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# Superplastic Forming 40 Years and Still Growing

***A.J. Barnes***

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**In late 1964 Backofen, Turner & Avery, at MIT, published a paper in which they described the "extraordinary formability" exhibited when fine-grain zinc-aluminum eutectoid (Zn 22 Al) was subjected to bulge testing under appropriate conditions. They concluded their research findings with the following insightful comment "*even more appealing is the thought of applying to superplastic metals forming techniques borrowed from polymer and glass processing.*" Since then their insightful *thought* has become a substantial reality with thousands of tons of metallic sheet materials now being superplastically formed each year. This paper reviews the significant advances that have taken place over the past 40 years including alloy developments, improved forming techniques and equipment, and an ever increasing number of commercial applications. Current and likely future trends are discussed including; applications in the aerospace and automotive markets, faster-forming techniques to improve productivity, the increasing importance of computer modeling and simulation in tool design and process optimization and new alloy developments including superplastic magnesium alloys.**

**Keywords** aluminum, fabricated metal, superplastic forming

## 1. Introduction

The year 1964 saw the public debut of two extremely special vehicles (Ref 1) one was the previously top secret A12 jet aircraft, the precursor to the famous SR71 "Blackbird" the other, the Ford GT prototype racing car, later to be known as the Ford GT40. The A12, constructed largely from titanium alloy and was able to withstand the rigors of speeds in access of Mach 3, which was the fastest and highest flying jet of it's time. The 200 mph plus GT with its unique body style hand crafted from sheet metal and fiberglass went on later to win the prestigious Le Mans 24 hr endurance race.

The construction of both these remarkable vehicles would have been made considerably easier if only suitable superplastic alloys and the superplastic forming (SPF) process had existed then. The year 1964 was also the year that Backofen et al. (Ref 2) published their landmark paper in which, for the first time, a superplastic "bubble" was pneumatically formed from a sheet of superplastic AlZn eutectoid alloy. This parturient moment signaled the emergence of a new technology: *superplastic forming*.

The remainder of this paper reviews how this technology has developed into a viable manufacturing process for a variety of industries and the significant advances that continue to be made.

## 2. The Early Days

The early history of superplastic forming; as distinct from that of superplasticity, which has been thoroughly reviewed elsewhere (Ref 3, 4), was an exciting and rapidly advancing period worthy of a more complete review than is possible here. It is appropriate however to chart the sequence of events and the key individuals and institutions who pioneered and shaped this unique technology.

Following the publication of Underwood's detailed review (Ref 5) of the early Russian work of Bochvor and Suiderskaya (Ref 6) relating to the phenomenon of superplasticity, Prof. Backofen and his team at MIT set about replicating some of the Russian work and established the importance of strain rate sensitivity to the remarkable neck-free tensile elongation characteristic of superplastic metals. Prior to the publication, late 1964 (Ref 2), of the Backofen, Avery and Turner paper laboratory experiments were undertaken demonstrating biaxial forming of ZnAl eutectoid sheet. This was chronicled in an MIT undergraduate laboratory report entitled "Blowing Bubbles in 70% Zn, 21% Al Sheet" (Ref 7) one of their remarkable bubbles is shown in Fig. 1. The young men undertaking this 'worlds first' demonstration, under the close guidance of Prof Backofen, were apparently unaware that they were witnessing the birth of a new technology (Ref 8). The significance of these experiments was, however, clear to Prof Backofen and his coauthors and in the final paragraph of their 1964 paper they stated "*even more appealing is the thought of applying to superplastic metals forming techniques borrowed from polymer and glass processing.*" Prof. Backofen, his coworkers and doctoral students went on to investigate many aspects of superplasticity and a variety of alloy systems, including; magnesium, copper, and titanium. He also undertook forming experiments including vacuum forming and blow molding of hollowware. The author had the great pleasure of visiting with Prof Backofen in the fall of 2005 at this home in New Hampshire. This ebullient octogenarian was eager to know the current status of superplasticity and SPF and was most

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**A.J. Barnes,** Superform USA, Riverside, CA 92504. Contact e-mail: aj.barnes@superformusa.com.

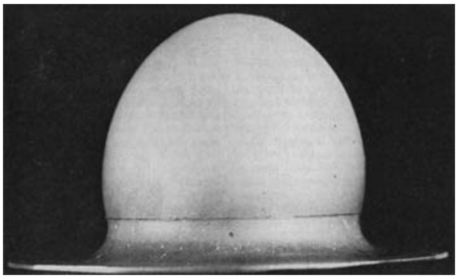

**Fig. 1** The 'first' superplastically formed bubble (1964)

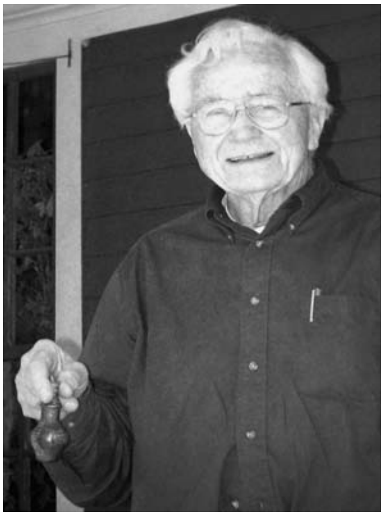

**Fig. 2** Prof W.A. Backofen (2005)

**Fig. 3** Dr. Fields with IBM's first superplastic forming (1965)

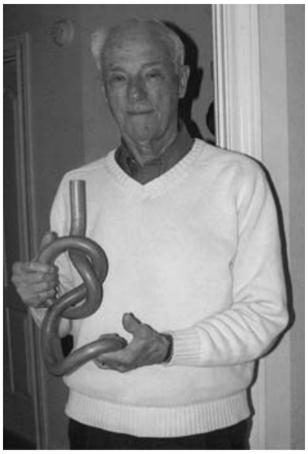

**Fig. 4** Dr. Fields in 2006 holding technological trophy circa 1966

interested in the ICSAM 2006 conference in Chengdu. Figure 2 shows Prof. Backofen holding a small superplastically blow-molded vase produced from the ZnAl eutectoid alloy (circa 1965).

It is, in the author's opinion, appropriate to see Prof. Backofen as having played a pivotal role in the emergence of a new forming technology and most deserving of the title 'Father of Superplastic Forming'. However, it was much earlier when the first pneumatically formed superplastic metal was reported. This was in Pearson's now memorable paper (Ref 9) of 1934 where fine grained lead-tin eutectic alloy tube was inflated until it burst yielding a circumferential strain of many hundreds of percent.

Another key figure in the early development of SPF was Davis Stuart Fields, Jr. Dr. Fields gained his doctorate in metallurgy at MIT in 1957 and coauthored several papers with Prof Backofen relating to strain hardening in aluminum alloys (Ref 10). At the time of the publication of the Backofen, Avery & Turner paper in December 1964 Fields was working at IBM's Office Products Division in Lexington, Kentucky. Earlier that year he had attended the ASM meeting where Backofen first described the work at MIT that illustrated the extraordinary formability possible with superplastic metals. Having had some first-hand experience of vacuum forming thermoplastics (Ref 11) he quickly realized the potential superplastic metals had. Fortunately the IBM environment in which he worked gave almost free-rein to bright ideas so by February 1965 Fields and his team had built the small vacuum forming rig, had cast, rolled and homogenized ZnAl eutectoid sheet and vacuum formed their first experiment part in a simple heated cavity die, see Fig. 3. By April 1965 Fields had filed the worlds first SPF patent application (Ref 12) covering a wide range of sheet- and tube-forming techniques previously used for thermoforming plastics. Clearly this was not going to be some scientific curiosity languishing in obscurity. The technology was moving forward at a pace, albeit with only one superplastic alloy suitable for forming useful parts. Forming developments at IBM were not limited to sheet. Various forms of compression molding were explored taking advantage of the low-flow-stress associated with the superplastic ZnAl eutectoid alloy. To demonstrate the characteristically low-deformation force associated with the superplastic state a one-inch diameter bar of ZnAl was heated and tied in a knot by hand! This technological trophy produced four decades ago is shown in Fig. 4, in a photograph of Dr. Fields taken by the author earlier this year (2006).

IBM's enthusiasm for SPF at this time was such that by 1969 they had produced an in-house Superplasticity Design Guide (Ref 13) and introduced a number of components into limited production including CRT bezels and corrugated heat ex-changer plates. The prototype display unit shown in Fig. 5 exemplifies the remarkable advances made by IBM's technologists in just 5 years since Backofen's 'proto-bubble'. This part was made from 2.5 m thick ZnAl eutectoid alloy and formed at 270 °C. It utilized two combined forming techniques aimed at limiting localized thinning. A limited slip technique was used as the sheet was initially 'plugged' into the heated complex female mold, using a male preformer, effectively drawing additional material into the forming before finally clamping and pneumatically stretching the preform into contact with the molds complex geometry. This procedure seems, to the author, to have anticipated aspects of more recently patented inventions (Ref 14, 15).

All this pioneering work being carried out in the United States did not go unnoticed overseas, particularly in the United Kingdom. It was not long after the first reports of Backofen's and Field's work that research and development aimed at the potential commercial exploitation of superplastic metals and SPF began in the UK. One of the first industry-based laboratories there to study SPF was the Electricity Council Research Centre, Capenhurst, Chester. Capenhurst was setup remarkably differently from many company linked R & D organizations in that they were eager to share their developments and ideas with the rest of industry; so promoting, they hoped, the greater and more efficient use of electricity in the UK. As part of this 'mission' they had in 1967 created a group focused on the metal Industries lead by Dr. Roy Johnson. Dr. Johnson had previously visited the USA in 1966 and met with a number of metal researchers, including Prof. Sherby at Stanford University. Accordingly he had first-hand knowledge of the superplastic developments taking place in the USA. Realizing the potential of SPF Johnson initially worked with ZnAl eutectoid; he too blew bubbles and made demo parts for the electric cable industry (see Fig. 6, 7)

Seeing the potential in the aerospace industry Johnson explored superplastic 'hard' metals and in 1968 produced the world's first titanium- and stainless-steel SPF parts. These small demo parts (see Fig. 8a, b, 9) were shown to British Aircraft Company (BAC) and along with Dr. Johnson's persuasive enthusiasm, convinced BAC personnel to setup a development facility at BAC Filton, the home of Concorde.

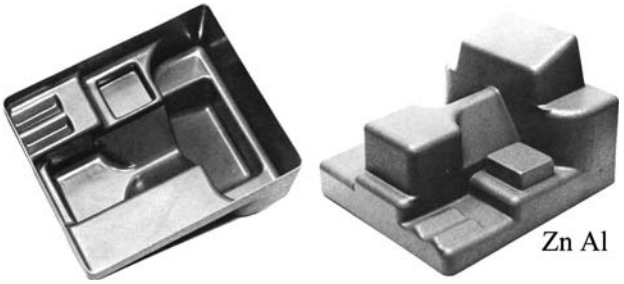

**Fig. 5** Complex female forming produced by IBM using their limited slip 'plug' assisted method

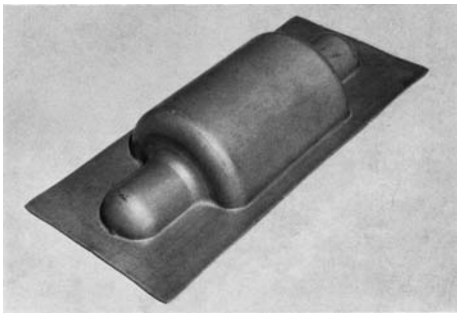

**Fig. 7** Early demo cable joint box formed at ECRC circa 1968

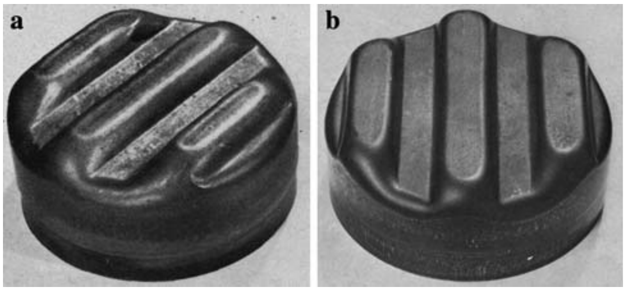

**Fig. 8** (a) 1st SPF titanium part and (b) 1st SPF stainless-steel part

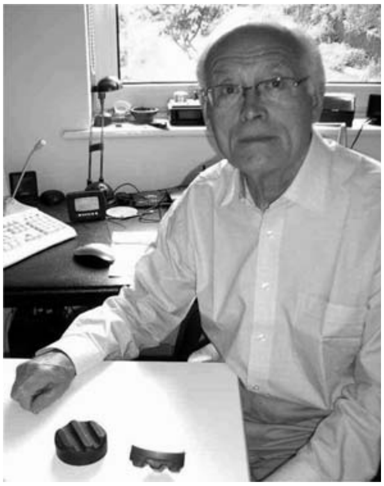

**Fig. 9** Dr. Johnson (2006) with original 'first formings'

**Fig. 6** Dr. Roy Johnson blowing a Zn Al Bubble

In 1969 the first conference on SPF was held at Capenhurst and was attended by more than sixty representatives from many different industries (Ref 16) including groups from Tube Investments Research Labs (TIRL), Hinxton Hall, Cambridge, British Aluminum Research Division (BARD), Chalfont Park, and from the Press Steel Fisher (PSF) Division of British Leyland. The PSF group, led by North and Hundy, were already developing large demonstration ZnAl alloy car body panels and were optimistic that production would soon become a reality (Ref 17, 18). See Fig. 10 and 11.

Unknown to most attendees at the conference the research work underway at TIRL and BARD; to develop the world's first dilute superplastic aluminum an alloy, as distinct from the eutectic and eutectoid duplex alloys available then, was closing in on success. Later that year (1969) TIRL demonstrated that superplasticity could be obtained in an Al-6%Cu-0.5%Zr alloy, later to be known as SUPRAL 100. The significance of this development would later have a profound negative impact on the future commercial application of ZnAl, however, at that time the commercial prospect for the ZnAl eutectoid alloy looked good.

**Fig. 10** SPF on Front Page of Design Engineering 1969

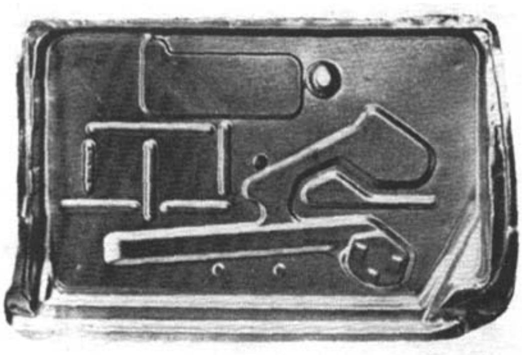

**Fig. 11** An early demo car door inner skin formed from Al Zn-Prestol alloy

## 3. Commercialization

To embark on a new commercial venture, particularly one based on a new technology requires a measure of considerable confidence, an innovative sense and shear courage. In addition to the above financial commitment is normally required from a parent company, bank or some other financial institution before such an enterprise can be embarked upon. Weighing the risks, market potential and technical credibility are some of the factors that the 'risk taker' has to evaluate. Such was the case for SPF.

In 1971 the prospect of producing complex-shaped components formed from ZnAl eutectoid alloy using low-cost tooling and forming times of just a few minutes was sufficiently attractive for a new company to be established; ISC Alloys Ltd., Avonmouth Bristol UK, the first commercial SPF company in the world. Initial applications included equipment housings, electronic enclosures and architectural panels. Figure 12 shows an encode-verifier card box holder (as used in the computer industry in those days) made in their version of the ZnAl eutectoid known as SPZ (superplastic zinc). In the same year (1971) the first commercial application in Russia was produced by the Non-ferrous Metalworking Plant in Kol'chugina. They formed highly decorative and detailed 'sugar-basins' from Bochvor's Zn22%Al alloy (Ref 4). Using split molds they were able to release the part's re-entrant geometry, see Fig. 13. Several thousands of these bowls were produced (Ref 19). It is somewhat surprising to the author, that the Russians had not utilized SPF in more practical ways bearing in mind the

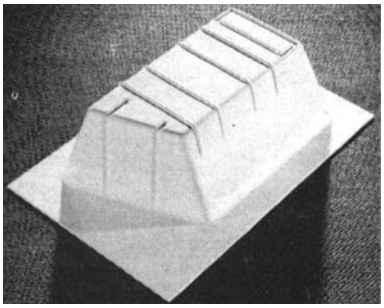

**Fig. 12** One of ISC Alloys original Commercial parts produced in SPZ (1971)

**Fig. 13** Russian decorative sugar basin—one of thousands produced from Bochvor's Zn Al Alloy

substantial body of research that had been undertaken in that country up to that time.

The first Superform company, based in Worcester, England was formed in December 1973, Superform Metals. In the years immediately following the first demonstration of superplasticity in a dilute-aluminum alloy, in 1969, much development activity was undertaken to scale up the special processing requirements needed to achieve a viable production route. Although the filing of the initial patent for dilute superplastic aluminum alloys (Ref 20) was in 1971, it was not until 1976 that a detailed description of how these alloys were rendered superplastic was first published (Ref 21, 22). The details of the management of this complete project, from research through to production, were discussed by Buchanon (Ref 23).

It is sufficient here to say that within the Tube Investments Group there were adequate and appropriate metallurgical, engineering and marketing recourses to steer the project to successful implementation. This included setting-up specialized casting and rolling equipment at one of British Aluminum's facilities and developing unique SPF processes and equipment.

Superform's unique male-forming process (Ref 24) allows, within a single-press cycle, for a superplastic sheet to be stretched with gas pressure into a bubble, which in turn can be engaged on its outside surface by a moving, or stationary, preforming tool so creating a 'shaped bubble'. A male tool can then be advanced at a controlled speed into the 'shaped bubble' engaging and further shaping the preform. Gas pressure can then be applied to the outside thus urging the upper (thinner) regions of the preform against the male tool which can then be further advanced with the 'locking' pressure maintained. By so preferentially thinning the thicker material in the lower regions of the preform while the thinner material is 'protected,' via friction and the locking pressure, from further thinning. This complex procedure allows deep-closed shapes to be formed and the degree and distribution of thinning strain can be controlled. This and other superplastic forming techniques are reviewed in detail by Laycock (Ref 25) and the criteria for selecting which technique to use for particular component size and geometry is discussed in a previous paper by the author (Ref 26). Figure 14 shows the first Superform male-forming machine installed in 1974 together with a schematic taken from the original patent. Figure 15 illustrates the depth and complexity attainable with this forming technique. Five of these unique forming machines have been built and operated over the passed 33 years. Four are still in daily operation. The first machine was 'retired' last year after more than 30 years of continuous use.

The introduction into the market place of a heat-treatable aluminum alloy (SUPRAL 100) capable of producing complex-shaped components inevitably impacted the future growth prospects for the ZnAl alloy. The almost 50% weight advantage of the aluminum alloy and the challenges experienced due to the 'modest' creep performance of ISC Alloys SPZ alloy resulted in a number of applications being converted over to SUPRAL 100 and the prospect of a ZnAl car body parts business never becoming a reality.

In the early 1970's another remarkable development was also underway within the Aerospace Industry, this was the SPF of titanium alloys and the 'break through' concept of combining SPF and diffusion bonding (DB) to create the unique fabrication process we now know as concurrent SPF/DB. Pioneered by Hamilton et al. (Ref 27) at Rockwell International in the US and by Summers et al. (Ref 28) at BAC in the UK. This technology advanced considerably throughout the 1970's and early 80s with the aid of significant government funding.

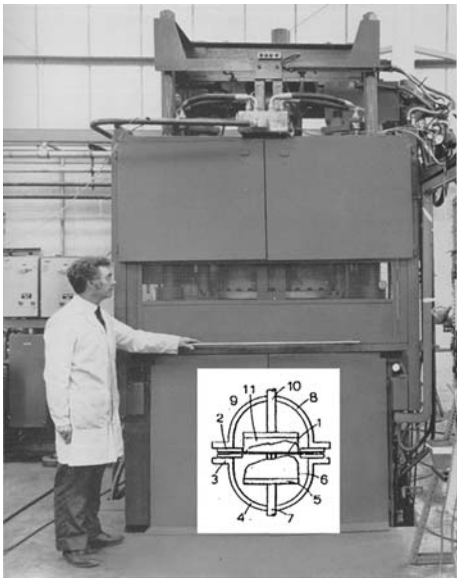

**Fig. 14** Superform's first male forming machine (1974)

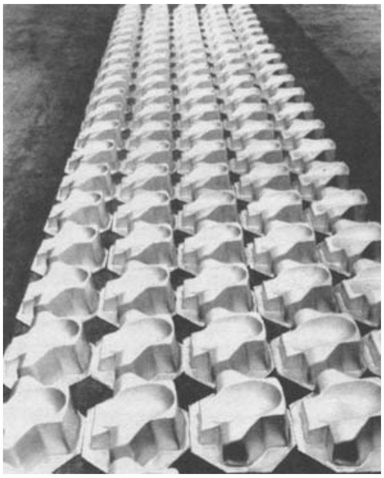

**Fig. 15** Complex male formed parts formed from SUPRAL100 (1974)

Hundreds of development parts, mostly fabricated from the Ti-6Al-4V alloy, many of them having unique 'weight saving' designs only achievable by SPF/DB technology, were produced during this period (Ref 29). Some of these remarkable structures are shown in Fig. 16.

However, changes in military aircraft needs and associated cancellations, during this period, resulted in very few SPF/DB components finishing up on actual planes (Ref 30). The first truly commercial application of SPF titanium (Ti6.4) was in 1981, some 13 year after Johnson had first demonstrated SPF a titanium alloy. This first commercial application was a jack housing produced by British Aerospace Filton (formally BAC) for the A310 Airbus aircraft (Ref 31). Four were required per aircraft with cost savings, over conventional forming, of more than 50%. Figure 17 shows both the conventional and SPF formed parts.

**Fig. 16** Remarkable and unique SPF/DB structures fabricated by Rockwell (1978)

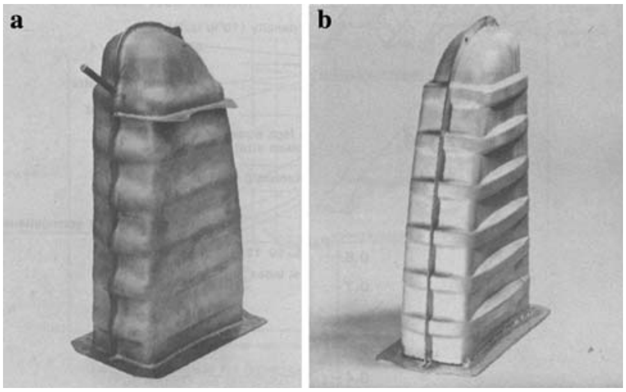

**Fig. 17** (a) Conventionally fabricated 'old design' and (b) SPF Ti64 new design 1st superplastic formed commercial titanium application (1981)

Production of SPF titanium rapidly expanded in the 1980s. Just 10 years later in 1991, one aerospace contractor, Rohr Industries, Chula Vista, Ca. had 10 full time production presses and was producing more than 400 different part numbers at an annual output of more than 20,000 SPF titanium parts (Ref 32).

## 4. Commercially Available Alloys

As the focus of this paper is on the evolving nature of SPF rather than the development of specific superplastic alloys it is not intend here to describe the evolution of each or detail the specifics of why certain alloys have been successful and others failures, but to simply outline the general trend, over the years, and list the alloys commercially available now.

Despite the considerable funding and efforts of many over an extended period (1975-1995) to develop new and improved alloy systems few have become established and remain commercially available today. Table 1 lists the superplastic alloys currently available, in sheet form, in the West. (Note: accurate details of alloys available in the former Soviet-Union countries and China are not known to the author.) The reasons for this apparently disappointing situation are many. Some alloys were fully developed and production quantities produced (e.g., SUPRAL 220, SUPRAL 5000, SP 8090, SP 2090, AlCaZn) others were only produced on a small scale for lab experiments and hot tensile testing (e.g., 2124-Zr, 7475-Zr, ALMgSc, Al-Pd). Each had its own Achilles' heel; whether it was too costly or difficult to produce, did not achieve the desired service properties, had insufficient demand to justify full-scale production, was superseded by another 'better' alloy or simply had inadequate superplasticity. The 'ideal' alloys are still somewhat elusive, awaiting some future generation of material scientists and engineers to create them. 'Ideal' superplastic alloys should be; fast forming with readily managed forming process windows, have excellent service properties achievable without expensive post-forming processing, manufactured by organizations/industries committed to efficiently making them at sustainable prices commensurate to their functional, economic and market value.

**Table 1 Commercially available superplastic sheet**

| | |
|---|---|
| Titanium | Ti-6Al-4V<br>Ti6Al2Sn4Zr2Mo<br>Ti3Al-2.5V<br>SP700 |
| Aluminum | SP2004 (Supral100)<br>SP7475<br>SP5083<br>SP2195 |
| Magnesium | AZ31B<br>ZK10 |
| Others | INCO718<br>IN744<br>NAS65 |

## 5. Controlling Cavitation in Structural Alloys

With the development of higher-strength aluminum alloys in the late 1970s/early 1980s the phenomenon of cavitation in superplastic materials became more important to the SPF practitioner. Cavitation, a characteristic of most, if not all, superplastic alloys when subjected to sufficient tensile elongation is more pronounced in superplastic aluminum alloys than titanium (Ref 33). At the upper-strain levels typical of SPF aluminum components (200-300% thickness strain) as much as 2-3% cavitation can result. If this is uniformly distributed this level of cavitation is acceptable for non-structural or lightly loaded applications. However in structural applications where fatigue and fracture toughness are important cavitation needs to be limited. Two processes were explored, post-forming hot isostatic pressing and Rockwell's patented method of forming using a hydrostatic confining pressure (Ref 34) later to be known as 'Back Pressure Forming'. Both methods proved effective in reducing or inhibiting cavitation in structural superplastic aluminum alloys, including SUPRAL 220 (Ref 35, 36) SP8090 and SP7475 (Ref 37). However, 'suppression' rather than 'removal' proved to be more efficient and so Back Pressure Forming (BPF) was the preferred method which is still used when needed today to produce 'high integrity' structural SPF parts in SP7475.

## 6. Current SPF 'State of the Art'

There are, and have been many recent innovations associated with the superplasticity in, and the forming of hard metals such as Ti, Fe, Ni, and others. However, the author having spent the last 35 years exclusively concerned with the development and commercialization of superplastic aluminum forming intends to defer to others, more able, the job of describing recent developments and 'state of the art' applications in these materials.

The technology for SPF aluminum alloys has advanced significantly in recent years. Rarely now is a flat sheet of superplastic alloy just heated and clamped to the perimeter of a simple cavity tool and pneumatically stretched into conforming contact with the tool surface (a large simple cavity formed part is shown in Fig. 18).

More often a non-planar clamp line tooling arrangement is used comprising of an upper and lower tool having a 'matched-die' clampline (see Fig. 19). After loading and heating the sheet and as the press closes, it is bent and drawn into conformance with the shaped clamp line. By so doing more unstrained material enters the tool and less strain is induced into the preformed sheet as it is pneumatically formed. This technique is used for either cavity forming or drape forming over a male-form tool. This method enables certain parts to be made more quickly with less strain and hence more uniform thickness distribution (see Fig. 20). It should be remembered that the goal in the practical world of production SPF is not normally to try to superplastically stretch the material as much as possible but meet functional and quality needs at the lowest cost. This method however has the propensity to create wrinkles resulting from buckling and local regions within the forming where too much material has been drawn in. A combination of stretch-draw techniques and 'off the part' wrinkle absorbers are used to solve these problems. The prediction and elimination of these problem areas has been more of an experienced based art than a science, often requiring several trial-and-error adjustments to be made to the tooling before success is achieved. However with the advancements now made in computer modeling and simulation of the forming process 'solutions' to problems of this nature are often possible before designs are finalized and tools are manufactured.

The GM QPF process has adapted this technique of mechanical preforming and Superform's bubble forming and with some additional innovative steps, has become a very significant advancement enabling the technology of SPF to break out of its niche markets into the main stream of volume manufacturing processes available to the auto industry. Figure 21 and 22 show views of the QPF equipment and GM's Malibu Maxx that incorporates two QPF panels.

The author refers the reader to the "GM QPF Process" paper given at ISCAM 2006 conference (Ref 40) for a more detailed description of this remarkable and highly automated volume production adaptation of the SPF process.

The male (bubble) forming process developed by Superform and described earlier, is still in everyday use and continues to be an effective way of producing 'deep' and complex components within the size range of the existing specialized equipment (3′×2′×12″). Two such parts are shown in Fig. 23 and 24.

**Fig. 18** Simple female forming produces this large one piece truck cab roof in SP5083 alloy

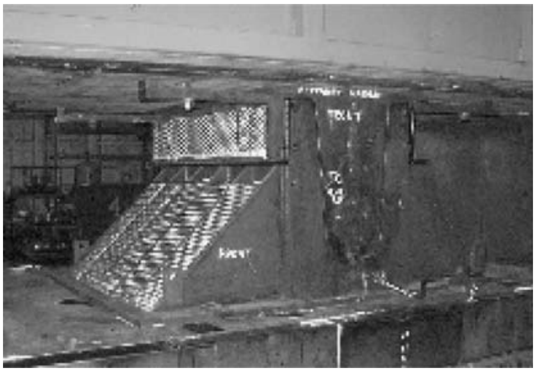

**Fig. 19** Example of extreme non-planar clampline tooling

**Fig. 20** More uniform thickness distribution resulting from non-planar clampline forming

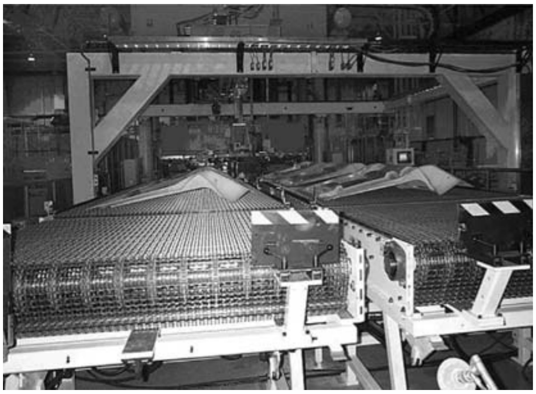

**Fig. 21** GM's QPF automated plant

**Fig. 22** GM Malibu Maxx with QPF liftgate formed from SP5083 alloy

**Fig. 23** Male formed C17 hydraulic covers made from SP2004 and heat treated to the T-6 condition

## 7. Forming Equipment and Tooling

Modern SPF is a sophisticated process requiring the simultaneous control of many critical parameters including; temperature, strain rate via applied gas pressure, clamping force to maintain gas seals and in some cases tool movement (position and velocity). Presses have become larger and over the years, 2 m × 3 m platen size is not uncommon and many presses have a clamping capability of more than 1250 tons to accommodate gas-forming pressures of up to 500 psi. Modern computerized electronic controls with robust microprocessors and automated precision gas valves have enables these requirements to be achieved in fully integrated programmable process control systems customized for each specific press installation.

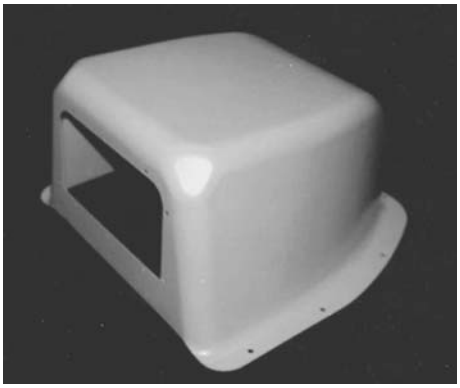

**Fig. 24** Helicopter electronic enclosure, male formed from SP2004 alloy

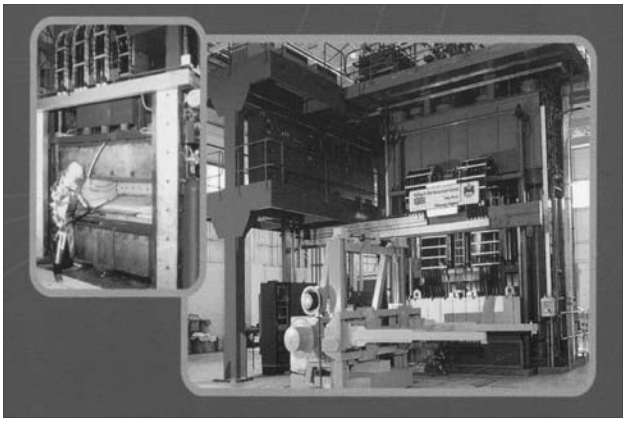

**Fig. 25** A modern SPF titanium press installation with mechanized part handling

Mechanical handling of sheet-in/part-out operations have been introduced and improved, handling the weight of larger parts minimizing distortion as well as speeding up production while protecting the operator from the harsh environment. Fully automated robotic handling has also been introduced where high volume output justifies the associated high capital cost. (i.e., the QPF process) Fig. 25 illustrates a modern press installation.

Fundamental to the success of most component manufacturing processes is tooling. SPF is no exception; in fact, it is at the heart of the economic viability of commercial SPF. New superior low-oxidation tool materials have been introduced for titanium forming and the hard facing of tools for QPF type aluminum forming operations (Ref 41) to withstand wear associated with their extended life time use, (hundreds of thousands of forming cycles). Possibly the most significant advance in recent years has been in the area of tool design. With the advent of computer-aided design virtually all SPF tooling is now CNC machined from electronic data. This has meant that 'good quality' electronic models of tool surfaces, including run-off areas, 'wrinkle pullers,' clamping geometry and other 'tricks of the trade' are now available to be imputed into contemporary process and modeling simulation software.

## 8. Process Modeling

From the early one dimensional membrane analysis of Ghosh and Hamiliton (Ref 42) to the innovations made over the years to develop realistic and reliable non-linear-finite element models of the SPF process much has been accomplished (Ref 43-47). Many of the anticipated advances (Ref 38) have now been realized. It is now possible to achieve reasonably accurate thickness predictions of complex 3D shaped forming and develop gas pressure profiles that can be down loaded directly to the presses gas-management system. Of greater significance from a practical standpoint, however is the ability of the latest software to allow the visualization of the sheet movement throughout the entire forming process. This is particularly useful when in-cycle preforming is used. As the sheet is drawn in and then pneumatically formed the ability to track the development of wrinkles and whether they are finally eliminated or encroach on the finished part is very useful. If they do the 'virtual tool' can be modified using off-the-tool features (wrinkle pullers) that will help absorb the surplus material. All this can be accomplished before the real tool is manufactured. Using commercially available software and today's powerful PC's, 'solutions' can be obtained in just a few CPU hours enabling tool design validation and process optimization to be accomplished. Examples of simulations and resulting forming are shown in Fig. 26 and 27.

There are still challenges and choices to be made regarding successful modeling of SPF including:

- Choosing between implicit and explicit codes,
- Having 'good' constitutive equations for each specific alloy
- Reliable lubrication and coefficient of friction data
- And good quality surface model of the tool.

The advances described here have not reduced the importance and value of skilled tool designers and experienced SPF specialists. Remember, the tool still has to be designed first and then, where necessary refined by the specialist using these powerful modeling tools.

## 9. Markets for SPF

Superplastically formed components are used because they meet functional and market needs and are competitively priced. Long gone are the days where they may have been 'tried-out' on the grounds of evaluation or novelty. Clearly SPF parts are not the panacea for every component application. They compete in a market place where competition with alternative processes and materials is fierce and where cost-competitive considerations are dominant in procurement decision making. Why and when SPF is chosen in preference to many alternatives has been

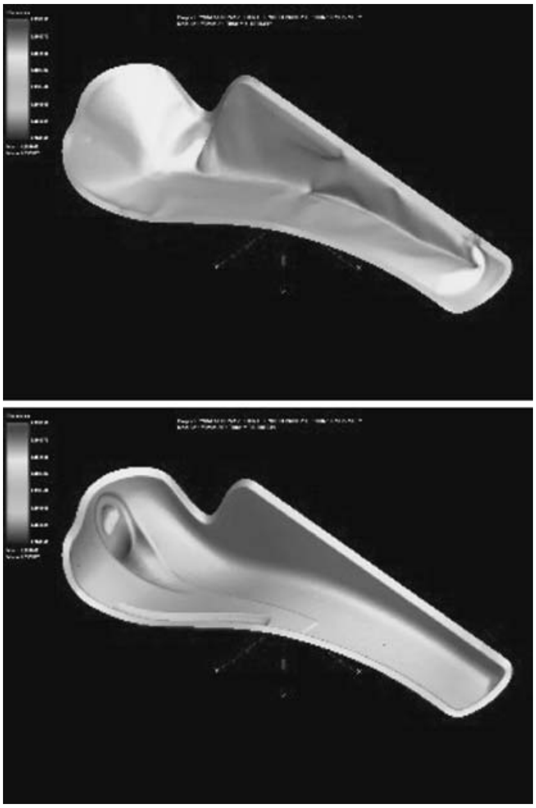

**Fig. 26** Simulation of a non-planar female formed front fender showing wrinkle absorption

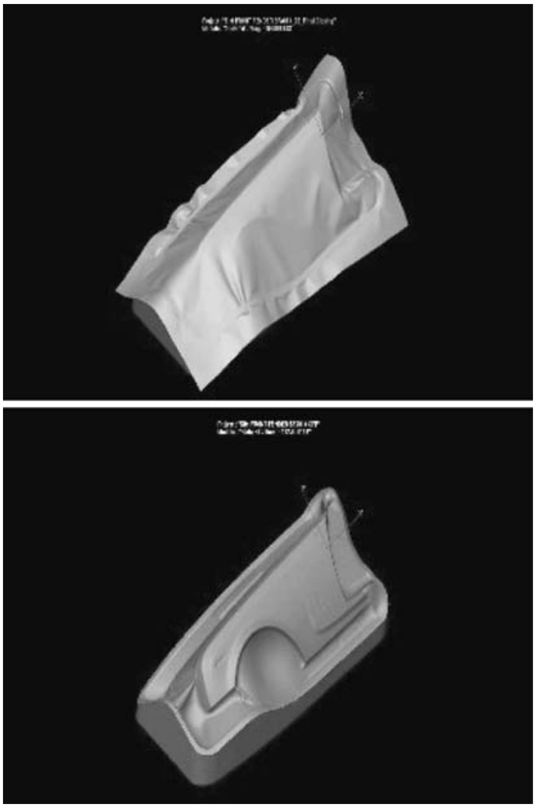

**Fig. 27** Simulation of a non-planar male formed front fender showing wrinkle absorption

discussed in some detail by the author in a previous paper (Ref 48) and need not be repeated here. The market for SPF aluminum has been caricatured as: "Planes, Trains and Automobiles and a whole lot more." This is a fair description. Currently more than 40 'in-production' aircraft and twenty different automobiles are using superplastically formed aluminum components. The following examples are given to exemplify successful applications of superplastic aluminum forming in a variety of high-added value end markets. (Fig. 28-33)

## 10. The Techno-Economics of SPF Aluminum

This topic has been discussed in some detail by the author in previous papers (Ref 48, 49). The underlying reasons why certain 'niche' markets, including specialist vehicles and limited series sports cars, are particularly suitable for SPF applications have been characterized as follows:

- SPF takes a relatively expensive material
- Forms it relatively slow into a complex shape
- Using relatively inexpensive tooling
- And is used in high-added value end products for low/medium-volume applications
- Where the attributes of aluminum are valued.

With the more recent applications of SPF via QPF to higher volume, more utility production cars aimed at achieving weight savings over steel stampings and styling benefits beyond the reach of traditional cold stamping of aluminum, a new paradigm is required to characterize this type of application.

- It uses as inexpensive material as possible, driving down the price via volume usage
- To form as fast as possible, not constrained by gas pressure or equipment limitations
- Using a high level of automation and sophisticated tooling
- To make light-weight parts not readily made by traditional volume production methods.

## 11. New and Emerging Superplastic Developments

Superplasticity and SPF continues to be actively pursued in academic, research organizations and industries R&D facilities around the world. These endeavors range from 'blue sky's' speculative research through to short-term process improvement projects.

The following list is not meant to be exhaustive but covers a range of topics of interest to the author and should

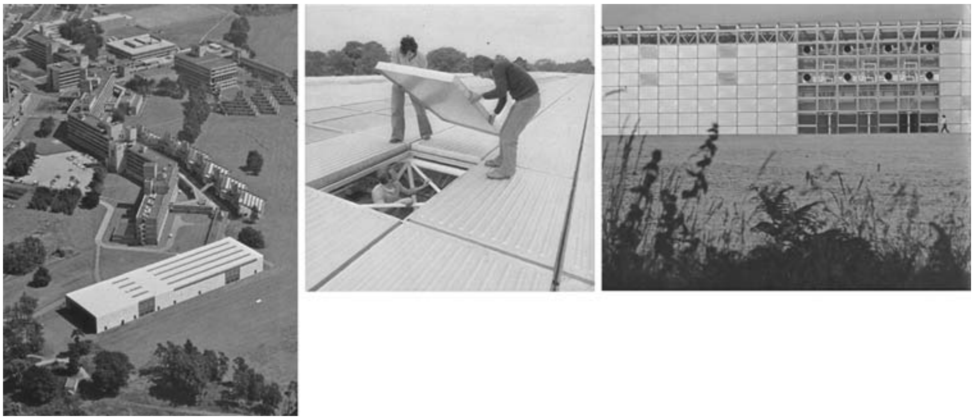

**Fig. 28** Largest superplastic structure. 4000 panels installed in 1977. Panels formed and anodized from Supral150

**Fig. 29** Structurally critical launch vehicle components formed from SP7475 alloy

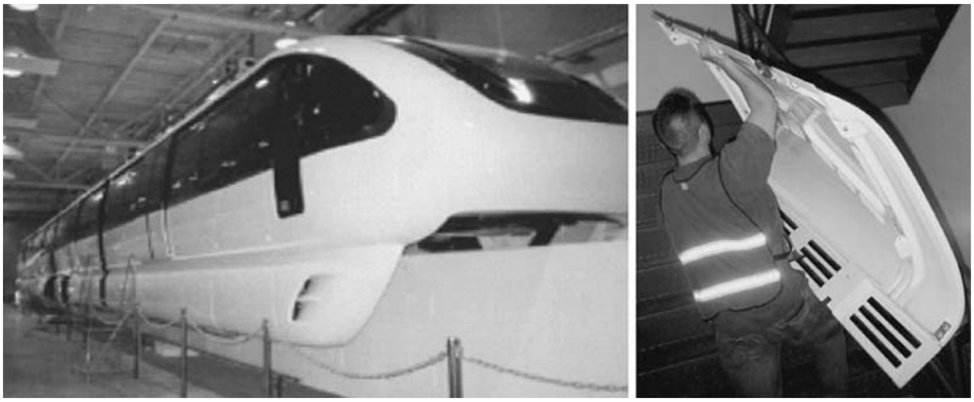

**Fig. 30** Light-weight SPF bonded panels clad much of the exterior of the Las Vegas monorail (one of many SPF rail applications.)

**Fig. 31** Forty years after its debut, the modern Ford GT supercar is clad with 10 superplastically formed, SP5083 alloy, body panels

**Fig. 32** The complete body of this 2005 showcar was SPF'ed in SP5083 alloy using low cost, 'cast to size' aluminum tooling

**Fig. 33** A fusion of old and new, superplastic forming technology makes this 2006 limited series reproduction of the 1954 classic Jaguar C-Type a practical reality

be of interest to other SPF practitioners; several of these listed are covered in papers presented at this years conference.

- SPF Magnesium Alloys
- Friction Stir Processing
- Friction Stir Welded Inserts
- Superplastic Tube Forming
- High-Strain Rate SPF
- Superplastic Ceramics
- Superplastic Glassy Metals

It is not intended here to give detailed analysis or exhaustive reviews of any of these topics, but simply highlight some developments underway at the author's company (Superform).

## 12. Light-Weight Magnesium Structures

The most profound characteristic of magnesium is its low density and the resulting high-specific stiffness and strength. However its intrinsically poor ductility, resulting from its hexagonal close-packed crystal structure, limits its cold formability. As a result, only limited use has been made of cold-formed magnesium alloys. The recent development of 'production ready' superplastic magnesium alloys should remove this limitation and allow complex, light-weight structures to be made by SPF. Superplastic formability trials have been carried out on a number of alloys including AZ31B, ZK10, and ZE10. Figure 34 shows cone test results for two alloys together with a 'special processed' AZ31B alloy which had undergone rapid solidification prior to rolling.

Other prototype and demonstration parts have been formed and are currently under evaluation. Two of these are shown in Fig. 35, 36.

## 13. Friction Stir Processes

At the last ICSAM conference in Oxford (2003) the first SPF parts incorporating regions of enhanced superplasticity resulting from locally friction stirring the 7475 alloy sheet before forming were, described (Ref 50).

More recently friction stir welded magnesium alloy (AZ31B) has been successfully superplastically formed. Figure 37 illustrates this.

Another combination of SPF and FSW in being investigated known as FSW inserts, in which one or more inserts are incorporated into another normally larger sheet before SPF. Unlike fusion welding techniques, that locally melt and depletes or eliminates the superplasticity in the weld region, FSW usually creates enhanced superplasticity in the weld its self. The insert can be made from a superior superplastic alloy or have a designed thickness variation or even be a 3D cup or preform. The location of the inserts is governed by the result intended in the final superplastic alloy formed component, for example a region where the local geometry will create more superplastic strain than the rest of the sheet can accommodate or where an unacceptable degree of local thinning would otherwise result. Figure 38 illustrates localized thinning resulting from conventional SPF. In some applications this is unacceptable. Using FSW in the local high-strain region a contoured blank can be inserted before forming, which when deformed, compensates for the localized strain and results in near uniform thickness distribution.

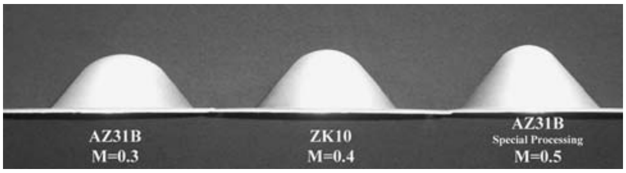

**Fig. 34** Formability evaluation using cone test method (440°C)

## 14. Superplastic Tube Forming

Greater attention is now being given to superplastic tube forming, albeit more than 70 years after Pearson's first PbSn Tubes (Ref 9). Production parts are already being manufactured by this route including parts flying on commercial aircraft and architectural columns. Figure 39 illustrated the inflation process in a 5083 alloy tube and a batch of production parts being chemically cleaned.

## 15. Superplastic Forming—The Future

The emergence of volume production SPF/QPF at GM and Honda has focused attention on improving productivity

**Fig. 35** Prototype auto parts *Superformed* from Magnesium Alloy (AZ31B)

**Fig. 36** Rotor craft offer many opportunities for light-weight *superformed* magnesium alloy components

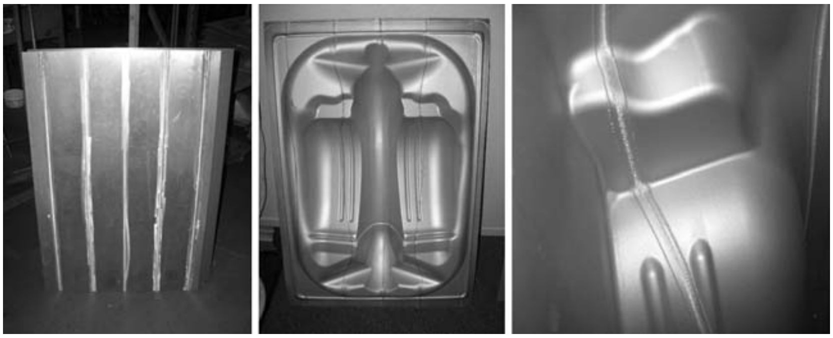

**Fig. 37** Friction stir welded AZ31B strips, superplastically formed, demonstrating the superplastic behavior of the FS weld

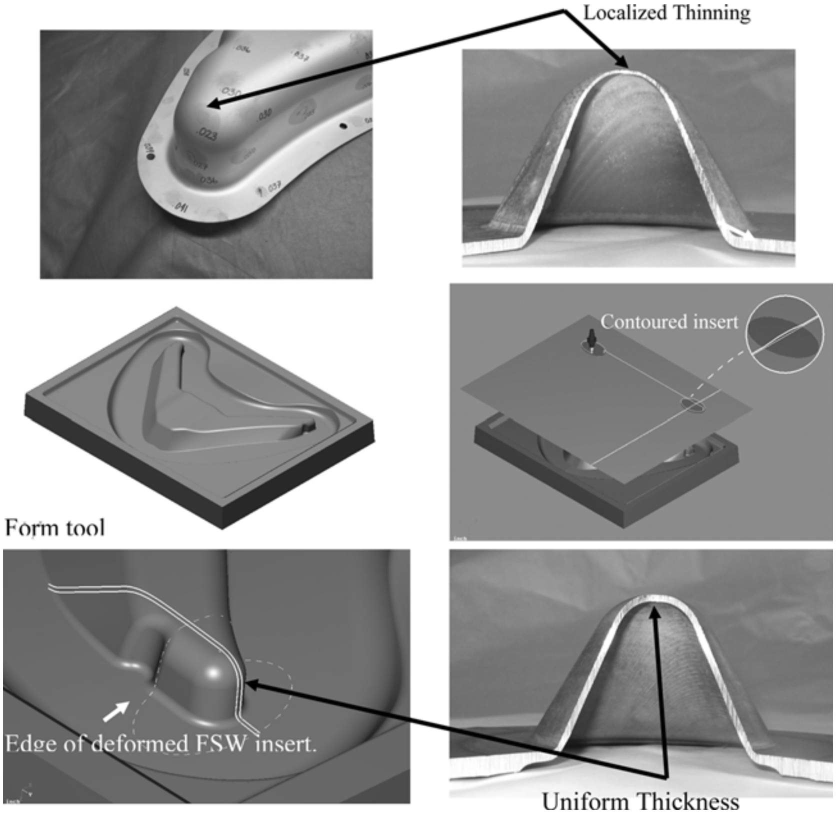

**Fig. 38** Illustration of the FSW insert concept to eliminate localized thinning by means of a contoured insert

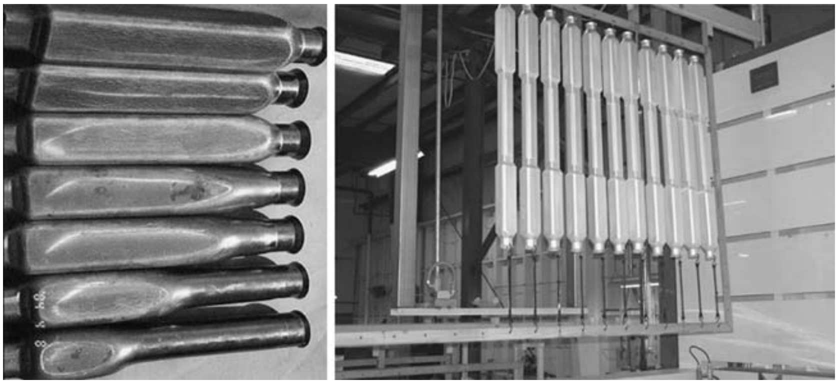

**Fig. 39** Superplastic tube forming from cold drawn 5083 alloy seamless tube

**Fig. 40** First bubbles superplastically formed from ceramic sheet (1992) and from bulk glass Zr.Ti.Ni.Cu.Be alloy (2006)

(i.e. faster forming) and containing or reducing material costs. This is only likely to increase as concerns over environmental issues and energy costs drive the auto industry to pursue more weight reduction initiatives that could in turn create even greater potential for SPF/QPF applications, including SPF/QPF magnesium alloys. This raises the question:

- Where are the 'production ready' high-strain rate fast forming SP alloys after almost twenty years of research and development?

Research relating to superplastic ceramics (Ref 51) and, more recently, bulk glass forming alloys (Ref 52) (glassy metals) has demonstrated their ability to be produced in sheet form, albeit small sheets, and pneumatically gas formed into bubbles. (see Fig. 40)

- Can we yet envision what applications they might be used for?

On a more positive note it is likely that:

- New markets will open up for superplastic tube particularly when a superplastic structural alloy tube becomes available.
- The ability to combine FSW and SPF is likely to create new and unique product forms and more economic solutions for light-weight aerospace components.
- Within the next 5 years computer modeling and simulation will have advanced to where 'intelligent' adaptive tool surfacing will be possible enabling SPF tools to be designed by 'smart' software.

## 16. Concluding Remarks

The history of SPF is fascinating and has developed over more than 40 years through the ideas, research efforts, imaginations and collaborations of scientists, material specialists and engineers from around the world. The pioneers discussed here are preeminent among many who have played their role of getting us 'from there to here'. Now it is to a new generation we turn and to task them to advance this most remarkable technology into the future on a 'Voyage of Discovery'.

## References

1. Popular Mechanics, Aug. 1964, p 62–68
2. W.A. Backofen, D.H. Avery, and J.R. Turner, Superplasticity in Al-Zn Alloy, *Trans. Am. Soc. Metals*, 1964, **57**, p 980
3. T.G. Langdon, *Towards Innovation in Superplasticity*, S. Hori, M. Tokizane, and N. Furshino, Eds. Fundamental Aspects of Superplasticity, JSRS, Japan, 1991, p 3–12
4. I.I. Novikov, *Superplasticity in Advanced Materials*, T.G. Langdon, Ed. Fundamental Aspects of Superplasticity ICSAM, Moscow, 1994, p 3–11
5. E.E. Underwood, A Review of Superplasticity and Related Phenomena, *J. Met.*, 1962, **14**, p 914
6. Bochvor and Sviderskajo, Superplasticity in Zinc-Aluminium Alloys, *Izvest. Akad. Nauk SSSR*, *OTN*, 1945, **N9**, 821
7. MIT 3.12 Lab Report. March 1964
8. Private Communication with Greg Garmong, 2005
9. C.E Pearson, The Viscous Properties of Extruded Eutectic Alloys of Lead-Tian and Bismuth-Tin, *J. Inst. Metals*, 1934, **54**, p 111
10. D.S. Field Jr. and W.A Backofen, Temperature and Rate Dependence of Strain Hardening in Aluminium Alloy 2024-0, *Trans. ASM*, 1959, **51**, p 946
11. Private Communication with Dr. Fields
12. US Patent #1120007 "Forming of Superplastic Alloy Sheet"
13. D.S. Fields Jr., "The Promise of Superplasticity", IBM document EN200276, 1972
14. Patent Number US 6581428 "Method and Apparatus for Superplastic Forming"
15. Patent Number US 5974847 "Superplastic Forming Process"
16. Attendees of Capenhurst Conference 1969 on Superplastic Forming
17. B.B Hundy, Plasticity and Superplasticity Inst Met London, *Rev. Con. Ser.*, 1969, **2**(3), p 73
18. D. North, Superplastic Alloy for Auto Body Construction, *Sheet Metal Ind.* 1970, p P13–P16
19. Private Communication with Prof. Valiev, 2005
20. British Patent Number 1387586 "Grain Refinement and Superplastic Forming of an Aluminum Base Alloy"
21. R. Grimes, M.J. Stowell, and B.M Watts, Superplastic Aluminum Based Alloys, *Metal Technol.*, 1976, **3**, p 154–160
22. B.M Watts, M.J. Stowell, B.L. Baikie, and D.G.E Owen, Superplastically in Al-Cu-Zr Alloys, *Met. Sci.*, 1976, (Part 1 and 2) p 189–206
23. J.A.F. Buchanon, Innovation Management in Metallurgy, *Inst. Mat. Rev. Courses Ser.*, 1975, **3**(4), p 8111-75-T
24. US Patent Number 4045986 "Forming Ductile Materials"
25. D.B. Laycock, Superplastic Forming of Sheet Metal, *Superplastic Forming of Structural Alloys*, N.E. Paton and C.H. Hamilton, Ed. (NY), AIME, 1982, p 257–271
26. A.J. Barnes, Design. Optimization for Superplasticity, TMS/AIME Conference in San Diego, 1982
27. US Patent No. 3927817 "Method for making Metallic Sandwich Structures"
28. British Patent No. 1398929 "Joining and Forming Sheet Metal Members" and 1429054 "Forming of Metal Panels"

29. C.H. Hamilton, Superplasticity in Titanium Alloys, Superplastic Forming Conference, ASM, 1984
30. C.J. Hamilton, Air Force Perspective on SPF and SPF/DB Titanium Technology, Ibid, p 63–69
31. R. Stephen, Designing for Superplastic Alloy, *AGARD Lecture Ser.*, 1989, **168,** p 7.1–7.37
32. M. Botolini, Rohr Industries, Boeing Superplastic Forming Seminar Proceeding, Oct 18, 1991
33. N. Ridley and Z.C. Wang, Cavitation in Superplastic ICSASM194 Met Sciences form 170-172, 1940, p 1997–186
34. US Patent Number 4092181 "Method of Imparting a Fine Grain Structure to Aluminum Alloys having Precipitating Constituents"
35. J. Pilling, "Effect of Hydrostatic Pressure Cavitation During Superplastic Deformation of SUPRAL220", Superplasticity in Aerospace – Aluminum. Cranfield July 1985, p 136–145
36. A.J. Barnes, "Commercial Superplastic Aluminum Alloys – Opportunity and Challenges", Ibid, p 424–447
37. C.C. Bampton, A.K. Ghosh, and M.W. Mahoney, "The Causes, Effects and Control of Cavitation in Superplastic 7475 Aluminum Airframe Structures", Ibid, p 1–35
38. A.J. Barnes, The Industrial Application of Aluminum Superplastic Forming, *MRS Symp. Proc.*, 1999, **601** p 207–221
39. L. Hefli, Production of SPF and SPF/DB Parts for Fights Aircraft SPF, Training Seminar Proceedings, 1991
40. P.E. Krajewski and J.G. Schroth, General Motors QPF Process, ICSAM, Chengdu, China, 2006
41. A.T. Morales, Evolution of Die Coating Superplastic Forming Processes, *Adv. Superplast. Superplastic Form.*, TMS Annual Meeting, 2004, p 51–57
42. A.K. Ghosh and C.H. Hamilton, Superplastic Forming of a Long Rectangular Box Section, ASM Conference in Process Modeling, 1908, p 303–331
43. R.S. Sadeghi and Z.S Pursell, *Met. Sci. Forum*, 1994, **170-172,** p 571–576
44. N. Rebelo and T.B. Wertheimer, Finite Element Simulation of Superplastic Forming, *Proc. 16th North American Manufacturing Research* (Douf. Urbana IL), 1998
45. E. Massoni, M. Bellet, and J.L. Arenot, *This Sheet Forming Numerical Analysis. Modeling of Metal Forming Processes*. Sophia Antipolis, France, 1988, 187–196
46. J. Bonet, R.D. Wood, and A.H.S. Wargadupuira, *Int J. Numerical Methods*, **30**, 1990, p 1719–1737
47. N. Chandra, S.C. Rama, and R.E. Goforth, Process Modeling of SPF Processes using Four Different Computational Methods, *Superplast Adv Mater, Jpn. Soc. Res. Superplast.* 1991, p 837–844
48. A.J. Barnes, Industrial Applications of Superplastic Forming – Trends and Prospects, *Mat. Sci. Forum*, 2000, **357-359**, p 3–15
49. A.J. Barnes, Superplastic Aluminum Forming – Expanding its Techno-economic Niche, *Mat. Sci. Forum*, 1999, **304-306**, p 785–796
50. M. Mahony, A.J. Barnes, W.H. Bihgel, and C. Fuller, Superplastic Forming of 7475 Al Sheet After Friction Stir Processing (FSP), *Mat. Sci. Forum.*, 2003, **447–448**, p 505–512
51. J. Wittenauer, T.G. Nieh, and J. Wadsworth, A First Report on Superplastic Gas Pressure Forming of Ceramic Sheet, *Metallurgica*, 1992, **26**, p 551–556
52. T. Waniuk, J. Schroers, and W.L. Johnson, Time Scales of Crystallization in Viscous Flow of the Bulk Glass-Forming Zr. Ti. Ni. Cu. Be. *Alloy, Phys. Rev. B,* 2003, **67**, p 184203