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Review Article

A Review on Superplastic Formation Behavior of Al Alloys

Xiao-guo Wang,[1,2] Qiu-shu Li,[1] Rui-rui Wu,[1] Xiao-yuan Zhang,[2] and Liyun Ma[3]

[1]*School of Materials Science and Engineering, Taiyuan University of Science and Technology, Taiyuan 030024, China*
[2]*Department of Mechanical and Electrical Engineering, College of Information, Shanxi Agricultural University, Taigu 030800, China*
[3]*Department of Mining Engineering, Luliang University, Lishi 033000, China*

Correspondence should be addressed to Qiu-shu Li; liqiushu@tyust.edu.cn

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Superplastic formation technology is considered to be an effective and promising method to conquer formation difficulties of Al alloys, especially thin-walled or complex structure. In this paper, fundamentals of superplastic deformation of Al alloys are summarized and the superplastic deformation behaviors of main kinds of Al alloys are summarized and compared, including Al-Mg alloys, Al-Li alloys, and Al-Zn-Mg alloys as well as aluminum matrix composites. Then, the superplastic deformation mechanism for different Al alloys is thoroughly discussed. Last but not the least, the factors affecting the superplastic deformation process are fully analyzed.

1. Introduction

1.1. Superplasticity of Materials. Generally speaking, superplasticity [1–6] is a characteristic of some materials with equiaxed and fine grains, when they are deformed in tension at relatively high temperature ($(0.5–0.7)T_{\mathrm{m}}$) and low strain rate [7, 8], which has been discovered in various materials. Remarkable elongation is a notable symbol of superplasticity, for example, Sn–Bi eutectic alloys [9] under superplastic tensile tests exhibiting outstanding elongation, as much as 1950%. The superplastic elongations of main Al alloys can vary from 200% to 2000%, and the elongation of some superplastic materials can be up to 8000%. The superplastic characteristics of materials tremendously improve their formability with reduced deformation resistance and viscous/semiviscous flow during plastic deformation, particularly for complicated structure components.

It is well acknowledged that strain hardening occurs during plastic deformation, of which the constitutive equation [10] is affected by strain-hardening exponent n, as shown in Equation (1). The constitutive equation of superplastic deformation at relatively low temperature abides to viscoplastic Equation (2) proposed by Rossard, which indicates that the process combines strain hardening with strain rate hardening. The constitutive equation of superplastic deformation at relatively high temperature acts up to flow stress Equation (3) proposed by Backofen et al., implying that the process is mainly manipulated by strain rate sensitivity exponent m:

$$\sigma = K\varepsilon^{n}, \tag{1}$$

$$\sigma = K\varepsilon^{n}\dot{\varepsilon}^{m}, \tag{2}$$

$$\sigma = K\dot{\varepsilon}^{m}, \tag{3}$$

where σ is the true stress, ε is the true strain, $\dot{\varepsilon}$ is the strain rate, n is the strain-hardening exponent, m is the strain rate sensitivity, and k is a parameter for material.

1.2. Superplastic Formability of Al Alloys. Because of their low density and high specific strength combined with exceptional corrosion resistance, Al [11–14] are the most widely utilized alloys in aerospace, automobiles industry, mechanical manufacturing, marine business, and chemical industry. Superplastic forming technology (SFT), which can dramatically decrease flow/residual stress and improve formation quality, has been commonly used to manufacture complex shapes in sheet or tube. The Al alloys used are capable of achieving equivalent thickness strains in excess of 300% at low strain rates. Companies like Superform and Alcoa have successfully applied SFT to produce Al alloy automobile parts (decklid, fenders, door inners, and brake disk) with 50% weight saving [15]. In 1991, 8090 Al alloys were used to produce military aircraft doors by SFT with 23% weight reduction and 68% cost reduction.

To enhance the superplastic formability of Al alloys, it is necessary to make the alloys to go through several advanced forming technologies, such as flake powder metallurgy [16] and cryo-deformation [17–20] as well as severe plastic deformation (SPD) [21], including friction stir processing (FSP) [22–28], equal-channel angular pressing (ECAP) [29–35], high-pressure torsion (HTP) [36], accumulative roll bonding (ARB) [37], multiaxial alternative forging (MAF) [38], and repetitive corrugation and straightening (RCS) [39, 40]. After SPD process, ultrafine grain, high superplasticity, and low flow stress are available for Al alloys. Yet, due to high cost, additionally required technologies may hold back the direct and full commercial application of SPD technology. Meanwhile, more and more energy and resources are pouring into developing new and convenient hot/cold mechanical processing for superplasticity of various Al alloys. Therefore, thermal-mechanical processing (TMP) [41–43], which is mainly based on the principles of static recrystallisation [44–47] and dynamic recrystallisation [48, 49], is also an important way to develop superplasticity of Al alloys.

2. Fundamentals of Superplastic Deformation of Al Alloys

2.1. Stacking Fault Energy. It is well known that Al and Al alloys are with high stacking fault energy (SFE) which is a significant intrinsic material parameter that would change mechanisms and grain refinement during superplastic deformation. In Al and Al alloys, recovery is not totally suppressed during superplastic deformation. Additionally, lowering the SFE would promote deformation twinning over dislocation slip and increase dislocation slip-twinning transition temperature [50, 51].

2.2. Strain-Hardening Ability. It is clear that strain hardening is a typical phenomenon in plastic deformation. In the primary stage of superplastic deformation, flow stress rapidly rises with flow strain due to appearance of massive defects (vacancies/dislocations/twinning). As the process goes on, strain softening, due to recovery/recrystallisation/cross slip, starts to offset or partially offset the increase of flow stress until there is a dynamic balance between the hardening and softening processes, namely, steady stage of superplastic deformation. The strain-hardening ability is strongly dependant on temperature and strain rate of superplastic deformation, as shown in Figure 1. The true stress increases with increase in strain rate and decrease in temperature, which is explained in Section 4.2.

2.3. Superplastic Deformation Behavior. After rolling or SPD, Al alloys consist of banded microstructure with subgrain boundaries (SGBs) and low-angle boundaries (LABs). Following homogenization annealing, Al alloys are recrystallised and the microstructure combined with equiaxed recrystallised grains with weakened banded grains is formed before superplastic tensile tests. The early stage of superplastic deformation of Al alloys is usually accompanied with static/dynamic grain growth and anisotropic grain elongation. It should be noticed that grains are more elongated in the tensile direction than in the transverse direction [53, 54]. Yet, the static/dynamic grain growth is closely related to the distribution of intermetallic precipitates, which is fully discussed in Section 4.2. With the increase in strain, the previous microstructure is replaced by a more equiaxed and uniform grain structure and the banded grains are vanished.

2.4. Crystallographic Texture. Crystallographic texture is a preferred orientation structure of grains in ploycrystalline materials.

Being subjected to the formation process (casting, rolling, recrystallisation, and heat treatment), Al and Al alloys, typical FCC ploycrystalline materials, would produce corresponding texture. The main crystallographic texture components in FCC metals are listed in Table 1.

Prior to superplastic deformation, the microtexture of rolled/SPD Al alloys is of a strong brass texture [17, 55], which is a dominant plane strain hot deformation texture for Al alloys. After homogenization annealing for proper period, Al alloys exhibit cube, near cube, rotated cube, or decreased brass component. As the strain of superplastic deformation increases, a randomization of the microtexture happens along with the increase in misoriented boundaries; therefore, the alloys exhibit a very weak texture component as cube, near cube, rotated cube, or decreased brass component. Figure 2 shows ODFs representative sections of Al-Zn-Mg-0.25Sc-0.10Zr during superplastic deformation. In summary, the overall texture intensity of Al alloys is substantially reduced following superplastic deformation and no new orientation is developed.

2.5. Strain Rate Sensitivity (m) and Deformation Activation Energy (Q). Usually, superplastic deformation can be described by an equation for power-law creep in the following form:

$$\dot{\varepsilon} = A\frac{D_0 G b}{RT}\left(\frac{b}{d}\right)^p\left(\frac{\sigma}{G}\right)^{1/m}\exp\left(-\frac{Q}{RT}\right), \quad (4)$$

where $\dot{\varepsilon}$ the is strain rate, Q is the activation energy of an appropriate diffusion process, A and p are the empirical material constants, G is the shear modulus, b is the Burgers vector, R is the gas constant, T is the absolute temperature, D_0 is the frequency factor, and m is the strain rate sensitivity exponent ($1/m$ is the stress exponent n, $n = 1/m$).

Strain rate sensitivity (m) is a critical parameter for superplastic deformation, as its value characterizes the ability of an alloy to resist necking spread during

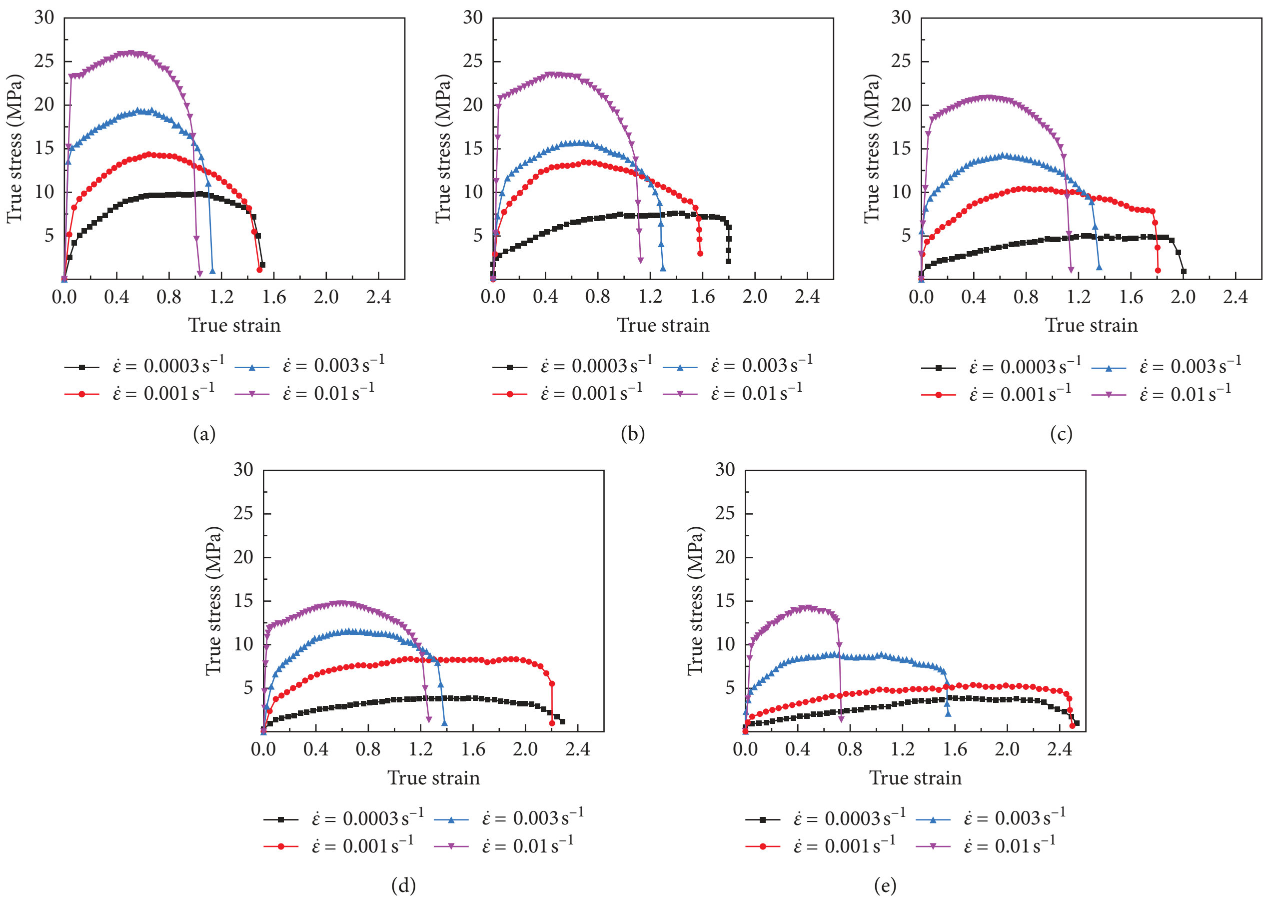


Figure 1: True stress-true strain curves of 7B04 Al alloy after superplastic deformation under different parameters: (a) 470°C; (b) 485°C; (c) 500°C; (d) 515°C; (e) 530°C [52].

Table 1: Main texture components in FCC metals.

Texture	{*hkl*}	<*uvw*>	Φ_1 (°)	Φ (°)	Φ_2 (°)
Cube	{0 0 1}	<1 0 0>	00	0	0
Rotated cube	{0 0 1}	<1 1 0>	45	0	0
Copper	{1 1 2}	<1 1 1>	90	35	45
Brass	{0 1 1}	<2 1 1>	35	45	0
Goss	{0 1 1}	<1 0 0>	0	45	0
S	{1 2 3}	<6 3 4>	59	37	63
R	{1 2 4}	<2 1 1>	57	29	63

deformation. The larger the value of strain rate sensitivity is, the greater the superplastic elongation will be. Additionally, it should be aware that m constantly varies during superplastic deformation. According to Equation (3), after logarithmic transformation, strain rate sensitivity can be stated as

$$m = \frac{\partial \ln \sigma}{\partial \log \dot{\varepsilon}}\bigg|_T. \quad (5)$$

Normally, the varying value of the strain rate sensitivity indicates different mechanisms of superplastic deformation. When the value of the strain rate sensitivity is around 0.3, the main mechanism of superplastic deformation of Al alloys is GBS accompanied with other accommodation mechanisms (Section 4.1). When the value of the strain rate sensitivity is around 0.5, the dominant mechanism of superplastic deformation of Al alloys is GBS. With increasing value of strain rate sensitivity, GBS gradually becomes the main mechanism of superplastic deformation of Al alloys and is responsible for the majority part of superplastic deformation of Al alloys.

During plastic deformation of metals, deformation activation energy Q represents the energy required for the transition atoms in each mole to jump across the barrier. Essentially, superplastic deformation is a thermal activation process. Equation (6) is applied to calculate the activation energy (Q), which is a critical dynamic parameter to indicate the level of difficulty of plastic deformation of materials at relatively high temperature. The values of the activation energy (Q) for different deformation mechanisms are different. During superplastic deformation, the value of Q for the dislocation pipe diffusion in aluminum is 82 kJ/mol, the value of the grain-boundary sliding is 84 kJ/mol, and the value of lattice self-diffusion of pure aluminum is 142 kJ/mol:

$$Q = \frac{R}{m}\frac{\partial \ln \sigma}{\partial (1/T)}\bigg|_{\dot{\varepsilon}}, \quad (6)$$

where R is the gas constant, m is the strain rate sensitivity, σ is the flow stress, and T is the absolute temperature.

Average values of m and Q during superplastic deformation of different aluminum alloys are listed in Table 2.

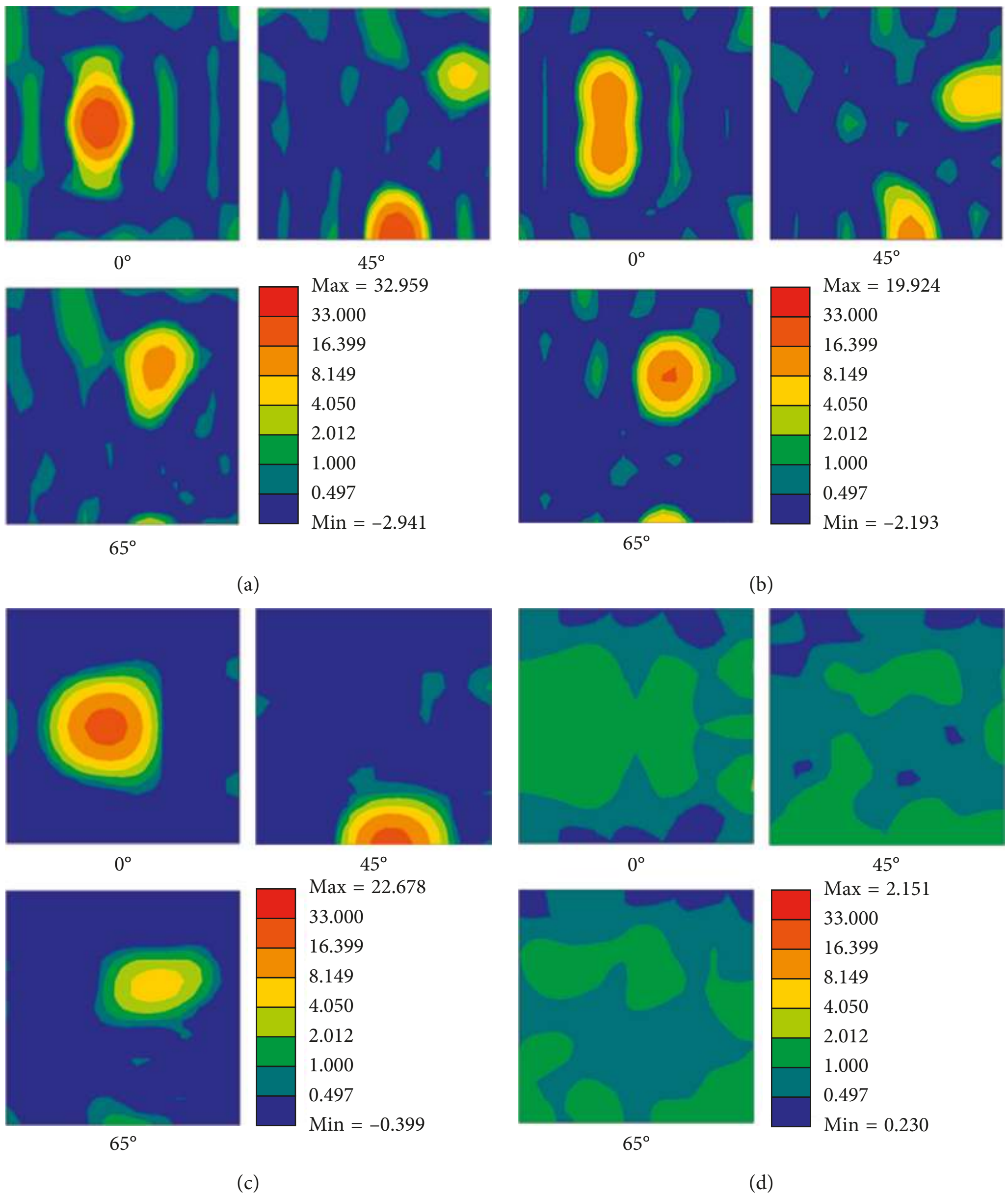


FIGURE 2: ODFs representative sections of the Al-Zn-Mg-0.25Sc-0.10Zr alloy deformed at 500°C and $1 \times 10^{-2} \cdot s^{-1}$ after interrupting the tensile test at different strains: (a) $\varepsilon = 0$; (b) $\varepsilon = 0.69$; (c) $\varepsilon = 1.10$; (d) $\varepsilon = 2.40$ [42].

TABLE 2: Reference data to illustrate range and average values of m and Q during superplastic deformation.

Alloy type	T (°C)	Strain rate (s^{-1})	M	Q (kJ/mol)	Reference
Al-Mg-Sc-Zr	450–525	1.67×10^{-3}–1×10^{-1}	0.36–0.42 0.39	90–126 107	[43]
Al-Zn-Mg-Sc-Zr	450–500	1×10^{-3}–1×10^{-1}	0.35–0.40 0.37	83.8–85.0 84.5	[42]
Al-Zn-Mg-Sc	450–500	1×10^{-3}–1×10^{-2}	0.46–0.51 0.50	83.8–85.6 85	[56]
Al-Mg-Sc-Zr	425–500	1×10^{-3}–1×10^{-1}	0.35–0.53 0.43	93.269–177.517 143.762	[57]
Al-Mg-Li	430–570	5×10^{-4}–1×10^{-3}	0.41–0.85 0.61	—	[58]
Al_3Ti/2024Al	450–540	0.15–1.5	—	206	[59]

3. The Superplastic Behaviors of Al Alloys

3.1. Al-Mg Alloys. Ye et al. [58, 60–67] developed a thermal-mechanical process to produce fine-grained Al-Mg-Si alloy plates with the chemical composition of Al-5.2%Mg-2.1%Li-0.12%Zr(wt.%) for superplasticity research. The uniaxial tensile tests were conducted at initial strain rates ranging from 0.01 to 0.0005/s in the temperature interval of 450°C–570°C. It turned out that great elongations of 580–915% were obtained at 510°C–540°C and initial strain rate between 0.001/s and 0.0005/s, in which the optimal elongation of about 915% occurred at a temperature of 525°C and an initial strain rate of 0.001/s.

Mikhaylovskaya et al. [68] put emphasis on the different superplastic deformation behaviors of two fine-grained AA5083 alloys, with and without chromium content, at elevated temperature from 500°C to 560°C and constant strain rates of 0.0005/s, 0.001/s, and 0.002/s. The sigmoidal shape of the stress-strain rate curves obtained for both alloys imply that they were subjected to superplastic deformation.

Duan et al. [41] studied the superplasticity of Al-Mg-0.15Sc-0.10Zr alloy, using a simple thermal-mechanical processing. Their work revealed that the cold rolled alloy sheet exhibited excellent superplasticity (elongation of ≥800%) at a temperature range of 450°C–500°C and a high strain rate range of 0.01–0.1/s. A maximum elongation of 1579% was achieved at 475°C and a high strain rate of 0.05/s.

Xu et al. [69] performed a research on high strain rate superplasticity of an Al-6.1Mg-0.25Sc-0.1Zr (wt.%) alloy by original asymmetrical rolling technology. The alloy sheets were subjected to both plane strain deformation and additional shear component along the rolling direction, simultaneously, owing to the different circumferential velocities of the two rotary rolls. The studied alloy exhibited fantastic superplasticity (elongation >1000%) at the temperature interval of 450°C–500°C and relatively high strain rates ranging from 0.01/s to 0.25/s. The highest ductility of 3200% is achieved at 500°C and 0.05/s. Compared with the same materials produced by traditional rolling, asymmetrical rolling technology can increase the optimum strain rate up to 10 times.

Li et al. [43] dealt with the superplastic behavior of an Al-5.8Mg-0.4Mn-0.25Sc-0.1Zr (wt.%) alloy at the temperature interval of 450°C–525°C and strain rates ranging from 0.00167/s to 0.1/s. Experimental results showed that the alloys exhibited nice elongation, ranging from 230% to 740%, and the maximum elongation of 740% was achieved at 500°C and the initial strain rate of 0.00667/s.

3.2. Al-Li Alloys. Xinming Zhang et al. [70–76] did superplastic investigation on 2A97 Al-Li alloy at the temperature range of 480°C–490°C and strain rates of 0.001–0.0025/s. The results indicated that the alloy exhibited promising elongation, ranging from 600% to 850%, and the highest elongation of 850% was achieved at 490°C and the initial strain rate of 0.002/s.

Zhang et al. [55] conducted superplastic investigation on 5A90 Al-Li alloy at the temperature range of 450°C–500°C and strain rate of 0.0003–0.0018/s. The results indicated that the alloy exhibited promising elongation, ranging from 310% to 1050%, and the greatest elongation of 1050% was achieved at 475°C and the initial strain rate of 0.0008/s.

3.3. Al-Zn-Mg Alloys. Wang et al. [77–86] performed superplastic investigation on the friction stir processed (FSP) Al-Zn-Mg-Cu alloy at the temperature of 500°C–535°C and a high strain rate of 0.01/s. The results proved that the FSP Al-Zn-Mg-Cu alloy possesses excellent thermal stability even up to incipient melting temperature; furthermore, a highest elongation of 3250% was obtained at 535°C and 0.01/s.

Mikhaylovskaya et al. [87] compared the superplastic deformation behavior of two aluminum AA7XXX alloys with Sc and Zr additions distinguished by the presence and absence of coarse eutectic Al_9FeNi particles. The experimental results were that the alloy with Sc(0.1%) and Zr (0.2%) additions and eutectic Al_9FeNi particles (a size of 1.8 μm and a volume fraction of 0.085) exhibits high superplasticity (elongation of 300%–915%) at the temperature interval of 400°C–500°C and strain rates ranging from 0.005/s to 0.01/s. The highest ductility of 915% is achieved at 480°C and 0.01/s. On the contrary, the alloy with same Sc (0.1%) and Zr(0.2%) additions and without Al_9FeNi particles did not elongate more than 340%, and there is no superplasticity at high strain rates (more than 0.01/s).

The superplastic performances of the abovementioned aluminum alloys are listed in Table 3.

3.4. Aluminum Matrix Composites. A great number of researchers [90, 91] have been constantly focusing on developing high strain rate and low temperature superplastic formation technology for aluminum matrix composites. The most recent works about superplasticity of aluminum matrix composites are listed in Table 4.

4. Discussion

4.1. Mechanisms of Superplastic Deformation. Enormous efforts and researches have been done on what is the exact mechanism of superplastic deformation, yet there is not a unified conclusion.

Generally speaking, superplastic deformation is mainly controlled by three mechanisms: grain-boundary sliding (GBS), dislocation slip/creep, and diffusion creep or directional diffusional flow [53]. Meanwhile, superplastic deformation is accompanied by various processes, for instance, grain-boundary migrations and static/dynamic grain growth, grain rotation [80, 99], recovery, recrystallisation, and polygonisation [87, 100, 101]. It is commonly accepted that GBS at low strain rates and creep by glide plus climb, also named slip creep, at high strain rates are the dominant controlling mechanisms that operate during high-temperature deformation of fine-grained metallic materials [102–104]. The contribution of GBS in the total strain varies with different Al alloys.

The work of Duan [105], Liu [106], and Cao [107] showed that GBS is a predominant mechanism of superplastic deformation of Al-Zn-Mg-Sc(Zr) alloys. Bate [108]

Table 3: Deformation conditions of optimal superplastic elongation of Al alloys.

Al alloys (wt.%)	Temperature (°C)	Strain rate (s^{-1})	Elongation (%)	Reference
Al-5.2Mg-2.1Li-0.12Zr	525	0.001	915	[58]
Al-Mg-0.15Sc-0.10Zr	475	0.05	1579	[41]
Al-6.1Mg-0.25Sc-0.1Zr	500	0.05	3200	[69]
Al-5.8Mg-0.4Mn-0.25Sc-0.1Zr	500	0.00667	740	[43]
Al-5.3Mg-2.1Li-0.11Zr	475	0.0008	1050	[55]
Al-5Mg-0.2Sc	520	0.056	2300	[88]
Al-3Mg-0.2Sc	400	0.033	2280	[89]
Al-3.8Cu-1.4Li(2A97)	490	0.002	850	[76]
Al-5.85Zn-2.56Mg-1.89Cu	535	0.01	3250	[86]
Al-6Zn-2.3Mg-1.7Cu(7B04)	530	0.0003	1105	[52]
Al-5.6Zn-2.2Mg-1.5Cu(7475)	515	0.0005	590	[46]
Al-5.41Zn-1.9Mg-0.25Sc-0.1Zr	500	0.01	1523	[76]
Al-5.36Zn-1.9Mg-0.1Sc-0.1Zr	500	0.005	1050	[56]
Al-5.4Zn-2Mg-0.25Sc-0.1Zr	200	0.01	539	[57]

Table 4: Deformation conditions of optimal superplastic elongation of aluminum matrix composites.

Composites	Temperature (°C)	Strain rate (s^{-1})	Elongation (%)	Reference
20wt.%Si_3N_{4P}/5052	545	0.001	700	[92]
10wt.%SiC_P/2024	480	0.001	345	[93]
20wt.%Si_3N_{4P}/2124	510	0.04	840	[94]
15wt.%SiC_P/IN9021	550	0.005	610	[95]
17.8wt.%SiC_P/2124	490	0.083	425	[96]
15wt.%SiC_P/6A02	560	0.00089	250	[97]
12wt.%SiC_P/5052	550	0.0011	405	[98]
5wt.%Al_3Ti/2024	510	0.15	640	[59]

concluded that the major superplastic deformation mechanism of Al-6Cu-0.4Zr alloy may be an intragranular dislocation slip. Katsas [109] considered that dynamic recrystallisation process results in the superplastic deformation of Al-1Zr alloy. Sotoudeh [110] and Bricknell [111] believed that diffusion creep is the main superplasticity mechanism of "supral type" alloys with banded microstructure. del Valle et al. [112] concluded that Al alloys that were composed of fine-equiaxed grains at the start of the superplastic test deformed mainly by GBS at low strain rate with only small evidence of dislocation activity and slip creep was the controlling mechanism at high strain rate superplastic deformation. The research of Wang et al. [86] indicated that the presence of a liquid phase because high experimental temperature plays a vital role in the extraordinary elongation of the alloy by relaxing the stress concentration and suppressing the the appearance of cavities during deformation. Jiao [59] also supported that a certain amount of liquid phase during superplastic deformation can properly enhance the superplasticity of aluminum alloys. Meanwhile, Johannes and Mishra [113] concluded that fiber (whisker) formation (Figure 3) was the evidence of the existence of liquid phases along grain boundaries. Furthermore, Duan et al. [56] thought the existence of fiber as an indirect evidence for GBS.

Commonly, fine and equiaxed grains are typical features of superplastic materials. It is fully established by a great number of theories and researches that grain-boundary sliding is the dominant reason that fine-grained materials are able to develop superplastic deformation. During deformation, materials migration and grain-boundary sliding happen simultaneously in order to assure intergranular accommodation. Moreover, it is necessary for another mechanism to accommodate stress concentration resulting from GBS. There are two main accommodation mechanisms for GBS, diffusion creep and dislocation sliding.

After a thorough research, Ashby and Verrall proposed the classic mechanism theory of GBS with diffusion creep for superplastic deformation, the theoretical model of which is shown in Figure 4. The Ashby–Verrall model (Figure 3) interprets how the equiaxed grains move by means of GBS. Though the shape of grains stay the same after sliding,the overall morphology changes, which is in agreement with macroelongation. Moreover, Ashby and Verrall explained that the strain difference between the initial and final circumstances is accommodated by grain-boundary diffusion and volume diffusion, as well as the ability of grain-boundary diffusion is much stronger than that of volume diffusion.

Currently, there are three models for theories of grain-boundary sliding accommodated by dislocation sliding, which are introduced in Table 5.

Additionally, it is considered that the mechanism of superplastic deformation for Al alloys is related to the microstructure status of the alloys prior to the deformation. After TMP, there are two ways to obtain fine grains for the alloys, which would result in different mechanisms of superplastic deformation. On one hand, if the thermal-mechanically treated alloys are subjected to recrystallisation annealing treatment, the main deformation mechanism of superplastically deformed alloys is concurrently controlled by

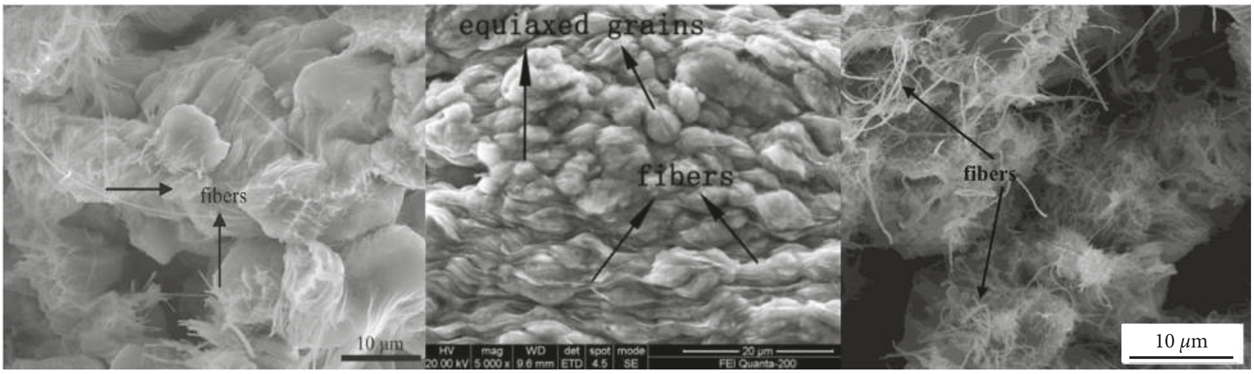


FIGURE 3: SEM image of fracture morphology of superplastically deformed Al alloys [41, 42, 57].

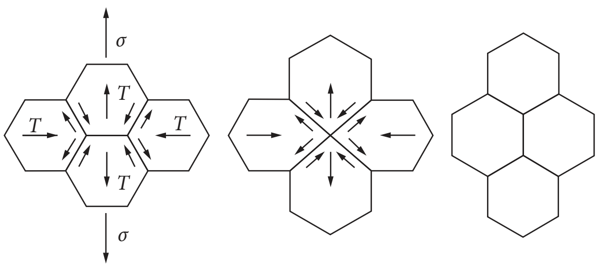


FIGURE 4: The Ashby–Verrall theoretical model for superplastic deformation. (a) Initial. (b) Intermediate. (c) Final.

both grain-boundary sliding (GBS) and accompanied accommodation mechanism which include dislocation motion [116–118], creep diffusion [119], and liquid phase [86], aiming to relax the stress concentration. On the other hand, when the thermal-mechanically treated alloys directly experience superplastic deformation, during the primary stage of deformation, the mechanism is controlled by deformation-induced continuous recystallisation (DICR) due to the occurrence of dynamic recrystallisation. Subsequently, the superplastic deformation mechanism is similar to static recrystallisation, after dynamic recrystallisation is completed.

4.2. Factors Affecting Superplastic Deformation Behavior

4.2.1. Temperature of Superplastic Deformation. Fundamentally speaking, superplasticity is a thermally activated phenomenon; therefore, the deformation temperature is a crucial factor. It is commonly accepted that there is a basic requirement for the Al alloys to exhibit superplasticity, which is that the deformation temperature shall be more than $0.5T_m$ (melting temperature). As the temperature keeps rising, the viscous forces within grain boundaries gradually reduce and grain boundaries become more and more unstable. As a result, the grain boundary begins to slide with relative ease, which makes the tensile test sample to show better elongation. However, if the temperature is too high, grain boundaries are excessively softened and grain-boundary binding force dramatically decreases, which lead to less elongations. It can be seen from Figure 5 that the superplastic elongations are intensively changed with different temperatures of superplastic deformation and there is an optimal temperature for each kind of aluminum alloy.

Zhang et al. [52] found out that superplastic property of Al alloys started to decline and became insensitive to deformation temperature when the alloys were superplastically deformed at relatively high strain rates.

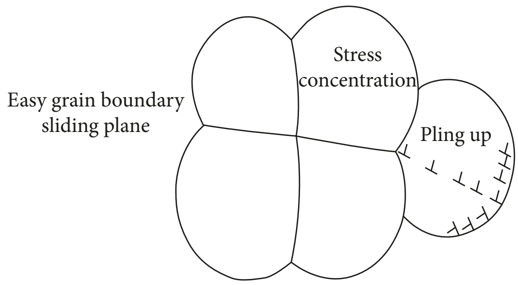
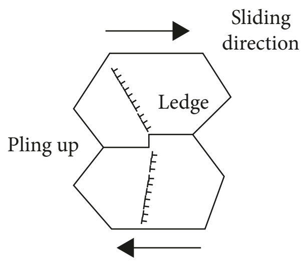
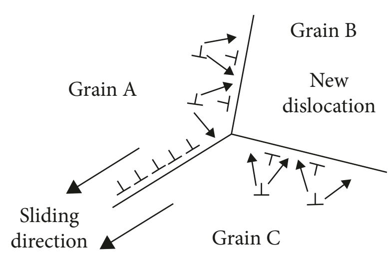
4.2.2. Strain Rates of Superplastic Deformation. Besides deformation temperature, stain rates also could notably influence the superplasticity of Al alloys. As shown in Equation (3), the true stress σ is highly dependent on the strain rate $\dot{\varepsilon}$, so it also means that the superplastic deformation process of Al alloys is significantly affected by the strain rate.

Researches [120, 121] indicate that one precondition of superplasticity is that the stain rates should be in the range of 10^{-4}–10^{-1}/s. Figure 6 shows the correlation between superplastic elongation and varying initial strain rates at different temperatures of different Al alloys. It can be seen that relatively low strain rates are in favor of better superplasticity. Deformed at lower initial strain rates, the Al alloys exhibit an extended strain-hardening phenomenon and decreased strain-hardening rates due to dislocation relaxation triggered by accommodation mechanisms of GBS. At the same time, the microstructure of Al alloys after superplastic deformation is partially determined by strain rates. Low strain rates could result in coarseness of the microstructure ascribed to recovery and recrystallisation processes. Better superplasticity resulting from relatively low strain rates comes at a price of great amount of time, which strongly restricts further application of superplastic deformation of Al alloys. Consequently, high strain rate superplasticity (HSRSP) [122–127], which can not only dramatically reduce the consuming time but also develop high superplasticity, is attracting more and more attention.

4.2.3. Precipitates Particles. Prior to superplastic deformation, particles with different size, locations, and shapes are distributed in the grains and at the boundaries, which will play a very important role during superplasticity.

By adding a few amount of trace element, high density of coherent fine precipitates (Al_3(Zr,Sc), ~30 nm [128–131]; Al_6(Mn,Cr), 38 ± 7 nm [68]) are formed and dispersed both at grain boundaries and within the grain interiors, which will strongly retard the grain growth during

Table 5: Three models for theories of grain-boundary sliding accommodated by dislocation sliding.

Models	Schematic illustration of the mechanism of superplasticity	Introduction of the models
Ball–Hutchison model [114]		During deformation, grain boundaries are properly aligned and slide as groups. When the sliding is blocked by other grains, the local stresses would result in dislocation in the blocking grain, piling up at the opposite grain boundary until the back stress stops further generation of dislocation. The piled up dislocations could climb into and along the grain boundary. Thus, grain-boundary sliding, which is governed by the kinetics of climb along grain boundary to annihilation areas, is feasible due to the constant replacement of the dislocation.
Mukherjee model [115]		The model elaborates dislocation accommodated sliding mechanism of single grain. Dislocations are generated at scraggy surfaces of grain boundaries. The alignment mechanism of the generated dislocations is the same as that of the Ball–Hutchison model.
Gifkins model [116]		Gifkins described grain-boundary sliding and accommodation process as grain-boundary dislocation motion and proposed the core-mantle model. Grain-boundary sliding around grain triple junctions is accommodated by generation of new dislocation and their climbing along the boundaries. Dislocation motion is constrained to occur at grain boundary and mantle area rather than in the core of grain. According to the model, grains are able to slide by switching places in three-dimensional space.

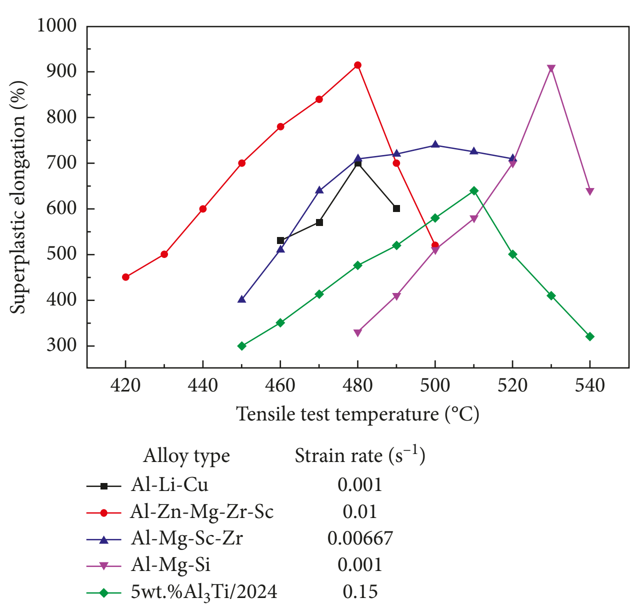


Figure 5: Variation of superplastic elongations of different Al alloys with initial strain rates at various temperatures.

recrystallisation and inhibit the movement of grain boundaries, subgrain boundaries, and dislocation by the Zener pinning effect (Figure 7). Furthermore, the stability of cavity can be partially attributed to additional interfacial energy of Al_3(Zr,Sc) particles.

Besides nanoscale particles, there are also existence of other coarse particles (Al_9FeNi, ~1.8 μm, Figure 8 [87]) that affect superplastic deformation. These coarse particles can form extensive deformation zones during rolling or SPD process, which can accelerate nucleation at preheating and at superplastic deformation ascribed to particles stimulated nucleation (PSN) and lead to grain refinement.

In addition, the presence of particle-depleted zones (PDZs) associated with diffusion creep is often detected in the Al alloys with uniform distribution of nanosized particles during superplastic deformation. The PDZ is often considered to facilitate the total elongation of Al alloys during SPF.

4.2.4. Thermal-Mechanical Processing. As stated in Section 1.2, thermal-mechanical processing plays a vital pole for Al alloys to obtain superplasticity. Even the alloys with experimentally approximate composition, such as Al-5.8Mg-0.4Mn-0.25Sc-0.10Zr [43] and Al-6.10Mg-0.3Mn-0.25Sc-0.10Zr [69], may exhibit superplasticity with huge difference, simply owing to distinguished thermal-mechanical processes. Both the elongations of the Al-5.8Mg-0.4Mn-0.25Sc-0.10Zr and Al-6.10Mg-0.3Mn-0.25Sc-0.10Zr alloys sample were tested at the temperatures ranging from 450°C to 475°C and at strain rates of 0.005/s to 0.1/s, however,

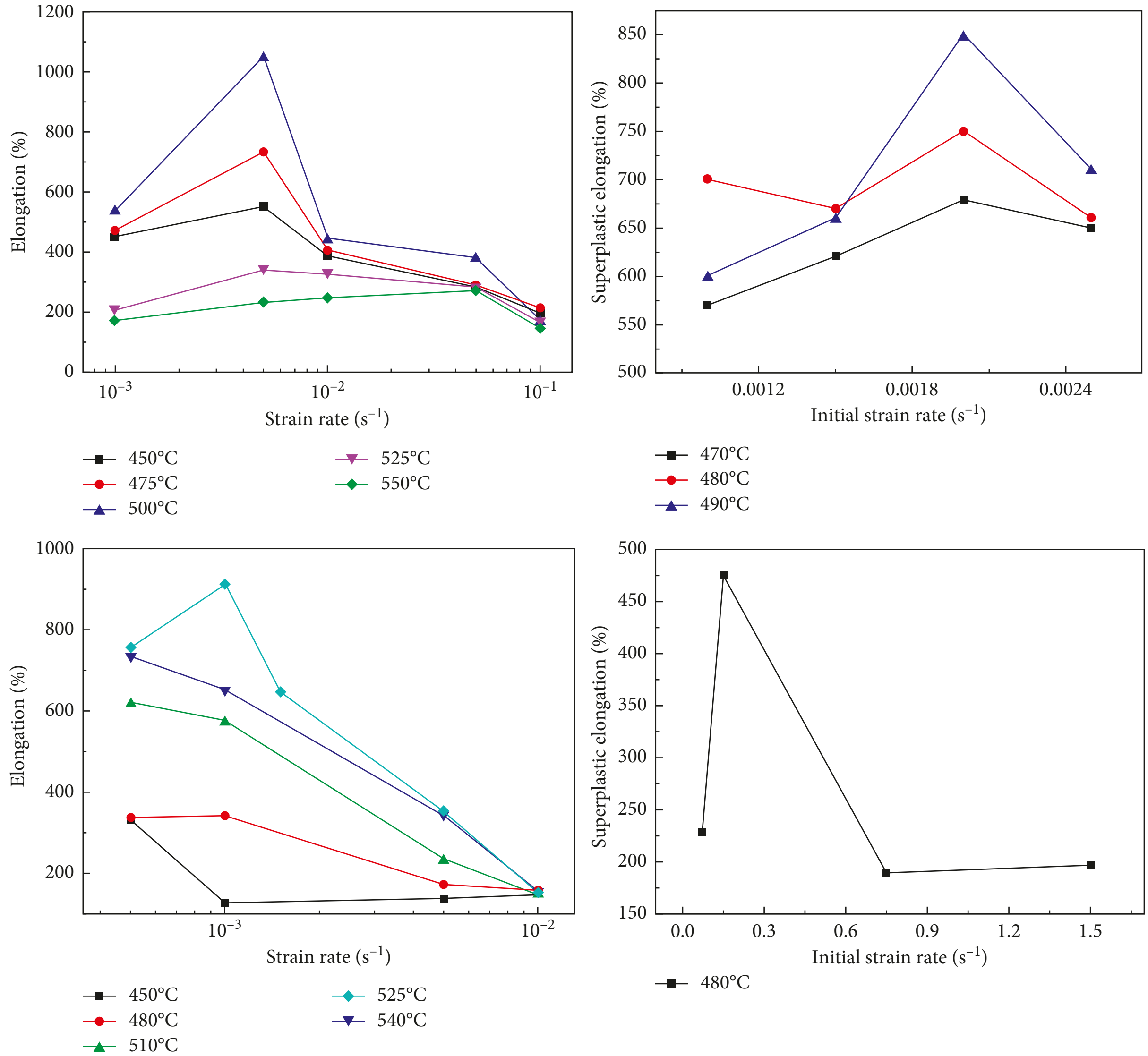
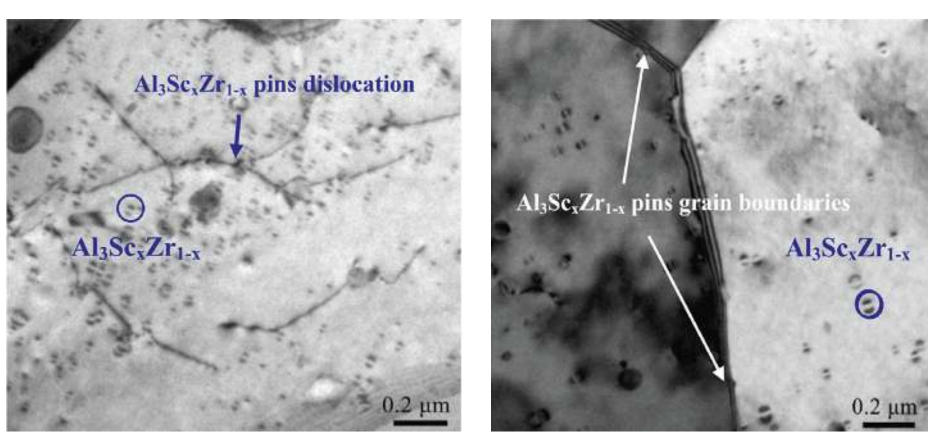
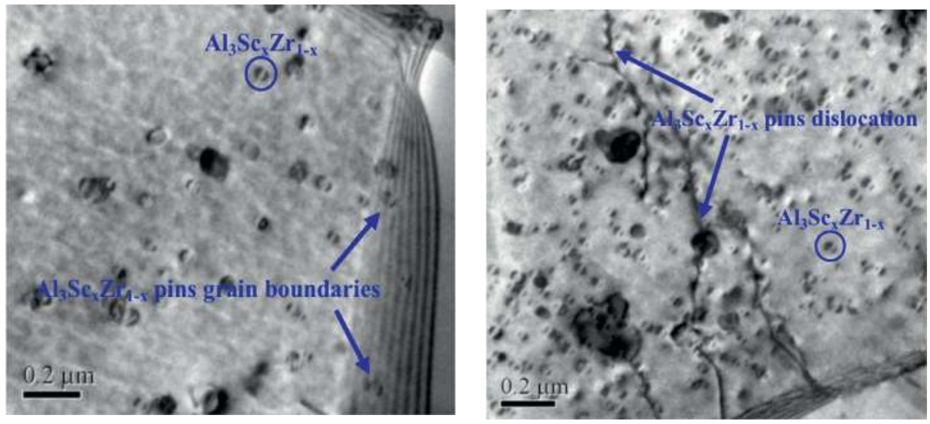


Figure 6: Variation of superplastic elongations of different Al alloys with varying initial strain rates at various temperatures. (a) Al-Zn-Mg-Sc-Zr [56]; (b) Al-Li-Cu; (c) Al-Mg-Si [47]; (d) 5wt.%Al_3Ti/2024.



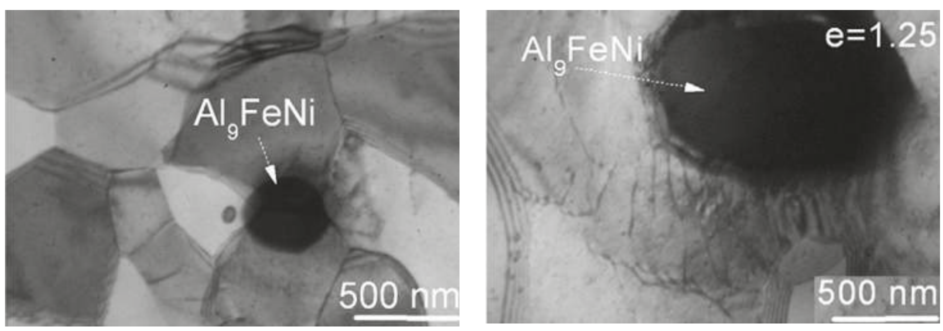
(a) (b)

Figure 7: Continued.



(c) (d)

Figure 7: TEM microstructures of superplastically deformed Al-Zn-Mg-Sc-Zr alloy [42, 56].



(a) (b)

Figure 8: TEM microstructures of Al-Zn-Mg-Sc-Zr alloy: (a) 20 minutes annealed at 480°C; (b) strain of 1.25 [87].

subjected to different thermal-mechanical processes, simple rolling and asymmetrical rolling, respectively (please check [43, 69] for details).

Figure 9 shows the comparison of maximum elongations of the two Al-Mg-Mn-Sc-Zr alloys under 4 tested temperatures of all tested stain rates. It is well established that the asymmetrical rolled alloy. The maximum elongations of asymmetrical rolled Al-Mg-Mn-Sc-Zr alloy is at least 3.1 times that of simple rolled Al-Mg-Mn-Sc-Zr alloy.

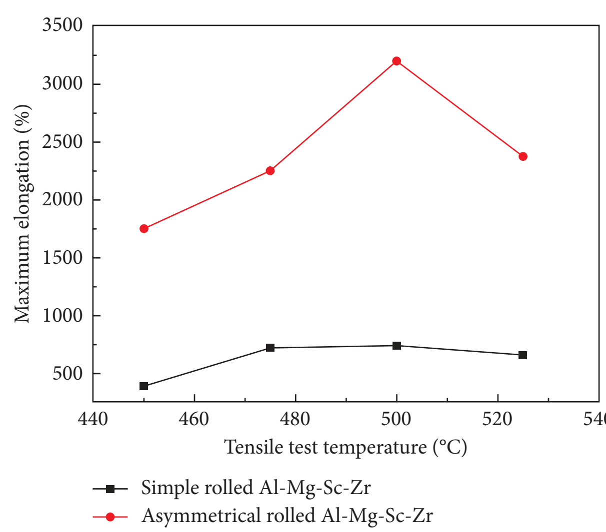


Figure 9: Comparison of maximum elongations of the two Al-Mg-Mn-Sc-Zr alloys under 4 tested temperatures of all tested stain rates.

4.3. Recovery and Recrystallisation. As described in Section 2.2, recovery and recrystallisation are of great importance in structural softening mechanism of Al alloys. Owing to high SFE of Al alloys, dynamic recovery is even more important to the softening process. Therefore, the following sections illustrate the softening process caused by recovery and recrystallisation in detail.

4.3.1. Dynamic Recovery. High density of defects (vacancies and dislocations) is generated and accumulated in the microstructure of plastic deformed Al alloys. High SFE and solute strengthening effect work together to make Al alloys undergo dynamic recovery mechanisms, which include (a) annihilation resulting in neutralization of dislocation dipoles and reduction in dislocation density, (b) polygonisation which involves systemic organization of randomly oriented dislocation into more stable microstructural elements called cells, and (c) proliferation of cells into fully developed subgrains [18]. Because

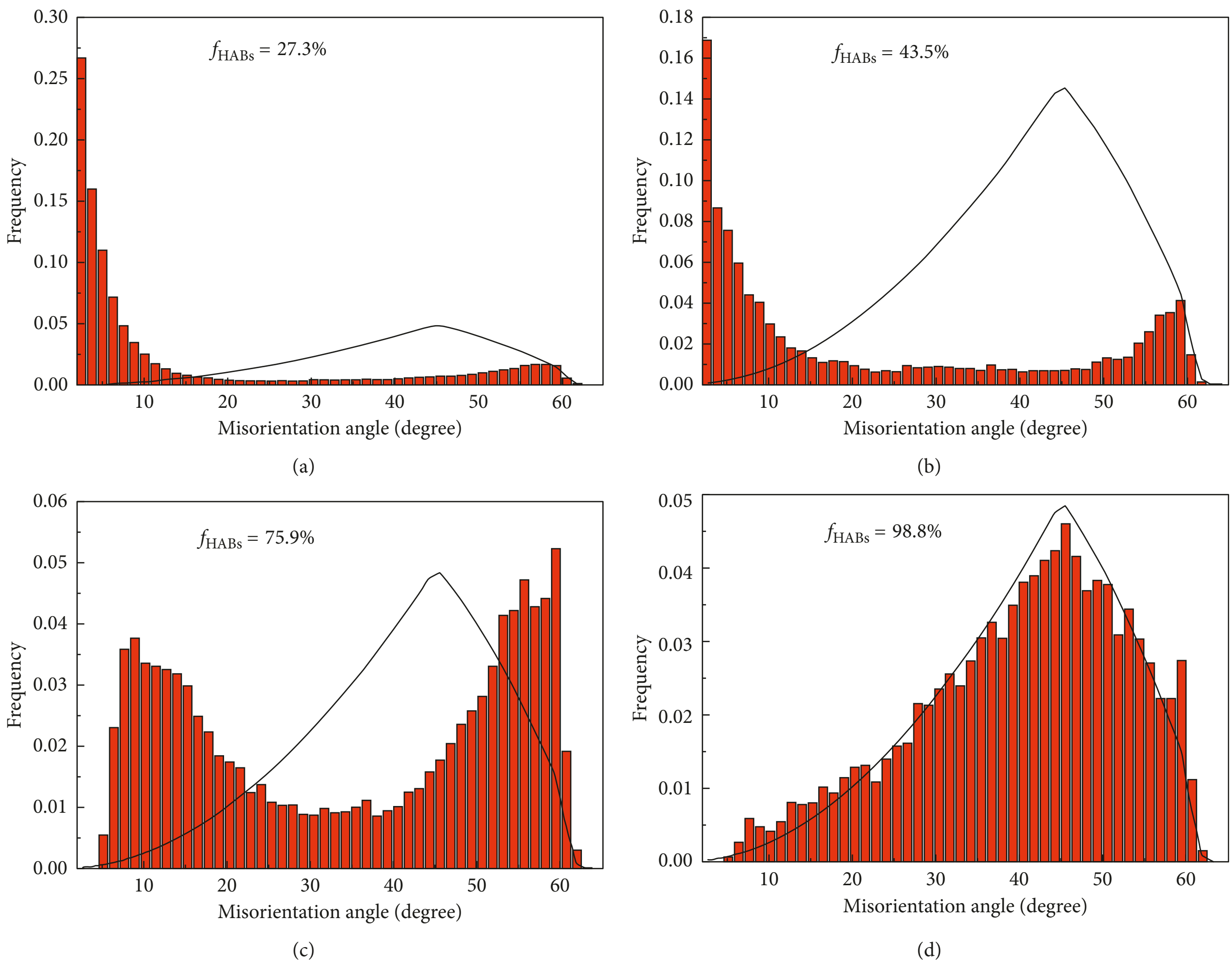


FIGURE 10: Misorientation angle distribution of the Al-Zn-Mg-0.25Sc-0.1Zr alloy deformed at 500°C and $1 \times 10^{-2} \cdot s^{-1}$ after interrupting the tensile test at different strains: (a) $\varepsilon = 0$; (b) $\varepsilon = 0.69$; (c) $\varepsilon = 1.10$; (d) $\varepsilon = 2.40$ [42].

of work hardening, tangled microstructure is formed and transformed into an ordered one by rearrangement of dislocations into micronscale entities called cells. Densly tangled dislocations are located along the boundaries of the cells, while less dislocations are found within the cell interiors resulting from annihilation of the internal dislocations. Subsequently, the cell boundaries turn into structured subgrain boundaries with higher misorientation.

4.3.2. Deformation-Induced Continuous Recrystallisation. If the alloy sheets subjected to severe rolling/SPD process are directly superplastically deformed without static recrystallisaion annealing, it is the fibrous structure rather than equiaxed grain structure that participate in the superplastic deformation. Thus, there are two stages existing during superplastic deformation, according to structure transformation. The initial microstructure of the deformed Al alloys consists of a large amount of LABs, which are not favorable for GBS because of their low misorientations, while it is well proved that HABs are desired microstructure for superplastic flow by GBS [132, 133]. In the first stage, when the superplastic deformation induced continuous recrystallisation, initial fibrous grain structures, typical LABs, along the rolling direction gradually shift into equiaxed grains, HABs keep increasing until the transformation of grains is completed (Figure 10), grain orientation is gradually randomized (Figure 11), and texture is weakened. After dynamic recrystallisation is finished, the second stage of superplastic deformation is mainly controlled by grain-boundary sliding.

5. Existing Challenges and Limitations

In spite of the inspiring and exciting research outcomes about superplastic formation behavior of Al alloys, there are still enormous unknown yet critical territories waiting to be found out and developed.

(i) There are still long way to go to develop a synthetical theory to utterly reveal the essence of superplasticity of Al alloys.

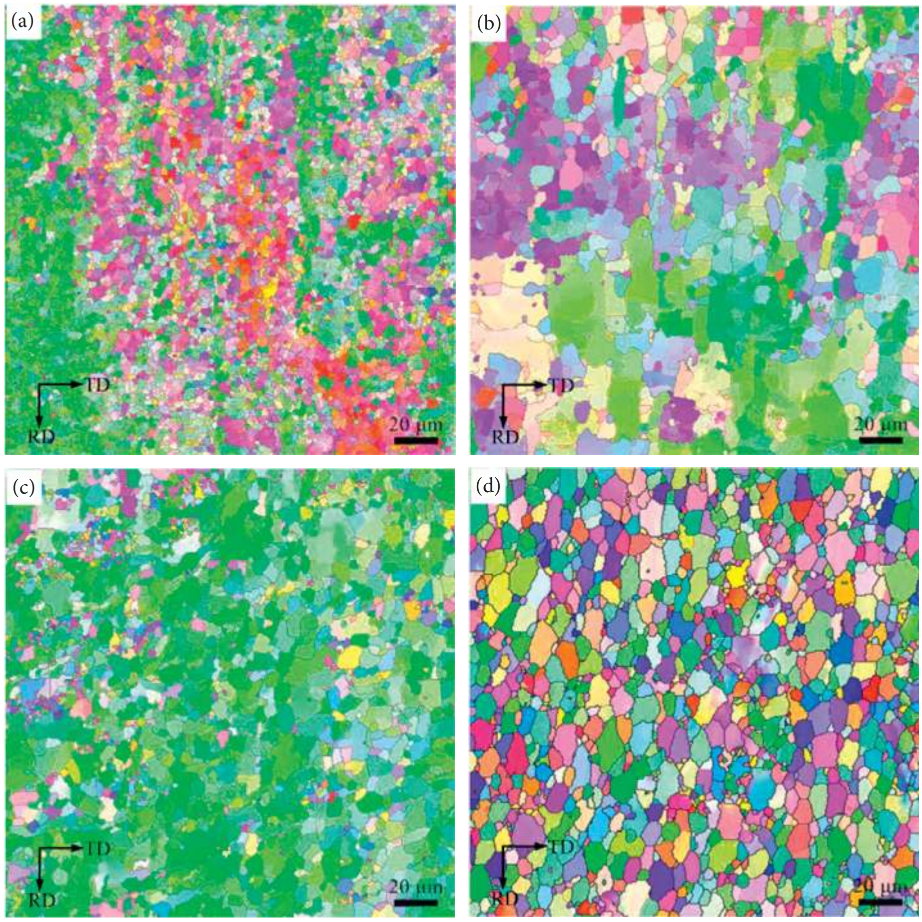


FIGURE 11: EBSD analyses of the Al-Zn-Mg-0.25Sc-0.10Zr alloy deformed at 500°C and $1 \times 10^{-2} \cdot s^{-1}$ after interrupting the tensile test at different strains: (a) $\varepsilon = 0$; (b) $\varepsilon = 0.69$; (c) $\varepsilon = 1.10$; (d) $\varepsilon = 2.40$ [42].

(ii) To exhibit superplasticity, the Al alloys need to meet the strict microstructure requirements, which are for the alloys to hold equiaxed and fine grains as well as the ability to recrystallisation.

(iii) Superplasticity of Al alloys also holds specific deformation requests, including high temperatures and low strain rates, which obviously limit the further industrialized and commercial applications of superplastic deformation.

(iv) For now, the applications of advanced severe plastic deformation (SPD) technologies, which are often used to activate superplasticity of Al alloys, are basically limited to scientific research and study. There is no sign to make SPD technologies fully utilize in commercial process.

(v) There are few researches about combining superplastic deformation with other forming technologies, such as welding and casting, to form complex-shaped components.

(vi) It is necessary to keep developing Al alloys with exceptional and comprehensive properties, including strength, ductility, superplastic formation ability, and stress corrosion resistance, so that the potentials of Al alloys can be fully released.

6. Conclusions

In this paper, the fundamentals and superplastic deformation behaviors of several series of Al alloys are described and it can be seen that currently the main different kinds of Al alloys all have exhibited outstanding superplasticity. Furthermore, the mechanisms of superplastic deformation are discussed and various theories regarding superplastic mechanism are summarized and analyzed, including theory of grain-boundary sliding with accommodation mechanism and deformation-induced continuous recrystallisation. Meanwhile, factors that affect superplastic deformation process of Al alloys are explained in detail, including temperatures, stain rates, and thermal-mechanical process. Subsequently, two significant superplastic deformation parameters of different Al alloys, strain rate sensitivity (m) and deformation activation energy (Q), are compared to help understand the relationship within these two parameters and superplastic deformation mechanisms. Finally, the existing challenges and limitations of current superplastic deformation of Al alloys are properly summarized.

Conflicts of Interest

The authors declare that they have no conflicts of interest.

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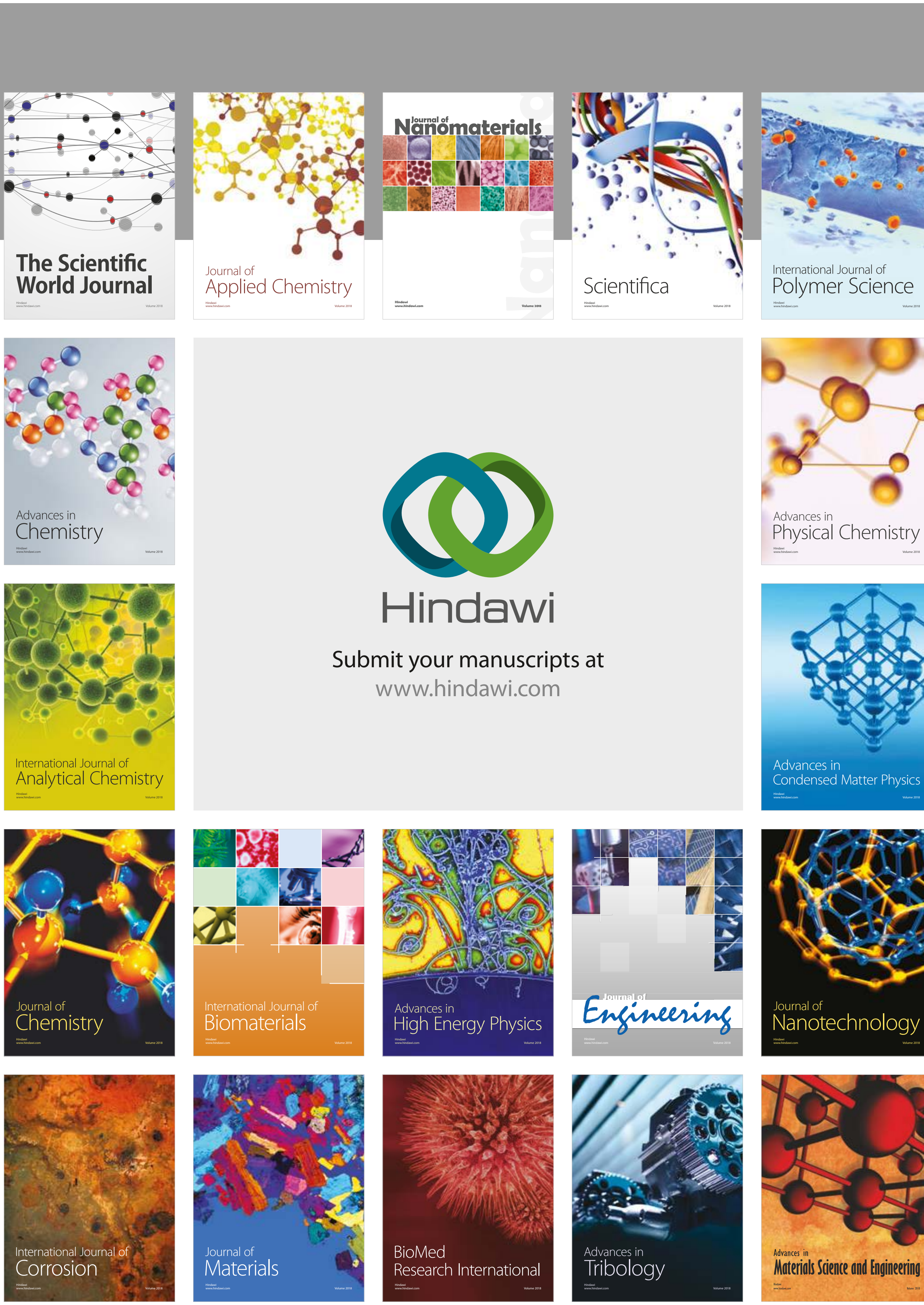
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