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A Short Review on Superplasticity of Aluminum Alloys †

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Abstract: Superplastic aluminum (Al) alloys can be used in the forming processes to fabricate complex geometry components for a wide range of applications in the automobile industry, where light weight and high stiffness are needed. Those alloys exhibit extreme tensile elongation of more than 300% at a high homologous temperature and appropriate low strain rate. Superplasticity occurs in Al alloys via the mechanisms of grain boundary sliding, solute drag creep and diffusion creep. Grain boundary sliding usually leads to extensive superplasticity. The activation of grain boundary sliding depends on grain size, strain rate sensitivity, deformation temperature and alloy chemical composition. A complete understanding of influencing factors on Al alloy superplasticity is the key to developing novel superplastic Al alloys. This review discusses the superplastic behavior of several Al alloys, especially focusing on Al-Mg 5xxx alloys. It highlights the mechanisms that govern superplasticity of Al alloys at a low and high strain rate. The factors which influence superplasticity are analyzed. As practice industrial applications, high-cycle-time superplastic forming operations such as quick plastic forming and high-speed blow forming are briefly discussed.

Keywords: aluminum alloys; superplasticity; grain boundary sliding; quick plastic forming; high-speed blow forming

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1. Introduction

Conventional metallic alloys usually exhibit a tensile elongation of less 100% [1]; however, superplastic alloys display tensile elongation of more than 300% [2]. Superplastic behavior of metallic alloys has been exploited commercially to fabricate complex geometry components, which are impossible to be formed via conventional cold forming operations [3,4]. The forming operation that harness the superplastic response of metallic alloys is called superplastic forming (SPF) [3,5]. SPF is an attractive forming process due to the use of low processing energy and simple tools, which reduces manufacturing cost [5–9]. However, SPF is a slow-cycle-time operation, and this limits its use in the automobile industry [3,10].

Metallic alloys that exhibit superplastic behavior include: titanium, magnesium, duplex stainless steels and aluminum alloys [4]. Among them, Al alloys have found extensive SPF application in the automobile sector due to the need to reduce the weight and minimize fuel consumption and hence greenhouse effect [11]. Superplastic Al alloys are usually employed for fabricating automobile body panels. Many Al alloys exhibit superplastic behavior; however, those of commercial interest are AA2004, AA7475 and AA5083 [12]. Among them, the Al-Mg 5xxx alloys are of special interest to automakers due to their good mechanical strength, good weldability, high corrosion resistance [5,7] and low production cost [13]. However, Al-Mg 5xxx alloys exhibit relatively low superplasticity compared to other superplastic Al alloys [7]. Hence there is an urgent need to develop novel superplastic Al-Mg 5xxx alloys for the automobile industry.

Superplasticity occurs in Al alloys via the mechanisms of grain boundary sliding (GBS), solute drag creep (SDC) and diffusion creep (DC). GBS usually leads to extensive superplasticity. The activation of GBS strongly depends on grain size (<10 μm), high strain rate sensitivity (m-value > 0.3) and low strain rate [14–16]. In contrast, SDC and DC are less sensitive to grain size [16–18] but usually lead to low superplastic elongation [1]. SDC involves both dislocation and diffusional processes and dominates superplastic deformation of Al alloys at a high strain rate and elevated temperature. DC involves diffusional material transport along grains boundaries (or within grains) at elevated temperature and low strain rates [1,19]. Superplasticity of Al alloys is greatly influenced by the grain size, strain rate sensitivity, strain rate, deformation temperature, alloy chemical composition and mechanism that dominates the deformation process. A complete understanding of the influencing factors on Al alloy superplasticity is the key to developing novel superplastic aluminum alloys.

This review discusses the superplastic behavior of several Al alloys, especially focusing on Al-Mg 5xxx alloys. It highlights the mechanisms that govern superplasticity of Al alloys at a low and high strain rate. The factors which influence superplasticity are analyzed. Alternative high-cycle-time superplastic forming operations such as quick plastic forming and high-speed blow forming are briefly discussed.

2. Superplastic Al Alloy

Many Al alloys exhibit superplastic behavior. AA2004, which is commercial known as Supral, is the first superplastic aluminum alloy developed in 1980 [7]. AA2004 exhibits thermal elongation of 1200% at a strain rate of 1×10^{-3} and 450 °C. It displays, however, moderate strength (315 MPa), and as such, it does not meet requirements for high-strength applications [7]. AA7475 alloys, which exhibited good superplasticity (1000%) and high strength (462 MPa), were developed for high-strength structural applications in the aircraft industry [7]. Several variants of Al alloys have been developed, and their superplastic performance has been the subject of much research, as shown in Table 1.

Table 1. Superplastic aluminum alloys.

Alloys	Temperature (°C)	Strain Rate	Elongation (%)	m-Value	Ref.
AA2004 (Al-6Cu-0.4Zr)	450	1×10^{-3}	1200	0.60	[7]
AA7475 (Al-5.5Zn-0.5Mg-1.5Cu-0.2Cr)	516	2×10^{-4}	1000	0.85	[7]
Al-3.9Zn-4.1Mg-2.8Ni-0.25Zr	440	1×10^{-2}	1200	0.47	[20]
Al-3.7Zn-4.2Mg-0.15Sc-0.20Zr	420	2×10^{-3}	800	0.47	[20]
Al-Zn-Mg-0.1Sc-0.1Zr	500	5×10^{-3}	1080	0.5	[21]
Al-4.8Mg-0.6Mn-0.2Cr	545	4×10^{-3}	300	0.65	[22]
Al-(6.5–7.8)Mg-0.7Mn-0.2Cr	519–527	4×10^{-3}	430	0.65	[22]
Al-Mg-Fe-Ni-Sc-Zr	460	1×10^{-2}	750	0.49	[5]
Al-Mg-Fe-Ni-Sc-Zr	460	1×10^{-1}	535	0.46	[5]

Recently, Al-Mg 5xxx superplastic alloys have been developed for application in automotive, architectural and aerospace industries. Superplastic Al-Mg 5xxx alloys are of special interest to automakers. However, they exhibit low superplastic elongation compared to other superplastic aluminum alloys, as shown in Table 1. Research efforts are currently focused on enhancing the superplastic response of Al-Mg superplastic alloys, especially at a high strain rate.

Mikhaylovskaya et al. [22] developed an Al-Mg 5xxx alloy which exhibits a superplastic elongation of 430% at a high Mg content (6.5–7.8 wt%). Similarly, Kishchik et al. [5] observed an improvement in the superplasticity of Al-Mg 5xxx alloys due to small addition of Ni, Sc and Zr. The alloy exhibited high-strain-rate superplasticity (HSRS) of 535% at a strain rate of 1×10^{-1} and 460 °C (Table 1).

Commercial superplastic Al alloys are produced through two distinct thermomechanical treatments (TMTs): (1) discontinuous recrystallization and (2) continuous recrystallization [23,24]. For the discontinuous recrystallization TMT method, the Al alloy is first subjected to overaging treatment to create coarse precipitate particles (about 1 μm in size) before rolling is carried out [24]. During cold rolling, heavily deformed zones are formed around the coarse particles, which serve as nucleation sites for the formation of a fine equiaxed grain structure (Figure 1a) [23–25]. This mechanism is called particle stimulate nucleation (PSN) [24], and it occurs during annealing treatment of the alloys prior to superplastic forming. Superplastic aluminum alloys produced via this method include AA5083 [23] and AA7475 [12,26].

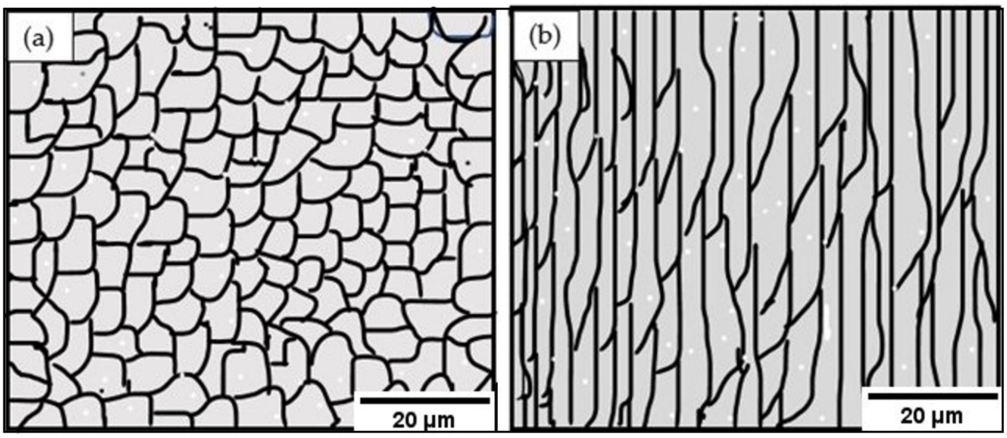

Figure 1. Schematic diagram showing microstructures of Al alloys (**a**) produced via discontinuous recrystallization and (**b**) produced via continuous recrystallization. (Actual images can be found in [23]).

For the continuous recrystallization TMT route, the cast Al alloys are usually heat-treated after hot rolling to form nanoscale (~10–50 nm) dispersoids in the microstructure [12,23,24]. The dispersoids suppress discontinuous recrystallization [25] during warm rolling and ensure the creation of a bonded microstructure as shown schematically in Figure 1b. The misorientations between the subgrains increase during superplastic deformation, and this results in the evolution of a fine-grained microstructure [23] via a dynamic recrystallization process. A fine equiaxed grain structure is usually required to enhance the superplastic response of Al alloys [12]. Superplastic Al produced by this method includes Supral (Al-Cu-Zr) and AA8090 [12,23].

3. Mechanisms of Superplasticity in Al Alloys

Superplasticity occurs via three main mechanisms, namely GBS, SDC and DC [27]. Pearson was the first to identify GBS as a mechanism of superplasticity [28]. GBS controls region II superplastic deformation (SD) where the stress exponent (n) is 2 [1]. GBS usually leads to extensive superplasticity (>400%) and its activation strongly depends on a fine grain size (<10 μm) and high strain rate sensitivity (m-value > 3) [14–16]. As the grains become finer, the stain rate sensitivity value (m-value) increases [29]. A high m-value impedes the flow localization, which enhances GBS [1]. GBS is believed to occur within grain boundaries (Figure 2b) and accommodated by dislocation activities [1] in narrow mantel-like regions close to the grain boundary [17,24].

SDC occurs through the gliding of dislocations at elevated temperatures, and it can yield tensile elongation between 100 and 400% [16]. The activation of SDC is independent of grain size [16–18], and as such, it can occur in coarse-grained alloys. SDC is the mechanism that controls region III superplastic deformation (stress exponent > 3) where the strain rate is high, and the strain rate sensitivity is low (<3) [1]. Typically, SDC-controlled deformation leads to the formation of subgrains, which results from the arrangement of dislocations into a low-energy configuration [1,16]. DC involves diffusional material transport along grains boundaries (or within grains) at an elevated temperature, as shown in Figure 3. It is observed within region I of superplastic deformation at a low strain rate and stress exponent of 1 [1]. DC does not involve any dislocation processes and is usually characterized by grain growth [1,19], which limits superplastic elongation.

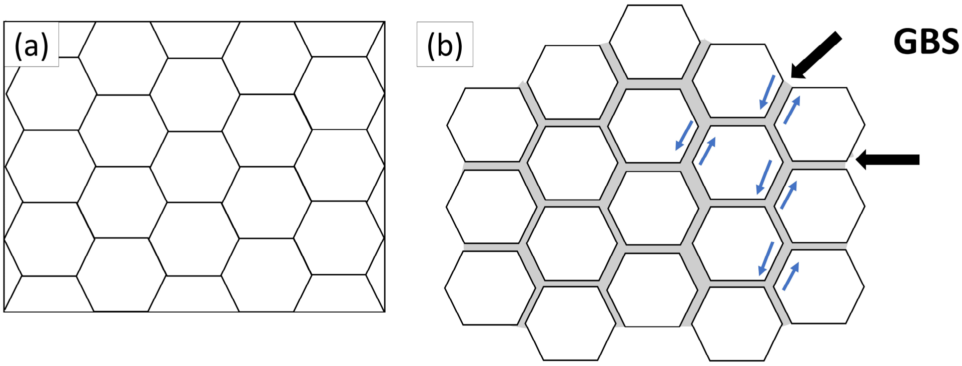

Figure 2. Schematic representation of GBS occurring in fine-grained Al alloys: (**a**) initial grain structure and (**b**) GBS mechanism. The blue arrows show the grain sliding direction.

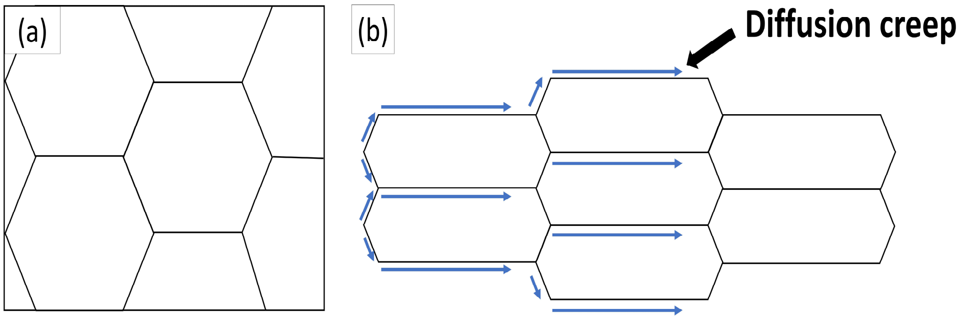

Figure 3. Schematic representation of DC occurring in coarse-grained Al alloys: (**a**) initial grain structure and (**b**) diffusion creep mechanism. The blue arrows show atomic transport along grain boundaries.

GBS is widely accepted as the main superplastic mechanism for Al alloys. However, several researchers contradict this popular view [18–20,23,30]. For superplastic Al-Mg 5xxx alloys, the main deformation mechanisms are SDC and DC [23,31]. SDC and GBS are believed to operate independently, and as such, the fastest one of the two mechanisms controls the superplastic response of the alloy at a given temperature and strain rate [24]. Studies have shown that the deformation mechanism can change during superplastic flow [17,18,24]. Hsiao and Huang [18] observed a transition from SDC to GBS for AA5083 alloy at large strains ($\varepsilon > 0.5$) during superplastic forming. The deformation mechanism changed with the change in deformation temperature. SDC dominated at low temperatures (<250 °C) and medium temperatures (300–400 °C), while GBS became the dominated mechanism at elevated temperature (>400 °C) [18]. McNelly et al. [17] observed a similar transition when the strain rate of the deformation of AA5083 alloy was changed, in which GBS dominated at low strain rates, while SDC became the dominate mechanism at high strain [17]. Some experimental studies confirmed SDC as the main mechanism for high-strain-rate superplasticity of Al-Mg 5xxx alloys. Kishchik et al. [5] developed a high-strain-rate superplastic Al-Mg-Fe-Ni with a small addition of Sc and Zr. The alloy displaced a superplasticity of 535% at a strain rate of 1×10^{-1} s^{-1} [5], and deformation was controlled by dislocation slip [14].

Superplastic Al-Mg 5xxx alloys exhibit comparatively low superplasticity due to the weak response to GBS. In these alloys, GBS is impeded due to the formation of Al-Mg clusters at grains boundaries (GB) [22]. A high-angle grain boundary (HAGB) promotes GBS; however, there is a higher tendency for Mg to segregate at an HAGB than at a low-angle grain boundary (LAGB) [32]. Thus, the formation of clusters at HAGBs is easier, and it suppresses GBS. The superplasticity of Al-Mg alloys can be enhanced through the development of a grain boundary structure which is responsive to GBS. The kinetics of GBS is greatly influenced by grain boundary structure and state [33]. The grain boundary structure approach has been explored in ultra-fined grained Al-Zn-Mg alloys [33,34]. In those alloys, Mg and Zn atoms segregate at the grain boundary and form a grain boundary structure, which responds readily to GBS [33,34]. Ultra-fine-grained Al alloys are produced via severe plastic deformation processes, including high-pressure torsion (HPT), friction stir processing (FSP), accumulative roll bonding (ARB) and equal-channel angular pressing (ECAP) [35], which are expansive and cannot be used for the large scale production of superplastic Al sheets [21].

Although GBS results in extensive superplasticity, it has been observed that cavitation growth rate is high under GBS compared to SDC [17]. During GBS, cavities can easily nucleate and grow within the vicinity of constituent particles, grain triple junctions and grain boundary ledges due to stress concentration [17,21], leading to the loss of formability and premature failure.

4. Factors Affecting Superplasticity of Al Alloy

4.1. Effect of Grain Size and Texture

As discussed earlier, Al alloys exhibit extensive superplastic elongation when deformation is controlled by GBS. It is well known that GBS is a grain size-sensitive mechanism [5,23,24,31]. The finer the grain size, the higher GBS contribution to superplastic elongation of the alloys [31]. Lui et al. [35] observed a high GBS contribution (72%) to the superplastic flow due to the presence of ultrafine grains (0.6 µm) in Al-Mg-Sc alloy produced via friction stir processing (FSP). The high GBS contribution was attributed to the high fraction of the high-angle grain boundary (HAGB) in the alloy prior to superplastic deformation [35]. Thus, grain size and texture have a profound influence on the superplastic response of Al alloys.

Duan et al. [21] reported a superplastic elongation of 1050% in a high-textured Al-Zn-Mn-Sc alloy produced via thermomechanical treatment. The high superplasticity was attributed to the transformation of the high fraction of the low-angle grain boundary (LAGB) to the HAGB during deformation to sustain GBS [21]. Kishchik et al. [5] observed a superplastic elongation of 750% in Al-Mg-Fe-Ni alloy, which had a banded microstructure prior to superplastic deformation. The dynamic recrystallization process led to the formation of equiaxed grains (2–4 µm) with an HAGB, which was ideal for GBS, and this accounted for the high superplasticity [5]. High-strain-rate superplasticity and low-temperature superplasticity can be achieved when the grains become finer [33–35].

4.2. Effect of Precipitation (Precipitates, Dispersoids)

Dispersoids and intermetallic phases have profound effect on the superplastic performance of Al alloys. Their presence promotes the formation of the required microstructure and ensures it remains thermally stable during superplastic forming [5,19]. The high content of fine (size < 100 µm) dispersoids enhances thermal stability by suppressing grain growth via the Zener pinning mechanism [5,23,36]. Also, ultra-fine (5–10 nm) dispersoids impede recrystallisation during heating of Al alloy (with a banded microstructure) to the deformation temperature [5].

Dispersoids are formed by the addition of transition metals such as Cr, Zr, Sc and Mn to aluminum [37]. Among them, Sc and Zr form coherent $Al_3(Sc,Zr)$ dispersoids, which are more effective at suppressing grain growth and enhancing superplasticity [21,26,36]. Yakovtseva et al. [14] observed an enhancement in the superplasticity of Al-Mg alloys due to the minor addition of Sc and Zr. In addition for impeding grain growth, Sc and Zr additions promote dynamic recrystallization, which results in the formation of a more refined grain structure, hence improving superplasticity [14,36]. Algendy et al. [38] also observed the formation of fine recrystallized grains in Al-Mg alloys during hot deformation due to the small addition of Sc and Zr.

Scandium is expensive [21], and it is desirable to reduce its content or find a suitable replacement. Kotov et al. [26] investigated the superplastic response of two Al-Zn-Mg-Cu-based alloys (A and B); alloy A contained Sc and Zr, while alloy B contained Zr and Ni without Sc. The Sc-free alloy exhibited extremely high superplasticity (1200%) compared to the Sc-containing alloy (430%) at constant strain rates of 1×10^{-2} and 440 °C. The Sc-free alloy contained bimodal particles (fine coherent Al_3Zr and coarse eutectic Al_3Ni particles), which facilitated the formation of a more refined and thermally stable grain structure compared to the Sc-containing alloy with only $Al_3(Zr,Sc)$) [26]. Similarly, Mikhaylovskaya et al. [36] observed that the addition of Ni and Fe to Al-Zn-Mg alloy (containing 0.1% Sc and 0.22% Zr) forms bimodal particles ($Al_3(Zr,Sc)$ dispersoids and eutectic Al_9FeNi particles), which enhanced the superplasticity of the alloy. In both reports, the dispersoids suppressed grain growth, while the coarse eutectic particles enhanced dynamic recrystallization via PSN during superplastic deformation [26,36]. Thus, the use of the bimodal particles approach could provide a viable means for developing novel superplastic aluminum alloys without the addition of Sc.

Recently, Mikhaylovskaya et al. [22] reported that increasing the Mg content from 4.8 to 6.5–7.6 wt% in Al-Mg-based alloys retarded grain size growth. Consequently, GBS was enhanced, while diffusional creep decreased, and it increased the superplastic elongation from 300 to 430% [22]. Similarly, Kishchik et al. [25] reported that an increase in Mg content from 4.9 to 6.8 wt% in Al-Mg-based alloys resulted in superplastic elongation of 475%. The enhancement of the superplasticity was attributed to the formation of a more refined recrystallized grain structure (4 ± 0.2 μm) due to the high volume fraction of uniformly distributed course (∼1 μm) Al_3Mg_2 particles [25].

4.3. Effect of Temperature

Superplasticity is essentially a thermally activated process, which occurs at a high homologous temperature [1,2,27]. Al alloys exhibit different superplastic responses at different temperatures due to the dynamic temperature effect on flow stress, strain rate sensitivity and thermal stability of the microstructure. The flow stress usually decreases with increasing temperature [12,39], which eases deformation. The strain rate sensitivity (m-values) is found to be high at elevated temperatures. Kotov et al. [26] reported m-values of 0.45–0.47 for Al-Zn-Mg-Cu-based alloys at 420–480 °C, which is ideal for GBS. Hsiao et al. [18] observed different superplastic response of AA5083 alloys due to the variation in m-values with temperature, and the m-values of 0.25 and 0.55 were recorded at 250 and 550 °C, respectively [18]. Elevated temperature deformation can lead to dynamic grain growth [19,23], which weakens GBS and affects the superplasticity of Al alloys. Recent research [33] focused for developing low-temperature superplastic Al alloys to ensure green and low-cost manufacturing.

5. High-Strain-Rate Superplastic Forming Processes

As mentioned earlier, superplastic forming (SPF) is cost effective and facilitates the fabrication of large and complex components [5–9]. However, the major drawback of SPF is the slow cycle time (low production rate), which limits its application in the automotive industry [3,10]. This is largely due to the fact that Al alloys display superplasticity at low strains. Increasing the deformation rate leads to a poor superplastic response. A recent work [14] focused on developing high-strain-rate superplastic aluminum alloys and, thus, Al alloys that can exhibit high superplasticity at a high strain rate (>0.01 S^{-1}).

An alternative approach to address the low-production-rate SPF is the development of high-cycle-time forming processes such as quick superplastic forming (QPF) and hybrid superplastic forming (HPF) [10]. HPF involves the use of mechanical deformation and SPF to fabricate parts. An example of HPF is high-speed blow forming (HSBF), which combines crush forming and SPF to fabricate complex automobile parts. The cycle time of HSBF is about 30 times higher than conventional SPF and can even be employed to fabricate parts from a low-superplastic metallic alloys sheet [10]. HSBF holds prospects for high-cycle-time forming operation; however, there is the need to study the effect of the forming parameters (temperature and strain rate) on the deformation mechanisms, microstructure evolution and superplastic response of the alloy. This will facilitate the optimization of HSBF and develop novel superplastic alloys tailored to HSBF.

6. Conclusions

1. The superplastic response of Al alloys is greatly influenced by the microstructure of the alloy prior to superplastic deformation and how the microstructure evolves during the forming process. This determines the deformation mechanism that operates and, hence, the amount of superplastic elongation.
2. Grain boundary sliding is the dominate mechanism in Al alloys, which exhibits high superplasticity. Al-Mg 5xxx alloys show limited superplasticity due to weak GBS. The weak GBS is due to the formation of Al-Mg clusters at grains boundaries. The GB structure modification approach could be a viable means for developing high-performance superplastic Al-Mg 5xxx alloys.
3. Diffusion creep and solute drag creep are the main deformation mechanisms in Al-Mg 5xxx alloys. Diffusion is characterized by grain growth, which impedes superplastic performance. Solute drag creep is the mechanism responsible for the high-strain-rate superplasticity of Al alloys.
4. Dispersoids and intermetallic phases have a profound effect on the superplastic performance. The bimodal particle approach that combines nano-sized dispersoids and micro-sized eutectic particles in the alloy is a key strategy for developing a fine-grained and thermally stable microstructure that is ideal for GBS. This approach allows the maximum exploitation of dynamic recrystallization to develop novel superplastic Al alloys.
5. High-speed blow forming is ideal for high-cycle-time forming processes. A deep understanding of the effect of the forming parameters (temperature and strain rate) on the deformation mechanisms, microstructure evolution and superplastic response of Al alloys will facilitate the optimization of HSBF operations and the development of superplastic alloys tailored to HSBF.

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