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Tool Life of Various Tool Materials When Friction Spot Welding DP980 Steel

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A thesis submitted to the faculty of
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Master of Science

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ABSTRACT

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In this study, friction spot welding was used to join DP980 steel sheet. Four different ultra-hard tool materials were used with the objective of determining which tool material produced the highest number of acceptable-strength welds. Three of the tools were composed of various mixtures of polycrystalline cubic Boron Nitride (PCBN), Tungsten, and Rhenium. These materials are referred to herein as Q60, Q70, and Q80, the "Qxx" designation denoting the percentage of the volume of the tool material composed of PCBN. The fourth tool tested was composed entirely of PCBN.

The Q70 tool produced approximately 1100 welds of acceptable strength before average weld strength decreased below the acceptable value, and the Q60 tool produced approximately 600 welds of acceptable strength. The Q80 material did not produce any welds with strengths above the acceptable value. However, Q80 produced the greatest number of welds of consistent strength. The PCBN tool, being the hardest, also did not produce any welds of acceptable strength, and failed at 257 welds. This failure is presumed to be a result of a tool/parameter mismatch which caused excessive loads on the tool.

This research revealed that the weld parameters and tool materials used in this study will not generally provide for feasibility of implementation in industry. Further advances in weld parameter selection, tool geometry, and tool materials will be necessary in order to make friction spot joining of high strength steels an economically viable option.

Keywords: Christopher Ridges, DP980, friction spot, Q60, Q70, Q80, PCBN

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1 INTRODUCTION

1.1 Background

The use of ultra-high strength steels (UHSS) in car bodies has become of interest to the automobile industry in recent years (Chen, 2005). Mounting legislative pressure to increase fuel mileage has driven automobile manufacturers to investigate new ways of making vehicles lighter. Ultra high strength steels have a much higher strength-to-weight ratio than the materials currently used in most car bodies. They can therefore be used in smaller quantities, which will reduce the weight of the car body while maintaining acceptable structural rigidity.

Along with the steadily increasing federal fuel mileage requirements, federal laws have been passed in the USA which also require an increase in car body resistance to crashes and rollovers. For example, a law was passed in 2009 that doubled the roof crush resistance of vehicles weighing less than 6000 lbs. from 1.5 times the vehicle weight to 3 times the vehicle weight (http://www.nhtsa.gov, 2009).

1.1.1 Spot Welding in High Strength Steels

Joining of high strength steel components poses a problem in that they cannot be reliably resistance spot welded in the same manner as mild steel or aluminum panels. High-temperature liquefying and rapid-cooling solidification caused by resistance welding creates a very brittle microstructure in ultra-high strength steels. This brittleness results in cracking in and around the welded area. Friction spot welding has been investigated as a solution to this problem. Experiments have shown that the lower process temperatures of friction welding result in a much more favorable microstructure with improved ductility and toughness (Ohashi, 2009). Also, it has been shown that lap shear strength of friction spot welds can be high enough to meet standards set by the American Welding Society (AWS) (Sederstrom, 2007).

1.1.2 Friction Spot Weld Tools and Tool Materials

Several different friction spot weld tool materials have been proposed for testing of durability, and they include Silicon dioxide, polycrystalline Cubic Boron Nitride (PCBN), and PCBN/Tungsten/Rhenium composites. It was unknown at the beginning of this study which tool material produced the most welds of adequate strength before tool failure. It is important for automobile manufacturers to know which tool material lasts the longest because of the cost of the tools. Individual tools can cost as much as $2500 USD because of the difficulty of processing the ultra-hard materials of which they are composed, as well as the cost of the tool material itself. Therefore, it is critical that a tool produce a number of welds before failure that justifies the cost of the tool.

1.2 Contribution of This Study

The proposed contribution of this study was to determine how many friction spot welds could be produced by a tool of a certain material composition using a specific set of welding operation parameters. This information would help automobile manufacturers to more accurately project process costs of using UHSS in the car bodies they produced.

The study only included a limited number of tool materials and geometries. It also included an analysis of spot welded material flow produced by various tool materials. The UHSS material used for testing was DP980 steel.

1.3 Research Questions

The questions addressed in this study included the following:

- What is the expected tool life (in number of welds) of a friction spot weld tool of a certain material composition and geometry using a specific set of welding parameters?
- Which tool material produces the most welds before failure or decrease in joint strength?
- What friction spot weld process parameters produce adequate weld strength?

1.4 Definition of Terms

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

DP780 - Dual phase steel consisting of martensite and ferrite phases with an ultimate tensile strength of 780 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.

W - element symbol for Tungsten

Re - element symbol for Rhenium

Dwell - the time, measured in seconds, that the spot weld tool spends at a certain point of its travel into the material

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. See Figure 1.

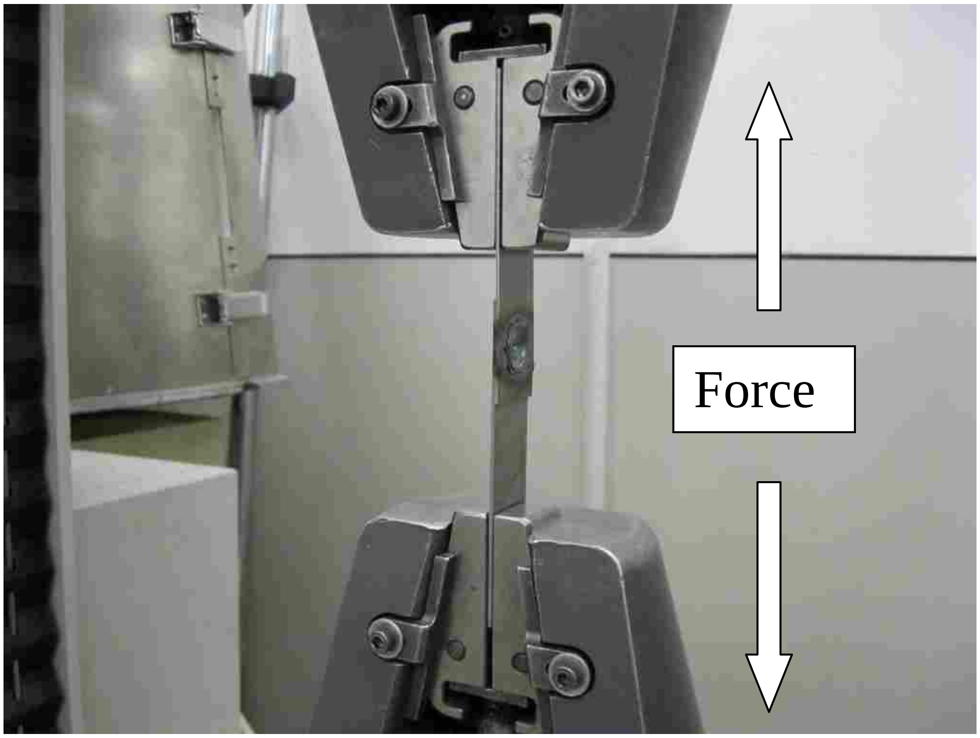


Figure 1: Lap Shear Test

1.5 Significance of the Study

The significance of this study lies in its potential to help facilitate the mass use of high strength steels in the automobile industry. This will greatly assist automobile manufacturers in achieving their goal of vehicle weight reduction. The study has the potential to make process costs more predictable by establishing a realistic expectation of friction spot weld tool life.

1.6 Delimitations

In this study, only four material combinations were tested. The testing included only one set of weld parameters which was used for all four of the tool materials. The four tools of different materials all shared the same tool geometry. Spot weld testing took place in 4” x 1” x .060” DP980 steel coupons, as well as 4” x 1” x .050” DP980 steel coupons. The testing was performed on one machine only, which is significant in that there is generally measureable variability in backlash and accuracy from one machine to another. This variability could affect weld strength, as it became evident during parameter development in this study that weld strength is highly sensitive to small parameter variations.

2 LITERATURE REVIEW

2.1 Overview

Friction welding was developed by The Welding Institute in 1991, but friction spot welding of high strength steels has only recently been investigated. Other ways of joining dual phase steels have been developed, but to date these methods have proven deficient in their ability to produce desired mechanical properties in the joint, and frequent failure of resistance spot welds in high strength steels has been reported (Weirzbicki, 2006). The tool materials in this study have yet to be tested for longevity and effectiveness in friction spot welding. However, other tool materials have recently been tested and provide a good starting point for the experiments performed in this study.

2.2 Discussion

Automobile manufacturers have become increasingly interested in using dual phase steels because of their strength and crash test performance. A study carried out by the Auto/Steel Partnership showed a 22.36 percent reduction in the mass of a part when DP980 was substituted for the baseline material. The DP980 component also performed comparably to the heavier baseline component in crash tests (Auto/Steel partnership, 2005).

2.2.1 Alternative Methods for Joining DP980

Various methods have been investigated for joining DP980, which include resistance spot welding, self-piercing rivets, and laser welding. Nikoosohbat performed resistance spot welding tests in 2mm sheets of DP980. Macrograph and micrograph images clearly showed that solidification shrinking had formed cracks in the center of the welds. These cracks, coupled with the Martensitic microstructure of the welds, suggest that resistance spot welds in high strength steel would be susceptible to crack propagation, and therefore unsuitable for use in automotive applications where vibration is common (Nikoosohbat, 2010).

It has been determined that laser welded DP980 experiences a softening in the heat affected zone (HAZ) due to tempering of the material around the weld which has not reached the austenization temperature during welding. This softened zone shows a significant reduction in fatigue limit when compared to that of the base material. Fatigue testing produces consistent failure in this soft zone (Farabi, 2010) (Xia, 2007). The low fatigue limit regions of laser spot welds in DP980 also make this method of joining unreliable when used in many automotive applications. Heat treatment can be used to improve the mechanical properties of the (HAZ) (Lin, 2008), but such post processing adds time and expense to the overall process

Self-piercing rivets are ineffective when joining DP980 due to the severe plastic deformation that occurs at the point of penetration. DP980 lacks the ductility required to withstand this amount of deformation without crack initiation.

2.2.2 Friction Spot Welding

In his thesis, Jack Hunter Sederstrom discussed research performed pertaining to the strength and ductility of friction spot welds performed in high-strength steel. He outlined the methods used to friction join the material, as well as the variable parameters used in testing such as rpm, plunge rate, dwell time, and plunge depth. A discussion of the tool materials used was also included along with the results of the use of each tool material. The results of the lap-shear and cross-tension strength tests were presented for friction spot welding, and they were compared with the results of the same tests performed on resistance spot welded joints. The advantages of friction spot welding over resistance welding were presented and included better ductility of friction spot welds as well as lower process temperatures and a decrease in hardness. This study revealed that PCBN is currently the most desirable tool material. Carbide and high speed steel tools were tested and quickly failed. Also, the study contained a description of the tool geometry found to perform the best in terms of strength of welded joints (Sederstrom, 2007).

Figure 2: Friction Spot Weld Tool

This tool material and geometry, when combined with proper weld process parameters, consistently produced welds with an acceptable lap shear strength in the range of 2900 to 3400 lbs. in DP780. Pouranvari achieved similar strength in 6 mm resistance spot welds in DP980, ranging from 3000 to 3400 lbs. Therefore, the strength of friction spot welded joints is comparable to that of resistance welded joints (Pouranvari, 2010).

Ohashi investigated microstructural evolution during friction bit joining in DP580. His findings helped to identify the reasons behind the successful joining and favorable mechanical properties of friction spot-welded high strength steels. This article discussed the evolution of the microstructure in DP590 steel during friction spot welding. After spot welding was performed, a cross section of the weld was analyzed and its microstructure characterized. Three microstructure zones were observed and classified as zones 1, 2, and 3. Zone 1 was the closest to the base material and was observed to be a dual-phase zone consisting of ferrite and martensite. Zone 2 lay between zone 1 and zone 3, and zone 3 was located at the center of the weld in the area where the tool pin passed through the material. Zones 2 and 3 were both completely martensitic, but zone 3 had a finer grain structure than zone 2. The fully martensitic structures of zones 2 and 3 were a result of the increase of temperature beyond the austenization temperature of the material during welding. Martensite was formed upon cooling. Zone 1 was not subjected to as much heat as zones 2 and 3, therefore only a portion of zone 1 reached the austenization temperature and re-crystalized into martensite, the other portion remaining ferrite. The presence of ferrite in zone 1 along with the larger grain size in zone 2 indicated the reasons for the increased ductility in friction spot welds when compared with resistance spot welds (Ohashi, 2009).

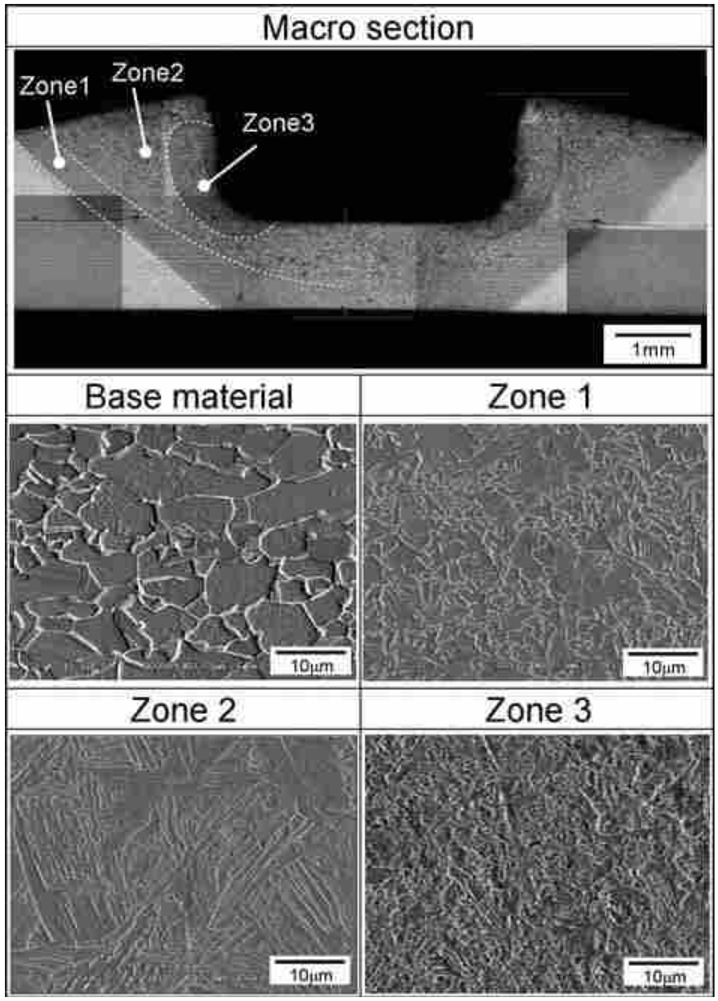


Figure 3: Spot Weld Microstructure Zones (Ohashi, 2009)

Ohashi also researched the effect of contamination on microstructure in friction spot welded DP590 steel. This article discussed the effect of argon shielding gas and tool coating on contamination of friction spot welds in DP 590 steel. Three conditions were used during spot welding:

- Non argon, non-tool coating welding
- Argon shielded, non-tool coating welding
- Argon shielded, coated tool welding

Cross sections of the welds performed under the three conditions were then analyzed to assess the amount of oxygen, silicon, and nitrogen contaminants in the welds. It was found that there was significant oxygen contamination in the non-gas-shielded welds, and some silicon and nitrogen contamination in all of the welds, assumed to be from decomposition of the tool during welding (a silicon nitride tool was used). The presence of oxygen, silicon, and nitrogen in the welds was thought to contribute to certain formations of martensite structure. The formation of coarse and fine martensite contributed to the mechanical properties (i.e. hardness, ductility) of certain areas of the welds (Ohashi, 2009).

PCBN and PCBN/Tungsten/Rhenium composite were used in this study, therefore the Silicon weld contamination was not an issue. However, it was anticipated that oxygen contamination of the welds might become an issue as the proposed methodology did not include the use of Argon shielding gas. The reason for the decision not to use Argon gas was the general desire in industry to keep process complexity to a minimum.

The heat affected zone (HAZ) has been shown to be significantly softer than the base material when friction welding DP980 steel. Failure in the HAZ during tensile testing has consistently been a problem during testing of linear friction welded DP980. However, in friction spot welding of DP980 the cross-sectional area of the bonded region is small enough to result in failure of the joint well before failure of the HAZ (Miles, 2009).

Jasthi performed linear bead-on-plate friction welding tests using tools made from PCBN, as well as Tungsten/Rhenium composite (Jasthi, 2008). Despite the differences in friction spot welding and linear friction stir welding processes, some useful conclusions were drawn from the results in these experiments. First, based on the results of the authors experiments, PCBN clearly outlasts WRe composite tools. Second, WRe composite tools generate more friction heat than

PCBN tools due to their softness. These two results suggested the possibility of a combination of PCBN and WRe that provides for acceptable tool longevity and adequate heat generation during welding. Combining these two materials could result in a reduction of cost of producing the tools when compared with the cost of producing 100% PCBN tools. PCBN tools are very costly to produce due to the hardness of the material and resulting difficulty of its processing.

2.3 Summary

These articles provided the basis for this study. It had been established that, of the tool materials tested, PCBN was the material of choice for friction spot welding when it came to tool longevity. It had also been suggested by certain experimental results that W/Re could be used in conjunction with PCBN for potentially less expensive tools with reasonable effectiveness. Therefore, the path had been cleared for research into tool longevity using different compositions of PCBN/WRe tools. Also, friction spot weld mechanical properties had been characterized for welds that were performed using a Silicon Nitride tool. This related to the study in that it established a benchmark for mechanical properties that were to be expected in a weld of acceptable strength and toughness.

The tool geometry used by Sederstrom was used in this study. Although it was assumed that there could be multiple variations of effective tool geometry, a study of various tool geometries was not performed in this study because Sederstrom's tool geometry had already been proven effective in producing spots of adequate strength. However, tool geometry development will likely become an important factor in the advancement of friction spot welding in high strength steels.

3 METHODS

3.1 Introduction

Four tool materials were tested for wear resistance in friction spot welding of DP980 steel: PCBN, Q60, Q70, and Q80. Smith Megadiamond, a developer and producer of ultra-hard materials for tool use, developed and supplied PCBN/WRe tools for testing in this study. The PCBN/WRe tools comprised a matrix of WRe containing embedded PCBN crystals, the objective being the combination of ductility in the WRe with the hardness of PCBN to create a material sufficiently tough to withstand the high pressures inherent in friction welding.

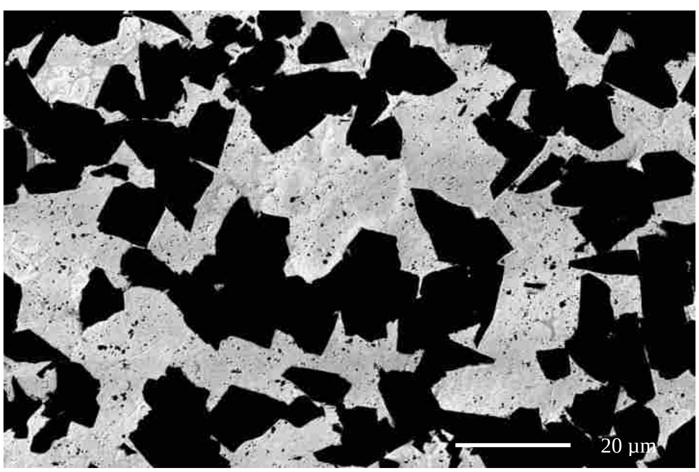


Figure 4: PCBN Crystals (Black Areas) Embedded in WRe Matrix (Peterson, 2009)

3.2 Weld Parameter Development

The study began by using a Q60 tool to develop spot weld parameters that consistently produced welds with at least 3000 lbs. of lap shear strength. These parameters included tool plunge rate, plunge depth, RPM, and dwell. Baseline parameters were obtained from Pacific Northwest National Laboratories (PNNL).

3.3 Test Equipment

The lap shear strength testing was performed on an Instron tensile tester as shown in Figure 5.

Figure 5: Instron Tensile Strength Tester

Microhardness mapping of sample cross sections was performed using a Leco LM100 AT microhardness mapping machine.

Spot welding was performed on a Kearney and Trecker 3-axis mill that had been converted to CNC operation with variable RPM, plunge rate, plunge depth, and dwell time.

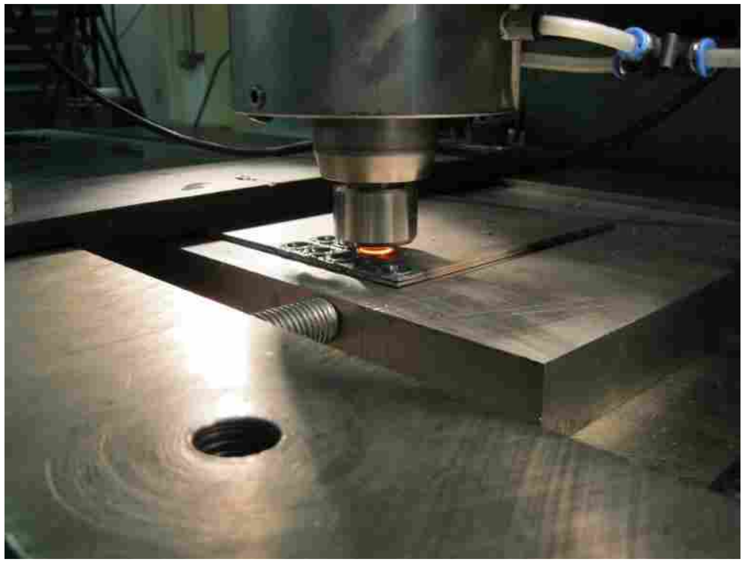


Figure 6: Friction Spot Welding in DP980

Figure 7: Kearney and Trecker CNC Mill

3.4 Friction Spot Welding

The spot welds were produced in a tight matrix pattern on two overlapped sheets of DP980 steel with an individual sheet thickness of .060”.

Figure 8: Friction Spot Welds

Following the first 50 welds, individual welds were performed separately on six pairs of 4” x 1” coupons of DP980 steel, also with an individual thickness of .060”. These separate samples were tested for lap shear strength and used for metallography. This process was repeated every 50 welds thereafter until 250 welds had been produced. From that point forward, the individual coupon pairs for lap shear strength testing and metallography were produced every 100 welds. The reason for the higher frequency of separate sample production near the beginning of testing was the assumption that tool wear might occur more rapidly than anticipated. Testing every 50 welds initially allowed for capture of rapid tool wear, had this become the case.

Figure 9: Friction Spot Welding of 4" x 1" Coupons for Lap Shear Testing

In this manner, lap shear strength was correlated to number of welds produced by a given tool material, as it was anticipated that weld strength would change with tool wear.

3.5 Wear Pattern Generation

Tool wear patterns were shown by overlapping images of each tool profile taken at various stages of testing. Each time a set of test coupons were produced (as described previously), the tool was placed on an optical comparator where its silhouette was photographed.

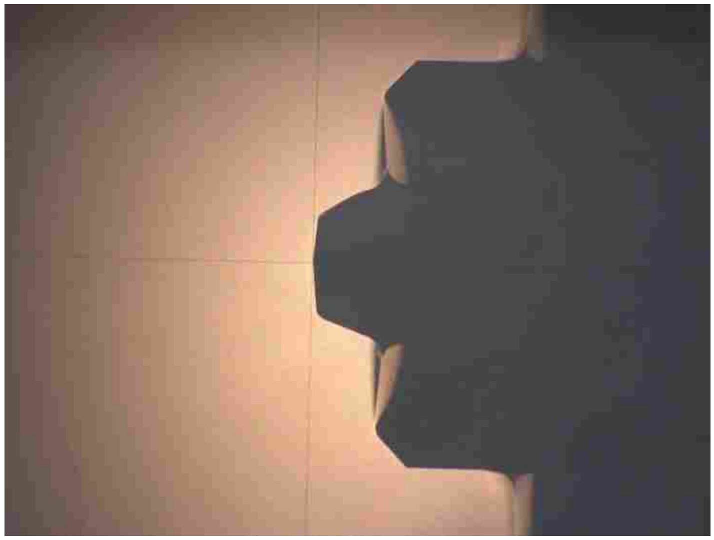


Figure 10: Tool Silhouette Photograph

Photo editing software was then used to convert the edges of the tool image to a solid colored line. These colored lines were overlapped to produce an image that showed areas of wear on the tool, as shown in Figure 11.

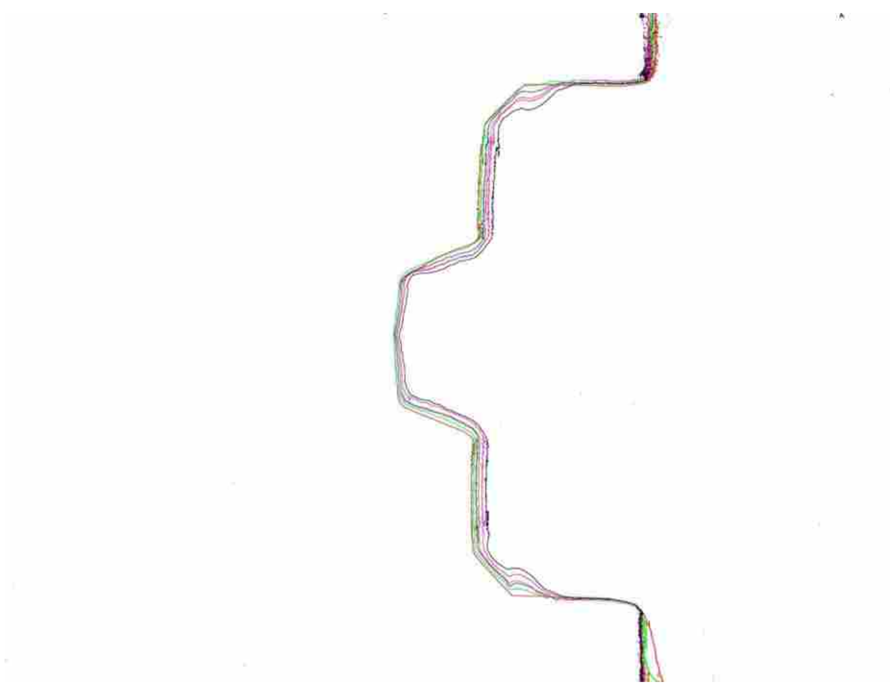


Figure 11: Overlapped Tool Outlines

4 RESULTS AND DISCUSSION

4.1 Weld Parameter Development

After testing several combinations of RPM, plunge rate, plunge depth, and dwell, the parameters in Table 1 were proven to consistently produce welds with lap shear strength greater than 3000 lbs. The parameters were developed using a Q60 tool, and were therefore tailored specifically to the mechanical properties and coefficient of friction of the Q60 tool. A two-stage plunge with a decreased plunge rate in the second stage proved to be the most effective in generating welds of acceptable strength. Also, liquid tool cooling was used for the tool holder for Q60 and Q70. An additional Q60 tool was tested without cooling, as were the PCBN and Q80 tools.

During testing, the supply of .060” DP980 sheets was exhausted. It is difficult to obtain DP980 steel, therefore it became necessary to use remaining sheets of .050” thickness. The second set of parameters was used in conjunction with the thinner sheets, and was adjusted according to the difference in thickness between the .050” sheets and the original sheets. By adjusting these parameters, the area of the contact surface between the tool and the DP980 was kept consistent.

Table 1: Weld Parameters for .060" and .050" Material

Material Thickness	RPM	Plunge Rate	Plunge Depth	Dwell
Stage 1				
.060”	1500	6”/minute	-.095”	No dwell
.050”	1500	6”/minute	-.075”	No dwell
Stage 2				
.060”	1500	.5”/minute	-.113”	No dwell
.050”	1500	.5”/minute	-.093”	No dwell

4.2 Tool Wear Patterns

The shoulder of each tool sustained the most significant wear. The higher surface speed at the perimeter of each tool resulted in wear in the form of a channel appearing around the outer edge of the shoulder of each tool as the number of welds increased. Also, radial surface cracks in the tool material appeared and increased in size as welding progressed. The reduced wear shown in the second Q60 and PCBN tools is attributed to early tool failure during testing.

The pin of each tool exhibited narrowing, but little reduction in length. This can most likely be attributed to low surface speed and relatively low friction at the center of the tool where the pin is located.

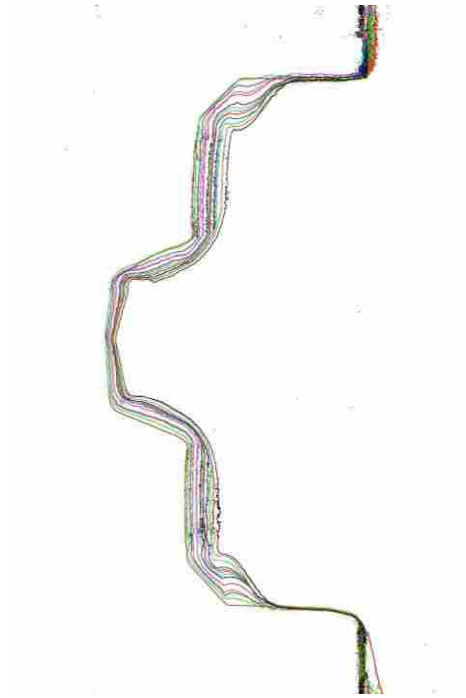


Figure 12: Q60 With Cooled Tool Holder Wear Pattern

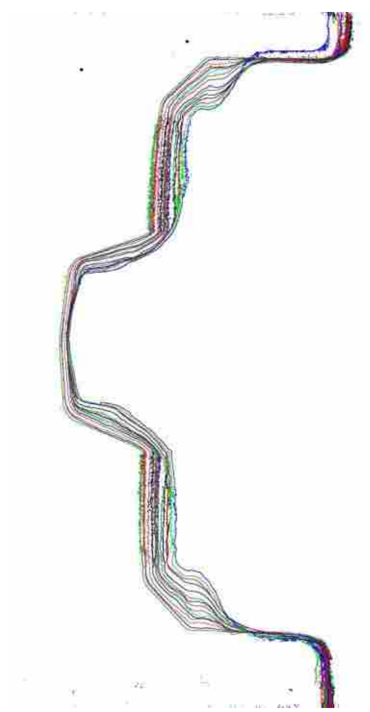


Figure 13: Q70 With Cooled Tool Holder Wear Pattern

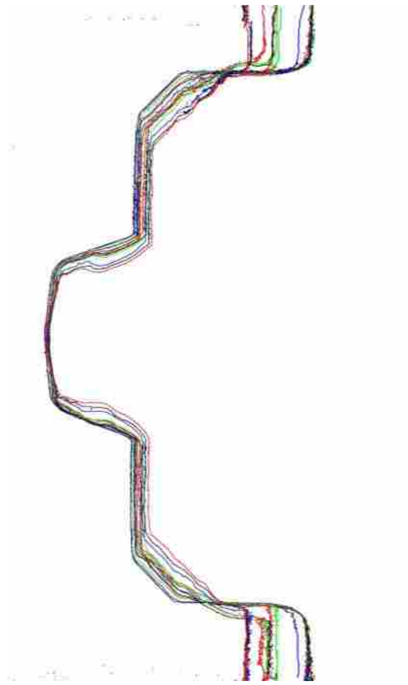


Figure 14: Q80 Without Cooled Tool Holder Wear Pattern

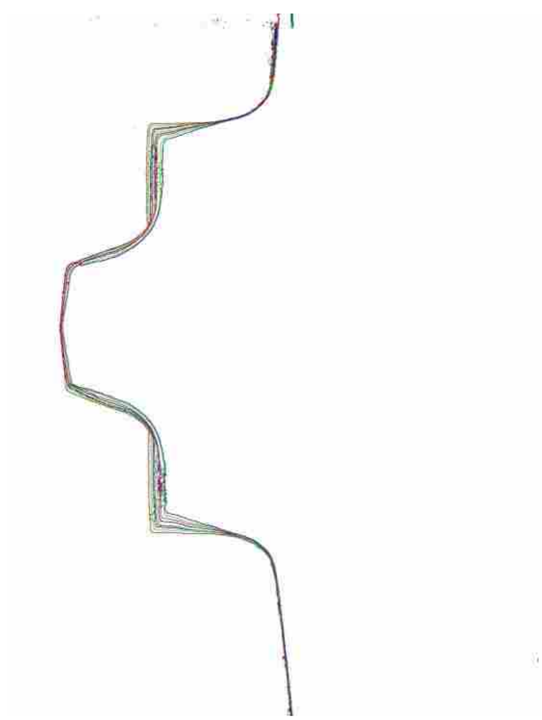


Figure 15: Q60 Without Cooling Wear Pattern

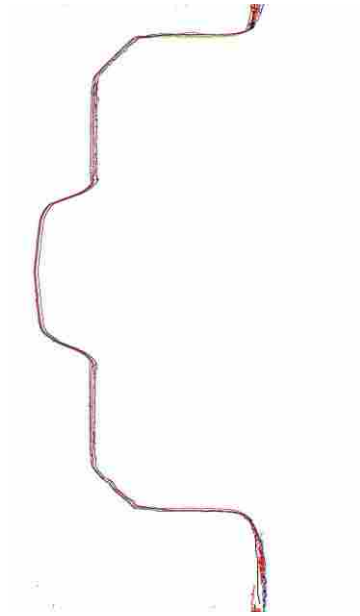


Figure 16: PCBN Tool Without Cooling Wear Pattern

Figure 17: Cracking in PCBN Tool at 250 Welds

As shoulder wear increased, the contact area between the tool and the DP980 decreased, as did the diameter of the tool. The reduced diameter of the tool resulted in a decrease in friction heat during welding, which in turn resulted in a decrease in lap shear strength of each weld.

4.3 Weld Cross Sections and Material Flow Images

The following images illustrate the change in material flow and heat generated as the tools wore down during welding. The images are accompanied by a table with information which includes the tool material used, the weld number, the average lap shear strength of the preceding three welds, and the average spindle z-axis load of the preceding three welds. This information can be used to correlate tool wear with decrease in weld strength.

The stirred and bonded area in the cross section images can be seen as a lighter area on either side of the pin indentation. This area is generally larger in the welds produced by the softer Q60 and Q70 materials, indicating better flow.

4.3.1 Q60 Tool Without Cooling in DP980

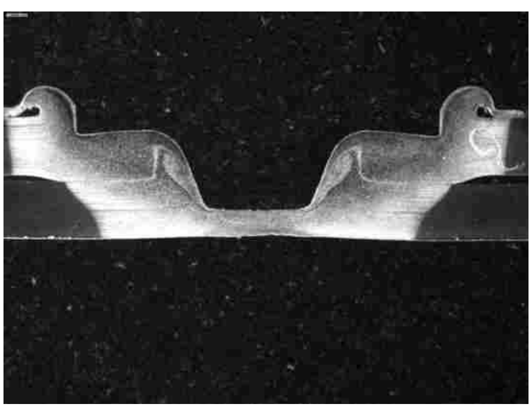


Figure 18: Weld #54

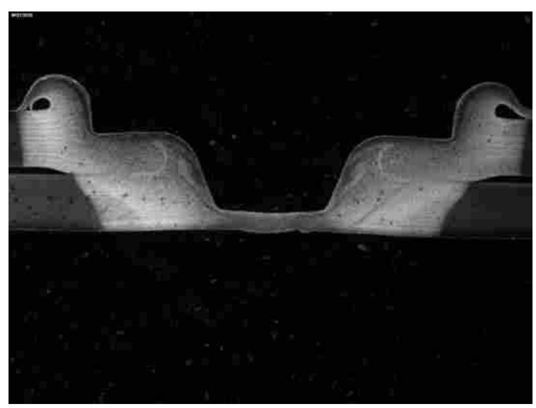


Figure 19: Weld #104

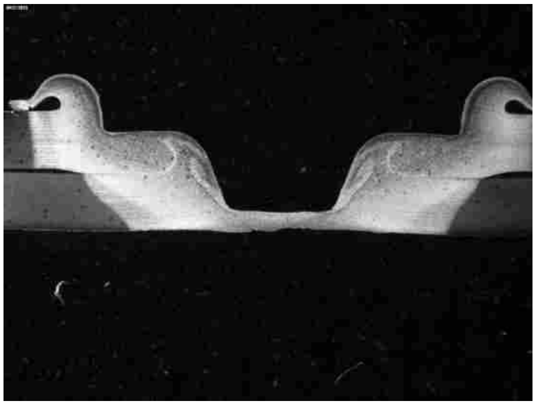


Figure 20: Weld #154

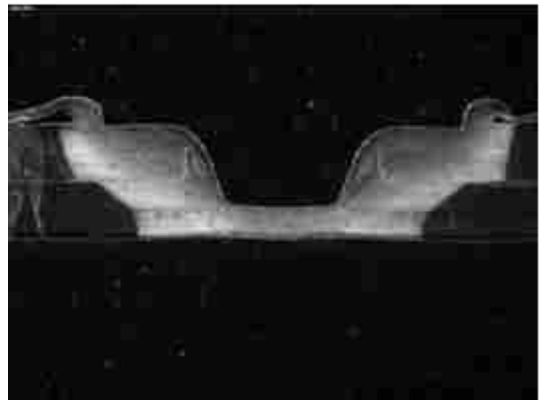


Figure 21: Weld #204

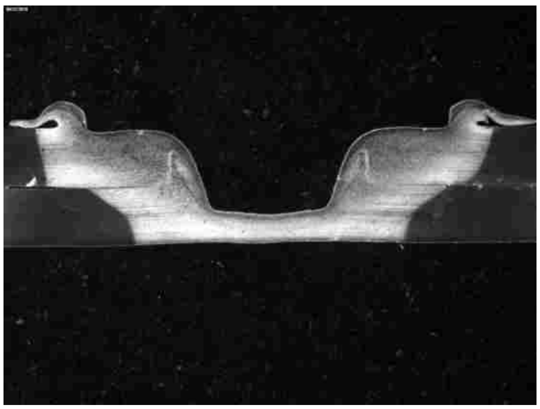


Figure 22: Weld #254

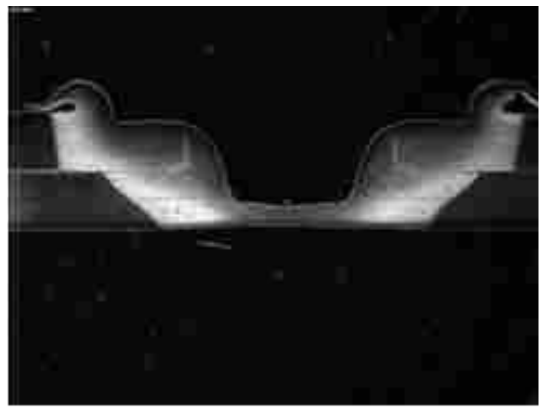


Figure 23: Weld #354

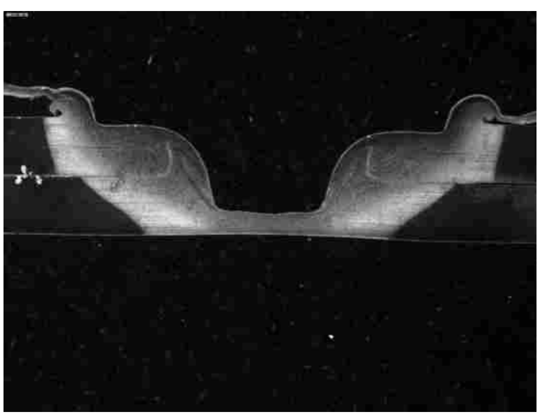


Figure 24: Weld #454

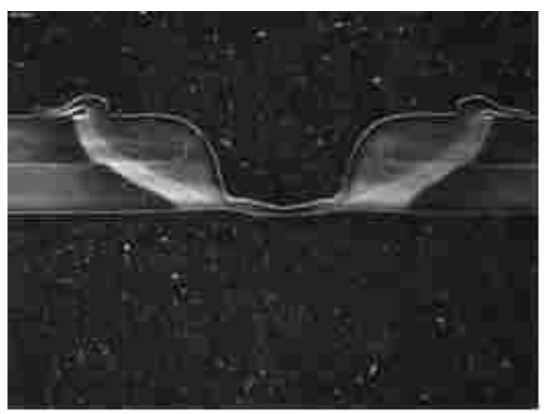


Figure 25: Weld #554

4.3.2 Q60 Tool With Cooled Tool Holder in DP980

Welds 245-360 were performed using a pitted anvil which artificially skewed the lap shear values and z-load values downward. They will not be shown here. The pitting in the anvil developed gradually during testing, and the anvil was replaced mid-test. Also, the weld numbers shown here for Q60 with cooling are different than those shown for the other tool materials due to a slight change in counting method. However, the intervals between welds are similar to those of the other tool materials, and the same overall weld evolution can still be seen.

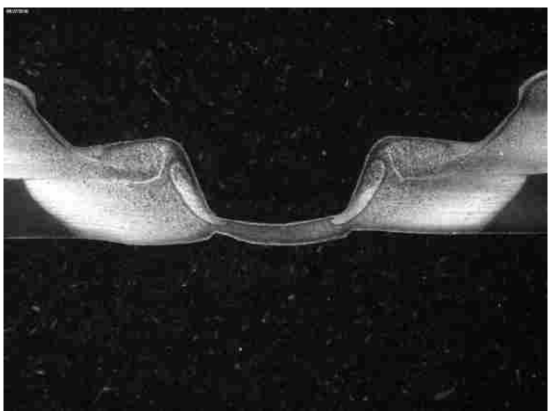


Figure 26: Weld #26

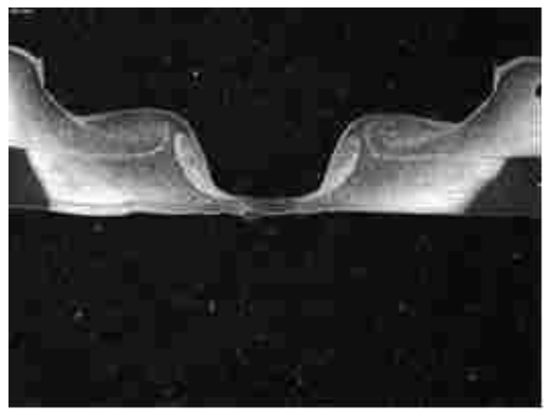


Figure 27: Weld #135

Figure 28: Weld #191

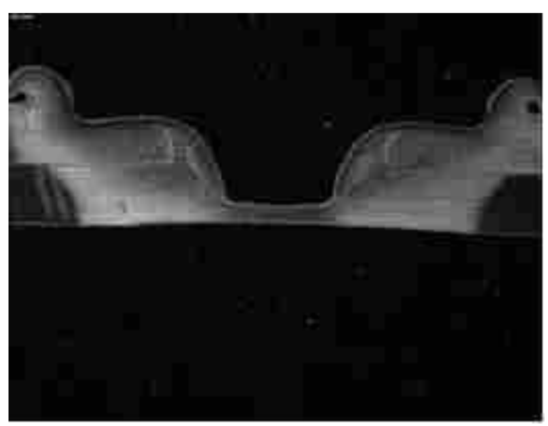


Figure 29: Weld #470

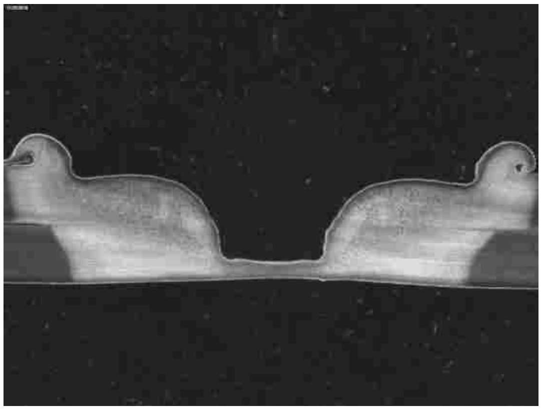


Figure 30: Weld #582

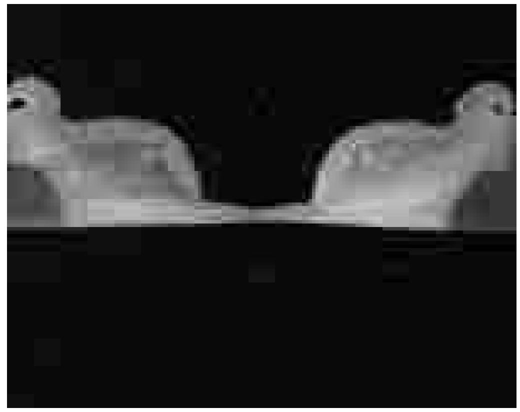


Figure 31: Weld #688

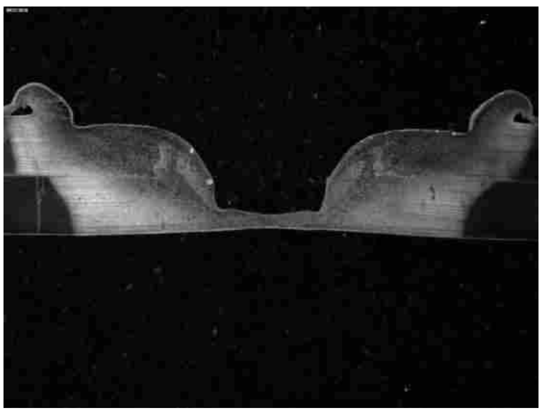


Figure 32: Weld #795

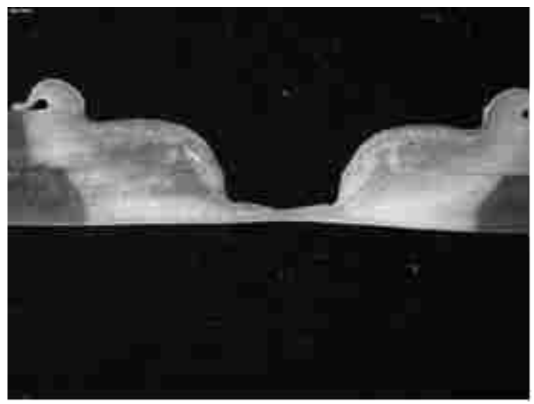


Figure 33: Weld #902

4.3.3 Q70 Tool With Cooled Tool Holder in DP980

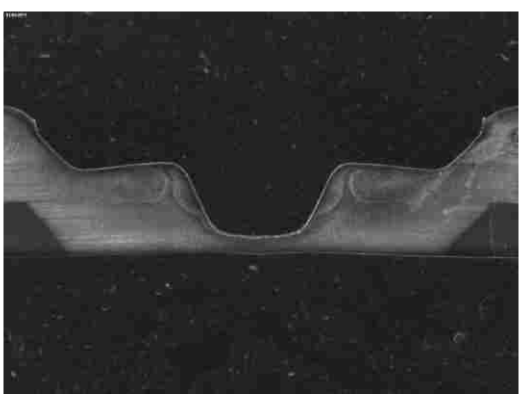


Figure 34: Weld #54

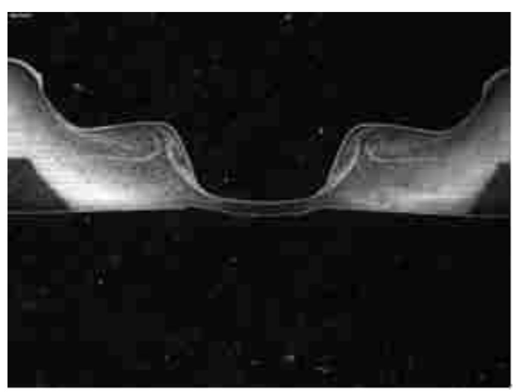


Figure 35: Weld #104

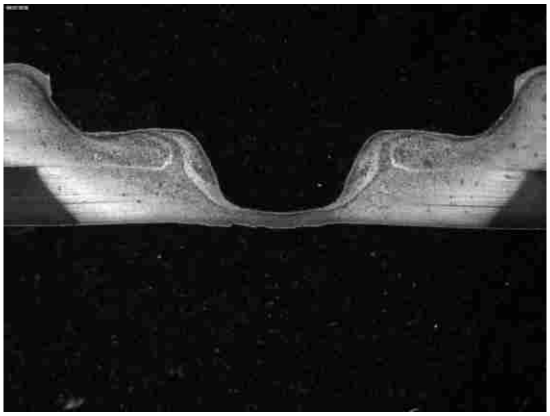


Figure 36: Weld #154

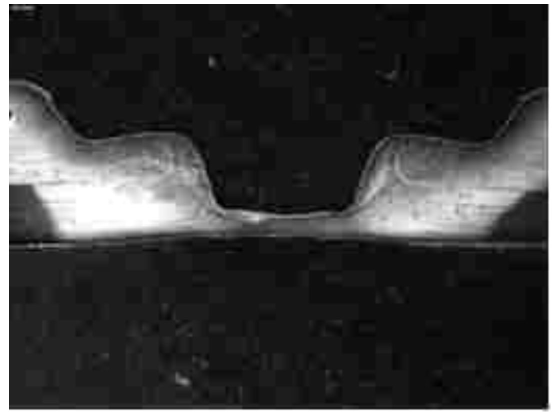


Figure 37: Weld #204

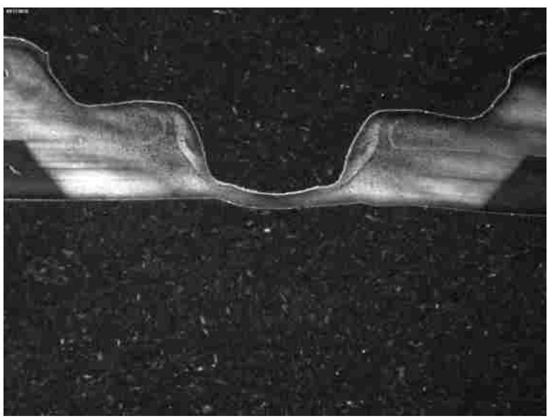
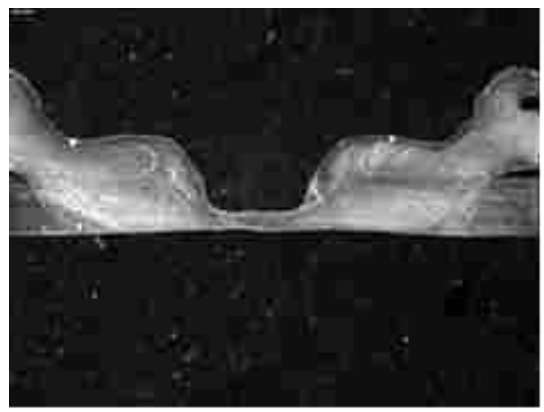


Figure 38: Weld #254



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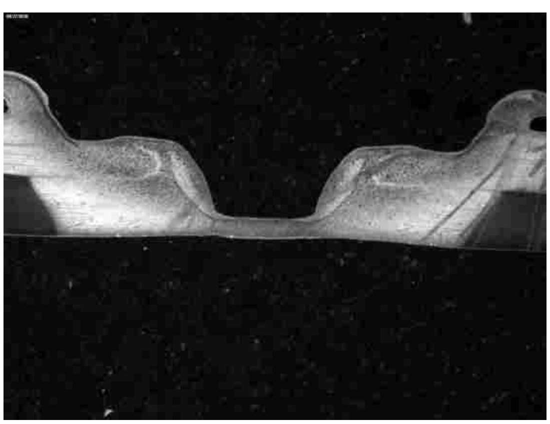


Figure 40: Weld #454

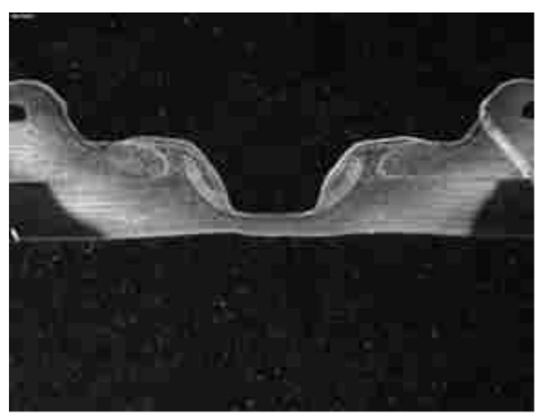


Figure 41: Weld #554

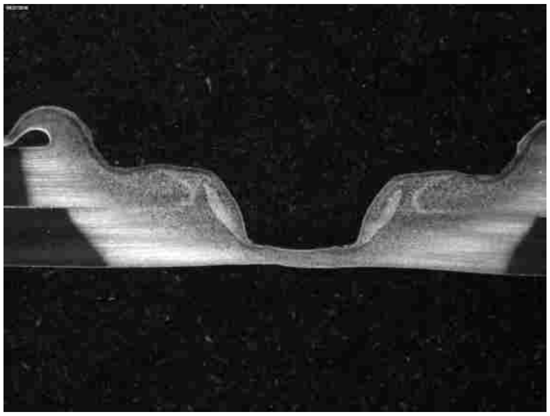


Figure 42: Weld #654

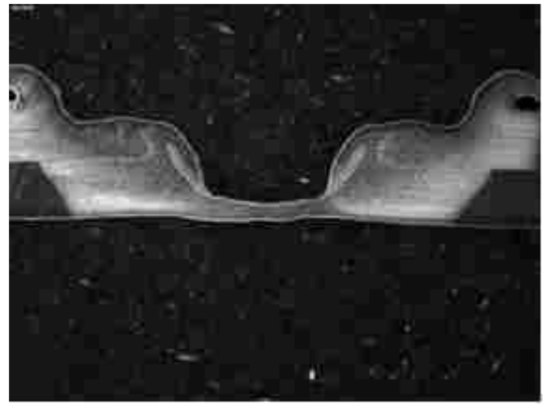


Figure 43: Weld #754

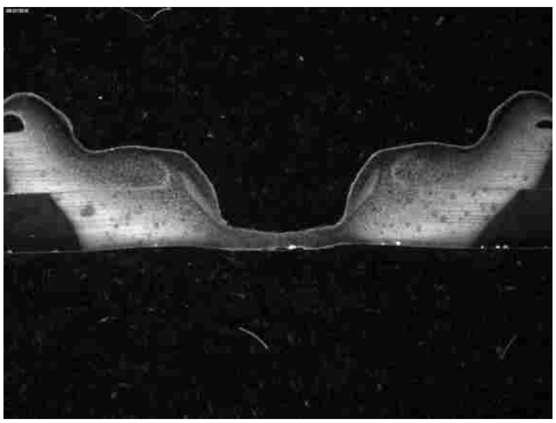


Figure 44: Weld #854

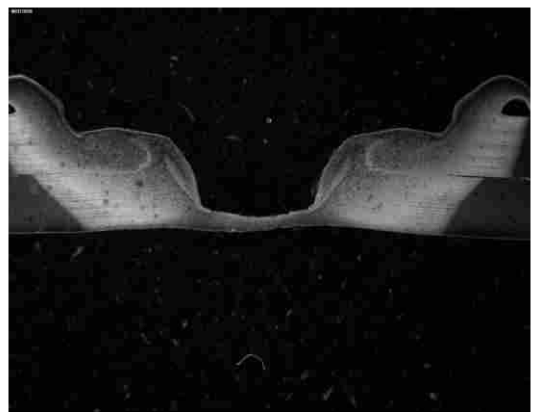


Figure 45: Weld #954

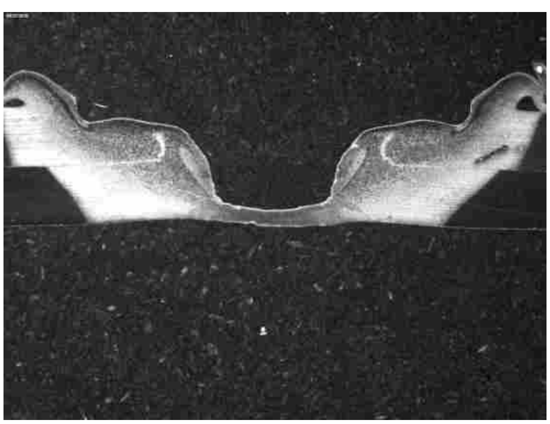


Figure 46: Weld #1054

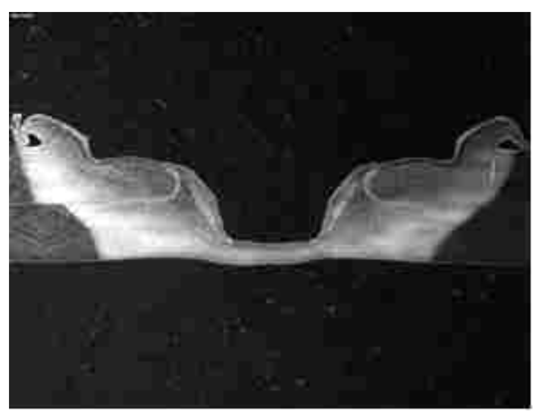


Figure 47: Weld #1154

4.3.4 Q80 Tool Without Cooling in DP980

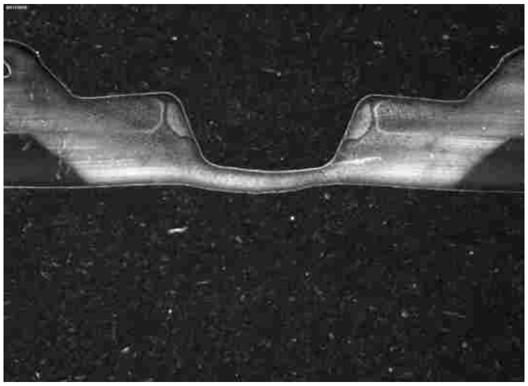


Figure 48: Weld #54

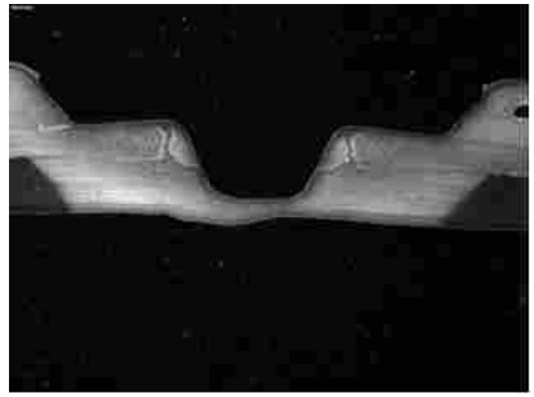


Figure 49: Weld 104

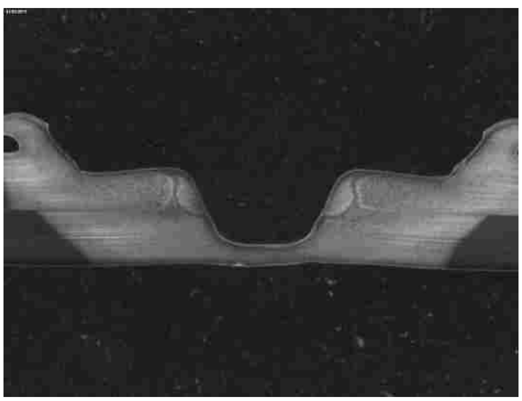


Figure 50: Weld #154

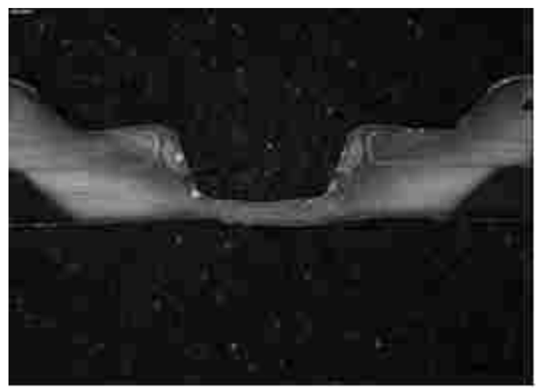


Figure 51: Weld #204

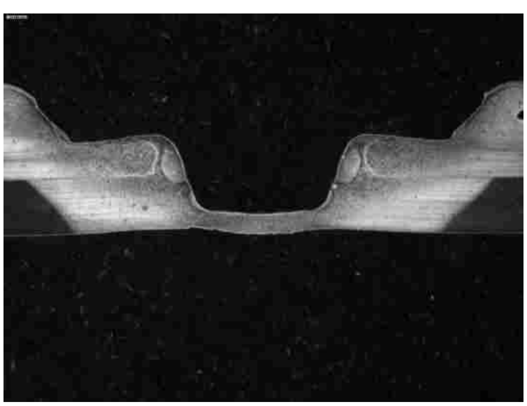
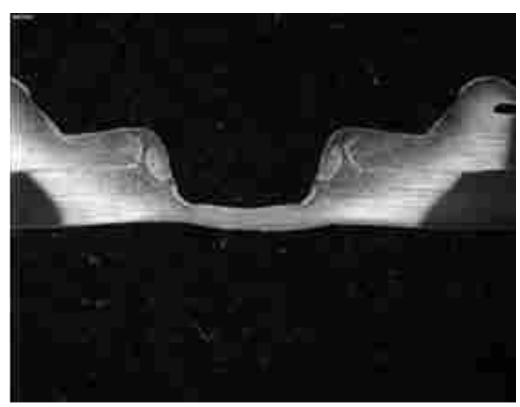


Figure 52: Weld #254



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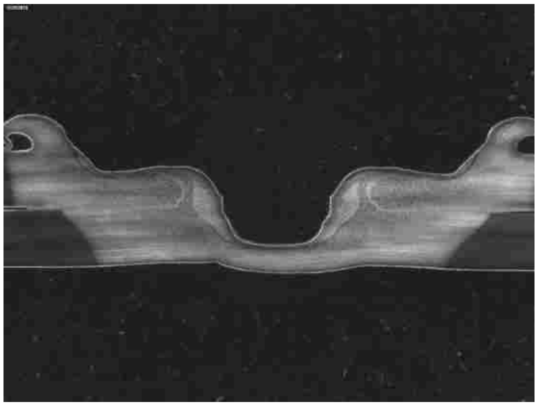

Figure 54: Weld #454

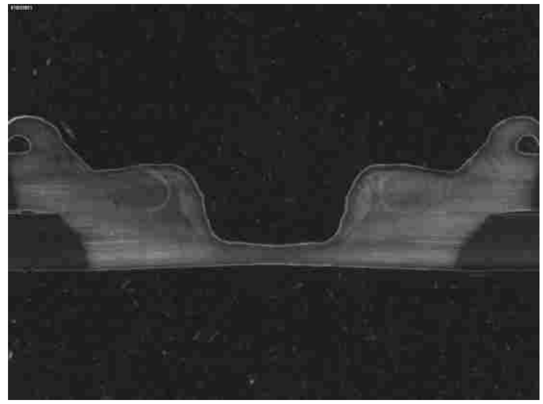

Figure 55: Weld #554

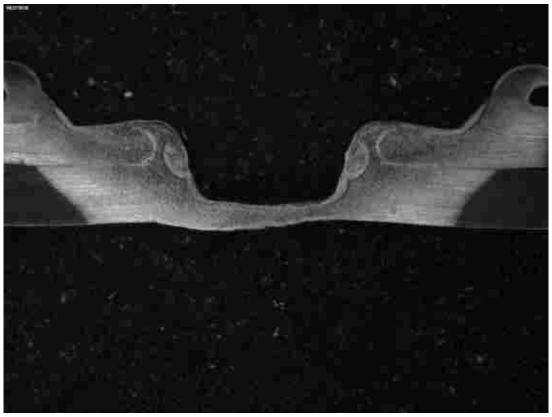

Figure 56: Weld #654

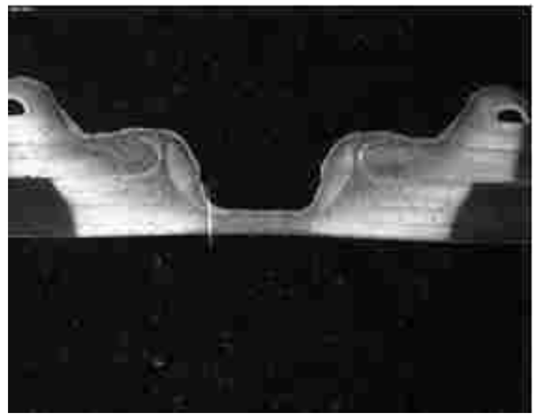

Figure 57: Weld #754

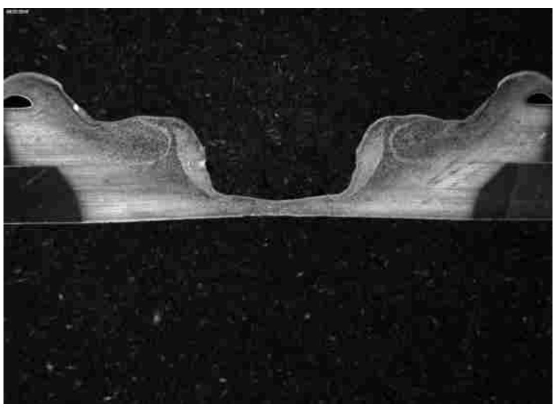

Figure 58: Weld #854

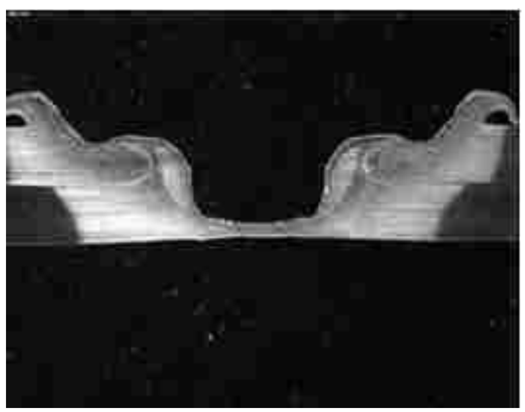

Figure 59: Weld #954

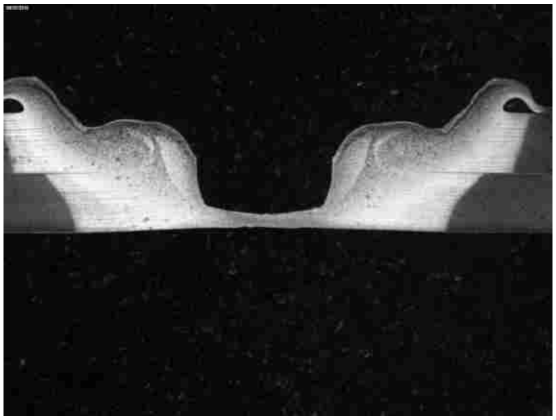

Figure 60: Weld #1054

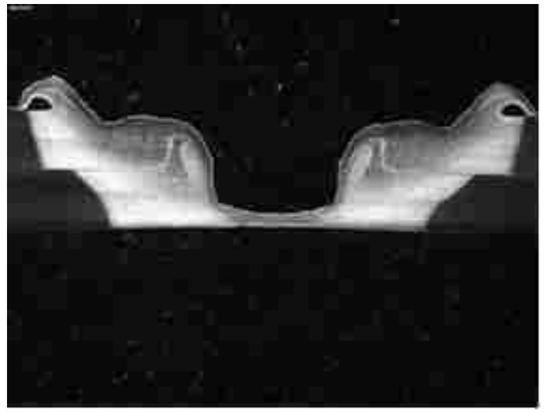

Figure 61: Weld #1154

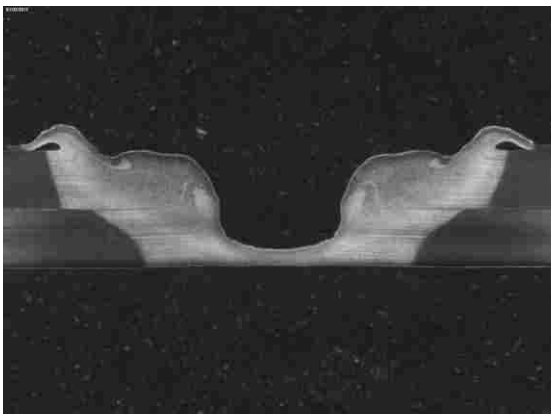

Figure 62: Weld #1254

4.3.5 PCBN Tool Without Cooling in DP980

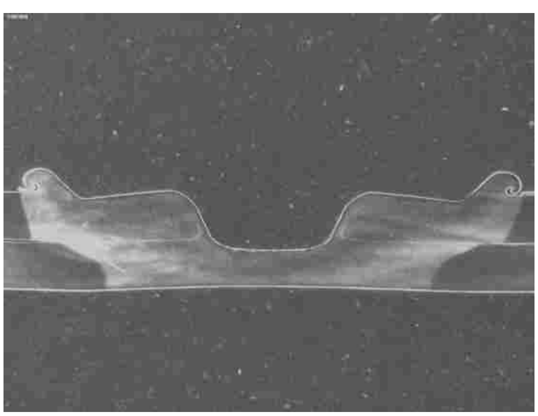

Figure 63: Weld #54

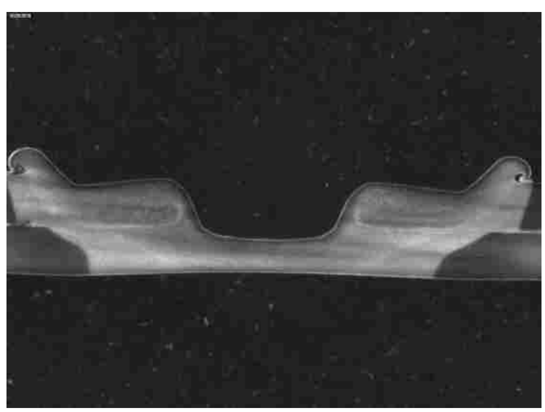

Figure 64: Weld #104

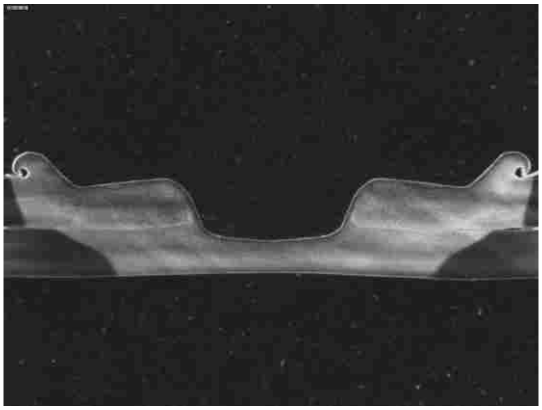

Figure 65: Weld #154

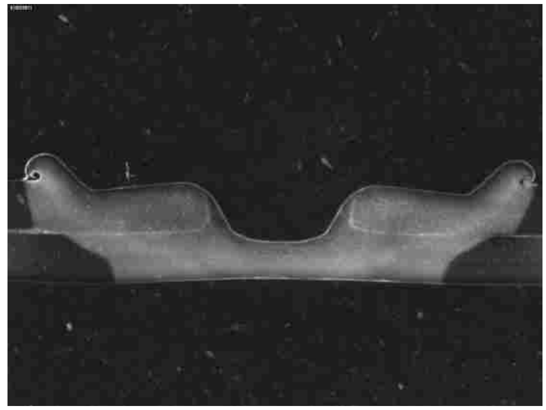

Figure 66: Weld #204

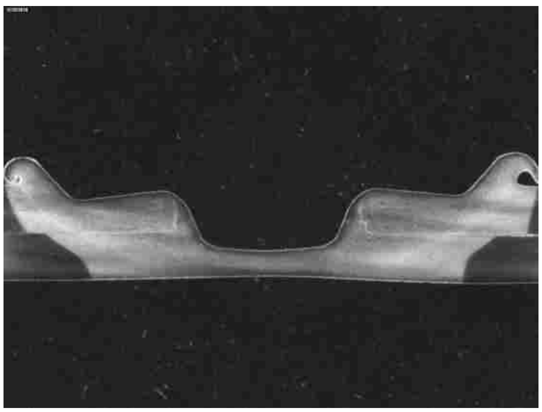

Figure 67: Weld #254

The spindle loads varied widely during testing, but there was an overall upward trend in spindle loads as increasingly harder tool materials were used. Q80 and PCBN regularly incurred z-axis loads in excess of 4000 lbs. The maximum spindle loads observed during testing averaged 5091 lbs., and were produced by the Q80 tool. The minimum spindle loads observed during testing averaged 2079 lbs., and were produced by the softest tool, Q60. The absence of stirred regions in the PCBN tool welds shown above indicates that sufficient heat was not present to adequately reduce the flow stress of the DP980 material.

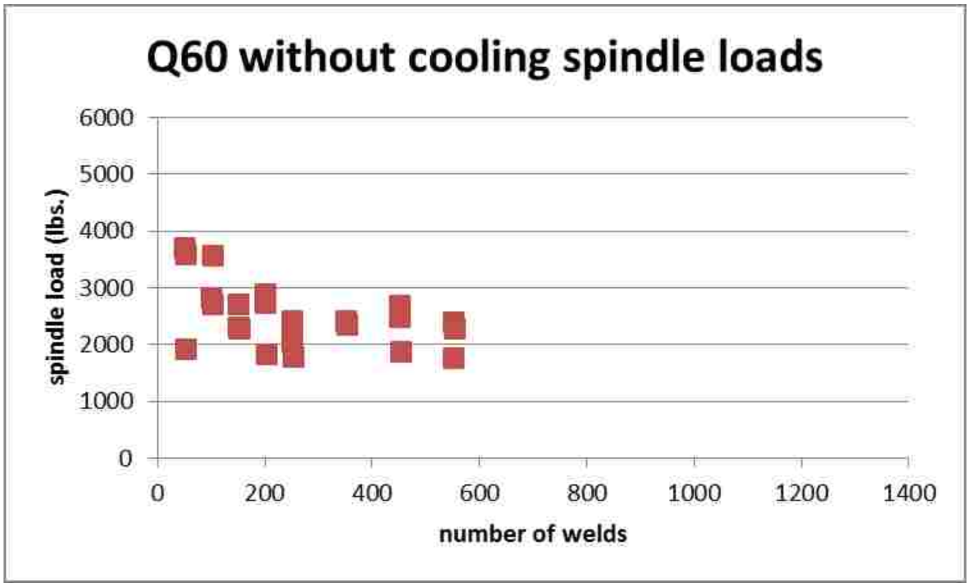

Figure 68: Q60 Without Cooling Spindle Loads

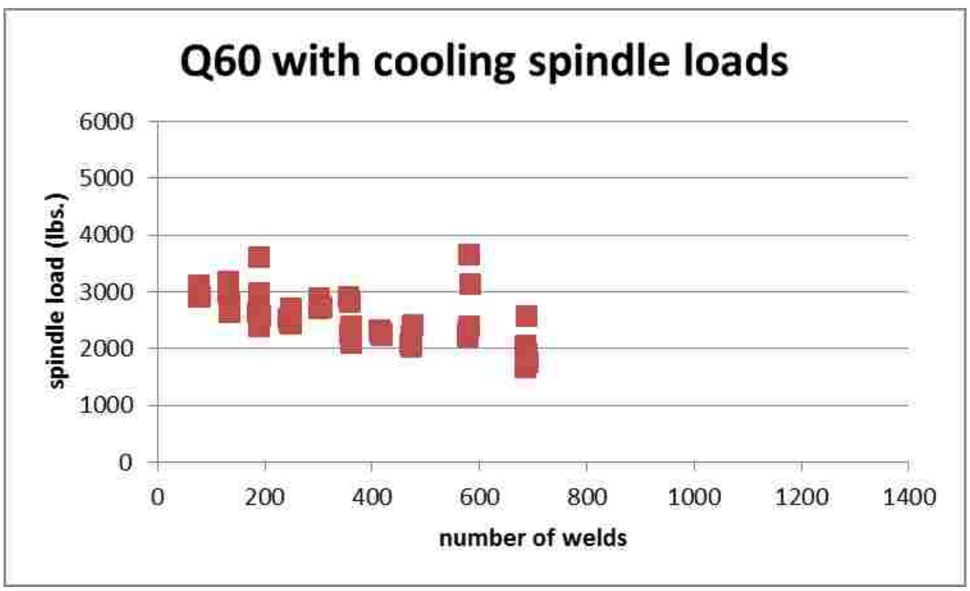

Figure 69: Q60 With Cooling Spindle Loads

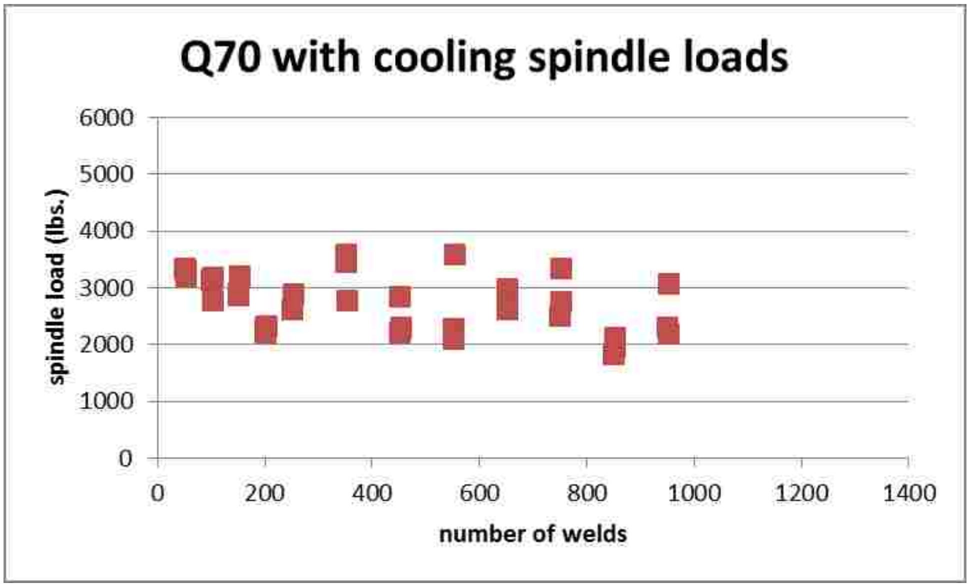

Figure 70: Q70 With Cooling Spindle Loads

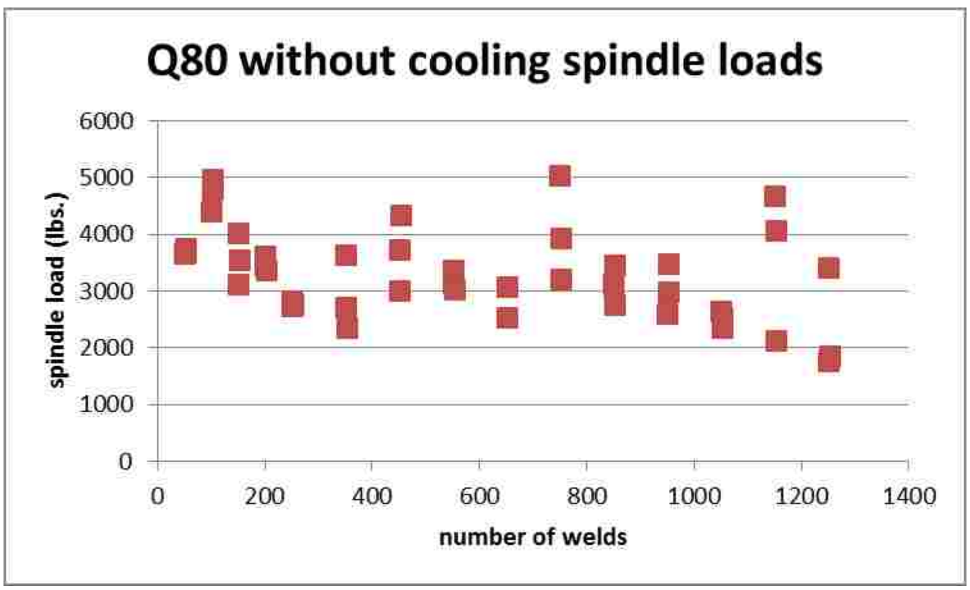

Figure 71: Q80 Without Cooling Spindle Loads

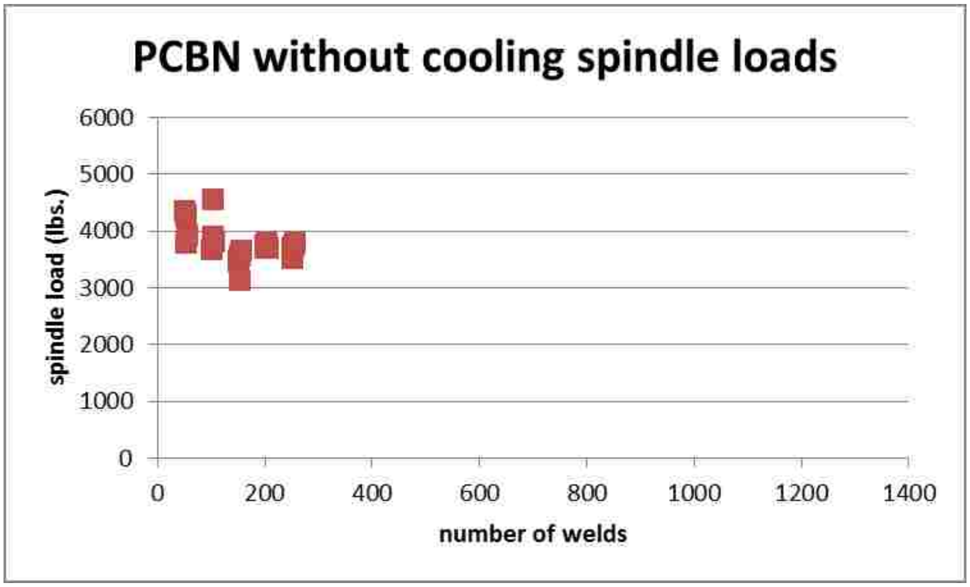

Figure 72: PCBN Without Cooling Spindle Loads

4.4 Tool Longevity

4.4.1 Q60 Without Cooled Tool Holder

The Q60 tool used without cooling showed a rapid decrease in lap shear strength.

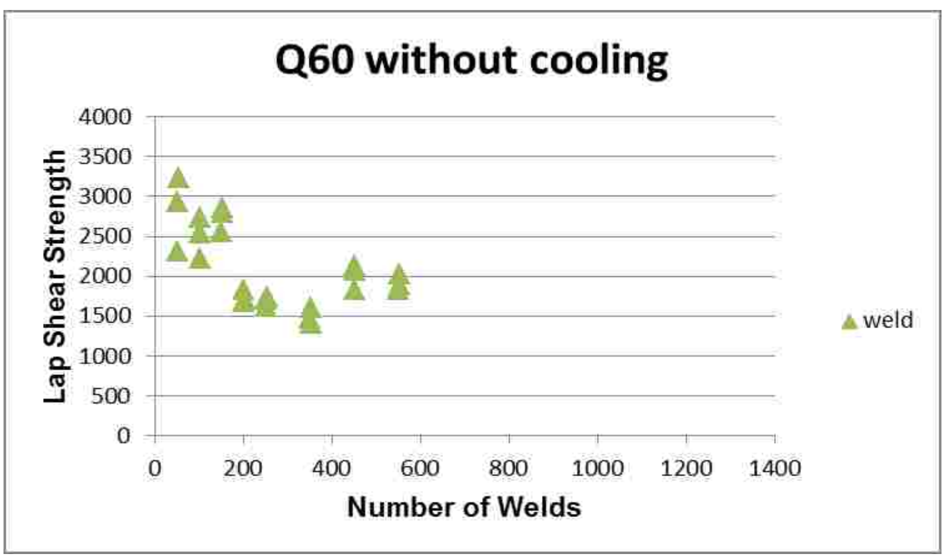

Figure 73: Q60 Without Cooling Lap Shear Strengths

4.4.2 Q60 With Liquid-Cooled Tool Holder

The Q60 tool used with cooling produced approximately 600 welds of acceptable lap shear strength. The data points shown between 200 and 400 welds were generated during the use of a pitted anvil which resulted in reduced weld strength. An anvil made from a case-hardened bolt was used for this study, but frequent changing of the anvil became necessary as the anvil lacked the hardness and thermal stability to withstand the pressures of friction spot welding in high strength steel. Interestingly, a .015" recess in the anvil resulted in reduction in lap shear strength of up to 1500 lbs. This served as an indication of the sensitivity weld quality bears toward the process parameters. The anvil was replaced and weld strength returned. The tool did not fail, but tool wear resulted in a sharp drop in weld strength after 600 welds.

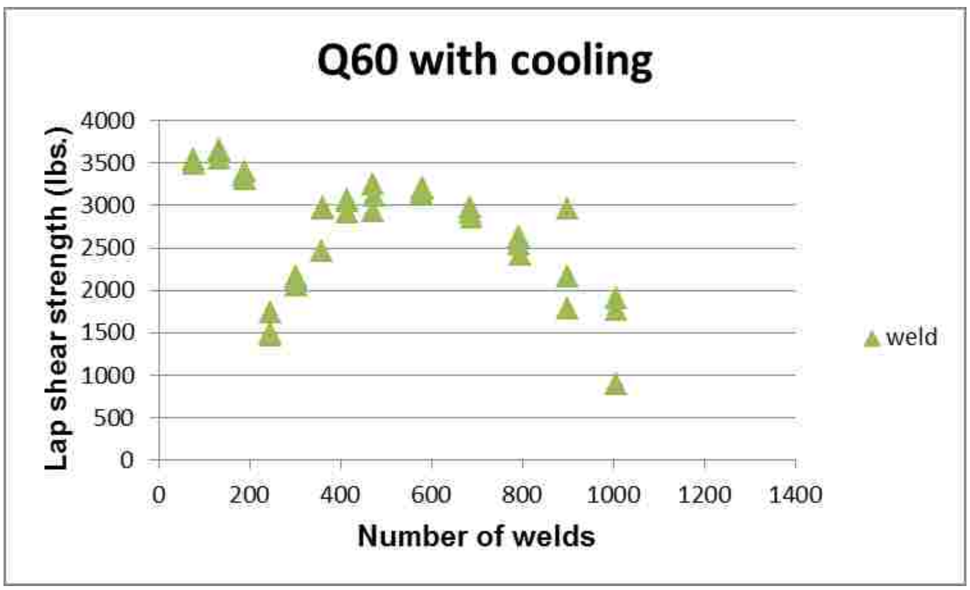

Figure 74: Q60 With Cooling Lap Shear Strengths

4.4.3 Q70 With Liquid-Cooled Tool Holder

Using the weld parameters for this study, Q70 performed the best of all the tool materials tested. Approximately 1100 welds of acceptable strength were produced, and the lap shear strengths of some of the early spots exceeded 3800 lbs. The tool did not fail, and was used until weld lap shear strength had decreased significantly below the acceptable level. The low value data point shown at approximately 250 welds was produced by an error in processing and should be disregarded.

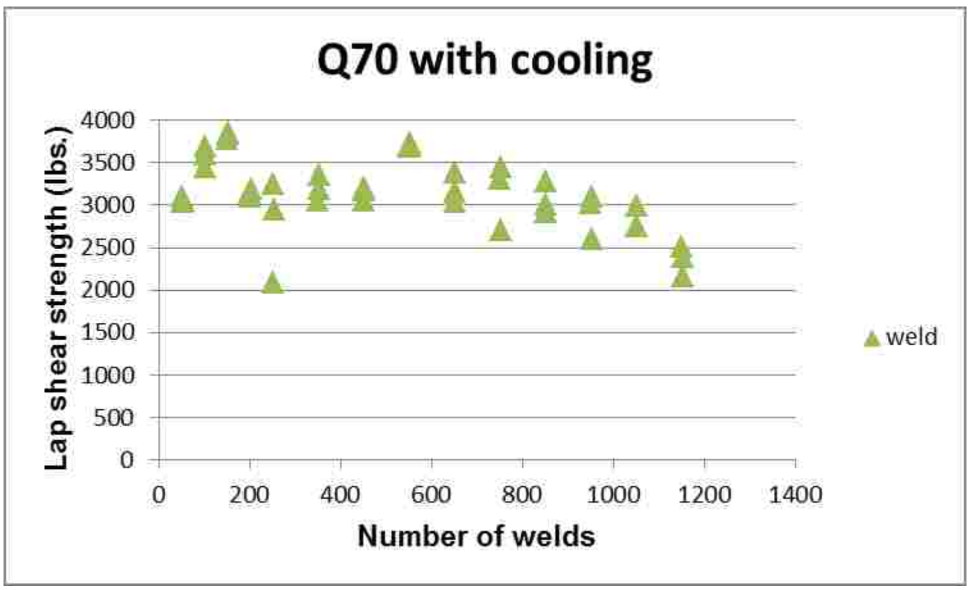

Figure 75: Q70 With Cooling Lap Shear Strengths

4.4.4 Q80 Without Cooled Tool Holder

The spots produced by the Q80 tool showed overall lower strength, with none of them reaching the acceptable 3000 lb. level. However, weld strength remained consistent until approximately 1100 welds, similar to the Q70 tool. One factor to be considered is that the weld parameters for tool testing were developed using a Q60 tool, and may not have been well-tailored to the harder Q80 tool. It is possible that a parameter adjustment could raise Q80 weld lap shear strengths to levels equal to those of Q70 welds. The Q80 tool did not fail, and was used until average weld strength decreased to well below 2000 lbs.

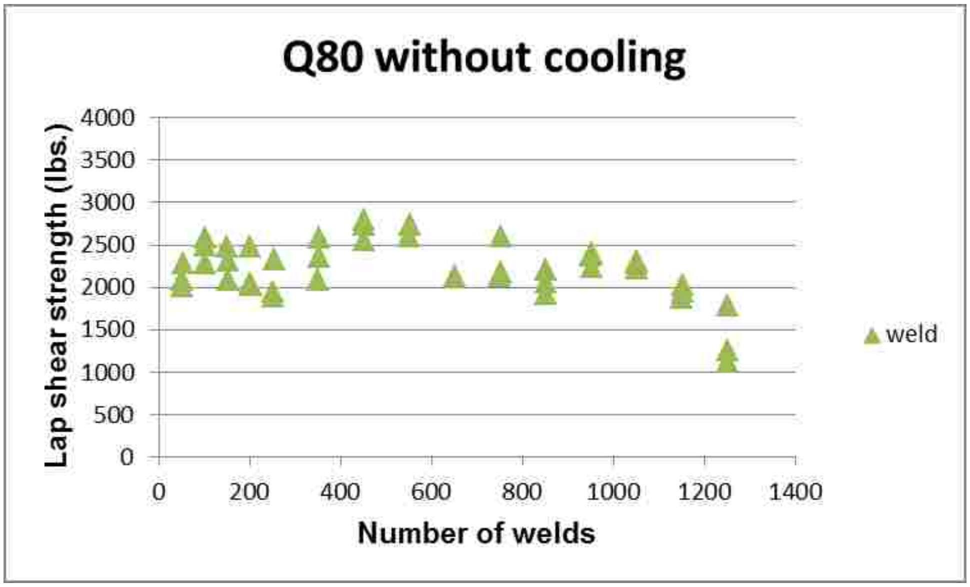

Figure 76: Q80 Without Cooling Lap Shear Strengths

4.4.5 PCBN Without Cooled Tool Holder

The PCBN tool failed early at 273 welds. Lap shear strengths were low and spindle loads were high, regularly exceeding 4000 lbs. Severe cracking was observed in the tool shortly after testing began, presumably due to the high z-axis loads. Up to the point of tool failure, a sharp increase in weld lap shear strength can be seen in the following graph. This is likely attributable to better bonding caused by an increase in friction heat during testing as the cracks in the tool made for a rougher tool surface.

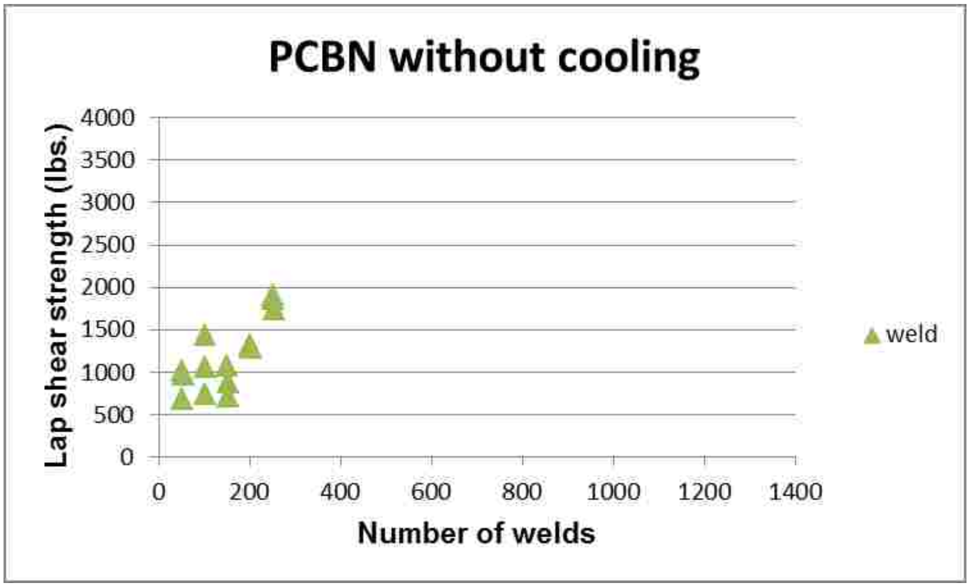

Figure 77: PCBN Without Cooling Lap Shear Strengths

4.5 Microhardness Maps

A cross section of weld number 54 from each tool test set was used for hardness mapping. The maps show the distribution of hardness in and around the weld, and indicate the differences in heat generated by each tool. These differences are evidenced in the size of the softened heat affected zone (HAZ). The numbers along the x and y axes of the maps are distances (in microns) from the corner of the sample. These maps could be used in future parameter development research by correlating the size of the HAZ with parameter sets. This correlation could then be used in an effort to minimize the size of the softened HAZ, thereby increasing the strength of the weld.

The Q60 tool used with cooling produced a HAZ that extended to the edges of the sample coupons, as shown by the darker blue soft region. The shoulder of the tool produced a hardened region shown in red. The hardened region was produced by the formation of martensite (as discussed in Ohashi's research) and plastic deformation under the high z-axis loads.

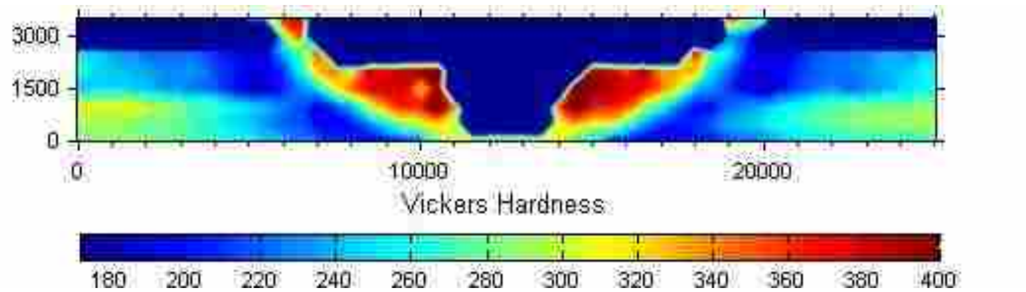

Figure 78: Q60 With Cooling Microhardness

The Q60 tool used without cooling showed a smaller HAZ than was produced by the Q60 tool with cooling. The area where the shoulder engaged the material was also softer, indicating that there was less heat present during welding.

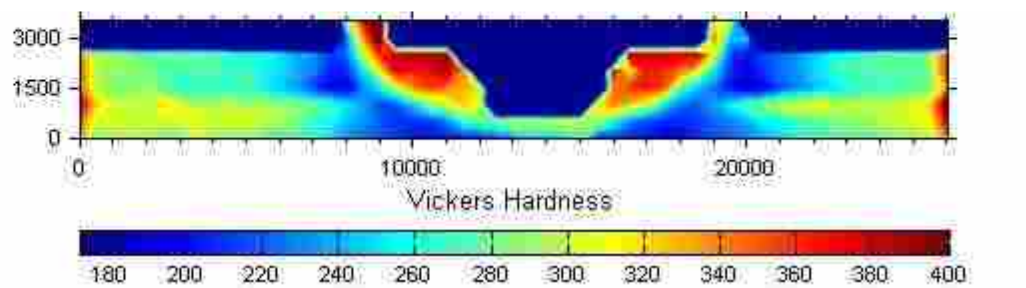

Figure 79: Q60 Without Cooling Microhardness

Q70 with cooling produced a smaller HAZ than Q60 with cooling, and the area of shoulder engagement was also softer. The higher strength values of the Q70 welds likely resulted from the increased weld toughness that can be inferred from the hardness map.

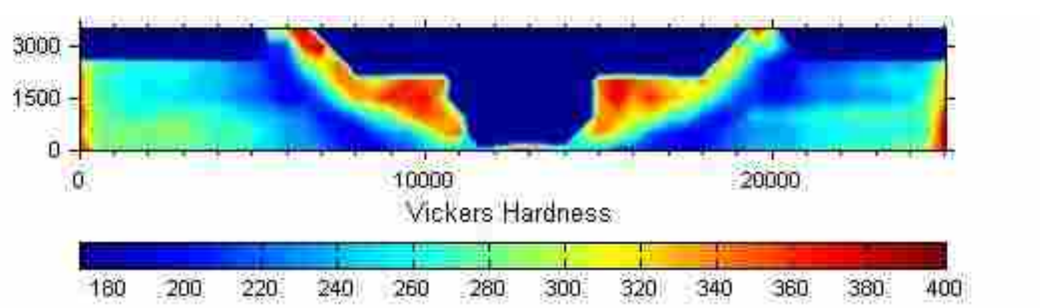

Figure 80: Q70 With Cooling Microhardness

Q80 without cooling produced less heat than Q70 as evidenced by a slightly smaller HAZ. This reduction in heat correlates to the generally weaker welds made by the Q80 tool.

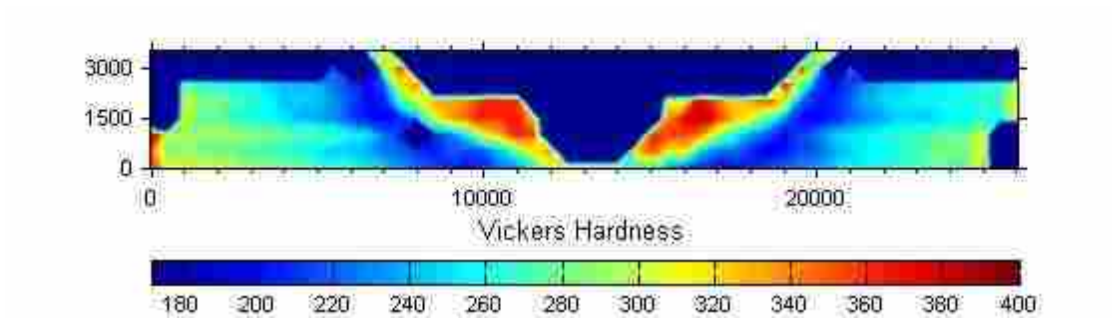

Figure 81: Q80 Without Cooling Microhardness

The PCBN tool produced a relatively small HAZ. The lesser heat produced by this tool correlates to the high spindle loads that were observed during testing. Temperatures during welding with this tool did not elevate sufficiently high enough to adequately reduce the flow stress of the material, and the resulting stress on the tool resulted in early failure. The decreased material thickness shown in Figure 77 was a result of the change in material thickness mentioned previously.

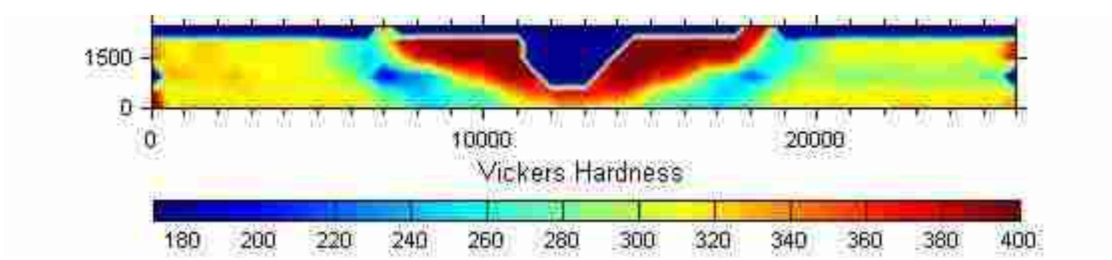

Figure 82: PCBN Without Cooling Microhardness

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

Friction spot welding using Q60 and Q70 tools can be performed successfully in joining DP980 steel sheet. Welds with lap shear strength of 3000 lbs. and above were repeatedly made using these two tools. Also, the Q80 tool showed good consistency of weld strength although welds of acceptable strength were not produced by this tool. However, the lower strength of these welds, as well as the early failure of the PCBN tool, are likely attributable to a tool material/weld parameter mismatch, as the weld parameters were developed using the softer Q60 tool.

5.1.1 Numbers of Acceptable Welds Produced

The Q60 and Q70 tools produced roughly 600 and 1100 acceptable welds, respectively. The Q80 tool produced approximately 1100 welds of consistent strength, with lap shear strengths in excess of 2000 lbs. The PCBN tool produced welds that were generally weak, with lap shear strength ranging from 600 to 1800 lbs. None of the Q80 or PCBN welds produced in this study would be acceptable in industry. Lap shear strength of the welds correlated closely with the size of the HAZ in each weld, with a larger HAZ generally corresponding to a stronger weld. The hardness map of a PCBN-generated weld showed that insufficient heat was induced in the weld as evidenced by a small HAZ. These welds were weak compared with those produced by softer tool materials. This suggests that a parameter change is needed to induce more heat into the weld in order to increase the lap shear strength of the PCBN and Q80 welds to an acceptable level.

5.1.2 Economic Ramifications of the Results

The cost of each tool ($2500) divided by the maximum number of quality welds produced (1100 by Q70) yielded a cost per weld of approximately $2.27 USD. This cost is prohibitive for implementing this process in industry. Tool cost could be reduced significantly using large volume production. However, the number of spot welds in a car ranges in the thousands (Palmonella, 2005), and time spent changing tools every thousand welds would also result in prohibitive costs.

5.2 Recommendations

Recommendations for further research include parameter development, tool material development, and tool geometry development. Also, as tool life improves and becomes more acceptable with further developments, fatigue testing and cross-tension testing should be performed in addition to lap shear strength testing.

5.2.1 Further Parameter Development

The parameters used in this study were developed using the softest of the tool materials, Q60. They were therefore not well suited to the harder tool materials tested. It is unknown at this time if a different parameter set would increase tool life in the harder tools, and new parameter sets for those tools should therefore be investigated as a means of increasing tool life. Also, the microhardness map of one of the stronger welds—produced by Q70—showed a large heat affected zone which could cause a weakening of the joint. A parameter adjustment may reduce the size of the HAZ and result in a stronger joint.

5.2.2 Tool Material Development

Changes in processing of PCBN along with the addition of new alloying elements may result in a tougher tool material than was used in this study. Radial cracks were observed in all of the tools tested, and it may be possible to eliminate brittleness in the tools by changing their material composition or processing methods.

5.2.3 Tool Geometry Development

A single tool geometry was used in this study. New tool geometries should be investigated along with new process parameters. Particularly with higher RPM friction spot welding, tool geometry should be changed to incorporate features that do not create excessive "grab" during the initial plunge of the weld. This may help to reduce the amount of torque applied to the tool during welding, which may reduce cracking.

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