JMEPEG (2004) 13:720-726
DOI: 10.1361/10599490421367

1059-9495/$19.00

# Developing a Superplastic Forming Application Using Aluminum Tube

*Franna Pitt*

(Submitted August 12, 2004)

**The outboard light housing on the Boeing 737 next generation aircraft was initially designed and manufactured as a cast aluminum part. Delays in delivery and other quality problems resulted in the part being redesigned as an aluminum superplastically formed (SPF) part. Advances in material use and tooling were necessary to successfully transition the part to the SPF form. The resulting part is lower in cost and lighter in weight than the original. This work summarizes the steps taken to implement the SPF outboard light housing.**

**Keywords** aerospace, aluminum alloys, ceramic dies, fused deposition modeling, rapid prototyping, seamless aluminum tube, superplastic forming, tapered seal, welding

## 1. Introduction

Although superplastic forming has been used to make aerospace parts for more than two decades (Ref 1, 2), the process is still considered "new" for many designers. It is often up to the manufacturing experts to know when and where to apply the process in the appropriate applications. Responsible application of any of the manufacturing processes is necessary to achieve a product that is both functional and cost effective. In this case, the Boeing 737 NG outboard light housing, the design team chose to make the part from an aluminum casting and ultimately changed to the superplastically formed (SPF) part when the cast part did not meet expectations.

The light housing part is an enclosed shape, somewhat tubular, oval shaped, and open at the aft end to receive the aft facing light, and triangular and closed at the forward end, which joins to another part of the wingtip. About half of the inboard side joins to the main wingtip box, while the rest of the surface is aerodynamic and highly visible. The part itself carries no structural load; however, it does have to sustain flight and maintenance loads. The part was installed on a 737 wingtip as shown in Fig. 1.

The light housing presented a number of challenges for superplastic forming, including a short time schedule, evaluating and choosing a material, developing the blank configuration to be formed, and developing the preform, tooling, and method for forming, while realizing significant cost savings. The major key to success, as it is with most SPF parts, is developing the optimal tooling configuration.

This paper was presented at the International Symposium on Superplasticity and Superplastic Forming, sponsored by the Manufacturing Critical Sector at the ASM International AeroMat 2004 Conference and Exposition, June 8-9, 2004, in Seattle, WA. The symposium was organized by Daniel G. Sanders, The Boeing Company.

**Franna Pitt,** The Boeing Company, Auburn, WA. Contact e-mail: franna.s.pitt@boeing.com.

This work describes the development of the SPF aluminum outboard light housing from concept stage through implementation.

## 2. Background

The outboard light housing was originally designed as a cast aluminum part after considering a number of alternatives, including SPF. At the time, SPF did not appear to meet the design requirements, while aluminum castings apparently did. Aluminum castings have made extensive technical advances and offer great advantages in cost savings when they are appropriately used (Ref 3). However, in the outboard light housing, the structure is hollow, thin skinned, and must meet strict surface appearance criteria because the part is highly visible. Neither casting nor SPF is an exact fit to the design requirements for the light housing; however, SPF would meet more of the requirements provided certain developments were successful.

One of the requirements for the SPF redesign of the outboard light housing was to replace the casting; no changes to the surrounding structure were allowed. As such, the SPF part would be an enclosed shape, flat on the two mating surfaces, and allow for existing assembly processes. Aluminum was selected as the material of choice. Although no reduction in cost or weight was required when development was initiated, a significant cost savings had to be projected to proceed with the SPF production part.

**Fig. 1** Outboard light housing, installed on the wing of the Boeing 737NG aircraft

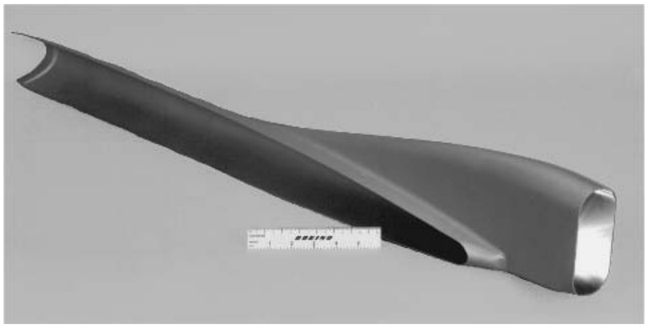

**Fig. 2** Titanium outboard light housing, development part

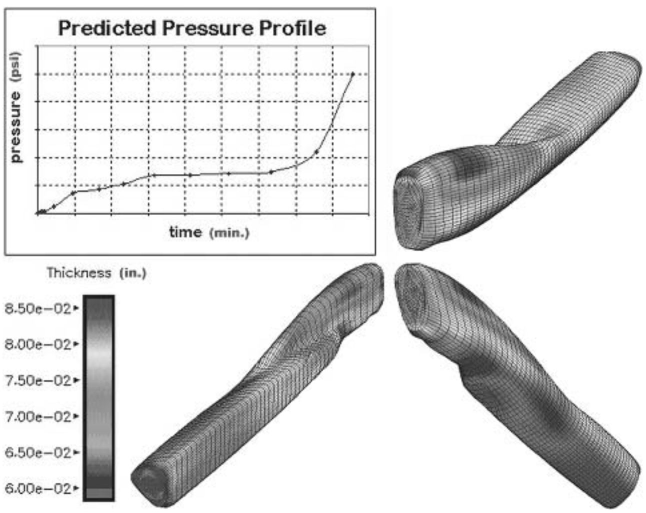


**Fig. 3** Initial FEM results for thickness distributions and strain

Previous development work had successfully shown that the enclosed light housing shape could be made with SPF Ti-6Al-4V starting with a cylindrical tube. The resulting development part is shown in Fig. 2. However, the strain in the completed titanium part was in excess of 150% and exceeded what is recommended for aluminum alloys. In addition, although a number of aluminum SPF parts are in production using multiple alloys, most require heat treatment after forming and none of the alloys was available in a tube shape for SPF, and none was preformed prior to SPF.

## 3. Development

A preliminary plan for fabricating the light housing is shown in Table 1. The plan was based on the previous titanium light housing development project. The key elements of the new development effort included identifying a suitable material in a form that could be used to make the final shape of the light housing, designing the housing so that a minimal amount of tooling would be needed to make the shape, minimizing the number of design changes to allow the SPF process to be used, and creating an efficient and reliable process to replace the existing problem-ridden parts. Ideally, the operator would take the material as received from the supplier, load it into the SPF die, initiate the forming cycle, and unload the completely formed part when the cycle was finished. The ultimate goal was to deliver a quality part, on time and at minimal cost.

**Table 1 Preliminary build plan for the SPF outboard light housing**

| Step | Description | Comments |
|---|---|---|
| 1 | Roll and weld sheet to tube | No aluminum SPF tube was available, some risk |
| 2 | Preform crease in tube | Development needed |
| 3 | Weld ends and gas tube | Existing in titanium, requires weldable aluminum alloy |
| 4 | Superplastically form | Existing process, weld at risk, lower elongation in aluminum |
| 5 | Trim, weld forward end | Existing process, requires weldable aluminum alloy |
| 6 | Clean, prime, paint | Existing process |

### 3.1 Material Development

The light housing design specified aluminum material, and the desired part was a single piece enclosed shape. At the time of development, no aluminum alloys were available in tube form that could also be superplastically formed. The plan was to roll and weld a tube shape that could be subsequently superplastically formed. Of the superplastically formable aluminum alloys, only 2004 and 5083 are weldable. Superplastic formable Al 5083 (Al 5083-SP) is a better choice for manufacturing ease, having produced more consistent results with no need for heat treatment following SPF (Ref 1, 4). There had been recent success using alloy 5083-SP for SPF airplane parts, including an additional light housing forward of the outboard light housing on the Boeing 737 aircraft. Using a material that is already in use on a commercial airplane is a major advantage in gaining approval for a new part using that same material.

Analysis of the light housing configuration showed that a 76.2 mm (3 in.) diameter tube was about the largest diameter that could fit into the configuration cavity with minimal preforming and little risk of moving outside of the cavity and being pinched between die halves. At the same time, a 76.2 mm (3 in.) diameter tube would only need approximately 100% maximum strain to form into the most severe part of the configuration, well within the forming guidelines for Al 5083-SP. Finite element modeling, as shown in Fig. 3, confirmed the strain estimate and provided an early estimate of material thicknesses after forming.

Two problems with the material needed to be resolved. In previous experience, aluminum SPF alloys that were locally cold worked before forming sometimes resulted in areas of extremely rapid grain growth. Also, welded aluminum material loses its superplastic forming capability and has minimal capacity for elongation (Ref 5). Small-scale testing of both of these conditions provided information.

Large grains formed as a result of rapid grain growth during processing (Fig. 4). The blanks for the 228.6 by 228.6 mm (9 by 9 in.) SPF pans were bent on the diagonal to several different radii using a cold brake press. The smallest brake-formed radii produced the largest area of grain growth. Radii of 19 mm (0.75 in.) and greater produced no grain growth. Preforming the 76.2 mm (3 in.) diameter tube to fit within the SPF

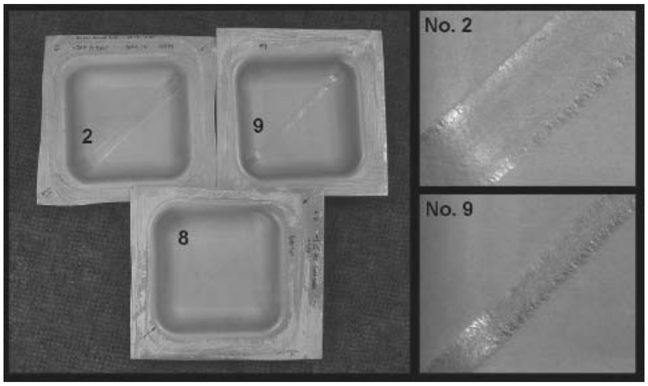


**Fig. 4** Formed test parts showing areas of large grains in material cold worked prior to forming

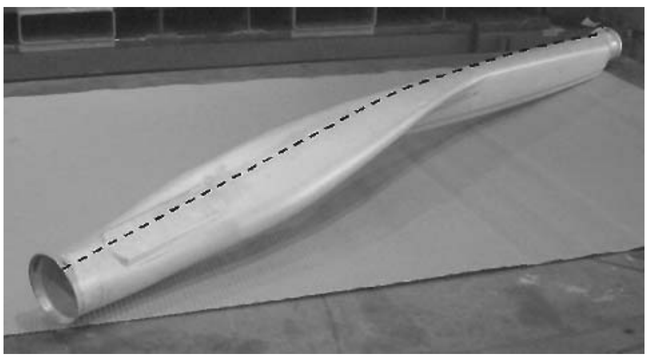

**Fig. 5** Gentle curve location for the longitudinal weld

die cavity would incur less cold work than the 19 mm (0.75 in.) radius, so the development proceeded.

The same 228.6 by 228.6 mm (9 by 9 in.) pan die was used to investigate the amount of elongation that could be expected from a welded seam in aluminum. Part blanks were welded on the diagonal and, subsequently, superplastically formed. At about 40% longitudinal elongation, the welds developed cracks through the thickness of the material. In the transverse direction, strain in the weld was minimized by the additional strain in the adjacent superplastic material. In the outboard light housing, the weld would have to be located in an area that required less than 10% strain. Fortunately, the gentle curve along the upper, outboard side of the part provided such a location. The curvature of the housing is shown in Fig. 5.

At this point, design concurrence was sought and, conditionally obtained. The thickness distribution, material strength, and corner radii of the SPF part would be different from the cast part, and some analysis was required to determine if these differences would be acceptable. Assuming successful analysis, the proposed SPF part would be made from a rolled and seam welded Al 5083-SP tube, preformed in a separate die, superplastically formed to final configuration, trimmed, and welded to the forward end cap after SPF.

### 3.2 Tooling Development

Ceramic tooling enables the rapid evaluation of new SPF parts and variations (Ref 6, 7). Ceramic tooling was used for two iterations of tooling for the outboard light housing. In addition, rapid prototyping (RP) methods were used to make casting models for the ceramic die pieces. The RP materials and methods were new to the ceramic die fabrication process at the Boeing SPF center.

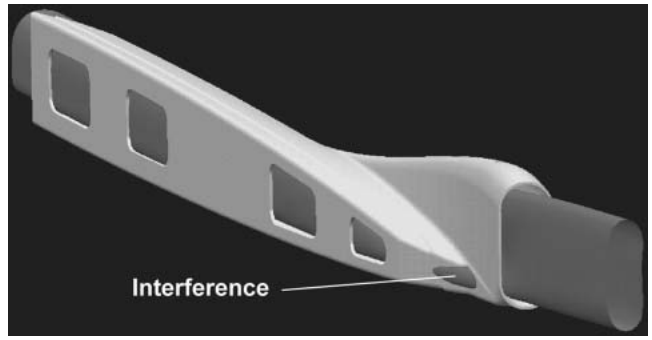


**Fig. 6** Finite element model of the preform die shape within the final part configuration

The initial plan would require two sets of tooling, one to make the preform shape and the other as the final form die. Because tooling is expensive and adds to the manufacturing complexity, it would be ideal to eliminate the preform die altogether. In addition, because the aluminum tube was larger in diameter than the previous titanium tube and would fit more closely in the final die cavity, the end caps had to be welded on following preforming and would be unique in shape and size, not a very good plan for ongoing production of airplane parts. Efforts proceeded to simplify the tooling even during the Phase I development with the two sets of dies.

### 3.3 Phase I Tooling

The first set of tooling consisted of two die sets, one for a preform die and the other for the final SPF forming. The preform shape was determined by finite element modeling (FEM), the goal being to produce a shape that could be placed into the final form die cavity and alloy the die halves to close without pinching any of the material on closing. This shape is shown in Fig. 6. The FEM analysis included starting with a straight 76.2 mm (3 in.) diameter tube and preforming it just enough to fit into the SPF die with a single vertical acting closure of the preform die. An orientation of the die parts was chosen to produce a preform configuration that appeared to fit within the part cavity. Small areas of interference were evident that would probably be negligible in the actual process.

To reduce the time of producing the preform die, a casting model was fabricated using fused deposition modeling (FDM), an RP process that uses melted, extruded thermoplastic material to form completed shapes (Ref 8, 9). One of the materials used in FDM is ABS plastic, an expected improvement over previously used photocured resins from the stereo lithography (SLA) process. The SLA materials tended to pick up moisture and warp during the warm and wet casting processes. This initial test of the ABS model was in making the preform dies due to the lower risk to the development program if the preform dies were not perfect and because the actual cast aluminum outboard light housing was used as the model for the Phase I final form die.

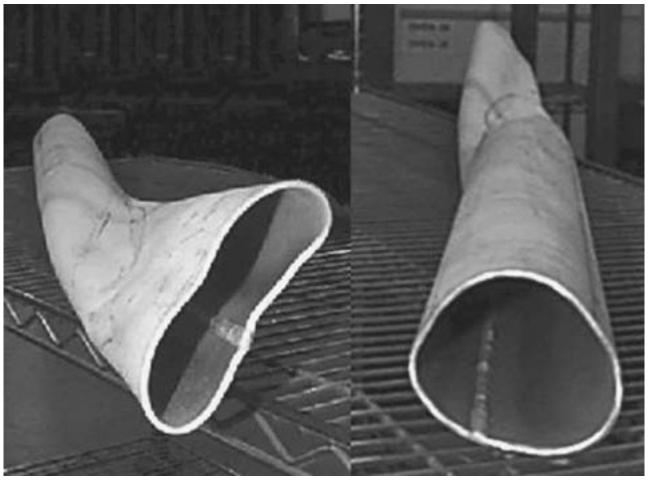

**Fig. 7** Phase I examples of preform shapes (test parts)

The FDM casting model was created and delivered ten days (which included the Thanksgiving Holiday) after transmitting the digital configuration file. Ten days is a significant improvement compared with the estimate of two months for a conventional machined casting model. This solid ABS model held up well to the casting process and did not appear to absorb moisture or warp significantly.

The preform die set was used to make several of the open-ended, Phase I tube preforms. The die was difficult to use because the tubes changed position within the cavity and were inconsistent in the final shape. Several of the preforms moved out of position enough to be pinched in the die periphery and would have been unusable as production components.

Acceptable preforms were made manually. The operator positioned the tubes at an angle on the edge of the die, partially closed the die and formed the aft “racetrack” end, then manually bent it to the slight angle. However acceptable the manually preformed tubes were, the process was awkward and time consuming, plus each tube was slightly different from the others. Examples of the ends of the preformed tubes are shown in Fig. 7.

Individually custom fit end caps and gas inlet tubes were welded to the preformed tubes, and then several were formed in the final die cavity with good results relative to forming the part itself, as shown in Fig. 8. However, none of the tubes formed fully to the extent of the cavity due to the weld in the end caps, exterior to the part, failing in one area or another. This custom welding of end caps was another process that would not be acceptable for production manufacturing.

The conclusion from Phase I was that the SPF aluminum tube method with welded Al 5083-SP would produce acceptable light housings, if the problems with the preform and end configurations could be resolved.

### 3.4 Phase II Tooling

It was somewhat fortunate at this point in the development to have some additional time to improve the tooling and the ultimate producibility of the parts. Evaluation of the strength properties of the Al 5083-SP in this part of the configuration took longer than anticipated and allowed another iteration of ceramic tooling to be built and tested.

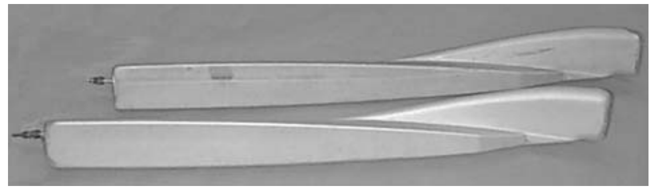

**Fig. 8** Phase I SPF outboard light housing prototype parts

Two major changes were incorporated into the Phase II tooling design: the first would stabilize the part within the tool and allow the use of a tapered plug method of sealing the part (Ref 10). The second major change resulted in eliminating the preform die set altogether by accomplishing the preform operation in the final form die.

Finite element modeling was again used to determine part orientation relative to the die halves. By rotating the part within the tool, an orientation was found that enclosed the 76.2 mm (3 in.) diameter tube within the plan view of the die cavity almost entirely. Along with the part rotation, each end of the die cavity was extended and blended into a 76.2 mm (3 in.) diameter cavity. This end configuration became a cradle for locating and containing the 76.2 mm (3 in.) tube material prior to SPF.

The 76.2 mm (3 in.) diameter ends could now theoretically be sealed using tapered plugs and actuators, thereby eliminating the whole process of welding custom end caps and fragile inlet gas tubes. A second set of ceramic dies was fabricated to evaluate the new part orientation, concurrent preforming, and extended, fixed ends. The completed ceramic die and tube illustrating the close fit at each end of the tube are shown in Fig. 9.

Fused deposition modeling was used once more to make casting models for the ceramic dies. Because the material used in FDM is relatively expensive, a method for reducing the amount of material was used. This method produces a honeycomb-type inner structure with a solid skin of a specified thickness. The honeycomb structure was strong enough to survive the casting process; however, it came apart in the unmolding process. The pieces of the casting model are shown in Fig. 10. Future use of the honeycomb FDM die models will use a thicker skin.

The Phase II test demonstration parts are shown in Fig. 11. Preforming was successfully accomplished on the single die with occasional small pinches of aluminum near the part crease. Data on the effects of friction with various die materials and coatings are not currently available. However, due to experience with the various die materials, it was thought that the steel production die would allow the material to slip more than the ceramic, avoiding the pinched areas and allowing the preform die to be eliminated from the production plan.

One of the Phase II demonstration parts was trimmed and evaluated on how well it fit into the rest of the wingtip. Even though this die was not intended to make production configuration parts, the FDM process used to make the die model for the ceramic die is one of the most accurate of the RP methods (Ref 11). As a result, the part fit into the wingtip assembly well within engineering requirements.

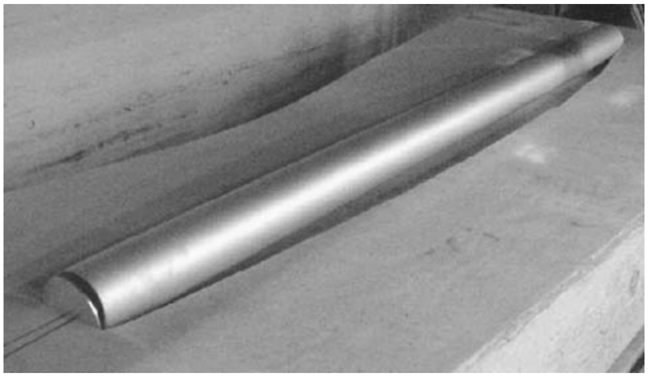

**Fig. 9** Phase II ceramic die showing the tube ends cradled inside the ceramic die cavity

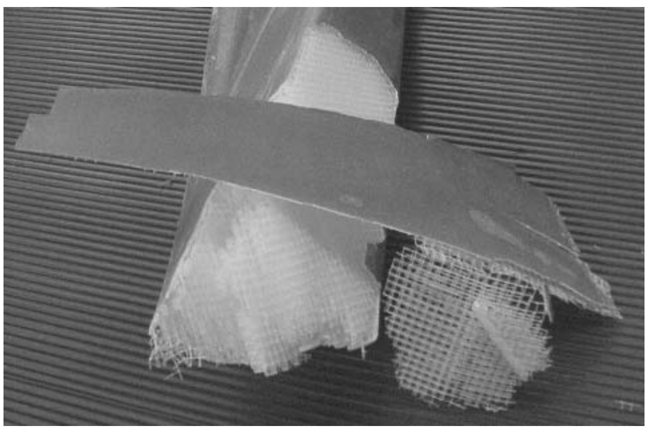

**Fig. 10** FDM honeycomb die model after unmolding


**Fig. 11** Phase II SPF light housing test demonstration parts

A separate, shorter die was fabricated in steel to evaluate the tapered plug seal. A detail that included the smallest radius needed for the completed light housing part was designed into the sidewall of the die. Figure 12 shows the tapered plug die and resulting SPF part. The 76.2 mm (3 in.) diameter tubes were formed on the tapered plug die. These parts were 100% successful at obtaining and maintaining a seal through the expected forming cycle and forming completely into the small radius of the detail. From this success, the production plan was revised to eliminate the welded end caps and incorporate the tapered plugs in the SPF steel production die. Each revision was accompanied by a corresponding decrease in the expected cost of the SPF aluminum light housing parts. The Phase II

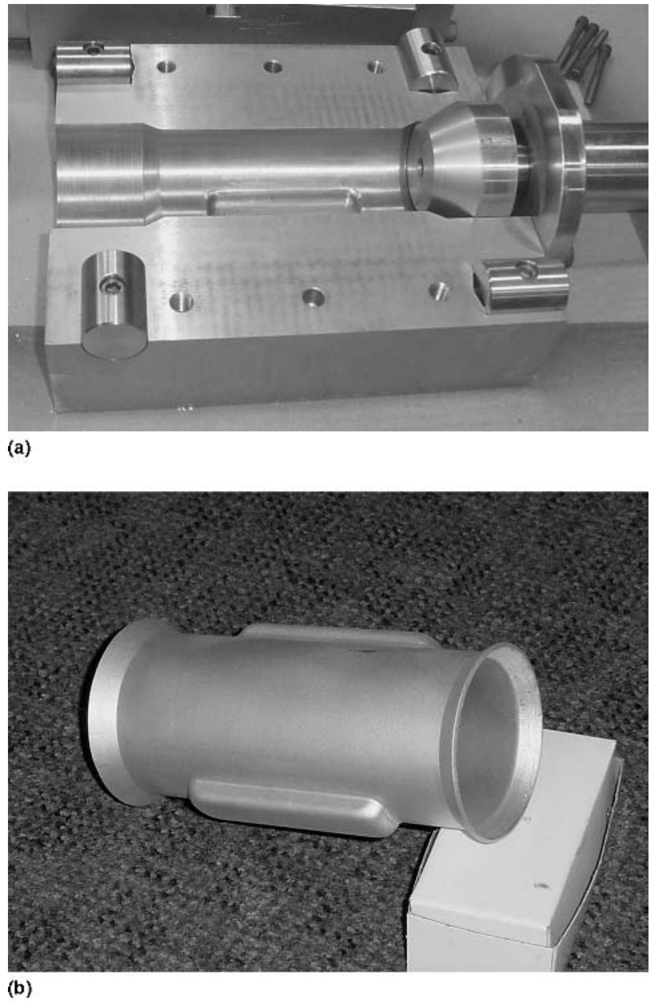

**Fig. 12** (a) Subscale tapered plug demonstration die and (b) resulting parts

development program resulted in a new, much more efficient production plan, as shown in Table 2.

### *3.5 Production Tooling*

All of the improvements were incorporated into the production steel die shown in Fig. 13. It would be nice to say that there were no remaining problems. However, that was not the case. Three minor problems were worked out in preproduction development.

Combining the tapered plug seal and the preforming process created a situation where the tube ends were pulled in during preforming and did not leave enough material to create a seal. Trimming the starting tube to an angle at each end readily solved this problem.

Two areas of the blank tube continued to be scraped by the closing die lid, although considerably less than they were by the ceramic die. It turned out that the length of the time allowed for the tube to preheat had an influence on the extent of the scraped area. A longer preheat tended to improve the result. In addition, the part of the die lid that scraped the tube most consistently was not in contact with the final part configura-

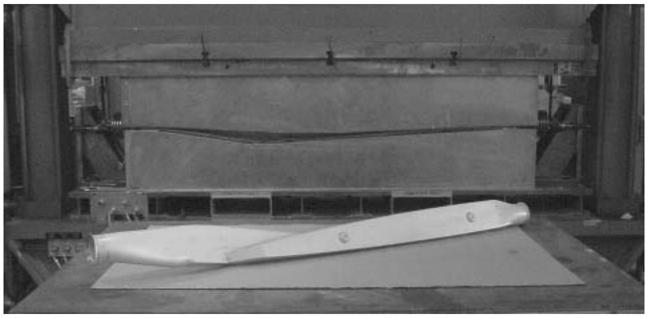

**Fig. 13** Production steel tooling and SPF part

**Table 2 Revised build plan for the SPF outboard light housing**

| Step | Revised plan | Original plan |
|---|---|---|
| 1 | Roll and weld sheet into tube, to be eliminated | Roll and weld sheet into tube |
| 2 | Eliminated | Preform crease in tube |
| 3 | Eliminated | Weld ends and gas tube |
| 4 | Superplastically form | Superplastically preform and form |
| 5 | Trim, weld forward end | Trim, weld forward end |
| 6 | Clean, prime, paint | Clean, prime, paint |

tion; it ended up in one of the radii. Therefore, increasing the size of the radius on the sharp corner in that area of the die lid allowed the material to slip by the tube much more readily and not affect the final part surface. The combination of longer preheat time and larger radius on the die edge resulted in acceptable outboard light housing parts.

The long, slender shape of the die resulted in more temperature variation in the part than had previously been allowed. Several parts were formed at temperatures above and below the standard 499 °C (930 °F) nominal temperature (Ref 12). Tensile and cavitation properties were evaluated along the length of each formed part after forming between 427 and 516 °C (800 and 960 °F). All results were acceptable, allowing the SPF temperature range for Al 5083-SP to be increased.

At this point, the initial vision of loading the part blank directly as received from the supplier, initiating the cycle, and unloading a completely formed part was realizable. Cost analysis showed an approximate 20% decrease in cost from the cast aluminum part. The weight of the SPF part was also decreased from the cast aluminum part by approximately 20%. Analysis of the Al 5083-SP material and the part configuration after SPF proved to meet engineering requirements. Everything was set to initiate production of the SPF aluminum outboard light housing.

## 4. Materials Revisited

Production of the SPF 737 outboard light housing was initiated in late 2002. Due to the process and tooling innovations that had been developed over the previous two years, the SPF portion of production went very well. However, the seam weld in the tube continued to be a source of perceived risk and actual problems.

**Fig. 14** Close-up of cavitation failure in early seamless tube

**Fig. 15** Al 5083 superplastically formed seamless tube test parts

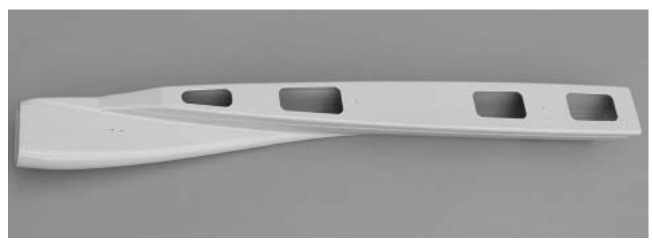

**Fig. 16** Completed SPF 737 outboard light housing

The ideal material form to start with would be seamless SPF tube. At the time the development was initiated, no seamless SPF aluminum tube was available. During Phase II, several experimental seamless tubes provided by ALCOA (Lafayette, IN) were evaluated. These tubes failed early in the SPF cycle from excessive cavitation, as shown in Fig. 14.

With the information provided from these failed tubes, ALCOA continued the development of SPF Al 5083 seamless tube. In early 2004, new seamless tubes from ALCOA were formed with great success. Two of these SPF seamless tubes are shown in Fig. 15. Analysis of the successfully formed seamless tube is continuing, and they should be implemented in the near future (Ref 13).

## 5. Conclusions and Remarks

To minimize cost, rework, redesign, and facilitate part production, manufacturing professionals need to use discretion in applying new manufacturing processes to fabricate components. The 737 outboard light housing in Fig. 16 is an example of a component that can be produced for less cost and weight as an SPF part than as a casting; however, the end form required a considerable development effort to implement.

The use of tube for SPF starting material makes new part configurations achievable. The introduction of seamless SPF aluminum tube opens up many new part families for aluminum SPF.

Ceramic dies and RP methods dramatically decrease the time needed for SPF development and/or increase the number of iterations of tool design that can be built. Fused deposition modeling casting models have the potential to be accurate enough for making production cast SPF dies.

The SPF 737 outboard light housing is an example of a successfully implemented SPF part on an existing platform, the 737 aircraft. While it is easiest to implement SPF as new parts on new or redesigned platforms, it is also possible to retrofit them in existing designs. Manufacturing professionals need to be cognizant of the strengths and weaknesses of the SPF process and materials so that new applications are both appropriate and reasonable, and encourage increased use of SPF and its associated cost and weight efficiencies.

The development and implementation of the Boeing 737 SPF aluminum outboard light housing involved the knowledge, experience, and efforts of many people within manufacturing and engineering at Boeing. The program was highly successful and could not have been accomplished without teamwork. These same processes can be applied to other areas to generate improvements and increase efficiency of many different types of parts.

## References

1. A.J. Barnes, Superplastic Forming of Aluminum Alloys, *Mater. Sci. Forum,* Vol 170-172, 1994, p 701-714
2. D.G. Sanders, The Current State-of-the-Art and the Future in Airframe Manufacturing Using Superplastic Forming Technologies, *Mater. Sci. Forum,* Vol 357-359, 2001, p 17-22
3. E.A. Starke, Jr. and J.T. Staley, Application of Modern Aluminum Alloys to Aircraft, *Prog. Aerospace Sci.,* Vol 32 (No. 2-3), 1996, p 135-137
4. "Sky Material Specification for Alnovi-1 Superplastic Formable 5083 Aluminum Alloy Sheet," SMS L-121, Sky Aluminum Company, Ltd, Tokyo, Japan, 1995
5. R.W. Davies, J.S. Vetrano, M.T. Smith, and S.G. Pitman, Mechanical Properties of Aluminum Tailor Welded Blanks at Superplastic Temperatures, *J. Mater. Proc. Technol.,* Vol 128 (No. 1-3), 2002, p 38-47
6. D.G. Sanders, A Production System Using Ceramic Die Technology for Superplastic Forming, *Mater. Sci. Forum,* Vol 447-448, 2004, p 153-158
7. D.G. Sanders, Reinforced Ceramic Dies for Superplastic Forming Operations, in *Euro SPF 04, Proceedings from the Third European Conference on Superplastic Forming,* July 7-9, 2004, Cepadues-Editions, p 109-1158
8. S.S. Crump, Apparatus and Method for Creating Three-Dimensional Objects, U.S. Patent No. 5,121,329, 1992
9. "US Rapid Prototyping Equipment Roundup," Rapid Prototyping Report, CAD/CAM Publishing, April, 2000, p 4-8
10. D.G. Sanders and B.M. Burg, Forming Metal Parts Using Superplastic Metal Alloys and Axial Compression, U.S. Patent No. 5,214,948, June 1, 1993
11. M. Shellabear, "Benchmark Study of Accuracy and Surface Quality in RP Models," Brite/EuRam Report BE-2051, Task 4.2, Report 2, RAPTEC, 1999.
12. R.M. Cleveland, A.K. Ghosh, and J.R. Bradley, Variation in Superplastic Response of Different 5083 Aluminium Alloys, *First and Second International Symposia on Superplasticity and Superplastic Forming Technology;* Proceedings from Materials Solutions 2001 and 2002, D.G. Sanders and D.C. Dunand, Ed., ASM International, 2003, p 25-32
13. J. Vetrano, R.W. Davies, and A. Borges, Superplastic Forming of Seamless Aluminum Tubes, *AeroMat 2004* (Seattle, WA), presentation at Symposium on Superplasticity and Superplastic Forming, June 2004