AN INVESTIGATION INTO METHODS TO INCREASE THE FATIGUE LIFE OF FRICTION STIR LAP WELDS

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The following faculty members have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirement for the degree of Master of Science in Mechanical Engineering.

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DEDICATION

To my parents

Wisdom is supreme; therefore get wisdom. Though it cost all your possessions, get understanding.

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ABSTRACT

Recent advancements in friction stir welding (FSW) technology have potential for applications in aerospace structures. Friction stir spot welds have been found to be much stronger than rivets in the same material thickness, while maintaining the discontinuous crack growth path preferred by aircraft designers. In this study, the test coupons have been investigated in fatigue with the weld aligned with the loading direction. The purpose of this study was to better understand crack initiation at friction stir weld exit holes in no-load transfer coupons representative of aircraft fuselage applications. The goal was to document the effects of weld exit location on fatigue life in discontinuous friction stir welded panels and to determine possible solutions in order to reduce the stress concentration around the exit hole location, thereby increasing the panel's fatigue life. Aluminum alloys 7075-T6 and 2024-T3, which are commonly used in conventional airframe construction, were chosen for the FSW lap welds in this thesis. The methodology of this research was to weld the coupons with discontinuous friction stir lap welding using different exit hole configurations. The weld parameters such as rotation speed, travel speed, lead angle and load force had already been evaluated prior to this investigation in an earlier study during the first year of this project by Josh Merry. Once all of the coupons were welded, the next step was to fatigue test them with constant amplitude in order to determine the number of fatigue cycles and then compare all the different coupon results with the baseline coupon result that were determined in the previous study.

This project investigated a number of weld exit strategies with conventional one-piece weld tools. This study also included welds produced with a two-piece weld tool called Retractable Pin Tool (RPT) in which the length of the tool probe can be adjusted during welding. The RPT weld tool was used to eliminate the exit hole of the weld in order to reduce or eliminate

the stress concentration around the weld exit. The ultimate goal of this research was to achieve equivalent or better fatigue life in discontinuous FSW joints as compared to riveted coupons.

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LIST OF ABBREVIATIONS

AAxxxx	Aluminum Alloy xxxx
AJPL	Advanced Joining and Processing Laboratory
AS	Advancing Side
DXZ	Dynamically Recrystallized
EST	Effective Sheet Thickness
FSW	Friction Stir Welding
FSSW	Friction Stir Spot Welding
FSP	Friction Stir Processing
FAA	Federal Aviation Administration
HAZ	Heat Affected Zone
HADZ	Heat and Deformation Affected Zone
NIAR	National Institute for Aviation Research
PDS	Process Development System
PFSW	Plunge Friction Spot Welding
PRZ	partially recrystallized zone
RFSW	Refill Friction Spot Welding
RPT	Retractable Pin Tool
RS	Retreating Side
SZ	Stir Zone
SCC	Stress Corrosion Cracking
TWI	The Welding Institute, Ltd.
TMAZ	Thermomechanically Affected Zone
WSU	Wichita State University

CHAPTER 1

INTRODUCTION

1.1 Background

A new technology and welding method was invented by Wayne Thomas and his colleagues at The Welding Institute (TWI) of Cambridge, England, which they patented as Friction Stir Welding (FSW) in December 1991 [1].

Research and study on friction stir welding in the United State of America began in earnest around 1995 at a few sites—the Lockheed Martin Corporation's Michoud Facility, NASA Marshall Space Flight Center, and the Boeing Company's Phantom Works division. Some of the applications for FSW in the U.S. were for aerospace applications like the welding of an aluminum-lithium alloy, Al 2195, for the Space Shuttle's external tank, the Delta II family of rockets, and the Delta IV Heavy Rockets. A great amount of FSW research has also been conducted by well known aircraft companies such as Bombardier Aerospace, Boeing, Embraer, Eclipse Aviation, and Spirit Aero Systems. Additionally, research has been conducted by national labs, welding institutes, and universities, including extensive work here at the National Institute for Aviation Research (NIAR) at Wichita State University (WSU) under the sponsorship of many aerospace companies.

Friction Stir Welding research began with a feasibility study, focused on the aeronautical and manufacturing applications of Friction Stir Welding due to the high level of interest in FSW by aircraft companies with operations in Wichita [43]. This study focused on the Aluminum 2XXX and 7XXX series alloys, in particular 2024 and 7075 which are conventionally used in airframe construction. [6] Based on this feasibility study, and by the acceptance of state grants, in October 2004 NIAR established the Advanced Joining Technology Laboratory for conducting research and development on FSW for aerospace applications. An MTS I-Stir™ friction stir welding machine was purchased with state and Federal Aviation Administration (FAA) funds, as well as the hiring of undergraduate and graduate students, and also full time research staff [45]. With the recent purchase of a new 6-axis ABB IRB Robot, and a 6-axis Kawasaki Robot, NIAR is developing methodologies for producing friction stir welded joints using equipment already present in most manufacturing companies [44].

1.2 Advantage of FSW

Friction Stir Welding has several benefits over traditional arc or fusion welding. FSW is a relatively new solid-state joining technology for joining metals and plastics and unlike fusion welding; it does not require melting or filler material. The most important variables of interest in the basic FSW process for a given workpiece material are 1) travel speed (feed rate), 2) plunge depth and/or forging load, 3) rotation (spindle) speed, 4) tool material, and 5) tool geometry.

FSW generates no fumes, results in improved weld quality and reduced distortion for the proper parameters, is adaptable to all positions, and is relatively quiet compared to other joining methods. Also FSW has a reduced defect rate and lower health hazard. FSW can improve mechanical properties such as fracture toughness, fatigue and ductility, and it simplifies dissimilar alloy welding [7].

1.3 Research Objective

The objective of this study is to facilitate the introduction of this new technology by local aerospace manufacturers by developing and obtaining fatigue property data for FSW lap-joints in 2024 and 7075 and to further study secondary crack initiation on fatigue life of discontinuous FSW lap welds.

CHAPTER 2

LITRATURE REVIEW

2.1 The Basics of Friction Stir Welding

2.1.1 The Beginning

Friction Stir Welding (FSW) is a solid–state, hot–shear joining process. To form a basic butt weld joint with this process a non-consumable rotating tool, with a shoulder and terminating typically in a threaded pin, is moved along the butting surfaces of two rigidly clamped plates placed on a backing plate [3, 7]. A schematic representation of this process is provided in Figure 1.

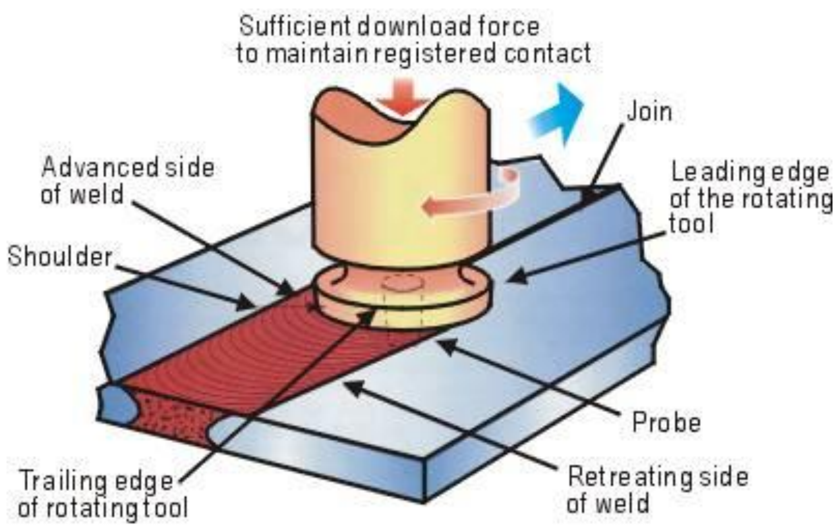


Figure 1 Illustration of FSW process [3]

There are many different weld joint configurations such as T- joints, lap joints, fillet joints, as well as butt joints which are currently employed in the aerospace, automotive, railway, maritime industries, and ship industries. In FSW technology, a cylindrical steel tool with a particular rotation speed rotates and is plunged into the joint line between the workpieces that are to be welded. This rotating, non-consumable tool generates a considerable amount of heat due to friction and the plastic deformation of the workpiece material [8]. Upon contact with the workpiece, the rotating shoulder, and to a lesser degree the probe surface, produce heat, causing the material to soften. As the tool plunges into the material being welded, severe plastic deformation and flow of this plasticised metal occurs coupled with large amounts of heat flow into the surrounding material. Once seated in the material, the tool is translated along the welding direction aided by the heating that occurs around the tool. As the tools is moved along the joint line, the rotating and translating action of the tool serves to transport material from the front of the tool to the trailing edge of the tool where the material is forged and extruded into a joint [2].

As illustrated in figure 1, moving the rotating FSW tool along the joint line produces what is conventionally called retreating and advancing sides. The advancing side is the side for which the surface of the tool is rotating in the same direction as the direction of travel. The retreating side is the other side of the tool where the tool surface is traveling opposite the direction of travel. This differing motion creates asymmetry in the weld [4].

FSW is called a solid-state process because the maximum temperature during welding does not exceed the melting temperature of the alloys, typically only reaching approximately 80% to 90% of the melting temperature. Originally the process was considered most appropriate for components which are long (sheets and plates) but can be adapted for pipes, hollow sections and positional welding [2]. However, applications using short or discontinuous welds are being developed, hence the need for this study.

2.1.2 Friction Stir Processing

Friction Stir Processing (FSP) is a variant of friction stirs welding. It was developed based on the basic concepts of Friction Stir Welding (a solid state welding process), but FSP is used to modify the local microstructure of a component as opposed to joining components together [12]. FSP may be used to modify surface material to introduce microstructural modification close to the near surface layer of metal components. It gives the ability to thermo-mechanically process selected locations on a structure's surface to a range of depths (from shallow to full penetration) to alter the properties of the material, e.g. grain size.

2.1.3 Friction Stir Welding Tools

The process of friction stir welding requires a non-consumable welding tool, sometimes referred to in the literature as a pin tool. A featureless weld or pin tool is illustrated in Figure 2. The function of the pin tool is to produce thermomechanical deformation in the workpiece through frictional heating and mechanical stirring. The tool is slowly plunged into the workpiece as it is rotated at a fixed speed.. Once the workpiece has been softened to the desired level through heating from friction and mechanical stirring, the material of the workpiece can be easily mixed by the probe and shoulder due to the low flow strength of the material. While the probe extrudes the material in a circular pattern, the tool shoulder keeps the plasticized material contained to provide the required forging pressure for forming a consolidated joint [4, 7].

The basic friction stirring tool consists of a shoulder and a probe, or pin. The probe can be integral with the shoulder or inserted in the shoulder as a separate piece, possibly of a different material. The design of the probe and shoulder is very significant for the quality of the weld as well as the rate of welding. When welding thin sheets of material as in this study, the shoulder generates much of the heat. As the thickness of the weld increases, such as in plate material, the probe of the tool generates an increasing amount of the heat and stirs the material being welded. The shoulder plays a decreasing part in overall heat generation as the thickness of the weld increases while preventing the plasticised material from escaping from the weld region [5].

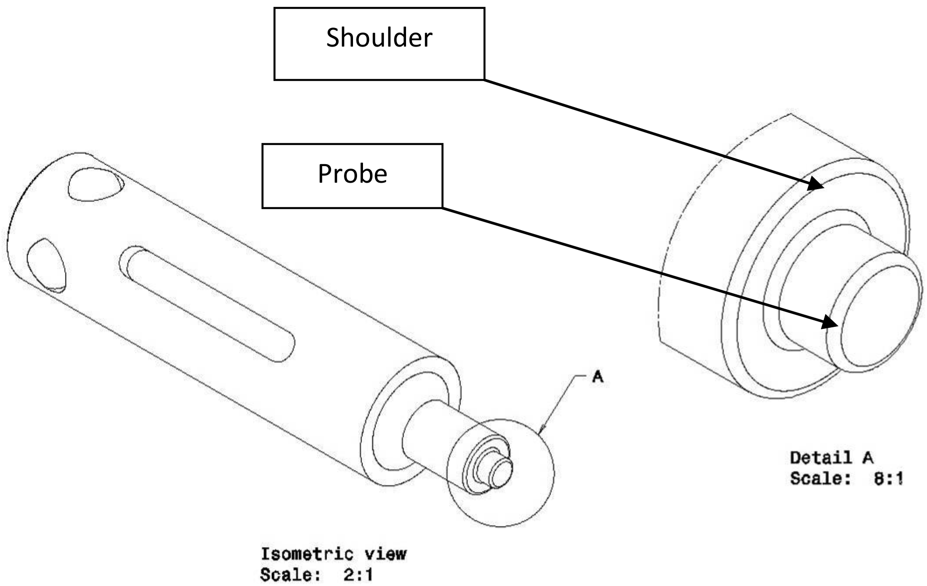


Figure 2 Generic pin tool [6]

The geometry of the probe can be cylindrical, quadrangle or conical. The material, structure and configuration of the FSW tool is related to the desired quality of the weld, material of the workpiece, rotation speed and travel speed (e.g. productivity). Usually a tool designer adds flutes and/or threads on the probe in order to promote better material flow and avoid the formation of defects and wormholes. A conventional probe, which is threaded and conical with a radiused tip, is shown as Figure 3.

In the welding of aluminum or aluminum alloys, the most common tool materials are tool steels (e.g. H13) and high strength steels (e.g. Maraging 300) that retain their strength and hardness at FSW processing temperatures (usually below 900F). Other materials, such as MP159, a cobolt-based bolt material for high temperature applications, are also used both in research and production. With the selection of appropriate welding parameters, a steel tool produces the proper weld quality and strengths without significant tool wear. However, if a steel tool is used to weld more abrasive materials such as metal matrix composites (MMC), tool wear becomes an important subject due to the presence of rough particles and the strength of the material to be welded. Tools made of more exotic materials such as Tungsten Carbide (WC), Tungsten (W), and Molybdenum (Mo) can be implemented to decrease or eliminate tool wear and distortion which have been observed in steel tools when welding in such materials at high rotation speed and/or forces[7,8].

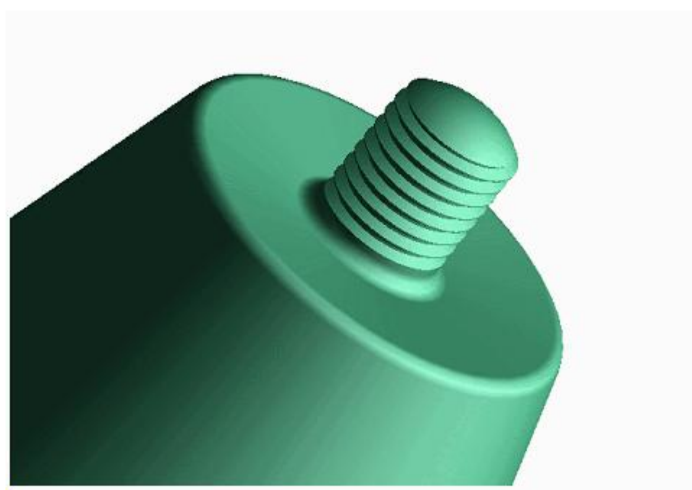


Figure 3 Typical weld tool profile [9]

2.1.3.1 Retractable Pin Tool

In this experiment a new style of pin tool, called Retractable Pin Tool (RPT), was tested along with more conventional tool designs. It was invented at NASA Marshall Space Flight Center to eliminate the exit hole produced by conventional FSW [46]. The retractable pin tool consists of separate actuated pin inside a shoulder. The pin and shoulder are typically rotated at the same rotational rate but can be rotated at different rates and in opposite directions. The main purpose of this tool design is to allow the pin length to change during FSW as shown in Figure 4 [7].

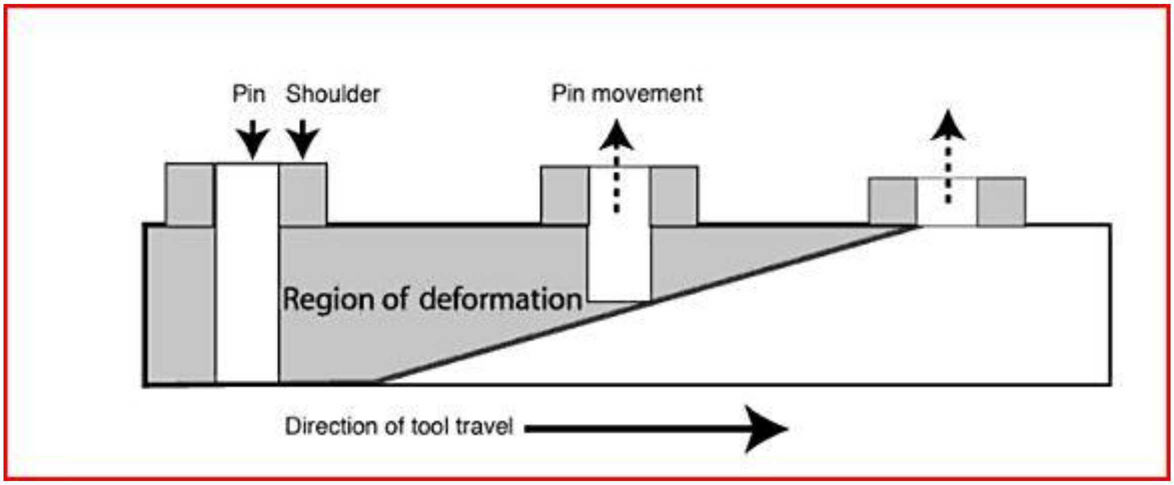


Figure 4 Example of retractable pin tool [7]

In welding large cylinders at NASA, the typical operational mode for these tools was to retract the pin at a prescribed rate as the tool traversed forward past the original start of the weld. This allowed the closure of the exit hole in the circumferential friction stir welds. Also, it was reported that pin lengths could be adjusted to ensure full penetration welds in workpieces with known thickness variations [7].

2.1.3.2 Threaded Counterflow Tool

Another pin tool that is used in this investigation is Counter Flow pin [47]. This pin was created in AJ&PL in NIAR. The main characteristic of this tool especially for lap weld application is that it produces high strength mechanical properties through enhanced local mixing in the TMAZ along the probe length. The threaded Counterflow™ tool used in this study was selected based on the work of Merry in prior work in this program [40]. It consisted of a concave shoulder and probe having threads and counterflowing flutes as shown in Figure 5.

Figure 5- Schematic of Counter flow pin tool [47]

2.1.4 Metallurgy of Friction Stir Welding

2.1.4.1 Metallurgical processing zones

The heating of the material during the friction stir welding process is not intended to bring the material above the solidus temperature, therefore making FSW a solid-state welding process. Also FSW can be considered to be a metal working process that includes both forging and extruding, which are related to processes used to create wrought manufactured goods [4].

2.1.4.2 Weld zones and joint profiles

TWI presented a comprehensive profile of a butt joint, characterizing it as an inverted trapezoid that consists of four zones as shown in Figure 6. The first zone, which was the furthest from the joint line, was called the unaffected base metal zone. In this zone there were no microstructural or property changes in the metal. The second zone (closer to the joint line from zone 1) is named the heat-affected zone (HAZ). In this second zone, the material does not experience plastic deformation; however, the heat of welding influences this region by causing some microstructural changes (mainly overaging in precipitation strengthened alloys). The third zone in towards the joint line is identified as the thermo-mechanically affected zone (TMAZ). In the TMAZ the material is affected by the heat generated by the FSW process and is also partially deformed. The fourth and final zone is named the nugget or stir zone. This zone is the dynamically recrystallized region bounded by the TMAZ. In this zone, the welded material was heavily deformed and corresponds to the pin location during the welding. These four zones were identified by TWI but their terminology is not used uniformly throughout the FSW community. For example, some authors recognize the nugget as the dynamically recrystallized zone (DXZ), while others refers to it as the stir zone (SZ). The TMAZ is also referred to as the HDAZ (heat and deformation affected zone) and the PRZ (partially recrystallized zone). The use of the term PRZ suggests that there are both recrystallized grains and also deformed grains present in this zone. TWI agrees to categorize the TMAZ and the region underneath the shoulder as two separate zones. Some authors categorize the region underneath the shoulder to be a region of rotation and therefore categorize it as a part of the SZ, while other authors continue to maintain that the SZ actually includes the nugget, the TMAZ, and the region immediately underneath the shoulder [10].

Figure 6 integrates some important elements, provided by several authors, into the TWI-proposed joint profile. More specifically, these elements are the deformed grains or swirl marks underneath the shoulder, identification of the advancing and retreating sides, the weld flash, and the onion ring pattern. The diagram in Figure 6 was based on results produced by an original tool design similar to the tool represented in Figure 3. Other tool designs, e.g. probes without threads, may produce welds without the appearance of an onion ring pattern.

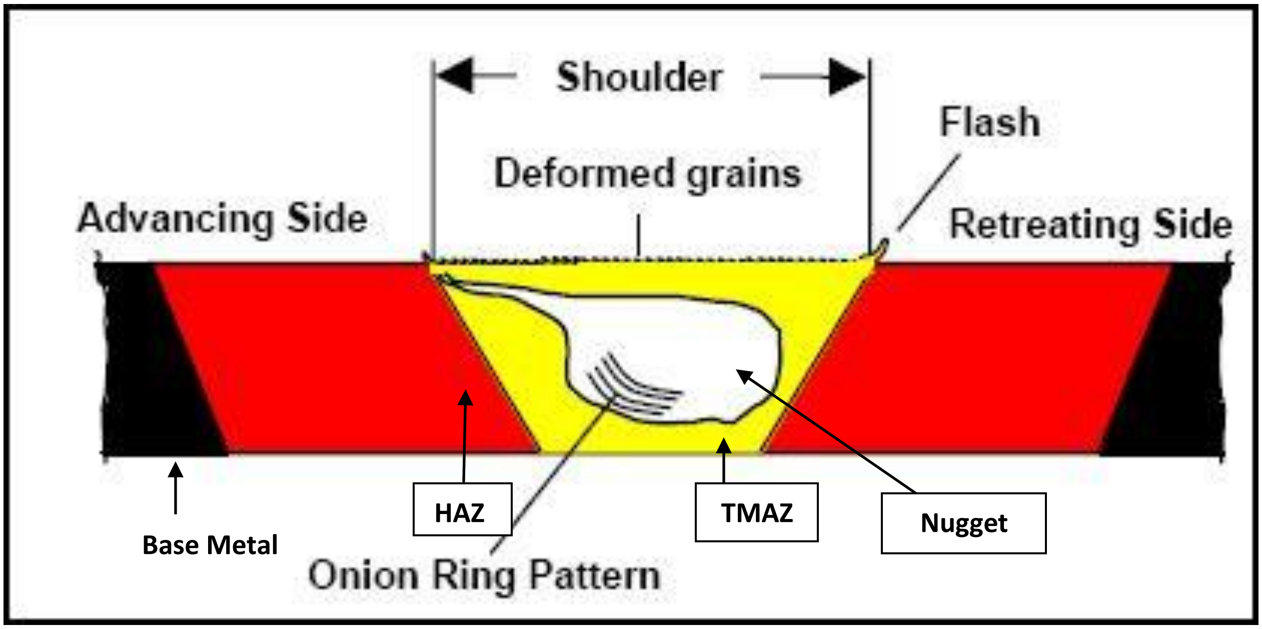


Figure 6 Schematic of a butt joint cross-section showing four distinct zones [10]

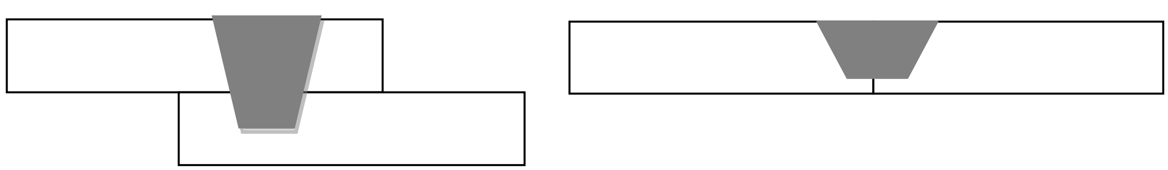
This figure now indicates the asymmetry of the nugget where it expands more towards the advancing side. However, Figure 6 does not illustrate that the onion ring pattern is seen more on the advancing side. The onion ring pattern is essentially a representation of banded microstructures brought together by the stirring action of the pin. There are some representations that have shown the onion ring pattern to be present throughout the nugget. Furthermore some authors depict that the onion ring pattern has no effect on properties, whereas others consider that it does in fact influence and modify the fracture path. The weld flash and swirl marks shown in Figure 6 can have a severe effect on fatigue performance and may require removal for certain applications. As a result, low plasticity burnishing has been suggested as a technique for this removal operation while simultaneously inducing constructive residual stress fields [10].

Tool geometry and a backup plate define the shape of the inverted trapezoidal profile of the joint, shown in Figure 6. The wide base of the trapezoid corresponds to shoulder contact area and heating, while the thin base responds to heating of the narrower pin profile, which is strongly influenced by the heat sink effect of the backup plate. This sort of joint profile has been observed and utilized for a broad range of FSW joints in a wide variety of metals [10].

In certain materials, such as titanium steels and alloy steels, the heat of welding may cause polymorphism, where these phase changes can cause recrystallization with no strain. Consequently, any TMAZ that may have formed will be likely recrystallized, causing difficulty in differentiating between the HAZ/TMAZ boundaries. Other materials, such as austenitic stainless steels and aluminum alloys, do not cause polymorphism and therefore simplifies the identification of the TMAZ [10].

2.2 Basic Types of Friction Stir Welding

The two primary types of joint configurations, the butt weld configuration and the lap weld configuration, are illustrated in Figure 7. There are many other types of joint configurations which are essentially variations or combinations of lap weld and butt weld. Details are discussed later in this chapter.



(a) Lap Weld **(b) Butt Weld**

Figure 7- Types of FSW joints

2.2.1 Butt joints

In this simplest form, for this method of welding, two sheets or plates with the same thickness are set next to each other on a backing plate and clamped tightly together along their square faying edges as shown in Figure 8 [10]. The main purpose of using rigid fixturing is to keep the two sheets from spreading apart or lifting during welding. The friction stir welding tool, consisting of a shoulder and pin, is then rotated to a particular speed and tilted with respect to the sheets normal. The tool is gradually plunged into the workpiece material at the butt line, until the shoulder of the tool forcefully contacts the upper surface of the material and the pin is embedded in the joint to a short distance from the backing plate. At this time the lateral forces (X and Y) are large enough that additional care is required to make sure the plates remain in the butt configuration and are not allowed to separate.

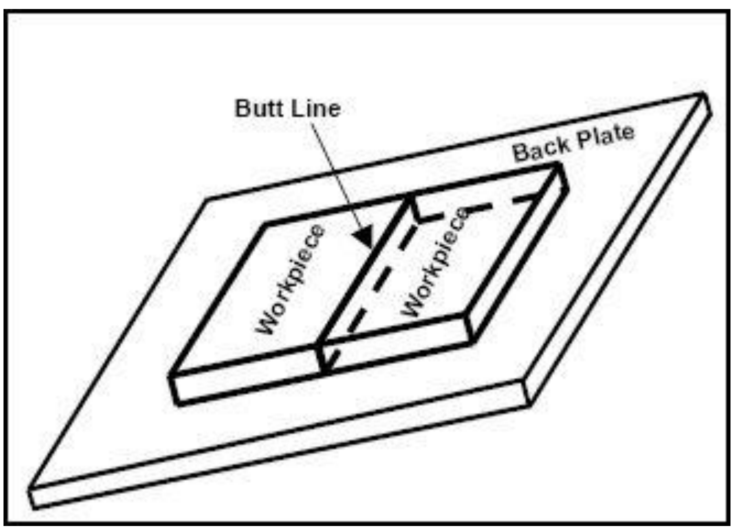


Figure 8 Butt joint sheets with clamp on backing plate [10]

To begin a weld, a downward force is applied through the tool to maintain the contact between plates. A short dwell time is then applied to allow for the growth of the thermal fields for softening and preheating the material along the joint line. At the end of the weld, the tool is moved up, while it is still being rotated, when the pin is retracted from the workpiece, normal to the surface of the plate. As a result, an exit hole remains at the end of the weld. The Shoulder contact on the material leaves a series of semi-circular patterns in the weld track, as illustrated schematically in Figure 9. Consequently, the start and end of the weld line will not be completely welded, especially at the end of the weld, where an exit hole is left. [10].

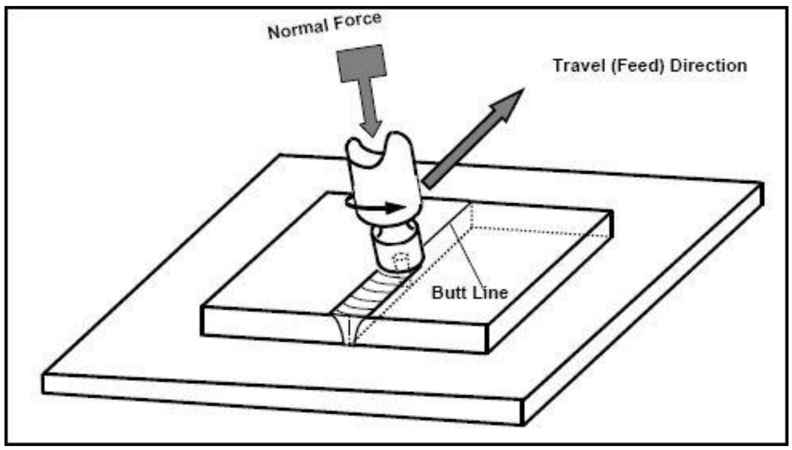


Figure 9 Force the tool at the desired travel speed along the butt line [10]

2.2.2 Lap Joints

A lap joint consists of two lapped sheets or plates clamped together. Depending on the bottom sheet thickness, a structurally supporting backing plate may or may not be needed. Conventionally, a rotating pin tool is plunged through the upper sheet normal to the surface and into the bottom sheet a set depth less than its thickness. Once the plunge phase of the weld is complete, the tool is traversed along the desired direction to join the two sheets together [7].

The same methods and principles mentioned in previous section for butt joints apply to lap welds with the exception of the following. In the lap weld there is no butt line, where the pin tool can be plunged among the sheets. Rather, the pin tool needs to be inserted through the top sheet. Also, it is necessary for the stirring movement to break up the oxides, scale and the other contaminants at the interface. This is the fundamental different between butt joints and lap joints. For butt welds, the main stirring is in the plane of the abutting surfaces being welded. In contrast, for lap welds, stirring is out-of-plane and across the interface of the two members being welded.

Brooker *et al*, [11] introduced an innovative lap weld tool. The major difference between their lap weld tool and conventional tools for butt joints is the introduction of a second shoulder, which is placed at the interface between the two sheets being welded (Figure 10). Most of the existing publications regarding lap welds indicate that drilling a starting hole is not required to produce a sound lap joint [11].

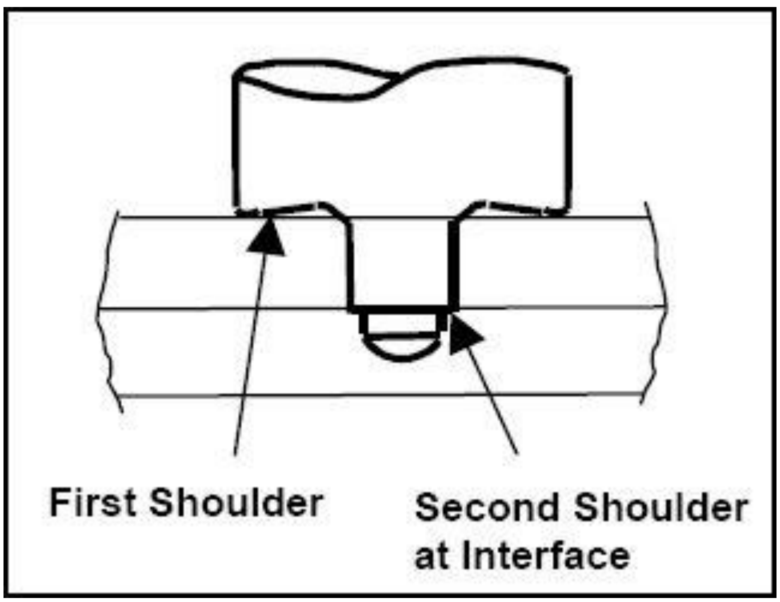


Figure 10 Schematic of lap joint pin tool [11]

In lap joints, the top plate of a lap joint must be distinguished from the bottom plate since it is in contact with the shoulder. The end of the pin needs to penetrate through the top sheet completely and enter a sufficient distance into the bottom sheet. It is not required that the end of the pin passes all of the way through the bottom sheet, since, in contrast to butt joints, there is no weld root closure involved. However, one must not underestimate the effect of the intrusion distance into the lapped (bottom) sheet on the mechanical properties of the weld. The notches on either side of the joint (Figure 11) are potential sites for crack initiation (under certain loading conditions) and, as such, they can have a significant effect on mechanical properties. While lap joints may not be as strong as butt joints they have been shown in several case studies to have sufficient fatigue and static properties to replace fastened joints [11].

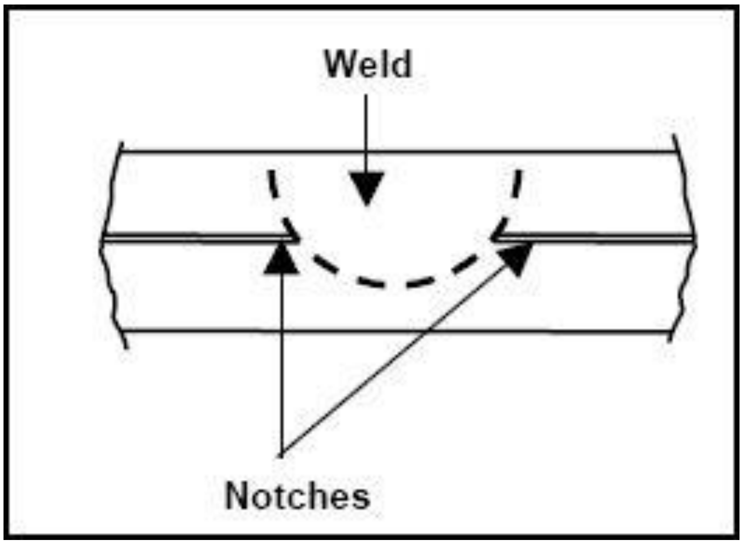


Figure 11 Notches location in lap joint [11]

2.2.3 Friction Stir Spot Welding

A variant of FSW is Friction Stir Spot Welding (FSSW), which creates a lap-weld with discrete joints similar to installed fasteners [refs – suggest Burford et al.]. As with FSW, there is no bulk melting in FSSW. It has been shown to be more efficient (cost savings and significant energy) compared to electric resistance spot welding [13]. The principle of FSSW is based on the continuous FSW process. However, in its simplest form, FSSW is much less complex in the sense that the actual welding time itself is very short but the process dynamics involved is still the same – tool plunge, material mixing (during dwell time) and tool retract. The key parameters important for FSSW are tool geometry, weld rotation speed, plunge depth and dwell time. Each of the parameters mentioned above have an important role in the weld in terms of material mixing, heat input, and weld cycle time, all of which are the key to achieving a good weld in terms of strength and material morphology [16].

Some spin-off technologies can be recognized by considering FSW as a ―controlled path extrusion” rather than a ―welding” process. Recently two variations of FSSW are being used in production: one is the ―Plunge” Friction Spot Welding (PFSW) method which was patented by Mazda in 2003 and the other is ―Refill” Friction Spot Welding (RFSW) method which was patented by GKSS- GmbH in 2002. [14]

2.2.3.1 Plunge Friction Spot Welding

In plunge friction stir welding (PFSW), a rotating fixed pin tool is plunged and retracted through the upper and lower workpiece of the lap joint to plasticize the metal locally and stir material from each sheet together as shown as Figure 12.

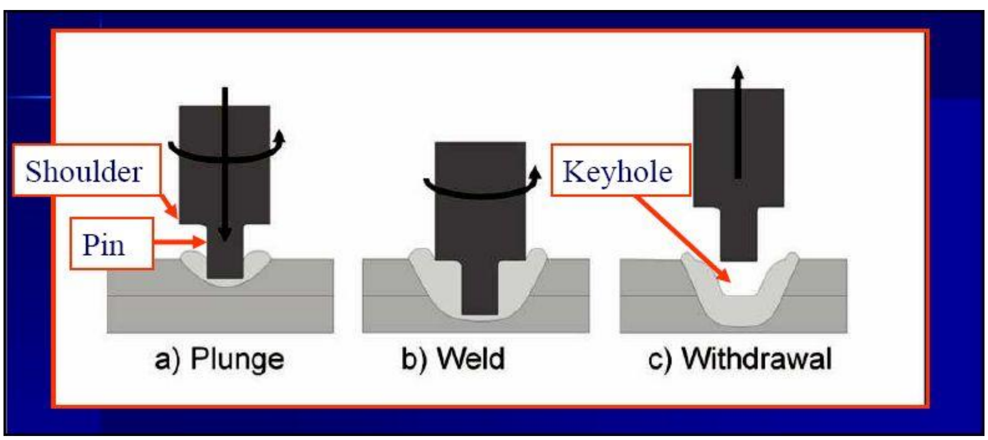
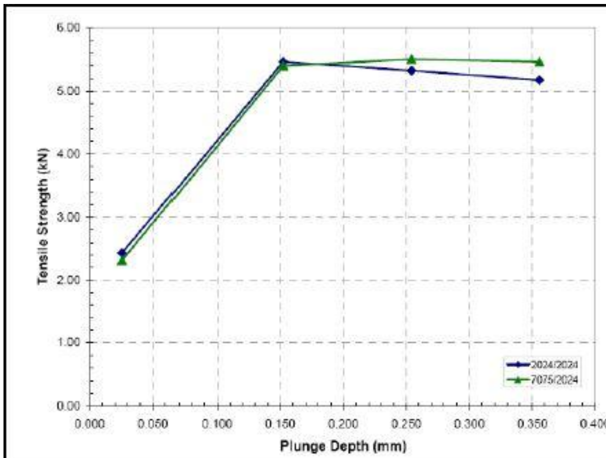


Figure 12 Plunge Friction Spot Welding [15]

Although this method creates an exit, or pull-out hole in the center of the spot, the fatigue life and strength is adequate to allow application at reduced the costs of production on the Mazda RX-8 aluminum rear door structure. Since 2003, the Mazda automotive company has produced up to 100,000 vehicles with this PFSW rear door structure. These rear doors reportedly have a very good structural stability against side impact and provide five star roll over protection [14].

Tweedy et al investigated the important parameters of FSSW on bare AA7075-T6 and 2024-T3 of 0.040 inch (1mm) thick lap joints. It was found in this study that the plunge rate had minor effect on the strength of the joint but that rotation speed of the tool was very important. Dwell time and plunge depth were also key factors. Once the FSW tool reaches a certain depth, the strength of the joint changes only slightly for increasing plunge depth, as shown in Figure 13, demonstrating that sufficient depth of probe penetration is achieved to produce a joint with consistently strong properties. As shown by figure 14, for the material to be mixed adequately, the tool must be in the material for a certain amount of dwell time. Once the ideal point is reached, not only more mixing will not increase strength of the joint but also dwelling longer may weaken the joint due to overheating [4, 17].



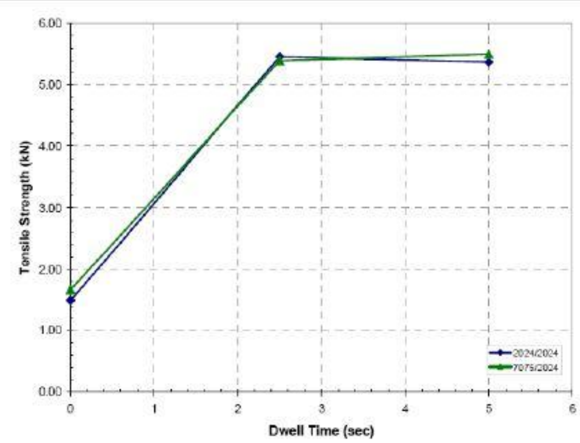


Figure 13 Effect of Plunge Depth [17]

Figure 14 Effect of Dwell Time [17]

2.2.3.2 Refill Friction spot Welding

The refill friction stir spot welding (RFSW) was developed GKSS and is currently being evaluated at the SDSMT AMP Center under license to RIFTEC-GmbH. In this process, a rotating pin tool with a separate shoulder and pin actuation system is used. During the first half of the cycle the plasticized material initially displaced by the pin is captured or contained by the shoulder. During the second half of the cycle the plasticized material is re-injected into the joint as illustrated in Figure 15. This process refills the joint nominally flush to the original surface of the top sheet. In addition to its being developed as a replacement technology for rivets in aerospace applications, RFSW is also being developed as a tacking technology to restrain and hold parts during over-welding by linear FSW [14].

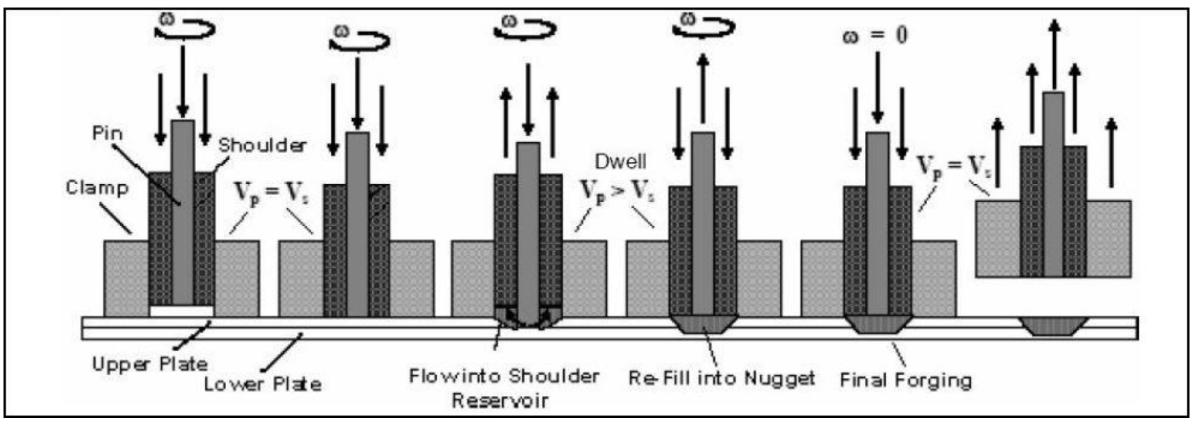


Figure 15 Schematic of Refill FSSW [18]

2.2.4 Swept Friction Stir Spot Welding

Swept FSW is the type of FSSW which is introduced by TWI. The main advantage of this technique compared to the traditional plunge FSSW is the increased joint strength that results from increased shear area and because of the elimination of sheet thinning and hooking [19]. Typically during the formation of the spot welds, the vertical translation of the joint interface occurs causing the change of the surface between the bottom and top sheets which forms a downturned or upturned interface. The effective sheet thickness decreases as a result. Both of these results are negative effects in linear lap welds. This translation of the interface is normally consumed during a swept spot weld. The resulting interface will have no downturn or upturn [4, 17].

The Octaspot™ Swept FSSW pattern involves the five basic steps illustrated in Figure 16. The first step is a plunge (poke) into the material. In second step the tool is moved out to the perimeter of the tool path. The third Step is the tool is traversed around the perimeter for no less than 360 degrees. The forth step is when the orbit is completed and the tool is moved back to the center of the spot weld. In the fifth step the tool is retracted.

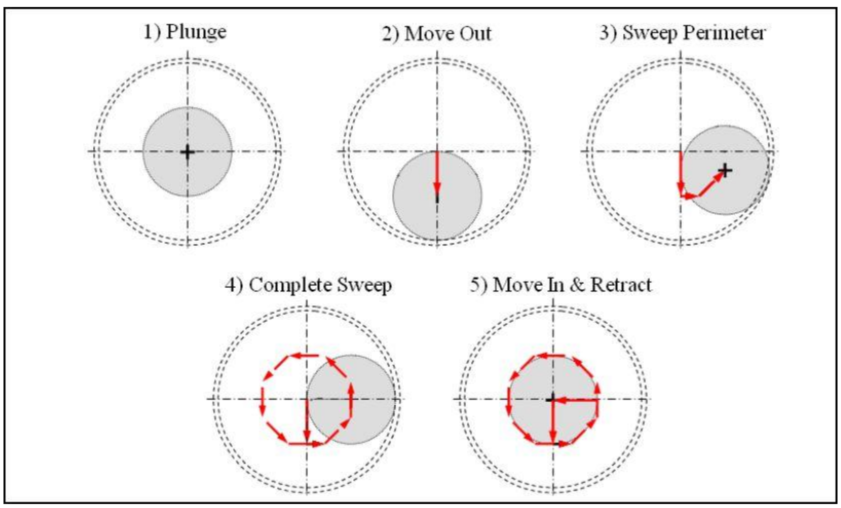


Figure 16 swept spot FSW [4]

Burford et al. investigated crack growth rates in 2024-T3 lap joint panels with AA7075-T6 stiffeners joined with swept FSSW. In this study, fatigue crack growth rates in flat, stiffened edge-crack panels were examined to evaluate the performance of weld joints produced by riveted and FSSW joints. According to the result of this study, lower crack growth rates were initiated in FSSW pre-crack panels than were observed in panels joined with rivets and un-stiffened panels. By testing stress relieved panels, it was observed that a beneficial residual stress field is presented around swept OctaSpot™ joints. It was also observed that the pad-up effect, resulting from mechanically forming discrete integral joints between the stiffener and sheet, contributes to the observed lowered crack growth rates in FSSW panels to a lesser amount than does the residual stress effect. In this study, it was concluded that the Swept FSSW welds provide an effective methods for reducing the stress concentration associated with the drilled holes required for installing conventionally installed fasteners [49].

2.2.5 Swing and Stitch Friction Stir Spot Welding

Swing FSSW was developed by Hitachi Company and Stitch FSSW was developed by the GKSS research center. In the conventional spot FSW, the tool plunges into the sheet which creates the weld and then it retracts. In swing FSW technique the tool moves a short linear distance after plunging and then it retracts, therefore it creates a larger contact area that leads to a higher strength which is considered an advantage [7]. In the Figure 17 the difference between Swing FSSW and Stitch FSW is illustrated.

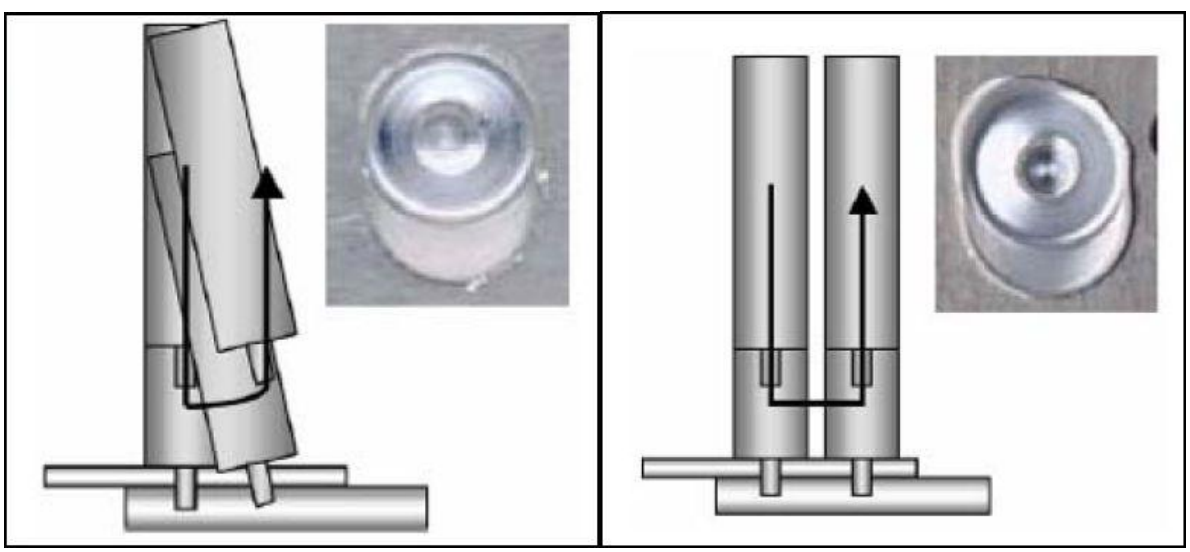


Figure 17 Swing (Left) and Stitch (Right) [41]

2.3 Corrosion

2.3.1 Description

Corrosive oxidation occurs when oxygen bonds to metal atoms to form a surface oxide layer. In other words, the metal combines with the oxygen in the air and becomes a non-metallic material. It has been approximated that the earth’s crust is about 8 % aluminum; and the majority of the 8 % is often found in the form of an oxide called bauxite. Since aluminum is the second most plentiful metal element on the planet, it is also one of the most highly used non–ferrous metals. Although it is less expensive per volume than other metals, it is more expensive on a tonnage basis due to its low density.

Aluminum alloys are separated into two broad classes, heat-treatable and non-heat-treatable alloys, and into different product forms including wrought (mechanically worked) and casting products [25].

The condition of the environment (acidity or alkalinity) considerably affects the corrosion behavior of aluminum and its alloys. At higher and lower pH, aluminum is likely to corrode but it doesn’t always do so. If one was to submerge an aluminum specimen into concentrated nitric acid, it would be found that the specimen would be resistant to the acid. However, if the same specimen were placed in a more alkaline solution, one in which the oxide film is perforated, then a more accelerated corrosion would take place. The accelerated corrosion is due in part to a more rapid rate of “attack”, which results in pitting of the specimen surface. In a highly acidic condition, a more general attack should result since the oxide is more susceptible to attack than the aluminum [25].

The aluminum resistance for corrosion is dependent upon a protective oxide film. When the pH is between 4.0 and 8.5 the film is stable in aqueous media. The film is self-renewing and accidental abrasion or other surface film mechanical damage is repaired quickly. The environment that promotes corrosion of aluminum and aluminum alloys, therefore, must be those that continuously abrade the oxide film mechanically or help conditions that locally degrade the protective oxide film and reduce the availability of oxygen to rebuild it [25].

2.3.2 Types of Corrosion

Corrosion is a significant issue for the majority of welded joints. Since corrosion is potentially present in every application, corrosion must be considered when evaluating the useful life of a structure. Several different types of corrosion exist [4].

Uniform corrosion is described by corrosive attack happening uniformly over the whole surface, or a large fraction of the whole area. It is uniform relatively in depth of influence over this area [36].

Galvanic corrosion basically happens between different metals and between different areas of the same metal when in electrical contact with each others. The galvanic corrosion attacks the anodic members when the metals are immersed in an electrolyte [37].

Pitting corrosion is limited to a small area of the surface which is defined by holes or “cavities” that are formed in the material. Since the smaller area can be described as anodic, and the larger surrounding area described as cathodic, a reaction between the two takes place, resulting in pitting on the surface of the corrosion specimen. The Pitting corrosion damages are more of a problem than uniform corrosion damages because it is more complicated to predict, detect and design against [36].

Crevice corrosion happens when there is an electrolyte at the faying surface of a joint. The term crevice corrosion explains the position of the attack rather than a form of corrosive action. Also other type of corrosion, such as pitting corrosion, may be taking place at the faying surface [4].

Intergranular corrosion is a localized form of corrosion occurring at the grain boundaries of the material. This form of corrosion is normally associated with specific phases precipitated on the grain boundaries or chemical segregation effects. In this process, the grains act as a cathode in contact with grain boundary that acts as an anode. Thus, a specific form of galvanic corrosion occurs [36].

Exfoliation corrosion is a particular form of intergranular corrosion which is associated with very high strength aluminum alloys. Those type of alloys that have been worked heavily or extruded, with a microstructure of elongated, flattened grains, are particularly prone to this damage. Corrosion products building up along these grain boundaries apply pressure between them and the end result is a lifting or leafing effect. The damage frequently initiates at end grains encountered in machined edges, holes or grooves and as a result can progress through whole section [38].

Stress corrosion cracking is the result of the interaction between stress and corrosive reactions. These stresses could be either applied externally or exist as residual streses. Stress corrosion cracking may explain any crack propagation that is assisted by the environment [39].

2.4 Aluminum Alloys

2.4.1 General Information

Aluminums can be described as having a silver-white surface color, with a sheen that can vary greatly from dull to shiny. It is a non-ferrous metal alloy with very good corrosion resistance when compared to other metals. With a specific gravity of 2.7 lb/ft^3, these metal alloys are often lighter than metals with comparable properties such as copper, steel, and nickel. Aluminum alloys also have very good machinability, workability as well as good thermal and electrical properties [20].

2.4.2 Characteristics

The characteristics of aluminum alloys can vary greatly depending on the type of alloy being described. In general, precipitation strengthened aluminum alloys subjected to extremely high temperatures, typically between 200 and 250 °C, tend to lose a percentage of their strength. The opposite occurs at subzero temperatures. Their strength increases while there is no noticeable change in their ductility. This makes aluminum an extremely useful low-temperature alloy. Aluminum alloys have a strong resistance to corrosion; which is the result of a stable oxide skin that forms as a result of reactions with the atmosphere. This corrosive skin is impervious to most chemicals, weathering conditions, and even many acids, thus protecting the aluminum that it encompasses. However, these alkaline substances are known to penetrate the protective skin and corrode the metal [20].

Although copper has an electrical conductivity of approximately 161% of aluminum; aluminum is still a very valuable material in terms of electrical conductivity. The electrical properties of aluminum make it a good cost efficient replacement for building wire. One problem however is the fact that aluminum connectors become loose after repeated use. This sometimes results in arcs or fires [20].

Aluminum is a very versatile metal and can be cast in any form known. It can be rolled, stamped, drawn, spun, roll-formed, hammered, and forged. The metal can be extruded into a variety of shapes, and can be turned, milled, and bored in the machining process. It also can be riveted, welded, brazed, or resin bonded. For most applications, aluminum needs no protective coating as it can be finished to look good; however it is often anodized to improve color and strength [20].

2.4.3 Classification

Basically the classification of aluminum alloys is base on their available strengthening mechanisms. The International Alloy Designation System is the most widely accepted naming scheme for wrought alloys. Each alloy is given a four-digit number, where the first digit indicates the major alloying elements as shown in the list below [21].

1. AA 1xxx denotes a pure aluminum alloy with a minimum 99% aluminum content by weight. This alloy can be work hardened .
2. AA 2xxx series alloys are generally alloyed with copper. They can be precipitation hardened, and have shown to have strengths comparable to steel. Also known as duralumin, this series was once the more predominate aerospace alloys. However this series is susceptible to stress corrosion cracking and are increasingly replaced by 7000 series in new designs.
3. AA 3xxx series alloys are alloyed with manganese. They can be work-hardened.

4. AA 4xxx series alloys are known as silumin, since they are alloyed with silicon.
5. AA 5xxx series uses magnesium as the alloying element. This series derives most of their strength from work hardening, and is well suited for cryogenic applications due to low thermal conductivity.
6. AA 6xxx series have very good machinability. They are alloyed with magnesium and silicon, and can be precipitation-hardened. However, the strengths are not as hight as the 2xxx and 7xxx series alloys.
7. AA 7xxx series can be precipitant hardened to exceed any other aluminum alloy. They are alloyed using zinc.
8. AA 8xxx series generally denotes lithium alloyed alloys.

2.5 Aluminum Alloy 7075 (AA7075)

2.5.1 Description

Aluminum alloy 7075 is a widely used heat treatable Al-Zn-Mg-Cu alloy. Due in part to its alloyed elements, it is one of the highest strength aluminum alloys available whose chemistry is shown below in Figure 18 [24].

CHEMICAL COMPOSITION LIMITS (WT. %)

Si	0.40	Zn	5.1-6.1
Fe	0.50	Ti	0.20
Cu	1.2-2.0	Others, each	0.5
Mn	0.30	Others, total	0.15
Mg	2.1-2.9	Balance, Aluminum	
Cr	0.18-0.28		

Figure 18 AA 7075 chemical composition [22]

Its strength-to weight ratio is excellent and it is ideally used for highly stressed parts. Introduced by Alcoa in 1943, AA 7075 has been the standard 7XXX series alloy used within the aerospace industry. A major difference between this alloy and other Al-Zn-Mg-Cu alloys is the addition of chromium to the alloying elements. Chromium helps to resist stress-corrosion cracking in sheet products. One unique property of this alloy is its formability in the fully annealed condition, and subsequently heat treated [22].

2.5.2 Applications

Although other 7XXX alloys have since been developed with improved specific properties, alloy 7075 remains the baseline with a good balance of properties required for aerospace applications. Alloy 7075 is available in several tempers of the T73, T76 and T6 types [22, 24].

Aluminum Alloy 7075 sheet and plate materials have a wide array of applications in the aircraft industry. A few of these applications include structural plate components in excess of 4 inches in thickness, aluminum clad skin sheeting, and typical aerospace applications involving aluminum. This alloy is widely used in the aerospace industry because of its high strength, superb corrosion resistance, and its moderate toughness [22].

2.5.3 Properties

Sheets of bare AA7075-T6 have an A-basis (99%) yield strength between 62 and 69 Ksi and an A-basis (99%) ultimate strength between 74 and 78 ksi. It has a 5% to 8% elongation at break [22].

The clad AA7075-T6 sheet has a nominal cladding thickness of 4% in gauges less than 1.57 mm (0.062 in). Clad T6 sheet has an A-basis yield strength of 58 ksi and an A-basis ultimate strength of 68 ksi. It has a maximum elongation between 5% and 9% [22].

Alloy 7075 sheet and plate products offer moderately good strength/toughness relationships and are the standard of comparison for more recent 7XXX series alloy developments. Alloy 7075 sheet and plate products are not offered with guaranteed minimum fracture toughness values. Alloy 7075 has been thoroughly evaluated for corrosion resistance of atmospheric weathering, stress-corrosion cracking and exfoliation in all currently available tempers. These values have been used as a standard for comparison in the development of more recent high strength aerospace alloys. Within the 7XXX series of alloys, resistance to general corrosion attack, SCC and exfoliation improves significantly in the overage tempers (T7 type) compared with peak strength tempers (T6) [22].

2.5.4 Corrosion

Thorough evaluation of the 7XXX series alloys has shown superior corrosion performance in the over aged (T7 type) when compared with peak strength tempers. Among these alloys, AA 7075 has been shown to have a high resistance to atmospheric weathering, stress-corrosion cracking, and exfoliation in all currently available tempers. These obtained values have been used as a comparison standard for other aerospace alloys [22].

2.6 Aluminum Alloy 2024 (AA2024)

2.6.1 Description

One of the most known and widely used Aluminum Alloys is AA 2024. This alloy is a heat treatable Al-Cu-Mg alloy with a composition shown in Figure 19.

Introduced in 1931 by the Alcoa Corporation, this alloy debuted as an aluminum clad sheet available in the T3 temper. AA 2024 was the first Al-Cu-Mg alloy to approach a yield strength of 50 ksi. This alloy soon replaced the popular 2014-T4 alloy made with duralumin, and the other 2XXX series aircraft alloys. Since the alloy has good fatigue resistance, and continues to be standardized and specified for many other aerospace applications, other alloys have branched from the success of AA 2024. AA 2124 and 2324 have improved strength while C 188, introduced in 1991, offers improved fracture toughness and resists fatigue crack growth while maintaining strength characteristics similar to the 2024 alloy [23, 24].

CHEMICAL COMPOSITION LIMITS (WT.%)

Si . . . 0.50	Zn 0.25
Fe. . . 0.50	Ti 0.15
Cu . . 3.8-4.9	Others, each . . 0.05
Mn . . 0.30-0.9	Others, total . . 0.15
Mg . . 1.2-1.8	Balance, Aluminum
Cr. . . 0.10	

Figure 19 AA 2024 chemical composition [23]

This alloy is available in various forms and tempers, including the popular bare and aluminum clad sheet and plate. AA 2024 is available in the T3, T4, T8, and various other tempers [23].

2.6.2 Applications

Aluminum Alloy 2024 is used widely in manufacturing applications. This alloy is used in plate products ranging from aircraft structural components, aircraft fitting, hardware, wing tension members to truck wheels, transportation industry parts, shear webs, and structural areas. Basically anyplace where stiffness, fatigue performance, and good strength are required, this alloy can be used. Sheet products of this alloy are typically used in the same manner, but in the aluminum clad finish. Aluminum Clad 2024 is used heavily in commercial and military aircraft applications involving fuselage skins, wing skins, engine casings, or basically anywhere an elevated temperature around 250°F (121°C) is encountered [23, 24].

2.6.3 Properties

AA 2024-T3 bare alloy has a yield strength of 42 ksi. This alloy also has an Ultimate Tensile Strength between 63 and 64 ksi, with an elongation at break ranging from 10-15 %. [23]

AA 2024-T3 clad sheet has a cladding thickness that is sheet dependent. For gauges less than 1.6 mm (.062 in.), the cladding thickness is typically 5% of the gauge thickness. Generally AA 2024-T3 clad has a yield strength of 39 ksi and an ultimate tensile strength of 58 ksi. Its elongation at break maxes out between 10-15 % [23].

Although the alumnum 2024-T3 alloy has excellent strength and toughness properties, the corrosion properties of this alloy are somewhat lacking. Alcoa recommends that this alloy be protected from corrosion and faying join surfaces [23].

2.6.4 Corrosion

Cladding of the 2XXX series alloys is almost a necessity in industrial and seacoast atmospheres. Since a clad surface is resistant to corrosive attack, cladding helps to reduce corrosion brought on by atmospheric conditions in these alloys. It is recommended that these alloys be protected, at a minimum, on the faying surfaces [23].

2.7 Sealants and Surface Treatment

2.7.1 Sealants

A sealant is a viscous substance with inert filler material that is applied to the faying surface of the joint and then changes state to become solid. Sealants form a barrier on other materials, resisting the penetration of air, liquid, dust fire, gas, noise, and smoke. They work very good for closing small openings that are not easily seen or closed off by other materials. In addition to the formation of barriers, sealants help increase corrosion resistance, aid in adhesion, and insolubility. Currently sealants are extensively used in many industry applications, such as, aerospace industries and automotive applications [26, 27].

Since sealants are used between materials with different elongation properties, it is imperative that they have proper flexibility and elongation properties. Sealants are formulated with an elastomer to give necessary elongation, flexibility, and low shrinkage, and are usually found in a paste consistency. Elastomers are an important part of sealants, as they need to have adequate adhesion to the substrates to resist environmental conditions, and stay bonded during the life of the joint. Adhesives differ in that they have lower elongations than do sealants [26, 27].

Since putties often have lower strengths, and adhesives higher strengths, putties often fall between the two spectrums. While caulks and putties are effective in keeping out putties and filling voids, sometimes they have electrical problems. Since they have good thermal and acoustical properties, they are often used as barriers [26, 27].

Basically a sealant, regardless the application, has three basic functions. The first function is filling the gap between substrates. The second function is forming a barrier through the physical properties of the sealant itself and by adhesion to the substrate. As last function, it maintains sealing properties for the expected lifetime, service conditions and environments [27].

Li et al. tested a series of friction stir lap welds made with AA 7075. Sealants were placed at the faying surface of the two plates. The welded plates were exposed to a corrosive environment, and observations showed that the hostile conditions did not cause a gap in the FSW lap welds [4, 28].

Similarly, in research conducted by Christner et al., he found that the curing of sealants is accelerated during FSW welding. His process included placing an uncured sealant on the faying surface between two weldable materials. He found that the heat generated from the friction stir welding accelerated the curing of the sealant in the joint [29].

2.7.2 Surface Treatment

Two major categories of aluminum alloys exist, these being wrought and casting alloys. Property development also acts to further differentiate each category. Many aluminum alloys respond to phase solubility thermal treatments, including solution heat treatments, quenching, and precipitant or age hardening [30].

Surface treatments can increase certain properties of an alloy by altering the surface of a metal.

Surface treatments arose as a way to increase wear and corrosion resistance of final products. Since different alloys respond in different ways, various surface treatments were designed. These surface treatments are divided into several different groups, for example electromechanical treatments, chemical treatments, and coatings [30].

One popular surface treatment is that of cladding, which involves metallurgically bonding a thin layer of pure aluminum to the aluminum surface. The anodic cladding layer adds a layer of corrosion protection to the cathodic material in which it encompasses. Since the cladding layer is usually very thin, the reduction of strength on the cladded material is generally minimal when compared to the same un-cladded material [31].

Another surface treatment, anodization, involves placing the metal in an electrolytic solution and passing a current through it. This in return creates an oxide film on the surface of the material [32].

Chemical conversion coatings form by an oxidation-reduction reaction. Chemical conversion generally acts by bonding oxide, phosphate, or chromate compounds to the surface of aluminum alloys. Just like anodization, chemical conversion coatings also create an oxide film on the surface of the material, improving corrosion resistance. Alodine is an example of a chromate based chemical conversion coating [33].

2.8 Application

Currently there are many instances of FSW being used in several industries such as aerospace industry and automotive industry. In 1995 FSW was introduced to U.S. market which has matured a great deal since then. The technology readiness level (TRL) for FSW of aluminum alloys is high with successful industrial implementations. As development efforts and property characterizations have shown that FSW can be used to process ferrous, stainless, nickel, copper, and titanium alloys [7, 14].

The metalworking nature of the process leads to the plunge and refill FSSW methods, with properties comparable to riveted and resistance spot-welded joints. Many applications today rely on friction stir processing of already joined materials via welds or castings. By modifying the microstructure by FSP, it has been shown that a weld can have increased strength, improved fatigue life, and also remove unwanted defects. FSP can successfully be used to create and join new material or combinations of surfaces. Using FSP to stir particulate materials into the surface has shown increased wear resistance and creates particulate-reinforced surface layers [7, 14].

Figure 20 Mazda's new friction stir welder making a weld on a body assembly [34]

Figure 21 the Eclipse 500 business-class jet with friction stir welded lap joint [7]

The environmental friendly and cost effective FSW process has been shown to reduce costs in a wide variety of applications. Since this process does not involve a phase change while joining metals, and also produces a higher-strength joint, this application has enabled the formation of new products. A variety of government, university, and industry collaborated projects are underway to accelerate the implementation of FSW into new productions [7, 14].

During the last decade, the defense and aerospace sectors have taken the lead in implementing FSW. Due in part to recent advances in tool designs and optimizing parameters for specific materials, many FSW and FSSW applications in the marine and transportation industries have excelled. Further development of low cost equipment, industrial standards, and a trained work force will allow the FSW to be implemented by a broader industry [7, 14].

CHAPTER 3
OBJECTIVES AND METHODS

3.1 Objectives

Friction stir welding (FSW) has been shown to have many advantages over traditional metal joining practices used in the aerospace industry. This technology has seen many applications for production such as Boeing’s Delta II and Delta IV Expendable Launch Vehicles, Lockheed Martin’s external tank for the space shuttle transportation system, and primary structures of ultra-lightweight jets like the Eclipse 500. Friction stir welding is also being increasingly used by the automotive industry. Mazda has pioneered friction stir spot welding (FSSW) for some applications in their automobiles, including the door panels of the Mazda RX-8.

Preliminary studies have shown that lap welds and friction stir spot welds (FSSW), in a single spot lap shear test, can be up to 250% stronger than rivets. Additionally, friction stir welded stiffened panels have been shown to be both stronger and to absorb significantly more energy before final failure in static diagonal tension tests than riveted panels. In real life production situations, continuous friction stir lap welds are not always practical, due to intersecting members or other access related issues. For this reason discontinuous friction stir welding and FSSW have become a joining method of interest to the aviation industry. [40]

The primary goal of this investigation was to determine the effects of exit weld location on fatigue life of friction stir welded panels. This was accomplished by coupon testing. In a previous study by Merry [40], he found that exit holes dramatically decreased the fatigue life in the ―no-load transfer” coupons designed and tested in his study. Basically exit holes are sites for crack initiation in fatigue as shown in Figure 22. The goal of this paper is to find a solution in order to reduce the stress concentration around the exit weld location and increasing the fatigue life of the weld termination location. Coupons were fatigued to determine the fatigue life.

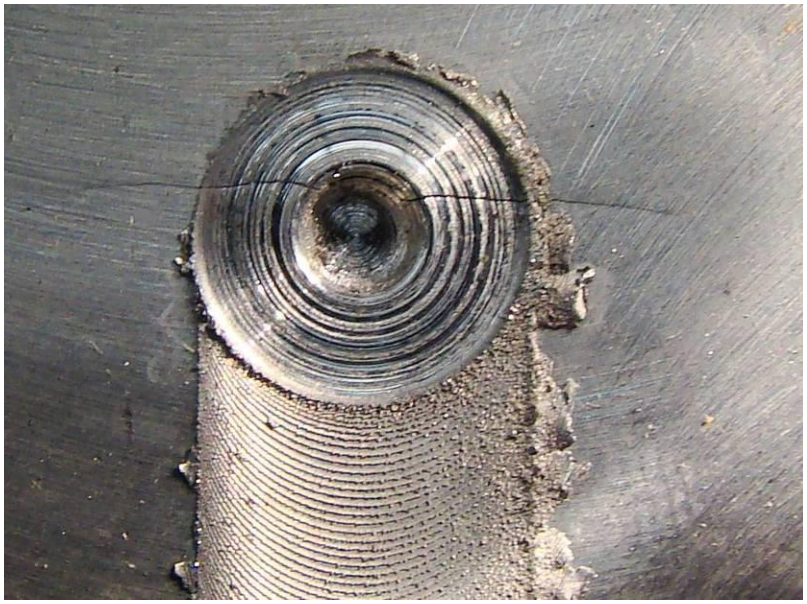


Figure 22 Crack initiation from exit weld location

AA2024-T3 and AA7075-T6 sheets material were used in this experiment. The sheets were 1 mm (0.040 inch) thick. The welding type that is used in this study was lap-weld.

The sealant is used for part of this study was the PRC-DeSoto PR-1432 GP, a 2-part dichromate polysulfide compound. The sealant cures in 72 hours. The sealant has an application time of 1 hour and a tack free time of less than 6 hours [35].

Different methods for eliminate the exit hole or increasing the fatigue life were used in this project. Some experiments on possible exit strategies have already been completed by Merry [40]. Additional possible solutions will be investigated in this research.

3.2 Preliminary Research

In the first year of the program, an evaluation of the weld properties of lap-welded 7075-T6 and 2024-T3 thin-sheet aluminum alloys was conducted by Merry to determine the properties of lap-welds made in the common aerospace alloys: 2024-T3 and 7075-T6 in bare 0.040-inch thick sheets [40]. In his study Merry made the baseline coupons in three different types as shown in Figure 23. The average number of fatigue cycles reported by Merry included in the figure was for the following test conditions: The constant amplitude of 9.6 ksi was conducted for all the coupons. Also all the samples were fatigued at a load ratio of R=0.1 and the frequency of 60 Hz.

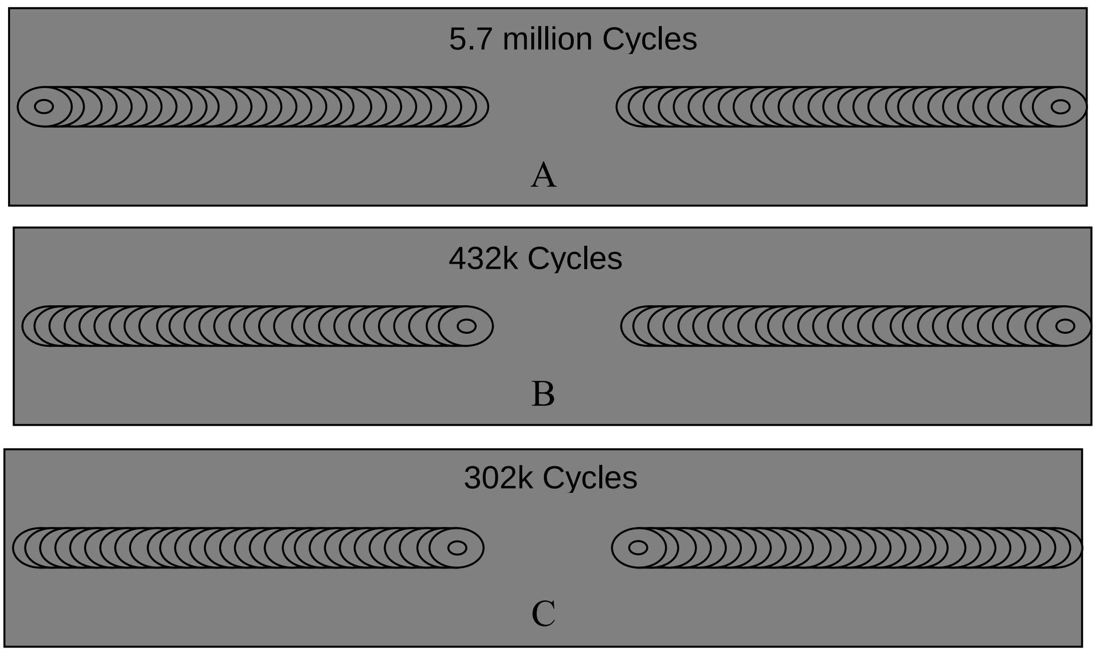


Figure 23 Different types of coupons (A, B and C) [40]

Average of five samples of each type was fatigued and the fatigue life for each type was determined. Type A with no exit hole at the middle of sample had the highest fatigue life with 5,680,000 cycles. Type B with only one exit hole had the second highest fatigue life with 431,631 cycles and finally type C with two exit hole at the middle of coupon had lowest fatigue life with 301,000 cycles. All failures were initiated from the weld exit location. Since secondary cracking was observed at the exit holes of the fiction stir welds, additional coupons were designed to test different weld termination strategies to eliminate or delay the onset of secondary cracking. This next phase of his work was conducted using the same sub-component coupons shown in Figure 23. In addition to testing the sub-component coupons in direct tension with exit holes, two weld exit strategies were also investigated, which included using FSSW and back-welding approximately one-half inch, reference Figure 24 .

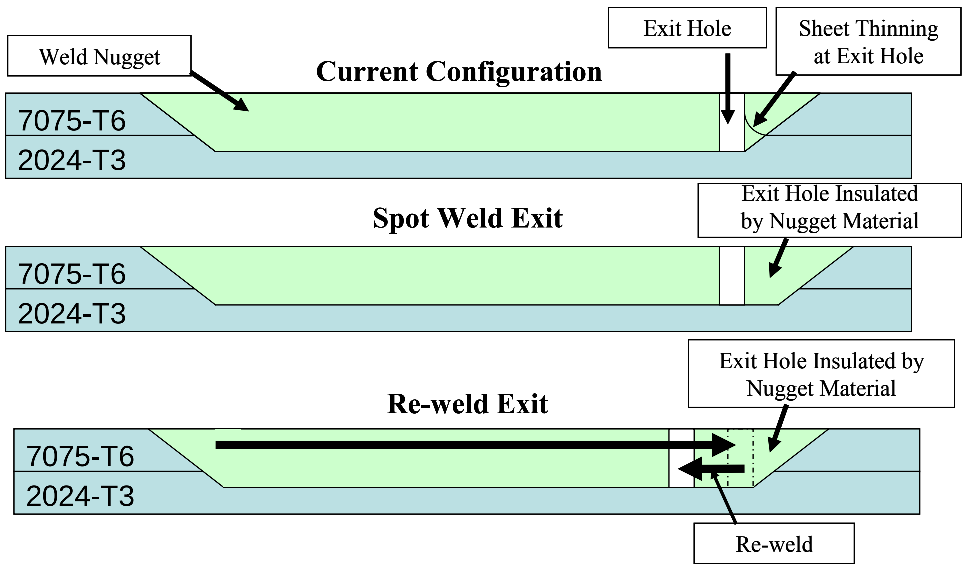


Figure 24 Diagram of weld termination strategies [40]

3.2.1 Adding Swept Spot Weld into the Exit Hole

The first approach to improve the fatigue crack resistance of the exit location of discontinuous welds was to add swept FSSW into the exit hole in order to insulate the exit hole from load with additional nugget material as shown in Figure 25. An average of five samples was fatigue tested and the highest result and lowest result for fatigue life was removed. As in the baseline coupons shown in Figure 23, all the fatigue failures initiated from the weld exit hole. Further, the fatigue life results for type B and Type C coupons with swept spot exit holes were lower than the baseline coupons. The five coupons with spot weld inside the exit hole had an average fatigue life of 356,000 cycles for type B and 311,000 cycles for type C 432,000 cycles and 302,000 cycles, respectively, of the baseline coupons fatigue cycles.

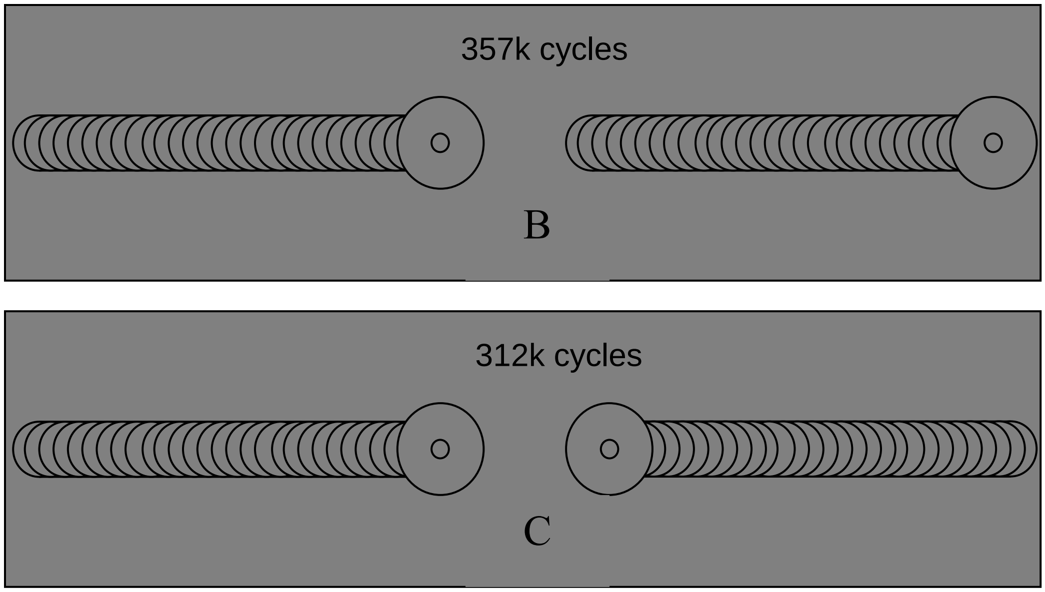


Figure 25 Swept Spot Weld added in to the Exit hole [40]

3.2.2 Re-Weld Exit Coupons

The second approach taken to address to improve the exit location of the discontinuous welds was to travel back along weld path in the reverse direction to place exit hole away from end of the weld as shown in Figure 26.

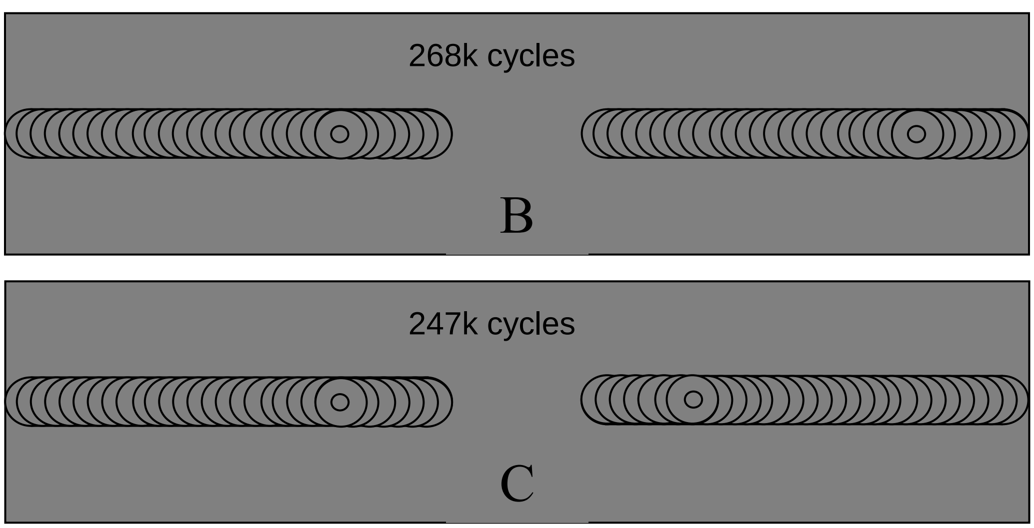


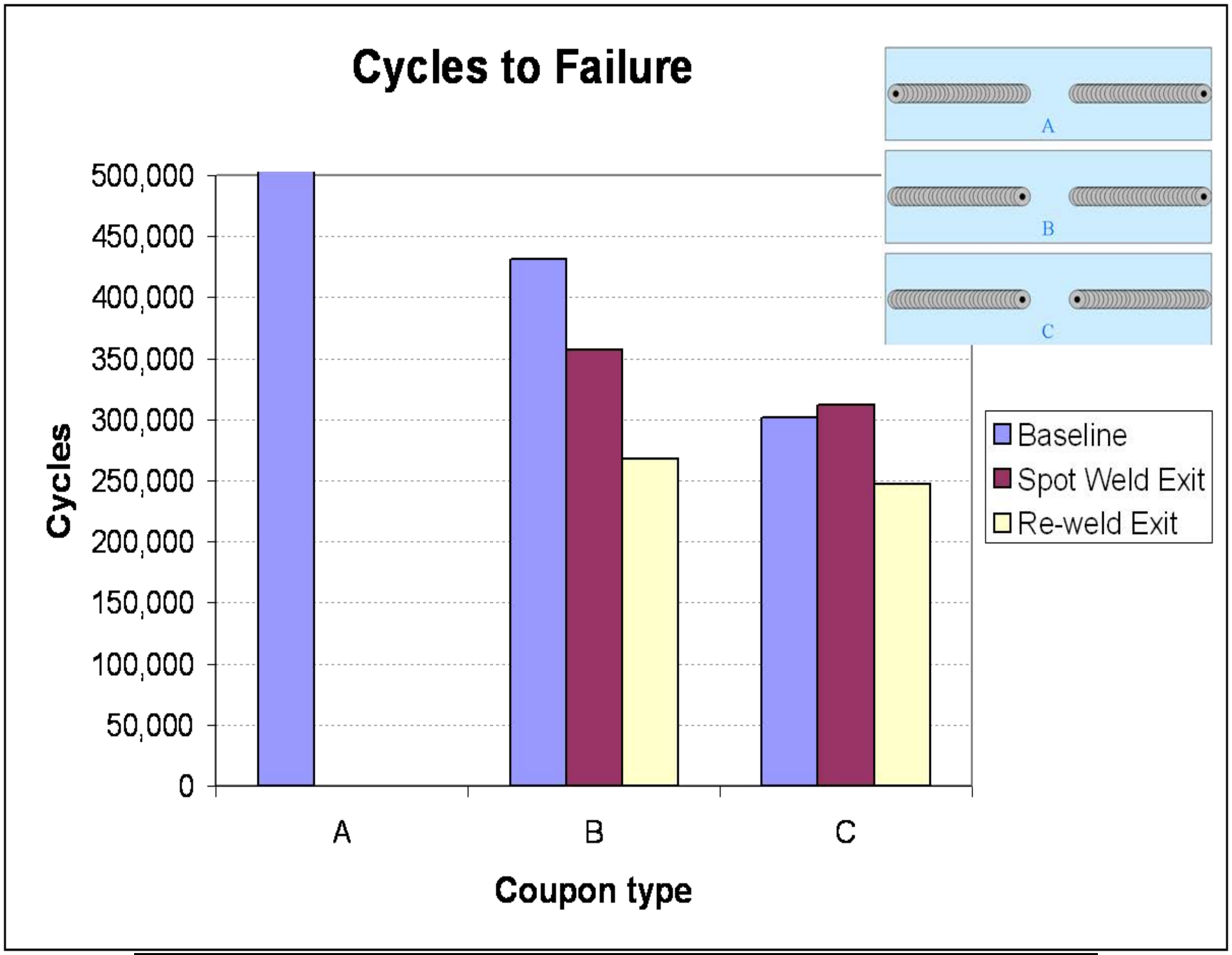
Figure 26 Re-welded coupons [40]

This was expected to remove the exit hole from primary load path. Similarly, five samples were fatigued and the coupons with the highest and lowest fatigue life were removed. The fatigue life results when compared with type B and Type C in baseline coupons were very low even more than the coupons with the swept spot weld exit holes. The five coupons with a re-weld exit hole had an average of 268,000 cycles for type B and 247,000 cycles for type C.

3.2.3 Summary of Results from Preliminary Research

Figure 27 shows the summarized results of the first attempts to develop methods to delay secondary crack initiation at the weld exit hole. There was an order of magnitude of difference between the type A coupons and the B and C.

None of the exit strategies attempted to date was found to delay or eliminate the initiation of fatigue cracks in the exit holes of the FSW lap welds. On The contrary, both back welding and FSSW appear to decrease the fatigue life of the coupons. This behavior can be explained by the simple fact that these are no-load transfer coupons. In these coupons, the same load passes through both sheets. The top sheet includes the exit hole that must naturally act as a stress concentration factor. Consequently, the presence of the exit hole leads to the initiation of fatigue cracks in that area. Furthermore, since FSW results in the formation of a nominal tensile residual stress area within the weld zone due to the sudden increase in temperature followed by rapid cooling, any additional processing of this area may result in the creation of slightly higher residual stresses, further increasing the likelihood of crack initiation. Both strategies were ineffective for the tool design evaluated for this study. As a continuation of the preliminary research by Merry to increase the fatigue life and decrease the stress concentration around the exit hole, new possible solutions were tested in this study. In the next chapter they will be discussed.



Coupon Type	Baseline	Spot Weld Exit	Re-weld Exit
A	5,680,614	-	-
B	431,631	356,980	268,076
C	301,937	311,868	247,272

Figure 27 Fatigue cycles to failure [40]

3.3 Welding of Coupons

3.3.1 General welding practices

The welding of all coupons took place in the Advanced Joining and Processing Lab (AJPL) of the National Institute for Aviation Research (NIAR) at Wichita State University (WSU). The discontinuous friction stir welds were made on an MTS I-Stir Process Development System (PDS) as shown in Figure 28.

Figure 28 5-axis MTS ISTIR™ PDS machine

The welding machine has the 5 axes of motion required to perform the complex movement in the discontinuous lap welds. All the coupons except one case were made from AA7075-T6 as top sheet (simulating a stiffener) and AA2024-T3 as bottom sheet (simulating an airframe skin panel). Based on the preliminary study conducted by Merry, the travel speed for all of the welds was 509 mm/min (20 IPM) and the rotation speed was 2000 rpm. The Counter flow pin length was 1.397 mm (0.055 inch) and 22.22 mm (7/8 inch) spacing used for clamps. All clamps torqued to 54.2 N-m (40 ft.lbs.). 180 grit sand paper was used to clean the oxide film on the sheets before being clamped. A Methyl Ethyl Ketone (MEK) wipe was used for wiping the workpiece. All mechanical testing occurred after a minimum of 100 hours after welding. This time allowed the 2xxx sheets to sufficiently naturally age.

3.3.2 Coupons configuration

An illustration of the sub-size coupon design for investigating fatigue crack initiation at the exit hole of a FSW is shown in Figure 29. The coupons configuration was based on preliminary study by Merry in the first year of this project [40].

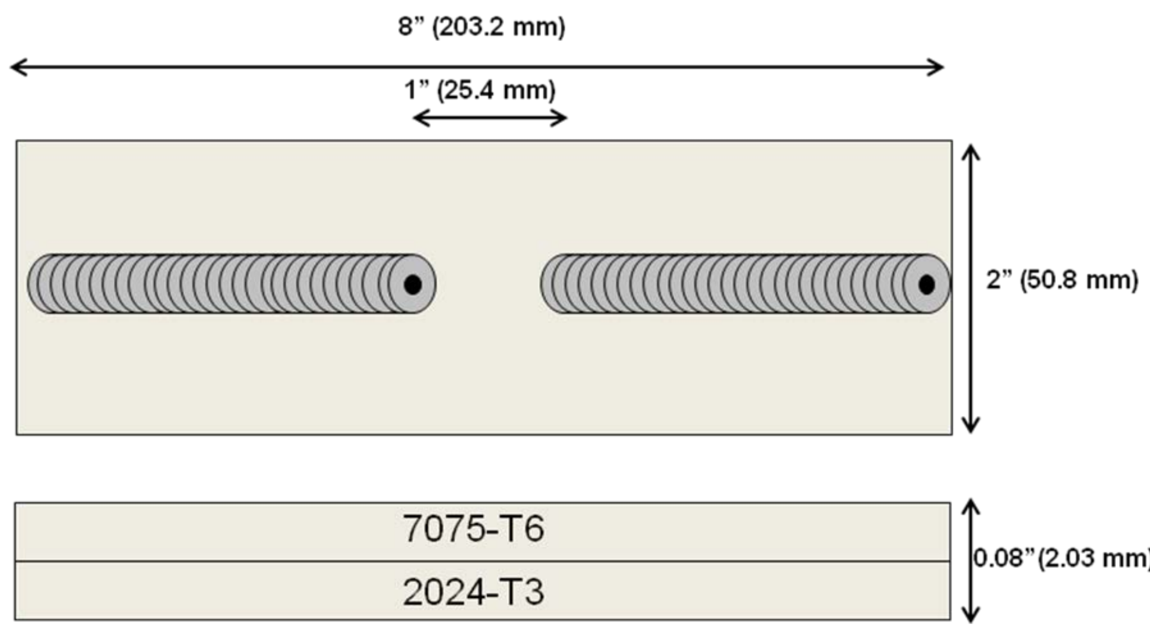


Figure 29 Configuration of coupon

The spacing specified for this coupon was determined by length, width, and thickness. Each sheet’s length was 203.2 mm (8 inch) and 50.8 mm (2 inch) in wide. The aluminum thickness was 1mm (0.04 inch). AA7075-T6 placed as top sheet and AA2024-T3 as bottom. The gap length between each weld line was 25.4 mm (1 inch). The coupon was clamped as illustrated in Figure 30. An overhead photograph of the clamping is provided in Figure 31.

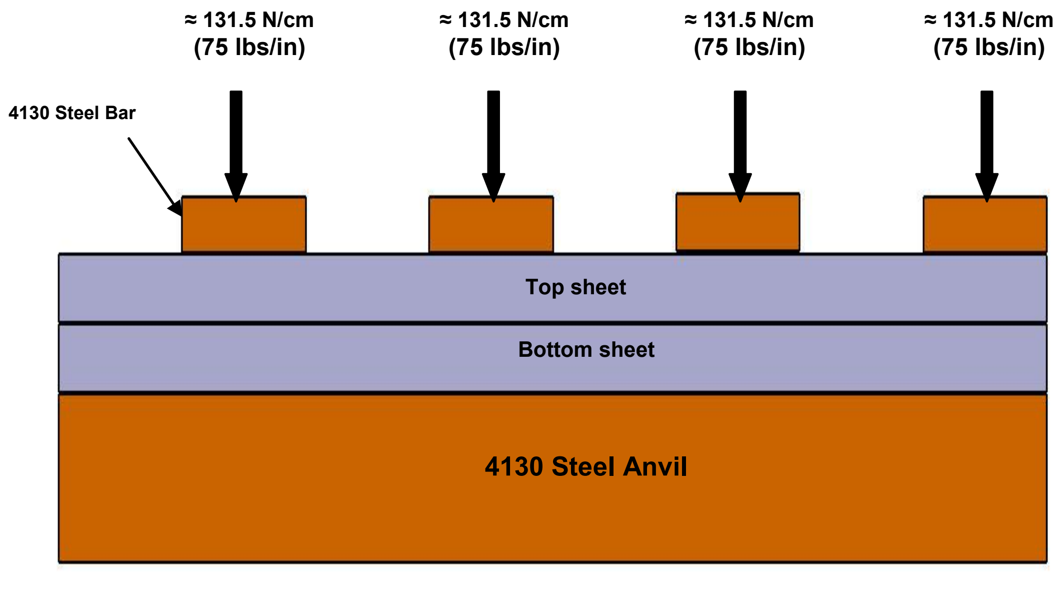


Figure 30 Cross section of coupon clamping

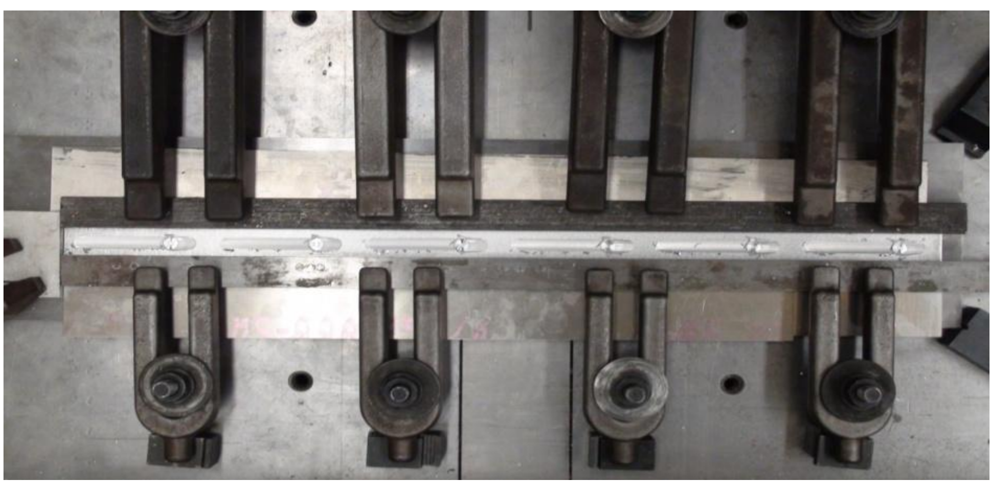


Figure 31 Overhead view of clamping

CHAPTER 4

EXPERIMENTATION

4.1 Tool Selection

4.1.1 Procedure

According to the study by Merry et.al [40], three different FSW tools were initially considered for lap weld applications in his project. Previous development had been completed with these tools in previous lap weld FSW studies. Three lap weld tools were evaluated; the Trivex™ Grande, Wiper Trivex™, and the CounterFlow™ are shown in figure 32, 33 and 34. The best tool for this application was found to be the CounterFlow™ tool. It produced little to no sheet thinning on the advancing side, and there was very little cold lap on the retreating side [40].

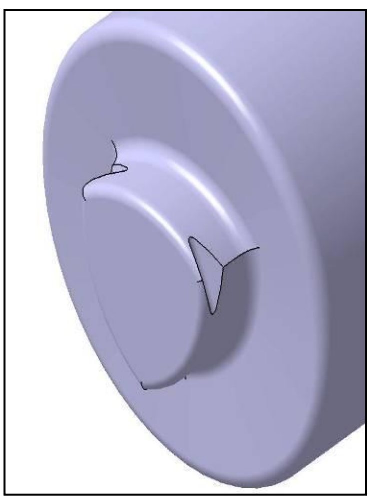


Figure 32- Trivex™ Grande

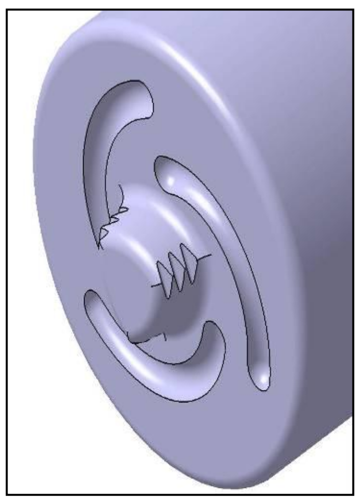


Figure 33- Wiper Trivex™[48]

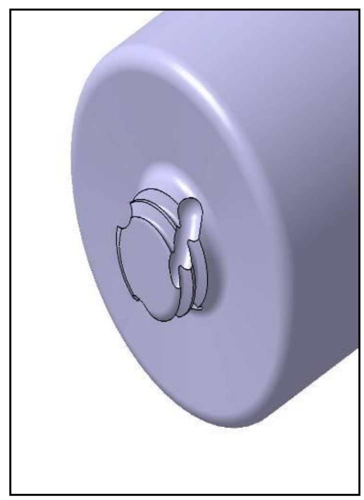


Figure 34- CounterFlow™[47]

The basic features of the three FSW tools were similar. The design of the shoulder and the length of the probe were the same for each tool. The shoulders had a concavity angle of 7° and a diameter of 10.2 mm (0.400 inch). The probe base diameter was of 3.5 mm (0.136 inch) and the length of the probe from the shoulder plane was 1.4 mm (0.055 inch).All the tools were also coated with a special Alpha ™ coating [47- 48].

4.1.2 Results

Unguided lap-shear tensile tests were conducted to evaluate the mechanical properties of the central portion of the welds completed in this study. In order to evaluate the overall performance of the FSW lap welds, two configurations were tested as shown in Figure 35.

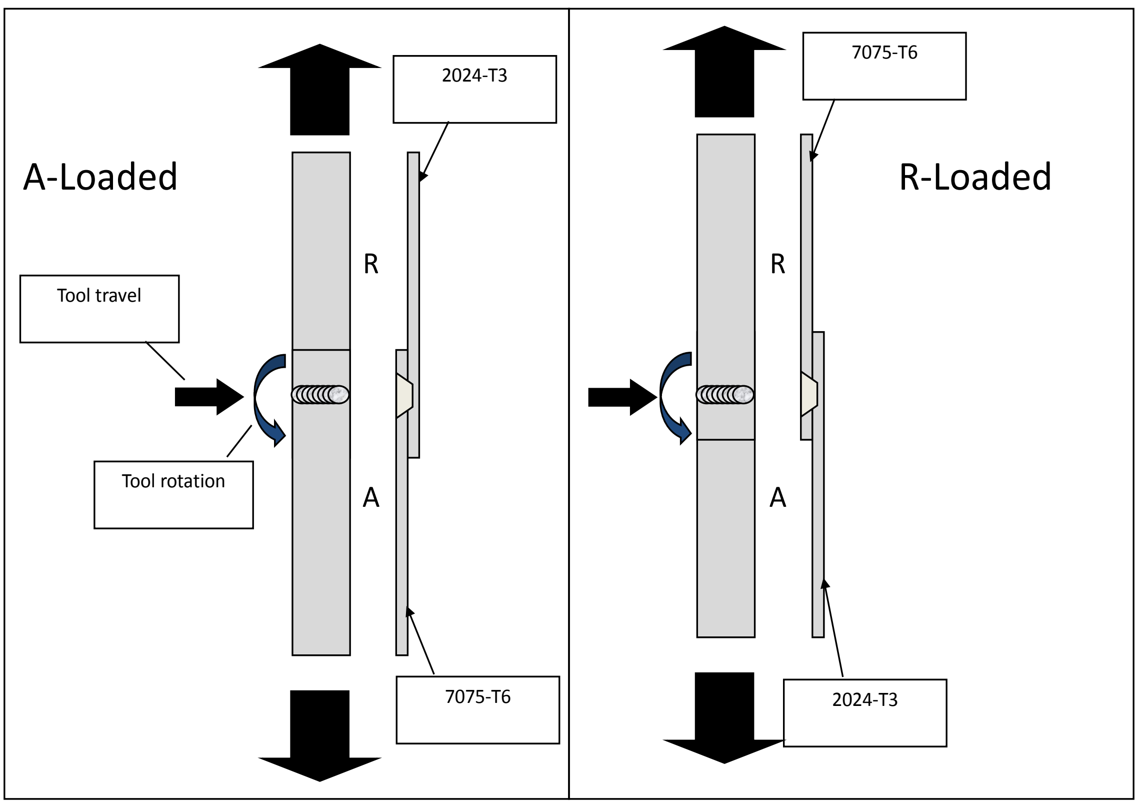


Figure 35 FSW coupons used to evaluate overall lap weld quality [40]

Two coupon configurations were fabricated and tested. The A-loaded coupons refer to the fact that the load path passes through the advancing side of the lap weld. In this case, any upward hooking of the faying surface interface into the top sheet would result in an effective sheet thinning and reduce the load carrying capability of the weld. The R-loaded coupons refer to the fact that the load passes through the retreating side of the weld. In that case, any cold lap defect present in the weld nugget, e.g. as a continuation of remnant oxide from the faying surface interface, would act to decrease the effective shear of the lap weld and hence again decrease its load carrying capability. By testing both configurations, a quantitative evaluation of those two potential weld defects and the overall quality of the lap weld can be made.

According to Merry et.al, two of the tools shown in Figures 32-34 were eliminated during process development due to the difficulty of producing welds with limited hooking and cold lap defects. Representatives from the development phase of the best welds produced with each tool are shown in Figure below. For the best tool, with a threaded CounterFlow™ probe, the retreating side-loaded coupons pulled 2184 lbs./inch, and the advancing side-loaded coupons pulled 2039 lbs./inch. A micrograph of the weld nugget of the Counterflow™ tool is shown in Figure 36. Close up of the advancing and retreating side faying surface interfaces reveal a well balanced weld nugget with almost no up-turn of the interface and very little cold lap present. Therefore, discontinuous lap weld fatigue coupons were fabricated using this tool [40].

The Wiper Trivex™ tool produced the second highest strength specimens of the three tools. The Trivex™ Grande tool produced the lowest strength specimens of the three tools tested. The failure mode for all specimens was plug pullout.

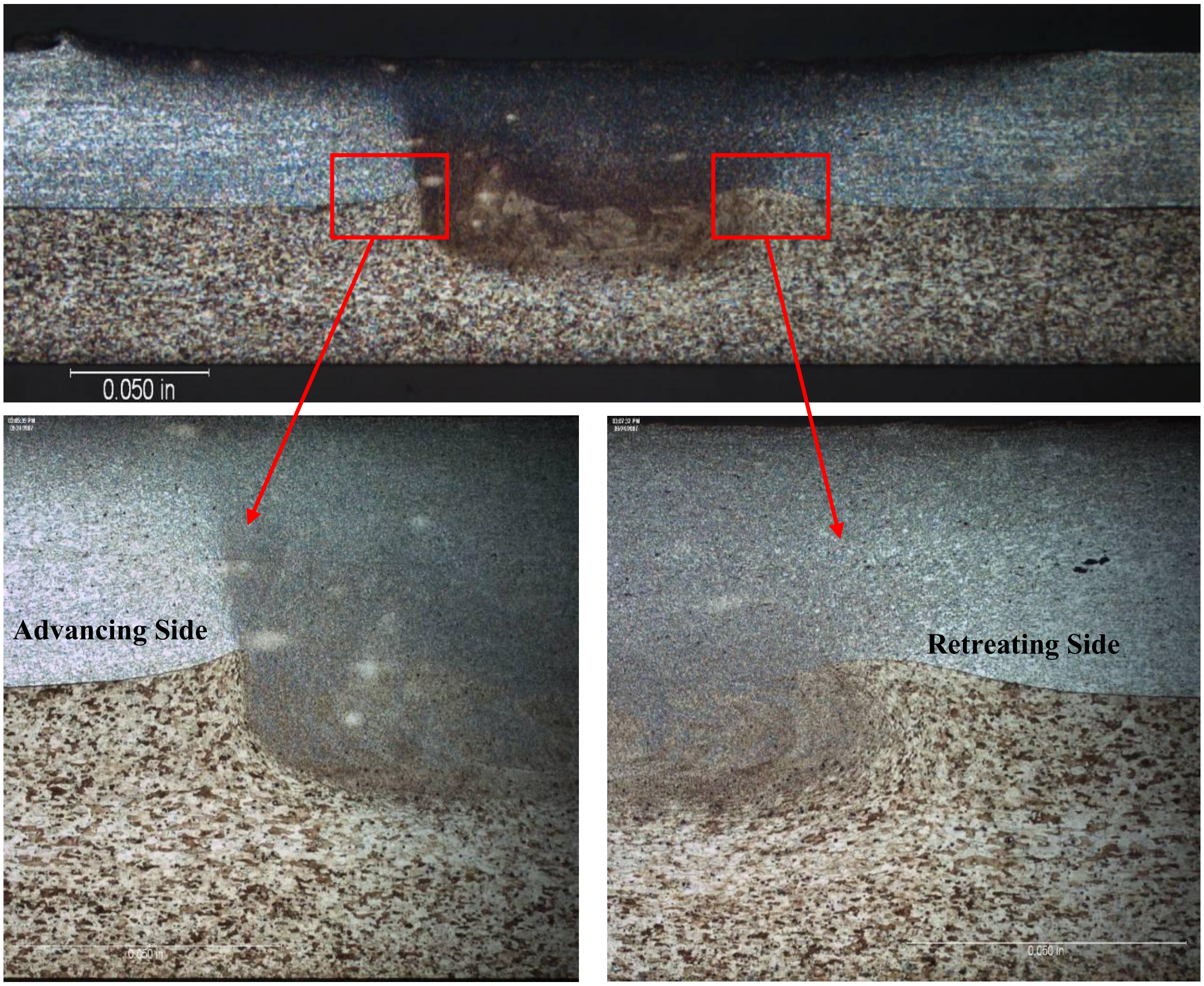


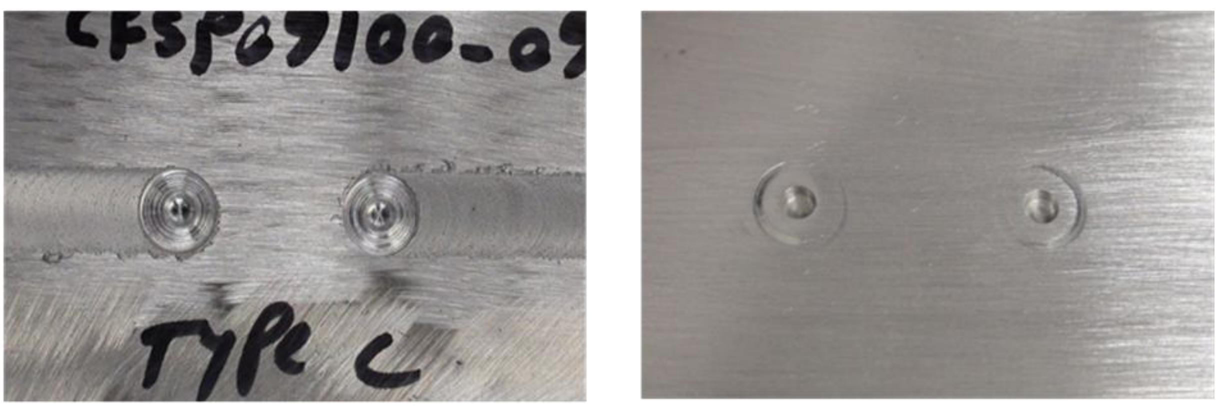
Figure 36 Micrograph of the weld nugget of the counterflow™ tool [40]

4.2 Methods and Possible Solutions

Six exit strategies were proposed for this study. Since the onset of fatigue crack initiation in the exit holes now appears to be due to the presence of the weld exit hole in no-load transfere coupons, several of these involve methods to eliminate the exit hole. Certainly the simplest and least practical method is to not terminate a weld in the structure; however, since there may be very few applications where weld terminations could easily be eliminated other methods are required.

4.2.1 Polishing inside the exit hole and the welded side surface

The idea was that pin tools with no threads on the probe typically produce smoother exit holes and, therefore, may improve fatigue life by delaying crack initiation. To that end, coupons were polished with 400 grit and 1200 grit sand paper in order to make a smooth surface inside the exit hole as wells as top sheet surface as shown in Figure 37. Five coupons were welded then polished and fatigue tested in MTS load frame machine. The constant amplitude load was conducted for all the coupons. Also all the samples were fatigued at a nominal stress of 9.6 ksi (1536 lbs) and load ratio of R=0.1. The same Fatigue parameters and conditions were applied for fatigue testing of all exit strategies. Five type B and five type C coupons were to be fatigued at a frequency of 60 Hz until they reached to 5 million cycles of loading then they were assumed to have reached runout. However, the welded coupons with polished exit holes had an average of 411,000 cycles for the type B coupons, and 320,000 cycles for the type C coupons.



Before After

Figure 37 Polished coupons with sand paper (before and after)

4.2.2 Installing Rivets

NAS1097AD4 rivets were installed inside the exit hole with the same diameter as base probe in two different configurations. In the first configuration the countersink was toward the un-welded side of the coupons and in the second configuration the countersink was toward the welded side of the coupons as shown in Figure 38 and 39. Five coupons were welded for each configuration and then fatigue tested in an MTS load frame machine at a constant amplitude load. The coupons were to be fatigued at a nominal stress of 9.6 ksi (1536 lbs) and load ratio of R=0.1, until they reached to 5 million cycles of loading, at which point it would be assumed that they had reached run-out. Type B coupons with the countersink toward the welded side reached an average of 2,111,000 cycles and coupon with type C reached an average of 3,452,000 Cycles. Similarly, coupon type B with countersink toward the un-welded side reached an average of 2,560,000 cycles and coupon with type C reached an average of 5,000,000 cycles.

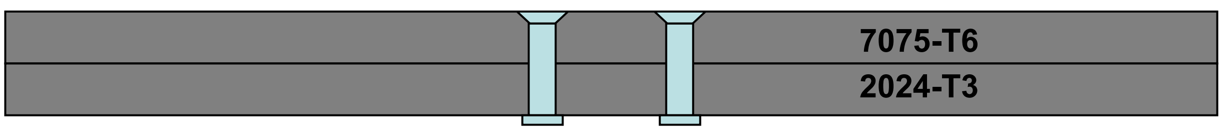


Figure 38 Countersink toward the welded side (Type B & C)

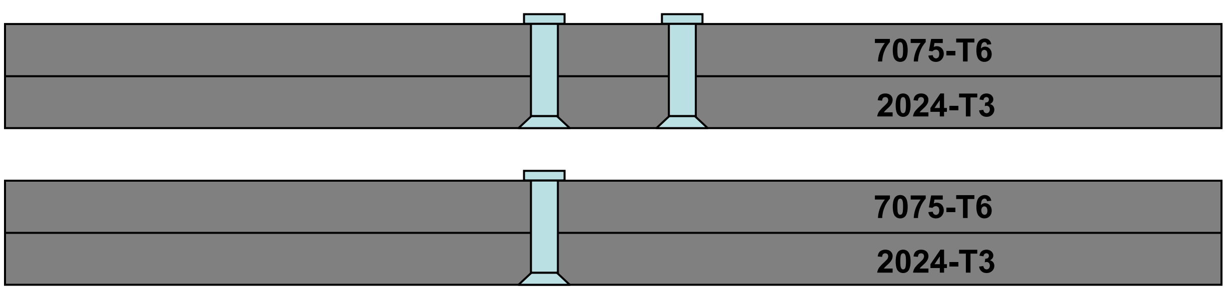


Figure 39 Countersink toward the Un-welded side (Type B & C)

4.2.3 Adding faying surface sealant

Brown et al [4] investigated welding through sealants in swept FSSW lap welds. The sealant was PRC-1432 GP, which is a two part dichromate polysulfide compound. The sealant cures in 72 hours. The sealant was applied using a roller with a 3/8 inch nap. It was applied on the faying surface of one sheet. The thickness was kept between 2.5 and 3.5 thousandths of an inch. This thickness range was within the suggested limits for this sealant in FSW applications. [41]. A schematic of the coupon with sealant between the top and bottom sheets is illustrated in Figure 40.

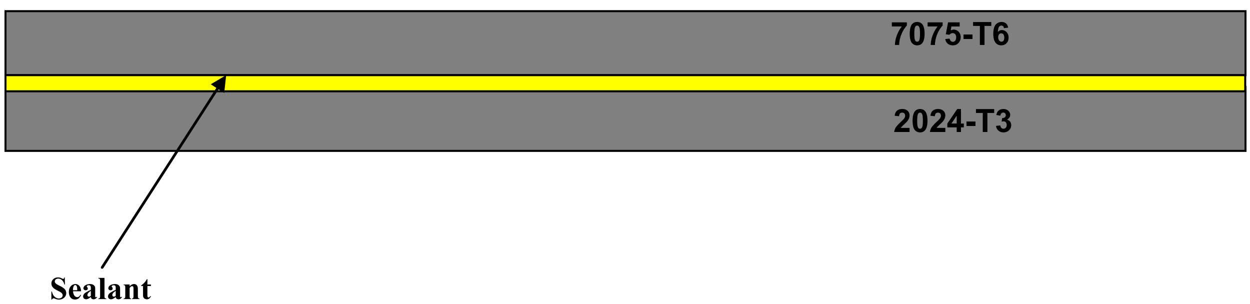


Figure 40 Coupon with Sealant Configuration

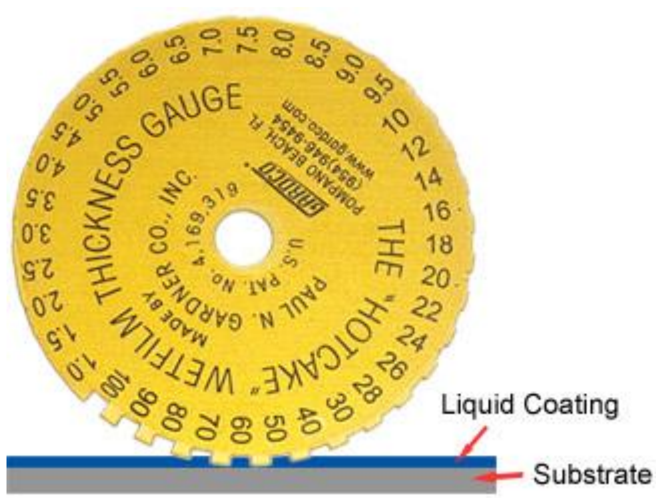


Figure 41 Hotcake wetfilm thickness gauge [4]

It was measured with the Hotcake wetfilm thickness gauge, shown in Figure 41. The joint was welded within 15 minutes of the application of the sealant [4]. Five coupons were welded and then fatigue tested in MTS load frame machine. The five Type B coupons achived an average of 417,000 cycles and the five type C achieved an average of 329,000 cycles.

4.2.4 Drilling the exit hole

Average of five welded coupons in baseline configuration were drilled out in each type (B and C) all the way through the top sheet and bottom sheet inside the exit hole using a drill bit with the same diameter as probe in order to investigate the difference in fatigue life between the coupons with general exit hole and coupons with open hole as shown in Figure 42.

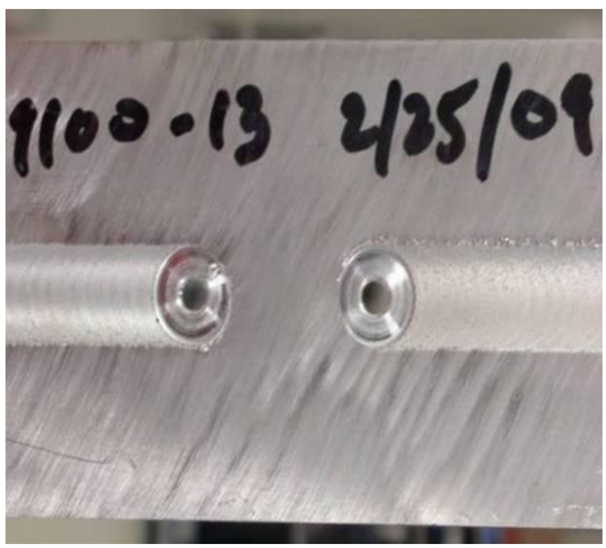


Figure 42 Type C with drilled exit hole

Five coupons were fatigue tested in MTS load frame machine. The five type B Coupons achieved an average of 371,000 fatigue cycles and the five type C coupons achieved an average of 290,000 fatigue cycles.

4.2.5 Reversing top sheet and bottom sheet

In this strategy, the top sheet and bottom sheet were reversed with the AA2024-T3 on top and the AA7075-T6 sheet on the bottom as shown in Figure 43. The same pin tool and weld parameters were used. Five coupons were welded and then fatigue tested in MTS load frame machine. The five type B coupons achieved an average of 470,000 fatigue cycles and the five type C coupons achieved an average of 419,000 fatigue cycles.

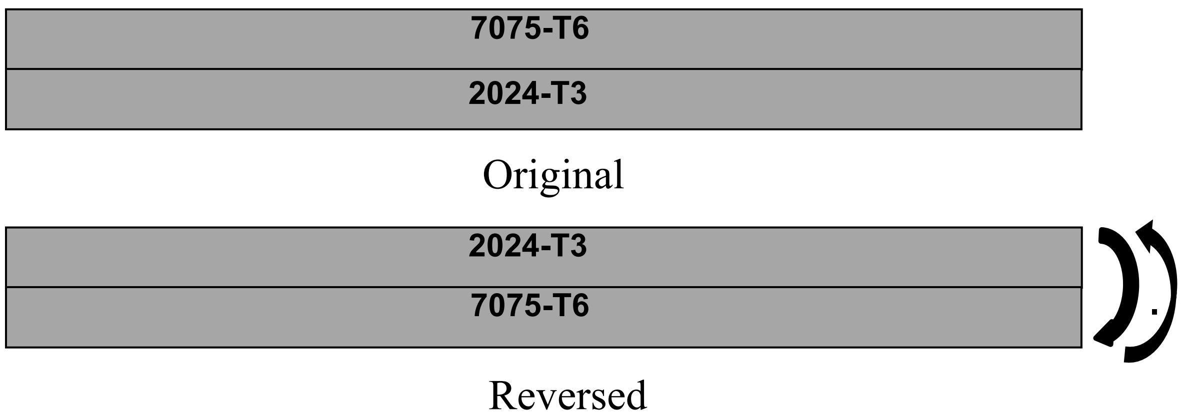


Figure 43 Schematic of reverse coupon

4.2.6 Use of retractable coupons

As discussed in Chapter One, the use of a retractable pin tool allows for the elimination of the exit hole. The pin of the tool is gradually raised during welding until the end of the pin is flush with the shoulder surface. Two methods were considered. In both methods coupons were welded using a retractable pin tool design that was based on the fixed pin design and using the same welding parameters as the fixed pin design.

In the first method, the weld direction was reversed at the end of the weld. Upon reversing the weld, the pin was retraced in at a constant rate over a distance 0.5 inch. Figure 44 shows a schematic of the welded coupons with traveling back-weld. Five coupons were welded and then fatigue tested in MTS load frame machine. The five type B coupons achieved an average of 744,000 cycles and the five type C achieved an average of 663,000 cycles. The fatigue results showed that the fatigue failures at the exit hole were eliminated, with failures now initiating at the weld end locations, and that the fatigue life was vastly improved in comparison to baseline coupons fatigue life with type B and C without special exit strategies.

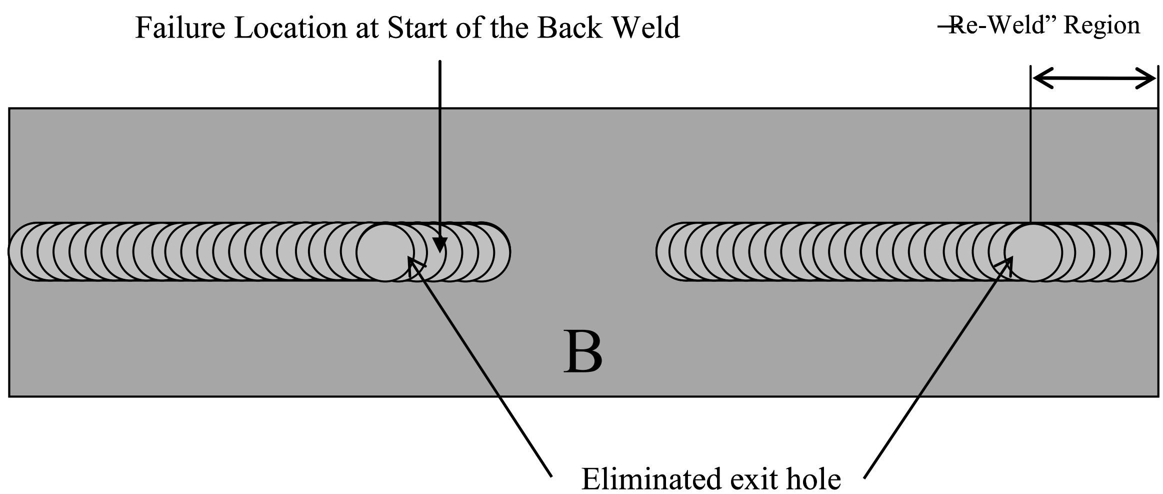


Figure 44 Retractable welded coupon with back-weld

It was noted that the fatigue failures initiated at the start of the weld path reversal i.e. at the start of the back weld as indicated in figure 44 of these coupons much sooner than in the Type A coupons using the fixed pin tool reported by Merry (where only weld starts were included in the test section). After a detailed analysis of the weld micrographs of the fixed pin and retractable pin tools, it was discovered that the retractable pin tool welds made at the same welding parameters as the fixed pin tools produced a deeper pin penetration and deeper flashes than the fixed pin tools. This leads to an increase in hooking of the faying surface interface as shown in Figures 45 and 46.

Therefore a second method was investigated in which the weld parameters for the RPT tool were modified. Also, there was no weld reversal or travel-back along the weld path. The pin was retracted at a constant rate beginning nominally 0.3 inch from the end of the weld to a position that was retracted to be flush with the shoulder surface. The duration of retracting the pin tool was determined to be 1.22 seconds based on the plot for signal values for forge force and pin position of friction stir welding machine as shown in Figure 45. A coupon with no exit hole and no traveling back or weld reversal is illustrated in Figure 47. Under the same fatigue conditions that were mentioned above, an average of 5 samples for each Type of the coupons (B and C) were fatigue tested. Both Types of coupons (B and C) had an average of 5,000,000 cycles. The result for case 2 showed that using the RPT for this configuration improved fatigue life of the coupons vastly.

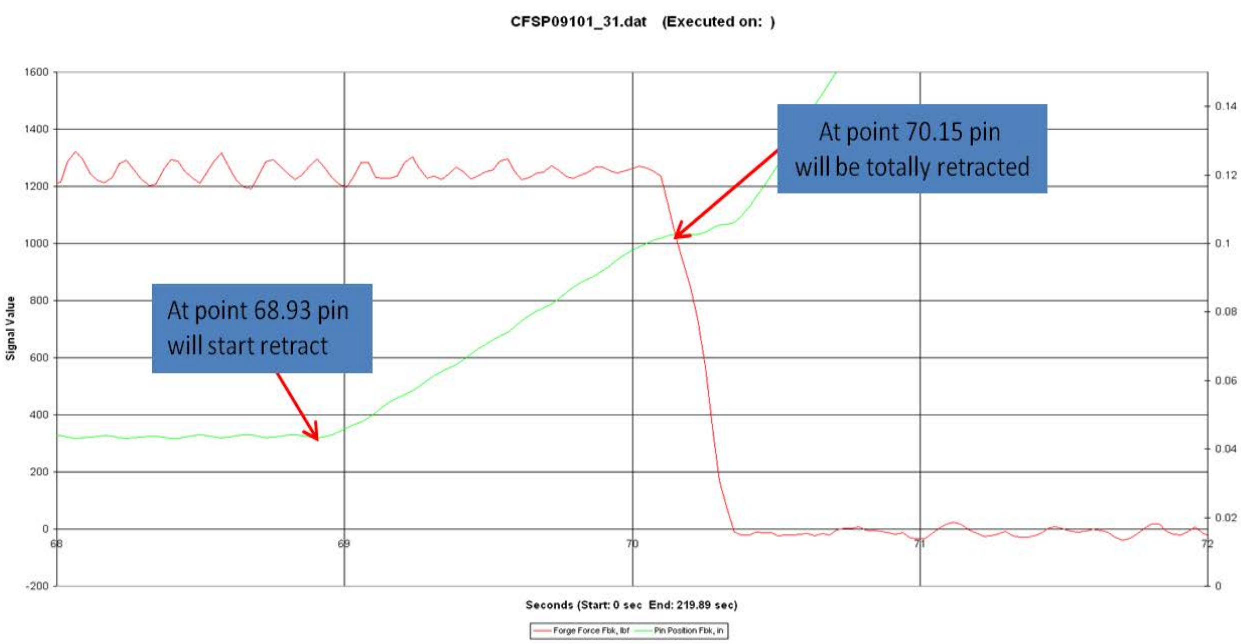


Figure 45 Forge force and pin position feedback

After a detailed analysis of the weld macrograph of the RPT for second method, it was observed that there was no hooking at the nugget of the weld where the RPT was retracted from the bottom sheet. In Figure 47 a macrograph of the weld zone for a coupon with no back weld is illustrated.

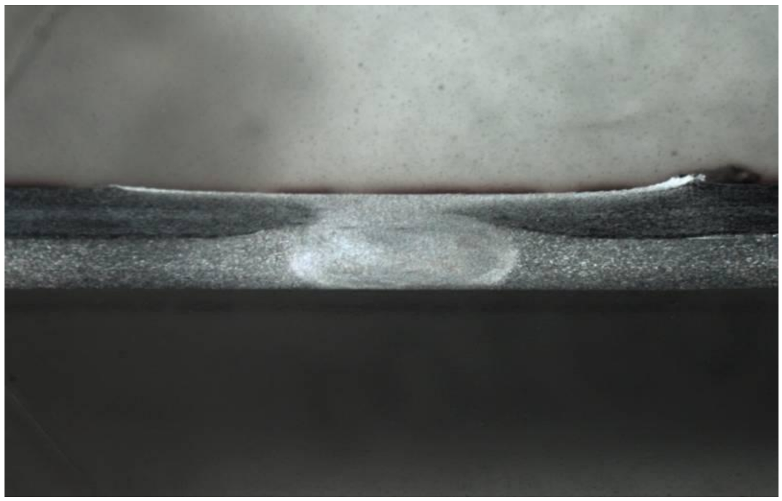


Figure 46 Micrograph of the retractable back-welded coupon with deeper penetration

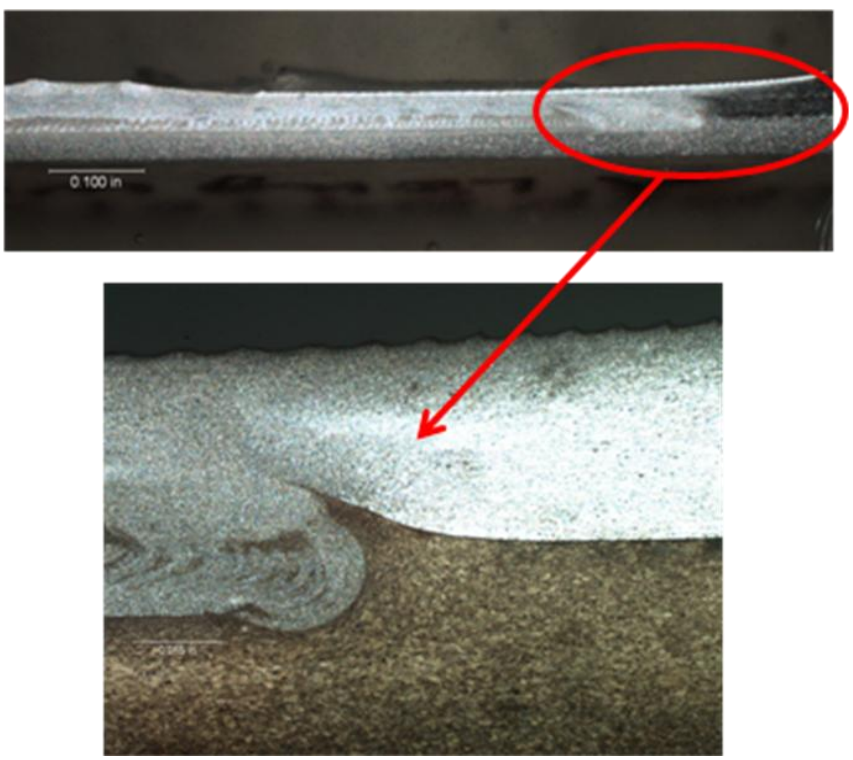


Figure 47 Micrograph of the retractable back-welded coupon with hooking

Figure 48 Coupon with eliminated exit hole

Figure 49 Micrograph of the retractable coupon without back-weld and hooking

4.3 Results and Discussion

Once all of the coupons in the different configurations described in the previous section were welded, they were then fatigue tested at a nominal stress of 9.6 ksi (1536 lbs) R=0.1.

The results for all fatigue coupons are provided on a Life-Cycle plot, in Figure 47.

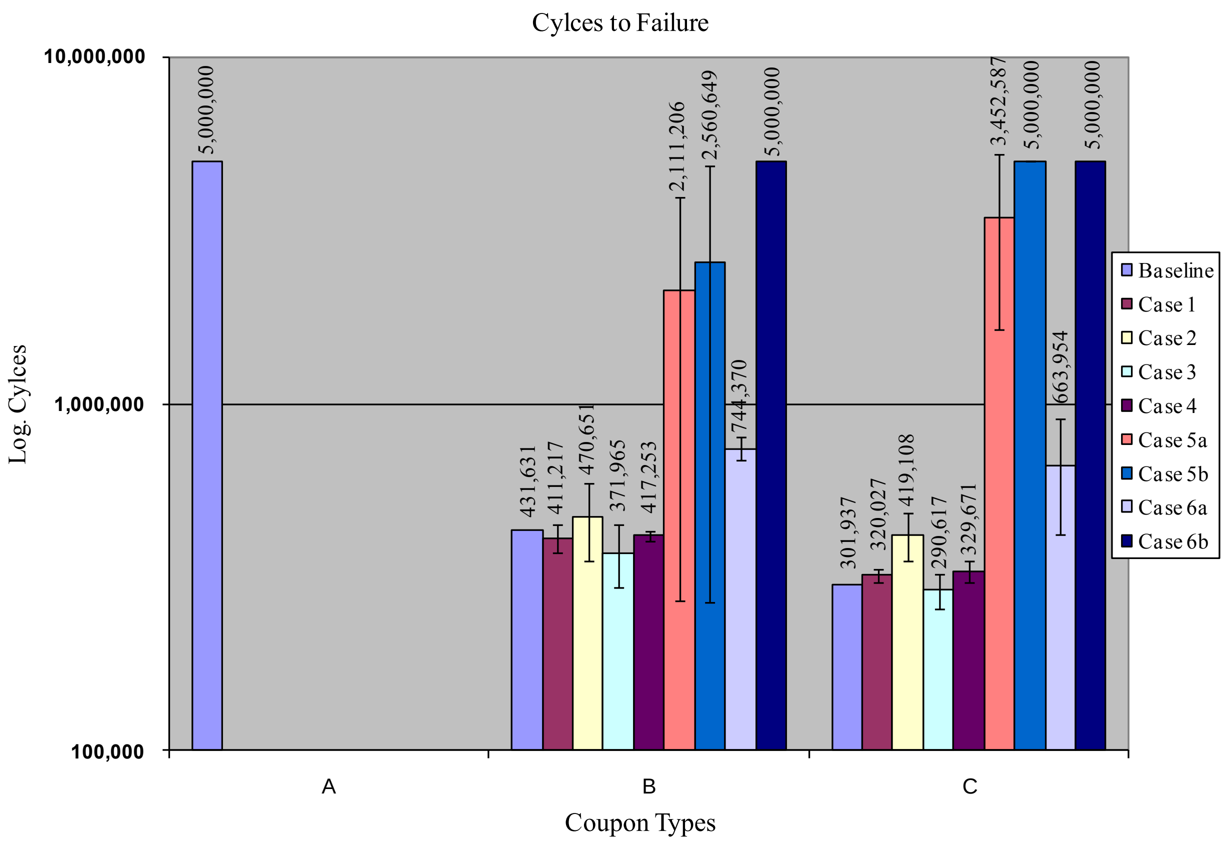


Figure 50 Fatigue life for tested coupons

The average of fatigue cycles for the different weld termination strategies evaluated in this study are shown in Table 1. Complete fatigue results for each type and each configuration are shown in Tables 2 – 9 in the Appendix.

Table 1 Average of fatigue cycle for each type

Coupons Type	Baseline (Cycles)	Case 1: Polish (Cycles)	Case 2: Reverse (Cycles)	Case 3: Drill (Cycles)	Case 4: Sealant (Cycles)	Case 5a:Rivet Toward Weld Side (Cycles)	Case 5b:Rivet Toward Un-weld Side (Cycles)	Case 6a: RPT with Back weld (Cycles)	Case 6b: RPT without back weld (Cycles)
A	5,000,000	-	-	-	-	-	-	-	-
B	431,631	411,217	470,651	371,956	417,253	2,111,205	2,560,649	744,370	5,000,000
C	301,937	320,027	419,108	290,617	329,670	3,452,586	5,000,000	663,955	5,000,000

High-cycle fatigue tests were conducted on the Type A coupons (no exit holes) and all of the coupons were run-out at five million cycles. These results were used as the baseline for a comparison of the rest of the coupon types. The high fatigue life is also the reason for not continuing the study of Type A coupons through the six study cases.

The results from Case 1 for Type B (polished weld surfaces & one exit hole) were roughly 20,000 cycles less than the baseline for the type B coupons developed under the preliminary research for this project. The Case 1 study for the Type C coupons resulted in a fatigue life approximately 19,000 cycles higher than the baseline. This difference is negligible when compared to the Type A baseline which is five million cycles. These results show that by polishing both the weld and exit hole produce no significant change in the fatigue life.

Case 2, which was reversing which material was on top and bottom, produced a little higher fatigue life than the baseline and Case 1 for Type B. Type C produced an even greater fatigue life in Case 2 than in the baseline or Case 1; however both values are still negligible when compared to the Type A base line. This is probably due to the higher durability and damage tolerance characteristics of the 2024-T3 material compared to 7075-T6. As a result it is more difficult for a crack to initiate and grow when the exit hole is placed in the 2024-T3 material instead of 7075-T6, giving a slight improvement in overall fatigue life. There are also some differences in material flow that could also be contributing to the apparent slight improvement in fatigue life.

Case 3 showed a slight drop in fatigue life in both Type B and Type C, which is due to the increased stress concentration formed by drilling the exit hole. This demonstrates that leaving the exit hole in place in these FSW coupons was certainly no worse than an open hole, and would be a conservative way of evaluating exit holes in a structure. Again, however, these changes in values are insignificant when compared to the Type A baseline.

Case 4, which was the baseline coupon plus a faying surface sealant, performed similarly to the baseline coupons in Type B and Type C. This demonstrates that the presence of a faying surface sealant in this case did not have a significant effect on fatigue life. The slight differences in fatigue life values observed were not significant when compared to the Type A baseline.

For case 5a (installing a rivet into the exit hole with the countersink in the 7075-T6 material on the welded side) the Type B coupons show a drastic increase in fatigue life when compared to the Type B baseline, however are still only about half of that of the Type A baseline. Type C coupons for Case 5a also showed a dramatic increase in fatigue life compared to the previous cases for this type, but again are only around two thirds of the Type A baseline. Case 5b (installing a rivet into the exit hole with the countersink in the 2024-T3 material on the un-welded side) showed the most significant increase for the rivet cases for both Type B and Type C coupons with a run-out value at five million cycles. The use of rivets to fill the exit hole clearly resulted in a dramatic improvement in fatigue life in both coupon types, regardless of from which side the rivet was installed. Because these are compression rivets and the test stresses were relatively low for high-cycle fatigue, there is some load transfer through the rivet, thus reducing the stress concentration associated with the exit hole.

The retractable pin tool (RPT) was investigated as the last potential method to enhance the fatigue life of the baseline coupons. The results for Case 6a (RPT coupons with back-weld) for both Type B and Type C coupons are almost similar and showed a drop in fatigue life from Case 5a & 5b (riveted exit holes) but are about twice that of the base lines of the coupon types with FSW exit holes. These values are still insignificant when compared to the run-out baseline of Type A. During these welds, there was a change in tilt angle of the pin tool in order to complete the back welding process, thus creating a hooking effect and decreasing the fatigue life of the weld. This is due to the increased stress concentration at the interface. The hooking effect may possibly be eliminated if a zero degree tilt angle was used, thus eliminating the stress concentrations created by the hook, however it was not investigated. Deep flash indentations also occurred during this weld which increased the probability of cracks and failures initiating. Case 6b (RPT coupons without back-weld) showed the most promising result of all of the cases for both Type B and Type C coupons with a run-out value of five million cycles, which is the same as the Type A baseline. By using the RPT, a smooth gradient, with no hooking of the faying surface, was created at the interface leaving no exit hole and thus greatly reducing any possible stress concentrations.

Table 2 Failure location for examined cases

Coupon		Failure Location %					
		Exit Hole	Weld Start	Weld Middle	Weld End	At/Near Grip	N/A
Baseline	Type A						100%
	Type B	100%					
	Type C	100%					
Case 1	Type B	100%					
	Type C	100%					
Case 2	Type B	100%					
	Type C	100%					
Case 3	Type B	100%					
	Type C	100%					
Case 4	Type B	100%					
	Type C	100%					
Case 5a	Type B		60%	20%			20%
	Type C					60%	40%
Case 5b	Type B		60%				40%
	Type C						100%
Case 6a	Type B				100%		
	Type C				80%	20%	
Case 6b	Type B						100%
	Type C						100%

In Table 2, the percentage of failure location for all the cases as well as baseline coupons is illustrated. As discussed before regarding the Type A baseline coupons, it was observed that none of them failed and were run-out at five million cycles. But in Type B and Type C of the baseline coupons the failure location was observed in the exit hole location, reference Figure 51. For the same reason, in cases 1 to 4 the failure location was also observed in the exit hole. The explanation for this before as discussed previously, is due a stress concentration at the exit hole which causes a reduction in fatigue life.

For Type B of case 5a and 5b, 60% of the failure locations were in the weld start of the coupons, shown in Figure 52, and it is due to having a relatively large hooking defect in this region. Also 20% of the coupons in Type B of case 5a failed in the middle of the weld, presumably due to crack initiation in the roughened surface of the weld track, reference Figure

53. For Type C of case 5a, 60% of the failure was occurred at the grip, shown in Figure 54, and 40% of the coupons did not fail, however Type C of case 5b, none of the coupons failed and were again run-out at 5 million cycles. It is important to note, that none of the failures occurred at or near the installed rivets. Therefore, the differences in fatigue life, as compared to the baseline type A coupons, could be the result of some minor variation in weld setup, process conditions, or a symptom of pin tool wear.

In Type B and C of the case 6a, all of the coupon failures were observed at the end of the weld due to existence of a hooking defect and deep weld flash in this zone, as discussed previously, reference Figure 55. There was, however, an exception with one failure occurring at the grip for Type C of case 6a.

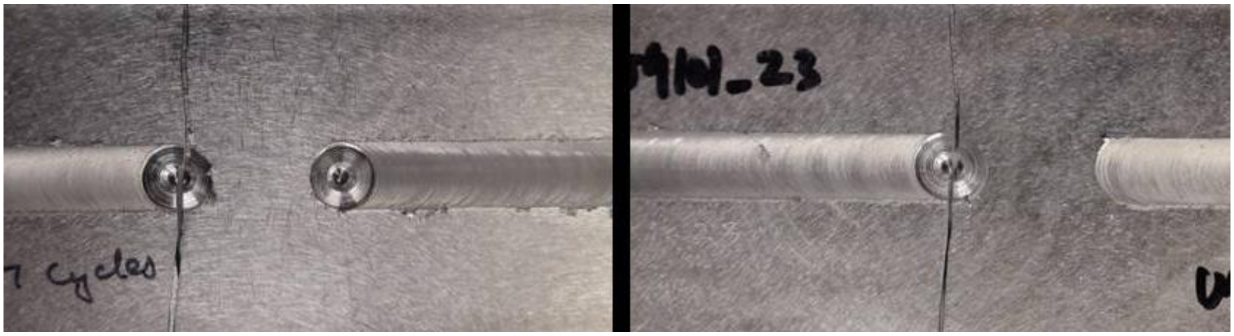


Figure 51 Example of failure location at the exit hole

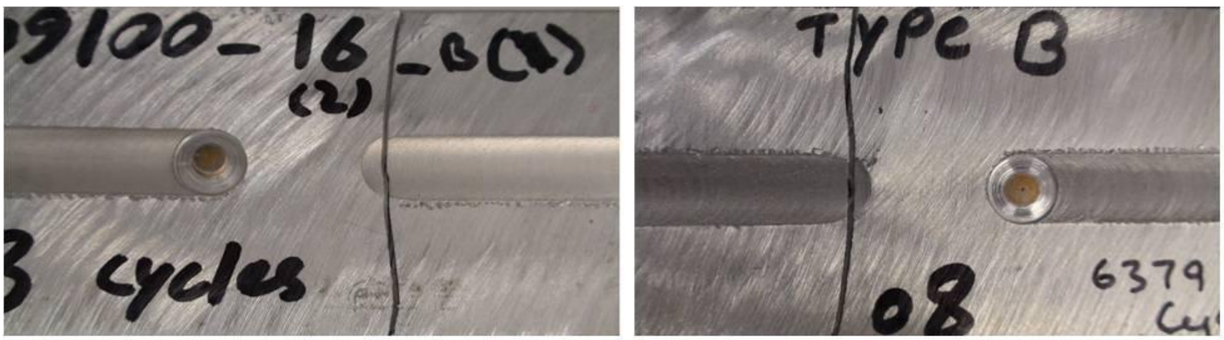


Figure 52 Example of failure location at the weld start

Figure 53 Example of failure location in the middle of the weld

Figure 54 Example of failure location at or near the grips

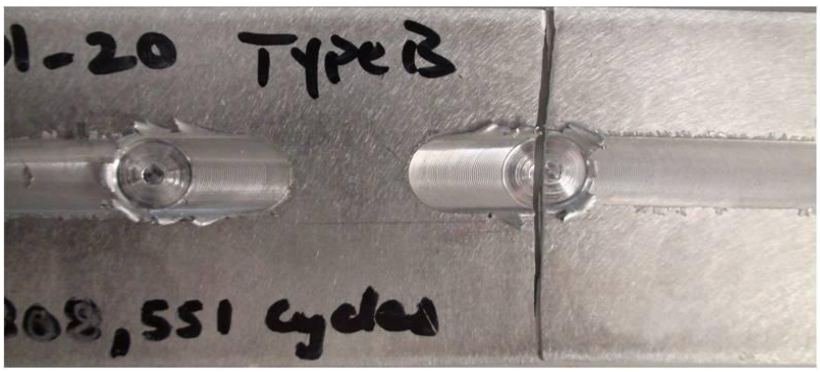


Figure 55 Example of failure location in weld end (exit hole eliminated)

CHAPTER 5

CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Secondary crack initiation in no-load transfer FSW panels was observed to initiate at the exit holes of discontinuous lap welds. None of the exit strategies attempted to date was found to delay or eliminate the initiation of fatigue crack initiation in the exit holes of the discontinuous FSW lap welds except for the use of the retractable pin tool (RPT), which is able to eliminate the exit holes completely. The results indicated that the number of fatigue life for friction stir retractable welded coupon with no back weld produced similar fatigue results as the fatigue life of the Type A baseline coupons produced by Merry. In Type A coupons there are also no holes in the gage section of the fatigue coupons. Also adding rivets inside the exit hole vastly increased the fatigue life of the coupons.

The other possible solutions tested in this study did not increase in fatigue life cycles, however. In fact, back welding, FSSW and drilling the exit hole appear to slightly decrease the fatigue life of the coupons welded with a fixed pin. This behavior can be explained by the simple fact that since the coupons are no-load transfer coupons, the load passes through both sheets. This means that the exit hole introduces a stress concentration that leads to the initiation of fatigue cracks at the weld termination location. Furthermore, since FSW results in the formation of a tensile residual stress field within the weld zone due to the sudden increase in temperature followed by rapid cooling, any additional processing of this area may result in the creation of slightly higher residual stresses, further increasing the likelihood of crack initiation. This hypothesis could be tested through modeling in follow up research.

The test results from these experiments on no-load transfer coupons show that exit holes in FSW dramatically decrease the fatigue life under the present testing conditions. Further, they can be sites for secondary crack initiation in fatigue panel testing as mentioned before.

The results from these experiments for using sealants show that they do not appear to have a significant effect on fatigue life under these test conditions.

The fatigue results for drilled coupons, all the way through the top and bottom sheet, in comparison to fatigue result for baseline coupons showed that stress concentration around the drilled holes is greater than stress concentration around the general holes of the baseline coupons, and it caused a drop in fatigue life of the coupons. Therefore, the FSW exit holes tested in this research do not result in a lower bound fatigue life limit (i.e. a worst case) for test conditions investigated. However, the open hole configuration does provide a lower bound condition.

5.2 Recommendations for Further Study

Potential areas for future work for discontinuous FSW in fatigue can be identified based on this study. It would be of interest to study the effect of other types of fatigue coupons with different configurations. It also may valuable to see how the welded coupons compete with rivets when the weld parameters or tool are optimized for fatigue life.

It may also be worthwhile to examine the effect of using the tools with different probe designs in the fatigue life of the discontinuous welded coupons. Probes without threads typically produce smoother exit holes. Smooth surface in exit holes may delay crack initiation in the exit hole and non-threaded tool design can maintain the joint properties while leaving a smooth exit hole if fatigue crack initiation is observed to initiate there.

Another experiment involving laser shock peening, or other methods such as low plasticity burnishing, to add a layer of compressive residual stress around the exit hole could potentially delay or halt secondary crack initiation. Modeling of the process would provide helpful insights into each of these potential areas of continued study.

Lastly, there is a possibility that by using zero degree tilt angle for the back weld the hooking effect observed in case 6a could be eliminated. Since the hooking appeared to be a source for early crack initiation in this study, attempts to eliminate hooking on the back weld could be another area of future investigation.

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APPENDIX

Table 3 Fatigue Results for Polished Coupons

Panel	Coupon Type	Pull Style	Guided/ Unguided	Frequency (Hz)	Max Stress (Ksi)	Fatigue load level (67%)	Cycles	Failure Location
1	B	Fatigue	Unguided	60	9.6	1536	458,506	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	331,979	Exit Hole
2	B	Fatigue	Unguided	60	9.6	1536	435,362	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	315,150	Exit Hole
3	B	Fatigue	Unguided	60	9.6	1536	403,899	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	311,037	Exit Hole
4	B	Fatigue	Unguided	60	9.6	1536	365,141	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	305,835	Exit Hole
5	B	Fatigue	Unguided	60	9.6	1536	393,178	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	336,135	Exit Hole

Table 4 Fatigue Results for Reversed Coupons

Panel	Coupon Type	Pull Style	Guided/ Unguided	Frequency (Hz)	Max Stress (Ksi)	Fatigue load level (67%)	Cycles	Failure Location
1	B	Fatigue	Unguided	60	9.6	1536	444,349	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	380,000	Exit Hole
2	B	Fatigue	Unguided	60	9.6	1536	665,550	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	494,100	Exit Hole
3	B	Fatigue	Unguided	60	9.6	1536	408,305	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	445,829	Exit Hole
4	B	Fatigue	Unguided	60	9.6	1536	476,760	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	323,972	Exit Hole
5	B	Fatigue	Unguided	60	9.6	1536	358,292	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	451,641	Exit Hole

Table 5 Fatigue Results for Drilled Coupons

Panel	Coupon Type	Pull Style	Guided/ Unguided	Frequency (Hz)	Max Stress (Ksi)	Fatigue load level (67%)	Cycles	Failure Location
1	B	Fatigue	Unguided	60	9.6	1536	342,892	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	314,805	Exit Hole
2	B	Fatigue	Unguided	60	9.6	1536	484,574	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	272,016	Exit Hole
3	B	Fatigue	Unguided	60	9.6	1536	409,332	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	244,009	Exit Hole
4	B	Fatigue	Unguided	60	9.6	1536	296,726	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	330,961	Exit Hole
5	B	Fatigue	Unguided	60	9.6	1536	326,300	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	291,295	Exit Hole

Table 6 Fatigue Results for Coupon with Sealant

Panel	Coupon Type	Pull Style	Guided/ Unguided	Frequency (Hz)	Max Stress (Ksi)	Fatigue load level (67%)	Cycles	Failure Location
1	B	Fatigue	Unguided	60	9.6	1536	423,132	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	309,831	Exit Hole
2	B	Fatigue	Unguided	60	9.6	1536	395,927	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	328,825	Exit Hole
3	B	Fatigue	Unguided	60	9.6	1536	428,657	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	308,249	Exit Hole
4	B	Fatigue	Unguided	60	9.6	1536	414,726	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	365,591	Exit Hole
5	B	Fatigue	Unguided	60	9.6	1536	423,823	Exit Hole
	C	Fatigue	Unguided	60	9.6	1536	335,858	Exit Hole

Table 7 Fatigue Results for Riveted Coupons (Countersink toward the Welded Side)

Panel	Coupon Type	Pull Style	Guided/ Unguided	Frequency (Hz)	Max Stress (Ksi)	Fatigue load level (67%)	Cycles	Failure Location
1	B	Fatigue	Unguided	60	9.6	1536	2,793,395	Weld Start
	C	Fatigue	Unguided	60	9.6	1536	771,165	Grip
2	B	Fatigue	Unguided	60	9.6	1536	637,920	Weld Start
	C	Fatigue	Unguided	60	9.6	1536	2,516,032	Grip
3	B	Fatigue	Unguided	60	9.6	1536	640,416	Weld
	C	Fatigue	Unguided	60	9.6	1536	5,000,000	None
4	B	Fatigue	Unguided	60	9.6	1536	1,484,298	Weld Start
	C	Fatigue	Unguided	60	9.6	1536	5,000,000	None
5	B	Fatigue	Unguided	60	9.6	1536	5,000,000	None
	C	Fatigue	Unguided	60	9.6	1536	3,975,736	Grip

Table 8 Fatigue Results for Riveted Coupons (Countersink toward the Un-Welded Side

Panel	Coupon Type	Pull Style	Guided/ Unguided	Frequency (Hz)	Max Stress (Ksi)	Fatigue load level (67%)	Cycles	Failure Location
1	B	Fatigue	Unguided	60	9.6	1536	5,000,000	None
	C	Fatigue	Unguided	60	9.6	1536	5,000,000	None
2	B	Fatigue	Unguided	60	9.6	1536	575,642	Weld Start
	C	Fatigue	Unguided	60	9.6	1536	5,000,000	None
3	B	Fatigue	Unguided	60	9.6	1536	5,000,000	None
	C	Fatigue	Unguided	60	9.6	1536	5,000,000	None
4	B	Fatigue	Unguided	60	9.6	1536	1,826,280	Weld Start
	C	Fatigue	Unguided	60	9.6	1536	5,000,000	None
5	B	Fatigue	Unguided	60	9.6	1536	401,323	Weld Start
	C	Fatigue	Unguided	60	9.6	1536	5,000,000	None

Table 9 Fatigue Results for Retractable Coupons (With Back-Weld)

Panel	Coupon Type	Pull Style	Guided/ Unguided	Frequency (Hz)	Max Stress (Ksi)	Fatigue load level	Cycles	Failure Location
1	B	Fatigue	Unguided	60	9.6	1536	689,862	Weld End
	C	Fatigue	Unguided	60	9.6	1536	746,743	Grip
2	B	Fatigue	Unguided	60	9.6	1536	744,369	Weld End
	C	Fatigue	Unguided	60	9.6	1536	492,695	Weld End
3	B	Fatigue	Unguided	60	9.6	1536	808,551	Weld End
	C	Fatigue	Unguided	60	9.6	1536	1,046,925	Weld End
4	B	Fatigue	Unguided	60	9.6	1536	790,013	Weld End
	C	Fatigue	Unguided	60	9.6	1536	443,501	Weld End
5	B	Fatigue	Unguided	60	9.6	1536	689,055	Weld End
	C	Fatigue	Unguided	60	9.6	1536	589,907	Weld End

Table 10 Fatigue Results for Retractable Coupons (Without Back-Weld)

Panel	Coupon Type	Pull Style	Guided/ Unguided	Frequency (Hz)	Max Stress (Ksi)	Fatigue load level (67%)	Cycles	Failure Location
1	B	Fatigue	Unguided	60	9.6	1536	5,000,000	None
	C	Fatigue	Unguided	60	9.6	1536	5,000,000	None
2	B	Fatigue	Unguided	60	9.6	1536	5,000,000	None
	C	Fatigue	Unguided	60	9.6	1536	5,000,000	None
3	B	Fatigue	Unguided	60	9.6	1536	5,000,000	None
	C	Fatigue	Unguided	60	9.6	1536	5,000,000	None
4	B	Fatigue	Unguided	60	9.6	1536	5,000,000	None
	C	Fatigue	Unguided	60	9.6	1536	5,000,000	None
5	B	Fatigue	Unguided	60	9.6	1536	5,000,000	None
	C	Fatigue	Unguided	60	9.6	1536	5,000,000	None