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Fatigue performance of Friction Stir Welded titanium structural joints

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ABSTRACT

The Friction Stir Welding process for producing corner and T-joints out of 6 mm Ti–6Al–4V was developed in this effort using previous work on butt weld joints as a starting point. A limited number of corner joints were also subjected to a bending fatigue test to preliminarily assess the applicability of the process in producing fatigue critical structures. These results were also compared to predictions made by applying stress concentration factors to previously generated uniaxial butt joint test data. While additional testing is still required to obtain a higher degree of confidence in the conclusions of this study, it was found that the performance of these corner joints in fatigue could be compared to butt joint data when a geometrically based stress concentration factor is applied. Furthermore, these welded joints possessed equivalent fatigue performance relative to identical test specimens machined from wrought product forms, both bar and extrusion. Thus, from the perspective of fatigue design, this study has shown that Friction Stir Welding is able to produce structures with the same performance as currently made from wrought materials.

1. Introduction

Friction Stir Welding (FSW) was invented in the early 90s and first applied to titanium in 2003 [1]. Since then, FSW of Ti has been demonstrated in thickness ranging from 2 mm [2] all the way up to 25 mm [3]. While in depth studies have been conducted on the process parameters required to achieve high quality welds in a variety of thicknesses [4,5], most evaluations conducted on titanium FSW joints have focused on weld microstructure, microhardness, and static strength properties [6–16]. In order to use FSW to fabricate structural titanium components, particularly in industries such as Aerospace, the durability and damage tolerance of the welds must be assessed and understood for a variety of different joint and loading configurations.

To date, there have been a limited number of studies on the fatigue [5,17,18] and fracture [18] behavior of Ti FSW joints. The fatigue performance of Ti FSW joints can be comparable to wrought material performance in some cases, but more commonly result in a reduction in life of approximately 20% at a given applied cyclic stress level. One of the key findings in these previous studies is that the weld tool marks, if left on a specimen subjected to fatigue, lead to degraded fatigue performance because they act as stress concentrations, in relatively notch sensitive material, and early fatigue crack initiation sites [17]. Thus, weld tool marks must be removed, by processes such as machining, prior to fatigue testing or when fabricating fatigue critical parts. This adds cost and labor to producing FSW Ti–6Al–4V components, but it is likely necessary to achieve high fatigue performance.

One challenge in fatigue design is being able to reliably relate the performance of simple coupons to more complexly shaped and loaded structures. All of the titanium FSW studies available in literature to date have been on simple flat butt joint configurations under uni-axial loading. Most real structures, such as the section of a titanium frame shown in Fig. 1, would require more complex joint configurations such as corner and T-joints. FSW of other joint types has been demonstrated on in other base metal alloy systems such as aluminum [19], but no reports have been made on the FSW for anything other than butt joints in titanium, much less the fatigue testing of such joints.

The difficulty with using fatigue data generated from simple butt weld coupons for application to more complexly shaped and loaded parts is that life estimates of structures made from that coupon test data typically need to be verified by testing the actual structure, or component, of interest [20]. Unfortunately, testing every possible joint and load configuration combination to completely cover the design space of structural possibilities would be cost prohibitive. Thus, it must be shown that data generated from simple tests can be applied to a wider range of joint configurations and loading scenarios to minimize non-recurring costs associated with component testing and enable more widespread implementation.

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This research will address the two key issues highlighted above where information is lacking in literature and needed to enable implementation of this new technology. First, the development of Ti FSW in corner and T-joint configurations will be conducted to demonstrate the capability of the process beyond simple butt joints. Tooling and process parameters will be identified for producing defect free corner and T-joints in 6 mm thickness Ti–6Al–4V plate material. These joints and thicknesses would be common in potential aerospace structural applications such as the Frame section shown in Fig. 1. Knowledge from previous process development efforts in Ti–6Al–4V butt joints of varied thickness [5] will be leveraged for this effort. After developing the techniques for successfully welding titanium corner and T-joints, fatigue testing will be carried out to determine if the results of previous fatigue evaluations on butt joints under axial loading [5] are comparable with other joints and loading scenarios, such as a corner joint in bending. Since there is no handbook data available to compare the fatigue performance of these corner joints to as a baseline, fatigue tests will also be conducted on specimens with identical geometry to the welded joints except fully machined from wrought materials.

2. Experimental procedure

The material used in this study was commercially available 6 mm thick Ti–6Al–4V titanium alloy grade 5 mill annealed plate. All materials were machined along edges where joining would occur and chemically etched to remove contaminates such as oxides, oils and dirt prior to welding. Test parts were made by joining two 300 mm long × 100 mm wide pieces to make either a corner, or T-joint as shown in Fig. 2a and b. In both cases, the weld tool entered from the top surface, with the pin penetrating downward and the shoulder remaining in contact with the top surface.

In addition to straight section corner and T-joints, it was also desired to demonstrate ‘‘5-axis’’ welding capability. Thus, corner welds were also made on a flat surface with a curved path, Fig. 2c, and over a curved surface along a straight path, Fig. 2d. These ‘‘5-axis’’ welds were only produced for capability demonstration purposes. Metallurgical analysis and fatigue testing would only be performed on the straight section welds. The radius of curvature for both of these parts was 600 mm. Prior to welding, the flat legs were made by water jet cutting from plate and then machining the abutting edge to be welded. The curved pieces were made by hot press forming to contour in a set of matched tooling (male and female die halves).

The same water cooled tungsten lanthanum (W–La) pin tool used in previous studies [5] was used here for all welds. However, instead of the water cooled W–La backing anvil used previously, a steel support tooling was fabricated. The area near the weld zone was hard faced with Stellite to improve the anvil strength at temperature. This tooling material was used due to cost and because improved weld penetration could be achieved with anvil materials of lower thermal conductivity than W–La, which retain heat in the root of the joint and promote material flow.

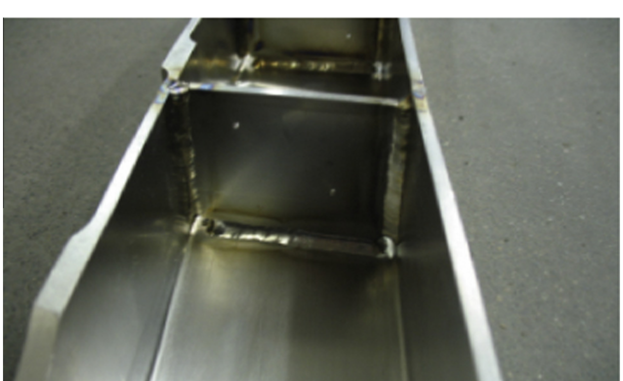

Fig. 1. Section of a typical titanium frame structure used in aerospace.

Weld parameters and tool designs were developed in an iterative fashion until acceptable joints were produced. Spindle speeds and feed rates tested for the corner and T-welds are given in Table 1. In corner and T-joints, the width of the weld zone is limited by the joint geometry because the pin of the tool must be narrower than the thickness of the vertical leg to prevent collision of the weld pin with the backing anvil. Also, for the corner joint, the width of the shoulder was limited so that it would not hang off the free side of the joint. This necessitated the use of a narrower tool diameter with a smaller shoulder for these welds than used in previous studies on butt joints. Higher spindle speeds, relative to those used for butt joints in similar gages [5], were used with this narrower tool design to achieve a sufficient amount of heat generation and material flow.

Prior to fatigue testing, all welds were subjected to a post weld heat treatment to relieve weld induced residual stress. During heat treatment, welds were held at 760C for 30 min in a vacuum furnace and then air cooled. Weights were also used to flatten and remove any distortion in the welded parts. This is a standard post weld thermal stress relief cycle used in industry. While the residual stresses in the welds produced in this study were not measured before or after stress relief, previous un-published research [21] conducted on the residual stresses in Ti FSW's pre and post stress relief showed that this standard thermal cycle is effective in removing weld induced residual stresses and thus weld induced residual stresses should not play a significant role (compressive being beneficial and tensile being degrading) in the fatigue test results in this study.

Microstructural evaluations were performed on weld cross sections near the start and stop of each weld. Welds were cut perpendicular to the welding direction with a band saw. Cross sections were then cut down to size and mounted for metallographic examination. All samples were polished on 5 μm, 1 μm and finally 0.3 μm alumina-oxide polishing wheels. The samples were then etched, using Kroll's reagent, to expose the microstructure and examined under an optical microscope.

Corner welds were selected for use in a custom bending fatigue test to assess the performance of the joint. The as-welded corner joints were fully machined on all surfaces prior to testing. A drawing of the cross section for the as-welded and machined-net corner joint are given in Fig. 3a. Fully machining the welded samples removes any surface imperfections left by the FSW tool shoulder and any potential root defects in the corner radius that would reduce fatigue life during testing. After machining the welds to the cross section shown in Fig. 3a, the parts were sectioned into 50 mm long pieces and trimmed the geometry shown in Fig. 3b. Holes were drilled into the short leg for attachment to the test fixture.

Fatigue specimens were also made from wrought Ti–6Al–4V 75 mm × 75 mm square bar and an L-shaped Ti–6Al–4V extrusions. These specimens were machined to the same dimensions as the machined-net welded specimens (Fig. 3b). The results of the corner joint data obtained from the machined bar and extrusion specimens would be used as a baseline comparison to the welded joint data since plate and extrusions are commonly used to fabricate the types of structures being considered for FSW.

The specimens were placed in a fixture and tested in fatigue by fixing one leg and fully reversed bending the other, Fig. 4. The short/thick leg of the specimen was bolted to a stationary fixture while the long end was placed in the mouth of an oscillating grip to cause the bending fatigue at the corner of the joint, in the weld.