Superplasticity of coarse grained aluminum alloys
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6 Summary and Outlook

Summary

Aluminum alloys may fulfill the increasing demands in automotive industry to reduce weight so as to enhance performance and to reduce fuel consumption, provided the formability could be improved to a level comparable with that of their steel counterparts. Aluminum alloy AA5083 is currently the referred material for the so-called Superplastic Forming (SPF) process, alternatively employed in industrial application. Affected by the deformation mechanism of Grain boundary sliding (GBS), this technique has the disadvantage of slow forming rates together with the requirement of high forming temperature and small grain size.

The patented Quick Plastic Forming (QPF®) technique is developed at significantly higher strain rate than SPF, capable of producing aluminum parts at relatively high volumes and extremely complex shapes. As the deformation mechanism switches to solute drag creep (SDC), coarse grained AA5182 plays the important role putting the cost-effective efforts even forward.

Mechanical Properties toward Superplasticity

Uniaxial tensile tests of AA5182 sheet material were conducted over a reach of conditions of temperature, strain rate and specimen geometry. The coarse-grained AA5182 with grain size of 21 μm and 37 μm (denoted by 21G and 37G), exhibited optimum deformation conditions at $\dot{\varepsilon} \sim 10^{-2} \text{ s}^{-1}$ and at $T \geq 425^\circ\text{C}$ and above $475^\circ\text{C}$, respectively, with maximum elongations to failure between 300 and 400% along, and at
45° to the rolling direction and approximately equal to 300% perpendicularly to the rolling direction.

The alloy 21G is essentially isotropic, exhibiting consistently uniform deformation at all orientations up to an elongation of 250%, at 425°C and at $10^{-2}$ s$^{-1}$, whereas the 37G is slightly anisotropic and demonstrated significant deviations from uniformity at 200%, as well as significant necking and numerous secondary necking instabilities at 250%.

Secondary necking instabilities were most likely to appear at the optimum deformation conditions, especially when elongations in excess of 400% were achieved, but their development could not be predicted. For both alloys these instabilities were most likely to appear in specimens along the rolling direction; their presence in specimens at 45° was less frequent and it was rare in those perpendicularly to the RD. These secondary necking instabilities are associated with regions of the gauge that contain a large volume fraction of soft grains and produce microstructures that exhibit maxima in the Cube and Goss component of the deformed grains. They exhibit slight grain refinement compared with the adjoining thicker and more uniformly deformed regions.

**Deformation, Recovery and Recrystallization processes**

The Electron Backscatter Diffraction (EBSD) maps were initially partitioned into deformed, recovered (RV) and recrystallized (RX) portions. The microstructure evolution of the texture, the grain size, the grain volume fraction, the sub-grain, low-angle and high-angle grain boundary density were investigated using predefined, sequentially increasing incremental values of the local strain, $e_L$, along the post-mortem gauge of
tensile specimens. This new approach permitted the comparative evaluation of the progress of these three processes, and thus produced important conclusions with respect to the total mechanism responsible for the microstructure modification along the gauge of specimens from AA5182 aluminum alloy upon “superplastic” extension.

From the analysis of grain size evolution, it is shown that continuous grain refinement does not result in large elongations. Maintaining a stable grain size, for a large regime of $\varepsilon_L$ seems to be more critical in obtaining large elongations prior to failure.

Grain coherency promotes the rotation of deformed grains into alternating Cube and Goss orientations, so as to allow for the operation of multiple slip systems across the grain boundaries at large values of $\varepsilon_L$. Consequently, an evenly balanced Cube and Goss texture is prone to produce larger elongations prior to failure.

Extended recovery or continuous dynamic recrystallization leads to homogeneous grain refinement. During recovery low-angle grain boundaries are converted into high-angle grain boundaries and the process reduces the number of grains showing large amount of dislocation induced distortions. The extended recovery can continue refining grains further until the combination of strain and heat renders the pinning action of the precipitates ineffective to prevent long range motion of the grain boundaries. Discontinuous dynamic recrystallization takes place leading to rapid necking.

**Deformation mechanisms**

Strain rate change mechanical tests were conducted to characterize the deformation behavior of four AA5182 specimens from two alloy materials. The activation energy for creep behavior, $Q_c$, was calculated to determine the deformation mechanisms. At very low flow stress region, the $Q_c$ has a low value around 110 kJ/mol
indicating the grain boundary diffusion actively participates during deformation by grain boundary sliding creep. At intermediate flow stress region $Q_c$ increases to $138 \pm 2$ kJ/mole supposing a solute drag creep deformation mechanism corresponding to the diffusion of Mg solute in the Al matrix ($Q_c = 136$ kJ/mol).

While the flow stress goes to the highest region, the $Q_c$ value increases to more than 180 kJ/mol. This value is higher than self-diffusion in Al ($Q_c = 142$ kJ/mol) and lower than solute diffusion energy in Al ($Q_{c,Mn} = 220$ kJ/mol, $Q_{c,Fe} = 213$ kJ/mol, $Q_{c,Cr} = 252$ kJ/mol). Therefore, it is concluded that this phenomenon is attributed to the Dislocation Glide Creep mechanism in high-stress region, which can be explained as the dislocation/dislocation interactions or the dislocation glide limited by dispersed particles.

**Outlook**

The conventional superplastic material of AA5083 has relatively high purity and fine grain size requiring significant thermo-mechanical processing. As a consequence the material production cost will be considerably high. Although various deformation mechanisms have been studied and deformation models were proposed, there are some intrinsic characteristics of the material that hamper industrial application. Because grain boundary sliding is the dominating controlling mechanism, the deformation strain rate can only typically be of the order of $10^{-4}$ s$^{-1}$. Subsequently the forming time of a component will be too long for the consideration of cost control in industry. Also, due to the grain boundary sliding mechanism, the deformation temperature has to be relatively high, namely close to the melting point of the material. None of the abovementioned
factors is cost-effectively favorable for the material to scale production as in industrial application.

As proved in this thesis work, our Aluminum alloy is demonstrated to be the perfect candidate to the new technique known as Quick Plastic Forming (QPF®). Compared to AA5083, the coarse-grained material studied in this thesis has bigger grain size and lower purity, making it easier and cheaper to produce. Above all, the deformation mechanisms not only rely on grain boundary sliding creep, but the combination of grain boundary sliding and/(or just) other creeps of solute drag creep and dislocation glide creep. These have the significant importance for reducing the forming time of a component as the strain rate is typically high at $10^2\text{s}^{-1}$. The deformation temperature is thereafter also much lower, 425°C compared to the 500°C employed for AA5083.

The deformation mechanisms are less established yet for the AA5182 material. A slight change in composition or different processing method applied by different industries may cause significant differences in mechanical performance. This is mainly due to the virginal starting microstructures and grain size. The distributions of dispersoids are different to hinder dislocation motion during the deformation, giving varied deformation performance and ductility. Hence, microstructural characterizations before and after the deformation should be conducted in order to formulate appropriate evolution models. Detailed investigation of the deformation mechanism is recommended for the design of new coarse grained alloys.