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Effects on the Surface Texture, Superplastic Forming, and Fatigue Performance of Titanium 6AL-4V Friction Stir Welds

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The speed and feed effects of the friction stir welding (FSW) process on the surface texture along the top of a butt welded nugget were studied. The tests were conducted using fine grain (0.8-2 μm) titanium alloy 6Al-4V with a nominal thickness of 2.5 mm. It was shown that the pin tool marks along the top surface of the weld can be highly detrimental to both the superplastic forming (SPF) characteristics and the fatigue performance of welded panels. Removing the marks by machining the top surface after FSW was found to eliminate the predominant tearing of the weld during SPF and most of the fatigue life of across the weld was also restored. Through additional development of the FSW process parameters, the butt welded nugget was made to have equivalent SPF characteristics as the parent sheet material. By using a water-cooled pin tool and other cooling techniques, it is believed that the weld zone can be kept below the beta transus temperature during FSW, which enables the formation of a grain structure that is uniquely conducive to superplastic behavior, when compared to conventional fusion welding processes.

Keywords fatigue, friction stir welding, superplastic forming, surface texture, titanium

1. Introduction

The purpose of this study was to investigate the enabling technologies that would be required to produce tailor-made titanium blanks for the fabrication of very large monolithic SPF formed components to be used on commercial jet aircraft. Prior to this development work, the size of titanium sheet metal components was severely limited by the maximum sheet material sizes produced by the rolling mills. Using a combination of FSW and SPF processes, the size of blanks that can be created and subsequently formed into complex shapes is no longer limited by the raw material.

The FSW process has only recently been adapted for the butt joining titanium and very little data is available on the fatigue properties of as-welded material. Most aircraft structures are subjected to fatigue loading due to the cyclical loading induced by the rigors of flight, pressurization of the hull, landing/take-off loads, wing loading/unloading and many other design factors. Previous studies have been made to investigate the mechanical properties of titanium FSW butt welds (Ref 1-3). However, in order to make a reasonable comparison between the FSW process and alternative joining methods, it was necessary to perform a high-cycle fatigue test across the weld joint.

The initial tests showed that FSW of titanium 6Al-4V is far more complicated than FSW of aluminum for a variety of reasons. Special methods and process controls had to be developed during the development to make a repeatable FSW butt weld without defects that would be considered production quality "class A" by aerospace standards. Figure 1(a) shows one of the initial FSW welds that was made at the University of South Carolina (Ref 2, 3) and Fig. 1(b) shows a weld made recently on a Boeing owned FSW machine designed specifically for titanium and using optimal process parameters. During the early stages of SPF tests across the as-FSW weld beads, it became clear that the pin tool marks, also known as pin tool marks, that are left behind on the top surface, were having a profound effect on the SPF forming characteristics of the test parts. In some cases, the rough texture was so severe that it caused tearing completely through the sheet along the weld bead joint during fabrication, as seen in Fig. 1(a). Note the improvement in terms of the reduction of the burr that is observed and roughness of the surface texture depicted in Fig. 1(b).

Figure 2 shows the cross section of a FSW that highlights the very sharp peaks and crack-like valleys created by the pin tool on the top surface of one of the firsts weld tests, without using an optimized process. It is the stress concentration created by these severe markings that caused the initial SPF test coupons to fail by cracking, and in later tests proved to be highly detrimental for the fatigue life.

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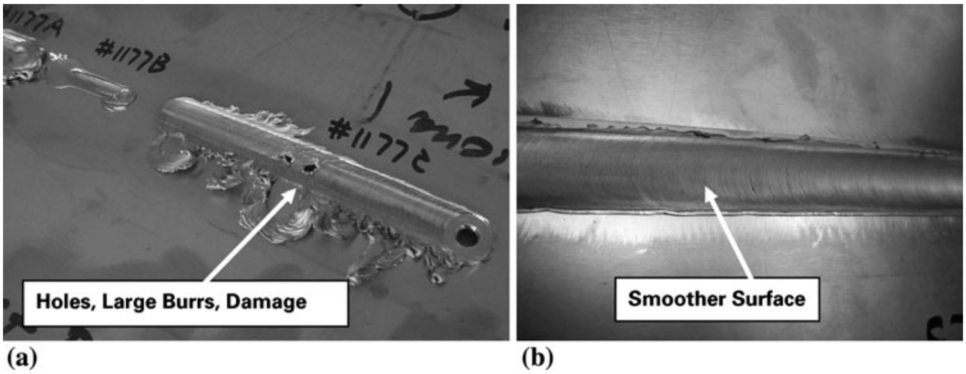

Fig. 1 The FSW seen in (a) is the result of one the very early attempts to FSW titanium and the test sample shown in (b) is the result of a recent test using highly optimized FSW parameters and equipment

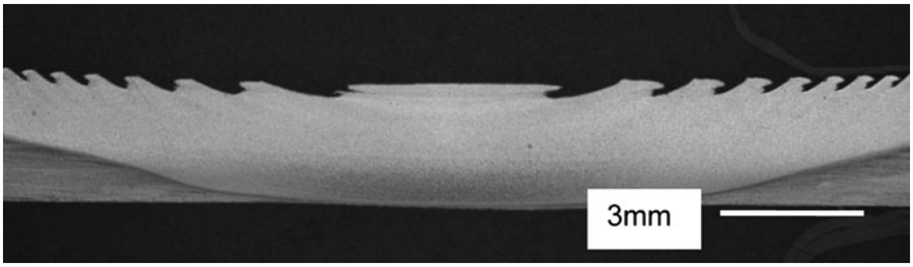

Fig. 2 A micrograph taken across the width of an FSW titanium test sample. It clearly shows the sharp peaks and valleys caused by the motion of the stir pin across top surface of the weld

2. Experimental Procedures

2.1 Friction Stir Welding Development

The stirring pins are subjected to high temperatures and stresses, making their design and material choice a critical element of the process. Shielding using inert argon gas is needed to avoid oxidation of the titanium, which means that a clumsy trailer must cover the stirred zone during cooling, which makes it difficult to observe the stirring process. Figure 3 shows a simple argon "trailer" box that was used to cover the hot FSW butt weld with argon gas as it cooled.

Titanium friction stir welds were performed in a temperature range in the weld nugget that is estimated to be between 750 and 950 °C (judging from the bright orange color that is observed during the process and metallography). The upper temperature gradient is very close to the beta transus temperature, which cannot be exceeded beyond a short period of time without severely altering the material properties. On the other hand, the FSW welds that were made with process parameters that caused colder than normal welds (~750 to 850 °C) tended to have highly refined grain structure, which resulted in ultra-fine grain sizes that were found to be far too superplastic when compared to the parent sheet and caused extreme thinning of the welds. It was found that heat must be removed from the stir area using water cooling of the pin tool and other proprietary cooling methods to obtain the desired results. It was observed that the overall process is extremely sensitive to small changes in the amount of heat removed.

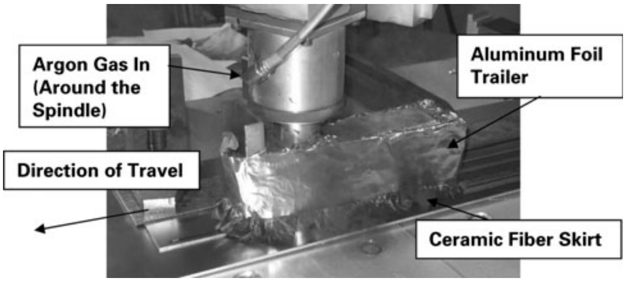

Fig. 3 A simple "trailer" is used behind the FSW pin tool & spindle to shield the weld from atmosphere with argon gas to prevent oxidation during welding and cooling

The primary FSW process parameters are the *z*-direction forging load or the *z*-dimension position relative to the backing anvil (sets the gap distance between the bottom of the rotating pin tool to the anvil, which is optimized at approximately 0.075 mm), the spindle RPM, the tool pin geometry, the water cooling factors for the pin tool (flow rate of water), and the feed rate. Each of these variables can be made to either add additional energy, hence heat into the stir zone, or to decrease it. Since FSW is a thermo-mechanical process, the stirring mechanism is governed to a large extent by the temperature of the weld nugget during the actual stirring. The frictional forces between the stirring should and pin tool can either be increased or decreased, for example increasing the RPM of the spindle would clearly increase the stir weld temperature, while slowing it down will cool it.

The basic process parameters (RPM and feed rate) for FSW titanium must be much better controlled than those for aluminum (Ref 4-6). RPM changes of 5 to 10 were found to

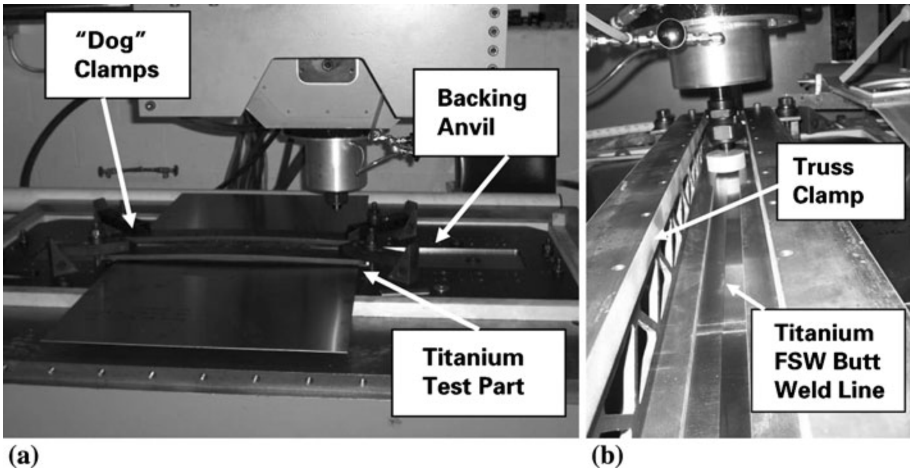

Fig. 4 (a) A simple clamping arrangement with insufficient clamping force. (b) A truss style clamping beam apparatus is used to tightly secure two sheets together while making a titanium FSW butt weld

cause dramatic differences in the outcome of the weld and feed rate changes of 5 to 15 mm/min were found to have a significant effect on the weld quality. These two parameters indicate that the titanium FSW process is roughly 5 to 10 times more sensitive to change than the FSW process is for aluminum. Because of this, very tight process control is required. The *z*-direction (axial) forging load is approximately 45 kN, which is more than triple the force required to stir a comparable aluminum component, which means that many FSW machines that were designed for aluminum welding may not be suitable for use with titanium. An extra effort must be made to clamp the sheets together tightly in the weld configuration order to keep the edges of the sheets butted together, such that splitting between the sheets does not occur in the transverse direction. Figure 4(a) shows a simple clamping device that was used to hold two test pieces together during welding and Fig. 4(b) shows a more secure system that was devised later at the University of South Carolina's FSW Laboratory, which features a pair of custom-made truss beams.

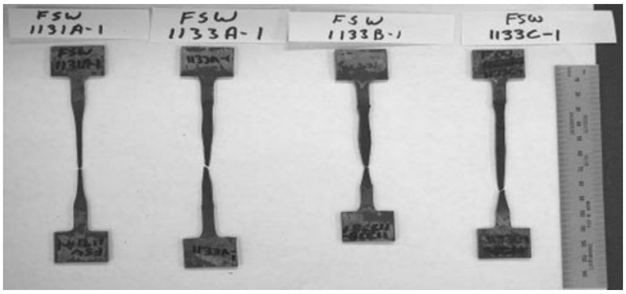

Fig. 5 Four FSW superplastic tensile test coupons are shown after stretching the parent metal and FSW zone to determine the relative superplasticity of each region (parent metal and weld)

2.2 Superplastic Forming Development

A study of the superplastic forming (SPF) characteristics of FSW joints was performed using mill annealed 6Al-4V fine grain titanium to determine whether the process would be suitable for fabricating complex shapes of deeply formed pans. The initial scoping test plan included the fabrication and testing of hot tensile test coupons with the FSW centered in the gage area, as shown in Fig. 5, whereby roughly half the gage length was kept as parent metal and the other half was FSW material. The superplastic properties were measured at the Pacific Northwest National Laboratory using a forming temperature of 774 °C and a constant strain rate of $2.7 \times 10^{-4}\ \mathrm{s}^{-1}$. In general, coupons were pulled to a total superplastic strain level between 70 and 100% before the test was stopped. Figure 5 is a photograph of several test coupons that were tested during this project.

Typical process parameters for achieving the titanium FSW with an equivalent superplastic strain between the parent and FSW weld zone were found to have an RPM range of 150 to 400, feed rate of 0.83 to 5.00 mm/s, and forge loads of approximately 25 to 65 kN. These can be compared to the aluminum 5083-SP FSW welds with equivalent superplasticity to the parent sheet, which has the much more forgiving process tolerance band of RPM of 200 to 1500, a feed rate of 1.25 to 6.67 mm/s, and typical forge loads of only 5 to 25 kN. To date, the best titanium 6Al-4V fine grain test welds that have been produced were made with RPM = 325, feed rate of 1.67 mm/s, and a forge load of 55 kN (using position control in the *z*-direction).

Superplastic tensile testing was followed by the manufacturing of a sub-scale SPF pans using an existing test die at Boeing that yields a test part that resembles half of a dirigible (lighter than air ship), which is often referred to as the "zeppelin" pan, reference Fig. 6. The FSW weld line is along the center of the width of the formed part. As the FSW process was developed more closely, the surface tearing and burrs were reduced, but tears were still observed inside width or along the length of the weld beads during SPF forming of test pans, reference Fig. 7.

Figure 8(a) shows a slightly enlarged macroscopic view of the FSW area that was highly effected by the pin tool marks on the top surface of the weld during SPF forming of a "zeppelin" pan. It can be seen that the small peaks and valleys of the pin tool marks have been subjected to very large elongations and local thinning of the material, which has also caused some of the valleys to widen out to varying degrees of severity between the peaks. The amount of forming across the valley features was found to be a function of how deep and sharp that the valleys were prior to forming. The

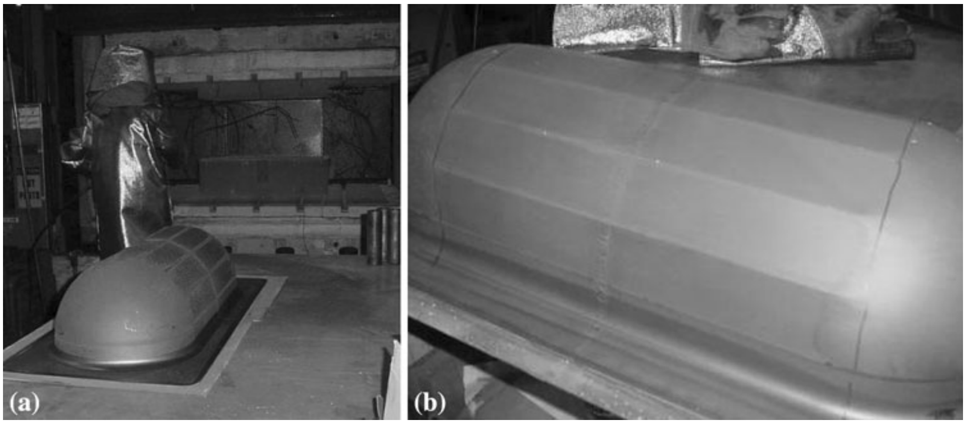

Fig. 6 (a) An SPF formed zeppelin test pan is shown cooling down immediately after being formed in a hot die. (b) The formed zeppelin pan with its flat facets, which are suitable for cutting test coupons

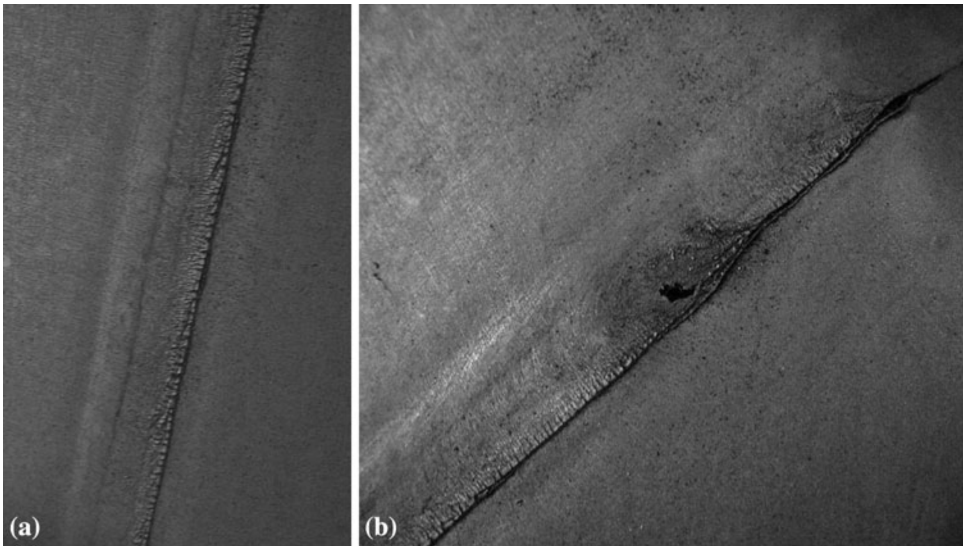

Fig. 7 One of the first zeppelin pans that was SPF formed is shown with severe FSW surface defects: (a) tears on the FSW top surface and (b) a torn hole through the entire thickness of the FSW

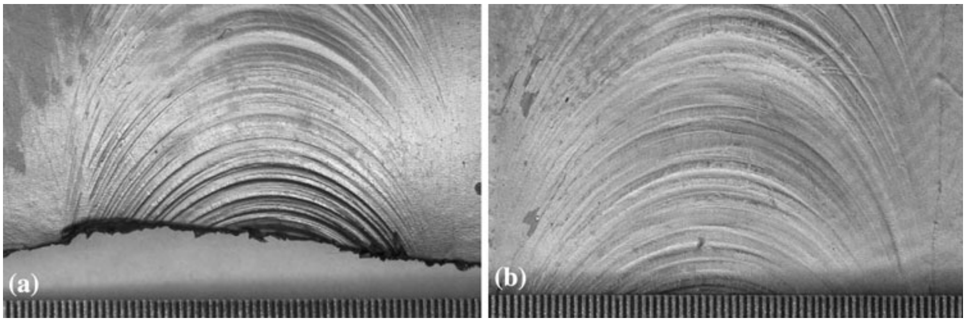

Fig. 8 (a) Macroscopic view across the top surface of a superplastic formed FSW welds with severe deformation between the peaks of the pin tool marks. (b) The pin tool swirl marks after SPF with numerous very small fissures between many of the highly elongated valleys

deepest pin tool swirl marks tended to have the worst localized stretching and in some cases the thinning caused forming cracks between peaks. Figure 8(b) shows an enlarged view of the top side of a highly elongated superplastic formed weld nugget with numerous very small fissures between the peaks of the circular pin tool marks.

After considerable development and testing, it was found that the best SPF performance could be realized by completely

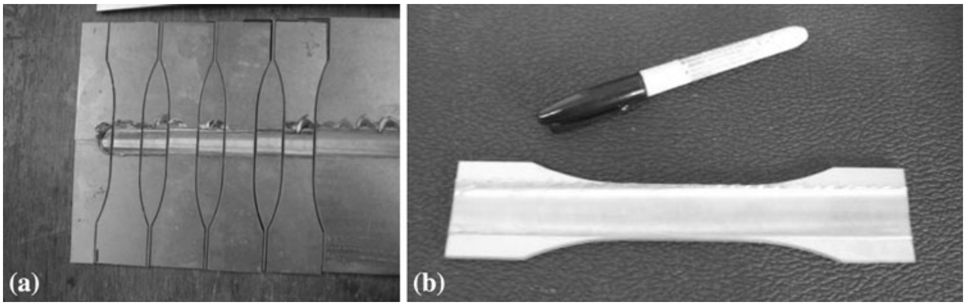

Fig. 9 (a) Four of the fatigue test coupons cut from an FSW panel with transverse FSW welds. (b) A longitudinal FSW fatigue coupon

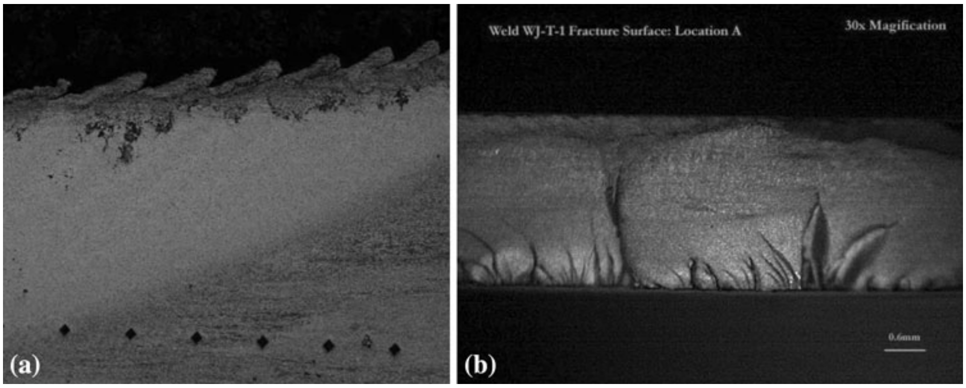

Fig. 10 Typical FSW specimen sub-surface and fatigue fractured surfaces: (a) a sectioned weld nugget at 5× and (b) multiple fatigue fractures across the top surface of a fatigue test coupon at 30×

machining or grinding away the pin tool marks prior to forming, whereupon the SPF performance across the weld was very similar to forming parent metal.

3. Results

As more data on the superplastic characteristics of the FSW became available via the use of subscale hot tensile superplasticity testing, the quality of the welds was greatly improved by adjusting the FSW process parameters. Eventually, this made the forming of zeppelin pans much easier and with far fewer defects. Although some facet coupons that did have defects were tensile tested despite their poor quality, the ones that were made later in the test regime with the better welds showed remarkable improvement in the mechanical tensile properties, with some resulting in mechanical properties that were very close the parent sheet, except for elongation (Ref 1).

Following the development of the basic FSW and SPF process, with fully optimized results, a test was performed to characterize the fatigue performance of the as-FSW weld beads. During the test regime, “zeppelin” forming tests had shown that tearing during SPF forming could be completely avoided if the jagged top surface of the FSW bead was removed by machining. Mechanical testing also showed tremendous improvement, nearly to parent metal properties, provided that the pin tool marks were either ground off or machined prior to testing (Ref 7). With this in mind, a fatigue test was performed to gage the relative performance in fatigue of coupons with both transverse and longitudinal FSW beads relative to the coupon length. Figure 9(a) shows the location of a set of FSW transverse weld beads and Fig. 9(b) is an image of a longitudinal FSW on a single fatigue test sample.

The microstructure of one of the first fatigue coupons tested was examined and found to have multiple fatigue cracks initiations that started from several of the pin tool mark valleys. A photo of an as-FSW top surface is shown in Fig. 10(a). Figure 10(b) is a 30 power magnification of the first fatigue test coupon made during this study, in which multiple fatigue crack initiations can be clearly seen all across the top FSW surface, which contains the repeating pin tool markings.

An experimental test plan was designed to evaluate the fatigue performance in tension of the as-FSW titanium and also to determine the fatigue improvement that would result from removing the tool marks via combinations of machining the as-stirred top surface flat, stress relieving and/or low plasticity burnishing. In the case of machining, the amount of FSW surface removed was 200-300 μm, which assured that the rough surfaces and shallow sub-surface defects were completely eliminated.

Test pieces made of 2.5 and 3.0 mm thick titanium 6Al-4V fine grain size sheet metal were FSW butt joined together to build 20 test panels that were 20 mm wide by 60 mm long. Figure 11 shows a photograph of four completed test panels prior to cutting out test coupons across the weld line.

The test panels used in this study were made using a FSW machine located at the Boeing Plant in Auburn, WA, and were provided to the University of Washington under a research contract. All panels were laser welded with a 1 mm wide by 1 mm deep bead on the bottom of the butt joint to eliminate any chance of Lack of Penetration (LoP) upon completion of the FSW. After FSW, the laser weld was obliterated, with the exception of a 1 mm wide × 0.05 mm deep weld nugget at the bottom center of the joint. The other key FSW parameters used were as follows: 300 RPM, 1.27 mm/s feed rate, a 3° tilt of the spindle away from the direction of travel and a forge load in the *z*-direction of 31 to 40 kN. Note that the recorded process loads are a resultant of the other parameters. That is, the forge load is not an input parameter for the process, because position control was used. However, loads are used to compensate for the defection in the equipment and maintain the desired plunge depth.

Following the FSW joining, most of the test panels were stress relieved using a vacuum furnace with a temperature of 730 °C and a soak time of 30 min, which was followed by furnace cooling. Table 1 gives the exact number of test coupons that were produced and fatigue tested using each of the various process parameter options, including the stress relieve and low plasticity burnishing (LPB) options.

The water jet cutter at the U.W. Mechanical Engineering's machine shop was used to cut out the dog bone specimens. After water jet cutting, the edges of the coupons were buffed using a fine composite buffing wheel, followed by wet hand sanding with 320, 400, and finally 600 grit sand paper. All nicks and edge steps were eliminated and the specimens were carefully packaged to avoid scratching prior to the fatigue tests. If a large protruding burr was present on either the advancing or retreating side of the top FSW surface, it was removed by snapping it off with a pair of needle nose pliers prior to the fatigue test.

For the tension-tension fatigue testing, a 50 kN computer controlled Material Test System (MTS) servo-hydraulic tension testing frame style machine located in the U.W. Material Science Department test laboratory was used. For all of the tests, the load ratio (R = stress min/stress max) was kept at 0.1 under the load control mode of operation. The sinusoidal waveform was set to a frequency of 15 Hz. Hydraulically actuated grips were used to hold the titanium coupons. An examination of the test coupons after the fatigue test showed that the as-welded coupons broke from cracking that occurred within the width of the FSW and the machined coupons tended to have brittle failure similar to the test pieces made entirely from parent metal (no FSW), reference Fig. 12. The results of the fatigue test are shown graphically in Fig. 13.

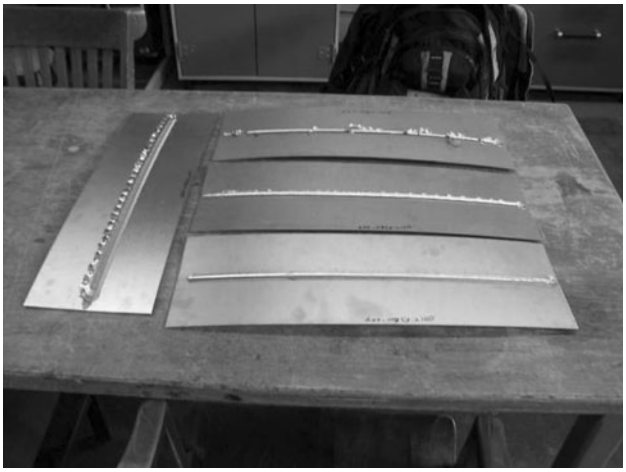

Fig. 11 A set of four of the FSW test panels is shown in this photo after joining

4. Conclusions

From the fatigue test results seen in Fig. 13, it can be estimated that the parent metal exhibited a fatigue endurance limit that was about 620 MPa. The next best performance was from the transverse FSW coupons that had the stirring pin tool marks removed from the surface by machining and also had LPB performed to induce fatigue-resistant compressive stress. The apparent endurance limit for this combination of processes was 565 MPa, which is 91% of the observed parent metal's endurance limit. This finding is quite remarkable, because other titanium welding processes have a much larger drop in fatigue performance. The tungsten inert gas (TIG), laser fusion and resistance welding processes are typically designed for fatigue applications using an endurance limit of 205 MPa, per the ASTM handbook that is often used for the design of non-aerospace mechanical equipment (Ref 8). The transverse FSW coupons that simply had the stirring pin marks removed by machining performed nearly as good as the parts with the LPB,

Table 1 Fatigue test coupons were produced for this study using the seven different FSW process combinations and post-welding conditions as shown

Condition number	Processes used	Original thickness, mm	Longitudinal or transverse FSW
1	Parent metal, no FSW	2.5	Not FSW welded
2	As FSW	2.5	Transverse
3	As FSW and stress relief	2.5	Transverse
4	FSW, stress relief add machined	3	Transverse
5	FSW, stress relief and LPB	2.5	Transverse
6	FSW, stress relief, mach., and LPB	2.5	Transverse
7	FSW, stress relief	2.5	Longitudinal

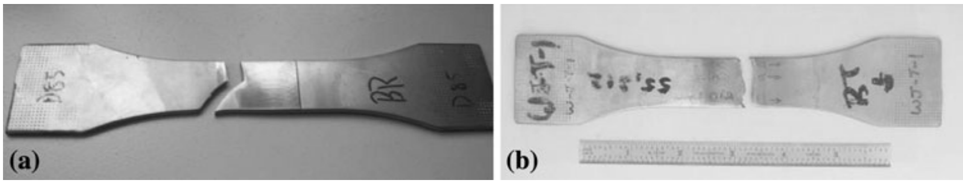

Fig. 12 The photos shown are fatigue life test coupons that were both FSW welded in the transverse direction. They are shown after fracture during the fatigue test. (a) A coupon that has been machined before the fatigue test and (b) a coupon that was left with the as-FSW surface

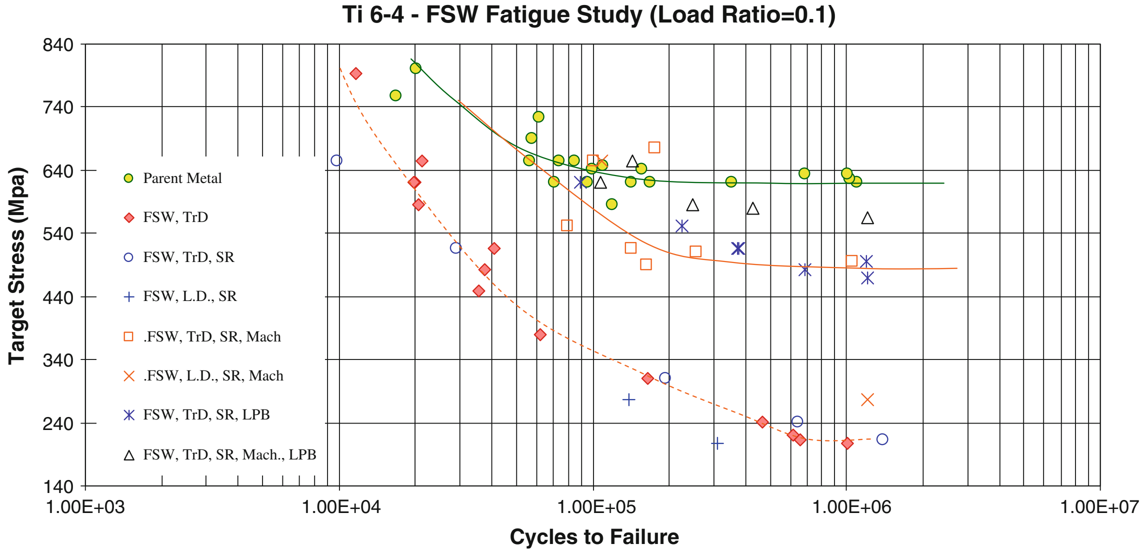

Fig. 13 The fatigue test data is shown plotted in clusters that correspond to the different process conditions that were used to fabricate them. The coupon identity and test conditions are further explained in Table 1

with an observed endurance limit of 496 MPa, which is 81% of the parent metal strength.

Acknowledgments

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