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Excellent high strain rate superplasticity of Al-Mg-Sc-Zr alloy sheet produced by an improved asymmetrical rolling process

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ABSTRACT

A fine-grained Al-6.10%Mg-0.30%Mn −0.25%Sc-0.1%Zr (wt. %) alloy with an average grain size of ~1.10 μm was subjected to an improved asymmetrical rolling (ASR) process. Superplastic behavior of the asymmetrical rolled alloy was investigated at 450–500 °C and strain rate range of 5×10^{-3} s^{-1} to 2.5×10^{-1} s^{-1}. It is indicated that the asymmetrical rolled alloy exhibited excellent superplasticity (elongations of >1000%) at high strain rates ranging from 1×10^{-2} s^{-1} to 2.5×10^{-1} s^{-1}, and maximum elongation of ~3170% was obtained at 500 °C and a high strain rate of 5×10^{-2} s^{-1}. The microstructural results showed that the shear components and the β-fiber rolling texture gradually transferred into a random texture, and LABs progressively changed to HABs during deformation. Such a microstructure can accelerate the cooperative grain boundary sliding leading to a higher superplasticity. Further, superior superplastic behavior of the asymmetrical rolled alloy can be ascribed to the fine (sub)grains which may slow down the rate of cavity growth and the stable coherent $Al_3(Sc_{1-x}Zr_x)$ nano-particles that can ensure a good stability of the fine-grained structure during superplastic deformation. Analyses on superplastic data and microstructure characteristic revealed that grain boundary sliding might be the main deformation mechanism during deformation.

1. Introduction

As the need for strong, light-weight materials has steadily been increasing, there has also been a growing interest in aluminum alloys which can be easily and inexpensively formed into components using superplastic forming techniques. Superplastic forming (SPF) is a well-established industrial process for the fabrication of complex shapes in sheet metals to reduce both weight and forming costs [1,2]. In practice, however, the widespread use of SPF of aluminum alloys is generally limited to low volumes of components due to the slow optimum strain rate for superplasticity [3]. From the viewpoint of practical industrial fabrication, therefore, it is highly desirable to achieve high superplastic elongations at strain rates faster than 10^{-2} s^{-1}, which is so-called high strain rate superplasticity (HSRS) [4].

On the other hand, it is well documented that grain refining in materials results in an increase in strain rate at which superplasticity appears [5,6]. Subsequently, several studies have reported the occurrence of HSRS in aluminum alloys with ultra-fine grains (UFG), where grain refinement was achieved by using different processing techniques, such as thermo-mechanical processing (TMP) [7,8], high-pressure torsion (HPT) [9,10], equal-channel angular pressing (ECAP) [11,12], fraction stir processing (FSP) [13,14]. Although, there is considerable interest in the possibility of achieving HSRS by the processes above, extra cost and additional technologies are required, and they are not suitable for engineering production. Furthermore, UFG materials prepared by FSP, ECAP and HTP processes also have some drawbacks, notably the small dimensions this approach yields, which limit their practical applications. Thus, a new, easy and inexpensive processing technique is needed for superplastic material to advance high-strain-rate superplastic forming into production oriented industries.

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Recently, it has been reported that asymmetric rolling (ASR) is a new, easy and inexpensive plastic deformation technique, and it is very suitable for producing larger structural materials with UFG [15]. In contrast to conventional rolling, Asymmetric rolling (ASR) is a rolling process in which the circumferential velocities of the upper and lower rolls are different [16]. This can be achieved either by changing the diameter of one of the rolls rotating with the same angular speed, or by maintaining the same diameter for both rolls but by varying the rotational velocities of one of the two rolls. ASR has been utilized to investigate on the grain refinement of many metals and alloys [17,18]. For example, F.Q. Zuo et al. [19] have reported that extremely fine grains with size of 500 nm are obtained in pure aluminum by ASR, and J.H. Jiang et al. [20] have reported that ultrafine-grained Al with an average grain size of <1 μm was obtained through the ASR process. These results clearly show the effectiveness of ASR for producing UFG materials that are amenable to HSRS.

Al-Mg-Sc alloys were developed as a class of highly formable aluminum alloys with superior properties (especially yield strength) compared to conventional Al-Mg alloys [21]. Besides, fine-grain Al-Mg-Sc alloys are the most common Al-Mg alloys for SPF of lightweight sheet-metal parts in the automotive and aerospace industries, because small particles of the Al_3Sc phase in Al-Mg-Sc alloys can ensure a good stability of the fine-grained structure up to temperatures where superplastic behavior can be expected [22]. Furthermore, some reports suggested that the highest stability may be reached by simultaneous addition of small amounts of zirconium and scandium [22], and this composition was also selected in our experiments. Therefore, in order to improve stability of the fine-grained structure in the superplastic materials and reduce the fabrication cost of SPF, it is of practical importance to investigate the possibility of achieving excellent superplasticity at high strain rates ($\geq 10^{-2}$ s^{-1}) in the Al-Mg-Sc-Zr alloy subjected to an ASR process. However, few researches about the superplasticity of the Al-Mg-Sc-Zr alloy processed by an ASR process have been reported so far. In this work, superplastic behavior of the Al-Mg-0.25%Sc-0.10%Zr alloy (wt. %) processed by an ASR process was investigated, and the superplastic data and the microstructure characteristic during superplastic deformation were analyzed to clarify the superplastic deformation mechanism.

2. Experimental

A semi-continuous ingot casting of Al-6.10%Mg-0.30%Mn-0.25% Sc-0.10Zr (in wt.%) with trace amounts of other elements (Fe, Si, Zn, Ti) were used as the initial material in this work. It was first homogenized at 300 °C for 12 h, and subsequently hot rolled to 8 mm. Then hot rolled plates were cold rolled to 2 mm with a pass reduction of 0.6 mm in an improved asymmetric rolling (ASR) mill. Schematic of the improved ASR was showed in Fig. 1. Generally speaking, ASR can be technically realized by maintaining the same diameter for both rolls but varying the rotational velocity of one of them, which is considered to be a more effective method of grain refinement [16]. In this investigation, the diameter for both rolls was 100 mm, and the velocity ratio of bottom and top roll speeds was equal to 1.5. Meanwhile, an offset displacement ($s = 4$ mm) of the slower roll in outlet direction was added in the rolling mill, which is termed the improved ASR. In the improved ASR, a force or moment will be applied to the plate in the opposite direction of bending because of the offset distance of the slower roll in outlet direction [23]. As a result, the plate is not only subjected to a large shear strain, but also can be processed smoothly in the following passes with a small curvature. During the improved ASR process, no lubrication was introduced to the rolls, and the surfaces of rolls were rasped to enhance the friction between the sample and the rolls. Moreover, it can be concluded that the shear strain of the "improved ASR" may be 0.22–0.27 via computer simulation and experimental measurement methods [19].

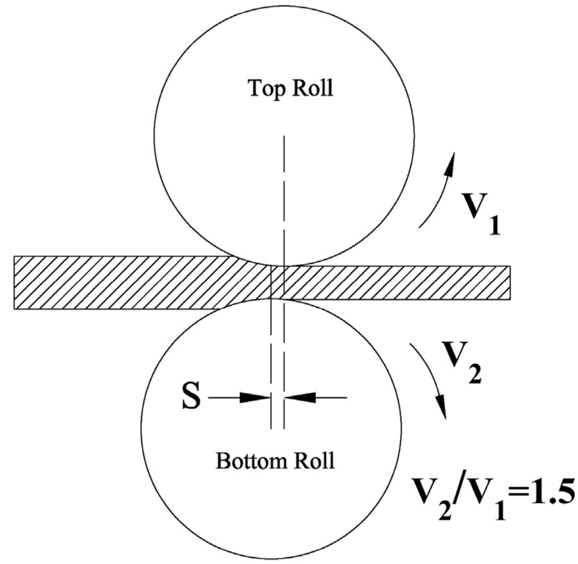

Fig. 1. Schematic of the improved ASR process: S is the horizontal offset distance, v_1 is the velocity of top roll, v_2 is the velocity of bottom roll, and v_2/v_1 is the velocity ratio.

Two "dog-bone" specimen geometries were used for mechanical testing of the ASR sheet: one a gage length of 3 mm and gage width of 2 mm, the other with a gage length of 12 mm and gage width of 8 mm. Both geometries used a thickness of 2 mm, and a shoulder radius of 2 mm. The sheet rolling direction was always oriented parallel to the tensile axis, and tensile test was performed according to the method for evaluation of tensile properties of metallic superplastic materials as described in GB/T 24172-2009. In order to investigate superplastic behavior, tensile tests were carried out in the temperature interval 450–550 °C and at strain rates ranging from 5×10^{-3} s^{-1} to 2.5×10^{-1} s^{-1}. Also three specimens were tested at the same experimental conditions to accurately measure the elongation to fracture. Prior to tensile deformation, each specimen was placed into the furnace approximately 30 min to approach the state of thermodynamic equilibrium. In addition, temperature was controlled to within ±1 °C along each specimen gage length using a resistance furnace with three independent heating zones. Thermocouples contacting each specimen at the extremes of its gage length were used to verify temperature uniformity during mechanical tests. Moreover, specimens were tested using rigid, shoulder-loading grips, which effectively prevent measurable plastic deformation within the sample grip region. This rigid grip design allows for accurate measurement of elongation from grip displacement. Specimens were tested at constant crosshead speeds by using an Instron 8032 electro-fluid servo-fatigue tester.

Textures were measured by using a standard X-ray Schulz back-reflection method using Cu K_α target, in which the accelerating voltage and current were 40 kV and 40 mA, respectively. The (111), (200) and (220) pole figures were measured up to a maximum tilt angle of 75°. The three-dimensional orientation distribution functions (ODFs) were calculated from the incomplete pole figures using the series expansion method with expansion to $l_{max} = 22$, and presented as plots of constant φ_2 sections in Euler space defined by the Euler angles φ_1, Φ and φ_2. Following a commonly used practice, only 3 sections are used in the present paper to represent the main features of the measured textures, namely the $\varphi_2 = 0°$, $\varphi_2 = 45°$ and