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Investigation on the maximum strain rate sensitivity (m) superplastic deformation of Mg-Li based alloy

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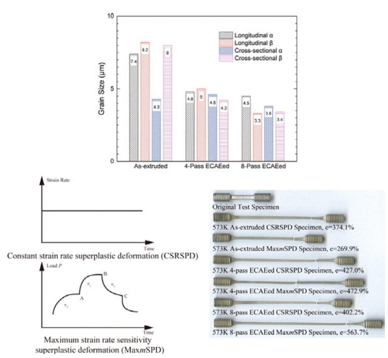
HIGHLIGHTS

- The best superplasticity of Mg-9Li-1Al alloy can be obtained at the temperature of 573 K.
- Equal channel angular extrusion facilitates the realization of superplasticity, and more passes of ECAE correspond with a larger m value.
- Maximum m superplasticity is better than constant strain rate superplasticity of the ECAEed Mg-9Li-1Al alloy at 573 K.
- Fracture occurs inside α-phase or at phase boundary and the α-phase increases near the fracture region.

GRAPHICAL ABSTRACT



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ABSTRACT

The maximum strain rate sensitivity (m) superplastic deformation (Max$m$SPD) of Mg-Li based alloys was conducted via realization of the maximum m value throughout the deformation process such that the optimum superplastic deformation (SPD) of materials is obtained. So far, the Max$m$SPD has only been successfully applied to titanium alloys, but its potential application in other alloys has not yet been explored and exploited. In this article, the Max$m$SPD of Mg-9Li-1Al alloy was investigated by conducting the Max$m$SPD and the constant strain rate SPD (CSRSPD) experiments and comparison of the SPD results. The materials with two different statuses were used in the investigation: as-extruded samples extruded from the as-cast material, and the samples with 4- or 8-pass equal channel angular extrusion (ECAE). The Max$m$SPD and CSRSPD experiments were conducted at the temperature of 548, 573 and 598 K. The maximum elongation is 563.7%, obtained by Max$m$SPD at 573 K using the 8-pass ECAEed samples. It was found that under certain conditions, the samples exhibit more elongation in Max$m$SPD. The microstructure of the samples is examined and compared, and the differences between Max$m$SPD and CSRSPD are discussed. The investigation thus provides an in-depth and epistemological understanding of the SPD mechanism of Mg-Li based alloys.

1. Introduction

Mg-Li alloys have the great promising potential for wide applications in industries due to its superior stiffness-to-weight ratio, low density (1.35–1.65 g cm^{-3}), excellent formability, and biodegradability,

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and these properties are favored by aerospace, military and medical fields [1–7]. The addition of Li improves the ductility of Mg by transforming the original hexagonal-close-packed (HCP) structure into the body-center-cubic (BCC) structure and reducing the axial ratio of the hexagonal Mg lattice [8]. When Li is <5.7 wt.% or > 10.3 wt.%, the alloy is either α-phase or β-phase; while as Li is between 5.7 and 10.3 wt.%, the alloy is a duplex structure containing both α-phase and β-phase, as shown in the phase diagram of the alloy in Fig. 1. The α-phase is solid solution of Li in Mg with HCP structure and the β-phase is solid solution of Mg in Li with BCC structure [9].

In order to efficiently fabricate the parts with complex shape and geometry using Mg-Li alloy, the superplasticity of the alloy can be exploited, which is the material property for undergoing large plastic deformation, generally represented by extremely high elongation (usually larger than 200%) in tensile tests under a certain deformation condition [11]. In general, the following conditions need to be met in terms of realization of the superplasticity deformation (SPD): (1) fine microstructure and small grains (typically the grain size < 10 μm) of materials; (2) deformation temperature near or over $0.5T_m$ [12,13]; and (3) the strain rate typically between 1×10^{-5} and $1 \times 10^{0}\ s^{-1}$ [14–16]. To refine the grains and microstructure of the alloy, the process of equal channel angular extrusion (ECAE) was used, in which a billet is pressed through a die with two intersecting channels with the same cross-section for extrusion with one or multiple passes to realize the simple shear deformation of material at the intersecting channel of the die. In such a way, the microstructure of the processing alloy can be refined [17]. Recently, attempts to investigate the SPD of Mg-Li alloys have been conducted [18–20]. From SPD perspectives, the research on the superplasticity of materials presently is more focused on realizing the SPD at lower temperature [21,22], with higher strain rate [23,24], and using the materials with relatively coarse grain structure [23,25,26], but few is more concerned about the realization method of SPD. The main efforts on SPD are still more on adopting the constant velocity SPD (ConstvSPD) and the constant strain rate SPD (CSRSPD), in which either the velocity or the strain rate is kept constant throughout the SPD process. However, the best superplastic state cannot always be maintained throughout the deformation process in the conventional SPD, as the strain rate sensitivity *m* value cannot always be kept to be the largest value, and the larger *m* value always facilitates the SPD via maintaining a resistance to necking and a better state of SPD [27]. The concept of the maximum strain rate sensitivity (*m*) superplasticity deformation (Max*m*SPD) was thus proposed by maintaining the maximum *m* value in the SPD process through simultaneous and in-situ measurement of *m* value and dynamic control of deformation strain rate and further the *m* value [27]. The process can be realized by a tailor-made tensile testing machine with a computer control system embedded with the Max*m*SPD program. From the industrial application point of view, the variation of strain rate in the forming process can be accomplished by using a servo-control system in the forming equipment. The Max*m*SPD has been successfully applied to the SPD of Ti alloys and the significantly enhanced superplasticity of Ti alloys was achieved compared to the conventional SPD [27,28], but its promising and potential application by other alloys has not been extensively explored yet.

Motivated by the potential of applying Max*m*SPD to Mg-Li based alloys to achieve the maximum superplasticity, this investigation aims to explore the best hot working process for fabricating micro-scaled biomedical microparts or implants such as heart stents. The alloy composition of Mg-9Li-1Al (LA91) was selected for this research, which has duplex α-HCP and β-BCC structure. The materials used for experiments are as-extruded samples which were extruded from the as-cast material, and the samples pre-processed by 4- or 8-pass ECAE after extrusion. Max*m*SPD and CSRSPD experiments were conducted using three types of LA91 alloy samples at the temperature of 548, 573, and 598 K. It is found that the Max*m*SPD demonstrated more promising SPD potential with the ECAEed samples than the as-extruded samples and the superplastic state becomes unsteady when the temperature is higher than 573 K. The deformation behavior was also studied and explored for better realization of SPD and accurate identification of the optimal hot working process of the alloy in the future.

2. Experimental procedures

2.1. Material preparation

The material for this research is LA91, which was originally cast from pure Mg, Li and Al in argon protection environment. The cast ingot was then extruded into rods with the diameter of 10 mm at the temperature of 563 K and with the extrusion ratio of 25. In order to determine the composition of the alloy, inductively coupled plasma optical emission spectrometer (ICP) was employed to examine its composition. The testing result shows the material contains 8.981% Li and 0.9969% Al (in wt.%), which is fairly close to the theoretical composition.

To refine the microstructure and grain size of the Mg-Li alloy, the technique of ECAE was adopted for further processing of the as-extruded material. The grain refinement in ECAE process is mainly determined by two factors: the intersection angle of the two channels 2Φ and the fillet angle 2ψ in the die. Experiments have shown that when 2Φ is very close to 90° and 2ψ is as small as possible, the ultrafine grain structure with equiaxed grains can be achieved [29–31], which is favored by SPD. In addition, the route of multi-pass ECAE is also crucial to the plastic deformation imparted to the billet. As the evolution of

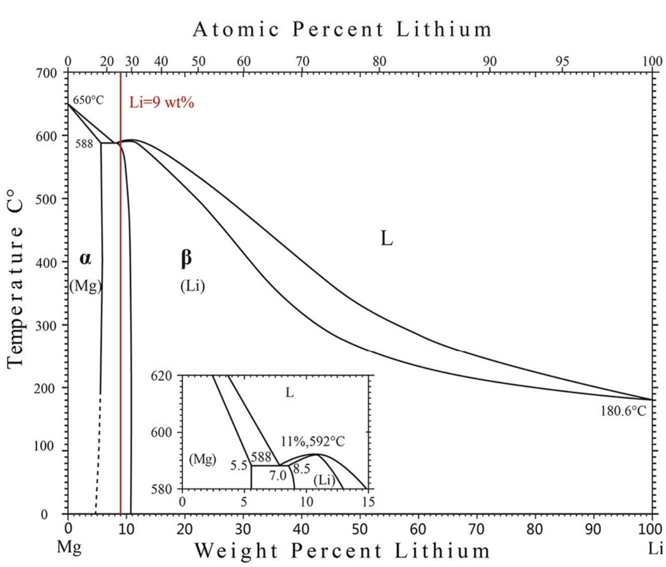

Fig. 1. Phase diagram of Mg-Li alloy [10].

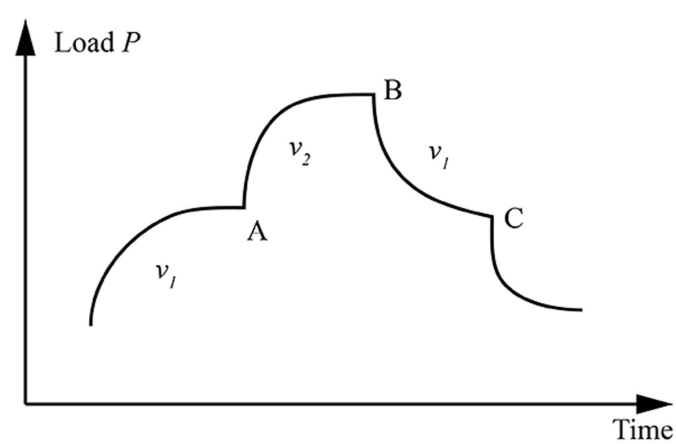

Fig. 2. Loading–time curve for measurement of *m* value [28].