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Superplastic Forming of Aluminium Alloys

Report

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Executive Summary

Superplastic forming in general and applying this process to aluminium alloys in particular has been investigated with great interest in the past several decades. The results are processes using this concept of forming for making parts that are difficult to make otherwise, due either to complex geometry of the component or to limited formability of the material. Aviation industry, where higher cost, lower number of parts and higher turn over time are easier to justify, has been the prime user of superplastic forming. More recently auto industry has tried superplastic forming to make aluminium parts for some specialty vehicles. The critical stride for aluminium superplastic forming is to become a vital forming technique for ordinary passenger vehicle; and to be in that position there are obstacles to overcome. Unlike, aviation sector, auto industry could not tolerate higher cost and turn over time. Part of the higher cost is due to the need for application of high-quality grade SP-5083 alloy. There is a great opportunity to optimize the process so commercial grade 5083 or other aluminium alloys could be used in the process. The more challenging opportunity would be optimizing the process for a lower turn over time so that the process could handle the larger number of parts required for ordinary passenger vehicles. Therefore the followings might be the auto industry investigation wish list for superplastic forming processes and alloys:

Study of the effect of large (>20 μm) second phase intermetallic particles or clusters on superplastic formability in commercial grade aluminium alloys, these large particles may lead to premature cavitation and failure as well as poor post-form properties.

The auto industry desires using commercial grade alloys that do not show premature necking even if the grain size is 20-30 μm.

Further development on higher strength, age-hardening superplastic alloys.

Methods to further reduce the grain size, either during the production or through dynamic recrystallization,

Study on texture development at medium and high Z value (SD creep regime) to verify if a preferred (non-random) texture suitable for superplastic forming exists.

Determine an optimum dispersoide size and distribution in superplastic alloys.

Study of superplastic behaviour in alloys with lower Mg content than AA5083.

Develop and enhance a continuously cast Al alloy suitable for superplastic forming combined with additional processing to reach the required grain size and surface quality.

In terms of constitutive equation, to develop a method for evaluating the effect of strain rate on stress-strain behaviour at higher strain rate where transition behaviour is observable.

In terms of the process itself, strain rate and temperature are very important parameters. Additionally, whenever gas pressure or vacuum are involved the pressure is also a critical parameter. This is author's personal view that developing a process that applies pressure on both sides of the blank and during actual superplastic forming pressure in each side changes coordinated with the other side would enhance formability. Since in

this case a uniform compressive pressure is maintained on the blank on thickness direction.

In terms of equipments should Aluminium Technology Centre decide to contribute in a project on superplastic forming of aluminium alloys, aside from the existing and planned equipments the followings might be considered:

- Orientation Imaging Microscope,
- "WYKO TM" type optical interface image system,
- Bulge test apparatus.

Table of contents

List of figures

Introduction

Superplastic Forming (SPF) refers to a metal forming process that takes advantage of the metallurgical phenomenon of superplasticity to form complex and highly contoured sheet metal parts. Superplasticity refers to the ability of certain metal alloys and other materials to undergo very large plastic strains with minimal necking [1]. Superplastically formable aluminium alloys have been used commercially since 1973. A large number of components have been formed in Supral (2004) alloy by Superform Metals at Worcester, England and by Superform USA in California [22]. As part of Ford's feasibility assessment, demonstration parts were superplastically formed by Superform USA out of 5083 [27]. In the past decade superplastically formed parts also used on vehicles such as the Dodge Viper, Panoz Roadster and Esperante, the Aston Martin Vanquish, Morgan Aero8, Ford GT, GMC Envoy, and the Oldsmobile Aurora [32].

Quick Plastic Forming, a patented technology at General Motors, has now reached a state of maturity where it can compete with other limited volume manufacturing systems in the marketplace. Further developments could enable even higher volume automotive panel production [3].

The goal of automotive industry has partly been to produce, characterize, and understand superplastic materials suitable for high volume production. Therefore, there has been significant amount of work on effects of alloy composition, second phase particles, and thermomechanical processing parameters that has led to detailed understanding of the alternative deformation mechanisms, elevated temperature fracture behaviour as well as surface phenomena [32]. Post-forming mechanical properties has also been studied.

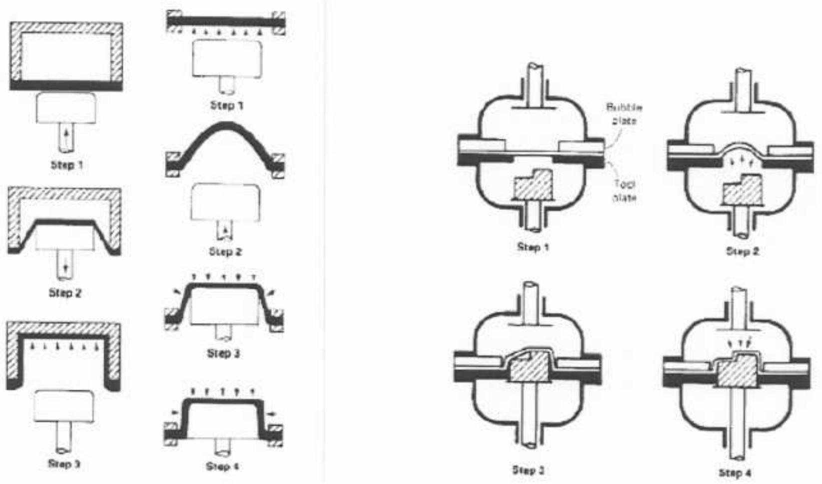
Terminology of the Processes

There are several processes that could be classified as Superplastic Forming (SPF) processes. Although the essence of the processes remains the same due to existing differences and also intellectual property/business policies there are different terminologies. General Motors has a patented process that is called Quick Plastic Forming (QPF) process [2]. Quick Plastic Forming (QPF) is a high-temperature gas-blow-forming process developed by General Motors in which pressurized air is used to form aluminium sheet into a single-sided tool [2]. QPF is similar to traditional superplastic forming (SPF) except that it is carried out at lower temperatures and higher strain rates, a processing regime where both grain boundary sliding and dislocation mechanisms play significant roles in the deformation process [7]. QPF of aluminium sheet has enabled the production of complex body closure panels that could not be manufactured by conventional stamping, and at higher production rates than would be possible with SPF.

Several years of experience at General Motors using QPF process to produce panels with complex shapes has shown that certain classes of automotive body panels are preferably formed in a two stage process that is called double action QPF. The first stage, called the 'pre-forming' stage, increases the blank surface area and introduces double curvature representative of the general shape of the final product. The pre-form shape and its nearly uniform thickness distribution facilitate the second and final QPF operation to produce wrinkle-free panels without excessive thinning. The first-stage of forming can be accomplished either by gas pressure or by mechanical warm forming. Double-action QPF tools are special tools that combine two forming stages into one compact tool geometry. Double-action QPF offers many advantages over its single-action counterpart in terms of attainable panel shape complexity, production cycle time, improved use of the press bed, etc. Kim et al. [8] described two main types of double-action tools: one based on punch pre-forming, and one utilizing air-pressure pre-forming.

Simplified double-action SPF operations are summarized in a chapter on superplastic sheet forming in the Metals Handbook, 9th Edition [9], which describes "plug-assisted forming" (Figure 1a), snap-back forming (Figure 1b), and a similar process, male forming, a term created to depict a process used at Superform USA (Figure 1c). In male forming, the blank is first bulged with gas pressure into free space to develop suitable lengths-of-line, then a punch having the part shape is moved immediately underneath the pre-formed shape, and the final forming is accomplished by reversing the gas pressure to force the blank onto the punch surface. Usually, the term snap-back is used when the initial, bulged shape has a feature that facilitates collapse of the pre-form shape onto the punch. The use of snap-back forming and male forming has been limited to small panels with substantial depth. The snap-back and male forming methods are limited in the panel size that they can produce because the punch must be supported by a shaft around which a pressure-tight seal must be maintained for the initial pre-forming operation.

In contrast with the above processes, GM's double-action SPF technology uses a female cavity in its tooling to define an optimized pre-formed panel shape prior to final gas-pressure application [8]. As shown in Figure 2 in QPF process also utilize the upper half opposing the punch for controlling the pre-formed blank shape.



1a 1b 1c

Figure 1 Double-action tool technology in the superplastic forming industries outside of GM [2].

(1a) Plug-assisted forming

(1b) Snap-back forming

(1c) Male forming at Superform USA

Note that none of these processes utilize the upper half opposing the punch for controlling the pre-formed blank shape.

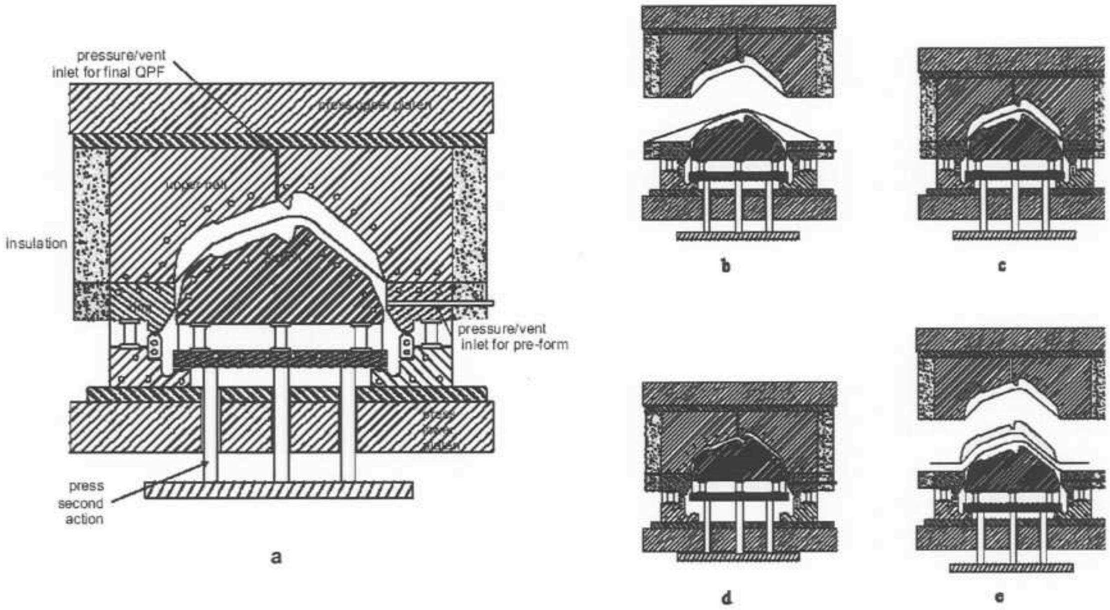


Figure 2 (a) General schematics of an air-pressure pre-forming double-action QPF tool with a floating-punch design. (b-e). Operating sequence of an air-pressure pre-forming double-action QPF tool. (b): tool open for blank loading; (c): tool closed and pre-forming the blank against the upper cavity; (d): punch moved up toward the pre-formed blank and QPF of the final panel against the punch; and (e): punch retracted and the tool open for panel extraction. [8]

Age creep forming is another process that absorbed attention in aerospace industry. This process consists of restraining a component to a specific shape during heat treatment, allowing the component to relieve stresses and creep to contour. The panel consists of a sheet metal that is applied to the die. A plastic foil covers the panel and is bonded onto the die. The air between the plastic foil and the die is pumped out. The vacuum means that the resultant shell fits the contour of the forming tool. All these elements are placed in the autoclave and heated. The forming temperature and time depend on the alloy. The stresses arising inside the shell relax until the shell is cooled and the pressure is removed, but the stresses inside the panel do not completely disappear. These residual stresses lead to spring-back in the part at the end of the forming process and currently represent the main problem in creep forming (Figure 3). The temperature and radiuses of the shape play a key role: they determine the speed of forming and the level of stress inside the panel before the temperature decreases.

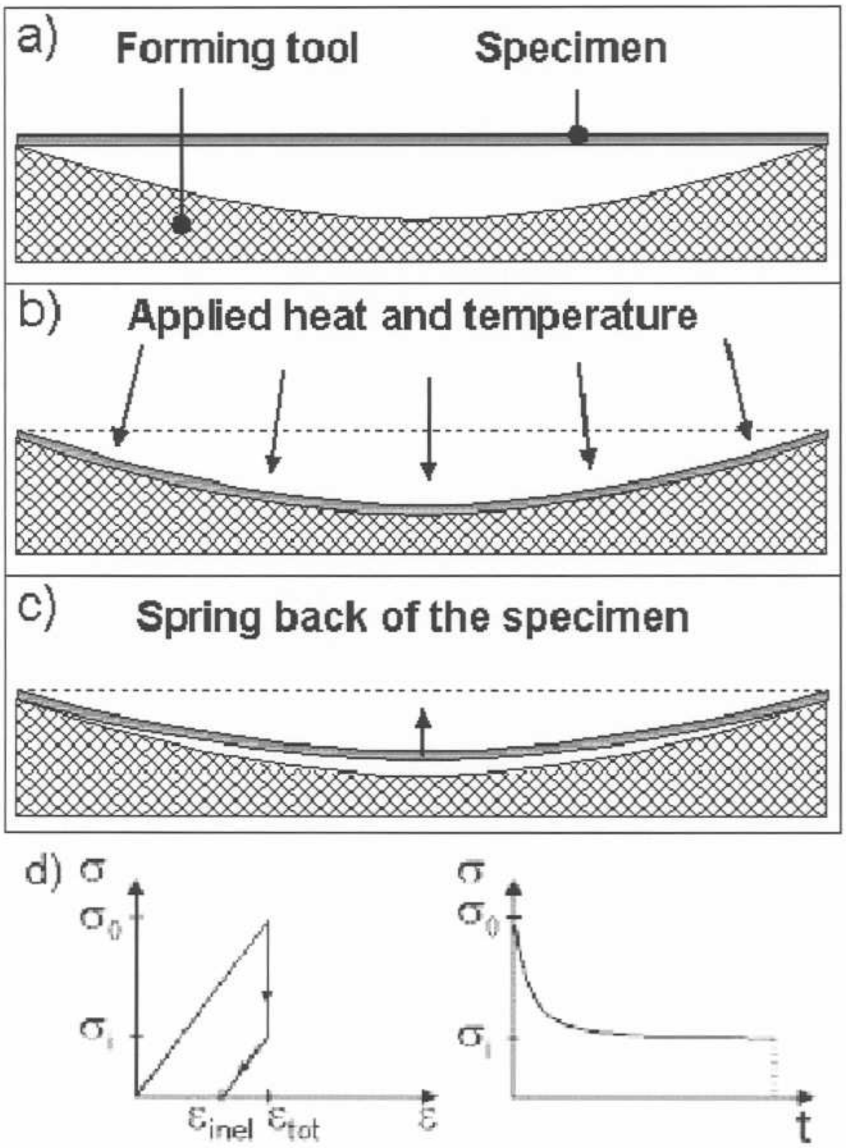


Figure 3 Principle behind the creep-forming process: a) sheet metal placed in the die; b) vacuum, pressure and heat are applied; c) residual stresses make the shell spring back; d) diagram showing stress relaxation that occurs during creep forming [13].

Metallurgical Aspects

For the SPF process to work properly, a fine grain material formed at an elevated temperature and at a constant strain rate [1]. Grain refinement for superplasticity in aluminium alloys can only be achieved by severe deformation and recrystallization. Empirical approaches have led to development of two distinct thermomechanical processing (TMP) routes, involving discontinuous or continuous recrystallization reactions. More details on these TMP routes are reported elsewhere [20]. A high volume fraction of intermetallic particles help in recrystallizing to and retaining a fine grain size. Specifically intermetallic particles promote particle-stimulated nucleation (PSN) of recrystallization during heating to superplastic forming temperatures and may also assist in retaining the fine, recrystallized grain size. Despite the clearly demonstrated superplastic behaviour of these specialty materials, as temperature decreases and strain rate increases, they revert to the deformation behaviour of their less exotic counterparts [14].

In general Mg containing aluminium alloys and their mechanical behaviour at elevated temperatures has been a topic of interest for a number of years. In this class of alloys interactions between Mg solute atoms and dislocations in the Al matrix is very important and distinctive. Mg solute atoms substitute within the Al lattice to fairly high concentrations and create significant local lattice strains. The linear misfit of Mg in the Al lattice is reported to be $\varepsilon = 0.1208$ [14]. Such a large lattice strain, which is primarily dilatational for Mg in Al, creates a strong elastic interaction between solute atoms and edge dislocations. This interaction leads to two interesting phenomena: the Portevin-Le Chatelier effect and solute-drag (SD) creep (also termed as dislocation creep). The former is characterized by a saw-tooth pattern in stress-strain curves generated at moderate temperatures and strain rates. SD creep, which occurs at higher temperatures and lower strain rates than does the Portevin-Le Chatelier effect, is characterized by inverse creep transients and a high strain-rate sensitivity ($m \approx 0.3$). This high strain-rate sensitivity can result in significantly enhanced tensile ductilities, from 100 to over 300%, which are of interest for commercial forming operations.

Low-impurity, binary Al-Mg alloys having wide ranges of Mg compositions have been the subjects of academic investigations over a number of years. SD creep is generally observed to occur over a range of elevated temperatures and low strain rates in Al-Mg alloys having Mg concentrations of approximately 2 wt. pct. and higher. At elevated temperatures, Mg atoms saturate dislocation cores for even small average concentrations [15]. Recent investigations have also confirmed the existence of SD creep in a number of commercial 5000-series alloys [16, 17]. However, the additional alloying elements present in these materials, particularly Mn, result in slight differences in behaviour from binary Al-Mg alloys. For example, as Mn concentration increases, strain rate sensitivity decreases, resulting in stress exponents near $n = 1/m \approx 4$ [14].

1. Deformation Mechanisms

Explaining the deformation mechanisms at elevated temperatures and slow strain rates is much easier using the data from either creep or strain-rate-change (SRC) tests. One way of doing that is plotting logarithm of the Zener-Hollomon parameter,

$Z = \dot{\varepsilon} \times \exp(Q_c / RT)$ versus the logarithm of modulus-normalized flow stress. In Zener-Hollomon parameter the exponential term is typical of a thermally activated phenomenon, in this case creep, R is the universal gas constant, T is absolute temperature, and Q_c is the activation energy for creep.

Depending on the system the value of Q_c would be in the same order of magnitude as the activation energy for diffusion of the solute in the solvent. Figure 4 shows such data from various 5000-series alloys; in which based on the slope of the curve, i.e. the stress exponent n in the phenomenological equation for creep, different deformation mechanisms are dominant. In the upper part of the plot at higher Z values ($Z > 4 \times 10^6 s^{-1}$), the values of the Q_c for several cases in the plot assumed to be a single value that is reasonable since the actual activation energies all are very similar. This in turn makes the data from a variety of temperatures and strain rates to collapse into a single curve for mechanisms governing the deformation. The n value of approximately 4 is maintained in the range $4\times10^{6} < Z < 10^{10}s^{-1}$ that is indicative of the deformation via SD creep mechanism. At the higher end of the Z values typical power-law-breakdown occurs and n gradually increases. To be sure that the SD creep is the dominant deformation mechanism, n ≈ 4 alone is not sufficient. In addition existence of the inverse primary creep transient must be confirmed [14]. This transition (Figure 5) has been shown to be the result of the transition from grain boundary sliding to SD creep as the active deformation mechanism [19]. It has been shown that this transition can be observed by a change in texture from essentially random to a strong fibre texture (at high Z values) [20]. Texture development is the topic of one of the following sections.

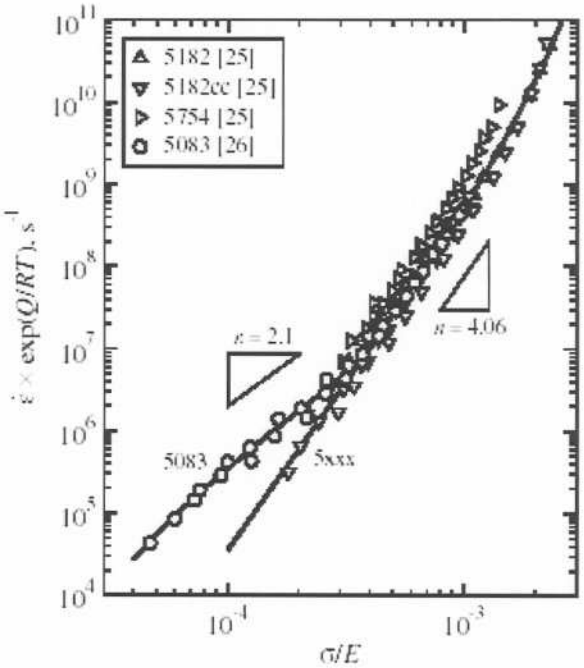


Figure 4 Data for creep deformation in commercial 5000-series alloys are plotted as the logarithm of the Zener-Hollomon parameter versus the logarithm of modulus-compensated stress [14].

At the low strain rate and high temperature corner of the Figure 4, $Z < 4\times10^{6}s^{-1}$, 5083 alloy deviate from the line to lower stress component n ≈ 2 and also lower flow stress, both are indication of deformation by grain-boundary sliding (GBS) creep. Superplasticity is associated to the latter mechanism; therefore within this range superplastic response is clearly expected.

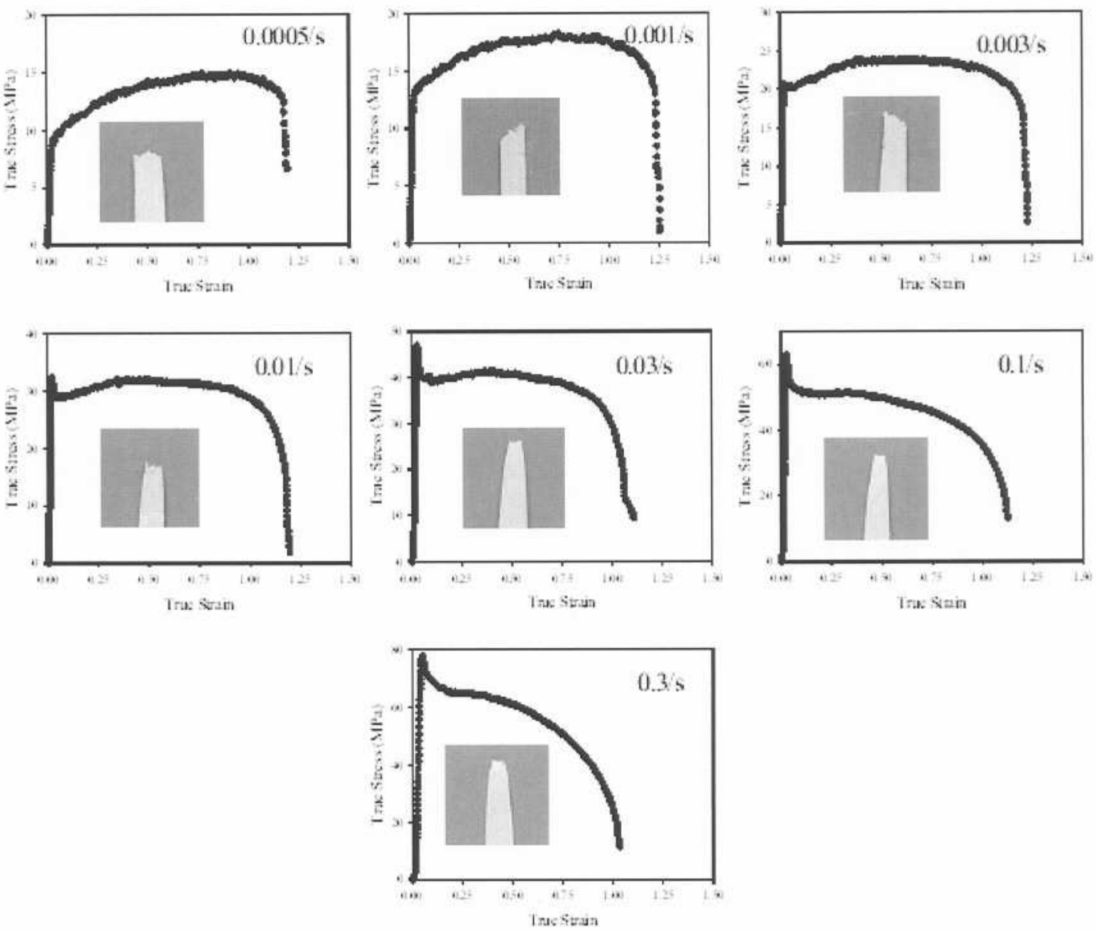


Figure 5 The effect of strain rate on AA5083 tensile curves shape at 450 °C, that also shows the transition of deformation mechanism [21].

2. Ductility at Elevated Temperature

Obviously ductility is a critical parameter in sheet metal forming processes. At elevated temperature and low strain rate tensile tests, deformation mechanism alone cannot determine the extent of tensile ductility. Tensile ductility also depends strongly on the active failure mechanisms in the system. Taleff [14] compared different 5000-series in terms of ductility. The comparison showed that a material produced by continuous casting (5182cc) exhibited the lowest ductility and that is the result of cavitation (void formation) most likely nucleated at intermetallic particles. This is despite of nearly the same deformation response displayed by all the 5000-series alloys at high Z values (Figure 4). In general, moving from high value of Z towards the lower values, tensile ductility initially increases as a result of decreasing n value due to transition from power-law-breakdown PLB to SD creep. Tensile ductility reaches a maximum at medium values of Z and with further reduction of Z (high temperature and low strain rate combined conditions) tensile ductility decreases (Figure 6). This decrease is a result of increased cavitation at low Z range.

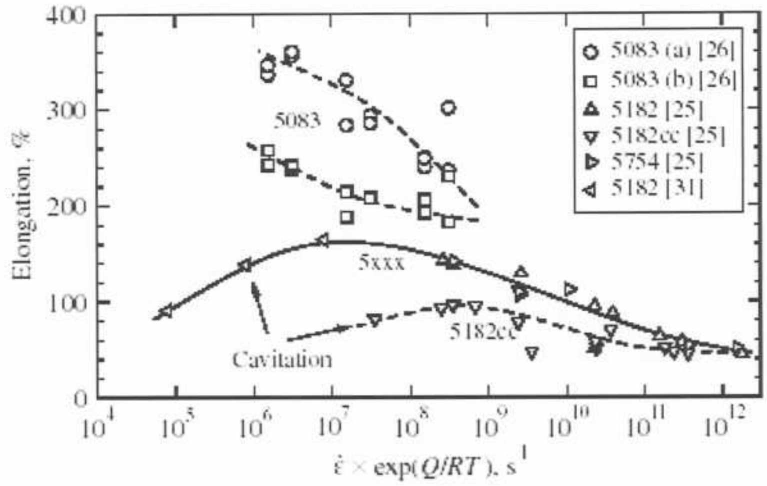


Figure 6 Data for tensile elongation are plotted against the logarithm of the Zener- Hollomon parameter for a number of 5000-series aluminium alloys [14].

Data from superplastic 5083 alloy, also shown in Figure 6, is clearly different from other ordinary 5000-series alloys, as there is no reduction of the tensile ductility at lower values of Z. specifically, within the range of $10^6 < Z < 10^9 s^{-1}$ the superplastic 5083 exhibits significantly greater elongations than do the other 5000-series alloys. However, as Z increases within this range, the elongation of the 5083 alloy approaches those of the other 5000-series alloys. Although GBS creep is shown to only dominates deformation in the 5083 alloy for $Z < 4 \times 10^6 s^{-1}$, the ductility of 5083 is still higher than that of the other 5000-series alloys well into values of Z for which SD creep dominates deformation of all the 5000-series alloys.

Further investigation of the tensile ductility in low-impurity, binary Al-Mg alloys (with grain sizes well in excess of 10 μm) suggests that at high Z values ($Z > 10^9 s^{-1}$), they produce similar results to those of the 5000-series alloys. Interestingly at lower Z values the elongation of these alloys are within the range of those produced by 5083 alloys. This is despite the complete absence of deformation by GBS creep throughout the range of the relevant Z values. Deformation in these binary alloys is consistently by SD creep.

There is a two- fold explanation for this result. First, these alloys exhibit smaller stress components (n ≈ 3.1 to 3.6) compared to those of other 5000-series alloys, e.g. 5182 or 5754 (n ≈ 3.7 to 4.2). This slight difference that may seem insignificant, indeed strongly affects the necking (localization of the deformation) behaviour in these alloys, i.e. decrease the rate of neck development. It is also for this reason that the 5083 alloys exhibit high elongations as Z approaches values for which GBS creep controls deformation. Within the region of transition between SD and GBS creep, the stress exponent of the 5083 materials is slightly less than that of the 5182 and 5754 materials, even though SD creep still dominates deformation. Secondly, low impurity Al-Mg binary alloys do not contain intermetallic particles or dispersoids that are responsible for cavitation in the 5000-series alloys.

Figure 7a shows the cavitation-initiated failure (without significant necking) of a 5083 specimen deformed at a low Z value. It should be noted that although at low stress component value produced by GBS creep deformation in 5083 alloys prevent significant neck development it does not prevent cavitation that limits tensile ductility in these alloys. In contrast a low impurity binary Al-Mg alloy deformed at a similar value of Z exhibits failure by necking nearly to a point (Figure 7b). Lack of cavitation in the latter case, allows necking to continue to very large strains before final rupture. It is important to note that although the AL-Mg alloys could produce comparable elongation to those of 5083 alloys, their uniform elongations are less. It is also possible to have a combination of the two failure mechanisms.

The 5083 alloys also exhibit this combination of failure mechanisms as deformation transitions from control by GBS creep to control by SD creep, as Z increases [19]. Based on a recent study on disorientation distributions across cavities, it seems that a final cavitation process occurs as a result of grain boundary separation, consistent with GBS mechanism, even for materials deformed under SD creep condition [29].

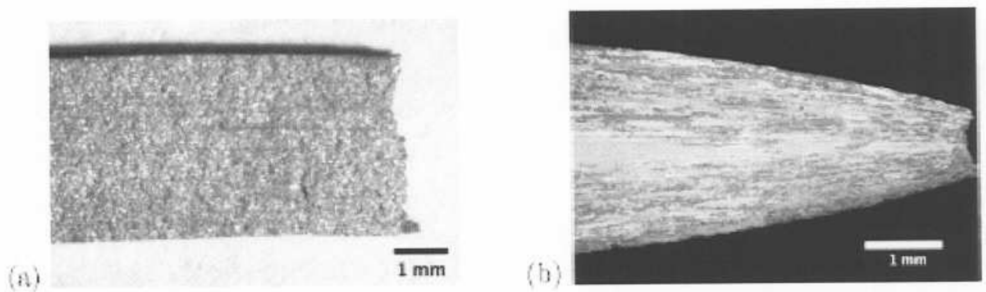


Figure 7 Micrographs are shown for (a) the surface of a 5083 tensile coupon at the failure region and (b) the etched cross-section of a failed tensile coupon of the Al-2.8Mg binary alloy [14].

In summary it can be concluded that the presence of GBS creep, even when it is subservient to SD creep is beneficial for tensile ductility. Aside from the controlling deformation mechanism texture development also affects ductility and fracture.

3. Recrystallization and Texture Development

Considering the range of temperature used in superplastic or other similar forming processes, recrystallization must play an influential role in the process and the post forming properties. Post failure characterization studies [21] on tensile specimens tested at different strain rates suggests that at lower strain rates, where GBS creep controls deformation, the grain size remains relatively fine right up to the fracture front. However, in specimens exhibited necking as a sign for SD creep regime, very large grains were observed, Figure 8. In the latter case the change in grain size is very abrupt and appears to be the result of dynamic recrystallization occurring at a critical strain. At higher strain rates (>0.01/s), a significant change in grain size occurred as moving inside the neck region towards the fracture front. They also found a linear increase in the length of the recrystallized region from the fracture front with increasing strain rate (up to 0.3 /s).

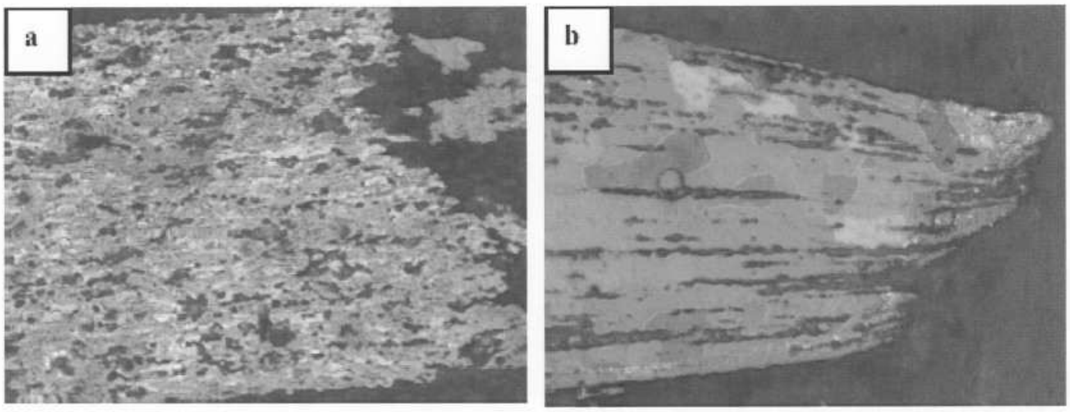


Figure 8 Optical image showing the grain structure near the fracture surface for AA5083 samples tested at 450 °C at a strain rate of (a) 0.0005/s and (b) 0.1/s [21].

The same investigators used texture intensities, a quantitative measure of texture, measured using pole figures to study texture evolution. Figure 9 shows a plot of texture intensity as a function of strain rate. Texture begins to develop at strain rate of 0.003/s and gets stronger for higher strain rates. Texture intensities for 0.1/s and 0.3/s are the highest and nearly the same. Relative to the grip section, no texture is seen for strain rates less than 0.003/s.

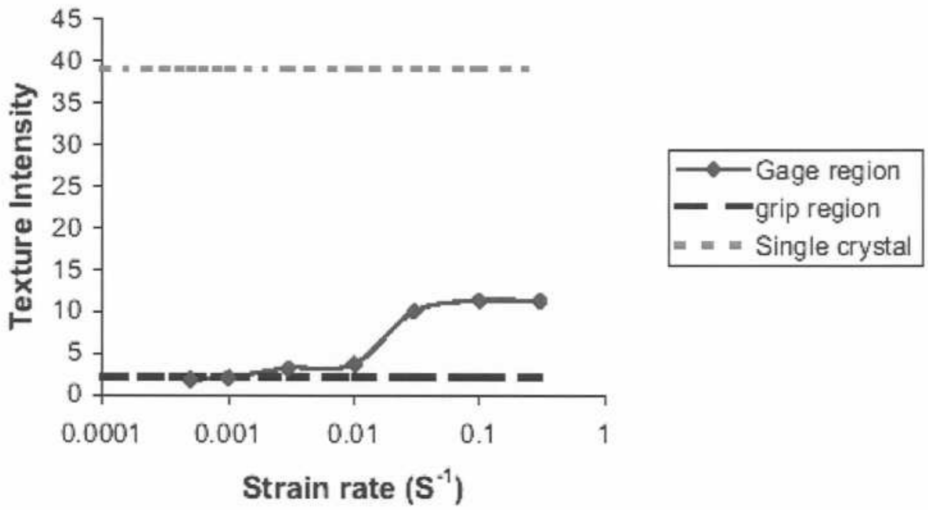


Figure 9 Variation of texture intensity with strain rate in AA5083 tested at 450 °C [21].

In summary, there is a clear change in texture development as the deformation mechanism changes from GBS creep to SD creep. Within the range of deformation by the former mechanism (low strain rate or low Z values) there is little texture after the deformation. At higher strain rates, texture develops as the deformation mechanism changes to SD creep. This is consistent with the previous understanding that SD creep would tend to reorient the grains in a preferred direction relative to deformation axis, whereas GBS creep would maintain a random orientation [20-21].

4. Post Superplastic Forming Properties

Post forming properties should be considered a critical subject in any forming process. Dunwoody et al. [22], reported that post-forming properties in 5083-SP alloy are considerably higher than those of commonly used aluminium alloys formed using conventional techniques. In another report, the investigators indicated that this alloy after forming, exhibits sufficient strength, microstructural stability, and resistance to cavitation, which meet materials requirements for many potential applications [27].

Bradley and Carsley [31] also investigated the post-form properties in AA5083 sheet formed superplastically and correlated the reduction in strength, uniform elongation and fatigue performance to the extent of cavitation and also to the size of recrystallized grain.

Due to finer grains in superplastic alloys, susceptibility to intergranular corrosion of the final component has been a point of concern particularly for aviation industry. Data of Dunwoody et al. [22], suggests that although 5083-SP alloy is more susceptible to corrosion, measured using the weight loss data, compared to 5251-H3 alloy the overall weight loss is still below the susceptibility ratings indicated in relevant ASTM standard [22]. However, should the component experience exposure to elevated temperature, the susceptibility to intergranular corrosion become a major issue as Hecht et al. [27] reported.

Specific Aluminium Alloys

Since several decades ago that superplastic forming was recognized as an attractive forming process, part of the efforts has been focused on development of specialty alloys suitable for this method. Many of the resulted alloys added "spf" or most often "sp" to the numeric material identification. Many demonstration or service parts have been made by 2004-SP, 7475-SP, and 8090-SP. Further developments have taken place in rendering non-heat treatable superplastic Al-Mg alloys by different investigators. These include patented alloys containing 8.4% Mg and 1% Cr [23], 0.6 %Cr-added 5083 [24], another modified version of 5083 with additions of Zirconium and up to 1.4% Fe [25] and 0.4% Zr-added 5251 alloy [26]. Finally Swiss Aluminium Ltd (Alusuisse) introduced its 5083-SP sheet of standard composition that sold commercially [22].

The aluminium alloy 5083-SP is now used to build a host of airplane and automobile components, and its use is increasing exponentially. It is likely that most automobiles produced in the U.S. will feature at least one SPF formed 5083-SP major component within five year's time and that a pseudo-SPF forming method will become the dominant means of building car panels within ten years [1].

Alloy 5083 that is produced in fine-grain superplastic sheet form contains 4 to 5% Mg which provides significant solid solution strengthening, as well as approximately 0.7% Mn and 0.1% Cr. The Mn and Cr, along with Si and Fe impurities, combine with the Al to form >1 μm constituent particles which help produce the fine recrystallized grain size, and sub micron dispersoids which inhibit grain growth [32]. Dispersion of intermetallic particles (Al6Mn and Al3Fe) [30] locally concentrates strain accumulated during severe deformation by cold rolling. Therefore, 5083 alloy achieves a recrystallized, linear-intercept grain size of $\bar{l}$ = 7 μm, which is adequately stable under deformation at temperatures below approximately 500 °C. It is this fine grain size, which allows deformation via GBS mechanism at low strain rates and high temperatures.

As the strain rate increases and temperature decreases deformation mechanism changes from GBS to SD creep. Since the latter mechanism provides relatively high strain rate sensitivity, although not as high as that observed under GBS, the alloy retains reasonable superplastic forming characteristics even when GBS no longer dominates [30]. This alloy exhibits reasonable superplasticity when tested uniaxially at strain rates 10 –4-10-3 S-1 and temperature around 500 °C. 5083-SP controlled for impurity content exhibited more than 600% elongation when tested at 525 °C and at 10-4 S-1. When alloyed with 0.6% Cu, this alloy exhibited even higher elongation, 700% at 550 °C [22, 24, 27].

It has also been reported that after a 5:1 cold-rolling reduction, a commercial grade AA5083 exhibited 300% elongation at 510 °C [28], the recrystallized grain size was about 10 μm, similar to the grain size observed in 5083-SP, indicating that the former, i.e. AA5083, alloy could be made moderately superplastic with additional standard thermomechanical processing.

Although alloy 5083 can produce a true superplastic response, it also can exhibit the same characteristics of solute-drag creep observed in other commercial 5000-series alloys and in low-impurity, binary Al-Mg and ternary Al-Mg-Mn alloys. Because of the high strain-rate sensitivity associated with SD creep, alloy 5083 can retain excellent tensile ductilities even when deformed at temperatures below, and strain rates above, those necessary for a superplastic response; superplasticity is associated with deformation by grain-boundary-sliding (GBS) creep. It is this effect of SD creep in alloy 5083 which makes it a relatively forgiving material during superplastic forming and likely plays a large part in its commercial success [14].

The behaviours of the 5000-series materials are compared with those of high-purity Al, low-impurity Al-Mg binary alloys, and low-impurity Al-Mg-Mn ternary alloys in Figure 10. The fits to 5000-series data shown in Figure 4 are reproduced in Figure 10. It is clear that data from low-impurity Al-Mg binary and Al Mg-Mn ternary alloys lay along the same curve as the 5000-series materials for $Z > 4 \times 10^6 s^{-1}$, suggesting that these materials and the 5000-series materials all deform by SD creep up to the onset of power-law-breakdown (PLB). This suggestion is confirmed by considering other factors, such as the presence of inverse creep primaries, and the lack of a flow stress dependence on grain size [18]. In all cases within Figure 6, the flow stress of pure Al is significantly less than that of the Mg-containing Al alloys, including the 5000-series materials; this is consistent with solid solution strengthening during SD creep [14].

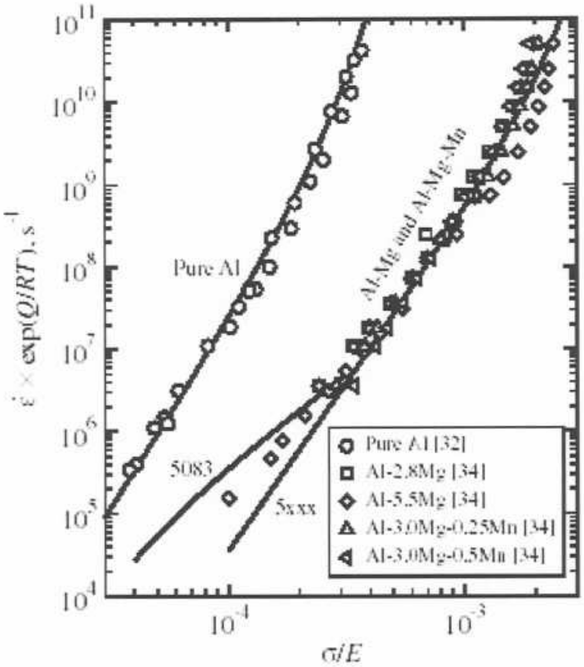


Figure 10 Data for creep deformation in high-purity Al, low impurity Al-Mg, and low-impurity Al-Mg-Mn alloys are plotted as the logarithm of the Zener-Hollomon parameter versus the logarithm of modulus-compensated stress [14].

An explanation of why AlMgSc alloys are particularly interesting for the application of creep forming is given below [12]. In the case of age-hardenable alloys, the temperature and duration of the process control precipitation hardening. This in turn defines the mechanical properties of the part. The forming temperature must be lower than 473 K (typically 448 K), because temperatures in excess of this would cause the alloy to age and exhibit degraded properties.

In case of creep forming of non-age-hardenable alloys like AlMgSc the forming temperature can be higher, if the chemistry and microstructure of the alloy allow. Two factors operate in the case of AlMgSc alloys and 5XXX alloys. The longer the alloy remains at a temperature between 423 K to 473 K, the more sensitive it is to corrosion, but the temperature must be below the range 573 K - 623 K in order to effect forming without greatly reducing the mechanical properties of the alloy obtained through cold rolling [12].

Heating the Sheet Material to the Required Temperature

Several techniques of forming sheet material into complex shapes use elevated temperature for improved formability. Warm Stamping, superplastic forming and warm hydroforming are some of these methods. Production cycle could not be limited by the heating of the sheet to the required temperature. The objective of a reliable heating method is to quickly attain a uniform and stable sheet temperature. Carsley and Hammar [4] investigated and modeled several heating methods in terms of conduction, convection and radiation modes of heat transfer. Specifically, they have tried to compare methods in 450 °C to 480 °C range, as needed for superplastic forming of AA5083.

Lubrication and Die Coating during the SPF process

At high forming rates, as required for mass production, attention has to be paid in choosing a lubricant. This is important for both part thickness management and in avoiding surface quality degradation. The mixed lubricant of graphite and boron nitride gave the best results in both aspects while tried in Japan [5]. Alternatively, it is possible to use die coatings. Considering that SPF parts are made from fine-grained sheet materials blow formed into a die that has been heated to the proper forming temperature, close contact between the die and the work piece is inevitable. At this condition, action of interatomic forces could result in adhesion and/or friction. It is a common practice to use solid lubricants to prevent sticking and bonding of the piece to the die. Tool coating optimized for SPF process can produce optimal surface quality for the forming process, significantly increase tool life and reduce or eliminate usage of solid lubricants [6].

Modeling Aspect and Constitutive Equation Development

Parallel with the development of SPF technologies, substantial efforts were made to use finite element capabilities. For instance, GM used an enhanced version of the commercial implicit finite-element code MARC along with its QPF technology, however due to the long turn-around time of the analysis, the code usefulness was limited to validation or quick 2D analyses [10]. GM initiated the development of PAM-QPF code, based on the existing PAM-STAMP code. The tool surfaces were optimized with extensive use of finite element analysis (FEA) of the forming process using the PAM-QPF code. GM tried to demonstrate the use of its QPF technology and PAM-QPF code in producing large body panels with complex shapes such as the fenders of the Chevrolet SSR [11]. Later on, for accurate simulations, GM developed pressure control algorithms to maintain the desired strain rate, a job-termination criterion to stop a simulation at the appropriate stage, and constitutive equations to describe material behaviour accurately. These tools have been used successfully in plane-strain, generalized-plane-strain, and 3D MARC analyses of QPF panels [10].

Harrison et al. [34] compared the influence of friction and die geometry on the forming simulation of AA5083 and AA5182 alloys using the ABAQUS/Standard finite element software. The 2-dimensional simulation of forming a long rectangular box where plane strain is assumed was performed using solid elements. The objective of their work lies in the understanding of the thinning behaviour of materials with different strain-rate sensitivities (m-value) through observation of depth of draw, forming time and pressure cycle.

The FEM models for superplastic forming use constitutive equations which relate the flow stress during forming to the strain rate, strain, temperature, and grain size using parameters such as strain rate sensitivity (m), work hardening exponent (n), grain growth exponents (static and dynamic) and creep activation energy. While successful, these models have focused on strain rates and temperatures that fall within the GBS regime. *At the higher strain rates and lower temperatures necessary to perform automotive superplastic forming at reasonable production volumes, modeling the mechanical behaviour of a superplastic alloy becomes more challenging. The combination of GBS and SD creep results in the stress strain curve with an initial transition region explained earlier in section on deformation mechanisms. A curve fitting exercise was used to represent this behaviour with phenomenological equations [33]. However, improved modeling of this behaviour is required, and improved testing techniques are required to accurately characterize the necking regime [32].*

Who is Who in Superplastic Forming

- Lawrence Livermore National Laboratory

The main focus has been on concurrent Superplastic forming (SPF)-Diffusion Bonding (DB) as an energy-saving and cost-effective manufacturing process. Activities include uniaxial tensile testing, biaxial (blow) forming to characterize the superplastic behaviour of various metals including 7475 and 8090 aluminium alloys.

- U.S. Department of Energy (DOE) / Pacific Northwest National Laboratory (PNNL)

Efforts have been made to develop low-cost SPF aluminium alloys and simulation tools to optimize forming cycles. In addition to materials testing, the works include modeling as well as alloy development. The SPF technology developed at PNNL has already been transferred to General Motors. Other industrial or academic partners include Boeing, Kaiser Aluminium, MARC Analysis, NASA, University of Michigan and Washington State University.

- General Motors and Alcoa

Collaborated on the development of the aluminium forming process—referred to as quick plastic forming (QPF), which enables the manufacture of more complex forms for production models. Previously, such shapes were limited to concept and low-volume niche vehicles. The QPF process was adapted from a hot blow forming aluminium process used in the aerospace industry.

- Boeing

The SPF technology developed at Boeing that is considered for forming of titanium, aluminium and steel also uses diffusion bonding for joining purposes. The process uses a ceramic die system instead of the common and more expensive stainless steel dies and uses induction heating.

- FormTech GmbH

Superplastic forming activities directed towards verifying the process and also producing small batches.

- Luxfer Group - Superform Aluminium, USA/England

This company fabricates parts and assemblies in both aluminium sheet and structural graphite composites. They are using CATIA based CAD for designing the tools suitable for Superform Process. Aluminium alloys include 5083-SPF, 2004-SPF, 7475-SPF.

- Barnes Aerospace Group, Inc.

This company is a producer of machined and fabricated components and assemblies for aerospace applications. Barnes Aerospace has nearly 4000 employees at 40 different locations worldwide. Superplastic forming is one of the technologies utilized in advanced sheet fabrication division. Superplastic forming presses range up to 1200 tons.

- Aeromet International

Activities concentrated on titanium sheet alloys and the company has developed a variety of hot forming and superplastic forming processes (SPF).

- Ducommun Aerostructures Company, Parsons Facility

Equipments includes a 100 Ton Press (34" x 54" Work Envelope) for superplastic forming. The press is capable of Temperatures up to 2000 Degrees.

- Swiss Federal Institute of Technology/Zurich

Activities focused on Numerical Simulation of Superplastic Forming (``SPForm") intended to develop and implement new, state-of-the-art models and algorithms for the numerical analysis of sheet metal forming processes in the superplastic range mainly for aerospace industry.

- University of Southern California, Terence Langdon Group

Activities directed towards development of low cost superplastic aluminium alloys.

- University of Michigan-Dr. Ghosh Group

The research on superplastic forming is focused on deformation mechanism and failure and supported by US Dept of Energy.

- University of Texas, Eric M. Taleff Group

Research activities includes the ductility of Al-Mg alloys at elevated temperatures, including superplasticity and superplastic alloys.

- McGill University, Department of Mechanical Engineering

There has been some activities related to finite element modeling of the Superplastic Forming (SPF) process using ABAQUS.

- University of Liege, Belgium, M. Hogge Group

Numerical simulations of metal forming processes including superplastic forming.

- Centre for Advanced Aerospace Materials (CAAM), Pohang University of Science and Technology, Korea

Research activities in a wide range of topics related to light weight materials that includes superplastic forming.

- Institute for Metals Superplasticity Problems (IMSP)/Russia

The focus is in fundamental research on areas such as "nature of strength, plasticity and superplasticity of polycrystalline materials", "mechanical aspects of superplasticity", "mathematical modeling of superplastic forming processes", "development of integral technologies like concurrent superplastic forming and diffusion bonding", " superplastic forging" and "tribology in superplasticity". In addition there are ANSYS-based numerical simulation activities. International partner include Lawrence Livermore National Laboratory, FormTech GmbH (Germany) and Rockwell Scientific.

- Accudyne Engineering & Equipment Company

Accudyne Company designs, develops and manufactures press systems utilizing Superplastic Forming (SPF) technology.

- Cyril Bath Company

Also manufactures a range of equipments that includes superplastic forming machines.

- ACB

This company provides a comprehensive range of products and services extending from presses to batch parts. ACB designs, manufactures and installs its LOIRE brand mark presses in different forming operations including superplastic forming.

- Savage Press

This company manufactures specialty presses for creep forming and superplastic forming of titanium and aluminium alloys.

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