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Superplastic forming of friction stir welds in Titanium alloy 6Al-4V: preliminary results

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The trend in design and fabrication of aerospace structure is moving rapidly towards the use of composite materials and the consolidation of many pieces into large monolithic assemblies. Titanium alloy 6Al-4V is more compatible with composite materials than aluminum alloys because of its superior corrosion resistance and closer match to the coefficient of thermal expansion. In addition, many components that are used for the newer composite based aircraft, and are subjected to high service temperatures, are fabricated from titanium using Superplastic Forming (SPF) and Diffusion Bonding (SPF/DB). However, the use of SPF titanium parts has been limited up until now due the size restriction of standard sheets from the titanium mills, which is generally available at a maximum size of 1.2 m x 3.6 m. The purpose of this study was to develop the Friction Stir Welding (FSW) process for both standard and fine grain titanium alloy 6Al-4V in a bid to find a process that would allow the joining of multiple pieces to fabricate much larger components. Further, the FSW process was refined such that the welds were made to have superplastic properties equal to those of the parent sheet. A secondary goal of this effort was to build full size SPF prototype parts of a generic jet engine nacelle Lipskin using one FSW titanium blank. SPF of 7475 aluminum had been reported previously in the literature by Mahoney, Barnes, Mishra and others. During this study, the FSW process for 5083 Superplastic grade aluminum was developed simultaneously along with titanium 6Al-4V. The aluminum material was used to reduce the cost of developing the SPF manufacturing process to fabricate full scale engine inlet test components. FSW blanks of both materials were used for the initial forming trials.

Keywords: Superplastic forming, friction stir welding, titanium alloy

1 Introduction

The worldwide Aerospace industry has a long history of developing both evolutionary and revolutionary materials and technologies to fabricate structure with less weight, better structural performance, improved fatigue life and lower cost. In recent years, there has been an emphasis placed on building monolithic assemblies in fewer pieces to replace traditional built-up hardware assembled with fasteners. Friction Stir Welding (FSW) of aluminum alloys has emerged as one of the top enabling technologies, allowing the fabrication of very large single piece components [1–4]. FSW has proven to be a significant benefit to the rocket industry for making butt welds along the length and the circumference of the liquid fuel barrel tanks for programs such as the Boeing Delta and the Lockheed Atlas rockets.

The elimination of detail parts is a positive development in many business aspects, but it must be accomplished using an extremely cautious approach because of the engineering design and material performance ramifications that could be adversely affected, such as the mechanical properties, localized stress concentrations, fatigue life, damage tolerance and durability of structures. Conventional aircraft design often utilizes the breaks between individual pieces and pad-up areas both as crack stoppers and to arrest other forms of damage before catastrophic failure can occur. These safety gaps are not present in the same form with monolithic design. Hence, when new joining technologies emerge that allow the fabrication of very large aircraft structure, it is essential to fully understand and quantify the effects that they will have on the durability and damage tolerance of the components produced.

To date, the purpose of the related research conducted in this study has been to merge SPF and FSW technologies in a way that is conducive for production of very large titanium structures and integrate substructure to reduce the part count of aircraft assemblies. Whether or not this technology is integrated into actual industrial applications will depend upon on the results of mechanical and fatigue performance of thousands of the FSW-SPF coupons built using a controlled process tested by in-house and private companies. However, additional experimental study will be performed during the course of this continuing research & development project to validate that the basic processes are sound when compared to alternative technologies.

1.1 Motivation

The purpose of this study is to develop the enabling technologies required for the fabrication of very large monolithic structures for the aerospace industry using titanium sheet metal that cannot be made in the sizes needed because of the limitations of existing welding and forming technology. The first such component, an engine inlet, is being developed by the Boeing Company and is described in a recent U.S. patent [5], as shown in *Figure 1.*

In order to build an engine inlet, or a similar aerodynamic airfoil with reduced drag, it is necessary to eliminate as many joints as possible in order to create a smooth surface. Fastener heads and the edge seams where sections of structure are joined together result in localized turbulence in flight, which causes drag and reduces the fuel efficiency of aircraft.

Recent developments in engine efficiency technology have caused the de-icing systems for leading edges to be heated with electrically generated heat rather than the engine bleed air that is the industry standard. The electric heaters produce localized temperatures that exceed 200 deg. C, which is above the recommended service temperature for aerospace grade

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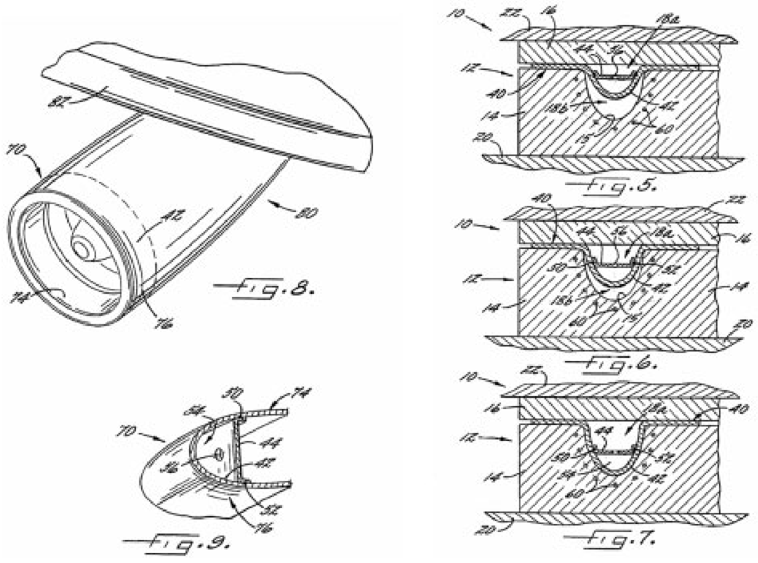

Figure 1. A notional jet engine inlet (left) with a monolithic structural bulkhead and the method to Superplastic Form it in a die (right). This image is taken from the U.S. patent [5].

aluminum alloys. Titanium 6Al-4V is a logical choice for replacing the aluminum because of its ability to withstand higher temperatures, excellent corrosion properties, light weight, compatibility with composites, favorable coefficient of thermal expansion and formability using Superplastic Forming. Titanium has also been found to perform exceptionally in bird strike tests and Foreign Object Damage (FOD) situations, in which the leading edges of engines are often damaged by incoming debris generated by the vacuum effect at the front of the inlet.

However, in order to fabricate a sheet metal component of the size required for the engine inlet, which is over 4 meters in diameter, it would be necessary to have flat sheets of the raw material available that are large enough and this was impracticable because the available size for titanium sheets are 1.2 m x 3.6 m. It became clear that a welding process was needed to join the titanium sheets together prior to forming.

Superplastic Forming (SPF) tests had previously been conducted on fusion welded aluminum sheet metal at the Pacific Northwest National Laboratory (PNNL) in an attempt to make tailor welded blanks of 5083-SP aluminum for use in making SPF automobile outer panels such as fenders, doors and hoods [3,4].

Several different attempts were made during this project to Superplastic Form titanium sheet metal using conventional welding techniques such as Tungsten Inert Gas (TIG), resistance welding and laser fusion welding. During SPF forming trials, these tests all failed because of localized necking adjacent to the welds and the welds themselves did not form at all because of the extremely large grain structure of the weld nugget, reference *Figure 2*. Many of the parts that were tested fractured during forming in or around the heat affected zone, which is immediately adjacent to the weld nugget. Initial experimental trials were conducted on titanium using TIG welding to produce 20 % size blanks. The SPF forming tests of small sub-scale engine inlet test articles proved that the TIG welds would not be acceptable to produce the required configuration. Fusion welding of blanks was abandoned when it became clear that the localized necking would be unacceptable for forming the needed shape.

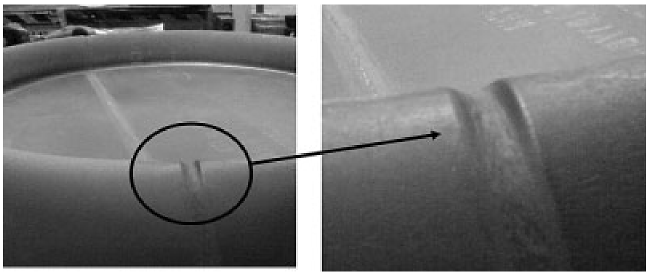

Figure 2. The Superplastic Forming test part (left) is a sub-scale pan formed into an airfoil shape. It built using titanium 6Al-4V standard grain size flat sheets, 2.5 mm thick, that had been fusion welded (TIG) together prior to forming. The close-up (right) clearly shows the lack of forming surrounding the welded region and the "orange peel" texture of the weld itself. There was one area of the weld that tore. TIG welding was abandoned after several of these tests failed.

1.2 Friction stir welding process overview

Friction Stir Welding (FSW) was initially discovered by Wayne Thomas at The Welding Institute (TWI) in Cambridge, United Kingdom, in 1991, hence it is a relatively new technology and is not yet fully understood in terms of its metallurgical mechanics [2]. FSW is a solid state welding process. The resulting weld is far stronger and more reliable than traditional welds. FSW also produces no fumes or splatter, creates far less distortion, is more energy efficient, and the FSW tool is non-consumable. Furthermore, FSW can be used on very thin sheets of material where making a fusion weld would be extremely difficult or even impossible. The FSW method has generated tremendous interest from the technical and industrial community because it provides a means to join materials together without melting of the metal and causes very little thermal distortion because far less heat is generated. The structural integrity of these welds has generally been found to be improved when compared to the conventional welding methods, especially in terms of strength and ductility.

The process relies on friction between a shoulder on the rotating stirring pin's working surface and the interface that it has with the material being stirred to provide frictional heating, ref. *Figure 3*. Once an optimum combination of temperature and plasticization of the material begins, the stirring pin is plunged downward to the required weld depth and brought to

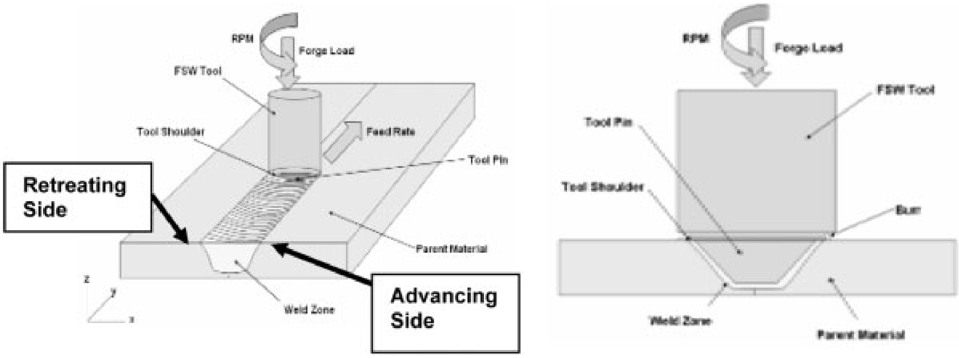

Figure 3. Left – basic FSW process for butt Welding. Right – FSW pin tool engaged with material during welding.

traverse the length of the piece using a feed rate and downward forging force that maintains optimum stirring conditions.

2 Materials

Because of the need to reduce cost for the full sized forming tests of engine Lipskin Inlets, it became necessary to develop the combined FSW-SPF processes for both 6Al-4V titanium and 5083-SP aluminum. At the time of this study, the 5083-SP material was approximately 10 % of the cost of the titanium, so the initial forming trials of the 4 meter diameter test parts were made using FSW-SPF aluminum blanks.

The two titanium material types used in this investigation are sheets of mill annealed Ti-6Al-4V alloy with different microstructures. One type was a standard Ti-6Al-4V whose grain size was typically on the order of 8 to 10 microns and the other version of the alloy was a fine grained material which had grain diameters between approximately 0.8 to 2 microns. Both material types had grain structures that were close to having equiaxed geometry.

3 Test Results and Findings

Trial experiments were conducted to identify the range of FSW process parameters that can be used to FSW aluminum 5083-SP and titanium 6Al-4V. One note is that the area above and below the surfaces of titanium that are being FSW stirred must be purged with an inert gas, such as welding grade argon. Initial tests resulted in butt joints with large burrs (flashing) on the top surface of the weld, reference *Figure 4*, but as the process was incrementally improved this was reduced substantially.

Figure 4. Titanium FSW produces a much larger burr than aluminum FSW, which is about 0.2 mm thick and very sharp. Note that the start of the weld is completely encased with titanium, while a hole is left behind at the end of the weld because of the extraction of the rotating pin.

Recent FSW test coupons made at Boeing have shown that FSW of titanium alloy 6Al-4V can produce butt joints with nearly the same mechanical properties as the parent sheet metal in gages of 2 mm to 3 mm in thickness, provided that a stress relieve operation is performed after the FSW welding.

Further development testing was performed to refine the FSW weld nugget microstructure, particularly the grain size, by adjusting the process parameters for revolutions per minute (RPM), the feed rate, the pin tool geometry, the z-direction force (forging) load and other key process variable parameters. By precisely tuning the FSW process, especially in regards to thermal control, it was found that the FSW joint can be designed and built in a way that duplicates the superplastic material performance of the parent material within the butt welded region. By combining the FSW and SPF processes together, extremely large flat sheet blanks can now be fabricated from titanium to manufacture complex contoured shapes that were not possible before this combination of technologies was demonstrated.

One of the most surprising findings during this study was the lack of a large Thermal Mechanical Affected Zone (TMAZ) and an extremely small Heat Affected Zone (HAZ) when compared with FSW of aluminum metals [6]. Figure 5 shows micrographs of a titanium coupon FSW

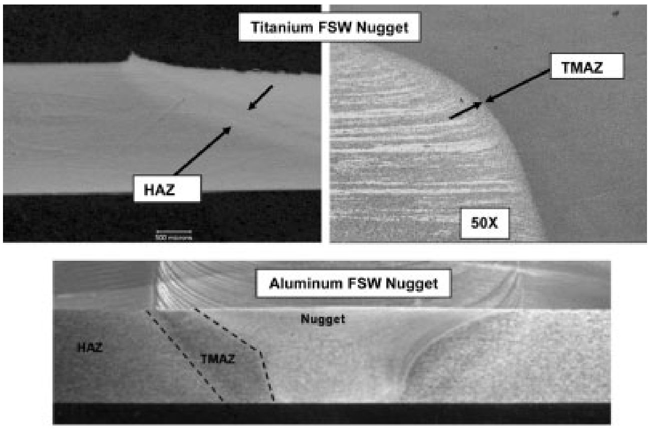

Figure 5. The two micrographs on the top depict the very small TMAZ (width <0.5 mm) and a nearly invisible HAZ of a titanium 6–4 alloy FSW compared to an aluminum FSW coupon (bottom) which has both a large TMA (width >2 mm) and an even larger HAZ (width >4 mm).

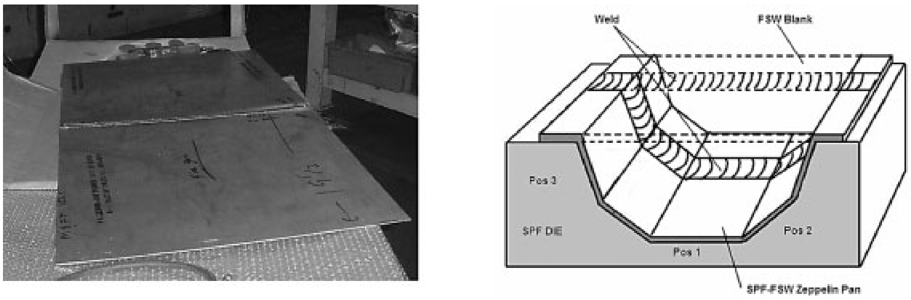

Figure 6. Schematic of zeppelin pan SPF forming tool, showing the cross section of the die. The FSW weld on the blank is stretched down against the side and bottom positions to make flat facets, which are ideal for making tensile test coupons. Note that the flat facet formed into position 1 would typically have 70 % superplastic elongation, while facets on position 2 will have 65 % and position 3 will have about 40 %.

that has a small HAZ and nearly no TMAZ, with a comparison photo of an aluminum FSW that does have both a large TMAZ and HAZ, which is typical of the FSW process for aluminum materials. The TMAZ for titanium 6Al-4V material, in either the conventional or fine grain condition, was found to be 1 – 3 grains in width. The difference between the thermal zones with titanium is likely due to its very small thermal conductivity (17 W/m-K) when compared to that of aluminum (210 W/m-K), which apparently results in nearly instant cooling of the plasticized material as the pin passes by it and it cools without spreading the FSW process induced heat widely across the weld zone or into the adjacent parent material.

In order to prove the viability of fabricating complex shapes of SPF parts using the FSW process to build larger sheet sizes, titanium 6Al-4V pieces of 2 mm to 3 mm thickness, with 600 mm x 600 mm size, were FSW butt welded together to make sheets that were 600 mm wide x 1200 mm long, with the weld joint running across the width. These blanks were used to form “zeppelin” pans using a 650 ton SPF press at the Boeing Hard Metals SPF Fabrication shop. *Figure 6* shows a typical FSW blank and has a schematic of the zeppelin die cross section with the blank overlaid both before and after forming.

SPF forming was accomplished at a temperature of 900 deg. C. for the standard grain material and at 785 deg C. for the fine grain material. The forming pressure cycle required for the 2 mm fine grain titanium was a nearly constant ramp from atmosphere to 1.5 MPa over 50 minutes time. *Figure 7* has images that were made during the fabrication zeppelin test parts.

Figure 7. The SPF fabrication of zeppelin pan test parts is shown. Left: An operator removes a hot part out of the zeppelin die. Right: A finished zeppelin pan that has cooled is shown on a table in front of the hot die.

After forming, the zeppelin pans were cut up using a band saw and a plasma cutter into individual facet sections. The facet “flats” were used to fabricate tensile coupons in order to assess the post SPF forming mechanical properties across the weld joint [7]. *Figure 8* shows zeppelin pans that are in the process of being cut up into individual facet sections. Hot tensile tests were conducted in parallel with the SPF zeppelin pan forming tests to further perfect the FSW process parameters. As improvements were made to the FSW pin tools, process and thermal conditions, the microstructure and surface appearance also improved, reference *Figure 9*.

Producing the required microstructure of the weld zone to match the superplasticity of the parent sheet metal proved to be very difficult, primarily because of the extreme sensitivity of the titanium 6Al-4V weld nugget microstructure to variations in the temperature of the active stirring weld zone caused by very small changes to the FSW process parameters such as RPM, feed rate, tool pin geometry and the z-direction loading on the pin. A series of successive tests were made using the small FSW test sheets to excise coupons for hot tensile superplasticity testing. Concurrent tests to quantify the mechanical properties, microstructure, surface roughness and other proprietary testing was performed at the University of Washing-

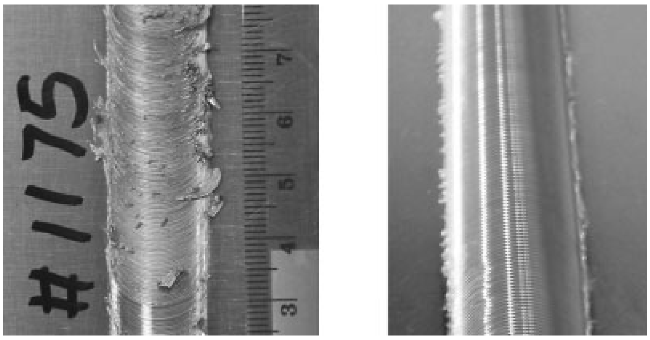

Figure 9. Left: An early FSW titanium attempt made during an earlier study [7]. Note the large burrs, deep surface tears and severely gouged circular bands along the length of the weld. Right: This is representative of the FSW titanium quality using optimized process parameters. The much better behaved, almost perfectly sinusoidal, machine mark pattern that is repeated along the length the FSW is seen. There are no severe texture defects present and the weld qualifies as “Class A” quality per AWS specifications for welds used in fatigue loaded aerospace components.

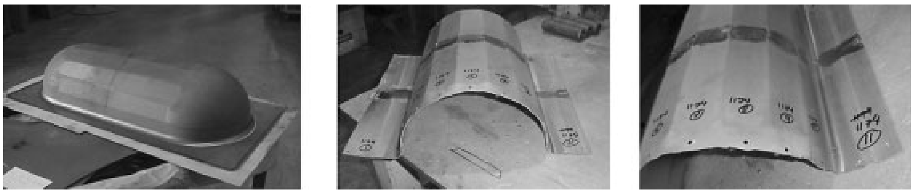

Figure 8. Zeppelin pans are shown being cut up into individual facet sections. Note that each of the facets is crossed by a FSW butt joint, such that the strength of the weld area can be tested.

Figure 10. A successfully formed approx. 4 meter diameter titanium engine inlet Lipskin test part.

ton laboratories under a contract with Boeing. Correlations were developed between the FSW process parameters and their individual effects on both the strength of the joint produced and the superplastic performance [8]. Full size test parts were successfully produced using the 5083-SP aluminum, fine grain and standard grain titanium 6Al-4V, reference *figure 10.*

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