

Communication

Effects of Different Heat Treatment on Microstructure, Mechanical and Conductive Properties of Continuous Rheo-Extruded Al-0.9Si-0.6Mg (wt%) Alloy

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Abstract: Al-0.9Si-0.6Mg (wt%) alloy conductive wires were designed and produced by continuous rheo-extrusion process. The effects of different heat treatment on microstructure, mechanical and conductive properties of the wires were studied. Results show that, after T6 heat treatment, conductive property of the alloy increased while elongation decreased with the higher aging temperature and longer aging time. After T8 and T9 heat treatment, acicular strengthening phase β'' -Mg₂Si homogeneously precipitated, which effectively improved mechanical and conductive property of the alloy. The tensile strength, elongation and resistivity of T8 heat treated alloy reached 336 MPa, 13.7% and 29.3 nΩm respectively. After T9 heat treatment, the alloy's tensile strength, elongation and resistivity was 338 MPa, 6.0% and 30.2 nΩ·m respectively.

Keywords: Al-0.9Si-0.6Mg (wt%) alloy; continuous rheo-extrusion; heat treatment; microstructure; mechanical properties

1. Introduction

In the past few decades, the All-Aluminum Alloy Conductor (AAAC) was more widely used in electrical engineering area. Compared with traditional All Aluminum Conductor (AAC), AAAC can afford better sag characteristics due to its high strength/weight rate [1]. From corrosion property's point of view, AAAC also exhibits higher corrosion-resistance than AAC and another widely-used conductor material Aluminum Conductors Steel Reinforced Conductors (ACSR) [2]. With promising mechanical and conductive properties, Al-Si-Mg alloys have been applied for manufacturing AAAC for transferring electrical energy over long distances since last century. Furthermore, Al-Si-Mg alloys' mechanical and conductive properties could still be improved by optimum of processing and heat treatment.

As a low-cost semisolid metal processing technique, continuous rheo-extrusion process has gained increasing research interest in recent years [3–5]. Heat treatment after rheo-extrusion process has been proved effective method to adjust aluminum alloys' mechanical property under high temperature, and therefore could be used to improve Al-Si-Mg alloy's mechanical and conductive property [6]. Since heat treatment conditions have great influences on the material's microstructure, mechanical and conductive properties, the conditions of heat treatment should be carefully investigated [7,8]. In this paper, by using a self-designed test machine, an originally designed Al-0.9Si-0.6Mg(wt%) alloy wire was achieved by continuous rheo-extrusion process, and two different solution treatments as well as three different aging treatments (T6, T8 and T9) were performed and compared. After investing the treated alloy's mechanical and conductive properties, the effects of heat treatment were concluded and the optimized technical parameters of heat treatment were gained.

2. Experimental Section

2.1. Continuous Rheo-Extrusion

A self-designed D-350 CSEP machine was used in the experiment. The principle of the machine is shown in Figure 1. Melt alloy flowed out of the tundish and entered the roll–shoe cavity, and it solidified continuously under the cooling by the water-cooled work roll and the shoe. Due to the actions of shearing and cooling by the roll, semisolid slurry consisting of non-dendritic solid phase and liquid phase was prepared. When the slurry met the block, its flow direction turned 90°, so the extending mold could be continuously filled with the slurry. The extending cavity was firstly filled by the slurry, and then the slurry was forced to fill the welding cavity through the splitflow orifices. Finally, the slurry was forced to flow out of the channel formed by the mold orifice and the wires were obtained.

Al-0.9Si-0.6Mg (wt%) alloy designed by our own which was melted by commercial pure aluminum ingots, pure magnesium ingots and Al-Si master alloy. The chemical composition of the alloy was analyzed using an inductively coupled plasma-optical emission spectrometer (ICP-OES; VARIAN, Palo Alto, CA, USA). In order to assure the alloy wires' high mechanical performance, alloying elements and impurity contents were strictly controlled during melting process. The solidus and liquidus temperatures of the alloy were *ca.* 607 °C and 654 °C, respectively. After being melted, the melt was refined by hexachloroethane for 3–5 min to remove the oxides, impurities and hydrogen.

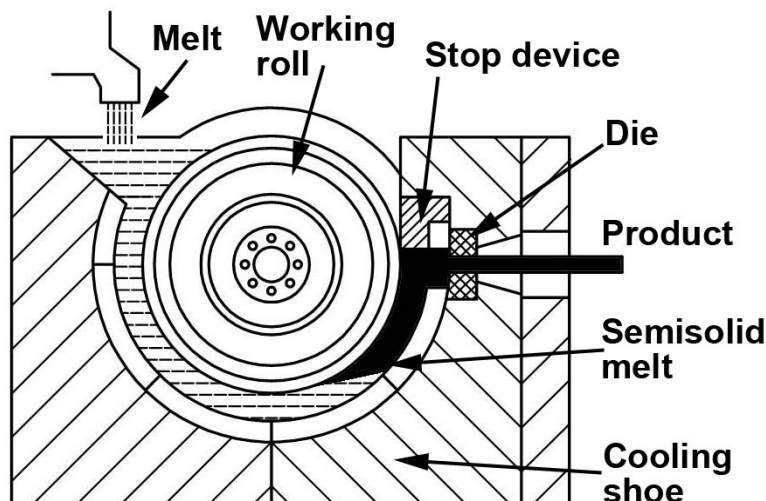


Figure 1. Schematic diagram of the continuous rheo-extrusion machine.

2.2. Heat Treatment Process

After extrusion, continuous solution treatment was applied for the alloy at 520–540 °C for 6 h. Aging treatment was then performed to obtain the optimized mechanical and conductive properties. Three kinds of aging treatment were carried out and compared: T6, T8 and T9, and the detailed technical parameters could be found in Table 1.

Table 1. Conditions of T6, T8 and T9 aging treatment.

Heat treatment	Solution temperature (°C)	Aging temperature (°C)	Aging time (h)
T6	520	150–190	2–14
T8	520	150–170	3–7
T9	540	150–170	3–7

2.3. Microstructure Analysis

Materials after different treatment were machined for next metallurgical and mechanical tests. Samples were first polished and etched, then analyzed by scanning electron microscopy (SEM; SSX-550, Shimadzu, Japan) for determining the distribution of phases. The corrosive solution used for corroding the alloys was: 15 mL HCl + 56 mL C₂H₅OH + 47 mL H₂O. Samples were processed into Φ 3 mm \times 0.5 mm discs using a linear cutting machine; the discs were then ground to a thickness of 80 μ m and thinned using an ion milling machine. The microstructure of the precipitate phase in the alloy was then analyzed by high-resolution transmission electron microscopy (HRTEM; G2 F20, Tecnai, Delft, The Netherlands).

2.4. Mechanical and Conductive Properties

The mechanical performance of these aged alloys formed using continuous rheo-rolling was investigated using an electronic tensile testing machine according to the manufacture's protocol

(Huaxing Experimental Equipments Co. Ltd., Jinan, China). Conductive properties were determined according to standard JB /T8640-1997.

3. Results and Discussion

3.1. Optimum of Technical Parameters of Continuous Rheo-Extrusion

The experimentally measured composition of the alloy was: Si 0.93 ± 0.01 wt.%, Mg 0.58 ± 0.02 wt.% and balanced Al. Impurities mainly composed by Ni (<0.003 wt.%), Fe (<0.002 wt.%) and Cu (<0.002 wt.%). Optimized technical parameters of continuous rheo-extrusion were obtained after experiment, which including: cooling water flow rate was 10–15 L/Min; pouring temperature was 680–720 °C and rolling speed was 0.18 m/s. By using these technical parameters, the extruded wires were manufactured continuously without surface defect and break. The outlook of the wire is shown in Figure 2.

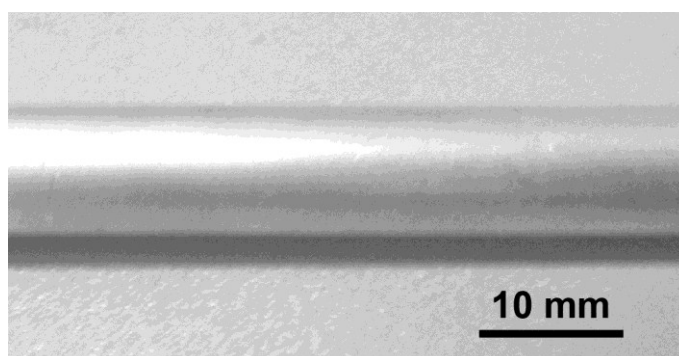


Figure 2. Outlook of Al-0.9Si-0.6Mg (wt%) alloy conductive wire produced by continuous rheo-extrusion.

3.2. Influence of T6 Aging Treatment on Microstructure and Properties

Distributions of Mg₂Si precipitate in alloy's matrix after T6 treatment by different aging time were observed by SEM and TEM microscope and present in Figure 3. At the beginning of aging treatment at 2 h under 150 °C, second phases precipitated homogeneously in spot form as shown in Figure 3a. With increasing aging time, spots form phases turned to spin form phases, and this trend could be clearly observed after 14 h aging (Figure 3d).

Materials' tensile strength, elongation ratio and electrical resistivity were summarized in Figure 4. It can be found that the wire's ultimate tensile strength (UTS) value turned bigger and then smaller with increasing aging time. This is due to the bigger size of the secondary phases brought by aging. According to Orowan's theory, growth of secondary precipitates promotes the impedance of dislocations, and therefore increases the UTS [9]. When aging time was beyond the peak time, the density of secondary phases became smaller due to the fast growth of phases, movement of dislocations happens between phases, and then made the tensile strength of the alloy decreased.

The elongation as well as the electrical resistivity always decreases with longer aging time. This trend was resulted by faster atom movement with higher aging temperature. As the size of secondary phases grew bigger, the difference deforming properties between secondary phases and matrix

decrease the elongation [10]. Another effect brought by faster atom movement is of dislocations' movement was also accelerated. As a result, the density of dislocations and grain boundary decreased, so the conductive properties were accordingly improved (electrical resistivity is smaller, Figure 4) [11].

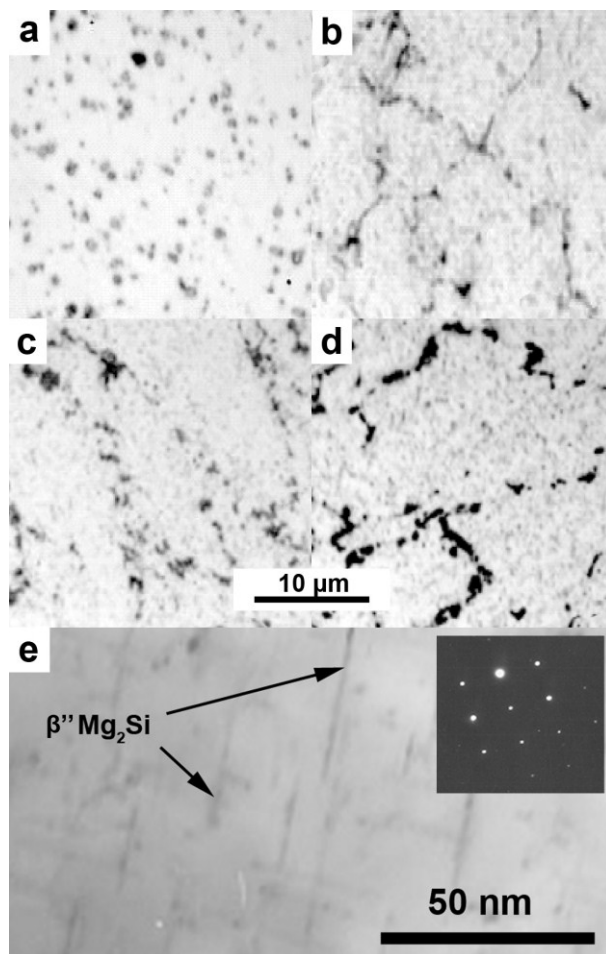


Figure 3. SEM and TEM images of precipitated phases in matrix after artificially aging treatment at 150 °C for different time: (a) 2 h; (b) 6 h; (c) 10 h; (d) 14 h; (e) 14 h TEM image with according diffraction pattern.

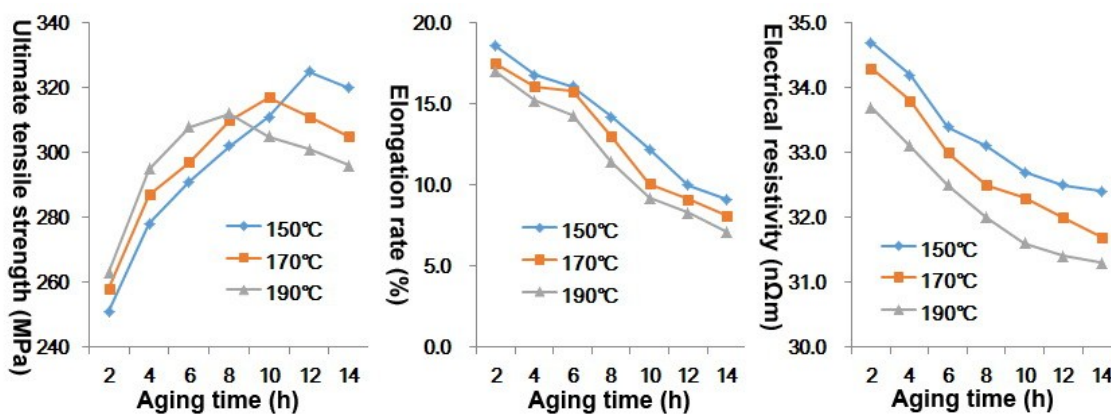


Figure 4. Relationship between tensile strength, elongation ratio and electrical resistivity of alloy conductors and T6 aging time.

3.3. Influence of T8 and T9 Aging Treatment on Microstructure and Properties

The effects of T8 treatment time on ultimate tensile strength, elongation and electrical resistivity of the alloy are summarized in Figure 5 (upper line). After complete T8 aging treatment, UTS of the alloy reached 336 MPa while elongation and electrical resistivity was 13.7% and 29.3.5 nΩm. In Figure 5 (lower line), the effects of T9 treatment time on ultimate tensile strength, elongation and electrical resistivity of the alloy are concluded. After complete T9 aging treatment, UTS of the alloy increased to 338 MPa while elongation and electrical resistivity was 6.0% and 30.2 nΩm respectively. Compare with the standard JB/T8640-1997 (UTS = 295 MPa; Electrical resistivity = 32.2 nΩm), the treated alloy's UTS increased by 13.2% and the conductive properties increased by 5.9%.

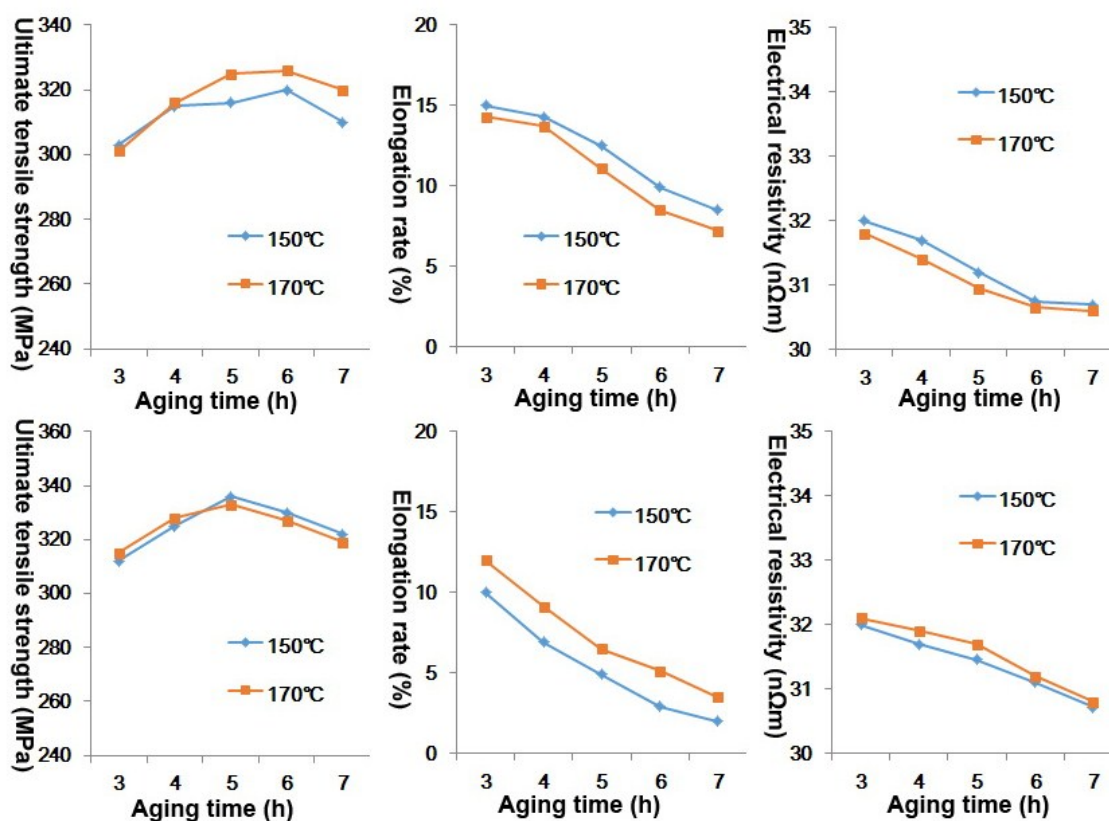


Figure 5. Relationship between tensile strength, elongation ratio and electrical resistivity of alloy conductors and T8 (upper)/T9 (lower) aging time.

The comprehensive mechanical properties and conductivity of the alloy wire can be effectively improved by the low temperature heat treatment, such as T8 process and T9 process. UTS of the T9 treated wire is the highest while elongation is the lowest. Conversely, UTS of the T8 treated wire is lower while elongation is higher. This result is related to a typical deformation structure: with the fragmentation of grain by extrusion and high density dislocation brought by T8 process or T9 process, dislocation grid was formed. Strength of the alloy wire increased due to work hardening by extrusion and precipitation strengthening by aging treatment. This process benefits from both aging strengthening and work hardening, so the tensile strength of T9 treated alloy climbed to the highest value. However, its elongation was lower due to serious lattice distortion. When aging temperature is

150 °C, less influence of strain hardening could be observe, so UTS of the T8 treated alloy is lower than that of T9 treated one. The smaller precipitated phases by lower aging temperature brought the electron scattering effect [12], leading to the decrease of electrical conductivity (Figure 4). Therefore, it is crucial to obtain balanced mechanical and conductive properties by adjusting the aging temperature. When aging temperature remained constant, aging time was the most important parameter which affected conductivity of the alloy as well as mechanical properties.

4. Conclusions

Optimized technical parameters of continuous rheo-extrusion include: cooling water flow rate of 10–15 L/Min, pouring temperature of 680–720 °C and rolling speed of 0.18 m/s. During T6 treatment to rheo-extruded alloy, conductivity increased with higher aging temperature and aging time, whilst the elongation decreased. After T8 and T9 heat treatment, the conductive and mechanical properties of the alloy both increased due to more homogeneous precipitation and distribution of secondary Mg₂Si β phase. After complete T8 aging treatment, UTS of the alloy reached 336 MPa while elongation and electrical resistivity was 13.7% and 29.3 nΩm respectively. After complete T9 aging treatment, UTS of the alloy increased to 338 MPa while elongation and electrical resistivity was 6.0% and 30.2 nΩm respectively.

Acknowledgments

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Author Contributions

Di Tie and Renguo Guan conceived and designed the experiments; Xiang Wang, Yang Zhang and Zhouyang Zhao performed the experiments; Ning Su and Jing Li analyzed the data; Di Tie drafted the manuscript.

Conflicts of Interest

The authors declare no conflict of interest.

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