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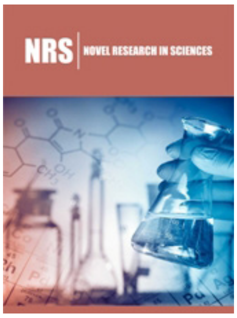
Research Article

ISSN: 2688-836X



Establishing A Superplastic Constitutive Model in Ultralight Microduplex Magnesium-Lithium Alloys

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Abstract

The constitutive model on superplastic ceramics is extended to superplastic metallic alloy, e.g. superplastic Mg-Li alloys. The newly established constitutive model is suitable for predicting typical super plasticity forming of Mg-Li alloys with high R-square of 0.99679.

Keywords: Mg-Li alloy; Super plasticity; Constitutive model; Deformation mechanism

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Submission: 📅 August 11, 2022

Published: 📅 August 22, 2022

Volume 11 - Issue 5

How to cite this article: Furong Cao*, Shuting Konga and Nanpan Guoa. Establishing A Superplastic Constitutive Model in Ultralight Microduplex Magnesium-Lithium Alloys. Nov Res Sci. 11(5). NRS. 000772. 2022.
DOI: 10.31031/NRS.2022.11.000772

Introduction

Super plasticity means the ability of a material to exhibit high ductility or elongation, typically elongation more than 400% under the condition of grain size smaller than 10μm, temperature higher than 0.5Tm where Tm is the absolute melting point [1,2]. During the early time, Ball A et al. [3], Mukherjee AK et al. [4], Gifkins RC [5], and Langdon TG [6] had proposed the superplastic mechanism of grain boundary sliding accommodated by dislocation slip, grain boundary ledge, and grain boundary nearby dislocations, and Ashby MA et al. [7] proposed the superplastic mechanism of grain boundary sliding accommodated by diffusion. They validated their models in simple system alloys. In recent years, Cao FR et al. [8] proposed a superplastic constitutive model and validated the equation in superplastic Mg-8Li alloy. Recently, Moshtaghioun BM et al. [9] proposed a superplastic constitutive model based on the energy of disclination dipoles and grain misorientation rotation and validated the model in typical ceramics. However, as we know, no one except the present authors establish a superplastic constitutive model in ultralight magnesium-lithium (Mg-Li) alloys. Hence, it is necessary to establish a superplastic constitutive model in Mg-Li alloys.

Mg-Li super plasticity has been studied for many years, and most reports are on the experimental superplastic behavior and microstructural evolution. To the best of the author's knowledge, little report is available establishing a superplastic constitutive model in Mg-Li alloys, no matter whether the alloy is simple system alloy or complex system alloy. Inspired by the report of Moshtaghioun BM et al. [9] in superplastic ceramics, we are going to extend this model to the metallic alloys, in particular, link this model to the experimental results of superplastic Mg-Li alloys. For this reason, this work is launched to establish a constitutive model in superplastic Mg-Li alloy.

Modeling and Results in Mg-Li Alloys

The superplastic model derived by Moshtaghioun BM et al. [9] is expressed as the following:

$$\dot{\varepsilon} = \frac{4\pi^3(1-\nu)}{\omega^3} e^{3/2} \frac{Gb}{kT} (\frac{\sigma}{G})^2 (\frac{b}{d})^2 D \quad (1)$$

where $\varepsilon^{\cdot}$ is the strain rate, ν is Poisson's ratio, G is the shear modulus, b is the magnitude of Burges vector of dislocation, σ is the true stress, D is the diffusivity, ω is the grain misorientation, k is Boltzmann's constant, T is the absolute temperature, and d is the grain size. Here, the dimensionless constant A is expressed as:

$$A = \frac{4\pi^3(1-\nu)}{\omega^3} e^{3/2} \quad (2)$$

Moshtaghioun BM et al. [9] do not mention whether diffusivity D is lattice diffusion or grain boundary diffusion. Here, effective diffusivity, Deff, is given by [10]

$$D_{eff} = D_L + x f_{gb} D_{gb} / D_L \quad (3)$$

Where D_L is the lattice diffusivity, $x=10^{-2}$ for super plasticity, $f_{gb}=\pi\delta/d$, δ is the grain boundary thickness, =2b, and Dgb is the grain boundary diffusivity. Atomic diffusion mechanism is judged by the following formula

$$\varnothing = X f_{gb} D_{gb} / D_L \quad (4)$$

when Ø>1, grain boundary diffusion dominates the diffusion process; when Ø<1, lattice diffusion dominates the diffusion process.

Shear modulus of Mg is given by [11]

$$G = 1.66 \times 10^4 [1 - 0.49 \ (\frac{T-300}{924})] \quad (5)$$

where T is the absolute temperature in Kelvin.

For dual phase Mg-Li alloy, the average grain size is determined by the following relation

$$d = X(\alpha)d_\alpha + x(\beta)d_\beta \quad (6)$$

where x(α) and x(β) are the volume fraction of α-Mg phase and β-Li phases, respectively. The volume fraction of α-Mg phase and β-Li phase is determined by metallographic level rule according to binary Mg-Li phase diagram [12].

To estimate the strain rate using model (1), experimental and physical parameters and estimated strain rates in different superplastic Mg-Li alloys are listed in Table 1. ω=4°=0.07 radian. ν =0.28 [13]. b=0.321nm [13]. k=1.38 x 10-23 J/K. Diffusivity D such as D_L and Dgb is calculated by the diffusivity formulae in our previous work [14]. Calculation as per Eq. (4) shows that lattice diffusion, $D_{L,}$ dominates the diffusion process.

Table 1: Experimental and physical parameters and estimated strain rates in different superplastic Mg-Li alloys.

Alloy	Temperature /K	Experimental strain rate $/s^{-1}$	True stress/ MPa	Grain size, d/μm	Diffusivity, DL/m^2 s^{-1}	Shear modulus, G/MPa	Estimated strain rate/s^{-1}	References
LZ91	473	3.33×10^{-4}	2.5	0.77	3.31×10^{-16}	15077	1.38×10^{-3}	Zhou MR et al. [15]
LZ81	548	1.91×10^{-3}	13.86[a]	6.88	1.35×10^{-14}	14417	1.95×10^{-2}	Mahrabi R et al. [16]
LZ85	473	1.0×10^{-3}	7.5	2.8	3.31×10^{-16}	15077	0.94×10^{-3}	Zhang TL et al. [17]
LZ82	563	1.5×10^{-4}	5.58	10	3.42×10^{-14}	14284.8	3.73×10^{-3}	Liu XH et al. [18]
L8	473	1.0×10^{-3}	21.45	0.5	3.31×10^{-16}	15077	5.09×10^{-4}	Matsuboshita H et al. [19]
LAZ1031	473	1.0×10^{-3}	10.5	6.38	8.32×10^{-17} [b]	15077	5.68×10^{-4}	Liu FC et al. [20]
L8	573	5×10^{-4}	2	7.5	4.27×10^{-15}	14197	1.05×10^{-4}	Cao FR et al. [21]
LAZ822	573	1.05×10^{-4}	2.5	1.52	4.27×10^{-15}	14197	4.0×10^{-3}	Cao FR et al. [22]
AZ1022	623	1.67×10^{-3}	6.1	3.75	5.78×10^{-13}	13756.62	1.12×10^{-2}	Cao FR et al. [23]

a: Conversion of shear strain rate and stress to normal strain rate and stress.

b: Corrected by phase ratio of α-Mg: β-Li=0.08:0.92.

Figure 1 presents the relation of theoretical strain rate and experimental strain rate. According to Figure 1, the following formula is obtained.

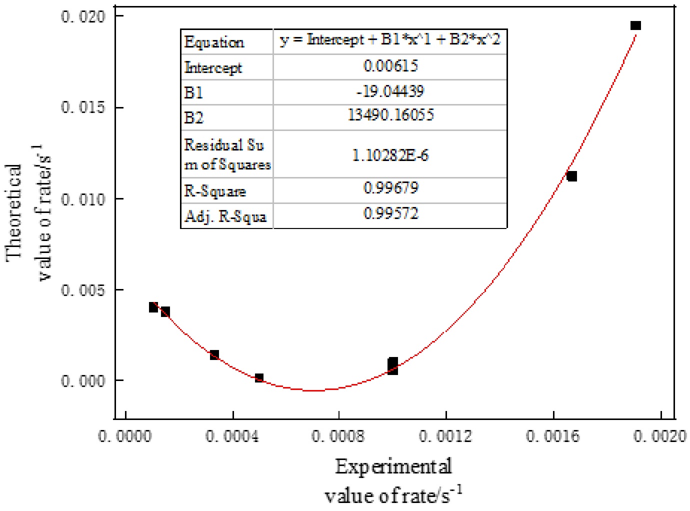

Figure 1: Relation of theoretical strain rate and experimental strain rate.

$$y = 0.00615 - 19.04439X + 13.490.16055X^2 \quad (7)$$

The R-square is 0.99679, indicative of high correlation. Based on Eq. (7), x is solved as follows.

$$X = \sqrt{7.41281\times10^{-5}y + 4.23537\times10^{-8}} + 7.05862\times10^{-4} \quad (8)$$

Since true strain rate is experimental strain rate, the following constitutive model is obtained.

$$\dot{\varepsilon} = \sqrt{87.1746456\frac{Gb}{kT}(\frac{\sigma}{G})^2(\frac{b}{d})^2 D_L + 4.23537\times10^{-8}} + 7.05862\times10^{-4} \quad (9)$$

Eq. (9) is the constitutive model that is suitable for superplastic Mg-Li alloys. As shown in Table 1, the scope of application of this model is suitable for micro duplex alloy with typical super plasticity. The scope of grain size ranges from ultrafine-grained to fine-grained alloy [15-23]. Estimation of strain rate in Ref. [18] indicates that larger derivation between experimental strain rate and estimated strain rate appears when pronounced dynamic grain growth occurs. Hence, the microstructure should be thermal stable without dynamic grain growth. In addition, the new model is not suitable for quasi-super plasticity or super plasticity-like Mg-Li alloys whose elongations are in the range of 200~300%. It is worth mention that a few reports [24-26] on typical super plasticity of Mg-Li alloys are not collected in Table 1 because they are lack of individual experimental data. The other relevant reports on typical super plasticity of Mg-Li alloys not mentioned in Table 1 are in like manner.

Conclusion

The constitutive model of Moshtaghioun BM et al. [9] report on superplastic ceramics is extended to superplastic metallic alloy, e.g. superplastic Mg-Li alloys. The newly established constitutive model is suitable for predicting typical super plasticity forming of Mg-Li alloys with high R-square of 0.99679.

Acknowledgement

This work is supported by National Natural Science Foundation of China (Grant no. 51334006).

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