Influencing Factors on Al Alloys Superplasticity

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Aluminum alloys can be used in the fabrication of intricate geometry and curved parts for a wide range of uses in aerospace and automotive sectors, where high stiffness and low weight are necessitated. Superplasticity is a process in which polycrystalline materials undergo several hundred to several thousand percent of tensile elongation at an appropriate temperature and strain rate. It is greatly effective in reducing the weight and production cost by minimizing the processing steps of machining and joining.

aluminum alloys superplasticity

1. Effect of Initial Grain Size on the Superplasticity of Al Alloys

In order to achieve the better mechanical properties of the superplastic alloy, the alloys should possess fine grain size and it should remain stable during deformation [1]. A fine-grained microstructure has a greater number of grains and grain boundaries than that of a coarse grain counterpart and is typically less than 10 µm. However, finer microstructure requires high severity processing than coarser ones during SPD, and consequently more energy is stored in the material. This stored energy gives rise to high nucleation density followed by rapid grain growth at elevated temperatures. Therefore, stored energy during SPD process is the driving force for abnormal grain growth at high temperatures. This lowers the maximum temperature where grain boundary sliding (GBS) can operate homogeneously in finer microstructure than for coarser microstructure [2][3]. It is well accepted that grain boundary migration due to extensive GBS results in strain induced grain growth in fine grained polycrystalline materials. Moreover, elevated test temperature and low strain rate can enhance grain growth during superplastic deformation process [4]. In addition, grain growth at high temperature results in strain hardening to stabilize neck free plasticity, determines the limit of ductility and increases the flow stress. It is generally believed that the possible microscopic grain growth mechanism is either grain boundary migration accelerated by superplasticity and/or rotation and coalescence of grains. Masuda et al. [5] proposed that a pair of neighboring grains should slide, rotate, and coalesce with each other in order to align in the tensile axis. Furthermore, change in the shape of grain and dynamic grain growth can also occur to avoid the formation of cavities during superplastic deformation [6].

In order to realize better superplastic property, grain shape should be equiaxed because the grain sliding mechanism cannot operate smoothly in a matrix with an elongated grain structure. Grain refinement not only increases the range of strain rate but also decreases the temperature for GBS mechanism [7]. Likewise, to achieve better superplasticity, grain boundaries should be of high angle character, because low angle boundaries are not able to slide. However, in some cases low angled grain boundaries can be changed to high by either by a static discontinuous recrystallization process prior to severe plastic deformation or through a continuous recrystallization process in the early stages of superplastic deformation [8][9][10]. With reduction in grain size, strain rate sensitivity increases, and optimum superplastic elongation can be realized at comparatively lower strain rate and/or temperature. Further, it is well known that deformation occurs mainly at boundaries and decreasing the grain size will increase the grain boundaries, which leads to higher elongation. Nevertheless, at relatively larger grain size, transition to GBS and dislocation creep does not occur at high strain rate, as a result superplastic property cannot be realized [11]. Further information on a range of aspects of grain size and grain growth may also be found in grimes et al. [12], Masuda et al. [5], Li et al. [13], and Tan et al. [11].

An equally significant aspect of superplastic deformation process is abnormal grain growth. Grain growth during superplastic deformation process is generally ascribed to grain boundary sliding or dislocation creep or diffusion creep. Since grain boundary migration, diffusion creep, and dislocation creep are temperature dependent, grain grows with an increase in temperature. Grain growth at high temperature results in strain hardening, consequently increasing the flow stress [6]. However, abnormal grain growth is a process through which few energetic grains grow at the expense of the finer matrix grains. In general, abnormal grain growth is more likely to occur when the usual grain growth of the matrix grain stagnates, when the second phase particles are unstable and when there is strong texture [14][15]. Charit et al. [16] claimed that the reduction of pinning force due to dissolution of particles and anisotropy in grain boundary energy and mobility promotes abnormal grain growth. Abnormal grain growth becomes a possibility when the pinning parameter, Z, lies within the range $0.25 < Z < 1$ ($Z = 3\ F_V R/d$, where F_V is the volume fraction of particles, R is the average grain radius, and d is the average particle diameter). Charit et al. [17] found that FSP 7475Al did not display superplastic elongation due to abnormal grain growth.

Mahidhara [18] compared the ductility of 7475 aluminum alloy with grain sizes ranging between 9 and 35 μm at 457 °C and 517 °C at the same strain rate of $10^{-4}\ s^{-1}$. They found that at temperature 517 °C, ductility decreases with increase in grain size until grain size reached 20 μm, beyond this, there was no appreciable drop in ductility whereas at temperature 457 °C, initially ductility increases with an increase in grain size until grain size reached 14 μm; beyond this ductility decreased with increase in grain size. This anomalous behavior of alloy at 457 °C is due to a high nucleation rate of cavities.

2. Effect of Temperature on the Superplasticity of Al Alloys

Superplastic deformation temperature plays a vital role in enhancing the mechanical property of superplastic alloy. Research suggests that superplastic deformation temperature should be more than the homologous temperature to achieve better mechanical properties [19][20]. With an increase in temperature, the viscous force within the grain boundary decreases gradually, which makes grain boundaries unstable. This causes GBS, which is the basic requirement for superplasticity. However, an excessive increase in temperature softens the grain boundary and grain boundary binding force, which declines the elongation [21]. Alhamidi et at. [22] studied the superplastic behavior of AA2024 alloy at 400 °C and concluded that elongation to failure increases with an increase in temperature till it reaches its peak, after which an increase in temperature decreases the elongation to failure. They claimed that the former increase in elongation with temperature is due to GBS but at a temperature higher than 400 °C, the contribution of GBS to total strain decreases because of grain growth and a decrease in grain boundary fraction.

An equally significant aspect of aluminum superplasticity is low temperature superplasticity, which is normally less than 300 °C. Noda et al. [23] carried out a low-temperature experiment on Al-Mg alloy by multi-axial alternative forging, which resulted in a grain size of 0.8 µm. Through their observations, elongation of 340% was found at temperature 200 °C and 2.8 × 10^{-3} s^{-1} strain rate. It was inferred from the microstructure evaluation that intragranular deformation due to dislocation movement and GBS were the main deformation mechanism of superplastic deformation at 200 °C. Ota et al. [24] conducted a series of experiments employing ECAP process on three different Al-3%Mg alloys containing 0.2% Sc, 0.2% Fe, and 0.1% Zr separately at 250 and 300 °C. Al-3%Mg-0.2%Sc alloy yielded maximum elongation of 640% when tested at 250 °C and 3.3 × 10^{-4} s^{-1} while 1280% when tested at 300 °C and 1 × 10^{-2} s^{-1}. Such a large elongation at 300 °C was possible due to the stable fine-grained structure at high temperatures.

3. Effect of Strain Rate on the Superplasticity of Al Alloys

Strain rate significantly influences the superplastic deformation behavior of Al alloys. Optimum superplastic behavior is generally observed at strain rates from 10^{-4} s^{-1} to 5 × 10^{-3} s^{-1}, and tensile elongation tends to decrease at lower and higher strain rates [25]. Generally, GBS and dislocation creep contribute significantly to deformation at low strain rates, but these processes are too slow to contribute to total deformation at high strain rates. Consequently, at high strain rate deformation occurs mainly due to dislocation creep [11]. According to Equation (1), true stress is dependent on the strain rate, which infers that stain rate also plays a key role in the superplasticity of Al alloys.

Strain rate interval at which superplasticity normally occurs (<1 × 10^{-2} s^{-1}) is often too slow from the viewpoint of industrial applications. Strain rate > 1 × 10^{-2} s^{-1} is suitable for industrial applications and would satisfy the current industrial manufacturing speed [26]. Mikhaylovskaya et al. [27] evaluated the impacts of high strain rate on two Al-Zn-Mg-Zr-Sc alloys distinguished by the presence and absence of Al_9FeNi particles. Alloy with Al_9FeNi particles displayed elongation to failure up to 915% while alloy without Al_9FeNi particles exhibited maximum elongation of 310% at strain rates up to 1 × 10^{-2} s^{-1} and a temperature of 480 °C. The partially recrystallized structure was observed in alloy without Al_9FeNi particles and superplastic indicators were significantly lower. Charit and Mishra [28] evaluated the effect of high strain rate on AA2024 alloy prepared by FSP. Superplastic experiments conducted at a strain rate of 10^{-2} s^{-1} and 430 °C and resulted in a maximum elongation of 525%. It is important to note that, even at a high strain rate of 10^{-1} s^{-1}, the elongation to failure was >280%. Very fine grain size (3.9 µm) and high angle disorientation of grain boundaries were largely responsible for the enhanced superplastic response at high strain rate. Straumal et al. [29] claimed that prewetting or premelting of the grain boundary is responsible for high strain rate superplasticity in Al-Mg alloys.

It is, however, important to note that the highest strain rate to obtain superplasticity in Al alloys is roughly 1 s^{-1}. Musin et al. [30] achieved an elongation to failure of about 500% at a strain rate of 1.2 s^{-1} in Al-Mg-Sc alloy. Such high elongation was attributed to the ultrafine grain structure (1 µm) produced by Equal Channel Angular Extrusion (ECAE) process and the presence of coherent Al_3Sc dispersoids. Likewise, Ma et al. [31] attained a maximum elongation of~ 450% in FSP Al-1Mg-4Zr alloy ascribed to fine microstructure with a grain size of 1.5 µm and uniform distribution of fine Al_3Zr dispersoids. It can be seen from the above analysis that high strain rate superplasticity (10^0–10^3 s^{-1}) might be interesting and would satisfy the current industrial manufacturing speed.

4. Effect of Strain Rate Sensitivity on the Superplasticity of Al Alloys

Strain rate sensitivity (m) is an indicator of a material of its superplastic potential and its value is derived from applied stress and corresponding strain rate [32][33]. For a material to exhibit superplastic properties, strain rate sensitivity should be more than or equal to 0.3. The higher value of strain rate sensitivity indicates that the material is more stable against the local strain rate increase and thus exhibits higher superplastic elongation. Experimental studies have shown that the value of strain rate sensitivity depends on temperature, strain rate, and strain [30][34].

Arieli et al. [35] analyzed the relationship between strain rate sensitivity and strain rate and concluded that strain rate sensitivity decreases rapidly at low and high strain rates as the strain rate increases, whereas the rate of decrease is slower at intermediate strain rates. Similarly, Friedman et al. [36] evaluated the influence of strain rate sensitivity and strain rate on AA5083 alloy at 5% elongation and found that deformation at lower strain rate is controlled by diffusional accommodation at grain boundaries but the deformation at relatively higher strain rate is controlled by thermally assisted dislocation motion.

5. Effect of Microstructure Refinement Techniques on the Superplasticity of Al Alloys

Superplastic deformation mechanism and mechanical properties differ with change in microstructure refinement techniques. Alloys with almost similar composition exhibit different mechanical properties because of different refinement techniques. Loucif et al. [37] prepared AA7075 alloy by HPT while Caballero et al. [2] prepared AA7075 alloy by FSP and they performed superplastic deformation test in the temperature range from 200–450 °C and strain rate from 1 × 10^{-4}–1 × 10^{-1} s^{-2}. Loucif et al. attained maximum elongation up to 400% at 350 °C and 10^{-1} s^{-2} while Caballero et al. obtained a maximum elongation of 126% at the same temperature and strain rate. In another experiment, Chentouf et al. [38] analyzed the superplastic behavior of AA5083 by hot and cold preform, whose average grain size was determined to be 8.32 and 7.95 µm respectively. They concluded that the number of cavities in the hot preform case were less than in the cold preform case and hot preformed samples led to an increase in the nucleation of subsurface discontinuities. Nevertheless, the average cavity size of hot preformed sample was higher than cold preformed sample. Large cavity sizes are susceptible to the formation of large sized voids and cracking. Furthermore, Smolej et al. [39] compared superplastic behavior of Al-4.5Mg-0.35Sc-0.15Zr alloy by rolling and FSP and claimed that in the temperature range from 350–500 °C and strain rate from 1 × 10^{-2} s^{-1}–1 s^{-1}, the elongation of the FSP-processed alloy is 7, 2.5 times higher than those of the rolled alloy. Rolled samples underwent incipient hardening followed by softening at higher strains whereas FSP samples exhibited smooth and rising hardening during the initial superplastic flow. Superior elongation of FSP samples was possible because of stable microstructure at high temperature, which was ensured by the addition of Sc and Zr.

Wang et al. [40] claimed exceptionally high elongation of 3250% using Al-Zn-Mg-Cu alloy. The alloy was prepared by FSP, which resulted in an equiaxed grain size of 6.2 μm. The tensile test was done in the temperature range of 500–535 °C and at a strain rate of 10^{-2} s^{-1}, which resulted in elongation of 3250% at 535 °C. Such high elongation was obtained due to the presence of a small amount of liquid phase at the grain boundaries, which helped remove the stress concentration and suppress the appearance of cavities during deformation. Further, relatively stable grain size at high temperature due to the pinning of a high-density Cr bearing dispersoids was responsible for high elongation. Park et al. [41] studied the superplasticity of a commercial Al-Mg alloy subjected to ECAP and ECAP + post rolling. The high strain rate superplastic elongation was remarkably enhanced during Post-ECAP rolling. ECAP + post rolled samples' microstructure consisted of elongated band structure delineated by lamellar boundaries and deformation was dominated by GBS whereas ECAP sample was governed by dislocation viscous glide. Post rolling after ECAP enhanced elongation by increasing the portion of high angle boundaries which changed the deformation mechanism from dislocation viscous glide to GBS.

SPD techniques provide an opportunity to achieve remarkable grain refinement by imposing large strain without any significant change in the overall dimensions of the sample, which leads to the occurrence of superplasticity not only at low temperatures but also at high strain rates. SPD techniques have the capability of altering the grain orientation by transforming the low angle boundaries to a large proportion of high angle grain boundaries. Nevertheless, the mechanisms underlying different SPD processing techniques are different. The evolution of dislocation cell structures and its transformation into a new grain structure with a large proportion of high angle grain boundaries in the process of straining is also different for different SPD techniques [42]. ECAP technique increases the mechanical strength of the metallic material by pressing it through a die constrained within a channel bent through a sharp angle near the center of the die [43]. In FSP, the friction between the rotating pin and metal surface results in a stirred zone with fine grain size [44][45]. HPT involves the application of a very high hydrostatic pressure on the material, which plays a major role in grain refinement [46][47]. Moreover, special rolling techniques for grain refinement like ARB, cryorolling, asymmetric rolling are affected by the amount of thickness reduction in each pass and the level of rolling friction [48]. ARB comprises deformation and bonding process, which on repetition can produce SPD of bulky materials [49][50]. Asymmetric rolling encompasses compressive and shear strain to maintain a high degree of friction between the sheet and the rolls. It not only decreases the rolling force and rolling torque but also improves the formability of the material [51][52][53]. Furthermore, cryorolling produces ultrafine grain microstructure in the light metals and alloys that require a comparatively lower load to induce severe strain for producing the sub-microcrystalline structure [54][55][56].

6. Effect of Addition of Trace Elements in Alloys on the Superplasticity of Al Alloys

In general, single phase materials do not exhibit superplastic behavior because grain grows rapidly at high temperatures. However, the addition of trace elements like Sc, Zr, Mg, Li, Cu [57] form nanoscale coherent Al_3Zr, Al_3Sc, $Al_3Sc_xZr_{1-x}$ precipitates at grain boundaries and within the grain interiors to resist grain growth during recrystallization at elevated temperature. Thermally stable second phase particles stabilize grain boundaries, subgrain boundaries, and dislocation by the Zener pinning effect [58][59]. Trace elements have strong interactions with dislocations and have ability to increase the dislocation production rate during deformation, which leads to higher strain hardening and subsequently to an increased ductility. Trace elements not only interact with all types of structural defects like void formation, stacking faults, dislocations but also modify the collective behavior of these defects [60]. The addition of trace elements not only influences the process of lattice dislocation incorporation into the grain boundary but also can change rate of boundary sliding through grain boundary segregation [61]. To achieve better superplasticity, size of the second phase should be fine (<1 µm) and its distribution should be uniform. Furthermore, the second phase must be able to deform with the matrix in order to avoid stress concentration and early fracture [8]. In addition, segregation of impurity atoms at grain boundaries not only contribute to grain boundary sliding but also influence the cavitation by decreasing the surface and grain boundary energy, further details can be found in [62]. Al alloys can provide good high-temperature properties using coherent intermetallic precipitates for strengthening.

The addition of Cu as an alloying element improves the heat treatability of alloy and at the same time decreases the eutectic temperature as well as melting point of the alloy. Furthermore, copper forms $CuAl_2$ phase and many other intermetallic compounds, which improves the strength of the casting parts [63][64][65][66]. Hossain et at. [67] studied the effect of addition of Cu in Al-6Si-0.5 Mg alloy and authors reported an increase in tensile strength and decrease in ductility of the alloy. They further elaborated that an addition of 2% of Cu showed maximum strength. Increase in tensile strength is attributed to the precipitation of copper rich precipitates and decrease in ductility to the formation of void and its coalescence. Moreover, Watanabe et al. [68], in another test, put emphasis on finding superplastic behavior of Al alloys with the addition of Copper. Their work revealed that finely dispersed particles in copper containing alloy inhibit subgrain growth during continuous recrystallization, which in turn results in finely recrystallized grain structures. The addition of 0.6% of copper in Al-5% Mg resulted in an increase in the value of m, enhanced the corrosion resistivity and increased total elongation by about 500%.

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