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A Simple Method for Evaluating Wear in Different Grades of Tooling Applied to Friction Stir Spot Welding

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A Simple Method for Evaluating Wear in Different Grades
of Tooling Applied to Friction Stir Spot Welding

Kirtis Frankland Kennard

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

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ABSTRACT

A Simple Method for Evaluating Wear in Different Grades of Tooling Applied to Friction Stir Spot Welding

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In this study tools consisting of a 5mm cylindrical pin and a 12mm shoulder held by a simple tool holder were used to compare the wear of 11 tooling materials. The objective was to determine if using these tools in a spot welding configuration to simulate friction stir welding could differentiate the potential performance of tooling materials. All tools were made of varying percentages of polycrystalline cubic boron nitride (PCBN), tungsten (W) and rhenium (Re). The materials are referred to herein as GV1, GV2, G1, G2, G3, G4, G5, G6, G7, G8 and G9.

The tools were run to 205 welds if they did not fracture first. The grades averaged the following quantities of welds before fracture failure GV-1:0; GV-2:200; G1:82; G2:204; G3:205; G4:205; G5:96; G7:102.73; G8:21.2; G9:38.5. Of the tools that ran the full 205 welds without chipping, the average calculated volume loss, which was the best indication of wear, was as follows G2:1.83%; G3:2.53%; G4:2.41%; G5:1.93%; and G7:2.30%.

The study showed that G2 had the least wear and G6 had the most wear, of those tools that completed all 205 spot welds. Fracture was the failure mode of all grades with over 70% CBN content. It was found that small CBN grain size was not correlated to better wear performance, as has been seen in a prior study.

Keywords: friction stir welding, wear, test, friction stir spot welding, steel, metal matrix composites, PCBN, tungsten, rhenium, FSW, FSSW

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1 INTRODUCTION

1.1 Background

Many industries such as shipping and marine, aerospace, railway and land transport, are exploring ways to improve material properties of their products (Sidhu, 2012; Lian 2012), Materials such as advanced high strength steels (AHSS), metal matrix composites (MMC), nickel alloys and titanium alloys are being tested (Yang, 2010). Novel methods for joining have been tested on these material such as fusion welding, diffusion bonding and brazing but have been shown to degrade the desired properties of the parent material (Kumar, 2009; Liu, 2005). Because of its ability to join at lower temperatures, and therefore without adversely affecting material properties, Friction Stir Welding (FSW) and Friction Stir Spot Welding (FSSW) are promising methods for joining these materials (Ridges, 2011; Santella, 2003) and have been studied extensively in alloys such as ferritic steels, stainless steels and heat resistant steels (Park et al 2009). The abrasive nature of high-strength steel (HSS) (Feng, 2005) and MMCs causes rapid tool wear and failure (Ridges, 2011; Gibson, 2011), making tool life the limiting factor for joining MMCs and steels with FSW (Prater, 2013; Peterson, 2010). The tool life is determined by tool wear and brittle fracture (Thompson, 2010). Tool material is the main determinant of tool life (Bhadeshia, 2009) therefore new tool materials need to be tested in order for FSW to become a viable alternative for joining these abrasive materials and a viable inexpensive test of tool wear needs to be devised and implemented.

1.1.1 State of the Industry

Tool improvement is needed to mitigate tool wear for higher melting point, higher hardness metals such as steel, titanium, and nickel based superalloys or metal matrix composites (Gibson, 2013). Because it is second only to diamond in hardness and doesn't have the chemical affinity to ferrous materials that diamond does, Cubic Boron Nitride (CBN) is the preferred material for tools made for FSW of hard materials (Rai, 2011; Peterson, 2010). Although abrasion resistance increases with Cubic Boron Nitride (CBN) content (Collier, 2003) the trade-off is increased propensity for fracture failure because of the harder materials are more brittle (Gibson, 2013). Fracture toughness can be so low that tools sometimes even experience fracture failure during the initial plunge (Rai, 2011). Concerns about fracture lead to not using the tool to the full extent of its life because the user is being conservative to ensure fragments of the tool do not break off and become deposited into the weld (Gibson, 2013). This leads to limited commercial application of FSW to hard alloys because of the high cost and short life of FSW tools (Rai, 2011).

Because of this need to push the limits of hardness while not becoming so brittle that fracture occurs there is a need to test many grades of material through both experimental and numerical analysis (Gan, 2007) and to receive rapid feedback on potential tool performance. A systematic study of the mechanical behavior of the tools under conditions of FSW is needed (Arora, 2011).

1.1.2 Contribution of This Study

The proposed contribution of this study is to determine a feasible way to distinguish tool wear potential early in the development of new tool grades. Once an inexpensive test is proven

and standardized it could be used on all new grades to determine if more should be invested into research and development of that grade.

1.1.3 Purpose of the Research

The purpose of this research is to determine the efficacy of using small diameter tools, (using a geometry and operating parameters chosen to accelerate wear) in a simple holding fixture, to test tool materials run in a Friction Stir Spot Welding (FSSW) configuration. While the test configuration is FSSW, for convenience and speed, the wear data is meant to evaluate suitability for friction stir welding (FSW). The test information could then be used to pare down a large set of possible tool grades to a smaller subset of tool grades for more expensive and time consuming full sized FSW tests.

1.2 Research Questions

The questions addressed in this study included the following:

- Will a spot welding test configuration, using small tools with simple geometry, be able to distinguish the tool life performance of different grades of PCBN tool material?
- Will materials with smaller CBN grain sizes exhibit less wear than tools with larger grain size for the same test conditions?

1.3 Definition of Terms

PCBN- Polycrystalline cubic boron nitride

CBN- Cubic boron nitride

FSW- Friction stir weld

FSSW- Friction stir spot weld

W- Tungsten

Re- Rhenium

Dwell- Time the tool is in the work piece

Plunge rate- Speed at which the tool is embedded into the work piece.

RPM- Rotations per minute

Plunge depth- Depth to which the tool is embedded in work piece

HAZ-Heat affected zone

TMAZ-Thermomechanically affected zone

AHSS-Advanced High Strength Steel

DP-Dual phase

CBN- Cubic Boron Nitride

Tool Grade- Unique powder composition used to create tools

WRh- Tungsten Rhenium

DP980 Steel- Steel with islands hard second phase martensite

1.4 Significance of the Study

This study could result in a new testing procedure with the possibility of accelerating tooling development for FSSW and FSW applications. It should also provide insight into the effect of tool material chemistry and microstructure on wear resistance.

1.5 Delimitations

This study only determines the ability of spot weld tools made with a specific geometry, using specific parameters, using DP980 steel plate of a specific thickness to cause repeatable comparable wear, thereby differentiating tool grades.

2 LITERATURE REVIEW

2.1 Overview

Friction Stir Welding (FSW) was invented in 1991 at The Welding Institute (TWI) of Cambridge, United Kingdom. It has been used commercially for joining soft metals such as aluminum since its invention. FSW is now beginning to be tested for use in joining steels up to 20 mm thick (Eff, 2013). It is also being tested in metal matrix composites (MMC) (Prater, 2013). There are many applications where friction stir welding is being explored as an alternative to other joining methods (Sidhu, 2012).

Because each unique application needs a tool that is “appropriate for that application” (Thomas, 2003) and because there is a need to straddle the line between brittle tools that will fracture and tough tools that will wear too quickly there is a need for testing tool grades. Running standard tools on the standard machines is expensive so there is a need for a simple experimental procedure that can simulate FSW conditions (Kumar, 2009)

To determine the best way to conduct a systematic test of tool grades the literature was reviewed for geometry of the tool, ways of promoting wear in a tool and the manner in which that wear can be compared.

2.2 Discussion

FSW of advanced materials is desirable because it could lower the cost of joining materials. For example one study showed it could decrease the cost of welding off shore pipes over traditional methods by 25% (Eff, 2013).

The cost and therefore viability of using FSW as a joining method for a material depends on how long that tool can produce good welds. Therefore tool life is often the limiting factor in whether FSW is a feasible joining process for a given application (Ridges, 2011).

Because of the expense of material and machine time there is a need for a simple inexpensive experimental procedure that can simulate the conditions of FSW (Kumar, 2009)

2.2.1 Tool Grades

The tools required to FSW HSTMs must be both hard (to decrease tool wear) and tough because brittle tools are susceptible to fracture. There are many tool grades that have been tested. According to Rai et. al., some of the tool materials that have been tested in the FSW of Steels are: W alloy, W-25%Re, WC-13%Co, WC-13%Co+6%Ni, 1.5%Cr₃C₂, WC based, Mo based, W based, Si₃N₄ with TiC coating, Si₃N₄ without coating, Si₃N₄ with TiN coating (Rai, 2011).

To satisfy both of the need to not fracture due to brittleness nor wear too quickly, Tungsten Rhenium (WRe) and Polycrystalline Boron Nitride (PCBN) or some combination of the two materials have been tested with some success. (Peterson et al,2010). In this case the addition of W-Re is done to improve toughness of the alloy. While several compositions of PCBN and W-Re have been tested in prior work, there is a need for additional study in order to

further understand the effect of composition and microstructure on optimal wear performance for FSSW and FSW of high strength steels and other abrasive alloys.

2.2.2 Geometry of Tools

A standard FSW tool has a taper and helix shoulder and taper and helix pin optimizes the weld strength (Hattingh, 2008; Ji, 2012; Arora, 2011), and has been used for wear tests (Arora, 2011; Prater, 2013; Ridges, 2011). A simplified tool design using a cylindrical pin with a flat shoulder has also been used to test material interactions and found to give viable results (Santella, 2003; Yang, 2010). A cylindrical tool is simpler to model and may remove discrepancies between the results of experimental tests and simulation when used to simulate more complex geometries (Prater, 2013). Even the wear mechanisms of cutting tools made of the same material as a FSW tool were found to have a direct correlation to the wear mechanisms of the FSW tool welding the same material (Collier, 2003).

PCBN and W-Re, the two constituents of FSW tools are expensive (Rai, 2011) and there is a need for a low cost way of testing tool life span (Kumar, 2009; Gan, 2007), so it would be better if the tool used less material by being smaller.

2.2.3 Promoting Wear

It has been shown that using a FSW tool grade on a cutting tool gives the same wear mechanisms as the actual FSW in the same material (Collier, 2003) therefore any process that causes friction between the tool and the work piece may provide comparable results. Gibson showed that wear is inversely proportional to traverse rate (Gibson, 2013) which means wear will increase as the traverse rate approaches zero. Taking that to the extreme would be no traverse at all or a simple plunge test. While Arbogast states that a single plunge test isn't

sufficient to determine wear life he says it is effective in determining the friction a tool experiences in a traverse operation (Abergast, 2003). Using a cylindrical pinned tool Gibson showed that one only need to traverse for 3-4 inches (76.2mm-101.6 mm) or 30 seconds to give results that can predict wear to failure (Gibson, 2011). Because a significant portion of wear occurs during the plunge stage of a weld (Mandal, 2012), a tool can just be plunged in into the target material in order to get satisfactory results on wear potential (Gibson, 2013). FSSW has been used to compare different grades of material and shown to distinguish those with higher and lower wear properties (Miles, 2011).

Because DP980 is known to be very demanding in terms of tool wear (Hartman, 2012), and because it has a number of potential engineering applications, it was chosen as the material to be used for wear testing.

2.2.4 Comparing Wear

Because the cross sectional area is proportional to the volume (Gibson, 2011), for an axisymmetric design, the cross sectional areas before and after running tools are often compared. A common way of comparing wear is to set the tool on an optical comparator, photograph the shadow then either trace the profile using graphic software and visually compare the profiles (Thompson, 2010; Ridges, 2011; Miles, 2011) or have a computer algorithm calculate the profile geometry and determine the percentage of cross sectional area that has been worn away (Liu, 2005), or cut out the profile and compare the weights of the cut outs (Prado, 2003). The quality of the weld shown in lap shear tests has been shown to correlate to the heat affected zone (Ridges, 2011). Higher tool wear is anticipated to affect the HAZ, as well as the bonded area of the joint, in this study.

In his study Hartman shows the relationship between bond area and wear and shows how bond area can be derived from sectioning the weld, mounting, polishing, and then examining under a microscope in order to estimate by linear measurement the bonded region (Hartman, 2015)

2.3 Summary

The current literature shows that, while there are various studies of the ideal tool geometry for optimizing weld strength in FSSW and FSW, a simple cylindrical pin has been shown to give viable results for the study of tool wear. Because of the high cost of materials it is preferable to use a smaller diameter tool and relate the wear of the tool via the abrasive wear that occurs from frictional sliding to its potential useful life in a FSSW or FSW application.

Comparing cross sectional area is a good indicator of volume loss, which is essentially the definition of wear. Because there is variation inherent in manually tracing shadows and in cutting out profiles made from photographed shadows, an image dimensioning system was used in this study to extract the tool dimensions that were used to calculate tool geometries. The lap shear strength and HAZ or the bond area of coupon welds was tracked as another measure of tool wear.

3 METHODS

3.1 Introduction

Eleven tool materials were tested by running spot welds in DP980 steel. They have been given the following names for easy reference: GV1, GV2, G1, G2, G3, G4, G5, G6, G7, G8 and G9 (see figures 1-9). MegaDiamond, a Schlumberger Company, formulated the tooling grades, with the objective of making a more wear resistant tool material. To that end each tool grade is a matrix of PCBN, with addition of WRe or W-MO, each being a unique variation of percentage CBN, CBN grain size, and process condition designed to obtain different microstructures. Below are images of the microstructures found in each of the eleven tool grades.

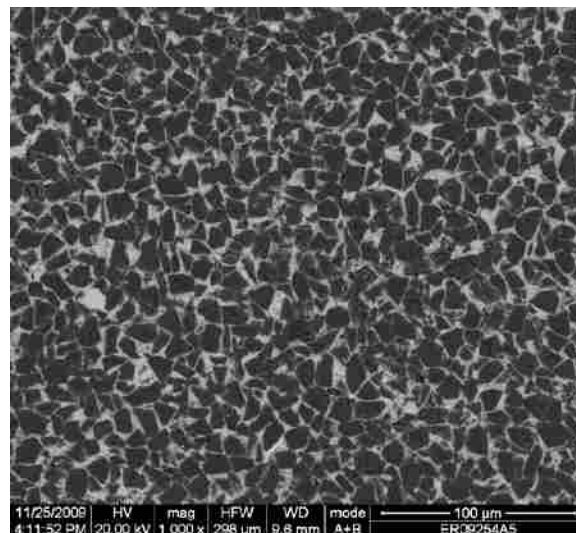


Figure 1: Microstructure of MS80 (G1, GV1 and GV2)

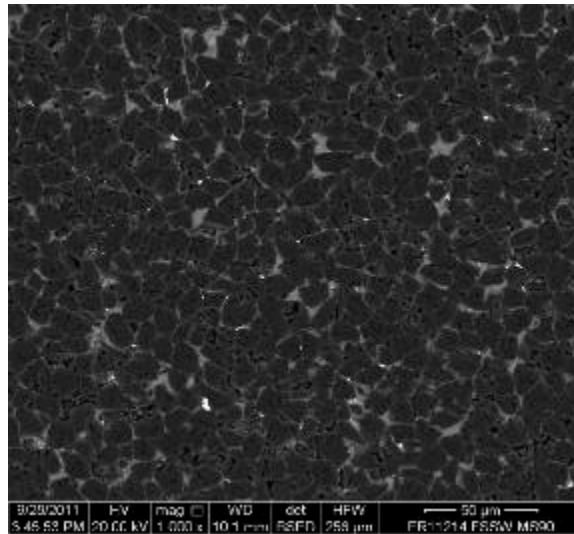


Figure 8: MS90 (G8)

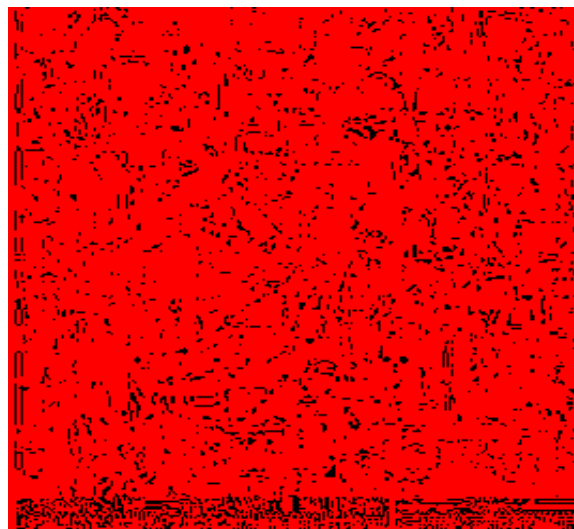


Figure 9: CS80 (G9)

MS80 (G1) and Q70 (G2) have been used successfully in the past and are therefore included as a control group to compare against. G3 is an attempt to match the durability of the W-Re matrix with the lower cost W-Mo material. G4 with 70% CBN and finer W-Re is an attempt at achieving better dispersion of W-RE and more uniform microstructure. G5 has 80% CBN with finer W-Re, this allows for more CBN content without agglomeration which should give better

wear resistance at a lower cost. G6 has 80% CBN with finer W-RE, which allows for more CBN content without agglomeration which should result in better wear resistance at a lower cost. G7 has 90% CBN and finer W-Re, which allows for more CBN content without agglomeration, and better wear resistance and lower cost as CBN content is increased. G8 has 80% CBN which is more CBN than standard Q70 and was thought to result in a harder tool with less propensity to wear. G9 is made from a new PCBN grade with more thermally stable ceramic binders. GV1 and GV2 were heat treated at 1000C in an attempt to induce AlB2 decomposition to AlB12 and Al. GV1 was heat treated after machining the OD to the final dimension and GV2 was machined to the final dimension after heat treatment to determine when heat treatment had the most effect on wear.

Based on the success of a FSSW test to compare wear in different tool grades (Miles, 2011), the test was modeled after that FSSW test. The experiments were run on a Kearney and Trecker 3-axis mill that has been converted to CNC operation with variable RPM, plunge rate, plunge depth, and dwell time.

Spot welds were produced on sheets and coupons of DP980 steel. Four spot welds were done in coupons followed by 196 spot welds in sheet and finally four more spot welds in coupons.

From each set of welded coupons three were used to test for lap shear strength of the welds and the remaining sample was used for optical microscopy.

The wear was measured using a Keyence image dimensioning system, a precision density balance, an instron lap shear tester and optical microscopy of half cut specimens.

3.2 Description

The tools were made using the following process. First the test grade powders were pressed by MegaDiamond: a Schlumberger Company, into blanks and ground to the print OD. Each blank was laser marked with its own unique identifier (G1-1, G1-2 etc.). At this stage each blank was inspected for internal voids and defects using an OKOS 250 scanning acoustic microscope as seen in (figure 10) to perform a c-scan (OKOS 250 Scanning Acoustic Microscope, 2015). A c-scan is a way of measuring material differences using sound, similar to sonar. The sound is sent out and the frequency at which it comes back is recorded. That information is then mapped using color. When looking at a c-scan image any variation in color could mean there is a void or a defect which could lead to premature tool failure. In preparation for testing all tool grades a blank was c-scanned as seen in the images in figure 10. This was done because it is difficult to determine the depth of any defect, that tool was marked at four



Figure 10: OKOS 250 Scanning Acoustic Microscope

depths around the outside diameter then C-scanned so that any defect found could be located within the three dimensional space of the tool. The images shown start in the top left corner then goes deeper alternatingly left to right then right to left and down. In figure 11 the scans at the top (upper left image) and bottom (lower right image) show variation from the difference between the tool material and the material above and below it.

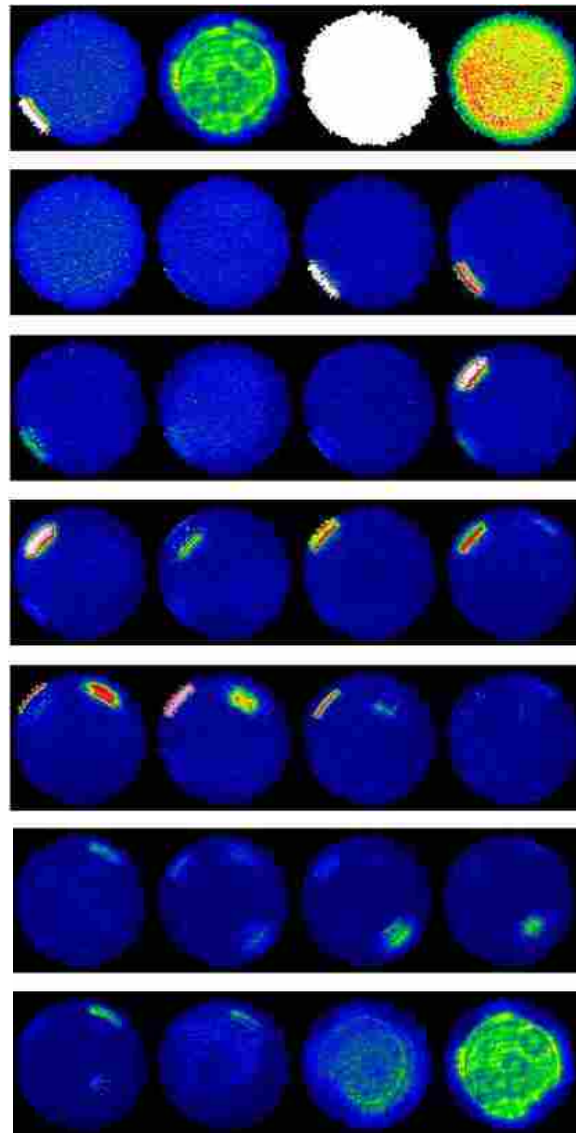


Figure 11: C-Scan of Laser Marked Sample Part

The four marks around the radius can also be seen. There are also other small pixel variances, but it is unknown if these are actual defects or just noise.

The final step in the manufacturing process was having Advanced Metal Products machine the tools to specifications seen in figure 12.

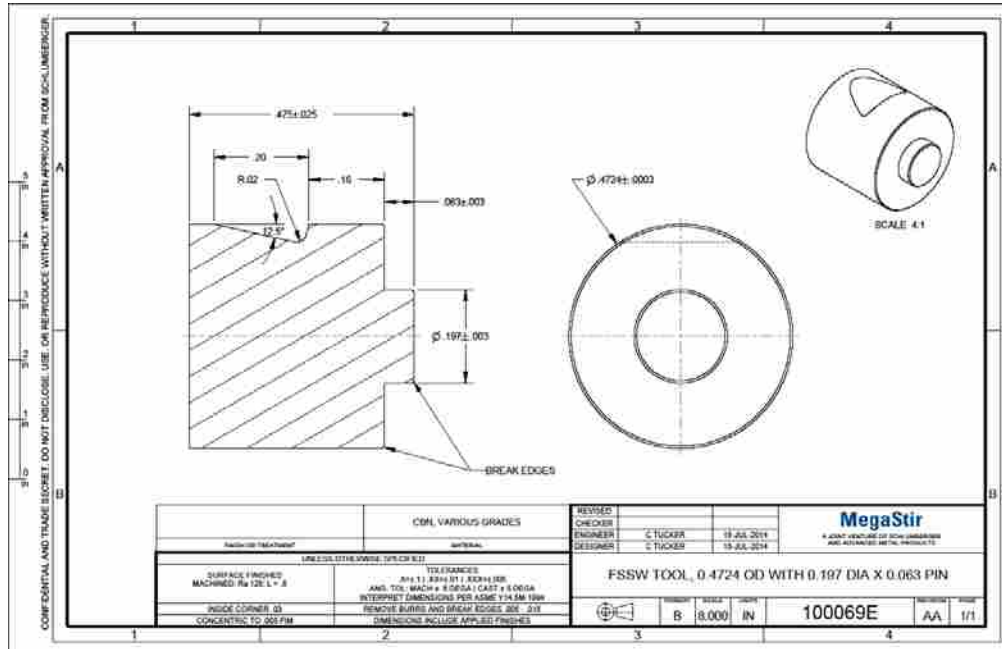


Figure 12: Print of Machining Dimensions

3.3 Weld Parameters

It was determined that the parameters established by Ridges for FSSW of DP980 steel would be used (Ridges, 2011) with the shallower plunge depth of -.083 inches rather than -.093 inches because the nominal pin height is only .063 inches and that still leaves about .020 inches of shoulder penetration as seen in table 1. The parameters were tested and found to give welds of sufficient strength to test coupon welds for consistency.

Table 1: Weld Parameters

Material Thickness	Stage	RPM	Plunge Rate	Plunge Depth	Dwell
.050"	1	1500	6"/minute	-.075"	No dwell
.050"	2	1500	.5"/minute	-.083"	No dwell

It was determined during this test that when welds appeared to be shallow or deep slight adjustments to the plunge depth would be made in an effort to equalize the wear stresses put on each tool.

3.4 Friction Spot Welding

Spot welding was performed on the same Kearney and Trecker 3- axis mill that has been retrofitted with CNC control, variable RPM, plunge rate, plunge depth and dwell time that was used by Ridges in his study (Ridges, 2011) seen in figure 13. The coupon welds were made in

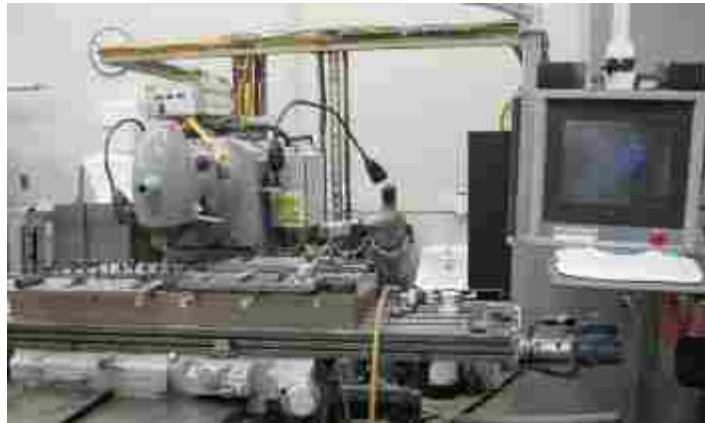


Figure 13: Kearny and Trecker Three Axis Mill

two 100mm x 25mm x 1.2mm coupons that overlap by 25mm with the weld connecting them as done by Hartman in his experiments (Hartman, 2012) as seen in figures 14 and 15.



Figure 14: Coupon Sample



Figure 15: Welding Coupon

The spot welds in plate were formed on overlapping 1.2 mm thick plates in a tight matrix as Ridges did in his study (Ridges, 2011) as seen in figure 16.



Figure 16: Spot Welds on Sheet in a Tight Pattern

3.5 Quantifying Wear

Wear was quantified by taking and calculating the following measurements before and after the 200 welds for each tool: cross sectional area of the tool, volume of the tool, tensile test of the weld, and bond area of weld.

3.5.1 Cross Sectional Area Loss

A (Keyence digital dimension measuring system, 2015) as seen in figure 18 was used to take five measurements: [1] pin height; [2] pin diameter; [3] tool height to shoulder; [4] left arc of pin wear; and [5] right arc of pin wear as seen in figure 19.



Figure 17: Keyence Digital Dimensioning System

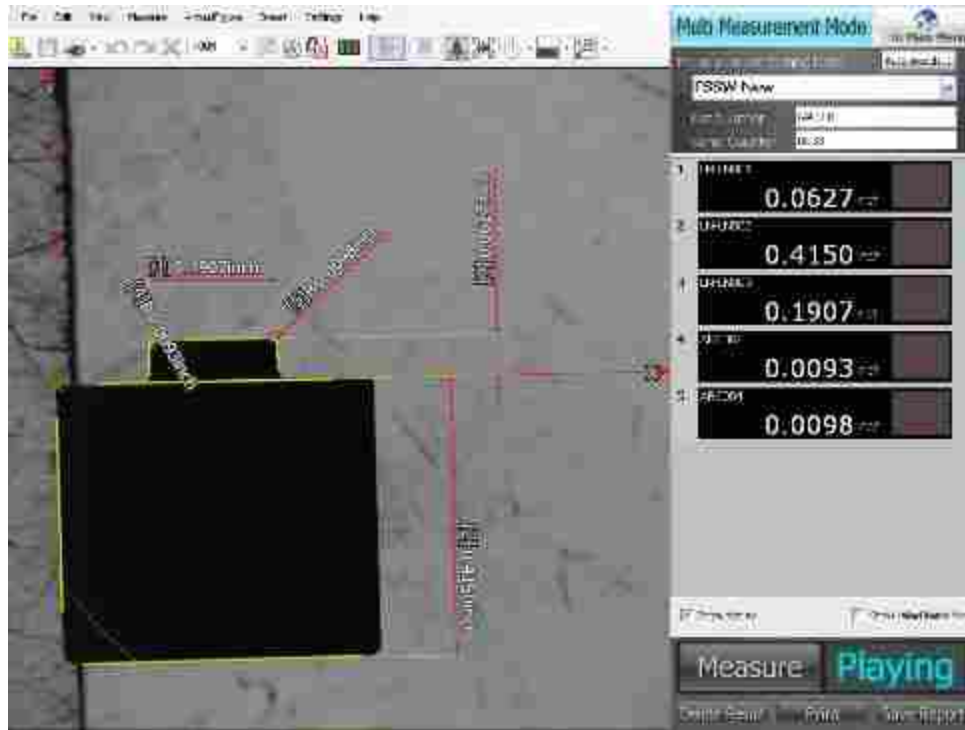


Figure 18: Screen Shot from Keyence Digital Dimensioning System.

The overall diameter of the tool was assumed to be the nominal size of .4724 inches as this is not a wearing surface it was not measured. The profile area of each tool was calculated using the following equation:

$$A = (h * d) - (2 * (a^2)) + (\pi * (a^2)) + (H * D) \quad (3.1)$$

Where A is the cross sectional area, h is pin height, d is pin diameter, r is average of the two measured wear arcs, H is the tool height to the shoulder and D is the assumed tool diameter. These measurements were used to calculate profile area and compared to determine cross sectional area percentage loss.

3.5.2 Volume Loss

On some samples before and after volumes were taken then compared to give percentage Volume loss using a precision balance similar to the one seen in figure 19.



Figure 19: Precision Density Balance

Volume was calculated by the following equation:

$$V_t = \frac{W_a}{\frac{W_a}{W_a - W_w} * D_w} \quad (3.2)$$

Where D_t is the Density of the tool, W_a is the weight of the tool in air, W_w is the weight of the tool in water, D_w is the density of water and V_t is the volume of the tool. Each measurement was taken three times and the average used. The difference between the beginning volume and the ending volume was then taken as a percentage of the beginning volume to give a percentage volume loss over the life of the tool.

3.5.3 Weld Area

In order to obtain the weld area the welded coupons were sectioned, mounted, polished, photographed and measured under an optical microscope then the data gathered was used to calculate the welded area.

3.5.3.1 Section Spot Weld

Coupons were half cut then a section approximately 6mm wide was removed.



Figure 20: Half Cut of Coupon Weld

3.5.3.2 Mount Weld Sections

The sections were mounted in sets of two or three in bakelite as seen in figure 21 (Hartman, 2012). The tool number, weld number and color of the clip holding the sample were engraved on the back of the bakelite



Figure 21: Bakelite Mounting

3.5.3.3 Polish

Once prepared the bakelite samples were mounted in a polishing wheel like in figure 22 then polished (Hartman, 2012). Polishing is a wet process and was done in stages. It started with 120 grit sand paper then progressed through 240, 400, 600, 800, and 1200 grit sandpaper. Polishing cycle times were 12 seconds each. To ensure the samples were polishing correctly they were dried off and inspected between grits. Any time any sample from the wheel failed inspection the parts were run again with that same grit.



Figure 22: Polishing Wheel

3.5.3.4 Etch

The samples were then etched with a 20% nitol etchant solution. The etchant was applied with cotton swabs and allowed to etch for approximately 13 seconds then removed with methonal. The sample was then dried with compressed air.

3.5.3.5 Optical Microscopy

The samples were then Placed under an Olympus SZX12 microscope and photographed at 200x magnification. Then the inside (d_i) and outside (d_o) diameters of the weld area were measured as seen in figure 23 (Hartman, 2012).

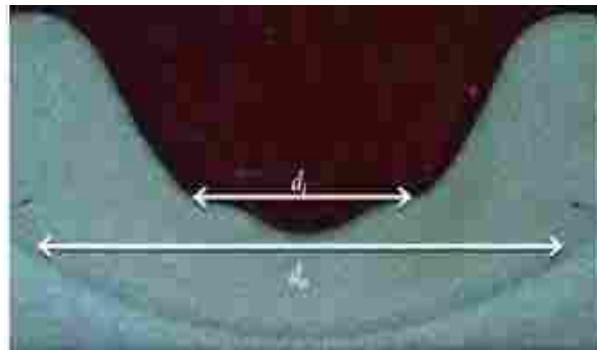


Figure 23: Bond Area Measurement

3.5.3.6 Calculation

The weld area was calculated from the inside and outside weld diameters using formula 3.2, where A is the weld area d_o is the outside diameter and d_i is the inside diameter:

$$A = \frac{\pi}{4} (d_o^2 - d_i^2) \quad (3.2)$$

3.5.4 Tensile Test

3 coupons were tested on the instron machine as seen in figures 24 and 25 for tensile strength (Ridges, 2011).



Figure 24: Instron Tensile Strength Test



Figure 25: Tensile Test on Instron

4 RESULTS AND DISCUSSION

4.1 Consistency of Tool Geometry Measurement

All of the measurements of one tool were taken multiple times before calculating the profile area and variance of each measurement (see table 2).

Table 2: One Tool Measured Multiple Times

part dia.	[1] overall ht.	[2] pin dia.	[3]right arc	[4]left arc	[5]ht to shoulder	Profile area
.4724	0.5034	0.197	0.0118	0.0091	0.4426	1.062883
0.4724	0.5036	0.1971	0.0105	0.0098	0.4433	1.063271
0.4724	0.5035	0.1971	0.0126	0.01	0.443	1.063088
0.4724	0.5036	0.1972	0.0127	0.0092	0.4428	1.0632
0.4724	0.5034	0.1972	0.0106	0.0096	0.4431	1.063077
0.4724	0.5034	0.1969	0.0098	0.0096	0.443	1.062933
0.4724	0.5034	0.1972	0.0107	0.0096	0.4427	1.062997
0.4724	0.5032	0.197	0.0115	0.0093	0.4426	1.062684
0.4724	0.5031	0.197	0.0124	0.0091	0.4424	1.062537
0.4724	0.5032	0.1973	0.0109	0.0096	0.4423	1.062761
0.4724	0.5033	0.197	0.0117	0.0094	0.4428	1.06282
0.4724	0.5036	0.1969	0.0111	0.0093	0.4429	1.063103
0.4724	0.503	0.1971	0.0127	0.0092	0.4424	1.062477
0.4724	0.5036	0.1973	0.011	0.0098	0.443	1.063296
0.4724	0.5032	0.1971	0.0099	0.009	0.4427	1.062767
0.4724	0.5031	0.197	0.0106	0.0093	0.4425	1.062573
0.4724	0.5031	0.1972	0.0103	0.0087	0.4424	1.062651
0.4724	0.503	0.1968	0.0098	0.0091	0.4422	1.062336
0.4724	0.5031	0.1971	0.0133	0.01	0.4428	1.06264
0.4724	0.5026	0.1971	0.0097	0.009	0.442	1.062031
0.4724	0.5024	0.197	0.0093	0.0092	0.4419	1.061769
0.4724	0.5027	0.1972	0.0107	0.0103	0.4422	1.062192
0.4724	0.5021	0.1974	0.0123	0.0092	0.4416	1.061556
0.4724	0.5026	0.1973	0.0097	0.0094	0.4422	1.062155
0.4724	0.5024	0.1971	0.0127	0.0092	0.4418	1.061759
0.4724	0.5027	0.1972	0.0094	0.0095	0.4424	1.062252
0.4724	0.5024	0.1972	0.0108	0.0093	0.442	1.061861
0.4724	0.5026	0.1973	0.01	0.0086	0.4422	1.06216
Variance	0.000433	0.000142	0.001167	0.000383	0.000425	0.000493

4.2 Pre-Machining C-Scan Images

The tools were set up in the scanner in the pattern shown in figures 26 and 28. A different gray and yellow pallet was chosen for higher contrast for the second sheet. The layers had nearly no anomalies with the exception of the one shown in figure 27 and a few layers directly above and below which have the same anomalies to slightly lesser degrees. Note that tool sets T and A are not in the study as they were destroyed during machining and initial setup.

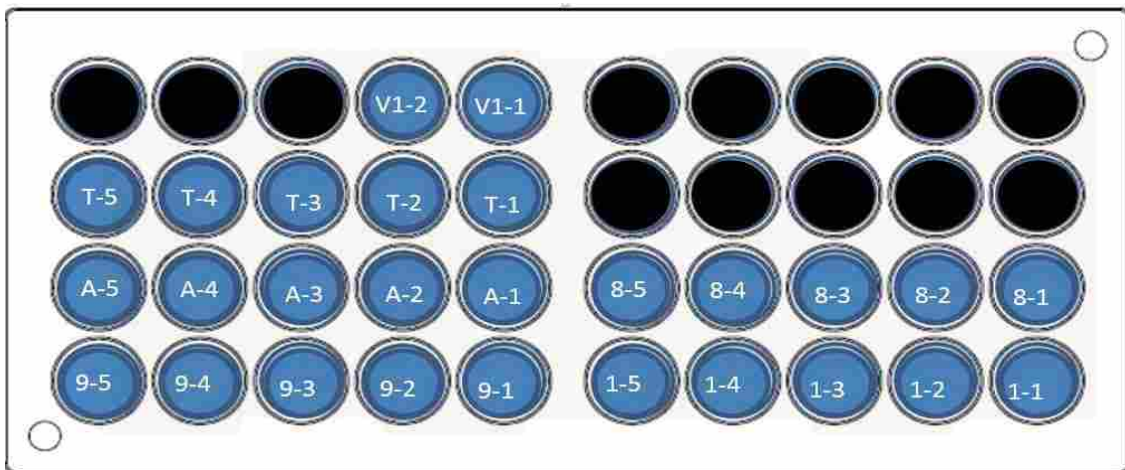


Figure 26: First Set Up of Tools for C-Scan

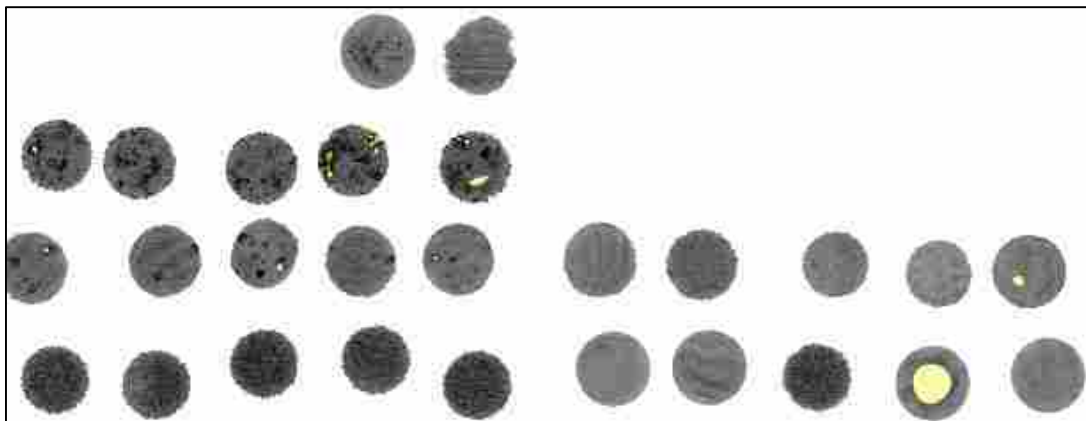


Figure 27: Image 20% Down Grades V1, 9, 8, and 1

In the second scan as seen in figures 28 and 29 tool numbers G1-2 and G8-1 show rather large anomalies while all of G9 and G1-3 appear to have slight anomalies. The second image is a little over 50 percent down through the part. G4-5 and G7-5 also appear to have anomalies but G4-5 lasted the entire length of the test and while G7-5 only lasted six welds and G7-1 and G7-2 only lasted eight and nine welds respectively. In the retest of G8-1 on the second image it still appears to have an anomalie but not nearly as big. There were also several false positives because of the height variation in the blanks.

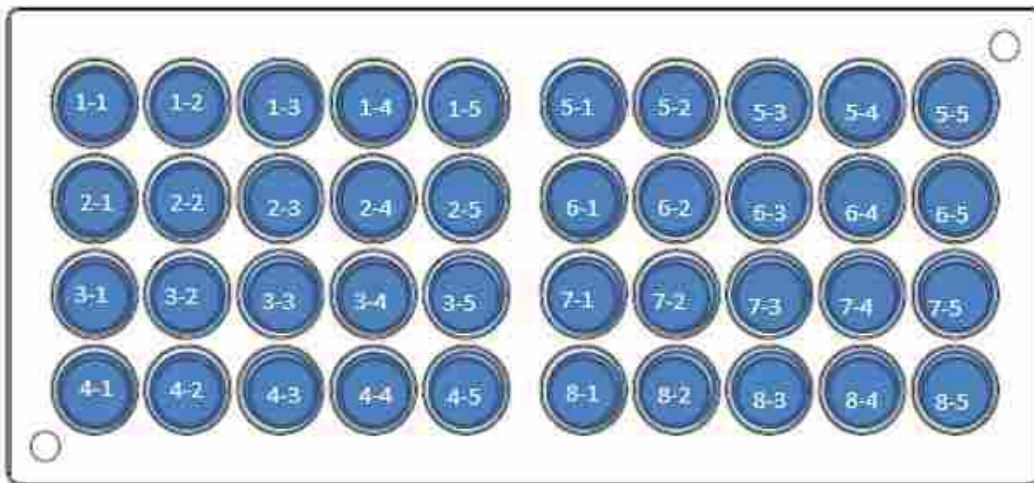


Figure 28: Second Set Up of Tools for C-Scan

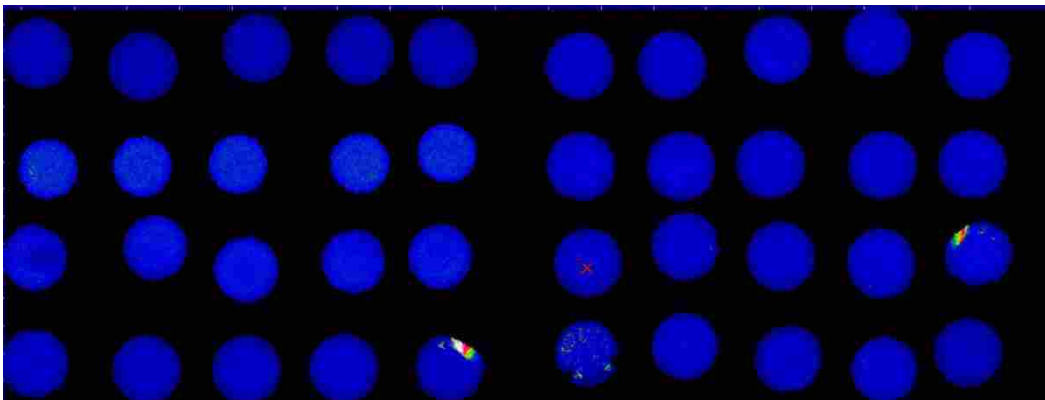


Figure 29: Image Over 50% Down Grades 1,2,3,4,5,6,7 and 8

4.3 Weld Results

4.3.1 Fracture Failure

The figure 30 shows the number of welds before failure. Note that if this number is 205 it indicates that the tool did not fail during testing. Tool numbers G5-3, G7-2, G5-4, and G5-5 all failed because they became imbedded in the sheet and broke as attempts were made to remove them. Tools G2-1, GV1-1, G6-2 and G5-1 broke during set up. G8-1 appeared to be spinning off center. G9-3, G5-3 and G6-4 chipped on the back side. G9-1 chipped on the shoulder.

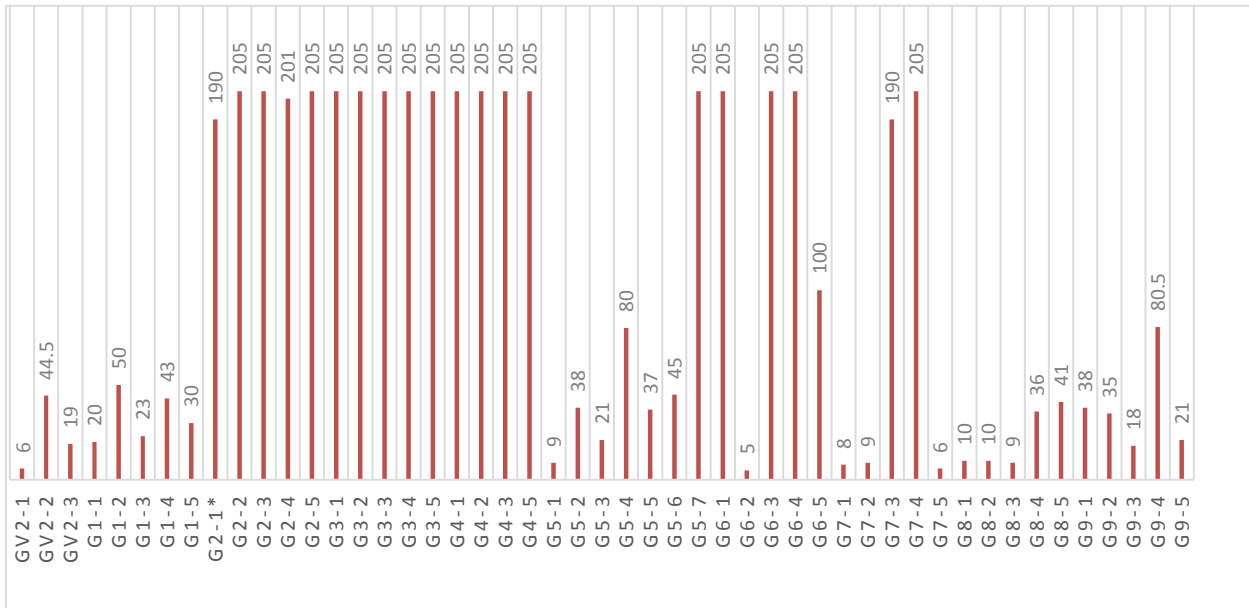


Figure 30: Welds to Fracture Failure

The pin in the original tool holder sheared several times before it was replaced with the drill chuck. As a result tools would remain embedded in the steel when the holder extracted. In trying to remove these tools from the plate, tool numbers G5-3, G5-4 and G5-5 broke. Using the

drill chuck, tool number G7-2 did the same thing. It is unknown if these tools had more adhesion between them and the plate or if it is strictly a tool design and chuck tightening issue or some combination.



Figure 31: G1-1 After Fracture Failure During Weld Number 20

Table 3 shows fracture breakage compared to percent CBN content by weight. As can be seen here the three tools that averaged the longest life before fracture failure were G2 at 201.2, G3 at 205 and G4 at 204. These all had 70% CBN content. The other tools had higher CBN content which would mean greater hardness and brittleness. Brittle material is more likely to fracture especially if it is not properly held during welding.

Table 3: Testing Matrix

grade	Grade name	average number of welds before failure	samples used for welds before fracture data	average profile area % loss (for tools that reached 200 welds)	samples used for this data	average % volume loss (for tools that reached 200 welds)	samples used for this data	%CBN
GV-1	MS80 – 1000C Heat Treat on Finished Cylinder		GV1-1	N/A	N/A	N/A	N/A	80
GV-2	MS80 – 1000C Heat Treat on Oversized Part Before Finishing	24.5	GV2-3	N/A	N/A	N/A	N/A	80
G1	MS80 (baseline)	33.2	G1-1, G1-2, G1-2, G1-4, G1-5	N/A	N/A	N/A	N/A	80
G2	Q70 with MegaDiamond W-Re powder	204	G2-2, G2-3, G2-4, G2-5	1.83%	G2-2, G2-3, G2-4, G2-5	0.13%	G2-3	70
G3	70 vol% cBN/W-Mo	205	G3-1, G3-2, G3-3, G3-4, G3-5	2.53%	G3-1, G3-2, G3-3, G3-4, G3-5	0.25%	G3-1, G3-3, G3-4, G3-5	70
G4	Q70 with finer MegaDiamond W-Re powder	205	G4-1, G4-2, G4-3, G4-5	2.41%	G4-1, G4-2, G4-3, G4-5	0.34%	G4-1, G4-2, G4-3, G4-5	70
G5	Q80 with finer MegaDiamond W-Re powder	96	G5-2, G5-6, G5-7	1.93%	G5-7	0.29%	G5-7	80
G6	Q80 with finer cBN and MegaDiamond W-Re powder	177.5	G6-1, G6-3, G6-4, G6-5	2.97%	G6-1, G6-3, G6-4	N/A	N/A	80
G7	Q90 with finer cBN and MegaDiamond W-Re powder	102.25	G7-1, G7-3, G7-4, G7-5	2.30%	G7-4	0.37%	G7-4	90
G8	MS90	21.2	G8-1, G8-2, G8-3, G8-4, G8-5	N/A	N/A	N/A	N/A	90

Tools in this test are less constrained than tools in standard friction stir welding. The tool holder is not an interference shrink fit, like it typically is during FSW. If there is a crack in the tool material in standard FSW it could be held in place and continue to provide good welds. Because the tool holder was a slip fit (with full backing), and the drill chuck was a tight fit with partial backing there would be more freedom to move (creating chatter) and if a crack did initiate it would be more likely to propagate. In a standard FSW tool, a crack that propagated to the point of breaking the tool in two or more pieces may still be held together by the shrink

interference fit allowing the tool to continue to weld but would lead to catastrophic failure in this experiment.

4.3.1.1 C-Scan

G1-2 had the largest anomaly in C-scan and was the tool that lasted the longest of the G1 tool grade before fracture failure, achieving 50 welds before failure compared to 20, 23, 43, and 30 in the other tools of that grade. G8-1 only lasted 10 welds before fracture failure but that is comparable to G8-2 and G8-3 which achieved 10 and nine welds respectively. It appears that the anomalies in the c-scan did not correlate with internal material defects that resulted in premature fracture failure.

4.3.2 Calculated Volume Loss Percentages

Volume loss of tool material is a direct measurement of its wear over a period of time. The volume loss percentage calculated from the mass in air and mass in water showed that G2 was the most wear resistant material and that G6 was the most wear prone material of those materials that had at least one tool survive without fracture failure through 205 welds. This can be seen in figure 32.

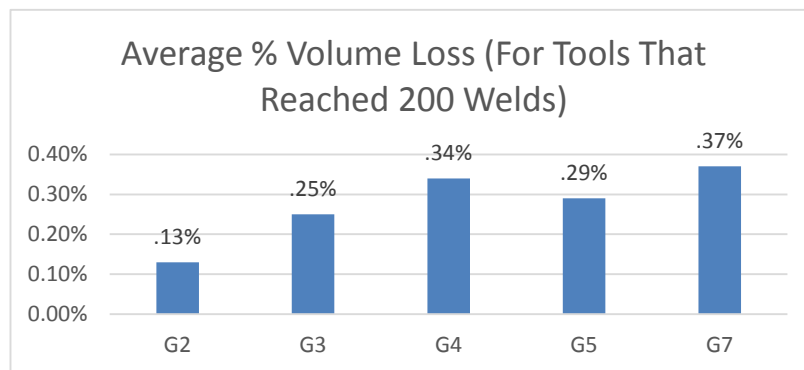


Figure 32: Average Volume Percentage Loss by Grade

G2 contains the same CBN percentage as G4 (70%) and less CBN than G5 (80%) and G7, (90%) but had better wear resistance. This can be attributed to the courser components in G2 powders which may not allow the metal matrix to wear away around the CBN particles causing them to loose support and fall out.

4.3.3 Calculated Cross Sectional Area Loss Percentages

The calculated cross sectional area loss also showed that G2 was the most wear resistant material and G6 was the most wear prone material of those tools that survived to 205 welds without fracture failure, as seen in figure 33. The ranking of wear on the remaining tool materials varied from that of the measured volume loss percentage. This could be attributed to the small sample size as G7 and G5 only had one sample each. The test was valuable in that it could provide data on the G6 tools that had been broken or retested without gathering the weight data first.

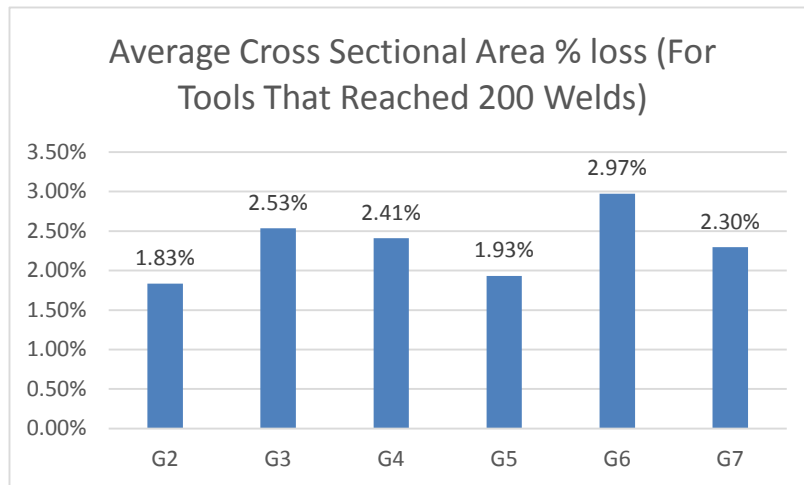


Figure 33: Average Cross Sectional Area Percentage Loss

4.3.4 Weld Strength

The average weld strength of the coupon welds for both the beginning and end is listed by grade in Figures 34 through 39.

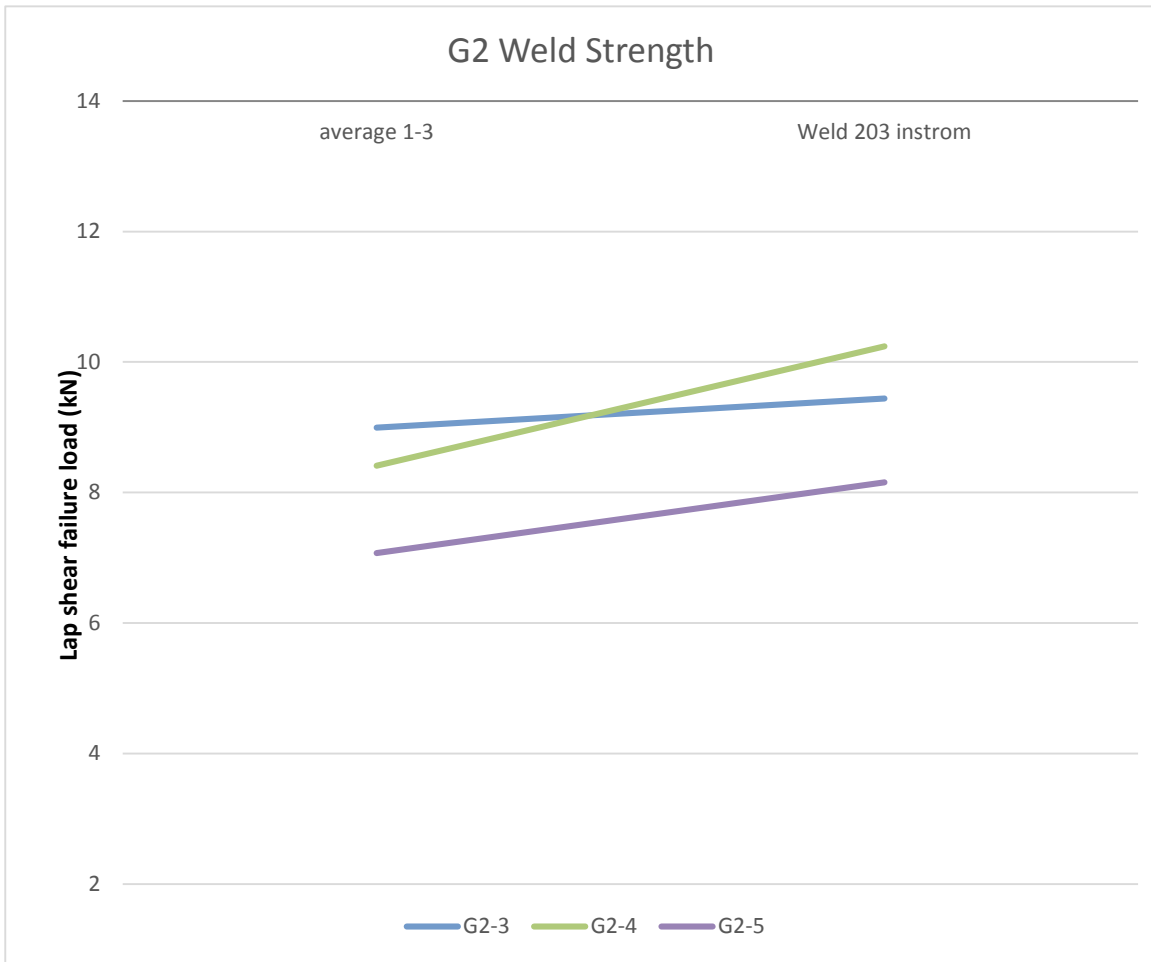


Figure 34: Measured Weld Strength for G2 Tools

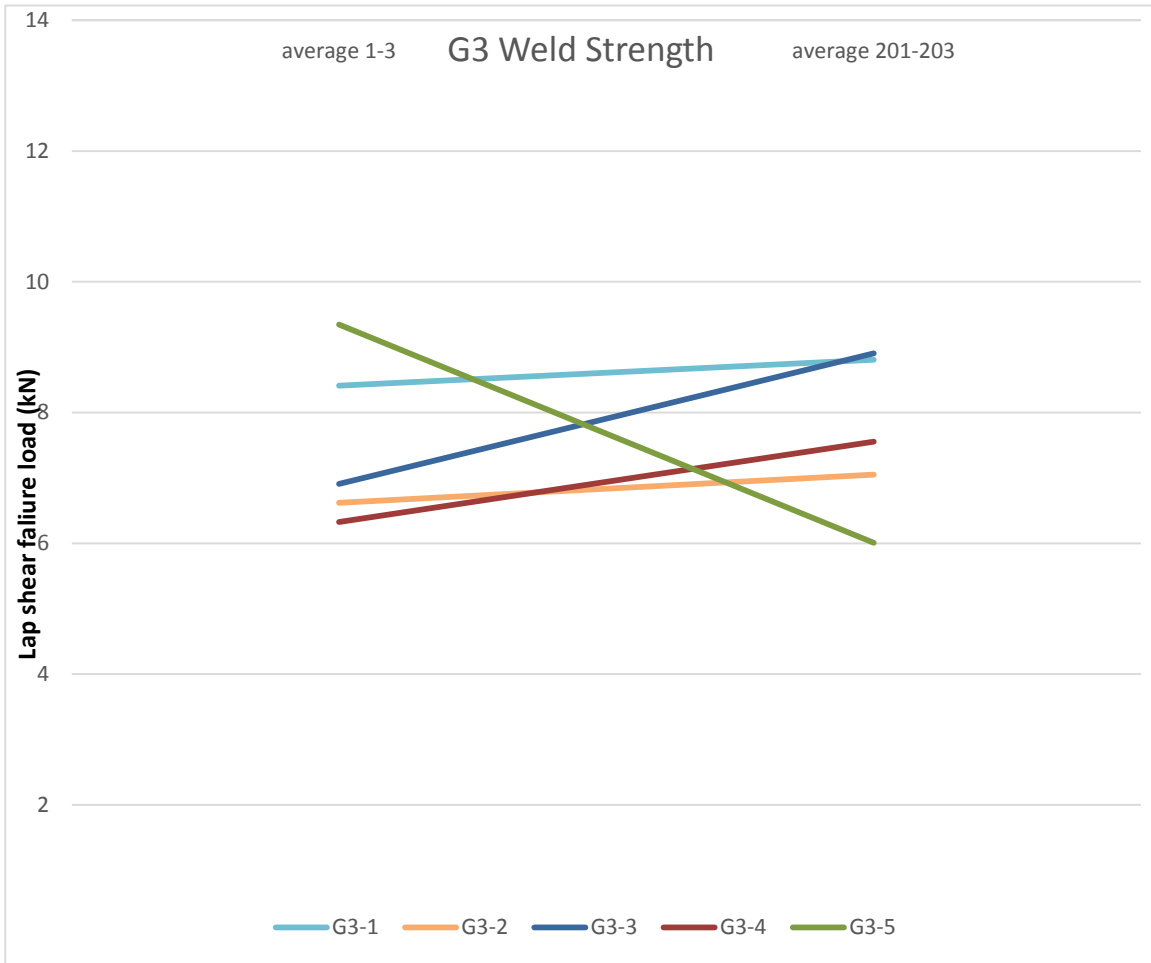


Figure 35: Measured Weld Strength for G3 Tools

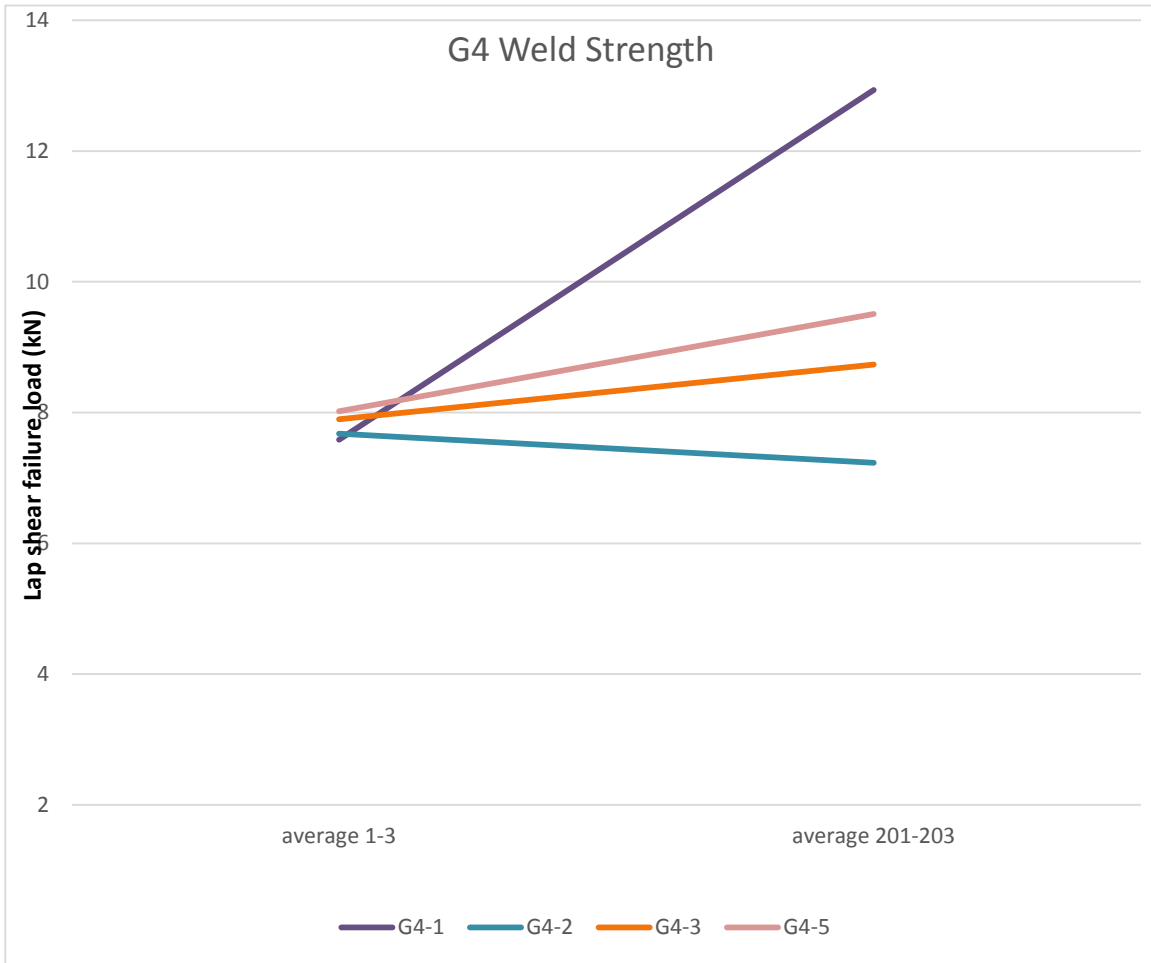


Figure 36: Measured Weld Strength for G4 Tools

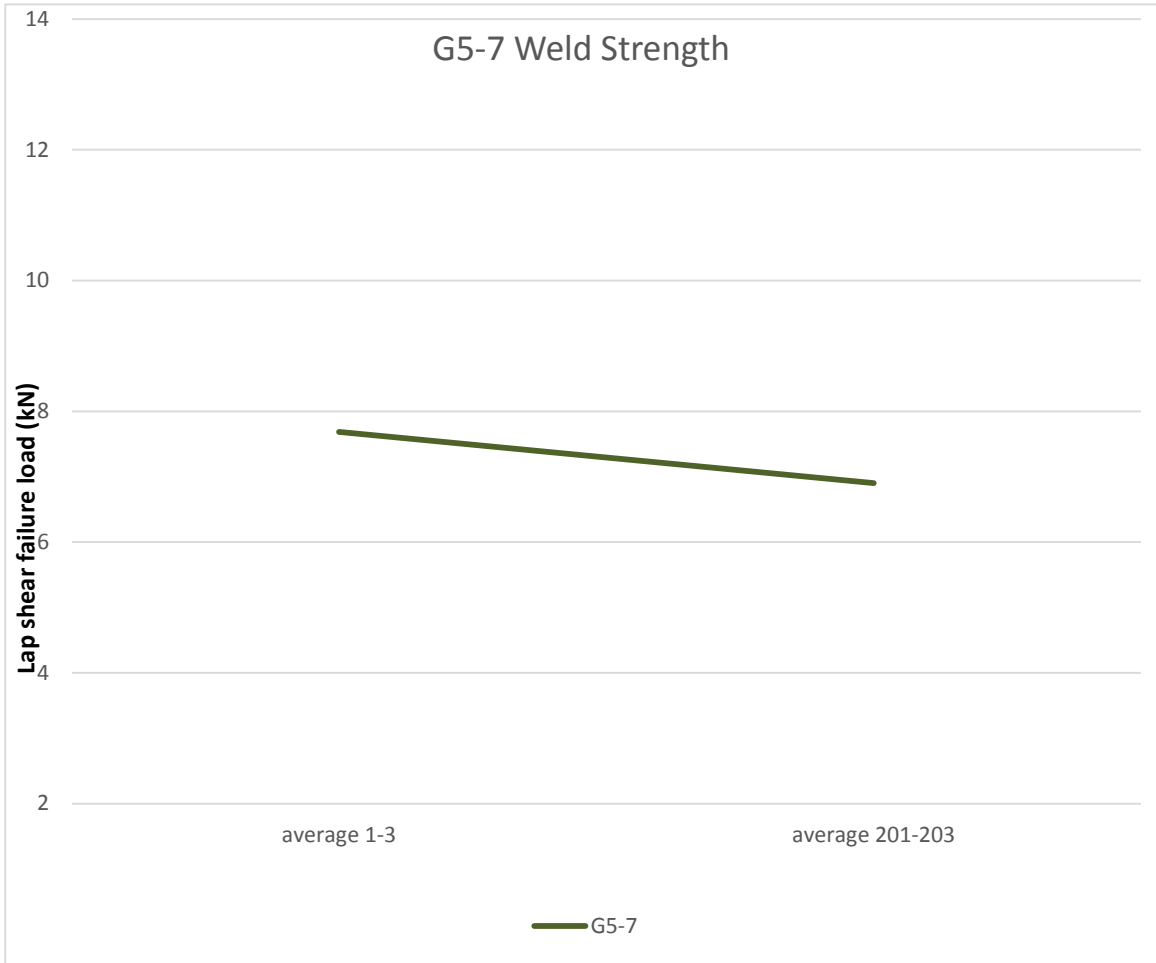


Figure 37: Measured Weld Strength for G5 Tool

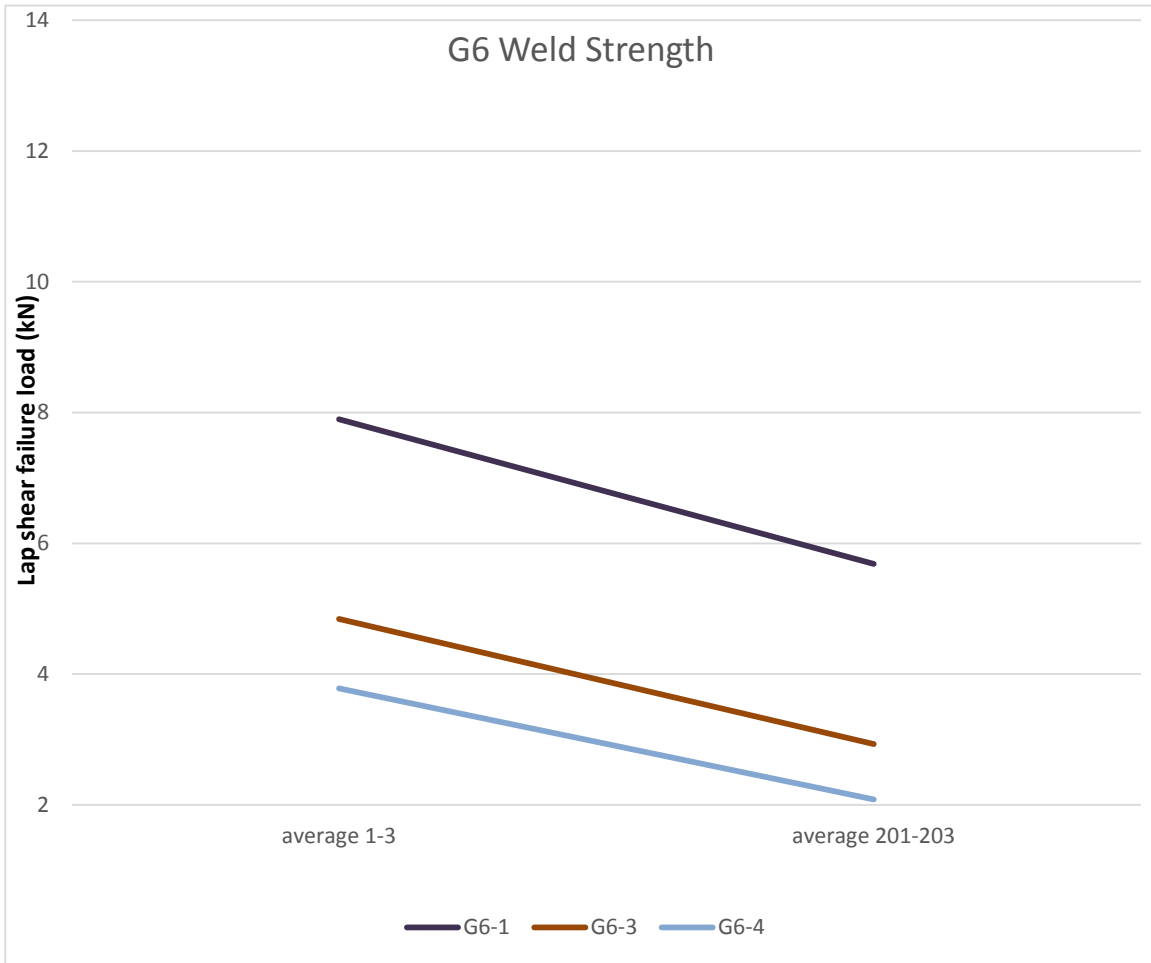


Figure 38: Measured Weld Strength for G6 Tools

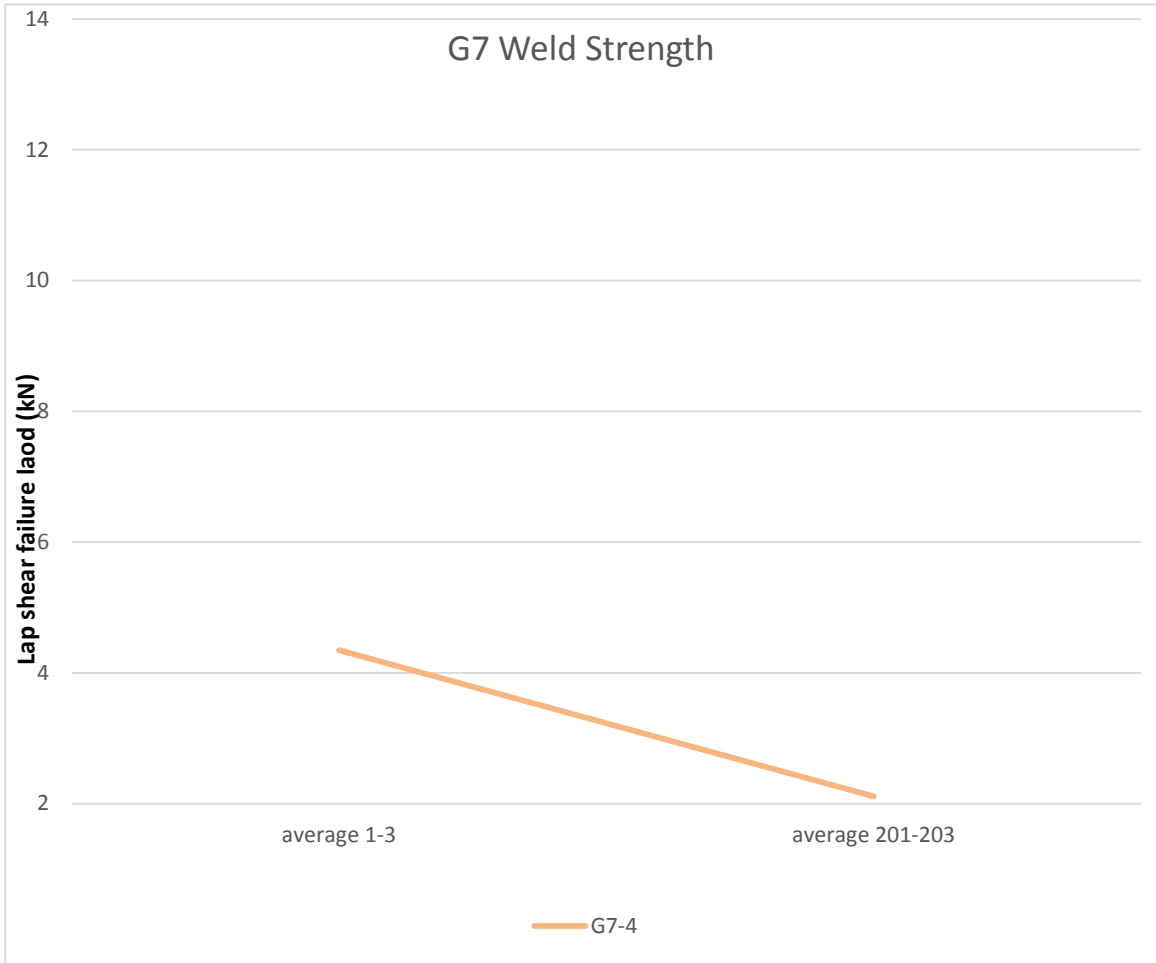


Figure 39: Measured Weld Strength for G7 Tool

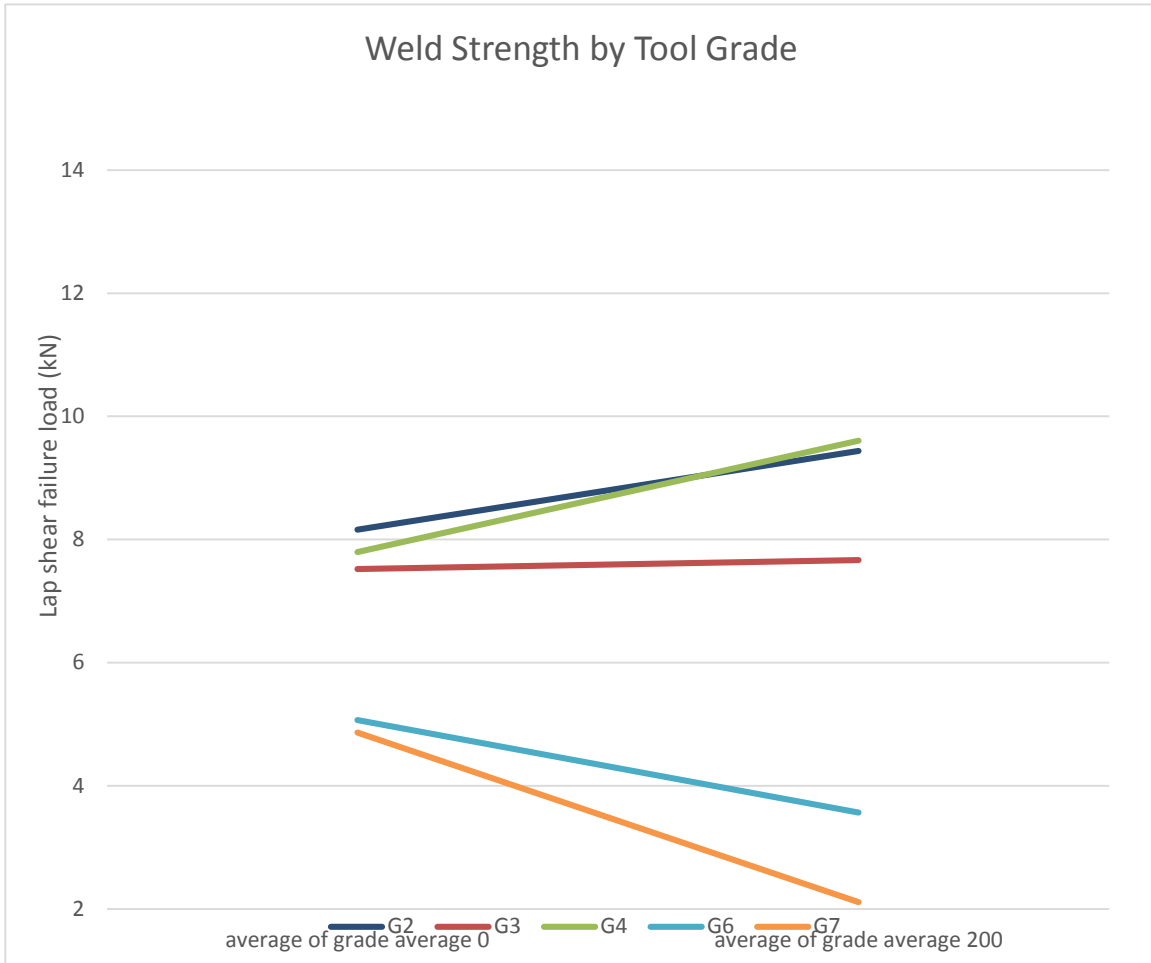


Figure 40: Average of Measured Weld Strength for All Tool Grades

In Figure 42 it can be seen that the percentage weld strength loss for tools grades G2, G3, and G4 were actually negative indicating that the welds gained strength with wear which is contrary to the literature.

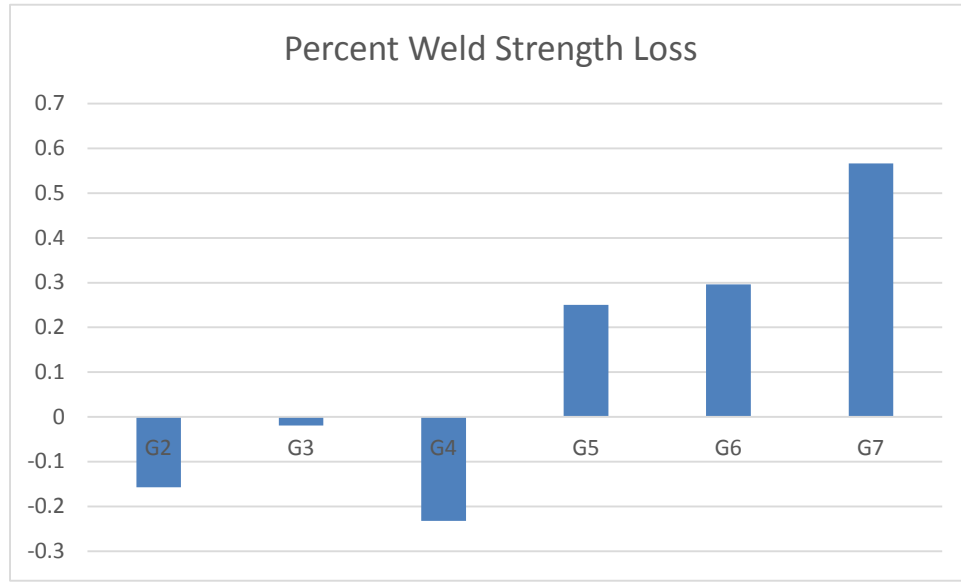


Figure 41: Percent Weld Strength Loss

4.3.5 Weld Area

Initial weld area for G7-4 was 0.0 mm² because a crack propagated from the joint on one side to the joint on the other. In figure 40 we see that the weld area decreases over time for all of the other grades that were able to complete through weld 204. The discrepancy between welded area and tool cross sectional area and tool volume can be attributed to the variation introduced by varying the tool plunge depths during testing

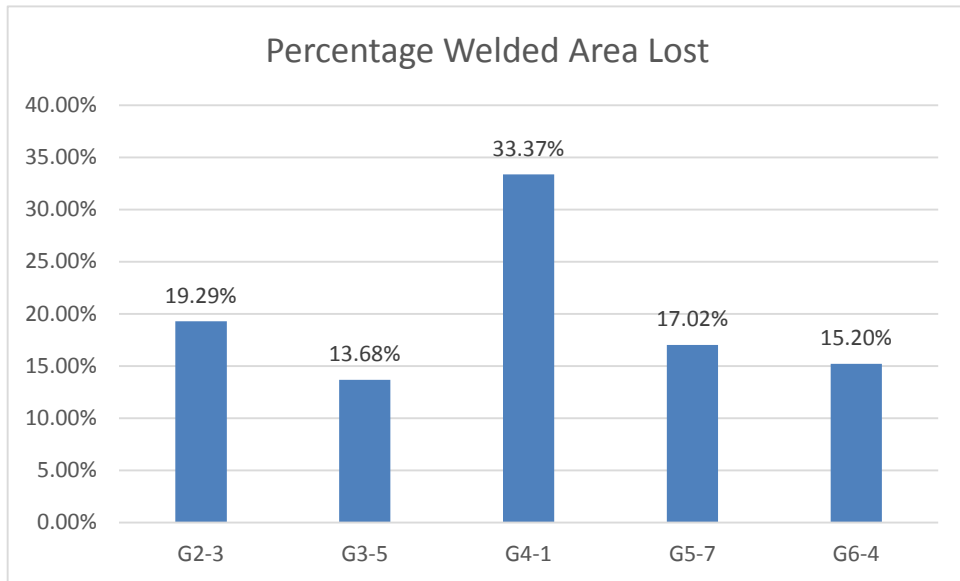


Figure 42: Percentage Weld Strength Loss by Tool Grade

5 CONCLUSIONS AND RECOMMENDATIONS

5.1 Conclusions

5.1.1 C-Scan

While C-Scan is able to provide data from inside the part there is not currently sufficient data to determine if an anomaly is a defect or noise.

5.1.2 Tool Holder Design

The 2 holders in this study were not ideal. The set screw would shear off and the Chuck didn't hold tight enough. There was too much freedom of movement which may have contributed to the fracture failure of most of the tools that were composed of more than 70% CBN.

5.1.3 Volume Loss Versus Cross Sectional Area Loss

Cross sectional area that was calculated based on measurements from a digital dimensioning system did not give wear data as precisely as using percentage volume lost. It does have the advantage of being more accurate when chipping occurs on a non-wearing surface. Both methods were sufficient in this study to distinguish the tools with the best wear resistance.

5.1.4 Weld Strength

Weld strength did give an idea of what the higher and lower wearing materials were but some tools showed an increase in weld strength with an increase in wear which is contrary to the literature. This variation may be attributed to manual adjustments to plunge depth made to compensate for varying weld depths noted by operators. Therefore, weld strength was too dependent on process conditions to be a good indication of tool wear resistance.

5.1.5 CBN Grain Size

It was found that smaller CBN grain size, other things being equal, did not equate to better wear resistance. This is contrary to the results of a prior study, but the binder for a given grade has an influence on wear, so the CBN grain size effect can only be compared when all other elements of tool composition and pressing conditions are the same.

5.1.6 Weld Area

Weld area did show three tools which distinguished themselves from the others. One of those tool grades (G6) was the highest wearing in cross sectional area loss. The discrepancy between the expected results and the results obtained can again be attributed to the variation introduced by adjusting plunge depths during tests.

5.2 Recommendations

5.2.1 Holding Improvement

While using the drill chuck for holding tools worked better than the custom made tool holder it was not an ideal set up and its contribution to premature tool failure needs to be further

studied. Tests should be done using off the shelf collets and collet stops. The tools should be machined to fit the collets to determine if the improved holding power would decrease chatter and improve performance of harder materials

5.2.2 Force Control

Tests should be done to determine if using force control would give consistent results while decreasing the chance of fracture failure of parts from variation in the welded material. It may also produce consistent weld depth.

5.2.3 Compare to FSW

Tests should be done to determine if these FSSW tests can be used not just to compare material grade but to predict tool life of a given tool grade in a given welded material.

5.2.4 C-Scan

Ideal c-scan parameters for PCBN should be explored. Tests to determine the efficacy of using c-scan to find defects in PCBN tools should be conducted. Both the rate of false positive and false negative should be determined.

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