Influence of Solution Treatment on Microstructure and Electrical Conductivity of Wrought Al-15Si Alloy

Fang Liu1,2*, Yongchao Jian1, Fuxiao Yu1,2* and Dazhi Zhao1,2

1 School of Materials Science and Engineering, Northeastern University, Shenyang 110819, People’s Republic of China
2 Key laboratory of Lightweight Structural materials, Northeastern University, Shenyang 110819, People’s Republic of China
Email: fxyu@mail.neu.edu.cn; liufang@smm.neu.edu.cn

Abstract. In the present work, the microstructures and electrical conductivity of Al-15Si alloy in casting, extruding and solution treatment conditions were investigated. The results indicate that the extruded Al-15Si alloy has higher electrical conductivity. It has been revealed that the morphology of Si, iron element and grain boundary impact on electrical conductivity of the Al-Si alloy. With the revolution of the microstructure, these factors which lead to the changing electrical conductivity of the alloy are discussed in detail.

1. Introduction
Hypereutectic Al-Si alloys have the advantages of low coefficient of thermal expansion, good wear resistance and corrosion resistance. Silicon could improve the casting properties of Aluminium alloy. However, silicon tends to formation of large eutectic Si plates and primary Si particles during solidification [1, 2]. Chemical modification [3, 4] and rapid solidification [5, 6] were employed to obtain refined morphology. The modifier like Phosphorous only limited effects on the refinement of the primary Si particles. Fe is a harmful impurity element due to forming of iron-rich intermetallic phases.

Most of the various alloying elements in aluminium alloys are dissolved in the aluminum lattice, or form precipitates to strengthen alloy and always lead to a marked reduction in conductivity [7, 8]. The electrical conductivity of alloys mainly depends on the content and existence of alloying elements [9]. Al-Si alloys with higher silicon contents worse electrical conductivity because large and platelet like silicon phases tends to form during the solidification. Adding elements such as Na and Sr modify the eutectic Si into fibrous eutectic mixture which increase alloys ductility and electrical conductivity [10].

Even though there are several studies on the electrical conductivity of Al-Mg-Si alloys and cast Al-Si alloys, no investigation is about wrought Al-Si alloys. In this paper, the semi-continuous casting combined with phosphorous modification treatment and hot extrusion was used to obtain wrought Al-Si alloy. The purpose of this study is to investigate the impact of solution treatment on the microstructure and electrical conductivity of wrought Al-Si alloys.

2. Experimental Details
Commercially pure Al, Si and Al-4.85 wt%P master alloy were used to manufacture Al-15Si alloy billet of 100 mm by direct chill casting. The pouring temperature was 830 °C and casting velocity
was 200 mm/min. The billet was pre-heat treatment at 450°C for 2 h, subsequently was extruded into plate with a thickness of 4 mm at the same temperature. The extrusion ratio was 11:1 and the extrudate speed was 7 mm/s.

As-cast specimens were made from the casting billets by cutting long the longitudinal direction. The extrusion plate was prepared from the extrusion direction to prepare solution treatment and electrical conductivity test specimens. The specimens were solution treated at 550 °C holding for 3, 5, 10, 15 h, respectively in a Muffle furnace and cooled at room temperature. The optical observation samples were prepared according to standard metallographic methods and examined using an optical microscope (Leica DMI 5000 M). In order to investigate the Si particle size quantitative analysis was performed using Image-Pro Plus image analysis software. The electrical conductivity of the alloys was measured with a Sigmascope SMP10 tester. The measurements were carried out on the unetched specimens for the optical observations. The electrical conductivity data for different conditions were the average of three test results.

3. Results and Discussion

Figures 1a and 1b show the microstructure of phosphorus modified Al-15Si cast alloy. It consists of primary Si particles, α-aluminum dendrite and Al-Si eutectics. The average size of the primary Si particles is 38 μm. It can be seen that the Al-Si eutectic microstructures contain refined and closely spaced fibrous silicon. The microstructure is deformed by hot extrusion and becomes uniformly distributed on the α-Al matrix, as shown in figures 1c and 1d. The size of primary silicon on average is 25 μm. The average diameter of the silicon particles is 2.83 μm.

Figure 1. Microstructures of the Al-15Si alloy: (a) (b) as-cast, (c) (d) as-extruded.

Figure 2 shows the microstructure of the extruded Al-15Si alloy after solution treatment for 3 h, 5 h, 10 h and 15 h, respectively. These figures indicate that the morphology and size of silicon particles have changed significantly. Most of the silicon particles are distributed at the equiaxed grain boundaries. With increasing the heat treatment time, the number of silicon particles per unit area
gradually decreases, and the grains also tend to grow gradually. It can be seen that the heat treatment reduces Si particles aspect ratio and make Si particles becoming gradually coarsened. No visible change in primary Si particle during heat treatment. The path-like second phase can be found at the grain boundary, and the number of these phases tend to increase as the heat treatment time increasing. The Si particles and primary Si sizes were obtained, as shown in figure 3. The average sizes of Si particles of the alloys heat-treated for 3 h, 5 h, 10 h, and 15 h were 4.25 μm, 4.40 μm, 4.72 μm, and 4.75 μm, respectively. The size of primary Si particles nearly remains unchanged, which is around 25 μm during heat treatment.

![Figure 2. Microstructures of wrought alloy after solution treatment at 550 ℃ holding different time. (a) 3 h, (b) 5 h, (c) 10 h, (d) 15 h.](image)

![Figure 3. The size of primary Si and Si particles in different conditions.](image)

After heat treatment, a few short rod-like precipitates appeared at the grain boundaries. The precipitated phase can also be observed from the microstructures at defined holding times, and the
size and number of the precipitated phases increase with increasing holding time. In order to determine the composition of this precipitated phase, EDS spectrum analysis was performed on the sample. In order to further determine the specific chemical composition of the iron-rich phase, Al-15Si alloy sample heat-treated for 10 h was analysed. Combined with EDS analysis in figure 4 and XRD patterns in figure 5, it indicates that the Fe containing precipitate is α-Al$_8$Fe$_2$Si and β-Al$_5$FeSi phase.

![Figure 4](image)

**Figure 4.** Microstructure and EDS analysis of the second phase in Al-15Si alloy after solution treatment.

![Figure 5](image)

**Figure 5.** XRD pattern of rich-Fe phase in Al-15Si alloys after solution treatment.

Figure 6 shows the electrical conductivity of Al-15Si alloy under different processing conditions. The sample had the lowest conductivity in the as-cast state, which is 18.27 MS/m. After hot extrusion, the conductivity increased to a maximum of 25.64 MS/m. As shown in figure 6, the conductivity decreases slightly with increasing the holding time. Many factors affect the electrical conductivity of aluminium conductors. The microstructure of as-cast alloys mainly contains α-Al dendrites, Al-Si eutectic and primary Si, is inhomogeneous structure. The lowest electrical conductivity of the as-cast sample is mainly due to inhomogeneous structure and the cast defects in the cast alloy. After hot extrusion, a large number of defects in the alloy disappeared, and the microstructure became more uniform, which lead to a dramatic increase of electrical conductivity. Compared with extruded state, solution treatment decreases the conductivity. As the holding time increasing, the conductivity of the alloy decreases slowly. After solution treatment, the iron-containing phases and grown Si particles hinder the movement of electrons or increase the probability of electron wave scattering, which reduce the electrical conductivity. Mamala et al. [11] have shown that iron has strongly effects on the conductivity of the α-Al solid solution. The influence of Si on the electrical conductivity of the alloy is related to the morphology of Si in the aluminum matrix. The grain boundaries play an important role in preventing electrons from moving in the same direction, making mean free path of electrons
smaller and reducing the mobility of electrons. Therefore, grain growth is a factor that reduces the resistivity of larger grains because larger grains decrease the grain boundaries per unit volume. However, research papers indicate that grain refinement down to ultrafine scale also without the sacrifice of their electrical conductivity [12, 13]. Grain boundary is not mainly factor to change the electrical conductivity.

![Figure 6. Electrical conductivity of Al-15Si alloy under different conditions.](image)

4. Conclusion
(1) The electrical conductivity of cast Al-15Si alloy is lower than extruded alloy, which is 18.27 MS/m because of inhomogeneous microstructure.

(2) After extruding, the electrical conductivity of the alloy increases. One reason is that the microstructures evolved from typical cast microstructures to refined with equiaxed grains and uniform Si particle. Another is that hot deformation eliminates casting defects.

(3) During solution treatment, the changing electrical conductivity is associated with the morphology of Si, Fe formed intermetallic compounds and grain boundary.

Acknowledgments
This work was funded by National Key R&D Program of China (2017YFB0306402) and the National Natural Science Foundation of China under the grant Nos. 50771030 and 51401047.

References
[1] Sano H 1994 Metal Powder Report 49 26-31
[2] Yamauchi I, Ohnaka I, Kawamoto S and Fukusako T 1986 Trans. Japan Inst. Met. 27 195-203
[3] Guiglionda G, Poole W J 2002 Mater. Sci. Eng. A 336159-169
[4] Mulazimoglu M H, Gruzeski J E 1993 Aluminium 691014-16
[5] Gremaud M, Allen D R, Rappaz M, Perepezko J H 1996 Acta Mater. 44 1669-81
[6] Steen H A H, Hellawell A 1972 Acta Metall. 20 363-68
[7] Lu L, Shen Y, Chen X, Qian L, Lu K 2004 Science 304 422-26
[8] Sun L X, Tao N R, Lu K 2015 Scr. Mater. 99 73-76
[9] Shercliff H R, Ashby M F 1990 Acta Metall. Mater. 38 1789-1802
[10] Dahle A K, Nogita K, McDonald S D, Dinnis C, Lu L 2005 Mater. Sci. Eng. A 413-414 243-48
[11] Mamala W, Sciężor 2014 Arch. Metall. Mater. 59 413-17
[12] Takata N, Lee S H, Tsuji N 2009 Mater. Lett. 63 1757-60
[13] Zhang Y, Li Y S, Tao N R, Lu K 2007 Appl. Phys. Lett. 91 211901