre-heated (200 °C) standard tensile testing mold and electrical conductivity testing mold. Considering good effect, test bars were then heat-treated in box-type heat treatment furnace in the following process. For Al-0.5Mg-0.35Si, solution treated at 530 °C for 1 h; water quenched; aging treated at 170 °C for 8 h, cooled in air. For Al-0.5Fe-0.2Si, at 630 °C for 6 h with homogenization treatment, then furnace cooling. Al-0.8Fe-0.2Cu was treated at 300 °C holding for 2 h and then furnace cooling.

Metallographic samples were mechanically grounded and polished through standard routines. The microstructure analysis was carried out by field emission scanning electron microscopy (FESEM). FESEM investigations were carried using a SU-70 scanning electron microscope operated at 15 keV and linked with an energy dispersive X-ray spectroscopy (EDS) attachment. The average grain sizes were determined using a linear intercept method. The electrical conductivity properties 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 unit of electrical conductivity is %IACS (International Annealed Copper Standard). The tensile properties test bars were machined to the ‘dog-bone’ type specimens (5 mm in diameter and 25 mm in length) and then tested on a CMT700 electronic all-purpose test machine according to the ASTM E21 standard. The hardness test bars were machined to the cube type specimens (30 mm in length, 20 mm in width and 20 mm in height) and then tested on a HBS-3000 digital brinell hardens tester according to the ASTM E10-14 standard. The electrical conductivity, $UTS_{25\ ^\circ C}$ and elongation data of each alloy reported below are an average value of five specimens.

3. Results and discussion

3.1. Boron treatment for the three alloys

From the previous study, we know that boron treatment can