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Influence of deformation and annealing on electrical conductivity, mechanical properties and texture of Al-Mg-Si alloy cables

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ABSTRACT

Al-Mg-Si alloys are medium-strength high-conductivity alloy cable materials that are ideal candidates for electrical engineering applications, but their related electrical conductivity, mechanical properties and textures must be studied in greater detail before such applications can be realized. Different deformation strains (0.98, 1.73 and 2.24) and annealing temperatures (200–500 °C) were applied to optimize these properties in Al-Mg-Si alloy cables. The results show that the recrystallized Al-Mg-Si alloy cables exhibit medium yield strength and higher electrical conductivity compared to the non-recrystallized Al-Mg-Si alloy cables with larger average grain sizes. After annealing, the main contributors to the overall texture were the Brass and Goss textures. According to theoretical evaluations, the significant increase in electrical conductivity and decrease in yield strength can be attributed to the decreasing dislocation density and changes to the grain boundaries.

1. Introduction

Al-Mg-Si alloys are medium-strength high-conductivity aluminum alloys with an excellent combination of material cost and properties, making them appealing for use in a wide range of applications such as in the building industry and electrical power transmission [1]. Increased interest in electrical engineering applications has led to intense investigations into the properties and mechanisms related to such cables, due to their good corrosion resistance, conductivity, mechanical properties and long service life [2]. For most Al-Mg-Si cables, an optimum combination of conductivity and mechanical properties is required for use.

Extrusion, drawing and annealing are essential methods used to prepare aluminum alloy cables. Different cumulative strains during cold-drawn and annealing treatment can form new microstructures with elongated or recrystallized grains, which can achieve improved strength and conductivity in the final material. During plastic deformation, work hardening occurs as the dislocation density increases through the interaction of dislocations with solute atoms or non-shearable precipitates [3], a phenomenon which is harmful to the electrical conductivity because of the scattered conducting electrons [4,5]. Annealing after cold deformation results in recrystallization which leads to a finer grain structure. Mavlyutov et al. [6] demonstrated that annealing of ultrafine grained CP Al alloy by high pressure torsion (HPT), within a temperature range of 90–200 °C, raises the electrical conductivity from 33.7% to 59.3%. Murashkin et al. [7] investigated the combination cold deformation with annealing heat treatment (400 °C for 1 h), which can improve the electrical conductivity of as-cast Al-8.5RE alloy from 49.5% IACS to 52.4%, and ultimate tensile strength (UTS) from 175 MPa to 274 MPa, with an average grain size of 136 nm. Valiev et al. [8] also found that low electrical conductivity (47.7% IACS) and high UTS (510 MPa) were obtained in Al-Mg-Si cables made by HPT at room temperature, but after HPT at elevated temperatures (130 °C), the conductivity increased to 55.6% IACS while its UTS decreased to 365 MPa, with an increase in the average grain size from 130 nm to 440 nm. However, few studies have been carried out concerning the combination of electrical conductivity and strength of Al-Mg-Si alloy cables.

For most cases, a change in texture occurs over the deformation and subsequent grain growth process [9]. In studying the recrystallization texture of Al-Mg-Si alloys, Wang et al. [10] reported that the cold-deformation textures transform from Cube textures (volume fraction of ~17.2%) to $Cube_{ND}$ (~23.9%) and P textures (~6.7%) after solution treatment at 555 °C for 25 min. Chen et al. [11] suggested that the recrystallization textures have a Cube orientation rotated by 15° to the normal direction and {011} < 122 > orientation in cold rolling samples, and the intensities of the Brass and Goss textures increase remarkably after recrystallization. Niranjani [12] found that the volume

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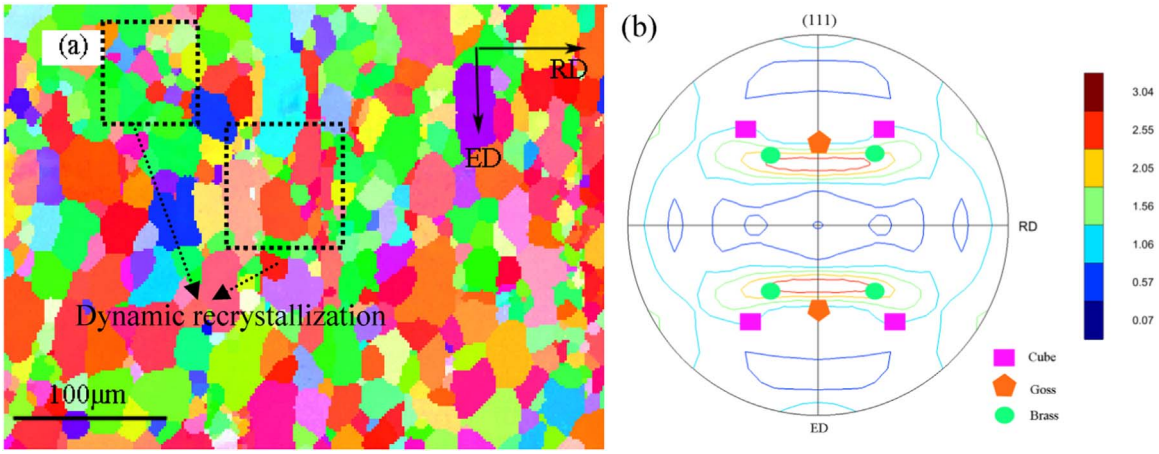

Fig. 1. (a) EBSD map of hot-extruded alloy and (b) (111) pole figure along the extrusion direction.

fraction of the S {123} < 634 > orientation is predominant (~40%) in Al-Mg-Si alloys subjected to severe cold rolling with a true strain of ~1.6, while little attention was paid to the change in textures of Al-Mg-Si alloys after annealing.

A better understanding of the deformation strain and annealing process would help in optimizing the comprehensive properties of these cables. To the best of our knowledge however, the influence of deformation and annealing conditions on the properties of Al-Mg-Si alloy cables have been extensively studied, particularly in terms of grain sizes and textures. The purpose of this study is to further investigate the microstructure development, strength, electrical conductivity and textures of Al-Mg-Si alloy cables under controlled deformation and annealing conditions.

2. Material and methods

Pure aluminum (99.99% Al), pure Mg, pure Cu, and master alloys of Al-5 wt% Si and Al-21.5 wt% Mn were used in this study. These raw materials were melted in an electric resistance furnace, and then cast into ingots (Φ50 mm × 200 mm) with iron molds. An alloy was obtained with a composition of 0.8 wt% Mg, 0.6 wt% Si, 0.15 wt% Cu, 0.1 wt% Mn, and Al as the remainder. The ingots were homogenized at 520 °C for 16 h in an air furnace. Subsequently, the ingots were then hot-extruded into rods of Φ 9.5 mm at 480 °C. Extruded aluminum rods were cold drawn into wires with diameters of 5.8 (A), 4.0 (B) and 3.1 mm (C). The deformation strain is typically defined by an equation such as $\eta = In(A_0/A_f)$, where A_0 and A_f are the initial and final cross sectional areas, respectively. The corresponding deformation strains of the wires are 0.98, 1.73 and 2.24 for Wires A, B and C, respectively. Wire segments 300 mm in length were selected for subsequent studies. Next, the wires were subjected to annealing treatment at temperatures of 200, 300, 400 and 500 °C for 3.5 h in an air furnace.

Electrical conductivity was measured using a standard DC four-probe method. Electrical resistivity was calculated and converted to electrical conductivity according to International Annealed Copper Standards (IACS). Specimens for tensile tests were fabricated from the as-extruded aluminum rods and as-drawn aluminum wires with lengths of 100 mm. Tensile tests were conducted on an MTS Landmark testing machine at room temperature. The fibrous textures were measured at the half thickness of the specimen along the extrusion or drawn axis, using a Bruker D8 Discovery X-ray system. The area of the surface analyzed by X-ray diffraction (XRD) was 20 mm^2. Three partial pole figures, {111}, {200} and {220} were measured by the parameters α (5–75°) and β (0–360°), using the Tex Calc data analysis program. Fibrous textures intensities and volume fractions were quantified on their inverse pole figures. Microstructural characterization was carried out using electron backscattered diffraction (EBSD) and transmission electron microscopy (TEM). To study the microstructures of the Al-Mg-Si alloy cables, microscopic EBSD studies were carried out in the RD-ED and DD-ED planes, corresponding to the radial (RD), extrusion direction (ED) and drawn direction (DD). TEM and EBSD samples were fabricated from longitudinal sections of Al-Mg-Si alloy cables by punching 3 mm diameter discs from 80 to 100 μm thick foils. The 3-mm diameter discs were grounded and subsequently twin-jet electro-polished with a solution of 25% perchloric acid and 75% methanol (vol%) at a temperature of −25 °C and direct current power of 20 V. EBSD measurements were performed on a FEI Hlios Nanolab 600i focused ion beam/scanning electron microscopy (FIB/SEM) system with an accelerating voltage of 20 kV. The HKL Channel 5 Analysis software was used to process the EBSD data. TEM observations were carried out with a FEI Tecnai F20 system operated at 200 kV.

3. Results

3.1. Hot-extrusion microstructure and texture

Fig. 1 presents the EBSD map and (111) pole figure of a hot-extrusion specimen (Φ 9.5 mm). The microstructure of the as-extruded aluminum rod consists of equiaxed grains (Fig. 1(a)) with grain sizes of 10–35 μm, with approximately 90% dynamic recrystallization based on analysis with the Channel 5 software. As shown in Fig. 1(b), the locations of texture components were analyzed using the (111) pole figure of the hot-extrusion specimen. The main dynamic recrystallization texture is comprised primarily of Cube {001} < 100 >, Goss {110} < 001 > and Brass {110} < 112 > orientations; the highest intensity of the main texture is the Cube orientation. A detailed analysis of the textures was carried out using Tex Calc, showing that the volume fractions of the Cube, Goss and Brass textures as distributed in the hot-extrusion specimen were 14.7%, 13.1% and 17.9%, respectively. Thus, the Brass texture is the dominant type in the dynamic recrystallization texture.

3.2. Cold-drawn microstructures and textures

Fig. 2 shows EBSD maps of the three alloy wires (Φ 5.8, 4.0 and 3.1 mm) after cold drawing; red indicates (001), blue for (111), and green for (101) as shown in the standard stereographic triangle (Fig. 2(c)). After intense cold drawing deformation, the microstructures of the cold drawing samples are remarkably different from those of the hot-extrusion samples. As the cold-drawn strain improves from Wire A to Wire C, the deformation microstructures features become more distinct, and the fibrous structures along the drawing direction gradually replace the original equiaxed grains. Moreover, the fibrous grains appeared to have relatively poor regularity and uniformity in all wire

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