Vacuum 149 (2018) 106–113

Contents lists available at ScienceDirect

Vacuum

journal homepage: www.elsevier.com/locate/vacuum

Effects of pre-aging and minor Sc addition on the microstructure and mechanical properties of friction stir processed 7055 Al alloy

C.Y. Liu [a, b, *], B. Zhang [c], Z.Y. Ma [b, **], G.B. Teng [a], L.L. Wei [a], W.B. Zhou [d], X.Y. Zhang [c]

[a] Key Laboratory of New Processing Technology for Nonferrous Metal & Materials, Ministry of Education, Guilin University of Technology, Guilin 541004, China
[b] Shenyang National Laboratory for Materials Science, Institute of Metal Research, Chinese Academy of Sciences, 72 Wenhua Road, Shenyang 110016, China
[c] State Key Laboratory of Metastable Materials Science and Technology, Yanshan University, Qinhuangdao 066004, China
[d] Alnan Aluminium Co., Ltd., Nanning 530000, China

ARTICLE INFO

Article history:
Received 2 December 2017
Received in revised form
18 December 2017
Accepted 19 December 2017
Available online 20 December 2017

Keywords:
Al alloy
Friction stir processing
Microstructure
Mechanical properties

ABSTRACT

The effects of Sc addition and pre-aging on the microstructure and mechanical properties of friction stir processed (FSP) 7055 Al alloy were investigated. The addition of Sc effectively inhibited the coarsening of grains in the FSP 7055 Al alloy due to the grain boundary pinning effect of $Al_3(Sc,Zr)$ particles. The high density of $Al_3(Sc,Zr)$ particles also provided more preferential nucleation sites for the precipitation of the η phase during FSP, and then inhibited the coarsening and increased the density of the η phase in the FSP 7055 alloy. The η′ phase precipitated in the 7055 and Sc-containing 7055 during artificial aging, and then dissolved into the Al matrix during FSP. Thus, pre-aging effectively inhibited the formation of the η phase during FSP, and increased the quantity of the solute atoms in the FSP samples. The mechanical properties of the FSP 7055 Al alloy were improved by the addition of Sc and pre-aging. The aged 7055–0.25Sc Al alloy with FSP showed the highest ultimate tensile strength of 578 MPa; and the aged 7055 Al alloy with FSP showed the largest elongation of 21%. This work provides an effective strategy to improve the mechanical properties of FSP Al alloys.

1. Introduction

Al alloys with ultra-fine-grained (UFG) structure have attracted wide attention due to their excellent physical and mechanical properties [1–4]. In the past few years, friction stir processing (FSP), which was developed based on the basic principles of friction stir welding (FSW) [5,6] has been used to fabricate UFG Al alloys, due to its simplicity, effectiveness and variability in grain refinement [7–10].

Al-Zn-Mg(-Cu) series (7xxx) alloys have been widely used in the aeronautics and astronautics industries due to their low density, ultra-high strength and fracture toughness [11–15]. UFG 7xxx Al alloys have also been successfully fabricated by FSP [16–20], and it has been found that the FSP 7xxx Al alloys exhibit superplasticity when the deformation temperature is higher than 200 °C. However, the investigation into the room-temperature mechanical properties of the FSP 7xxx Al alloys is limited so far.

Softening in the stir zone (SZ) has been widely reported in the 7xxx Al alloys during FSW [21–29]. The 7xxx Al alloys are typical aging-hardened alloys, and precipitation occurs in these alloys during FSW or FSP owing to the friction-induced temperature rise. The structure, size, density and distribution of the precipitated phases strongly affect the room-temperature mechanical properties of the FSP 7xxx Al alloys, such as the tensile strength and ductility. Clearly, controlling the precipitation process is the key to producing FSP 7xxx Al alloys with excellent room-temperature mechanical properties.

The precipitation sequence of 7xxx Al alloys is described as: supersaturated solid solution → GP zones → metastable η′ phase → stable η phase [30]. The high density of the η phase, which corresponds to the over-aging state of the 7xxx Al alloys, has always been obtained in the SZ of FSW or FSP 7xxx Al alloys due to the large heat input [19,21], resulting in reduced strength of these FSP/FSW samples. Chen et al. [21] and Sharma et al. [25] found that applying the aging treatment before FSP/FSW can affect the precipitation process of the Al-6Zn-2.2Mg-1.6Cu (7B04) and Al-4.7Zn-2.4Mg-0.7Mn (7039) alloys during FSP/FSW, and therefore enhance the hardness of the SZ. This implies that the room-temperature

* Corresponding author. Key Laboratory of New Processing Technology for Nonferrous Metal & Materials, Ministry of Education, Guilin University of Technology, Guilin 541004, China. Tel.: +86 773 5896436.
** Corresponding author. Tel.: +86 24 83978908.
E-mail addresses: lcy261@glut.edu.cn (C.Y. Liu), zyma@imr.ac.cn (Z.Y. Ma).

https://doi.org/10.1016/j.vacuum.2017.12.030
0042-207X/

Table 1
Chemical composition of the 7055 and 7055–0.25Sc alloys.

	Zn	Mg	Cu	Zr	Sc
7055	7.82	1.95	2.24	0.16	–
7055–0.25Sc	7.81	1.93	2.24	0.16	0.25

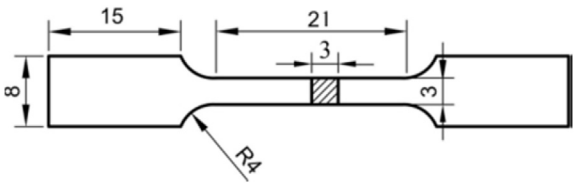

Fig. 1. Schematic drawing of the tensile specimen (mm).

mechanical properties of the FSP 7xxx Al alloys can be improved by optimizing the pre-aging.

The room-temperature mechanical properties of the FSP 7xxx Al alloys are also affected by the grain size. A low rotation rate is effective in reducing heat input during FSP/FSW [30–33], and can therefore can inhibit grain coarsening and enhance the strength of FSP/FSW samples. Furthermore, Deng et al. [29] found that the addition of Sc can also refine the grains of the SZ in the FSW joints of 7xxx Al alloys. The addition of Sc has been proven to be an effective approach in refining the grains of several Al alloys during heat treatment or deformation [34–37]. Thus, the room-temperature mechanical properties of the FSP 7xxx Al alloys are expected to improve through both a low rotation rate and the addition of Sc.

In the present study, an 7055 Al alloy was used as a raw material to investigate the effects of pre-aging and Sc addition on the microstructure and mechanical properties of the FSP 7xxx Al alloys with a low rotation rate (300 rpm). The aim is to fabricate UFG 7xxx Al alloys with excellent room-temperature mechanical properties.

2. Experimental methods

3 mm thick rolled sheets of 7055 Al alloy and 7055 Al alloy containing 0.25% (mass ratio) Sc (7055–0.25Sc) were used as raw materials. The chemical compositions of these two alloys are shown in Table 1. The sheets were subjected to a solution treatment in a vacuum furnace at 470 °C for 2 h, and then water quenched (defined as SS). Some of the SS 7055 and 7055–0.25Sc samples were aged at 120 °C for 12 h.

Both the SS and aged samples were subjected to FSP at a constant traverse speed of 100 mm min^{-1} with a low tool rotation rate of 300 rpm. A tool with a concave shoulder 10 mm in diameter and a taper threaded pin 2.7 mm in length and 5 mm in diameter was used.

The microstructures of the samples were examined using optical microscopy (OM), electron backscattered diffraction (EBSD) and transmission electron microscopy (TEM, JEM-2010). EBSD measurements were carried out using a Hitachi S-3400N-II scanning electron microscope. The films were prepared for TEM by grinding to a thickness of 50 μm, followed by thinning using a twinjet electropolishing device. Differential scanning calorimetry (DSC) was used to examine the transition temperature of the samples at a heating rate of 10 °C/min.

The tensile tests were conducted on an Instron-3369-type testing machine at a strain rate of 4×10^{-4} s^{-1}. The specimens for tensile testing were machined parallel to the FSP direction. Fig. 1 shows the dimension and shape of the tensile specimen. The fracture surfaces following the tensile tests were observed using scanning electron microscopy (S-4800).

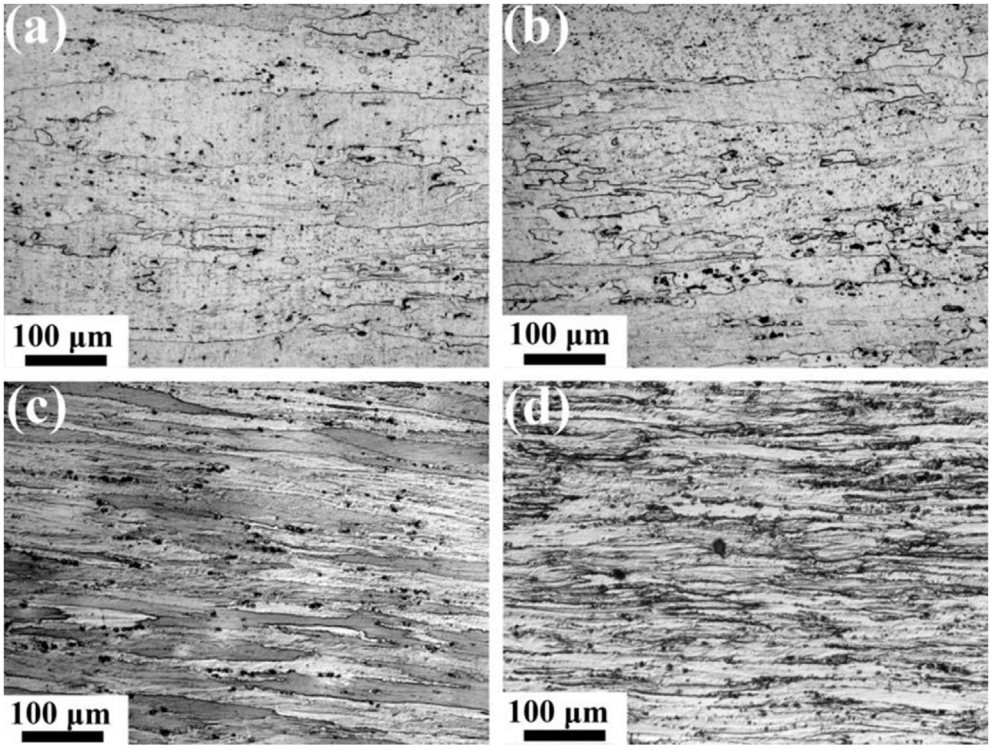

Fig. 2. OM micrographs of (a) SS and (b) aged 7055 samples, and (c) SS and (d) aged 7055–0.25Sc samples.