2007-03-12

Spot Friction Welding of Ultra High-Strength Automotive Sheet Steel

Jack H. Sederstrom
Brigham Young University - Provo

SPOT FRICTION WELDING OF ULTRA HIGH-STRENGTH

AUTOMOTIVE SHEET STEEL

by

Jack Hunter Sederstrom

A thesis submitted to the faculty of

Brigham Young University

in partial fulfillment of the requirements for the degree of

Master of Science

School of Technology

Brigham Young University

April 2007

BRIGHAM YOUNG UNIVERSITY

GRADUATE COMMITTEE APPROVAL

of a thesis submitted by

Jack Hunter Sederstrom

This dissertation/thesis has been read by each member of the following graduate committee and by majority vote has been found to be satisfactory.

Date	Michael Miles, Chair
Date	Kent Kohkonen
Date	Charles Harrell

BRIGHAM YOUNG UNIVERSITY

As chair of the candidate's graduate committee, I have read the dissertation/thesis of Jack Hunter Sederstrom in its final form and have found that (1) its format, citations, and bibliographical style are consistent and acceptable and fulfill university and department style requirements; (2) its illustrative materials including figures, tables, and charts are in place; and (3) the final manuscript is satisfactory to the graduate committee and is ready for submission to the university library.

Date

Michael Miles
Chair, Graduate Committee

Accepted for the Department

Barry Lunt
Graduate Coordinator, School of Technology

Accepted for the College

Alan R. Parkinson
Dean, Ira A. Fulton College of Engineering and Technology

ABSTRACT

SPOT FRICTION WELDING OF HIGH-STRENGTH SHEET STEEL

Jack Hunter Sederstrom

School of Technology

Master of Science

Spot friction welding (SFW) was performed on ultra high strength steel (UHSS) steel sheet commonly used in automobile manufacturing. Alloys studied included DP780, DP780EG, DP980, and DF140T sheet steel of varying thickness from 1.2 mm to 1.4 mm. Welding was accomplished using a PCBN standard tool. Weld strengths were then compared to a proposed AWS standard. Initial hardness readings were taken in cross sectioned samples. Grain structure in a SFW is presented. Resistance spot welds were created in three steels. This study focuses on the strength of SFW joints as compared to traditional resistance spot welding (RSW) in welding like materials to one another. Cycle times of SFW were also evaluated and compared to production rate cycle times of RSW.

ACKNOWLEDGMENTS

It is difficult to list all of the people who have provided support and encouragement, as there are so many who have helped.

I wish to thank the professors of BYU who have led, taught, and assisted in this work; specifically, Mike Miles for having faith in me and this thesis; Kent Kohkonen (Brother K.) for teaching me all about machining and trusting me with his machines; and Clint Bybee for his friendship and giving me employment during my studies.

MegaDiamond and Smith Lift have contributed to this work by providing tools and machinery for this research, for which I am grateful. Of particular mention are Scott Packard, Russell Steel, and Chris Fisher, who have greatly helped. Ford Motor Company has generously provided welds and given support through Tsung Yu Pan, whom I thank for his involvement in this research. Mittal Steel generously provided the steel sheet used in this research, for which I also give thanks.

In preparation for this research the good people at Rayloc supported me in my desire to complete a master's degree. I am grateful for their support and friendship.

Lastly and most importantly I thank my parents, grandparents, in-laws, and other relatives who have encouraged me to finish. Above all, I thank my wife, Kristen, for her love and patience as she has listened to me and helped us get through graduate school and who takes care of our children who have brought smiles when they were needed.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1 Introduction

1.1 Background

Recently a new method of welding, spot friction welding (SFW) or friction stir spot welding (FSSW) has been developed as an extension of friction stir welding (FSW) [1]. This new joining method may have lower energy requirements, lower equipment costs, and better weld properties in steels than current resistance spot weld (RSW) technology. Indeed, this new joining process can be used to replace RSW in specific applications. Spot friction welding has successfully been used on aluminum alloys in industrial applications [2] and has been the subject of numerous journal articles [3, 4, 5, 6]. While almost all of these articles have addressed FSSW and SFW in aluminum, few have attempted to address the use of steel.

1.1.1 Resistance spot welding

Resistance spot welding (RSW) is currently used as a principle means of joining sheet metal together in a multitude of industries including automotive, appliance, furniture, aviation, recreation products, and other manufacturing applications. Usually materials of similar composition and thickness are blanked, formed, and then welded together to form parts used in an assembly such as an automobile door, computer case, storage cabinet, or any number of products which require sheet metal joining [7].

RSW has been used for decades as a reliable method of joining like metals because it is relatively fast, repeatable, and its weaknesses are well understood. RSW joins metals by passing electrical current through the area to be welded, melts a nugget where the two metals touch, and then allows the metal to cool. RSW requires large amounts of energy and cooling equipment when used in industries with heavy duty cycles. Extra welds are also common because of the possibility of a faulty weld [2].

In RSW, bonds are frequently strong yet lack ductility due to the heat affected zone (HAZ) becoming softened during the welding process. The heat affected zone is the location where RSW bonds fail in the majority of cases, so testing commonly measures the nugget size of the weld [8].

1.1.2 Spot Friction Welding and Friction Stir Spot Welding

Spot friction welding (SFW) is a new type of welding process in which a rotating tool is plunged into a material under high force to create a bond (**Figure 1**). Friction stir spot welding (FSSW) is a similar process which may or may not include a refill process to flow the material back in to the void created by the withdrawing tool [9]. It should be noted that FSW and FSSW are often used interchangeably by different organizations as this process is very new and terminology is not yet well defined. Both terms may use a fixed pin tool, while FSSW may also use a retractable pin.

Interestingly, using a fixed pin requires less energy to bond materials while eliminating the cooling equipment used in RSW. Additionally, the weld properties generally show more ductility than RSW and have a stronger HAZ due to finer grain structure [10].

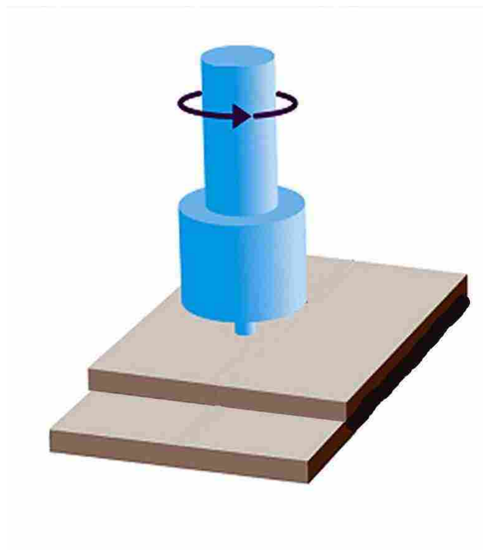


Figure 1: Example of a Spot Friction Welding Tool Setup. [11]

Research has been done in aluminum alloys with SFW and FSSW and has shown favorable results such that Mazda has begun to implement SFW in a production automobile [2, 12]. Very little research has been done with ultra high strength steel sheet due to limited availability of some of some of these new materials and lack of machine tools that can handle the higher loads and temperatures of steel as compared to aluminum. The properties of a spot friction weld vary greatly depending on machine rigidity, tool rpm, tool material, dwell time, tool geometry, and feed rate. Because very little is known regarding the flow of material due to the friction at the tool and material interface of the weld, multiple experiments are required to produce satisfactory results

[8, 13]. It is under investigation as to what quality of weld can be produced in sheet steel, particularly in ultra high-strength steels (UHSS) [10].

One of the challenges in creating a weld in UHSS sheet is to create a bond which is both strong and ductile. Recently the automotive industry has begun to move towards thinner sheet metal in an effort to reduce the overall weight of automobiles. In order to maintain similar strength, safety ratings, and reduce cost, higher grades of UHSS are being investigated [14].

1.1.3 Advantages of SFW in Aluminum

Mazda has reported a 99% energy savings, a 40% investment reduction, a weight reduction, and elimination of water, air, and welding power supplies vs. RSW in production [2].

1.1.4 Potential Applications of SFW in Steel

Applications where SFW can be used are varied and limited only by the quality of the weld produced and accessibility of the weld location. Since the automobile industry is one of the largest producers of spot welds, initial potential applications in an auto include [15]:

- A post reinforcement
- Upper and lower dash reinforcement panels
- Suspension mounting reinforcement

- Door inner reinforcement
- Body side reinforcement
- Rear floor and panel reinforcement
- Rear quarter reinforcement
- Suspension top
- Tailgate inner
- Roof inner panel
- Hood (bonnet) inner panel
- Other non-automotive applications

1.2 Problem Statement

Friction stir welding technology has led to the development of FSSW and SFW technology, which has promise and has shown to have considerable cost savings in a production facility, but only in a very small and specific application. Much has been done to further the knowledge base of aluminum using this process due to the success in spot stir welding aluminum. However, steel is still the largest (by weight and volume) and most common material welded in the automotive industry [2]. In an effort to reduce weight, auto makers are in search of thinner steels capable of the same mechanical characteristics of their predecessors. This has led to the development of UHSS alloys. The challenge with UHSS is its high alloy content which leads to the degradation of the weld and large grain structure when fusion welding is applied [10]. It is therefore reasonable to conclude that if SFW can be adapted to UHSS, SFW could potentially yield great cost savings and superior weld quality compared to RSW [1].

1.3 Hypothesis

The hypotheses that guided this research are as follows:

Hypothesis 1: Spot friction welding can produce acceptable spot weld strength in UHSS DP780EG/DP780.

Hypothesis 2: Spot friction welding can produce acceptable spot weld strength in UHSS DP980/DF140T.

Hypothesis 3: Spot friction welding is capable of producing an acceptable weld in UHSS in less than 3 seconds.

Hypothesis 4: Spot friction welding can produce equal or greater spot weld strength than RSW in any above UHSS material used in this study.

Hypothesis 5: Spot friction welding can produce superior spot weld hardness (lower) in the above UHSS materials than RSW.

1.4 Methodology

Material for this experiment will be 1.2 mm to 1.4 mm steel sheet of DP780, DP780EG, DP980/DF140T. Uniform coupons will be cut and welded by RSW using the best known welding parameters for each respective material and thickness. Identical coupons will also be cut and welded by SFW on a laboratory style spot friction welder.

Since no best known parameters exist, a systematic method for finding the best working parameters will be used. Select samples will be cross sectioned for hardness testing. Select samples will be tested in a peel, lap, or cross tension test and compared as RSW vs. SFW.

1.5 Delimitations

This study will only test RSW and fixed pin SFW in the materials DP780, DP780EG, and DP980/DF140T in thicknesses of 1.2 mm and 1.4 mm. This study will not include any other materials.

1.6 Thesis Contribution

The purpose of this study is not to examine welds of differing thicknesses or materials. It is hoped that the data obtained will enlighten the welding community to the strengths and weaknesses found in this process using the variables presented. It is also hoped that this research will improve automobile safety through better quality welds in UHSS and contribute to cost savings at manufacturing facilities in the future.

1.7 Definition of Terms

Acceptable weld – a weld which meets the minimum strength as defined by AWS

AWS - American Welding Society

DP – Dual phase steel consisting of martensite and ferrite

DP780 – A dual phase steel with an ultimate tensile strength of 780 MPa consisting of 40% martensite and 60% ferrite

DP780EG –An electro-galvanized DP steel with an ultimate tensile strength of 780 MPa

DP980 - A dual phase steel with an ultimate tensile strength of 780 MPa consisting of 60% martensite and 40% ferrite

DF140T- A dual phase steel with an ultimate tensile strength of 140 kN consisting of 60% martensite and 40% ferrite and approximately 980 MPa

EG- Electro-galvanized

FSSW- Friction Stir Spot Weld

Friction Stir Spot Weld- A type of weld created by either a rotating fixed pin or a retractable pin

HAZ- Heat Affected Zone

Heat Affected Zone- The area between the weld nugget and base material

Resistance Spot Weld- A type of weld which is created by passing electric current through the material

RSW- Resistance Spot Weld

Spot Friction Weld- A type of weld typically created by using a rotating fixed pin

SFW- Spot Friction Weld

TWI- The Welding Institute

UHSS – Ultra High-Strength Steel, steels with a rating of 600 MPa and above

2 Review of Literature

2.1 Introduction

Much of the available literature on the topic of spot welding centers on resistance spot welding and addresses any material which can be resistance welded or, in the spot friction welding arena, addresses mainly aluminum, magnesium, and touches on UHSS alloy DP600. Therefore, literature was reviewed with an emphasis on obtaining as much information as possible on current spot welding techniques and previous research carried out in SFW and FSSW in order to better understand the process, challenges, and known limitations.

2.2 Materials

Producing spot welds using FSW technology has been generally limited to aluminum, magnesium, aluminum alloys with magnesium, and recently ultra high-strength steels. These studies have gathered information about weld strength, nugget size, grain size, peak temperatures, material flow, and tool force [3, 4, 9, 16, 17].

2.3 Weld Quality and Testing Methods

There are various testing methods to determine the characteristics of a spot weld including shear, tension, hardness, bend, impact, strain, and others. For the purpose of this experiment only four tests will be used as described in the following sections.

2.3.1 Lap Shear Test

Lap shear testing is a fast, inexpensive, and widely used method to evaluate spot welds in ferrous and non-ferrous materials in shear. In order to perform this test, material is sheared and welded together in a lap weld (**Figure 2**). The specimen is then pulled in a suitable tension testing machine and data is recorded [18].

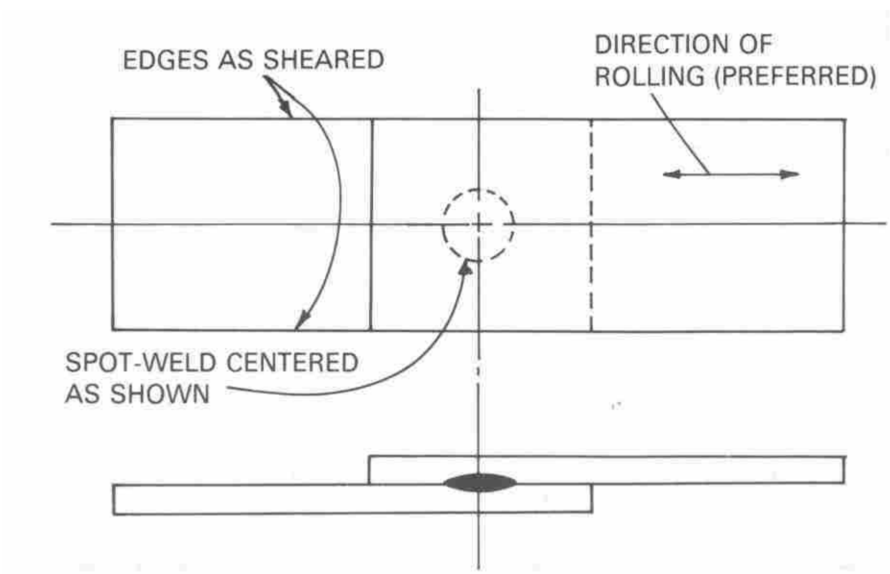


Figure 2: A tension-shear specimen. [18]

2.3.2 Other Tension Tests

Direct tension tests are used to evaluate the maximum load in the direction normal to the spot weld joint. There are two types of direct tension tests: cross tension and U-test.

Cross tension specimens are prepared in a "T" configuration with the weld at the center and holes on each tab (**Figure 3**). A special jig is used to pull the cross-tension specimen which is pictured in **Figure 4**. This jig provides adequate clamping for testing in a tensile testing machine [18].

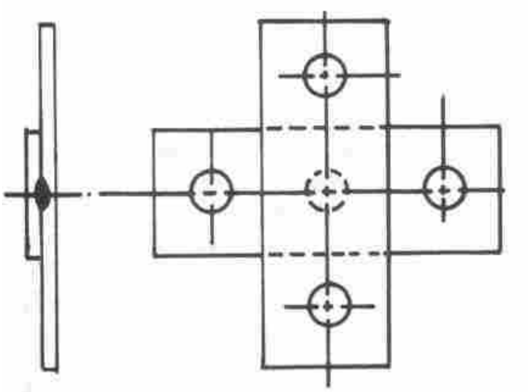


Figure 3: A cross tension specimen. [18]

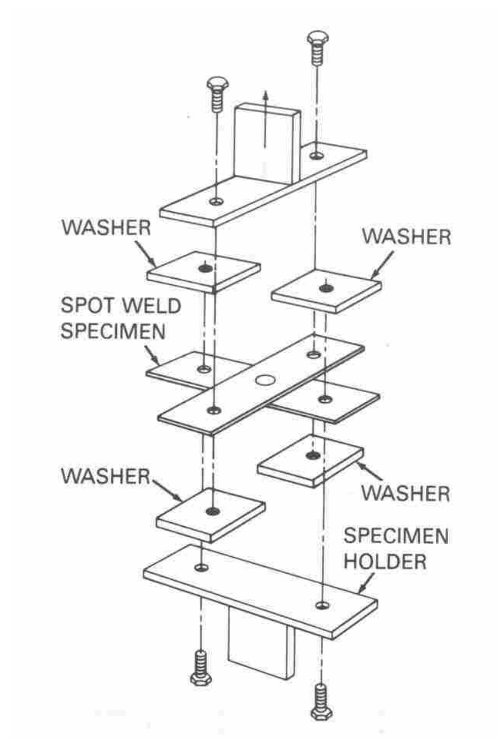


Figure 4: A cross tension jig for thicknesses up to .19 in. (4.8 mm). [18]

The second type of direct tension test, the U-test, is performed by welding two U-shaped pieces together (**Figure 5**). The specimen is then attached to a pulling apparatus and data is recorded [18].

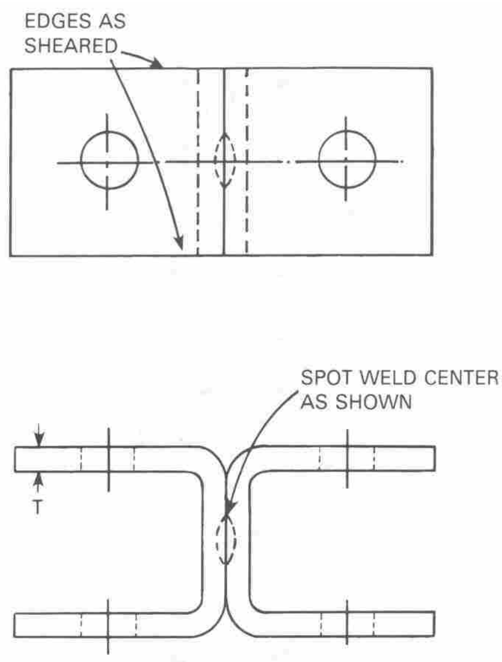


Figure 5: U-test specimen. [18]

2.3.3 Peel Test

A commonly used production test, the peel test, is fast and inexpensive to use on the production floor. The test is performed by lap welding two pieces of metal together, and then peeling the pieces apart (**Figure 6**). Weld strength is measured according to nugget size after the weld is pulled and compared to known acceptable sizes for the particular application [18].

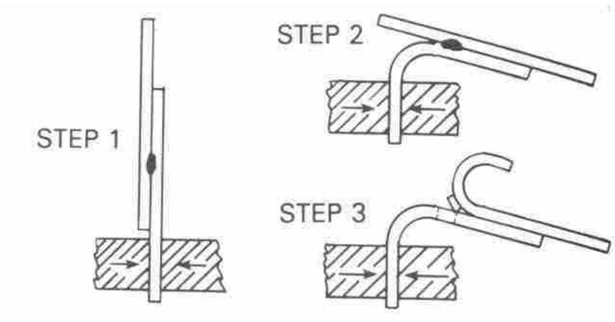


Figure 6: Peel test. Step 1: Grip in vice. Step 2: Bend. Step 3: Peel pieces apart. [18]

2.3.4 Hardness Test

Hardness testing may be performed on a weld by using Brinell, Knoop, Vickers, or Rockwell methods. Each test uses a different sized probe to indent and measure hardness. As probe size increases, measurements become more generalized. As probe size decreases, measurements become more localized, with micro-hardness tests being able to measure individual grains and inclusions [18].

2.3.5 Ductility Measurement

Ductility is measured in spot welds by comparing the direct-tension load to the tension-shear load. Ratios greater than .5 are considered ductile. Typical ratios for various metals are given in (**Table 1**) [18].

Table 1: Ratio of direct-tension to tension-shear test specimen loads [18].

Material	Typical Ratio Range
Low carbon steel	0.60 to 0.99
Medium carbon steel (.02C)	0.18 to 0.21
Low alloy high strength steel	0.21 to 0.28
Austenitic stainless steel	0.55 to 0.82
Ferritic stainless steel	0.25 to 0.33
Aluminum-base	0.37 to 0.43
Nickel-base	0.71 to 0.81
Titanium-base	0.27 to 0.52

2.4 Applications

Spot welding is used where metal assemblies allow for lap joints and will not require leak tight seams. Typically, sheet metal is 3.2 mm (.125 in) or thinner. Spot welding is preferred to riveting or screwing when disassembly will not be required. Common products welded include many low carbon steel components in automobiles, cabinets, furniture, appliances, and similar items [7]. Other potential applications include using spot welds and self piercing rivet replacement technology [19].

2.5 Welding Processes

Joining processes which will be reviewed are resistance spot welding, friction stir spot welding, spot friction welding, and variants of each process as necessary.

2.5.1 Resistance Spot Welding

Spot Welding is defined in the Resistance Welding Manual as:

> A resistance welding process wherein coalescence is produced by the heat obtained from resistance to the flow of electric current through the work parts held together under pressure by electrodes. The size and shape of the individually formed welds are limited primarily by the size and contour of the electrodes [8].

Spot welding in the most widely used type of resistance weld and is performed with two stationary electrodes pinching in contact with the material to be welded. Electric current is then passed through the electrodes and the material being welded until a suitable amount of material has been heated to an acceptable temperature in order to bond the material being welded (**Figure 7**) [8, 20].

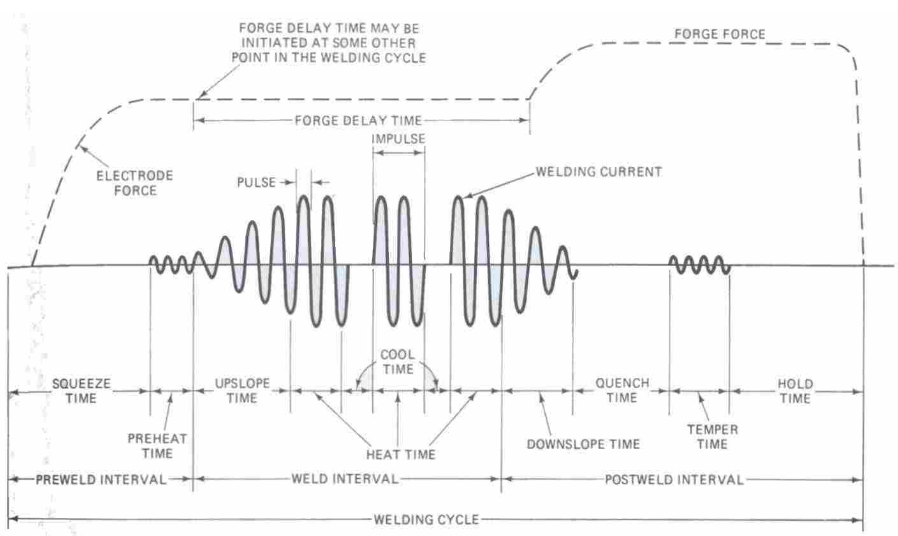


Figure 7: Typical RSW Cycle. [21]

Advantages of resistance spot welding include good portability, with machines varying from hand held units to industrial robots. Cycle times are short, in the range of a few seconds down to a few fractions of a second [8]. Resistance spot welding requires less skill than brazing or arc welding and is faster to perform [7].

Limitations and disadvantages of RSW also exist. These include:

(1) Disassembly for maintenance or repair is very difficult.

(2) A lap joint adds weight and material cost to the product, when compared to a butt joint.

(3) The equipment costs are generally higher than the costs of most arc welding equipment.

(4) The short time, high-current power requirement produces unfavorable line power demands, particularly with single phase machines.

(5) Spot welds have low tensile and fatigue strengths, because of the notch around the periphery of the nugget between the sheets.

(6) The full strength of the sheet cannot prevail across a spot welded joint, because fusion is intermittent and loading is eccentric due to the overlap [8].

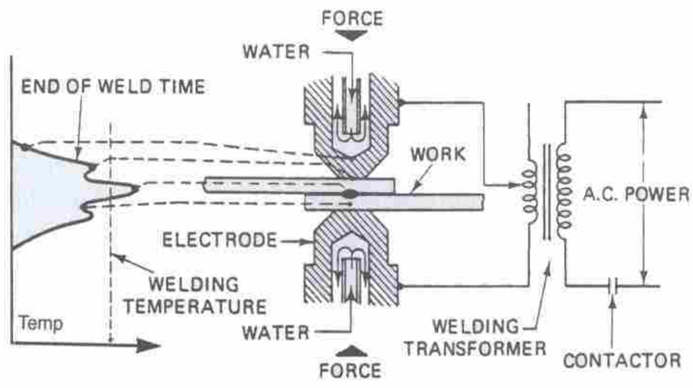


Figure 8: Typical RSW setup. [21]

When producing resistance spot welds, the following characteristics are important factors in producing acceptable lap welds [8, 22]:

- Electrode Space- Only the electrode tip may touch the material (**Figure 8**).
- Edge Distance- The weld nugget must have sufficient distance from the edge of the material to support the weld.
- Throat Depth- The machine performing the weld must be able to accommodate the weld location (depth from the edge of the material) on the material being joined.
- Weld Overlap- The sheets being welded must have a minimum of twice the overlap distance.
- Weld Strength- The strength of the weld must be acceptable. The maximum strength from any lap weld is 90% of the parent metal.
- Surface Conditions- The surfaces to be joined must be free of contaminants to obtain the best possible joint.

- Fit-up of Parts- The pieces to be joined should not be under force during welding and should fit together properly.
- Electrode Tip Size- The size of the electrode tip must be suitable for the thickness of the material to be welded and is given by the following equation where *t* is one thickness of the material to be welded.

$$\text{Tip Diameter} = 0.1 + 2t \qquad (1.1)$$

- Welding Force- There must exist sufficient clamping force on the materials being joined so as to create a good bond.
- Squeeze Time- After current has created a weld, hold time may be necessary to allow the weld to cool.
- Welding Time and Current- Current flows as shown in **Figure 9**. The equation used to calculate the required heat to make a spot weld is:

$$H = I^2RTK \qquad (1.2)$$

Where I = current flowing through the weld in amps
R = resistance in ohms from one electrode tip to the second tip
T = time of current flow in seconds
K = loss factor

- Coated Metals- In order to produce a quality weld in a galvanized steel higher current, higher pressure, and lower weld time must be used.

Resistance spot welding equipment is well established. Industrial applications make use of automated welding, electrode wear compensation, and track energy use [18].

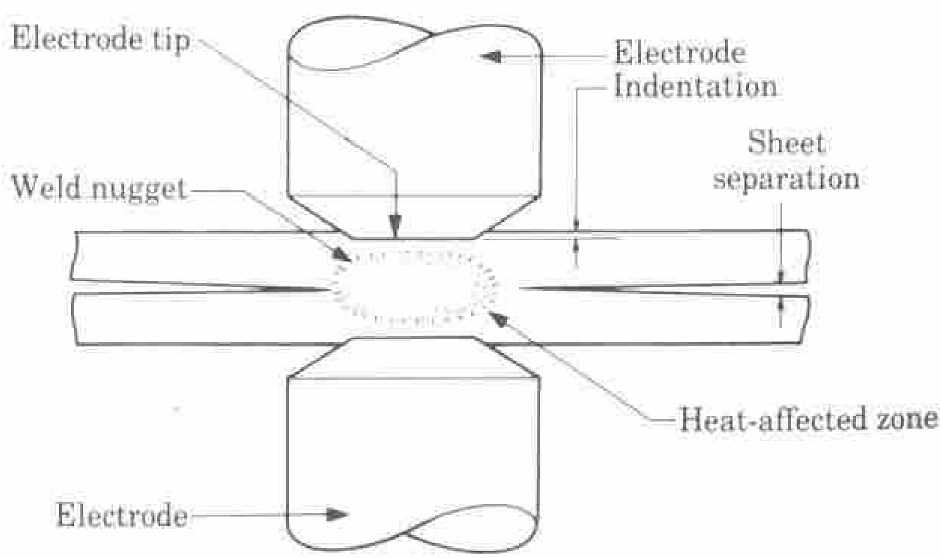


Figure 9: Illustration of the formation of a spot weld. [23]

2.5.2 Friction Stir Spot Welding

Fiction Stir Spot Welding (FSSW) is a variant of Friction Stir Welding (FSW). FSW was invented in 1991 by The Welding Institute (TWI). FSSW was developed and patented by GKSS, a German company, using a three stage process (**Figure 10**) [5]:

- Pre-process- the pin a shoulder are placed on the material surface to heat the material in order to plunge
- First-half- the shoulder is plunged into the material while retracting the pin
- Second-half- the pin the extended while retracting the shoulder

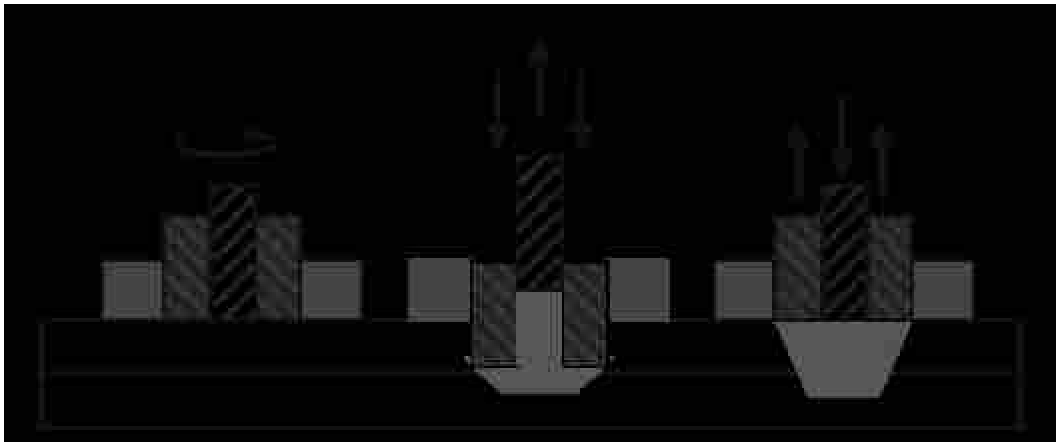


Figure 10: FSSW as patented by GKSS. [24]

This type of welding may involve a fixed pin (**Figure 11**) or a retractable pin with a clamping ring for refilling the void typically created by the pin (**Figure 12 - Figure 15**). As noted earlier, there are several variations in FSSW processing, as researchers attempt to refine the process [24].

The Advanced Materials Processing and Joining Laboratory of South Dakota School of Mines has developed a retractable pin approach, called fixed-position refill FSSW, in aluminum [9]. While this approach had not been tested in steel, it is of note to mention this novel process.

Stage 1: The rotating pin and shoulder move towards the upper plate.

Stage 2: The pin plunges to depth and the shoulder reservoir fills with the displaced material from the pin.

Stage 3: The pin retracts while the shoulder advances, filling the pin hole.

Stage 4: Optional dwell is added time for better mixing.

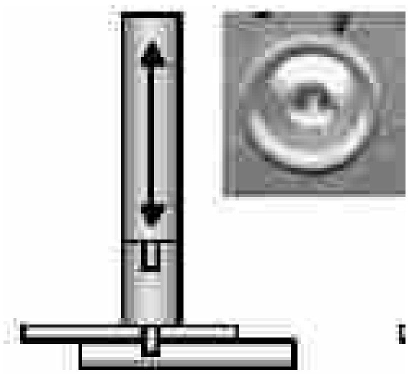


Figure 11: Fixed pin FSSW Example. [16]

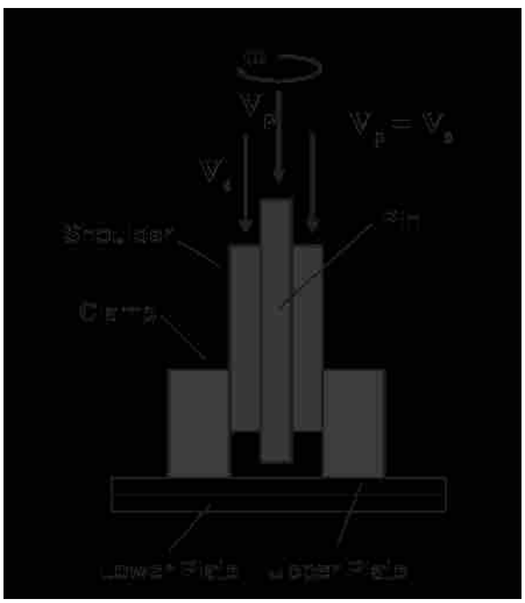


Figure 12: Stage 1 of the FSSW process. [9]

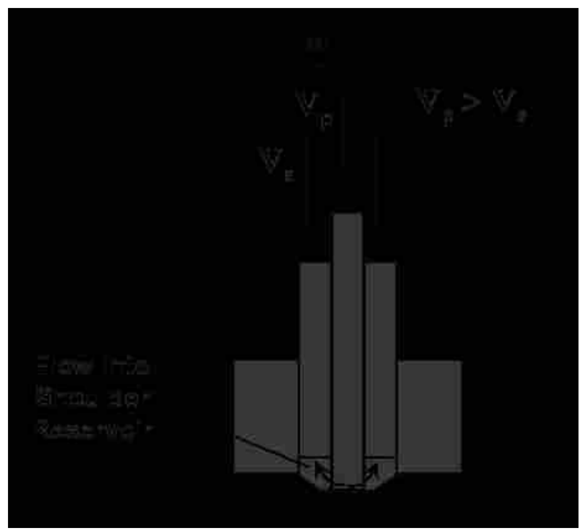


Figure 13: Stage 2 of the FSSW process. [9]

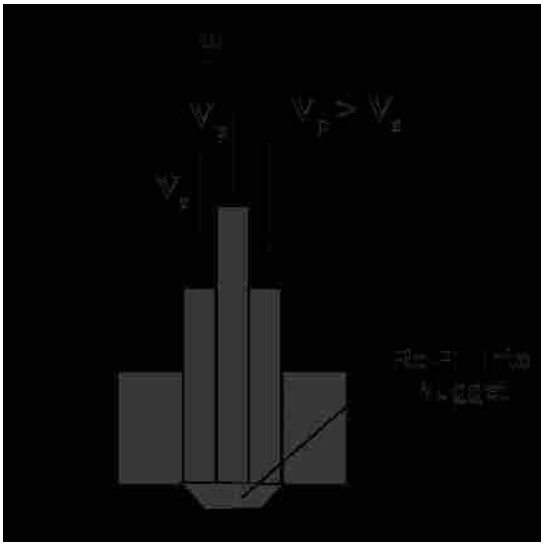


Figure 14: Stage 3 of the FSSW process. [9]

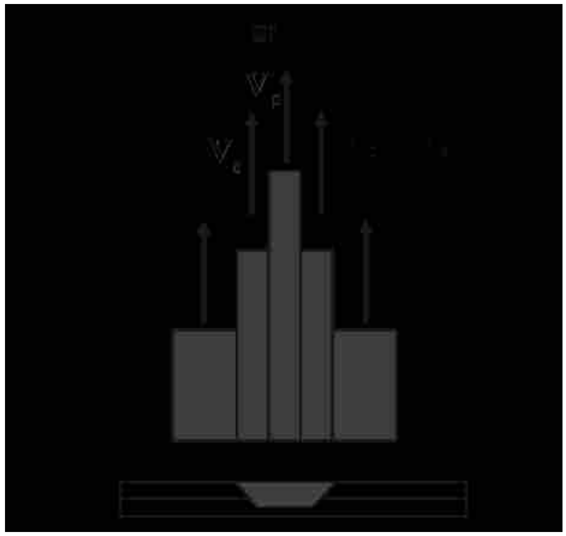


Figure 15: Stage 4 of the FSSW process. [9]

2.5.3 Spot Friction Welding

Spot Friction Welding (FSW) is a more refined term for fixed pin FSSW. In effect, it is only using a fixed pin approach and does not use a retractable shoulder. However, several variants have emerged including swing FSW and stitch FSW.

Typical FSW is performed in three steps (**Figure 16** and **Figure 17**):

- Plunging the tool into the material
- Stirring the material with an optional dwell time
- Drawing out or retracting the tool

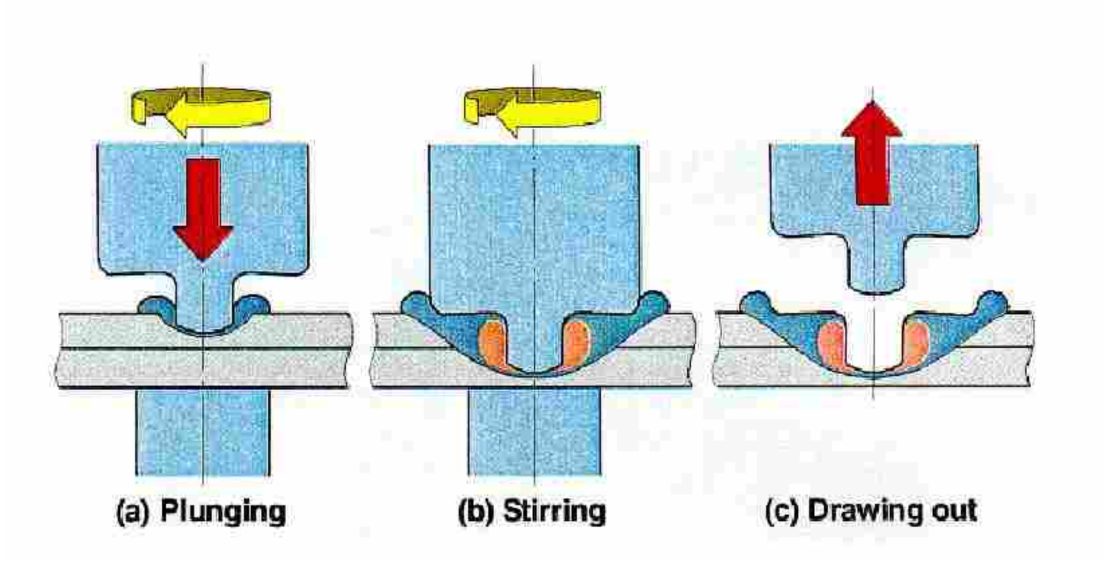


Figure 16: SFW example. [1]

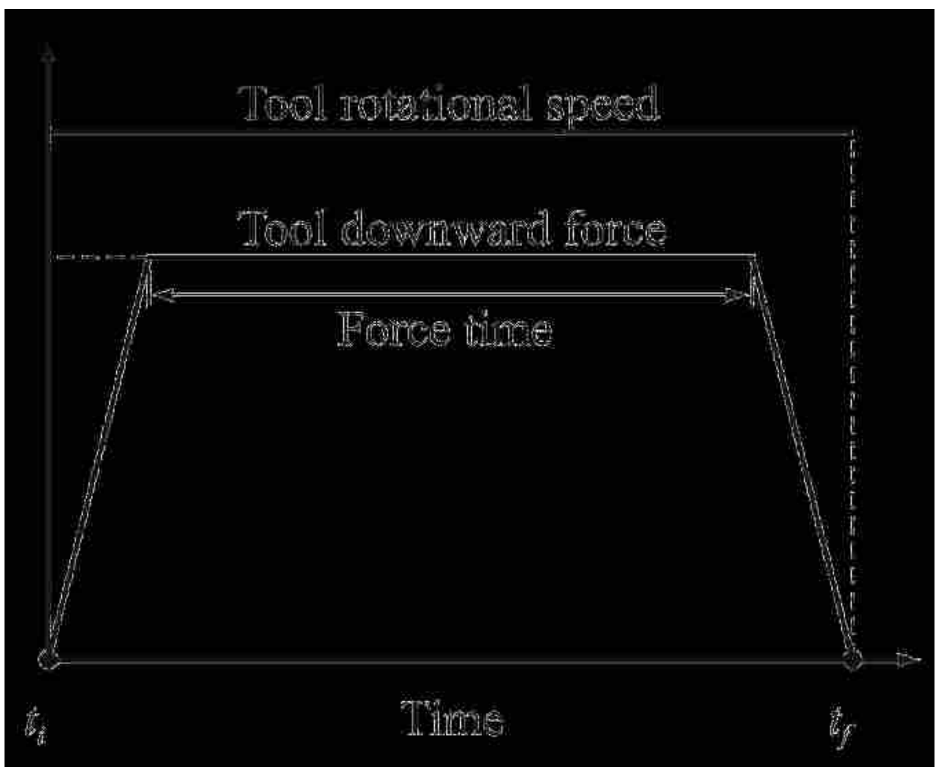


Figure 17: SFW operation chart. [1]

2.5.4 Stitch FSW

This variant of FSSW incorporates linear FSW into a spot weld. In essence, it is an extremely short linear weld which can be produced in the same amount of time as a FSSW joint. When compared to FSSW joints and RSW, it is stronger due to an increased bonding region. It has only been tested in aluminum alloy [16].

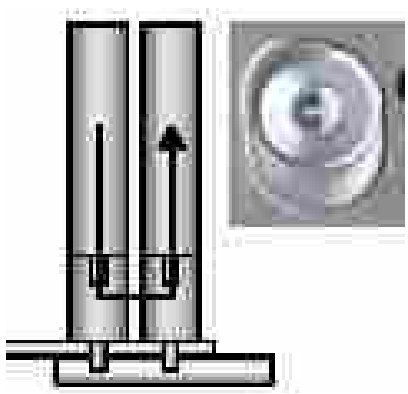


Figure 18: Stitch FSW example. [16]

2.5.5 Swing FSW

Swing FSW developed out of stitch FSW with the idea that, given a large enough radius, a stitch weld could be approximated using simplified machinery while retaining similar weld strength (**Figure 19**). Due to the success of swing FSW, a prototype C-frame "swing stir" gun (**Figure 20**) was created for a multi-articulate robot for use in automotive closure panel fabrication applications [16].

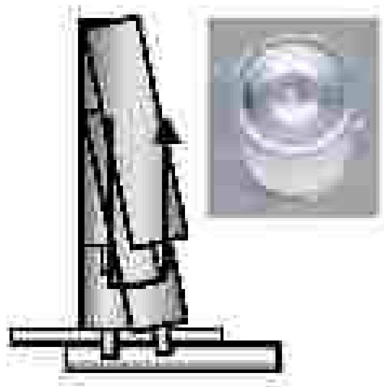


Figure 19: Swing FSW example. [16]

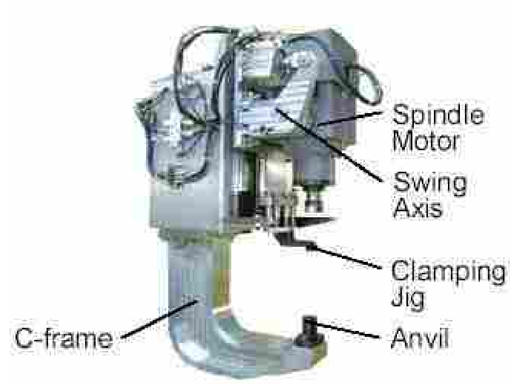


Figure 20: Swing stir gun. [16]

2.6 Tool Designs and Heat Generation

RSW tooling will not be discussed in depth due to the extensive amount of literature available on the subject. However, it will be stated that RSW tooling has been well established for decades and must include a power source, cooling method, clamping method, distribution method, and electrodes. Weld strength has traditionally been linked to nugget size, or the size of the bonded area of two metals. If nuggets are improperly formed, incomplete, have voids, are too small, or have other irregularities the integrity of the part may be compromised [13]. Heat input must therefore be sufficient to bond the materials and produce a suitable nugget [8]. Typical temperatures in a mild steel weld are shown in (**Figure 21**).

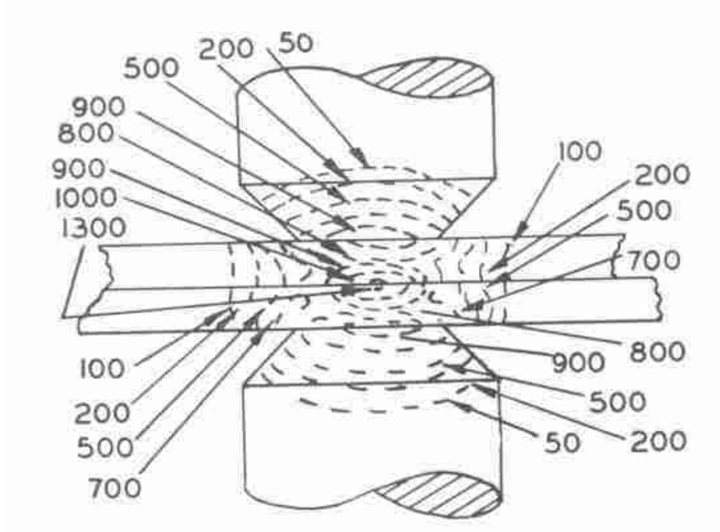


Figure 21: Estimated instantaneous spot welding temperature in degrees centigrade at the instant of completion of the weld. [8]

FSSW and SFW tooling has been created out of H13 tool steel, carbide, and PCBN. Tooling is generally in the shape of a fixed or retractable pin and may vary in diameter with common sizes seen in literature of 8 mm to 10 mm. Tool geometry is a critical factor in SFW processing [25].

It is of importance to note the amount of friction generated at the tool/material interface. Increased friction can result in material buildup during withdrawal of the tool from the material. Likewise, sufficient friction and heat must be supplied to stir the materials together by either mechanical interface such as threads, or downward pressure [17]. However, it is still not well understood how much heat is due to the tool-material interface and how much is due to the shearing forces within the material itself. Studies have been conducted in a effort to arrive at a mathematical formula to describe heat generation [6, 26].

In UHSS steels heat input has been adequate but the rapid cooling of the nugget has rendered undesirable highly brittle microstructures [17]. Additionally, RSW of UHSS steels produce problematic solidification related weld defects [25].

2.7 Costs

Cost savings of the FSSW fixed pin approach vs. RSW in aluminum were reported by Mazda when implemented on a model 2003 production vehicle (**Figure 22**). Savings included 90% operation energy savings and 40% capital investment savings compared to RSW [17].

Figure 22: FSW in the rear door of the 2003 Mazda RX-8. [1]

2.7.1 Power Requirements

FSW technology has shown that it uses significantly less energy and has lower environmental emissions than fusion weld methods [17, 6, 27]. Attempts have been made to determine the factors which determine joint mechanical properties in aluminum and magnesium alloys while using energy input equations and evaluating fracture morphology [4]. One study did confirm that in FSSW experiments, higher power requirements (shown by forge force and rpm) did not equate to higher tensile strengths in aluminum (**Figure 23**) [24].

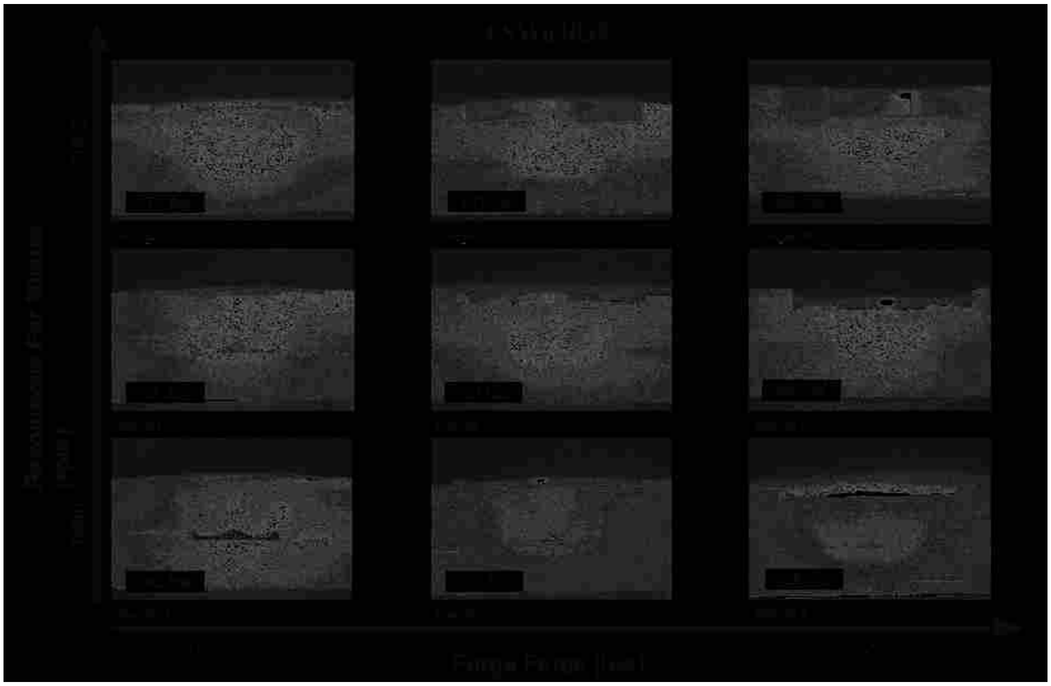


Figure 23: Process development matrix for the fixed position refill FSSW method. [24]

2.7.2 Consumables

In RSW, tips of the electrodes wear from use and may either be dressed, replaced, or caps may be used [8]. In UHSS steels electrode life is degraded compared to other steels [25]. In SFW or FSSW the tool, generally 10 mm in diameter, may show no noticeable wear when used as specified and made of polycrystalline cubic boron nitride (PCBN) [10, 4, 17].

2.7.3 Cycle Times

Cycle times for refill and fixed pin methods vary, with refill methods accounting for estimated longer cycle times due to the amount of material which must be formed and reformed. Mazda used the first application of a fixed pin approach on the 2003 RX-8. It is unknown how long the cycle time was in the Mazda application. Weld times in ultra high-strength steels have be recorded at 2-3 seconds in one laboratory study for the fixed pin approach [17]. A different study reported times from 1.7 to 9.75 seconds with feasible 4 second weld times. Maximum SFW strengths in UHSS DP780 were achieved with slow plunge rates (.4 mm/s) and 3 second dwell times [25].

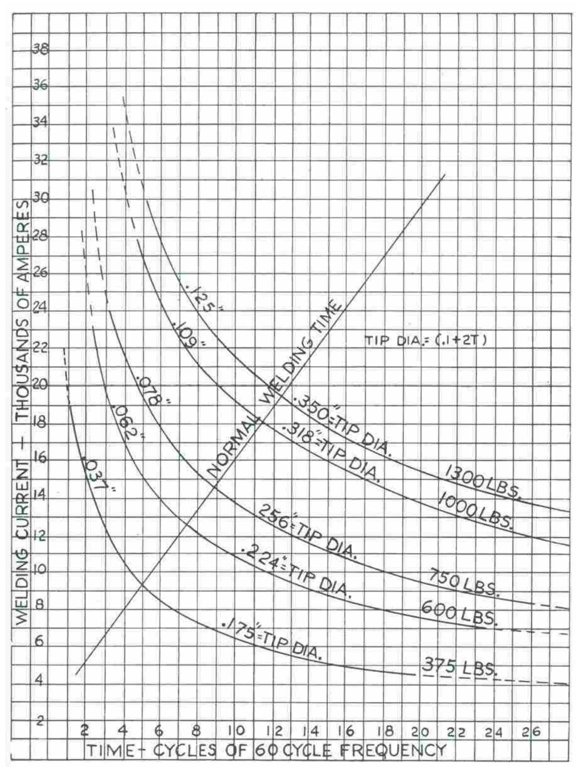


Figure 24: Time-Current curves in two equal thicknesses of clean, low carbon steel from 1/32in to 1/8in. [8]

Weld times for RSW vary according to sheet thickness (**Figure 24**) and are influenced by the squeeze time required for weld cooling [8]. Typical weld times are well under 1 second for welding two sheets of 1 mm each [28].

2.8 Conclusions

From the reviewed literature it can be seen that FSSW and SFW have been examined primarily in aluminum applications and have shown significant promise to the point that limited production applications have been implemented. Preliminary research has begun in UHSS steels up to DP780 using PCBN tooling; however there have not yet been any documented attempts on stronger UHSS materials. There is no doubt as to the usefulness and understanding of RSW technology; however, it must be investigated at to whether cycle times for UHSS steel can be reduced and weld quality increased with SFW technology.

3 Research Procedures

3.1 Materials

Alloys DP780 and DP780EG of 1.2 mm and 1.4 mm, respectively, were used for welding experiments. Alloys DP980 and DF140T of 1.25 mm and 1.5 mm were also used. The purpose of this study is not to weld with dissimilar gages, but rather to test the weld characteristics of the materials by two different welding methods, RSW and SFW. The sheets used in this study were automotive grade alloys: DP780 and DP980/DF140T were uncoated and DP780EG was electro-galvanized. Applications for these materials vary but may be used in body and underbody structures in automobiles depending on sheet thickness.

3.2 Specimen Size

Samples for this study were sheared coupons of 50.8 mm x 152.4 mm (2 in x 6 in). Excessive burrs were removed prior to welding.

3.3 Resistance Spot Weld Data Collection

Resistance spot welds were produced by Ford Motor Company in Deerborn, MI in DP780EG and DP980 sheet. Parameters which produced satisfactory welds were recorded after welds were tested using the peel test method at the Ford facility. Parameters included:

- Material
- Thickness
- Cap diameter
- Weld force
- Welder type
- Control mode
- Squeeze time (cycle)
- Weld time (cycle)
- Cool time (cycle)
- Hold time (cycle)
- Weld current
- Button diameter

3.4 Spot Friction Weld Variables

Variables noted while producing spot friction welds included:

- Tool material
- Tool geometry

- Material
- Thickness
- Downward federate of the tool
- Dwell at the bottom of the feed
- Tool rpm
- Depth of the tip of the tool from the top of the material
- Force used to produce the weld

3.5 Weld Micro-Hardness

Transverse samples were made from RSW and SFW welds and measurements were taken for micro-hardness evaluations. Samples were cut with a Sodick Mark XI wire EDM and then mounted in epoxy. Samples were then polished in steps from 800 grit sandpaper up through 6 micron diamond paste. Vickers micro-hardness tests were then performed using an automated 8 second dwell at 300 grams. The indents were made across the base material through the weld and then to the base material on the opposite side.

3.6 Imaging

Samples were polished to 1 micron with diamond paste and then etched to reveal grain structure. Images were taken at various magnifications using a light microscope with a digital camera.

3.7 Mechanical Testing

Lap tensile and cross tension tests were performed on all materials at 10 mm/min (.3937") pull on an Instron tensile machine at room temperature. Data was collected at .25 sec intervals. Ultimate tensile and tension strength was used as a comparison between materials in both lap and cross tension tests. Lap shear specimens were shimmed to reduce uneven loading and then pulled in the jaws of the tensile test machine. Cross tension specimens were pulled in a custom built fixture following guidelines used specifically for this purpose on the tensile test machine (**Figure 25**). This fixture was later modified to hold square washers to hold samples flat as they were pulled.

Figure 25: The cross tension pulling fixture used in this study.

3.8 Welding Machinery

RSW machinery used in this study was a MFDC Servo Gun. SFW machinery was a friction stir weld converted Kearny and Trecker mill (**Figure 26**). The fixture used included a convertible plate which had holes for pins to align the samples in a cross (**Figure 27**) and holes for pins to align the samples in a linear fashion for lap welds (**Figure 28**).

Figure 26: Friction stir weld machine used in this study.

Figure 27: A fixture used in this study for creating cross tension SFW welds.

Figure 28: A fixture used in for creating lap SFW welds.

3.9 Tool Breakage

Tools used during this experiment consisted of PCBN and carbide tip materials. When tools failed, parameters were noted and generally accepted as beyond the capable limits of the tool, material, or configuration of geometry for the particular circumstance in which the tool failed.

4 Data Results and Discussion

4.1 RSW Welding Parameters Used

The followings parameters were used to weld DP780EG and DF140T in order to achieve a minimum button size of 4.8 mm. Welds were made using industrial MDFC servo gun RSW machines.

Table 2: RSW variables for DP780EG

Amps	7.2 KA
Force	4893 N (1100 lbs)
Cap	6 mm
Button (min)	4.8 mm
Squeeze time (cycle)	25
Weld time (cycle)	17
Hold time (cycle)	5

Table 3: RSW variables for DF140T

Amps	6.7 KA
Force	4893 N (1100 lbs)
Cap	6 mm
Button (min)	4.8 mm
Squeeze time (cycle)	25
Weld time (cycle)	17
Hold time (cycle)	5

4.2 SFW Variables Used

All welds were produced on a laboratory style linear friction stir machine which was adapted for use as a spot friction welder.

Spot friction welds were produced in DP780 at speeds of 500 rpm to 1000 rpm and at feed rates from 2 inches/minute up to 6 inches/minute. Weld depth (penetration) was measured from the top of the sample and was varied from 2.159 mm (.085") to 2.667 mm (.105"). Dwell times varied from 0 to 2 seconds. A standard PCBN tool of 10 mm diameter with three flats ground on the sides was used to produce the welds. Several other tool geometries and materials were also tested including an annulus made of carbide, a larger diameter shoulderless PCBN pin, and a convex high speed steel tool.

4.3 Tool Results

The carbide annulus tool was tested to determine if higher pressures developed by trapping material in the annulus would help bond the materials together. The tool was a carbide cylinder with a concave radius ground into one end. It could not be determined if this theory would work, as the tool failed on the first weld. Failure occurred when the tool was not able to handle the uneven loads generated at its circumference. Uneven loads were generated due to the lack of a centering mechanism; the tool was completely concave on its end. It was noted that the steel began to stick to the tool in this trial.

The larger diameter shoulderless PCBN pin tool was tested to determine if a shoulder was necessary in order to create a bond in the plates. In each trial with this tool one of two results occurred: either no bonding occurred or the tool punctured through the top plate and a micro weld was formed. The micro weld was easily pulled apart by the operator using hand force. This tool did not have sufficient taper at the tip and when increased downward feedrate was used in an attempt to create more stirring action, the tool failed. It is assumed that failure was due to the lack of taper angle on the tip and as a result rotation was no longer concentric causing failure.

The high speed steel tool was tested in order to find out if a lower grade tool material could be used. The tool was convex and turned on a lathe. The tool failed on the first weld due to heat buildup and friction.

Figure 29: Example of a PCBN SFW tool. [25]

The standard PCBN tool (**Figure 29**) used in this study was tested to determine if it would function as well as it had in lower strength steels such at DP600 and below. As testing progressed, the tip of the tool was ground down by .508 mm (.020 in). Tool failure was noted in only three situations: manufacturing flaw such as bad PCBN mix, non-precision grinding of the tool tip, or extreme loading in a cyclic nature. So far, this tool has created the best welds in a repeatable manner.

4.4 Tool Geometry

Tool geometry was an important factor in this study. As already stated, three types of geometry were tested. As the study progressed and it was determined that the standard PCBN tool was the most promising, it was noted that deeper penetration into the material generally produced better weld strengths. A limit was reached when the tip of the PCBN tool began to touch the welding fixture. In order to produce deeper welds, the top of the tool was ground down by .508 mm (.020 in). As a result, weld strengths increased until the shoulder of the tool began to break through the top plate of steel into the bottom plate. At this point, the tool had effectively displaced enough material to produce a hole instead of a weld.

4.5 Mechanical Testing Results

4.5.1 DP780 and DP780EG

RSW mechanical tests were performed on DP780EG in lap tensile, cross tension, and peel tension according to accepted test methods used in the auto industry. All welds in this material used the same weld parameters. It should be noted that peel testing was reported only as informational in order to compare loads to other tests. No peel testing was performed in SFW samples. A summary of results is presented in **Table 4**.

Table 4: RSW results in DP780.

DP780 Lap		
Min	13.42	kN
Max	15.52	kN
Avg	14.58	kN

DP780 Peel		
Min	1.93	kN
Max	2.61	kN
Avg	2.28	kN

DP780 Cross		
Min	8.63	kN
Max	10.88	kN
Avg	9.55	kN

All RSW results shown (**Figure 30**) are from optimal and identical settings and have variation inherent to the welding process. Since RSW in UHSS alloys is still relatively a new process, it is possible that these values may rise in the future and the process may exhibit less variation.

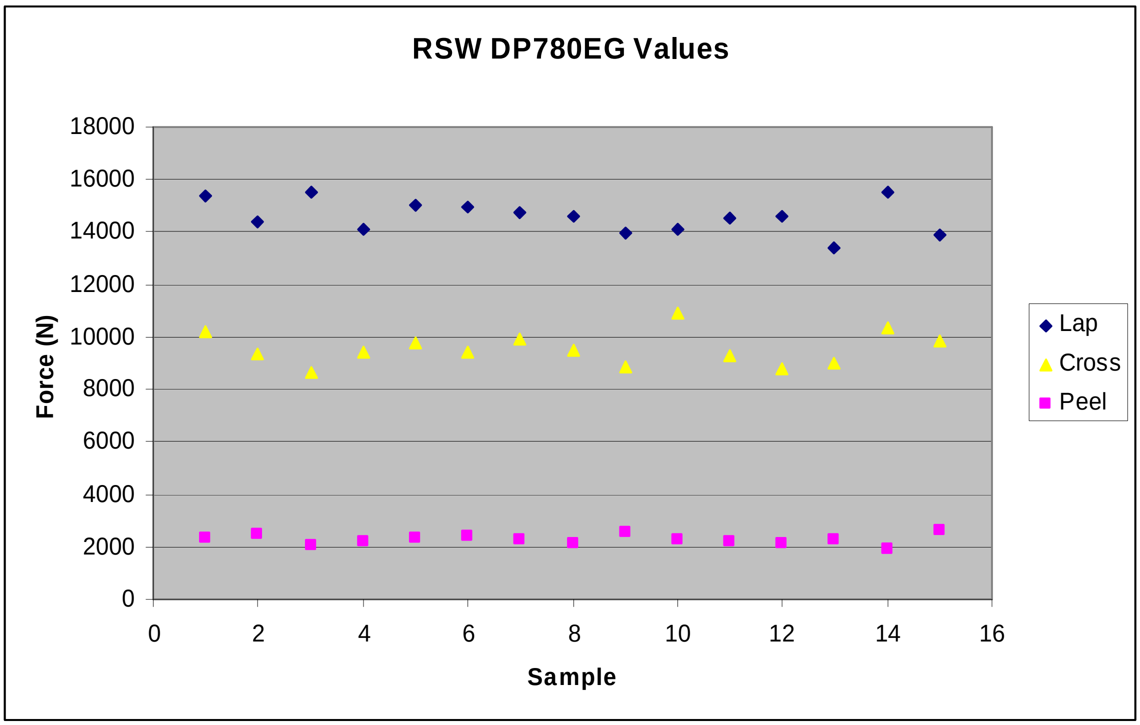


Figure 30: Graph of RSW DP780EG values.

The friction stir welds were produced in DP780 at speeds of 500 rpm to 1000 rpm and at feed rates from 50.8 mm/min (2 in/min) up to 152.4 mm/min (6 in/min). Weld depth (penetration) was measured from the top of the sample and was varied from 2.159 mm (.085 in) to 2.667 mm (.105 in). Dwell times varied from 0 to 2 seconds. A standard PCBN tool was used to produce the welds.

SFW tests were performed on DP780 and DP780EG in the same manner as the RSW samples. Lap tensile test results varied from 4.89 kN (1100 lbs) to 10.67 kN (2400 lbs) depending on the variables used in welding. Cross tension weld results ranged from 4.00 kN (900 lbs) to 6.22 kN (1400 lbs). The best welds generated were 2.413 mm (.095 in) in depth, 1 second dwell, 800rpm, 101.6 mm/min (4 in/min) feed with a standard PCBN tool (**Table 5**).

Table 5: SFW results in DP980.

DP980 Lap		
Min	4.89	kN
Max	10.67	kN
Avg	6.99	kN

DP980 Cross		
Min	4.00	kN
Max	6.22	kN
Avg	4.44	kN

Several geometries of tool were tested in DP780 other than fixed pin PCBN including annulus, scroll, and concave profiles. In all cases the tool failed or the weld held less than 3.114 kN (700 lbs) of force. A carbide tool was also tested; however, the tool's coefficient of friction was not low enough to prevent it from bonding to the sample while welding.

SFW results shown (**Figure 31**) are cumulative from all samples welded from DP780EG and DP780 sheet. Results include a wide spectrum of processing variables with certain combinations exhibiting higher strengths in load testing. Additional charts and graphs are in the appendix of this document. The maximum lap shear force was 10.82 kN (2432 lbs) and the maximum cross tension was 6.28 kN (1412 lbs).

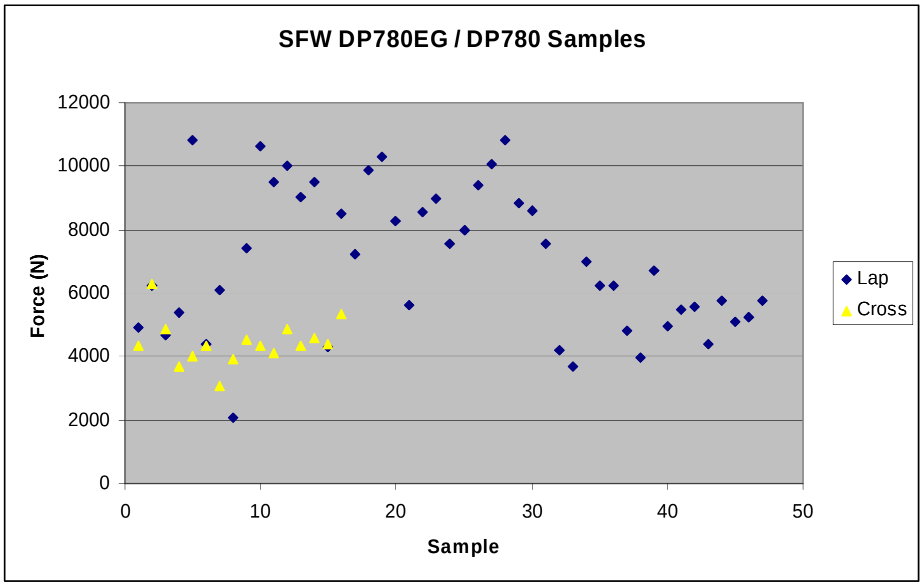


Figure 31: Graph of SFW values in DP780EG / DP780.

While some samples in SFW did approach the loads of RSW, none of the SFW samples were able to match RSW strengths in DP780EG or DP780. However, according to the proposed American Welding Society (AWS) standard of 10.04 kN (2257 lbs) in lap shear and 2.40 kN (540 lbs) in cross tension, several of the SFW samples exceed the minimum load and are acceptable.

4.5.2 DP980 and DF140T

RSW mechanical tests were also performed on DF140T in lap tensile, cross tension, and peel tension according to accepted test methods used in the auto industry.

All welds in this material used the same weld parameters. It should be noted that peel testing was reported only as informational in order to compare loads to other tests. No peel testing was performed in SFW samples. A summary of results is presented in **Table 6.**

Table 6: RSW results in DF140T.

DF140T Lap		
Min	16.12	kN
Max	17.17	kN
Avg	16.67	kN

DF140T Peel		
Min	1.93	kN
Max	2.61	kN
Avg	2.28	kN

DF140T Cross		
Min	7.32	kN
Max	10.03	kN
Avg	8.68	kN

All RSW results shown (**Figure 32**) are from optimal and identical settings according to material and have variation inherent to the welding process. Again, since RSW in UHSS alloys is still relatively a new process, it is possible that these values may rise in the future and the process may exhibit less variation.

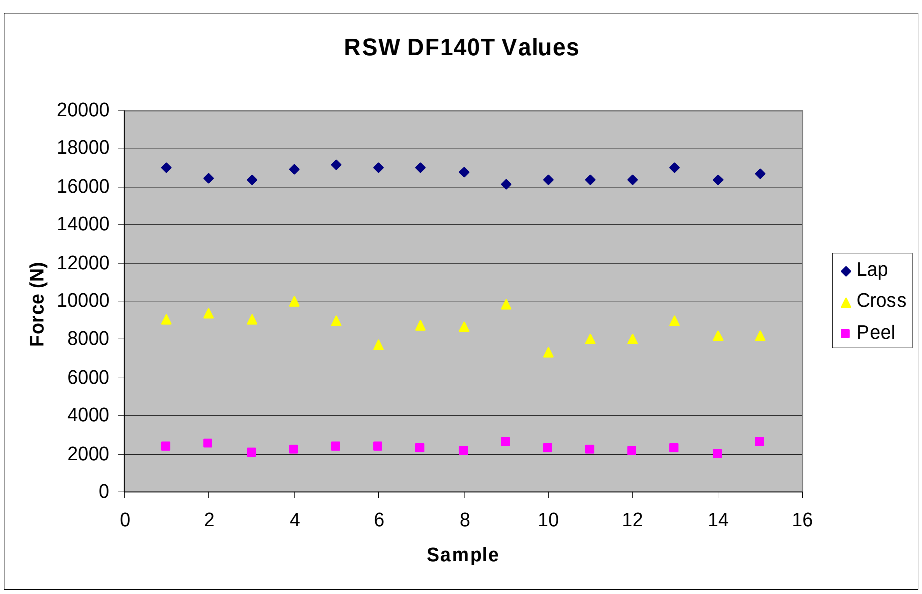


Figure 32: Graph of RSW DF140T values.

The friction stir welds were produced in DF140T and DP980 at speeds of 800 rpm and 1000 rpm and at feed rates of 101.6 mm/min (4 in/min) up to 152.4 mm/min (6 in/min). Weld depth (penetration) was measured from the top of the sample and was varied from 2.413 mm (.095 in) to 2.642 mm (.104 in). Dwell times varied from 0 to 2 seconds. A standard PCBN tool was used to produce the welds.

SFW tests were performed on DF140T and DP980 in the same manner as the RSW samples. Lap tensile test results varied from 2.40 kN (540 lbs) to 9.84 kN (2212 lbs) depending on the variables used in welding. AWS minimum proposed weld strength for this material and thickness in lap tensile is 11.97 kN (2691 lbs). Cross tension weld results ranged from 2.45 kN (552 lbs) to 3.38 kN (760 lbs). AWS minimum proposed weld strength for cross tension is 2.93 kN (659 lbs). The best welds generated were 2.642 mm (.104 in) in depth, 1 second dwell, 1000 rpm, 101.6 mm/min (4 in/min) feed with a PCBN tool. No other geometries of tool were tested in these materials.

SFW results shown (**Figure 33**) are cumulative from all samples welded from DF140T and DP980 sheet. Results include a wide spectrum of processing variables with certain combinations exhibiting higher strengths in load testing. Again, additional charts and graphs are in the appendix of this document. The maximum lap shear force was 9.84 kN (2212 lbs) and the maximum cross tension was 3.38 kN (780 lbs). None of the samples in SFW approached the loads of RSW in these materials.

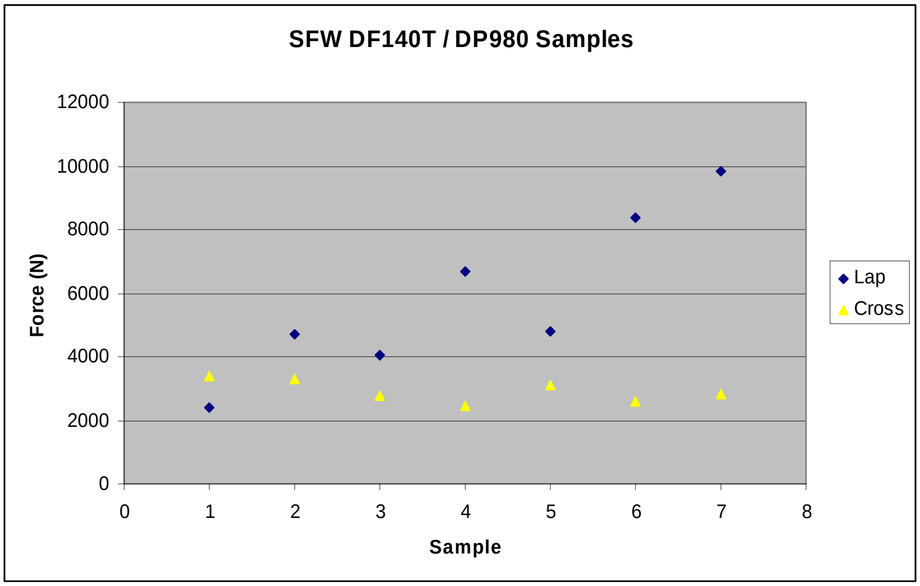


Figure 33: Graph of SFW values in DF140T / DP980.

4.6 Hardness Results

The hardness testing of the RSW weld data show a maximum hardness of 410 Vickers in DP780EG while the SFW hardness shows a maximum hardness of 325 Vickers. These results confirm that SFW induces less harness than RSW in similar materials of DP780 and DP780EG (**Figure 34**).

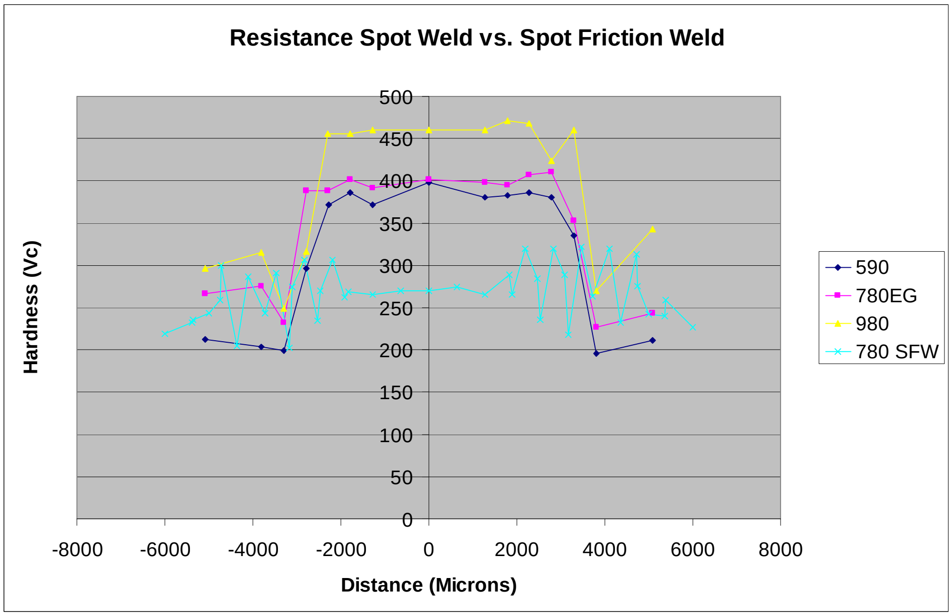


Figure 34: Chart of RSW hardness vs. SFW hardness

4.7 RPM Results

RPM plays an important part of SFW bonding, although the data is inconclusive as to how rpm interacts with the feed of the tool, geometry, tool material, and to what depth the tool is fed.

As can be seen in **Figure 35**, the data shows two peaks at 800 and 1000 rpm for ultimate force of lap welds. Cross tension welds also show a peak at 800 rpm and it is expected that another peak would form at 1000 rpm. Due to experimentation on lap welds in the 1000 rpm range with high feed rates in DP980, tool failure prevented further testing of cross tension welds.

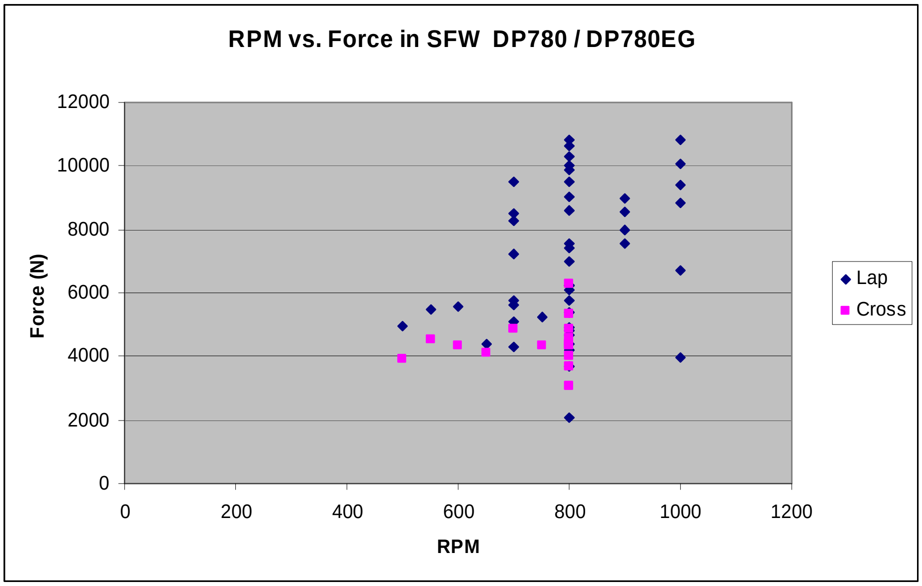


Figure 35: RPM vs. Force in DP780 / DP780EG.

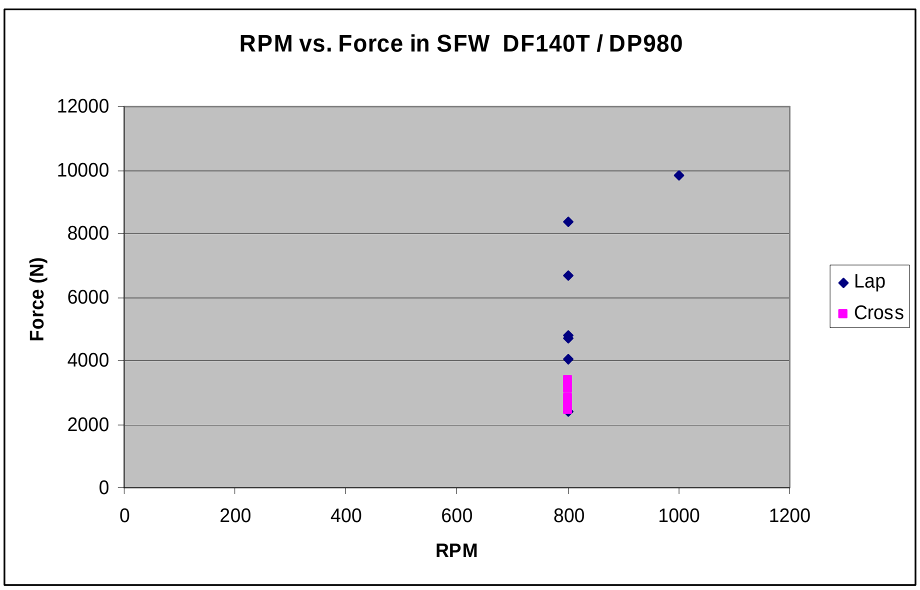


Figure 36: RPM vs. Force in DF140T/DP980.

Testing of rpm in higher strength materials resulted in few data points as tool failure became more prevalent. It is suspected that the materials became work hardened with the heating of the material upon tool entry into the specimens. In an attempt to counteract this hardening the tool was fed more rapidly into the specimens which resulted in higher loading of the tool. Data acquired is presented in **Figure 36**.

4.8 Depth of Weld Results

During testing it was noted that an increase in depth generally resulted in higher strength welds in this tool until:

- The tip of the pin broke through the lower specimen and hit a fixture
- The edge of the tool broke through the upper specimen

Therefore, greater depths increase weld strength up to a limiting factor. In testing it was noted that a specified distance between the shoulder of the tool and the interface between materials was a critical factor in obtaining stronger welds (**Figure 37)**. In the materials tested with the standard PCBN too geometry it was found that a distance of .508 mm (.020 in) produced the best welds. Upon knowing this, the depth of plunge for each material thickness will be:

$$p = t + h - (s + c) \quad (1.3)$$

Where:
p = total depth of plunge as measured from the pin tip
t = one thickness of the material
h = total height of pin
s = height of shoulder measured from base of pin
c = critical clearance between shoulder and weld interface

During testing it was noted that a larger stir area would result in higher strength bonds. As the shoulder is the largest circumference which can contact the material to be welded, it was desired that the shoulder created more bonding through friction with the interface. As a result, plunge depth became more critical relative to the shoulder and the function of the pin was understood to be a centering device rather than a bonding device.

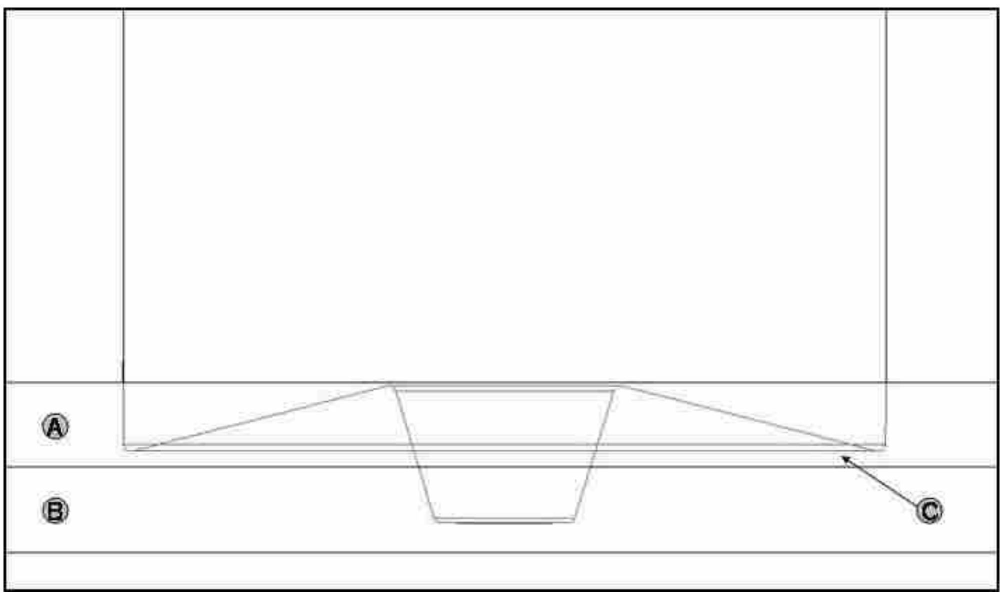


Figure 37: Figure showing specimens (A) and (B) being welded with critical distance (C) to the interface.

4.9 Down Feed Results

Feed results in the downward (Z) direction suggested that feed is critical factor in creating a weld, but it is not certain what specific role it plays. Both strong and weak bonds occurred at low feed rates and higher feed rates. It was determined that higher feed rates at lower rpm did increase the load on the tool, and at times resulted in tool failure. Therefore, higher feed rates were approached cautiously since feed rate was determined to be the primary cause of tool failure. During the course of the experiments it was thought that higher feed rates would result in more pressure, friction, and bonding. However, this has not been supported or disproved by the data. It has been observed that material flow is still an unknown and that feed, rpm, tool geometry, weld material, tool material, and dwell time are all factors.

4.10 Cycle Time Results

Cycle time of SFW is an important factor to consider when weighing cost of producing a weld. Feed rate is a critical factor in weld time, as the distance the tool is fed does changes cycle time by more than 3 seconds, however, weld quality appears to be more important than cycle time. Dwell time is also a critical factor in SFW as it has been noted that, given the tooling used, increased dwell times have stronger bonds. If dwell time can be reduced or eliminated, cycle times can be reduced to only the feed time. Currently the cycle times for the strongest welds produced were approximately 1.5 seconds for feeding, 1 second for dwell, and .75 seconds for withdraw. It should be noted that withdraw time can be reduced significantly to .25 seconds by increasing travel rate as this motion is theoretically a rapid move and does not contribute to weld strength. Cycle time for this study therefore was 3.25 seconds for successful welds with a theoretical possibility of 2.75 seconds. Actual time needed to create the weld was 2.5 seconds which excludes withdraw time.

4.11 Imaging Results

Images of the welds revealed that the grain structure of the SFW (**Figure 38**) bond was much smaller than that of the RSW (**Figure 39**). This suggests that the SFW is more ductile and less brittle than RSW.

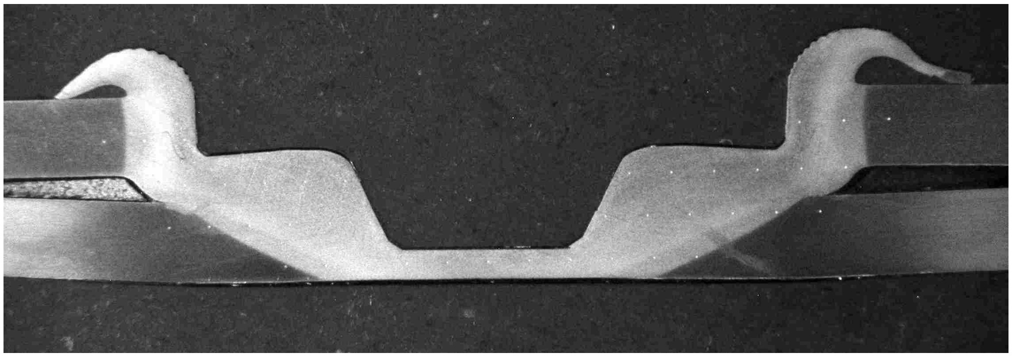


Figure 38: A cross section of a SFW in DP780. This is sample #25 in the appendix.

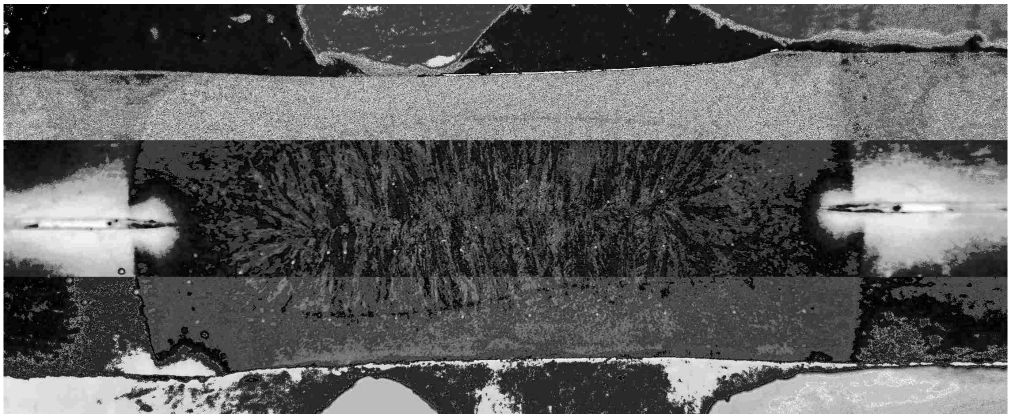


Figure 39: A cross section of a RSW in DP780EG.

5 Conclusions

5.1 Conclusions

SFW has been developed as an extension of friction stir welding as a new joining method which may have lower energy requirements, lower equipment costs, and better weld properties in steels than current RSW technology. This new joining process has many potential applications within the automotive industry and may replace RSW in specific applications.

The intent of this study was to determine if SFW in UHSS was capable of producing acceptable spot welds according to proposed AWS standards, in less than a 3 second weld time, with lower hardness than RSW, and then compare the results to RSW.

Therefore, the hypotheses that guided this research are concluded as follows:

Hypothesis 1: Spot friction welding can produce acceptable spot weld strength in UHSS DP780EG/DP780 has failed to be rejected because SFW has produced cross tension spot weld strength in DP780EG/DP780 of 6.28

kN (1412 lbs) and a lap shear force of 10.82 kN (2432 lbs) which are acceptable strengths according to proposed AWS standards for this material and thickness.

Hypothesis 2: Spot friction welding can produce acceptable spot weld strength in UHSS DP980/DF140T is rejected in lap tension and has failed to be rejected in cross tension because SFW has produced a cross tension spot weld strength in DP980/DF140T of 3.38 kN (760 lbs) which is an acceptable strength according to proposed AWS standards for this material and thickness. However, the maximum lap shear force of 9.84 kN (2212 lbs) is not acceptable according to AWS proposed standards.

Hypothesis 3: Spot friction welding is capable of producing an acceptable weld in UHSS in less than 3 seconds has failed to be rejected because SFW has produced acceptable welds in less than 3 seconds of weld time. All welds were produced in 2.5 seconds of weld time including plunge and dwell time.

Hypothesis 4: Spot friction welding can produce equal or greater spot weld strength than RSW in any above UHSS material used in this study is rejected because SFW did not produce any welds of equal or greater strength than RSW.

Hypothesis 5: Spot friction welding can produce superior spot weld hardness (lower) in the above UHSS materials than RSW has failed to be rejected because SFW did show reduced hardness when compared to RSW through an entire weld.

It is also noteworthy to mention that grain size in SFW samples was visually smaller than grain size of RSW welds. Furthermore, hardness values in SFW were lower than RSW which suggests more favorable impact resistance and lower weld hardness.

5.2 Tool Geometry

During testing it became apparent that the pin of the tool with the geometry used in the study was used primarily for centering the device and preventing it from rotating in a non-concentric motion. If, at any time, the tool became loaded bi-axially it was at risk for failure if the tool material was not strong enough to withstand the forces.

Pin length of the tool is also a critical factor in that it must be short enough to allow the shoulder of the tool to come into contact with the interface of the two samples being joined within .508 mm (.020 in) in order to create maximum weld strength in this tool geometry.

Given the tools used in this study and their material composition, is apparent that tooling used must have a low coefficient of friction if it is to be non-consumable. So far, PCBN is the material of choice due to its wear resistance for steel.

5.3 Recommendations

It is still unclear how material flow affects the quality of the weld since there are many variables in producing a SFW. Since each tool's geometry affects material flow, the options for material flow study are nearly as endless as the type of geometry for tools. Nevertheless, it is of great interest to understand this phenomenon and how it relates to obtaining stronger welds. Suggestions for further study may include:

- the use of a tool with a scribed scroll on the tapered pin portion
- the use of a tool with a 10 mm pin and no shoulder (scrolled)
- understanding material flow in UHSS with SFW
- further hardness testing in SFW samples with other tool geometries
- cyclic failure testing
- obtaining the relationship between weld strength and feed, RPM, dwell, and depth of plunge for a given tool through a full DOE

6 References

[1] Pan T., *Friction stir welding in automotive applications – present and future*, Presentation in Author's Possession, 2004

[2] Mahmood H., Ford Motor Company, 2003, www.autosteel.org accessed 6/5/2006

[3] Gerlich A. *et al*, *Peak Temperatures and microstructures in aluminum and magnesium alloy friction stir spot welds,* Science and Technology of Welding and Joining 2005 vol 10 no 6, 647-652

[4] Su A. *et al*, *Friction stir spot welding of aluminum and magnesium alloy steels*, 2005 SAE World Congress, 2005-01-1255, April 11-14, 2005

[5] Muci-Kuchler K. H. *et al*, *Numerical Simulation of the friction stir spot welding process,* 2005 SAE World Congress, 2005-01-1260, April 11-14, 2005

[6] Buck G., *Non-dimensional characterization of the friction stir/spot welding process using a simple coquette flow model Part I: Constant property bingham plastic solution*, 2004 Materials Processing and Design: Modeling, Simulation, and Applications 1283-1288

[7] O'Brien, R. L., *Welding Handbook Eighth Edition: Volume 2 Welding Processes*, American Welding Society, 1991

[8] Del Vecchio, E. J., *Resistance Welding Manual Third Edition: Volume 1*, Resistance Welder Manufacturers' Association, 1956

[9] Muci-Kuchler K. H. *et al*, *Visualization of material flow in friction stir spot welding*, SAE International, 2005, 2005-01-3323

[10] Feng Z. *et al*, *Friction Stir Spot Welding of Advanced High-Strength Steels – A Feasibility Study,* 2005-01-1248, SAE World Congress, April 11-14, 2005

[11] Miles, M. *et al. Spot Welding Technologies for High Strength Automotive Steel*, seminar presented at Tohoku University, Japan on June 23, 2006

[12] Schmidt H. *et al*, *An analytical model for the heat generation in friction stir welding*, Modeling and Simulation in Materials Science and Engineering (12) 2004 143-157

[13] Yang L. *et al*, *Measurement of nugget size of spot weld by digital shearography*, Proceedings of SPIE vol. 5880, 2005, 50-57

[14] Nelson T. *et al*, Friction stir welding using a superabrasive tool, 2003, US Patent No 6648206

[15] Kallee, S., 1st International Symposium on Friction Stir Welding, Thousand Oaks, CA, June 14-16, 1999

[16] Okamoto K. *et al*, *Development of friction stir welding technique and machine for aluminum sheet metal assembly- friction stir welding of aluminum for automotive applications*, 2005 SAE World Congress, 2005-01-1254, April 11-14, 2005

[17] Feng Z. *et al*, *Friction stir spot welding of advanced high-strength steels – a feasibility study*, SAE International, 2005, 2005-01-1248

[18] O'Brien, R. L., *Welding Handbook Eighth Edition: Volume 1 Welding Technology*, American Welding Society, 1991

[19] Mortimer J., *Jaguar "Roadmap" rethinks self piercing technology*, Industrial Robot: An International Journal 2005, vol 32 no 3, 209-213

[20] Jefferson, T. *The Welding Encyclopedia: Eleventh Edition*, The Welding Engineer Publishing Co., 1943

[21] Cary, H. B., *Modern Welding Technology Third Edition*, Prentice Hall Inc, 1994

[22] Althouse, A. D., *Modern Welding*, The Goodheart-Willcox Company, Inc, 2004

[23] Kalpakjian S., *Manufacturing Processes for Engineering Materials*, Addison-Wesley Publishing Company, 1985

[24] Allen C. *et al*, *Evaluation of friction spot welds in aluminum alloys*, 2005 SAE World Congress, 2005-01-1252, April 11-14, 2005

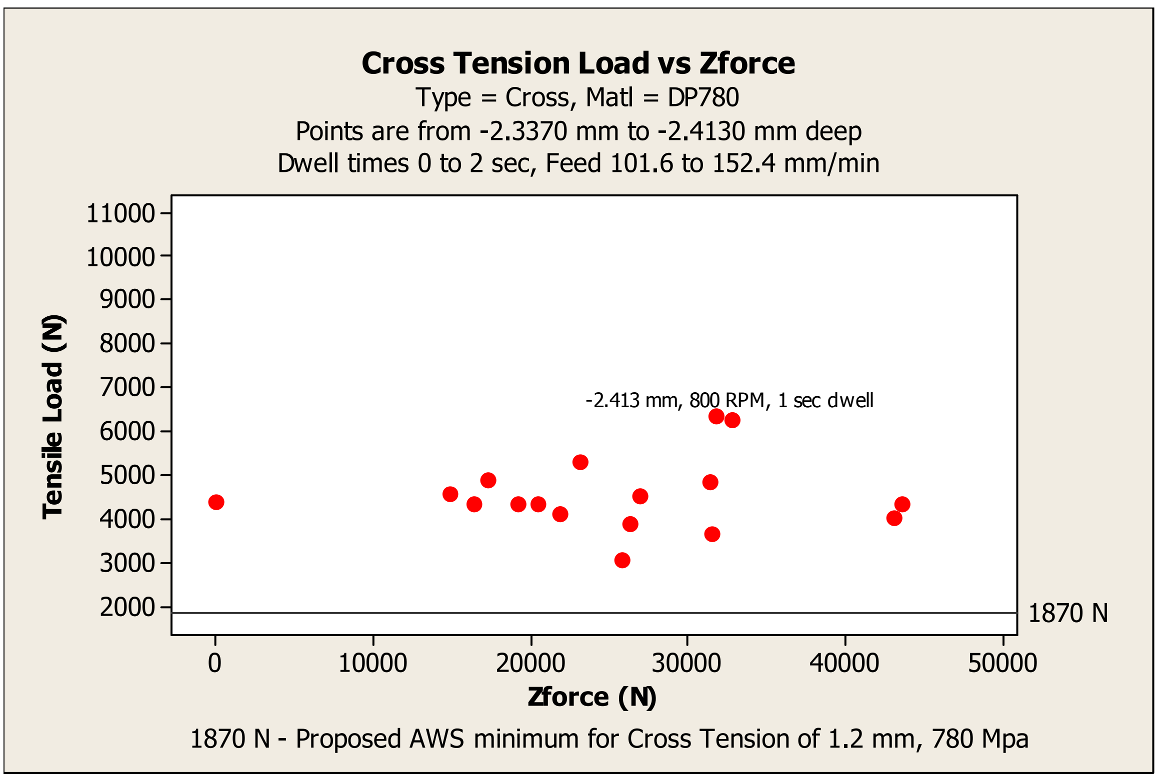
[25] Pan, T. *et al*, *Friction-Stir Spot Welding of Advanced High-Strength Steel*, 2006, www.autosteel.org, accessed 6/5/2006

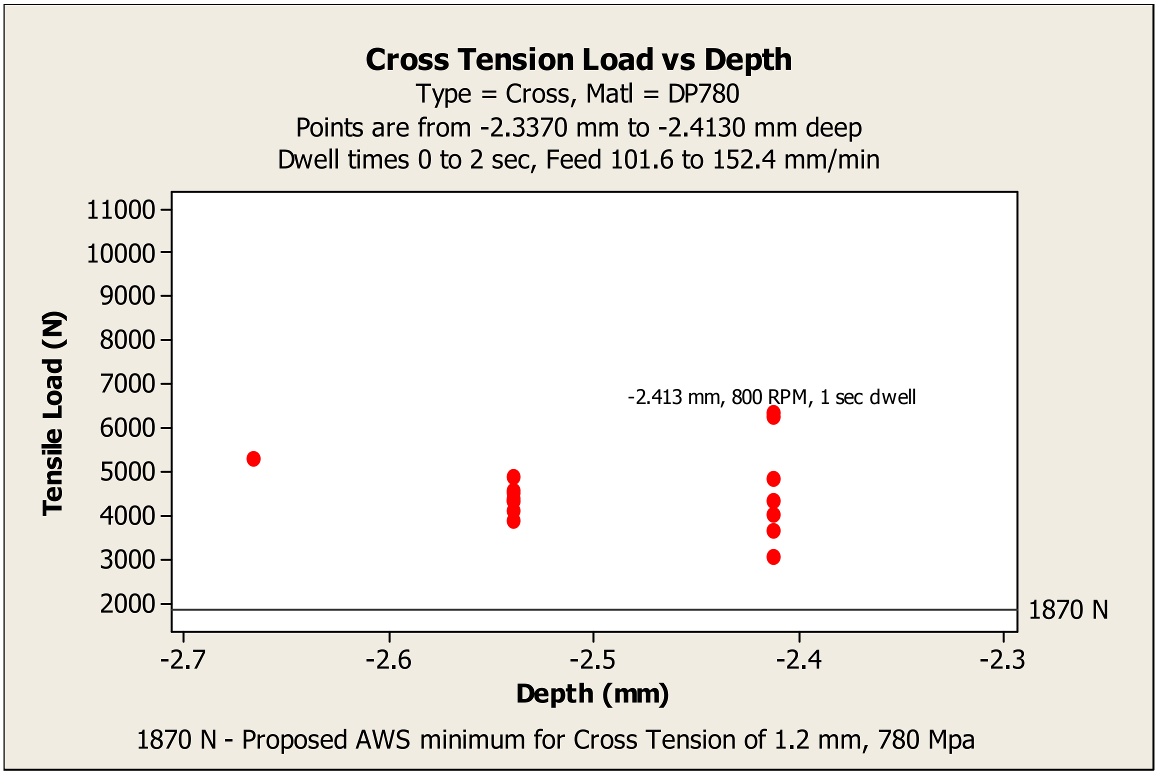
[26] Awang M. *et al*, *Thermo-Mechanical Modeling of friction stir spot welding (FSSW) process: Use of an Explicit Adaptive Meshing Scheme*, 2005-01-1251, 2005 SAE World Congress, April 11-14, 2005

[27] Grant, G. *et al*, *The formability of friction stir welds in automotive stamping environments*, 2005 SAE World Congress, 2005-01-1258, April 11-14 2005

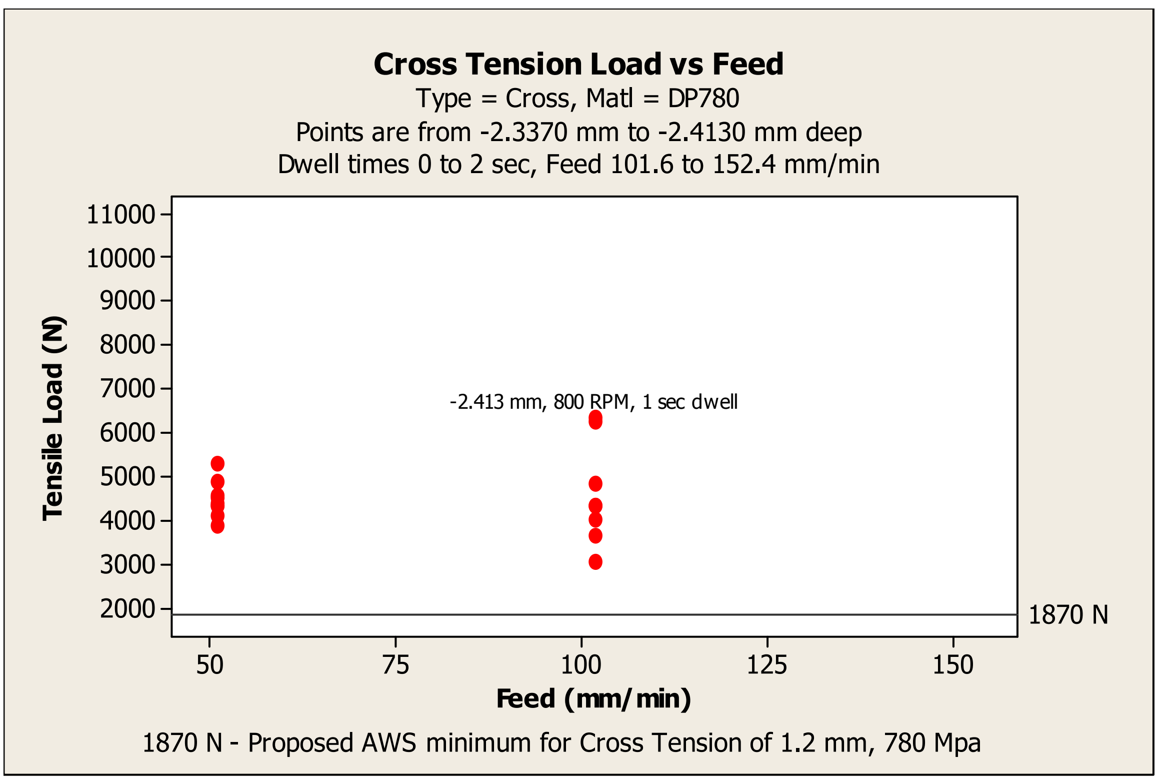
[28] Weman, K., *Welding Processes Handbook*, CRC Press, 2003

7 Appendix

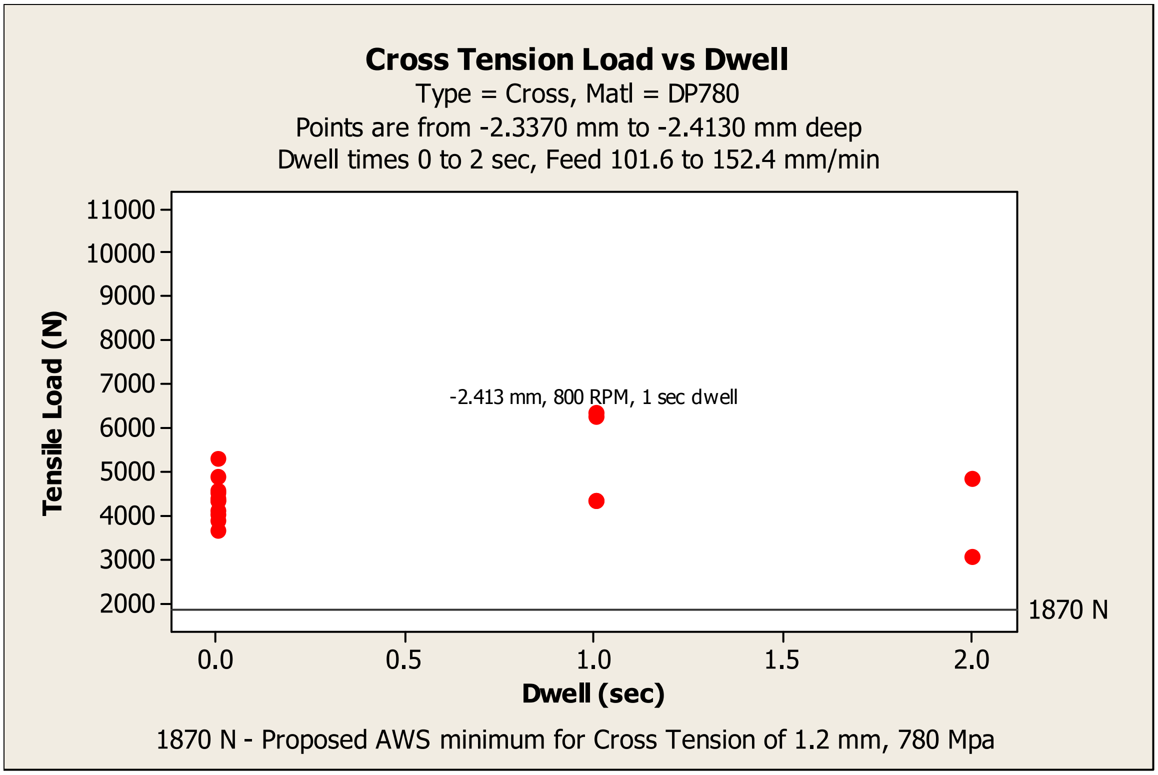

Cross Tension Load vs Zforce
Type = Cross, Matl = DP780
Points are from -2.3370 mm to -2.4130 mm deep
Dwell times 0 to 2 sec, Feed 101.6 to 152.4 mm/min
Tensile Load (N)
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
-2.413 mm, 800 RPM, 1 sec dwell
1870 N
0
10000
20000
30000
40000
50000
Zforce (N)
1870 N - Proposed AWS minimum for Cross Tension of 1.2 mm, 780 Mpa

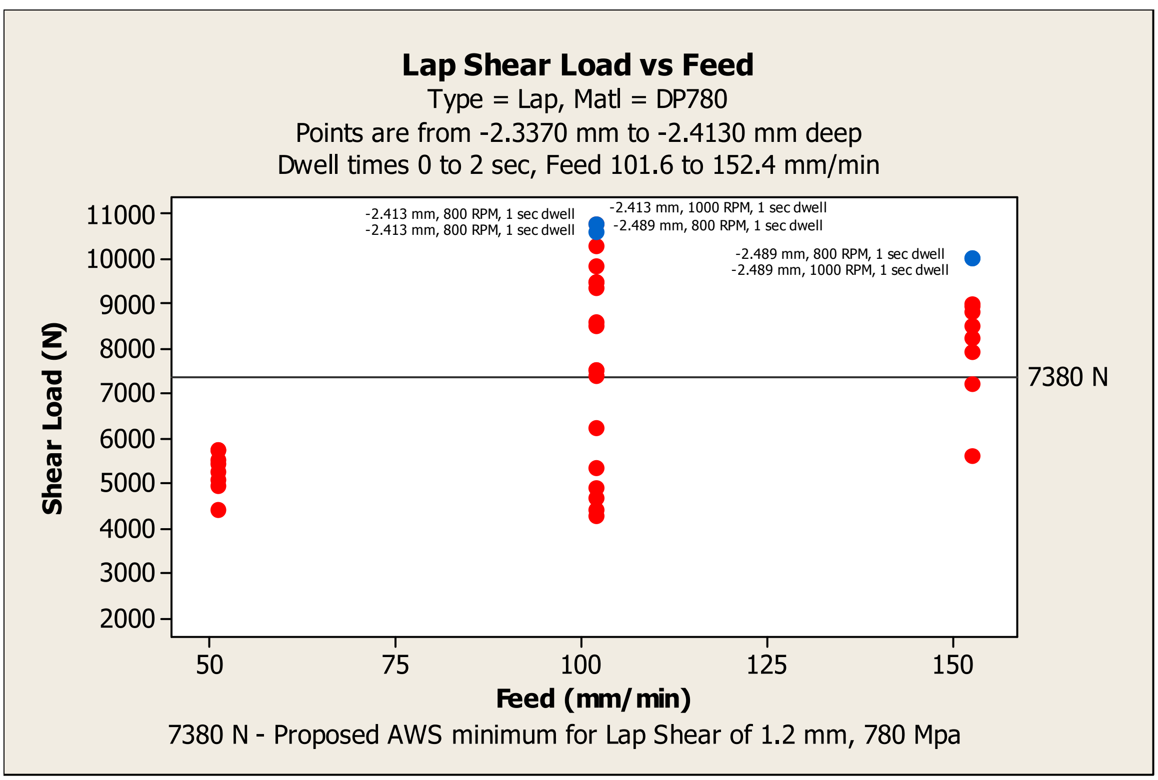


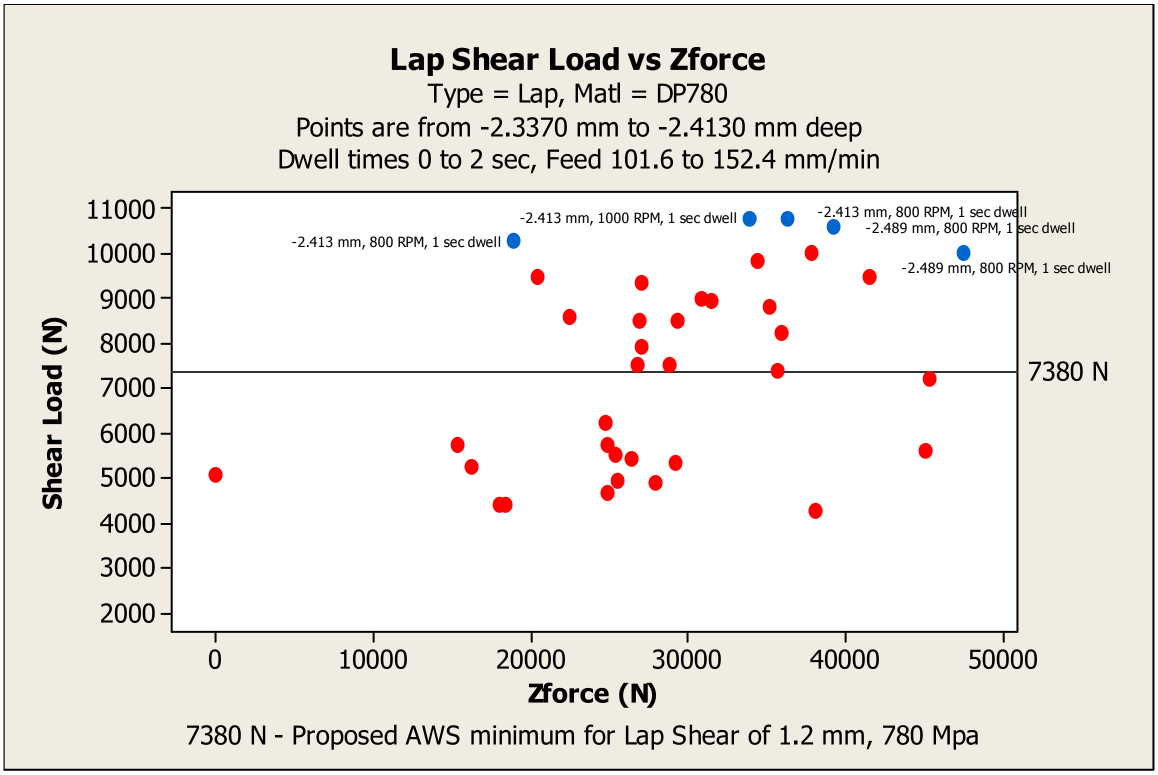
Cross Tension Load vs Depth
Type = Cross, Matl = DP780
Points are from -2.3370 mm to -2.4130 mm deep
Dwell times 0 to 2 sec, Feed 101.6 to 152.4 mm/min
Tensile Load (N)
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
-2.413 mm, 800 RPM, 1 sec dwell
1870 N
-2.7
-2.6
-2.5
-2.4
-2.3
Depth (mm)
1870 N - Proposed AWS minimum for Cross Tension of 1.2 mm, 780 Mpa

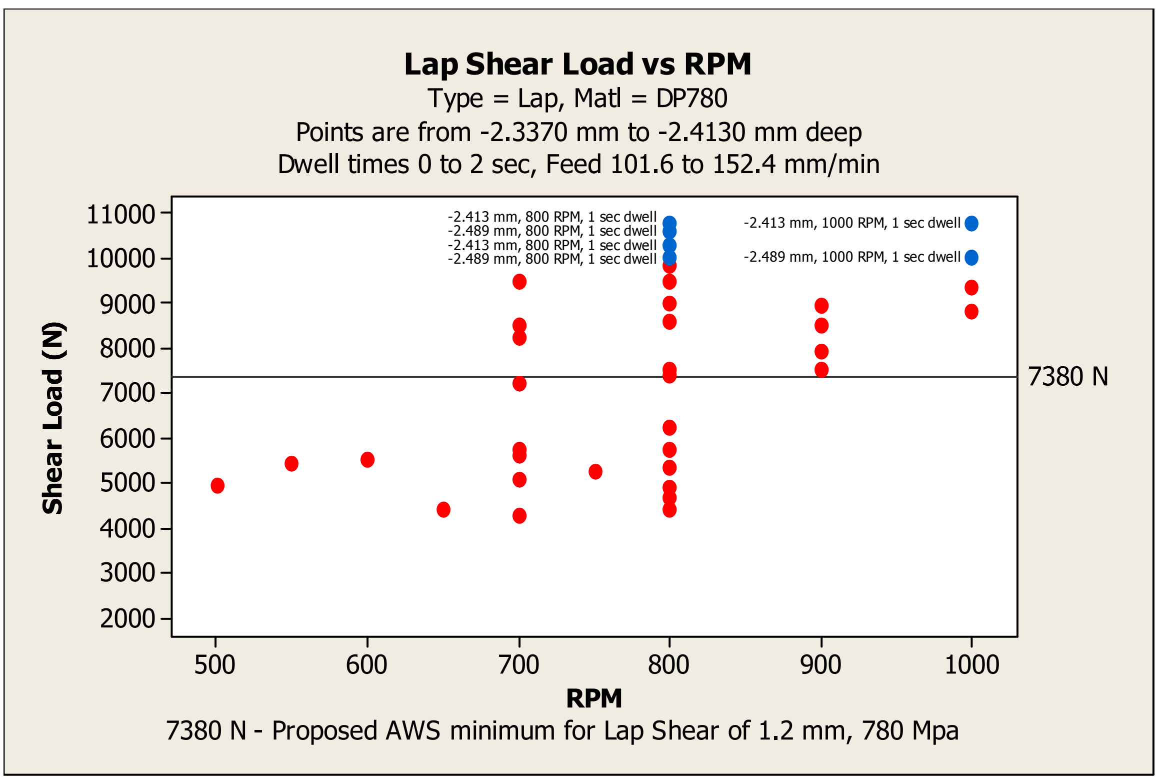


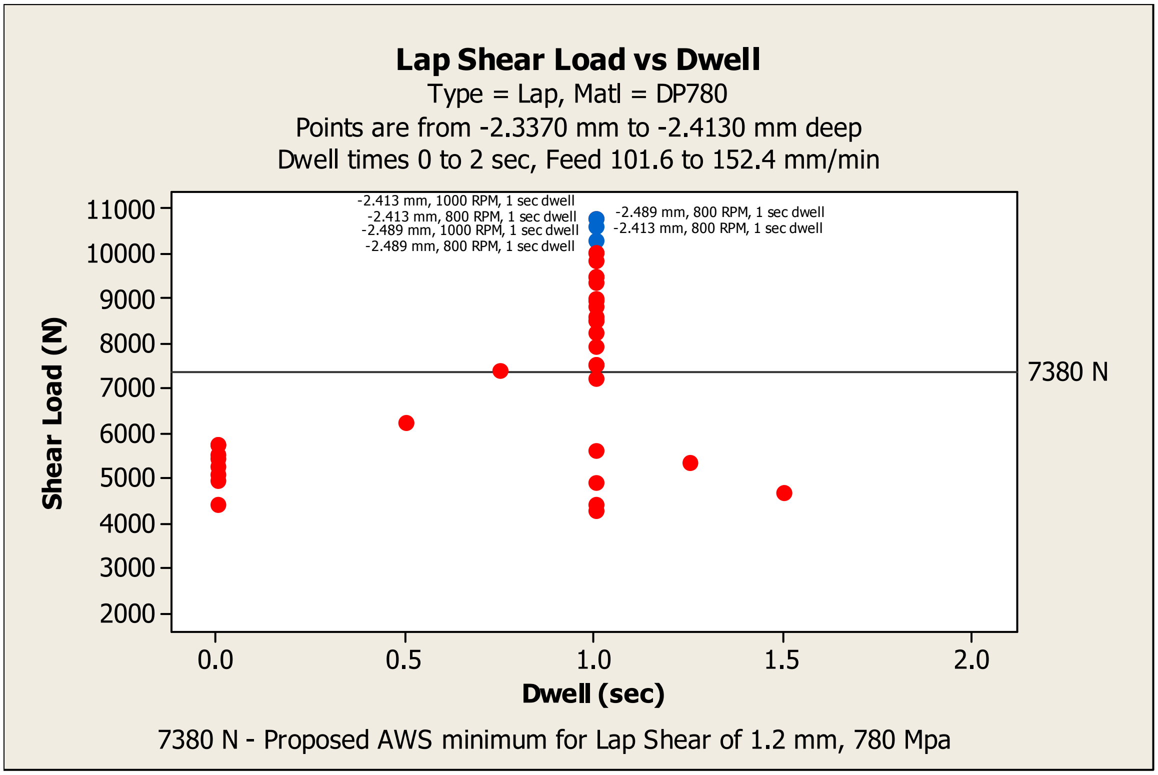
Cross Tension Load vs Feed
Type = Cross, Matl = DP780
Points are from -2.3370 mm to -2.4130 mm deep
Dwell times 0 to 2 sec, Feed 101.6 to 152.4 mm/min
Tensile Load (N)
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
-2.413 mm, 800 RPM, 1 sec dwell
1870 N
50
75
100
125
150
Feed (mm/min)
1870 N - Proposed AWS minimum for Cross Tension of 1.2 mm, 780 Mpa

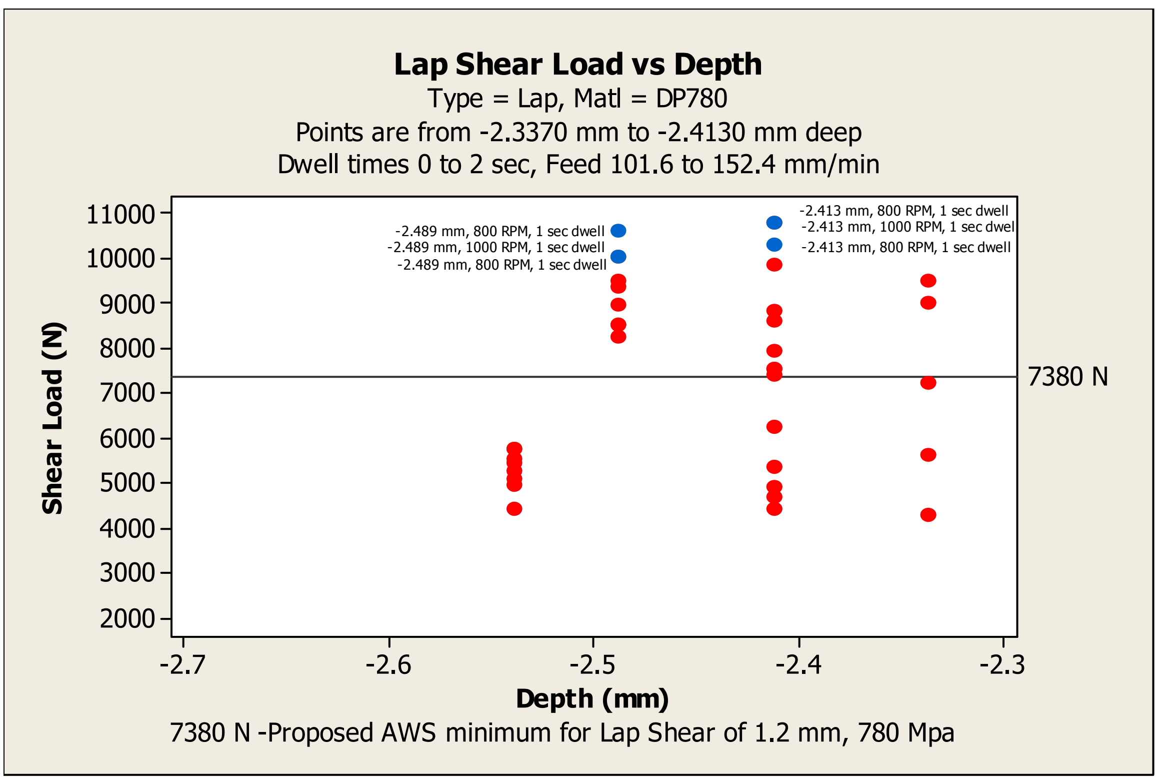

Cross Tension Load vs Dwell
Type = Cross, Matl = DP780
Points are from -2.3370 mm to -2.4130 mm deep
Dwell times 0 to 2 sec, Feed 101.6 to 152.4 mm/min
Tensile Load (N)
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
-2.413 mm, 800 RPM, 1 sec dwell
1870 N
0.0
0.5
1.0
1.5
2.0
Dwell (sec)
1870 N - Proposed AWS minimum for Cross Tension of 1.2 mm, 780 Mpa


Lap Shear Load vs Feed
Type = Lap, Matl = DP780
Points are from -2.3370 mm to -2.4130 mm deep
Dwell times 0 to 2 sec, Feed 101.6 to 152.4 mm/min
Shear Load (N)
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
-2.413 mm, 800 RPM, 1 sec dwell
-2.413 mm, 800 RPM, 1 sec dwell
-2.413 mm, 1000 RPM, 1 sec dwell
-2.489 mm, 800 RPM, 1 sec dwell
-2.489 mm, 800 RPM, 1 sec dwell
-2.489 mm, 1000 RPM, 1 sec dwell
7380 N
50
75
100
125
150
Feed (mm/min)
7380 N - Proposed AWS minimum for Lap Shear of 1.2 mm, 780 Mpa


Lap Shear Load vs Zforce
Type = Lap, Matl = DP780
Points are from -2.3370 mm to -2.4130 mm deep
Dwell times 0 to 2 sec, Feed 101.6 to 152.4 mm/min
Shear Load (N)
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
0
10000
20000
30000
40000
50000
Zforce (N)
-2.413 mm, 1000 RPM, 1 sec dwell
-2.413 mm, 800 RPM, 1 sec dwell
-2.489 mm, 800 RPM, 1 sec dwell
-2.413 mm, 800 RPM, 1 sec dwell
-2.489 mm, 800 RPM, 1 sec dwell
7380 N
7380 N - Proposed AWS minimum for Lap Shear of 1.2 mm, 780 Mpa


Lap Shear Load vs RPM
Type = Lap, Matl = DP780
Points are from -2.3370 mm to -2.4130 mm deep
Dwell times 0 to 2 sec, Feed 101.6 to 152.4 mm/min
Shear Load (N)
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
500
600
700
800
900
1000
RPM
-2.413 mm, 800 RPM, 1 sec dwell
-2.489 mm, 800 RPM, 1 sec dwell
-2.413 mm, 800 RPM, 1 sec dwell
-2.489 mm, 800 RPM, 1 sec dwell
-2.413 mm, 1000 RPM, 1 sec dwell
-2.489 mm, 1000 RPM, 1 sec dwell
7380 N
7380 N - Proposed AWS minimum for Lap Shear of 1.2 mm, 780 Mpa


Lap Shear Load vs Dwell
Type = Lap, Matl = DP780
Points are from -2.3370 mm to -2.4130 mm deep
Dwell times 0 to 2 sec, Feed 101.6 to 152.4 mm/min
-2.413 mm, 1000 RPM, 1 sec dwell
-2.413 mm, 800 RPM, 1 sec dwell
-2.489 mm, 1000 RPM, 1 sec dwell
-2.489 mm, 800 RPM, 1 sec dwell
-2.489 mm, 800 RPM, 1 sec dwell
-2.413 mm, 800 RPM, 1 sec dwell
Shear Load (N)
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
7380 N
0.0
0.5
1.0
1.5
2.0
Dwell (sec)
7380 N - Proposed AWS minimum for Lap Shear of 1.2 mm, 780 Mpa


Lap Shear Load vs Depth
Type = Lap, Matl = DP780
Points are from -2.3370 mm to -2.4130 mm deep
Dwell times 0 to 2 sec, Feed 101.6 to 152.4 mm/min
-2.489 mm, 800 RPM, 1 sec dwell
-2.489 mm, 1000 RPM, 1 sec dwell
-2.489 mm, 800 RPM, 1 sec dwell
-2.413 mm, 800 RPM, 1 sec dwell
-2.413 mm, 1000 RPM, 1 sec dwel
-2.413 mm, 800 RPM, 1 sec dwell
Shear Load (N)
11000
10000
9000
8000
7000
6000
5000
4000
3000
2000
7380 N
-2.7
-2.6
-2.5
-2.4
-2.3
Depth (mm)
7380 N -Proposed AWS minimum for Lap Shear of 1.2 mm, 780 Mpa

Sample	Type	Tool	Mat'l	Feed	Dwell	RPM	Depth	Zforce	Tensile
1	Cross	PCBN Standard - .020" grind	DP780	4	1	800	-0.100	9800	976
2	Cross	PCBN Standard - .020" grind	DP780	4	1	800	-0.095	7362	1412
3	Cross	PCBN Standard - .020" grind	DP780	4	2	800	-0.095	7038	1096
4	Cross	PCBN Standard - .020" grind	DP780	4	0	800	-0.095	7086	826
5	Cross	PCBN Standard - .020" grind	DP980	4	0	800	-0.095	6091	760
6	Cross	PCBN Standard - .020" grind	DP980	4	1	800	-0.095	6876	740
7	Cross	PCBN Standard - .020" grind	DP980	4	2	800	-0.095	5242	626
8	Cross	PCBN Standard - .020" grind	DP980	4	0	800	-0.095	8928	552
9	Cross	PCBN Standard - .030" grind	DP780	4	0	800	-0.095	9678	903
10	Cross	PCBN Standard - .030" grind	DP780	4	1	800	-0.095	4579	978
11	Cross	PCBN Standard - .030" grind	DP780	4	2	800	-0.095	5803	690
12	Cross	PCBN Standard - .030" grind	DP980	4	2	800	-0.095	8510	700
13	Cross	PCBN Standard - .030" grind	DP980	4	1	800	-0.095	8311	586
14	Cross	PCBN Standard - .030" grind	DP980	4	0	800	-0.095	7268	630
15	Lap	PCBN Standard - .020" grind	DP980	6	0	800	-0.095	9679	540
16	Lap	PCBN Standard - .020" grind	DP780	4	1	800	-0.095	6276	1107
17	Lap	PCBN Standard - .020" grind	DP780	4	0.5	800	-0.095	5573	1403
18	Lap	PCBN Standard - .020" grind	DP780	4	1.5	800	-0.095	5580	1056
19	Lap	PCBN Standard - .020" grind	DP780	4	1.25	800	-0.095	6554	1209
20	Lap	PCBN Standard - .020" grind	DP780	4	1	800	-0.095	8174	2434
21	Lap	PCBN Standard - .020" grind	DP780	4	1	800	-0.095	4129	993
22	Lap	PCBN Standard - .020" grind	DP780 EG	4	1	800	-0.105	8867	1371
23	Lap	PCBN Standard - .020" grind	DP780 EG	4	1	800	-0.095	5694	471
24	Lap	PCBN Standard - .020" grind	DP780	4	0.75	800	-0.095	8009	1668
25	Lap	PCBN Standard - .020" grind	DP780	4	1	800	-0.095	7799	-
26	Lap	PCBN Standard - .020" grind	DP780	4	1	800	-0.098	8828	2389

27	Lap	PCBN Standard - .020" grind	DP780	4	1	800	-0.092	4578	2136
28	Lap	PCBN Standard - .020" grind	DP780	6	1	800	-0.098	10682	2256
29	Lap	PCBN Standard - .020" grind	DP780	6	1	800	-0.092	6929	2032
30	Lap	PCBN Standard - .020" grind	DP780	4	1	700	-0.098	9325	2136
31	Lap	PCBN Standard - .020" grind	DP780	4	1	700	-0.092	8572	969
32	Lap	PCBN Standard - .020" grind	DP780	6	1	700	-0.098	6583	1917
33	Lap	PCBN Standard - .020" grind	DP780	6	1	700	-0.092	10194	1626
34	Lap	PCBN Standard - .020" grind	DP780	4	1	800	-0.095	7727	2221
35	Lap	PCBN Standard - .020" grind	DP780	4	1	800	-0.095	4244	2319
36	Lap	PCBN Standard - .020" grind	DP780	6	1	700	-0.098	8084	1863
37	Lap	PCBN Standard - .020" grind	DP780	6	1	700	-0.092	10124	1266
38	Lap	PCBN Standard - .020" grind	DP780	4	1	900	-0.098	6055	1923
39	Lap	PCBN Standard - .020" grind	DP780	6	1	900	-0.098	7083	2020
40	Lap	PCBN Standard - .020" grind	DP780	4	1	900	-0.095	6025	1697
41	Lap	PCBN Standard - .020" grind	DP780	6	1	900	-0.095	6062	1791
42	Lap	PCBN Standard - .020" grind	DP780	4	1	1000	-0.098	6067	2114
43	Lap	PCBN Standard - .020" grind	DP780	6	1	1000	-0.098	8517	2259
44	Lap	PCBN Standard - .020" grind	DP780	4	1	1000	-0.095	7624	2434
45	Lap	PCBN Standard - .020" grind	DP780	6	1	1000	-0.095	7906	1989
46	Lap	PCBN Standard - .020" grind	DP780	4	1	800	-0.095	9267	-
47	Lap	PCBN Standard - .020" grind	DP780	4	1	800	-0.095	5036	1936
48	Lap	PCBN Standard - .020" grind	DP780	4	1	800	-0.095	6477	1700
49	Cross	PCBN Standard - .020" grind	DP780	4	1	800	-0.095	7133	-
50	Lap	PCBN Standard - .020" grind	DP980	4	1	800	-0.095	4789	1056
51	Lap	PCBN Standard - .020" grind	DP980	4	0	800	-0.095	7384	914
52	Lap	PCBN Standard - .020" grind	DP980	4	1	800	-0.098	8547	1500
53	Lap	PCBN Standard - .020" grind	DP980	4	0	800	-0.098	8846	1080
54	Lap	PCBN Standard - .020" grind	DP780 EG	4	1	800	-0.101	8766	946

55	Lap	PCBN Standard - .020" grind	DP780 EG	4	1	800	-0.098	7030	833
56	Lap	PCBN Standard - .020" grind	DP780 EG	4	1	800	-0.104	8539	1568
57	Lap	PCBN Standard - .020" grind	DF140T	4	1	800	-0.104	9262	1885
58	Lap	PCBN Standard - .020" grind	DF140T	4	1	1000	-0.104		2212
59	Lap	PCBN Standard - .020" grind	DP780 EG	4	1	900	-0.107	11351	
60	Lap	PCBN Standard - .020" grind	DP780 EG	6	1	900	-0.107	8710	
61	Lap	PCBN Standard - .020" grind	DP780 EG	4	1	900	-0.109	8061	
62	Lap	PCBN Standard - .020" grind	DP780 EG	6	1	900	-0.109	8307	
67	Lap	PCBN Standard - .020" grind	DP780 EG	4	1	800	-0.110	7656	1401
68	Lap	PCBN Standard - .020" grind	DP780 EG	4	1	800	-0.110	14248	1406
69	Lap	PCBN Standard - .020" grind	DP78 0EG	4	1	800	-0.120	7484	1083
70	Lap	PCBN Standard - .020" grind	DP780 EG	4	1	1000	-0.120	10004	897
71	Lap	PCBN Standard - .020" grind	DP78 0EG	4		1000	-0.107	6368	1506

NA	Cross	PCBN Standard	DP780	2	0	500	-0.100	5900	880
NA	Cross	PCBN Standard	DP780	2	0	550	-0.100	6050	1024
NA	Cross	PCBN Standard	DP780	2	0	600	-0.100	4300	974
NA	Cross	PCBN Standard	DP780	2	0	650	-0.100	4900	927
NA	Cross	PCBN Standard	DP780	2	0	700	-0.100	3870	1099
NA	Cross	PCBN Standard	DP780	2	0	750	-0.100	3670	977
NA	Cross	PCBN Standard	DP780	2	0	800	-0.100	3320	1030
NA	Cross	PCBN Standard	DP780	2	0	800	-0.100	-	985
NA	Cross	PCBN Standard	DP780	2	0	800	-0.105	5200	1200
NA	Lap	PCBN Standard	DP780	2	0	500	-0.100	5742	1116
NA	Lap	PCBN Standard	DP780	2	0	550	-0.100	5940	1227
NA	Lap	PCBN Standard	DP780	2	0	600	-0.100	5700	1248
NA	Lap	PCBN Standard	DP780	2	0	650	-0.100	4050	991
NA	Lap	PCBN Standard	DP780	2	0	700	-0.100	5600	1300
NA	Lap	PCBN Standard	DP780	2	0	700	-0.100	-	1147
NA	Lap	PCBN Standard	DP780	2	0	750	-0.100	3660	1183
NA	Lap	PCBN Standard	DP780	2	0	800	-0.100	3450	1300