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# Friction Stir Spot Welding of Ultra-High Strength Steel

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# Friction Stir Spot Welding of Ultra-High Strength Steel

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# ABSTRACT

Friction Stir Spot Welding of Ultra-High
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Friction stir spot welding (FSSW) is quickly becoming a method of interest for welding of high strength steel (HSS) and ultra high strength steel (UHSS). FSSW has been shown to produce high quality welds in these materials, without the drawbacks associated with fusion welding.

Tool grade for polycrystalline cubic boron nitride (PCBN) tools has a significant impact on wear resistance, weld quality, and tool failure in FSSW of DP 980 steel sheet. More specifically, for a nominal composition of 90% CBN, the grain size has a significant impact on the wear resistance of the tool. A-type tools performed the best, of the three grades that were tested in this work, because the grain size of this grade was the finest, measuring from 3-6 microns. The effect of fine grain size was less adhesion of DP 980 on the tool surface over time, less abrasive wear, and better lap shear fracture loads of the welds that were produced, compared to the other grades. This is explained by less exposure of the binder phase to wear by both adhesion and abrasion during welding of DP 980. A-type tools were the most consistent in both the number of welds per tool, and the number of welds that reached acceptable lap shear fracture loads. B-type tools, with a bimodal grain size distribution (grain size of 4 – 40 microns) did a little bit better than C-type tools (grain size of 12-15 microns) in terms of wear, but neither of them were able to achieve consistent acceptable lap shear fracture load values after the first 200 welds. In fact only one out of five C-type tools was able to produce acceptable lap shear fracture loads after the first 100 welds.

Keywords: DP980, FSSW, UHSS, PCBN, micro-hardness, lap shear fracture load, vertical welding load

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# 1. INTRODUCTION

## 1.1 Background

There has been a lot of interest in the past several years in improving efficiencies of the automobile. To improve efficiencies the industry has made major technological improvements. While many of the improvements have been focused around developing more fuel efficient engines and drive trains there have also been many promising developments with structural materials used to build automobiles. Many of these structural developments have involved ultra-high strength steels (UHSS) and high strength steels (HSS). UHSS have two major advantages; they are very strong and very lightweight. This translates into a much more desirable strength to weight ratio. This combination of qualities allows auto manufactures to accomplish the following two goals simultaneously: improve crash safety, and improve fuel efficiency. Although UHSS has these two very desirable properties, ie., very high strength and light weight, there is one detail that needs to be addressed which is its weldability. This will help ensure optimal mechanical properties as well as consistency. It needs to be demonstrated that the metal's mechanical properties can be maintained at acceptable levels after the welding process (Takahashi, 2010).

Currently there is interest in developing Friction Stir Spot Welding (FSSW), as an alternative to Resistance Spot Welding (RSW) for joining high-strength steels that possess high carbon and alloy contents. When used with these steels RSW creates a heat affected zone (HAZ), which degrades the mechanical properties of the steels causing the joint to become brittle due to the rapid heating and cooling. However, with FSSW the heat generated during the joining process is considerably less than with RSW, which helps reduce the extent of the HAZ. By reducing the HAZ the metal retains more of its original mechanical properties, this means typical problems associated with RSW like softening and brittleness can be reduced to a minimum or eliminated with FSSW. Friction stir welding, which is very similar to FSSW, has been used for some time to join metals with low melting points such as aluminum, because the temperatures involved are comparatively lower than those involved with other joining methods especially, when considering fusion welding methods. The ability to control the temperature during the welding process and keep it relatively low compared to other welding methods allows FSSW to join metals, while minimizing the extent of the HAZ, where the weld nugget is typically harder than the base material and where the zone outside the weld nugget is softer than the base material. For this reason FSSW is promising for this application, because during the welding process the steel is kept well below its melting point. This avoids rapidly heating the metal and then allowing the metal to rapidly cool causing the metal in the HAZ to become hard and brittle.

### 1.1.1 Friction Stir Spot Welding (FSSW)

Friction stir spot welding is quickly becoming a method of interest for welding HSSs and UHSSs. FSSW is also a good fit, because it allows the joining of UHSSs without the drawbacks of fusion welding. “The joining of high carbon steels without transformation can be achieved when FSW is conducted under appropriate conditions. The FSSW joints have improved ductility due to the homogeneous microstructure in the joints (Chung, 2010).” In many situations, especially for automotive body structures, it is not possible to heat treat after the welding process, so it is best to use a process which ensures good weld properties without creating excessively hard weld nuggets or excessively soft HAZ areas around the weld.

### 1.1.2 Friction Stir Spot Welding Tools and Tool Materials

The tools used in the welding process significantly affect the quality of weld. Two important factors to take into consideration are the tool's contour and the material composition of the tool. These two factors are essential to understand, because they affect the quality of the weld and the tool production costs associated with the actual welding. For the purposes of the research the focus will be on two different kinds of tools, one made of Silicon Nitride ($Si_3N_4$) and the other of polycrystalline Cubic Boron Nitride (PCBN). It is important to keep the costs involved with tooling to a minimum, to justify the use of FSSW. Currently a major motivation of the research is to try and bring the cost savings seen with FSSW and aluminum applications to high strength and ultra-high strength steel applications. "As a general rule, for medium to high volume automotive production, FSW welds cost 20% less than arc welds and FSSW costs 25% less than RSW. If indirect costs are considered (post weld operations, rework, repair, distortion) then the costs of FSW are dramatically less than GMAW (CB Smith, 2004)."

## 1.2 Contribution of This Study

The contribution of this study is to effectively show the impact of tool material and welding process conditions on joint strength and tool life for FSSW of UHSS. Part of the purpose of the study is also to validate a model of FSSW with regards to temperature, pressure, and time during welding. The goal of the model is to predict the bond strength of a weld, and thereby to optimize tool design using computer simulations, rather than trial and error experimental methods. The model will be validated by experiments, to ensure that the predictions of the model are accurate. While the modeling of FSSW is not a significant part of this thesis, the experimental validation work will be described and some preliminary comparisons between model and experiment will be presented.

### 1.3 Research Questions

The questions addressed in this study are the following:

1. Are there significant differences in the wear resistance of 3 different grades of PCBN, for FSSW of DP 980 steel?
2. Are there significant differences in the lap shear fracture loads of welds produced by 3 different grades of PCBN over time?
3. What are the wear mechanisms observed in the 3 different grades of PCBN after sustained wear testing and how is the final tool failure manifested?

### 1.4 Definition of Terms

DP980 - Dual phase steel consisting of martensite and ferrite phases with an ultimate tensile strength of 980 MPa

PCBN - polycrystalline cubic Boron Nitride, an ultra-hard material used in machining tools and friction spot weld tools. PCBN is formed by applying extreme pressure and temperature to cubic Boron Nitride, which causes the formation of a polycrystalline cubic crystal structure.

Dwell - the time, measured in seconds, that the spot weld tool spends at a certain point of its travel into the material, without advancing

Plunge rate - the speed, measured in inches per minute, at which the spot weld tool travels downward into the material

RPM - revolutions per minute. This refers to the speed of rotation of the spot weld tool as it travels into the material

Plunge depth - the prescribed distance, measured in thousandths of an inch, that the spot weld tool penetrates into the material

Lap shear strength - the strength of the welded joint between two steel coupons, as measured by its resistance to shearing when the coupons are pulled in opposite directions in the same plane.

RSW- Resistance spot welding

GMAW – Gas metal arc welding

### 1.5 Significance of the Study

The significance of this study revolves around the testing of three different grades of PCBN tools to provide data that will be useful to determine which of the three PCBN grades will provide the best combination of wear resistance and spot joint strength in DP 980 steel. To evaluate the tools the testing will focus on lap shear fracture loads, how the tools wear over time, and what the failure mechanisms are. This will provide information that will be useful when considering the pros and cons of using FSSW with PCBN tools for joining of UHSS. The study will also provide experimental data to help validate work being done on a model being built to simulate FSSW.

### 1.6 Delimitations

The purpose of this study was to evaluate three different grades of PCBN tools to decide which will perform the best under real world working conditions. The experiments also served to help create a valid model that will be used to predict the bond strength of FSSWs. Only tools with a material composition of either PCBN or Silicon Nitride were used. The experiments were done exclusively with DP980 steel coupons, which measured 4” x 1” x .047”. All of the welds were performed on a Fadal CNC mill. The spindle speed and the spindle load were kept at or below 6,000 RPM and 2,000lbs respectively.

## 2. LITERATURE REVIEW

### 2.1 Overview

Joining of materials through welding has been around for a long time. Similar to many other technologies and processes, welding has come a long way from its initial beginnings. Welding techniques have been improving and evolving, largely because the materials being welded are changing.

High carbon steels and other high alloy steels, which are commonly referred to as ultra-high strength steels (UHSS) or high strength steels (HSS), have very desirable mechanical properties. They are much stronger than mild steel, which is advantageous for the auto industry as well as the aircraft industry, because thinner gauge material can be used, which helps with weight reduction. All industries that are concerned with increasing the strength to weight ratio of structural steels can benefit from UHSSs.

However, weldability is an issue. The high carbon content increases the hardenability of the metals to a point where they no longer respond well to conventional welding techniques. Problems that arise have to do with the heat-affected zone (HAZ) of the weld(s). When the welding procedure is performed the heat changes the micro structure of the heat-affected zone, making the weld harder in the stir zone and softer in the material next to the stir zone, which compromises the strength of the joint. The only way to address this problem is to heat treat the materials after the welding process has been performed, but this can be time consuming, expensive, and impractical in most cases.

An effort to improve mechanical properties of welded UHSS has resulted in an interest in Friction Stir Welding (FSW). FSW is a solid state joining process that is currently used with light metals like aluminum, because the tooling required is able to withstand the stress and temperatures that occur during FSW. The low temperatures involved with FSW made it a practical choice for welding processes to be used with UHSSs. It was found that FSW refined the grain size in the stir zone of the weld, which actually increases the strength of the weld(s) (Chun, 2010).

With increasing safety and emissions standards being placed on the auto industry there has been a lot of interest in high strength steels, because of their favorable strength to weight ratios. UHSSs typically exceed yield strengths of 550 MPa while conventional steel has average yield strength of around 240 MPa (Zrnik, 2006). The increased strength of the UHSSs is significant, because it reduces the amount of material needed to achieve the desired strength, which allows the manufacturer to reduce overall weight. Weight reduction in the automobile industry is essential to help improve the overall fuel efficiencies. Studies have shown that the implementation of high strength steels can reduce the curbweight by around 19%. When these weight savings are applied to the compact car category it is estimated to increase the fuel mileage by 3-4 mile per gallon (Hyung-Ju Ki, 2011). It should also be noted that, although less material is needed when using UHSSs, the crash worthiness and safety of the cars meet or exceed that of cars made from conventional steels (Manabu TakahashiI, 2003).

## 2.2 Fusion Welding of UHSS

The major hurdle the auto industry has encountered with UHSS is that they do not respond well to conventional fusion-welding processes. This is the case, because with fusion-welding processes you exceed the melting point of the metal, which significantly changes the microstructure of the metal when the weld pool solidifies. The changes in the microstructure compromise the original mechanical properties of the metal, and in the case of UHHS this causes the HAZ to become brittle (S. Daneshpour, 2009). The weld is brittle, because of high alloy content and high cooling rates, which result in a significant fraction of martensite in the weld, as well as microcracks which form during solidification. By minimizing the heat produced in the welding process, as is the case with FSW and FSSW, it is possible to reduce the extent of the HAZ and improve the mechanical properties of the weld, relative to a fusion welding process like resistance spot welding (RSW). Upon close inspection of the HAZ of a weld produced by RSW, it was noted that along with the microstructure changes there were cracks that were visible (Nikoosohbat, 2010). RSW cooling rates play a major role in causing the HAZ to become hard and brittle, "RSW… cooling rates...range from over 100,000°C/s for gauges less than 0.5 mm, to roughly 2000°C/s at a 2.0-mm gauge (Gould, 2006)." The advantage RSW has is that it is already widely used in the auto industry, so it is much more economical to use when compared with other welding methods that would require new tooling and possible layout changes.

Laser beam welding (LBW) is another fusion welding method that has been investigated to be used with UHSSs. LBW uses a highly concentrated laser beam to join metal together. This results in good penetration into the metal as well as the ability to focus the welds very accurately. These qualities result in a small HAZ. However, because LBW produces very high temperatures with high cooling rates, the HAZ is still an issue. When LBW is used with UHSSs it is likely that the HAZ will become more martensitic, which creates conditions where it is more likely for failure to occur at the joint, because of brittle fracture. When destructive testing is performed on LBW samples it has been observed that the martensite formation was detrimental to the integrity of the joint (Gould, 2006). Again much like RSW, LBW shares the same drawback of the cooling rates. The range of cooling rates is scattered between 200° to 5000°C/s. These rates are largely dependent upon the parameters that are used (Gould, 2006).

Gas metal arc welding (GMAW) is a third fusion welding process that is commonly used in the auto industry. This process shares the same drawbacks as RSW and LBW especially when used with UHSSs. The micro structure of the metal in the HAZ changes, causing the metal in the HAZ to become more martensitic. This makes the welded joint become brittle, degrading the metals original mechanical properties and making it more likely to fail in fatigue. The cooling rates associated with GMAW largely depend on the parameters used, but generally range between 20° to 300°C/s (Gould, 2006).

**2.3 Mechanical Fastening of UHSS**

In the auto industry it is becoming more common to use steels and aluminums side by side, in order to reduce the weight of the automobile frame. However, joining aluminum to UHSSs has proven difficult. A method, which has received some attention over the past 5 years or so, is self-piercing riveting (SPR). This process uses a consumable rivet along with a die. The rivet is punched through both pieces of metal from the top, and enters the die and flares out. Lap joints are usually produced when riveting. This process has worked well when joining aluminum with mild steels, but has not been as successful with UHSSs. The increase in strength of the UHSSs creates problems with riveting, because the metal is less ductile, which causes the UHSSs to rupture when riveted; this can cause corrosion or failure. Another common problem is the rivet flaring before penetrating the UHSS; no joint is created when this happens. It was found that UHSSs with a tensile strength of less than 590 MPa are ideal for riveting, but UHSSs above 590MPa do not respond well to riveting and tend to rupture when the rivet is able to penetrate (Abe, 2009).

### 2.4 Diffusion Bonding of Steel

In an effort to maintain the original mechanical properties of the metals being joined, a method of joining known as diffusion bonding has shown potential. Diffusion bonding relies on pressure and heat applied over time to join two pieces of metal through the exchange of atoms across the joint, due to concentration gradients. This method of joining has proven effective with non-weldable high alloy steels (V. Rajinikanth, 2010). Although diffusion bonding has proven effective with bonding otherwise non-weldable metals it is a long process that can take 1-2 hours at temperatures that are 50-70% of the metals melting point under the pressure of very heavy uniaxial loads. This process is very time and energy intensive.

### 2.5 FSSW of Steel

Friction Stir Spot Welding (FSSW) is also a form of diffusion bonding, but requires a fraction of the time and energy to create a bond. FSSW when described in its most basic form is diffusion bonding, but without some of the drawbacks. Two advantages FSSW has over conventional diffusion bonding are it uses less energy, and it is a much quicker process.

FSSW is a good alternative to fusion welding processes, because it allows the joining of metals without significantly altering the micro structure of the metals being joined, ensuring the metals will retain most of their original mechanical properties (Chung, 2010). When comparing FSSW to riveting when dealing with UHSSs, FSSW has the advantage of being able to join

UHSSs with tensile strengths greater than 590 MPa. Riveting is not recommended for metals with yield strengths higher than 590 MPa, because of the high rate of failures that happen when rivets are used (Abe, 2009).

For FSSW to achieve wide spread acceptance in industrial settings the tooling needs further development. Tool life has been a major limiting factor to implementation of the FSSW with UHSSs. Tool composition generally is a very high percentage of PCBN. This brings pros and cons. The pros are that the tool wears well due to the hardness of PCBN, but on the other hand if the tool is too hard it becomes brittle and tends to crack resulting in premature failure before abrasive tool wear caused the eventual failure of the tool (Miles, 2011). Since FSSW is a relatively new method for joining UHSSs, a lot of effort is being made to understand what the best practice is for implementation.

In a study comparing FSSW to RSW the tool plunge was experimented with in an attempt to meet or exceed a minimum lap-shear value of 10.3kN. The end plunge depth was kept consistent and so was the total weld time. The test compared a constant plunge rate to a two stage plunge rate where the tool started with a high plunge rate flowed by a slower rate. This study showed that the welds done with the two stage plunge rate were able to exceeded 10.3kN. This demonstrated that FSSW is a viable replacement for RSW as far as lap-shear strengths are concerned (Santella, 2008).

Low welding temperatures are a major advantage FSSW has over other more conventional welding methods, but this is not the only advantage FSSW has. It has been demonstrated that FSSW has been able to successfully join dissimilar grades of steels with different thicknesses. The joints have even exceeded strength requirements set by the American

Welding Society (AWS) (Santella, 2012). Progress has also been seen recently with the tooling used with FSSW. A high volume low cost silicon nitride tool has been developed and evaluated as an alternative tooling material to PCBN. PCBN tools are generally very expensive to make and are produced at a lower volume than is possible with the silicon nitride tools (Santella, 2012).

When considering FSSW over other joining methods it is becoming a more and more viable alternative, because of the substantial progress that is being made with respect to the weld quality and the costs associated with performing the welds. For these reasons PCBN tools, and to a lesser extent $Si_3N_4$ tools, will be studied for wear resistance and capability of producing appropriate joint strength in DP 980 steel, as will be described in chapter 3.

**2.6 Polycrystalline Cubic Boron Nitride (PCBN)**

"PCBN composites are produced by sintering micron CBN (cubic boron nitride) powders with various ceramics, so as to produce extremely hard and thermally stable tooling materials. Most PCBN materials are integrally bonded to a cemented carbide substrate. CBN is the second hardest material known after synthetic diamond, but has high thermal and chemical resistance properties. PCBN composites provide extreme resistance to deformation and wear at high temperatures – typically an order of magnitude better than the nearest ceramic materials (Element Six, 2012)."

PCBN tools are seeing an increase in use for machining hardened steels, because of their high thermal resistance and their hardness. These two characteristics are reasons why PCBN has been a tooling material of interest for performing FSSW in UHSSs such as DP980.

An effort to improve PCBN tools is an ongoing task. These efforts include developing tougher more wear-resistant grades of PCBN, which is important; because many times the PCBN "…tool strengths are only marginally higher than the alloys being welded (Nelson, 2007)." To accomplish this CBN grain size and distribution were evaluated through testing different samples. Two tests were carried out the first was a turning test on 304L stainless steel, which determined if the tool had greater wear resistance, if it did, it passed on to the second test. For the second test wear and toughness were evaluated again, but this time through FSW in 304L. The results from evaluating the grain size and distribution were successful and resulted in the development of tougher more wear resistant tools (Nelson, 2007). This is fits nicely with the work done in this study on PCBN tools and FSSW, because three different grades of PCBN with different grain sizes have been evaluated and the data which has been collected shows that the CBN grain size has a direct effect on not only the toughness and wear resistance of the tool, but also the overall quality of the welds.

### 2.7 Silicon Nitride (Si3N4)

The Silicon Nitride tool material is commercially known as EKasin S, EKatherm, which is made with a process called gas pressure sintering. Tools made from this material have qualities that give them high temperature resistance, and high thermal shock resistance (Ceradyne, 2012). These qualities make silicon nitride tools a good choice for FSSW in UHSSs, because the tools can sometimes reach red hot temperatures, and depending on the cycle times for the weld, the welding can be very cyclic, which causes the tool to rapidly heat and cool causing thermal shock.

Wear resistance is an important characteristic with the tooling used in FSSW. Studies that have been previously carried out have shown that silicon nitride tools when compared to PCBN tools experience a much more rapid rate of tool wear (Santella, 2009). This results in an earlier drop off of lap shear fracture load values resulting in a much shorter tool life. However, silicon nitride tools are not without their advantages. PCBN tools may have a longer tool life, but silicon nitride tools provide a low-cost alternative. According to studies done at the Pacific Northwest National Laboratory silicon nitride tools have the potential to provide a "…two order magnitude reduction in tooling cost for FSSW (Hovanski, 2011)." This is significant, because many times the biggest barrier to adoption of a new process is the cost.

## 3. EXPERIMENTAL APPROACH

The experimental approach was designed to ensure the data collected would offer valuable new information about FSSW of UHSS. The following are two goals that were used to create the testing methodology of this research project:

1. Evaluate three different grades of PCBN tools for wear resistance, or tool life, for FSSW of DP 980 steel.
2. Evaluate joint strength over time for three different grades of PCBN tools, to determine the relationship between tool material, tool life, and joint strength.

The DP 980 steel used for the experiments had the following composition, in weight percent: 0.15% C, 1.44% Mn, 0.011% P, 0.007% S, 0.32% Si, and 0.02% Cr, where the balance was Fe. To ensure that useful data is gathered the variables that will be controlled during the experiments are those which have an impact on temperature, pressure, and welding time. The variables are the following: spindle speed, plunge rate, dwell time, and plunge depth.

In order to evaluate the joint strength produced by FSSW lap shear tension testing will be done over the course of wear testing of the tools. The **lap shear specimens** will be produced on a FADAL CNC Mill (see figure 3.1) where one lap joint sample will be welded at a time.

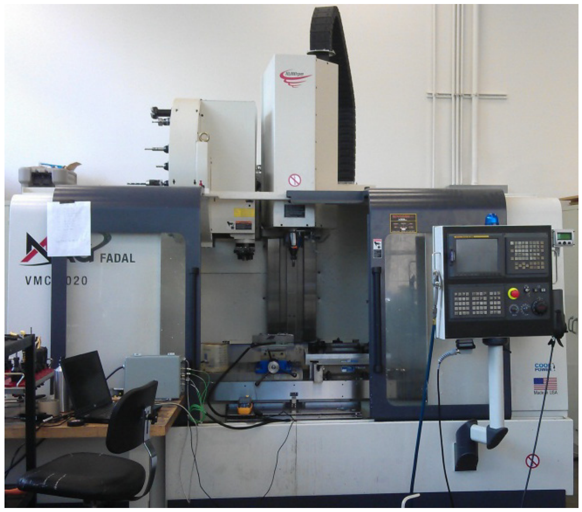


**Figure 3.1: Fadal CNC Mill**

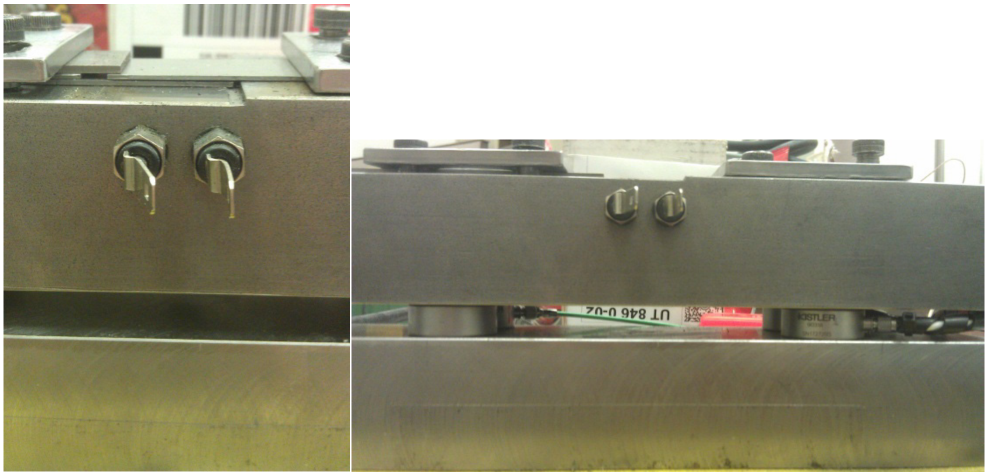
The sample will consist of two coupons of DP980 steel (see figure 3.2) the dimensions of 100 mm x 25 mm x 1.2 mm thick in a lap joint with the top coupon over lapping the bottom coupon by 25 mm.


**Figure 3.2: DP980 Coupon**

Adjustments to the variables were made to achieve a set of welding parameters which resulted in at least the minimum required lap shear fracture load, which is 2.4 kN for 1.2 mm DP 980 steel. The lap shear fracture load was measure on an Instron Tensile Tester (see figure3.3 a)) that will pull the samples in a lap shear configuration (see figure 3.3 b)) until the welded joint fails.

**Figures 3.3 a) & 3.3 b): Close Up of Lap Shear Tensile Test and Instron Tensile Tester**

The spindle load during welding was provided through four load cells located on each corner of the rectangular fixture that holds the welding samples in place (see figures 3.4 a). , 3.4 b). , 3.5). As the tool plunges into the sample the data from the load cells is then sent electronically to a data acquisition system which then inputs the data into an excel spreadsheet. The first 100 points recorded by the acquisition system are averaged and the average is either added or subtracted from the whole data set to compensate for any noise that might be in the system. This ensures we have an accurate zero value.



**Figures 3.4 a) & 3.4 b): Lap Configuration and a View of the Load Cells**

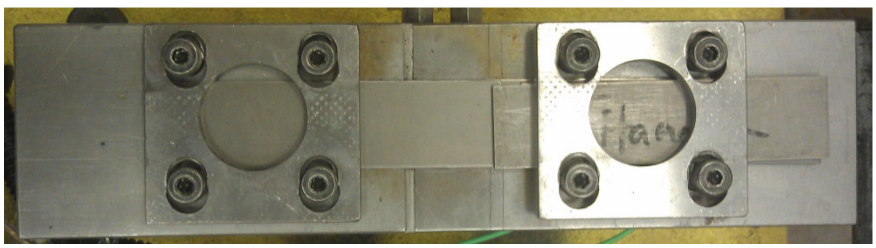


**Figure 3.5: Top View of the Clamping Mechanism**

The weld temperature was provided through an Omega Data Logger Thermometer, with two thermo couples attached to it. One thermo couple will read the ambient temperature as a control, and the other will be placed in a groove on the fixture under the sample to allow accurate recording of the temperature. The data is automatically collected and brought into an excel spread sheet.

The wear test was also done on a FADAL CNC Mill. For this test four initial lap shear tests were performed with the parameter set that consistently provided the strongest welds. The data was recorded as stated above; however, the fourth sample was not tested in the Instron Tensile Tester. It was sectioned on a wire EDM and then polished and etched; this allowed further inspection of the microstructure of the sample and the tool profile by optical microscopy. This provided a better understanding of how FSSW affects the mechanical properties of ultra-high strength steels, because it provided information on how the microstructure of the steel had been changed, which can be related to mechanical properties of the joint. After the lap shear tests, the wear test began on two 330.2 mm x 330.2 mm x 1.19 mm pieces of DP980 one laid on top of the other (see figure 3.6).

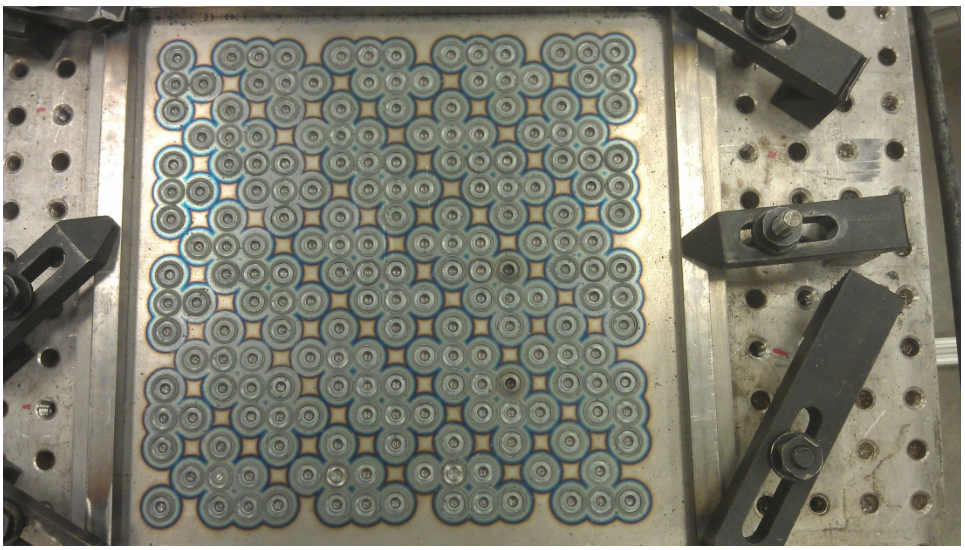


**Figure 3.6: Wear Test Plates and Fixture**

During this test 96 welds were carried out and then four more lap shear tests were performed and a picture was taken to compare the tool wear. The pictures were be taken of the fresh tool with no welds, and then at approximately every 100 welds after that. This process was repeated until there is tool failure. Tool failure is identified with the following criteria:

When a tool's lap shear fracture load drops significantly and will not increase with an increase in the tool's offset setting.

When the tool wear causes a chip or a crack that significantly alters the tool geometry making the tool unable to weld.

A major part of the research was preparing samples for optical microscopy to look at the cross sections of the welds every 100 welds. The sample preparation involved several steps.

1. Every 4th lap shear sample was held back

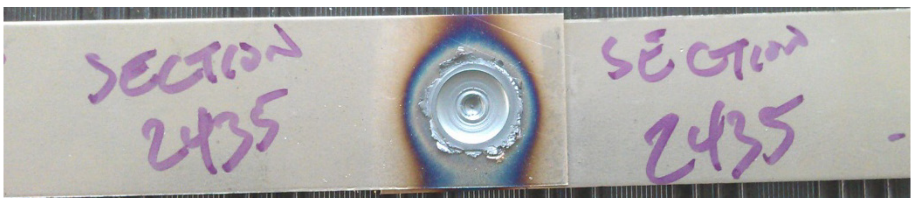



**Figure 3.7: Forth Lap Shear Sample for Sectioning**

2. The sample was cut on a Wire Electrical Discharge Machine (Wire EDM) down the center of the weld.


**Figure 3.8: Sectioned Sample**

3. The sectioned sample was mounted in Bakelite in sets of three with the weld numbers and serial numbers of the tools engraved on the back side of the Bakelite sample.

**Figure 3.9: Bakelite Sample with Three Weld Profiles**

4. Polishing of the samples was carried out in stages and was done wet with a constant stream of water. The process started with 120 grit sand paper and continued through 240, 400, 600, 800, and 1200 grit sand paper. Polishing cycle times ran for 12 minutes, and at the end of each cycle the samples were rinsed off with water and inspected to make sure they were polishing correctly, and if needed the step was repeated. After the sand paper portion of the polishing was completed, a polishing compound was used to create a mirror like finish on the samples. The polishing compound started with a 6 micron paste, then to a 3 micron paste, and then finally a 1 micron paste and followed the same pattern as the sand paper grits, but without water.

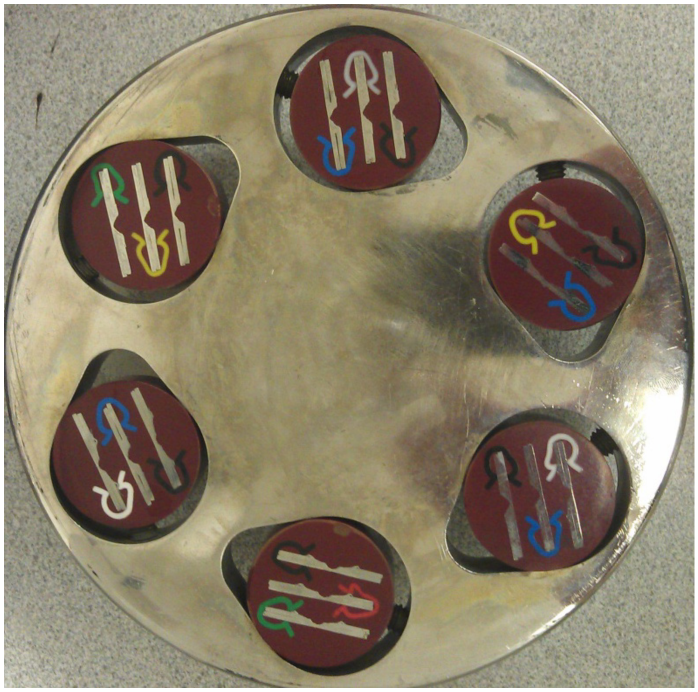


**Figure 3.10: Polishing Wheel with Samples Mounted**

5. Etching the samples was the final preparation step of the process. Etching the samples makes the micro structure of the sample become more visible. This was done with 20% Nital etchant. The etchant was applied with cotton swabs and was left on for around 30 seconds. It was then rinsed with methanol to neutralize the Nital and rinse it from the sample. Finally the sample was air dried with compressed air.

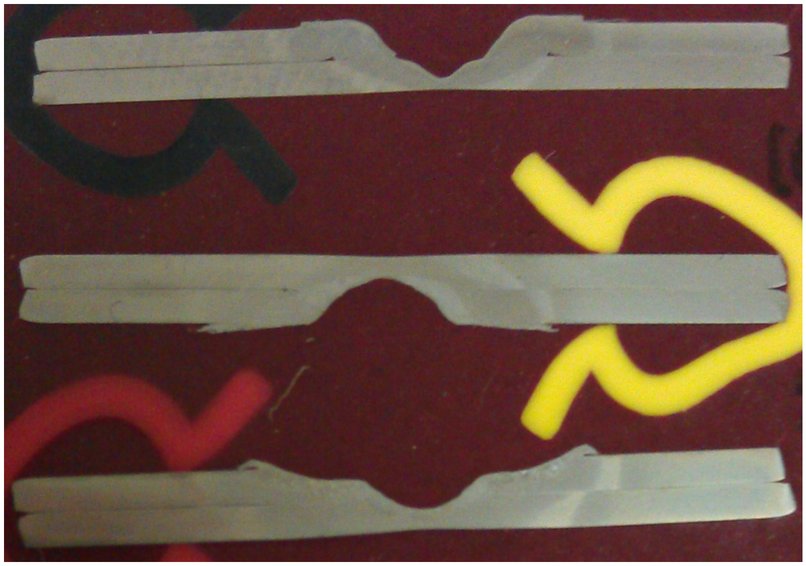


**Figure 3.11: Polished Cross Sections with Nital Etching**

6. The last step of the process was the optical microscopy or taking pictures of the samples with a microscope. This was done to provide closer inspection of the welding hooks, the bond area, weld geometry, and micro structures of the samples.

**Figure 3.12: Three Examples of Pictures Taken with a Microscope. From Left to Right the Pictures Show the Geometry, the Bond Area, the Welding Hook, and All of them Show the Microstructure**

The final part of the testing involved making maps of the micro hardness of six cross sections. One tool was selected from each tool type, and micro hardness tests were be run on the first cross section and the last cross section made with the tool. This was done to compare the tools to each other, and to see how the number of welds on a particular tool affects the hardness of the weld in the HAZ.

**Figure 3.13: Micro Hardness Machine**

# 4. RESULTS AND DISCUSSION

## 4.1 Weld Parameters

A set of welding parameters was developed and used to compare three different tool types. The tools are different grades of PCBN, labeled A, B, and C. Five different tools of each grade were tested to provide a sample size large enough to identify which tool type is best for UHSS applications. The development of the welding parameters was done using a PCBN tool while adjusting the following variables to optimize the lap shear fracture load values: RPM, feed rate, and plunge depth. Figure 4.1 contains the parameter set used for testing.

**Table 4.1: Weld Parameters Used for Lap Shear Testing and Wear Testing**

| Plunge Depth (mm) | Feed Rate (mm/min.) | RPM | Weld Time (sec.) | Rotations |
|---|---|---|---|---|
| -1.016 | 25.4 | 6000 | 2.40 | 240 |
| -1.778 | 50.8 | 6000 | 3.30 | 330 |
| -2.413 | 7.62 | 6000 | 8.30 | 830 |

Welding was done with a three stage plunge (the tool advanced into the material in three steps) with different feed rates at each stage of the weld. The only adjustments made during testing were offset settings to account for tool wear.

## 4.2 Lap Shear Fracture Load

During lap shear testing the target fracture load was 10.68kN, while not exceeding vertical welding loads of 8 kN. To evaluate each tool the fracture load and the vertical welding loads were recorded for three welds out of every 100 welds done. This provided information that enabled a performance profile to be built for each tool tested. The performance profile takes into account the number of welds the tool was able to perform, the fracture loads of the welds, and the vertical welding loads.

### 4.2.1 A-Type Tool

The A-type tool had the best overall performance profile. The type A-1 tool lasted for 1200 welds, and was able to maintain average fracture loads of 9.47 kN. At 600 welds its average fracture load was 10.96kN, and at 400 welds the average fracture load was 11.05 kN. The average fracture loads were taken at 400 and 600 welds to allow comparison across different tool grade types. Most of the tools lasted to or past 600 welds, while one tool only lasted up to 400 welds before tool failure. With the A tool type it was observed that the first three welds had an average vertical welding load of 6.22 kN and after the first 100 welds on the tools the vertical welding load decreased to an average of 4.5 kN for the remainder of the tool life up until the last three or four welds where the vertical welding load increased. The offset setting was adjusted throughout the testing of the tools to compensate for tool wear and to keep lap shear fracture loads above acceptable levels. Adjusting the offset of the plunge depth also helped to keep the vertical welding load consistent throughout the welding process until close to the end of the tool life. For each type A tool right before tool failure the fracture load values dropped off significantly while the vertical welding load values increased (see figures 4.2-4.6). Figures 4.7-4.8 provide a comparison of the lap shear fracture loads and the vertical welding loads for each type A tool tested. Both lap shear welding load and vertical welding load plots show a pretty consistent grouping from weld 1 to weld 600, which reflects the consistence of the A-type tool up to 600 welds.

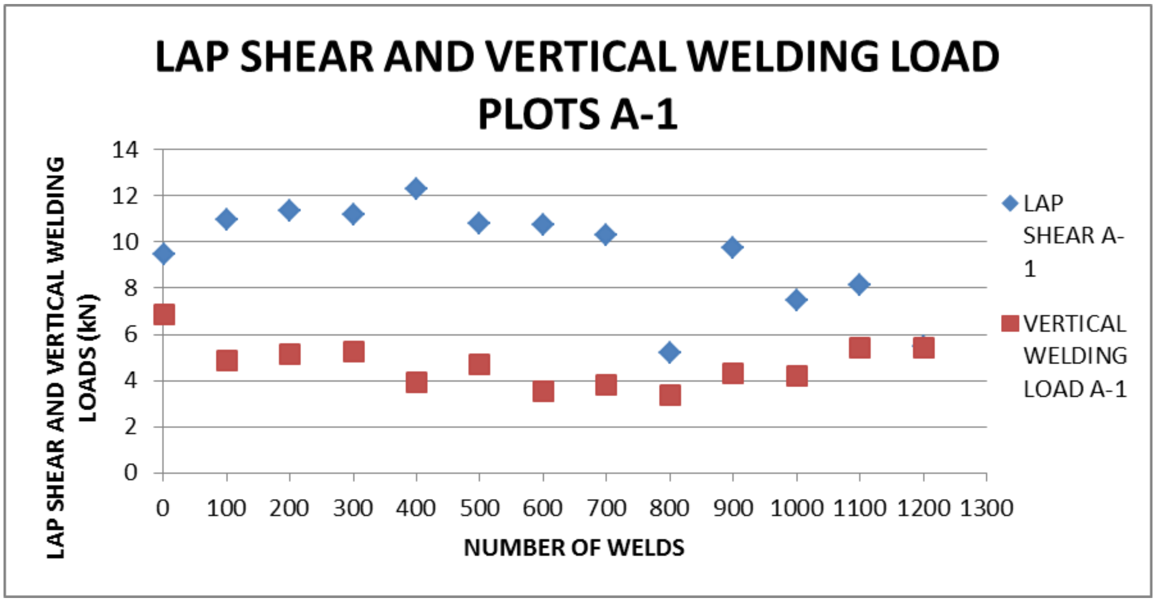



Figure 4.1: A-1 Lap Shear and Vertical Welding Load Plot

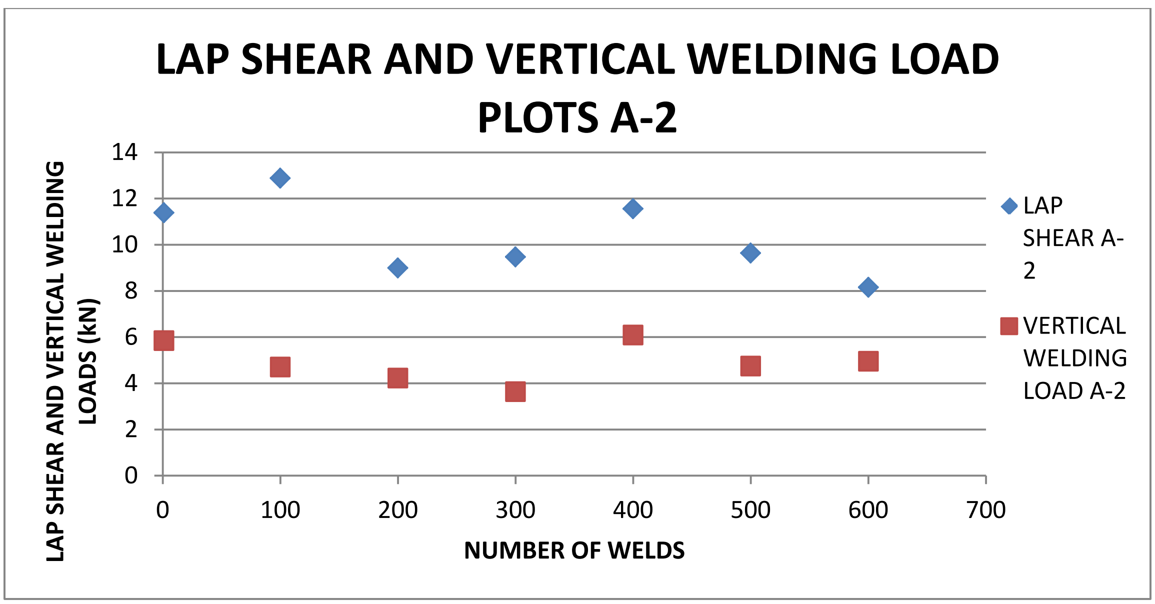



Figure 4.2: A-2 Lap Shear and Vertical Welding Load Plot

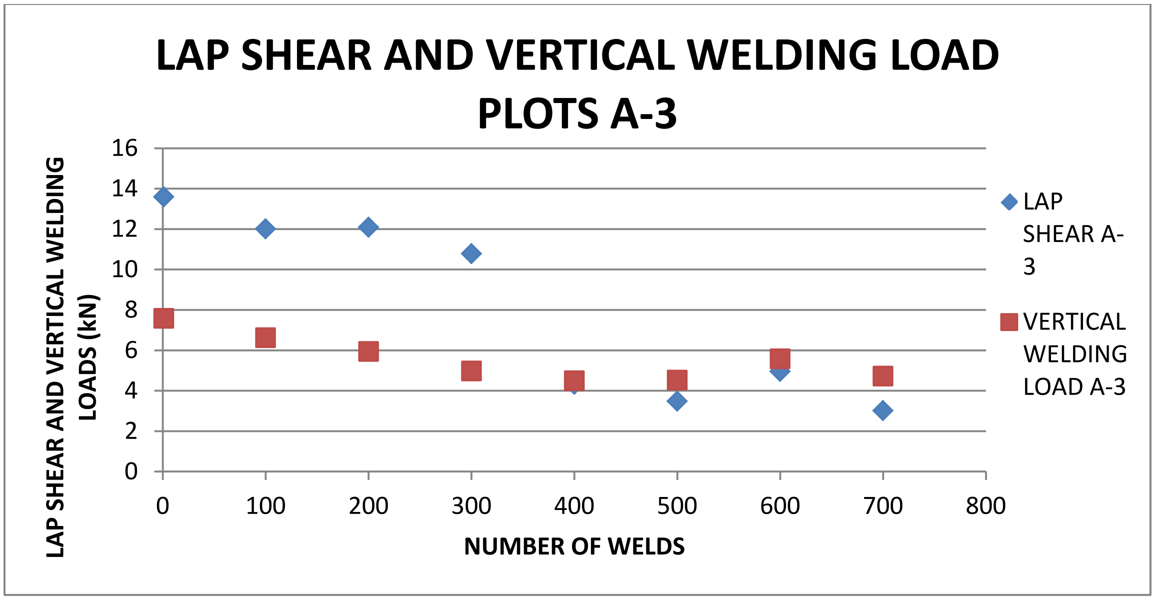



Figure 4.3: A-3 Lap Shear and Vertical Welding Load Plot

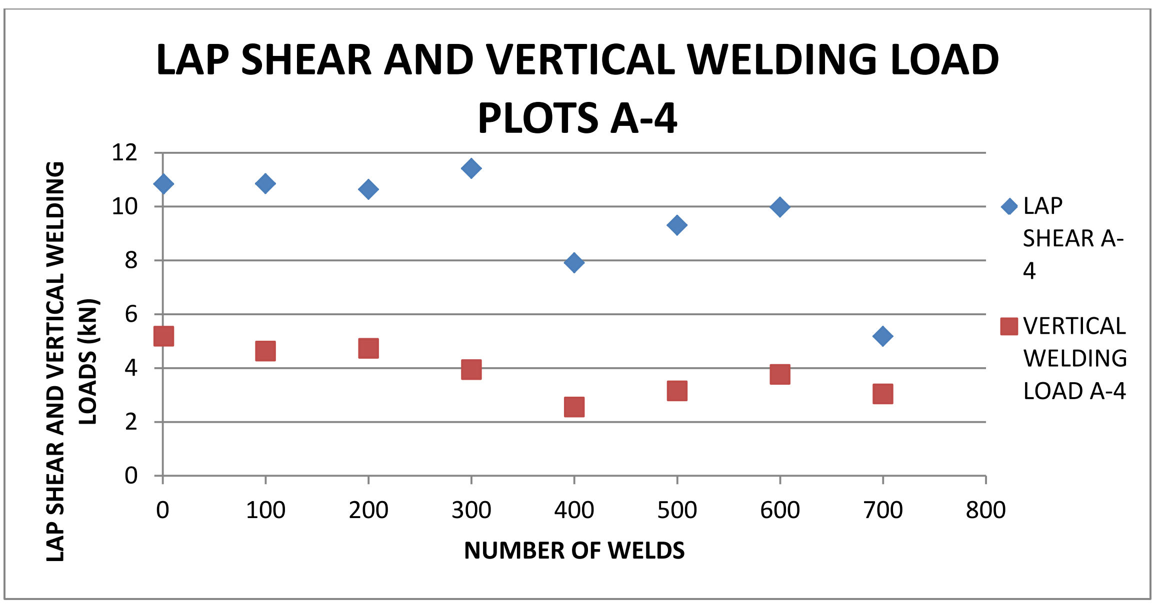



Figure 4.4: A-4 Lap Shear and Vertical Welding Load Plot

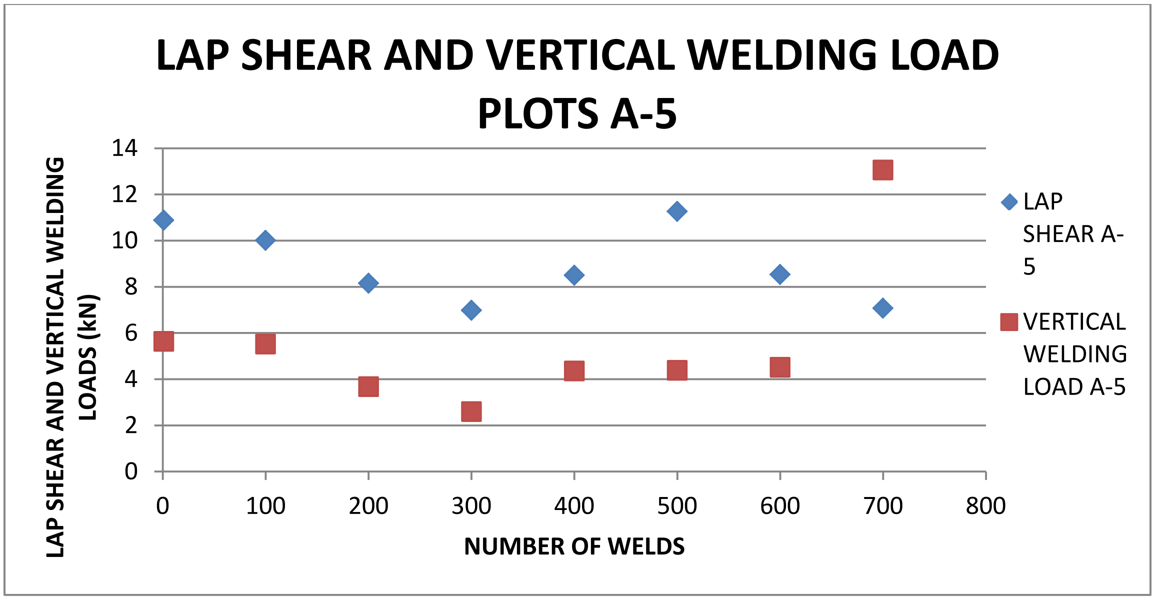



**Figure 4.5: A-5 Lap Shear and Vertical Welding Load Plot**

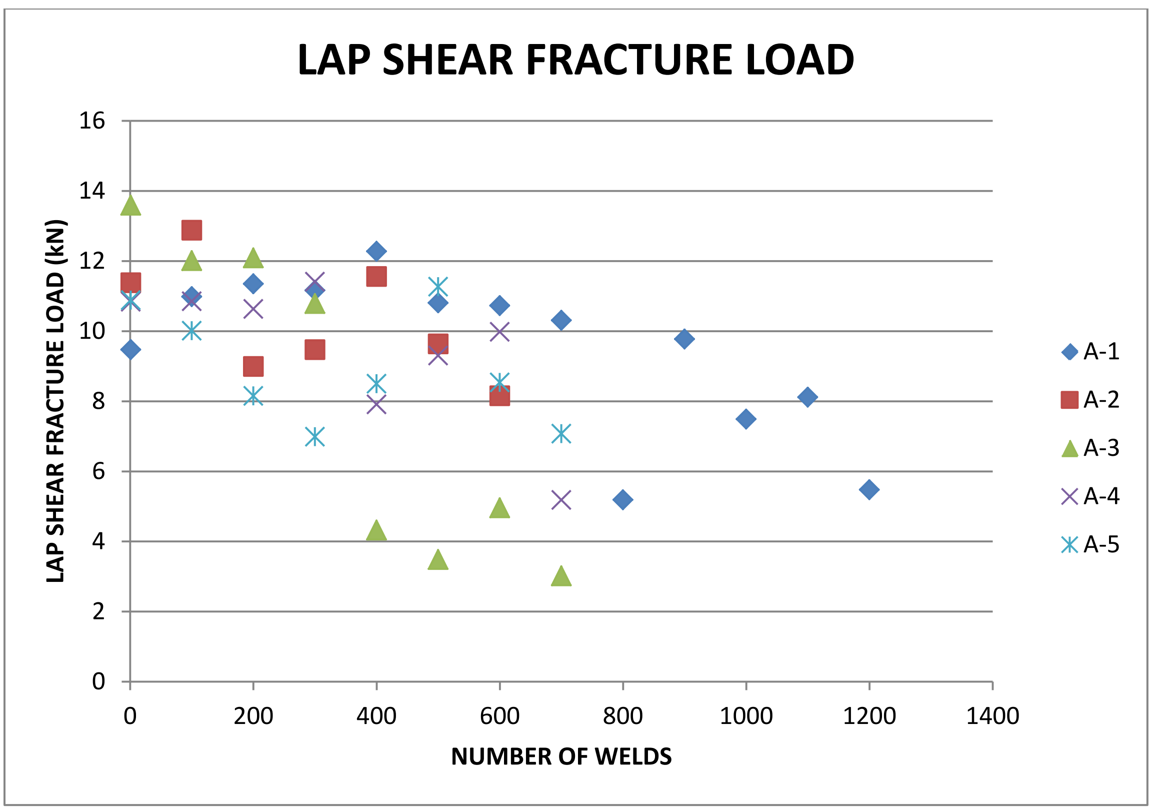



**Figure 4.6: A-Type Tool Lap Shear Fracture Load Plot**

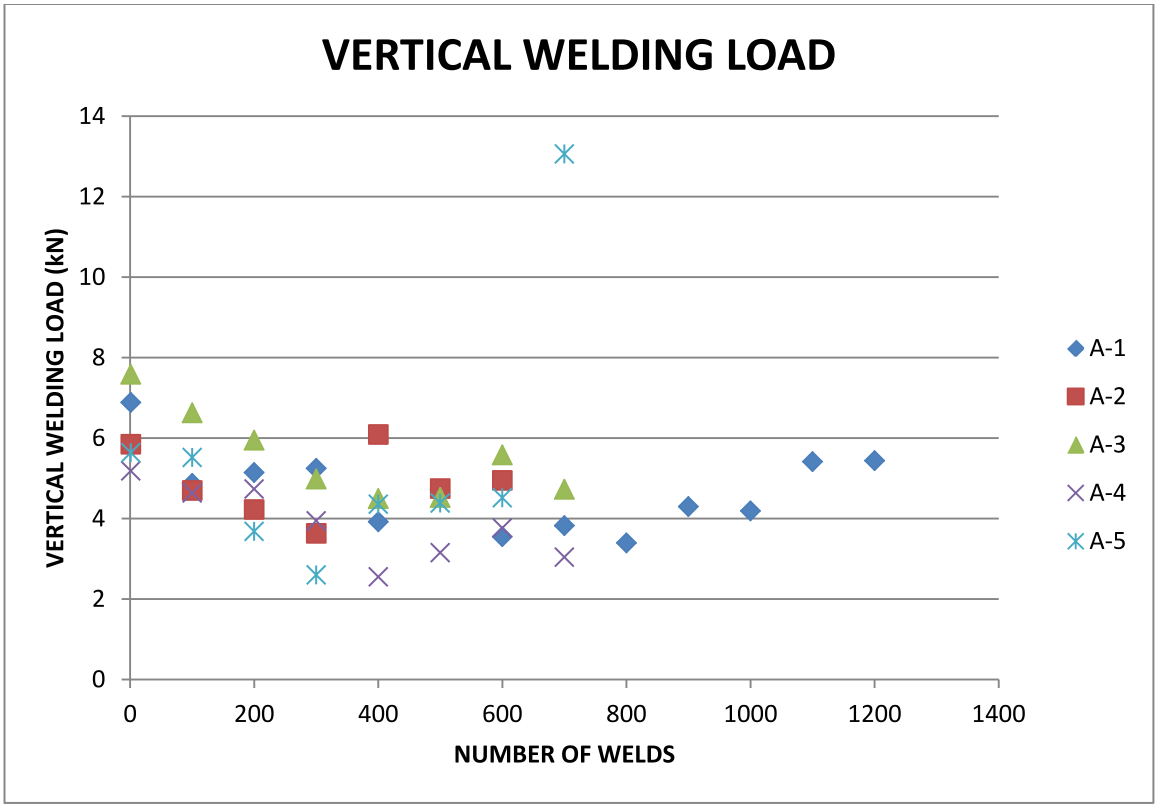



**Figure 4.7: A-type Tool Vertical Welding Load Plot**

**Table 4.2: Shows the Average Values for all A-type Tools Tested**

| | LAP SHEAR FRACTURE LOAD (kN) | VERTICAL WELDING LOAD (kN) |
|---|---|---|
| AVERAGE 400 WELDS | 10.34 | 4.92 |
| AVERAGE 600 WELDS | 9.87 | 4.77 |

### 4.2.2 B-Type Tool

The B tool type had the second best performance out of the three tool types tested. The tool B-5 experience premature failure during testing, but is included in the data to show tool performance at the beginning of the tool life. Figures 4.10-4.14 show the relationship between the lap shear fracture load and the vertical welding load for each tool tested. Towards the end of the tool life the lap shear fracture load curves and the vertical welding load curves show the lap shear values slightly decrease as the welding load values tend to increase. Figures 4.15-4.16

provide a comparison of the lap shear fracture loads and the vertical welding loads for each B tool tested.

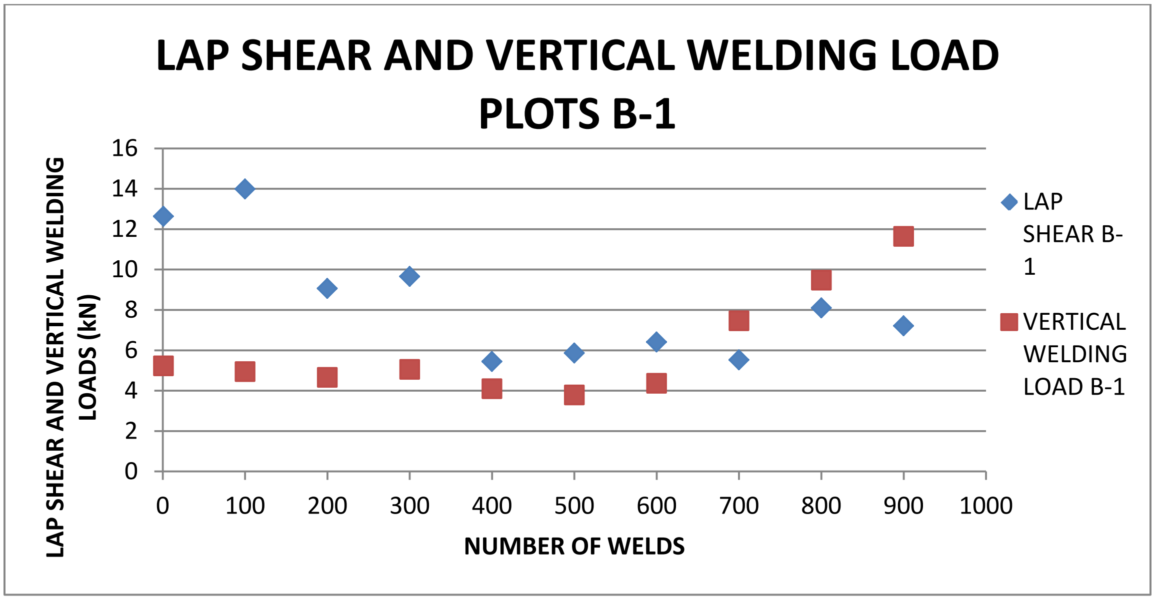



**Figure 4.8: B-1 Lap Shear and Vertical Welding Load Plot**

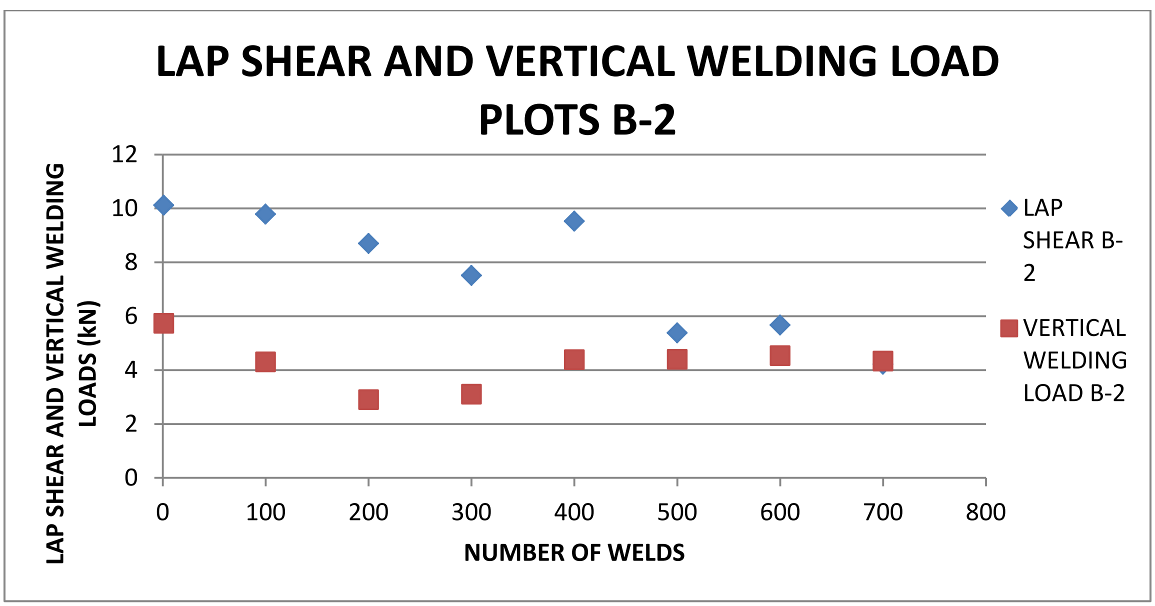



**Figure 4.9: B-2 Lap Shear and Vertical Welding Load Plot**

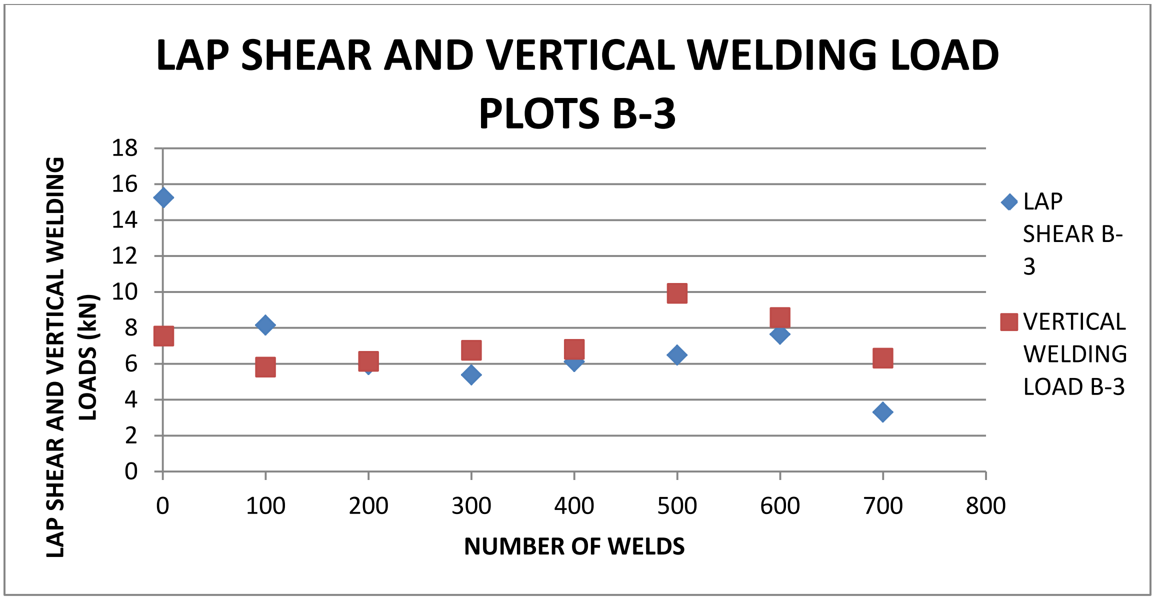



**Figure 4.10: B-3 Lap Shear and Vertical Welding Load Plot**

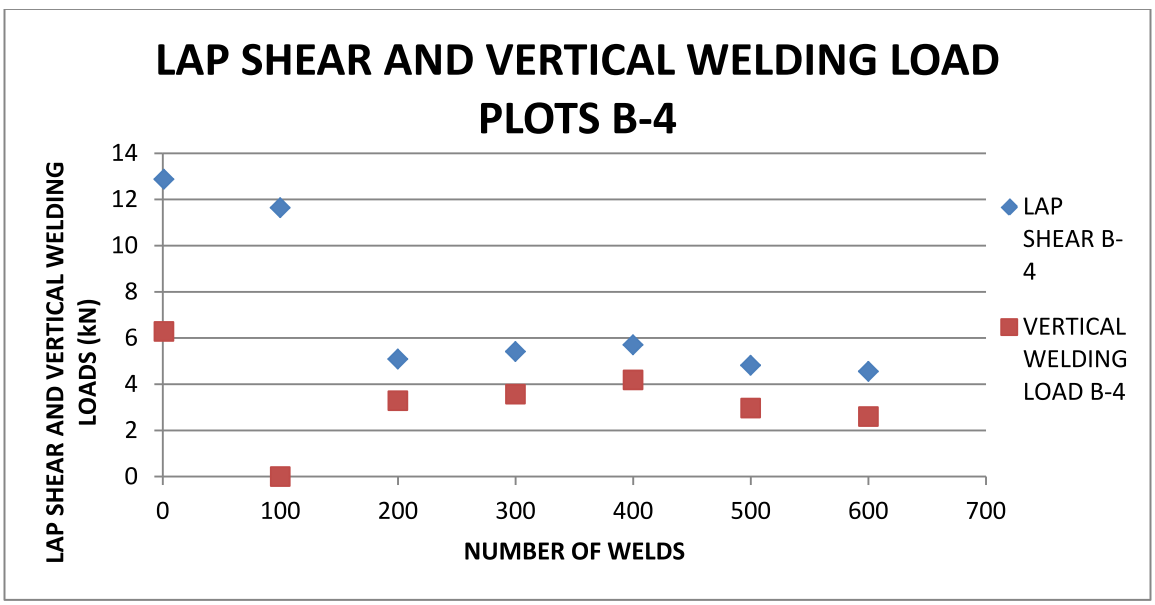



**Figure 4.11: B-4 Lap Shear and Vertical Welding Load Plot**

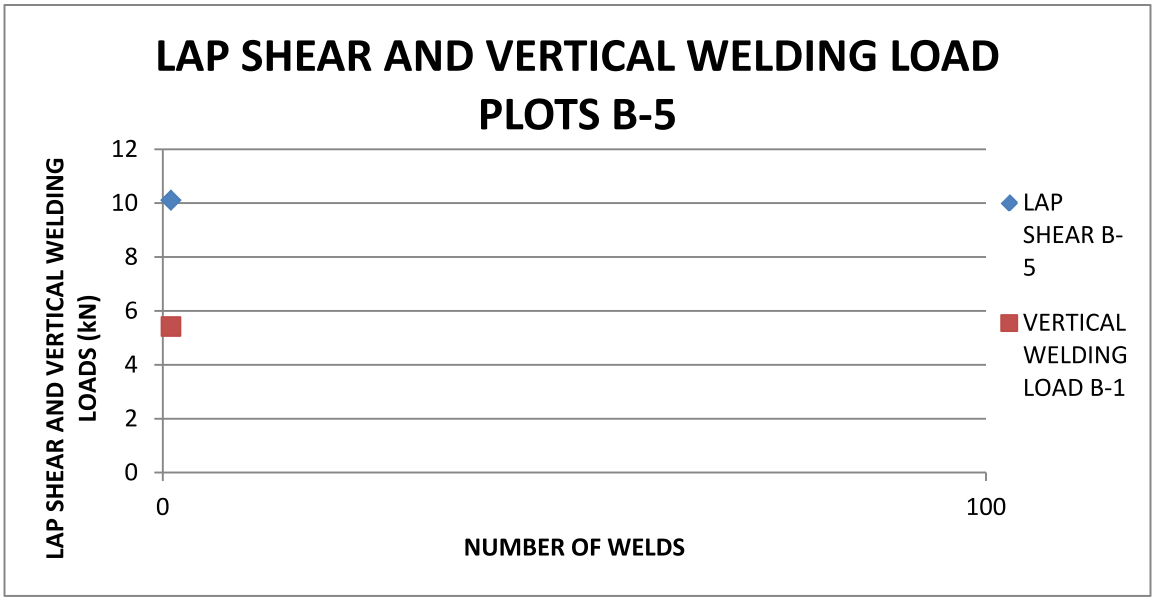



**Figure 4.12: B-5 Lap Shear and Vertical Welding Load Plot**

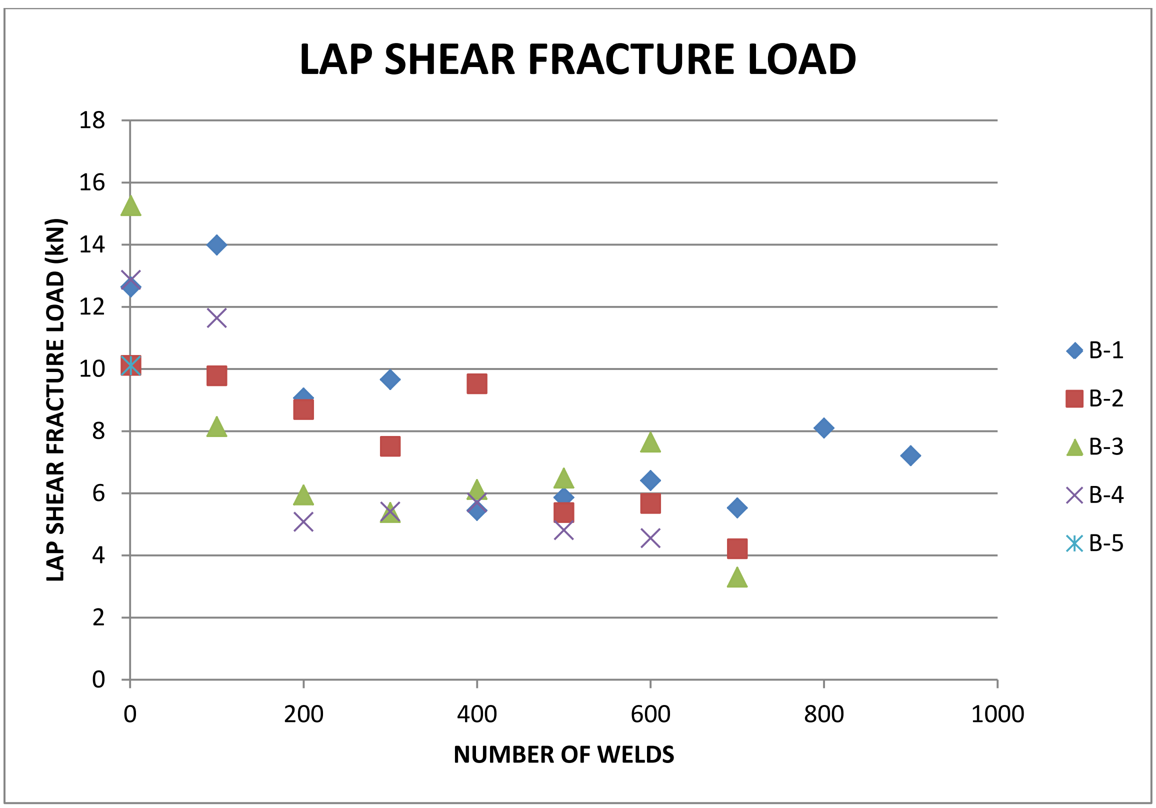



**Figure 4.13: B-Type Tool Lap Shear Fracture Load Plot**

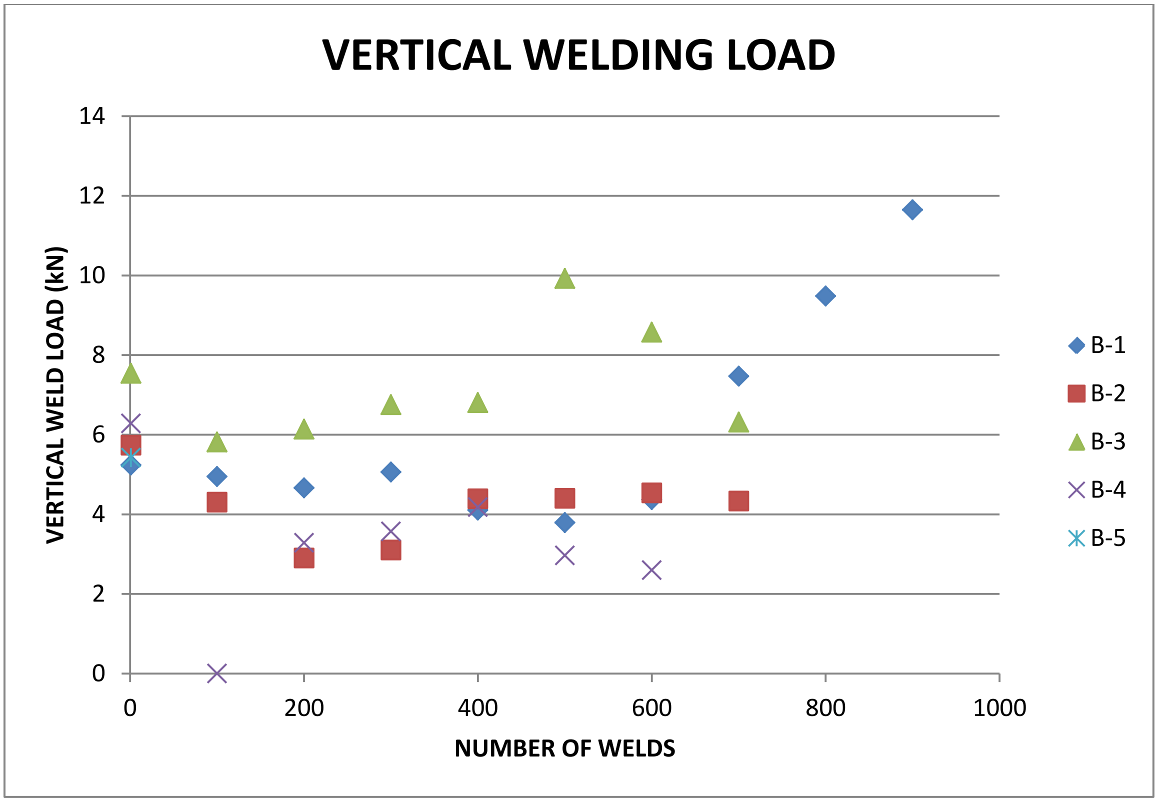



**Figure 4.14: B-Type Tool Vertical Welding Load Plot**

**Table 4.3: Shows the Average Values for all B-Type Tools Tested**

| | LAP SHEAR FRACTURE LOAD (kN) | VERTICAL WELDING LOAD (kN) |
|---|---|---|
| AVERAGE 400 | 8.90 | 4.96 |
| AVERAGE 600 | 7.61 | 4.99 |

### 4.2.3 C-Type Tool

The C type tool was very similar to the B type tool, but had slightly lower average lap shear fracture loads and a little bit shorter tool life. Figures 4.19-4.22 show the relationship between the lap shear fracture load and the vertical welding load for each tool tested. Figures 4.23-4.24 provide a comparison of the lap shear fracture loads and the vertical welding loads for each C type tool tested.

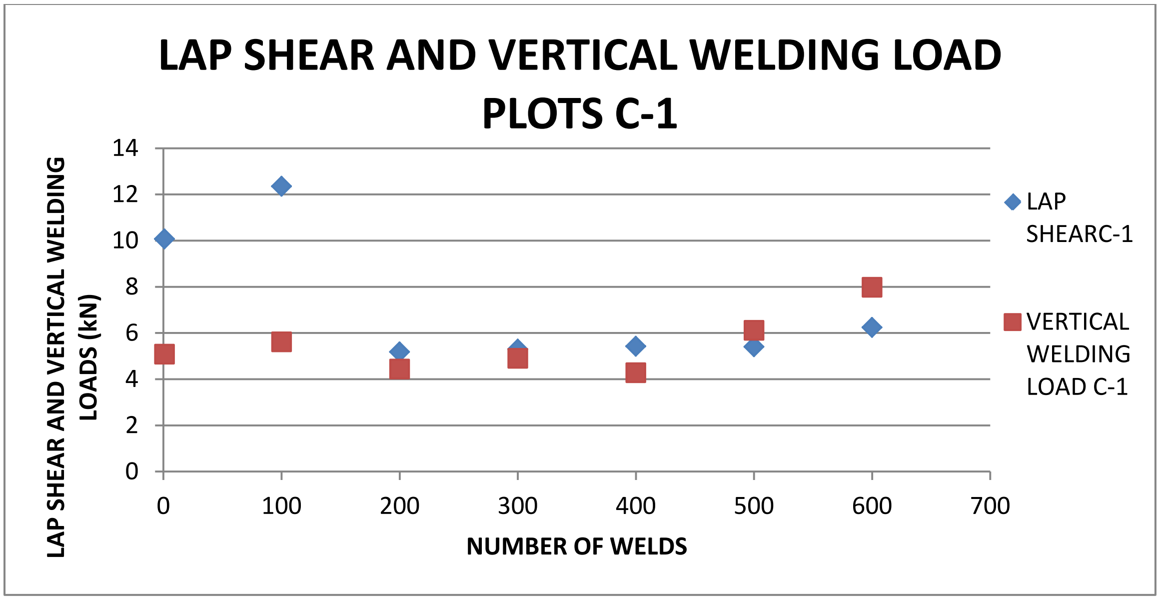



**Figure 4.15: C-1 Lap Shear and Vertical Welding Load Plot**

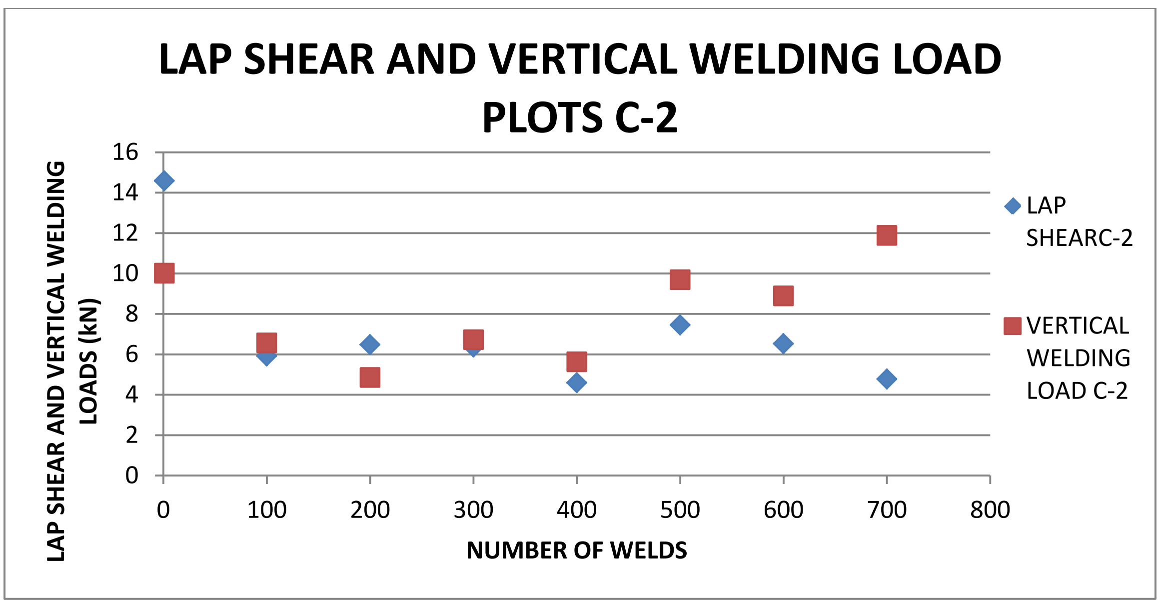



**Figure 4.16: C-2 Lap Shear and Vertical Welding Load Plot**

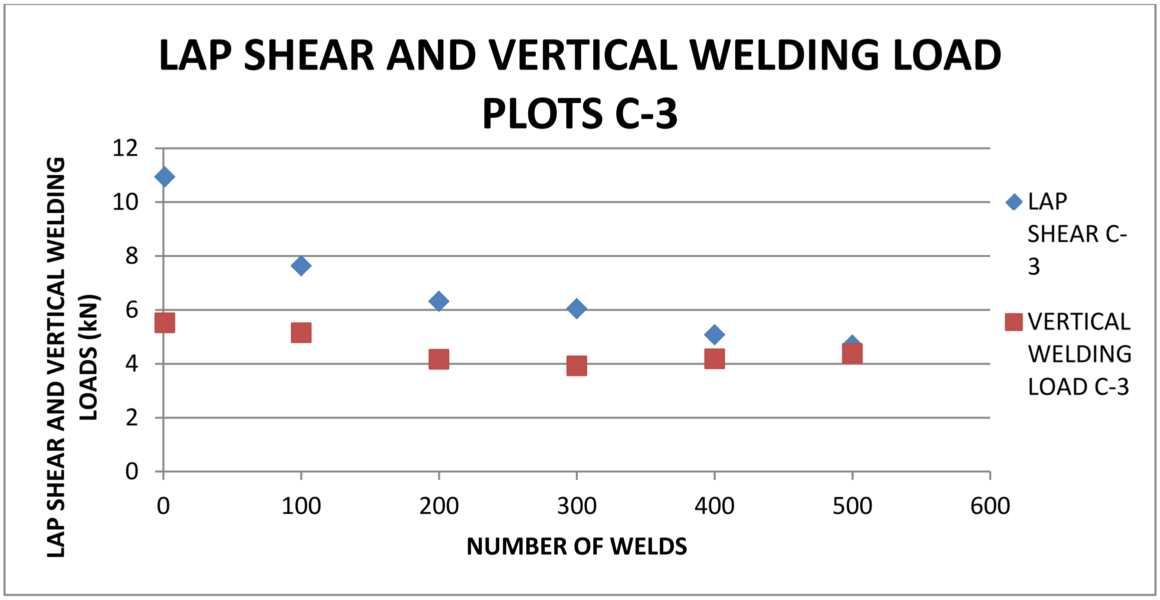



**Figure 4.17: C-3 Lap Shear and Vertical Welding Load Plot**

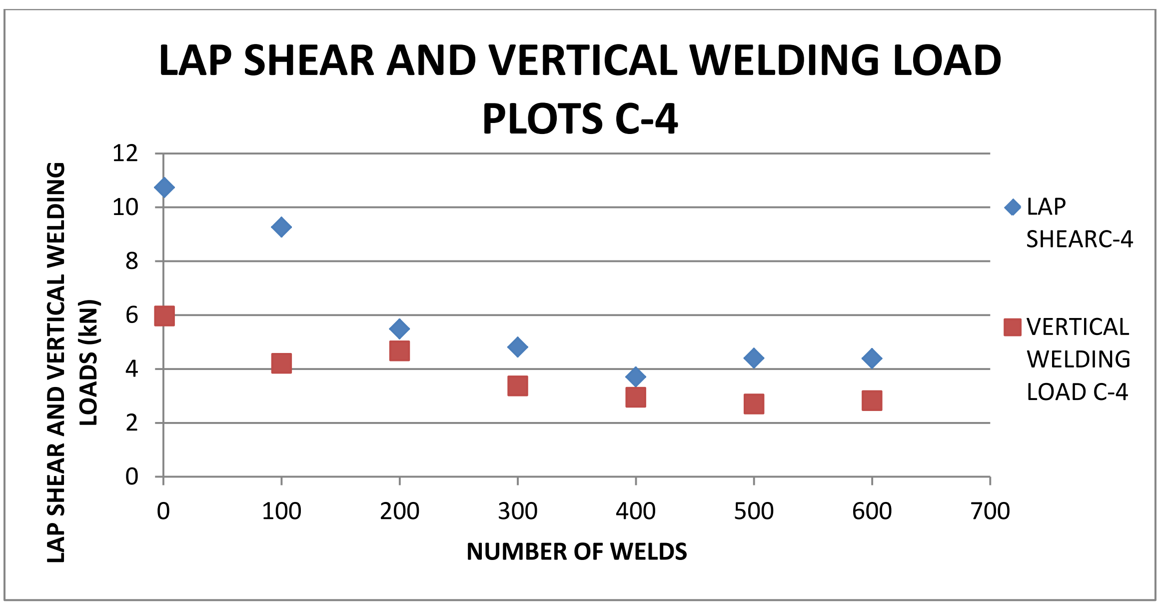



**Figure 4.18: C-4 Lap Shear and Vertical Welding Load Plot**

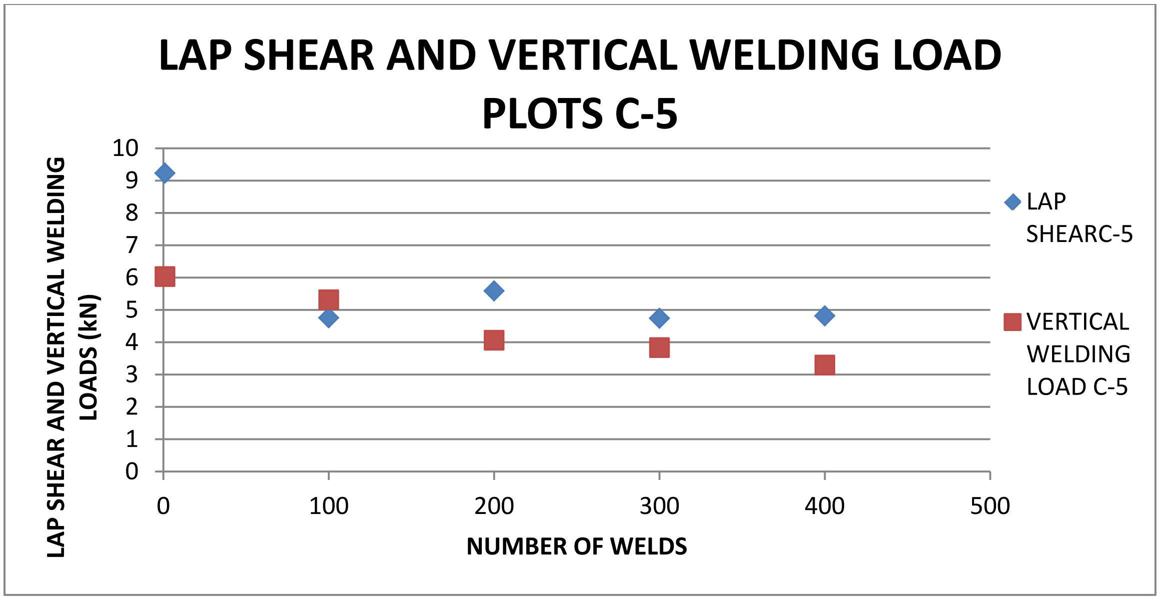



**Figure 4.19: C-5 Lap Shear and Vertical Welding Load Plot**

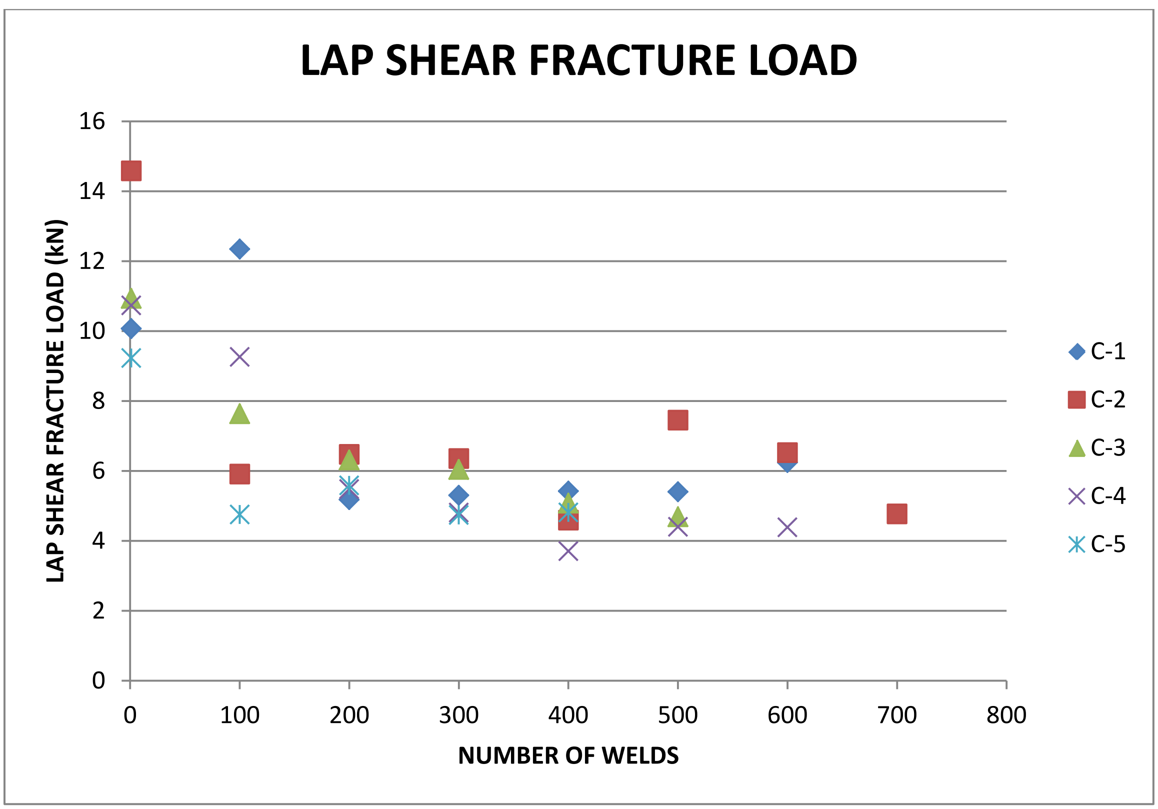



**Figure 4.20: C-Type Tool Lap Shear Fracture Load Plot**

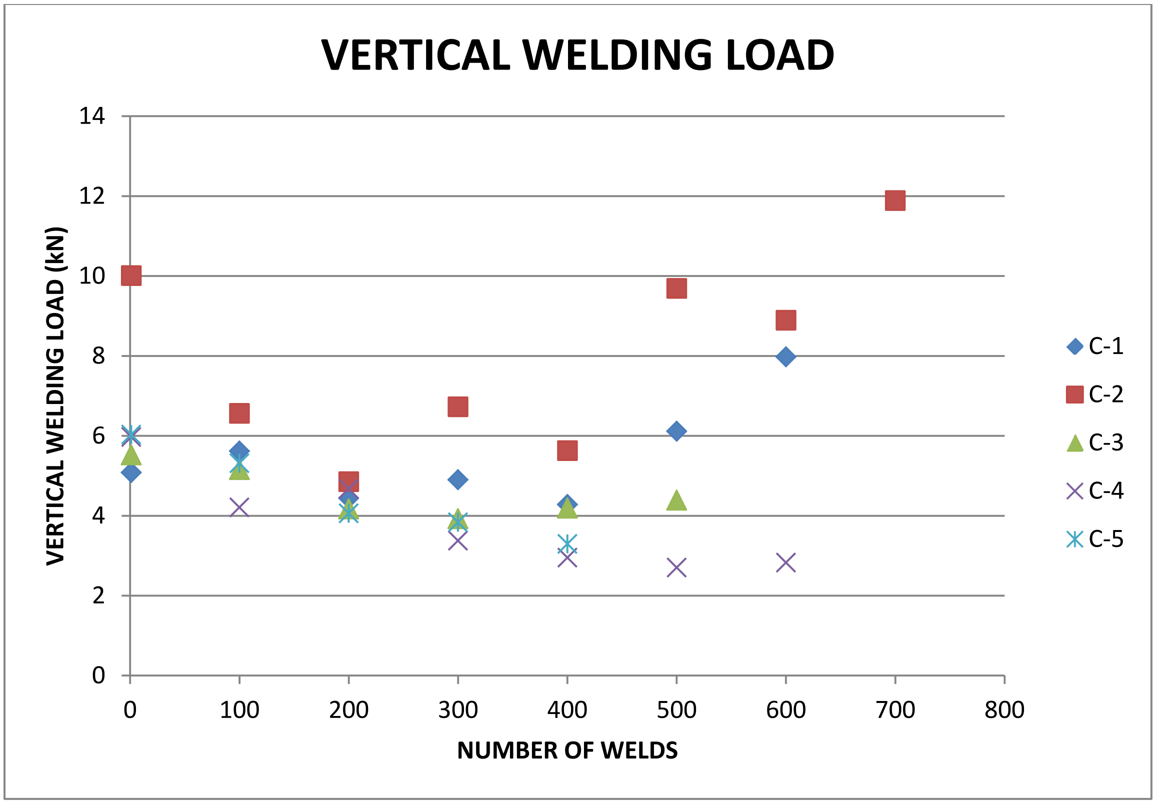



**Figure 4.21: C-Type Tool Vertical Welding Load Plot**

**Table 4.4: Shows the Average Values for all Type-C Tools Tested**

| | LAP SHEAR FRACTURE LOAD (kN) | VERTICAL WELDING LOAD (kN) |
|---|---|---|
| AVERAGE 400 | 7.02 | 4.99 |
| AVERAGE 600 | 6.78* | 5.59* |

*Only three of five tools reached 600 welds

### 4.3 Tool Life

Tool life is an important factor when evaluating the performance of the three tool grades that were studied. It provides insight into how well the tool might perform when used in real world applications. Figure 4.26 is a comparative table that shows the average number of welds each tool type can be expected to last, as well as the average lap shear fracture loads of the last three welds of each tool type. B and the C type tools tested very similar and share more in common with each other than either of them have in common with the A type tool.

**Table 4.5: Average Number of Welds Each Tool Type Can be Expected to Last and the Average Lap Shear Fracture Load of the Last Three Welds**

| | Average Number of Welds | Average Lap Shear Fracture Load of Last 3 Welds (kN) |
|---|---|---|
| A | 820 | 5.45 |
| B | 725 | 4.82 |
| C | 560 | 4.98 |

### 4.3.1 A-Type Tool

The A-type tools were the most wear resistant, and had the least amount of material buildup of the three tool types tested. The failure mode was a combination of abrasive tool wear and tool pin chipping. Tool type A performed the best out of all of the tools tested. It lasted the most number of welds, and was the tool that had the greatest number of lap shear fracture loads over 2,000lbs over the course of testing. Figures 4.22 and 4.23 show the of tool wear by visual inspection for tool type A, as well as corresponding cross sections of welds made by the tool.

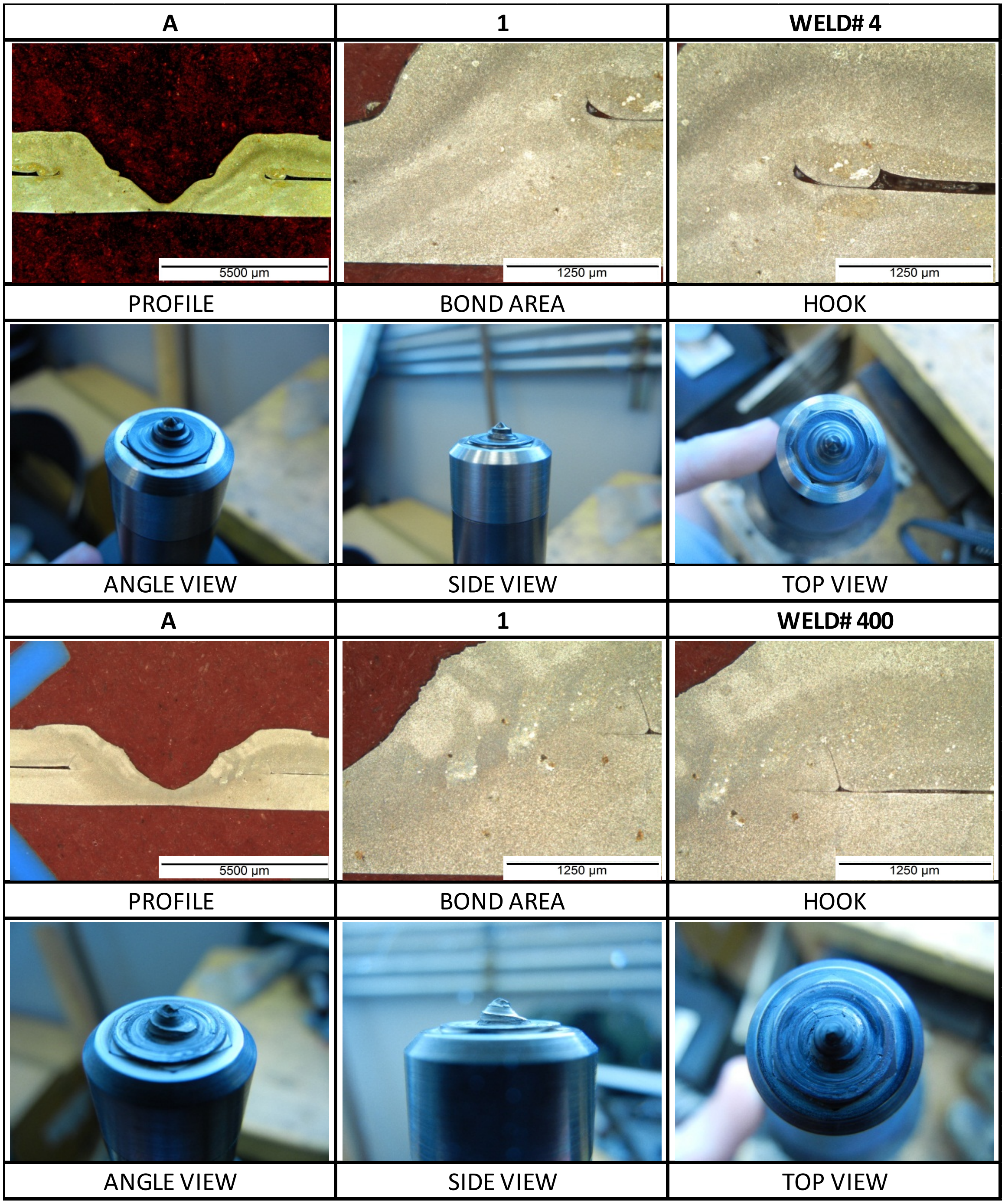



**Figure 4.22: Microscope Cross Section Pictures and Tool Wear Pictures Show How the Geometry of the Tool Changes with Relation to Number of Welds**

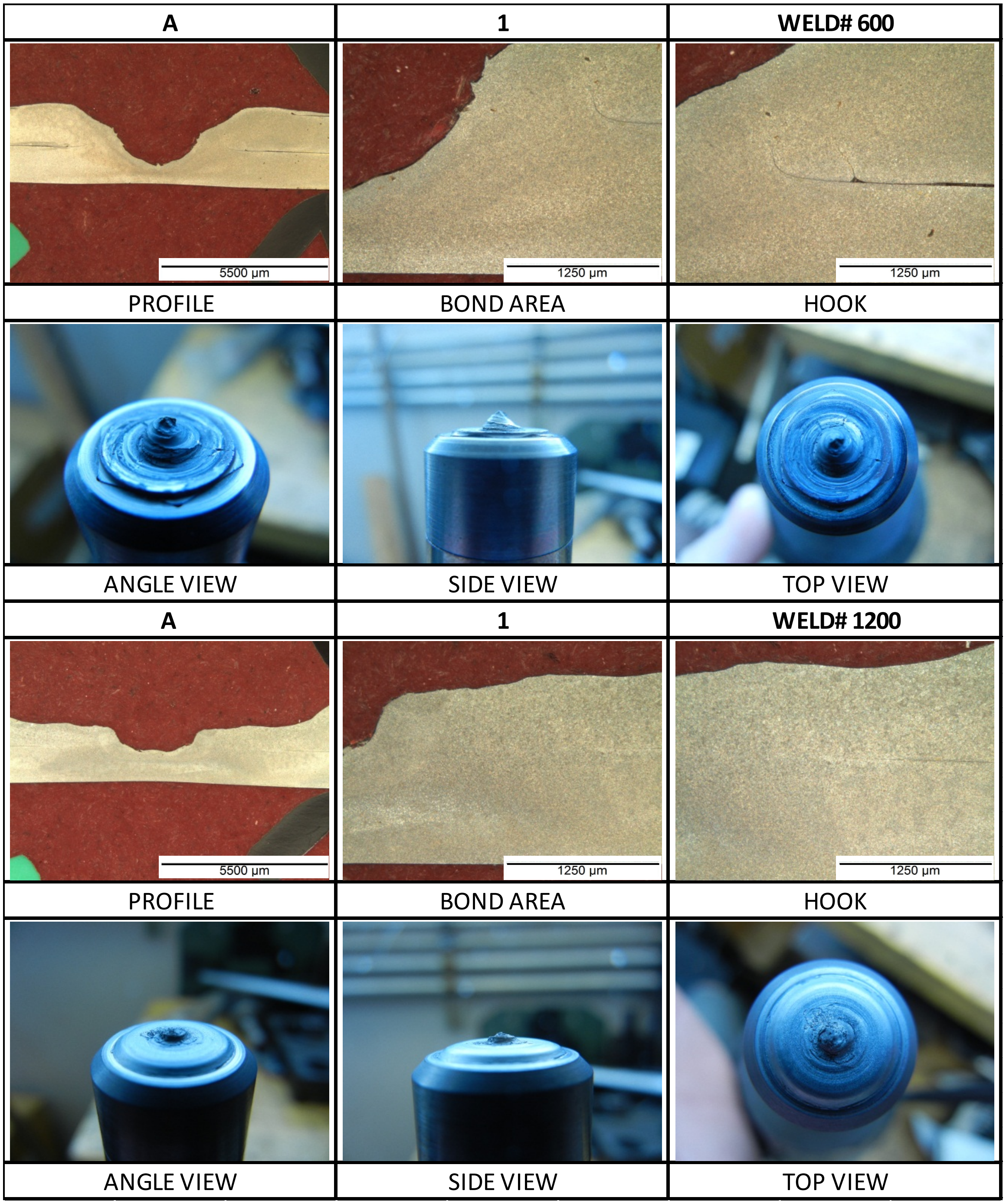



**Figure 4.23: Microscope Cross Section Pictures and Tool Wear Pictures Show How the Geometry of the Tool Changes with Relation to Number of Welds**

### 4.3.2 B-Type Tool

Failure mode for the B type tools is a combination of abrasive tool wear and extreme material build up on the tool, by adhesion. During welding the B type tools had substantial amounts of buildup on the surface of the tool very early in the testing. Inspection of figures 4.29 and 4.30 show how the tool's profile changed to due to material build up and tool wear. It can also be seen that the pin wore progressively over time and also experienced some chipping. This tool, with the buildup that occurred on the surface, created significant hooking at the interface between the two sheets, which effectively reduced the bond area and the resulting lap shear fracture load that the welds could sustain.

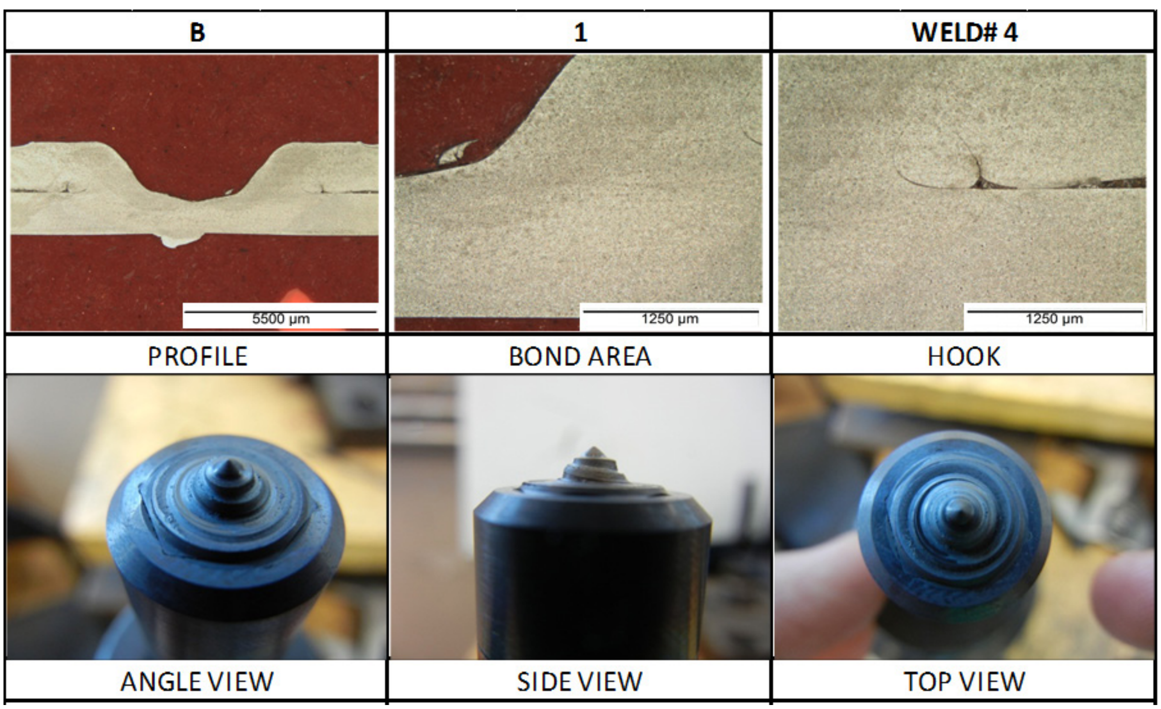



**Figure 4.24: Microscope Cross Section Pictures and Tool Wear Pictures Show How the Geometry of the Tool Changes with Relation to Number of Welds**

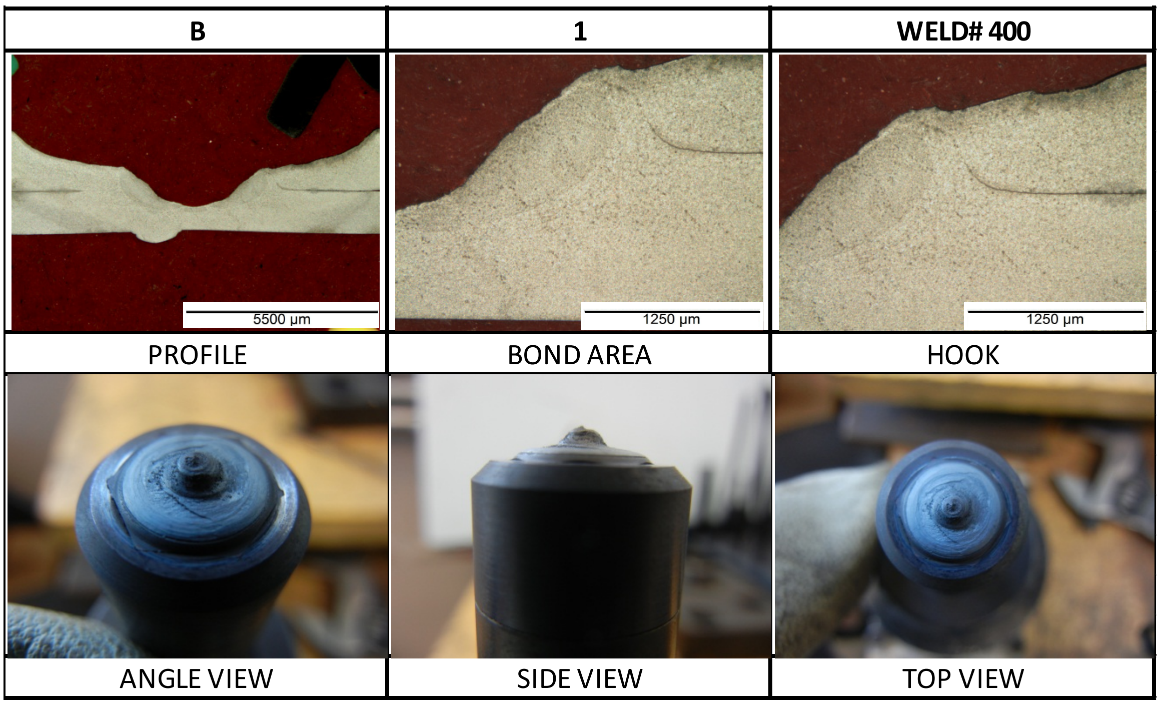



**Figure 4.25: Microscope Cross Section Pictures and Tool Wear Pictures Show How the Geometry of the Tool Changes with Relation to Number of Welds**


**Figure 4.26: Microscope Cross Section Pictures and Tool Wear Pictures Show How the Geometry of the Tool Changes with Relation to Number of Welds**

### 4.3.3 C-Type Tool

Failure mode for the C type tools was nearly the same as the failure mode for the C type tools. The only difference was that the B type tools tended to last longer than the C type tools. Tool failure typically resulted from abrasive tool wear, some chipping of the pin, and extreme material build up, as can be seen in Figures 4.31 and 4.32. For some reason, there was much less hook development at weld #400 in the case of the C type tool compared to the B type tool.

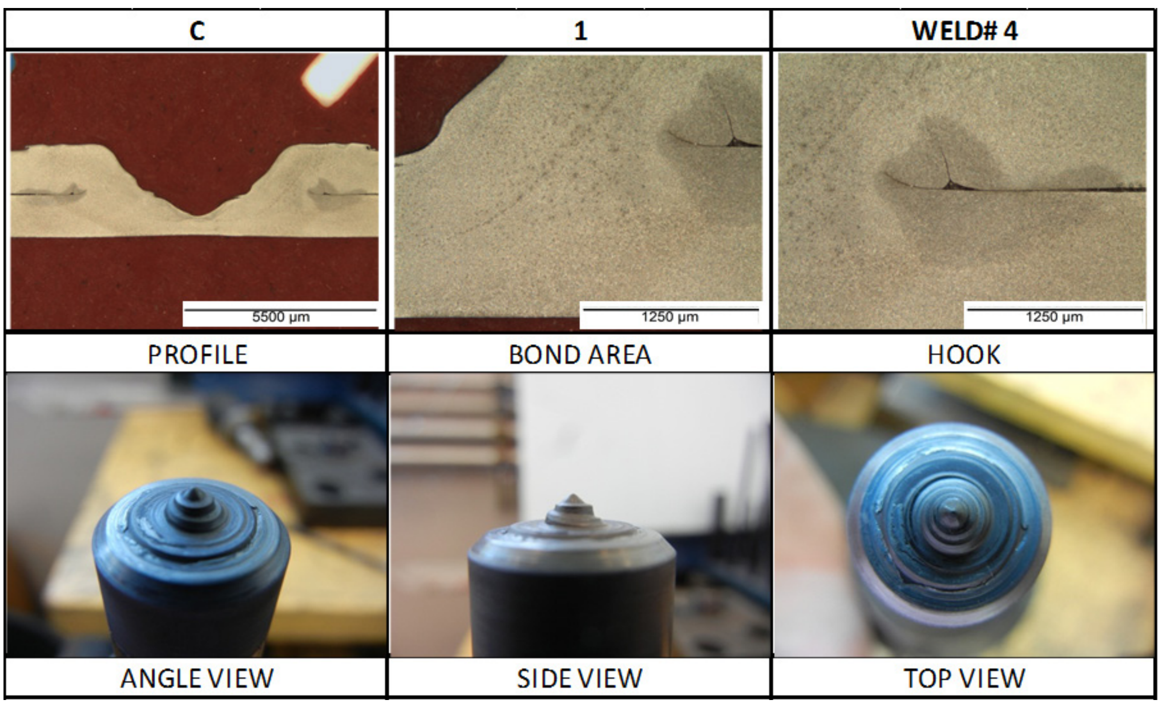



**Figure 4.27: Microscope Cross Section Pictures and Tool Wear Pictures Show How the Geometry of the Tool Changes with Relation to Number of Welds**

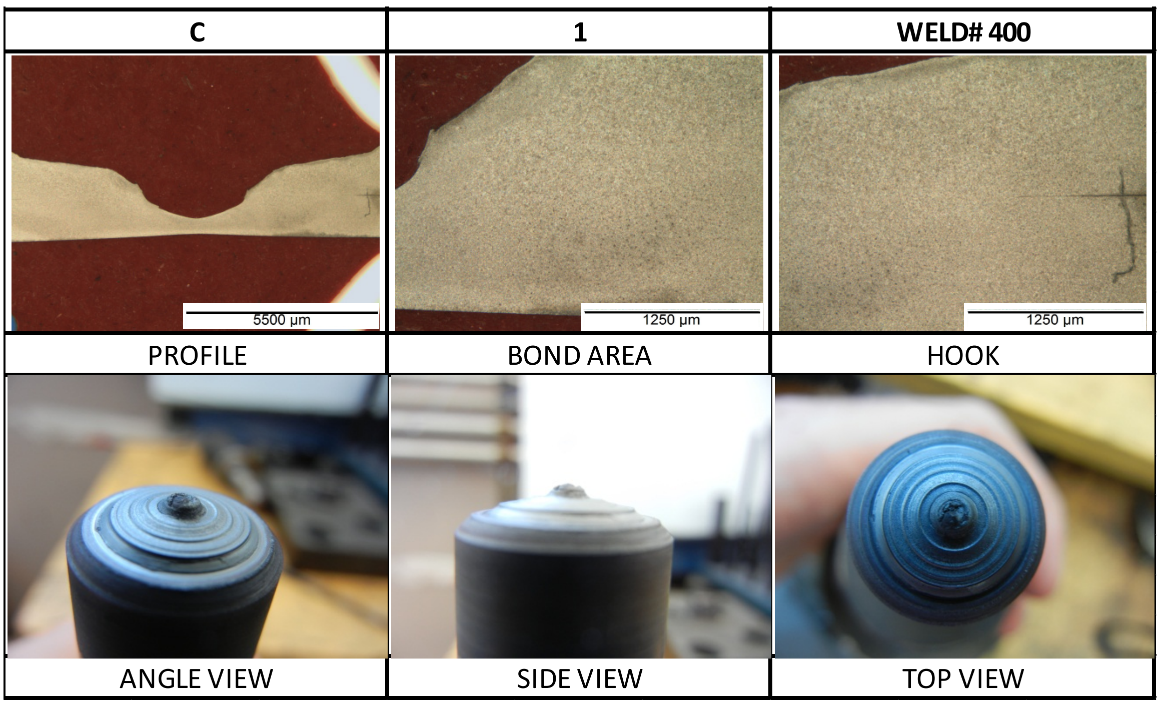



**Figure 4.28: Microscope Cross Section Pictures and Tool Wear Pictures Show How the Geometry of the Tool Changes with Relation to Number of Welds**

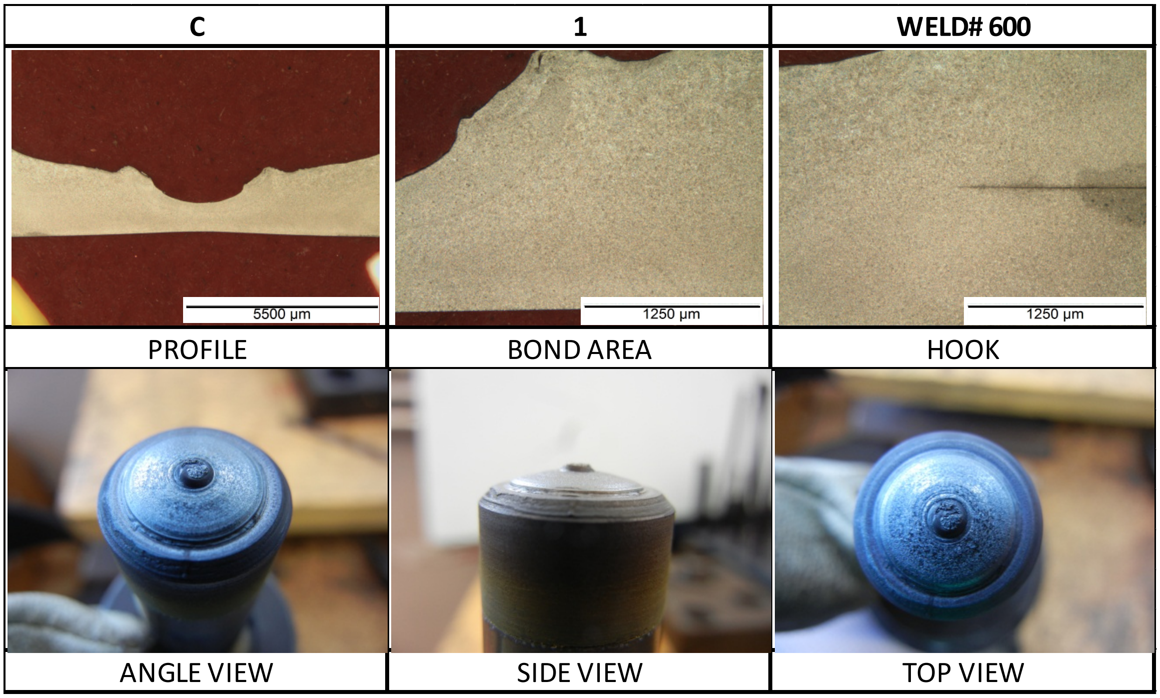



**Figure 4.29: Microscope Cross Section Pictures and Tool Wear Pictures Show How the Geometry of the Tool Changes with Relation to Number of Welds**

### 4.4 Micro-Hardness Evaluation of Welds

Micro-hardness testing was used to see how properties of the welds changed as a function of tool wear, as well as how the weld properties were different between the three different PCBN tool grades. Micro-hardness maps were made for the first weld cross section and the last weld cross section for the A-1 tool, the B-1 tool, and the C-1 tool. The hardness of the welds is shown in and around the weld on the maps. This information provides an indication of the heat generated by each tool at the beginning and the end of tool life. Inspection of an iron-carbon phase diagram shows that as DP 980 reaches temperatures of $870^0$ C and up it austenitizes. Upon rapid cooling from the austenite temperature, which would be a cooling time of less than 10 seconds based on the time-temperature-transformation diagram for this alloy, virtually all of the austenite is transformed to martensite.

The differences in the maps show how each tool produced a different size of HAZ, which can directly affect the weld properties. The numbers along the X and Y axes of the micro-hardness maps are distances (microns). The maps start at the center of the weld and move out to the right. The right half of the cross sections was used for the maps, because the cross sections are symmetrical about the center.

### 4.4.1 DP980 Micro-Hardness Map

A baseline map was made as a control to show the hardness profile of DP980 before welding. This provides a comparison of how FSSW with the three different PCBN tool types change the hardness of the metal. Before welding the hardness maps shows that DP980 has a hardness that ranges between 300-350 Vickers. After FSSW the hardness maps show that the hardness of the DP980 coupons ranges between 300-500 Vickers.

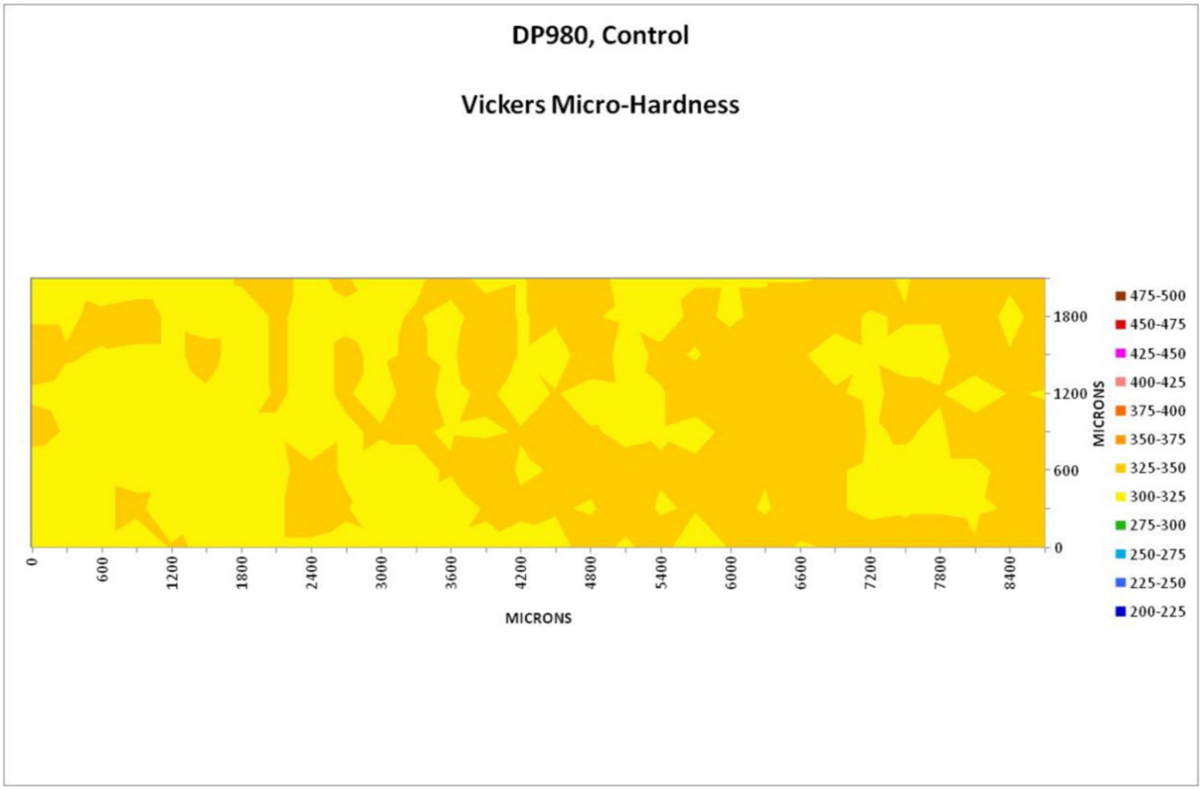



**Figure 4.30: Vickers Micro-Hardness DP980 Control Map**

### 4.4.2 Micro-Hardness Maps A-Type Tools

The A-1 tool produced a relatively small HAZ, as shown in Figure 4.33. The region that appears to have heated up the most is at the base of the pin where the micro-hardness map indicates the sample is the hardest. In this area, the temperature reached austenitizing levels, which resulted in a larger fraction of martensite, and the point of failure for the joint. This makes sense considering that welds 1-3 when pulled in the Instron machine all had nugget pull out that is consistent with the micro-hardness map. At the end of the A-1 tool life the HAZ increased slightly in size and hardness see figure 4.34. This can be attributed to the change in tool geometry due to wear and slight material build up and a subsequent increase in tool offset, which increased the vertical welding load, in an effort to increase lap shear fracture loads. Even with the increase in offset the lap shear fracture loads dropped with increasing tool wear.

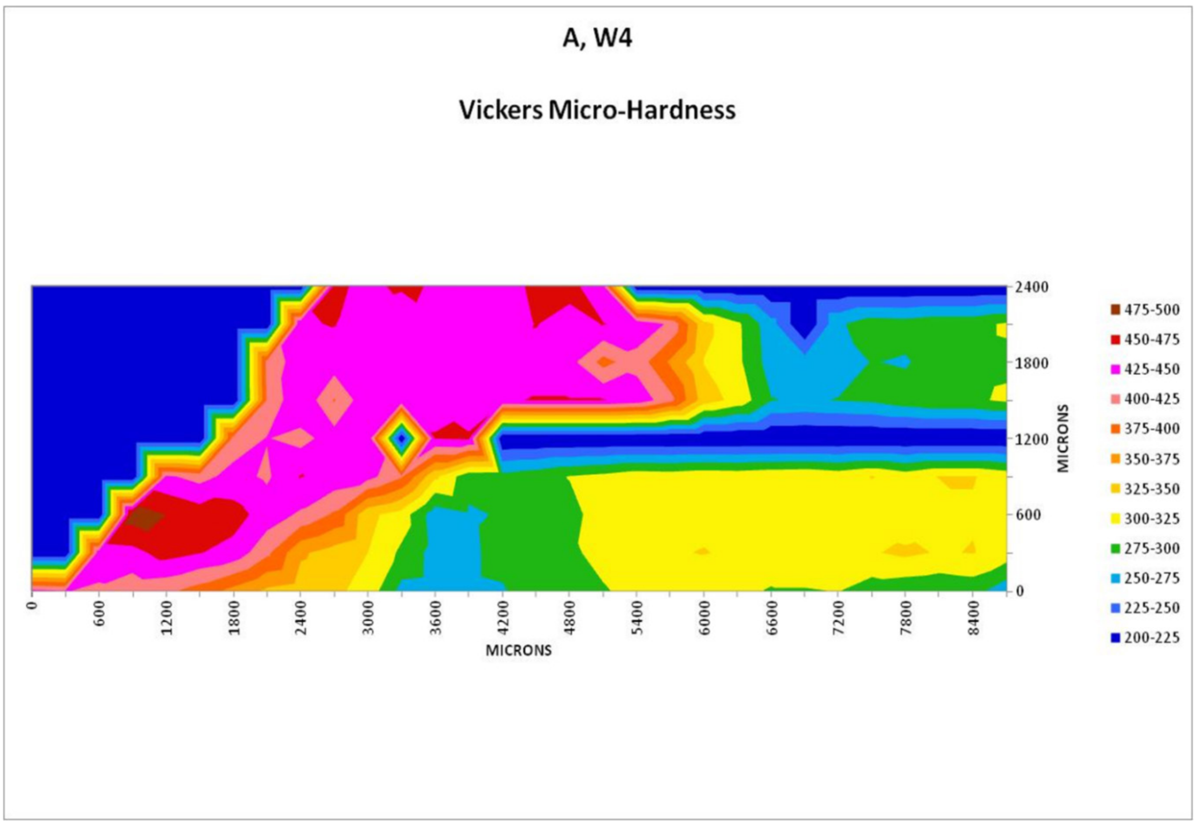



**Figure 4.31: Tool A-1 Weld 4 Vickers Micro-Hardness Map**

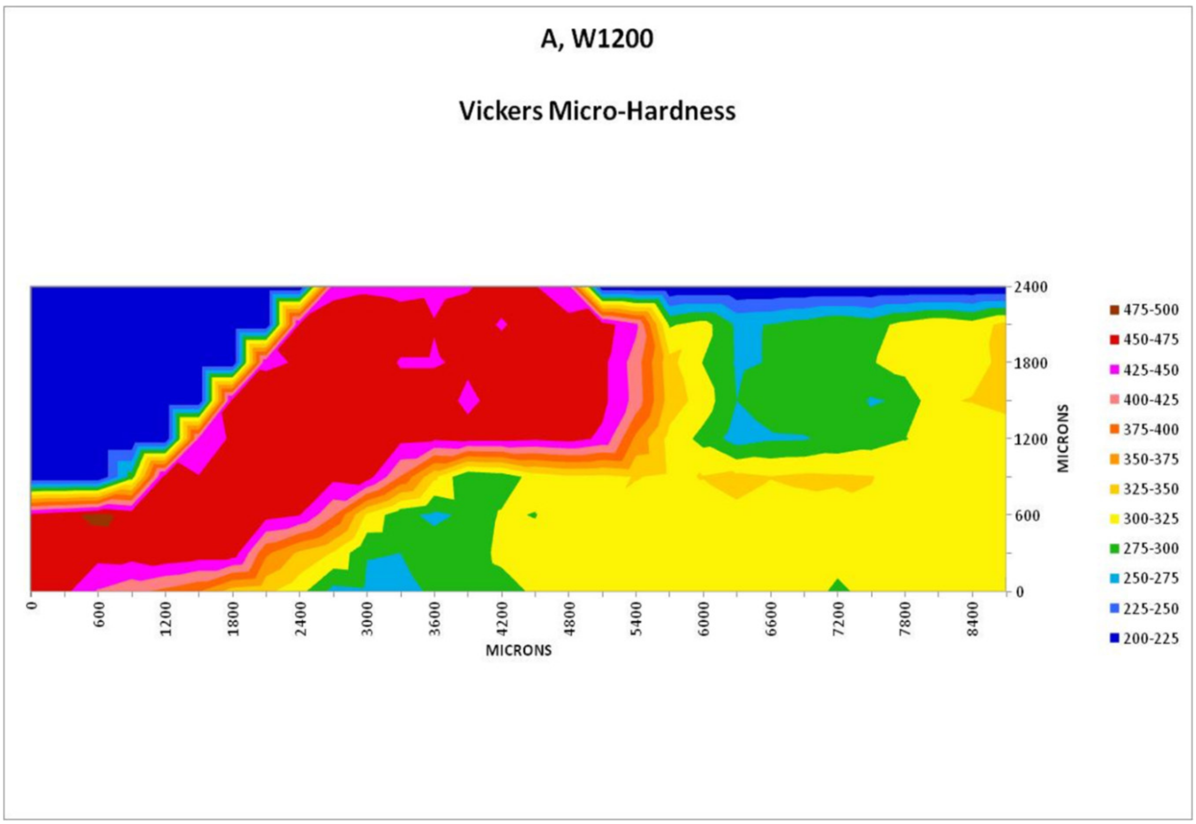



**Figure 4.32: Tool A-1 Weld 1200 Vickers Micro-Hardness Map**

### 4.4.3 Micro-Hardness Maps B-Type Tool

The two micro-hardness maps for the B-1 tool appear similar. However, there are two differences between B-1 W4 and B-1 W900. The first difference is that the HAZ on W4 is smaller than the HAZ on W900. The second difference is that there is a small section of softer metal surrounding the pullout region around the pin on W4, but on W900 this section nearly disappears. This is largely because of the tool wear, and the change in the tool's geometry. In this case it appears that the change in geometry affected the weld properties more in the final shape of the weld and the bond area that was produced, than by the hardness that resulted.

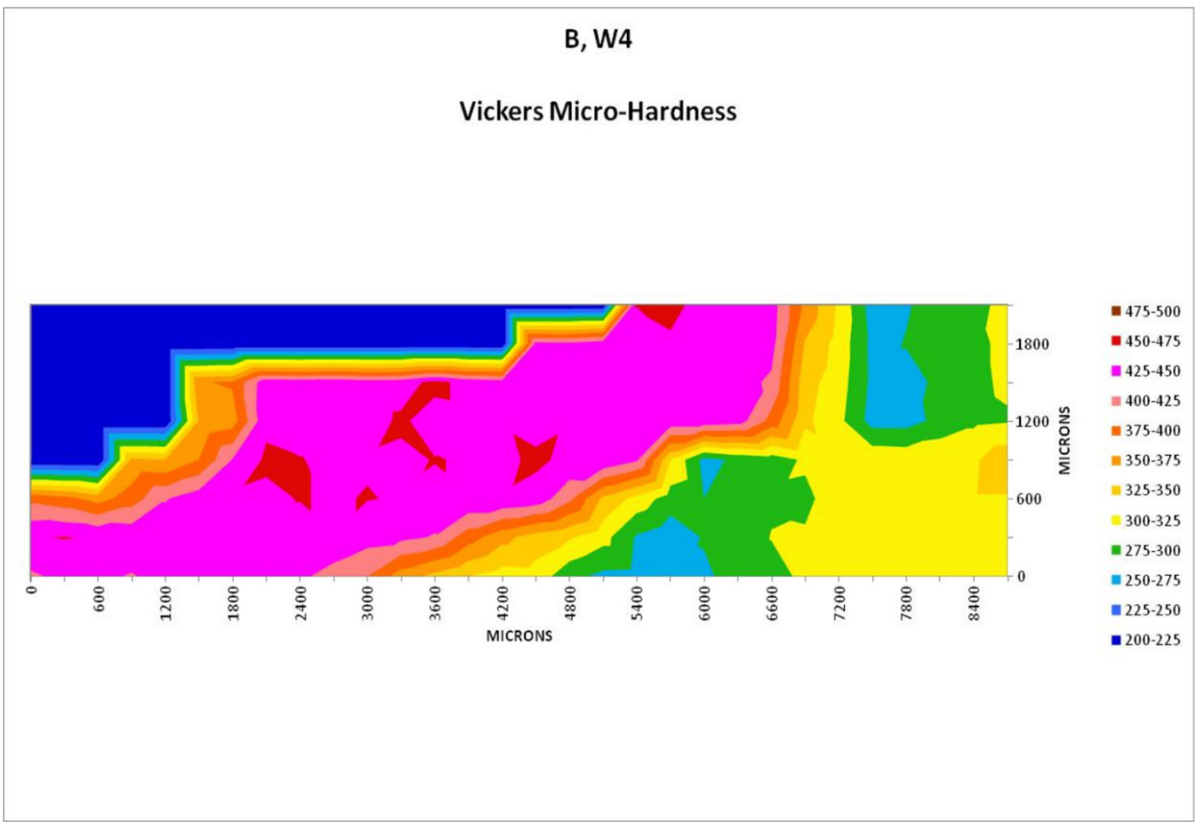



**Figure 4.33: Tool B-1 Weld 4 Vickers Micro-Hardness Map**

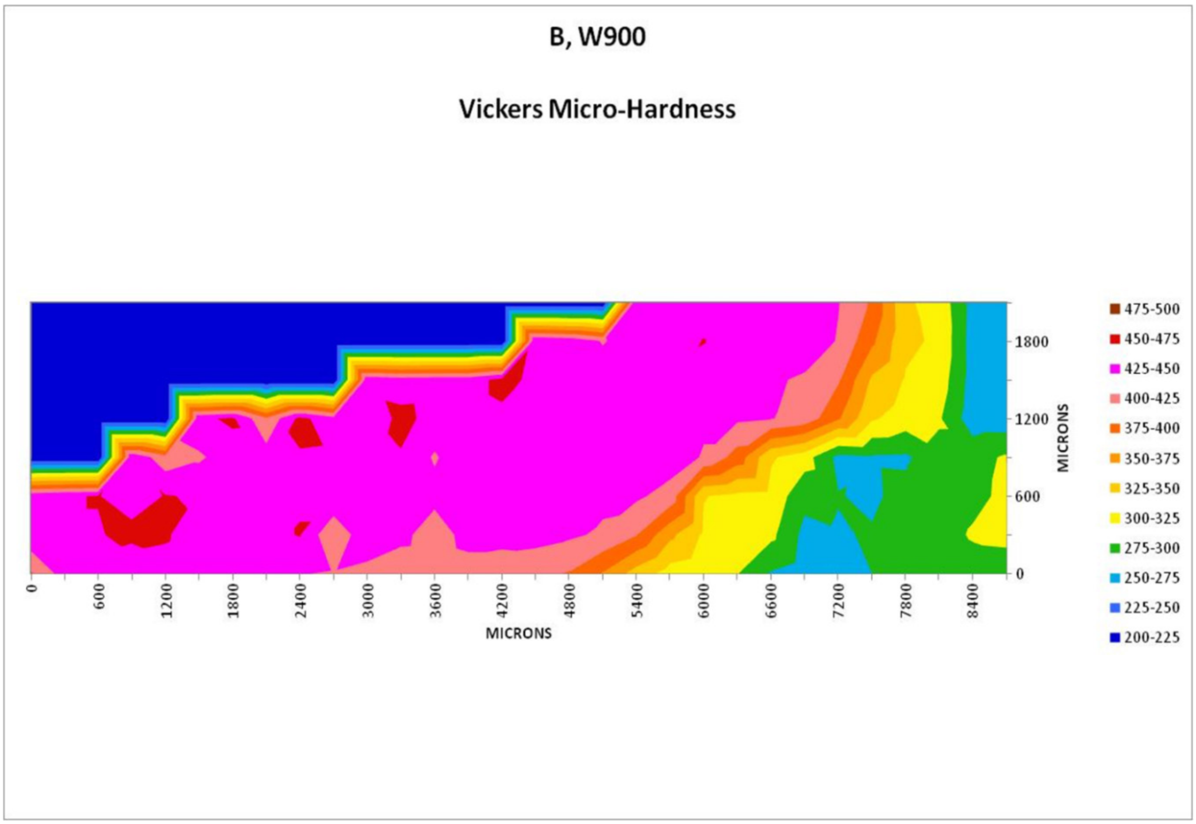



**Figure 4.34: Tool B-1 Weld 900 Vickers Micro-Hardness Map**

### 4.4.4 Micro-Hardness Maps C-Type Tool

Out of all three of the tools C-1 had the hardest HAZ. As the tool wore the HAZ became larger. With tool wear the extent of the HAZ increased, resulting in a larger band of soft material just outside of the weld nugget. Most of the difference between weld 4 and weld 600 was due to the change in geometry of the tool as it wore.

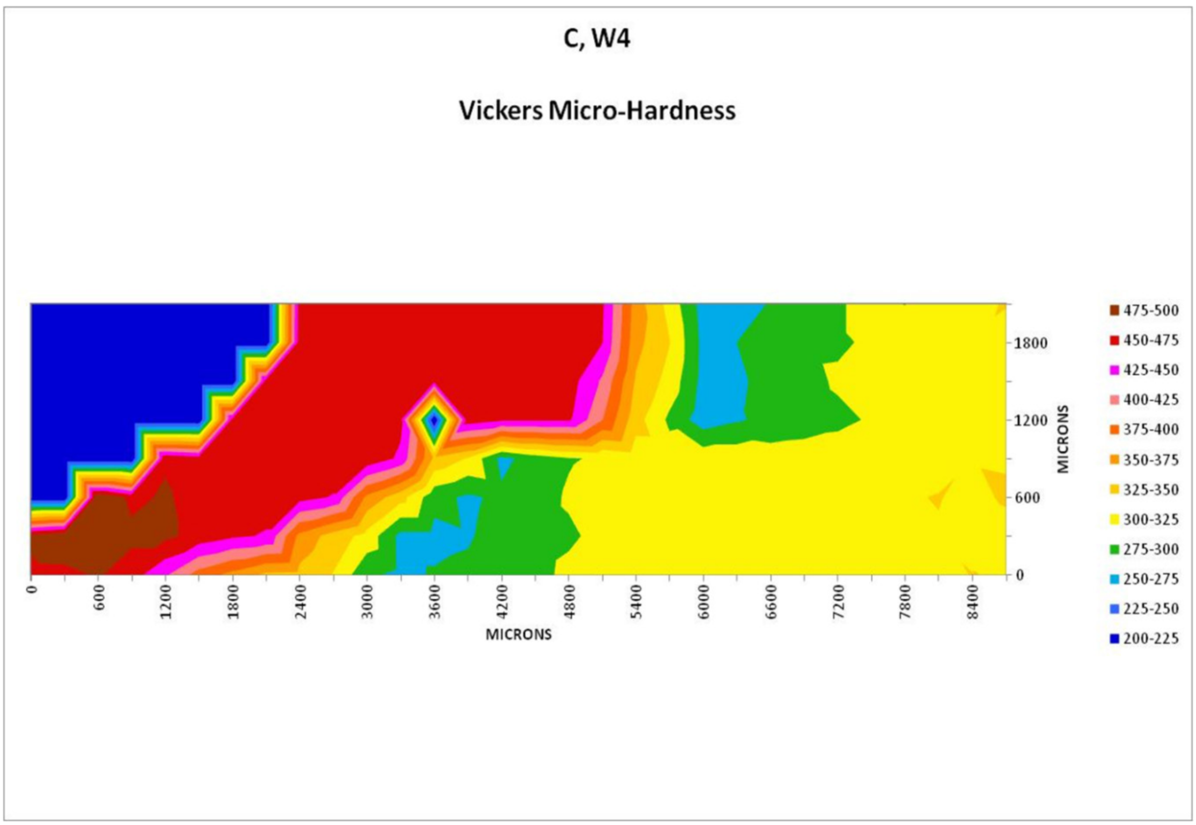



**Figure 4.35: Tool C-1 Weld 4 Vickers Micro-Hardness Map**

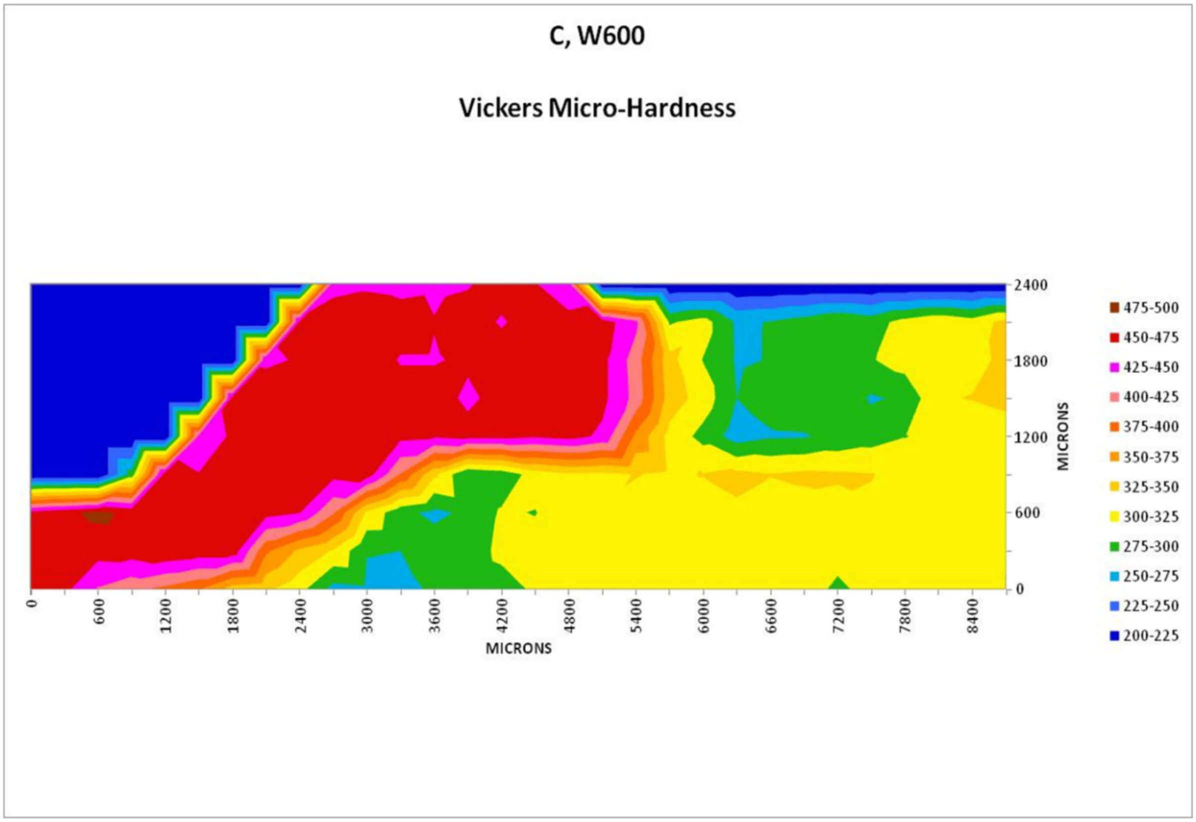



**Figure 4.36: Tool C-1 Weld 600 Vickers Micro-Hardness Map**

### 4.5 Summary and Tool Type Discussion

Each tool grade that was tested had the same 90% CBN content, but the grades differed from each other in CBN grain size. A-type tools had a fine grain size, ranging from 3-6 microns, B-type tools were made using a multi-modal-grain size distribution, ranging from 4-40 microns, while C-type tools had a medium grain size ranging from 12-15 microns. These distinctions are important, because it provides some understanding of why A-type tools performed better than the other two tool types. For PCBN tools, there are two main phases present in the microstructure: cubic boron nitride (CBN), which is a hard, ceramic phase with a hardness second only to diamond, and a metallic binder, such as Co or TiN. In this work, the composition of the binder was not known, because the supplier that provided the PCBN for this research wanted to keep that information proprietary. However, the binder was the same for each tool that was tested. The difference in grain sizes of the tools that were tested would have had an influence on the exposure of the binder to various types of wear during welding. A finer grain size of the hard CBN phase would expose less binder surface to wear than tools with larger grain CBN. This resulted in greater tool life for the finer grain tools, while also maintaining higher lap shear fracture load values for the welds that were produced. For all three types of tools, tool wear changed the geometry of each tool, reducing its effective area and requiring adjustments to the tool displacement in an effort to maintain bond strength. In summary, for the same nominal composition and same tool design, the finer grain PCBN tool had much better wear resistance than the other grades with larger grain sizes.

To provide further analysis of tool performance, both F-tests and T-tests were carried out with 95% confidence intervals and 99% confidence intervals looking at the average lap shear fracture load values of the first 600 welds for each tool group. The lap shear fracture load data used for the F-tests and T-tests was the data from all five tools lumped together for each grade, for a total of 15 tools. For each tool an average of 3 lap shear fracture loads were measured after every 100 welds were completed during the wear test, all the way up to 600 welds. The following chart shows the pairing of the tool types for the tests.

**Table 4.6: Pairing of the Tool Types for the F-tests and T-tests**

| F-tests | | T-tests | |
|---|---|---|---|
| A | B | A | B |
| A | C | A | C |
| B | C | B | C |

The results from the F-test showed that at both 95% and 99% confidence intervals that A-type tools had a smaller variance in lap shear fracture load values, than both B-type and C-type tools. When the B-type and C-type tools were compared there was no significant difference in the variances of their lap shear fracture load values.

The T-test showed similar results. When A-type tool lap shear fracture load values were compared to both B-type and C-type tools, the A-type tools produced higher fracture loads than B and C-type tools at both the 95% and 99% confidence intervals. However, there was no significant difference in the mean values of the lap shear fracture loads of the B and C-type tools.

This shows that the performance of A-type tools, when based on lap shear fracture load values, is superior to B-type and C-type tools. The tests also showed that B-type and C-type tools were basically the same in the joint performance that they produced.

# 5. CONCLUSIONS AND RECOMMENDATIONS

## 5.1 Conclusions

Tool grade for PCBN tools has a significant impact on wear resistance, weld quality, and tool failure in FSSW of DP 980 steel sheet. More specifically, for a nominal composition of 90% CBN, the grain size has a significant impact on the wear resistance of the tool. A-type tools performed the best, of the three grades that were tested in this work, with the finest grain size in the group, of 3-6 microns. The effect of fine grain size was less adhesion of DP 980 on the tool surface over time, less abrasive wear, and better lap shear fracture loads of the welds that were produced, compared to the other grades. This is explained by less exposure of the binder phase to wear by both adhesion and abrasion during welding of DP 980. A-type tools were the most consistent in both the number of welds per tool, and the number of welds that reached acceptable lap shear fracture loads. B-type tools, with a bimodal grain size distribution (grain size of 4 – 40 microns) did a little bit better than C-type tools in terms of wear, but neither of them were able to achieve consistent acceptable lap shear fracture load values after the first 200 welds. In fact only one out of five C-type tools was able to get acceptable lap shear fracture loads after the first 100 welds. B-type tools had a multi-modal-grain ranging from 4-40 microns, while C-type tools had a medium size grain ranging from 12-15 microns.

F-tests and T-tests were performed to see how significant the differences were between the tools when comparing their ability to maintain acceptable lap shear fracture loads as the number of welds increased. The F-test was used to compare the variance of lap shear fracture load values of each tool, and the T-test was used to compare the difference of the means of each tools lap shear fracture load values. The results of both tests confirmed the conclusion that the A-type tools outperformed both B-type and C-type tools when looking at the tools ability to maintain acceptable lap shear fracture loads. During testing B-type tools appeared to perform slightly better than C-type tools, but after comparing them with the F-test and T-test it showed that any difference they may have had was statistically insignificant.

### 5.1.1 Tool Failure

Keeping the spindle load consistent as the tool wore was done by adjusting the offset setting, which helped avoid large drop offs with the lap shear fracture load values. This was not done perfectly, but it did help to maintain vertical welding loads and lap shear fracture loads at a reasonably consistent level, as far as it was possible to do so given the state of tool wear at each moment. This was important, because it helped create an indicator for tool failure. As the tool came closer to the end of its tool life the spindle load values increased exponentially, while the lap shear fractures loads experienced an abrupt drop off. This became more apparent in the later tools that were tested as the methodology for adjusting the offset settings had been refined by this point.

## 5.2 Recommendations

To further the understanding of FSSW as it applies to joining of UHSSs further research should include accurate temperature measurement during welding, as well as modeling of the process in order to study the effect of tool geometry and process conditions on joint strength.

The tool geometry used in this study had a threaded pin. The same tool geometry was used with three different grades of PCBN. The A-type tool outperformed the other two tool types, because of its composition. A smooth tool made of the same material as the A-type tool could possibly improve tool life by reducing the stress and wear on the pin while maintaining acceptable lap shear fracture load values, because chipping of the pin was one of the factors that limited tool life, even for A-type tools.

A final recommendation would be to have the ability to control the welding load with an automatic load control. This would help create more consistent welds, and provide a better idea of how tool life would be affected by consistent welding load values.

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# APPENDICES

## Appendix A: A-B F-test and T-test 95%

| | Data Set 1 | Data Set 2 |
|---|---|---|
| 1 | 11.5087552 | 11.52097 |
| 2 | 11.151136 | 12.1311676 |
| 3 | 11.0417152 | 12.9389748 |
| 4 | 11.6590976 | 11.5312475 |
| 5 | 11.1609216 | 10.7839725 |
| 6 | 11.222304 | 10.3520807 |
| 7 | 10.5293056 | 8.1036485 |
| 8 | 10.0142272 | 6.7071035 |
| 9 | 10.1850304 | 6.787021 |
| 10 | 9.8158464 | 7.1039365 |
| 11 | 10.0711616 | 6.551453 |
| 12 | 10.003552 | 7.3162175 |
| 13 | 8.8257216 | 7.0348977 |
| 14 | 9.01832 | 5.6990838 |
| 15 | 8.89662272 | 7.357491 |
| 16 | 8.98513792 | 5.6135734 |
| 17 | 8.55919744 | 5.705038 |
| 18 | 9.15238272 | 5.5883925 |
| 19 | 8.31784896 | 5.8730345 |
| 20 | 8.8435136 | 6.05156175 |
| 21 | 8.2519296 | 6.2869818 |
| 22 | | |
| 23 | | |
| 24 | | |
| 25 | | |
| 26 | | |
| 27 | | |

Do you need to know if the mean of Data Set 2 is:
- Statistically **H**igher (H) than Data Set 1,
- Statistically **L**ower (L) than Data Set 1,
- **E**ither higher or lower (E) than Data Set 1

Enter H, L or E: E

| **F Test Results** | | | |
|---|---|---|---|
| p value | 0.05 | St Dev 1 | 1.115171069 |
| F statistic | 4.8552 | St Dev 2 | 2.457224994 |
| Deg Free 1 | 20 | Var 1 | 1.243606514 |
| Deg Free 2 | 20 | Var 2 | 6.037954672 |
| F critical | 2.1242 | | |

**You CAN say that the variation in Data Set 2 is different from the variation in Data Set 1.**

| **t Test Results, Unequal Variance** | | | |
|---|---|---|---|
| p value | 0.05 | Avg 1 | 9.86732035 |
| t statistic | 3.2479 | Avg 2 | 7.954183217 |
| Deg Free | 28 | | |
| t critical | 2.048409442 | | |

**You CAN say that the mean of Data Set 2 is different from the mean in Data Set 1.**

## Appendix B: A-B F-test and T-test 99%

| | Data Set 1 | Data Set 2 |
|---|---|---|
| 1 | 11.5087552 | 11.52097 |
| 2 | 11.151136 | 12.1311676 |
| 3 | 11.0417152 | 12.9389748 |
| 4 | 11.6590976 | 11.5312475 |
| 5 | 11.1609216 | 10.7839725 |
| 6 | 11.222304 | 10.3520807 |
| 7 | 10.5293056 | 8.1036485 |
| 8 | 10.0142272 | 6.7071035 |
| 9 | 10.1850304 | 6.787021 |
| 10 | 9.8158464 | 7.1039365 |
| 11 | 10.0711616 | 6.551453 |
| 12 | 10.003552 | 7.3162175 |
| 13 | 8.8257216 | 7.0348977 |
| 14 | 9.01832 | 5.6990838 |
| 15 | 8.89662272 | 7.357491 |
| 16 | 8.98513792 | 5.6135734 |
| 17 | 8.55919744 | 5.705038 |
| 18 | 9.15238272 | 5.5883925 |
| 19 | 8.31784896 | 5.8730345 |
| 20 | 8.8435136 | 6.05156175 |
| 21 | 8.2519296 | 6.2869818 |
| 22 | | |
| 23 | | |
| 24 | | |
| 25 | | |
| 26 | | |
| 27 | | |

Do you need to know if the mean of Data Set 2 is:
- Statistically **H**igher (H) than Data Set 1,
- Statistically **L**ower (L) than Data Set 1,
- **E**ither higher or lower (E) than Data Set 1

Enter H, L or E: E

**F Test Results**

| | | | |
|---|---|---|---|
| p value | 0.01 | St Dev 1 | 1.115171069 |
| F statistic | 4.8552 | St Dev 2 | 2.457224994 |
| Deg Free 1 | 20 | Var 1 | 1.243606514 |
| Deg Free 2 | 20 | Var 2 | 6.037954672 |
| F critical | 2.9377 | | |

**You CAN say that the variation in Data Set 2 is different from the variation in Data Set 1.**

**t Test Results, Unequal Variance**

| | | | |
|---|---|---|---|
| p value | 0.01 | Avg 1 | 9.86732035 |
| t statistic | 3.2479 | Avg 2 | 7.954183217 |
| Deg Free | 28 | | |
| t critical | 2.048409442 | | |

**You CAN say that the mean of Data Set 2 is different from the mean in Data Set 1.**

## Appendix C: A-C F-test and T-test 95%

| | Data Set 1 | Data Set 2 |
|---|---|---|
| 1 | 11.5087552 | 10.7009984 |
| 2 | 11.151136 | 11.5301056 |
| 3 | 11.0417152 | 11.1057664 |
| 4 | 11.6590976 | 7.9423488 |
| 5 | 11.1609216 | 8.37851968 |
| 6 | 11.222304 | 7.6274304 |
| 7 | 10.5293056 | 6.4780672 |
| 8 | 10.0142272 | 5.1605696 |
| 9 | 10.1850304 | 5.7859584 |
| 10 | 9.8158464 | 5.6516288 |
| 11 | 10.0711616 | 5.21020928 |
| 12 | 10.003552 | 5.4879424 |
| 13 | 8.8257216 | 4.8185184 |
| 14 | 9.01832 | 4.62218368 |
| 15 | 8.89662272 | 4.7291136 |
| 16 | 8.98513792 | 6.474064 |
| 17 | 8.55919744 | 5.285892 |
| 18 | 9.15238272 | 4.7040936 |
| 19 | 8.31784896 | 5.453248 |
| 20 | 8.8435136 | 5.785217067 |
| 21 | 8.2519296 | 5.912874667 |
| 22 | | |
| 23 | | |
| 24 | | |
| 25 | | |
| 26 | | |
| 27 | | |

Do you need to know if the mean of Data Set 2 is:
- Statistically **H**igher (H) than Data Set 1,
- Statistically **L**ower (L) than Data Set 1,
- **E**ither higher or lower (E) than Data Set 1

Enter H, L or E: E

| **F Test Results** | | | |
|---|---|---|---|
| p value | 0.05 | St Dev 1 | 1.115171069 |
| F statistic | 3.7244 | St Dev 2 | 2.1521483 |
| Deg Free 1 | 20 | Var 1 | 1.243606514 |
| Deg Free 2 | 20 | Var 2 | 4.631742306 |
| F critical | 2.1242 | | |

**You CAN say that the variation in Data Set 2 is different from the variation in Data Set 1.**

| **t Test Results, Unequal Variance** | | | |
|---|---|---|---|
| p value | 0.05 | Avg 1 | 9.86732035 |
| t statistic | 6.1559 | Avg 2 | 6.611654761 |
| Deg Free | 30 | | |
| t critical | 2.042270353 | | |

**You CAN say that the mean of Data Set 2 is different from the mean in Data Set 1.**

## Appendix D: A-C F-test and T-test 99%

| | Data Set 1 | Data Set 2 |
|---|---|---|
| 1 | 11.5087552 | 10.7009984 |
| 2 | 11.151136 | 11.5301056 |
| 3 | 11.0417152 | 11.1057664 |
| 4 | 11.6590976 | 7.9423488 |
| 5 | 11.1609216 | 8.37851968 |
| 6 | 11.222304 | 7.6274304 |
| 7 | 10.5293056 | 6.4780672 |
| 8 | 10.0142272 | 5.1605696 |
| 9 | 10.1850304 | 5.7859584 |
| 10 | 9.8158464 | 5.6516288 |
| 11 | 10.0711616 | 5.21020928 |
| 12 | 10.003552 | 5.4879424 |
| 13 | 8.8257216 | 4.8185184 |
| 14 | 9.01832 | 4.62218368 |
| 15 | 8.89662272 | 4.7291136 |
| 16 | 8.98513792 | 6.474064 |
| 17 | 8.55919744 | 5.285892 |
| 18 | 9.15238272 | 4.7040936 |
| 19 | 8.31784896 | 5.453248 |
| 20 | 8.8435136 | 5.785217067 |
| 21 | 8.2519296 | 5.912874667 |
| 22 | | |
| 23 | | |
| 24 | | |
| 25 | | |
| 26 | | |
| 27 | | |

Do you need to know if the mean of Data Set 2 is:
- Statistically **H**igher (H) than Data Set 1,
- Statistically **L**ower (L) than Data Set 1,
- **E**ither higher or lower (E) than Data Set 1

Enter H, L or E: E

| **F Test Results** | | | |
|---|---|---|---|
| p value | 0.01 | St Dev 1 | 1.115171069 |
| F statistic | 3.7244 | St Dev 2 | 2.1521483 |
| Deg Free 1 | 20 | Var 1 | 1.243606514 |
| Deg Free 2 | 20 | Var 2 | 4.631742306 |
| F critical | 2.9377 | | |

**You CAN say that the variation in Data Set 2 is different from the variation in Data Set 1.**

| **t Test Results, Unequal Variance** | | | |
|---|---|---|---|
| p value | 0.01 | Avg 1 | 9.86732035 |
| t statistic | 6.1559 | Avg 2 | 6.611654761 |
| Deg Free | 30 | | |
| t critical | 2.042270353 | | |

**You CAN say that the mean of Data Set 2 is different from the mean in Data Set 1.**

## Appendix E: B-C F-test and T-tests 95%

| | Data Set 1 | Data Set 2 |
|---|---|---|
| 1 | 11.52097 | 10.7009984 |
| 2 | 12.1311676 | 11.5301056 |
| 3 | 12.9389748 | 11.1057664 |
| 4 | 11.5312475 | 7.9423488 |
| 5 | 10.7839725 | 8.37851968 |
| 6 | 10.3520807 | 7.6274304 |
| 7 | 8.1036485 | 6.4780672 |
| 8 | 6.7071035 | 5.1605696 |
| 9 | 6.787021 | 5.7859584 |
| 10 | 7.1039365 | 5.6516288 |
| 11 | 6.551453 | 5.21020928 |
| 12 | 7.3162175 | 5.4879424 |
| 13 | 7.0348977 | 4.8185184 |
| 14 | 5.6990838 | 4.62218368 |
| 15 | 7.357491 | 4.7291136 |
| 16 | 5.6135734 | 6.474064 |
| 17 | 5.705038 | 5.285892 |
| 18 | 5.5883925 | 4.7040936 |
| 19 | 5.8730345 | 5.453248 |
| 20 | 6.05156175 | 5.785217067 |
| 21 | 6.2869818 | 5.912874667 |
| 22 | | |
| 23 | | |
| 24 | | |
| 25 | | |
| 26 | | |
| 27 | | |

Do you need to know if the mean of Data Set 2 is:
- Statistically **H**igher (H) than Data Set 1,
- Statistically **L**ower (L) than Data Set 1,
- **E**ither higher or lower (E) than Data Set 1

Enter H, L or E: E

| **F Test Results** | | | |
|---|---|---|---|
| p value | 0.05 | St Dev 1 | 2.457224994 |
| F statistic | 1.3036 | St Dev 2 | 2.1521483 |
| Deg Free 1 | 20 | Var 1 | 6.037954672 |
| Deg Free 2 | 20 | Var 2 | 4.631742306 |
| F critical | 2.1242 | | |

**You CANNOT say that the variation in Data Set 2 is different from the variation in Data Set 1.**

| **t Test Results, Equal Variance** | | | |
|---|---|---|---|
| p value | 0.05 | Avg 1 | 7.954183217 |
| t statistic | 1.8835 | Avg 2 | 6.611654761 |
| Deg Free | 40 | | |
| t critical | 2.021074579 | | |

**You CANNOT say that the mean of Data Set 2, is different from the mean in Data Set 1.**

## Appendix F: B-C F-test and T-tests 99%

| | Data Set 1 | Data Set 2 |
|---|---|---|
| 1 | 11.52097 | 10.7009984 |
| 2 | 12.1311676 | 11.5301056 |
| 3 | 12.9389748 | 11.1057664 |
| 4 | 11.5312475 | 7.9423488 |
| 5 | 10.7839725 | 8.37851968 |
| 6 | 10.3520807 | 7.6274304 |
| 7 | 8.1036485 | 6.4780672 |
| 8 | 6.7071035 | 5.1605696 |
| 9 | 6.787021 | 5.7859584 |
| 10 | 7.1039365 | 5.6516288 |
| 11 | 6.551453 | 5.21020928 |
| 12 | 7.3162175 | 5.4879424 |
| 13 | 7.0348977 | 4.8185184 |
| 14 | 5.6990838 | 4.62218368 |
| 15 | 7.357491 | 4.7291136 |
| 16 | 5.6135734 | 6.474064 |
| 17 | 5.705038 | 5.285892 |
| 18 | 5.5883925 | 4.7040936 |
| 19 | 5.8730345 | 5.453248 |
| 20 | 6.05156175 | 5.785217067 |
| 21 | 6.2869818 | 5.912874667 |
| 22 | | |
| 23 | | |
| 24 | | |
| 25 | | |
| 26 | | |
| 27 | | |

Do you need to know if the mean of Data Set 2 is:
- Statistically **H**igher (H) than Data Set 1,
- Statistically **L**ower (L) than Data Set 1,
- **E**ither higher or lower (E) than Data Set 1

Enter H, L or E: E

| **F Test Results** | | | |
|---|---|---|---|
| p value | 0.01 | St Dev 1 | 2.457224994 |
| F statistic | 1.3036 | St Dev 2 | 2.1521483 |
| Deg Free 1 | 20 | Var 1 | 6.037954672 |
| Deg Free 2 | 20 | Var 2 | 4.631742306 |
| F critical | 2.9377 | | |

**You CANNOT say that the variation in Data Set 2 is different from the variation in Data Set 1.**

| **t Test Results, Equal Variance** | | | |
|---|---|---|---|
| p value | 0.01 | Avg 1 | 7.954183217 |
| t statistic | 1.8835 | Avg 2 | 6.611654761 |
| Deg Free | 40 | | |
| t critical | 2.021074579 | | |

**You CANNOT say that the mean of Data Set 2, is different from the mean in Data Set 1.**