ADVANCES IN METALS PROCESSING

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INTRODUCTION

Research on metals processing is being conducted at the Langley Research Center to develop improved forming and joining methods with the potential of reducing the weight and cost of future aerospace structures. The approach followed is to assess the state of the art for fabricating a given structural system, define candidate methods for improving processing, evaluate the merits of each, fabricate and test subelement components, and then scale up the process to demonstrate validity.

This paper reports on the development and the state of the art of weldbrazing, superplastic forming (SPF), superplastic forming and codiffusion bonding (SPF/DB) and superplastic forming and weldbrazing (SPF/WB) for titanium and the SPF of aluminum. While the technology was developed for aerospace applications, potential uses are anticipated in the nonaerospace industries.

WELDBRAZING OF TITANIUM

Weldbrazing is a process developed at the Langley Research Center that combines the use of resistance spotwelding and brazing to produce structural joints having mechanical properties superior to similar joints produced by either of the processes alone (ref. 1). The steps employed in the process for fabricating a titanium structural component are shown in figure 1. The two mating parts are formed, chemically cleaned, and spotwelded together. Spotwelding parameters were selected so that a uniform faying surface gap was established between mating parts due to weld nugget expansion. A 3003 aluminum braze alloy (foil strips) was then placed adjacent to faying surfaces. The assembly was placed in a vacuum furnace and heated to the brazing temperature. Due to the spotwelds fixing and maintaining alignments of the components, no tooling was required for brazing. Upon melting the braze was drawn into the faying surface gap by capillary action to establish a hermetically sealed joint. The braze foil, which was originally placed adjacent to the flange of the hat component, completely penetrated the joint to form a filet between the face sheet and hat stringer, as shown in the photomicrograph below. Structural joints produced by this process have been shown to have superior tension, compression, and fatigue properties, as well as improved corrosion resistance compared to joints produced by riveting, spotwelding, or brazing alone. Additional studies by the Northrop Corporation have shown that weldbrazing can offer a 30-percent reduction in labor costs compared to riveting (ref. 2). Although the process was developed for joining titanium, the technology should also be applicable for use with other metals that can be joined by welding and brazing. A similar process for joining aluminum also exists, called weldbonding, where spotwelding and adhesive bonding are combined to produce joints having similar advantages.

Figure 1

SUPERPLASTIC FORMING OF TITANIUM

Superplastic forming of titanium is an emerging technology which has the potential to revolutionize the fabrication of many titanium components. An example of the superplastic behavior exhibited by titanium is depicted in figure 2, which shows a specimen as machined and following superplastic stretching. The as-machined specimen was heated to 1700°F in vacuum, loaded in tension to a stress of 2 ksi, and stretched to a total elongation of over 1000 percent. As shown, the specimen elongated uniformly without experiencing localized necking. Since the flow stress required for stretching is low, the use of gas pressure to blow form or superplastically form the material was developed. Early studies shows that titanium parts could be superplastically formed to exacting tolerances to eliminate the springback and minimum bend radii problems encountered in conventional forming. Also, the high degree of formability permitted the fabrication of configurations not possible with conventional methods. These features have led to the fabrication of new design concepts having improved structural efficiency. Further work demonstrated that superplastically forming multiple parts in a large tool and a single operation resulted in cost savings of 50-70 percent compared to forming by conventional means.

Titanium can also be easily diffusion bonded at the superplastic forming temperature of 1700°F, and as a result methods have been developed to exploit the combined use of superplastic forming and diffusion bonding (SPF/DB). Early studies predicted cost savings of 30-50 percent and weight savings of 20-30 percent for SPF/DB titanium structure compared to similar components fabricated conventionally. As a result, NASA Langley initiated studies to evaluate the potential of SPF/DB titanium structures for application on future high performance aircraft.

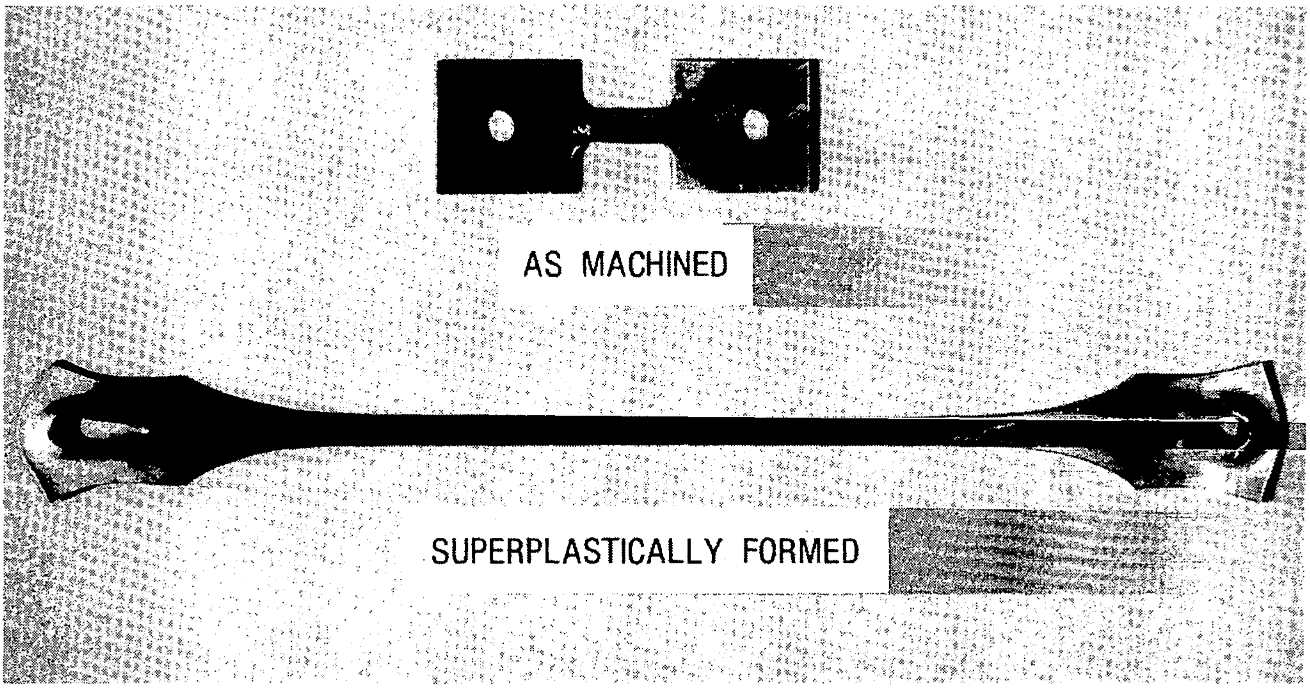

Figure 2

SPF/DB OF TITANIUM TRUSS CORE SANDWICH STRUCTURE

The method for superplastically forming and codiffusion bonding titanium sandwich structure, using the selective application of stop-off material, (ref. 3), is schematically represented in figure 3. In the first step, both sides of the center sheet are selectively coated with a ceramic stop-off material. The three sheets are then stacked and placed in the tool. The assembly is then positioned between resistance-heated ceramic platens that are mounted in a press or loading device. Load is applied and a gas-tight seal is established between the tool and the three titanium sheets due to the pinching action of the projections machined on the upper tool. The cavity of the tool is then purged with argon gas and the assembly heated to 1700°F. Argon gas is then injected into the tool at a pressure of 300 psi to compress the three sheets against the flat side of the tool. Pressure is maintained for three hours to diffusion bond the titanium sheets together in the regions where stop-off was not applied. Gas pressure in the tool cavity is then released and inert gas is injected through the preplaced tubes into the stop-off material between the sheets. Once separation of the sheets occurs, the gas pressure is increased at a programmed rate to a pressure of 100 psi to superplastically form the outer sheets to the contour of the mold cavity. As the face sheets are separated by the gas pressure, the center core sheet is superplastically stretched to form the truss core configuration. Gas pressure is equalized within the sandwich during forming by means of premachined holes. Following SPF/DB the panel is chemically milled to remove surface contamination and to obtain the desired skin thicknesses. This process has been patented and has been used to fabricate a wide variety of large components.

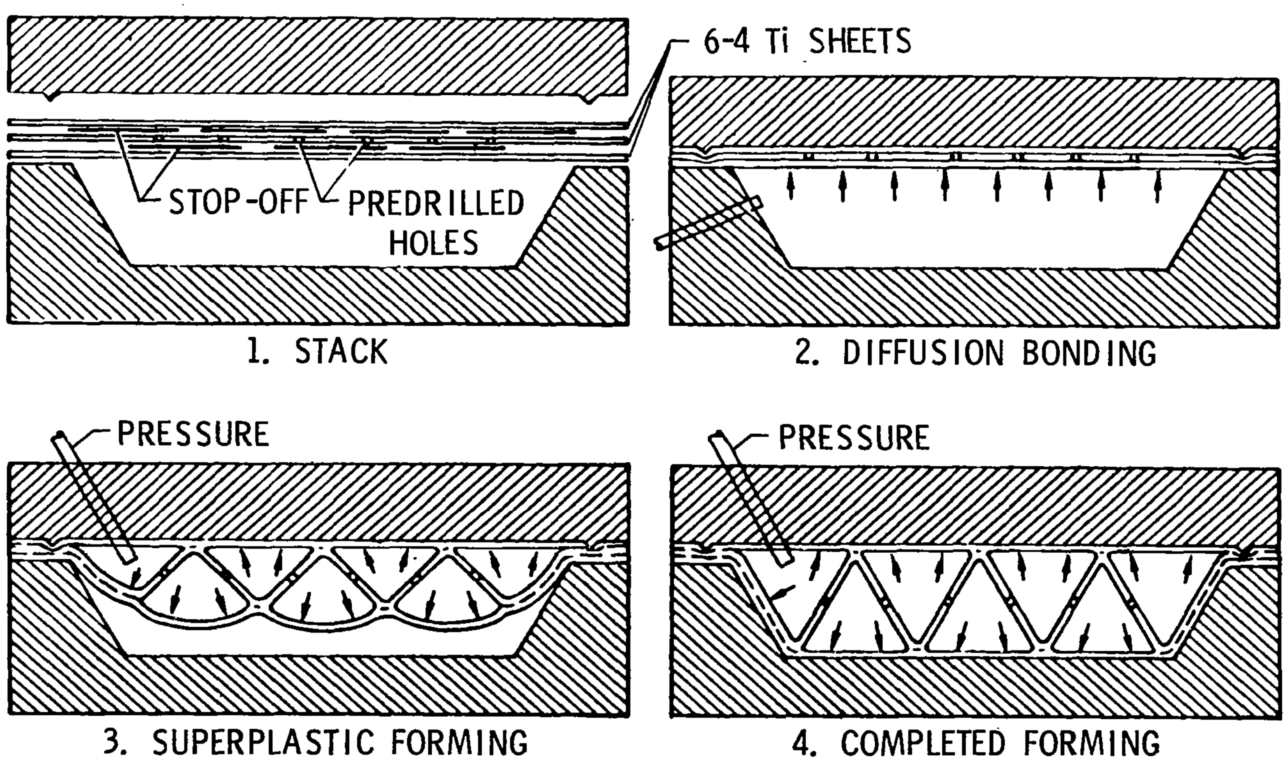

Figure 3

SCR YF-12 PANEL PROGRAM

In support of NASA's Supersonic Cruise Research (SCR) Program, LaRC initiated a study to develop and evaluate innovative processes suitable for use in fabricating flight-quality hardware for use on future supersonic aircraft. The study, designated as the YF-12 structural panel program, was a joint NASA Langley and Dryden Research Center activity.

To focus this research, an upper wing panel on the NASA YF-12C airplane was selected as a suitable structural component to validate processing methods for incorporating advanced materials into flight-quality hardware. The panel location on the YF-12 is shown in figure 4. This 16- × 28-inch panel was considered to be part of the primary structure and design critical in shear. The original wing panel was an integrally stiffened structure machined from a single plate. Panels were fabricated and evaluated through both ground tests and flight tests on the YF-12 at airspeeds up to Mach 3. Seven different panel concepts were evaluated in the program (ref. 4). Details on the fabrication of weldbrazed and SPF/DB panel concepts are discussed in following figures.

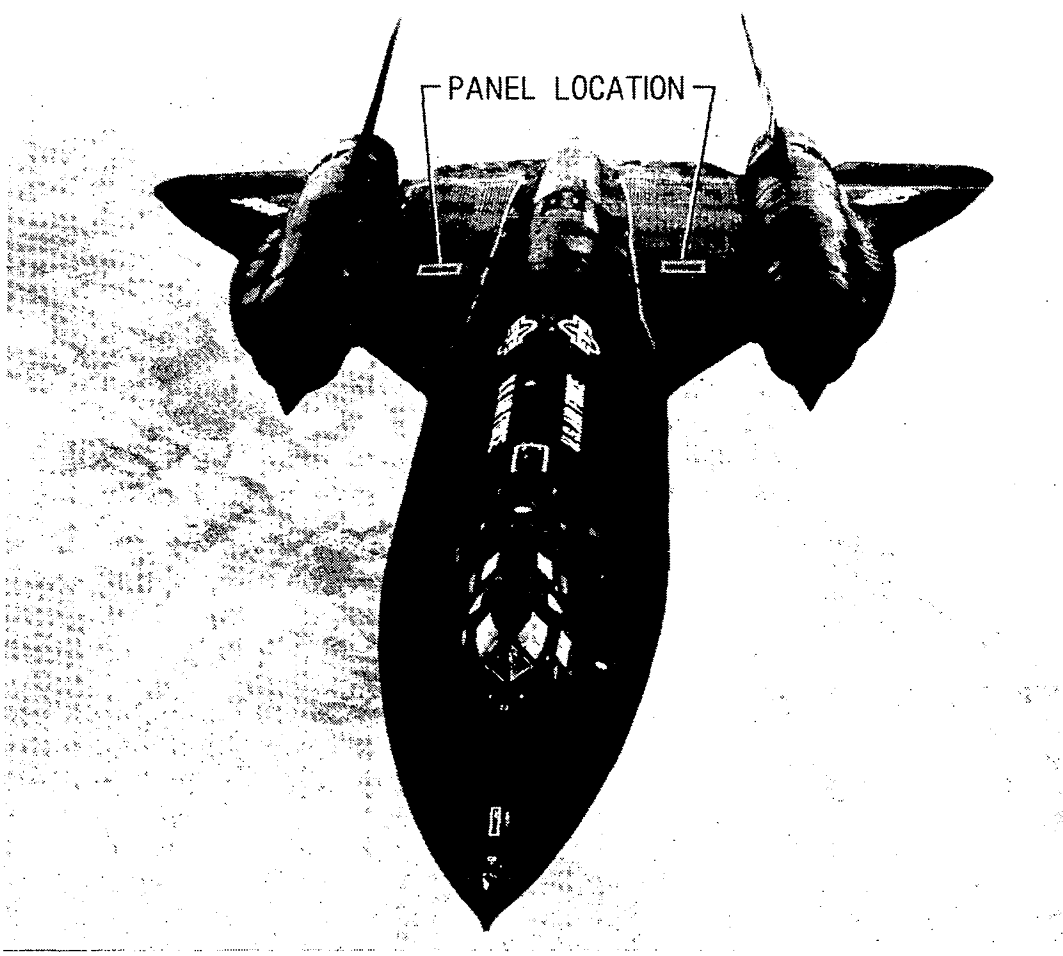

Figure 4

WELDBRAZED TITANIUM SKIN-STRINGER YF-12 PANEL

The first panel concept for the YF-12 panel program was a Ti-6AL-4V titanium alloy skin-stringer structure. The panel was fabricated by Lockheed-Advanced Development Projects using the NASA LaRC weldbrazing process. The general configuration and construction details of the weldbrazed YF-12 panel assembly are shown in figure 5. The panel measures 16 inches × 28 inches and consists of an annealed Ti-6AL-4V titanium alloy skin, chemically milled in the center to a thickness of 0.70 inch, and thirteen Ti-6AL-4V "Z" stiffeners formed from 0.050-inch sheet. The stiffeners were spot-welded to the skin using a welding schedule that produced a 0.003- to 0.004-inch gap at the faying surface. Narrow strips of 0.016-inch-thick 3003 aluminum alloy alloy sheet, scarfed to a knife-edge along one side, were wedged in the faying surface gap at the foot of each stiffener to hold them in place during brazing. Brazing was accomplished in a vacuum furnace at 1290°F for 10 minutes at a vacuum of 10^{-5} torr. A total of ten panels were fabricated. Test results obtained showed that all panels exceeded design requirements. One panel was installed on the NASA YF-12 airplane and flown for a total of approximately 100 hours with 30 hours at airspeeds in excess of Mach 2.6. Based on these results, weldbrazing is considered to be a simple and viable process for fabricating flight-quality titanium structure.

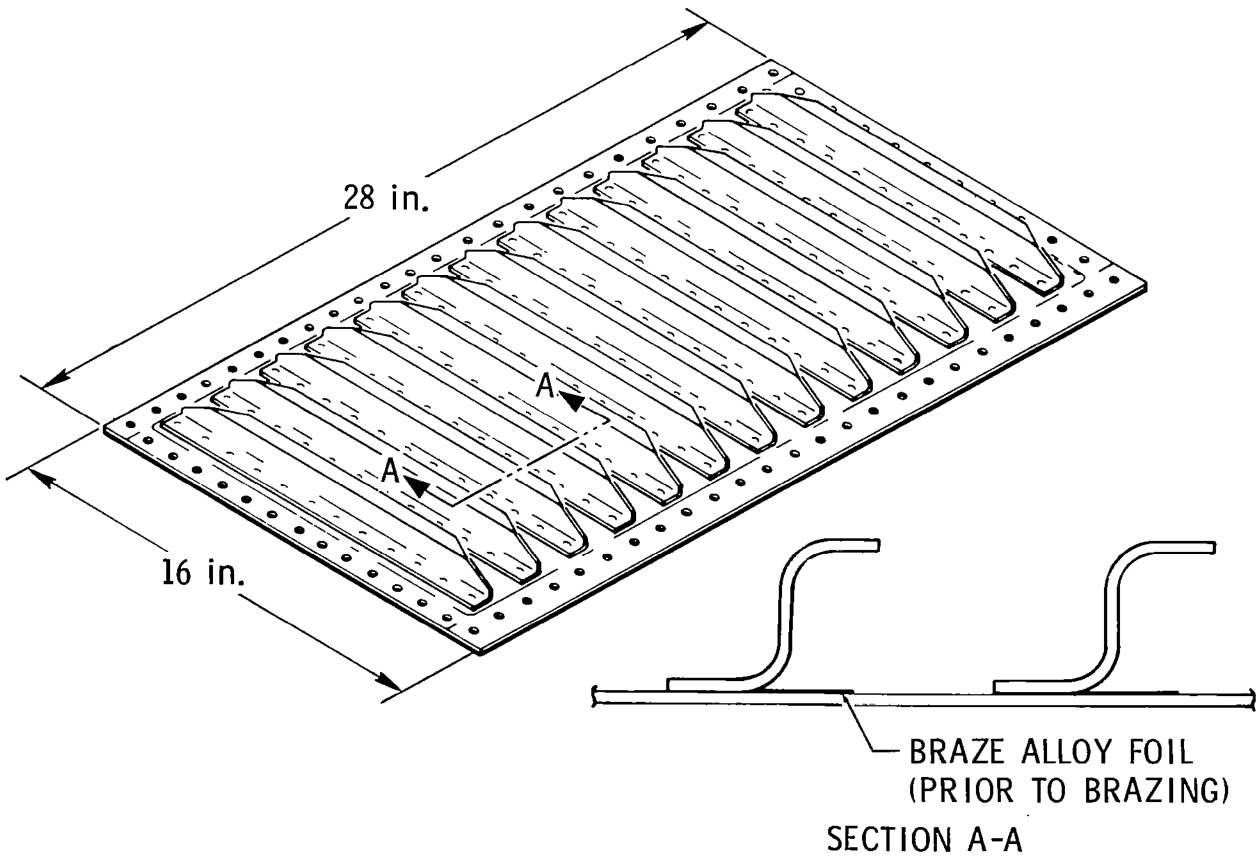

Figure 5

SPF/DB TITANIUM SINE WAVE TRUSS CORE SANDWICH YF-12 PANEL

To assess the potential of SPF/DB for fabricating efficient titanium structure a YF-12 wing panel was designed and fabricated using the selective stop-off process. The panel concept developed is shown in figure 6 and consists of a sine wave truss core sandwich structure. The design thickness of the inner and outer face sheets was 0.029 inch and the core web thickness was 0.013 inch. The panel was fabricated from three flat sheets using the process described in figure 3. The next figure shows the center core sheet of the panel prior to SPF/DB and fabrication details are presented in the accompaning text.

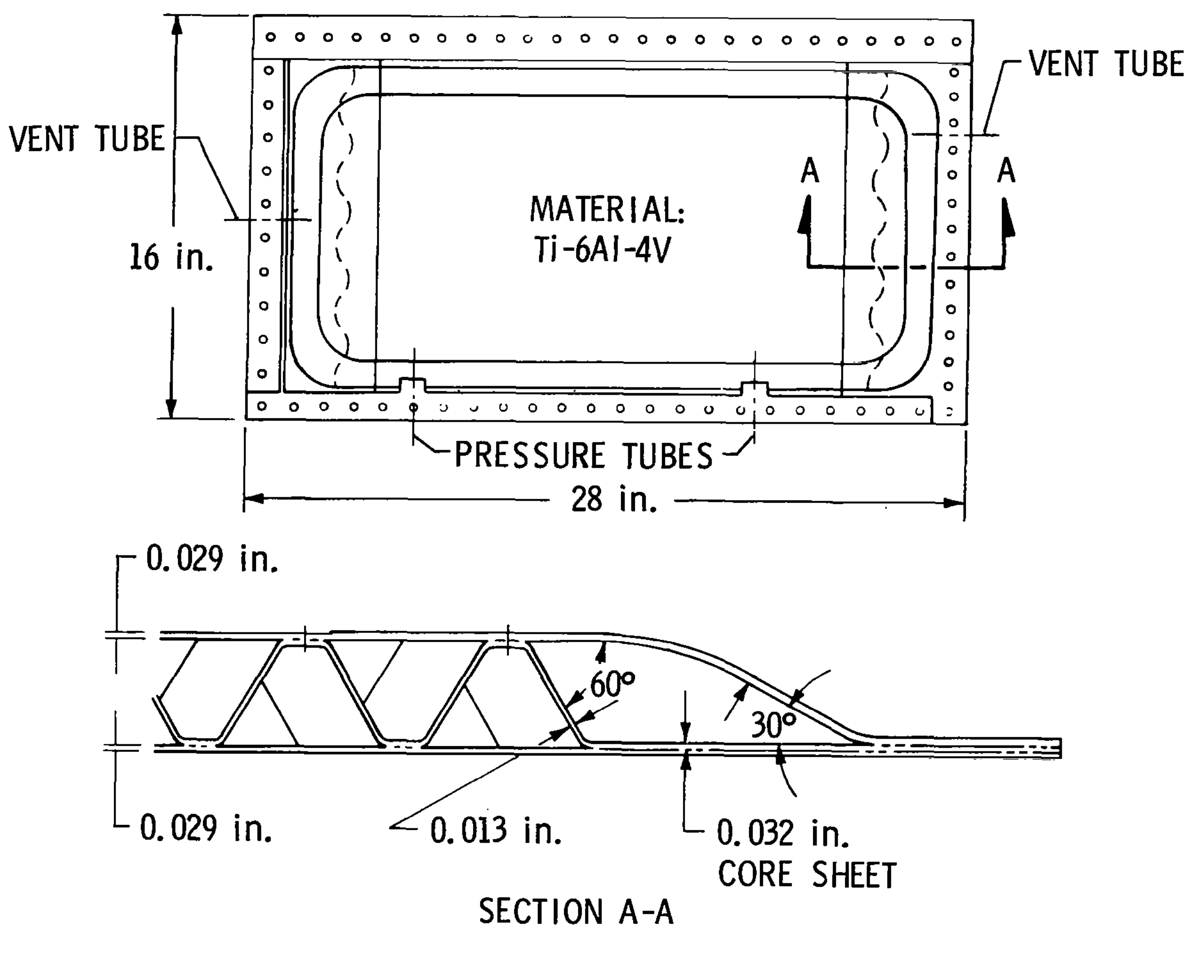

Figure 6

CORE SHEET FOR SPF/DB YF-12 PANEL

The center core sheet used in fabricating the SPF/DB titanium sine-wave truss core sandwich panel for the YF-12 program is shown on figure 7. The core sheet was slotted to accommodate stainless steel pressure and vent tubes and ceramic stop-off material was selectively applied to both sides using a silk screening process. The core sheet was then sandwiched between the two face sheets and tack welded together with the vent and pressure tubes in place. This assembly was then placed in a steel tool between ceramic platens and the panel was SPF/DB in accordance with the Rockwell process previously described. A total of seven panels were successfully fabricated. Six panels were tested to demonstrate structural adequacy prior to installing one panel on the YF-12 for flight service evaluation. All panels met the requirements of the program and demonstrated that SPF/DB is a viable process for fabricating titanium structure for high-performance aircraft.

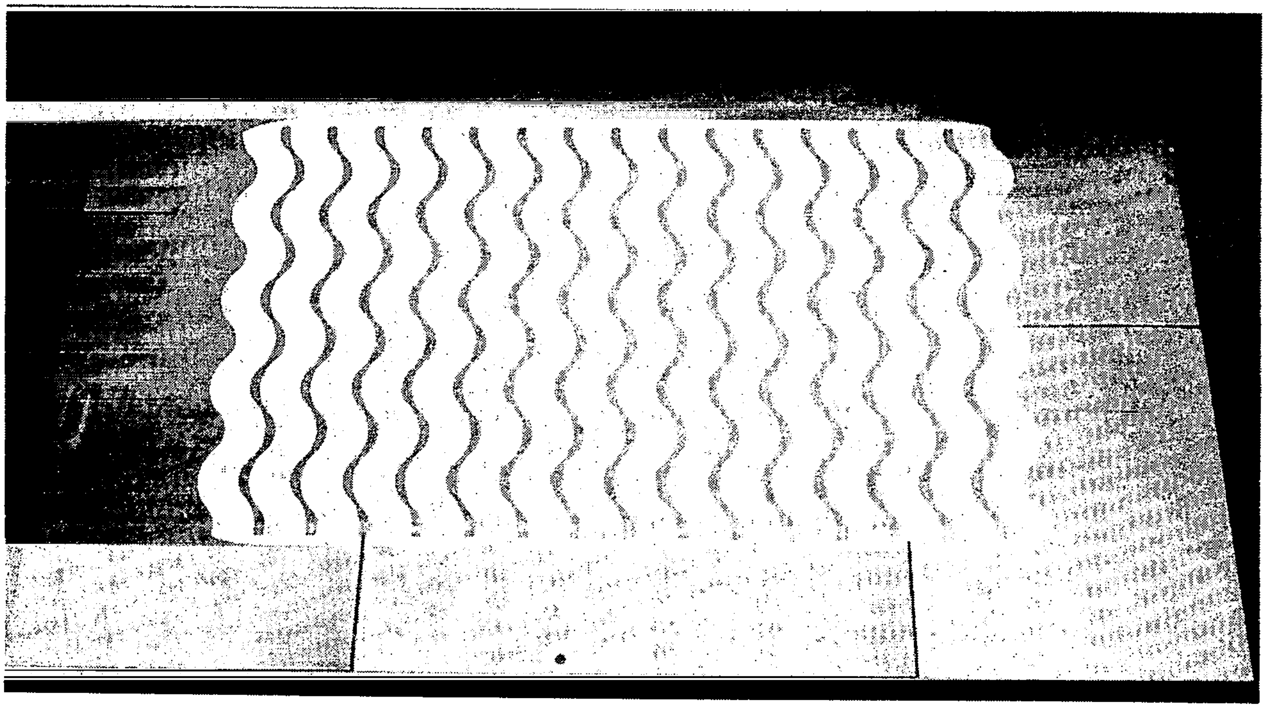

Figure 7

FOUR-SHEET SPF/DB TITANIUM PANELS

A process which combines the use of resistance spotwelding and SPF/DB to fabricate titanium sandwich panels has also been developed (ref. 5). The steps involved in this process are shown in figure 8. The two titanium sheets which make up the core are first spotwelded together in a selected geometric pattern as shown in the upper part of the figure. Gaps are periodically left between the overlapping welds to provide for equalization of pressure during forming. The welded core sheets are positioned between the face sheets in an appropriate tool, and the assembly is heated to 1700°F using ceramic heated platens. Gas pressure is introduced between the core sheets and the core sheets separate in a pillow fashion as shown in the center of the figure. Forming continues using an argon gas pressure of 30 to 100 psi until the individual sections of the core sheets contact the face sheets and each other. Argon gas pressure is then increased to 300 psi and maintained for 3 hours to diffusion bond all mating surfaces. The part is then cooled and removed from the tool. Limited chemical milling is required to remove surface contamination. The process has been used to fabricate a wide variety of parts containing different core geometries.

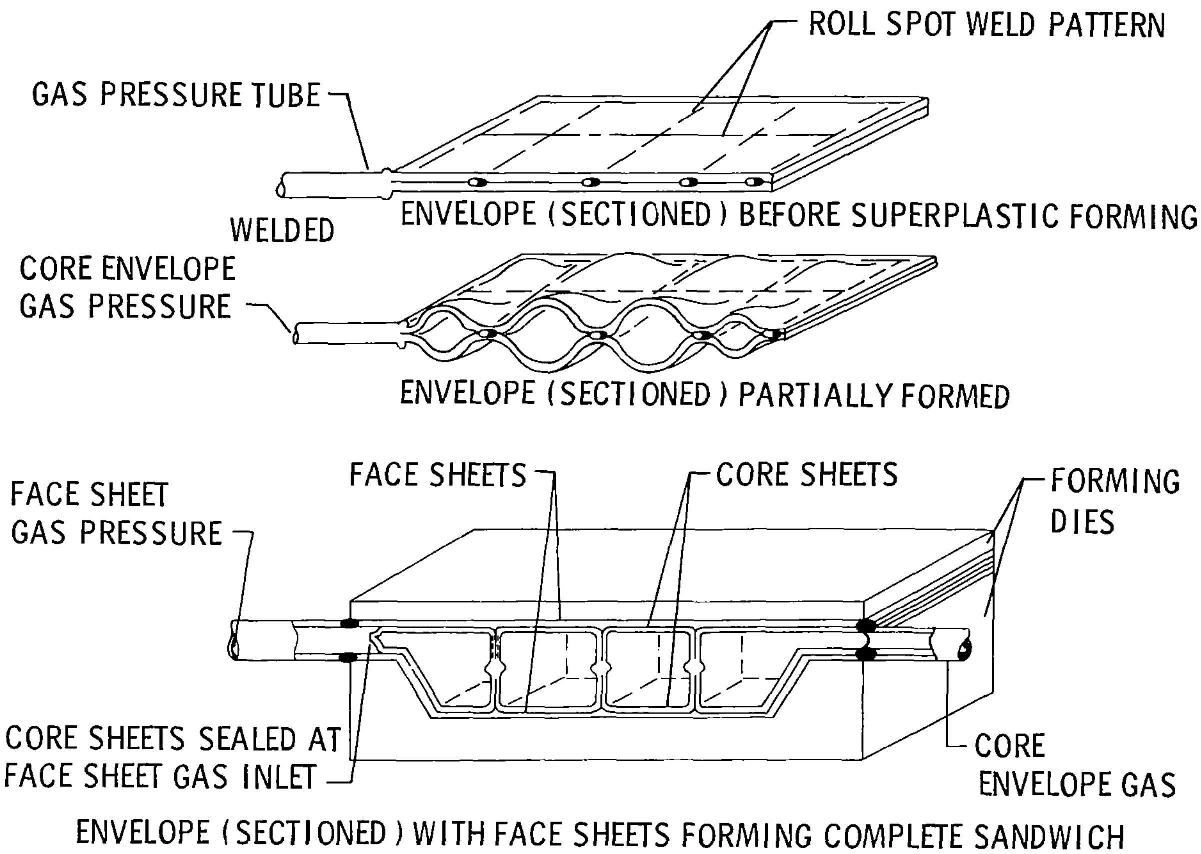

Figure 8

SPF/DB FOUR-SHEET TITANIUM WING PANEL

To further evaluate the potential of the SPF/DB four-sheet process, a processing study was conducted for a large structural component. A 3- × 5-foot panel was selected and designed to meet the loading requirements of a supersonic transport wing. Also, selected studies were made to determine the effects of the SPF/DB process on the mechanical properties of Ti-6Al-4V. Two full-size panels were fabricated on the rectangular cell core expanded sandwich design. Figure 9 shows one of the completed panels. Spectrum fatigue and compression testing of the panels were conducted at the design conditions. Both panels met the design requirements. Mechanical properties of the SPF/DB titanium were comparable to conventionally processed material.

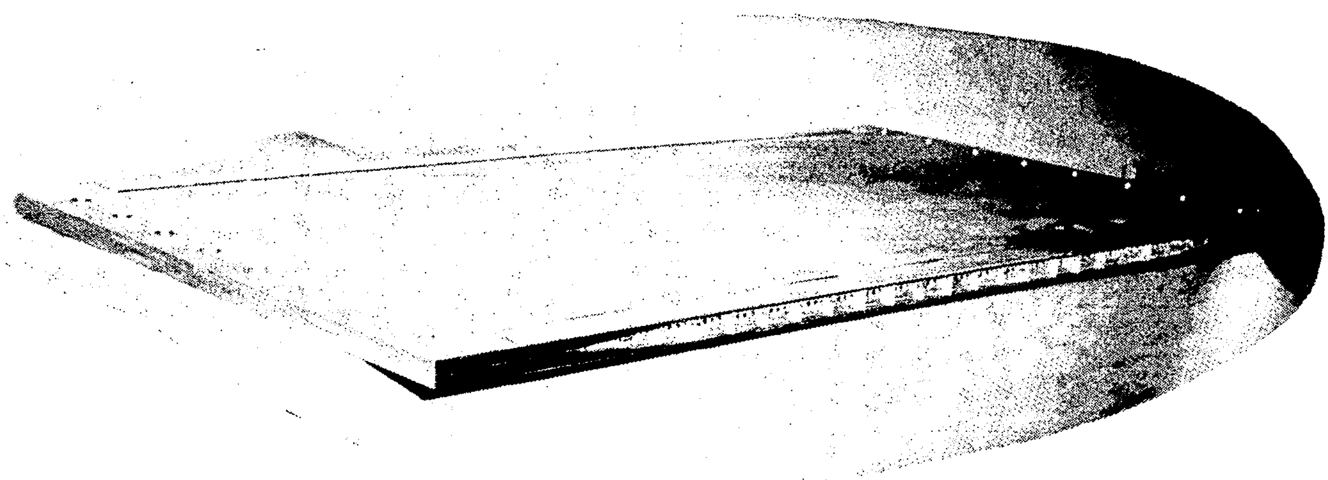

Figure 9

SUPERPLASTIC FORMING AND WELDBRAZING

While SPF/DB components are reported to have significant potential for reducing the weight and cost of titanium structure, processing times of 6 to 10 hours are commonly required. In an attempt to simplify processing, NASA LaRC initiated a study to separate the forming and joining processes. The process selected for study was the combined use of superplastic forming and weldbrazing (SPF/WB). The specimen selected for evaluation was a small 10-inch-long compression panel.

The steps involved in the process are shown in figure 10. A pan-like component is first superplastically formed to fabricate the stringer. To form the part, a single sheet of titanium is placed in the tool and blown or superplastically formed over a male tool. Forming requires processing at 1700°F for a period of 30 minutes. The formed stringer is then spotwelded to a flat face sheet. Strips of 3003 aluminum braze alloy are then positioned adjacent to the joint and the assembly is placed in a vacuum furnace for brazing. Brazing requires no tooling and is accomplished at a temperature of 1250°F for a period of 5 minutes. Total elevated-temperature processing time required for a SPF/WB component is approximately 35 minutes. Following weldbrazing the final specimen shown on the lower portion of the figure is machined. Advantages of SPF/WB compared to SPF/DB for the fabrication of selected components are reduced elevated-temperature processing and improved inspectability (ref. 6).

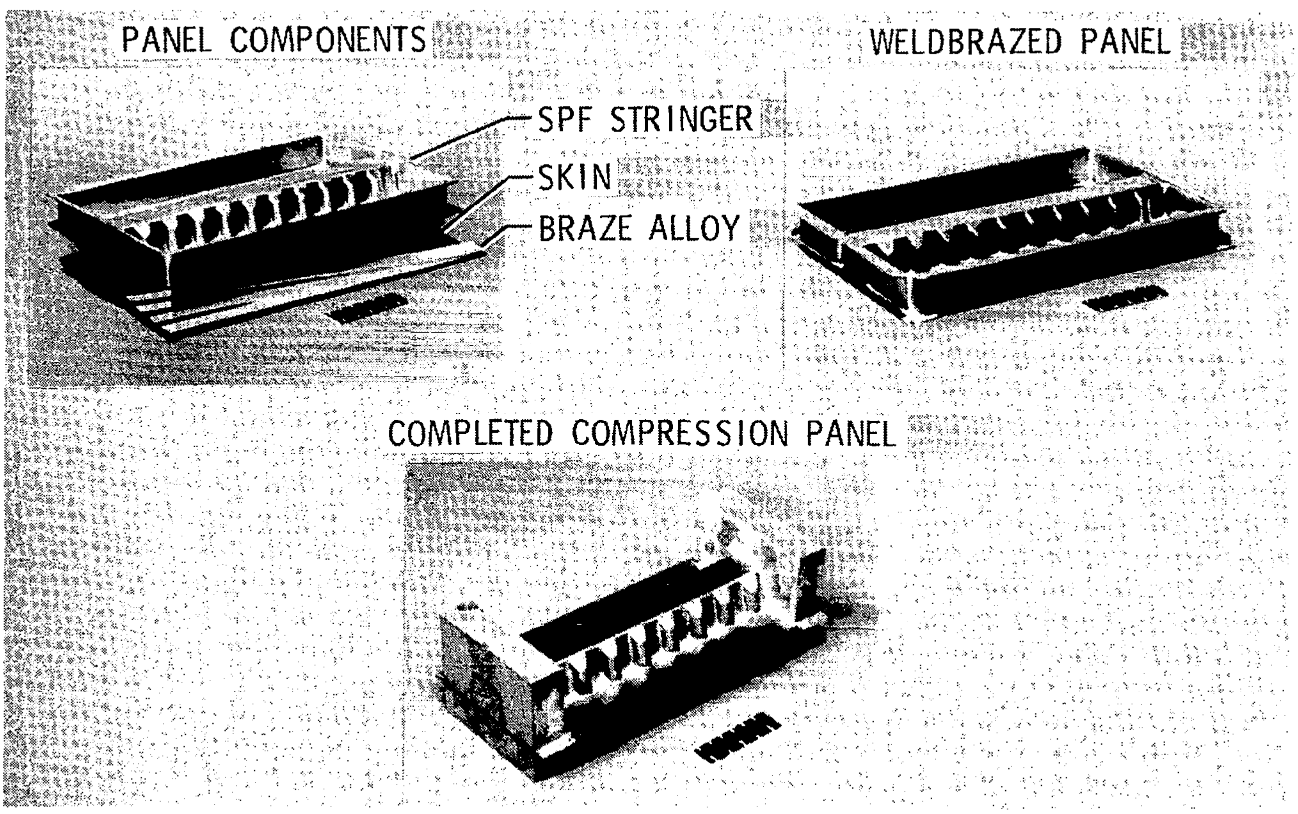

Figure 10

SPF TOOLING AND STRINGER CONFIGURATIONS

The simple steel female tool and the various male inserts used to superplastically form the titanium stringers for the superplastic forming and weldbrazing (SPF/WB) study are shown in figure 11. The stringer configurations selected for evaluation were based on their potential to offer increased structural efficiency in compression compared to conventional hat stiffeners. The configurations selected also exploited the increased formability of superplastic forming. Other than the conventionally shaped stringer, the configurations would be difficult if not impossible to form using conventional titanium fabrication methods. As shown in the figure, the stringer configurations that were evaluated consisted of a conventional hat, a stepped hat, a ribbed-web hat and a beaded-web hat. As previously stated, the stringers were superplastically formed at 1700°F using a single sheet of titanium which was blown down into the cavity using argon gas at a pressure of 30 to 125 psi. Each of the stringers formed in this manner were of equal weight. Following forming the pan-shaped stringer components were chemically cleaned for subsequent weld-brazing.

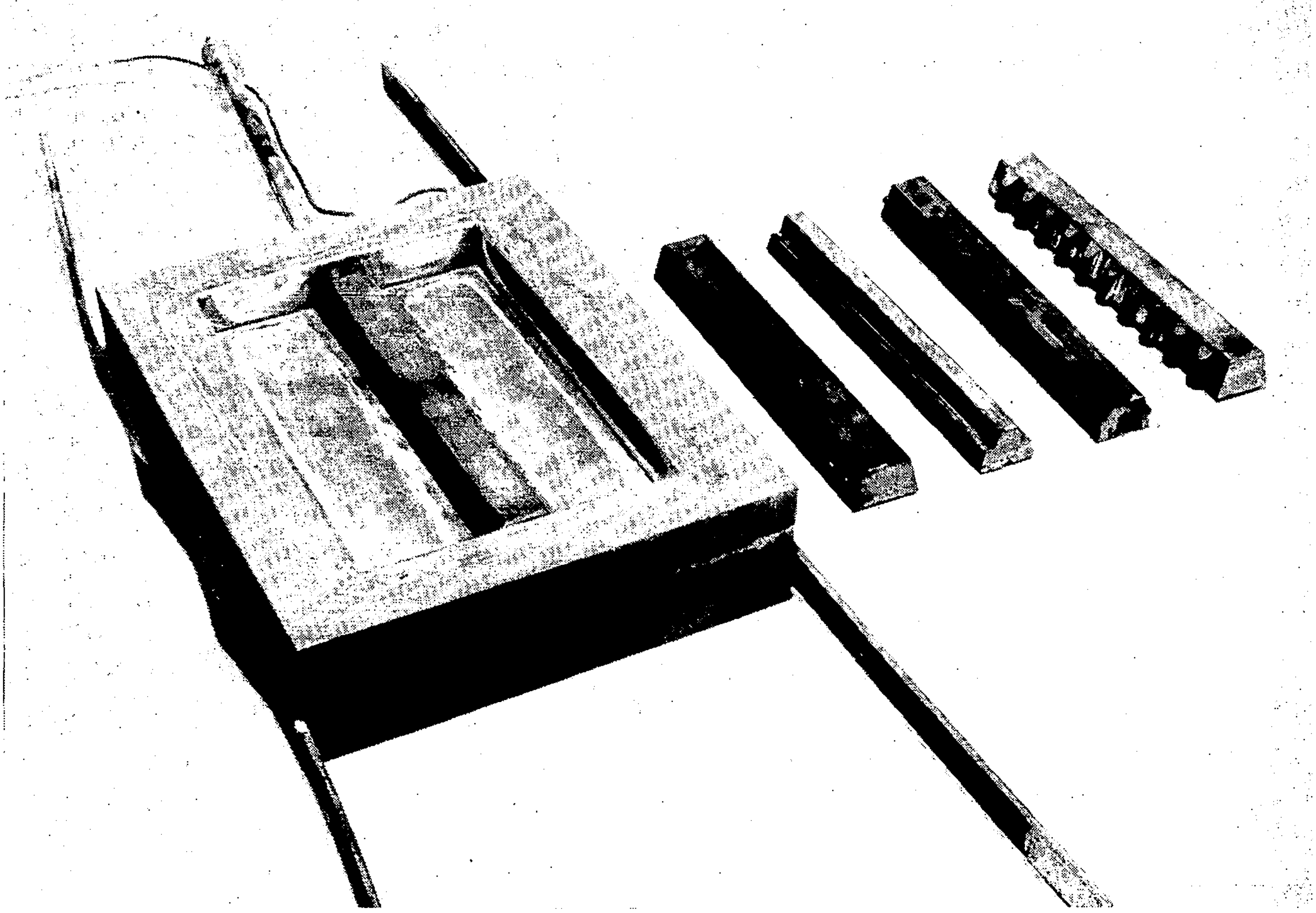

Figure 11

RELATIVE BUCKLING STRENGTHS OF SPF/WB TITANIUM PANELS

Three compression specimens of each of the four stringer configurations described on the previous figure were fabricated and tested. The relative local buckling loads of these specimens are shown in figure 12. Each bar represents the average value of three tests. Since each of the specimens were of equal weight, regardless of configuration, the data are also an indication of relative structural efficiency. As shown on the figure, the buckling strengths of the beaded web hat, the ribbed hat, and the stepped hat specimens were all greater than the buckling strenghts of the specimen fabricated with a conventional hat stringer. The buckling loads or strengths of specimens with beaded-web, ribbed-web, and stepped-web shaped stringers were 20 percent, 50 percent, and 60 percent higher, respectively, than the specimens with conventional hat stringer configuration. As demonstrated by these data, superplastic forming affords appreciable opportunities for improvements in structural efficiency and corresponding weight reductions of titanium structures designed to carry compression loads.

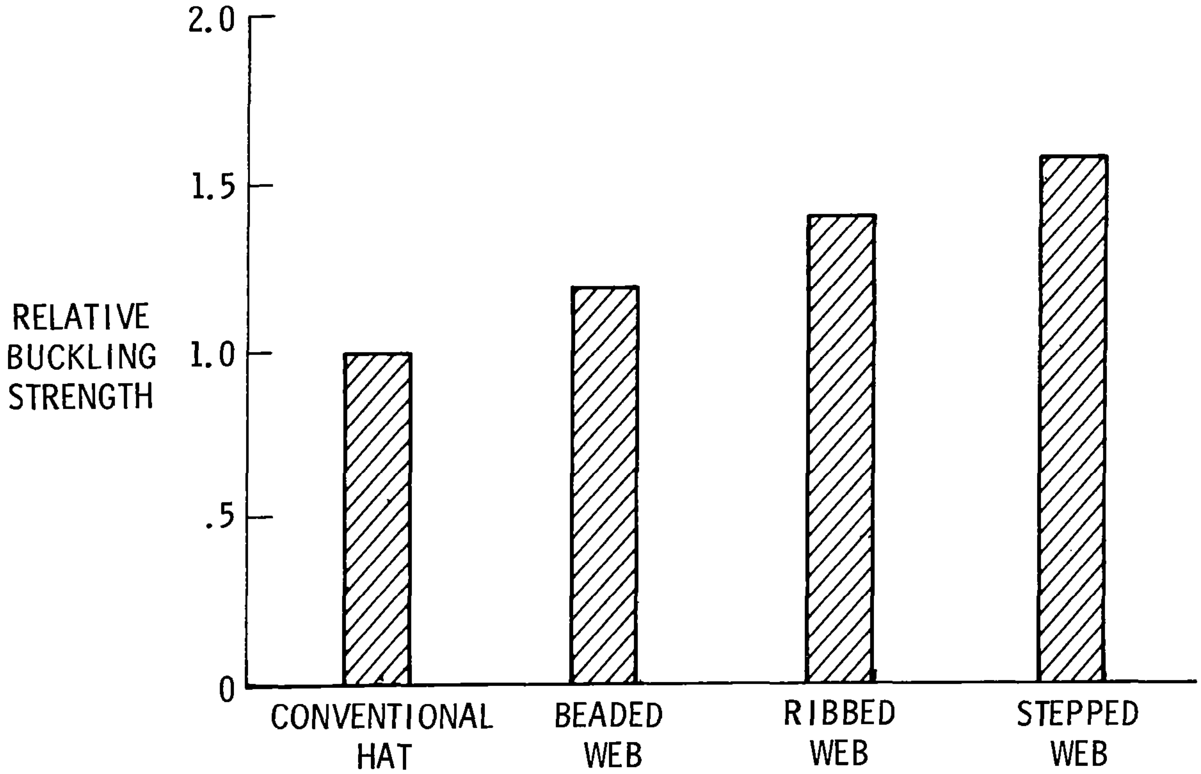

Figure 12

SPF/WB MULTIPLE STRINGER TITANIUM COMPRESSION PANELS

To further assess the potential of SPF/WB for fabricating titanium compression panels, LaRC is scaling up the SPF/WB process to fabricate and test multiple stringer panels. A tool having multiple inserts has been fabricated to superplastically form a multiple stringer or corrugated sheet from a single piece of titanium using the same parameters and processes established for the small single stringer specimens described in figures 10, 11 and 12. A photograph of a 22-inch × 30-inch SPF/WB panel fabricated having nine conventional hat stringers is shown in figure 13. This panel will be tested to serve as a baseline for comparison with multiple-stringer panels having a stepped-hat or beaded-web configurations. Panels will also be fabricated with stringers running in the longer direction to evaluate the column buckling behavior of SPF/WB titanium compression panels having different stringer configurations. Based on the results obtained to date, SPF/WB is considered to be a promising process for fabricating titanium compression panels and offers significant improvements in structural efficiency.

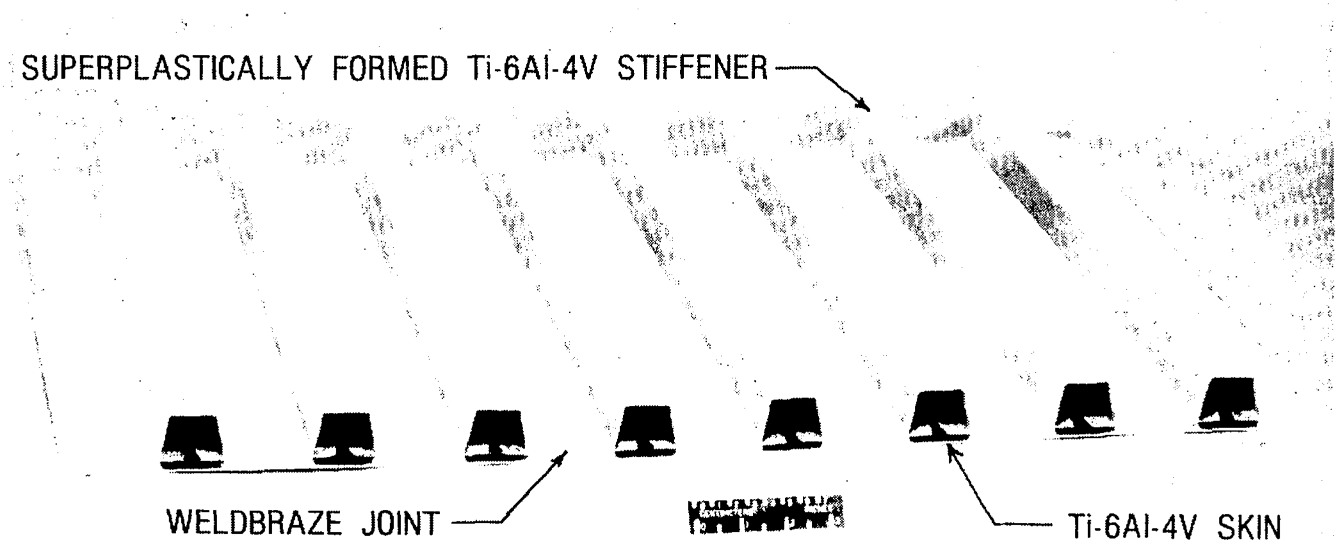

Figure 13

SUPERPLASTIC FORMING OF ALUMINUM ALLOYS

The advent of the superplastic forming of titanium created an interest in the aerospace community regarding the superplastic behavior of other metals and the benefits that may be derived. A natural focus of this interest was on high-strength aluminum structural alloys such as 7075, 2024 and 6061. However, early studies showed that the large elongated grains inherent in conventionally processed aluminum sheet severly limited their degree of superplasticity. Subsequent studies sponsored by the Army and conducted at Rockwell International Science Center showed that refinement of the grain size of 7475 aluminum sheet by thermomechanical treatment resulted in material having a high degree of superplasticity. The major aluminum companies have also recently developed fine-grained 7475 aluminum alloy sheet for superplastic forming. An example of the superplastic behavior of 7475 aluminum is shown in figure 14. The as-machined specimen was heated to 960°F and pulled at a strain rate of 1×10^{-4} in./in.-sec. Total elongation to failure was approximately 800 percent. The flow stress or stress to superplastically stretch the specimen was 4 ksi, which indicates that there is a similar potential for blow-forming or gas-pressure-forming aluminum as has been demonstrated for titanium. Consequently, superplastic forming of aluminum has been projected to have the potential of reducing the weight of future aerospace structures by 20 percent and the cost by approximately 30 to 50 percent. As a result NASA LaRC has initiated a study to evaluate the potential of SPF aluminum for aerospace structural applications. The program will follow a similar course as the programs for titanium. Processing parameters and methods will be evaluated to provide for improved structural efficiency of future aluminum structures.

Several low-strength aluminum alloys (Al-Zn,Al-Ca-Zn,Al-Cu-Zn) have also been developed which exhibit a high degree of superplastic behavior. A United Kingdom firm, Superform Metals, Ltd., is currently in production on a large number of superplastically formed aluminum components. Applications appear aimed at the nonaerospace industry for fabricating automotive body components, typewriter covers, and various types of deep containers. The improved formability offered by superplastic forming makes it possible to fabricate components which cannot be formed by conventional means and to reduce the cost of others made by conventional forming methods.

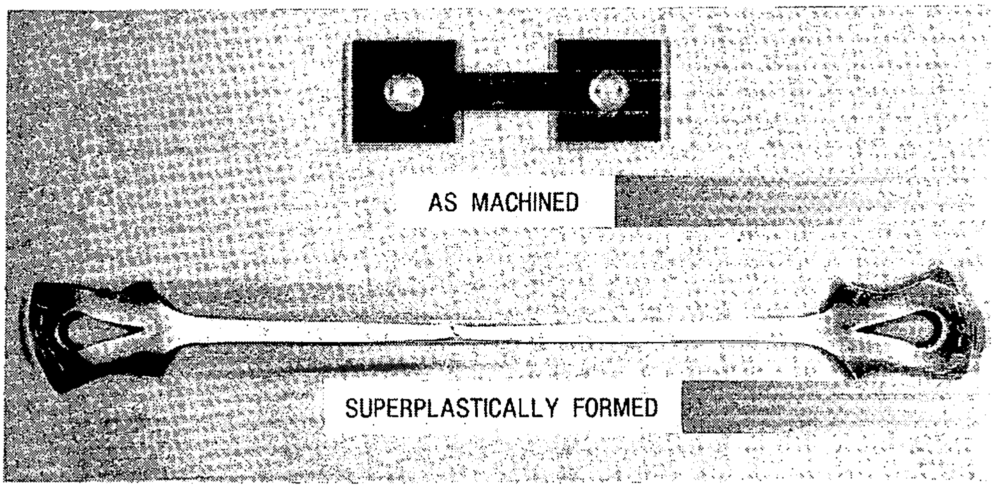

Figure 14

SUMMARY

Significant advances have been made in the processing of titanium in recent years (fig. 15). Research studies have demonstrated that weldbrazing, SPF, SPF/DB, and SPF/WB are viable processes for fabricating titanium structures that exhibit improved efficiency. The large reduction in manufacturing costs afforded by these processes will substantially reduce the finished-part cost of titanium components. This cost driver combined with the high mechanical properties at temperatures up to 600°F and the excellent corrosion resistance of titanium should promote wider spread applications in industries involved with chemical processing, food handling and processing, manufacturing products exposed to a marine environment, and, possibly, components for high-performance internal-combustion engines. Due to the relative simplicity of SPF alone, compared to the other combined processes discussed, it is considered to have the greatest impact in the near term.

The development of the superplastic forming of high-strength aluminum alloys may substantially expand the use of aluminum for structural and nonstructural applications. If the projected cost savings for the technology are realized, aluminum components will be increasingly cost competitive with other metal and nonmetal products.

TITANIUM - WB, SPF, SPF/DB, SPF/WB

- ADVANCED Ti-PROCESSING TECHNOLOGY

  GREATER STRUCTURAL EFFICIENCY POSSIBLE THROUGH FORMING OF UNIQUE COMPONENTS

- TECHNOLOGY BASE REASONABLY MATURE
- COST SAVINGS POTENTIAL COULD INCREASE NONAEROSPACE APPLICATIONS

ALUMINUM - SPF

- POTENTAIL FOR WEIGHT AND COST SAVINGS
- FORMABILITY OFFERED BY SPF MAY EXPAND APPLICATIONS
- TECHNOLOGY BASE EMBRYONIC FOR HIGH-STRENGTH STRUCTURAL ALLOYS
- U.K. WORLD LEADER IN PRODUCTION OF COMPONENTS USING LOW-STRENGTH ALLOYS

Figure 15

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