ADVANCES IN HIGH ROTATOINAL SPEED – FRICTION STIR WELDING FOR NAVAL APPLICATIONS

A Thesis by

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Bachelor of Engineering, Wichita State University, 2009

Submitted to the Department of Mechanical Engineering
and the faculty of the Graduate School of
Wichita State University
in partial fulfillment of
the requirements for the degree of
Master of Science

May 2009

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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 with a major in Mechanical Engineering

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DEDICATION

To Jill, Rocky, Apollo, Callaway, and to the future Baby

ACKNOWLEDGEMENTS

I would like to express my profound gratefulness to my advisor, Dr. George Talia, for his unyielding support, encouragement, supervision, and valuable suggestions throughout this research work. Through advices for course work to life in general, his support and continued guidance enabled me to complete my work successfully. I am grateful to have his support. I also would like to thank my friends and family that have put up with me and my quest for higher education. I express my sincere thanks to my family, both abroad and here at home for their support. To my twin sister Victoria who valiantly succeeded in writing a paper at the same time as I was. Thank you for your positive support.

All of this would not possible, but for my wife Jill. She has pushed me when I have stalled, picked me up when I have fallen, and straightened me out when I have veered off course. Therefore, I am especially indebted to her for her love and support.

ABSTRACT

Changing operational requirements within the Navy defines the need for lighter, faster ships with increased range and payload. To achieve these requirements the Navy is investing in new hull forms and aluminum alloys for the Littoral Combat Ship (LCS), the Landing Helicopter Assault (Replacement) Ship, and the Joint High Speed Vessel. Friction stir welding (FSW) has proven to be a viable means for joining aluminum during the vessel manufacturing process for LCS, and is a likely joining process for other high speed aluminum vessels. While producing welds of high quality, FSW is characterized by high equipment costs and lack of field repair methods. This report outlines a U.S. Navy-Wichita State University research effort to develop high rotational speed – friction stir welding (**HRS-FSW**), a process that offers the potential for significant reductions in the size, mass, and cost of FSW systems for both assembly and repair (conventional and/or "in-situ") welding.

The objective of this work is to evaluate the effects of HRS-FSW on the microstructure, mechanical, and corrosion properties of aluminum welds. A spindle speeder was used to increase the rotational speed of the pin tool up to 12,000 rpm.

To inhibit defect formation(s), <u>flash suppression technology</u> was employed. Through the use of this technology, transverse cross sections of the completed welds not only demonstrated a typical consolidated FSW microstructure, but

also, a unique secondary induced stir zone beneath the normal stir zone, effectively doubling the penetration of the weld. Transverse tensile tests resulted in failure of the parent material away from the weld nugget and the heat affected zone (HAZ).

Exfoliation corrosion testing of the welded samples revealed the majority of the corrosive effects occurred on the weld nugget surface, while the thermo-mechanically affected zones (TMAZ) demonstrated a lower propensity for corrosion than the rest of the material (i.e. cathodic behavior).

The use of high rotational speeds resulted in a significant reduction in all axial forces, and, in combination with a flash suppression technology, produced a unique secondary induced stir zone. The results show promise in both reducing the size, and the welding forces required for welding. Optimized HRS-FSW machine/tool designs have the potential to reduce machine size and cost, while providing a viable solution to portability and “in situ” repair challenges.

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CHAPTER 1

1.0 INTRODUCTION

Friction Stir Welding (FSW) was conceived in 1991. The Welding Institute (TWI) filed for a world-wide patent. The breakthrough with FSW is that the weld is made in the solid phase, no melting takes place[1]. This solid state welding is characterized by mechanical mixing, where most of the heat is generated by friction, allowing the material to be plasticized and consolidated/forged, while the temperature does not reach the materials melting point.

Friction Stir welding uses a rotating tool with a shoulder and a pin. The shoulder has the “pin” protruding from its center. The pin generally has some features to aid in the dispersion and displacement of material around itself. On the other hand, the shoulder is the principal source of heat, which is generated by friction and induces the forging forces into the material. The profiled pin and shoulder are rotated at a fixed rpm and slowly plunged into a joint of two similar or dissimilar metals. The material can either be butted together or lapped over each other. While the tool is reaching its down force (forging), heat is being generated. The heat generated by friction, the stirring of the tool, and the traversing path of the tool, moves material in a plastic state from the front of the pin to the rear of the pin as it travels through the joint line.

Friction Stir Welding is a fairly new technique. The process is still in an experimental stage. Some of the appealing aspects of FSW are that a non-consumable tool is used. Filler or shielding gas is not necessary, nor is there any need for current or voltage controls, and FSW produces much stronger welds. For all the different series of aluminum available for industry use, FSW has been able to join all of them, i.e., 2XXX, 5XXX, 6XXX, and 7XXX series. Up to 1 inch (25 mm) thick plates have been joined successfully[2]. All of these welded alloys present uniform welds with minimal heat input, distortion, and loss of strength. Of the small list of disadvantages of FSW, one is that high forces must be brought to bear on the work piece or equipment. This can lead to equipment with a significantly higher cost value.

Aluminum has proven to be the highly sought after material for aircraft and, as of lately, also for military naval ships. The ability to join aluminum structures has brought wide spread attention, initiating research and development in the naval and aeronautical industries. Since there are so many established advantages of FSW over fusion welding techniques, the motivation to commercialize FSW and FSW techniques becomes imperative to obtain lean industries, and help the US economy. Figures1-3 presents typical aspects of the FSW process; one can observe the travel of the rotating tool, and the material consolidation remaining in the wake of the tool, thereby joining the plates.

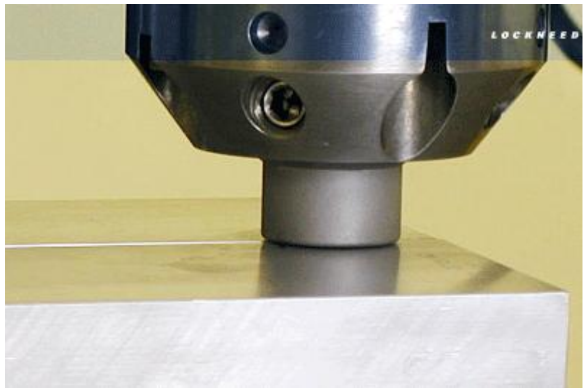

Figure 1 Photograph of the Friction Stir Weld in Process[3]

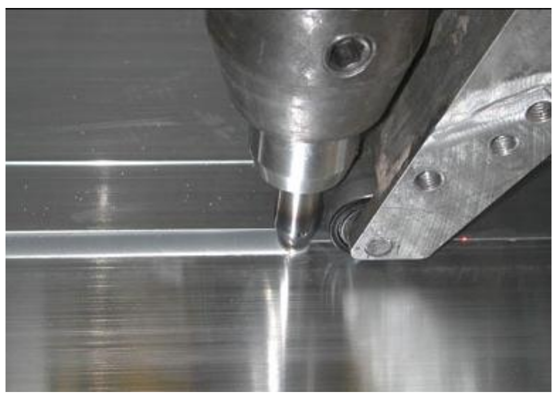

Figure 2 Example of the Friction Stir Weld in Process with rolling plate[4]

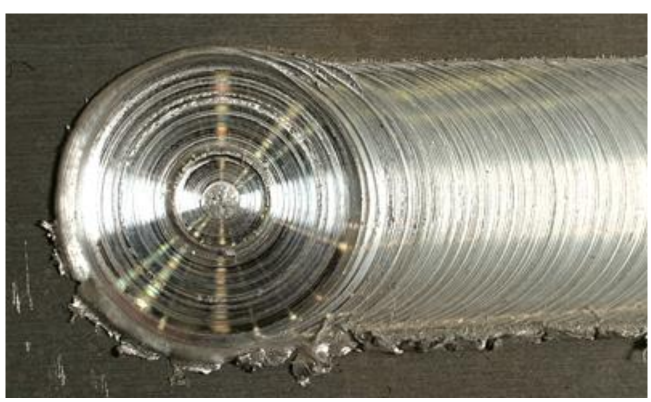

Figure 3 Macrograph of End of Friction Stir Weld Process[5]

The basis for Friction Stir Welding is a relatively simple process. In addition to the two main variations of Friction Stir Welding two pieces of aluminum together, butt and lap welding, other configurations are possible; however, they are not being explored as thoroughly as the two listed above. Due to the large welding forces, the material needs to be clamped to an unyielding backing plate; to avoid joint line separation and consolidation. Industrial standards have not yet been set; there is however a set of principles or guidelines that have narrowed the amount of error incurred in finding a suitable set of parameters or weld properties for certain aluminum alloys. Using these guidelines, material can be joined successfully using FSW techniques that make metallurgically sound welds, regardless of alloy or plate thickness. These welds may be free from defects, but alterations in weld parameters could yield different mechanical properties of the weld, either through direct modification of the weld microstructure, or by an indirect influence, such as, the generation of large internal stresses.

1.1 Welding

Welding has been around for many years. Historically speaking, welding has been used to weld utensils out of copper. The use of welding traces back to the Sumerian civilization around the 14th century B.C. The role of welding has become more increasingly important since the 20th century. After the First World War, the Treaty of Versailles prohibited any country from building a ship larger than 10,000 tons. Germany[6] then began an investigation of using welding on warships, which was saving 1000's of *tons* of material. This allowed Germany to build large warships that were still less than 10,000 tons in weight, therefore not violating the treaty.

Weight has been described to be a leading factor in ship building, though the motivation for Germany was ill suited; the thought process was leading the industry of manufacturing to a new heightened level of thinking. From an economical stand point, welding is by far the most cost effective means of joining materials. Not only does it reduce the weight of a completed project by reducing the amount of rivets and bolts; welding reduces the time-cost of manufacturing.

Joining of similar or dissimilar materials can be accomplished in a variety of ways. Regardless of the technique chosen, most materials can be joined. If adhesives are chosen, ensuring a suitable bond can be difficult. Bolting, riveting, stapling, and snap fittings are commonly used to join polymers and metals. These options have a feature that they can be disassembled if necessary. Welding is the largest class of joining processes. Over the last couple of years, welding polymers and aluminum has grown quite significantly. Specialized techniques have evolved to deal with each class.

Anytime a material of any class is welded, there are always internal stresses that reside; these stresses may reach values roughly equal to the yield strength of the parent material. This residual stress can be relaxed by means of heat treatment and ultrasound after welding, both techniques increase operational expenses. It is important to point out that reducing internal stresses is always good to achieve a better design, since the stresses may be responsible for dimensional changes, failures, and/or corrosion.

1.2 Materials Weldability

Imperfections of fusion welds can be due to the lack of proper planning and procedures. Thin and uniform oxide films, such as those obtained on pickled stainless steels and Nimonic alloys, may not give consistent welding properties, particularly with high electrode forces. Rust, paint and grease also influence negatively towards weld consistency, and should be removed. In addition, Metallic coatings may seriously reduce weldability; therefore, consistency may be diminished and electrode tip life in spot welding may be reduced[7]. For aluminum alloys, most of the fusion welds' strength are much lower than the strength of the parent material.

1.3 Classification of the Weld Process

There are two major classes of the welding process; fusion, practically without applied forces, and solid state welding, with large pressures/forces associated with the process. The fusion welding method is a joining operation where the materials are melted and then solidified. No external forces, if any, will have an effect on the production of material coalescence. However, friction welding and FSW rely on the heat generated by friction, deformation, and pressures in order to create a bond. Solid state welding uses high externally applied forces to aid the joining process. The Solid state welding operating temperatures and forces/pressures complement each other. In essence, this welding process can be done at either low temperature with relatively high forces/pressures, or at elevated temperatures with low forces/pressures[8].

1.3.1 Types of Welding

There are a large number of welding techniques, as cited below.

1. Arc Welding
    - Shielded Metal Arc Welding
    - Submerged Arc Welding
    - Gas Metal Arc and Flux Cored Arc Welding
    - Gas Tungsten Arc Welding
    - Plasma Arc Welding
    - Electro-slag and Electro-gas Welding
2. Resistance Welding
3. Flash Welding
4. Oxy-fuel Gas Welding
5. Solid State Welding
    - Friction Welding
    - Friction Stir Welding

- High Rotational Speed-Friction Stir Welding
- Diffusion Welding
- Reactive Welding

6. Electron Beam Welding
7. Laser Beam Welding
8. Brazing
9. Soldering
10. Induction welding

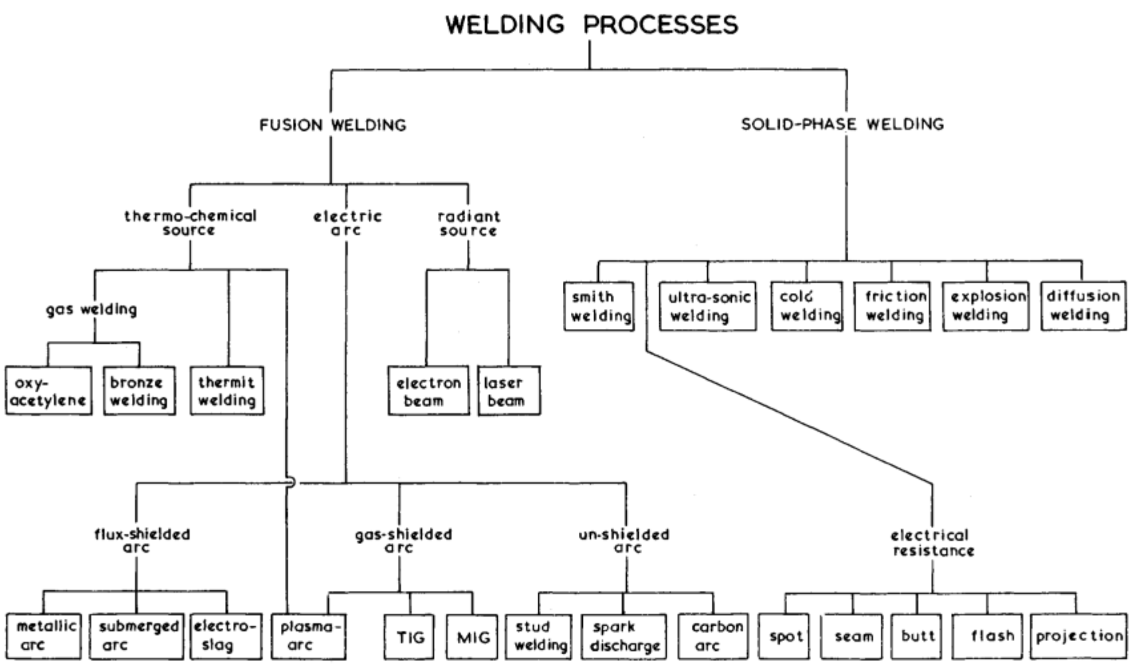

Table 1 Welding Process[9]

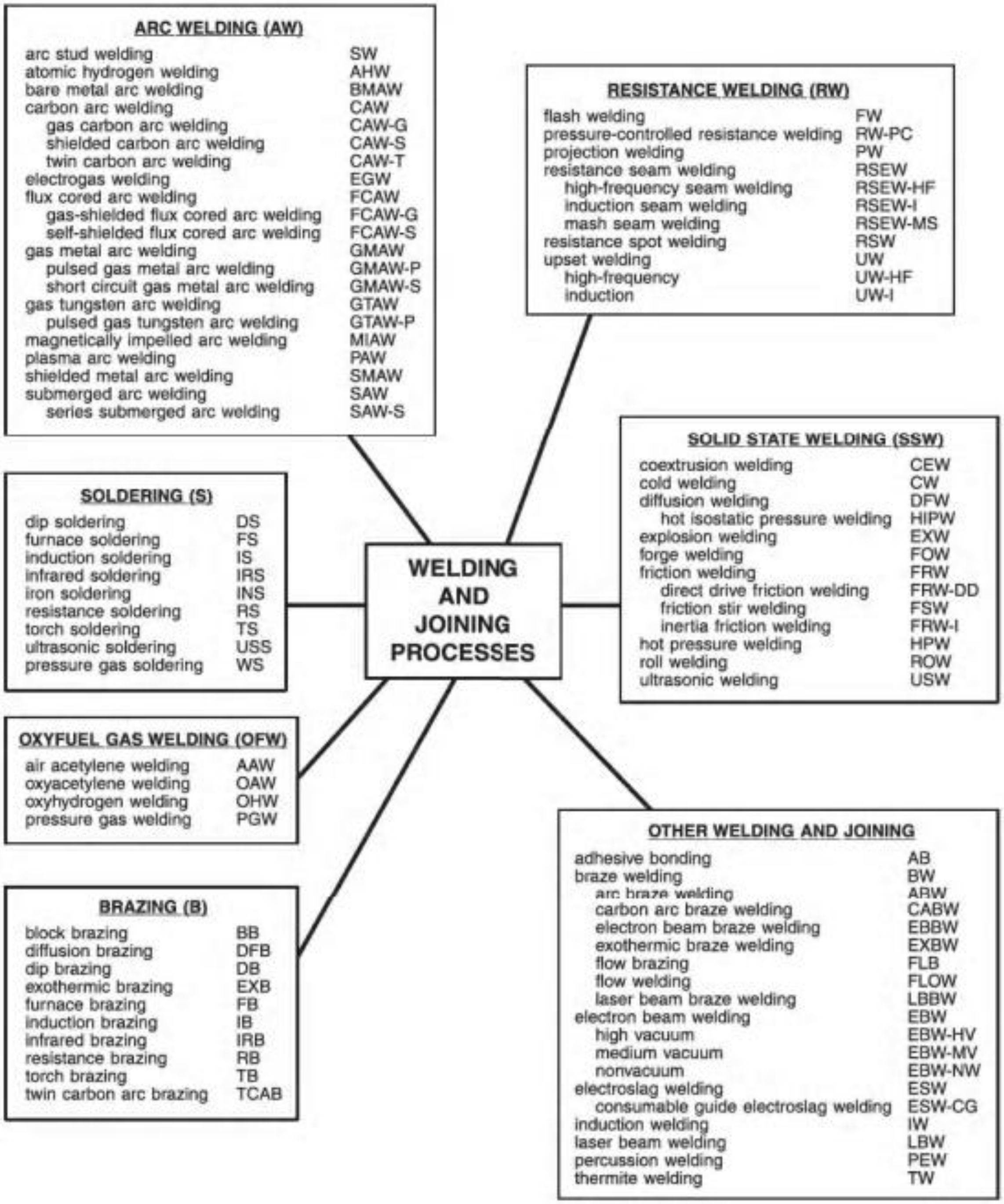

Table 2 Master Chart of Welding and Joining Processes[10]

1.3.2 General Characteristics of Weld Microstructure

The parent material of two similar metals will generally exhibit a finer crystal structure compared to the structure of the fusion weld. This is due to the significant heat increase that is necessary during a weld. A cross-section of a weld shows a course crystal structure, compared to the adjacent parent material.

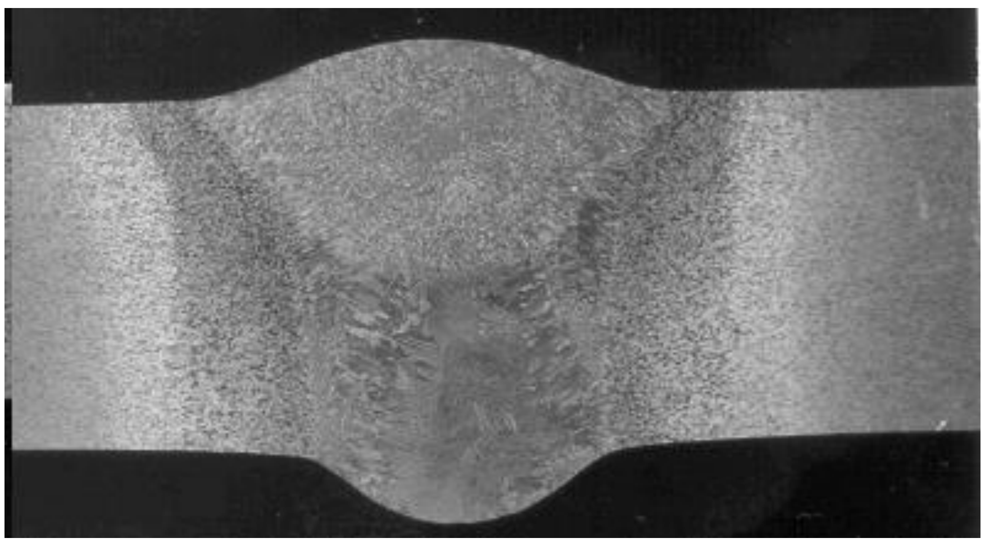

Figure 4 Typical Microstructure of a fusion Weld[11]

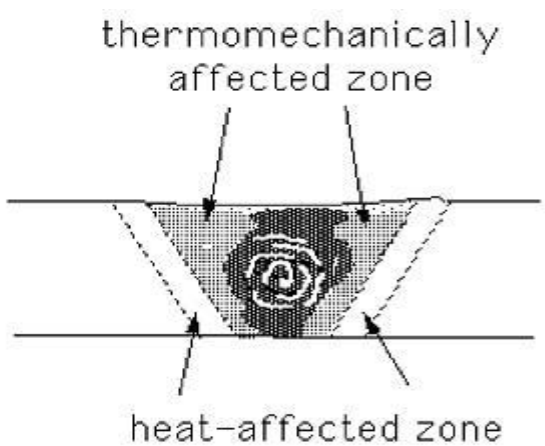

Figure 5 Typical sketch of a Weld Microstructure[12]

To weld two pieces of material as one; in theory, the atoms of each joining surface needs to be brought together close enough to create a natural chemical bond. To aid this process, the materials in question should have relatively "perfect" plane surfaces to join[13]. The two surfaces should be drawn together until the distance separating them "emulate" as close as possible, the inter-atomic spacing. Thus the two joining materials would unite to form a single work piece. Fusion welding is a very effective method of bringing together the molten and solid surfaces.

1.3.3 Solid State Welding (SSW)

Solid state welding encompasses a group of welding processes that produce bonding by the application of pressure, at a temperature below the melting temperatures of the base metal and filler[14]. Some of the common SSW and more historical types of welding processes are forge welding. Due to technological advances, other types of solid state welding include Explosion welding, Ultrasonic welding, Diffusion welding, Pressure welding, and Friction welding.

1.3.3.1 Friction Welding (FW)

Friction welding is a process composed of rubbing two pieces of material together using linear and rotating movements until bonding occurs. This welding procedure is a solid state joining process that produces a weld under compressive joining forces that generate heat. The heat is produced at the weld interface because of the continuous rubbing and applied pressure of the contact surfaces, which in turn, causes a temperature rise and subsequent softening of the material. Eventually, the material at the interface starts to flow plastically, increasing the surface contact, and forms an up-set collar. After a certain amount of upsetting has occurred, the friction is stopped and the compressive force is maintained or slightly increased to consolidate the weld[15].

1.3.3.2 Friction Stir Welding (FSW)

Friction Stir Welding (FSW) is a solid state welding process first discovered and patented by The Welding Institute of Cambridge U.K. in 1991. First production use in the US was in 1998 for The Boeing Company on the Delta Launch Vehicle.

Friction Stir Welding (FSW) is a well established joining process for welding aluminum and other low melting temperature metals. The application of this process to steels and stainless steels has primarily been limited by the availability of suitable tool materials. Friction stir welding was recently identified by leading aircraft manufactures as “key technology” to replace riveting for fuselage and wing manufacturing[16].

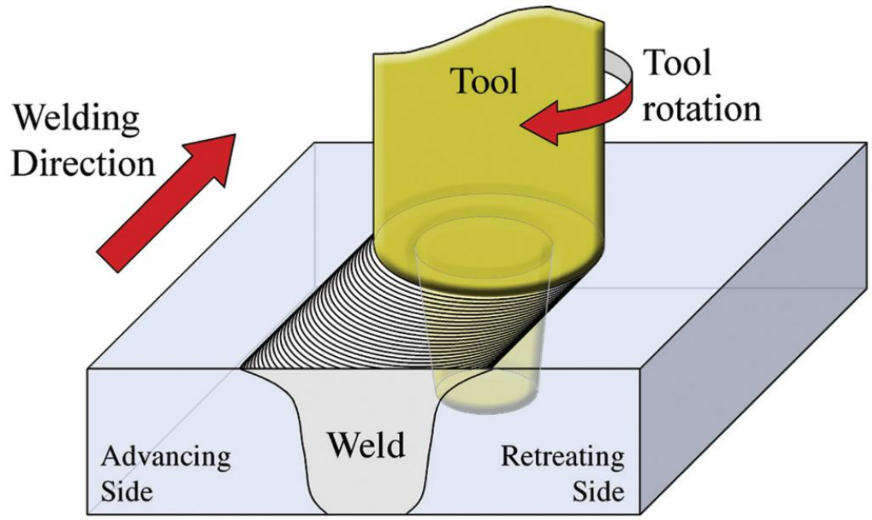

Figure 6 Schematic of the friction stir welding process[17]

The Process steps consist of the usage of a rotating, non-consumable weld tool that plunges into the base material and moves forward. The usage of non-consumable tools differentiates FSW from FW. Frictional heat caused by the rotating pin creates a plasticized tubular shaft around the pin. Also, pressure provided by the shoulder of the welding tool, induces the plasticized material to follow the pin contour. The material at the back of the weld cools and consolidates to form a strong joint, close to the strength of the parent metal. Figure 6 represents the cross section of the weld pin tool into base material and the subsequent "stir" action taking place during a weld.

<u>Process Highlights are:</u> No melting occurs during welding; Welds all aluminum alloys; increased weld strength over fusion welding; fatigue resistance; reduced distortion over fusion welding; no consumables used; no shielding gasses

required; repeatable; no environmental impact; and increases energy savings. See Figure 6 for a schematic view of the friction stir welding process.

1.3.4 High Rotational Speed–Friction Stir Welding (HRS-FSW)

FSW as we know it today is performed on a conventional or specially built CNC milling machine. The major limitations of this process are high forge and process loads, and geometrical constraints. There are existing milling machines that are capable of operating at higher speeds. However, High Rotational Speed – Friction Stir Welding is not performed on these machines because the overall process is not well understood[18]. HRS-FSW is a promising technology that can reduce these loads significantly, and in turn, reduce the dependency on clamping, large machines, and operating costs, while increasing productivity.

Basically, rigid machines provide a robust platform for low speed friction stir welding. Low speed FSW incurs a high input of forces necessary to gain adequate energy for the FSW process to occur. This makes for large and cumbersome machines that are not agile enough for complex shapes or designs. On the other hand, High Rotational Speed FSW benefits from the ability to input most of the energy by the high rotational speed, reducing the size and mass of the machine and tooling. Experiments and calculations indicate that the friction force requirement is inversely proportional to the rotational speed. The reduction of the friction force will permit the design and fabrication of small portable machines, capable for use of the “in field” repairs and builds.

In order to apply lean manufacturing to any industry, design of precision high speed friction stir welding processes is necessary; there is a need for friction stir welding to be more versatile and transportable. The development of new technologies in the past five years makes HRS-FSW possible. High rotational speed spindles and precision adapters substantially make this process practical. The key to effective implementation of HRS-FSW is the knowledge and information of the process itself. This includes, the basic physical principles, the dynamics of weld formation, the relationship between the tools and work pieces, and the characteristics of different materials. Because, industrial standards have not yet been established, there is not much helpful or usable information regarding HRS-FSW of aluminum[19], or other materials.

1.3.5 Microstructure of Solid State Welds

The nugget and thermo-mechanically affected zone should be classified together as thermo-mechanically affected zone. In aluminum alloys, the possibility of substantial deformation in this region without re-crystallization differs from all other metals being examined after friction stir welding; re-crystallization occurs with little or no visible deformation[20]. Macrostructure observations of transverse cross-sections of welded aluminum specimens often reveal “onion-ring” type structures, as shown in Figure 7. The phenomenon of the very well detailed mechanism of the pattern termed “onion-ring” is not that well understood, but has been linked to the flow of the material during the FSW process[21].

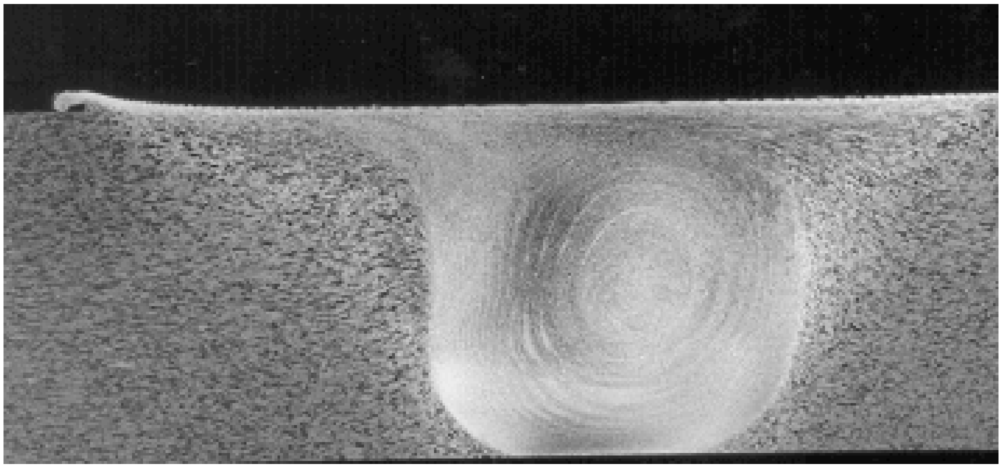

Figure 7 Typical cross section of FSW weld nugget cross section[22]

1.4 Aluminum Welding

Typically aluminum is difficult to join. Welding aluminum and its alloys creates a number of problems. The ideal weld incorporates a complete joint comprising of the weld metal, heat affected zones, and the adjacent parent metal. Those components should have the same properties throughout the material, and those problems are associated with any aluminum welding[23]. Some of the features and defects that can cause the loss of properties comprise of the following:

- Gas porosity
- Oxide inclusion sand oxide filming
- Solidification (hot) cracking or hot tearing
- Reduced strength in the weld and HAZ
- Lack of fusion

- Reduced corrosion resistance
- Reduced electrical resistance

1.4.1 General Characteristics of Welding

There are a number of characteristics that effect aluminum welding. Porosity is a main problem that is confined to the welded material. Porosity can arise from moisture and/or hydrocarbons on the surface of the material being welded that might decompose and create hydrogen. When the aluminum is in a molten state, the hydrogen is very soluble. As the weld cools, the hydrogen has a tendency to get trapped and form voids in the weld. This causes porosity in the weld. Porosity is a problem confined to the weld metal. It arises from gas dissolved in the molten weld metal becoming trapped as it solidifies, thus forming bubbles in the solidified weld.

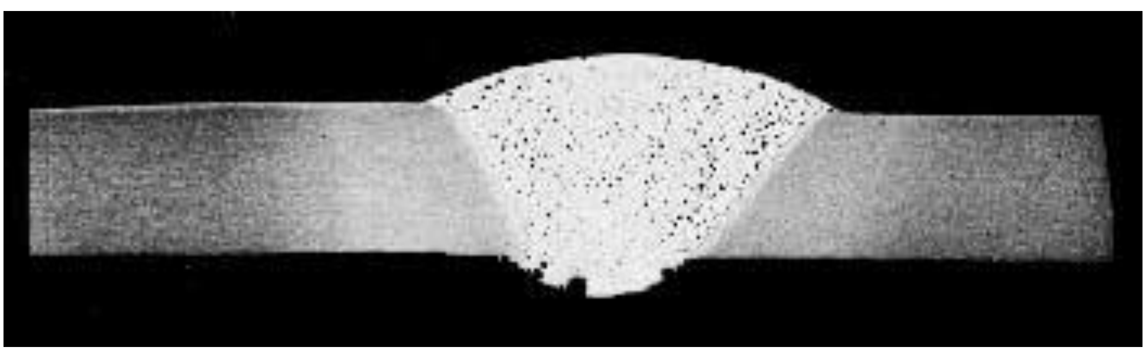

Figure 8 Finely distributed porosity in TIG plate butt weld[24]

Hydrogen plays a large role in porosity with the welding of aluminum. Porosity is the presence of gas pockets or inclusions in a weld. Aluminum is highly susceptible to excessive porosity, as shown in Figure 8, due to molten aluminum as it solidifies. The hydrogen solubility is diminished, generating gas pockets in the quasi solidified weld[25].

Figure 9 depicts porosity due to hydrogen, which again has a high solubility in molten aluminum, but very low solubility in the solid.

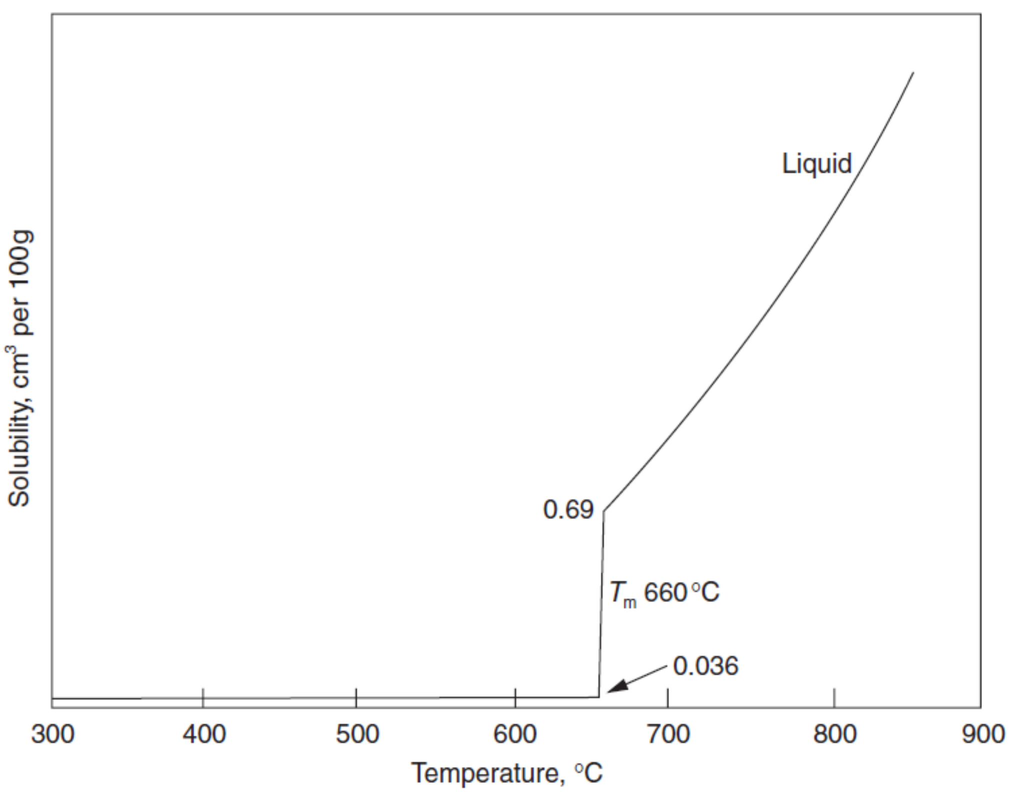

Figure 9 Solubility of hydrogen in aluminum[26]

Figure 9, shows a decrease of solubility to the order of 20 times as solidification takes place, a drop in solubility so pronounced, that it is extremely difficult to produce a porosity-free weld in aluminum.

A critical aspect in welding aluminum is oxidation[27]. Aluminum and its alloys almost attract a refractory oxide film when exposed to air, readily forming a thin layer or film of oxidation. This is the same corrosion-resistant qualities that aluminum gains. This oxide film has to be removed before adequate welds can be made. This oxide film has a higher tolerance to temperature; its melting point is far above that of the parent material, approximately 1400 ºC. Most oxides of other materials will melt at a lower temperature than that of the parent material and float on top of the weld pool like molten slag. The oxide film has to be removed correctly before welding to prevent oxidation porosity.

Other issues are present when welding aluminum. Hot Cracking poses a formidable threat to adequate aluminum welds. This is based on the volumetric differences between the molten and solid aluminum. In essence, upon solidification, the welding nugget shrinks and generates internal stresses, ergo, cracking. Hot cracking is accentuated by the incipient melting temperature of the solidifying grain boundaries and the solidification stresses.

1.5 FSW of Aluminum – Introduction

Friction Welding was used primarily before the conception of Friction Stir Welding. Friction welding is dependent on moving one piece or two work pieces together. This relative motion is awkward and requires the input of pressure to obtain cohesion. Friction welding can really only be used with simple, solid shapes. The pressure and the short relative motion used in friction welding are near impossible to join sheets or even plates of aluminum. This process, unlike the conventional rotary or linear motion process, is capable of welding longitudinal seams in a flat plate[28]. Friction Stir Welding (FSW) employs a tool that localizes the welding and transports the process following the seams to be joined. This innovation permits the welding of non-linear patterns necessary for manufacturing of modern structures. As the weld sequence starts, a tool is slowly plunged into the joint line of two pieces of sheet or plate material which are either butted together or lapped. Both of the work pieces are secured in each axis or plane. The forging-axis, or up and down, is secured by using a heavy anvil or backing plate. The anvil prevents the tool from pushing the material down. Movement of the material in the horizontal axis is prevented by using clamps to the sides and to the rear of the soon to be welded material. Mainly, the heat is generated by the shoulder of the wear free tool with the work pieces. The tool travels through the seams of the work pieces. This results in a solid phase bond between the two pieces of material. This is often considered a solid phase keyhole welding technique, due to the fact that as the tool travels through the weld sequence, there is hole that is generated and then filled during the weld process.

1.5.1 Additional Details of the Friction Stir Welding Process

FSW is a rapidly maturing solid state joining process that offers significant benefits over conventional joining processes. The process shown schematically in Figure 10 is initiated by a rotating welding tool. The rotational speeds can range anywhere from 200 rpm up to 1,500 rpm.

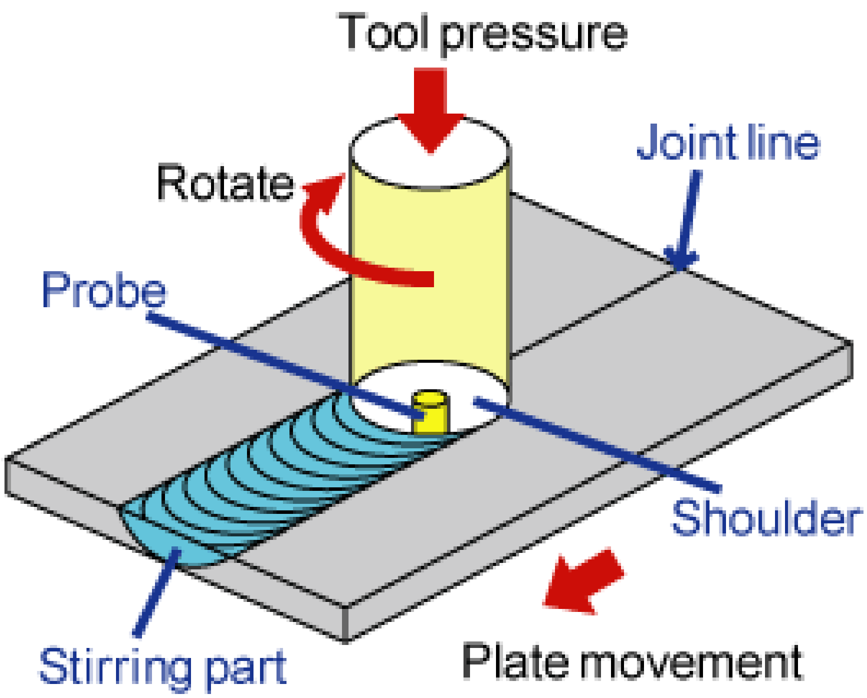

Figure 10 Friction Stir Welding

For typical friction stir welding, there are a series of main components necessary to perform this type of welding. These components include the pin tool, work pieces, and work piece holders. The pin tool is usually made of hardened tool steel, consisting of a single piece. The shoulder is the larger diameter and the probe has the smaller diameter. The aluminum plates to be welded, range in sizes and thicknesses, are clamped rigidly to the work piece holder, preventing lateral movement and or deflections relative to the work piece holder, see Figure 10. The application of FSW can be done in many different manners. A traditional CNC machine, a lathe, or even a hand-held router can even be used.

When a CNC machine is used, it is necessary to secure the work pieces to the bed or anvil of the machine and the pin tool is then held by the spindle. The pin tool in the spindle is held at a precise angle called the lead angle. The lead angle makes the trailing edge of the spinning tool below the surface of the two pieces of material, and continues down the joint line while rotating at a controlled rate of speed. Friction between the surfaces of the spinning pin tool and the surface of the work pieces generates a significant amount of heat, which in turn "plasticizes" the material. The plasticized material is then merged together to form a uniform bond or cohesion of one piece of aluminum, where before there were two pieces. Typically the weld turns out to have a finer grain than the parent metal, especially in a hot worked condition where little to no oxides or gas porosity is entrapped. In order to join aluminum using FSW, where low rotational speed is required, large inputs of energy is necessary to generate adequate heat for the stirring process. This energy input employs a large massive machine capable of handling large loads. Therefore, low speed friction stir welding requires a machine that is very strong, rigid, and takes up a large amount of floor space. See Figure 11.

Figure 11 NIAR-WSU Friction Stir Welding Machine[29]

High rotational speed-friction stir welding does not require high forge loads or power inputs. Therefore, machines necessary to achieve friction stir welds using high rotational speed do not have to be as massive. The energy input is by the high rotational speed of the tool, thereby reducing the overall size of the machine. It is imperative for a lean industry to employ compact and low cost FSW machines. Another aspect of these machines is the request for in-field use or “in-situ” repair. High rotational speed-friction stir welding techniques could take advantage of an industrial friction stir welding machine, i.e., HRS-FSW equipment.

1.5.1.1 Tool Terminologies

The tool in friction stir welding is the focal point of the process. The “pin” is the part of the tool that is embedded into the material during the weld sequence. “Probe” is used as a more technical term. The probe can have many distinguishing characteristics. Most often, it is not like a pin at all. In more recent probe designs, the probe is manufactured to optimize material stirring. The flat part of the tool that makes contact with the surface of the work piece is the shoulder. The shoulder has a larger diameter. Recent studies are trying to indicate a proper shoulder diameter to pin diameter ratio. The most up to date designs of the shoulder are optimized to the stirring of the work piece material. Even though the tool is cylindrical and rotating at a high speed, at any instantaneous time the tool will have a “leading face” and a “trailing face”. In most cases the complete tool will be tilted. This causes the leading face to be higher than the trailing edge. This causes the trailing face, or “heel”, to be slightly plunged into the surface of the work pieces, termed the “heel plunge depth”. The angle at which the tool is held during the weld process is the “tilt angle” or “travel angle”. There is in some cases a tilt sideways. This angle is called the “sideways tilt angle” or “work angle”.

Spindle speed, measured in RPM (rotations per minute), in conjunction with the friction forces, determines the amount of energy that is being input per unit time. The travel speed, measured in IPM (inches per minute), also determines the temperature of the weld zone. The plunge depth controls the forging force behind the pin tool and ensures the formation of a defect free joint[30].

1.5.1.2 Process Terminology

The welding process has some fundamental aspects; "traversing speed" or "welding speed", one infrequently used term is "traversing rate". This is the speed at which the tool travels down the joint line. "Tool rotational speed" is used to describe the speed at which the tool rotates. In order to distinguish which direction the tool is rotating, the decided view is from above the work pieces. Either "clockwise" or "counterclockwise" is used. "Anti-clockwise" is used in international forums. Procedural terminology also covers the forces necessary to make a weld. The force applied parallel to the axis of rotation of the tool is the "downward or forging force" (Z-axis). The force applied parallel to the welding direction is the "traversing force" (X-axis). Finally, the "lateral force" (Y-axis) normal to the weld path, is a reaction to the rotating momentum.

1.5.1.3 Weld Nugget Terminology

The tool comes into contact with the work pieces; this contact area is termed "tool shoulder foot print". The side of the weld where the local direction of the tool rotational movement, is the same as the traversing direction, is termed the "advancing side". The adjacent side is the "retreating side". Terms such as "shear side" and "flow side" are less commonly used, but mean the same.

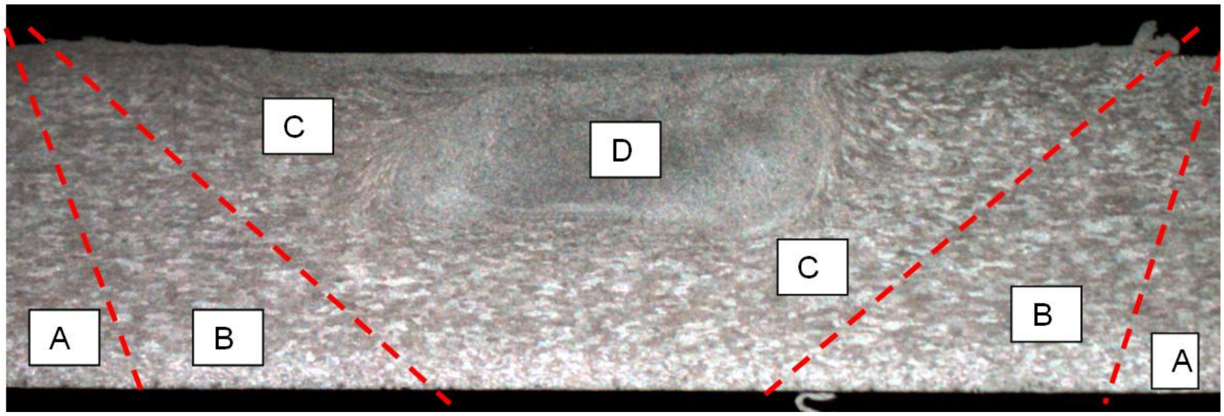

Figure 12 Microstructure regions on a typical FSW cross section

From Figure 12, the weld regions can be assessed. This is the actual weld number 17 that was performed in this experiment, without the aid of a microscope, the Parent, HAZ, and TMAZ are not clearly defined. However, the microstructure of the weld nugget is unmistakably obvious.

A. This is material remote from the weld that has not been deformed and that, although it may have experienced a thermal cycle from the weld, is not affected by the heat in terms of microstructure or mechanical properties.
B. In this region, which lies closer to the weld-center, the material has experienced a thermal cycle that has modified the microstructure and/or the mechanical properties. However, there is no plastic deformation occurring in this area.
C. In this region, the FSW tool has plastically deformed the material, and the heat formed by the process will also have exerted some influence on the material. In the case of aluminum, it is possible to obtain significant plastic

strain without recrystallization in this region, and there is generally a distinct boundary between the recrystallized zone (weld nugget) and the deformed zones of the TMAZ.

D. The fully recrystallized area, sometimes called the stir zone, refers to the zone previously occupied by the tool pin. The term *stir zone* is commonly used in friction stir processing, where large volumes of material are processed[31].

1.5.2 Process Advantages

There is large number of advantages, backed up by numerous studies, to friction stir welding. Increase in joint efficiency and process performance, also; there is a greater range in applicable alloys that can be joined. Dissimilar alloys can be joined with little to no repercussions. The material that is the focal point of FSW is aluminum; material previously thought to be “un-weldable” can now be easily welded. There are some composite materials that are even aspirant to the process. Friction stir welding employs a solid-phase, low distortion weld. These welds are achieved with relatively low costs, use low cost energy sources, and do not require high operator experience or training. The friction stir weld process takes place in the solid phase, below the melting point of the material to be joined. The advantages include the ability to join materials that are difficult to weld, for example 2xxx and 7xxx aluminum.

Other advantages are listed here[32]:

- Low distortion, even in long welds
- Excellent mechanical properties as proven by fatigue, tensile and bend tests
- No fume, No porosity
- No spatter
- Low shrinkage
- Can operate in all positions
- Energy efficient

The ability of just about any 3-to-5 axis machine can be transformed into a friction stir welding mechanism. The relatively simple operation of friction stir welding lends itself to the adaptability for robot use. The process advantages are:

- Non-consumable tool, no filler wire
- One tool can typically be used for up to 3200 ft of weld length in 6000 series aluminum alloys
- No gas shield needed for welding aluminum
- No welder certification required
- Some tolerance to imperfect weld preparations, some oxide layering can be accepted
- No grinding, brushing or pickling required

There are some limitations to friction stir welding. Through extensive research any process disadvantages are methodically reduced. However, there are some limitations to list:

- Welding speeds are moderately slower than those of some fusion welding processes
- Work pieces to be welded must be rigidly clamps
- A backing bar is required
- Key hole at the end each weld must be dealt with

1.5.3 Application

Currently the aerospace industry is adopting friction stir welding techniques. Friction stir welding lends itself well to welding skins to spars, ribs, and stringers for use in military and civilian aircraft. There are numerous advantages as opposed to riveting or machining from solid. This makes for a reduction in manufacturing costs and weight savings. Shipbuilding and Marine Industries plays a vital role in manufacturing. FSW is suitable for many applications under shipbuilding such as manufacturing of hulls, panels for decks, aluminum extrusions, offshore accommodation, etc. The Railway industry has monopolized on the simple designs of railway tankers, containers, and container bodies. FSW lends itself well to the applications in this industry. FSW can be used in many applications. Almost every aspect of manufacturing can be improved by friction stir welding. Aluminum and all its qualities, now able to be easily joined, can lead to a plethora of possibilities.

1.5.4 Common Friction Stir Welding Equipment

Mainly all Friction Stir Welding machines all are quite similar. Either the tool is able to move in all directions that will weld a fixed work piece, or the work piece is moveable, still kept rigid, and is able to move to the tool. Most of the machines available are large and costly. These massive machines use high forge loads to perform a friction stir weld, and require large servo motors and bulky hardware.

There are a number of companies that are manufacturing friction stir welding machines. Companies like MTS Systems and MCE Technology have been making significant advancements in consistently reproducing welds. Companies that manufacture full scale products are looking for alternatives that are more cost effective, reduce weight, and trim down specific tooling and personnel. NASA's Marshall Space Flight Center has been using, successfully, friction stir welding to weld the external tank of the space shuttle. Other options at NASA's disposal are to use friction stir welding technology to weld on the longitudinal barrel for both liquid oxygen and hydrogen tanks.

Eclipse Aviation Corp, Albuquerque, has harnessed the advancement of friction stir welding to successfully join the stringers and spars to aluminum cabin panels for the Eclipse 500 jet. This reliable technology has been proven for over 6 years.

Figure 13 Eclipse Aviation[33]

MCE Technology, Seattle, is developing the largest five axis curvilinear stir-welding machine for Concurrent Technologies Corporation of Johnstown, Pa. It will be used to weld materials up to 2.0 in thick and on the amphibious assault-vehicle program. The unit has a retractable pin and independent pin rotation speed, and will handle work pieces 26ft long and 13 ft high[34].

Friction Stir Link, Waukesha, through extensive research, has been able to manufacture in-depth turn-key FSW systems. The FSW systems they offer can perform some or all of the friction stir welding technologies (friction stir welding, friction stir processing, and friction stir spot welding). Friction Stir Link can offer a

Robot C-Frame Solution, Bench-Top Solution, Press Type Solution, and Custom, Fixed Friction Stir Welding Systems. Through the progression of the friction stir welding, more and more applications are implemented after rigorous testing.

CHAPTER 2

2.0 EXPERIMENTAL EQUIPMENT

2.1 Tool Design

Each of the friction tool parts (pin and shoulder) has a different function. Therefore, the best tool design may consist of the shoulder and pin constructed of different materials[35]. The important elements in the process of friction stir welding are the tools and tool designs. The shoulder plays the role of mixing the material from individual parts, which is one of the key features of the friction stir welding process. The heat input is generated by the tool, but comes mainly from the shoulder[36]. In principle the pin stirs the material towards the rear of the weld, leaving a consolidated trail that joins the work pieces.

The tools presented in Figures 14 & 16, show a series of "grooves"/channels that the aluminum would follow in a quasi fluid state during the FSW process. The channels pump material into the middle, thus, increasingly mixes the plasticized aluminum (Dynamic Flash Suppression Technology). Also, Figure 14 depicts a "container ring", the ring acts as a "valve", increasing the material inflow and reducing the outflow; localizing the consolidation pressure. Figure 16 shows the dynamic flash and defect reduction, note the "pin flats' and "pumping" features.

Figure 14 Picture of Dynamic Forging Tool

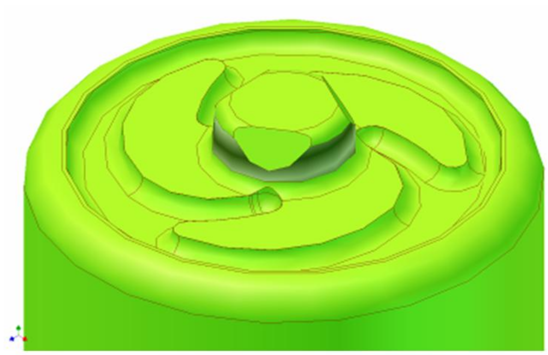

Figure 15 Design of Dynamic Forging tool with container ring to increase localized forging

Figure 16 Picture of Dynamic Flash Tool to be used with a non-rotating shoulder

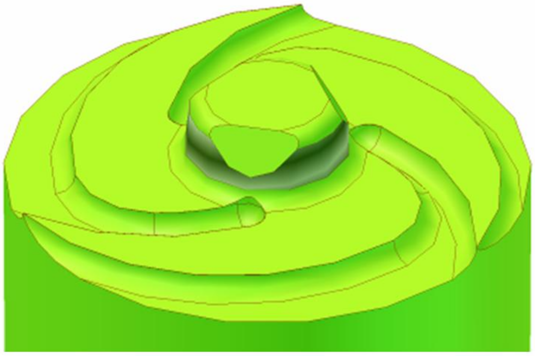

Figure 17 Design of dynamic flash and defect reduction tool with "pin flats" and "pumping features"

2.2 Friction Stir Welding Machine (MTS)

The Friction Stir Welding Machine is located in the National Institute for Aviation Research Laboratory for Advanced Joining & Processing at Wichita State

University. The MTS ISTIR PDS 5-axis motion, 7-axis force monitoring friction stir welding machine, 120-inch x 25-inch x 40 inch work envelope, see Figure 18.

Figure 18 Picture of MTS Friction Stir Weld Machine

The machine used in this experiment is only able to reach speeds up to 2,000 rpm. Since the scope of this work was to study the effect of high rotational speed, well above 3,000 rpm, a spindle speeder was connected “in-line” to achieve the higher rpm.

2.3 Spindle Speeder

The High Speed Spindle speeder can reach speeds beyond 12,000 rpm. These speeds are necessary for the experiment to be carried out. The Spindle Speeder Type is an 824-022, Part # HN824-022-500, with a ratio of 1:6. The speeder bodies are machined entirely from tubular steel, which makes the speeders extremely rigid. In addition, an adapter to connect the speeder to the FSW machine is necessary. The configuration of the speeder and the adapter are shown below in Figure 19.

Figure 19 Spindle Speeder

2.4 Non-rotating Shoulder

HRS-FSW and non-rotating shoulders (zero rpm) are two of the innovations investigated at WSU. Conventionally, weld tool rotational speeds in FSW are on the order of 200 - 2,000 rpm. However, it has been demonstrated that FSW can be performed at much higher spindle speeds (greater than 3,000 rpm). Related HRS-FSW work conducted by Crawford et al at Vanderbilt University showed that as rpm increases above 5,000 rpm the material flow dynamics change and appear to become more “fluid.” The potential advantage of operating at higher rotational speeds is the ability to reduce spindle torque and forging loads. Ensuring defect-free welds (e.g. free of voids and wormholes), but requires careful control of process parameters and tooling. One approach has been to include a non-rotating shoulder surrounding the rotating pin (Static Flash Suppression Technology). The shoulder must be constructed such that it is able to maintain a sufficient forging load to prevent weld defects, and the entrainment of weld flash between the pin and shoulder[37].

A disadvantage to using HRS-FSW is that reduced forging loads create more opportunities for the formation of weld defects such as voids, wormholes, and increased porosity. An introduction of the non-rotating shoulder surrounding the rotating pin, maintains the necessary forging loads to prevent material flow; therefore, it reduces or eliminates welding defects and inconsistencies.

The non-rotating shoulder tool has been shown to have an observable impact of the microstructure and resulting microhardness. It was also shown that the tendency to create weld porosity and wormholes can be totally or largely suppressed[38]. The system shown below in Figure 20 consists of a double wall cylinder capable of applying variable air pressures to create a variable force on the non-rotating shoulder.

Figure 20 Non-rotating Shoulder

The air connection shown in Figure 20, is connected to shop air that is easily adjusted either prior to the weld sequence, or even during the weld process. Figure 21, below, shows the non-rotating shoulder connected to the MTS friction stir welding machine. Note that the air hose is connected to the side of the non-rotating shoulder.

Figure 21 HRS-FSW Setup with a Non-rotating Shoulder on an MTS ISTIR™ PDS System

The primary objectives of the non-rotating shoulder design are to improve surface finish and eliminate weld flashing. This is accomplished by suppressing the nature of the material to flow outwards during a weld. The reduction in flashing could also lead to enhanced fatigue and corrosion response, due to a lack of initiating porosity. Therefore, the non-rotating shoulder would increase weld strength through better forging. This all takes place while significantly reducing energy use and reactionary forces.

Figure 22 Non-rotating Shoulder Head

The tool shoulder surface would protrude just past the shoulder head, shown in Figure 22, just enough to create the necessary friction to heat the material. Simultaneously, the non-rotating shoulder head would then slide over the freshly welded surface to suppress flashing and “smooth” the joint line.

2.5 Optical Microscope

Typical optical microscopes cannot resolve images smaller than the wavelength of light used to illuminate the specimen. The near-field microscope is an advanced optical microscope that is able to resolve details much smaller than the wavelength of visible light.

Visual inspection was performed on all welded samples to verify weld quality. In some cases, impurities, wormholes, and/or surface imperfections were observed. A very useful feature upon obtaining proper microscopic representation is to be able to pull conclusions from the imperfections to make adjustments to the welding parameters. These adjustments can lead to a stronger weld. For instance, if a weld that is examined under a microscope exhibits a lack of penetration, then adjustments can be made to the plunge depth to correct that issue.

2.6 Microhardness Tester

The microhardness test is used to determine the hardness over very small areas for ascertaining the hardness of a delicate machine part. The test is accomplished by forcing a diamond indenter of specific geometry under a test load of 1–1000gf (0.0098–9.8 N) into the surface of the test material and to measure the diagonal or diagonals of indentation optically (ASTM E384-84). Usually, the Knoop hardness number or the Vickers hardness number are used to represent microhardness. Hardness was recorded and analyzed using the Vickers Hardness scale. Relevant standards: BS EN ISO 6507-1:1998, ASTM E92-82 (1997). A diamond indenter, in the form of a right pyramid with a square base and an angle of 136° between opposite faces, is forced into the material under a load *F.* The two diagonals, *d1* and *d2* of the indentation left in the surface of the material after removal of the load, are measured and their arithmetic mean *d* calculated. The area of the sloping surface of the indentation is calculated, the indentation being considered as a right pyramid with a square base of diagonal *d* and vertex angle of 136°. The Vickers hardness is the quotient obtained by dividing the load *F,* expressed in kilograms-force, by the sloping area of the indentation expressed in square millimeters[39].

Symbols:

F = load in kilograms force (kgf) where 1 kgf = 9.806 65 N

d = arithmetic mean of the two diagonals *d1* and *d2*in millimeters (mm)

HV = Vickers hardness

= 2 F sin (136°/2) J2

= *l.854 F/d2*

The loads employed vary from 1 to 100 kgf and are maintained from 10 to 15 seconds. Hardness numbers are expressed as 440 HV30 for example where a hardness f 440 is measured using a 30 kgf load.

Some of the values that were recorded had averages of approximately 130 HV over the complete weld with a maximum on weld number 17, which was recorded as 144 HV. The values will be discussed in a following section.

2.7 Tensile Tester

The tensile test serves as the basis for determining several important mechanical properties of materials. In this test, as described in ASTM E8, the yield strength, tensile strength, elongation, and reduction in area of a material specimen are determined. In addition, the modulus of elasticity, modulus of resilience, and modulus of toughness of a material are found from the stress-strain curve measured during the tensile test[40]. The test specimen is loaded in a uni-axial tension, until the specimen fractures. Certain standards have been set that govern the appropriate data collected. Those standards determined under ASTM E8 are:

- Testing machines
- Specimen types
- Testing speed
- Determination of values of material properties

(a)

(b)

Figure 23 (a) & (b) MTS Tensile Test Machine

2.8 Bending Tester

Many welding codes require bend tests as part of the testing required to qualify welders and welding procedures specifications (WPSs). The concept of a bend test for welds is simple: two plates are welded together and a flat strap of metal is cut from the welded plates. Next, the flat strap of a prescribed size is bent into a

“U” shape, stretching the material on the outer surface while compressing the material on the inside surface[41].

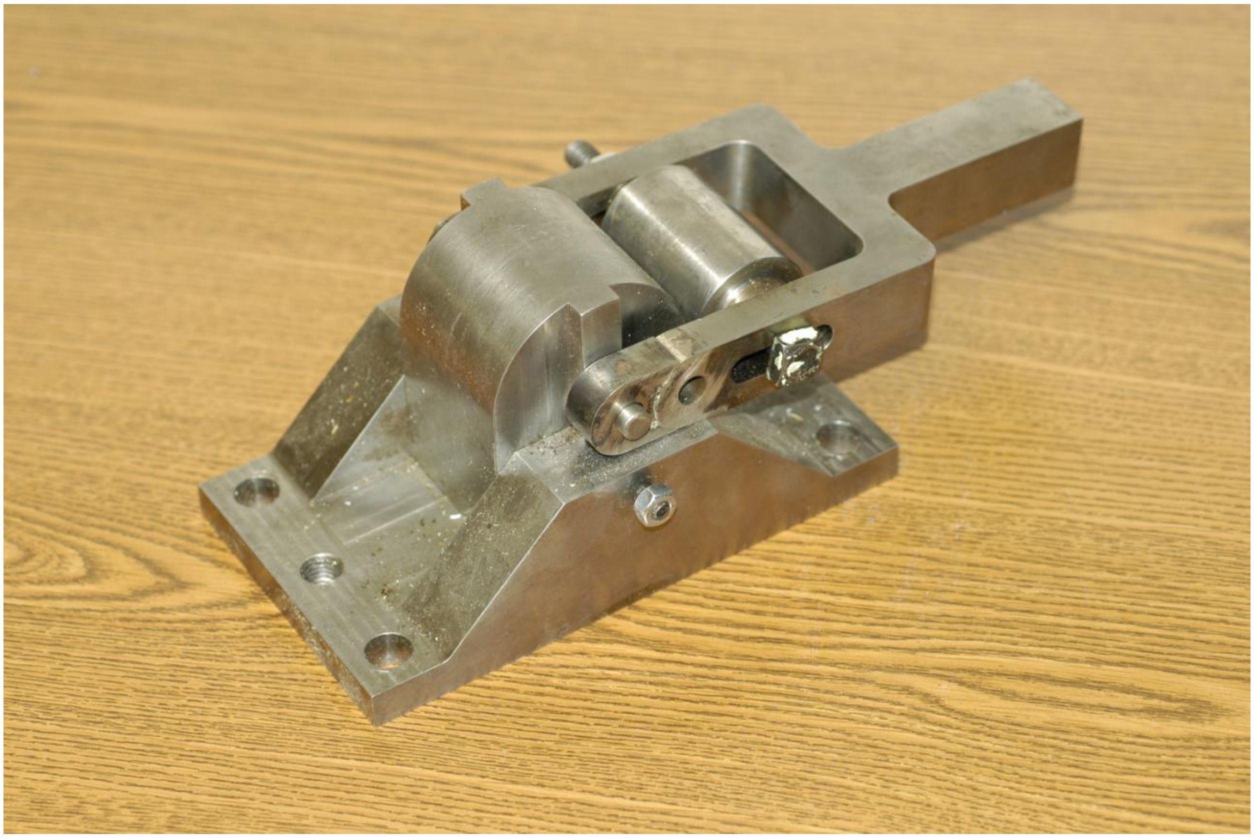

Figure 24 Specimen Bender

2.9 Conductivity Tester

The conductivity, σ, of a material is the reciprocal of volume resistivity or $1/\rho$. It is the relative value of conductivity of any nonferrous metal, to the arbitrary value set for commercially pure copper, and is usually expressed in percent

International Annealed Copper Standard (percent IACS or %IACS), at 20°C by definition, where copper = 100 %IACS.

The test is conducted in this manner: maintain the temperature of the test probe, the standards and the test material within 3°C (5.4°F) of each other. Operate the electrical conductivity instrument in accordance with this standard and the manufacturer's recommendations. When tests are being made, the probe must be firmly pressed against the surface of the material or part. The condition of the part or material being tested shall meet the requirements. Readings of unsatisfactory or questionable conductivity must always be verified by a recheck of the instrument calibration standards, and then a hardness measurement must be performed on the material before making a disposition[42].

CHAPTER 3

3.0 EXPERIMENTAL PROCEDURE

3.1 Flow Chart

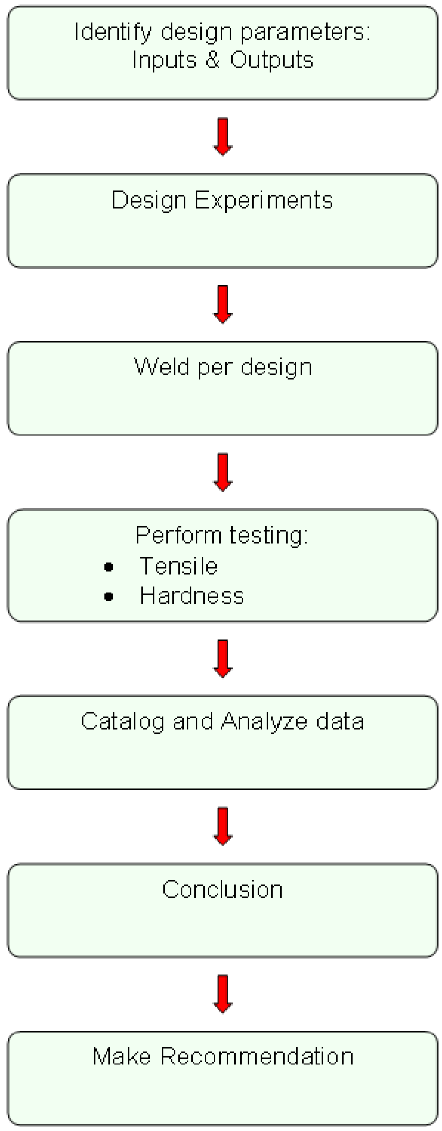

Table 3 Process Flow Chart

3.2 Material (Al 5456-H111)

Aluminum 5456 is the highest strength alloy of the Al-Mg group. It has high resistance to corrosion, but should not be used in strain-hardening tempers at temperatures above 150°F because of possible sensitization to stress-corrosion cracking. Al 5456 is an alloy of aluminum and magnesium with good strength; it is good for structural use because it is of good weldability[43]. It is commonly used in the manufacture of high strength welded structures, pressure vessels, marine applications, and in storage tanks.

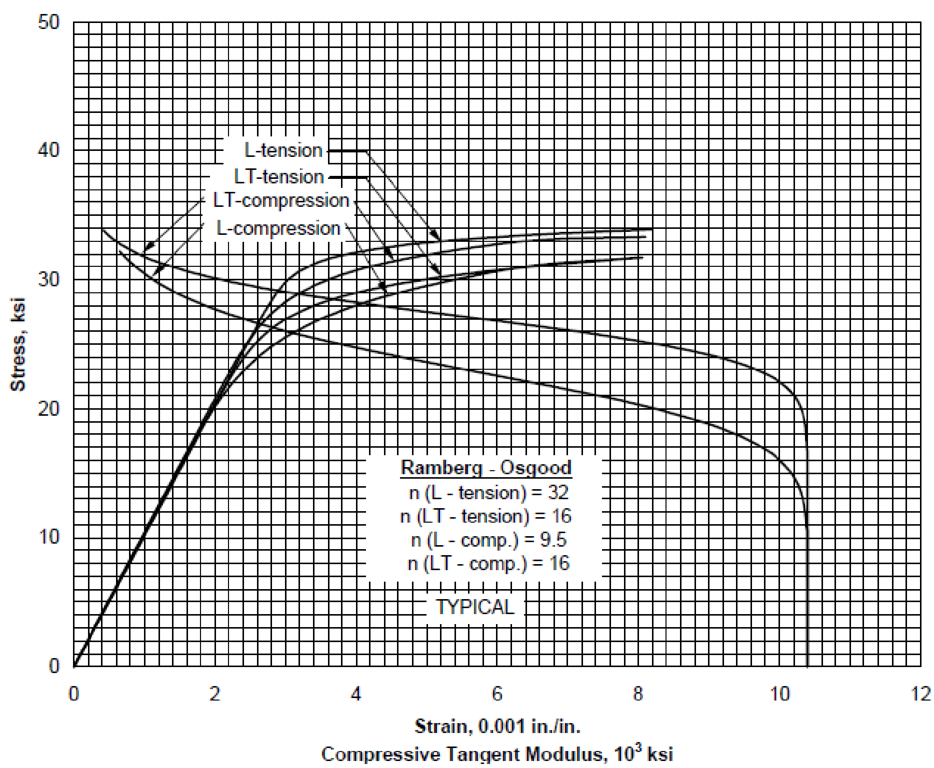

Table 4 Typical tensile and compressive stress-strain and compressive tangent-modulus curves for 5456-H111 aluminum alloy extrusion at room temperature[44]

3.2.1 Optical Microscopy

A simple optical microscope can magnify the surface topological details to a level revealing critical details not visible to the naked eye. With the use of appropriate optics, the microscope utilizes optical reflections from a surface of interest to generate an image of the surface structure. However, it does not allow for the identification of the chemical nature of surface structures. The spatial resolution of this technique is limited to approximately 1 μm. This simple technique generally can be an important first step to survey the macroscopic surface details of a sample[45].

3.2.2 Microhardness Tests

Microhardness test is used to determine the hardness over very small areas or for ascertaining the hardness of a delicate machine part. The test is accomplished by forcing a diamond indenter of a known geometry under a test load of 1-1000 gf (0.0098-9.8 N) into the surface of the test material and to measure the diagonal or diagonals of indention optically (ASTM E384-84)[46].

3.2.3 Tensile Tests

The tension test, defined for metallic materials in ASTM E8, is the simplest and most common tests for mechanical behavior[47]. During tensile testing, the ultimate strength is the largest applied stress measured in the specimen section. The proportional limit, often call the yield strength, indicates the onset of plasticity where the assumption of linear stress-strain behavior is violated. Since there are many definitions of proportional limit, it is imperative that the physical meaning of the limit be clearly defined when presenting the results.

3.2.3.1 Tensile Tests

The tensile strength of a material is defined as the maximum force reached during tensile deformation of a bar of unit cross-sectional area. In practice a test-piece of known cross-sectional area is gripped in the jaws of a testing machine and subjected to a tensile force which is increased by suitable increments. For each increment of force, the amount by which the length of a pre-determined 'gauge length' on the test piece increases, and is measured by some device. The test piece is extended in this way until fracture. A force-extension diagram can then be plotted, Figure 25. At first, the rate of extension is very small, and such extension is directly proportional to the applied force; that is, OQ is a straight line. If the applied force is removed at any point before Q is reached, the gauge-length will return to its original dimensions.

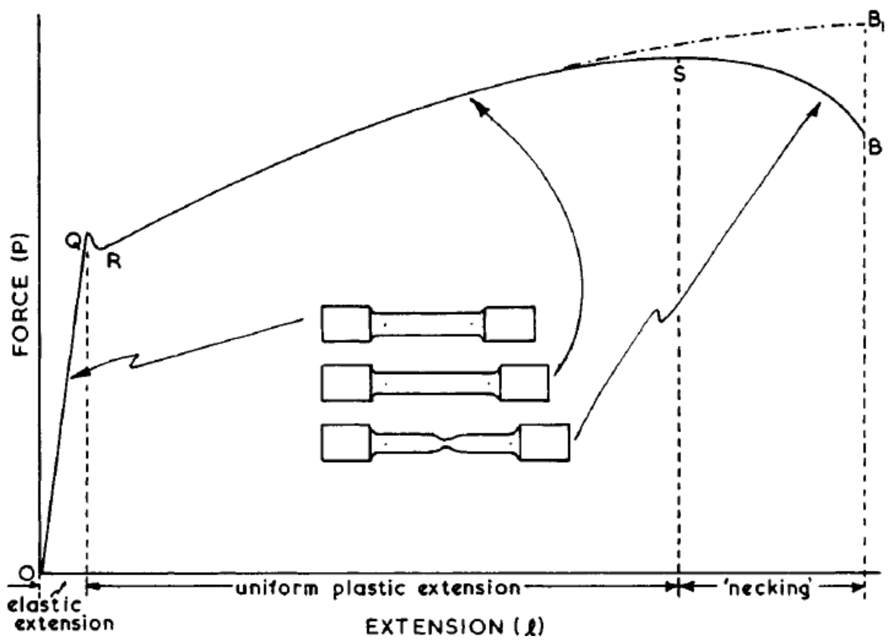

Figure 25 Force Extension Diagram[48]

Thus, the extension between O and Q is *elastic* and the material obeys Hooke's Law, which states that, for an elastic body, the strain produced is proportional to the stress applied. The value Stress— is constant and is equivalent to the slope of OQ. This constant value Strain is known as *Young's Modulus of Elasticity* (E) for the material. Consider a test piece of original length, L, and cross-sectional area, 'a', stretched elastically by an amount, T, under a force, P, acting along the axis of the specimen, then:

E= Longitudinal Stress/Longitudinal Strain

= (P/A)/ (1/L)

= (PL)/ (al)

Young's Modulus is in fact a measurement of the *stiffness* of the material in tension. This value, and the stress range over which it applies, is of great importance to the engineer. Young's modulus is measured in the same units as those of stress, since:

E=Stress/Strain

= [Stress]/ [length]/ [length]

= [Stress]

If at any point on the part of the curve under consideration the force is relaxed, then the test piece will return to its original length, extension at this point being entirely elastic[49].

3.2.4 Bend Tests

A purpose for the bend test is to determine the weld penetration since, in most cases; the weld is performed on one side. In essence, the bent-beam specimens are designed for rapid testing at stress levels below the elastic limit of the alloy. Furthermore, the bend test will prove that a weld is strong by testing the weld in both tension and compression. This test can demonstrate a lack of penetration or improper consolidation. When the weld is conformed to a bend test, the actual weld goes under a prescribed amount of tension and compression. The upper half of the weld undergoes compression where it is most susceptible for shear between the weld nugget and the HAZ or TMAZ. Simultaneously the lower half of the weld is subjected to tension. This tension would have a propensity to force the lower half of the weld to tear and/or deform the weld enough to fracture. See Figure 26, to demonstrate the potential tensile and compressive forces during a bend test.

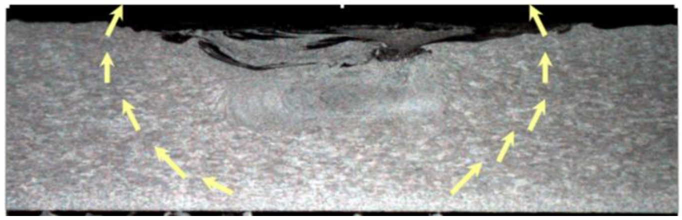

Figure 26 Picture of a Microstructure of a weld depicting bend test forces

3.2.5 Corrosion Tests

Following ASTM G66-95; an accelerated Test Method for Visual Assessment of Exfoliation Corrosion Susceptibility of 5XXX Series Aluminum Alloys (ASSET Test), which is designed for determining the stress-corrosion behavior of alloy sheets and plates in a variety of environments. Some of the double pass welds were examined for corrosive properties of the weld nugget by placing the samples in an exfoliating solution for Al alloys for 96 hours.

Exfoliation corrosion is a delamination parallel to the metal surface caused by the formation of corrosion product, and is also called the *lamellar, layer,* or *stratified* corrosion. The corrosion product causes the material to swell, pushing flakes of metal up at the surface. This kind of corrosion is accelerated in slightly acidic environments, and when aluminum is electrically coupled with a cathodic material. Unlike stress corrosion cracking, it is unaffected by the presence of stress. Exfoliation is greatly increased by exposure to salts such as those found in de-icing salts and salt water.

Alloys most prone to exfoliation are the 2xxx and 7xxx series and some cold-worked 5xxx series alloys. Aluminum-magnesium alloys with more than 3% magnesium, such as Al 5456, held at temperatures above 150°F, are also susceptible. Resistance to exfoliation may be measured by immersion tests such as ASTM G66, *Test method for Visual Assessment of Exfoliation Corrosion Susceptibility of 5xxx Series Aluminum Alloys* (ASSET Test), and ASTM G34, *Test Method for Exfoliation Corrosion Susceptibility in 2xxx and 7xxx Series Alloys* (EXCO Test). Specimens are compared to referenced photographs so they can be ranked according to the following code[50]:

- P- Pitting
- EA- superficial corrosion
- EB- moderate corrosion
- EC- severe corrosion
- ED- very severe corrosion

Both full immersion and salt spray tests are allowable standards. Salt Spray (fog) Tests have long been used to determine the corrodibility of metals and the degree of protection provided by inorganic or organic coatings. The reproducibility of these tests, and their correlation to actual service performance, has been extensively discussed. However, they are easily performed, and are acceptable standards for comparing the behavior of materials and coatings. In several regulations the test procedures and specific conditions are standardized, but some companies and institutions have established their own standards and procedures.

Immersion Tests, in certain cases, complete immersion of the test sample in a corrosive solution, is the best simulation. However, the test conditions need to be controlled to ensure reproducible results. The solutions are usually selected according to the actual problem (e.g., seawater or wastewater, liquids used in technical processes, or biological agents such as sweat or saliva). They are often made of increased concentrations, in order to accelerate the corrosion process. For the most part, standardized test conditions are applied. The parameters are solution composition, temperature, aeration, velocity, duration, and cleaning at the conclusion of the exposure[51].

3.2.6 Conductivity Tests

The corrosive properties of the aluminum welds may be estimated by conductivity testing. The conductivity test may be associated to the relative amount of free electrons throughout the material. Most metals have high conductivity due to the definitive properties of the metals bonding and sharing of electrons. This ability to conduct an electrical current depends on these mobile or “free” charged particles, either electrons or ions. In metal, only loosely held electrons are free to move.

When the aluminum undergoes the mechanical and thermal process of a FSW, the conductive properties of the material are affected. Understanding where there is a tendency for either a lower or higher density of electrons, also known as cathodic or anodic disposition, is essential for proper weld analysis. Therefore, where there is a high density of electrons (anode) in the material, corrosion will occur. Likewise, an area having a lower density of electrons is cathodic and corrosion does not occur.

3.3 Welding Parameter Studies

The welding speed, the tool rotational speed, the vertical pressure on the tool, the tilt angle of the tool, and the tool design, are the main independent variables that are used to control the FSW process. The heat generation rate, temperature field, cooling rate, x-direction force, torque, and the power, depend on these variables. The effects of several of the independent variables on the peak temperature have been discussed in the previous sections. In short, peak temperature increases with increasing rotational speed, and decreases with welding speed. Peak temperature also increases with an increase in the axial pressure. Fig. 27, shows significant increase in peak temperature with increase in rotational speed.

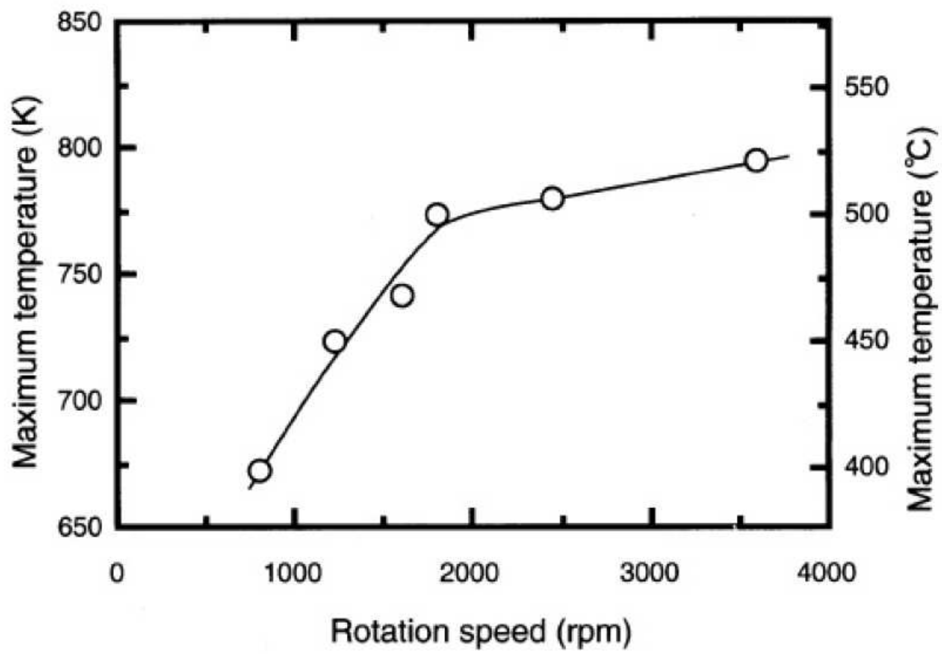

Figure 27 Relationship between rotational speed and peak temperatures in FSW[52]

From Figure 27, it can be deduced that HRS-FSW requires lower forces due to the increase in heat input. Though FSW does not input as much heat, it does require very high forces, which in turn require very large machines.   During FSW, the torque depends on several variables such as the applied vertical pressure, tool design, the tilt angle, local shear stress at the tool material interface, the friction coefficient, and the extent of slip between the tool and the material. Measured torque values can offer some idea about the average flow stress near the tool, and the extent of slip between the tool and the work piece for certain conditions of welding, when other variables are kept constant[53].

3.3.1 Welding Procedure

The welding procedure conducted for friction stir welding is relatively simple. After the proper tooling, parameters and material specimen have been chosen, the key components to achieving a weld has begun. The material to be welded, whether it is to be butted, lapped, or bead on plate, is secured to the backing anvil in a secure fashion. The material is free from movement in any and all directions. During the material clamping process, a tool which has been scientifically determined to achieve an optimal set of objectives is installed into the MTS machine. After which all mechanical connections have been thoroughly checked for tightness.

The operator of the MTS machine will skillfully lower the tool to approximately ½” over the surface of the material, at the start point of the weld. To ensure the coordinates of the end position of the weld procedure, the tool is relocated in the same path as the following weld procedure, to establish the welds termination point. All the parameters for the ensuing weld are saved in the MTS machine. Plunge depth, dwell time, and rotation speed have been determined and the weld sequence can begin.

3.3.2 Optical Micrography and Dynamics Outputs

Optical Micrography is easy to obtain and a readily available means of weld inspection. Preliminary inspection, with the naked eye, can determine if a weld has proper mixing or cohesion. With this preliminary picture of the cross-section of the weld, individual welds can be initially categorized as either not satisfactory (Figures 28-43), or satisfactory (Figures 44-48), by this simple and effective technique. The following present a series of macrographs (Figures from which the optimal welding parameters were selected). Additional tensile tests confirm the parametric window selected for the process (See Table 5).

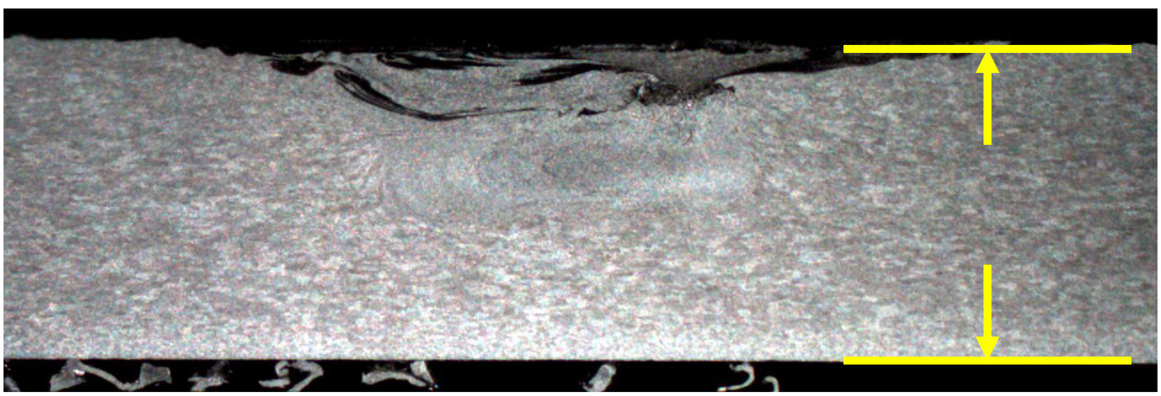

Figure 28 Macrograph of Weld # 9

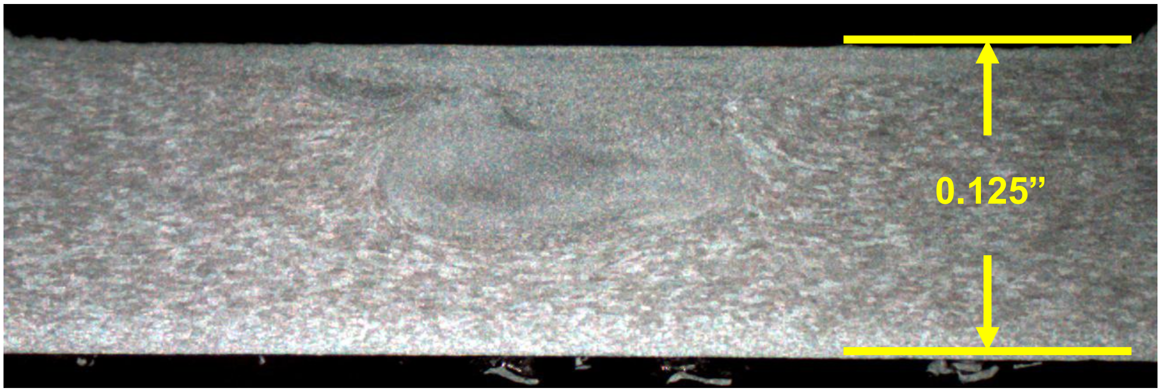

Figure 29 Macrograph of Weld # 10

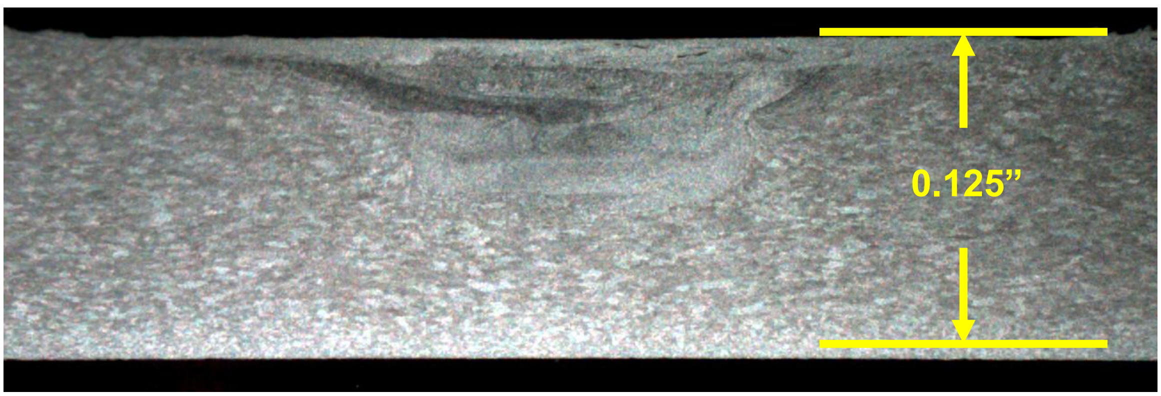

Figure 30 Macrograph of Weld # 11A

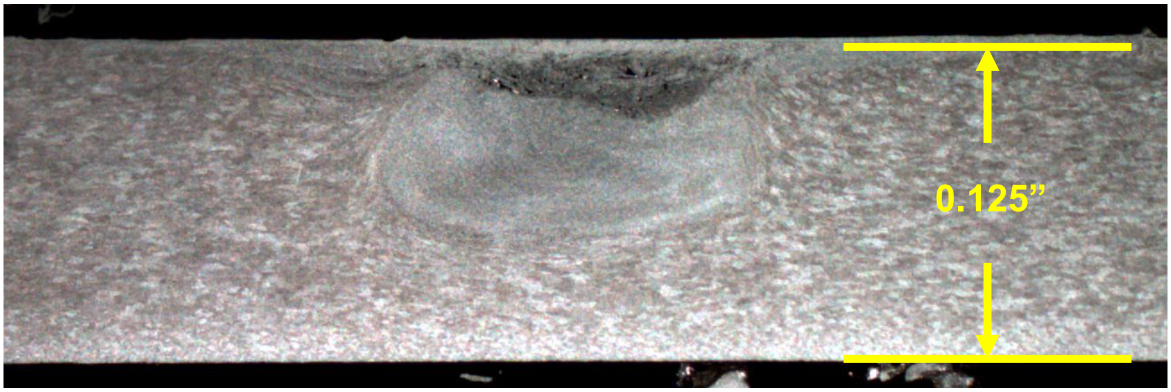

Figure 31 Macrograph of Weld # 11B

Figures 30 & 31, are from the same weld number-from the same set of parameters, “A” is closer to the start of the weld, and “B” is towards the end of the weld. Visually, one can see that at the start of the weld, the weld consolidation was not of high-quality; however, the upper section of the weld proves to be without voids. At the end of the weld, one can see that consolidation of the weld improved, but voids are becoming present at the upper surface of the weld. It can be shown graphically that during the weld, the X-force feedback amount increased and leveled out at a larger value. See Figure 32 below; the X-Force (green) averages out to the highest average of all the welds performed.

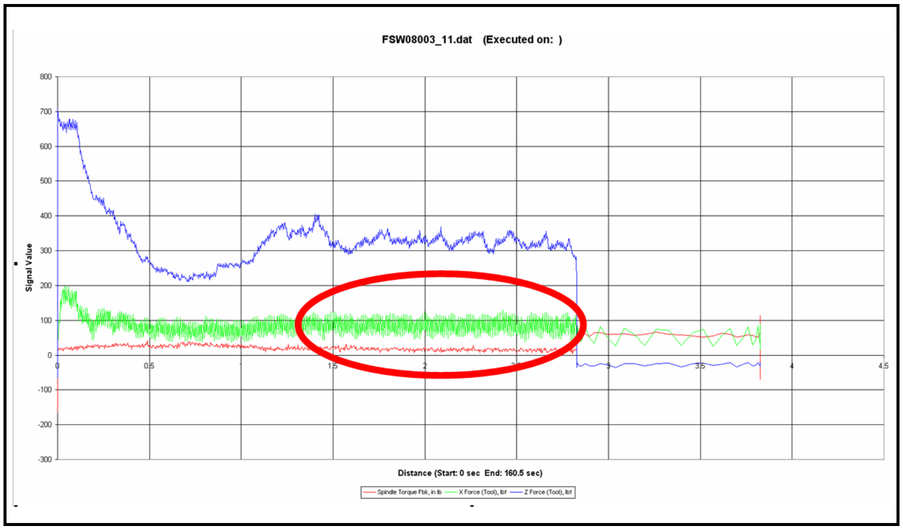

Figure 32 Graphical representation of the force feedback for Weld # 11

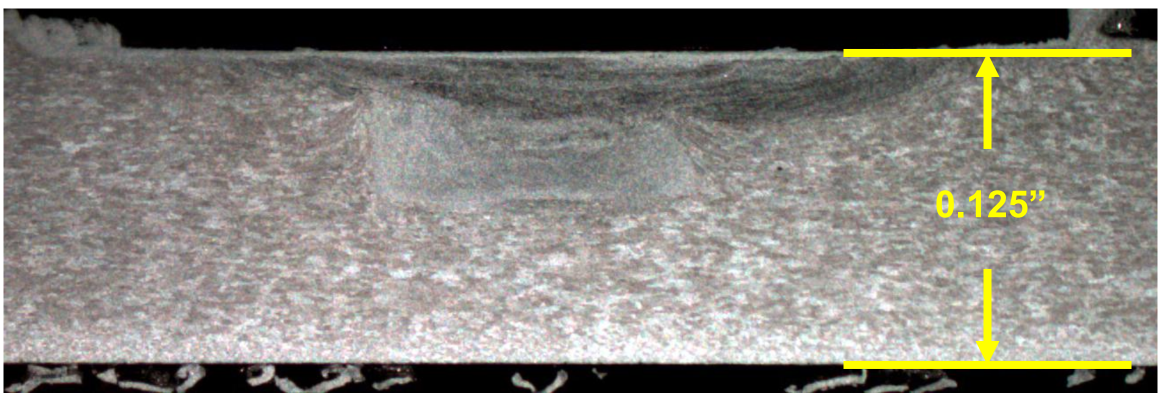

Figure 33 Macrograph of Weld # 12A

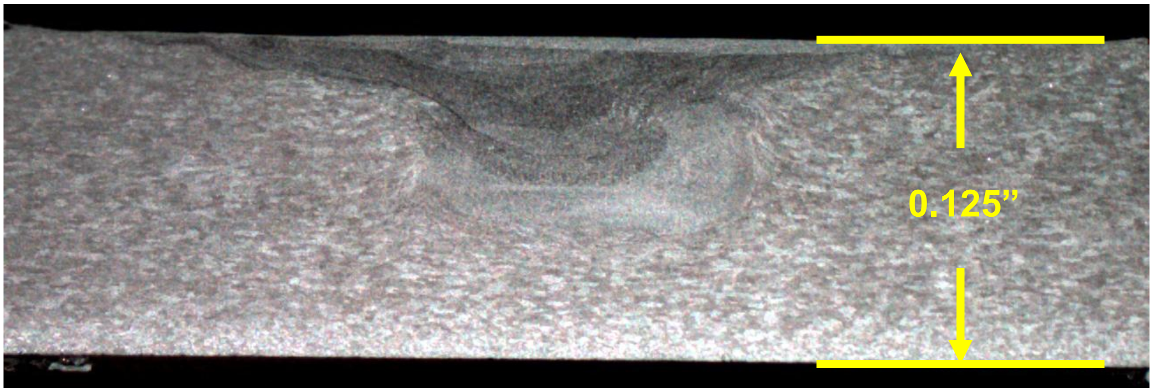

Figure 34 Macrograph of Weld # 12B

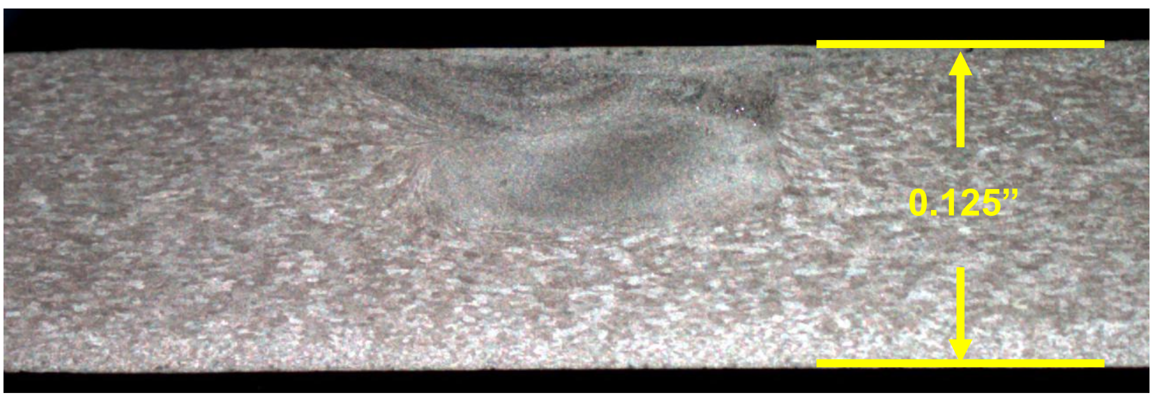

Figure 35 Macrograph of Weld # 13A

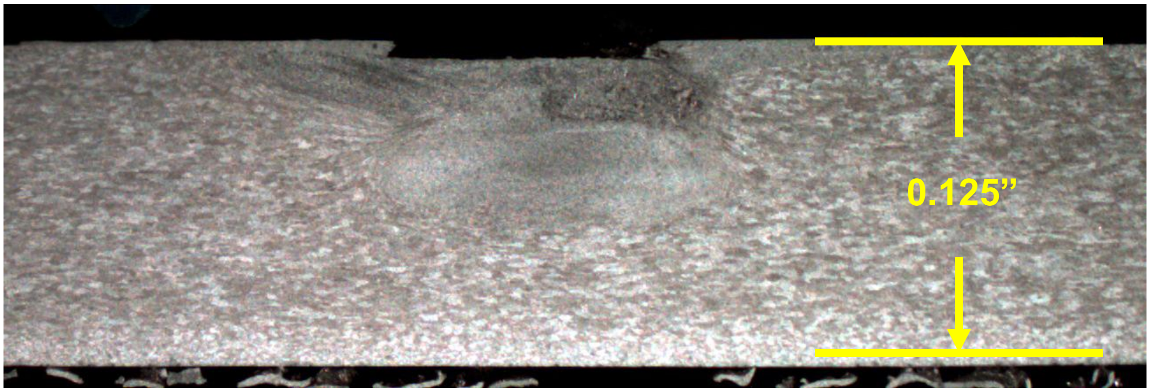

Figure 36 Macrograph of Weld # 13B

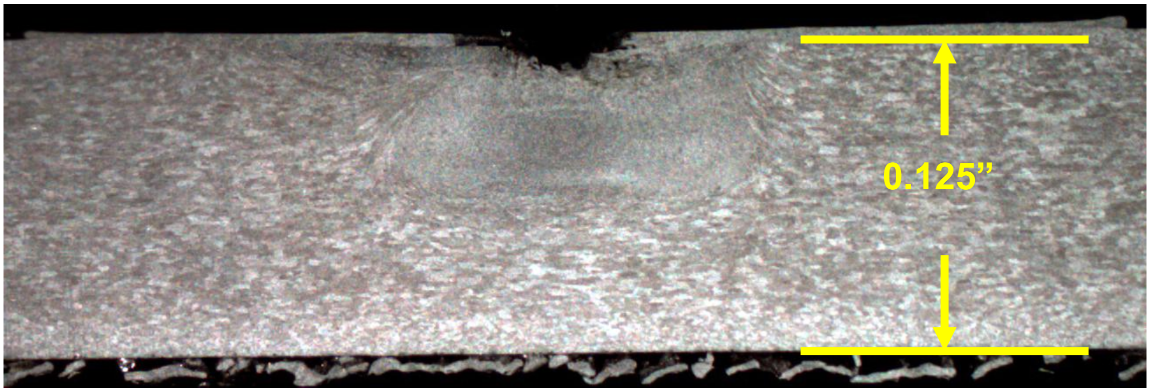

Figure 37 Macrograph of Weld # 18A

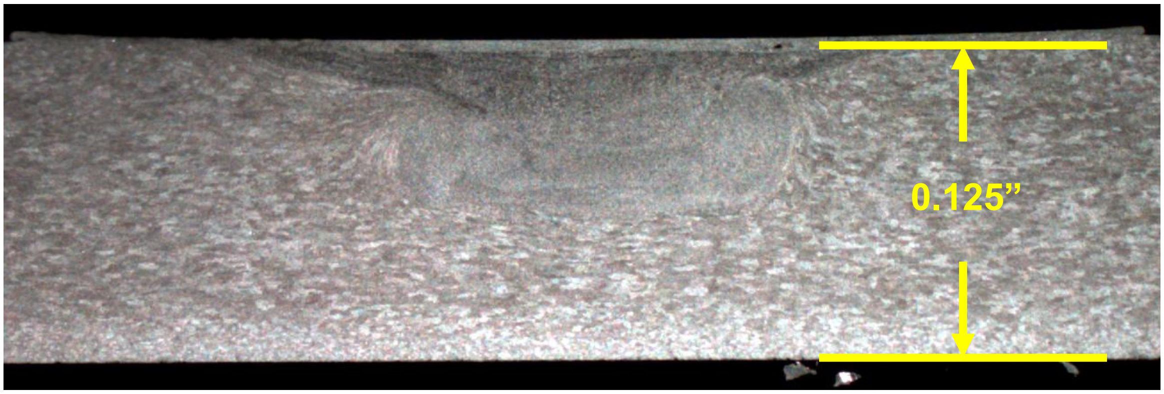

Figure 38 Macrograph of Weld # 18B

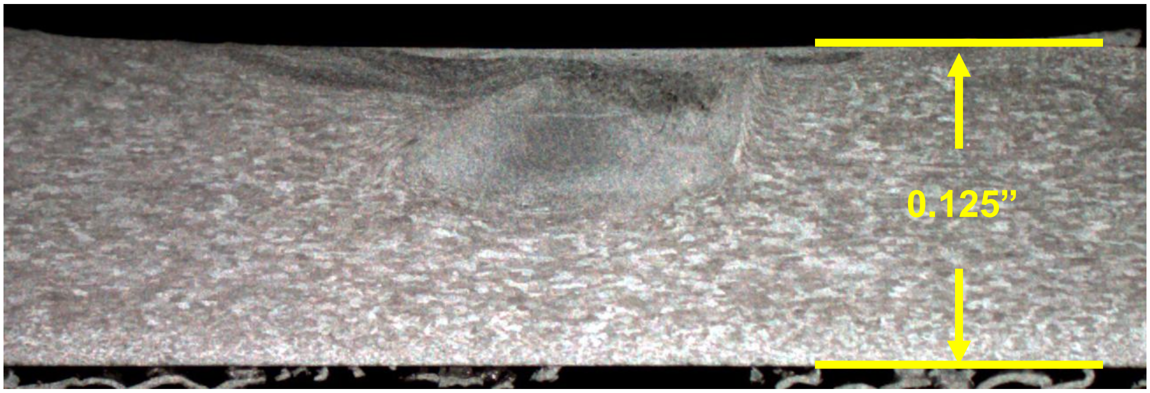

Figure 39 Macrograph of Weld # 19A

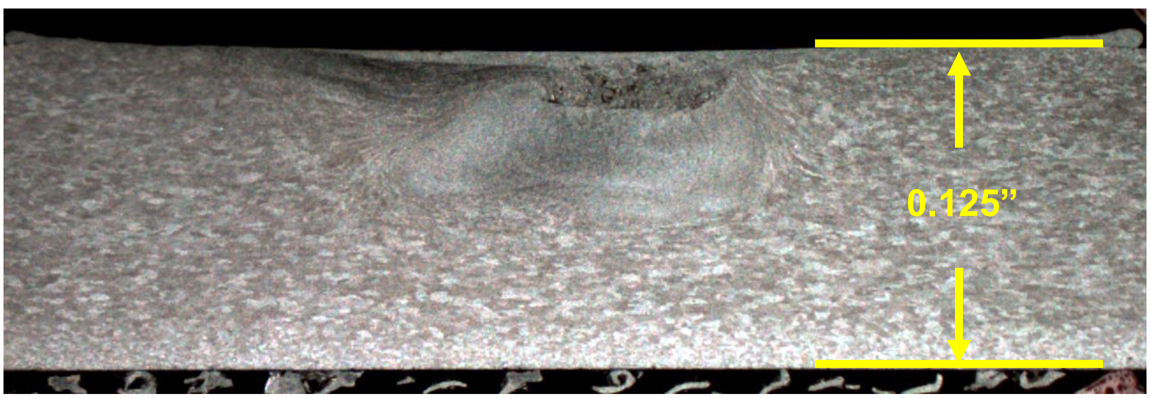

Figure 40 Macrograph of Weld # 19B

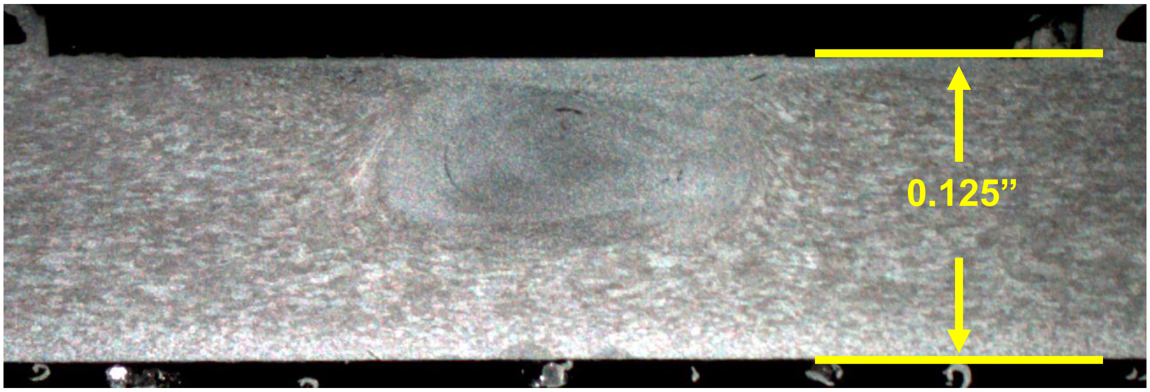

Figure 41 Macrograph of Weld # 14

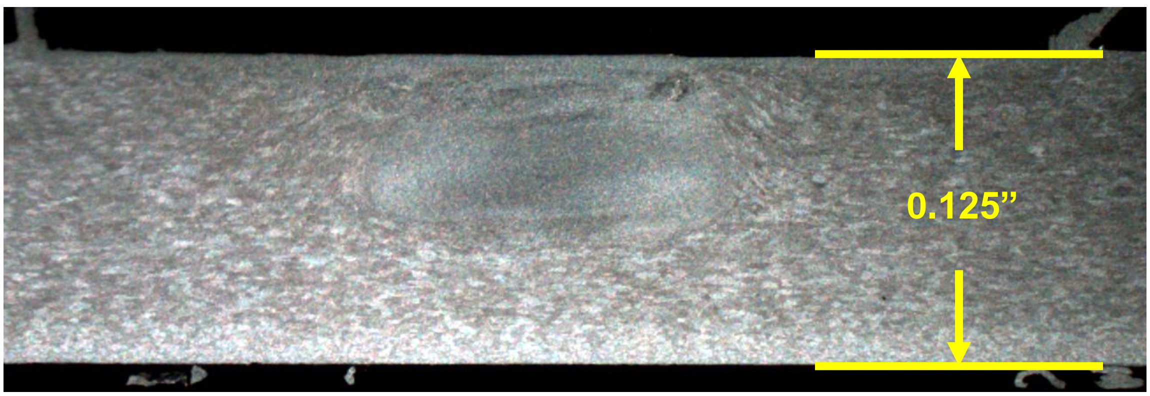

Figure 42 Macrograph of Weld #15A

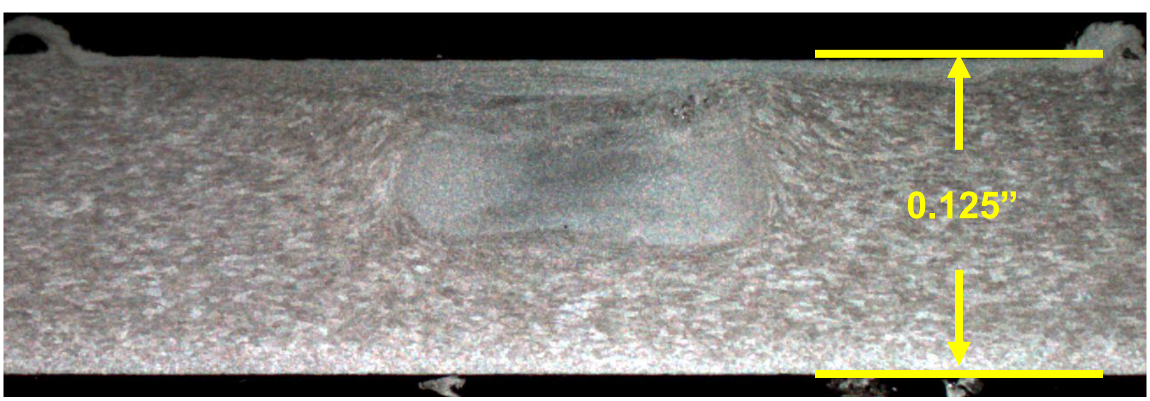

Figure 43 Macrograph of Weld #15B

Figures 28-43, all demonstrate a poor weld quality. Overall X-Force feedback signals were higher than that of the following micrographs. These values are compared in the graphs Figures 49 & 50.

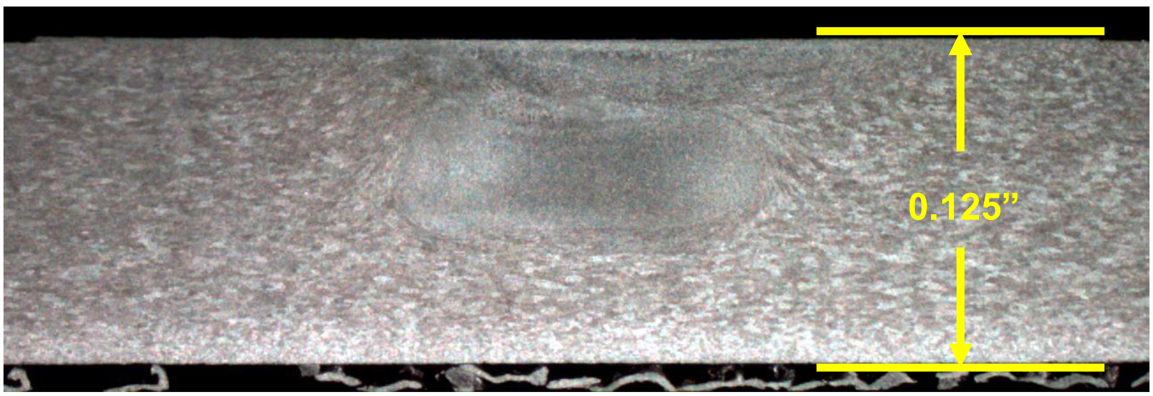

Figure 44 Macrograph of Weld # 16A

Figure 44 of the weld macrograph is accompanied with the welding forces feedback graph displayed in function of the welding distance, Figure 45, showing FSW Plotted macro. Red = Spindle Torque Feedback, in lb. Green = X Force (Tool), lbf. Blue = Z Force (Tool), lbf. From Figure 44, a dynamically recrystallized grain structure in the weld zone is portrayed. Proper shoulder contact, indicated by the upper surface stepping, potentially brought the material to an optimal temperature. It is important to notice that the force values are very small, as expected.   Also the weld consolidation presented in Figure 41, is repeatable as demonstrated by Figures 41 – 44 and 46 - 48. These figures were obtained from additional welds using the same input parameters.   Therefore the welds used in the experimental results are based on the following parameters:

Material		5456-H111			
FSW08003	-9	Lead Angle	0.0	LC/PC	PC
Rpm	12000.0	Ipm	1.0		
FSW08003	-10	Lead Angle	0.0	LC/PC	PC
Rpm	12000.0	Ipm	1.0		
FSW08003	-11	Lead Angle	0.0	LC/PC	PC
Rpm	12000.0	Ipm	2.0		
FSW08003	-12	Lead Angle	0.0	LC/PC	PC
Rpm	12000.0	Ipm	4.0		
FSW08003	-13	Lead Angle	0.0	LC/PC	LC 300#
Rpm	12000.0	Ipm	4.0		
FSW08003	-14	Lead Angle	0.0	LC/PC	PC
Rpm	12000.0	Ipm	1.0		
FSW08003	-15	Lead Angle	0.0	LC/PC	PC
Rpm	12000.0	Ipm	2.0		
FSW08003	-16	Lead Angle	1.0	LC/PC	PC
Rpm	12000.0	Ipm	2.0		
FSW08003	-17	Lead Angle	1.0	LC/PC	LC 400#
Rpm	12000.0	Ipm	4.0		
FSW08003	-18	Lead Angle	1.0	LC/PC	LC 400#
Rpm	12000.0	Ipm	4.0		
FSW08003	-19	Lead Angle	2.0	LC/PC	LC 400#
Rpm	12000.0	Ipm	4.0		

Table 5 Actual program input sheet for utilized parameters

Accompanying each weld was recorded data, such as Figure 45. From the data recorded, each weld demonstrated a relatively steady feedback response in the (X) force and Spindle torque. The (Z) force, lbf, showed an erratic response that typically was high at the beginning of the weld and subsequently diminished as the weld continued. Reading further into the (Z) force and its overall decaying trend could possibly be due to the tool and work piece coming to a stable temperature range. Figures 49 & 50 show the low, average, and high feedback responses for both (X) Force Signal and Spindle Force for the recorded welds, weld number 16, is highlighted to indicate an optimal reactionary forces. One important note to take into account when reviewing the reactionary forces attributed to the welds performed is that they are derived from bead-on-plate welds. Therefore, the reactionary forces will be significantly less when the same weld parameters are used on plates that are butted together for welding.

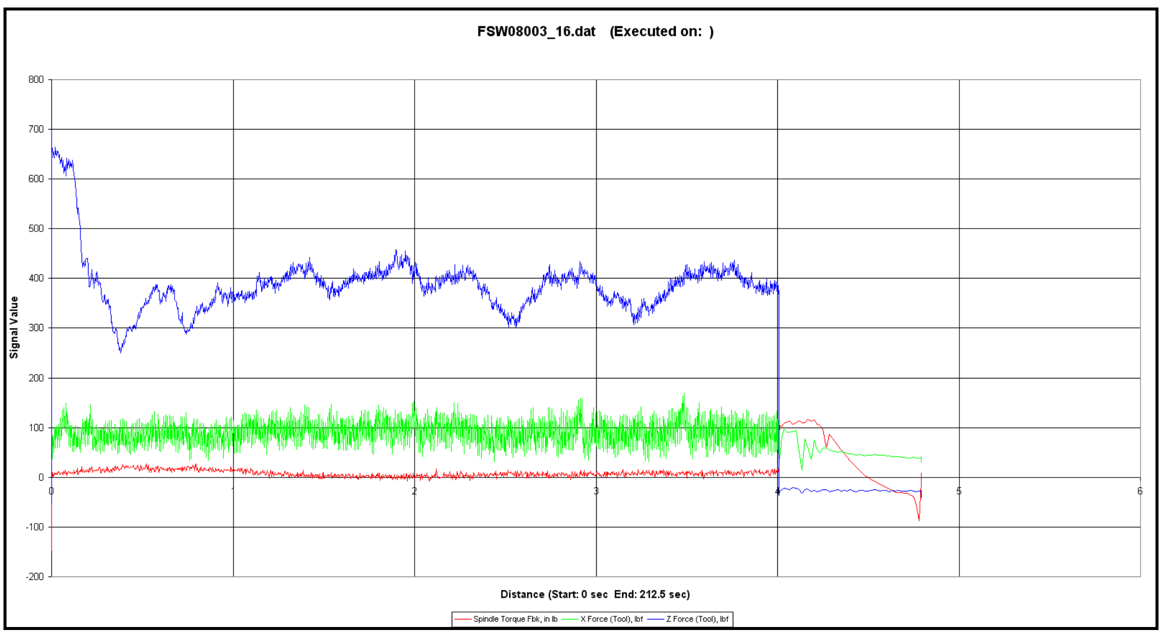

Figure 45 Forces generated for Weld # 16A

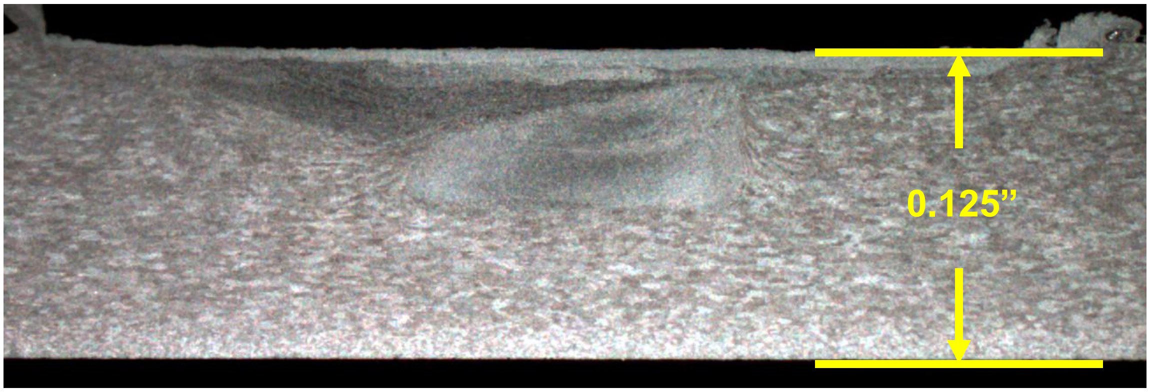

Figure 46 Macrograph of Weld # 16B

Figure 47 Macrograph of Weld # 17A

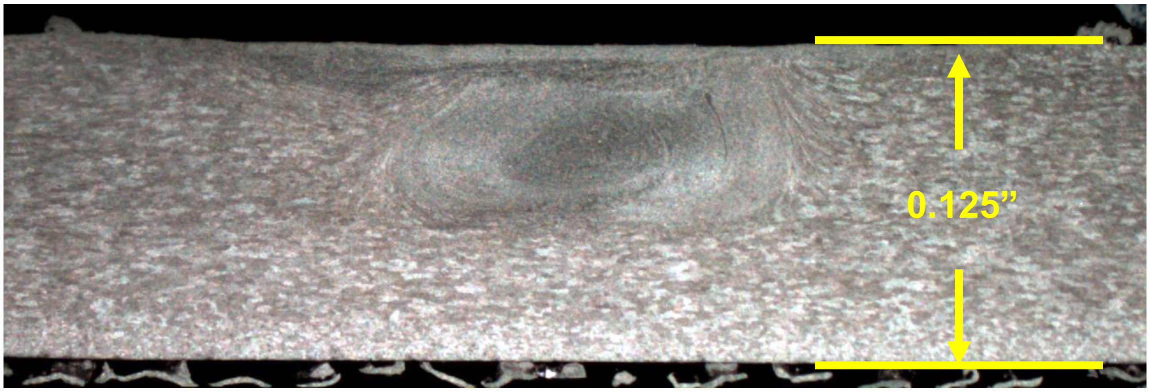

Figure 48 Macrograph of Weld # 17B

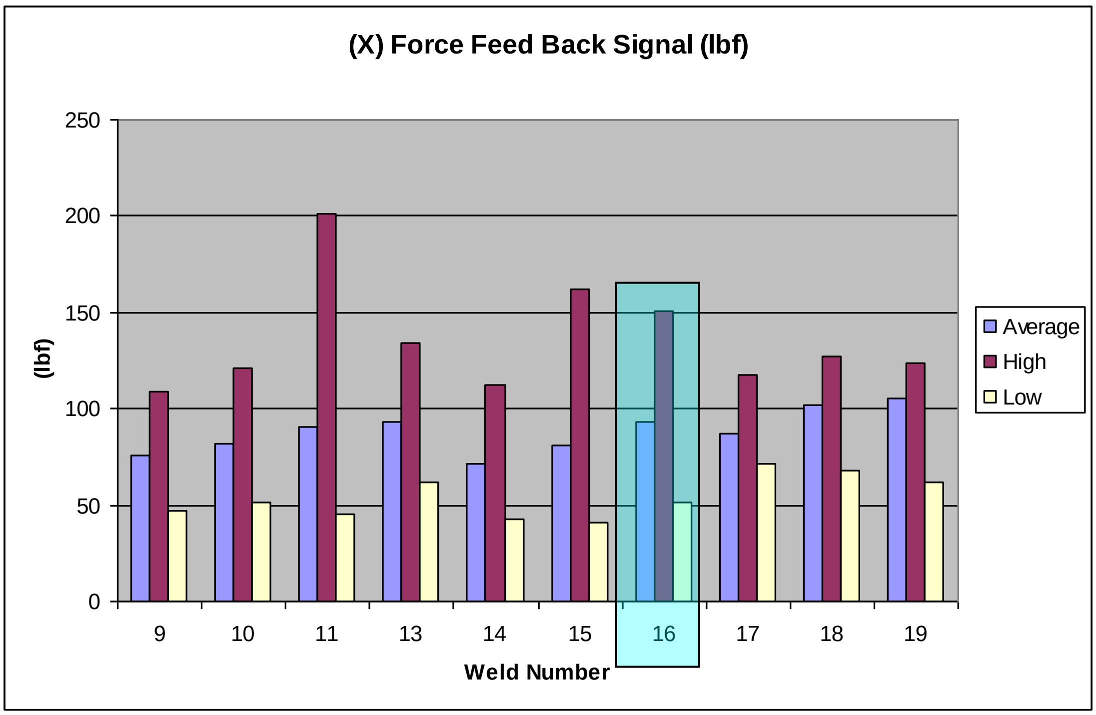

Figure 49 (X) Force Feed Back (lbf), Weld # 16 highlighted

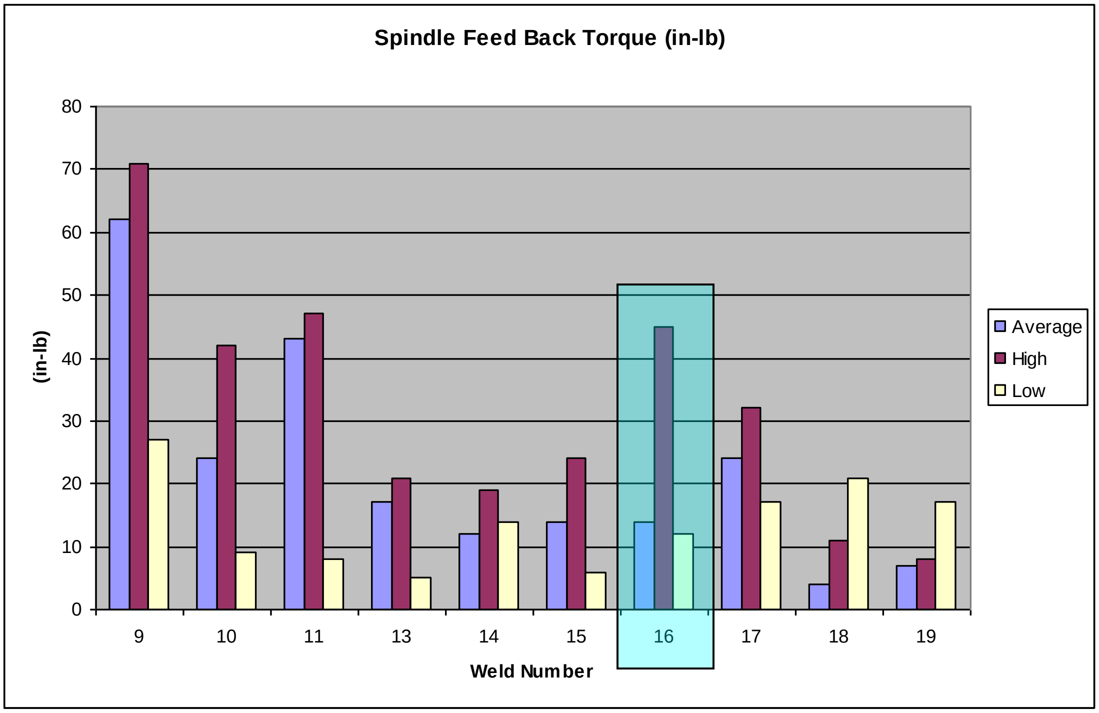

Figure 50 Spindle Feed Back Torque (in-lb), highlighted: refer to Figure 41 & 42 for Weld # 16

The traditional experimental technique for optimal parameter selection has been and is the most effective process. The technique uses the varying of one parameter while holding the other parameters constant. Although, the conventional parametric design of the experimental approach, which might be time consuming, lends itself to be the most effective means for correct parameter selection. The parameters chosen for this experiment started with a rotating speed of 12,000 RPM's, this remained constant throughout the experiment. The advancing speed varied from 1 IPM and as high as 4 IPM, as well as the forging force was varied from 250 lbs to 400 lbs. Another input variable which was adjusted throughout the experiment was the tool tilt angle. Despite the fact that it seems trivial, the tilt angle has an effect on the weld quality. This parameter is thought to change throughout the experiment just by looking at a current weld and making a well educated adjustment per weld.

Weld #	Material	Thickness	Rotat. Speed	Advancing Speed	Advancing Force	Forging Z Force	Lateral Y Force	Torque	Tool Angle
								on spindle	
dimensions		Inches	rpm	inch./min	lbs.	lbs.	lbs.	in-lbs	Degrees
08003_09	5456-H111	0.125	12000	1	70	250	20	35	0
08003_10	5456-H111	0.125	12000	1	70	300	20	30	0
08003_11	5456-H111	0.125	12000	2	90	350	25	30	0
08003_12	5456-H111	0.125	12000	4	100	400	30	40	0
08003_13	5456-H111	0.125	12000	4	80	300	30	30	0
08003_16	5456-H111	0.125	12000	2	90	350	20	30	1
08003_17	5456-H111	0.125	12000	4	90	400	30	30	1
08003_18	5456-H111	0.125	12000	4	90	400	20	10	1
08003_19	5456-H111	0.125	12000	4	90	400	30	10	2
08003_20	5456-H111	0.125	12000	4	20	400	<10	50-25	1
08003_21	5456-H111	0.125	12000	3	20	400	<10	<20	1

Table 6 Welding parameters and summary of results for Al5456-H111 procedure

Note from Figures 44 & 47, the microstructures of Weld #16 & 17; the selection of the welding parameters could be similar to the ones selected in weld 17. Further testing shows slightly better tensile strength for 16. Therefore, the welding parameters of weld 16 were selected for some of studies presented in Chapter 4.

Microstructural features such as the weld nugget are clearly visible; the appearance will be subsequently enhanced after a round of precision etching has taken place. In etching, the specimen is immersed in an alloy-specific solution which functions to further expose the weld's microstructure for microscopic evaluation. The second step in the etching process is to use a Keller's reagent, an etchant composed of 5% Nitric acid, 5% Hydrochloric acid, and 5% Hydrofluoric acid. Once the etching process has been completed, an optical microscope can be used in conjunction with a computer, with imaging software to capture and characterize the grain structure of the weld, as well as capture the macrograph images, which reveal the weld nugget and/or macro and microscopic defects such as wormholes[54].

CHAPTER 4

4.0 RESULTS AND DISCUSSION

This section presents the characteristics of the welds. These welds are the result of the parametric study, presented above, to select the most appropriate weld conditions to obtain good quality welds. The "macro" after the first pass is depicted in Figure 51; note that the welding nugget is deeper than the length of the pin (0.052"). As explained before, HRS-FSW generates an induced stir zone (at 18,000 RPM this zone is more prominent).

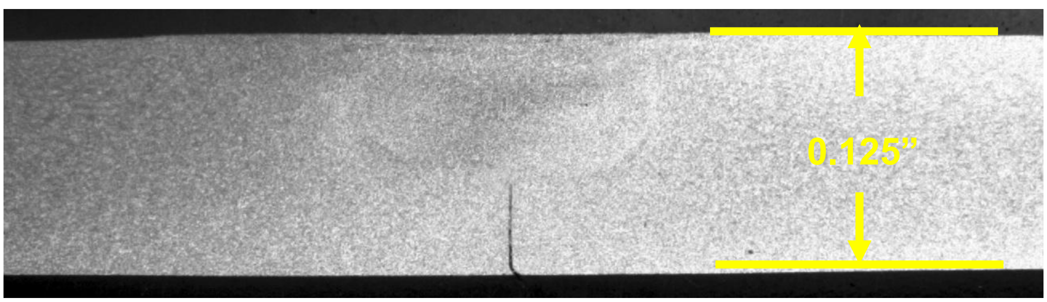

Figure 51 Macrostructure of single pass butt weld AL5456-H111 - 0.125

Figure 51, presents the macro of single pass butt weld. Figures 52, presents the cross section of a double pass weld. It is possible to observe some cosmetic problems on the second weld surface, represented by the unevenness of the lower surface (some galling). Since, during the second welding pass, it was noted that the material was softened by the first pass. It is possible that the unevenness on the weld surface is caused by the softening generated by the first pass.

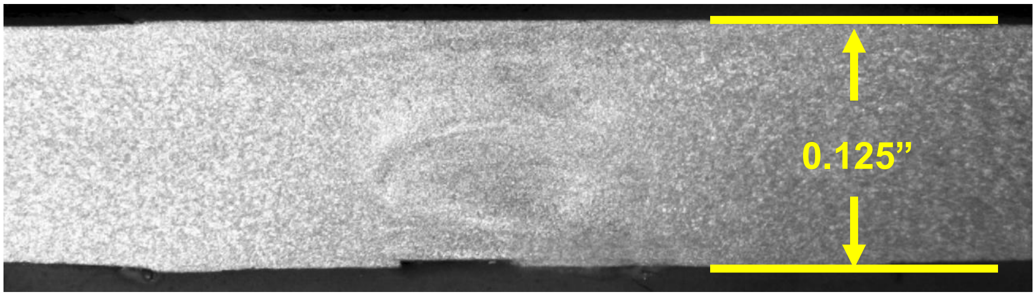

Figure 52 Macrostructure of double pass butt weld Al5456-H111 - 0.125"

Note that the nugget covers a depth larger that the length of the pin (0.051”) due to induced stirring zone typical of the HRS-FSW process. To illustrate this phenomenon a lap weld is presented in Figure 53, where the weld nugget surpasses the thickness of the plate (0.062)

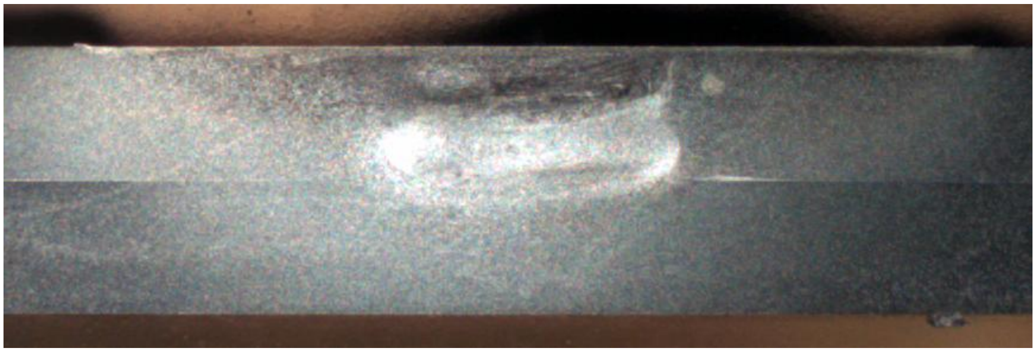

Figure 53 Cross section of a lap weld.

4.1 Hardness Test

Figure 54 is a macrograph of the 2-pass weld nugget at lower magnification than Figure 52. It is presented to be compared with Figure 55. Figure 55 presents a microhardness map of the 2-pass weld. The nugget is harder than the heat affected zone, but softer than the parent metal. In addition, a microhardness profile of the average hardness is presented in Figure 55. Figure 55, also depicts a softer material surrounding the nugget with harder parent metal at both end of the macro. Figure 56, presents the hardness of the central part of the welded plates.

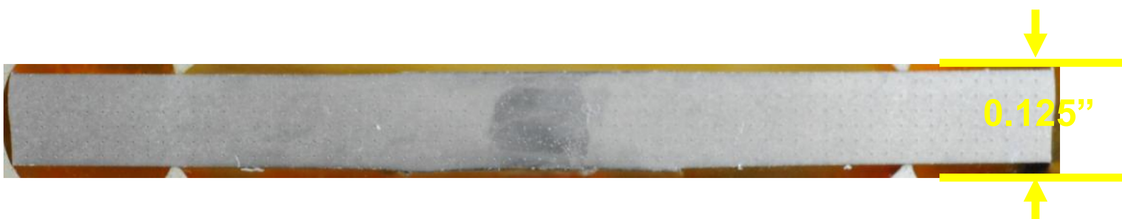

Figure 54 "Macro" where Microhardness measurements were performed

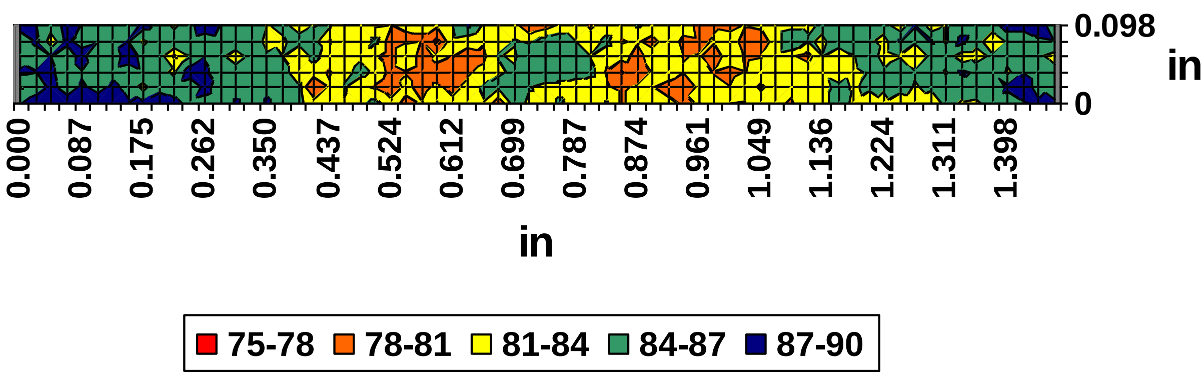

Figure 55 Microhardness map of the 2-pass weld nugget

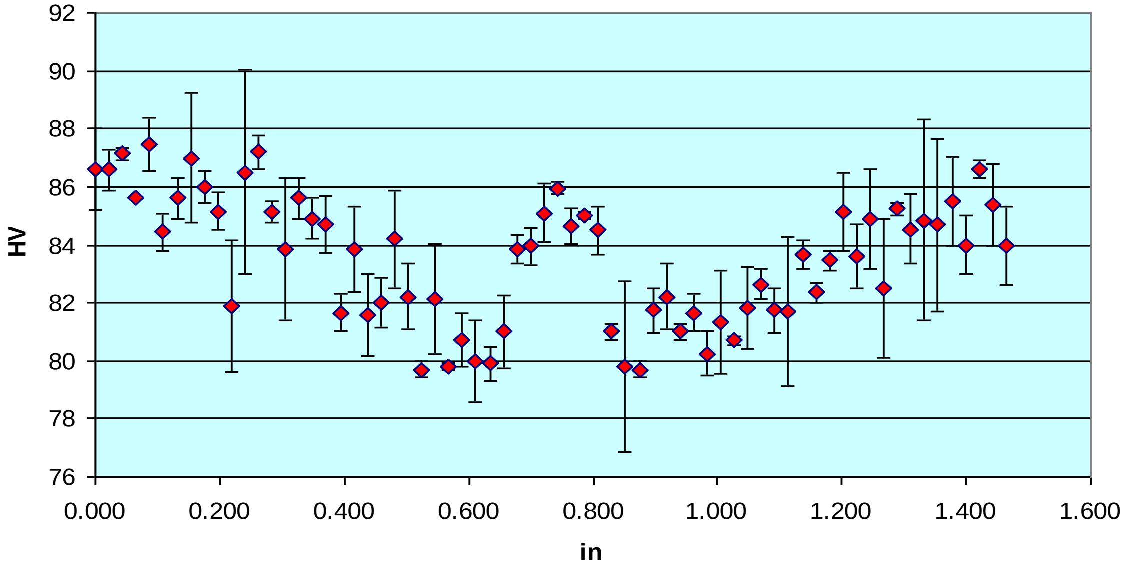

Figure 56 Average microhardness profile of the 2-pass weld nugget

In Figure 57, the vertical arrows present the approximated position of the tensile fracture of the above samples, before deformation. All the samples have failed on the retrieving side of the weld or in the parent metal. The tensile failures occurred at least .200” away from the softer HAZ. Note that the tensile direction on the figure is horizontal on the page.

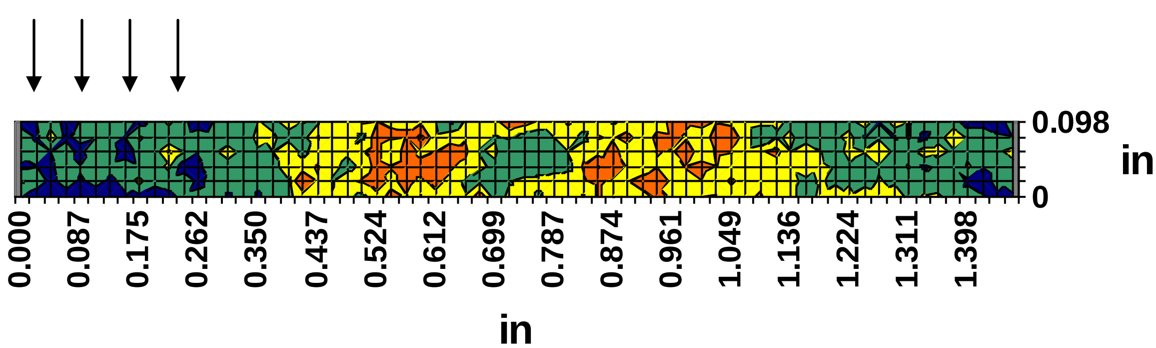

Figure 57 Relative position of the tensile failure aligned with the hardness map

According with the second pass welding data, the material was softened by the first pass. This was verified using the hardness map of the 1-pass weld, which is presented in Figure 57. This one pass weld has a nugget as hard as the parent metal. Again the harder nugget is bordered by soft material. This soft material is likely part of the heat affected zone. Figure 58, is a macro of the 1-pass partial depth weld; the Figure has been modified for comparative ease. Figure 60, is similar to Figure 56, and represents the hardness of the center of the partially welded plates. Note that in general the values of Figure 56 are lower than the ones presented in Figure 60.

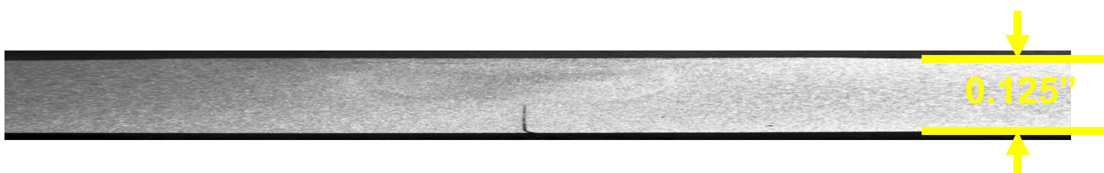

Figure 58 Macro (1-pass) showing partial depth welding of Weld # 20

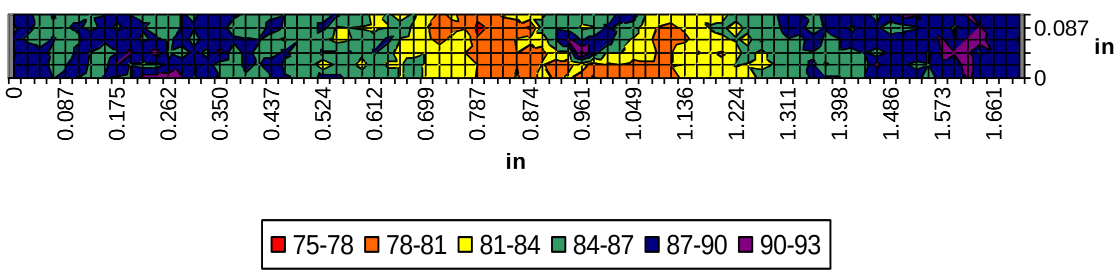

Figure 59 Microhardness map of the 1-pass weld nugget

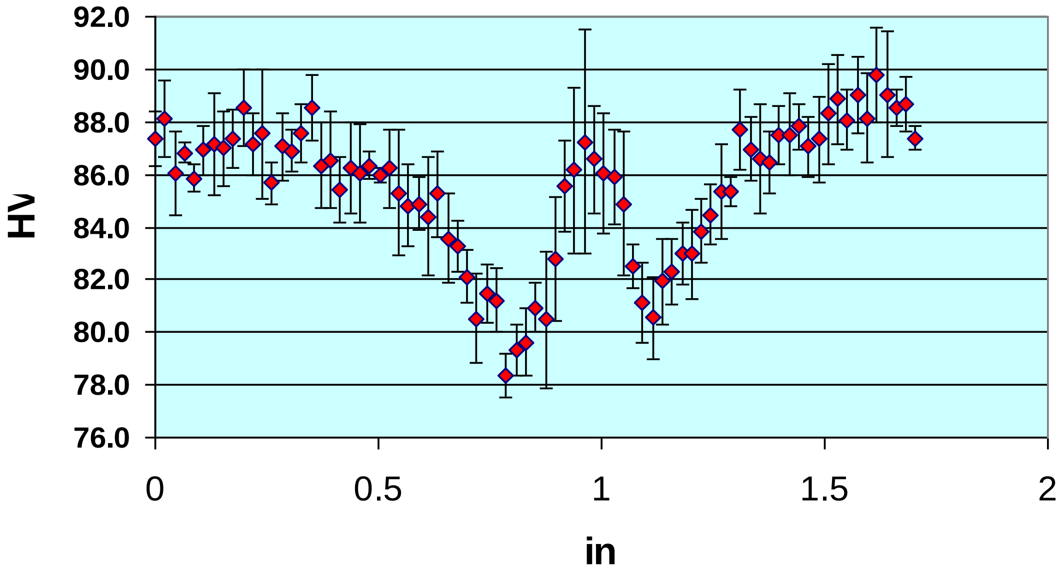

Figure 60 Average mircrohardness of Weld # 20

For comparative reasons, Figure 61 below shows a FSW hardness map. Like Figure 59, there is a relative increase in hardness in the nugget area. However, the same hardness is found well outside the weld zone, located in the parent material. Efforts are being made to make the scale readings more uniform. Also the forces generated by the FSW process was nearly five times larger, in combination with the clamping, may have generated additional internal deformation.

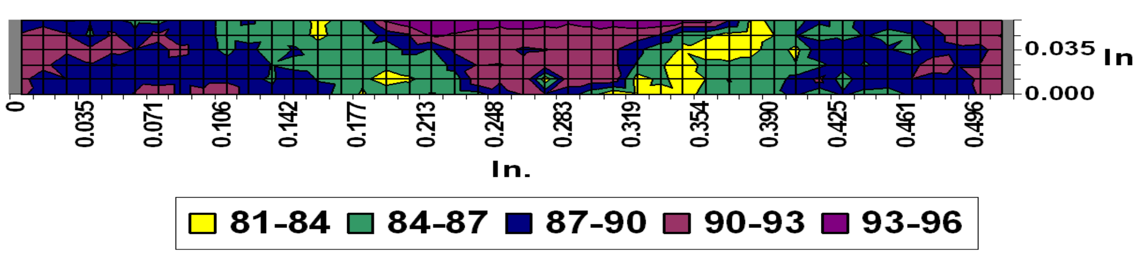

Figure 61 Macrohardness map of FSW

4.2 Tensile Test

The table below shows some of the tensile test results for a number of the initial welds. Both LRS & HRS welds broke either in the parent material or the nugget. A variation in parameter selections could improve both cases.

AJP09004								
upper shoulder				Material	5456-H111			Room 110
lower shoulder				Parent UTS				
Weld Number	Tensile	Width	Thickness	Tensile Load (lbs)	2% Yield (ksi)	UTS (ksi)	% Elongation	Failure Location
AJP09004LS-1	T1	0.491	0.125	2714	24.3	44.2	13.4	Parent
	T2	0.499	0.125	2766	24.1	44.4	14.1	Parent
	T3	0.500	0.125	2758	24.2	44.1	13.4	Parent
	T4	0.492	0.125	2721	24.3	44.2	13.6	Parent
AJP09004HS-1	T1	0.497	0.125	2632	22.0	42.4	9.6	Nugget
	T2	0.501	0.125	2678	22.2	42.8	9.4	Nugget
AJP09004HS-2	T1-250#	0.508	0.125	2780	22.0	43.8	12.5	Parent
	T2-250#	0.498	0.125	2723	22.2	43.7	12.5	Parent
	T3-300#	0.497	0.125	2709	22.0	43.5	11.9	Parent
	T4-300#	0.503	0.125	2472	21.9	39.3	6.1	Nugget
AJP09004HS-3	T1-250#	0.486	0.125	2656	22.3	43.7	13.1	Parent
	T2-250#	0.486	0.125	2679	22.6	44.1	14.1	Parent
	T3-300#	0.480	0.125	2535	21.7	42.3	9.4	Nugget
	T4-300#	0.479	0.125	1883	21.7	31.5	2.6	Nugget
AJP09004HS-4	T1-250#	0.487	0.125	1632	23.7	26.8	5.5	Nugget
	T2-250#	0.489	0.125	1826	18.2	29.9	5.6	Nugget
	T3-300#	0.500	0.125	1716	22.5	27.4	2.9	Nugget
	T4-300#	0.496	0.125	1729	22.6	27.9	2.9	Nugget
	T5-350#	0.490	0.125	1000	16.3	16.3	1.9	Nugget
	T6-350#	0.493	0.125	1345	20.8	21.8	2.1	Nugget
AJP09004HS-5	T1-250#	0.496	0.125	1510	23.4	24.4	2.2	Nugget
	T2-250#	0.495	0.125	1458	21.7	23.6	2.6	Nugget
	T3-300#	0.495	0.125	1554	22.1	25.1	3.0	Nugget
	T4-300#	0.497	0.125	1581	21.7	25.5	3.0	Nugget
	T5-350#	0.493	0.125	1359	21.1	22.0	2.8	Nugget
	T6-350#	0.499	0.125	1383	21.2	22.2	3.2	Nugget
AJP09004HS-6	T1-250#	0.495	0.125	1863.3				Nugget
	T2-250#	0.496	0.125	1910.90	25.60	30.8	2.6	Nugget
	T3-300#	0.499	0.125	1894.40	25.20	30.4	2.2	Nugget
	T4-300#	0.498	0.125	1688.40	24.30	27.1	2.0	Nugget
	T5-350#	0.493	0.125	1475.50	23.00	23.9	1.4	Nugget
	T6-350#	0.496	0.125	1273.50	20.20	20.2	1.2	Nugget
FSW08017 (sample id 5)	T1	0.268	0.120	1468.60	25.23	46.0		Parent
	T2	0.263	0.124	1467.50	24.52	45.0		Parent
	T3	0.264	0.124	1486.70	24.70	45.4		Parent
	T4	0.027	0.124	1450.40	24.32	43.8		Parent
FSW08017HS (sample id 5)	T1	0.257	0.123	1414.50	23.88	44.8		Parent
	T2	0.238	0.124	1309.70	23.58	44.4		Nugget
	T3							
	T4	0.237	0.125	1172.80	22.37	39.6		Nugget

Table 7 Tension test results

Cross Weld Tensile Tests**:** The objective of this experiment was to determine the tensile properties of standard test specimens and compare those with that of the base metal. The properties investigated include Yield Stress and Ultimate Tensile Stress. The values obtained are presented in Table 8.

FSW08003_20_21								
Tensile #	**RPM**	**IPM**	**Tensile Load**	**Width**	**Thickness**	**UTS**	**Yield St.**	**Failure Location**
T1			2568	0.453	0.123	46	23.4	parent material
T2			2537	0.454	0.122	45.8	23.5	parent material
T3			2544	0.454	0.122	45.9	23.5	parent material
T4			2547	0.454	0.123	45.6	23.1	parent material
T5	12000	4	2557	0.455	0.123	45.7	23.4	parent material
PM1			1154	0.212	0.119	45.7		parent material
PM2			1168	0.212	0.119	46.3		parent material
PM3			1267	0.24	0.119	44.4		parent material
PM4			1277	0.24	0.119	44.7		parent material
PM5			1154	0.213	0.119	45.5		parent material
PM6	12000	3	1259	0.241	0.119	43.9		parent material

Table 8 Tensile values of welded (ASTM standard samples) and parent

Figure 61, illustrates the failure location of the five welded samples tested in tension. Again, all of them failed on the parent material away from the weld nugget. Therefore, the weld nugget is stronger than the parent material.

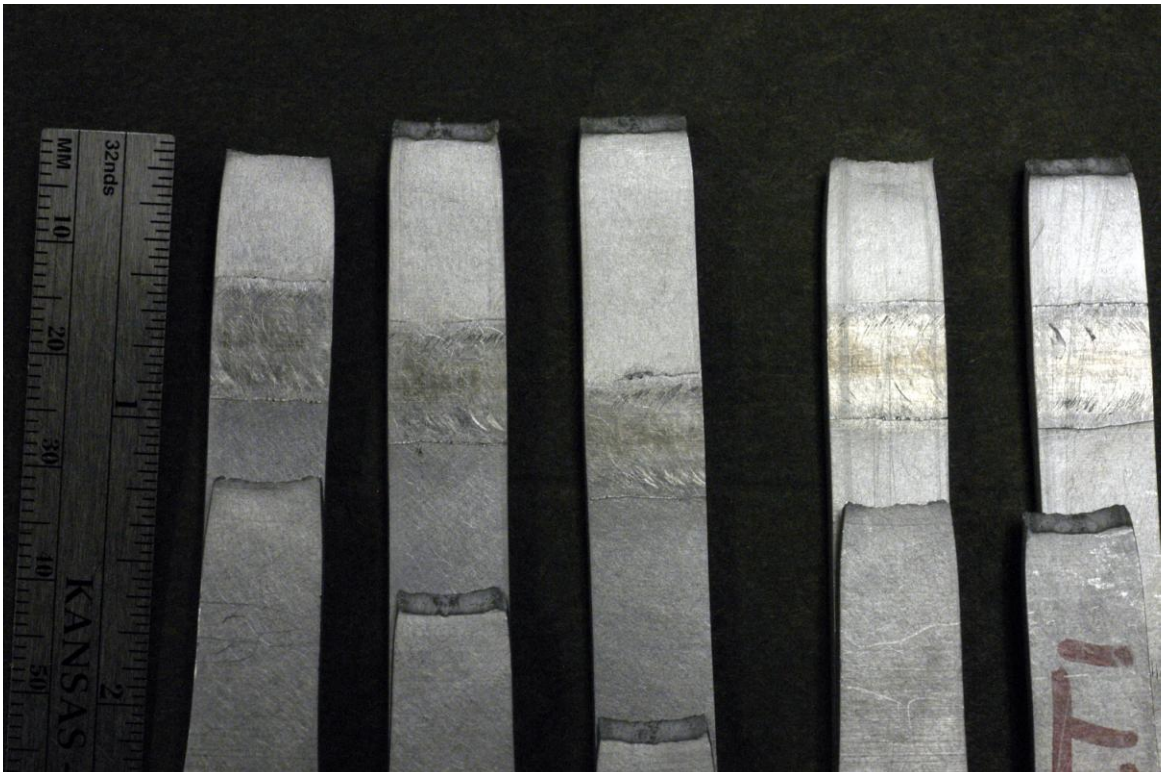

Figure 62 Parent metal failure during tension of Al 5456-H111 – 0.125 thick HRS-FSW welds.

Figure 63 Tensile results of FSW; failures in Nugget and Parent Material

Figure 63, shows five tensile results for FSW. Notice that there are some failures in the nugget associated with a poor weld quality, or lack of penetration. These Figures indicate that FSW is not the viable option.

Figure 64 Parent Material Failures HRS - FSW Tensile Results

4.3 Bend Test

The bend test dictates the proof in the weld ductility. The following bend test results evaluate the materials ability to resist cracking at the weld and also to prove there are no surface irregularities during one continuous bend.   After the material was bent, the convex surface of the bend is examined for evidence of any cracks or surface defects.   Under the macroscopic and microscopy points of view, in either case no surface cracks were observed. Even under high deformation as presented in Figures 65 and 66.

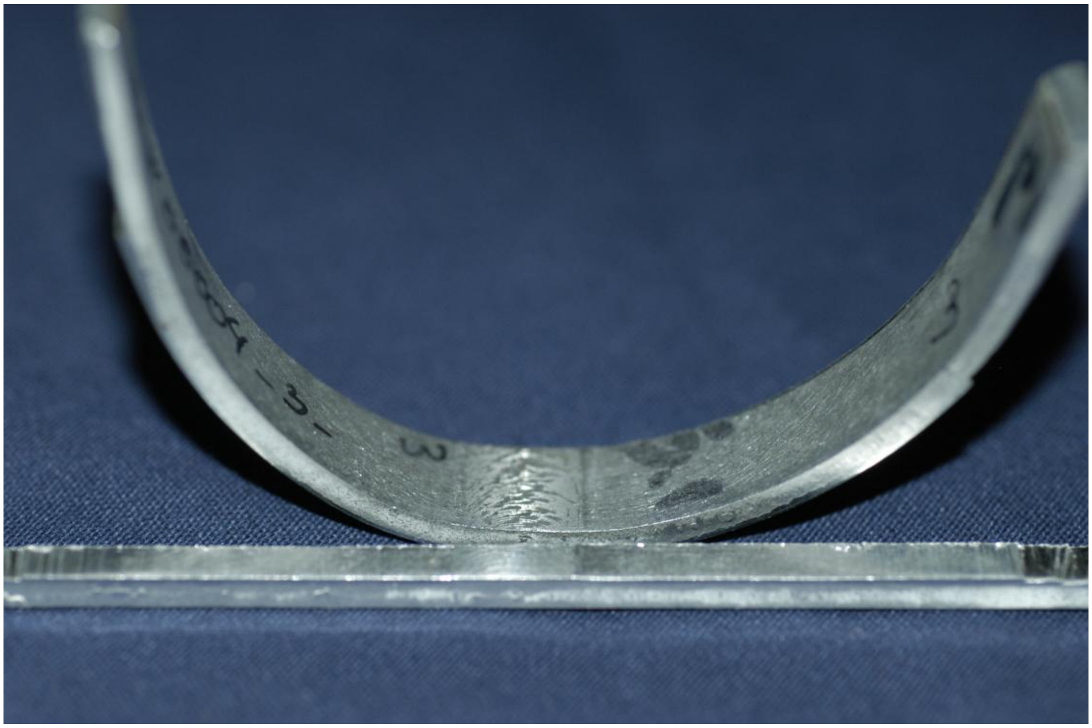

Figure 65 HRS – FSW bend specimen

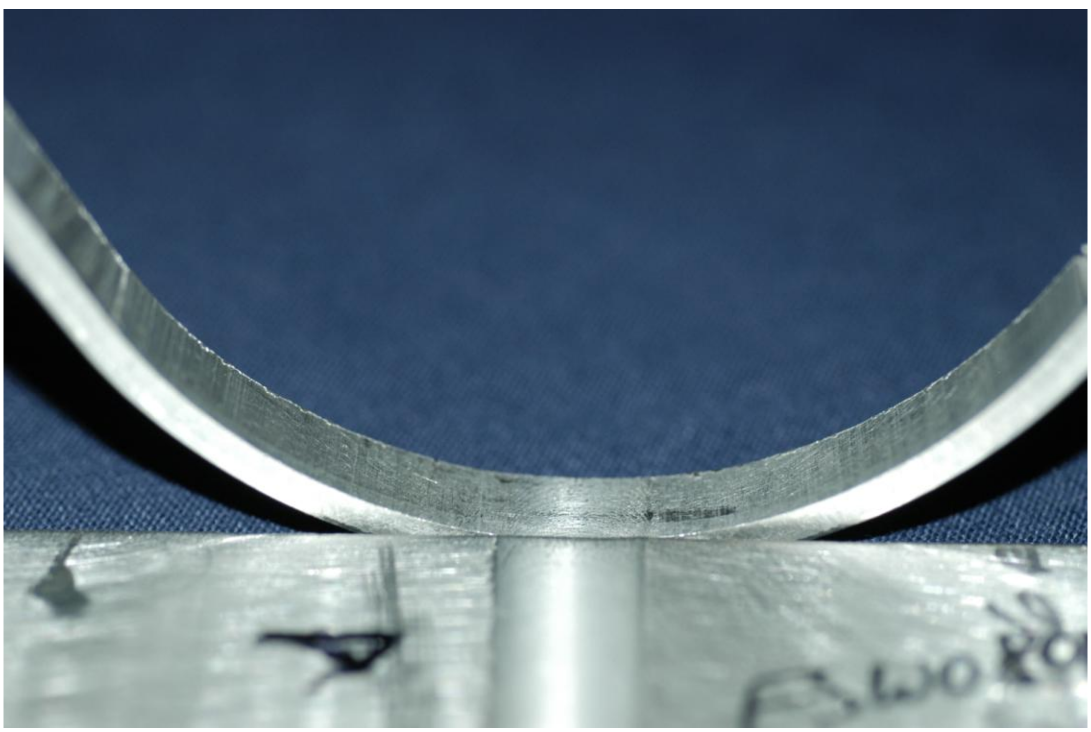

Figure 66 LRS - FSW bend specimen

In Figure 67, the FSW specimen underwent a sharp bend test. This sharp bend test shows significant strength in the weld zone. Almost all of the tensile and compressive forces attributed during a sharp bend test are focused primarily in the weld zone. Al5456-H111 aluminum is confirming high strength and ductility.

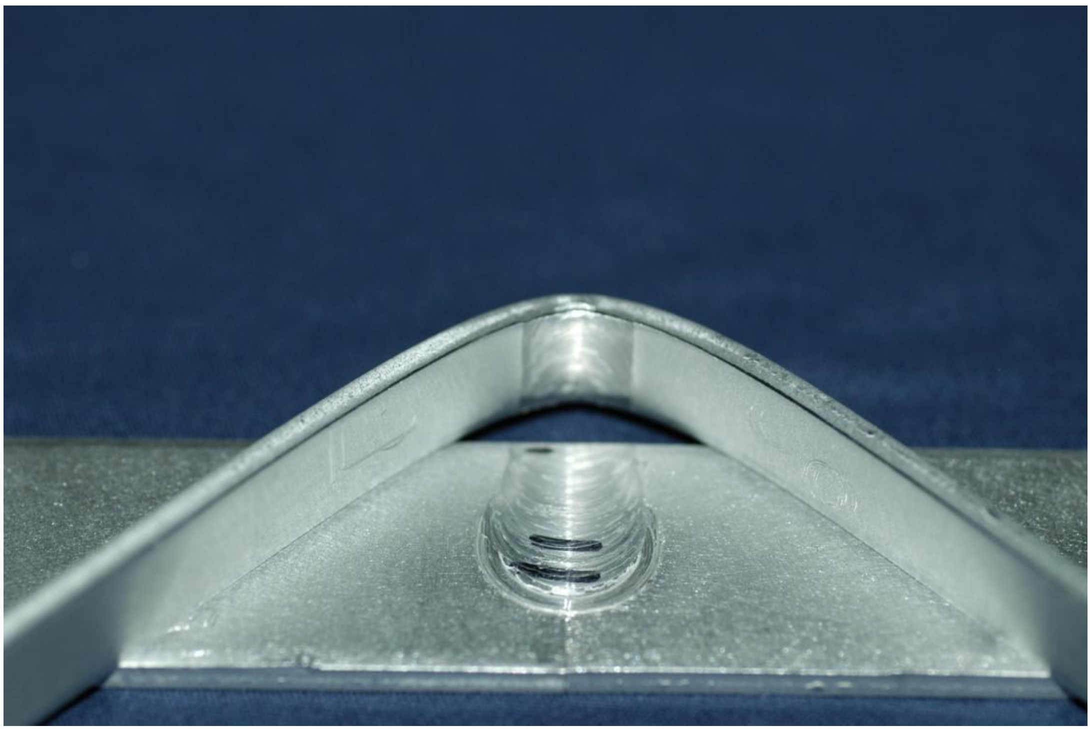

Figure 67 HRS-FSW Unbroken bend specimen

Figure68 Example of a FSW unbroken bend specimen

Through the bending process, each of the specimens was bent; stretching the material on the outer surface of the “U”, while compressing the material on the inside surface. If the base material was significantly stronger than the weld, the bending strains would concentrate in the weld, creating a potential break point either at the weld or in the weld. Therefore, each of the bend test specimens exhibit strong weld cohesion.

4.4 Corrosion Test

Figure 68, represents the surface condition of the “as received” (parent) Al 5456-H111 material. In this figure, you will notice a typical surface generated by the extrusion process, bright and clean. In contrast, Figure 69, shows the effect of the exfoliation; the brightness of the surface was replaced by a grayish surface, typical of the exfoliation process.

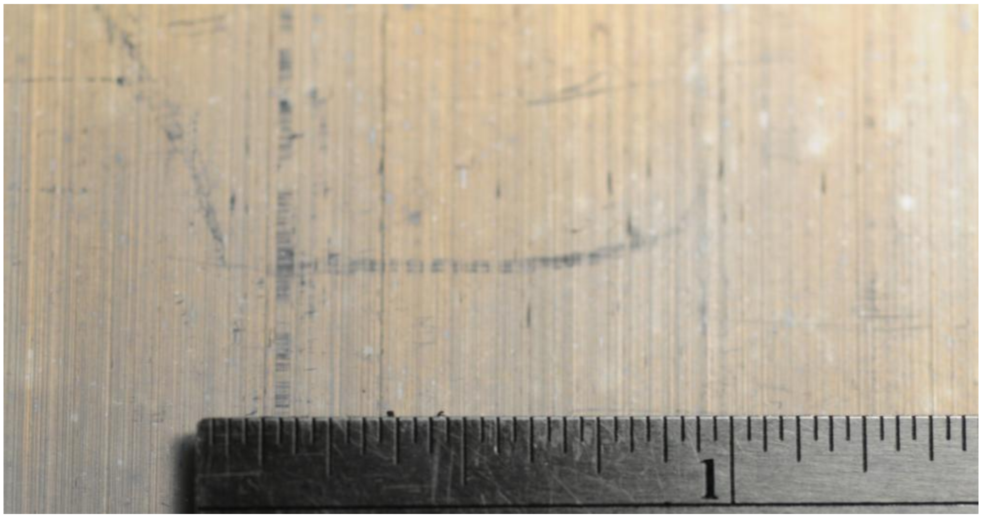

Figure 69 “As received” parent Al5456-H111 metal

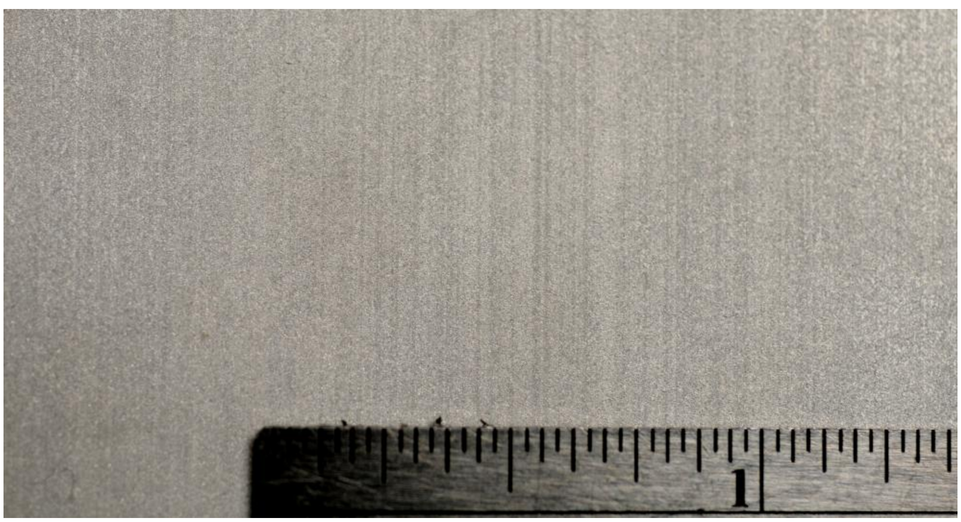

Figure 70 Exfoliated parent Al5456-H111 metal

Examination of the exfoliated first pass surface revealed that most of the corrosive effect of the exfoliation bath occurred on the parent metal surface (See Figure 71; Note the pitting far from the nugget). In general, most FSW welds are heavily exfoliated (pitted) at the nugget. On the contrary, this experiment presents a nugget practically unaffected by the chemical process. The thermo-mechanically affected zone shows a cathodic behavior, i.e., lower propensity for corrosion than the rest of the material. Note that the width of the “un-corroded” area is about .25”, or nearly the same width of the nugget (Refer to Figure 70).

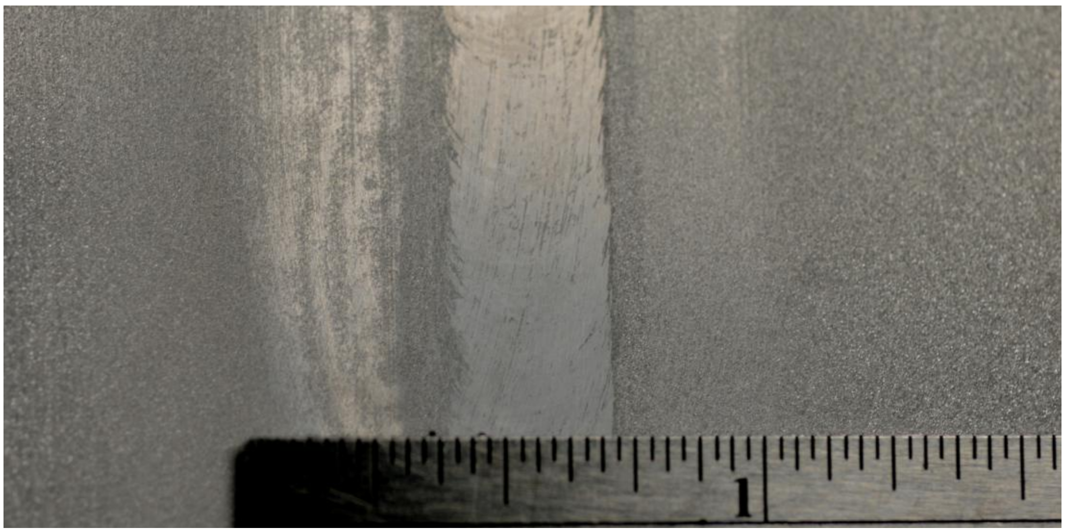

Figure 71 FSW: Exfoliated weld - First pass surface (upper surface of weld nugget macrograph - Figure 70)

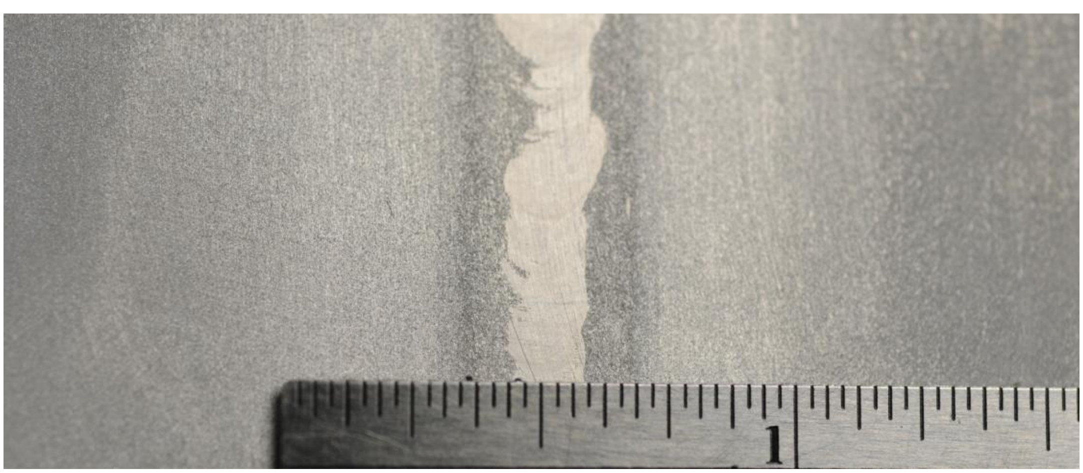

Figure 72 Exfoliated weld - Second Pass

The exfoliation test of FSW samples presented opposite results. Comparing Figures 71, 72 with Figures 73-75 (As welded sample), it is possible to observe that low rotational speed weld nuggets are susceptible to corrosion. Also the advancing side presented a higher corroded surface than the retreating side. This is evidence of the effect of the internal stresses on the corrosion event. These two figures are on the following page for comparison reasons.

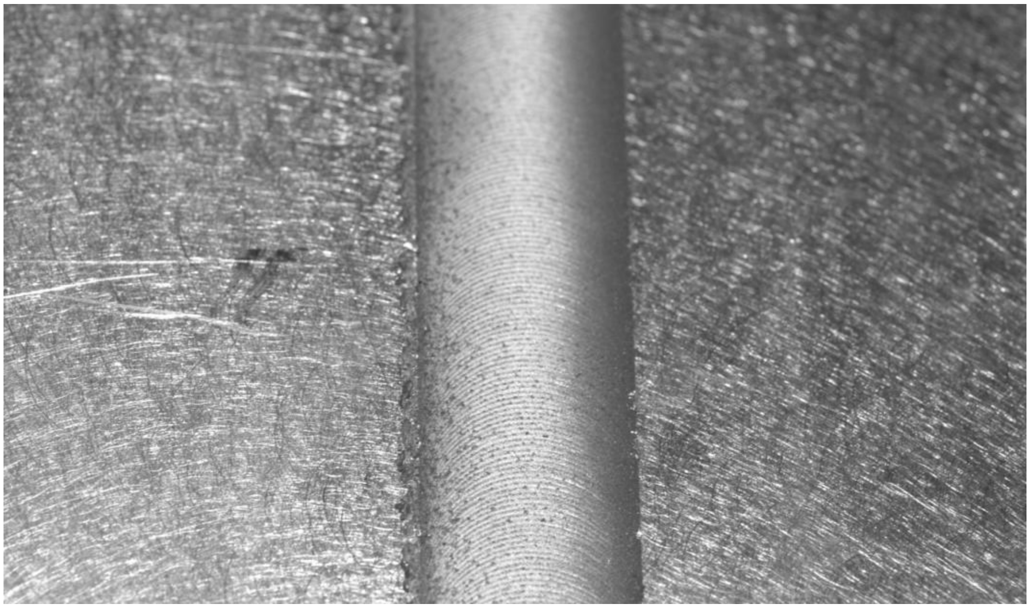

Figure 73 FSW without exfoliation process

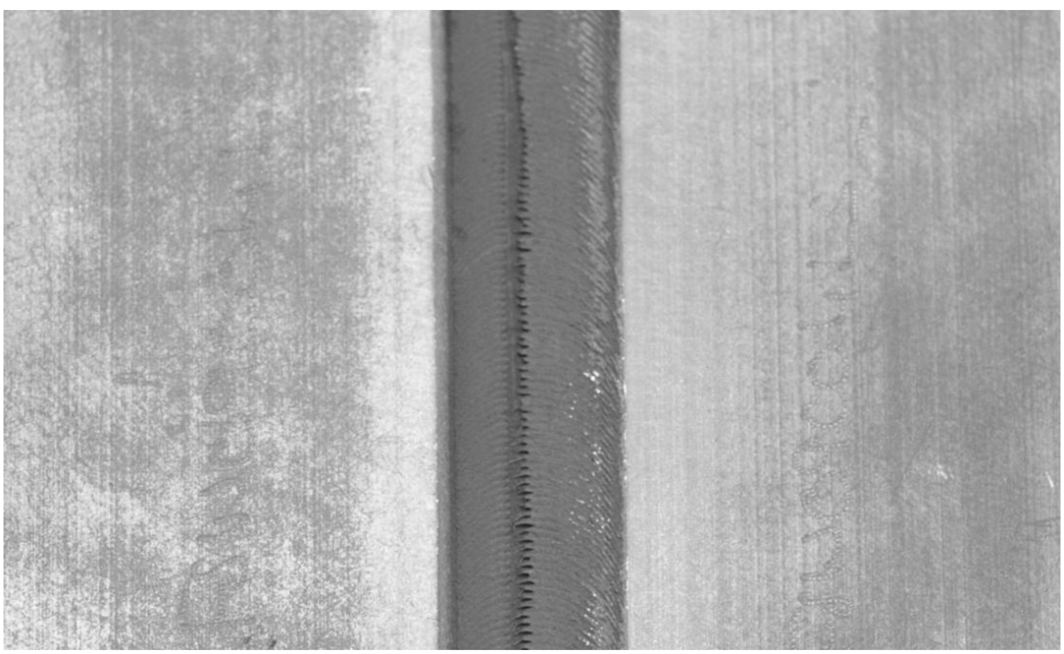

Figure 74 FSW Exfoliated Weld

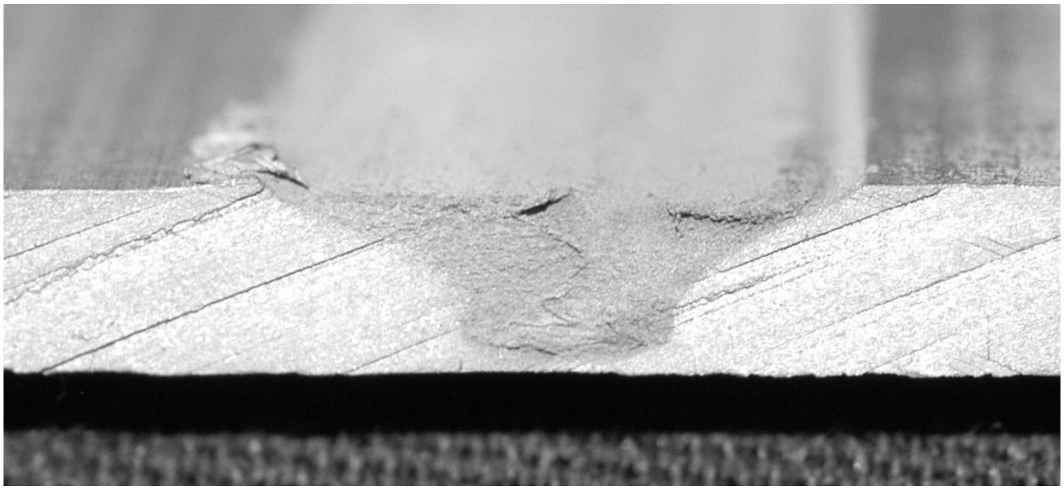

Figure 75 Picture of side view of FSW after exfoliation bath

A potential reason for why the weld nugget is seemly unaffected by the exfoliation bath could be due, in large part by the fact that HRS-FSW causes much lower residual stresses in the weld zone then compared to low rotational speed friction stir welds. Figures 74 & 75, makes clear that FSW is highly susceptible to corrosion compared to that of the same material welds of HRS-FSW, Refer to Figure 71.

4.5 Conductivity Test

To verify the visual results of the corroded surfaces, the surface relative electrical continuity (w/ Pure Cu 100%) of the samples before exfoliation process was measured and the values are presented in Figure 76.

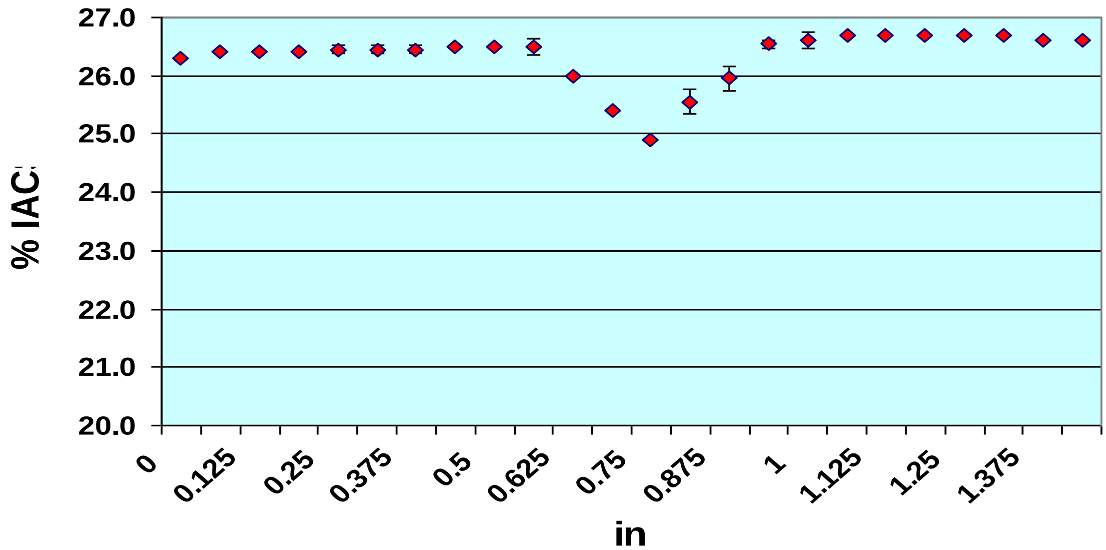

Figure 76 Graph of a HRS –FSW upper surface of weld nugget Conductivity (Pure Cu 100%) (First pass surface)

The drop in continuity (about 7%) observed at the nugget surface is evidence that the nugget area has a lower density of electrons; therefore, it is "more electrically positive." In other words, the nugget is "cathodic" and the parent metal is anodic. Corrosion does not occur in cathodic areas, leaving the weld unaffected as observed in Figure 72. Similar results were obtained for the exfoliated second pass surface. These are presented in Figures 77, "optical surface evaluation" and Figure 76 "relative electrical conductivity" (with a drop at the nugget near 6.6 %.). The only important difference observed is the cathodic area of the nugget appears to by reduced. In this surface, the cathodic area has a width average near .125" (Compare Figure 71 and 77)

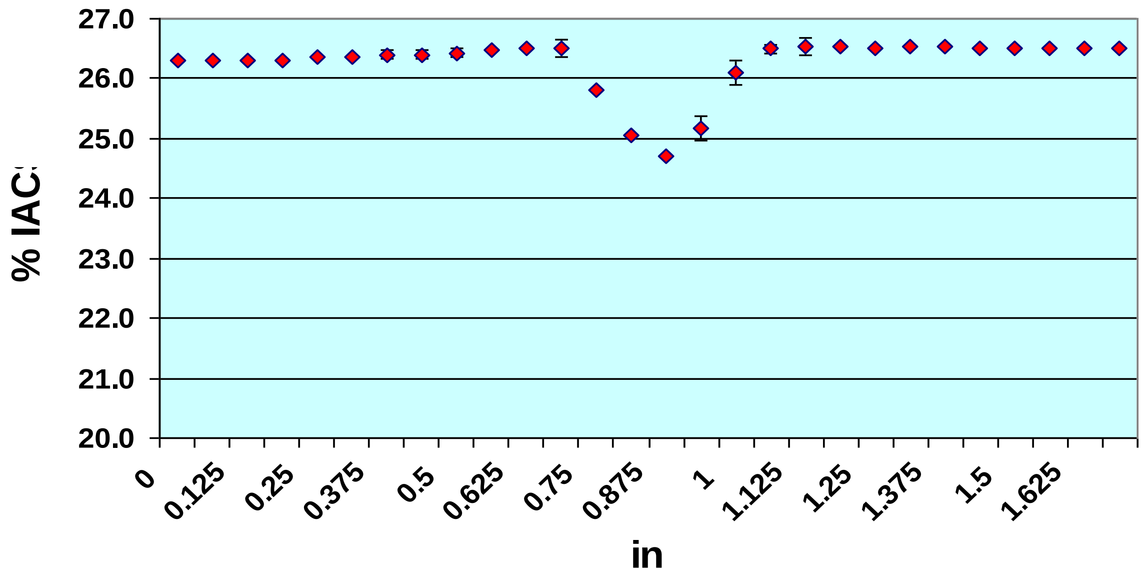

Figure 77 Graph of a HRS –FSW lower surface of weld nugget Conductivity (Pure Cu 100%) (Second pass surface)

The rise in continuity, shown in Figure 79, is additional evidence of a higher density of electrons at the nugget. Therefore, this leads to a conclusion that the nugget is anodic. The anodic behavior is a sign that it has the tendency to corrode. Refer back to Figure 73, where it proves an anodic or corrosive manner. For the low speed FSW sample after the conductivity test, it can be seen that there is a high amount of corrosion in the weld nugget. It might be possible that the FSW would have internal stresses that are too great for the exfoliation process which uncovers the truth. Note that the welding forces of the LRS processes are more than then times larger-generating larger internal stresses.

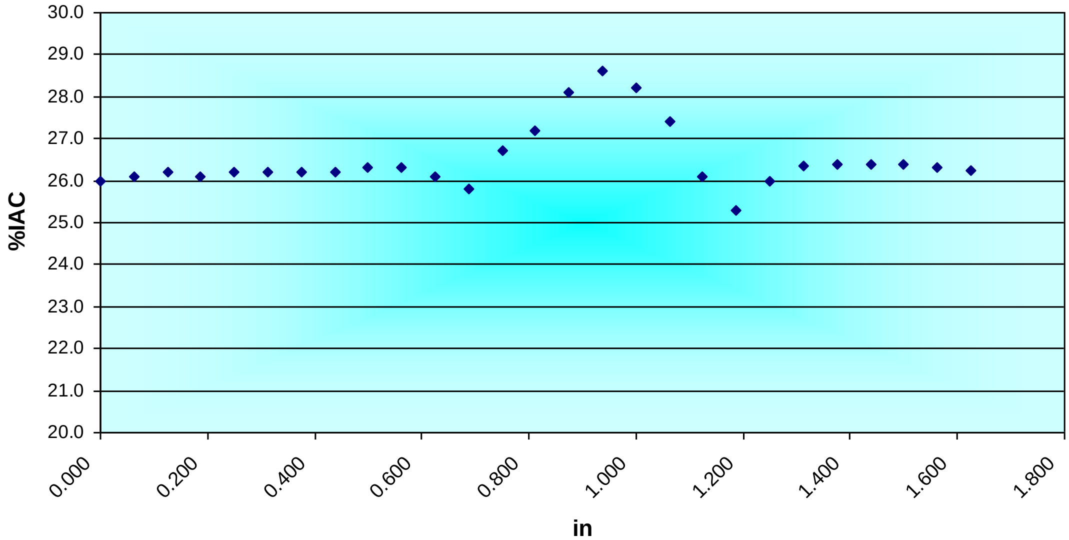

Figure 78 Graph of a LRS –FSW weld nugget Conductivity (Pure Cu 100%)

4.6 Non-rotating Shoulder Results

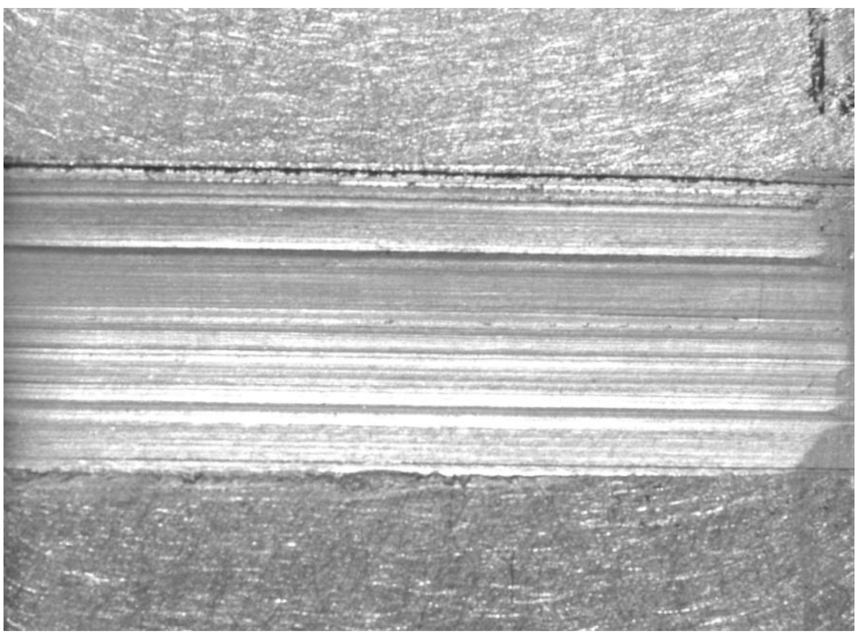

Figure 79 Typical Weld Produced by a Non-Rotating Shoulder

Figure 79, is a typical weld generated by a non-rotating additional shoulder which virtually eliminates flashing. This tool allows a reduction in the minimal forging pressure to obtain well consolidated welds from an archetypal FSW of 350 lbs to about 140 lbs. The physical constraint added by the fix shoulder, maintains a more uniform stress field, holding the would-be flash material down. Nevertheless; this type of tools need to be investigated to optimize the performance. Note the grooving produced by the fix shoulder(See Figure 80) may be reduced with appropriate dimensions and/or parameters. Obviously, the reduction of the welding loads gives evidence of the possibility to create really portable machines.

Figure 80 No visible weld defects using Non-rotating Shoulder

Further investigation is shown visually in Figure 81, where the geometrical constraints induced by the non-rotating shoulder, eliminates a preexisting defect.

Previously, this was observed by Widener et al[55], which shows the elimination of an internal worm hole.

It is a well know fact that the lack of a rotating shoulder in contact with the work piece, produces a surface wormhole-like defect. Using this idea, an initial weld without the non-rotating shoulder was preformed, with poor rotating shoulder contact. Figure 81, depicts the phenomenon explained above. During the initial part of the weld, performed without the non-rotating shoulder, a typical surface defect appeared. After about a quarter of an inch of welding the fix shoulder was applied without stopping the weld sequence: The wormhole-like defect, which was generated during the HRS-FSW process without the non-rotating shoulder, dissipated completely, after a welding distance of about one fix shoulder diameter length.

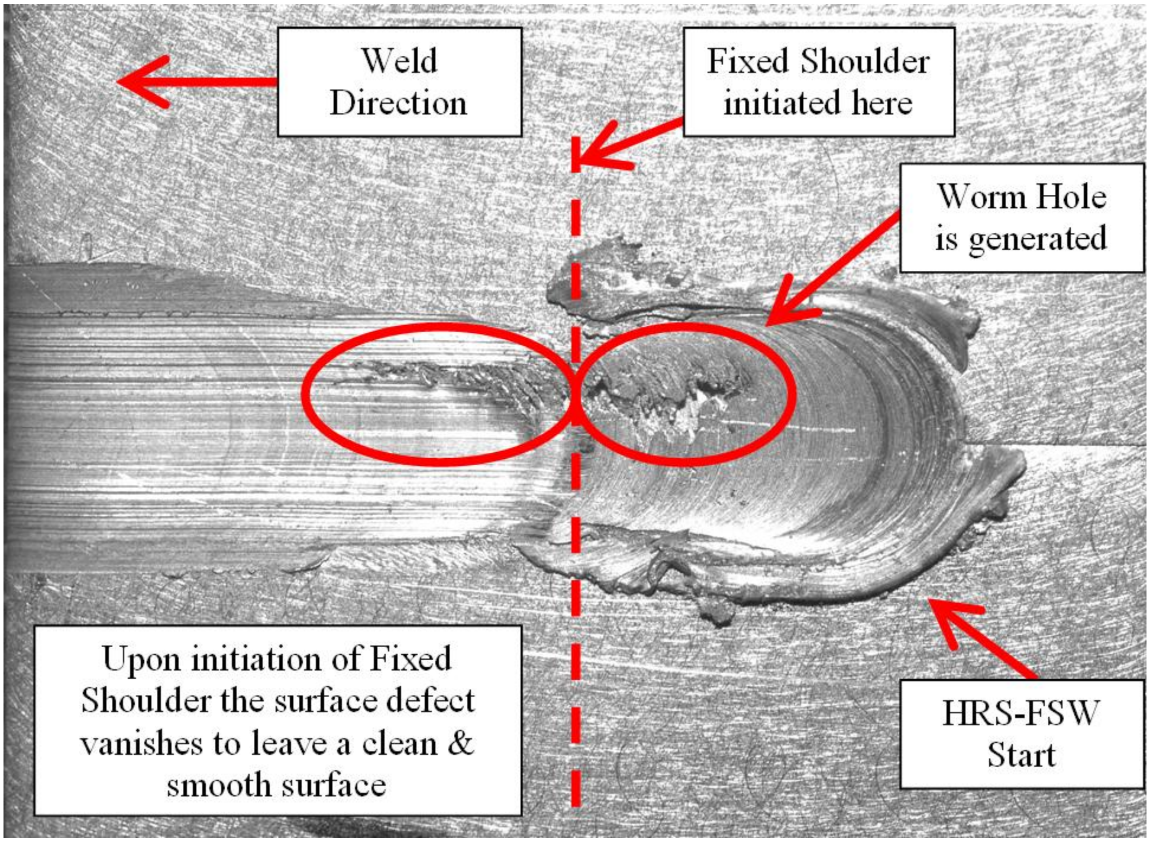

Figure 81 Generation of weld defect that dissipates after application of Non-rotating Shoulder

Due to the reduced forging loads applied to the shoulder of the friction stir welding tool during a weld, defects have the ability to occur more in HRS-FSW then compared to FSW. However, this problem is easily solved by the usage of the non-rotating shoulder technology, as proven by the above experiment.

4.7 Overall Results and Observations

Using Al 5456-H111, extensive studies were conducted to prove the ability of HRS-FSW to join naval materials. The welded plates presented strengths through a specific joining process as good as typical FSW. In addition, HRS-FSW is a low cost joining process matched with a valuable and low risk outcome, which confirms its ability for naval service. Slight modifications in the joining process performed in this experiment can lead towards a highly rewarding outcome. The tool design has proven to be of sound quality, and the parameter selection has shown to be optimal for corrosion prevention.

Throughout this experiment HRS-FSW has proven to present welds as strong as FSW welds. Any and all variables to differentiate the outcomes have been removed. Each weld was made from the same heat number and lot number of material. Each comparative weld was made with the same FSW tool. Each weld has been carefully examined and has shown equal strength, rigidity, hardness, and flexure.

In contrast, HRS-FSW showed an astonishing propensity to be corrosive resistance. Refer to FSW weld Figure 73, which demonstrates the parent material being resistive to the exfoliation process; however, the nugget of the weld shows a very low resistivity to corrosion prevention.

The application of the HRS-FSW in conjunction with the Non-rotating Shoulder makes for low forging forces combined with a sound weld quality. Figure 81, shows conclusive confirmation that an application of a non-rotating shoulder during a HRS-FSW can increase the weld quality dramatically. The HRS-FSW process can be the leap necessary to make aluminum joinable in a safe and economical manner. Due to the low forging forces necessary for a HRS-FSW, there tends to be a poor shoulder contact interface between the work piece and the tool itself. Therefore, a non-rotating shoulder application will add healing effects through the weld. This will yield an increase in weld quality and strength.

The corrosion properties of HRS-FSW joined with a non-rotating shoulder application could make it possible for a defect free weld, both internal and external, that could be made in a safe and economical manner, requiring no back filling, sanding, or otherwise post weld treatment.

CHAPTER 5

5.0 CONCLUSION AND FUTURE SCOPE

All the experiments performed showed remarkable strength in HRS-FSW with the parameter selection. The following conclusions hold good for the HRS-FSW of Al5456-H111 as the parameters used:

1. Utilization of the tools specifically designed for this experiment and their intricate design features. Both of which, employ the use of pumping features, that clearly make for a stronger joining process.
2. The HRS-FSW exhibits extreme corrosion properties capable of surpassing the FSW weld. This could lead to auxiliary analysis of the potential ability of corrosion prevention that the HRS-FSW process can offer.
3. Overall hardness across the weld duplicates that of a FSW. Lending HRS-FSW to be just as capable for sound, quality welds.
4. The tensile testing of HRS-FSW proved that the weld is superior to even the parent material. Proven corrosion quality and tension strength establish that Al 5456-H111 welded with HRS-FSW is an advanced option for naval vessels.
5. Proper tool design is the cornerstone of a complete and effective weld process. The pumping features demonstrates a clear process improvement.

6. Non-rotating Shoulder application proves to be a superior process, especially joined with the HRS-FSW process. Application of the non-rotating shoulder demonstrated significant healing effects on the weld.

Further study needs to be considered to explore possible tool design limitations. This further exploration should also be able to uncover a closer look at the corrosion properties of a HRS-FSW in Al 5456-H111. The weld nugget showed considerable corrosion prevention properties, which could lead to an optimum choice in material design in naval vessels. Additional experiments should be performed using the non-rotating shoulder device.

RERFERENCES

REFERENCES

1 Mathers, G., Welding of Aluminum and Its Alloys, Woodhead Publishing, Cambridge, England, 2002, pp. 161-165.

2 Harper, C.A., Handbook of Materials for Product Design, McGraw-Hill, New York, NY, 2001, pp. 2.152-2.153.

3 Adams, G., Hartley, P., "FRICTION STIR WELDING", Friction Stir Welding Process [online journal], URL: http://www.lockheedmartin.com/data/assets/8651.gif, [cited 16 April 2008].

4 Polt, W., "A little friction at Boeing", Boeing Frontiers [online journal], Vol. 3, Issue 5, URL: http://www.boeing.com/news/frontiers/archive/2004/september/photos/sept_i_tt.jpg, [cited 15 September 2004].

5 Turner, H., "Friction Stir Welding", Engineering and Construction, [online journal], Photo: National Research Council of Canada, URL: http://www.nrc-cnrc.gc.ca/multimedia/picture/images/html/nrc-iar_technology-lr.jpg, [cited 10 August 2007].

6 Hicks, J., Welded Design - Theory and Practice, Woodhead Publishing, Cambridge, England, 200, pp. 7-9.

7 Gale, W.F. and Totemeier, T.C., Smithells Metals Reference Book, 8th ed., Elsevier, Boston, MA, 2004, pp. 33-37.

8 Smith, E. H., Mechanical Engineer's Reference Book, 12th ed., Butterworth-Heinemann, Oxford, England, 1998, pp. 16-54 - 16-63.

9 Higgins, R. A., Engineering Metallurgy - Applied Physical Metallurgy, 6th ed., Arnold, London, England, 1993, pp. 490.

10 Ramsey, M.D., Safety in Welding, Cutting, and Allied Processes, ANSI Z49.1:2005, American Welding Society, Miami, FL, Jul 2005.

11 Craig, E., "MIG Welding and Flux Cored", MIG & Flux Cored Training Resources, [online journal], URL: http://www.weldreality.com/FLUX-CORED-ROOT-CERMIC-BACK.jpg, [cited 15 May 2001].

12 Raikoty, H., "Thermal and Thermo-Mechanical Analysis of High-Speed Friction Stir Welding" MS Thesis, Department of Mechanical Engineering, Wichita State University, Wichita, KS, 2005.

13 Higgins, R. A., Engineering Metallurgy - Applied Physical Metallurgy, 6th ed., Arnold, London, England, 1993, pp. 496-497.

14 Harper, C.A., Handbook of Materials for Product Design, McGraw-Hill, Lutherville, MD, 2001, pp. 2.151-2.153.

15 Grong, Ø., Metallurgical Modeling of Welding, 2nd ed., Maney Publishing, Norwegian University of Science and Technology, Department of Metallurgy, Trondheim, Norway, 1997, pp. 18-21.

16 K.V. Jata, M.W. Mahoney, R.S. Mishra, S.L. Semiatin, T. Lienert, TMS (2003). Friction Stir Welding and Processing II. (pp.165). The Minerals, Metals & Materials Society.

17 Kumar. K. and Kailas. V., “The Role of Friction Stir Welding Tool on Material Flow and Weld Formation”, MS Thesis, Department of Mechanical Engineering, Indian Institute of Science, Bangalore, India, 2007.

18 Hosain, M.D., “Development of High Speed Friction Stir Welding Machine”, MS Thesis, Mechanical Engineering Department, Wichita State University, Wichita, KS, 2004.

19 Roa, R.S.A., “Microstructure and mechanical properties of high speed friction stir welded aluminum alloys”, MS Thesis, Mechanical Engineering Departments, Wichita State University, Wichita, KS, 2004.

20 Rao, R. S., “Microstructure and Mechanical Properties of High Speed Friction Stir Welded Aluminum Alloys” MS Thesis, Mechanical Engineering Department, Wichita State University, Wichita, KS, 2004.

21 Schneider, J.A. and Nunes, A.C., “Characterization of Plastic Flow and Resulting Microtextures in a Friction Stir Weld”, Metallurgical & Materials Transactions B, Vol. 35, No. 777-783, 2004.

22 Chen, Y., Liu, H.L., and Feng, J., “Friction Stir Welding Characteristics of Different Heat-Treated-State 2219 Aluminum Alloy Plates”, National Key Laboratory of Precision Hot Processing of Metals, Harbin Institute of Technology, Harbin, Chine, 2005.

23 Mathers, G., (2002). Welding of Aluminium and Its Alloys. (pp. 10-12). Woodhead Publishing.

24 Mathers, G., Welding of Aluminum and Its Alloys, Woodhead Publishing, Cambridge, England, 2002, pp. 19.

25 Anderson, T., “Welding Aluminum: Different, not Difficult”, Automotive Industry Trends [online journal], New letters, URL: http://auto.ihs.com/news/newsletters/auto-apr03-welding.htm, [cited 16 April 2003].

26 Mathers, G., Welding of Aluminum and Its Alloys, Woodhead Publishing, Cambridge, England, 2002, pp. 19.

27 Lucian, J.S., “Role of the filler wire compositions in crack nucleation and propagation in aluminum-lithium 2195 alloy welds”, MS Thesis, Mechanical Engineering Department, Wichita State University, Wichita, KS, 2002.

28 Mathers, G., Welding of Aluminum and Its Alloys, Woodhead Publishing, Cambridge, England, 2002, pp. 162.

29 National Institute for Aviation Research, Advanced Joining Laboratory, “FSW machine from above”, Photo, URL: http://www.niar.wichita.edu/media/images/Image%20Gallery/Advanced%20Joining/NIAR_AdvancedJoining_02.jpg, [cited 16 April 2009].

30 Widener, C. A., “Evaluation of Post-Weld Heat Treatment for Corrosion Protection in Friction Stir Welded 2024 and 7075 Aluminum Alloys”, MS Thesis, Mechanical Engineering Department, Wichita State University, Wichita, KS, 2005.

31 Mishra, R. S. and Mahoney, M. W., ASM International (2007), Friction Stir Welding and Processing. (pp. 2). ASM International.

32 Reitz, V., "Friction stir welding joints previously unweldable materials", Machine Design, Causing a stir in welding [online journal], URL: http://machinedesign.com/article/causing-a-stir-in-welding-0321 [cited 21 March 2002].

33 Colegrove, P., "Assessing the Friction Stir Welding Process with Mathematical Modeling", Tech Briefs [online journal], Nasa Tech Briefs, URL: http://www.techbriefs.com/component/content/article/2338 [cited 01 September 2007].

34 Reitz, V., "Friction stir welding joints previously unweldable materials", Machine Design, Causing a stir in welding [online journal], URL: http://machinedesign.com/article/causing-a-stir-in-welding-0321 [cited 21 March 2002].

35 Mishra, R. S. and Mahoney, M. W., ASM International (2007), Friction Stir Welding and Processing. (pp. 12). ASM International.

36 Mukiri, S. R., "Design of Tool for Friction Stir Welding", MS Thesis, Mechanical Engineering Department, Wichita State University, Wichita, KS, 2004.

37 Burford, D., Widener,C., Tweedy, B., "Advances in Friction Stir Welding for aerospace applications", *Airframer* [online journal], Issue 14, National Institute for Aviation Research, Wichita State University 2006.

38 , Widener, C.A. , Talia, J.E. , Tweedy, B.M., and Burford, D.A., “HIGH-ROATIONAL SPEED FRICTION STIR WELDING WITH A FIXED SHOLDER”, *6th International Symposium on Friction Stir Welding*, 2006.

39 Gale, W.F. and Totemeier, T.C., Smithells Metals Reference Book, 8th ed., Elsevier, Boston, MA, 2004, pp. 21-3.

40 Pilkey, W. D., Formulas for Stress, Strain, and Structural Matrices, 2nd Edition, John Wiley & Sons, Hoboken, NJ, 2005, pp. 154-155.

41 Blodgett, O., “Understanding Bend Tests”, *Welding Magainzie*, http://weldingmag.com/blodgett/wdf_13719/, Omer W. Blodgett, [21 Mar 2006]

42 Military Handbook - MIL-STD-1537C, Department of Defense, Test Method for Electrical Conductivity Test for Verification of Heat Treatment of Aluminum Alloys Eddy Current Method, U.S. Department of Defense, Jun 2002

43 Military Handbook - MIL-HDBK-5H: Metallic Materials and Elements for Aerospace Vehicle Structures, U.S. Department of Defense, pp. 3-244.

44 Metallic Materials Properties Development and Standardization (MMPDS-04). Battelle Memorial Institute, Federal Aviation Administration, 2008, pp.3-309.

45 ASM International, ASM Handbook, Volume 13A, Corrosion: Fundamentals, Testing, and Protection, Application of Modern Analytical Instruments in Corrosion, Analytical Methods, ASM International, 2005

46 Pilkey, W. D., Formulas for Stress, Strain, and Structural Matrices, 2nd Edition, John Wiley & Sons, Hoboken, NJ, 2005, pp. 164-165.

47 Kutz, M., Handbook of Materials Selection, John Wiley & Sons, Hoboken, NJ, 2002, pp. 524-527.

48 Higgins, Raymond A., Engineering Metallurgy - Applied Physical Metallurgy, 6th ed., Arnold, London, England, 1993, pp. 36.

49 Higgins, Raymond A., Engineering Metallurgy - Applied Physical Metallurgy, 6th ed., Arnold, London, England, 1993, pp. 34-37.

50 Harper, C.A., Handbook of Materials for Product Design, McGraw-Hill, New York, NY, 2001, pp. 2.102 - 2.105.

51 ASM International, ASM Handbook, Volume 5, Surface Engineering, Corrosion Testing of Coatings, Laboratory Corrosion Tests, ASM International, 2002

52 Y. Sato, M. Urata, and H. Kokawa. Parameters controlling microstructure and hardness
during friction-stir welding of precipitation-hardenable aluminum alloy 6063. Metallurgical &
Materials Transactions A, MS Thesis, Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, U.K., 2002.

53 Nandan, R., DebRoy T., and Bhadeshia, H. K. D. H., Recent Advances in Friction Stir Welding – Process, Weldment Structure and Properties, Department of Materials Science and Metallurgy, University of Cambridge, Cambridge, U.K., , 2008.

54 Prated, T., An Investigation Into The Friction Stir Welding Of Al 6061 And Al 6061/SiC/17.5p Using Diamonds Coatings, MS Thesis, Mechanical Engineering, Vanderbilt University, Nashville, TN, 2008.

55 Widener, C.A. , Talia, J.E. , Tweedy, B.M., and Burford, D.A., “HIGH-ROATIONAL SPEED FRICTION STIR WELDING WITH A FIXED SHOLDER”, *6th International Symposium on Friction Stir Welding*, 2006.