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High Speed Friction Stir Spot Welding on DP 980 Steel:

Joint Properties and Tool Wear

Nathan Saunders

A thesis submitted to the faculty of
Brigham Young University
in partial fulfillment of the requirements for the degree of

Master of Science

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ABSTRACT

High Speed Friction Stir Spot Welding on DP 980 Steel:
Joint Properties and Tool Wear

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With the desire to improve passenger safety and fuel efficiency, Ultra High Strength Steels (UHSS) have been developed for use in the automotive industry. UHSS are high strength steels with high ductility and strength. DP 980 is one of these UHSS being applied in automobile manufacturing. DP 980 is difficult to join with Resistance Spot Welding (RSW) because of the high carbon content and alloying in this material. The weld becomes brittle when it solidifies during the welding process.

With the desire and motivation of widely using UHSS, new welding processes are needed to be developed in order to effectively join DP 980. Friction Stir Spot Welding (FSSW) is a developing welding process aimed to replace RSW in the automotive industry because of its ability to join materials at a lower temperature.

Currently the welding loads of the tools are higher than 2000 pounds, ranging from 3,000 to 5,000 pounds, which exceeds the limit of the welding robots in the automotive factories. It is proposed that the welding loads can be reduced by increasing the spindle speed of the FSSW tool. Other focuses in the research include increasing the life of the tool and developing acceptable welding parameters for High Speed FSSW.

The experimental work done for this thesis provided support that weld strength can be obtained at levels above the acceptable standard for DP 980 material (greater than 2400 pound lap shear fracture load for 1.2 mm material) while keeping the vertical load on the welding machine spindle below 2000 lbs.

Keywords: Nathan Saunders, high speed friction stir spot welding, DP 980, PCBN, ultra high strength steel

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1 INTRODUCTION

1.1 Purpose and Motivation for Study

With the desire to lighten the frame while keeping its strength, Ultra High Strength Steels (UHSS) have been developed for use in the automotive industry. Because of their higher strength-to-weight ratio than the traditional steels in automobiles, UHSS aids in complying with the strict safety regulations for the automobiles, while lowering the weight of the frame. Joining UHSS has become an issue because of the microstructure, and new joining methods are needed.

Friction Stir Spot Welding (FSSW) has been a topic of study in aluminum alloys and is beginning to gain popularity in the steel alloys. It has proven to reduce the manufacturing cost in aluminum alloys (Arbergast 2006). Research has been performed on FSSW of UHSS alloys with spindle speeds below 2000 RPM. However with the current welding parameters, the welding tools for FSSW have not been able to withstand the desired number of welds. Other problems include the tool wearing quickly and the welding loads being higher than the FSSW machines can handle.

The motivation of this study is in the potential of enabling the wide use of UHSS in the automotive industry. UHSS will help the automotive industry meet the higher standards of lighter and stronger automobiles. It is currently in use, but is joined with difficulty using Resistance Spot Welding (RSW). Upon successful results, FSSW can be adapted into the automotive industry as the common practice in joining UHSS.

1.2 Ultra High Strength Steels

UHSS have been developed to be used in the automotive industry for the purpose of reducing the weight of the automobile without jeopardizing the strength of the frame. DP 980 is one alloy of steel that has been created for this purpose. It is a dual-phase, martensitic and ferritic steel with an ultimate tensile strength of 990 Mpa and has an elongation. The material composition can be found in Table 1-1.

Table 1-1: Composition of Alloys, wt%

Material	C	Mn	P	S	Si	Cr
DP 980	0.150	1.440	0.011	0.007	0.320	0.020

Because of its material properties, fusion and resistance welding cause the weld joint to become brittle during the welding thermal cycles. In laser welding, the Heat Affected Zone (HAZ) becomes soft reducing its formability and fatigue strength (Farabi, Chen and Zhou 2010) (Sreenivasan, et al. 2008). With cyclical loading, the weld joints can then crack and fail. In FSSW, the base material does not reach melting temperature. This allows for a smaller heat cycle while joining the metals together. With the lower heat input into the weld of FSSW when compared to RSW, the end result of the weld material is tougher and less brittle microstructure.

1.3 Friction Stir Spot Welding Tools

Polycrystalline Cubic Boron Nitride (PCBN) tools have been developed for FSSW of UHSS. It is a hard synthetic material that is used in friction welding and also machining hardened steels and cast irons. In previous tests, at low spindle speeds, hard PCBN tools would crack and break during the FSSW welding process.

A mixture of tungsten and PCBN tool is needed to withstand the welding forces. Tungsten PCBN tools are softer and tougher than PCBN tools which allows them to withstand the axial loads of FSSW. The problem is that the tools will wear quickly and not withstand the needed cycles to produce the desired number of welds. The axial loads need to be reduced in order to use the hard PCBN tools and increase the life of the welding tool.

1.4 Resistance Spot Welding in Ultra High Strength Steels

Resistance Spot Welding (RSW) is a process where electricity is passed through copper electrodes, melting the base material to form a weld. RSW is currently the most used welding process on car frames in the automotive industry (Khan, et al. 2007). The RSW process causes a rapid high temperature liquefying and solidification cycles causing a brittle microstructure in UHSS alloys. This brittle microstructure commonly results in solidification cracking in the weld nugget.

1.5 Problem Statement

This research is a continuation of past research conducted on FSSW of UHSS. Past research has focused on adjusting and researching process parameters and tool design to achieve desired weld strength and tool life. This work has resulted in tensile strengths that are adequate for the production setting, but the tool life is not to a level that is applicable for production. Also the axial load required to achieve the desired strength in the weld is larger than the welding robots can withstand.

This research will be focused on reducing the welding load to less than 2000 pounds, increasing the tool life, and developing welding parameters to produce a weld in DP 980 that is acceptable for production parts.

1.6 Hypotheses

The hypotheses for this research are as follows:

Hypothesis 1: High spindle speed (6000rpm) will reduce loads on the welding machine to less than 2000 lbs.

Hypothesis 2: PCBN tool will be able to withstand welding loads at high spindle speed without premature cracking before 100 spot welds

Hypothesis 3: PCBN tool will produce acceptable welds for over 5,000 welds

1.7 Methodology

The material that will be used in this testing is 1.2mm thick DP 980 steel that has been sheared into uniform dimensions. Because high speed FSSW is a relatively new concept, a systematic approach to finding the best settings to make an acceptable weld per American Welding Society (AWS) specifications will be performed.

Once the acceptable welding parameters are found, wear testing will be performed on the tool. The tool geometry will be checked after a set of 96 welds wear test welds, and 4 individual samples for inspection have been completed. Individual lap shear and metallography samples will be welded to analyze when tool performance declines.

Welds will be performed on the Fadal mill with tool spindle speed between 2,500 and 8,000 rpm. Data will be collected using a welding load cell fixture, Instron tensile testing machine, and metallography samples will be polished and viewed at Brigham Young University.

1.8 Delimitations

This study will is limited to FSSW on DP 980 Steel in thickness of 1.2mm. It will also is limited to wear testing on the PCBN tools. It will not cover FSSW on any other base or tool material. Testing will be performed on the same machine to reduce variability between machines.

1.9 Definition of Terms

DP – Dual phase steel consisting of a martensitic and ferritic microstructure

DP 980 – A dual phased steel with an ultimate tensile strength of 990 Mpa. (Nikoosohbat, et al. 2010)

Heat Affected Zone (HAZ) – The area of metal that changes material properties between the thermo mechanically affected zone and the base material that if affected by the heat of the welding process

Feed Rate – The speed, measured in inches per minute, at which the welding tools travels into the base material.

Friction Stir Spot Welding (FSSW) – A friction welding process performed by plunging a tool into both layers of metal and then retracted

Fusion Welding – Welding processes that rely on melting the base material to create a welded joint.

Fusion Zone – The area in the weld where the two pieces of material have formed a bond

Lap Shear Strength – the strength of a welded lap joint pulled in shear.

Polycrystalline Cubic Boron Nitride (PCBN) – an ultra-hard synthetic material used in friction stir spot welding tools and machining tools. PCBN is created by applying high temperatures and pressures to Cubic Boron Nitride, which aids in forming a polycrystalline cubic crystal structure.

RPM – Revolutions per minute. This is the spindle speed of the welding tool during the welding cycle.

Thermo Mechanically Affected Zone (TMAZ) –the portion of a friction weld that is affected by heat and stirring of the welding tool on the edge of the stir zone of the weld.

Welding parameters – A set of parameters that adjust the feed rate, plunge depth, and spindle speed of the welding tool to produce a weld.

2 LITERATURE REVIEW

2.1 Introduction

Friction Stir Spot Welding (FSSW) is a relatively new topic in the welding industry. Most research in FSSW has been performed with aluminum and magnesium alloys. Little information has been published on FSSW steel and its different alloys. There has been some research done on DP 600, an Advanced High Strength Steel (AHSS) alloy, and hot stamped boron steels in comparing the process to Resistance Spot Welding (RSW). Little research has been done with DP 980 in both FSSW and RSW, and no research has been done on high speed FSSW.

The literature that will be reviewed in this study will focus on studies involving FSSW of aluminum and steel alloys and how these results compare with RSW of those same alloys. It will also include a study of the current welding processes of DP 980.

2.2 Friction Stir Spot Welding

Currently there are two methods of FSSW, refill and plunge FSSW. Refill FSSW involves using a tool that has a separate rotating pin and shoulder actuation system. The pin is first plunged into the material, and the shoulder captures the material that was displaced by the pin while the pin is welding the two plates of material together. When the pin retracts, the material captured by the shoulder is then forced back into the weld joint, leaving the material without a divot from the tool (Arbergast 2006). This process has successfully been used in welding aluminum alloys.

Plunge FSSW uses a similar tool as friction stir welding. The tool has a fixed rotating pin attached to the shoulder of the tool, which is plunged into both layers of metal and then retracted. This leaves a pull out hole as shown in Figure 2-1, but the weld has sufficient strength for its applications (Arbergast 2006).

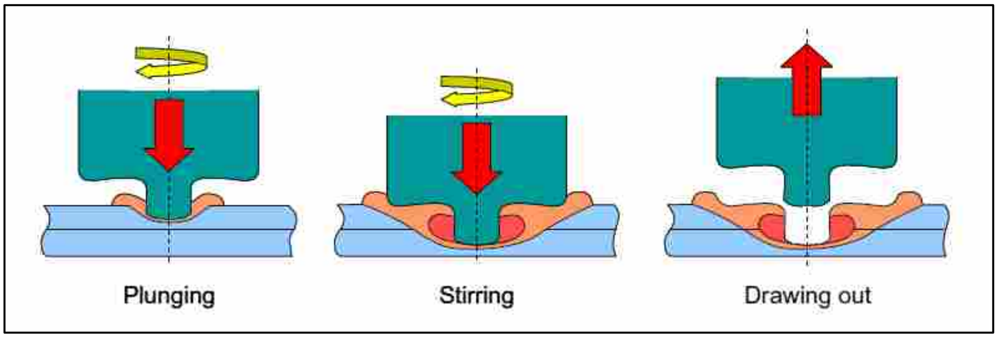

Figure 2-1: Three Stages of the FSSW Process (Hovanski, Santella and Grant 2007)

2.3 Benefits of Friction Stir Spot Welding in Aluminum

Replacing RSW with FSSW in aluminum alloys has great benefits in regards to saving energy and tooling costs. It takes more electricity to RSW aluminum alloys as compared to steel alloys. Aluminum alloys have a very low resistance as compared to steel. Electricity will pass through the aluminum weld zone with less resistance than steel alloys. The lower resistance creates less heat when the electricity passes through the two plates. In order to create enough heat to form an acceptable weld nugget, more electricity has to be applied to the aluminum samples than the steel samples of similar thickness and size.

A FSSW machine uses less electricity per weld when compared to RSW in aluminum alloys. Mazda reported production savings when they switch from RSW to FSSW on the car doors of the Mazda RX-8 car doors (Arbergast 2006). The energy savings in just the welding process would yield savings in utility costs in a production factory replaced RSW with FSSW in aluminum alloys.

Tooling costs are also lower in FSSW aluminum than that of the tooling required to FSSW steel alloys. Aluminum can be welded using a hardenable steel or tungsten alloy tool material (Mitlin, et al. 2006) (Yuan, et al. 2011). These materials are considerably less expensive than the PCBN tooling used in FSSW of DP980. The softness of aluminum, when compared to steel alloys, allows for it to be friction stir welded together relatively easily. This proves cost effective when the tooling costs are low and the number of welds that can be welded with a tool is high. These two factors decrease the cost of each weld.

DP 980 takes more force to weld together, reducing the number of welds that can be welded per tool because of cracking and wear issues that come from the welding process. The cost of the tool is higher than the aluminum tools to compensate for the difference in base materials. The savings have been proved in the FSSW of aluminum alloys, whereas FSSW of steel needs more research and advancement in order to be cost effective.

2.4 Resistance Spot Welding of Advanced-High-Strength-Steel

RSW and FSSW are the leading canidates for spot welding AHSS (Khan, et al. 2007). RSW has been used for years as the primary sheet metal joining practice in the auto industry. The RSW robots are already in the assembly line and changing them over would be a large cost to the company. As the auto industries have shifted to the use of AHSS and Ultra High Strength

Steels (UHSS), the current welding process has been reviewed to ensure that the car frames still has the strength needed in the welds.

From a comparative study of RSW and FSSW on DP 600 it was noted that the microstructure of the welded samples with the RSW process resulted in a hard martensitic grain structure. The base material has a hardness that ranged from 150-200 HV, while the fusion zone has a harndess ranging above 350 HV (Khan, et al. 2007). This

RSW samples result in a harder microsture than that of FSSW. As a result, the material welded with RSW is more brittle, and is more prone to cracking (Khan, et al. 2007) than FSSW samples. In the quenching process of the weld, the grains initiate solidification from the outside diameter of the weld, and grow inward. In AHSS and UHSS, this leaves needle looking grains pointing to the center of the weld because of the carbon content and alloying found in the material. These grains, and grain boundies around the grain, acts as paths where cracks can propegate throught the center of the weld.

2.5 Friction Stir Spot Welding of Ultra-High-Strength-Steel

FSSW has its benefits over RSW when it comes to welding UHSS. FSSW has a lower heat cycle, peak temperature, and heating and cooling rates are lower than RSW (Santella, et al. 2010), which has a smaller effect on the microstructure of the base material. FSSW also avoids other welding defects such as porosity and voids in the weld. FSSW resulted in hardnesses lower than that of RSW with hardenss levels around the key hole right around 300 HV (Khan, et al. 2007).

One major issue found in FSSW of high strength steels is the formation of the hook in the Thermo-Mechanically Affected Zone (TMAZ). The hook is formed in the TMAZ where the two plates are not joined together. This portion of the weld is stirred into the TMAZ, and forms a hook as shown in Figure 2-2. This causes a stress riser that can crack and propagate through the weld zone, and cause failure to the spot weld (Hovanski, Santella and Grant 2007) (Feng, et al. 2009).

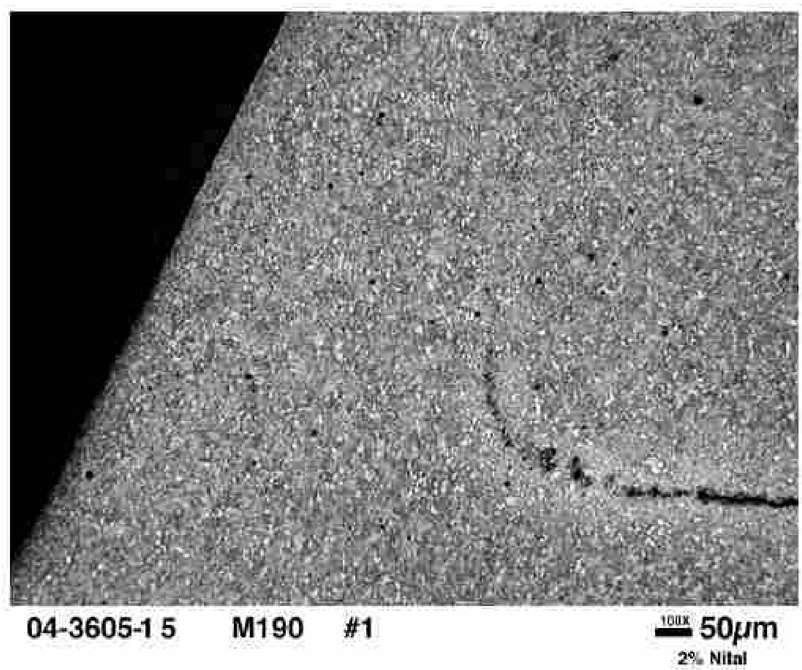

Figure 2-2: Image of Hook Formed from FSSW M190 Steel (Feng, et al. 2009)

FSSW is a solid state welding process, with the weld area not reaching melting temperatures. This reduces the thermal cycles in the material, allowing to form less martensite in the TMAZ. The heat input to the weld area, and the thermal cycles of the weld area are less than those samples welded by RSW (Santella, et al. 2010).

A study done on DP780 steels was conducted using four different PCBN tool geometries. Welding time, spindle speed, and plunge rate was altered throughout the study. The initial results showed that with all four tools that the lap shear stregth increased as the welding times was increased. The lap shear results also increased as the spindle speed was increased from 800 to 1600 rpm. Santella, et al. also concluded that they achieved the same result when they used a two staged plunge. This allowed them to have a short dwell at the bottom of the weld, while keeping pressure on the weld joint (Santella, et al. 2010).

In the above study, a cost analysis of tool life was conducted based on the amount of resistance spot welds that are performed on an automobile assembly line. The needed tool life of the PCBN tools in relation to the tool cost was calculated in order to make it useful in the production setting. Santella, et al. caclulated that if a PCBN tool cost $100, then it would need to last 26,000 welds in order to be the same price per weld as a RSW. Santella, et al. also state that the major obsicles for adapting FSSW into industry are reducing tool cost and increasing the duability of the tool. Other studies have shown that tool life and geometry needs to be further developed in order apply FSSW into a production setting (Hovanski, Santella and Grant 2007).

2.6 Welding Processes for DP 980

Rapid heating and quenching cycles of common fusion welding processes creates a hard and brittle martensitic microstructure in the fusion zone of DP 980 steels. This microstructure is prone to cracking with cyclic loading. In order to use this steel in the automotive industry, acceptable joining processes are needed to be developed. So far only the laser and RSW processes have published literature on welding DP 980.

2.6.1 Laser Welding of DP 980

A study for laser welding of DP 980 steels was conducted using two different types of lasers: A Diode and an Nd:YAG laser. This study included varying the travel speeds with the two lasers. The report reviewed the formability of the steel after it had been welded into butt joints. The results of this test were that with fast travel speeds and key hole resulted in the best formability after welding. This was because less heat was put into the material to perform the weld which resulted in a smaller Heat Affected Zone (HAZ) (Sreenivasan, et al. 2008).

The softening of the HAZ was the limiting factor in the formability of the DP 980 steel after welding. The outer edges of the HAZ were tempered from the weld, causing those portions of the material to be softer than both the weld and the base material. In this study, the outer edge of the HAZ was the location of failure in both the limiting dome height test and tensile test (Sreenivasan, et al. 2008). In these results, Sreenivasan et al. only shared the best process to weld DP 980 with lasers, and didn't specify whether laser welding met any codes, or if it is acceptable to use in industry.

Laser welding also affects the fatigue strength of DP 980 Steels. In a study conducted on the fatigue strength of laser welded DP 980 steels, the fatigue limit dropped approximately 100 MPa when compared to the fatigue limit of the base metal. In the study, the welded samples of DP 980 all failed in the softened HAZ, even when the stress amplitude was lowered (Farabi, Chen and Zhou 2010).

2.6.2 Resistance Spot Welding of DP 980

With resistance welding equipment in the production line, the auto industry would like to use the same equipment in joining the car frames. RSW produces a good surface finish, which is also desirable in the auto industry when welding parts that are visible to the end user (Khan, et al. 2007). The quality of the RSW is important to the safety and durability of the vehicles (Pouranvari and Marashi 2010). The mode of failure affects the strength of the weld, and ultimately the strength of the welded parts.

In a study conducted on RSW of DP 980, the failure method was discussed as the limiting factor of the strength of the weld. If the weld nugget pulls out of the base material, then the weld can carry higher loads. The weld is able to transmit higher loads to the surrounding base metal, causing it to plastically deform, increasing the strength of the weld. If the welds fracture through the weld nugget, then the weld is classified as brittle fracture. This fracture mode is called interfacial failure. The study continues to state that dual phased steels are highly susceptable to interfacial failure. This is attributed to cooling crackes in the center of the weld nugget (Nikoosohbat, et al. 2010).

The RSW samples form a hard martensitic microsturcture in the weld nugget. The hard microstructure is caused from the rapid heating cycle in the RSW process. Also the copper tips are water cooled, which quenches the spot weld after the heating cycle. The RSW cycle is short, creating a rapid solid to liquid to solid heat cycle in the weld. The result is martiensite in the fusion zone, and well as an increased probablility in forming solidification cracks in the center of the weld nugget.

Figure 2-3: Resistance Spot Welded DP 980 Sample (Nikoosohbat, et al. 2010)

Cooling cracks form from the thermal cycles of the steel. When the RSW quences from a liquid to a solid, the formation of the grains starts at the outside surfaces of the weld. As the solidification continues, the microstructure grains grow inward towards the center of the weld. Figure 2-3 shows the microstructure of the RSW sample with the martensitic grain structure pointing to the center of the weld. Voids form in the weld when the solidification reaches the center of the weld with no more liquid metal to bond the two sides together, thus forming the voids in the center of the weld.

This void is also aligned with the faying surface of the steel sheets, allows for a smaller bond area between the void and the faying suface notch of the weld. The crack initiates at the faying surface notch, and then propegates through the center of the weld nuggett (Nikoosohbat, et al. 2010).

2.7 Conclusions

From the review of the literature, the welding procedures and processes of DP 980 have not yet been proven successful or cost effective. RSW of DP 980 results in a brittle microstructure along with high probability of voids forming in the center of the weld. The combinations of these two problems have a tendency to fail with an interfacial failure. Laser welding has been tested for its formability after welding, and not to the extent of applying the process to the production floor.

The literature found on FSSW in other alloys touched lightly on the tool life. One major difference from my study and all other research performed on FSSW of UHSS is that the spindle speeds that were used were below 3000rpm. Hovanski, Santella and Grant have stated that further development in extending the tool life, reducing cost of the tools, and tool geometry needs to be further researched in order to apply FSSW into a production setting.

3 METHODOLOGY

3.1 Introduction

Multiple threaded Polycrystalline Cubic Boron Nitride (PCBN) tools, as seen in Figure 3-1, were tested for wear testing in Friction Stir Spot Welding (FSSW) of DP 980 steel. Each tool was tested using different welding parameters in order to identify the best tool material and welding parameters to maximize the life of the PCBN welding tool.

Figure 3-1: Threaded PCBN Tool

3.2 Weld Parameter Development

High speed FSSW is a relatively new concept. For each tool, a systematic approach will be used to find the best welding parameters to produce an acceptable weld. These parameters include the RPM, plunge feed rate, and plunge depth. Other considerations in parameter development are welding time and force. Parameters were optimized to constantly produce welds over 2400 pounds of lap shear strength.

3.3 Experimental Design

Once acceptable welding parameters are identified, the testing will begin with a set of four individual samples as seen in Figure 3-2, welded on a load fixture. These four samples include three lap shear specimens and one metallography sample. A set of 96 welds, to add up to 100 welds between evaluating the tool, will be performed on two sheets of DP 980 sheared into 12” x 13” pieces. The welds will be placed in a random pattern to reduce sheet warping during the welding process as shown in Figure 3-3. A feed of 1.0 inches per minute starting from .1667 inches above the top plate will be programed into the machine to simulate time between welds needed to reposition the welding robots in the automotive factory. The tool wear will be checked after the set of 96 welds.

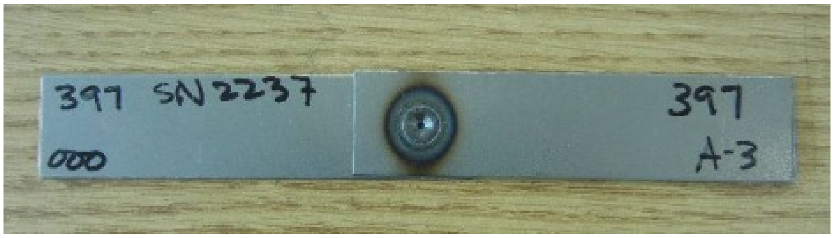

Figure 3-2: Individual Friction Stir Spot Welded Sample

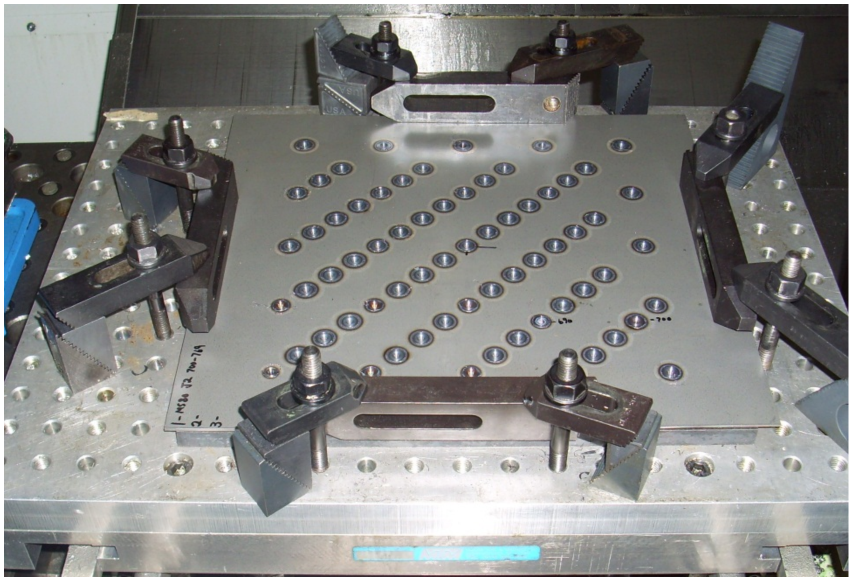

Figure 3-3: Wear Fixture

If the tool fails during the programed 96 weld set, the program will be stopped at that point of the testing. The weld number will be noted, and pictures of the tool will be taken to document the failure of the tool.

After each set of 96 welds, four samples will then be welded and tested for lap shear and metallography, to analyze when tool performance declines. Pictures of the tool will be taken before testing and after each set of 4 individual weld samples, to document tool wear. Welds will be performed on the Fadal mill with tool spindle speed between 2,500 and 6,000 rpm.

The metallography samples will be sectioned using a Sodick Wire EDM machine. They will then be mounted in a Bakelite material, and polished to a 1 micron finish. Samples will then be etched to reveal the microstructure with a 2% nital solution. Images of the microstructure will be taken using a light microscope at different magnifications to view the depth of the Thermal-Mechanically Affected Zone (TMAZ) and the microstructure of the weld.

3.4 Data Collection Methods

Welding loads will be recorded and saved for each of the four samples. Wear testing will not have the loads recorded. Data will be collected using load cells in the individual sample welding fixture as shown in Figure 3-4, and will be collected using a data collection software. This data will be exported to Microsoft excel for data analysis.

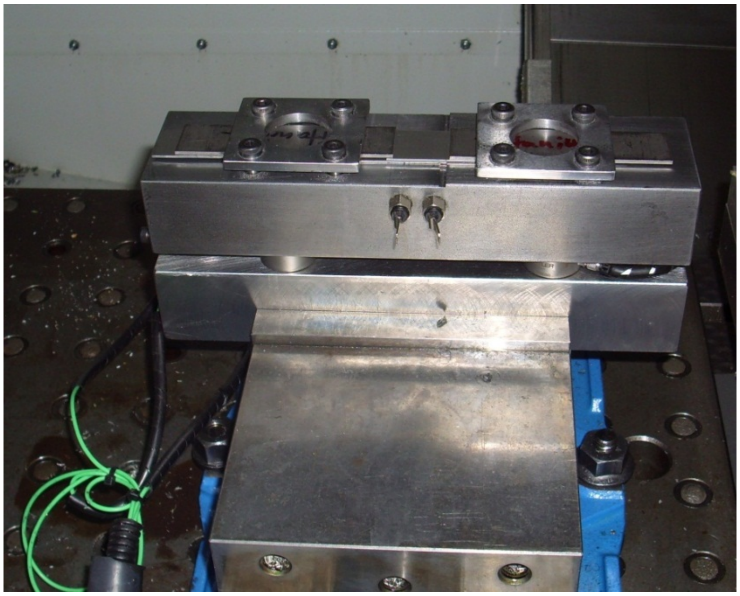

Figure 3-4: Welding Load Fixture

Lap shear testing was performed on an Instron tensile machine. The pull rate for lap shear testing will be 0.4 ipm for all samples. Peak loads will be compared between the samples. The lap shear samples were shimmed to prevent un-even loading on the weld.

3.5 Data Analysis Methods

Data was reviewed to observe correlations and trends between the welding loads and the lap shear results. Run charts were made of the welding loads and lap shear to map the trends as the wear testing progressed.

4 RESULTS AND DISCUSSION

4.1 Welding Parameter Development

The testing for each tool began with determining a best set of welding parameters based on the testing and knowledge learned from the previous tool. Welding parameters consist of altering a combination of RPM, feed rate, and plunge depth of the PCBN tool. Wear testing was then performed on each tool once an acceptable welding parameter set was identified. Different welding parameters were used on each tool to analyze the effects they had on tool life of the tool. Parameters were optimized in order to decrease welding load, while increasing tensile strength and tool life. The parameters used for each tool can be found in Table 4-1.

Table 4-1: Final Welding Parameters for PCBN Tools

Tool	Stage	Plunge Depth (inches)	Feed Rate (ipm)	RPM	Welding Time (sec)
MS 80 SN 2236	Stage 1	-0.04	1	6000	6
	Stage 2	-0.05	5	3500	
	Stage 3	-0.09	5	2500	
	Stage 4	-0.095	0.1	2500	
MS 45003	Stage 1	-0.04	1	6000	8.3
	Stage 2	-0.07	2	6000	
	Stage 3	-0.095	0.3	6000	

Table 4-1: Cont'd

MS 80 J1	Stage 1	-0.02	1	6000	4.8
	Stage 2	-0.064	4	6000	
	Stage 3	-0.091	3	4000	
	Stage 4	-0.095	0.1	2500	
MS 80 J2	Stage 1	-0.02	1	6000	3.64
	Stage 2	-0.064	4	6000	
	Stage 3	-0.093	3	4000	
	Stage 4	-0.095	0.1	2500	
MS 45005	Stage 1	-0.02	1	6000	5.02
	Stage 2	-0.064	3	6000	
	Stage 3	-0.091	3	4000	
	Stage 4	-0.095	0.1	2500	

4.1.1 Welding Stages

Initial weld and wear testing with a constant high spindle speed resulted in overheating the tool. The excess heat resulted in the formation of an oxide layer on the outside edge of the tool as shown in Figure 4-1. The base material also bonded to the welding surface of the tool. Stages, or steps in the welding process, with decreasing spindle speeds in the welding process were introduced to solve these problems. These stages also aided in achieving different results in the weld quality.

Figure 4-1: Red Oxide Layer on MS80 SN 2236 After 800 Welds

One reason for having different spindle speeds at the different stages of the weld cycle was reflective of the diameter change during the welding process. As the tool plunges into the base material, a larger diameter of the tool is in contact with the material. As the diameter increases, a slower spindle speed is needed to maintain a constant surface speed for the tool. The machining spindle speed formula represented in Equation 4-1 was used to calculate a theoretical best spindle speed as the tool contact diameter increased.

$$\boldsymbol{Spindle\ Speed = \frac{12 \times Surface\ Speed}{Diameter \times \pi}} \quad \textbf{(4-1)}$$

To find the surface speed of the PCBN tool, the pin of the tool was plunged into the base material at 6000 RPM on the wear plates. After a number of welds, the tool was inspected to identify if the welding process polished the pin. Equation 4-1 was used to determine the surface speed of the tool, using the diameter of the pin, which was approximately .160 inches. With this dimension, the surface speed was calculated to be 240. With the shoulder being 10mm, or 0.3936 inches, the spindle speed for the shoulder would approximately be 2500 rpm.

It has been noticed that welding time has a large effect on the tool life and end quality of the weld. The longer the tool is in contact with the base metal, the more heat that is generated to produce the weld, which increased the lap shear values. The negative effects of a long weld time is that it takes more time up in the manufacturing setting to complete the weld. Also the tool has the tendency to wear faster because of the increased time it is in contact with the base material.

4.1.2 Welding Parameters for MS80 SN2236 Threaded PCBN Tool

The parameters used for the MS80 SN 2236 tool were the best parameters tested on the MS80 SN 2235 tool. The SN 2235 tool was first used for parameter testing, and some wear testing. Material bonded to the tool during the wear test. After the wear test, while welding lap shear samples, the material came off and chipped the shoulder of the tool shown in Figure 4-2. The SN 2235 tool lasted 204 welds.

Figure 4-2: Chipped Shoulder and Radial Cracks of PCBN MS80 SN2235

The PCBN MS80 SN 2236 started with the original parameter set of the SN2235 PCBN tool. After 45 welds, the welding parameters were changed to a shorter welding time because material started to build up on the shoulder of the tool as shown in Figure 4-3. This tool welded 1003 welds before testing stopped.

Figure 4-3: Material Build-up on MS80 PCBN Tool at 45 Welds

During the wear testing process it was observed that the first sample welded after a set of 96 welds had a higher lap shear value than the following two samples. The PCBN tool is hotter on the first weld because of the retention of heat from the wear testing. Subsequent welds drop in lap shear value because the tool is allowed to cool during changeover of the weld coupons. The difference in lap shear results can be seen in Figure 4-4.

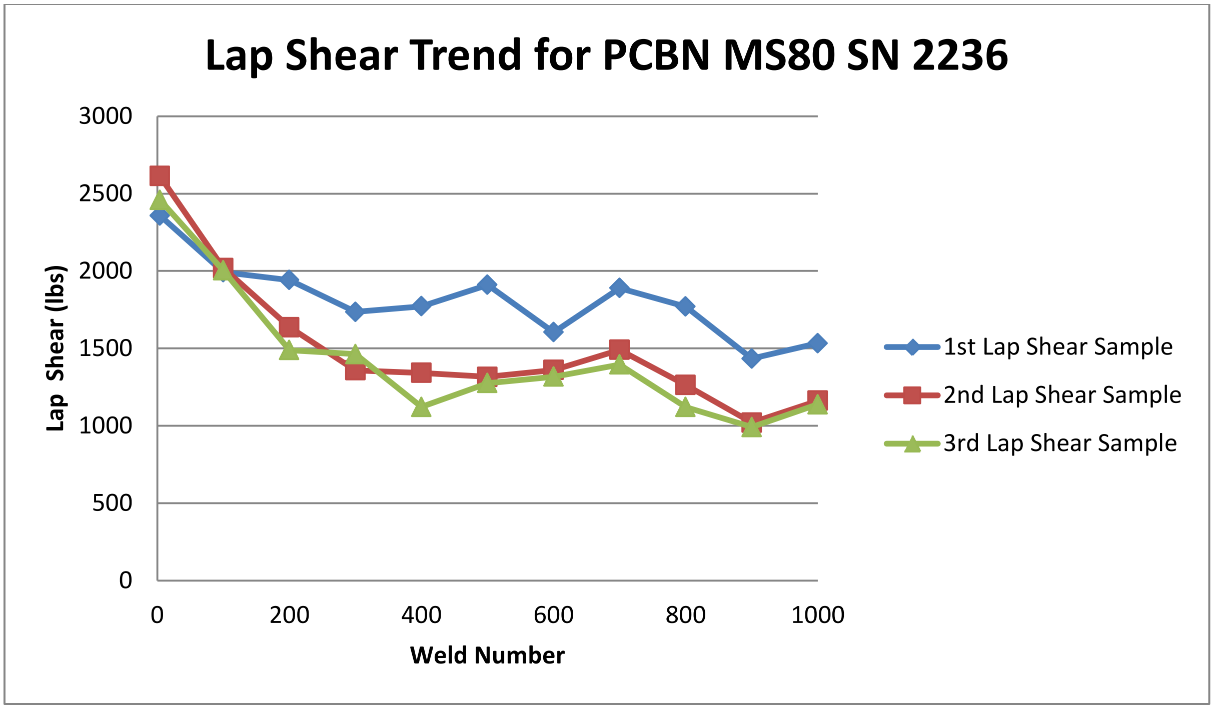

Figure 4-4: Lap Shear Results for PCBN MS80 SN2236 Tool

4.1.3 Welding Parameters for MS80 J1 Threaded PCBN Tool

The MS80 J1 tool was first used for parameters testing. The set of parameters that were tested for this tool can be found in Appendix A. Parameter sets "G" and "H" resulted in the highest lap shear values, with lap shear results above 3000 pounds, with a weld time of 5.6 seconds, and a spindle speed starting at 8000 rpm. The higher spindle speeds and welding time were used in order to decrease the welding loads. The parameters were further changed to the wear test parameter set to reduce the spindle speed to 6000 RPM and the weld time to 4.8 seconds. This was because the current FSSW machines used, can reach spindle speeds of 6000 RPM, and the welding time was decreased to speed up the manufacturing process. The welding load didn't change with the shorted welding time, but the lap shear results dropped slightly as shown in Figure 4-5 and Figure 4-6. Parameter set "I" was used for the wear testing for this tool.

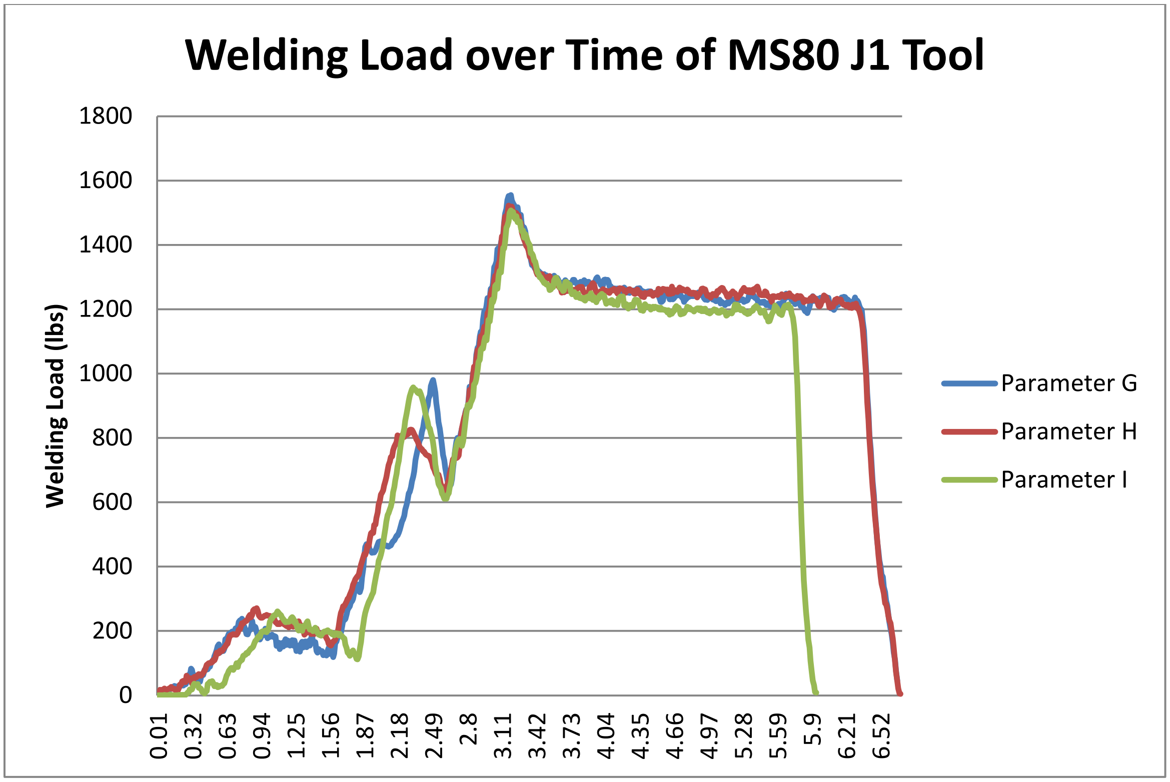

Figure 4-5: Welding Load Over Time of MS80 J1 PCBN Tool

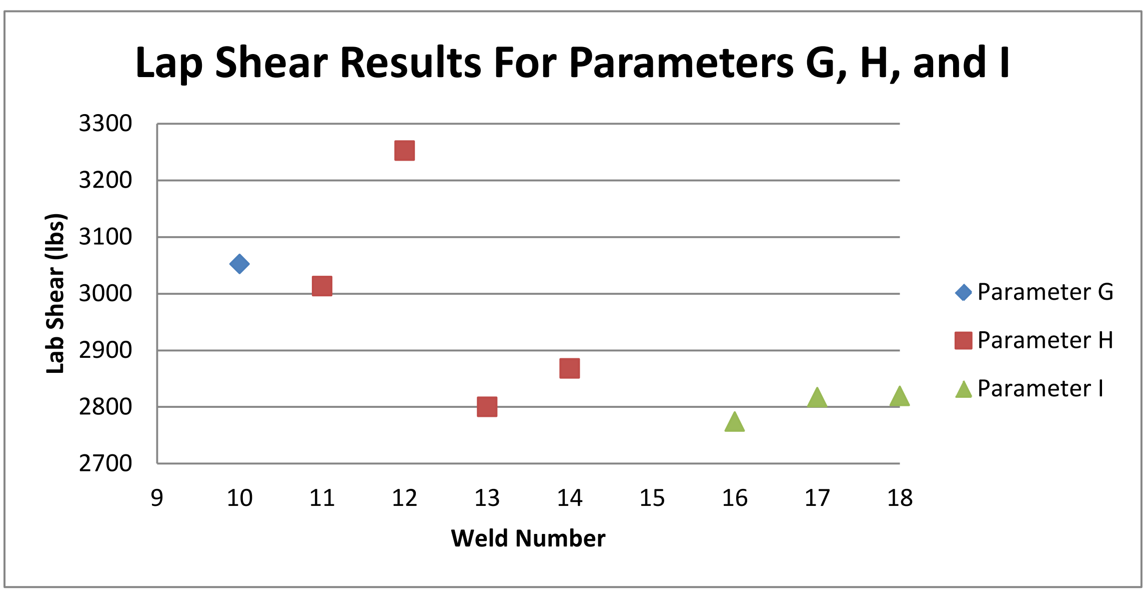

Figure 4-6: Lap Shear Results for Parameters G, H, and I

4.1.4 Welding Parameters for MS80 J2 Threaded PCBN Tool

The MS80 J2 tool moved to a shorter weld time than that of the J1 tool, trying to maximize the life by reducing the heat input into the tool. This was accomplished by increasing the distance traveled in stage 3 and decreasing the distance traveled in stage 4 of the welding parameters.

This parameter change resulted in initially having a higher welding load than that of a weld with a longer welding time. This can be seen in Figure 4-10 where the MS80 J2 tool had a higher welding load when compared to the MS80 J1 tool at the beginning of the wear test. As the wear testing progressed, the welding loads averaged out as shown in Figure 4-7. After 200 welds, the welding loads for all the tools followed a similar level and path.

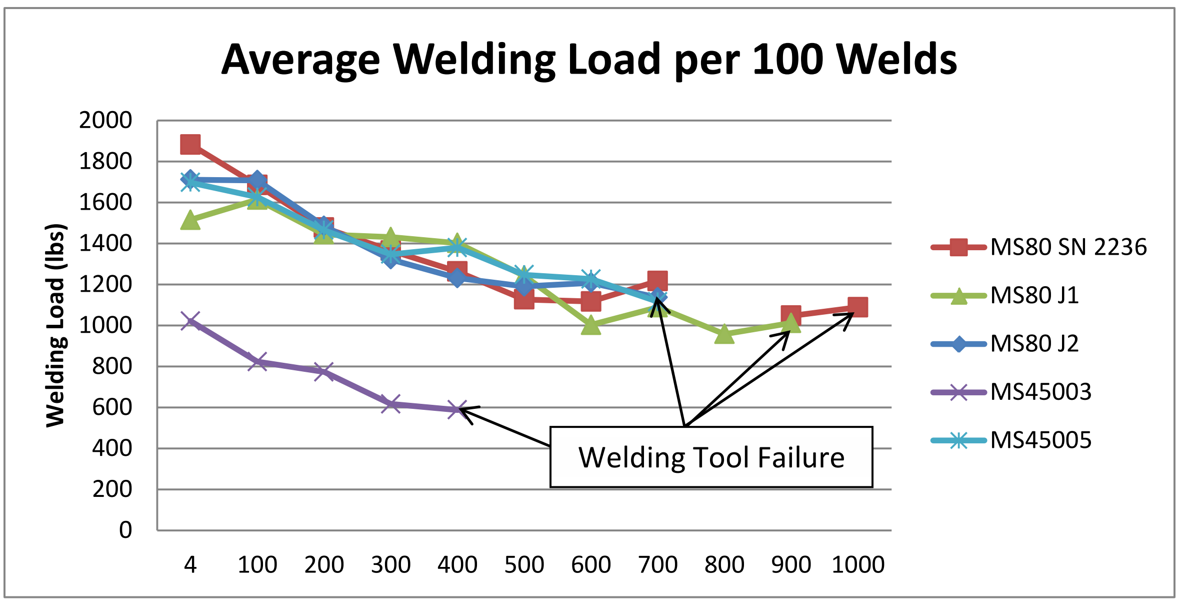

Figure 4-7: Average Welding Load per 100 Welds

The shorter weld time also resulted in a lower lap results in the MS80 J2 PCBN tool as shown in Figure 4-8. The only time that the MS80 J2 tool had a higher lap shear strength what when the MS80 J1 tool was allowed to cool before welding the lap shear samples during weld samples 597-600. The MS80 J2 tool also was offset down by .002 inches at this point to compensate for wearing on the tool. It was common to offset the tool down .002-.004 during the wear testing to compensate for the PCBN tool wearing. Offsetting the tool down contributed to the increase in lap shear results at that point in the wear test.

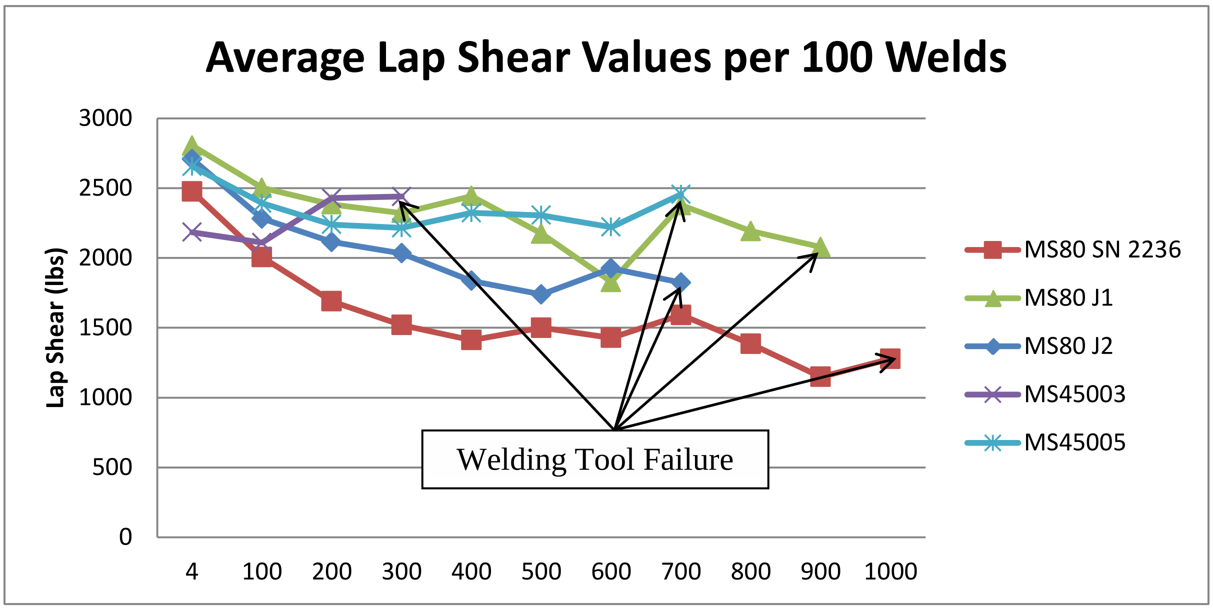

Figure 4-8: Average Lap Shear Values per 100 Welds

4.1.5 Welding Parameters for MS45003 Threaded PCBN Tool

The parameters for the MS45003 tool were developed with a MS45004 tool. Testing on the MS 45004 tool started with using the same welding parameters as the PCBN MS80 SN 2236 tool. For the initial three welds, the lap shear samples pushed apart by the material from the top plate that was displaced from the welding tools as it was plunged into the base material. This is a result of the lower heat that was produced for these tools because of the difference in the coefficient of friction between the different tool materials.

After the first weld from the MS45004 PCBN tool, more clamping pressure was put on the samples to keep the sheets from separating. After the third weld with continued sheet separating, it was determined to change the parameters in order to create more heat in the weld. Acceptable welds were not created until the spindle speed was raised to 6000 RPM throughout every stage. Once the best parameters were selected, a wear test on this tool was started, but broke after 4 welds into wear testing. The same parameters were used to do wear testing on the MS45003 PCBN tool.

4.1.6 Welding Parameters for MS45005 Threaded PCBN Tool

Welding parameters used for the MS45005 tool were developed from the parameters used by the MS80 J1 PCBN tool. The MS45005 tool was first used for parameter testing. The welding time was adjusted from the MS80 J1 tool by changing the depth of plunge in the final stage of the welding process. These parameters are shown in Appendix B. The final stage was originally set at .090”, which had lap shear results averaging 3108 lbs. In an effort to reduce the welding time to lengthen the tool life on the welding tool, the final stage was altered to .091” to have a calculated welding time of 5.02 seconds. This resulted in the starting lap shear average to be 2655 lbs.

4.2 Welding Load and Lap Shear

Each tool had a different weld time and parameter set which resulted in a different load graph of the tool. The welding loads are adjusted by the plunge rate and the spindle speed of the tool. As feed rates are decreased and the spindle speed increased, the load on the tool also decreased. This is proven with the wear testing on the MS45004 tool. Figure 4-9 shows that the first few parameter sets with a decreasing spindle speed weld provided higher lap shear values then that of a parameter set with a constant high spindle speed. The full set of parameters can be reference in Appendix B.

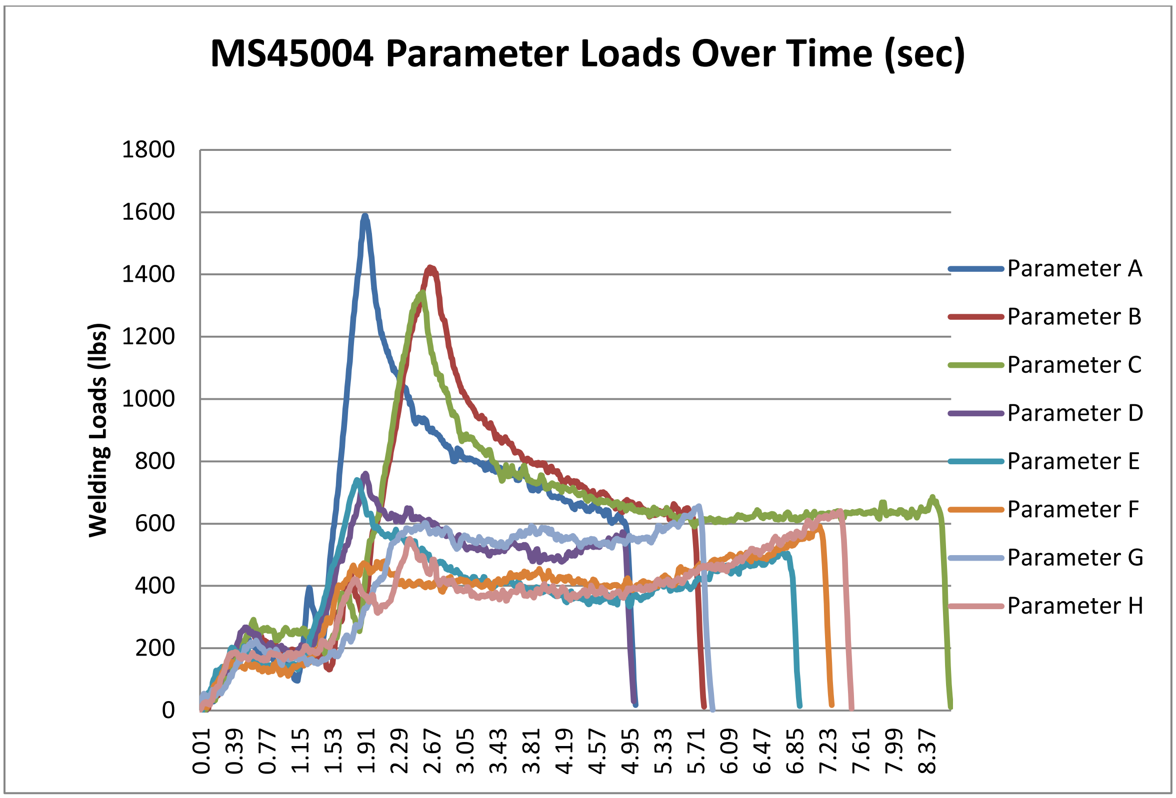

Figure 4-9: MS45004 Parameter Loads Over Time

Figure 4-10 show a comparison between the different welding tools used in this study at weld 100. Shorter welds have a tendency to have a higher welding load. One reason for the higher welding loads with shorter welds is that the tool is in contact with the material for a shorter length of time. This creates less heat in the weld, and the base material takes more force to move around the plunging tool.

The main cause for the spike in the welding loads is caused from the change in spindle speed, when the spindle speed of the PCBN is dropped to 2500 rpm in the final stage of the weld. Every major movement in the welding load chart is caused from a change in the welding parameters; ether the feed rate, or the spindle speed.

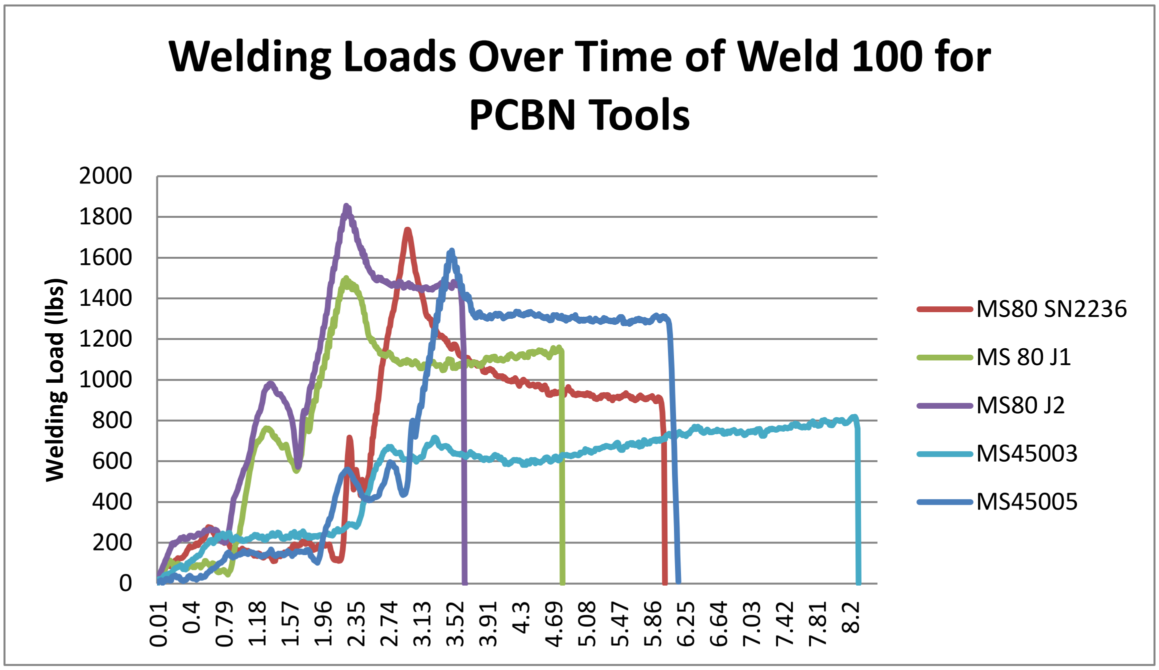

Figure 4-10: Welding Loads Over Time of Weld 100 for PCBN Tools

Welding loads dropped as the wear test progressed. The average welding load for each set of four welds was plotted on a line chart and can be seen in Figure 4-7. It shows that as the tool geometry wears away the welding load decreases. This has an effect on the lap shear results. The weld characteristics change as the tool wears away in the treaded tools. The threads are there to move material around as it is stirring the weld. Without the features on the tool, less material is being moved around in the TMAZ, which results in lower lap shear values and welding loads. Figure 4-8 shows and average of the three lap shear values after each set of 96 welds are complete. The trend is that the lap shear results decrease as the tool geometry wears away. Figure 4-11 shows the welding loads for each 100 weld of the PCBN MS80 J1 tool stacked on top of each other. It shows that the welding loads decrease as the tool wears during the wear testing process.

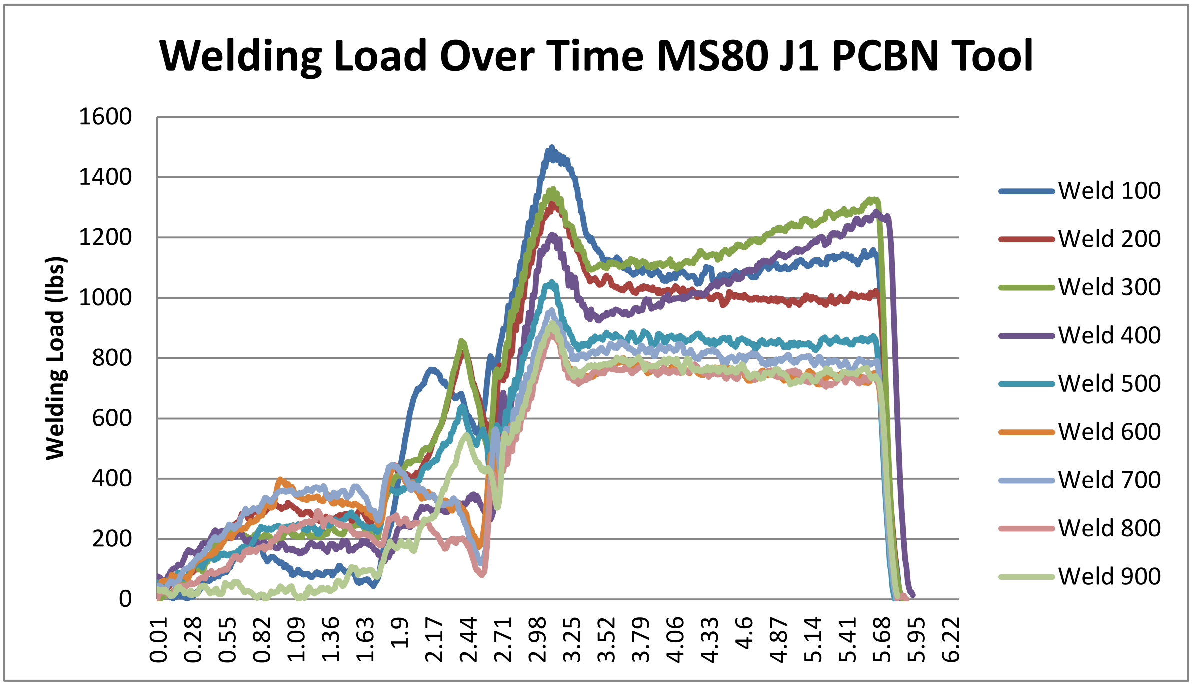

Figure 4-11: Welding Load Over Time of the MS80 J1 PCBN Tool

4.3 Tool Wear

The threads were critical in moving material around during the high speed FSSW process. The major thread geometry is worn away in the first few hundred welds as seen in Figure 4-15, which produce and uneven welding insert. Even through the major thread geometry is worn away, there is still uneven features on the welding tool that moves material around during the welding process. The tool wear also reveals an abrasive surface, as seen in Figure

4-13. It is proposed that the revealed abrasive surface increases the surface area that is in contact with the base material, creating more friction and heat and raising the probability for material adhesion to the tool.

It is noticed that the wear of the tool is on the more vertical features of the welding tool. It is proposed that the sharp edges of the welding tool have less support than the inner portion of the features, allowing for it to be worn away with more ease. Figure 4-12 through Figure 4-20 shows the progression of tool wear every 100 welds.

Figure 4-12: MS 80 J1, SN2236, J2 Welding Tools at Weld 100

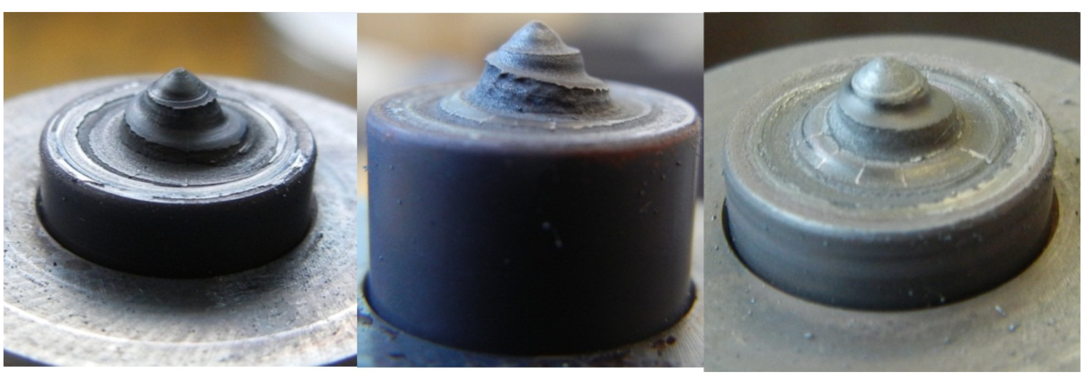

Figure 4-13: MS 80 J1, SN2236, J2 Welding Tools at Weld 200

Figure 4-14: MS 80 J1, SN2236, J2 Welding Tools at Weld 300

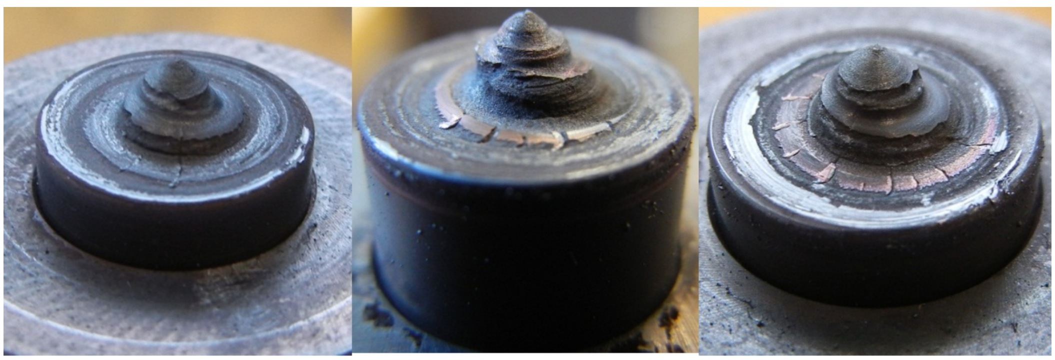

Figure 4-15: MS 80 J1, SN2236, J2 Welding Tools at Weld 400

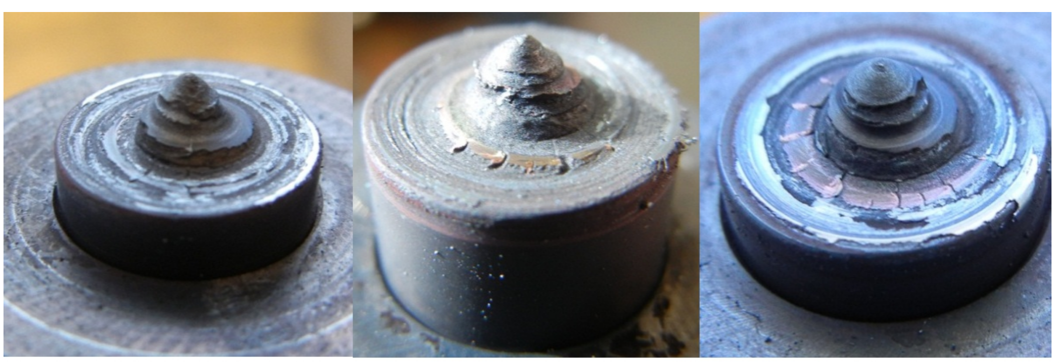

Figure 4-16: MS 80 J1, SN2236, J2 Welding Tools at Weld 500

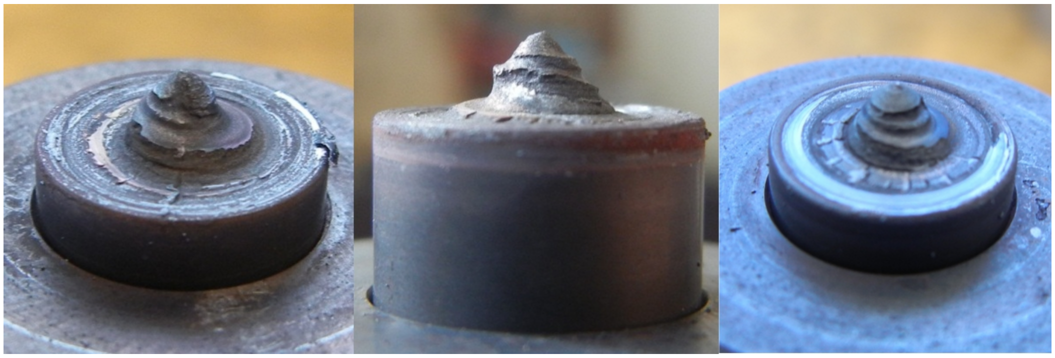

Figure 4-17: MS 80 J1, SN2236, J2 Welding Tools at Weld 600

Figure 4-18: MS 80 J1, SN2236, J2 Welding Tools at Weld 700

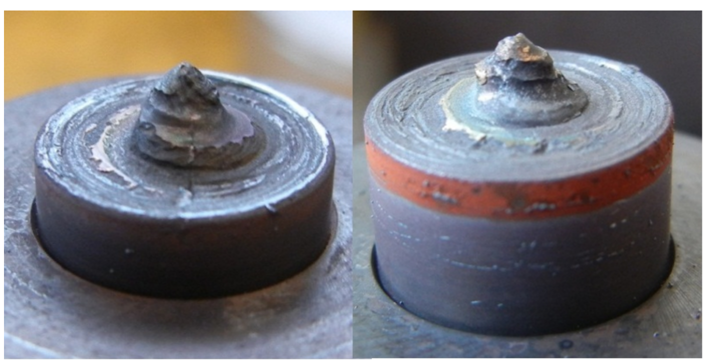

Figure 4-19: MS 80 J1, SN2236 Welding Tools at Weld 1800

Figure 4-20: MS 80 J1, SN2236 Welding Tools at Weld 900

4.4 Weld Cross Sections

Cross sections of the weld revealed the hook, Heat Affected Zone (HAZ), microstructure, and stir zone of the welds. Figure 4-21 reveals four zones of the weld, which include an inner and outer TMAZ, a HAZ, and the base metal. The hook of the weld is located in the outer TMAZ of the weld. This zone is still hard, but is not as affected by the heat and stirring motion of the welding tool. Most of the heat is focused at the upper sheet of the weld. The different zones of the welds are wide at the top of the sample and taper down to the bottom point of the weld. The more heat that is focused at the joint will increase the bonding area of the weld, and the weld will increase in strength. This cross section shows that there is a lot heat dissipated on the top sheet of the weld, which is not transferred through the weld joint.

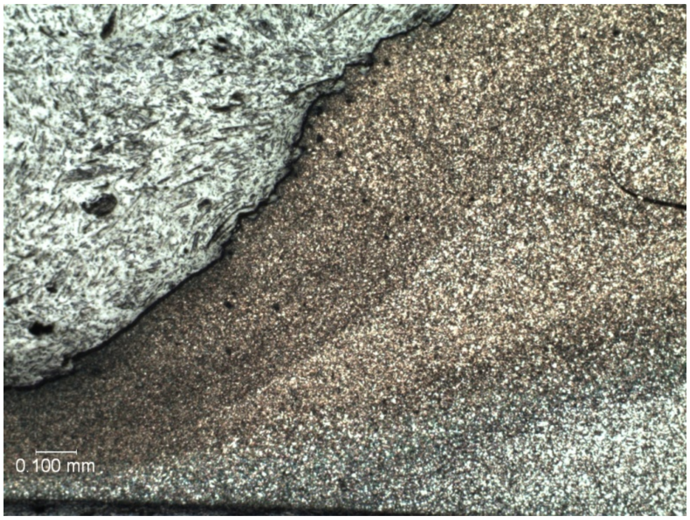

Figure 4-21: TMAZ, HAZ and Base Metal of MS45005 Weld 604

Figure 4-22 shows the TMAZ on the top sheet to extend further away from the center of the weld than the bottom sheet. Part of this problem is created by the sheet separation in this particular weld. The heat was not able to transfer through the plates when there was separation. Other samples were similar in nature, but with the sheets in contact the heat was able to flow through the joint with less resistance.

The hook on these samples point away from the weld joint. The difference can be seen when comparing Figure 2-2 and Figure 4-22. The hook found in Figure 2-2 is small, but is pointed towards the surface of the tool indentation, whereas in Figure 4-22 it shows the hook pointing away from the tool indentation. This can aid in strength of the weld. The stress and energy applied to the weld is directed away from the weld indentation, and towards the softer HAZ and base material.

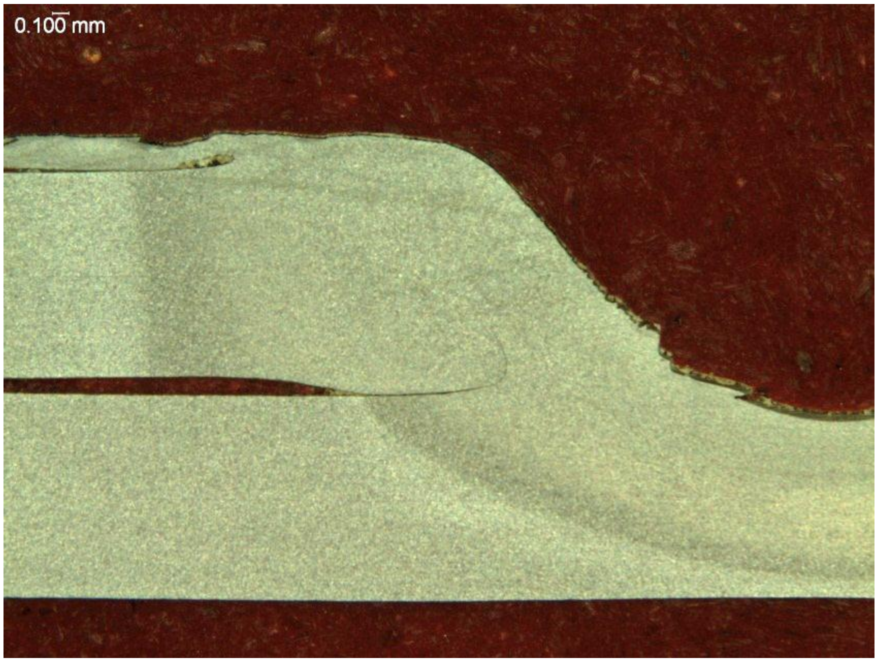

Figure 4-22: MS80 J2 Weld 202 Cross Section

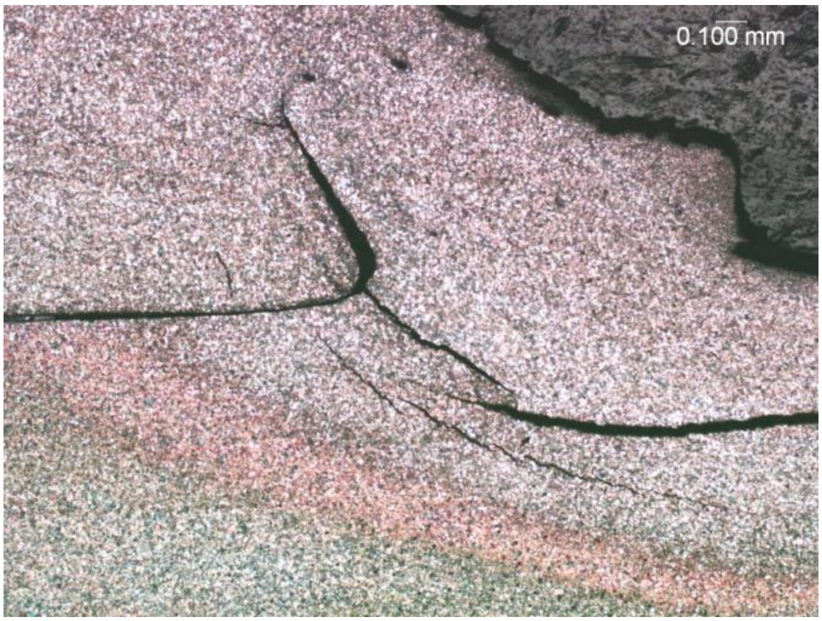

Figure 4-23: Cracks in Cross Section of PCBN J2 Weld 503

Only one of the cross sectioned samples revealed cracking in the TMAZ. Figure 4-23 shows the cracks forming at the bend of the hook. In reviewing the load and lap shear data for welds 500 to 503, the lap shear values were at the lowest point of the wear testing for this tool. The tool was then offset down .002 when welding welds 600-603, increasing the lap shear results. The lap shear results would increase as the tool was offset into the base material.

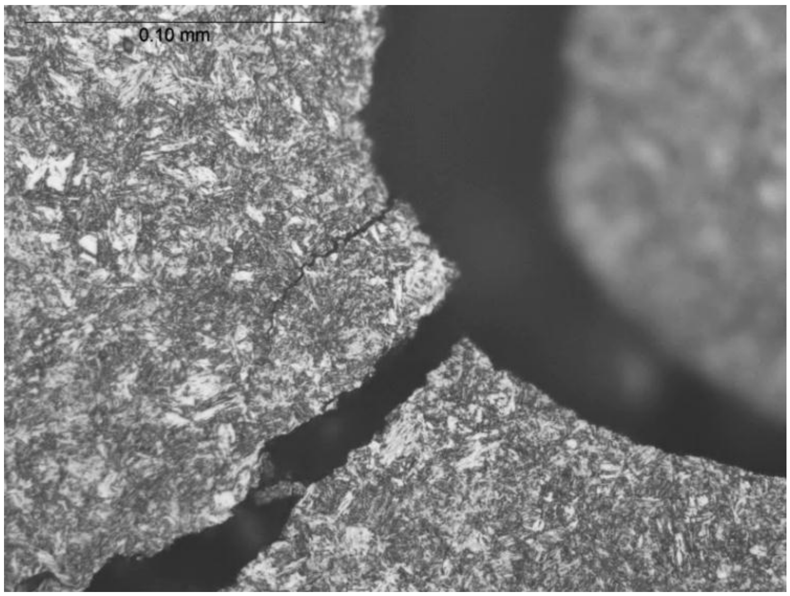

Figure 4-24: Microstructure View of Cracks Found in PCBN J2 Weld 503

Figure 4-24 shows the crack at the bend of the hook. The surface of the hook is jagged, combined with the hard martensitic microstructure creates crack initiation points in the weld. At first glance this portion of the material should be in compression because of the bending direction. It is proposed that this surface of the material is in tension, being stretched around the upper plate, creating a location for the crack to initiate. It is also proposed that with adequate welding force this problem can be avoided.

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

High spindle speed Friction Stir Spot Welding (FSSW) was able to successfully join DP 980 and reduce the welding load below 2000 pounds with threaded PCBN tool. Welds with lap shear results above 2400lbs were produced using this process. The PCBN tool was able to withstand the welding forces for 700-1,000 welds, but was not able to withstand up to 5,000 welds. This is mostly attributed to the aggressive tool design.

5.1.1 Results from High Spindle Speed

At high spindle speed FSSW does reduce the load of on the welding tool. The welding tool generates more heat by friction at high speed, which softens the material and consequently decreases the vertical load on the machine spindle. Another benefit from a high spindle speed and reduction of welding load reduced stress on the PCBN tool. In previous tests at a low spindle speed, the hard, brittle PCBN tool would crack and break after a few hundred welds. The tools used in this study formed small cracks at approximately 200 welds into the wear test, and lasted several hundred welds after that. However, a higher welding spindle speed uncovers some negative issues in the process. Some of these issues are the increased abrasive wear on the tool, as well as overheating of the tool.

Overheating of the tool, abrasive wear, and high welding loads were mitigated to some extent by putting staging the welding process into different levels of feed and speed. These stages varied the RPM, feed rate, and distance traveled by the tool, optimizing the welding loads and lap shear results. For example, Figure 4-1 shows a red oxide layer around the perimeter of the tool after 800 welds on the MS80 SN2236 tool, and Figure 5-1 shows no oxide layer after 976 welds on the MS80 J1 tool.

Figure 5-1: Failed MS80 J1 PCBN Tool After 976 Welds

The experimental work done for this thesis has provided support for the hypothesis that weld strength can be obtained at levels above the acceptable standard for DP 980 material (greater than 2400 pound lap shear fracture load for 1.2 mm material) while keeping the vertical load on the welding machine spindle below 2000 lbs.

5.2 Recommendations

Recommendations on further research include developing the tool designs with smooth profiles, in order to reduce tool wear in the high speed welding domain, and modeling the welding process in order to better understand the relationship between tool design and welding process conditions. As research progresses in these areas, it is recommended that cross tension specimens, fatigue testing and micro-hardness testing be performed in addition to the lap shear and metallography samples completed during this study.

5.2.1 Surface Speed/ Parameter Optimization

Like in machining, the surface speed of FSSW has an influence on the life of the PCBN welding tool. Better understanding the relationship between surface speed and abrasive tool wear will allow for improved development of welding process parameters. It can also have a large effect on the life expectancy of the welding tool.

5.2.2 Tool Geometry

The threads on the tools aided in moving material around in the weld joint, which increased bond area and improved the lap shear results. The majority of the threads are worn away after the first few hundred welds leaving an uneven welding tool. The uneven tool still moves material around during the welding process, creating an acceptable weld; however, this also reduces tool life to unacceptable levels. New smooth tool designs and high speed welding parameters may be the answer to improved tool life, acceptable spindle loads, and acceptable joint strength.

5.2.3 Tool Material Development

New grades of PCBN and other hard materials like silicon nitride should be tested to see if improved wear resistance can be obtained. The joint performance for friction stir spot welded DP 980 has been shown to be acceptable, and in some cases very good. Tool life is therefore a significant barrier to industrial implementation of FSSW of ultra high strength steels.

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APPENDIX A

Welding Development Parameters for MS80 J1 PCBN Tool

Parameter Set	Stage	Plunge Depth (inches)	Feed Rate (ipm)	RPM	Welding Time (sec)
A	Stage 1	-0.04	1	8000	7.85
	Stage 2	-0.064	4	6000	
	Stage 3	-0.07	4	3500	
	Stage 4	-0.095	0.3	2500	
B	Stage 1	-0.04	1	8000	8.00
	Stage 2	-0.064	3	6000	
	Stage 3	-0.07	3	3500	
	Stage 4	-0.095	0.3	2500	
C	Stage 1	-0.04	1	8000	7.85
	Stage 2	-0.064	4	6000	
	Stage 3	-0.07	4	4000	
	Stage 4	-0.095	0.3	2500	
D	Stage 1	-0.02	1	8000	6.95
	Stage 2	-0.064	4	6000	
	Stage 3	-0.07	4	4000	
	Stage 4	-0.095	0.3	2500	
E	Stage 1	-0.02	1	8000	6.24
	Stage 2	-0.064	4	6000	
	Stage 3	-0.07	4	4000	
	Stage 4	-0.095	0.35	2500	
F	Stage 1	-0.02	1	8000	5.25
	Stage 2	-0.064	4	6000	
	Stage 3	-0.09	4	4000	
	Stage 4	-0.095	0.1	2500	
G	Stage 1	-0.02	1	8000	5.60
	Stage 2	-0.064	3	6000	
	Stage 3	-0.09	3	4000	
	Stage 4	-0.095	0.1	2500	

H	Stage 1	-0.02	1	6000	5.60
	Stage 2	-0.064	3	6000	
	Stage 3	-0.09	3	4000	
	Stage 4	-0.095	0.1	2500	
I	Stage 1	-0.02	1	6000	4.80
	Stage 2	-0.064	4	6000	
	Stage 3	-0.091	3	4000	
	Stage 4	-0.095	0.1	2500	

APPENDIX B

Welding Parameters used for MS45004 PCBN Tool

	Depth(in)	Feed Rate(ipm)	RPM		Depth(in)	Feed Rate(ipm)	RPM
Set A	-0.04	1	6000	**Set E**	-0.04	1	6000
	-0.05	5	3500		-0.07	3	6000
	-0.09	5	2500		-0.095	0.3	6000
	-0.095	0.1	2500				
Weld Time (sec)		**6**		**Weld Time (sec)**		**8**	
Set B	-0.04	1	6000	**Set F**	-0.04	1	6000
	-0.05	3	3500		-0.07	2	6000
	-0.09	3	3500		-0.095	0.3	6000
	-0.095	0.1	2500				
Weld Time (sec)		**6.4**		**Weld Time (sec)**		**8.3**	
Set C	-0.04	1	6000	**Set G**	-0.04	1	6000
	-0.05	3	3500		-0.07	1.5	6000
	-0.085	3	3500		-0.095	0.5	6000
	-0.095	0.1	2500				
Weld Time (sec)		**9.3**		**Weld Time (sec)**		**6.6**	
Set D	-0.04	1	6000	**Set H**	-0.04	1	8000
	-0.07	3	6000		-0.07	1.5	8000
	-0.095	0.5	6000		-0.095	0.5	8000
Weld Time (sec)		**6**		**Weld Time (sec)**		**6.6**	