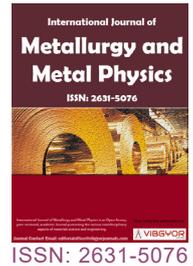


# Cavity Nucleation Study during Quasi-Superplasticity of an Ultralight Coarse-Grained Rolled Mg-7.28Li-2.19Al-0.1Y Alloy



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## Abstract

Cavity or cavitation is a phenomenon in superplasticity and creep and is significant to the prediction of cavity mechanism. However, compared to cavity growth, cavity nucleation is rarely reported in magnesium alloy, especially Mg-Li alloy. To investigate the cavitation nucleation, a novel Mg-7.28Li-2.19Al-0.1Y alloy has been fabricated by hot rolling and cold rolling; its flow stress and microstructural cavitation at elevated temperatures were investigated by optical microscopy and tensile tester. The maximum elongation to failure of 265.8% was demonstrated in this alloy at a temperature of 623 K and a strain rate of  $5.0 \times 10^{-4} \text{ s}^{-1}$ . Experimental results revealed that cavity or cavitation nucleated at interphase boundary and  $\alpha$ -Mg grain boundary in quasi-superplasticity Mg-7.28Li-2.19Al-0.091Y alloy. The present alloy had coarse grain sizes and cavity nucleation was easy to initiate in this coarse-grained alloy. Helmholtz free energy map was plotted to predict the easy and difficulty of cavity nucleation in the present alloy. This work will enhance the workability and understand the fracture initiation behavior in the present  $\alpha$ -Mg phase dominated alloy.

## Keywords

Magnesium, Cavitation nucleation, Quasi-superplasticity, Flow stress, Microstructure

## Introduction

Magnesium-lithium (Mg-Li) alloy is the lightest nonpoisonous alloy. Due to extremely low density, excellent specific stiffness, good weight-to-density ratio, good electromagnetic shielding property, and damping property, studies on Mg-Li alloys have attracted extensive attention from the researchers, not only for room temperature property and microstructure [1-3] but also for high temperature behavior, in particular, superplasticity [4-9]. Under this background, we designed and fabricated a novel two-phase Mg-7Li-2Al-1Y alloy and investigated its high temperature behavior.

Superplasticity reflects the capability of materials to exhibit exceptional ductility or elongation, typically several hundred, and occasionally thousands [10]. Superplastic forming can realize the forming of the complex components such as thin wall high rib components under a small load. During superplasticity study, extensive researches are devoted to the high temperature flow deformation mechanism. In the meantime, cavity or cavitation study also has carried out the limited investigation.

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Cavity or cavitation nucleation, growth, coalescence, and interlinkage fracture reflect different stages of fracture. Cavity or cavitation phenomenon originated from the report in Zn-22Al superplasticity [11]. In recent years, cavity growth has been moderately studied in oxygen free copper [12], 5A70 aluminum alloy [13], 5083 aluminum alloy [14], Al-4.7Mg-Mn-Fe alloy [15], Zn-22Al zinc-based alloy [16], and so forth. However, compared to the cavity growth study, cavity nucleation is rarely reported. To the best of our knowledge, only a few reports are devoted to the experimental study of superplastic Mg-Li-Zn cavity growth [17,18], and no information is available studying on the cavity nucleation behavior of Mg-7Li-2Al-1Y alloy designed and processed by rolling. Thus, it is necessary to investigate the flow stress and microstructure cavitation through hot tensile tests and microstructural characterization. Meanwhile, aiming at the facts of only limited experimental researches on cavity phenomenon recently, it is necessary to use our cavitation nucleation model to plot the free energy map to depict the variation in free energy with cavity radius in this new alloy.

In this work, our investigation contents include three aspects: (i) A novel Mg-7.28Li-2.19Al-0.1Y alloy has been fabricated by hot rolling and cold rolling; (ii) Its flow stress and microstructural cavitation at elevated temperatures were investigated; (iii) The free energy map was plotted to analyze the cavitation nucleation mechanism and corroborated in this alloy.

## Experimental Procedures

Raw materials Mg, Al, and Li (purity more than 99.9 wt.%) and Al-30 wt.% Y master alloy were melted in an electric furnace with a flux of LiCl and LiF (3:1) under the protection of argon (Ar) atmosphere, as detailed in elsewhere [19]. The melt was cast in a water circulated copper mold to obtain an Mg-7Li-2Al-1Y alloy (wt.%) ingot. The analyzed chemical composition of the ingot was Mg-7.28Li-2.19Al-0.1Y. After homogenization at 473 K for 20 h, the ingot was hot rolled at 573 K to a plate 5 mm in thickness with a percent reduction of 77.3% and cold rolled to a sheet 2 mm in thickness with a percent reduction of 60%. The annealing system was 623K for 3h. Dog-bone samples with dimensions of 10 mm in gauge length, 6 mm in width, and 2 mm in thickness whose direction was parallel to rolling direction were stamped on a hydraulic press. Tensile tests were conducted on CMT5105 microcomputer controlled electronic universal tester at temperatures of 423-623 K at initial strain rates of  $1.62 \times 10^{-2}$ - $1.67 \times 10^{-4} \text{ s}^{-1}$ . Samples for cavity or cavitation observation were polished by conventional metallographic methods and etched in a solution of 10% HCl + 90% EtOH. The etched samples were observed on Olympus DSX500 optical microscope. The grain size was measured by Image-Pro Plus (IPP) software.

## Our Cavity Nucleation Model

Helmholtz free energy model of cavity nucleation is given by the following formula according to our report on typical superplasticity of Al-Si-Mg alloy [20]:

$$\Delta G = -r^3 F_v(\alpha) \sigma_p + r^2 [\gamma F_s(\alpha) - \gamma F_b(\alpha)] - r^3 F'_v(\alpha) \sigma_p^2 / 2E \quad (1)$$

where  $r$  is the cavity radius, the first term is the work done by the applied stress on the system, the second and third terms are the change in surface and grain boundary areas, respectively and hence energies, and the fourth term is the change of elastic strain energy in the system.  $F_v$ ,  $F_b$  and  $F_s$  are dimensionless functions which when they are multiplied by  $r^3$  and  $r^2$ , give the volume, the surface area and the grain boundary area consumed by the cavity, respectively.  $F'_v$  multiplied by  $r^3$  gives the volume within which the elastic strain energy is relaxed due to the formation of the cavity,  $\sigma_p$  is the pile-up stress of dislocations, and  $E$  is Young's modulus.

Through derivation, one gets

$$\Delta G = -2.53 \left( \frac{2}{3} \times \frac{d}{1.74b} \times \frac{\sigma^2}{G} \right) r^3 + [9.31\gamma - 0.5 \times 2.93\gamma] r^2 - 3.79 \times \frac{\left( \frac{2}{3} \times \frac{d}{1.74b} \times \frac{\sigma^2}{G} \right)^2}{2E} r^3 \quad (2)$$

where  $d = 1.74L$ , here  $L$  is the linear intercept grain size or the length of dislocation pile-up,  $\sigma$  is the applied stress,  $b$  is the magnitude of Burgers vector, and  $G$  is the shear modulus,  $E = 2G(1 + \nu)$  [21], here,

$\nu$  is Poisson's ratio.

Differentiate Eq. (2), let  $\frac{\partial \Delta G}{\partial r} = 0$ , the critical radius of cavity nucleation,  $r_c$ , is obtained:

$$r_c = \frac{\gamma}{\sigma} \left[ \frac{40.95}{7.89 + 2.18 \left( \frac{d}{b} \right) \left( \frac{\sigma}{G} \right) \left( \frac{\sigma}{E} \right) \left( \frac{d}{b} \right) \left( \frac{\sigma}{G} \right)} \right] \quad (3)$$

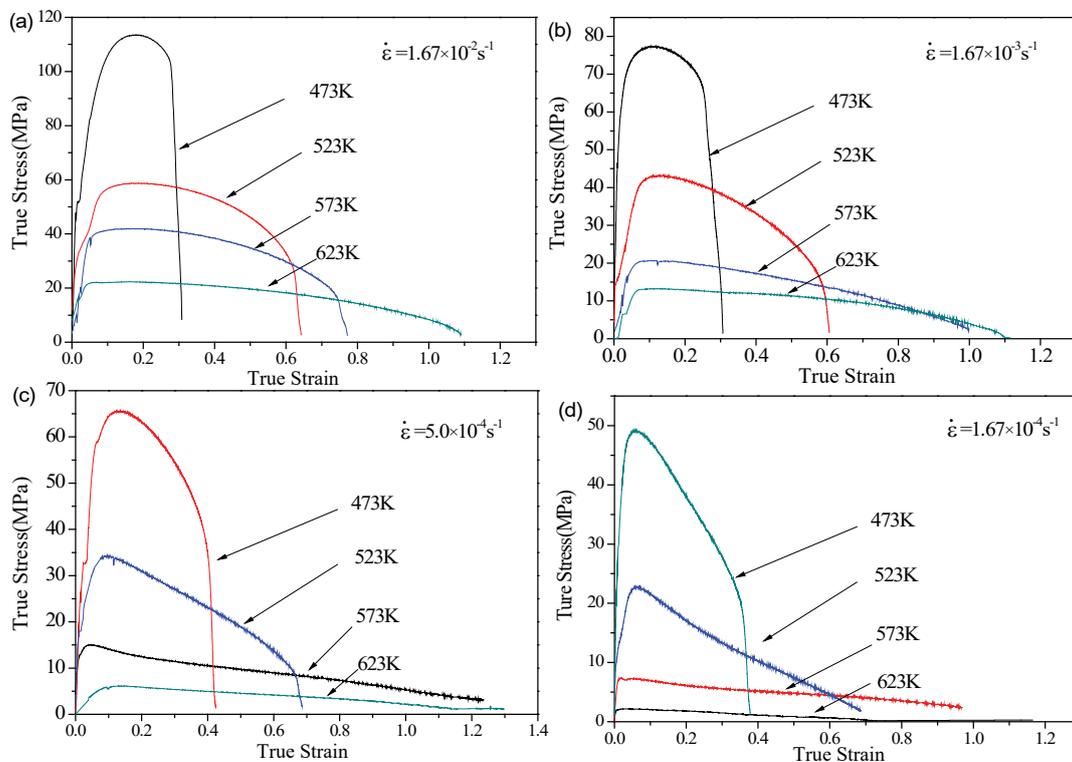
Further, Eq. (3) was simplified into the following form:

$$r_c = 5.2 \left( \frac{\gamma}{\sigma} \right) \left( \frac{b}{d} \right) \left( \frac{G}{\sigma} \right) \quad (4)$$

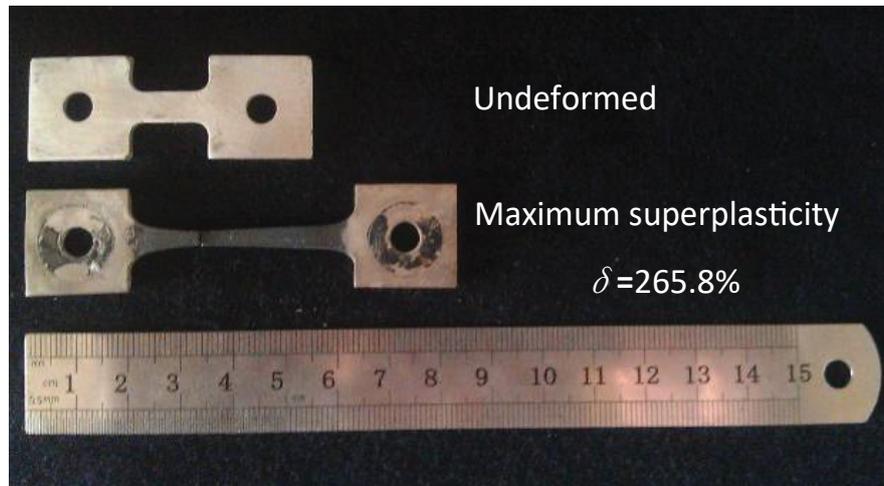
## Results and Discussion

### Flow stress curves and microstructural cavitation morphology

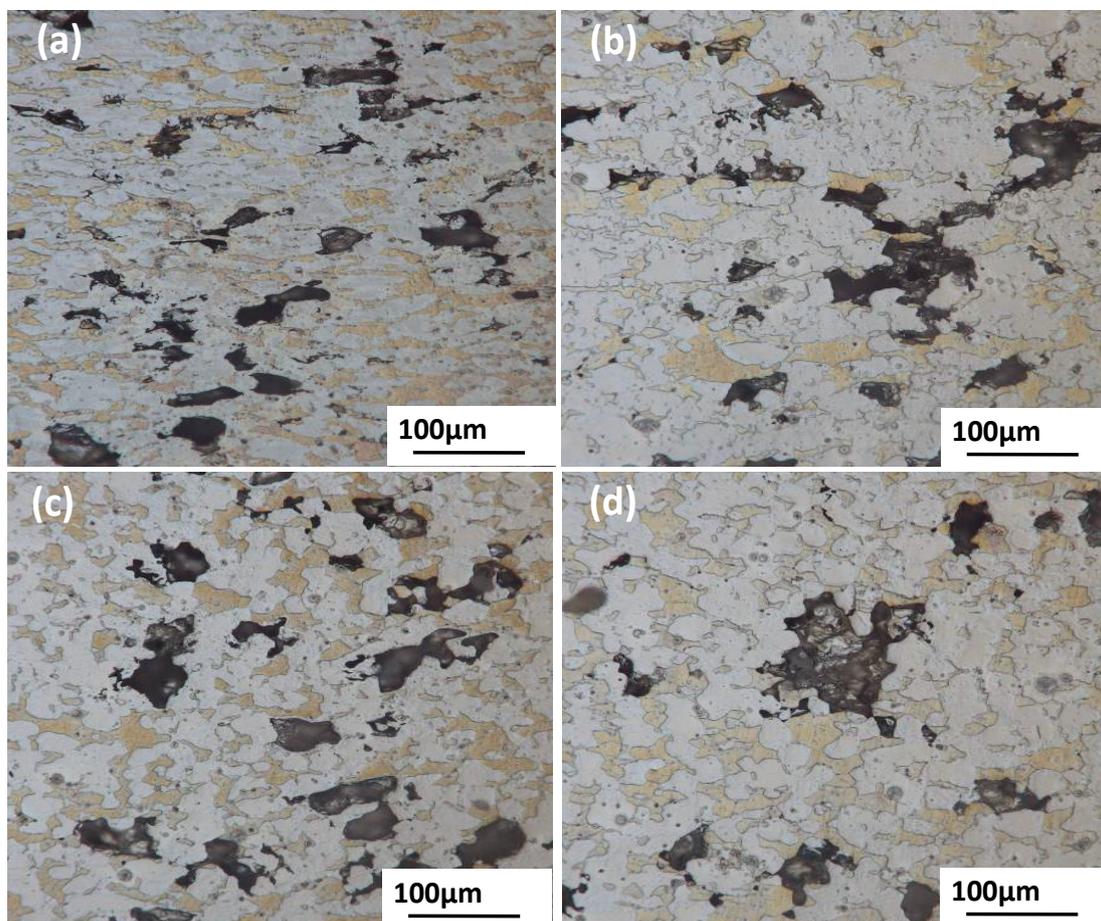
Figure 1 presents the true stress - strain curves of Mg-7.28Li-2.19Al-0.091Y alloy at different tensile temperatures at the same initial strain rate. For different flow stress curves, the flow stress level decreases with increasing temperature and/or decreasing strain rate. That is because with the increase in temperature, thermal activation and atomic diffusion accelerate, dislocation density decreases, and flow stress decreases; with the decrease in strain rate, the tensile deformation time prolongs, the alloy has sufficient time to promote thermal activation and atomic diffusion, dislocation density decreases, and flow stress decreases. For single flow stress curve, the curves exhibit single peak form and are typical dynamic recrystallization curves. Due to dynamic recrystallization, after the peak stress, the flow stress exhibits a slow decreasing true stress with increasing strain, i.e., strain softening. As shown in Figure 1c, at a temperature of 623 K and a strain rate of  $5.0 \times 10^{-4} \text{ s}^{-1}$  the true strain of 1.297 corresponds to the elongation to failure of 265.8% according to the relation: true strain =  $\ln(1 + \text{engineering strain or elongation})$ , exhibiting quasi-superplasticity.



**Figure 1:** True stress - strain curves of Mg-7.28Li-2.19Al-0.091Y alloy at different tensile temperatures at the same initial strain rate: (a)  $1.67 \times 10^{-2} \text{ s}^{-1}$ ; (b)  $1.67 \times 10^{-3} \text{ s}^{-1}$ ; (c)  $5 \times 10^{-4} \text{ s}^{-1}$ ; (d)  $1.67 \times 10^{-4} \text{ s}^{-1}$ .



**Figure 2:** Specimens showing the maximum superplasticity of Mg-7.28Li-2.19Al-0.091Y alloy.



**Figure 3:** Cavitations in Mg-7.28Li-2.19Al-0.091Y alloy specimen after tensile test to fracture at temperature of 573 K with different initial strain rates and grain sizes: (a)  $1.67 \times 10^{-2} \text{ s}^{-1}$ ,  $d = 40.4 \text{ } \mu\text{m}$ ; (b)  $1.67 \times 10^{-3} \text{ s}^{-1}$ ,  $d = 35.5 \text{ } \mu\text{m}$ ; (c)  $5 \times 10^{-4} \text{ s}^{-1}$ ,  $d = 31.7 \text{ } \mu\text{m}$ ; (d)  $1.67 \times 10^{-4} \text{ s}^{-1}$ ,  $d = 33.4 \text{ } \mu\text{m}$ .

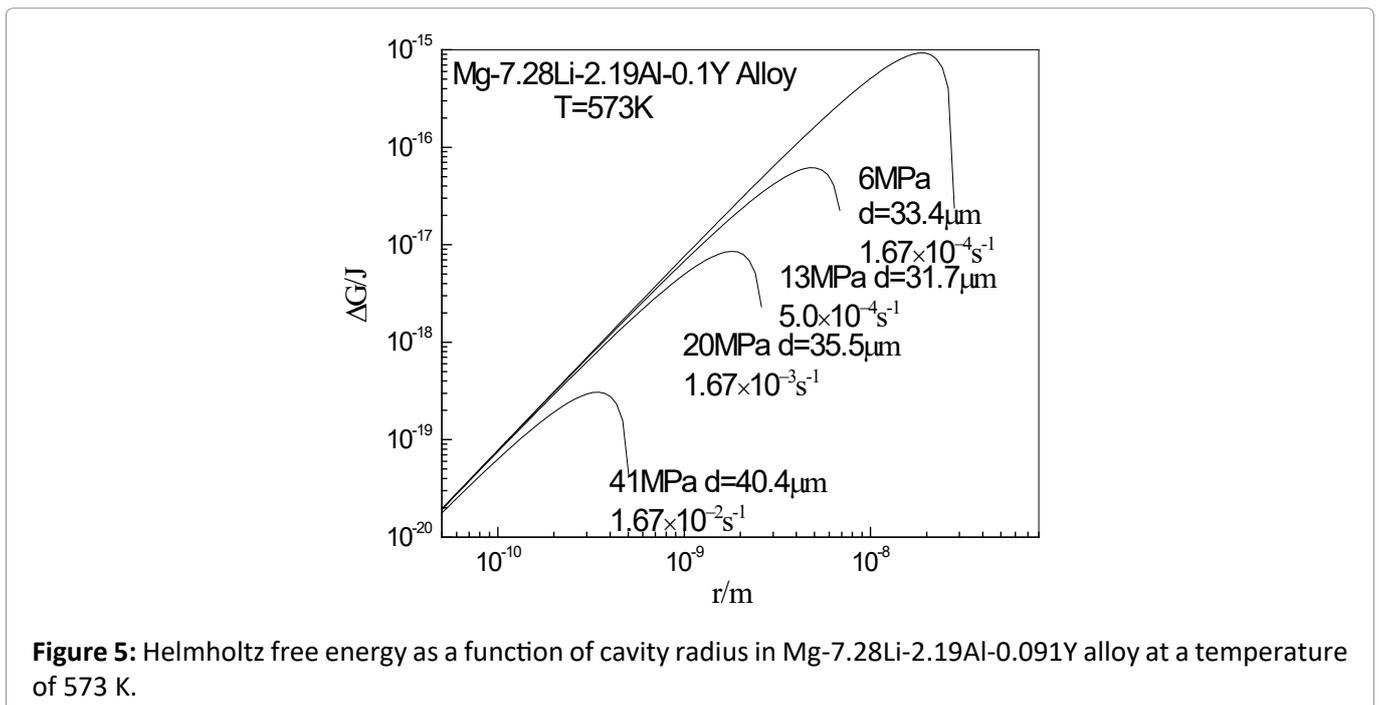
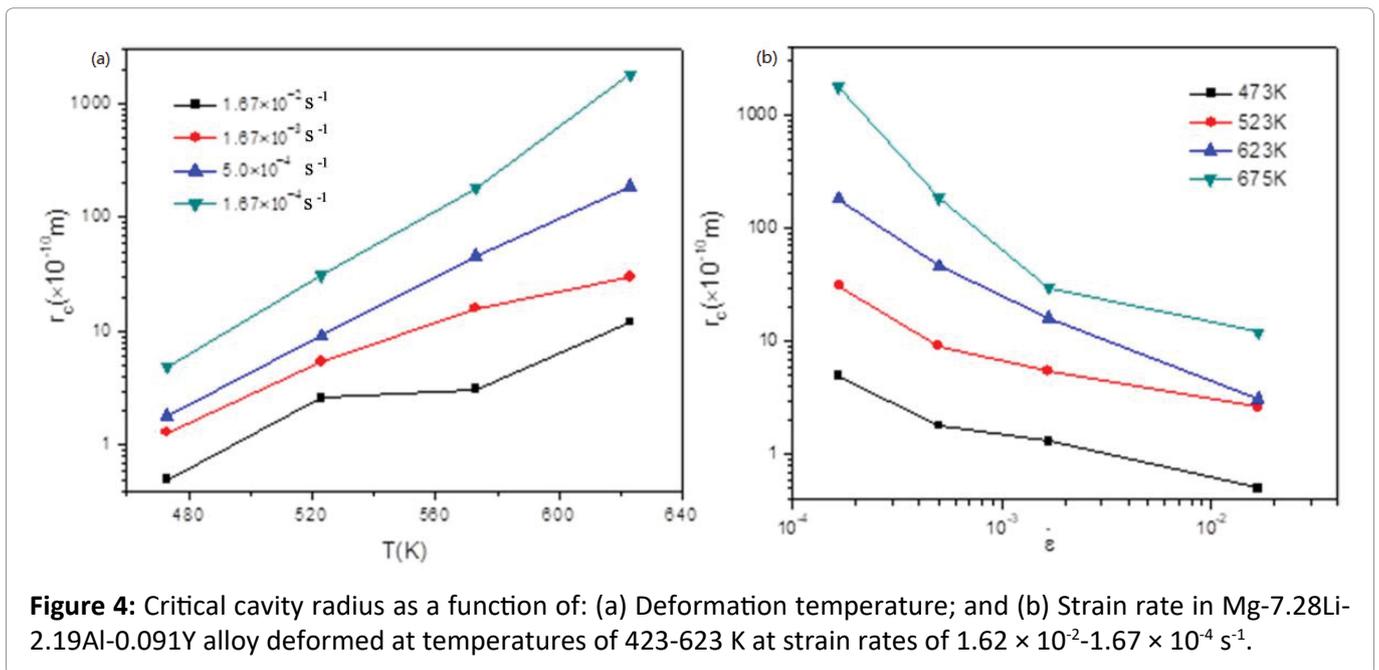
Figure 2 displays the macroscopic appearance of maximum superplasticity in Mg-7.28Li-2.19Al-0.091Y alloy. The maximum elongation to failure of 265.8% is obtained at a temperature of 623 K and a strain rate of  $5.0 \times 10^{-4} \text{ s}^{-1}$ .

Figure 3 shows the cavitations in Mg-7.28Li-2.19Al-0.091Y alloy specimen after tensile test to fracture

at the temperature of 573K with different initial strain rates. White grain is hexagonal closed-packed structured  $\alpha$ -Mg matrix. Yellow grain is body-centered cubic structured  $\beta$ -Li phase. Black part indicates the cavity or cavitation. The grain sizes ranging from 31.7 to 40.4  $\mu\text{m}$  exceed 10  $\mu\text{m}$ , and the present alloy is a coarse-grained alloy. Hence, this alloy is a two-phase coarse-grained alloy. It is visible that cavity or cavitation nucleates at interphase ( $\alpha$ -Mg/ $\beta$ -Li) boundary and  $\alpha$ -Mg grain boundary. In Figure 3b, cavity interlinkage (long strip-like cavitation) can be seen while in Figure 3d, cavity coalescence can be seen. In addition, cavity distribution is not homogeneous due to the local accumulation and relaxation of stress concentration.

### Calculation of cavity nucleation

To perform estimation of the critical cavity radius and plot Helmholtz free energy curves under different deformation conditions, the following experimental data and physics parameters or constants are collected. Flow stress,  $\sigma$ , is obtained from Figure 1 at a true strain of 0.2 ; Grain size,  $d$ , is obtained



from Figure 2;  $v = 0.28$  [22];  $b = 3.21 \times 10^{-10}$  m [22];  $\gamma = 1$  J/m<sup>2</sup> [23];  $G$  for Mg is given by [17]

$$G(\text{MPa}) = 1.66 \times 10^4 [1 - 0.49(T - 300) / 943] \quad (5)$$

where the definition of  $G$  and  $T$  are the shear modulus and absolute temperature in Kelvin.

Figure 4 displays the critical cavity radius as a function of deformation temperature and strain rate in Mg-7.28Li-2.19Al-0.091Y alloy. It is noted that at the given strain rate, critical cavity radius increases with increasing temperature, and cavity nucleation becomes difficult; at the given temperature, critical cavity radius decreases with increasing strain rate, and cavity nucleation becomes easy.

Figure 5 displays the curve of Helmholtz free energy as a function of cavity radius in Mg-7.28Li-2.19Al-0.091Y alloy at a temperature of 573 K. High flow stress leads to low peak free energy, and cavity nucleation becomes easy, whereas low flow stress leads to high peak free energy, and cavity nucleation becomes difficult. It is known from Eq. (4) that critical cavity radius,  $r_c$ , decreases with increasing applied stress,  $\sigma$ , which indicates that cavity under high applied stress is more apt to nucleation than that under low applied stress at given grain size. Meanwhile, it is known from Eq. (4) that critical cavity radius,  $r_c$ , decreases with increasing grain size,  $d$ , which indicates that coarse-grained alloy is more apt to cavity nucleation than fine-grained alloy at the given stress. The present alloy has coarse grain sizes and cavity nucleation is easy to initiate in this coarse-grained alloy, as proved by Figure 2.

## Conclusions

- (1) Cavity or cavitation nucleated at interphase boundary and at  $\alpha$ -Mg grain boundary in quasi-superplasticity Mg-7.28Li-2.19Al-0.091Y alloy subjected to rolling.
- (2) Helmholtz free energy map was plotted to predict the easy and difficulty of cavity nucleation in the present alloy. The present alloy had coarse grain sizes and cavity nucleation was easy to initiate in this coarse-grained alloy.
- (3) The maximum elongation to failure of 265.8% was demonstrated in this alloy at a temperature of 623 K and a strain rate of  $5.0 \times 10^{-4}$  s<sup>-1</sup>.

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