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Effect of minor Sc addition on microstructure and stress corrosion cracking behavior of medium strength Al–Zn–Mg alloy

Zhaoming Li [a,b], Haichang Jiang [a,*], Yunli Wang [a], Duo Zhang [a], Desheng Yan [a], Lijian Rong [a,*]

[a] CAS Key Laboratory of Nuclear Materials and Safety Assessment, Institute of Metal Research, Chinese Academy of Sciences, Shenyang 110016, China
[b] University of Chinese Academy of Sciences, Beijing 100049, China

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ABSTRACT

Influence of Sc content on microstructure and stress corrosion cracking behavior of medium strength Al–Zn–Mg alloy have been investigated by optical microscopy, scanning electron microscopy, electron backscatter diffraction, transmission electron microscopy and slow strain rate test. The results indicate that the addition of Sc results in the formation of the quaternary coherent Al_3(Sc, Zr, Ti) dispersoids during homogenization treatment, which will inhibit the dynamic recrystallization behavior. The number density of Al_3(Sc, Zr, Ti) particles increases with the increase of Sc content, and thus the recrystallization fraction of hot-extruded alloy is reduced and the peak strength in two-stage artificial aging sample is enhanced. At the same time, the wide of precipitation free zone is reduced, and the content of Zn and Mg in grain boundary particles and precipitation free zone is increased with the increase of Sc content. In peak-aged state, the 0.06 wt% Sc added alloy shows the better stress corrosion cracking resistance than the Sc-free alloy because of the reduction of recrystallization fraction and the interrupted distribution of grain boundary precipitates along grain boundary. However, the further addition of Sc to 0.11 wt% will result in the deterioration of stress corrosion cracking resistance due to the increase of electrochemical activity of grain boundary particles and precipitation free zone as well as hydrogen embrittlement.

1. Introduction

Medium strength Al–Zn–Mg alloys, 7xxx series Al alloys, are mainly used for structural material in rail transit field because of high specific strength, good weldability and low quench sensitivity [1–3]. However, the requirements for good mechanical strength and high resistance to stress corrosion cracking (SCC) are known to be contradictory [4,5]. For example, over-aged treatment can decrease SCC sensitivity but the strength decreases by 10% to 15% compared with the peak-aged condition. The SCC behavior of 7xxx series alloys is closely related to the microstructural characteristics, in particular recrystallization, grain-boundary microstructure and grain-boundary microchemistry. SCC crack always propagates along grain boundaries (GBs) due to the galvanic interaction between active grain boundary precipitates (GBPs) and the adjacent matrix [6,7]. GBs characteristics influence the nucleation and growth kinetics of the GBPs in 7xxx series alloys. The number of GBPs changes with the difference in the GBs energy, and the GBPs and precipitation free zone (PFZ) easily form along high-angle GBs with higher GBs energy, while GBPs difficultly form along low-angle GBs with lower GBs energy [8]. The continuous distribution characteristic of GBPs along recrystallization grain boundaries had been observed in previous researches [9–11]. Many evidences verified that SCC resistance of Al alloys were enhanced through inhibiting recrystallization [12,13]. However, study from Ryabov et al. [14] indicated that suppressing the recrystallization processes also could reduce the resistance of localized corrosion. It was also reported that wide PFZ could increase the SCC sensitivity because of considerable differences in electrochemical property between the grain boundary area and the grain interior [15]. Recently, Liu et al. [16] reported that GBPs with a higher content of Zn and Mg tend to decrease its corrosion resistance resulting in low resistance to localized corrosion.

In practical applications, medium strength Al–Zn–Mg alloy is mainly processed into large-size complex Al sections through hot extrusion. However, these products generally compose of a large volume fraction of recrystallized grains because of high temperature (above half the melting point, $0.5T_m$) during hot extrusion

* Corresponding authors.
E-mail addresses: hcjiang@imr.ac.cn (H. Jiang), ljrong@imr.ac.cn (L. Rong).

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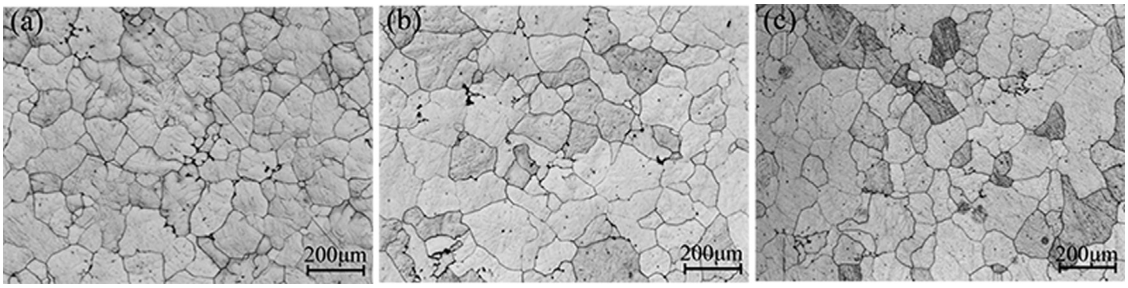

Fig. 1. The as-cast microstructures of the studied alloys: (a) A0; (b) A1; (c) A2.

Table 1
Chemical compositions of experimental alloys (in wt%).

Alloy	Zn	Mg	Mn	Cr	Zr	Ti	Sc	Al
A0	4.19	1.36	0.32	0.21	0.10	0.06	–	Bal.
A1	4.08	1.35	0.30	0.19	0.11	0.06	0.06	Bal.
A2	4.08	1.35	0.32	0.20	0.10	0.06	0.11	Bal.

[17]. In order to inhibit recrystallization and get a combination of improved mechanical strength and enhanced SCC resistance, adding transition elements and/or rare earth elements are feasible methods [11,18,19]. Interest in Sc element is due to its considerable potential for inhibiting recrystallization and improving mechanical properties [20]. The recrystallization temperature of Sc-bearing Al alloys can be increased to above 600 °C [21,22], which is mainly attributed to the pinning effect of coherent and nano-sized Al_3Sc particles on the movement of the grain boundaries [23]. Moreover, Sc addition is beneficial to weldability of 7xxx series Al alloys by inhibiting crack formation in welding [24]. The synergistic effect of Sc and Zr is more effective for improving recrystallization resistance and strength of 7xxx series alloys due to the formation of extremely fine Al_3(Sc, Zr) particles with a dual layer structure [25,26].

In recent decades, high strength 7xxx series Al alloys with Sc or Sc and Zr additions have attracted enormous interest [27–29]. However, only limited literature is available on effects of Sc addition on the recrystallization behavior and SCC properties of medium strength Al–Zn–Mg alloy. Thus, the purpose of this work is to improve mechanical properties and SCC resistance of medium strength Al–Zn–Mg alloy with trace Zr and Ti through addition of Sc to inhibit the recrystallization and strengthen alloy.

2. Materials and methods

Three kinds of Al–Zn–Mg alloys with 0 wt% Sc-containing (A0), 0.06 wt% Sc-containing (A1) and 0.11 wt% Sc-containing (A2) were prepared by an electrical resistance furnace melting and casting in a metal mould. Table 1 shows their composition based on chemical analysis. After homogenization treatment (470 °C for 24 h), the ingots were preheated at 450 °C for 1 h, then hot extruded into plates with a cross section of 17 mm × 35 mm (extrusion ratio of 22.3:1), followed by water quenching. The plates were placed in ambient environment for 3 days, then exposed to two-stage artificial aging.

Microstructures were analyzed by optical microscopy (OM), scanning electron microscopy (SEM), electron backscatter diffraction (EBSD), and transmission electron microscopy (TEM) equipped with energy disperse spectroscopy (EDS). The samples for EBSD analysis were electrolyzed polishing at 20 V for 60 s in a mixed solution (10% perchloric acid in alcoholic solution) after mechanical polishing for eliminating surface stress layer. TEM thin foils were prepared by twin-jet electropolishing at 15 V in a solution composed of 30% nitric acid and 70% methanol solution at −25 °C. For consistent results, all specimens for microstructure characterization and mechanical properties tests were prepared in L–T (longitudinal–transversal) orientation at the central portion of the extrusion plates.

Vickers hardness was measured using micro hardness tester applying a 200 g load for 15 s. Tensile tests were performed on the electronic universal testing machine with the loading speed of 2 mm/min at room temperature. SCC susceptibility was studied using slow strain rate test (SSRT) technique at a strain rate of $1.0 \times 10^{-6}\ s^{-1}$ in laboratory air and 3.5 wt% NaCl solution. Flat tensile specimens were prepared with gauge dimensions of 30 mm × 6 mm × 3 mm. The specimens were polished to 2000 grade SiC paper and degreased by acetone before loading. Each test was repeated at least three times in order to ensure reproducibility of the experiments. The SCC susceptibility index (I_{SCC}) was calculated using Eq. (1)

$$I_{SCC} = (1 - \delta_{sol}/\delta_{air}) \times 100\% \quad (1)$$

where δ_{air} and δ_{sol} were the specimen elongation in air and in solution, respectively.

3. Results

3.1. Microstructures

Fig. 1 shows the representative as-cast microstructures of three experimental alloys. The grain size of A0 alloy, A1 alloy and A2 alloy are 110 μm, 113 μm and 109 μm, respectively, which indicates that the grain refining effect does not occur when the addition of Sc is less than 0.11 wt%.

Modifying effect of as-cast structure due to grain refiner addition is controlled by two factors. One is the number of primary particles nuclei in a unit melt volume; and the other is their capacity to become heterogeneous nucleants for α-Al. For Sc-doped Al alloys, the Al_3Sc can be precipitated prior to the nucleation of α-Al during the solidification. The primary Al_3Sc particles are efficient heterogeneous nucleants because of their similar lattice parameter and crystal structure with α-Al [30]. Therefore, refining effect of Sc on grain structure depends mainly on the number of primary Al_3Sc nuclei of crystallization. In binary Al–Sc alloys, the inoculating action of Sc manifest itself at a content exceeding eutectic composition (corresponding to 0.55 wt%) [31]. However, the required Sc content for grain refinement starts from 0.18 wt% when Al–Zn–Mg alloy contains 0.10 wt% Zr, which results from the shift to the left of phase equilibrium of the primary Al_3Sc particles and Al melt [31]. In the current study, maximum 0.11 wt% Sc is added into Al–Zn–Mg alloy containing 0.10 wt% Zr, which is below the critical value (0.18 wt%). Thus, refining effect of Sc on as-cast grain does not happen.

The microstructures of three experimental alloys after hot extrusion are characterized by EBSD technique, and orientation maps are shown in Fig. 2(a–c). In the EBSD mappings, the broadly black and thinly white lines represent the high-angle grain

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