Preliminary Investigation of the Strength and Durability of Superplastic Formed Aluminum

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This paper describes a program to evaluate the potential of superplastic formed (SPF) aluminum for load-bearing structural applications. The alloy evaluated was Supral 220—the British alloy roughly comparable to the U.S. 7075. Components for the T-46 (Next Generation Trainer) Aircraft were formed, treated to the T6 condition, and cut into test coupons. Tensile yield and ultimate strengths, and fatigue crack growth rates all fell between the values expected for 6061-T6 and 7075-T6. Fatigue initiation times were shorter than expected, but most initiation sites were at the specimen surfaces, indicating that surface finish and cladding may be more of a factor than cavitation. The overall first impression is that SPF aluminum alloys behave predictably and have the potential for load-bearing applications, provided that an "initial flaw" concept is used during design.

Nomenclature

Hz	= Hertz (cycles per second)
ksi	= 1000 psi
k_t	= stress concentration factor
R	= stress ratio (min/max)
SPF	= superplastic formed
%EQS	= percent equivalent strain

Introduction

AS emphasis on reducing the cost and weight of aircraft structures increases, superplastic forming is receiving a great deal of attention. SPF components require much less machining and fewer detail pieces than their conventional counterparts, reducing cost by as much as 50%, and resulting in significant weight savings. The potential of SPF titanium was proven during the BLATS program.[1] Since then, new applications have been emerging continuously. This has not been the case for aluminum alloys. Lightly loaded SPF aluminum parts have been flying in Europe for years, and will undoubtedly fly in U.S. aircraft soon. Unfortunately, the lack of a reliable design data base for SPF aluminum alloys has severely limited structural applications of this very promising technology.

Materials suitable for superplastic forming generally have an equiaxed, fine-grain microstructure.[6,12] At the superplastic-forming temperature (85-90% of melting temperature), this fine-grain microstructure allows the material to elongate up to ten times its original length without necking. Without the material's resistance to necking, superplastic forming would not be possible.

Before forming, a sheet of superplastic material is clamped around its periphery in a hollow, airtight tool. The sheet and tool are then heated to the forming temperature and a differential air pressure is exerted on one side of the sheet, forcing it into the cavity of a die. This operation is called "blow forming."[7] When the sheet lies fully against the die contour, the pressure is released, the tool is opened, and the part is removed in its final configuration.

During the blow-forming operation, the material's internal energy is very high. The resulting stress-free environment allows individual grains to slide over one another and rearrange themselves, compensating for the extreme elongation by uniform thinning. The very small grains common to superplastic materials (on the order of 10 microns) readily flow into any gaps or tears that might occur as a result of forming. The result is a material with properties virtually identical to the conventional alloy.

Current aluminum alloys have grain sizes larger than optimal for superplastic forming. Consequently, when the material is stretched during forming, small voids form at the grain boundaries and triple points. This process is known as "cavitation." The presence of large or numerous voids can lower a material's strength and durability by reducing effective area or by providing fatigue initiation sites. Unless voids are eliminated altogether, their effect on properties must be considered.

The objective of the current U.S. Air Force programs is to provide an understanding of the behavior and durability of selected SPF aluminum alloys in relation to conventional aluminums. The program discussed in this paper compared the performance of British SPF alloys with familiar baselines such as 7075-T6 and 6061-T6. This phase of the project is unique in that all SPF material tested came directly from components formed under production conditions, and based on design criteria for the T-46 trainer. There was no special processing of the material, flattening, or polishing of specimens before testing. After this "quick look" at the present quality of SPF production material is complete, more extensive testing is planned with laboratory control of selected production variables.

Experimental Procedure

The material for this program was taken from superplastic-formed inlet lips designed for the T-46. The British alloy Supral 220 (clad) was formed to shape under production conditions, solution heat treated, quenched, and aged to the T-6 temper.[8] Completed inlet lips were shipped to the United States, where they were cut into test coupons and evaluated. Sheet thickness after forming ranged from 0.035 to 0.055 in. All starting thicknesses were 2 mm (0.0787 in.), with the cladding layer comprising approximately 5% of the total thickness. Each coupon was measured in at least three places

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within the test section, and the average thickness was calculated. Using this value, the change in thickness from the original 2 mm sheet was determined as follows:

$$\%EQS = \left(\frac{t_i}{t_f} - 1\right) \times 100 \quad (1)$$

where %EQS is equivalent strain in percent, t_i is the original sheet thickness, and t_f is the sheet thickness after forming.

The alloys selected as a baseline for this project were 7075-T6 and 6061-T6. There were several reasons for their selection. 1) The composition of Supral 220 (6% Cu) is closer to that of 7075 (5% Zn) than to that of other U.S. alloys. 2) The inlet lips evaluated in this program were originally designed as 6061-T6 parts, due to fusion welding requirements. 3) The properties of the two alloys bracket those claimed for Supral 220.[3] 4) Both of these alloys are commonly produced in the T6 condition.

All testing of Supral 220 and 6061-T6 specimens was done in laboratory air at 75° F and 50% humidity. Stresses were calculated individually for each specimen based on the applied load and specimen cross section. Possible effects of varying specimen thicknesses (and therefore equivalent strains) were considered, but no firm conclusions were possible. Data for 7075-T6 were obtained from Ref. 9.

The word "strain" refers to the primary direction of elongation during forming. It is roughly equivalent to the rolling direction in conventional terms. However, while there is always *one* rolling direction, SPF strain is often the result of simultaneous elongation in several directions. In such cases, the strain is referred to as "mixed."

Tensile Tests

Subsize tensile specimens[4] were prepared in accordance with ASTM Standard E-8. Gage sections were 0.25 in. by 3.0 in. Tests were conducted using an axial displacement rate of 0.05 in./min. Data were automatically recorded on a strip chart. Strain gages affixed to both sides of the specimens were used to verify the strip chart readings. Yield strength was calculated using the 0.2% offset line. Elongation was also determined from the load-displacement chart.

Fatigue Initiation Tests

The intent of the fatigue tests was to emphasize crack initiation from defects or cavities. Consequently, specimens were designed with a constant radius ($k_t = 1.0$) within the test section.[4] ASTM Standard E-466 was complied with, except that the ratio of minimum width (0.5 in.) to thickness was more than 6. Testing was done at 30 Hz, with a maximum stress of 20 ksi and stress ratio (R) of 0.1.

Crack Growth Rate Tests

Center-cracked panels were prepared in accordance with ASTM Standard E-647. Specimens were 3.0 in. by 10.0 in. with a 0.20-in. centered, sharpened slot introduced by electrodischarge machining (EDM). Each specimen was individually tested in a servocontrolled axial loading frame. Specimens were cycled at 20 ksi maximum stress with an R of 0.5, and at 10 ksi with an R of 0.1. Loading rate was 15 Hz. Crack lengths were measured periodically with an optical microscope. Accuracy was ±0.001 in.

Results

In general, test results were quite encouraging. Supral 220 behaved as expected for an aluminum alloy of its composition and treatment. Table 1 shows the results of tensile tests conducted during this program. As mentioned before, "strain" refers to the primary forming direction. Table 2 shows values from Ref. 2 and 8 for several other materials.

Fatigue testing was not nearly so simple. The constant radius ($k_t = 1.0$) specimen was chosen to emphasize the effects of cavities on crack initiation. Unfortunately, it also emphasized every tool mark and flaw in the cladding. Most cracks initiated at the specimen surfaces, and several were traced directly to surface features other than cavities. This problem was discussed with the manufacturer. During part forming, the superplastic material takes on the exact shape of the die which it is blown into—including surface finish. Figures 1 and 2 show typical surface defects which served as fatigue initiation sites. The defects could have been avoided by careful laboratory control of production conditions or by polishing specimens before testing. However, that would have distorted the main objective of this study—to evaluate the current quality of SPF production. Cleaning and polishing the forming dies before use should be a simple solution.

Since the effects of surface defects could not be accounted for, data were simply collected and considered conservative. Tables 3 and 4 show the results of fatigue testing.

Center-cracked panels for crack growth rate testing were all prepared such that loading was parallel to the strain direction. Crack growth rates for Supral 220 were determined for each condition and compared to other materials using the Walker equation.

$$\frac{da}{dN} = C(\Delta K(1-R)^{m-1})^n \quad (2)$$

Table 1 Tensile properties of Supral 220-T6 clad

Strain	%EQS	Yield, ksi (0.2%)	Ultimate, ksi	Elongation, %
Mixed	50.8	57.31	66.00	5.3
Mixed	51.1	55.38	64.62	7.2
Mixed	52.8	56.25	65.08	6.8
Mixed	57.1	57.26	66.21	5.8
Mixed	60.6	56.61	66.12	6.5
Mixed	60.9	55.37	65.04	5.9
Mixed	63.3	56.25	65.00	5.0
Parallel	69.2	55.17	62.50	3.8
Parallel	70.7	57.39	64.78	5.4
Average	59.6	56.33	65.87	5.7

Table 2 Typical tensile properties for selected materials

Material	Yield, ksi (0.2%)	Ultimate, ksi
6061-T6	40	45
6061-T6 clad	37	42
2024-T3	50	70
2024-T3 clad	45	65
7075-T6	73	83
7075-T6 clad	67	76
Supral 220-T6		
100% EQS	60	70
150% EQS	56	64

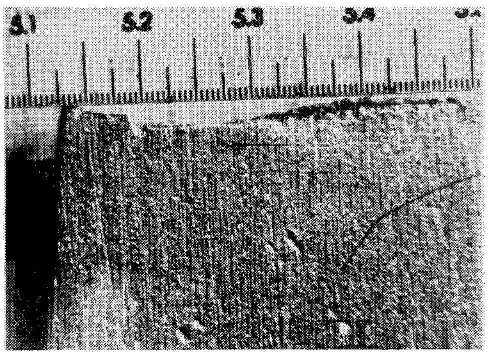

Fig. 1 Typical view of specimen surface features. Note defect at edge of flat fatigue surface (magnification: 7.5x).

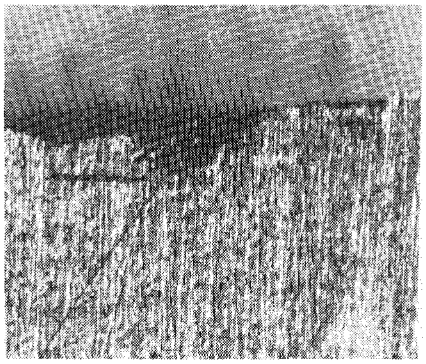

Fig. 2 Enlarged view of initiation site (different specimen). Dark region is the edge of a scratch or tool mark (magnification 15x).

Table 3 Fatigue lives for $k_t = 1.0$ specimens loaded at 20 ksi parallel to strain

Test	%EQS	Cycles to failure
1	64.0	1,120,630
2	67.4	3,677,320
3	71.1	1,583,840
4	71.1	1,027,220
5	71.1	1,973,800
6	71.1	715,610
Average	69.3	1,683,070

Table 4 Fatigue lives for $k_t = 1.0$ specimens loaded at 20 ksi perpendicular to strain

Test	%EQS	Cycles to Failure
1	71.1	516,070
2	74.9	580,700
3	78.9	696,410
4	87.4	692,220
5	87.4	547,430
6	92.0	435,550
7	96.8	427,590
Average	84.1	556,567

For all materials, only data in the linear portion of the crack growth rate curve were considered. Data were not smoothed or filtered in any way. For 7075-T6, the following values[9] were used: $C = 3.26 \times 10^{-9}$, $m = 0.5$, and $n = 3.39$. Data for 6061-T6 were not readily available, so center-cracked panels were prepared and tested. A Walker fit was generated for the data to provide a suitable baseline curve. The resulting constants were $C = 7.56 \times 10^{-9}$, $m = 0.6$, and $n = 2.82$. Figures 3 and 4 show test results for Supral 220 along with curves for 7075 and 6061. Data points represent six separate tests at each of the specified conditions.

At first, the data scatter for a nominal stress of 10 ksi looked rather large. However, realizing that all specimens experienced the same loading and accounting for varying thickness showed that actual stress levels ranged from 10.0 to 11.3 ksi. The same phenomenon occurred at 20 ksi (20.7 to 23.2), but the higher stress ratio masked the effects somewhat.

Since Walker constants were also available for 2024-T3, an additional comparison was made. The tensile strengths of Supral 220 and 2024-T3 are reasonably similar. Consequently, their relative crack growth rates should be of interest. Figures 5 and 6 include a Walker fit of the Supral 220 data shown above, along with the same 7075-T6 reference line. Data for 2024-T3 were plotted using the following Walker constants: $C = 9.677 \times 10^{-10}$, $m = 0.682$, and $n = 3.501$.[10] The Walker fit

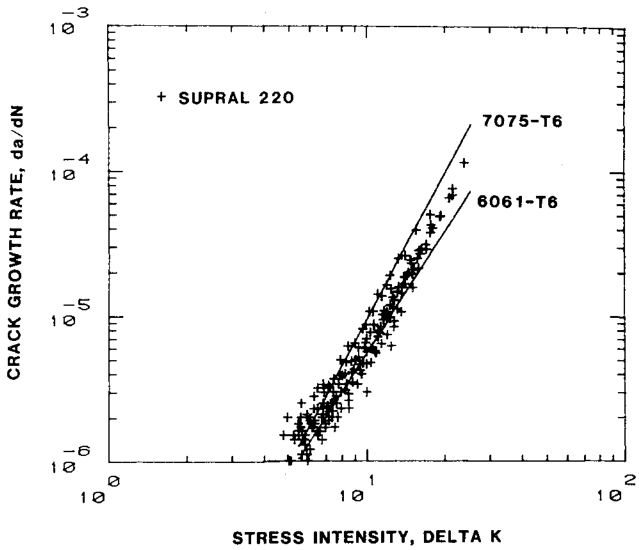

Fig. 3 Crack growth rates for Supral 220 vs 7075-T6 and 6061-T6 at 10 ksi, $R = 0.1$.

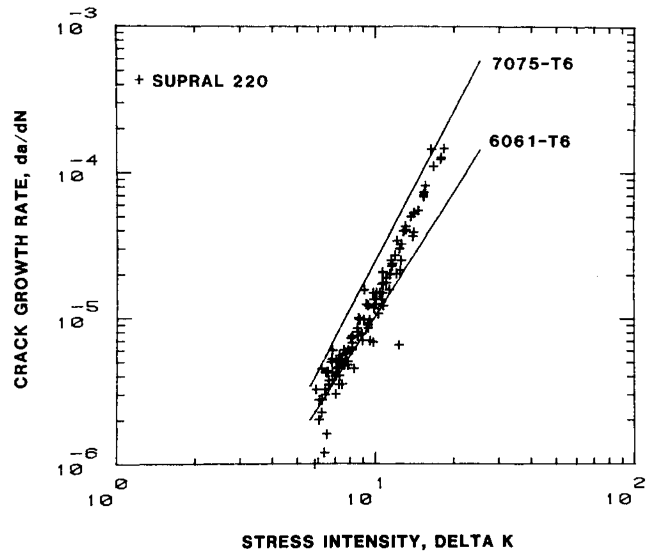

Fig. 4 Crack growth rates for Supral 220 vs 7075-T6 and 6061-T6 at 20 ksi, $R = 0.5$.

of Supral 220 yielded the constants $C = 4.72 \times 10^{-9}$, $m = 0.6$, and $n = 3.09$.

Discussion

Measured properties for Supral 220-T6 agreed well with data provided by the manufacturer. This agreement was especially encouraging since the specimens evaluated were cut from actual aircraft parts formed under production conditions. Interpretation of results was complicated somewhat by the presence of cladding. However, it is interesting to note that the cladding layer remained intact and functional after undergoing the SPF process.[11]

The primary focus of testing during this program was to determine if SPF aluminum was ready for applications on U.S. aircraft. Consequently, more attention was given to obtaining specimens formed under production conditions than to controlling specific paramenters. Equivalent strains were generally rather low and very few conclusions could be drawn concerning the effects of strain level. The data that were collected, however, indicated that Supral 220 behaves predictably.

For its initial debut on U. S. aircraft, SPF aluminum is being limited to applications designed for low- to moderate-strength aluminum alloys.[5] Since Supral 220 shows better tensile properties than either 6061-T6 of 2024-T3, it can easily replace many high-cost parts made from those alloys. Data indicate that behavior is predictable. Yield strengths for the nine specimens tested varied by only 4%. Ultimate strengths all fell within 6% of each other. There should be no problems associated with SPF secondary structure formed at moderate equivalent strains (around 100%).

After SPF aluminum technology is proven in flight (in the United States), it must be evaluated for more demanding applications. Figures 3 through 6 showed that crack growth rates for Supral 220, while not quite as good as those for 2024-T3 or 6061-T6, were noticeably better than those of 7075-T6. This conclusion was expected based on the relative tensile strengths of the three materials. SPF Supral 220 can compete directly with these conventional alloys for several reasons. Some of the weight saved by reducing piece count and fastener requirements can be used to lower stresses in SPF parts by increasing their thickness. SPF parts are often self-stiffening due to complicated geometries. Supral 220 is readily weldable,[5] while 7075 is not. SPF parts are generally cheaper and easier to produce, so even if weights are the same as for conventional parts, superplastic forming may still be desirable.[7]

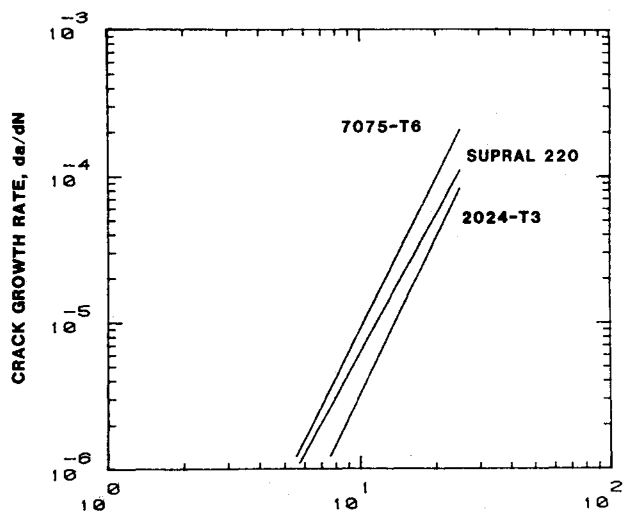

Fig. 5 Crack growth rates for Supral 220 vs 7075-T6 and 2024-T3 at 10 ksi, $R = 0.1$.

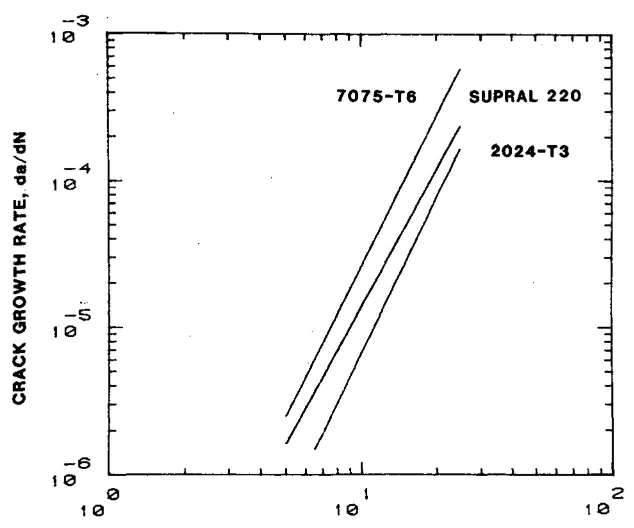

Fig. 6 Crack growth rates for Supral 220 vs 7075-T6 and 2024-T3 at 20 ksi, $R = 0.5$.

The potential of SPF parts for applications requiring substantial fatigue initiation times could not be determined. The presence of cladding on test specimens apparently accounted for the shorter than expected lives.[8] In addition, several surface flaws served as fatigue initiation sites. These problems are undoubtedly present whenever a thin specimen is fatigue-tested unless measures are taken to control them. Since tight controls are very costly on the production floor, actual SPF parts will probably be affected by these factors.

The reason for the $k_t = 1.0$ tests was a concern over the effects of cavitation in SPF aluminum. The possibility that cavitation shortened fatigue lives could not be ruled out. Therefore, it is recommended that an "initial flaw" concept be used in design until sufficient data can be obtained to justify an alternate analysis method. The initial flaw concept merely implies that the presence of small flaws cannot be ruled out. Therefore, each part is designed assuming that some flaw of a given size exists in the most critical location of the structure. Allowable and design stresses are then calculated based on the presence of the assumed flaw rather than on the assumption of a perfect structure.

Tables 3 and 4 support the theory that fatigue initiation time is shorter when loading is perpendicular to the forming strain direction than when loading is parallel to strain. Although equivalent strains were not the same for both groups of specimens, differences in fatigue lives were too great for %EQS to be a major factor. The shortest life measured parallel to the strain direction was nearly 20,000 cycles longer than the longest life perpendicular to strain. The difference in average lives for the two groups of specimens was over 200%.

Conclusions

The superplastic-formed alloy Supral 220-T6 performed as expected during tensile and crack-growth-rate testing. There were no surprises, and data were consistent from test to test. Based on these results, the authors feel that the tensile and crack-growth properties of SPF Supral 220 are reasonable and predictable. Fatigue initiation times were shorter when loading was perpendicular to forming strain than when loading was parallel to strain. No firm conclusions were possible concerning the effects of cavitation or strain level on specimen behavior. It is therefore recommended that an initial flaw concept be used whenever SPF parts are used in structurally demanding applications. This is not because of any inherent material weakness, but simply because there are currently not enough data to support any other approach.

Recommendations

No problems were encountered during this program that would not be expected for any material of the thickness tested. Therefore, it is recommended that:

1) Future testing focus on the effects of equivalent strain (and cavitation) on the properties of a given SPF material instead of comparing SPF to conventional materials.

2) Load-bearing SPF parts should be designed with an initial flaw approach.

3) Dies used for forming SPF parts should be polished before use, and cleaned regularly.

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