

Mechanical Properties of an Inconel Dissimilar Metal Weld

By
Steven Knapp, B.A.Sc.

Submitted to the Faculty of Graduate and Postdoctoral Studies
In partial fulfillment of the M.A.Sc. program in
Mechanical Engineering

Ottawa-Carleton Institute for
Mechanical and Aerospace Engineering

University of Ottawa
©Steven Knapp, Ottawa, Canada, 2014

Master of Applied Science (Submitted in December 2013)

The Ottawa-Carleton Institute for Mechanical and Aerospace Engineering
Ottawa, Ontario

Title: Inconel Dissimilar Metal Weld

Author: Steven Knapp

Supervisor: Dr. Arnaud Weck

Number of Pages: 117, xii

Abstract

A pipe consisting of Inconel 600 welded to grade 106-B Carbon-Steel using Inconel 182 weld filler is used to transport heavy water in nuclear reactors. A confidential report concluded that cracking is one of the problems these pipes are currently facing.

The literature review in this thesis reviews the mechanical properties, cracking information, and material characterization techniques related to this pipe. The literature reveals:

1. That no one has analyzed the mechanical properties of a weld that consists of these three materials.
2. Crack interactions have been studied in detail in the past few years but not many authors looked at crack growth path compared to material in a welded structure.

The goals of this thesis are to:

1. Determine the mechanical properties of the Inconel 600, Inconel 182 weld filler, Carbon Steel grade 106-B weld.
2. Create a model using the mechanical properties determined and model the tests that were completed to prove that the model works.
3. Observe the fracture mechanisms of the pipe including cracking.

This thesis analyzed the pipe at various length-scales using optical microscopy, micro-hardness testing, small and large scale tensile testing and digital image correlation (DIC). This thesis successfully achieved its goals of determining the mechanical properties and creating a model of the Inconel dissimilar metal weld. It partially met the goal of observing fracture mechanisms as it was able to observe fracture in tensile samples but was not able to successfully track crack growth.

The mechanical properties reveal that the heat affected zones contribute to the mechanical properties of the pipe. Future work should be done to create a model that includes the heat affected zones of carbon steel and Inconel. In addition a future finite element model should include a damage model capable of modeling cracking.

Acknowledgements

I would like to thank my supervisor, Dr. Arnaud Weck, for his guidance, advice, and assistance during the course of this project. Without his involvement the project would not have been successful.

I would like to thank Dr. Mohammed Yandouzi for providing SEM images, EDS analysis, and training on the Hardness Machine. Also, I would like to thank my colleagues in the Fracture Ottawa Group as each of them helped me in some way during this project.

Finally, I would like to thank my family for all of their support during this project.

Contents

Abstract.....	iii
Acknowledgements.....	iv
1. Introduction	1
2. Literature Review.....	2
2.1 Microstructure of Dissimilar Metal Welds.....	2
2.1.1 Microstructure	2
2.1.2 Precipitates in Inconel 600.....	4
2.1.3 Recrystallization in Inconel 600	4
2.2 Weld Composition.....	5
2.3 Mechanical Properties of Dissimilar Metal Welds.....	6
2.3.1 Average Mechanical Properties	7
2.3.2 Local Mechanical Properties	9
2.4 Fracture Mechanisms.....	16
2.4.1 General Fracture Mechanisms of Dissimilar Metal Welds.....	16
2.4.2 Fracture Surface and Toughness.....	17
2.5 Cracking.....	18
2.5.1 Crack Propagation Tests.....	19
2.5.2 Evidence of Cracking and Crack Interaction in Welded Structures.....	21
2.5.3 Multiple Surface Flaws.....	21
2.6 Residual Stress	25
2.7 Modelling Mechanical Properties of Dissimilar Metal Welds.....	26
2.7.1 Finite Element Analysis	26
3. Research Proposal.....	28
4. Experimental Procedure	30
4.1 Introduction	30
4.2 ASTM Standards.....	31
4.3 Microstructure Characterization.....	32
4.3.1 Experimental and Sample Design	32
4.3.2 Sample Preparation.....	33
4.3.3 Experimental Procedure	34

4.4	Hardness	34
4.4.1	Experimental and Sample Design	35
4.4.2	Sample Preparation.....	36
4.4.3	Testing Procedure	36
4.5	Scanning Electron Microscope (SEM) with Electron Dispersive Spectroscopy (EDS)	36
4.5.1	Experimental and Sample Design	37
4.5.2	Sample Preparation.....	37
4.6	Large Tensile Testing.....	38
4.6.1	Experimental and Sample Design	38
4.6.2	Experimental Set-Up	39
4.6.3	Sample Preparation.....	40
4.7	Large Tensile Testing with Digital Image Correlation (DIC).....	41
4.7.1	Sample Preparation.....	41
4.7.2	Experimental Procedure	41
4.8	Miniature Tensile Testing.....	42
4.8.1	Experimental and Sample Design	42
4.8.2	Experimental Set-Up	43
4.8.3	Sample Preparation.....	43
4.8.4	Experimental Procedure	45
4.9	Artificial Crack Initiation.....	46
4.10	Finite Element Analysis	46
5.	Results.....	47
5.1	Microstructure Characterization.....	47
5.2	Hardness	51
5.3	Scanning Electron Microscope (SEM) with Electron Dispersive Spectroscopy (EDS)	56
5.4	Large Tensile Testing.....	62
5.5	Large Tensile Testing with Digital Image Correlation (DIC).....	64
5.6	Miniature Tensile Testing.....	72
5.7	Finite Element Model.....	75
5.8	Artificial Crack Initiation.....	79
6.	Discussion.....	84
6.1	Temperature Evolution During Welding Process.....	84

6.2	Hardness Compared to Temperature, Microstructure, and Composition	89
6.3	Miniature Stress vs. Strain Compared to Hardness and DIC.....	93
6.4	Large Stress vs. Strain Compared to Finite Element Analysis	95
7.	Conclusions and Future Work.....	97
7.1	Conclusions	97
7.2	Future Work	98
	Bibliography	99
	Appendix A: Welding Techniques	104
	Appendix B: Detailed Polishing Procedure	106
	Appendix C: Detailed Microscopy Procedure and Grain Size Using Line Method	111
	Appendix D: 4-Point Bend Test	112
	Experimental and Sample Design	112
	Experimental Set-Up	114
	Sample Preparation	115
	Experimental Procedure	117
	Results for Four Point Bend Test.....	117

List of Tables

Table 1: Time Required for Recrystallization of Inconel 600 [6]	4
Table 2: Composition of Carbon Steel, Inconel 82 Weld Filler, and Inconel 600.....	6
Table 3: Tensile Test Results of the two base metals (SS and Inconel) and the base metals combined with the filler metals [8, p. 617].....	8
Table 4: Room- Temperature Properties of All-Weld-Metal Deposits [6]	8
Table 5: Inconel 600 - Modulus of Elasticity [9].....	9
Table 6: Radial Variations in Strength [5]	12
Table 7: Failure Mechanisms in Austenitic Welds	17
Table 8: Charpy V-Notch Results [2]	18
Table 9: Alignment Rules for Multiple Flaws [53]	22
Table 10: Experimental Test types and their purpose	30
Table 11: Location on Pipe vs. Weld Region vs. Experimental Test Type	31
Table 12: ASTM Standards	31
Table 13: Polishing Procedure for Microscopy	34
Table 14: Position Procedure for SEM and EDS	37
Table 15: Polishing Procedure for Large Tensile Specimens.....	40
Table 16: Polishing Procedure for Miniature Tensile Specimens	44
Table 17: Elastic properties used in the FEA model.....	76
Table 18: EDS Scan for composition of ductile area of large sample with crack that failed in brittle manner.....	82
Table 19: EDS Scan for composition of brittle area of large sample with crack that failed in brittle manner	82
Table 20: Parameters and Definitions for Rosenthal Equation and Model [68].....	86
Table 21: Constant Parameters in Welding Model.....	86
Table 22: Polishing Procedure for 4-Point Bend Specimens.....	116

Table of Figures

Figure 1: Heavy Water Nuclear Reactor [1]	1
Figure 2: SEM Images (a) Inconel 82 Weld, (b) Weld at High Magnification, (c) Interface with Inconel 657, (d) Interface with Stainless Steel [2]	2
Figure 3: Microstructure of Inconel 82/182 weld fusion zone: a) Root Area; b) Middle; c) Top of Weld; and d) 182/F316 fusion boundary [5]	3
Figure 4: Cold Reduction vs. Vickers Hardness for Inconel 600 and Others [6].....	5
Figure 5: Specification for the Tensile Test Specimens [8]	7
Figure 6: High Temperature tensile properties of welds made with Inconel welding electrode 182 [6].....	9
Figure 7: Hardness Values Across the Weld [2]	10
Figure 8: Hardness Values Across the Weld [8]	11

Figure 9: Miniature Tensile Sample (mm) [5]	12
Figure 10: Sheet Sample Locations in Bulk [5]	12
Figure 11: Yield Strength and Ultimate Tensile Strength of 9 mm diameter round bar specimens [8]	13
Figure 12: Longitudinal and Transverse Samples Scheme [17]	14
Figure 13: Digital Image Correlation, Vickers Hardness, Stress-Strain Curves for an Aluminum Friction Stir Weld [17].....	15
Figure 14: 3-D Digital Speckle (Image) Correlation of a Rubber Sample [18]	16
Figure 15: Ductile Fracture Surface of Inconel 657 [2]	18
Figure 16: Ductile Fracture Surface of SS 310 Base Metal [2]	18
Figure 17: Creviced -Bent - Beam (CBB) Test Set-Up [45].....	19
Figure 18: SCC type crack in fusion boundary layer of Inconel 182- Low Allow Steel A533B [44]	19
Figure 19: Refreshing water loop with autoclave and integrated electro-mechanical tensile machine [46]	20
Figure 20: 4-Point Bend Set-Up with two surface cracks [47]	20
Figure 21: 4-Point Bend Test Set-Up on pipe with circumferential cracks [9].....	21
Figure 22: Tensile Loading with multiple surface flaws [15].....	21
Figure 23: Load Displacement Curves for Type A Samples where DD-1 through DD-4 had crack depth 8 mm (out of 10 mm thickness).....	23
Figure 24: Load Displacement Curves for Type B Samples where (out of 10 mm thickness) DD-5 through DD-8 had crack depth of 4 mm.	23
Figure 25: Three Types of Crack Propagation. Type 1: Vertical distance less than plastic zone; Type 2: Vertical distance larger than plastic zone; Type 3: Vertical Distance even larger	25
Figure 26: Residual Stress (Hoop) vs. Position Across the Weld [38]	26
Figure 27: Residual Stress (Hoops) vs. Distance Across the Weld for a Buttered Weld Sample [38]	26
Figure 28: FEA Model of Dissimilar Metal Weld [59].....	27
Figure 29: FEA vs. Experimental Data of Crack-Mouth-Opening Displacement (CMOD) at the center of the through-wall crack. Where the moment is the external bending moment applied to the pipe[59] ...	27
Figure 30: Left to Right - Inconel 600, Inconel 82 Weld Filler, Carbon Steel Grade 106-B	29
Figure 31: Nikon Optiphot - 100 Microscope Set-Up.....	32
Figure 32: Microscopy sample mounted in thermoplastic mold	33
Figure 33: Visual Inspection Sample showing locations where the indents will take place (Note: Small silver dots on image are actual indents that were taken)	35
Figure 34: Vibratory Polisher (with blue polishing suspension and two samples)	36
Figure 35: Vibratory Polisher From Above (samples are under brass cylinders which are used for weight)	36
Figure 36: Scanning Electron Microscope (SEM) with Multiple Imaging Options	37
Figure 37: EDS sample, note copper tape glued to the sample to increase conduction	38
Figure 38: Large Tensile Sample Location and Dimensions	38
Figure 39: Large Scale Tensile Test Set-Up viewed from Polished Side	39
Figure 40: Large Scale Test Set-Up Viewed from Speckle Pattern Side	39
Figure 41: Miniature Tensile Sample Location and Dimensions	43
Figure 42: Miniature Tensile Testing Set-Up.....	43

Figure 43: Manual Load Controller	43
Figure 44: Polishing Apparatus for Miniature Samples. Small puck cylinder in the front left has sample mounted on it and puck is placed in large cylinder on right. Cylinder in back left is placed on top of puck within larger cylinder acting as weight.	44
Figure 45: Mounting Options. Left - Cylindrical sample mounted in resin. Right - Miniature Tensile Sample glue to cylindrical puck as completed in this project.....	44
Figure 46: Left- Incoloy Pipe Sample As Machined, Center - Polished to Desired thickness (200 μm), Right – Sample after laser machining using femtosecond laser. (Note: Samples part of different project, used as an example)	45
Figure 47: Miniature Tensile Samples After Laser Machining	45
Figure 48: Femto-second laser used to machine and insert cracks into the samples	46
Figure 57: (Left to Right) Inconel 600, Inconel 82 Weld Filler, Carbon Steel Grade 106B	48
Figure 58: The microstructure from the large tensile sample, after polishing but before testing occurs .	49
Figure 59: The deformed microstructure of the sample after testing was completed. Note: The blue colour seen is a manipulation by the optical microscope software so that the microstructure can be seen easily.	50
Figure 52: Vickers Hardness tests taken over a small region 30 mm away from the weld	52
Figure 53: Vickers hardness tests taken over a small region 50 mm away from the weld	52
Figure 54: Vickers Hardness on Inconel region away from the weld.....	53
Figure 55: Vickers Hardness testing done on all three base materials (away from the heat affected zones)	53
Figure 56: Vickers Hardness on Inconel region moving into the weld region. Test completed at 0.3 mm from the outer diameter of the pipe.	54
Figure 57: Vickers Hardness on Inconel region moving into the weld region. Test completed at 3.3 mm from the outer diameter of the pipe.	55
Figure 58: Vickers Hardness on Inconel region moving into the weld region. Test completed at 7 mm from the outer diameter of the pipe (1 mm from the inner edge).	56
Figure 59: Electron Dispersive Spectroscopy testing on the interface between Carbon Steel and the Weld near the inner diameter.....	57
Figure 60: EDS Map by Element of Area Shown in Figure 59	57
Figure 61: EDS analysis of Inconel 82 weld filler and Inconel 600 base metal below center of the pipe...	58
Figure 62: EDS Map by Element of area in Figure 13.....	58
Figure 63: EDS Analysis of Carbon Steel to Weld Interface near the middle of the weld.	59
Figure 64: Composition of the Weld-Inconel interface 0.3 mm from the outer edge of the pipe as analyzed from EDS.	60
Figure 65: Composition of the Weld-Inconel interface 3.3 mm from the outer edge of the pipe as analyzed from EDS.	61
Figure 66: Composition of the Weld-Inconel interface 7 mm from the outer edge of the pipe as analyzed from EDS.	61
Figure 67: Tensile Tests on 1 mm thick samples taken from the outer diameter, inner diameter, and middle diameter of the sample	62

Figure 76: Large Tensile Samples Post Testing. Polished surface shows deformation, especially in the weld region. The width of the weld region post testing is listed on the right of the images.	63
Figure 77: Digital Image Correlation Results: Early Stages	64
Figure 70: Digital Image Correlation Results: Local Strain vs. Engineering Stress	65
Figure 71: Sample 2A. Strain as determined by DIC vs. location on the sample at different global stress levels. Note that as the strain increases, the sample elongates and the different zones shift slightly to the left on the graph. This is due to the left side being fixed and the right side free to elongate.	66
Figure 72: The Stress vs. Strain curves for each region as extracted from the Digital Image Correlation Software.....	67
Figure 73: Sample 3A. Strain as determined by DIC vs. location on the sample at different global stress levels.	68
Figure 74: Stress vs. Strain as extracted by DIC for Sample 3A. Sample taken from the middle diameter of the pipe	69
Figure 75: Crack in sample 3B (Image Under 5x microscope)	69
Figure 76: Stress vs. Strain as determined from DIC. (Left: DIC strain vs. location; Right: Corresponding stress vs. strain curves)	70
Figure 77: Stress vs. Strain Curves for Inconel as extracted from DIC.....	71
Figure 78: Stress vs. Strain curves for Carbon Steel as extracted from DIC.....	71
Figure 79: Stress vs. Strain curves for the Inconel 82 weld filler as extracted from DIC.	72
Figure 80: True Stress vs. True Strain for Carbon Steel. Test data from old miniature tensile machine..	73
Figure 81: True Stress vs. True Strain for Inconel from old miniature tensile machine.	73
Figure 82: True Stress vs. True Strain for the Weld Region from old tensile machine.	73
Figure 83: Miniature True Stress vs. True Strain for the Outer diameter of the pipe	74
Figure 84: Miniature True Stress vs. True Strain from the Inner Diameter of the Pipe.	75
Figure 85: Miniature True Stress vs. True Strain for the middle thickness of the pipe.	75
Figure 86: Plastic properties for FEA of the inner sample. This represents sample 2A from the large tensile samples.....	77
Figure 87: Plastic properties for FEA of the middle sample. This represents sample 3A from the large tensile samples.....	77
Figure 88: Plastic properties for FEA of the outer sample. This represents sample 1B from the large tensile samples.....	78
Figure 89: Finite Element Analysis of Large Tensile Samples	78
Figure 90: Finite Element Analysis of Large Tensile Sample (3A). The carbon material is at the bottom and the Inconel at the top near the legend. Plastic Equivalent Strain (PEEQ) vs. Engineering Stress	79
Figure 91: Prior to Loading (Large Tensile with crack Test 1)	80
Figure 92: Prior to Loading (Large Tensile with crack Test 2)	80
Figure 93: Brittle Failure between crack and bottom edge, top edge still loaded (Large Tensile with crack Test 1)	80
Figure 94: Loaded sample, crack opening in ductile manner (Large Tensile with crack Test 2).....	80
Figure 95: Ductile failure at top edge (Large Tensile with crack Test 1).....	80
Figure 96: Ductile failure at top and bottom edges(Large Tensile with crack Test 2)	80

Figure 105: Scanning electron microscope images of the first large tensile test with a crack and DIC. The images show the fracture surface which is ductile on the left and brittle on the right.	81
Figure 98: EDS Line Scan of Fracture Surface in Test 1 Brittle Fracture.....	83
Figure 99: Parameters of the Rosenthal Equation for a semi-infinite plate [68].....	85
Figure 100: Temperature vs. Location of Rosenthal Welding Model	87
Figure 101: Temperature vs. Location of Rosenthal Welding Model	88
Figure 102: Temperature required for recrystallization vs. time for different amounts of cold work.....	88
Figure 103: Inconel and Weld hardness near the outer diameter compared to the microstructure	89
Figure 104: Inconel and Weld hardness near the middle of the sample thickness compared to the microstructure	91
Figure 105: Inconel, Weld, and Carbon Steel hardness as compared to the microstructure.....	92
Figure 106: True Stress vs. True Strain for the outer diameter of the pipe. Comparing small curves as extracted from large DIC samples and small curves as extracted from mini samples with DIC.....	93
Figure 107: True Stress vs. True Strain for the inner diameter of the pipe by region. It compares the small curves as extracted from the large DIC versus the small curves as extracted from the mini samples with DIC.....	94
Figure 108: True Stress vs. True Strain of middle of the pipe. Comparing small curves as extracted from large DIC to small curves as extracted from the mini samples.....	94
Figure 109: True Stress vs. True Strain comparing large tensile samples as extracted from DIC and the FEA models.....	96
Figure 110: Metaserv 2000 Polishing Machine.....	106
Figure 111: Digital Ultrasonic Bath/Cleaner – Eumax UD100SH-3L.....	109
Figure 112: Model #1 - Basic Bending 1 mm thick sample	113
Figure 49: Model #2 - Bending with Crack (1 mm thick).....	113
Figure 114: Model #3 - Bending with Crack and Supports (1 mm thick)	113
Figure 115: Model #4 - Bending with Off-Center crack and supports (1 mm thick).....	113
Figure 116: 4-Point Bend Grip Design (Dimensions in mm)	114
Figure 117: 4-Point Bend Grips (as tested).	115
Figure 118: 4 Point Bend Samples (Top: Side #1 DIC Paint Speckle, Bottom: Side #2 Etched (Carbon on right))	115
Figure 119: Machining Drawing for 4-point bend samples. Locations compared to the start-stop location of the weld were recorded.	116
Figure 120: 4-Point Bend Sample (with trimmed edges and crack)	117
Figure 121: Crack Tip as seen through the Microscope (4 point bend sample)	117

1. Introduction

A dissimilar metal weld is used to connect two different metals together. The weld filler material is usually a material that has similar properties to both of the base metals. Dissimilar metals are used where a pipe, or other object, is subjected to multiple environments in one application. The advantage of dissimilar metal welds is that each section of pipe can be optimized for its specific application. An example would be a heavy water pipe from a nuclear reactor (see Figure 1). The pipe travels near the fuel with high levels of radiation and high temperature, then moves away from the fuel into a boiler where the temperature of the pipe is significantly decreased. The pipe material can be optimized for each environment it passes through.

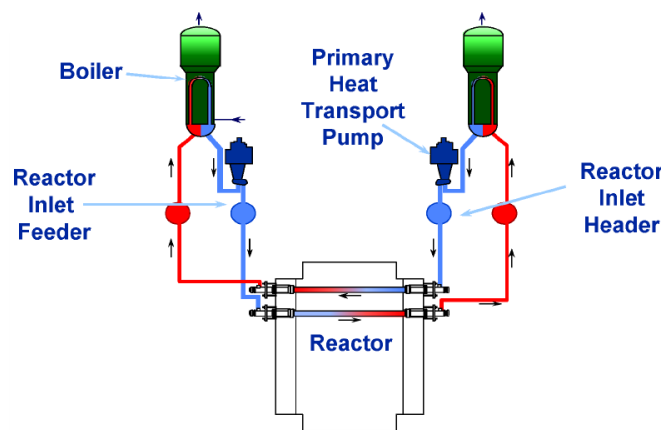


Figure 1: Heavy Water Nuclear Reactor [1]

The major disadvantage of dissimilar metal welds is that the area around the weld is subjected to uneven heating during welding creating a mixture of materials which have unknown material properties. Pipes used to transport heavy water in Candu reactors contain dissimilar metal welds. These welds consist of Inconel 600 welded to grade 106-B Carbon-Steel using Inconel 182 weld filler. A confidential report concluded that one of the problems the company is currently facing is the cracking of these dissimilar metal welds. Cracking poses concerns for the safe operation of the Candu reactors. Failure of these dissimilar metal welded pipes could lead to costly reactor shut down (for repair) and/or the release of heavy water. Consequently, the mechanical and fracture properties of these welded pipes need to be better understood

2. Literature Review

2.1 Microstructure of Dissimilar Metal Welds

2.1.1 Microstructure

Many experiments have been completed on dissimilar metals welds and several conclusions can be made about the microstructure. The regions near the fusion boundaries on both sides of the weld differ significantly from their bulk material properties, composition, and microstructure [2]. The region has been called the unmixed zone, filler-metal-depleted area, partially mixed zone, intermediate zone, and hard zone (See Figure 2 (d)). The unmixed zone (UZ) is a lamellar region where some of the base metal has melted and re-solidified without undergoing filler metal dilution [2], [3], [4]. The partially melted zone (PMZ) is formed just inside the heat affected zone (HAZ). It is formed when the material is heated above the solidus temperature but below the liquidus temperature, hence partially melted.

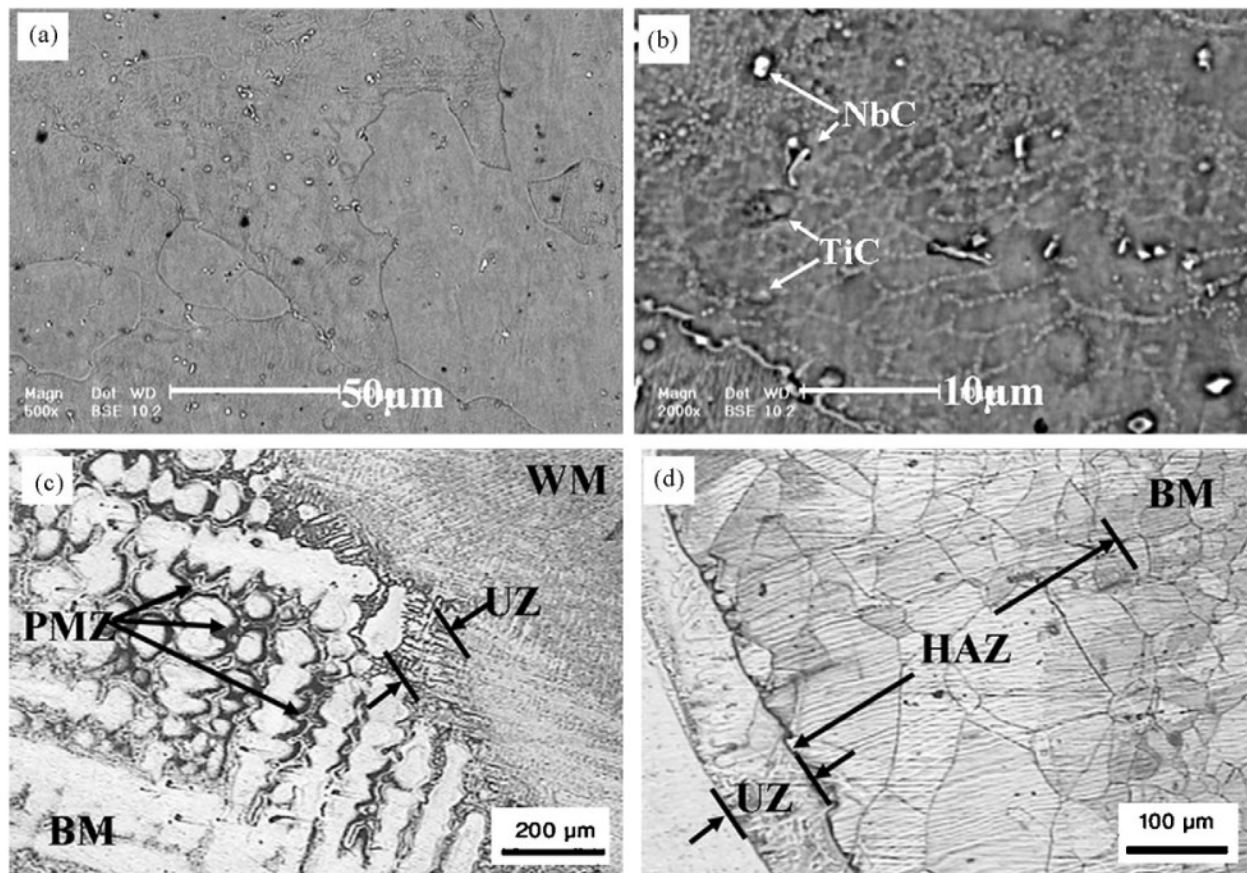


Figure 2: SEM Images (a) Inconel 82 Weld, (b) Weld at High Magnification, (c) Interface with Inconel 657, (d) Interface with Stainless Steel [2]

Figure 2 shows images taken with a scanning electron microscope (SEM) at different locations of the Inconel 657 /Inconel 82 / Stainless Steel weld. The unmixed zone, partially melted zone, weld metal region, and base metal regions are identified.

According to [2] the dendritic boundaries found in Inconel 657 tend to melt due to the increased levels of Niobium. Niobium generally lowers the melting point and forms low-melting carbide-austenite eutectics during solidification. The dendritic boundaries can be seen in Figure 2, inside the partially melted zone.

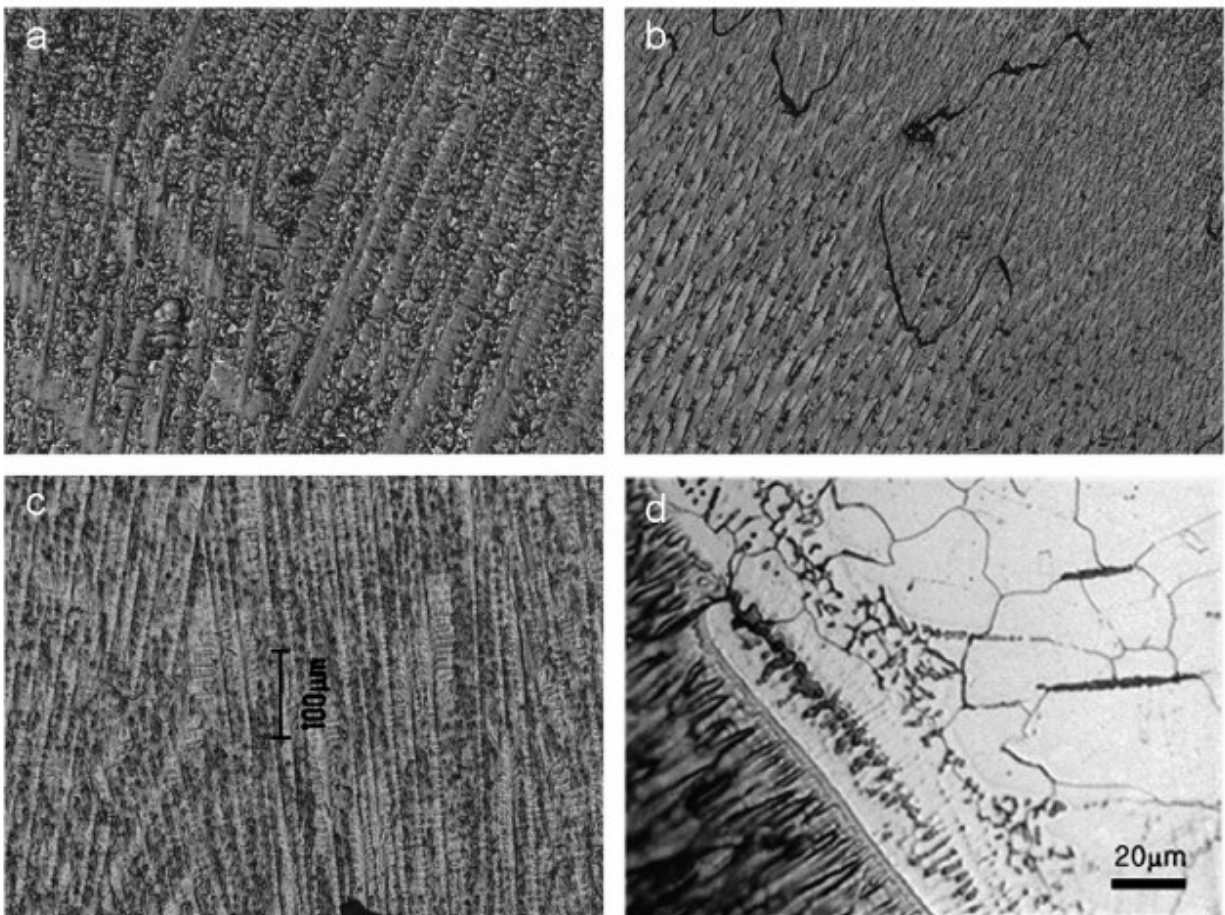


Figure 3: Microstructure of Inconel 82/182 weld fusion zone: a) Root Area; b) Middle; c) Top of Weld; and d) 182/F316 fusion boundary [5]

A detailed analysis of a weld containing SA508, Inconel 82 weld buttering, Inconel 182 weld, F316 stainless steel was completed in [5]. Specifically, Figure 3 shows the Inconel 82/182 weld fusion zone and the Inconel 182 and F316 stainless. The authors found that the dendrite microstructure was more closely spaced at the bottom of the weld than the top. Another observation was significant segregation

and secondary phase precipitates between the dendrites. The authors concluded that a large number of inclusions were present in the Inconel 182 weld metal. The inclusions were also confirmed by Sireesha in [4]. In addition, the authors observed a portion of the stainless steel base metal melted and solidified during welding at the fusion boundary layer with Inconel 182 (Figure 3c).

2.1.2 Precipitates in Inconel 600

In Inconel 600 the precipitate phases present in the microstructure are titanium nitrides, titanium carbides, and chromium carbides. At temperatures between 540° C and 980° C chromium carbides precipitate out of the solid solution at the grain boundaries and into the matrix. Grain growth occurs at temperatures above 980° C. At that temperature the carbides that inhibit grain growth begin to coalesce. Solution of carbides begins at 1040° C and treatment for 1 to 2 hours between 1090° C to 1150° C dissolves carbides completely, resulting in increased grain size. The melting temperature is 1384°C. [6]

2.1.3 Recrystallization in Inconel 600

The Inconel 600 pipe used in this thesis was milled out of a solid block of Inconel. The machining caused the pipe to be cold-worked. The time required to recrystallize cold-worked Inconel 600 material can vary widely depending on the amount of cold-work and specific composition (Table 1). The table shows the temperature required for recrystallization decreases with increasing cold working

Table 1: Time Required for Recrystallization of Inconel 600 [6]

Cold Reduction, %	Temperature Required for Recrystallization in							
	15 min		30 min		60 min		120 min	
	°F	°C	°F	°C	°F	°C	°F	°C
5	1775	968	1750	954	1700	927	1700	927
10	1650	899	1600	871	1550	843	1550	843
20	1525	829	1475	802	1425	774	1425	774
50	1350	732	1325	718	1275	691	1275	691
80	1250	677	1225	663	1200	649	1200	649

The process of cold working hardens the material. The percent of cold reduction is compared against the Vickers hardness for various materials including Inconel 600 in Figure 4. For Inconel 600, a cold work (reduction) of 40% results in a yield stress twice as high as the non-cold worked material.

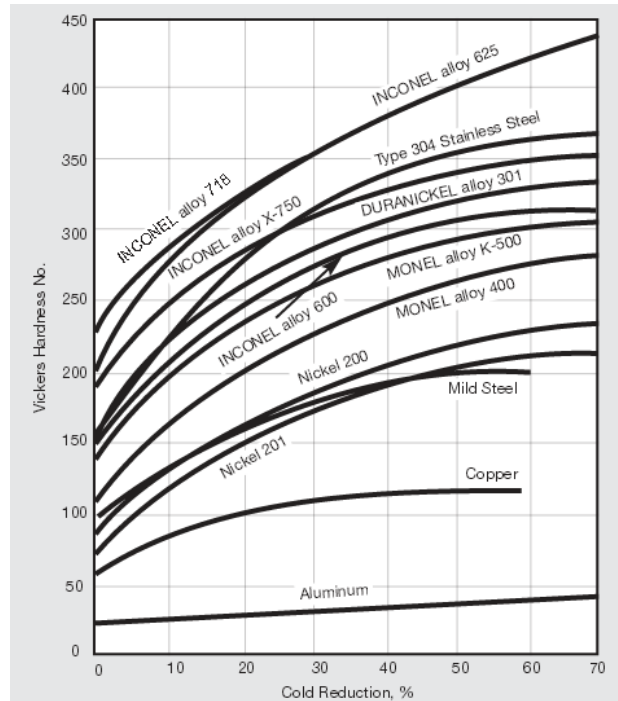


Figure 4: Cold Reduction vs. Vickers Hardness for Inconel 600 and Others [6]

2.2 Weld Composition

The pipe used in this thesis is made up of Inconel 600, Inconel 182 weld filler, and Carbon Steel (grade 106-B). The typical composition of the base materials from literature can be seen in Table 2. These compositions were taken from manufacturers and from the literature. In [8] the composition was determined using a scanning electron microscope equipped with energy dispersive spectroscopy (EDS) point analysis.

Table 2: Composition of Carbon Steel, Inconel 82 Weld Filler, and Inconel 600

Element	Carbon Steel Grade 106 – B (%) [7]	Inconel 182 Weld Filler (%)		Inconel 600 (%) [6]
C	Max 0.30	Max 0.1 [2]	Max 0.1 [8]	Max 0.15
Si	0.1 min	0.5	0.5	Max 0.5
Mn	0.29-1.06	3	3	Max 1
Fe	Remaining	3	3	6-10
Cr	Max 0.4	20	20	14-17
Mo	Max 0.15	-	-	-
Co	-	-	0.12	-
Ti	-	1	1	-
Nb	-	3	3	-
Al	-	-	-	-
Ni	Max 0.4	Remaining	67 min	72 min (nickel with colbalt)
Cu	Max 0.4	0.5	0.5	Max 0.5
Su	Max 0.035	-	-	Max 0.015
P	Max 0.035	-	-	-
V	0.08 min	-	-	-

2.3 Mechanical Properties of Dissimilar Metal Welds

Many dissimilar metal welds are used to join pipes together which is the case in this thesis. Some authors have been able to use the whole pipe as the test specimen [9] and [10] . The authors in [9] used four-point bending to analyze circumferential cracking. A similar type of experiment was completed in a confidential report. When the whole pipe is analyzed the global properties of the material can be determined. But it is difficult to understand what is happening on a finer local scale, especially to understand fracture. The round cross section of a pipe can be difficult to test so in some instances flat plates are used as a model [8],[5],[2]. This also makes for much easier sample preparation.

The average or global mechanical properties of a material can be found by testing specimens that have regions that represent the whole pipe. In the case of a welded material that would be the two base

materials, the weld material and the heat affected zones around the weld. Examples of this type of testing include large tensile testing and full-pipe bend tests. To better understand how and why the global material behaves the way it does, the local material properties of each region are studied. Local mechanical properties can be extracted through hardness testing, miniature tensile testing, and digital image correlation (DIC).

2.3.1 Average Mechanical Properties

Large Tensile Testing

The average mechanical properties of a dissimilar metal weld can be determined by testing a sample that consists of the entire weld and surrounding materials. The results obtained will represent the material properties of the specimen as a whole unit. Similarly, if there was enough material available a large tensile test could be done on each individual material or region to reveal its own (local) properties.

Such tensile testing was completed in [2], [8], [11], [12], [13], [14], [15]. The samples in [2] and [8] were round transverse weld specimens produced and tested using the ANSI Standard Methods for Mechanical Testing of Welds (AWS-B4).

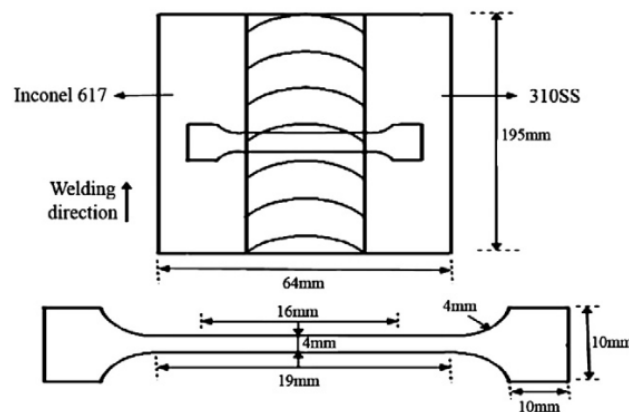


Figure 5: Specification for the Tensile Test Specimens [8]

Fracture usually occurs in the weaker parent material during tensile testing as seen in [2] and [8]. The authors in [8] used different filler metals to optimize a weld consisting of 310 stainless steel and Inconel 617. Table 3 shows the mechanical properties that the authors determined for the materials. All of the tests failed in the heat affected zone of the 310 stainless steel base material, which is the weakest material tested. The tensile test is a good way to determine many material properties of a dissimilar metal weld as a whole.

Table 3: Tensile Test Results of the two base metals (SS and Inconel) and the base metals combined with the filler metals [8, p. 617]

Filler and base metal type	Yield strength (MPa)	Ultimate tensile strength (MPa)	Total elongation (%)	Reduction in area (%)	Location of failure
310 SS base metal	272±5	565±20	72±7	68±3	–
Inconel 617 base metal	425±16	837±27	61±4	45±2	–
Inconel 82 filler metal	405±14	617±11	43.5±5	61.75±3	310 SS base metal
Inconel 617 filler metal	420±8	644±22	48±4	59.98±2	
310 SS filler metal	440±25	615±12	24±2	27.95±1	

Table 3 shows that the yield strength of Inconel 617 (similar to Inconel 600) is around 425 MPa with an ultimate tensile strength of 837 MPa. The yield stress of Inconel 82 filler metal is 405 MPa with an ultimate tensile strength of 617 MPa. This is very similar to the technical specifications of Inconel 82 filler metal given in [6] seen in Table 4. The yield strength for Carbon Steel grade 106B is a minimum of 241.3 MPa with a minimum tensile strength of 413 MPa [7].

Table 4: Room- Temperature Properties of All-Weld-Metal Deposits [6]

Welding Material	Tensile Strength		Yield Strength (0.2% Offset)		Elongation in 1.25 in. (31.75 mm), %
	ksi	MPa	ksi	MPa	
INCONEL Filler Metal 82 ^a	96.20	663.3	57.10	393.7	45
INCONEL Welding Electrode 182 ^a	92.40	637.1	55.10	379.9	44
INCONEL Welding Electrode 182 ^b	98.80	681.2	61.40	423.4	40

^a0.505-in. (12.83 mm)-dia. specimen.

^b0.252-in. (6.40-mm)-dia. specimen.

Environmental Effects on Mechanical Properties

Any testing done on a material only reveals the properties of the material in the environment it was tested in. Testing at room temperature can be much easier than testing at operational temperatures. For example, the testing in both [2] and [8] was done at room temperature whilst the materials are used for high temperature applications.

Table 5: Inconel 600 - Modulus of Elasticity [9]

Temperature	Young Modulus	Shear Modulus	Poisson's Ratio
°C	GPa	GPa	
22	214	80.8	0.324
100	210	79.6	0.319
200	205	78.0	0.314
300	199	76.2	0.306
400	193	74.2	0.301
500	187	71.9	0.300
600	180	69.2	0.301
700	172	65.9	0.305
800	164	62.1	0.320
900	154	57.9	0.330
1000	143	53.4	0.339

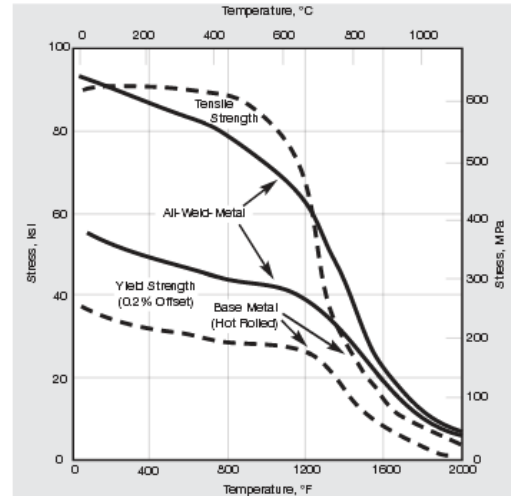


Figure 6: High Temperature tensile properties of welds made with Inconel welding electrode 182 [6]

The change in temperature can affect the results drastically as seen in Table 5 and Figure 6. These figures show that the yield stress and ultimate tensile strength decrease significantly with increasing temperature. The elongation at failure increases with increasing temperature. Another factor is the environment the sample is being subjected to. Testing done on Inconel 657 revealed it is the weaker parent metal and thus the location of failure [2]. However this weld is known to fail under stress corrosion cracking. Since Inconel 657 has a high resistance to oxidization and carburization at high temperatures, it is deemed to be a good material for this situation.

2.3.2 Local Mechanical Properties

Hardness Testing

Indentation testing is done to obtain the hardness of a material in many different locations. For a dissimilar metal weld the testing is often done across the weld, determining the hardness profile. The hardness profile will reveal the trend across the weld and the specific hardness in each region of the material (Base Material, Weld, Heat Affected Zone).

The hardness profiles within the weld metal, heat affected zone, and the base metals were determined in [2] and [8] using a Leitz Microindentation Hardness Tester with loads of 100 g and 300 g respectively. A general conclusion that can be drawn from both papers is that the hardness in the weld has a positive gradient towards the harder base metal. Although both papers showed the increase, the weld fillers in [8] all had the same hardness as the softer base metal at their junction. The weld fillers then saw a

gradual change towards their final hardness, Inconel fillers increase in hardness from the stainless steel base metal. The gradual increase is due to a compositional gradient most likely caused by diffusion during the welding process [8]. The relationship was quite different in [2] where there was a sharp change in hardness moving from one region to the next. The hardness values seen in the heat affected zone of the base metal Inconel 657 showed a distinct pattern in [8]. There was a sharp increase in hardness (260 to 375 HV) moving from the base metal into the heat affected zone of the Inconel 657. The increase in hardness was not a function of weld filler material.

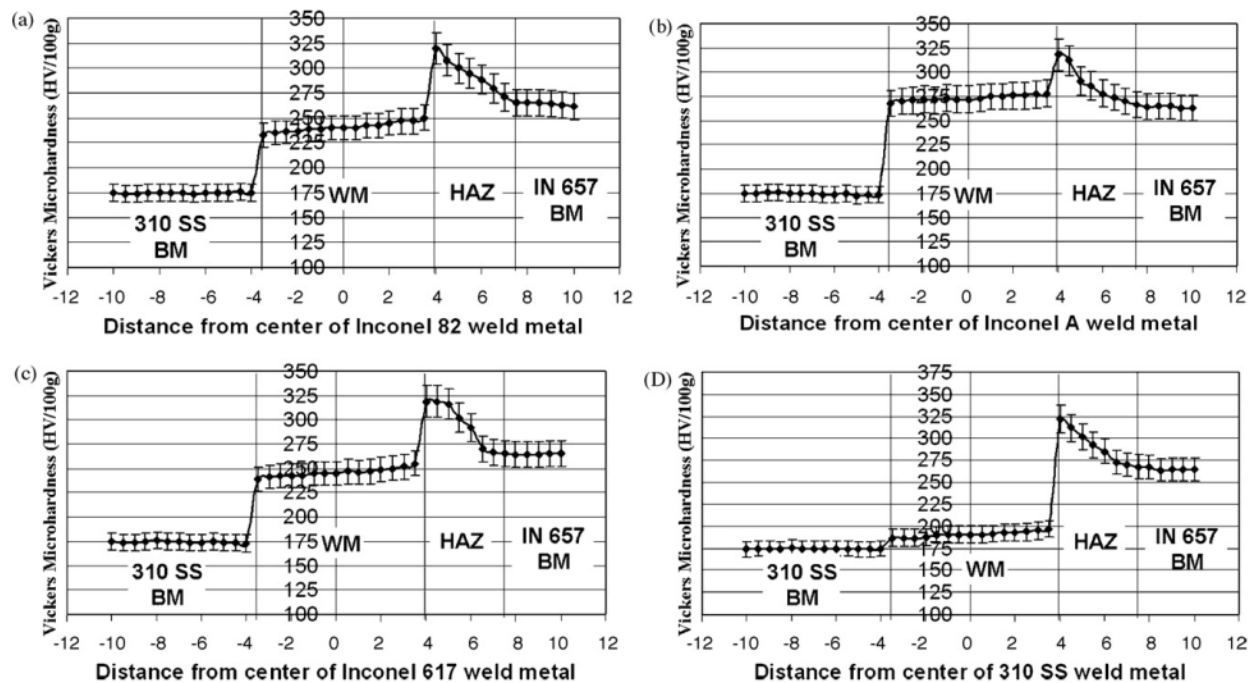


Figure 7: Hardness Values Across the Weld [2]

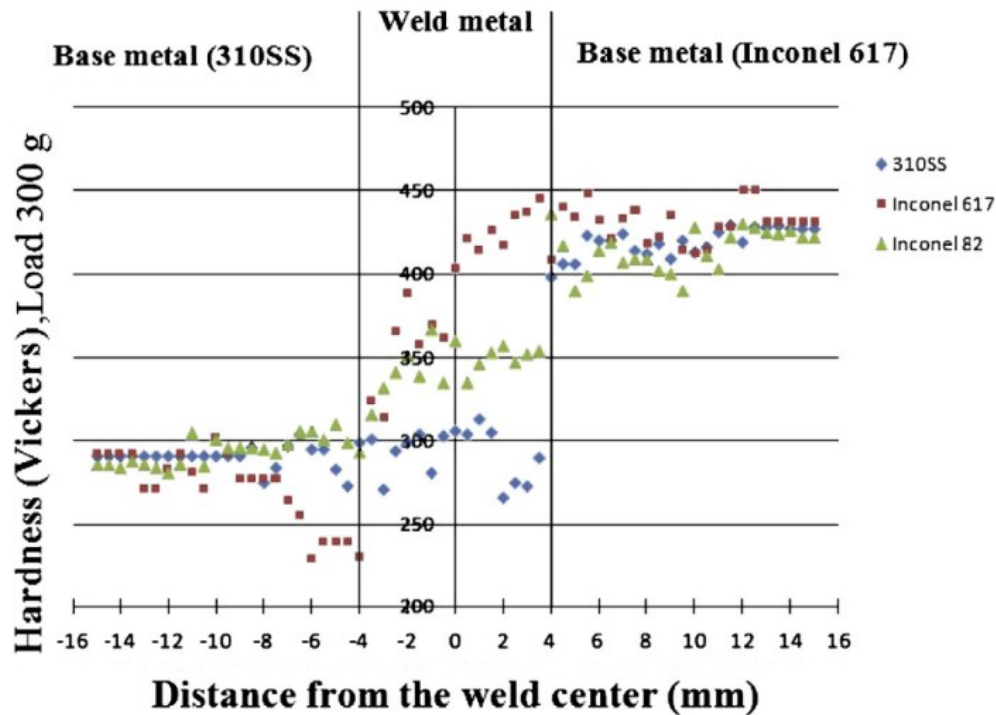


Figure 8: Hardness Values Across the Weld [8]

Miniature Tensile Specimens

A miniature tensile specimen is used in the same way as a large size specimen but much smaller regions can be tested. In dissimilar metal welds the properties change significantly in different locations near the weld (longitudinally and radially). The regions across the weld include the heat affected zone, unmixed zone, partially melted zone. In larger welds where multiple passes need to be done the properties will also change radially. This is due to the high heat applied during the welding process. Many base materials already have different materials properties in different regions. These regions will react differently to the welding process resulting in even larger variations.

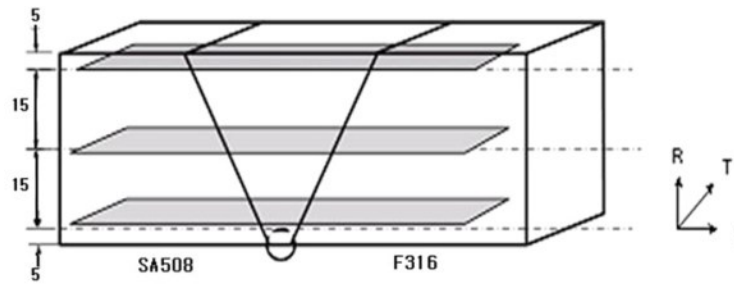
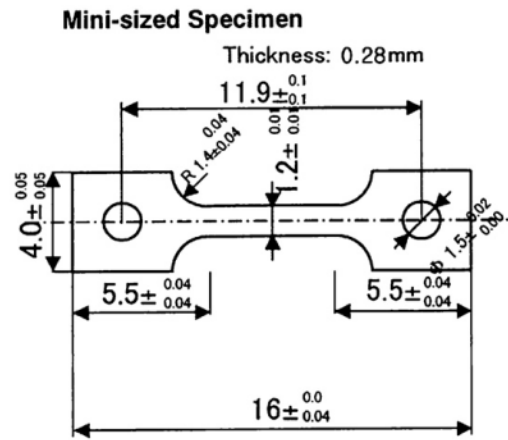


Figure 10: Sheet Sample Locations in Bulk [5]

Figure 9: Miniature Tensile Sample (mm) [5]

The authors in [5] welded two 40 mm plates together in order to analyze the effect of the welding process on the weld filler and base materials. The weld filler material is weaker near the top of the weld than at the bottom of the weld (See Table 6 and Figure 11). The effect of heat from the welding process can be seen in the stainless steel base metal. The authors observed a significant increase in strength near the fusion boundary. The size of the hardened zone is larger at the bottom of the weld. The sources of hardening are an increase in grain recrystallization and carbide precipitation [5], [16]. These effects are multiplied when multiple weld passes are used [5].

Table 6: Radial Variations in Strength [5]

Tensile properties in different parts of the dissimilar welds measured by mini-sized specimens

Location	Yield strength (Mpa)			Ultimate tensile strength (MPa)		
	SA508 Cl.3	Inconel 82/182 weld	F316	SA508 Cl.3	Inconel 82/182 weld	F316
Top	471.0 ± 10.4	355.7 ± 21.3	389.4 ± 12.9	597.3 ± 11.6	502.9 ± 35.0	616.2 ± 16.3
Middle	455.9 ± 18.4	396.6 ± 28.1	365.2 ± 13.0	582.0 ± 22.2	543.0 ± 31.9	582.4 ± 14.5
Bottom	456.7 ± 24.7	403.4 ± 21.7	361.5 ± 20.4	586.8 ± 30.5	544.8 ± 30.4	594.4 ± 12.0

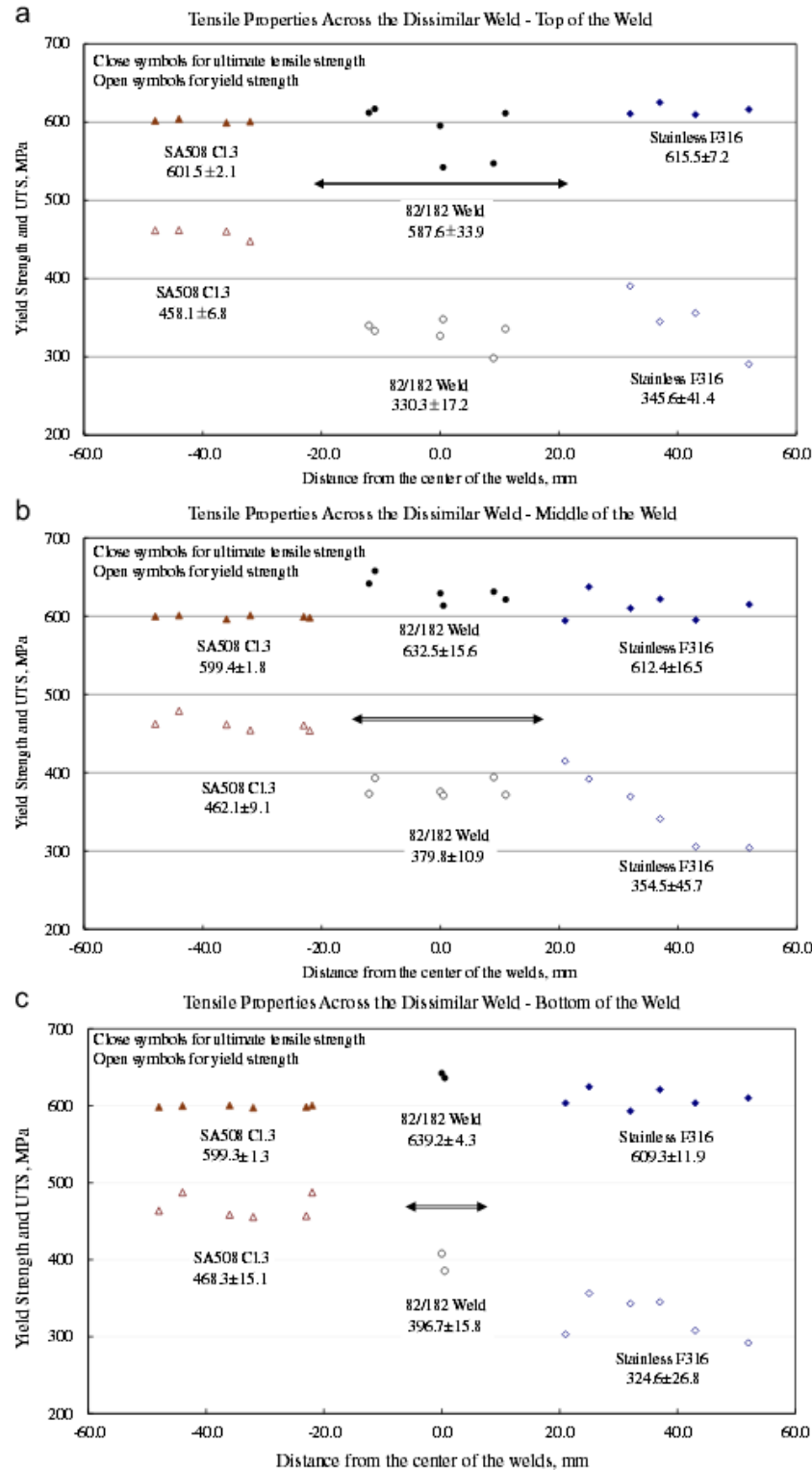


Figure 11: Yield Strength and Ultimate Tensile Strength of 9 mm diameter round bar specimens [8]

Digital Image Correlation

Digital Image Correlation (DIC) is used to map the strain at any point on the object being tested. It uses visual identifiers on the surface of the material to track the motion of the sample. The process is completed by software that translates the motion of the identifiers in each element, to the deformation vector field into the strain field. If a tensile sample consisting of a dissimilar metal weld is tested using DIC, the software can track the strain seen in each material. Using the loading data for the testing machine and the software, DIC is able to determine the stress-strain curves for the individual regions of the weld. This is a large advantage over other macro techniques because the global and local properties are being recorded. The other advantage over miniature tensile tests is that the behaviour of each region is recorded including the interaction with neighbouring regions (not just the testing the region itself).

In [17] the author used DIC to analyze an aluminum friction stir weld. A tensile test was used to analyze two types of tensile specimens, transverse and longitudinal. Figure 12 shows that the authors would extract the stress strain curves out of the whole gauge length of the longitudinal sample and only specific regions (labelled 1 and 2) for the transverse sample. The longitudinal sample consists of only the weld material. The transverse sample consisted of the weld material and the base materials. The authors were able to compare the data retrieved from both samples in Figure 13.

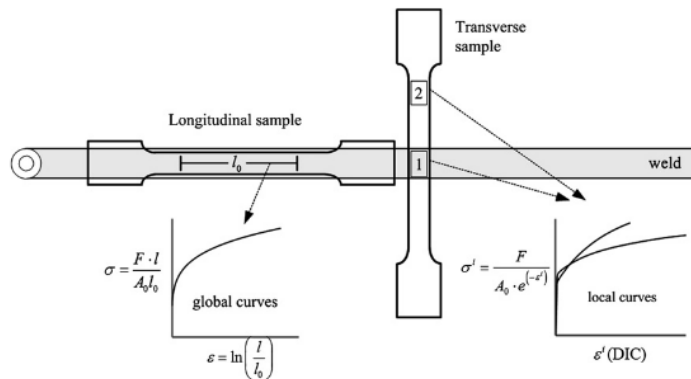


Figure 12: Longitudinal and Transverse Samples Scheme [17]

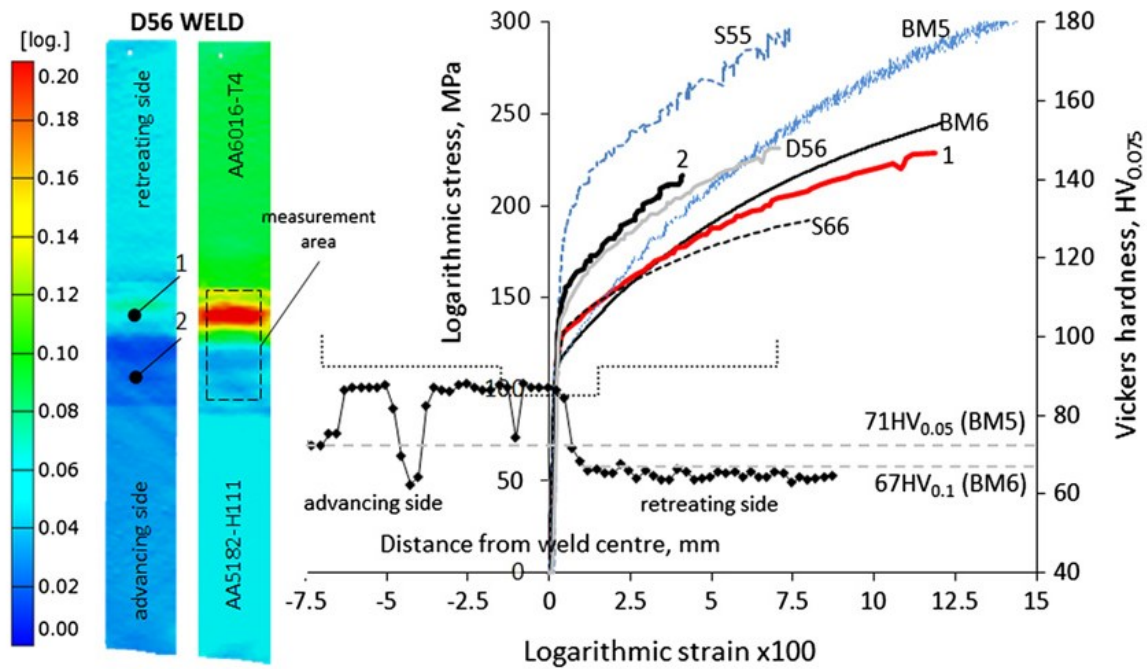


Figure 13: Digital Image Correlation, Vickers Hardness, Stress-Strain Curves for an Aluminum Friction Stir Weld [17]

In Figure 13, the global stress strain curve consisting of base metal 5 and base metal 6 is labelled D56. The stress strain curve of a sample containing just the base metal of aluminum alloy (labelled BM6) is compared against the stress strain curve extracted using DIC from the base material region of the large sample (labelled 1). The authors also completed a similar metal weld, welding BM6 to BM6 and plotted the properties as S66. The same comparison was made for the other base metal, comparing just the base metal (BM5) to the DIC extracted data (2) to the similar weld of BM5 to BM5 (S55). The authors concluded that the DIC tests were accurate in predicting local properties and deemed them to be easier than hardness profiles.

Standard DIC has been used to determine the strains in a weld and has also been used to calculate the strain at a crack tip in other materials. In [18] the authors used multiple cameras to create a 3-dimensional strain field. The method used was called the 3-D digital speckle correlation method and can be seen in Figure 14.

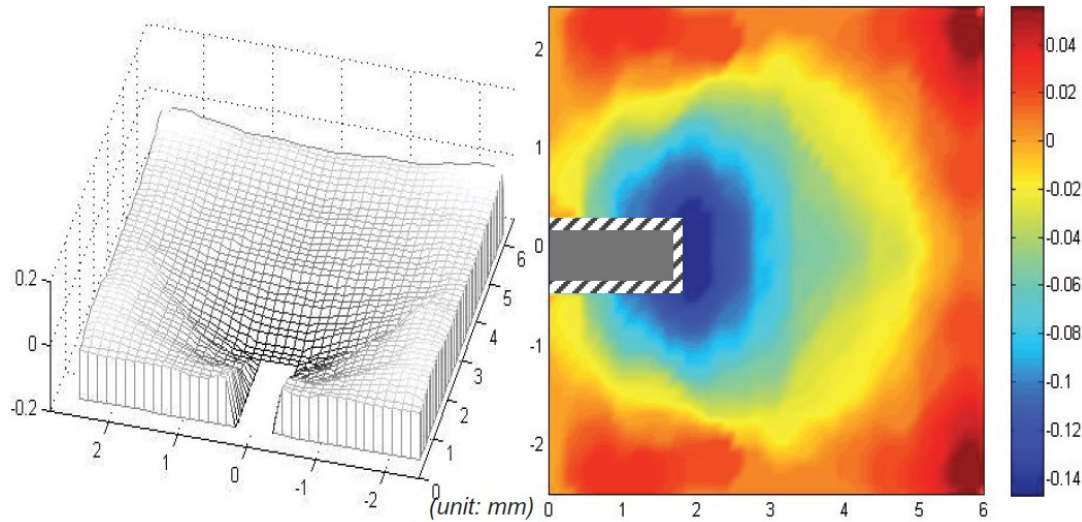


Figure 14: 3-D Digital Speckle (Image) Correlation of a Rubber Sample [18]

2.4 Fracture Mechanisms

2.4.1 General Fracture Mechanisms of Dissimilar Metal Welds

In a dissimilar metal weld failure can occur due to differences between the mechanical properties and coefficients of thermal expansion of the base materials. One author found that cyclic stresses occurred during high temperature service because of differences in the coefficients of thermal expansion. These differences caused thermal stress which internally leads to cracking along the fusion line and in the heat affected zone [19]. Other authors found similar creep failure at the interface due to differences in thermal expansion ([19], [20], [21], [22]).

During the welding process problems can occur due to the alloying of the base materials. An example of this is the formation of a brittle phase and dilution ([23], [24]). A dilution phase can be created as carbon migrates out of one region and into another. In a stainless to ferritic steel weld, carbon migrates into the stainless steel and out of the ferritic steel. This weakens the HAZ of the ferritic steel which can lead to failure in this zone ([20], [21], [25], [26], [27], [28], [29], [30], [31], [32], [33]).

Another cause of failure in dissimilar metal welds is residual stress. There is evidence, especially in power plants, that residual stress in the weld and in the heat affected zone can lead to cracking and can assist crack growth during service ([22], [19], [34], [35], [36], [37]). The authors in [38] found that the residual stress at the weld interface was 280 MPa and 300 MPa in the center of the weld. These stresses are close to the yield stress of the material and can reduce service life significantly.

Failure in dissimilar metal welds can also be due to preferential oxidation at the interface ([34], [39], [40]). Authors found that a less protective inner scale is developed in the heat affected zone which causes a higher oxidation rate than in the weld or base metals. The less protective scale can also result in a subscale zone where extensive void formation and internal oxidation occur. It also causes grain boundary cavitation in the adjacent alloy matrix [39]. The void formation and cavitation can exclusively cause in-service mechanical failures as concluded by the authors [39].

In [38] a review of 24 papers was completed to determine the failure mechanisms for ferritic to austenitic welds. The results have been tabulated below:

Table 7: Failure Mechanisms in Austenitic Welds

Mechanism	# of Instances
Differences in mechanical properties and coefficient of thermal expansions across the weld joint causing creep failure at interface	4 [20], [21], [22], [19]
General alloying problems of the base metals (brittle phase formation and dilution)	2 [23], [24]
Carbon migration from the ferritic steel into the stainless steel weakening the HAZ in the ferritic steel	11 [20], [21], [25], [26], [27], [28], [29], [30], [31], [32], [33]
Preferential oxidation at the interface	3 [39], [40], [34]
Residual stresses present in weld joints (cracking in weld and HAZ regions)	5 [22], [19], [34], [35], [36], [37]
Surface conditions & other factors	3 [41], [42], [43]

Another important conclusion that was drawn from this review was that in 17 of 24 cases the welds failed earlier than the expected service life [38].

2.4.2 Fracture Surface and Toughness

Visually the fracture surface can reveal the type of fracture: ductile, brittle, or combined, See Figure 15 and Figure 16. Another way to determine the type of fracture is from the impact energy required to fracture the material. Fracture toughness, impact energy, results have been tabulated in Table 8 for

various types of Inconel and stainless steel. The energy it takes to fracture a ductile material is much higher than the energy required to fracture a brittle material [8],[2].

In both [8] and [2] , the Charpy V-notch impact test was conducted using the Amsler Impact Tester. The samples were machined perpendicular to the weld direction with the notch in the center of the weld metal.

Table 8: Charpy V-Notch Results [2]

Material	Impact energy (J)	Type of fracture
Inconel 657 (base metal)	13	Fully brittle
Type 310 stainless steel (base metal)	217	Fully ductile
Inconel 82 weld metal	121	Fully ductile
Inconel A weld metal	100	Fully ductile
Inconel 617 weld metal	51	Ductile-brittle
310 SS weld metal	100	Fully ductile

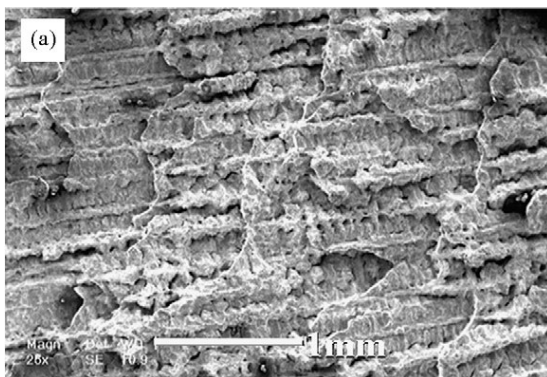


Figure 15: Ductile Fracture Surface of Inconel 657 [2]

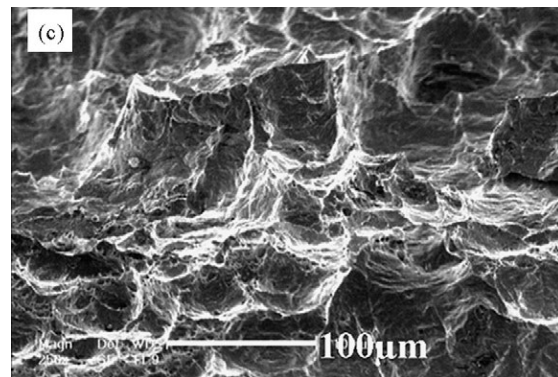


Figure 16: Ductile Fracture Surface of SS 310 Base Metal [2]

2.5 Cracking

A confidential report that was reviewed during this literature review raised concerns regarding the resistance of dissimilar metal welds between Inconel 600 and carbon steel to Pressure Water Stress Corrosion Cracking (PWSCC). Since this material is susceptible to cracking a review of cracking was completed. Specifically, this section will review crack initiation/propagation tests, tests on cracking in welded structures, and tests on multiple surface flaws with crack modelling.

2.5.1 Crack Propagation Tests

The authors in [45] completed a Creviced-Bent-Beam (CBB) test in an SEM with the sample subjected to water and sulfate at 288 °C for a time of 2243 hours. A CBB test, as shown in Figure 17, places a sample between two curved plates. Graphite fiber wool is placed between the plate and the sample to allow the environment access to the surface. In the CBB test, authors were able to observe crack growth due to stress corrosion cracking in the fusion boundary layer of Inconel 182 and Low Alloy Steel A533B [44]. Another author completed similar CBB testing and was able to observe the formation of many stress corrosion cracks (SCC) in stainless steel [45].

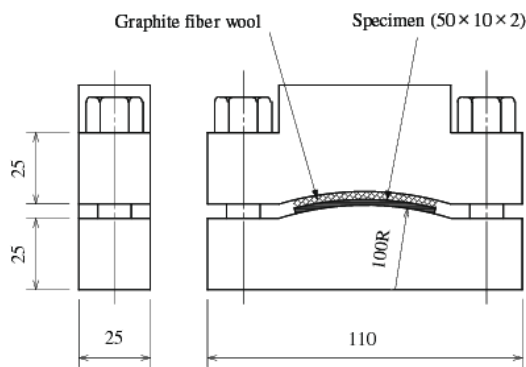


Figure 17: Creviced -Bent - Beam (CBB) Test Set-Up [45]

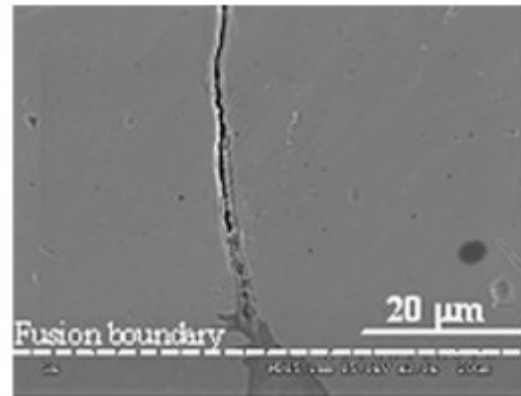


Figure 18: SCC type crack in fusion boundary layer of Inconel 182- Low Alloy Steel A533B [44]

Environmentally-assisted cracking in Inconel 182 with SA 508 Low alloy steel was completed using both 25 mm and 12.5 mm thick compact tension samples [46]. The authors found that the SCC cracking is usually confined to the Alloy 182 weld metal and the low alloy steel interface represents a barrier for crack growth. Although the interface acts as a barrier the authors did note that in some cases the crack may propagate through the fusion line [46].

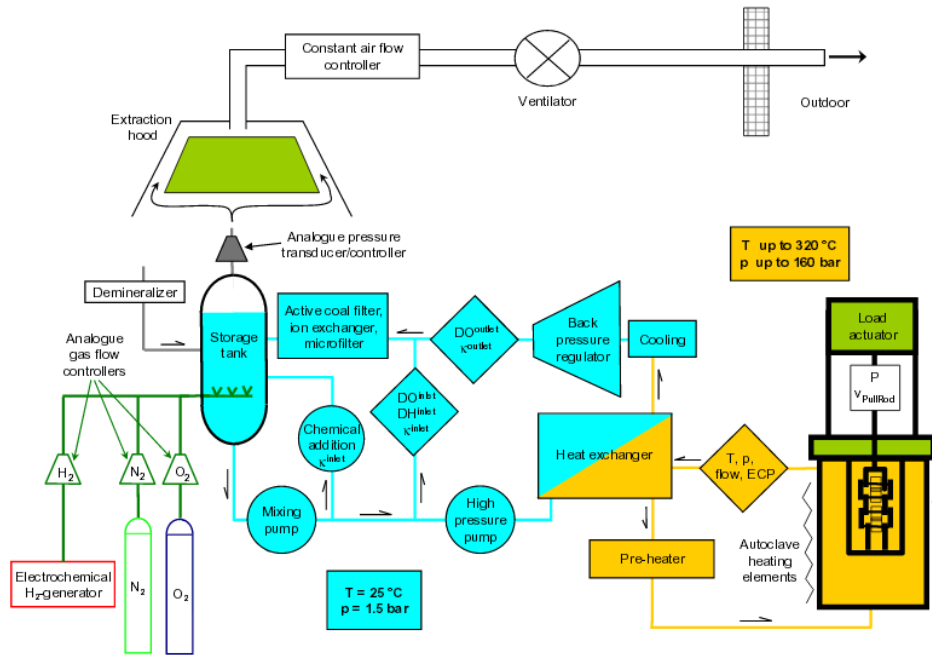


Figure 19: Refreshing water loop with autoclave and integrated electro-mechanical tensile machine [46]

There are several testing methods used to propagate an artificial crack. One type of testing is the 4 point bend test, where the crack is inserted on or near the edge of the large span. This test method was completed on a plate under fatigue by [47] in order to observe multiple surface flaw growth and coalescence. 4 point bend testing was completed on a pipe in [9] and [10] to observe circumferential crack growth in multiple flaws.

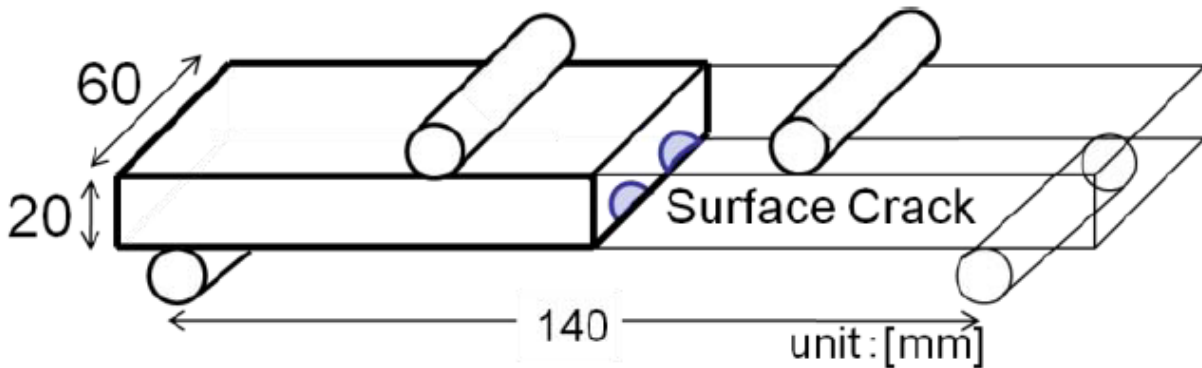


Figure 20: 4-Point Bend Set-Up with two surface cracks [47]

Another type of testing is tensile static loading. Cracks are placed on the surface of the sample in the middle of the gauge length and width. This method was used to analyze crack penetration through the thickness of the sample and crack growth in the width direction in [11], [12], [13], [14], [15].

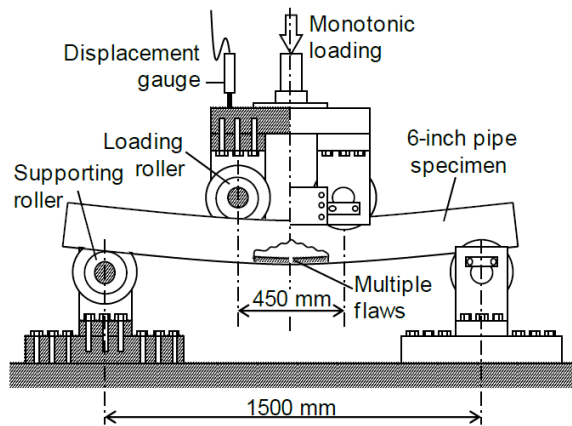


Figure 21: 4-Point Bend Test Set-Up on pipe with circumferential cracks [9]

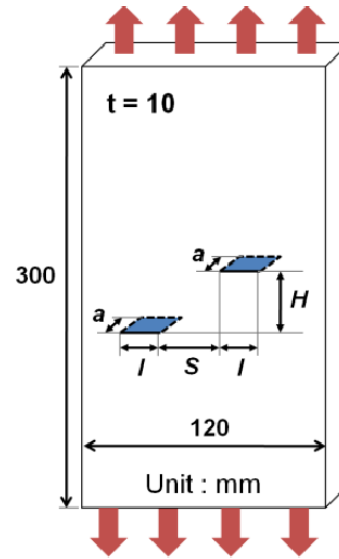


Figure 22: Tensile Loading with multiple surface flaws [15]

2.5.2 Evidence of Cracking and Crack Interaction in Welded Structures

One general conclusion that can be made is that the samples were found to fail in the weaker parent material during tensile testing [8], [2].

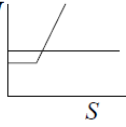
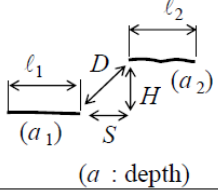
During the failure analysis of a 2.25 Cr-1Mo ferritic steel and AISI type 316 stainless steel sample the crack growth path was recorded. Crack nucleation occurred at the root of the weld, with the initial propagation along the fusion line (ferritic & weld). Then the propagation moved into HAZ of ferritic steel in the middle of the sample, then reaching the fusion line again, and finally following the fusion line in the crown region of the weld [38], [22], [19]. The failure mechanisms in this case were deemed to be carbon migration, differences in coefficient of thermal expansion, and residual stresses from welding.

2.5.3 Multiple Surface Flaws

In real life applications, materials contain more than one flaw. Metallurgists already have a good understanding of how one crack propagates and how a crack with a certain size affects the life of a material. Multiple surface flaws have been studied in detail recently to try and understand how multiple flaws interact and how they affect the life of a material. Most of the focus is surrounding the flaw alignment rules. These are the rules that determine if two flaws are to be considered as “aligned” or “not aligned”. Flaws that are considered not aligned are treated like they act independently of one another. Flaws that are aligned are often treated as one combined flaw with a larger net-section area

[14]. Hasegawa et al. [14] summarized the flaw alignment rules for fitness-for-service codes ([48], [49], [50], [51], [52], [53], [54], [55], [56], [57]) as follows:

Table 9: Alignment Rules for Multiple Flaws [53]

ASME	$H \leq 12.5 \text{ mm}$	
JSME	NDI : $H \leq 12.5 \text{ mm}$ Growth: $H \leq 10 \text{ mm}$, if $S \leq 5 \text{ mm}$ $H < 2S$, if $S > 5 \text{ mm}$ Fracture : $H \leq 12.5 \text{ mm}$	
WES	$H \leq 0.5 \min(\ell_1, \ell_2)$ for through-wall flaws $H \leq \min(a_1, a_2)$ for surface flaws	
API 579	$H \leq 0.5(\ell_1 + \ell_2)$ $H \leq 0.5(\ell_1 + \ell_2)$ & $S \leq 0.5(\ell_1 + \ell_2)$	
FITNET	$H \leq \min(\ell_1, \ell_2)$	
BS 7910	$D \leq 0.5(\ell_1 + \ell_2)$	
FKM	$D \leq 0.5(\ell_1 + \ell_2)$	
A16	$D \leq 0.5(\ell_1 + \ell_2)$	
GB/T 19624	$D \leq \min(\ell_1, \ell_2)$ for through-wall flaws $D \leq \min(a_1, a_2)$ for surface flaws	
RSE-M	 Interaction rectangles	

$$P_{c,nonalign} = \sigma_f (W - l_1) t \quad \text{for Flaw \#1} \quad (1.a)$$

$$= \sigma_f (W - l_2) t \quad \text{for Flaw \#2} \quad (1.b)$$

$$P_{c,align} = \sigma_f (W - l_1 - l_2) t \quad (2)$$

Equation 1: Equations for Plastic Collapse Load for Aligned and Not Aligned Flaws

Where flaw 1 has a length, l_1 and flaw 2 has a length, l_2 ($l_1 > l_2$). σ_f is flow stress. W is width and t is the wall thickness of the specimen [14]

This table shows that there is no consensus rule to determine if multiple flaws are aligned or not. That being said there is a general consensus that some ratio of flaw size and distance between flaws relates to alignment [14]. The plastic collapse loads were calculated for aligned and not aligned flaws and compared against the codes. It was determined that the codes were conservative and that if one flaw is much larger than the other flaw then, that set of flaws is not sensitive to the alignment rules [14].

An experimental study was done on non-aligned flaws in a plate and the authors proposed a new equation for estimating maximum plastic collapse load in tension [58]:

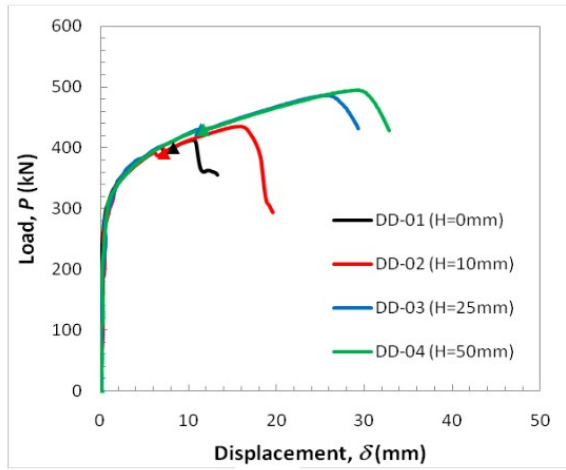
$$P_{\max} = F_c + (F_s - F_c) \times \frac{H}{\ell} \quad \text{for} \quad \frac{H}{\ell} \leq 1$$

$$P_{\max} = F_s \quad \text{for} \quad \frac{H}{\ell} \geq 1$$

Equation 2: Plastic Collapse Load for Aligned Flaws

Where F_s is equal to $P_{c,\text{nonalign}}$ and F_c is equal to $P_{c,\text{align}}$ from the equation in Equation 1.

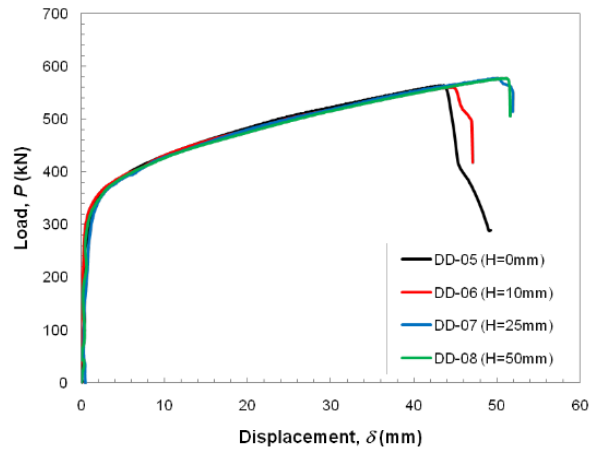
In addition to being created in [58] the model was tested and found to be valid in [11], [12], and [13]. In addition to following the new model, [11] classified two distinct load displacement relations.



Type A
Load displacement curve of DD-1 to DD-4



Flawed surface
Back surface
Experimental result of DD-3



Type B
Load displacement curve of DD-5 to DD-8



Flawed surface
Back surface
Experimental result of DD-7

Figure 23: Load Displacement Curves for Type A Samples where DD-1 through DD-4 had crack depth 8 mm (out of 10 mm thickness)

Figure 24: Load Displacement Curves for Type B Samples where (out of 10 mm thickness) DD-5 through DD-8 had crack depth of 4 mm.

Type A maximum load occurred after the crack penetrated through thickness. Type B through thickness penetration occurred at maximum load. The authors in [13] saw the same two relations (Figure 23 and Figure 24).

In [12], the authors stated that l_1 and l_2 can both be replaced by l_{max} , the longer of the two crack lengths. They also noted that the interactions between two cracks are not negligible when the distance along the vertical direction, H , is less than the crack length of the longer crack ($H < l_{max}$). The authors in [13] agreed with both of these conclusions regarding l_{max} .

Unlike [11],[12] and [13] which use a formula to confirm results, the authors in [15] uses results to determine contributing factors. The authors in [15] determine that the ratio $\frac{h}{2a_1+2a_2}$ can be used to determine the effect of two off-set cracks where h is half the vertical distance and a is half the crack lengths.

The authors defined type 1 (see Figure 25) as cracks that merge quickly due to the overlapping of their plastic zones. Type II cracking occurs when the two tips pass each other, the crack twist towards one another. Type III cracks are defined by two small changes in direction [15].

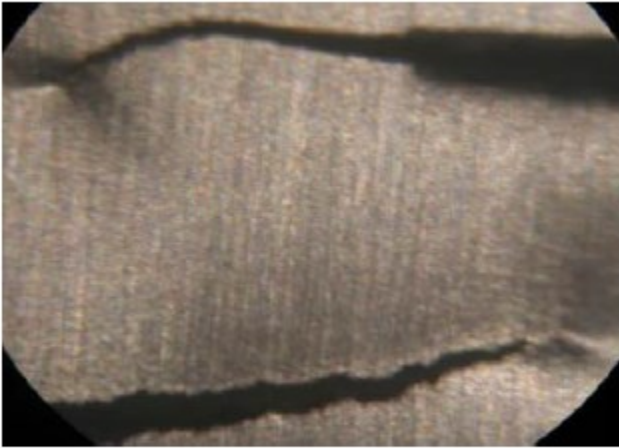
When two cracks are collinear, the smaller crack has an effect on the larger crack [15]. This effect exists until the ratio between the distance between the cracks, s , and the length of the smaller crack with length $2a_2$ is above 6 ($\frac{s}{a_2} > 6$).



(a) Type 1



(b) Type II



(c) Type III

$$\text{Type 1: } \frac{h}{2a_1+2a_2} < 0.143$$

$$\text{Type 2: } 0.143 < \frac{h}{2a_1+2a_2} < 0.21$$

$$\text{Type 3: } 0.21 < \frac{h}{2a_1+2a_2}$$

Figure 25: Three Types of Crack Propagation. Type 1: Vertical distance less than plastic zone; Type 2: Vertical distance larger than plastic zone; Type 3: Vertical Distance even larger

2.6 Residual Stress

Residual stress was found to have little to no impact on crack stability analysis for materials with toughness levels similar to that of Inconel 182 welds at high temperatures and therefore it can be neglected [59],[60]. Residual stress was found to have a different effect on ferritic/austenitic metal welds. It was found to assist cracks in propagating.

X-Ray diffraction was used to characterize the residual stress in a weld with and without weld buttering [38]. The authors found that adding a small amount of a transitional material (buttering) to the weld

surface of the ferritic steel prior to welding can reduce the residual stress at the interface. Once the buttering material is applied, the combined material can undergo stress relief heat treatment before the welding process. This will reduce the residual stresses. Figure 26 and Figure 27 show the residual stress for the buttered and un-buttered samples. The maximum residual stress is the same in both cases (300 MPa) but the residual stresses are reduced in the buttered sample at the vulnerable interface (160 MPa vs. 280 MPa) [38].

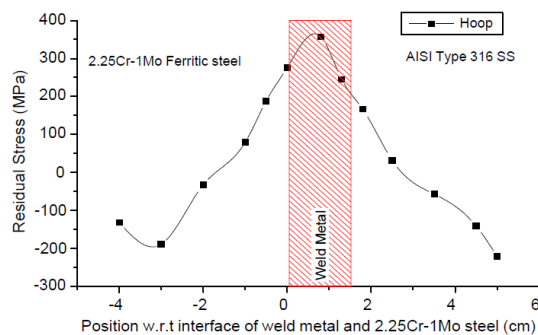


Figure 26: Residual Stress (Hoop) vs. Position Across the Weld [38]

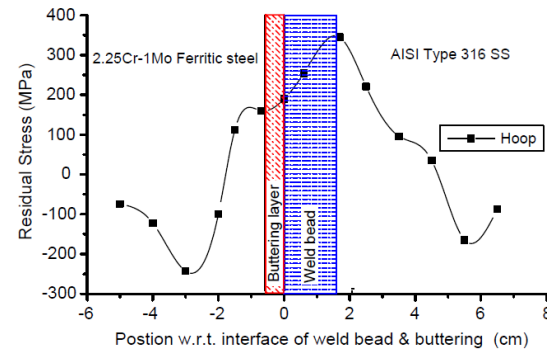


Figure 27: Residual Stress (Hoops) vs. Distance Across the Weld for a Buttered Weld Sample [38]

2.7 Modelling Mechanical Properties of Dissimilar Metal Welds

2.7.1 Finite Element Analysis

Finite Element Analysis (FEA) uses the specific material properties and geometry input by the user to model a situation. FEA can be used to output stresses, strains, failure locations, crack path propagation, and many other properties. The software uses average properties over an element to display the results. As elements are created a grid is formed and this grid is called mesh. Although FEA is an estimation or prediction, it has found to be very accurate when the input information is correct.

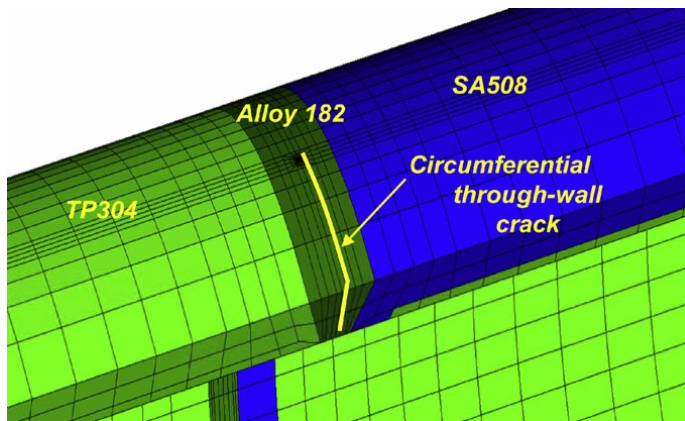


Figure 28: FEA Model of Dissimilar Metal Weld [59]

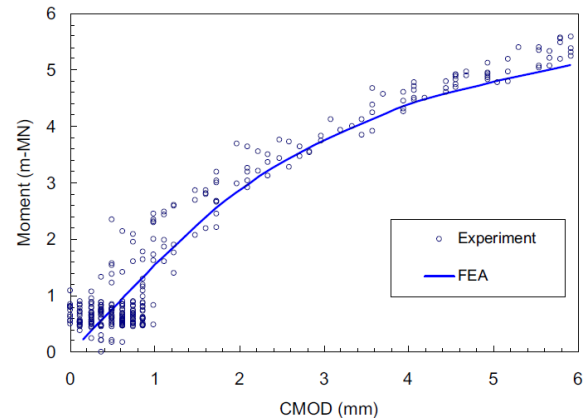


Figure 29: FEA vs. Experimental Data of Crack-Mouth-Opening Displacement (CMOD) at the center of the through-wall crack. Where the moment is the external bending moment applied to the pipe[59]

The authors in [59] used FEA to model a weld between pipes made of TP304 and SA508 steel using Inconel 182 weld filler. In

Figure 28, FEA is used to determine the stress that causes failure and the deformation field around the crack. The mesh is coarse outside the weld and fine inside the weld. The mesh is extremely fine at the crack tip (i.e. the end of the yellow line). The smaller the element size of the mesh, the more information can be collected. The more information input the more precise the results will be.

A comparison between experimental and FEA data can be seen in Figure 29. This figure shows that not only can FEA be used to calculate standard relationships like stress and strain, but unique ones like crack-opening-displacement (CMOD) compared to the external bending moment applied to the pipe.

Many authors have used finite element models on crack growth and multiple flaws. In order to model flaws a damage model must be incorporated into the analysis. Tensile static loading on multiple flaws was compared against FEM using a damage model in [11], [12]. A fatigue crack path prediction using a damage model was used in [61], [62] and [63]. Fatigue growth and coalescence was modelled in [64], [65] and [47].

3. Research Proposal

A company is having issues with stress-corrosion cracking of Inconel dissimilar metals welds. The purpose of this work is to better understand the mechanical properties of the weld and how failure takes place in the materials. Subsequent work will look at the effect of the environment and temperature on the pipe, but this is not in the scope of this thesis.

In general, many authors and papers were interested in the characterization of failure properties and failure mechanisms in dissimilar metal welds. The literature review revealed that although many authors have looked at similar welds, no one has analyzed this specific weld in detail. The welded pipe made up of Inconel 600, Inconel 182 weld filler, and grade 106-B Carbon Steel was donated to us by a company. Many of the authors had to weld their materials together based on a model or specifications of their real life applications. Since our materials were already welded together, they should mirror exactly the weld used in their nuclear reactors. Obtaining the material properties of this weld will allow other authors to use predictive modelling to more accurately model this welded pipe.

In addition to the literature review, the initial exploratory research conducted includes the analysis of the weld region at various length-scales using optical microscopy and Vickers hardness testing. It was found that large grains are in the weld region and smaller grains are in the Inconel and carbon steel base metals. Also, the heat affected zone of Inconel has larger grains than the base material and the heat affected zone of carbon has smaller grains than the rest of the carbon region. Micro-hardness profiles showed variations across the weld and through the weld thickness.

The exploratory research revealed variations in material properties through the weld thickness and emphasizes the need for obtaining a complete map of the mechanical properties in the weld region for predictive models to be accurate.

To obtain a complete map of mechanical properties, the following research will be undertaken. Deformation and fracture properties will be obtained using miniature tensile samples from 9 different locations. The Inconel, Weld, and Carbon Steel will be analyzed at the inner, middle, and outer diameters of the pipe. These 9 areas are shown in Figure 30. These samples will be tested and will provide the local material properties of these regions. Next, using Digital Image Correlation (DIC) on larger tensile samples, obtain the material properties locally and over the entire weld. DIC uses a computer program to map deformations on the sample surface and by selecting a region of interest, the

program can be used to obtain localized deformation. A Finite Element Model (FEM) will be built using the material properties discovered in the first part of the study. The FEM will be created using the ABAQUS software. The purpose of the analysis is to confirm the experimental results and predict material behaviour under load.

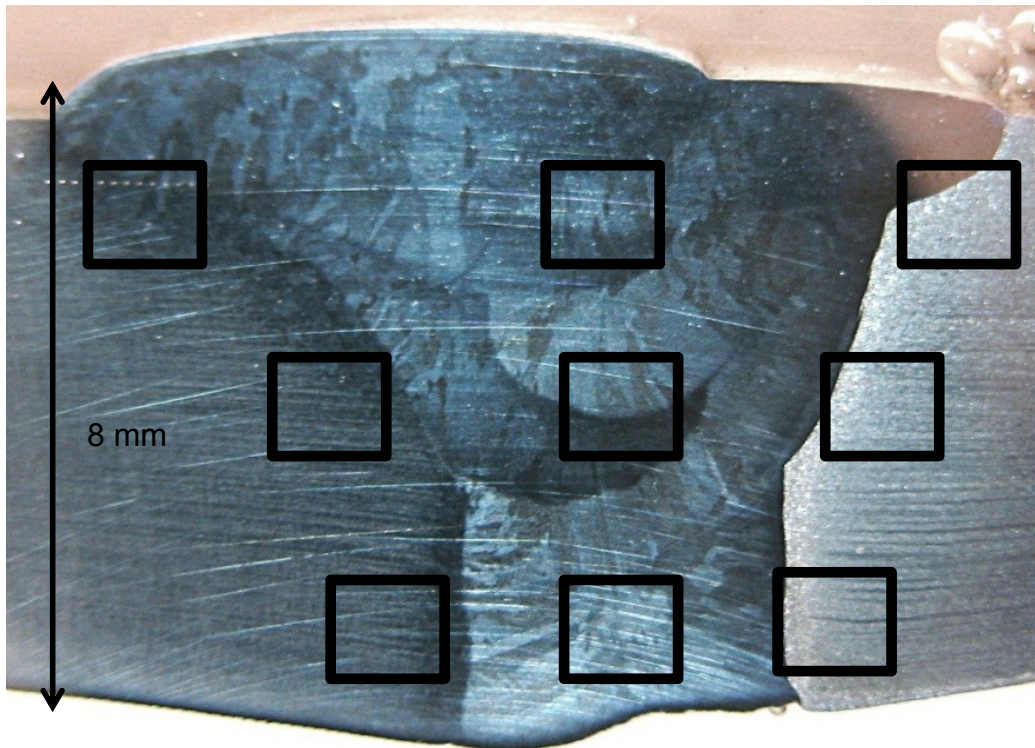


Figure 30: Left to Right - Inconel 600, Inconel 82 Weld Filler, Carbon Steel Grade 106-B

Once the basic properties and behaviours are fully understood the next step is to analyze the fracture mechanisms in the weld. This research will intend to better understand how cracks propagate through the weld. Many of the papers look at crack interactions between multiple surface flaws. No information was found on crack interactions in a welded material. The next step would be to look at crack interactions in a welded material. This analysis would include the interactions between the cracks and how the interactions are affected by the welded material.

The ultimate goals are to obtain detailed material properties of the weld, use these properties in a finite element model, and gain a better understanding of the fracture mechanisms of the weld.

4. Experimental Procedure

4.1 Introduction

One of the main goals of this thesis is to determine the detailed material properties of the Inconel 600 - Inconel 182 – Carbon Steel welded pipe. Although some information is available on this weld, there isn't enough information or consistency to use previously recorded material properties. As such, the testing was chosen to first obtain the global properties before narrowing down to local properties. Once the material properties were better understood the final tests were used for looking at failure mechanisms by inserting a crack into vulnerable regions of the weld. Table 10 lists the experiments that were chosen.

Table 10: Experimental Test types and their purpose

Test Order	Experimental Test	Purpose	# of Samples
1	Microscopy	Observe the Microstructure	1
2	Hardness	Local properties	1
3	Large Tensile	Global	9
4	Large Tensile w/ DIC	Local/Global	9
5	Miniature Tensile	Local	27
6	EDS	Local	1
7	Large Tensile w/ crack and DIC	Local/Global	2
8	4 Point Bending	Global	2
9	4 point Bending w/ Crack	Local	1

* Note microscopy, hardness, and EDS samples were tested many times

Table 11 lists the 3 locations in the pipe that were tested: Inner, Middle, Outer diameter of the pipe versus the material regions of the pipe: Carbon Steel, Weld, Inconel. The content of the table indicates which experimental test was completed on the regions listed.

Each thesis section will detail why each test was chosen, what information is being extracted, how the sample were prepared, and a detailed procedure on how to the experiments were carried out.

Table 11: Location on Pipe vs. Weld Region vs. Experimental Test Type

Location in Pipe	Full Test	Carbon Steel	Weld	Inconel
Inner Diameter	Large, Large w/ DIC	Mini, Mini w/ DIC, Large w/ DIC	Mini, Mini w/ DIC, Large w/ DIC	Mini, Mini w/ DIC, Large w/ DIC
Middle of Pipe	Large, Large w/ DIC	Mini, Mini w/ DIC, Large w/ DIC	Mini, Mini w/ DIC, Large w/ DIC	Mini, Mini w/ DIC, Large w/ DIC
Outer Diameter	Large, Large w/ DIC	Mini, Mini w/ DIC, Large w/ DIC	Mini, Mini w/ DIC, Large w/ DIC	Mini, Mini w/ DIC, Large w/ DIC
Full Thickness	EDS, Microscopy, Hardness, Bend			

4.2 ASTM Standards

ASTM standards were followed wherever possible. The most notable standards are as follows:

Table 12: ASTM Standards

ASTM #	ASTM Standard Name
ASTM E3-01	Standard Guide for Preparation of Metallographic Specimens
E3-01-7	Cutting
E3-01-7.1.1	Sawing- Can be used on all materials with hardness below 350HV
E3-01-9	Mounting of Specimens
E3-01-9.4.3	Compression Mounting
E3-01-11.	Grinding and Polishing
E3-01-11.2.5	Clean Specimen thoroughly after grinding. Ultrasonic bath is recommended
E3-01-11.3.2	Rough polishing is often sufficient for routine evaluations like microindentation hardness and grain size. Note: It was found that rough polishing hardened that surface of the specimen.
E3-01-11.3.3	Ultrasonic cleaning is required between polishing steps
E3-01-11.5	Move the specimen in a circular path around the wheel against the direction of the rotation of the wheel.
E384-10	Standard Test Method for Knoop and Vickers Hardness of Materials
E384-10-8.11	Spacing of Indentations- 2.5d from all edges and previous indentations where d is the Vickers Diagonal.

4.3 Microstructure Characterization

Microscopy was used to identify the microstructure of the materials. An inspection of the material was required in each base material and in the heat affected regions around the weld. In addition the inspection was required to identify if there were any changes in the base materials from the inner to the outer edge of the pipe and to analyze the entire weld base material as it was created using 7 weld passes and the weld could have variations throughout.

4.3.1 Experimental and Sample Design

The experimental set-up uses a Nikon Optiphot-100 microscope at differing magnifications to inspect a through-thickness sample that had little to no surface defects. The microscope was chosen as it was available and has a sufficient magnification to observe individual grains in each material. The samples would have to be polished to a mirror finish in order to remove any surface defects.

Once microscopy was completed on the sample with the mirror finish, the sample was etched to further reveal the microstructure.

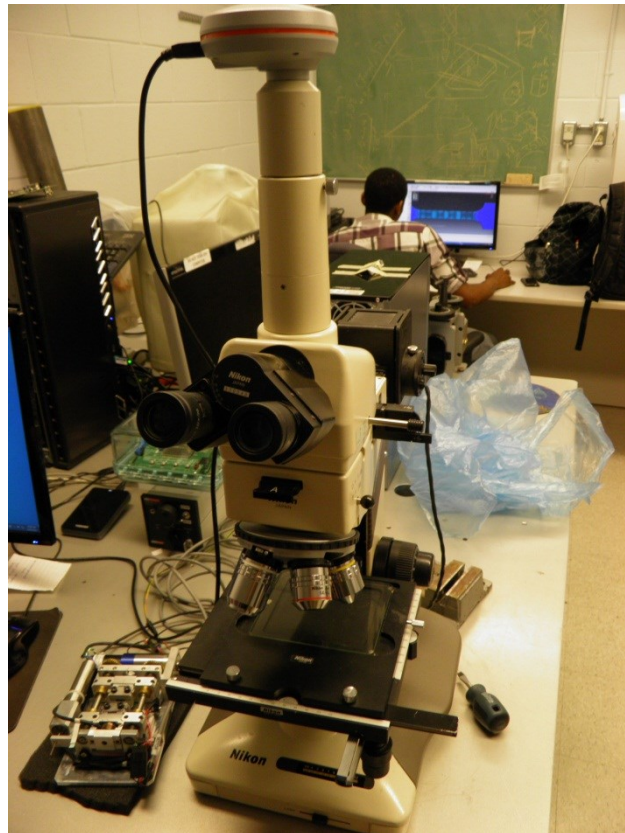


Figure 31: Nikon Optiphot - 100 Microscope Set-Up

4.3.2 Sample Preparation

The sample that was chosen was full thickness, taken longitudinally out of the pipe so that it contained all base materials. The circumferential variation was deemed to be minimal with the exception of the start/stop zone of the weld. As such the sample was not taken from the start/stop zone.

The sample was then mounted into a thermoplastic resin. This was done to make it easier to polish the sample. The sharp edges along with the long and thin dimensions of the sample made holding onto the sample difficult. It also made it impossible to apply an equal amount of pressure for creating a flat surface. By mounting the sample in resin an even amount of pressure could be applied during polishing and a flat surface could be obtained.

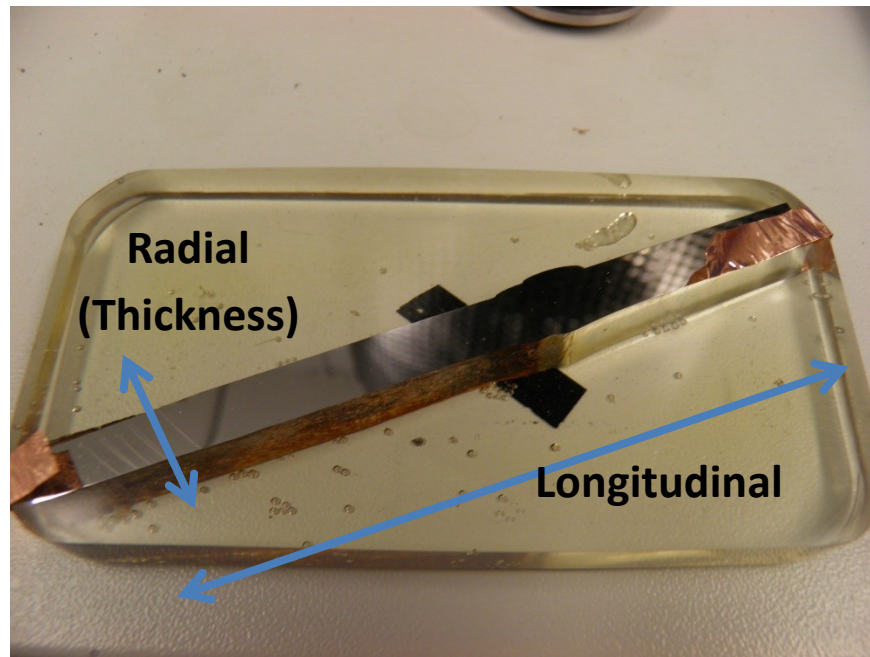


Figure 32: Microscopy sample mounted in thermoplastic mold

A dissimilar metal weld consisting of Inconel 617, 310 Stainless Steel and a variation of filler materials was prepared using grinding, polishing and etching. Grinding was done in stages using SiC paper with surface roughness (grit) of 120, 240, 320, 600, 800 and 1200. The final polishing was done using 5 μm alumina powders and the sample was etched using Marbel Solution [8]. The recommended etchant for nickel-based alloys was confirmed by other sources as the Marbel Solution/Reagent (10 g CuSO_4 + 50 cc of HCL + 50 cc of H_2O) [8], [2], [66], [67]. This polishing procedure was used as a guideline for preparing samples, and the process was subsequently optimized for the specific material.

The sample was polished using a Metaserv 2000 polishing machine. The sample was rotated around the plate of the machine as the machine rotated the plate in the opposite direction. In order to create a defect-free surface a meticulous polishing procedure was implemented. The polishing procedure started with rough grit silicon paper, then fine grit silicon paper, finishing with suspended particle polishing and using an ultrasonic bath between steps (see Appendix B for details).

Table 13: Polishing Procedure for Microscopy

Step	Grit	Time	Lubricant
1	500 Silicon Carbide Paper	Until flat	Water
2	1200 Silicon Carbide Paper	5 min	Water
3	4000 Silicon Carbide Paper	5 min	Water
4	3 μm Suspended diamond particles	3 min	Minimal amount of water
5	0.04 μm OPS (Oxide Polishing Suspension)	1.5 min	Adding OPS, rinse with water

Variations from Standard Polishing Procedure

This sample was so large that it could not be move around the plate properly. The sample was held in place and rotated in place. This caused the polishing times to be much longer (5 min) than typical (90 sec) to achieve the same result.

4.3.3 Experimental Procedure

The detailed procedure for optical microscopy can be found in Appendix C. Once the image was captured from the microscope, the grain size was determined using the line method. The line method uses the length of the line divided by the number of grain intersections to get the average grain size in the direction of the line.

4.4 Hardness

Hardness testing is aimed at revealing changes in material properties across the sample. The weld consists of three base materials and 2 heat affected zones. In order to determine the material properties prior to welding, the base materials should be tested away from the weld. The base materials were tested radially, from the inner to the outer edge of the pipe to reveal differences in the base material itself. The key test is to reveal property changes across the weld. Hardness indents were taken starting

in one base material, moving longitudinally into the weld and the other base material crossing the heat affect zones. These indents remained an equal distance from the outer edge of the pipe during the test for consistency. The test was repeated at different distances from the outer edge to reveal radial differences. These tests revealed the differences in hardness in the radial and longitudinal directions, not along the circumference differences which were predicted to be minimal.

4.4.1 Experimental and Sample Design

A Vickers's Hardness testing machine was used for determining the hardness. The machine is a Duramin 1 made by Struers. The machine can use different loads to indent the sample. Small indents are ideal as more indentations can be completed. If the indents are too small the polished finish can have an effect on hardness measurements. As such, a load of 500 g applied for 10 seconds was chosen.

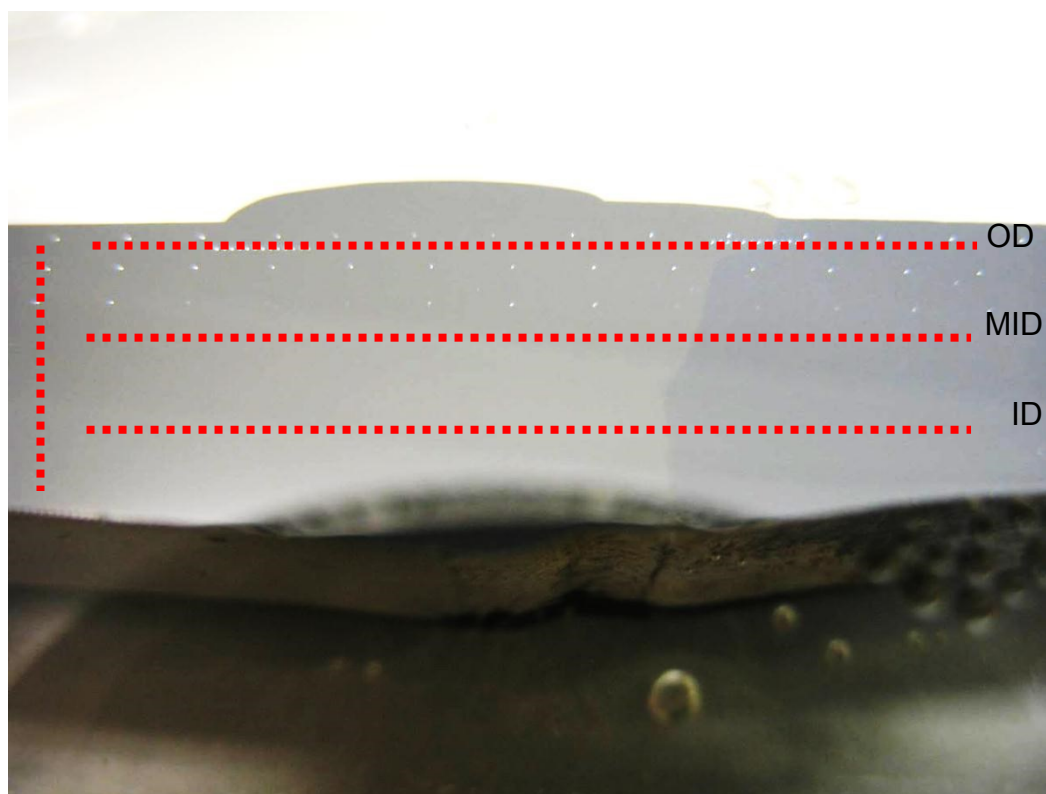


Figure 33: Visual Inspection Sample showing locations where the indents will take place (Note: Small silver dots on image are actual indents that were taken)

At any load, indent spacing must be at least $2.5d$ to avoid an overlap in plastic deformation zones, where d is the diagonal of the indent. After creating test indents, 0.250 mm was chosen for the spacing between the centers of the indents.

4.4.2 Sample Preparation

The sample is the same used for optical microscopy. It was already polished using the procedure listed in that section. The sample was furthered polished using the vibratory polisher Vibromet 2.



Figure 34: Vibratory Polisher (with blue polishing suspension and two samples)



Figure 35: Vibratory Polisher From Above (samples are under brass cylinders which are used for weight)

The vibratory polishing procedure appears at the end of Appendix B.

4.4.3 Testing Procedure

The sample was placed on the hardness machine's slide and the slide was moved to the end of its range. This way the slide can be moved its full range, allowing for indents across the largest range. The edge of the sample was used for aligning the sample horizontally. Since the spacing was constant, only the indent number and hardness value were recorded.

4.5 Scanning Electron Microscope (SEM) with Electron Dispersive Spectroscopy (EDS)

SEM with EDS was chosen to analyze the composition of the materials. The base materials would need to be analyzed to determine their composition before the weld. Next the composition map would need to be determined to identify any changes occurring across the weld.

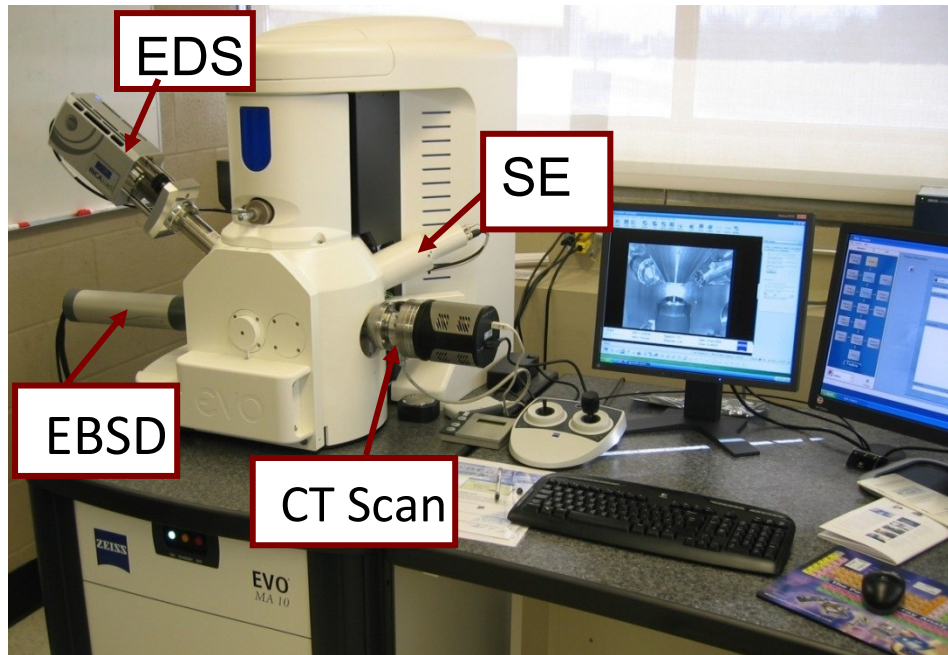


Figure 36: Scanning Electron Microscope (SEM) with Multiple Imaging Options

4.5.1 Experimental and Sample Design

The sample used for microscopy was re-used for this experiment. The SEM is made by Zeiss and the model is EVO MA 10. The EDS is a model INCA x-ACT made by Oxford Instruments. Testing was conducted by Mohammed Yandouzi (Ph.D., Research Associate at the University of Ottawa using 20 KeV.

4.5.2 Sample Preparation

Table 14 shows the polishing steps that were completed beyond the steps that were already completed on the microscopy sample.

Table 14: Position Procedure for SEM and EDS

Step	Grit	Time	Lubricant
1	3 μm Suspended diamond particles	60 sec	Minimal amount of water
2	0.04 μm OPS	60 sec	Adding OPS, rinse with water
3	0.04 μm OPS Vibratory Polishing	5 min	None
4	Clean with Ethanol		



Figure 37: EDS sample, note copper tape glued to the sample to increase conduction

4.6 Large Tensile Testing

4.6.1 Experimental and Sample Design

The large tensile test was chosen to understand the global properties of the weld. The tensile direction of the sample corresponded to the longitudinal orientation of the pipe, Figure 38. This direction was chosen because it is the only direction with enough material to create a large flat specimen. Sample dimensions were chosen based on ASTM standards. The samples were 12.5 mm in gauge width, 1 mm thick, and 50 mm in gauge length. The overall length of the sample was 150 mm and the overall width was 25 mm (See Figure 38).

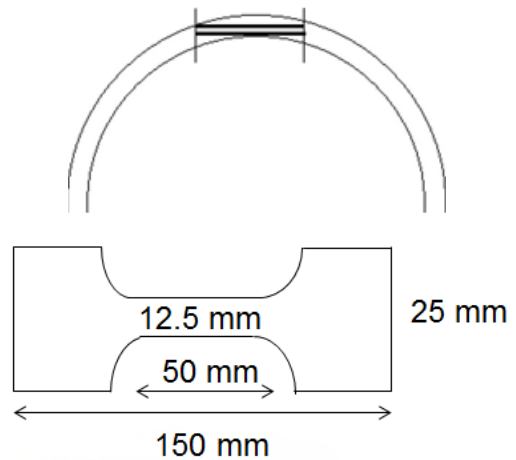


Figure 38: Large Tensile Sample Location and Dimensions



Figure 39: Large Scale Tensile Test Set-Up viewed from Polished Side

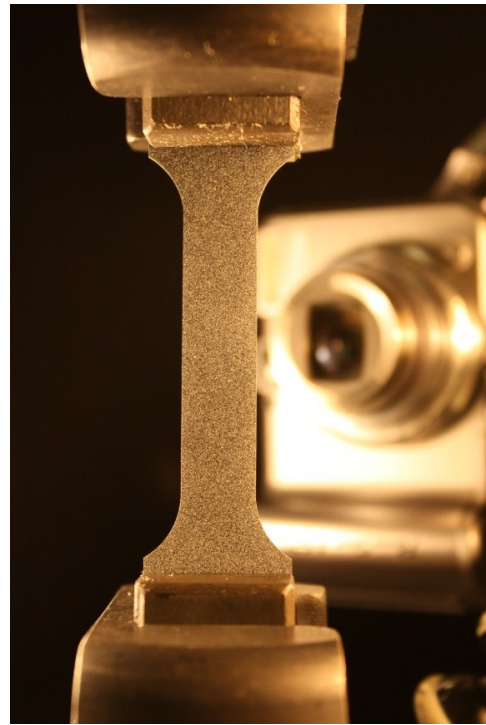


Figure 40: Large Scale Test Set-Up Viewed from Speckle Pattern Side

4.6.2 Experimental Set-Up

The Instron Tensile machine was ran at an elongation rate of 1 mm/min, translating into a strain rate of 0.00033 s^{-1} . Load, displacement and time we recorded. The stress vs. strain and true stress vs. true strain curves were obtained using the equations below with the exact dimensions of each sample.

Equation 3: Engineering Stress

$$\sigma_{eng} = \frac{P}{A_0}$$

Equation 4: Engineering Strain

$$\epsilon_{eng} = \frac{l_f - l_i}{l_i}$$

Where P is load, A_0 is initial cross-section area, l_f is final length in the strained direction, and l_i is the initial length in the strained direction.

Equation 5: True Stress

$$\sigma_{true} = \frac{P}{A_i}$$

Equation 6: True Strain

$$\epsilon_{true} = \ln\left(\frac{l_f}{l_i}\right)$$

Where P is load, A_i is the instantaneous cross-section area at the time P is being applied, l_f is final length in the strained direction, and l_i is the initial length in the strained direction.

During a test it was very difficult to observe/record the change in cross-sectional area. After simplification the true stress can be written as follows:

Equation 7: True Stress

$$\sigma_{true} = \sigma_{eng}(1 + \epsilon_{true})$$

Using the load-displacement data, the true strain equation and the modified true stress equation, can be used to get the true stress vs. true strain curve. However, Equation 7: True Stress is not valid once necking starts. It should be noted that the DIC software can predict true stress more accurately where this equation is not valid.

4.6.3 Sample Preparation

Table 15: Polishing Procedure for Large Tensile Specimens

Step	Grit	Time	Lubricant
1	500 Silicon Carbide Paper	Until flat	Water
2	1200 Silicon Carbide Paper	3 min	Water
3	4000 Silicon Carbide Paper	3 min	Water
4	3 μ m Suspended Diamond Particles	3 min	Minimal amount of water
5	0.04 μ m OPS	1.5 min	Adding OPS, rinse with water

4.7 Large Tensile Testing with Digital Image Correlation (DIC)

Digital image correlation testing was chosen because of its ability to extract local properties from a global test. DIC only requires one side of the sample be speckle patterned. Meaning the other side can be polished to a mirror surface for visual inspection during the test. Since there is a very limited amount of material (2 pipes were provided), getting the most data per sample is important.

4.7.1 Sample Preparation

The sample was cleaned with ethanol and dried. The sample was then sprayed with a black opaque paint using an airbrush with a 0.18 mm tip size. The black paint was allowed to dry and then a light coating of white opaque paint is applied. In order to get small evenly spaced particles using the white paint the air brush was held several feet away from the sample. This allowed the paint to disperse before hitting the sample. Smaller particle size will lead to more accurate results from the DIC software.

4.7.2 Experimental Procedure

The camera was set to take pictures every 0.5 seconds. After the test was over the pictures were cropped and saved onto the computer. The pictures were then imported into DaVis 8.1.4, the DIC software. The first step in DaVis was to stabilize the images through shift and rotation correction because there were slight vibrations occurring during the test. The next step was to run the software to track the strain on the sample. Once the sample had been analyzed the strain in the loading direction (y), ϵ_{yy} , and the strain in the transverse (x) direction, ϵ_{xx} , are plotted against the picture number.

The next step is to determine the instantaneous area in order to get an accurate true stress throughout the test. Assuming the sample does not change in volume during the test, which is a good assumption for plastically deforming samples, if one direction is positively strained another direction must be negatively strained. This leads to the following equation:

Equation 8: Zero change in volume

$$\epsilon_{yy} + \epsilon_{xx} + \epsilon_{zz} = 0$$

$$\epsilon_{zz} = -\epsilon_{yy} - \epsilon_{xx}$$

The equations for true strain can be written in each direction as follows (where the subscripts denote the direction):

Equation 9: True strain in the x and z directions

$$\epsilon_{xx} = \ln \left(\frac{l_{fxx}}{l_{ixx}} \right) \quad \epsilon_{zz} = \ln \left(\frac{l_{fzz}}{l_{izz}} \right)$$

Since the cross sectional area is $l_{xx} * l_{zz} = A$, the above equations result in an equation for the final cross sectional area:

Equation 10: Final cross sectional area

$$A_f = e^{\epsilon_{xx} + \epsilon_{zz}} A_i$$

This equation can provide the cross sectional area at any time during the test. The final step to create the true stress vs. true strain curve is to link the image number taken during the test to the load at that time during the test. Since the time vs. displacement relationship is linear and the image number vs. time is known, the relationship between image number and displacement is known. The overall displacement is divided by the total number of images to give the amount of displacement per image. To find the load that corresponds to each image, multiply the image number by the amount of displacement per image and find the load that corresponds to that displacement. Using the load and the area, the true stress is known for each picture.

The above process was repeated for each region in the large sample (Inconel, Weld, and Carbon Steel). The only difference was that individual regions were selected in DaVis before exporting the strain values.

4.8 Miniature Tensile Testing

Miniature tensile testing was chosen to confirm the material properties of specific areas of the weld. Samples could be extracted out of a small region where only the material in the gauge length is actually tested.

4.8.1 Experimental and Sample Design

The experimental set-up already existed in the lab and was sufficient to extract the required data. The sample size and set-up were dictated by the equipment available. The two limiting factors were the load cell capacity and the laser machining. The capacity of the load cell was 1000 lbs which dictates thin samples but the most limiting factor was the laser. The samples had to be very thin so that the laser would cut through the sample after only a couple of passes. The exact sample size was a scaled down version of an ASTM standard.

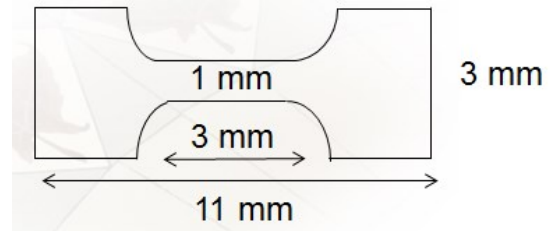


Figure 41: Miniature Tensile Sample Location and Dimensions

4.8.2 Experimental Set-Up

The load cell was screwed into one grip of the tensile machine (the brass cylinder on the left of Figure 42 is the load cell). The grips are interchangeable; in fact this machine is also used for four-point bending tests. The controller can be used manually or through the computer it is connected to. The manual controls are only used to position the grips or during the assembly of the machine. The computer controls are used during testing.

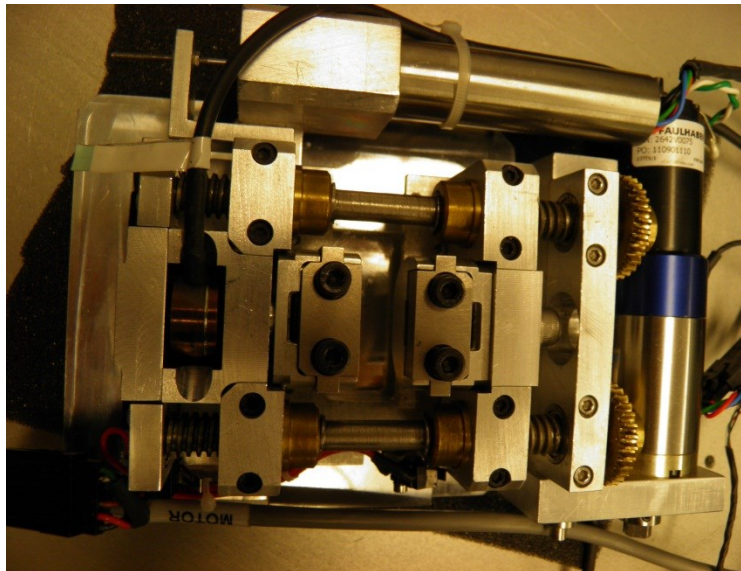


Figure 42: Miniature Tensile Testing Set-Up



Figure 43: Manual Load Controller

4.8.3 Sample Preparation

The polishing procedure outlined in Table 16 for miniature tensile samples is very similar to the procedure used on the visual inspection samples.

Table 16: Polishing Procedure for Miniature Tensile Specimens

Step	Grit	Thickness (μm) or time (Side 1/Side 2)	Lubricant
1	500 Silicon Carbide Paper	400 / 250	Water
2	1200 Silicon Carbide Paper	60 sec	Water
3	4000 Silicon Carbide Paper	60 sec	Water
4	3 μm Suspended diamond particles	60 sec	Minimal amount of water
5	0.04 μm OPS	60 sec	Adding OPS, rinse with water

Variations in Polishing Procedure

Samples are mounted on a cylindrical puck using super glue, see Figure 44. The cylindrical puck is placed in a larger cylinder. The two cylindrical faces are always parallel two each other which leads to even loading and creates a flat sample with uniform thickness. The sample is placed in a bath of acetone for at least 12 hours to dissolves the super glue.



Figure 44: Polishing Apparatus for Miniature Samples. Small puck cylinder in the front left has sample mounted on it and puck is placed in large cylinder on right. Cylinder in back left is placed on top of puck within larger cylinder acting as weight.



Figure 45: Mounting Options. Left - Cylindrical sample mounted in resin. Right - Miniature Tensile Sample glue to cylindrical puck as completed in this project.

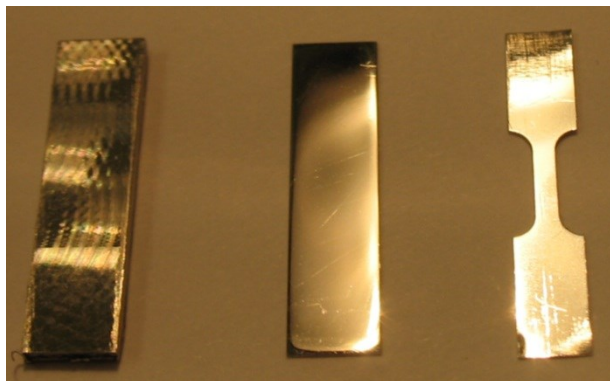


Figure 46: Left- Incoloy Pipe Sample As Machined, Center - Polished to Desired thickness (200 μm), Right – Sample after laser machining using femtosecond laser. (Note: Samples part of different project, used as an example)

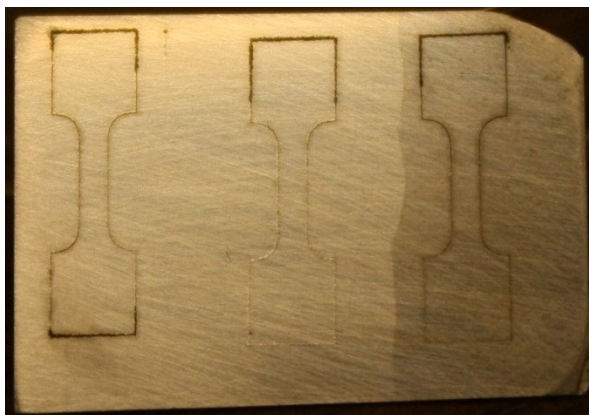


Figure 47: Miniature Tensile Samples After Laser Machining

4.8.4 Experimental Procedure

The strain rate of 0.00033 s^{-1} was chosen because it was the same one used in the large tensile samples. This converts to 0.001 mm/s when using the gauge length of 3 mm. The samples are tested in the miniature tensile machine as show in Figure 42. For the first batch of samples only load, displacement, and time are recorded. True stress and strain are found in the same way as the large samples without DIC.

For the second batch of samples, each sample is photographed every 2 seconds for DIC analysis. The images are cropped and saved to the computer. Image stabilization is completed using shift and rotation correction. The test lasted approximately 20 minutes which resulted in over 600 pictures. In order to speed up the analysis, an interval of 2 pictures was chosen which results in a data point every 4 seconds (half of the pictures are analyzed). The process explained in the large tensile DIC is completed here to find the true stress vs. true strain curves.

Rigidity Factor

The tensile machine is made out of mainly aluminum. As such the machine can deform slightly during the test skewing the displacement results. This problem only affects the samples that are not tested with DIC as the camera tracks the sample deformation not the tensile machine.

4.9 Artificial Crack Initiation

The sample is susceptible to stress corrosion cracking. As such the crack is not induced by mechanical means. Inserting a crack into the test samples using a femtosecond laser allows for a better reproduction of the samples failure mechanism in application. The femtosecond laser is used as it creates virtually no heat affected zone around the crack.

The crack is inserted either at the interface between Inconel and the weld or centered in the weld. The laser uses a 1 kHz repetition rate, 50 fs pulse length, and energy per pulse of 40 μJ . The laser is stationary but the stage the sample rests on moves. To insert a crack the stage is moved back and forth for many (20+) passes. To machine the small tensile samples, the sample shape is programmed into the stage and only a few (3-5) passes are required.

Note: The laser was not powerful enough to machine through the 1.2 mm 4-point bend samples. Electrical discharge machining (EDM) was used to machine the crack and the laser was used to make the crack tip finer.

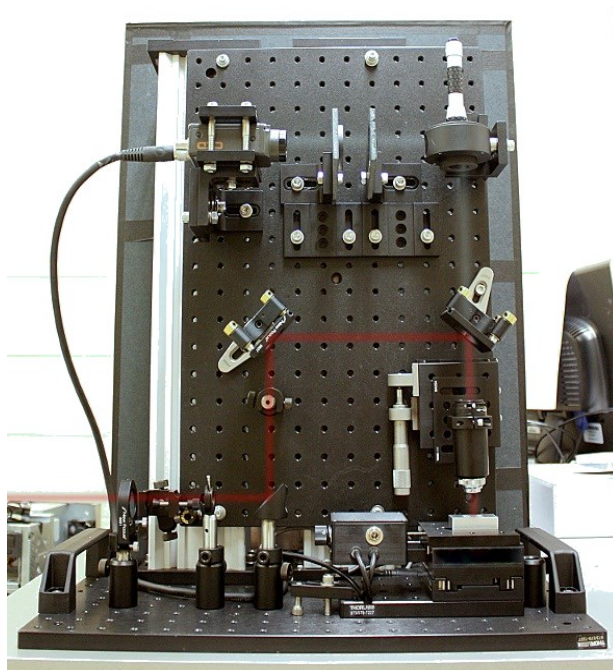


Figure 48: Femto-second laser used to machine and insert cracks into the samples

4.10 Finite Element Analysis

The finite element analysis was completed using ABAQUS software. A brief summary of how the model was created is as follows: Treat each section of the tensile sample as its own part. Assign the material

properties (elastic and plastic properties from DIC stress vs. strain curves) to each individual region. Merge the parts together creating one part with the same size and dimensions as the large tensile samples. The model used 11280 linear hexahedral elements with type C3D8R. One side of the sample was fixed and all of the nodes on the other side were set to move at a constant displacement for up to 100 mm. The mechanical properties inputted into the model were taken from the miniature tensile sample and the DIC samples. The specific properties are shown in the FEA results section.

Note: The Luder Band in the Carbon stress strain curve creates errors in this FEA software. As such the stress-strain curve is modified by adjusting the plateau to have a negative slope (decreasing 10 MPa over the length of the plateau).

5. Results

5.1 Microstructure Characterization

Since the pipes were welded together, the region around the weld will contain spatial variations in microstructure and material properties. These variations will be most prominent when transitioning from one material to the next.

The weld is created using Inconel 82 weld filler and 7 weld passes. The different passes are visible in Figure 49. The 7 different weld passes means the inner edge of the sample would have been subjected to a different amount of heat and heating repetitions compared to the outer edge of the pipe. This area of base material that was subjected to high temperatures due to the welding process is called the heat affected zone. The 7 weld passes means the heat affected zone could vary drastically from the inner to outer edge of the pipe. The weld region contains extremely large grains (more than 100 μm in size), compared to the rest of the pipe, and those grains are visible in Figure 49. Marbel solution was used to etch the sample and it was very effective to reveal the microstructure of the weld region but created a black substance on the Carbon Steel.

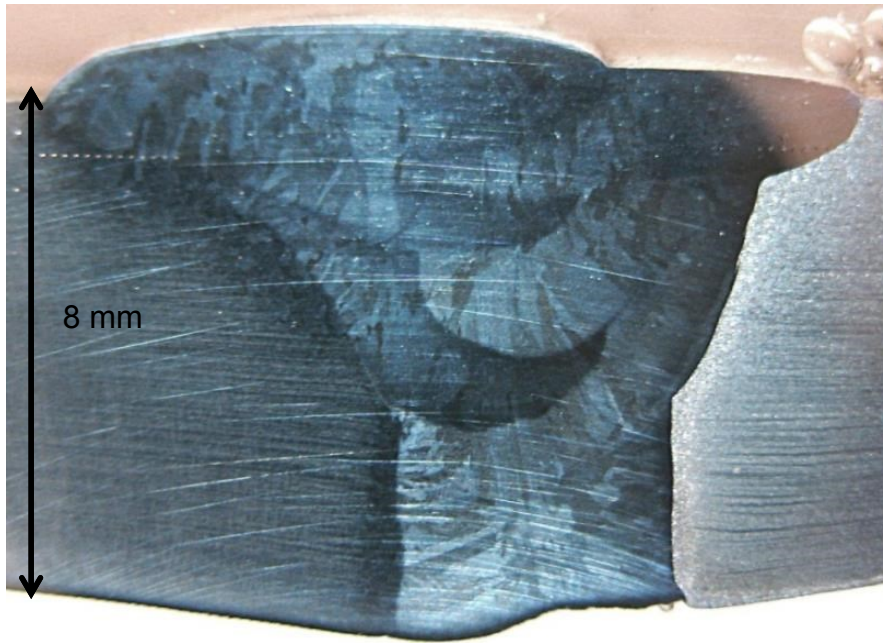


Figure 49: (Left to Right) Inconel 600, Inconel 82 Weld Filler, Carbon Steel Grade 106B

Figure 50 below, shows a large (150 mm gauge length) tensile sample prior to testing. Using the optical microscope images were taken of the different regions of the sample which represent the different regions of the pipe. The microstructure is clearly visible in the images.

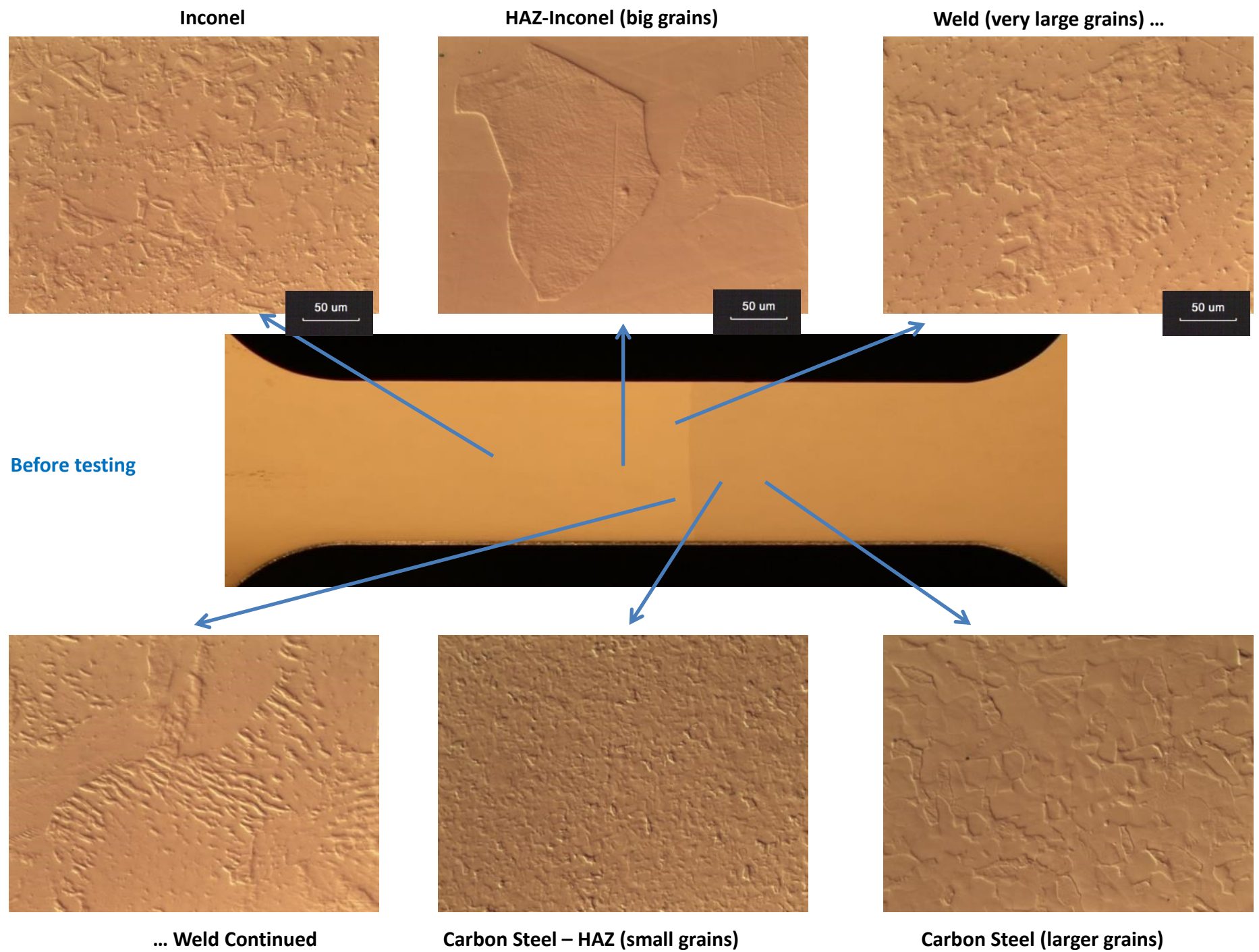


Figure 50: The microstructure from the large tensile sample, after polishing but before testing occurs

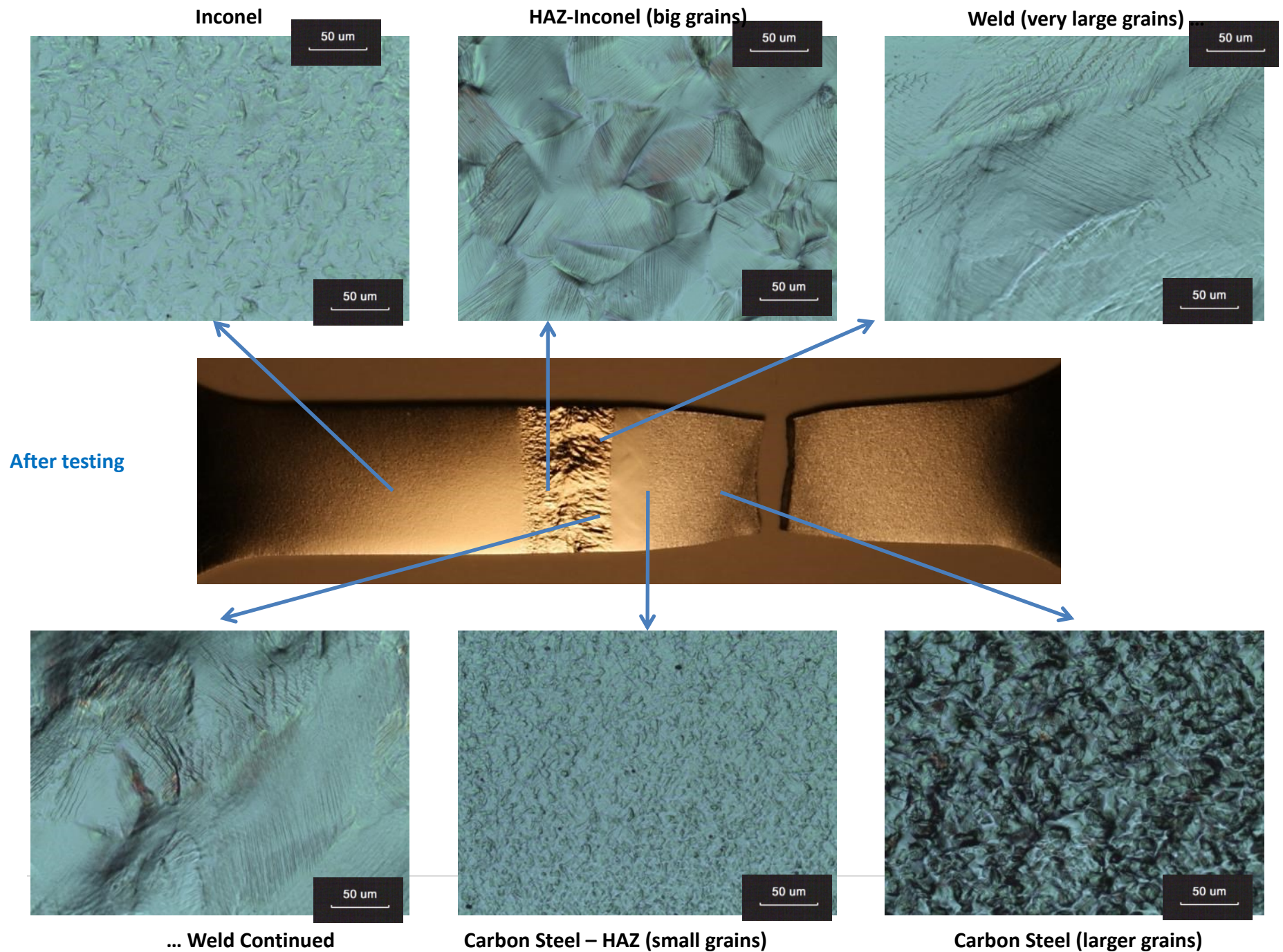


Figure 51: The deformed microstructure of the sample after testing was completed. Note: The blue colour seen is a manipulation by the optical microscope software so that the microstructure can be seen easily.

In Figure 50, the Inconel region has grains in the 10 – 20 μm range. The Inconel heat affected region is visible as the grains significantly change in size and are approximately 100 μm in size. The transition to the weld region is visible as the grains become even larger, greater than 100 μm in size. Also visible in the weld region is its dendritic structure. The transition to the heat affected carbon steel region is visible without a microscope as the material has a slightly different colour. Under the microscope the transition is shown as the grains significantly decrease in size from the weld, to a size of approximately 10 μm . As we move away from the weld in the carbon steel zone the grains become larger around 20 μm in size.

Figure 51 shows the same sample in Figure 50 after testing. The sample failed in the weakest base material, the Carbon Steel (to be discussed in the Large Tensile Section). The most distinct change in the sample is in the surface roughness. The surface was polished to a mirror finish prior to testing and after testing, the surface is visibly altered, even without a microscope. This is caused by the grains orienting themselves in the direction of strain. Since the grains are so large in the weld region small changes in orientation are very evident.

In Figure 51, the Inconel region shows small amounts of deformation in the microstructure. Transitioning into the heat affected zone of Inconel the deformation is much larger and slip lines are visible on the grains. In the weld region, the rotation of the grains really shows how large the grains are in that region. Slip lines are clearly visible and significant deformation has occurred. Moving into the carbon steel heat affected zone, the grains remain almost unchanged. Finally transitioning into the carbon steel base material significant deformation is visible which led to the failure of the sample.

The distinct change in microstructure confirms that there are spatial variations in the pipe and in the base materials around the weld. This variation in microstructure will lead to variations in mechanical properties.

5.2 Hardness

The first mechanical test that was completed on the pipe was Vickers Hardness. Figure 52 shows a Vickers hardness test on a small Inconel region away from the weld. The tests were done at the same radial distance from the center of the pipe. The result is a hardness value of 211 +/- 6 HV.

Figure 53 shows the variations in carbon steel hardness away from the weld. The result is a hardness of 170.9 +/- 4 HV. Both the Inconel and carbon steel hardness variation tests showed that the hardness tests are consistent over a small area.

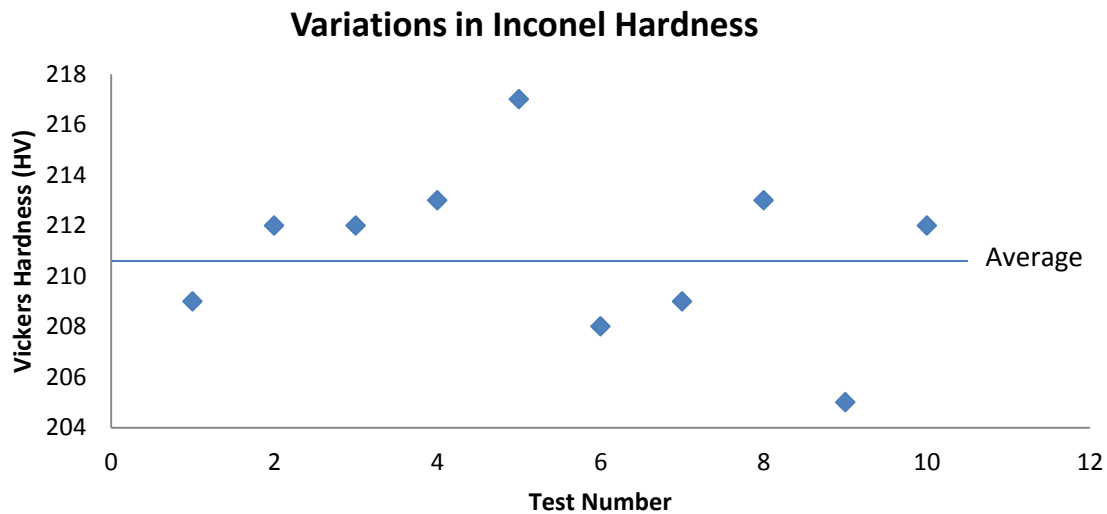


Figure 52: Vickers Hardness tests taken over a small region 30 mm away from the weld

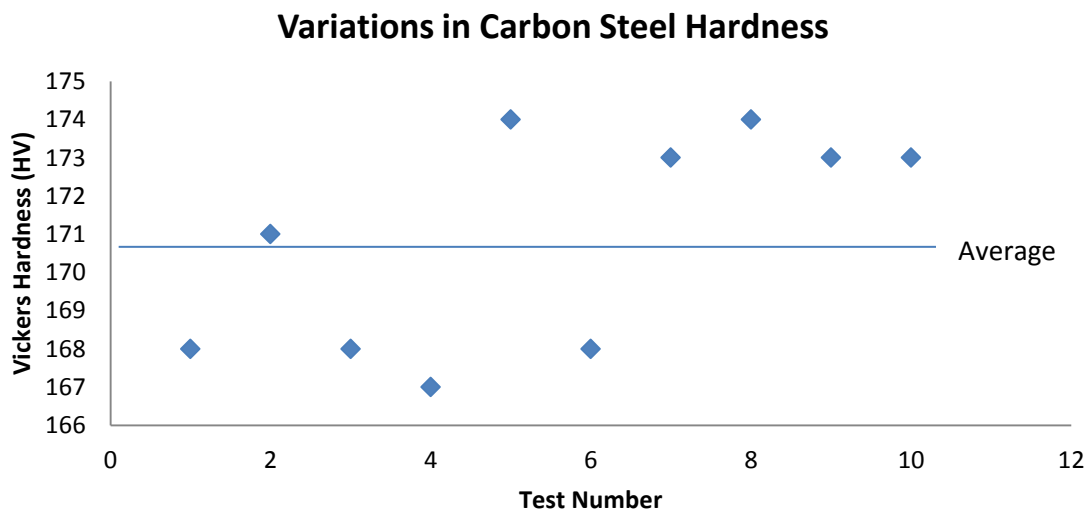


Figure 53: Vickers hardness tests taken over a small region 50 mm away from the weld

Figure 54 shows hardness tests that were completed on the welded pipe in the Inconel region away from the weld. The test shows a small peak in hardness of 203 HV at 150 μm from the inner most edge of the pipe. The hardness then follows a relatively linear gradient starting from 176 HV at 900 μm going to 297 HV at 7900 μm (less than 100 μm from outer edge). This test represents the Inconel material properties of the Inconel that was not affected by the welding process which is the same as the properties prior to welding.

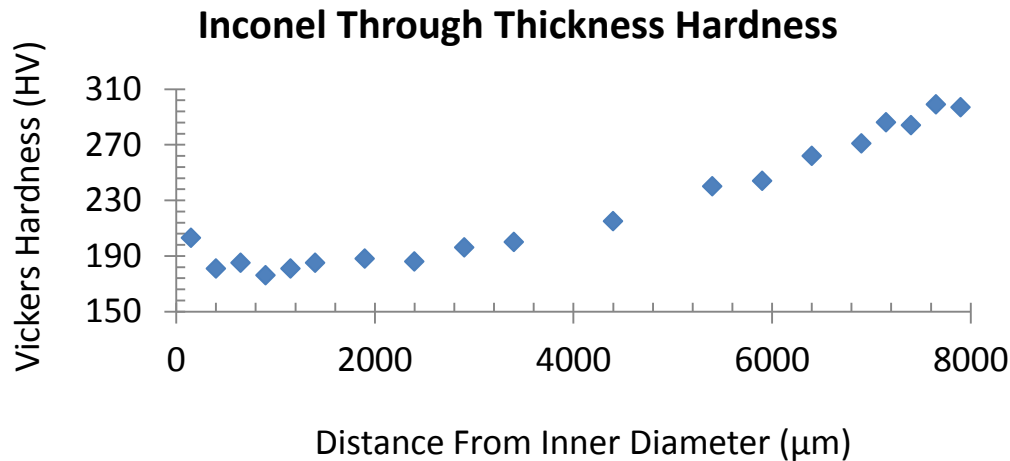


Figure 54: Vickers Hardness on Inconel region away from the weld

Figure 55 shows the through thickness hardness of the three base materials. The results for Inconel are already explained in Figure 54 but note that in the x-axis is in the opposite direction. For the weld, indents were done in the area of the weld that is thicker than the other two base materials (i.e. the points at -1 and -0.5 mm). There is no evident trend in the hardness of the weld. The hardness range for the weld was 184 to 224 HV with exception of the outer most point (248 HV at -1 mm). The hardness of Carbon Steel was much more consistent ranging between 170 and 184 HV.

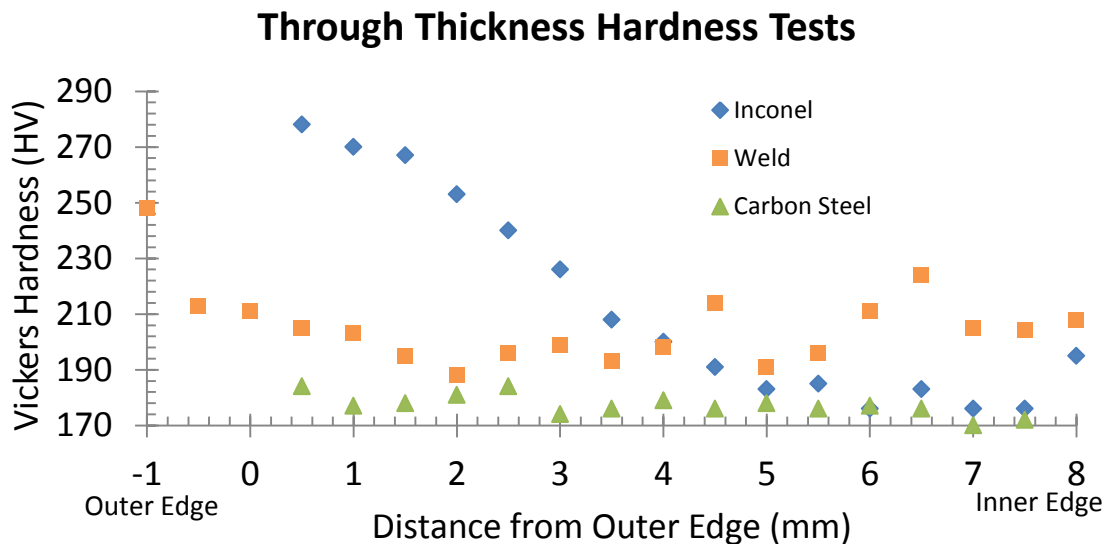


Figure 55: Vickers Hardness testing done on all three base materials (away from the heat affected zones)

Figure 56 shows the Inconel hardness as it moves towards the weld at a distance near the outer edge of the pipe. The hardness starts around 280 HV away from the weld. The hardness value is relatively unchanged for the first 5 mm of the test. The hardness then drops significantly from 279 HV at 5250 μm down to 183 HV at 9250 μm . This is a drop of 200 HV as you move 4 mm to the start of the weld. The weld region has a hardness value between 183 and 199 HV.

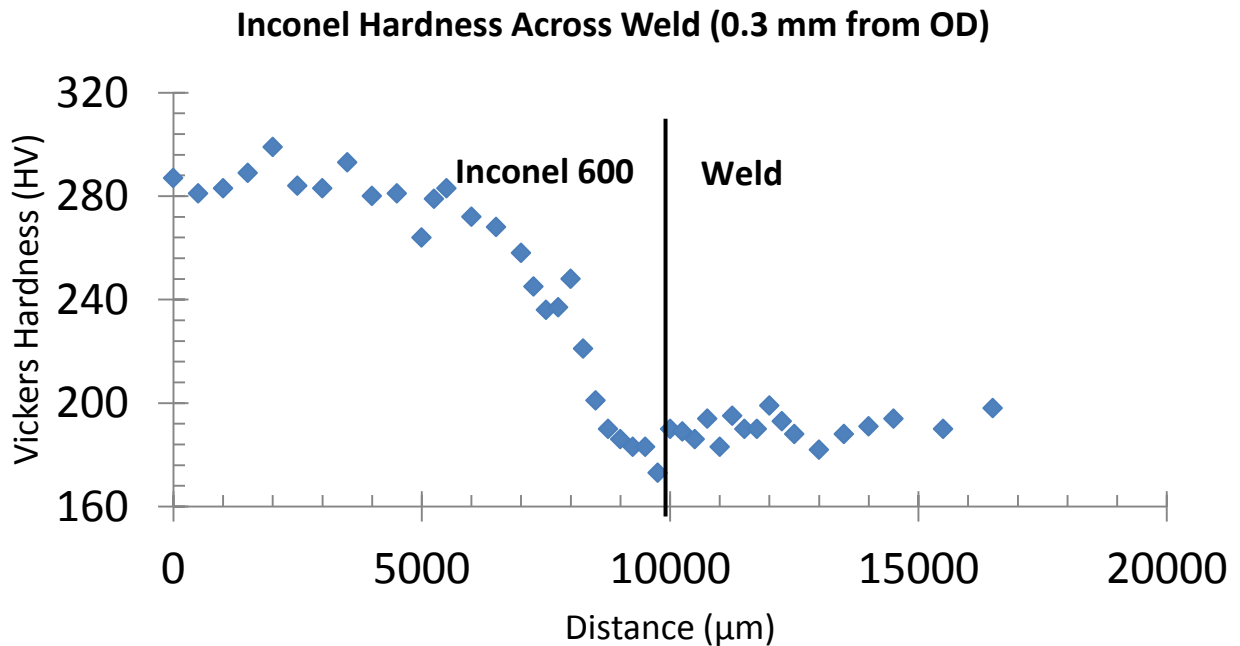


Figure 56: Vickers Hardness on Inconel region moving into the weld region. Test completed at 0.3 mm from the outer diameter of the pipe.

Hardness tests were done near the outer edge, in the middle, and near the inner edge of the pipe. Figure 57 shows the hardness results taken across the Inconel region towards the weld at a distance of 3.3 mm from the outer diameter (near middle of pipe). The test shows some variations in hardness for the first 5 mm ranging from 207 to 218 HV. It is worth noting that the Vickers Hardness scale in Figure 57 is only 60 HV in range whereas the scale in Figure 56 is 160 HV range. This means the variations will be much more apparent in Figure 57 than Figure 56. The gradient in hardness as we move from the Inconel region to the weld is much lower than the outer diameter test. The hardness changes from 218 HV at 6000 μm to 188 HV at 13250 μm , a change of 30 HV over 7.25 mm. Another notable difference is the distinct appearance of the heat affected Inconel zone. The zone is shown to have a hardness value between 172 and 180 HV with a width of 1 mm. The weld hardness is higher than the outer diameter case ranging between 204 and 217 HV.

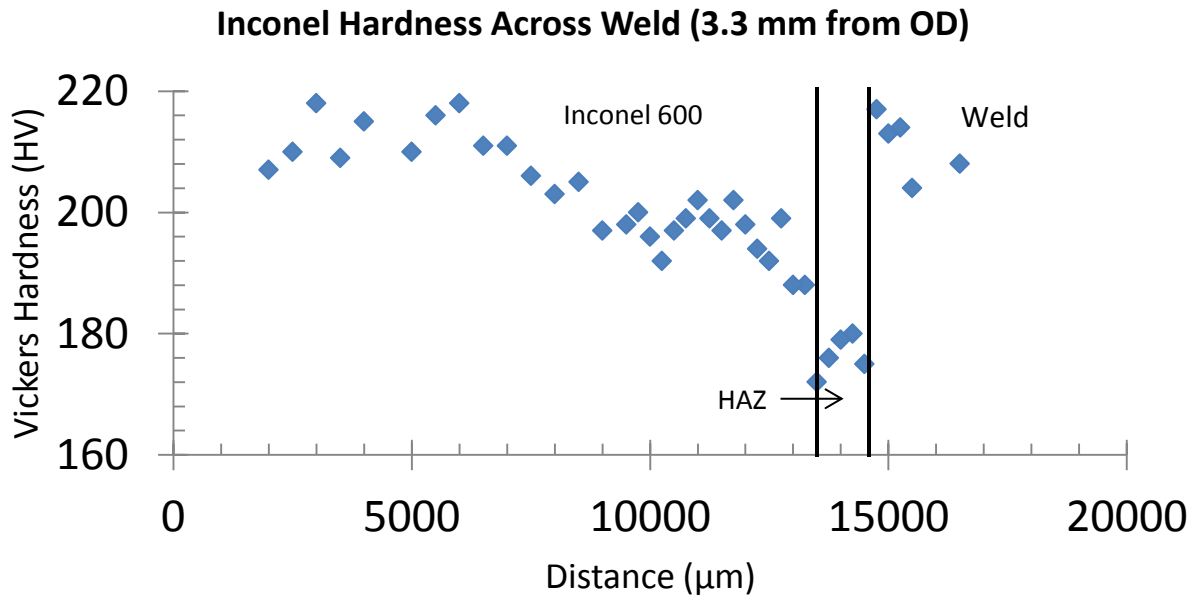


Figure 57: Vickers Hardness on Inconel region moving into the weld region. Test completed at 3.3 mm from the outer diameter of the pipe.

Figure 58 shows the hardness 7 mm from the outer edge (1 mm from the inner edge) of the pipe, starting from the Inconel region moving right through to the Carbon Steel region. This test was able to reach the carbon steel zone because the weld region is much thinner at the inner edge than the outer edge of the pipe (15 mm at the outer edge and 3 mm at the inner edge). As shown in Figure 54, the Inconel hardness is much lower near the inner edge. At 1 mm from the inner edge the Inconel hardness ranges between 185 and 195 HV. There is an increase in hardness moving from 10 mm away from the weld to 5 mm away from the weld. The hardness of the Inconel then plateaus around 210 HV with some variations as we move towards the weld from 5 mm away. This variation ranges between 195 and 215 HV. The heat affected zone of the Inconel is also very thin near the inner edge of the material and as such only one indent was place in this region (187 HV at 19500 μm). The weld region has a hardness value varying between 193 and 207 HV. Finally the Carbon steel has a hardness value of 176 HV near the weld.

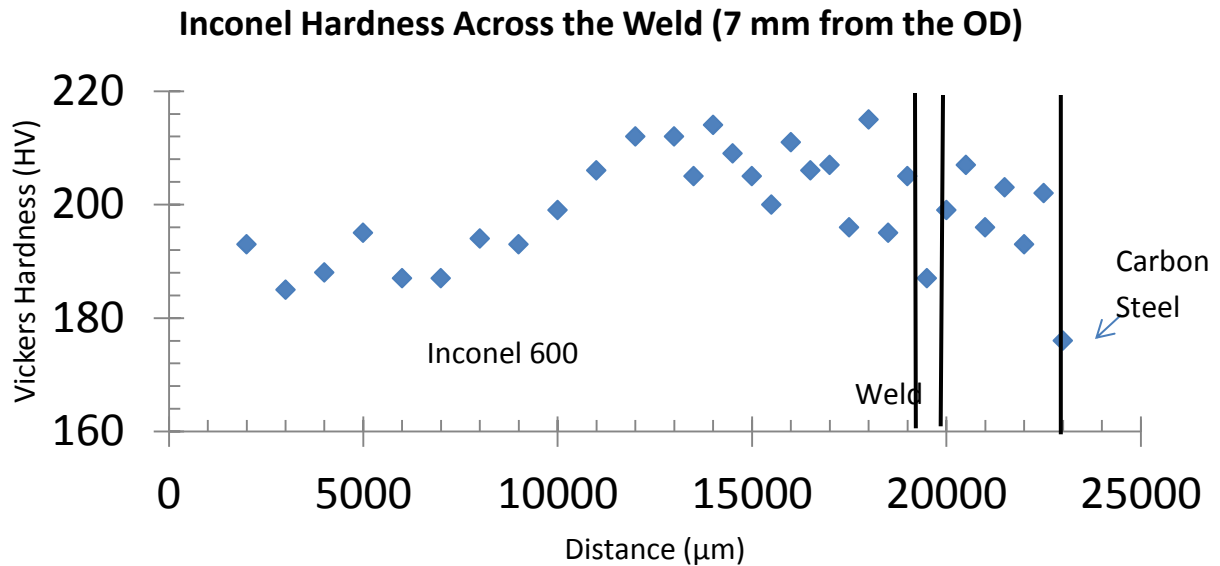


Figure 58: Vickers Hardness on Inconel region moving into the weld region. Test completed at 7 mm from the outer diameter of the pipe (1 mm from the inner edge).

5.3 Scanning Electron Microscope (SEM) with Electron Dispersive Spectroscopy (EDS)

EDS was used to reveal the composition of the material. The first tests completed were line scans across the carbon steel-weld interface and the Inconel-weld interface. The line scan only gives a comparative result as the units are “counts” received in the EDS testing (not weight percent). The line scan at the Carbon Steel – Weld interface near the inner diameter of the pipe showed a compositional gradient (Figure 59). In addition to the gradient, inside the weld matrix, a thin vertical region of Carbon Steel like composition can be observed (Figure 60). Finally, the level of Iron in the weld at this location is much higher than elsewhere in the weld.

Figure 61 shows the line scan on the Inconel interface near the middle of the pipe. Looking closely at the microstructure this line scan takes place just inside the first weld pass (root weld), which is the same weld pass as the line scan in Figure 59. This line scan also shows higher than normal levels of iron in the weld region. Using the EDS element map seen in Figure 62, the high levels of iron are restricted to the first weld pass. The Inconel region and the second weld pass (seen in the top right of Figure 62) have similar lower levels of iron. The general trend seen in Figure 61 is that there is little to no composition gradient between the Inconel and the weld at the interface. This line scan closely matches the others at the inner and outer edge of the Inconel interface. Figure 63 shows the line scan at the carbon steel

interface near the middle of the pipe. The results match closely with the results at the outer edge of the same interface.

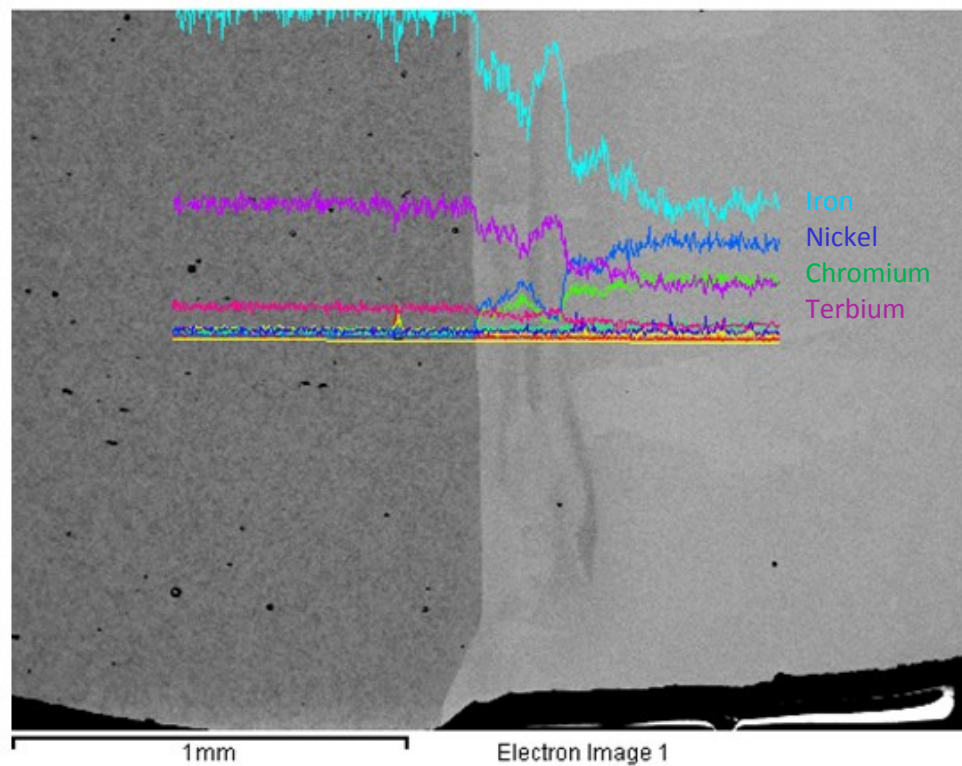


Figure 59: Electron Dispersive Spectroscopy testing on the interface between Carbon Steel and the Weld near the inner diameter.

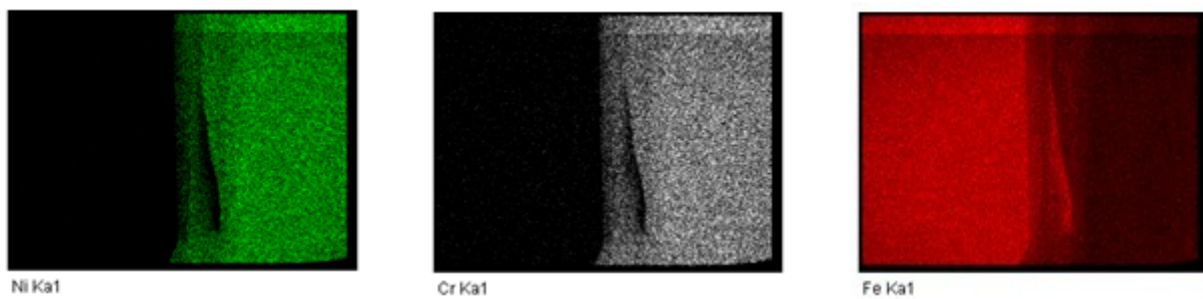


Figure 60: EDS Map by Element of Area Shown in Figure 59

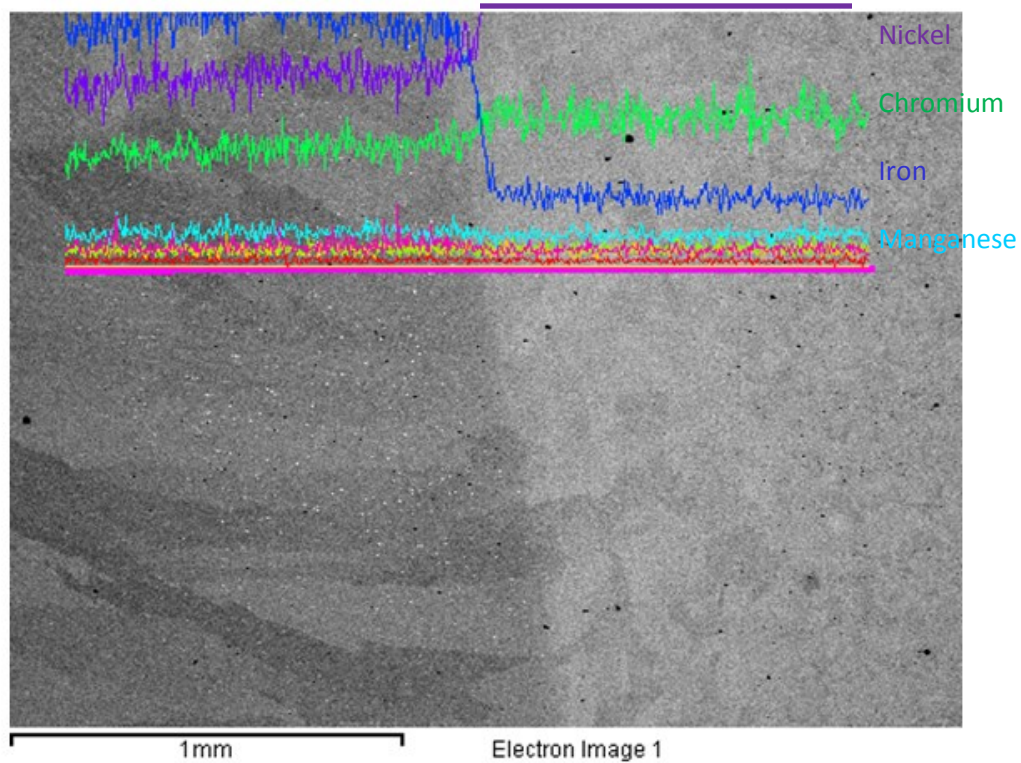


Figure 61: EDS analysis of Inconel 82 weld filler and Inconel 600 base metal below center of the pipe.

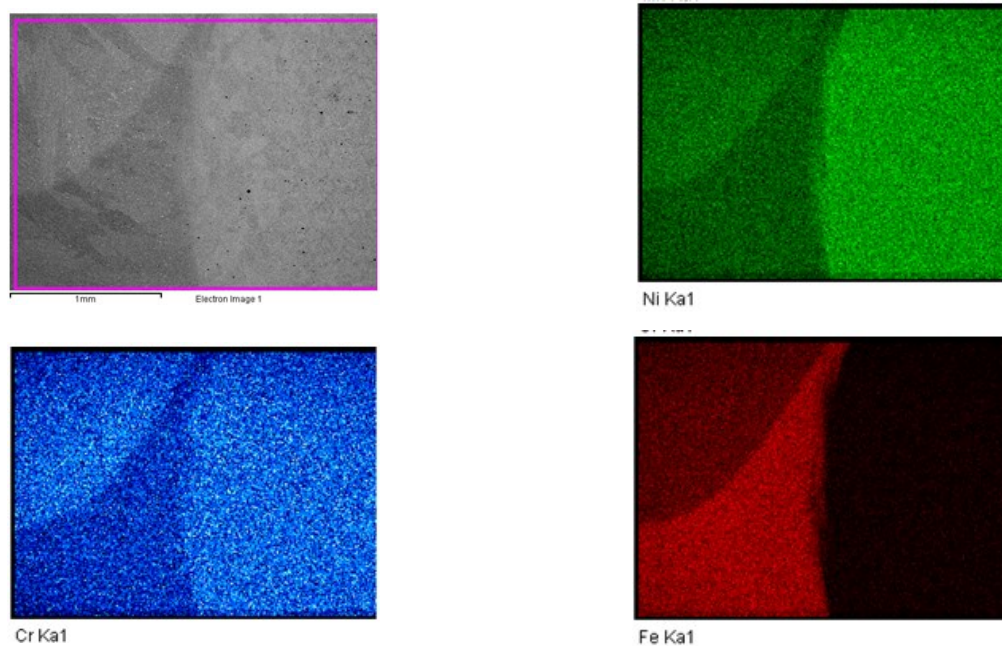


Figure 62: EDS Map by Element of area in Figure 13

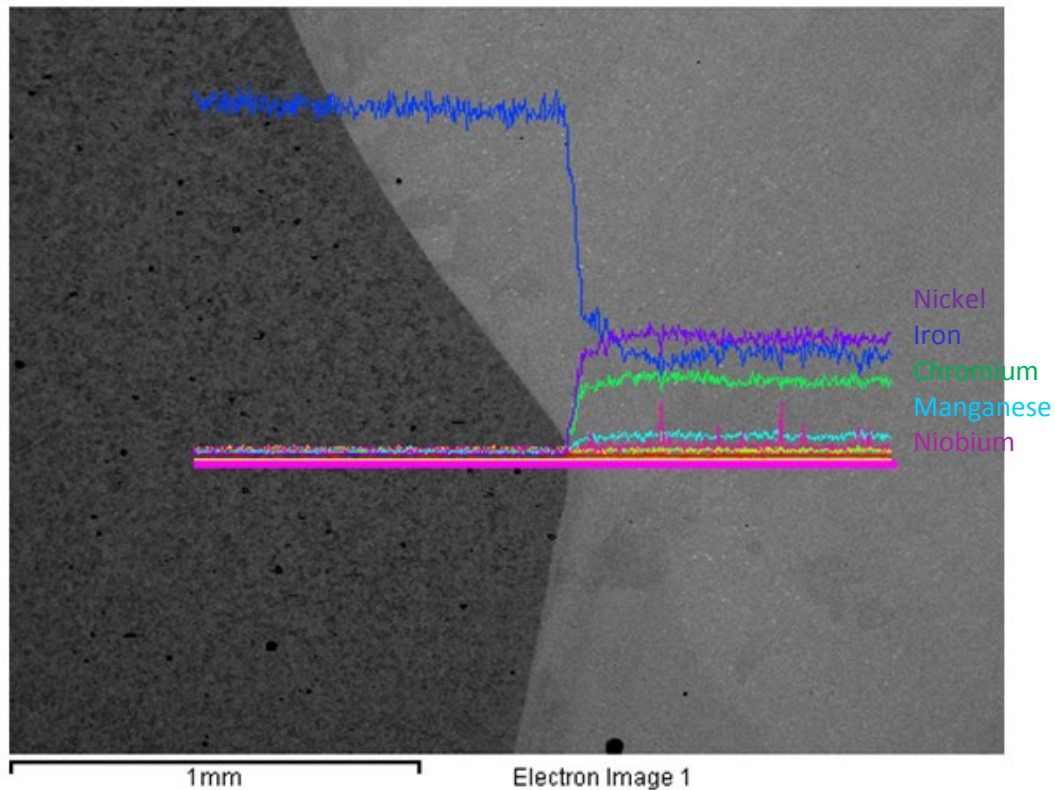


Figure 63: EDS Analysis of Carbon Steel to Weld Interface near the middle of the weld.

Figure 64, Figure 65, and Figure 66 show the composition by weight percent from EDS point scans. The point scans were completed as close to the indents from the hardness test as possible. Figure 64 shows the composition profile 0.3 mm from the outer edge of the pipe. The weld and the Inconel have an extremely similar composition across this profile. The main elements are Nickel at 70%+, Chromium at 17%, and Iron at 9%. These results agree with the line scan done near the outer edge of the pipe. Figure 65 shows the composition 3.3 mm from the outer edge of the pipe. The compositions between the weld and Inconel are very similar. They also match closely with the composition at 0.3 mm from the outer edge. There is a very slight increase in Chromium in the weld near the interface but a line scan nearby does not support this as a trend. Figure 66 shows the composition of the pipe 7 mm from the outer edge (1 mm from the inner edge). The composition here has a much different make-up than elsewhere in the weld with Iron reaching 38%, Nickel 48%, and Chromium 12%. The trend that the bottom of the weld has an increased level of iron is confirmed by the line scans.

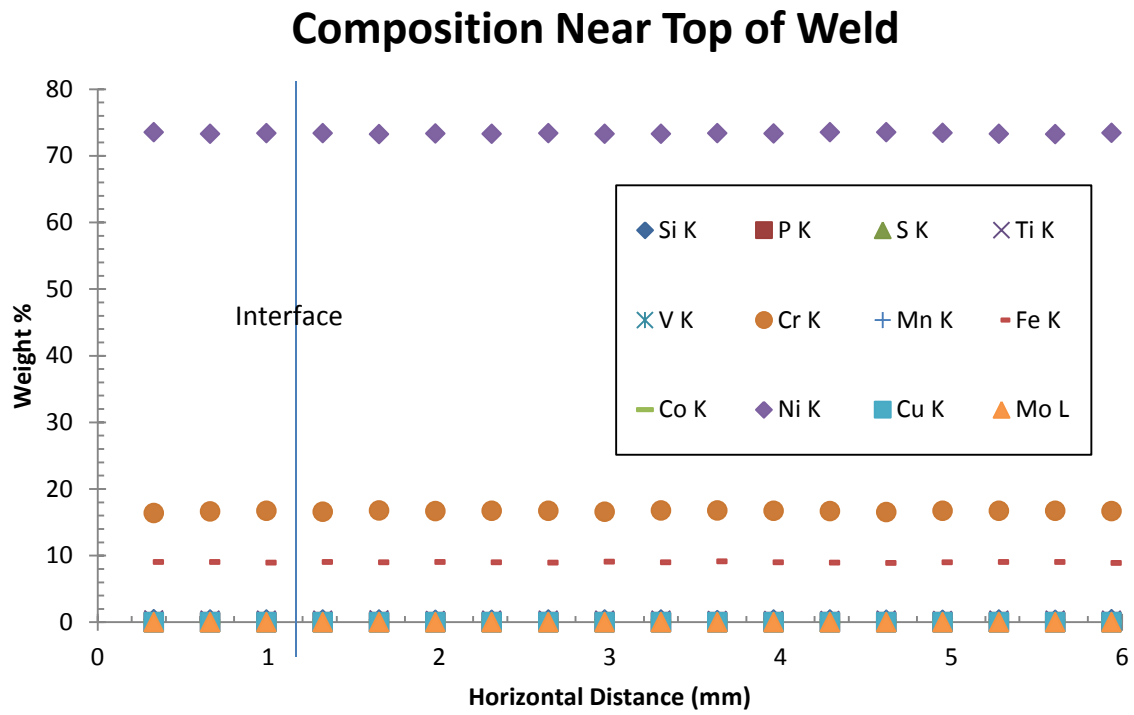


Figure 64: Composition of the Weld-Inconel interface 0.3 mm from the outer edge of the pipe as analyzed from EDS.

Composition Near the Middle of the Weld

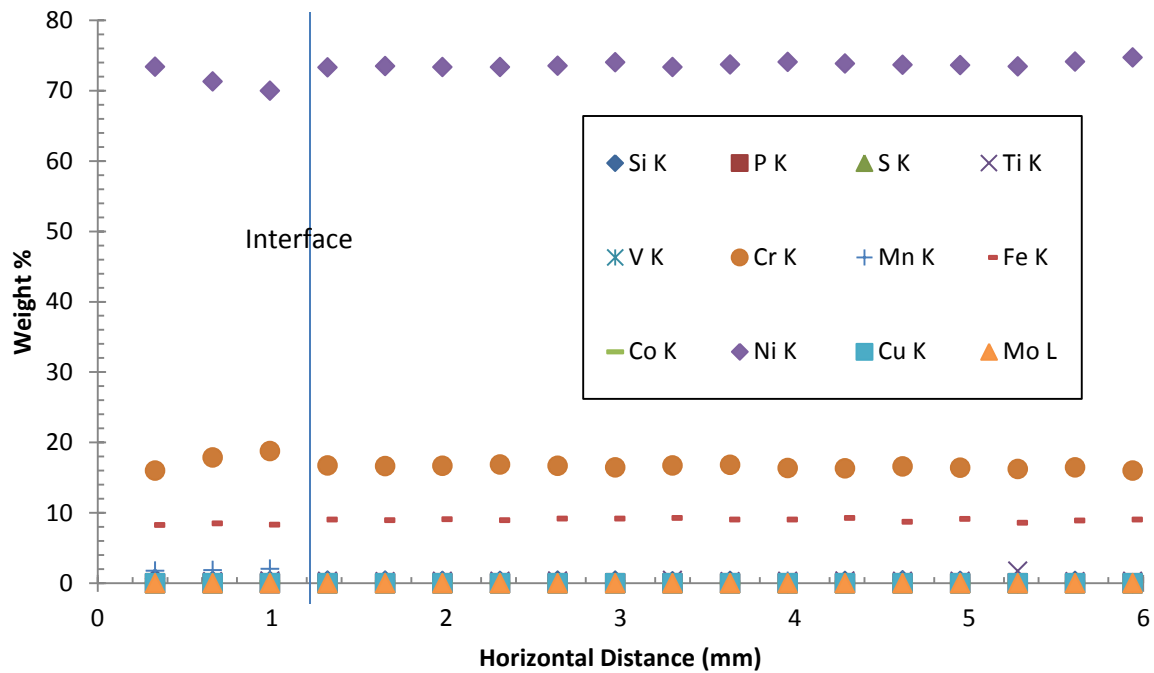


Figure 65: Composition of the Weld-Inconel interface 3.3 mm from the outer edge of the pipe as analyzed from EDS.

Composition Near the Bottom of Weld

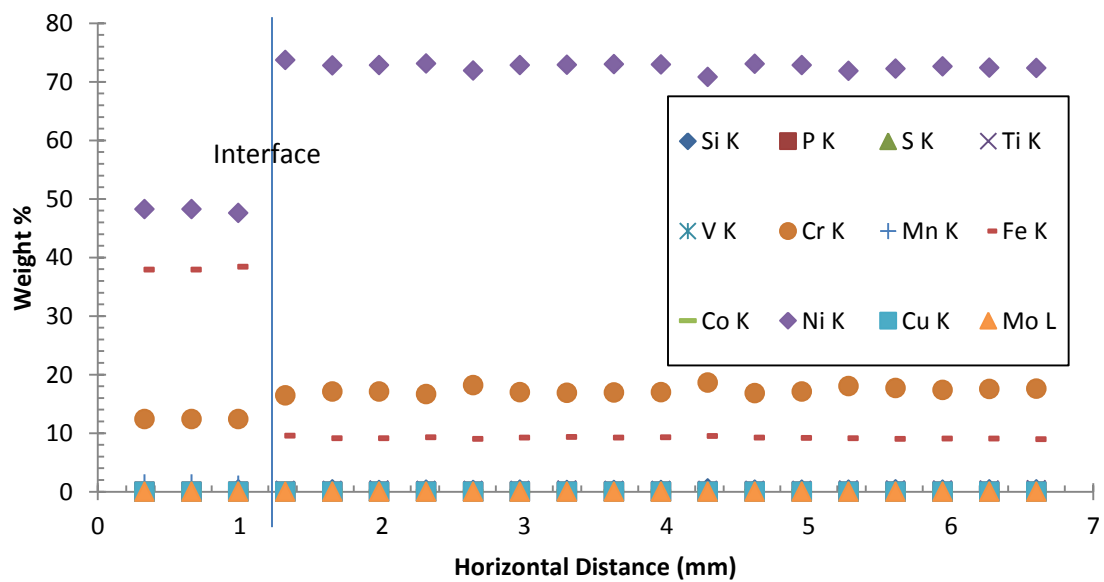


Figure 66: Composition of the Weld-Inconel interface 7 mm from the outer edge of the pipe as analyzed from EDS.

5.4 Large Tensile Testing

The large tensile samples were tested at three different thickness locations, outer, middle, and inner diameters. Figure 67 shows the stress-strain curve of samples taken from the outer diameter, middle and inner diameter regions of the weld. The yield strength of the material is around 350 MPa. All three curves are almost identical until yielding. All the tests show a small plateau at yielding typical but smaller than carbon steel stress vs. strain curves. The inner test has an ultimate tensile strength (UTS) of 493 MPa, the highest of all the tests. The middle sample has a UTS of 481 MPa and the outer sample has a UTS of 489 MPa. The inner test failed at a strain of 0.142. The middle and outer tests failed at about the same strain of 0.188.

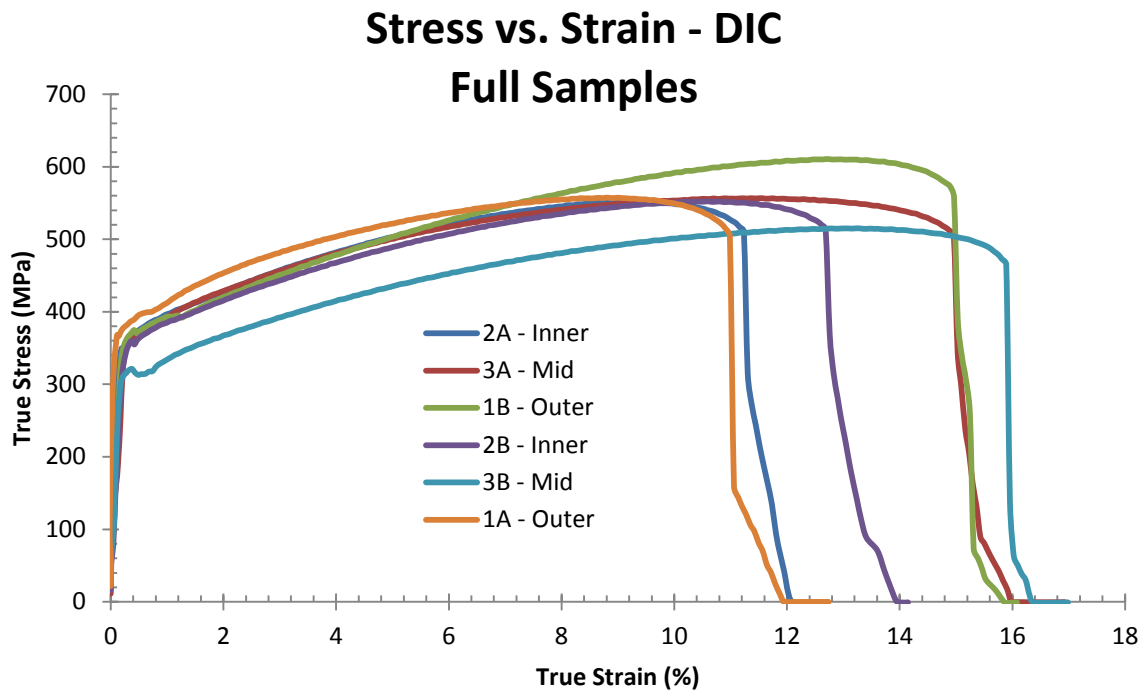


Figure 67: Tensile Tests on 1 mm thick samples taken from the outer diameter, inner diameter, and middle diameter of the sample

The large tensile sample started as a smooth surface and became rough during testing (Figure 68). As the sample is tested, grains re-orient themselves to accommodate the tensile deformation. The larger the grains, the more the changes in orientation are visible at the surface. Slip steps are clearly visible in the large grains (above 25 μm) in the weld and Inconel regions. The regions with small grains (under 10 μm) see little overall deformation (as seen in microstructure section).

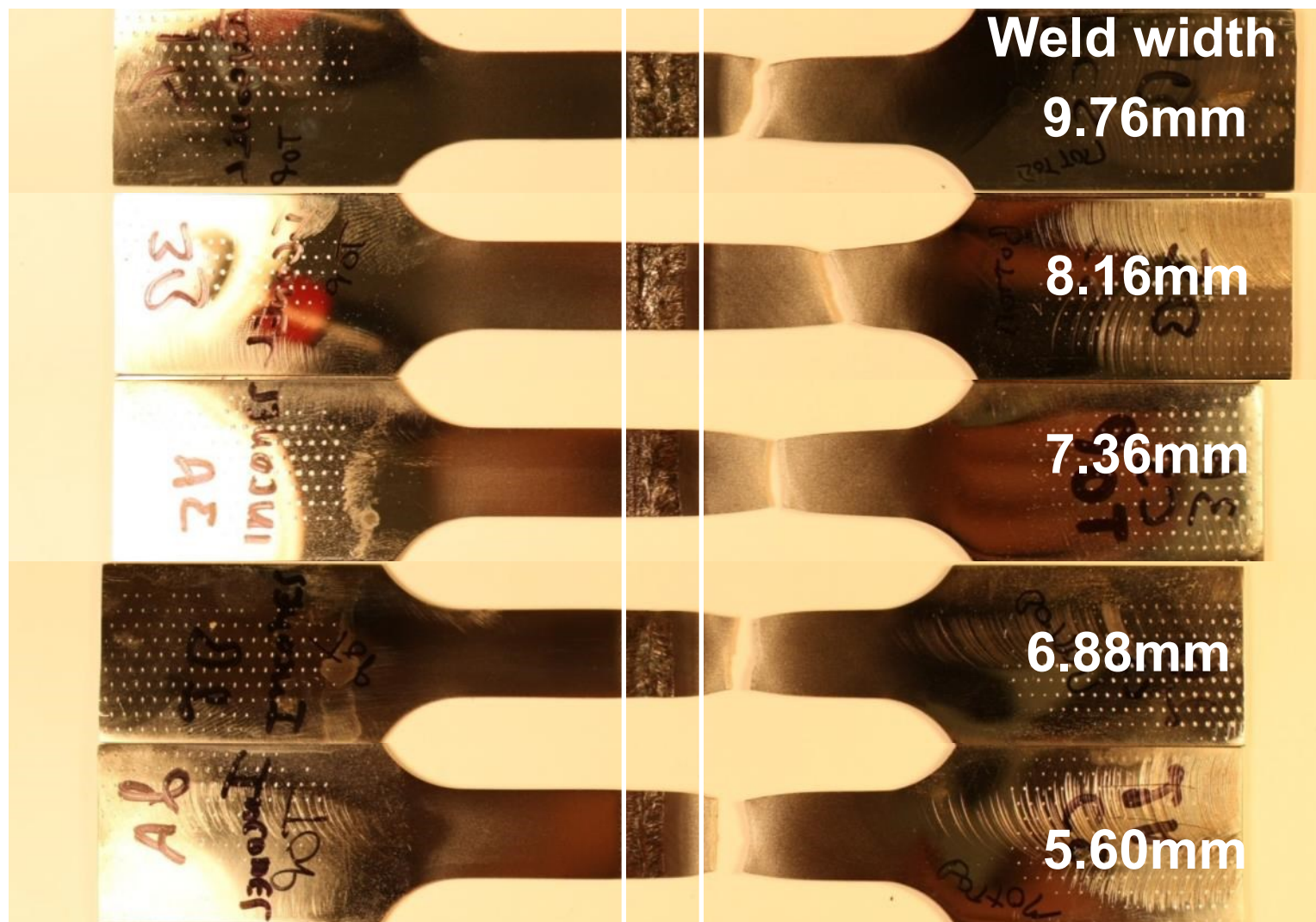


Figure 68: Large Tensile Samples Post Testing. Polished surface shows deformation, especially in the weld region. The width of the weld region post testing is listed on the right of the images.

5.5 Large Tensile Testing with Digital Image Correlation (DIC)

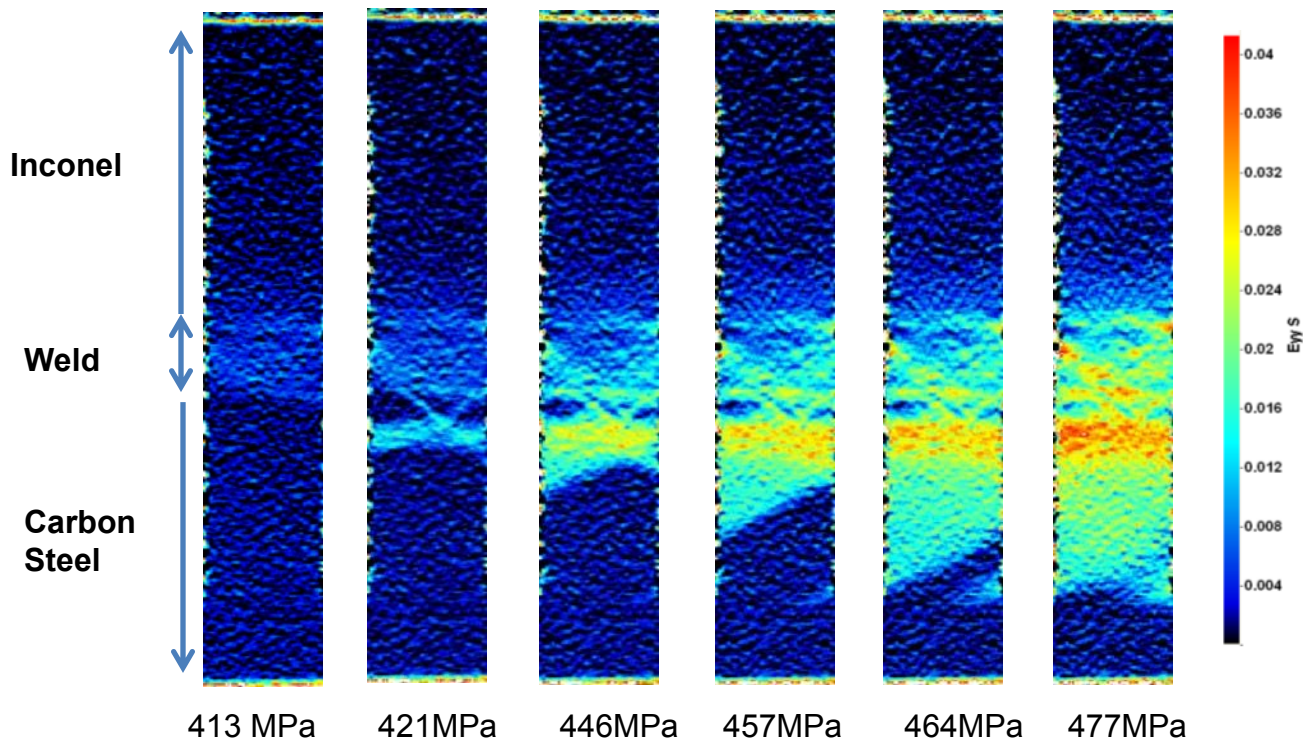


Figure 69: Digital Image Correlation Results: Early Stages

The Digital Image Correlation (DIC) results show strain first accumulating in the weld region. The maximum strain value then varies in location between the weld and the carbon steel regions. The formation of Lüder's Bands is evident after 400 MPa in the Carbon Steel region. The heat affected zone of the Carbon Steel sees very little deformation compared to the rest of the region.

Figure 70 shows a summary of the full DIC test. The weld and steel regions compete for the highest level of strain before the final accumulation of strain in the Carbon Region leads to failure. These two regions are distinctly visible because they are separated by the heat affected zone of carbon steel. The weld region never sees uniform strain across the region, it is always scattered.

The stress obtained during the tensile test can be coupled to the local strain from the DIC result in order to obtain local stress-strain curves (Figure 71). The DIC software was used to create the stress vs. strain curves based on the maximum strain value in each region corresponding to the engineering stress applied at that time (Figure 71 and Figure 73). The Inconel and Weld regions undergo less strain than the

Carbon region because the strain accumulated in the Carbon region leading to failure. When the stress value goes to zero for the Inconel and Weld regions those regions are being unloaded not failing. The maximum level of stress is actually the same for all of the materials and represents the UTS for Carbon Steel (493 MPa). At the failure of sample 2A (Inner) the Carbon Steel region has accumulated a strain of 0.40, the Inconel region 0.066, and the weld region 0.128. In sample 3A (middle) the failure stress is 540 MPa with strains of 0.63 in the Inconel, 0.90 in the weld, and 0.45 in the Carbon region. Sample 1B (outer) has a failure stress of 540 MPa with strains of 0.9 in Inconel, 0.16 in the weld, and 0.4 in Carbon Steel.

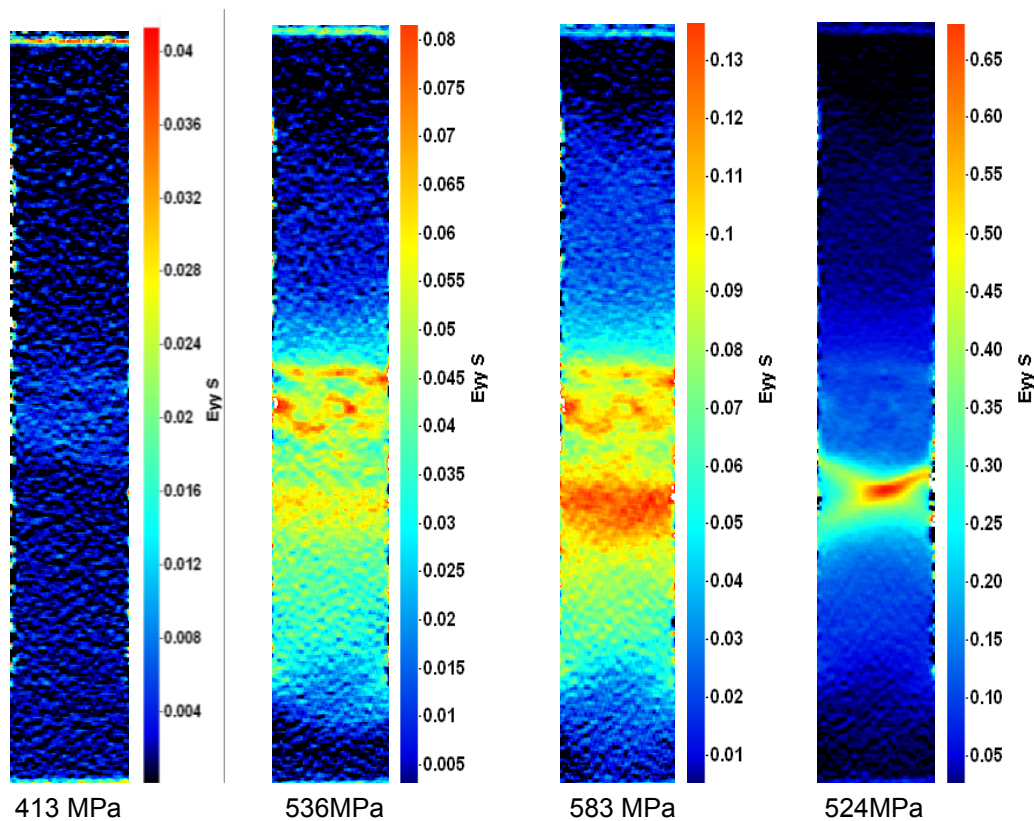


Figure 70: Digital Image Correlation Results: Local Strain vs. Engineering Stress

After analyzing the full size tensile specimens, the next step is to extract the stress vs. strain curves for each region. In order to do that, a map of the strain vs. location is created along the sample (Seen in Figure 71 and Figure 73). The map shows the levels of strains on the y-axis and the corresponding location in terms of pixels (x-axis) for different levels of stress (each coloured line is of a different stress). Each region of the material strains differently and you can identify the different regions through the changes in strain.

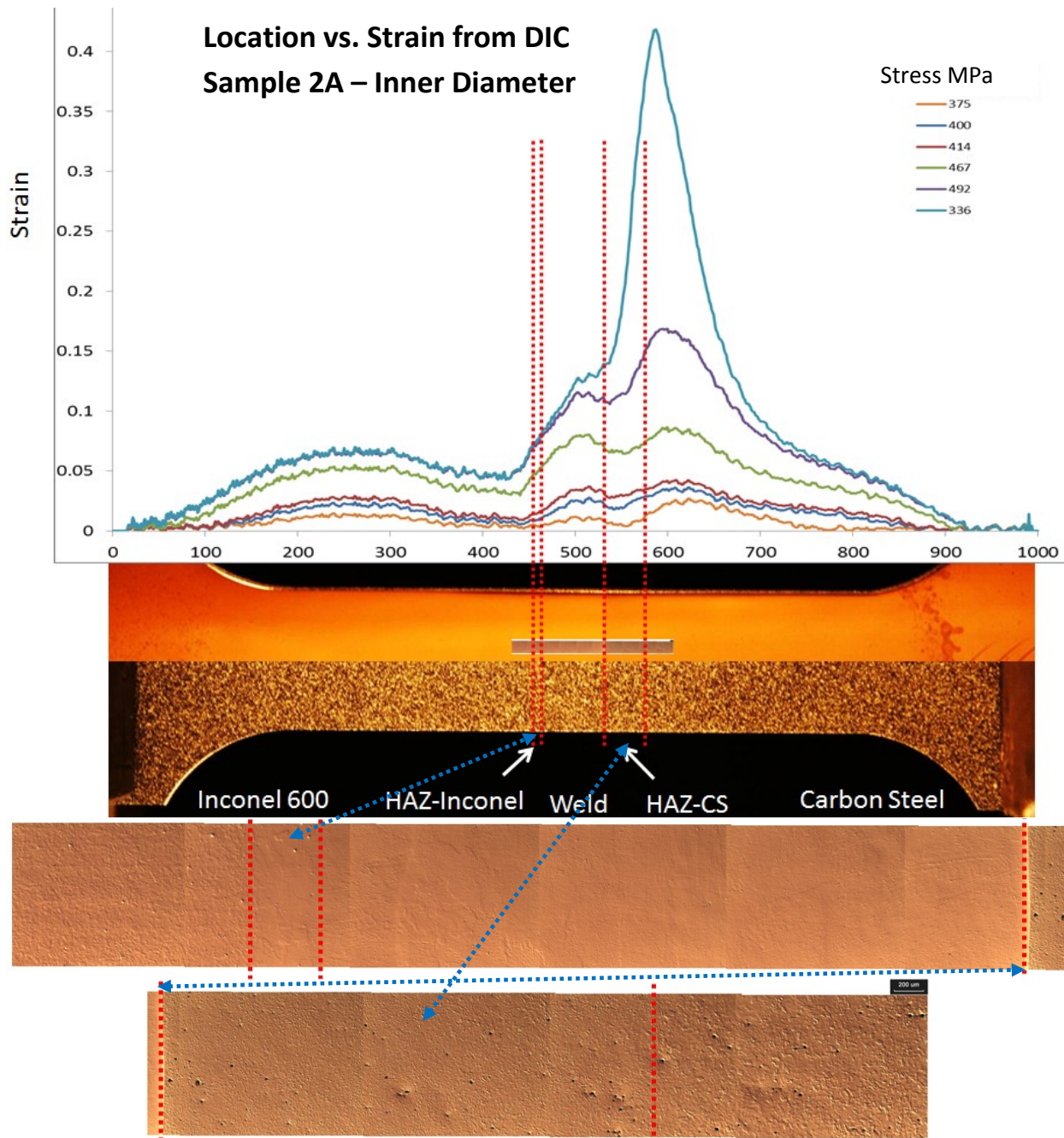


Figure 71: Sample 2A. Strain as determined by DIC vs. location on the sample at different global stress levels. Note that as the strain increases, the sample elongates and the different zones shift slightly to the left on the graph. This is due to the left side being fixed and the right side free to elongate.

The highest level of strain seen in every sample is in the carbon steel region. In Figure 71 a slight drop is seen next to the highest strain which corresponds to the heat affected carbon steel region. The spike in strain near the middle shows the weld region. This spike is distinct as there are variations in strain within

the weld region. Next there is a gradual decrease between the weld and Inconel region, right through the Inconel heat affected zone. Finally, there is a gentle increase in strain near the middle of the Inconel region. In order to confirm the region locations, the samples were photographed under the microscope before the test started. The images are stitched together and superimposed onto the large sample (as seen in Figure 71 and Figure 73). The large samples are then matched against the pixels in the DIC software. Note that the sample elongates so the peaks can shift slightly from line to line.

Figure 72 and Figure 74 show the stress strain curves that are extracted from the DIC data. The yield strength of each material within a specific sample seems to be very similar as seen in all the tests. The Inconel region in every sample is the strongest and sees the least amount of strain during the test. The weld region competes with the carbon region to be the weakest material at the start of the test. The welds strength increases with strain more than carbon steel does and failure occurs in the carbon steel region. The carbon steel regions have a Luder plateau at yielding which is typical of carbon steel materials. The weld region always has the second highest level of strain and the carbon steel has the highest level of strain. Since failure occurs in the carbon steel region, that region is the only one that strains to failure. The final strain for the weld and Inconel is just the strain at which they are unloaded. Finally since all of the regions are in the sample, they all see the same load. The true stress of carbon is so much higher than the other regions because the cross-sectional area of the carbon region decreases during necking.

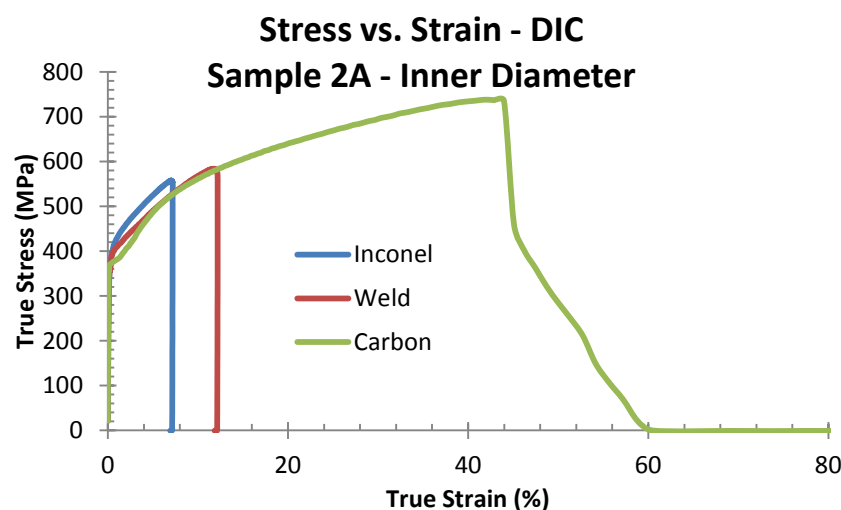


Figure 72: The Stress vs. Strain curves for each region as extracted from the Digital Image Correlation Software.

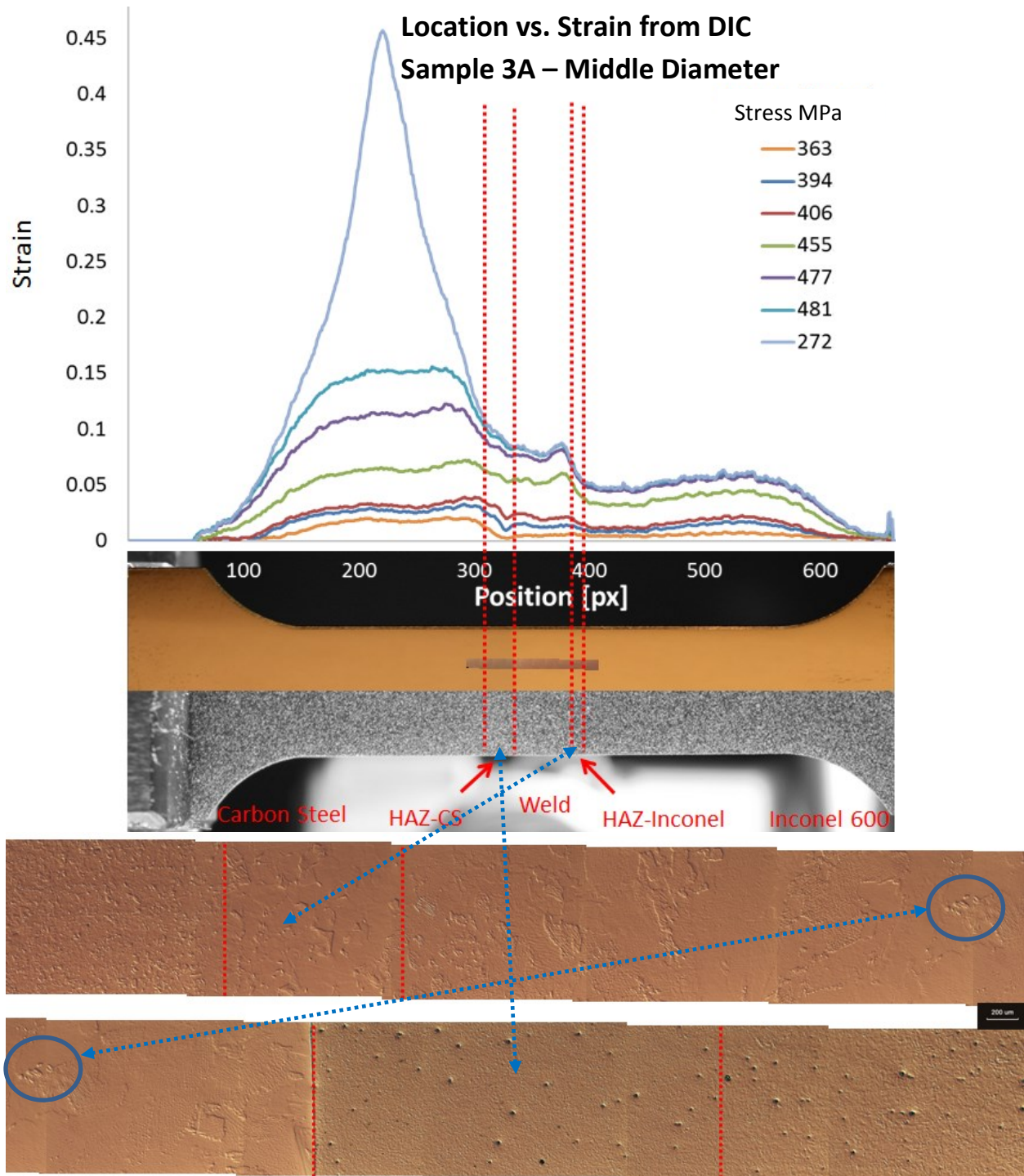


Figure 73: Sample 3A. Strain as determined by DIC vs. location on the sample at different global stress levels.

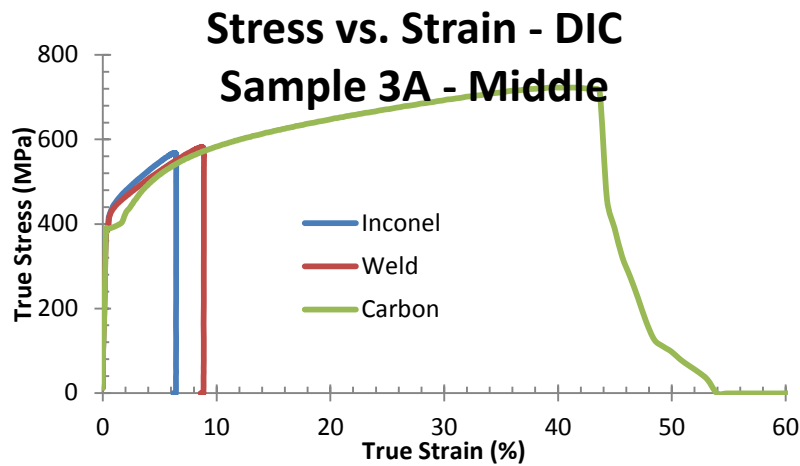


Figure 74: Stress vs. Strain as extracted by DIC for Sample 3A. Sample taken from the middle diameter of the pipe



Figure 75: Crack in sample 3B (Image Under 5x microscope)

The trends described can be seen in all of the samples but sample 3B shows a large peak in stress near the Inconel –Weld interface. This spike was actually due to a crack that formed almost immediately upon loading the sample. The crack that formed was horizontal almost completely across the width of the sample. Even with such a crack size, the crack did not propagate at all once it formed. The crack formed on the painted speckle side of the sample and could not be seen on the polished side (blind crack) (see Figure 75)

Figure 77, Figure 78, and Figure 79 show the stress strain curves by material. The carbon steel curve shows the most consistency through thickness and across the different samples. The weld region saw the largest range in strains and a large range in stresses. The Inconel region also saw a large range in stresses and strains. Across all the materials, from the large DIC alone, there isn't an obvious trend between the inner, middle, and outer samples.

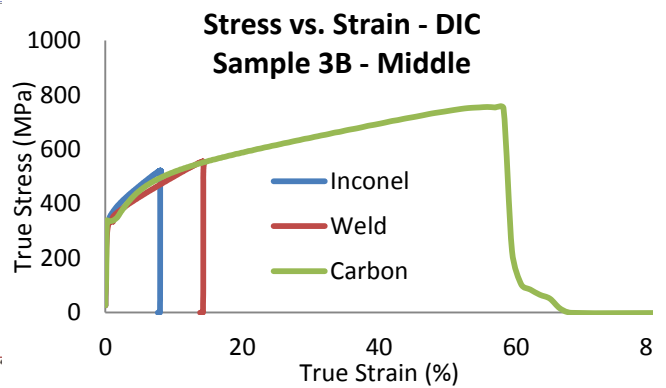
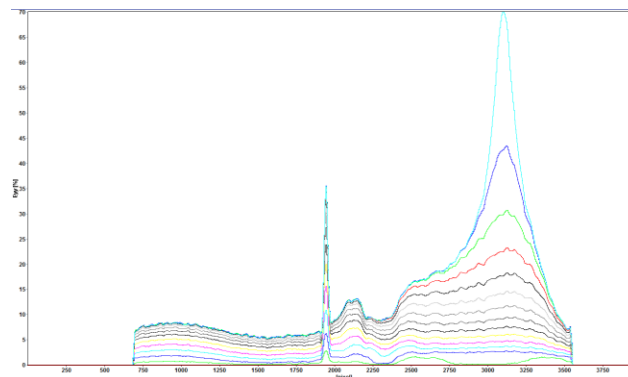
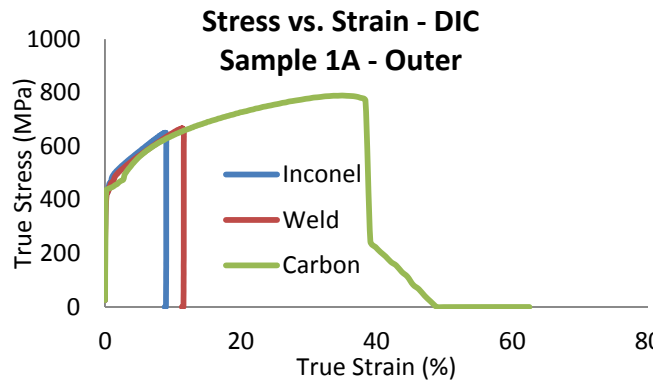
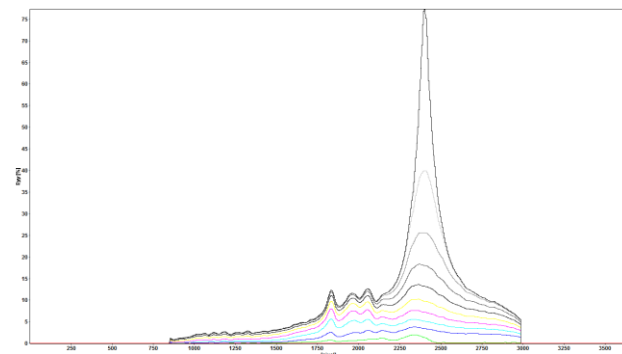
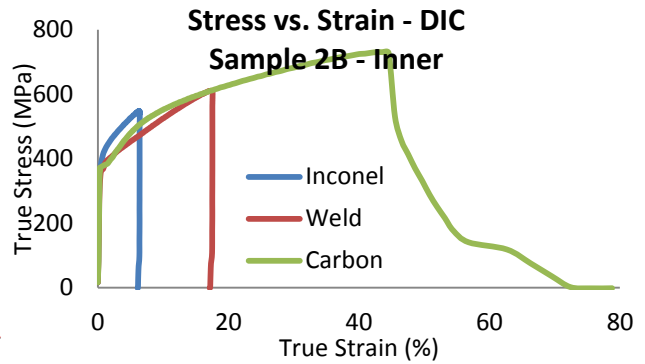
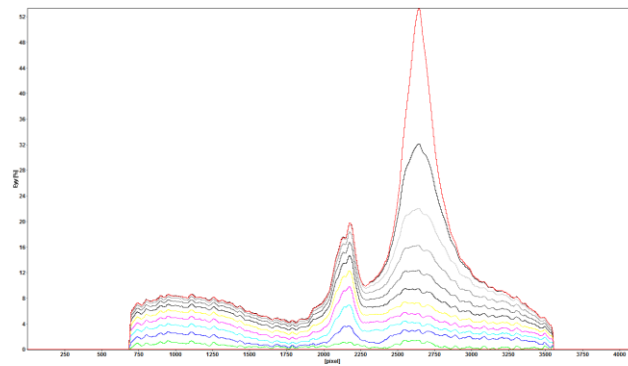
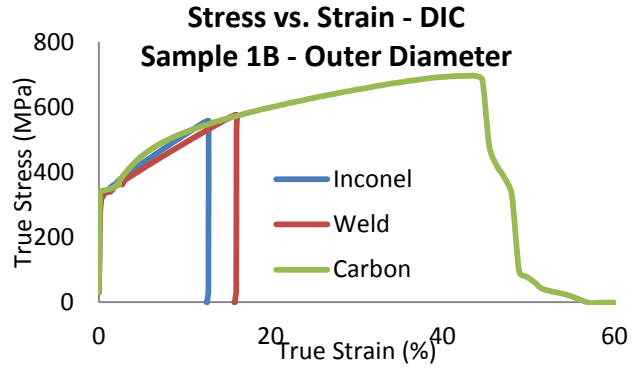
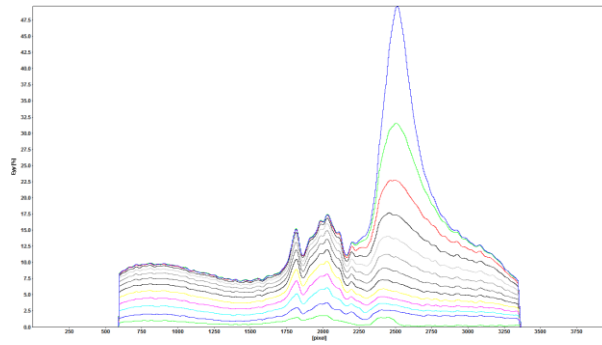


Figure 76: Stress vs. Strain as determined from DIC. (Left: DIC strain vs. location; Right: Corresponding stress vs. strain curves)

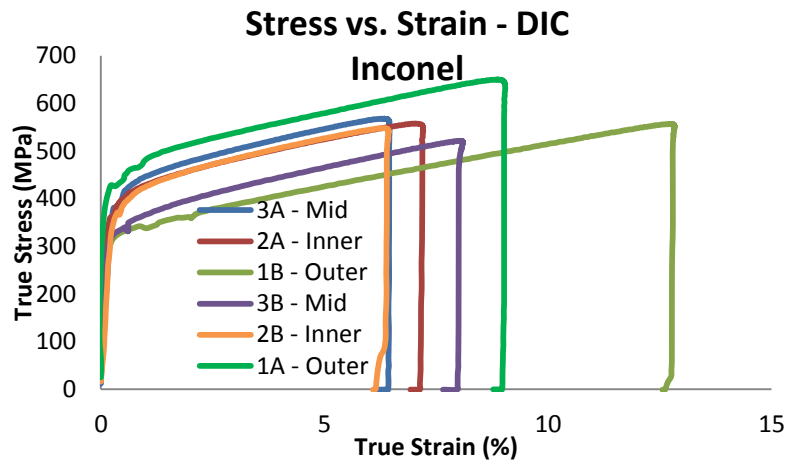


Figure 77: Stress vs. Strain Curves for Inconel as extracted from DIC.

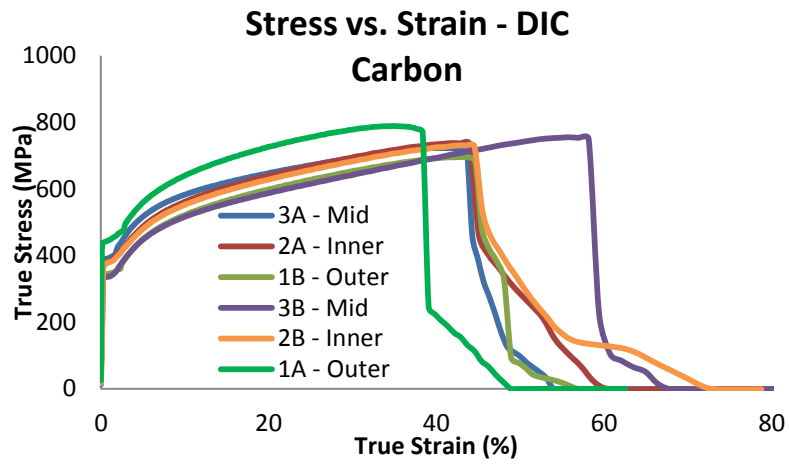


Figure 78: Stress vs. Strain curves for Carbon Steel as extracted from DIC.

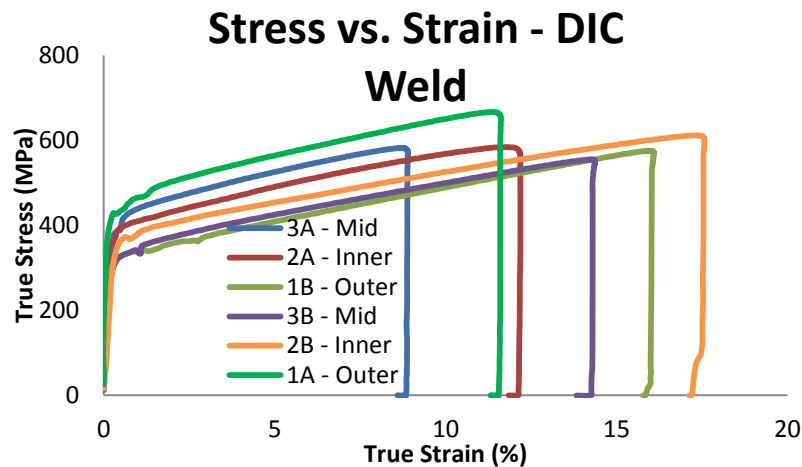


Figure 79: Stress vs. Strain curves for the Inconel 82 weld filler as extracted from DIC.

5.6 Miniature Tensile Testing

The first set of miniature samples was tested using a different tensile machine than the second batch. The second machine is much more rigid and the results are therefore more accurate. The rigidity factor for the new miniature tensile machine ranged between 1.2 and 1.5. This means that the displacement read by the machine is 1.2-1.5 times the real displacement (as determined by the DIC). The rigidity factor for the old tensile machine is not a linear relationship. The elastic portion of the curves is so far off the expected results, that the results were not adjusted. Instead the results for the old tensile machine are shown as comparison purposes and the new tensile results are used to compare to the other testing methods (large tensile test with DIC).

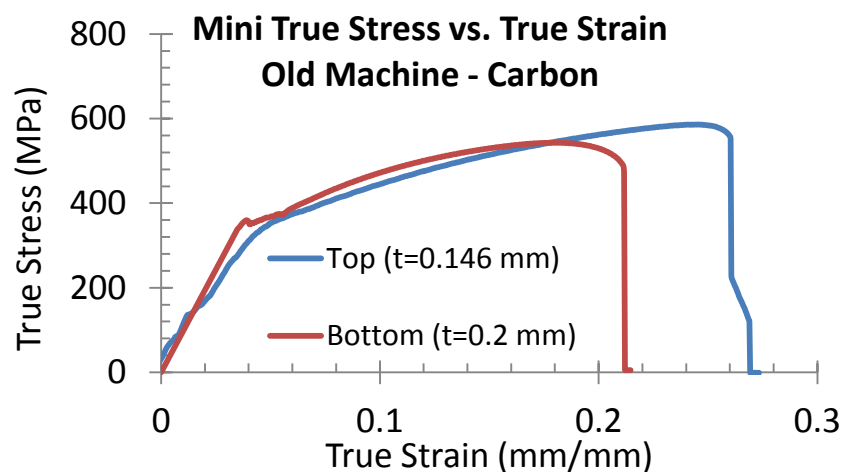


Figure 80: True Stress vs. True Strain for Carbon Steel. Test data from old miniature tensile machine..

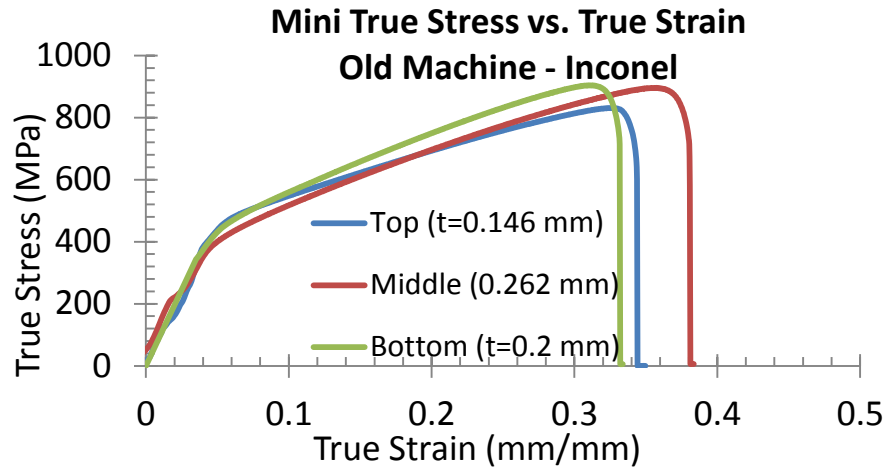


Figure 81: True Stress vs. True Strain for Inconel from old miniature tensile machine.

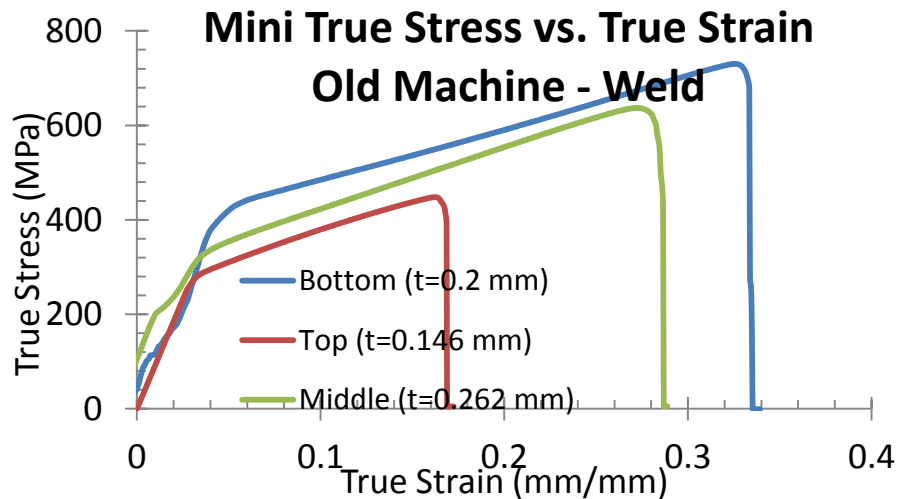


Figure 82: True Stress vs. True Strain for the Weld Region from old tensile machine.

The results shown in Figure 80 show the carbon steel samples taken from different regions. These samples have similar properties but with different levels of failure strains. Figure 81 shows the Inconel small samples from different regions have very similar properties and failure strains. Figure 82 shows that the weld region has varying properties through thickness. According to these results the weld is the weakest/softest at the top and in the middle with the bottom being the hardest/strongest.

The results from the new miniature tensile machine were modified using DIC. As such the results are valid even if significant changes in cross-sectional area occurs (necking). The results from the outer

diameter samples show repeatability as seen in Figure 83. The Inconel region is the strongest material with the highest yield strength. The carbon steel sees the next highest yield strength but the lowest failure stress. The weld region shows very low yield strength but sees a significant increase in strength with straining. The material first deforms elastically in all the materials, then the highest strain is seen in the weld, as the stress increases the maximum strain moves into the carbon region where failure occurs. This is consistent in the outer, middle, and inner samples.

Figure 84 shows the miniature tensile tests for the inner diameter of the pipe. During the Inconel test the camera shutter failed just after the material yielded. Using the yield point and the Inconel curve from the outer sample, the rest of the inner Inconel curve was forecast. One inner carbon sample was destroyed during machining and technical difficulties occurred with the other sample. As such the “2 outer” carbon sample was used in its place. Since there are little variations in the carbon curves seen elsewhere in experiments, this is a reasonable model.

The results from the middle of the pipe show the same trends discussed above. The middle Inconel sample was destroyed during machining. “2 outer” Inconel was used in its place. Inconel shows consistency across the samples so this model reflects what would have been seen.

In these models the weld shows variations in mechanical properties. The outer sample shows the lowest yield with the inner and middle showing significantly higher yield stresses. The outer samples also show the highest failure strains, 15% higher than the others.

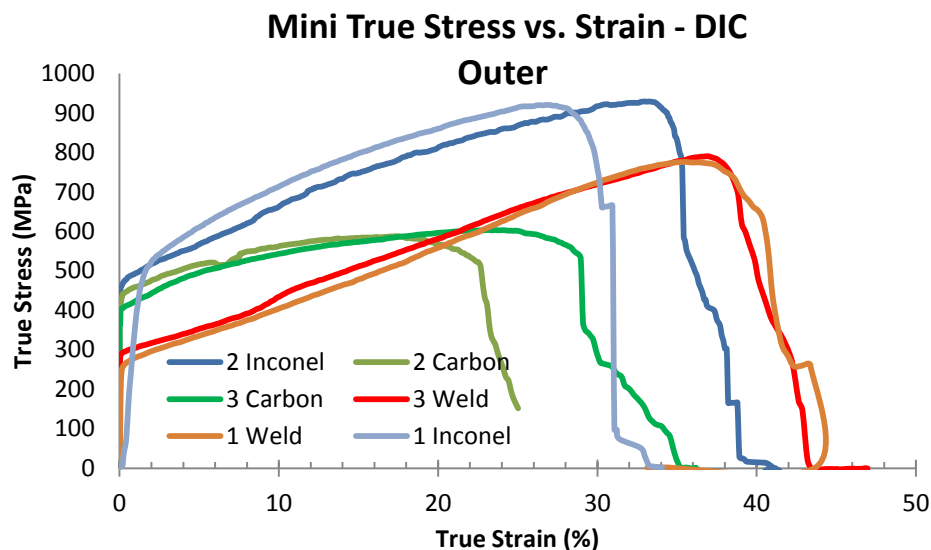


Figure 83: Miniature True Stress vs. True Strain for the Outer diameter of the pipe

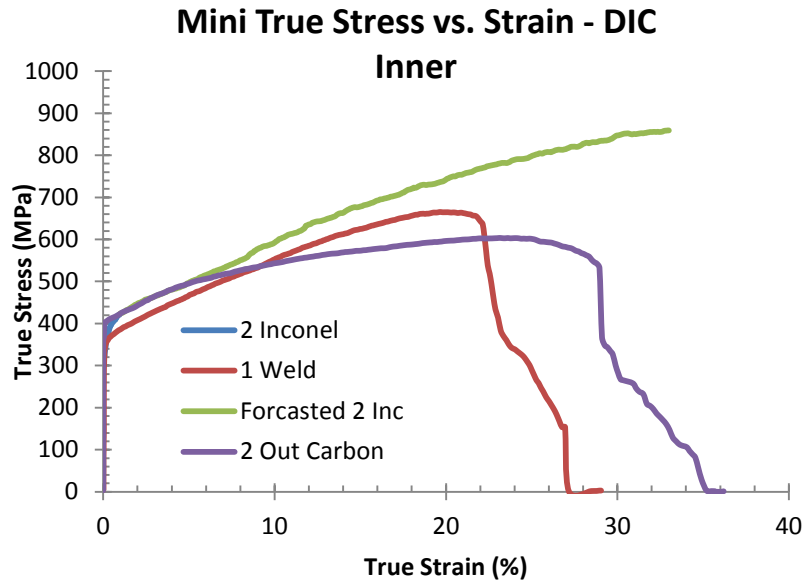


Figure 84: Miniature True Stress vs. True Strain from the Inner Diameter of the Pipe.

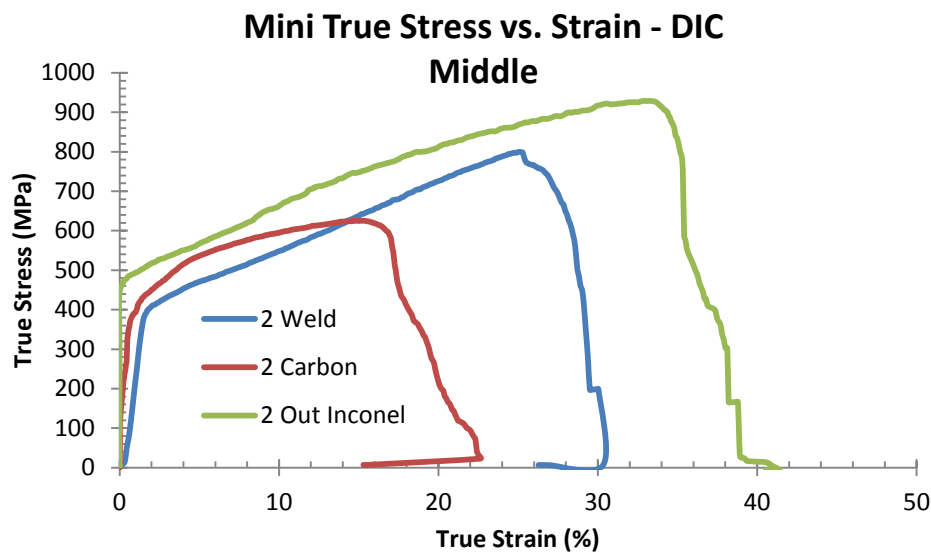


Figure 85: Miniature True Stress vs. True Strain for the middle thickness of the pipe.

The grains are very large (up to 1mm in size) in the weld region. As such some of the grains span the gauge width. These grains can be seen in the DIC as they have different strains than there surrounding.

5.7 Finite Element Model

The finite element model uses elastic and plastic properties from each region. Originally, the data from the large DIC extracted from each region was going to be used but the Inconel and weld regions undergo

very little straining (as the material fails in the carbon region). In the future, a crack is to be introduced into the model in the weld or Inconel regions. If the shortened curves were used the model would not be correct if straining ever surpasses the amount. Instead the miniature tensile samples are used for the Inconel and weld regions with the carbon data coming from the DIC. The curves from the carbon DIC were used instead of those from the miniature tensile samples because the miniature tensile samples were extracted close to the weld which actually represented the heat affect zone of carbon not the bulk. In addition, the inner and middle Inconel elastic properties had to be forecasted as those mini tensile tests had issues (as explained in the previous section). The elastic properties (Young's modulus and Poisson ratio) were taken as seen in Table 17. The plastic properties taken from the experimental data (with the elastic part removed) can be seen in Figure 86, Figure 87, and Figure 88. The plastic properties for Inconel and the weld fit well with polynomial trend lines of degree 2. The trendlines were used instead to help speed up the simulations. The carbon curves contain Luder's plateau and could not be modelled with a trend line so the raw data was used.

Table 17: Elastic properties used in the FEA model

Material	Youngs Modulus	Poisson Ratio
Carbon Steel	210 GPa	0.33
Inconel 600	214 GPa	0.324
Weld (Inconel 82)	214 GPa	0.324

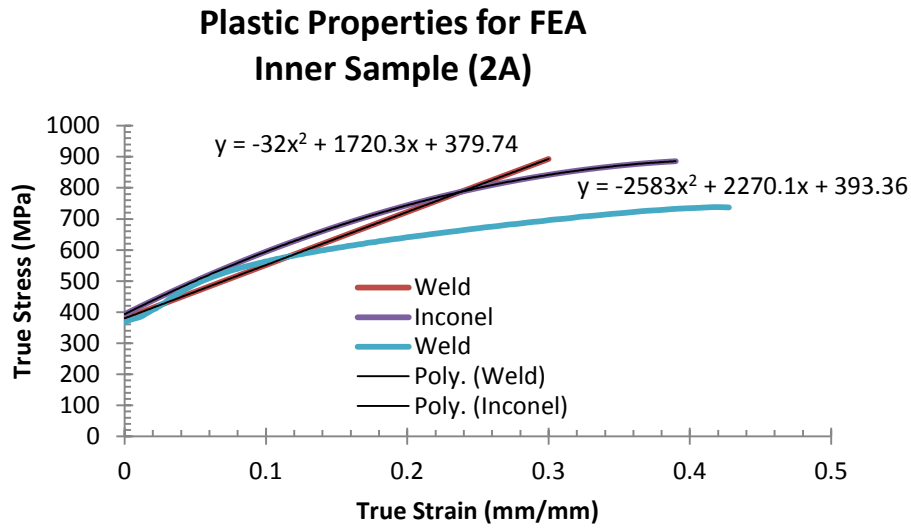


Figure 86: Plastic properties for FEA of the inner sample. This represents sample 2A from the large tensile samples.

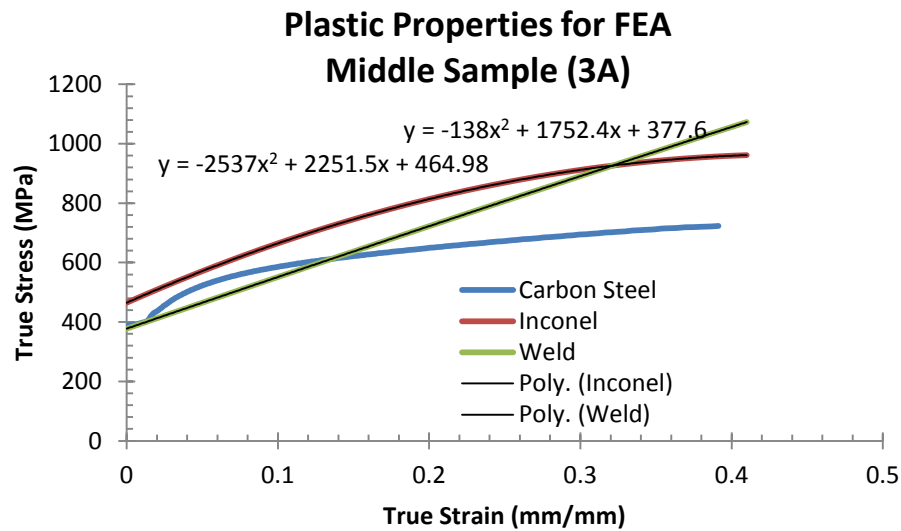


Figure 87: Plastic properties for FEA of the middle sample. This represents sample 3A from the large tensile samples.

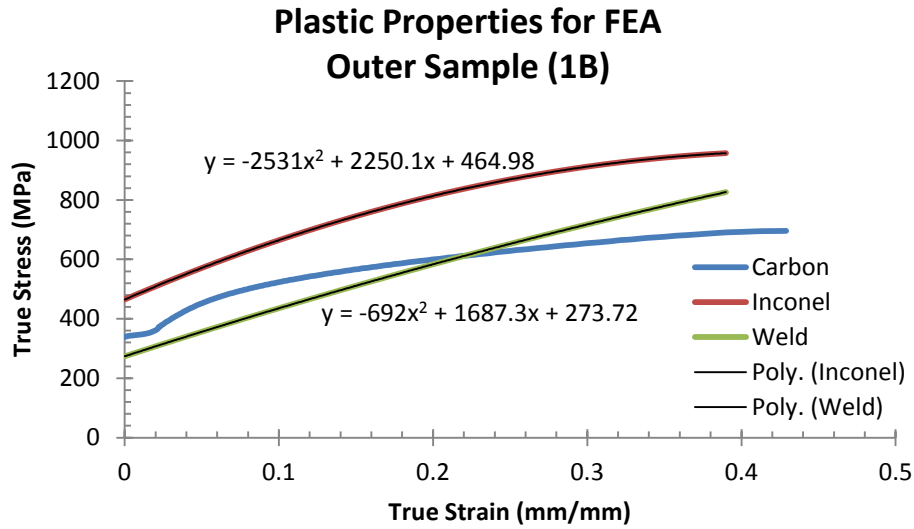


Figure 88: Plastic properties for FEA of the outer sample. This represents sample 1B from the large tensile samples.

The finite element model results for the large tensile samples are shown in Figure 89. The model shows that the middle sample is much softer than the other samples. This is due to the softness of the middle weld properties that were retrieved from the miniature tensile data. The inner curve has the highest failure stress and strain. The outer curve has the lowest failing strain.

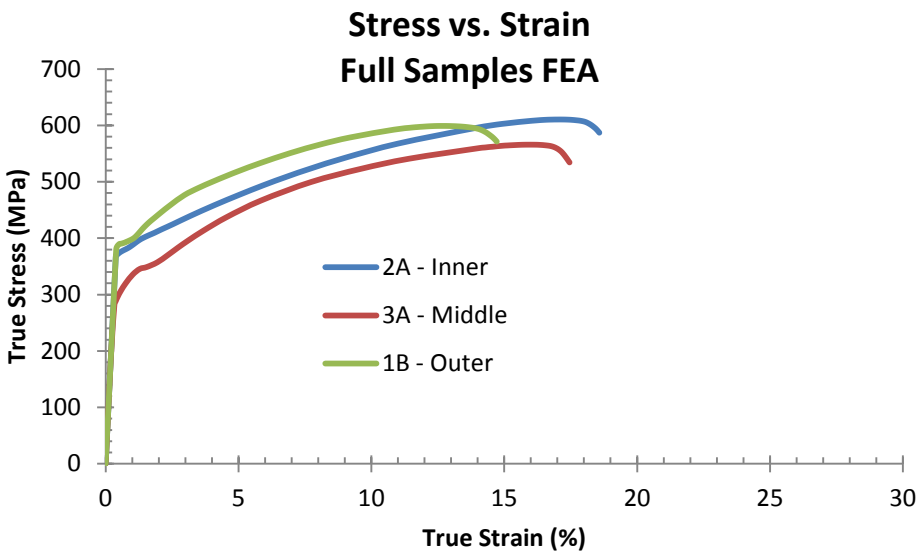


Figure 89: Finite Element Analysis of Large Tensile Samples

Figure 90 shows the evolution of strain in the FEA model at different stresses. The Luder band can be seen propagating in the carbon steel zone up until 400 MPa. The weld and carbon regions then compete for the highest level of strain with the strain eventually isolating in the carbon region after 530 MPa.

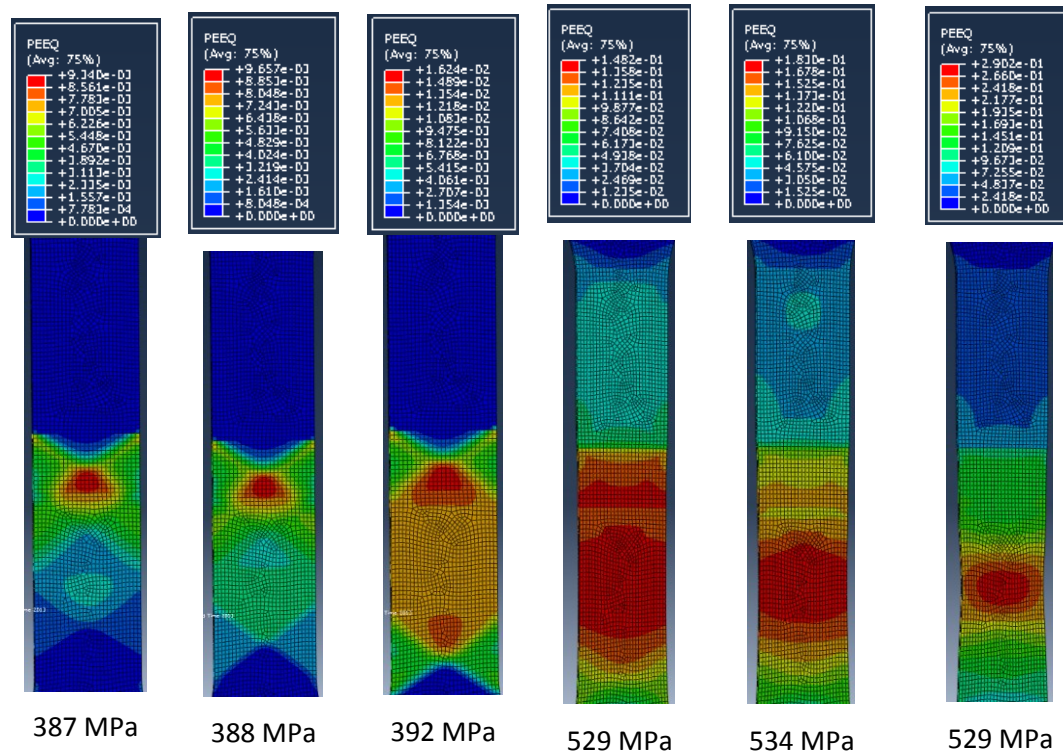


Figure 90: Finite Element Analysis of Large Tensile Sample (3A). The carbon material is at the bottom and the Inconel at the top near the legend. Plastic Equivalent Strain (PEEQ) vs. Engineering Stress

5.8 Artificial Crack Initiation

Figure 91 to Figure 96 are SEM images that show the large tensile testing with DIC and a laser machined crack placed in the weld region. In the first of two tests the sample failed in a brittle manner. The crack propagated in a brittle manner on one side and a ductile manner on the other side of the sample. This was extremely unusual as the material is supposed to be completely ductile. Test 2 was completed and the crack propagated in a ductile manner on both sides, as expected.

*Artificial Crack Test with Large Tensile
Sample – Test 1 Brittle Failure*

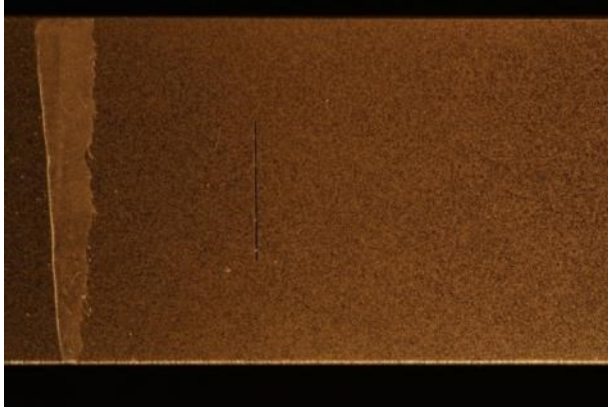


Figure 91: Prior to Loading (Large Tensile with crack Test 1)

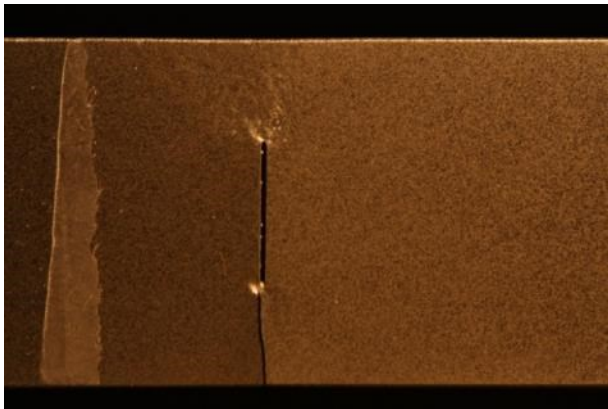


Figure 93: Brittle Failure between crack and bottom edge, top edge still loaded (Large Tensile with crack Test 1)

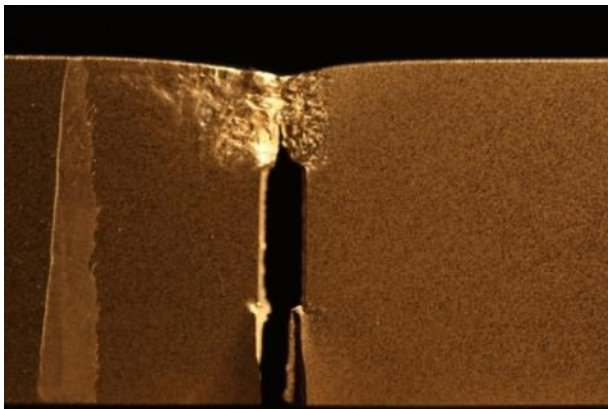


Figure 95: Ductile failure at top edge (Large Tensile with crack Test 1)

*Artificial Crack Test with Large Tensile
Sample – Test 2 Ductile Failure*

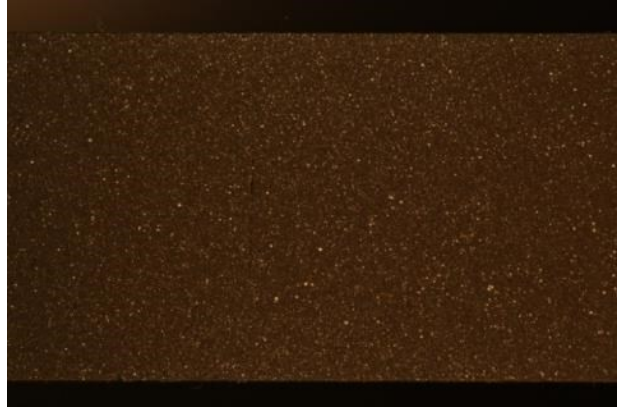


Figure 92: Prior to Loading (Large Tensile with crack Test 2)

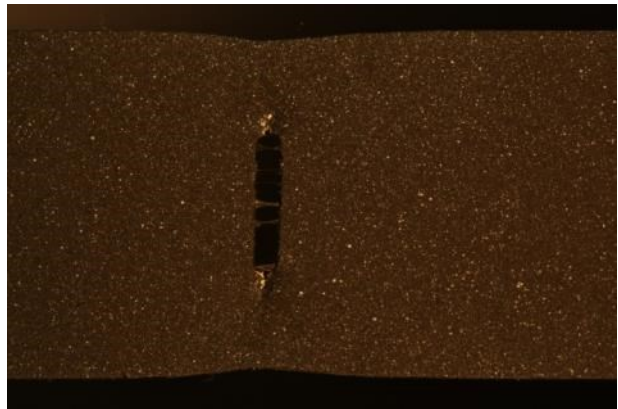


Figure 94: Loaded sample, crack opening in ductile manner (Large Tensile with crack Test 2)

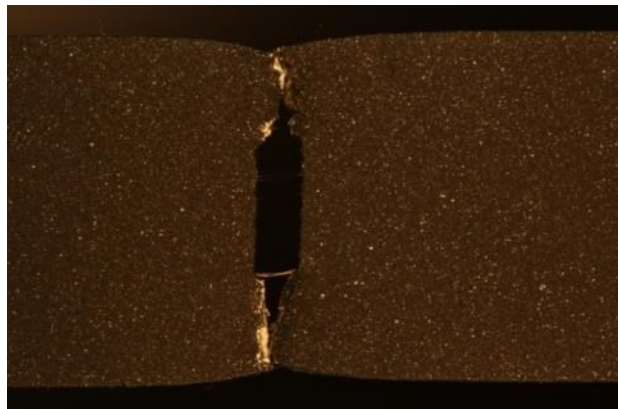


Figure 96: Ductile failure at top and bottom edges (Large Tensile with crack Test 2)

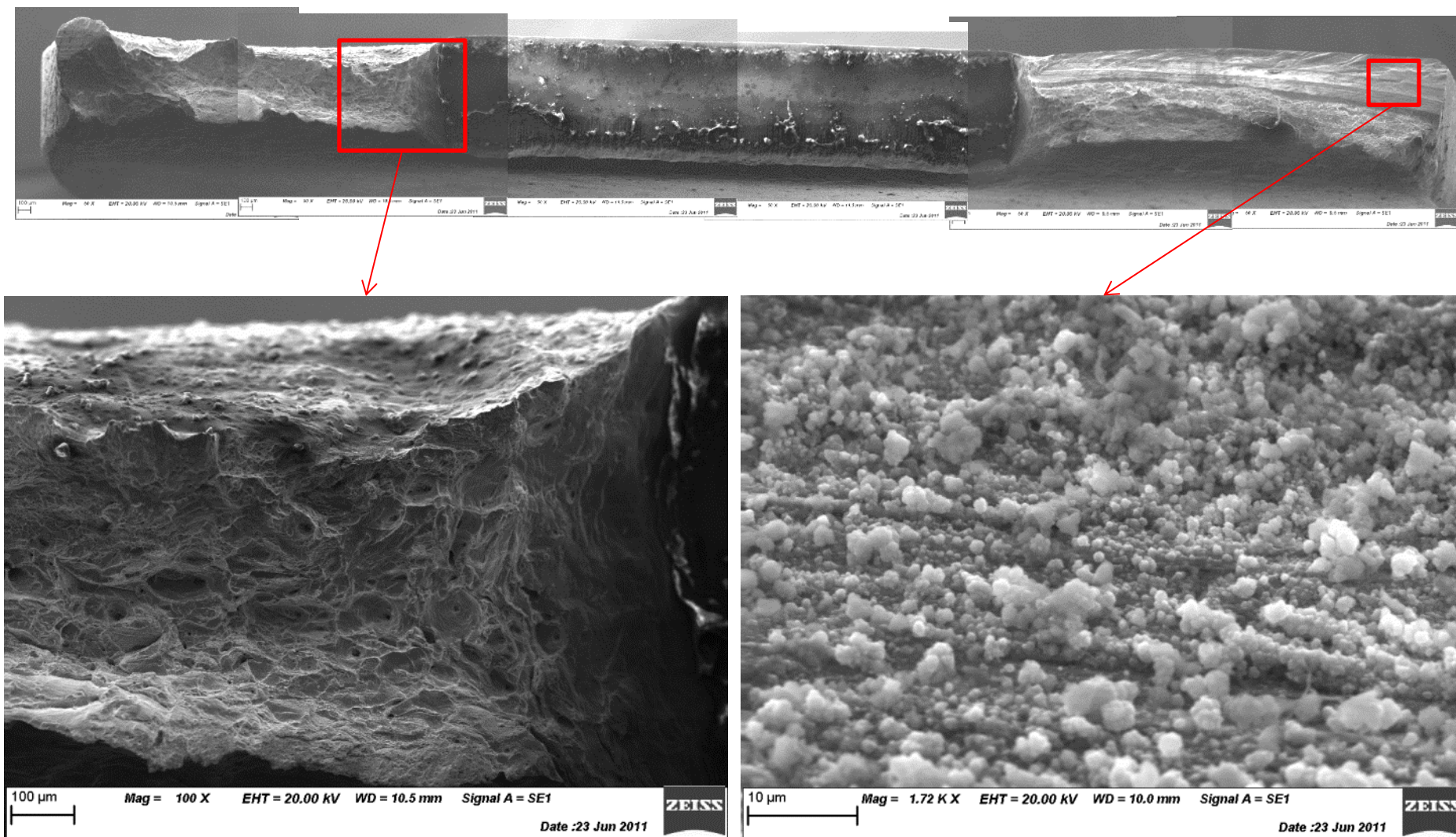


Figure 97: Scanning electron microscope images of the first large tensile test with a crack and DIC. The images show the fracture surface which is ductile on the left and brittle on the right.

Table 18: EDS Scan for composition of ductile area of large sample with crack that failed in brittle manner

Element	Weight%	Atomic%	Report
O K	0.99	3.42	-
Al K	0.54	1.11	-
Cr K	17.03	18.15	16.3
Fe K	8.69	8.62	8.49
Ni K	72.75	68.69	73.7

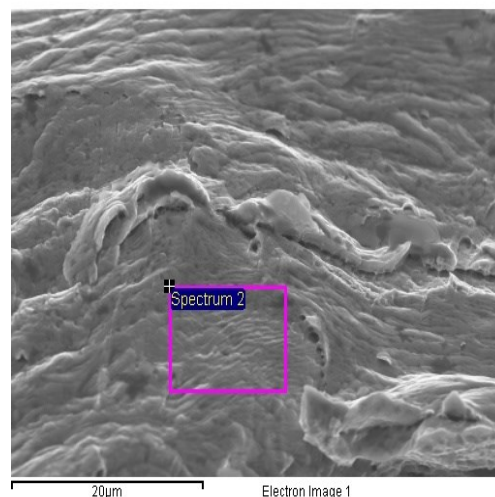
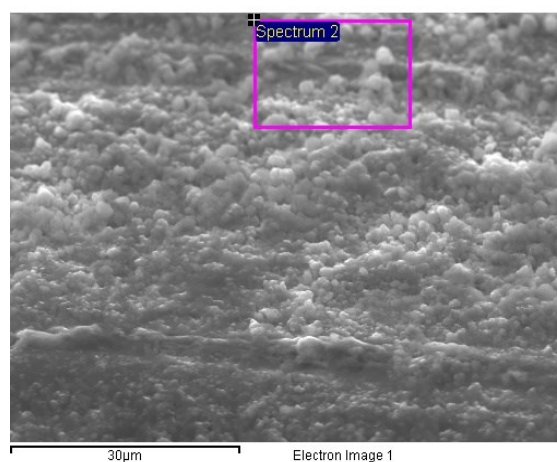


Table 19: EDS Scan for composition of brittle area of large sample with crack that failed in brittle manner

Element	Weight%	Atomic%
O K	33.31	55.53
Mg K	20.79	22.79
Si K	0.24	0.22
Ti K	0.33	0.19
Cr K	8.64	4.43
Mn K	2.98	1.45
Fe K	3.98	1.90
Ni K	29.73	13.50



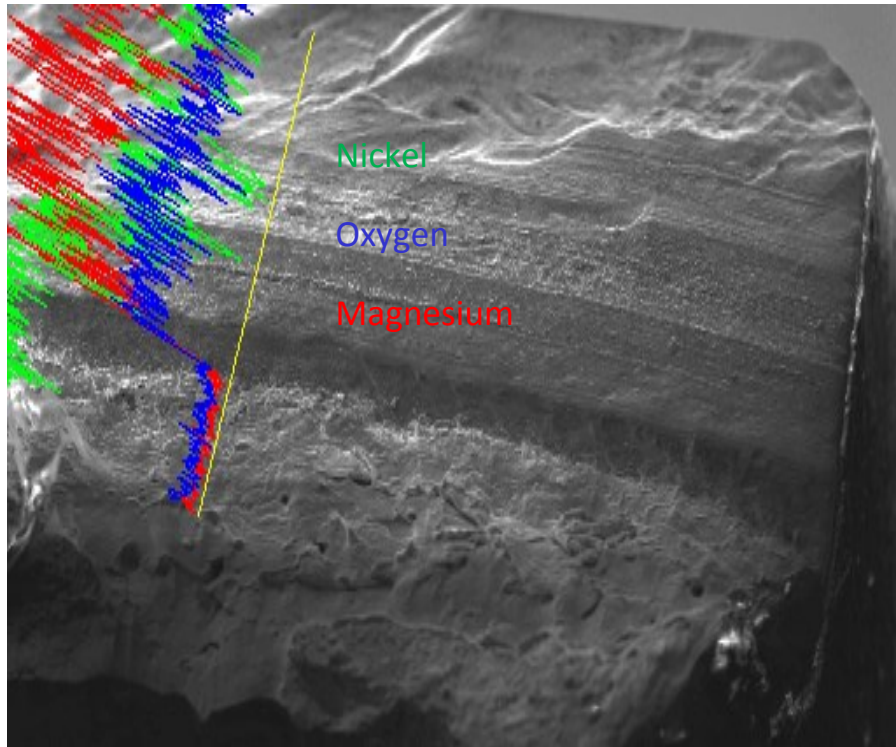


Figure 98: EDS Line Scan of Fracture Surface in Test 1 Brittle Fracture

Figure 98 and Figure 97 show the fracture surface of test 1 of the large tensile test with a crack. The right side of the sample shows a smooth surface in the middle and rough surfaces on the top and bottom. The smooth surface indicated a brittle fracture and the rough surface a ductile fracture. An EDS line scan across that area indicated a large spike in magnesium and oxygen in the brittle area. An EDS point scan confirms an increase in magnesium from negligible to 21 weight percent. Oxygen increased from 1% to 33 weight percent.

6. Discussion

6.1 Temperature Evolution During Welding Process

In order to discuss the effects of the welding process, specifically temperature on the material the welding procedure is required. This information was requested but the company said the information was confidential.

Using a basic understanding of thermodynamics, it is understood that the material closest to the weld will reach very high temperatures. Through conduction the temperature will travel into the rest of the material eventually returning to the ambient temperature at a certain distance away from the weld. It is also understood that the outer edge of pipe and the top of the weld will cool much faster than the middle of the pipe. The inner edge will cool faster than the middle but slower than the outer edge because the air inside the pipe isn't as free to move as outside the pipe.

It was determined that even with this basic understanding, a model would have to be created to understand if the heating could have caused grain growth, recrystallization, and tempering that can be seen near the weld. The Rosenthal Equation was chosen to model the welding process as it is proven and relatively simple [68]. The simple part being critical as almost all variations will have to be assumptions.

Rosenthal used the following assumptions:

1. Steady-state heat flow
2. Point heat source
3. Negligible heat of fusion
4. Constant thermal properties
5. No heat losses from the work piece surface
6. No convection in the weld pool

Looking at the models parameters for a semi-infinite plate in 3-D is best represented by Figure 99. Where the weld pool is travelling in the x direction and the point heat source is at the center of the ellipsoidal shaped weld pool.

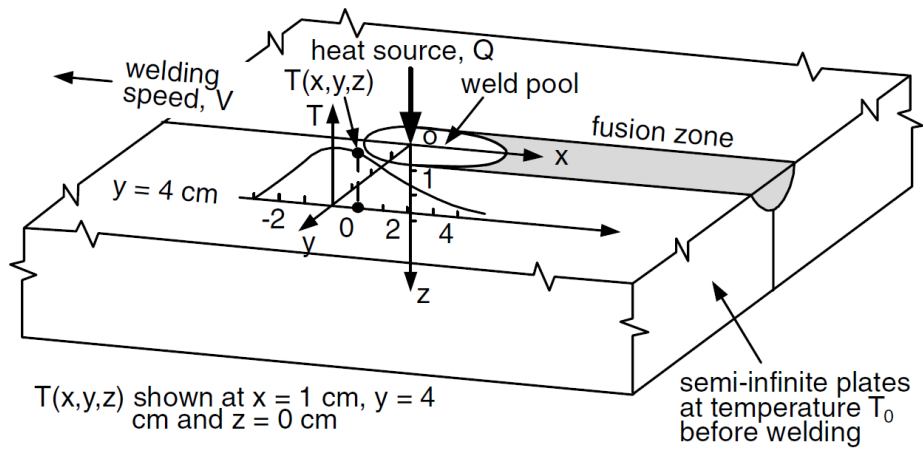


Figure 99: Parameters of the Rosenthal Equation for a semi-infinite plate [68]

Equation 11: Rosenthal 3-D Equation [68]

$$\frac{2\pi(T - T_0)kR}{Q} = \exp\left(\frac{-V(R - x)}{2\alpha}\right)$$

Table 20: Parameters and Definitions for Rosenthal Equation and Model [68]

T	Temperature
T_0	Workpiece temperature before welding
T_m	Workpiece melting temperature
k	Workpiece thermal conductivity
Q	Heat transferred from heat source to workpiece or heat input divided by speed
V	Travel speed
α	Workpiece thermal diffusivity, $\frac{k}{\rho C}$, where ρ is density and C is specific heat of the workpiece
K_0	Modified Bessel function of second kind and zero order
R	Radial distance from the origin or $(x^2 + y^2 + z^2)^{1/2}$

Table 21: Constant Parameters in Welding Model

Quantity	Value	Unit
k	18.3 [68]	J/msK
ρC	3900000 [68]	J/Km ³
Q	2000 [69]	J/s or watt
V	0.0025 [70]	m/s
T_0	300	K
T_m	1673 [68]	K
α	4.69231E-06 (calculated)	m ² /s

We can plot the temperature curves for varying locations and times using Excel. In order to simplify the model further, we set $z=0$ to reduce the model to 2-D which represents the surface of the pipe. The constant parameters for the model are seen in Table 21. Figure 100 shows the first set of temperature curves. It represents a snap-shot in time where the point heating source is now at $x=0$ but has just travelled from $x = 0.1$ m. The temperature at a given distance in the y -direction (in meters) is plotted against the location of the point source (moving in the x direction). The model uses a point heat source which means that at the origin the temperature would be infinity. To make the model more realistic, a maximum temperature is set to the melting temperature of Inconel 600. In fact, the points that reach the melting temperature actually represent the weld pool. In our model the $y = 0.005$ curve just reaches the melting temperature and the next curve does not. As such the weld pool has a width of 10 mm (+/- 0.005 m). The melting temperature plateau in Figure 100 is 10 mm in length which represent the length of the weld pool in the x -direction.

In order to understand the temperature effects of the weld on the surrounding material we will look at the temperatures just outside the weld pool ($y = 0.006$ m and higher). Figure 101 shows the

temperature at given y-locations versus time. Note that the weld was actually created with 7 weld passes which means that each point would see elevated temperatures 7 times. In addition, if the weld was not allowed to cool between passes the ambient temperature (in the equation) would increase and the temperature curves would shift upwards every time. This could significantly increase the temperatures near the top of the pipe.

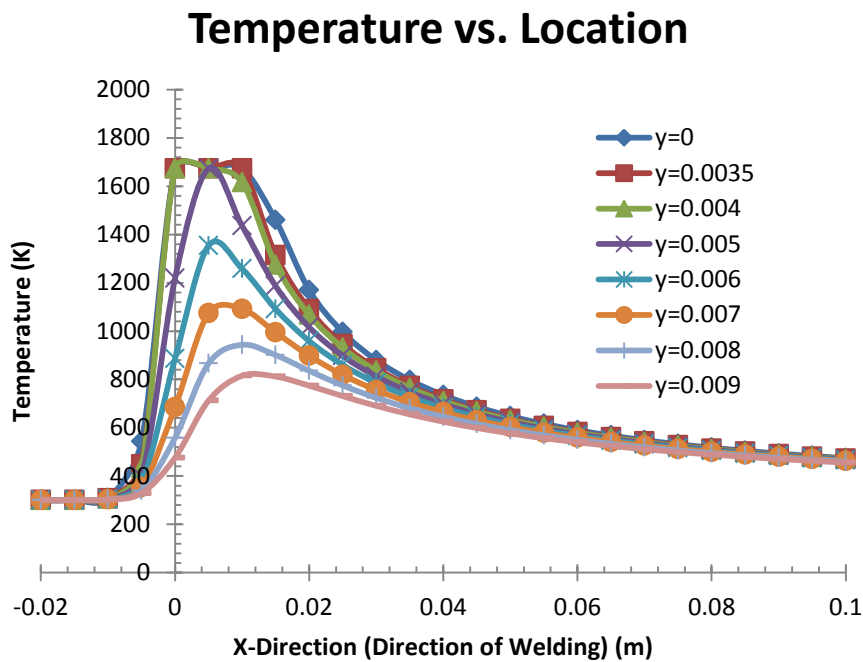


Figure 100: Temperature vs. Location of Rosenthal Welding Model

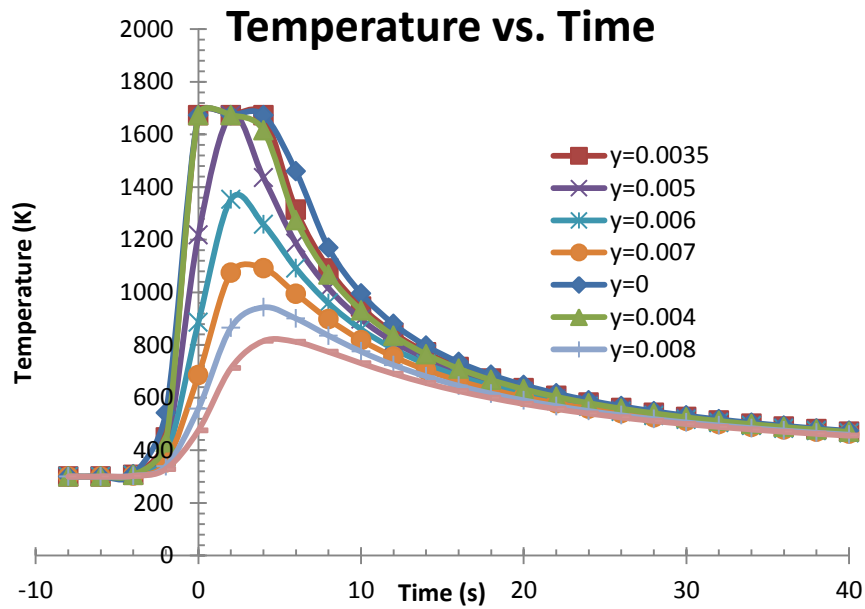


Figure 101: Temperature vs. Location of Rosenthal Welding Model

According to the Rosenthal equation, $y=0.006$ (1 mm from the weld pool) the temperature reaches 1350 K, is above 1200 K for 4 seconds, and is above 1000 K for 7 seconds. At $y=0.007$ (2 mm from the weld) pool the temperature reaches 1090 K and is above 100 K for 5 seconds. At $y=0.008$ (3mm from the weld pool) and $y=0.009$ (4mm from weld pool) the temperature reaches 943 K and 815 K respectively.

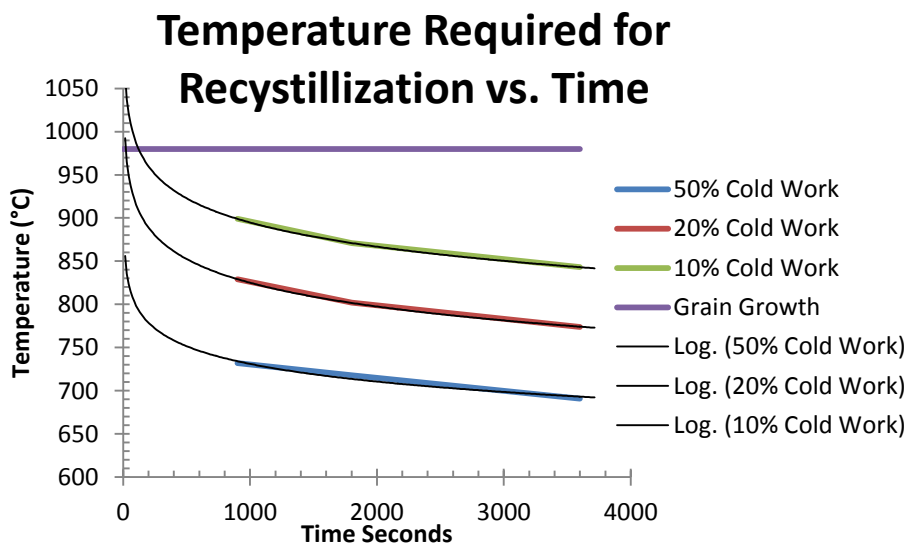


Figure 102: Temperature required for recrystallization vs. time for different amounts of cold work.

The next step is to look at the temperature and time required to manipulate the material, specifically temperature required for grain growth and for recrystallization. From literature the time and temperature required for recrystallization was given in a table format with only a couple of data points. The lowest time in the table is 15 minutes. During welding the heat effects occur over a much shorter time (less than a minute), as such the points are plotted and fit with a logarithmic curve (See Figure 102). This curve is only given as a rough estimate. Literature states the grain growth in Inconel begins at 980 °C, it is also given on Figure 102. According to the model, grain growth could occur for 3 seconds within the first 1 mm of the Inconel heat affected zone. Looking at the images of microstructure in Figure 50, Figure 51, Figure 71, Figure 73, Figure 103, Figure 104, and Figure 105 the area of large grains (above 50 μm) in Inconel is between 200 and 750 μm . The largest heat affected zone for Inconel is in the middle of the pipe (around 750 μm) and tapers down to 200 μm moving towards the inner edge of the pipe. The top of the pipe also shows an Inconel heat affected zone around 200 μm but this area is more difficult to measure as the weld interface is at varying steep angles compared to the rest of the interface (a horizontal measurement would not be perpendicular to the interface and not be accurate).

6.2 Hardness Compared to Temperature, Microstructure, and Composition

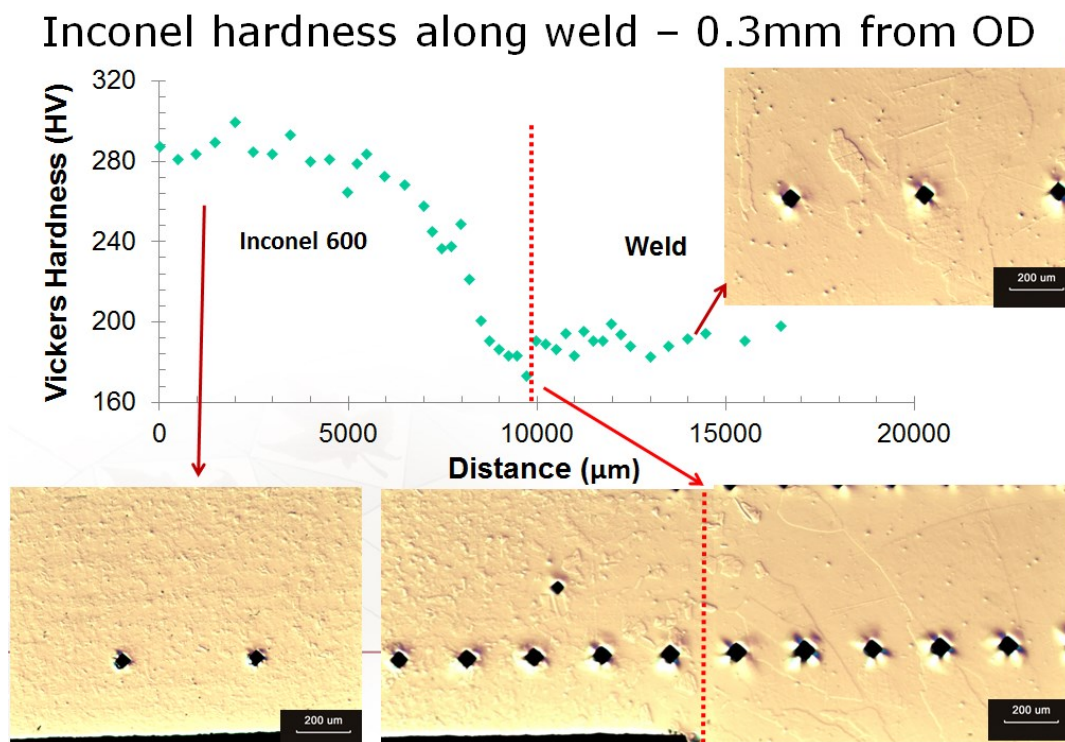


Figure 103: Inconel and Weld hardness near the outer diameter compared to the microstructure

There are several factors that cause the hardness at the top of the Inconel region to decrease near the weld. The first factor is an increasing grain size causing a significant decrease in hardness. Looking at Figure 103, there seems to be one indent in the grain growth area with a hardness of about 175 HV. The next factor is the welding heat releasing the cold working through recrystallization. The cold working occurred when the original Inconel pipe was machine from a solid block. The hardness at the outer edge was near 300 HV and near the inner edge was 180 HV away from the weld. According to literature, Inconel 600 with hardness near 300 HV has been cold reduced by approximately 40%. Using the logarithmic approximation in Figure 102 the temperature required for recrystallization over a very short period of time (seconds) is 850 °C. According to the Rosenthal model, that temperature is reached up to 2 mm away from the weld. The prediction can be made that recrystallization is occurring between the grain growth region and 2 mm from the weld near the top of the pipe. The recrystallization results in a hardness between 190 and 205 HV. There is an increase in hardness between 2 mm and 5 mm away from the weld. Here there are still elevated temperatures which would cause a tempering effect on the material. The tempering effect decreases hardness and is a stronger effect closer to the weld. Tempering no longer has an effect on the material further than 5 mm away from the weld.

The composition was analyzed along the same path as the hardness and no trend was observed. In addition a line scan was completed at the interface revealing no gradient in composition. As such, the composition is not a factor in the changes in hardness.

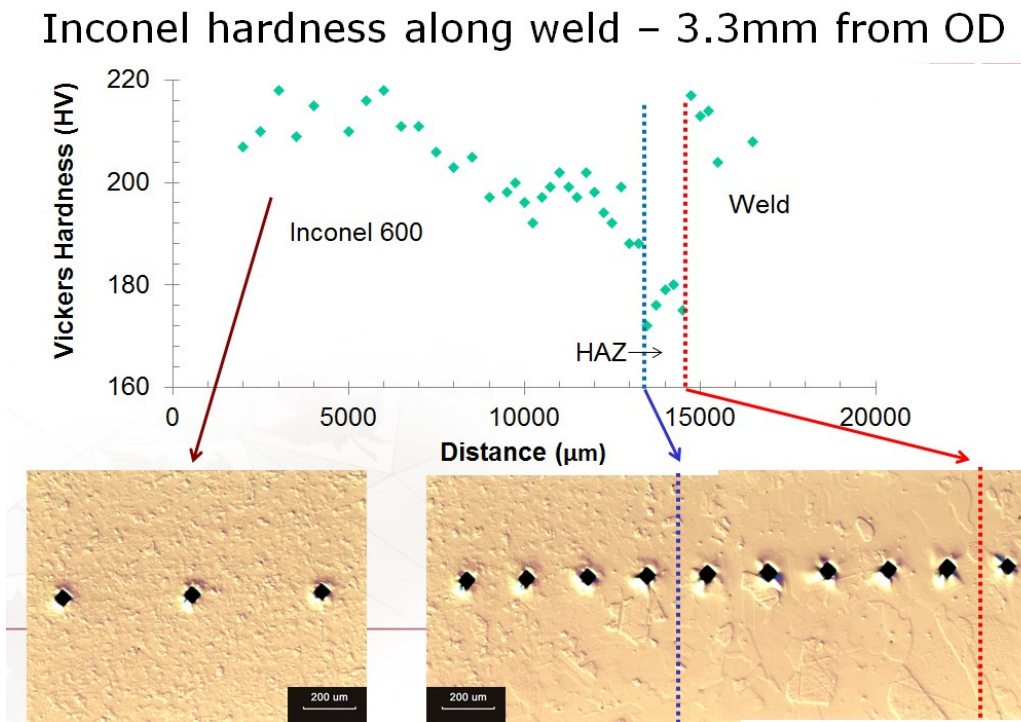


Figure 104: Inconel and Weld hardness near the middle of the sample thickness compared to the microstructure

The same two factors that caused the trend near the top of the weld are present in the middle of the weld. At 220 HV, the Inconel 600 near the middle of the weld has seen a cold reduction of approximately 15%. According to the logarithmic estimate in Figure 102 the temperature required for recrystallization over only a few seconds approaches the temperature for grain growth. In Figure 104 there are at least 5 indents with hardness between 170 and 180 HV in the grain growth area (area approximately 750 μm in width). In the Rosenthal model there are many factors that are not accounted for. In the middle of the weld the heat affected zone is more than triple the size of the one in the outer diameter which is not modelled. It is most likely due to the cooling rate in the inside of the pipe being much slower than the outer and inner edge of the pipe. The edges of the pipe are subjected to conduction through the pipe and convection with the outside air. Although the cooling rate is faster at the outer edge as the air in the inside of the pipe is tempered as it is not free to move around like the air on the outside. So even though the model states that the temperatures required for recrystallization are only reached between 750 μm (grain growth) and 1.25 mm (for only 1 second) in the middle of the pipe, it can be predicted that the region is larger than this. The region in hardness between 195 and 205 HV in Figure 104 ends about 5 mm away from the weld. Considering the grain growth region is triple that of the outer region, triple that area of recrystallization of the outer region would give 6 mm zone in the

middle. Given all of this, it is predicted that the area between 0.75 mm and 5 mm in the middle has seen recrystallization. The gradient in hardness between 5 and 10 mm away from the weld is from tempering effects.

Like the top of the weld, the composition was analyzed along the same path as the hardness and no trend was observed. In addition a line scan was completed at the interface revealing no gradient in composition. As such, the composition is not a factor in the changes in hardness.

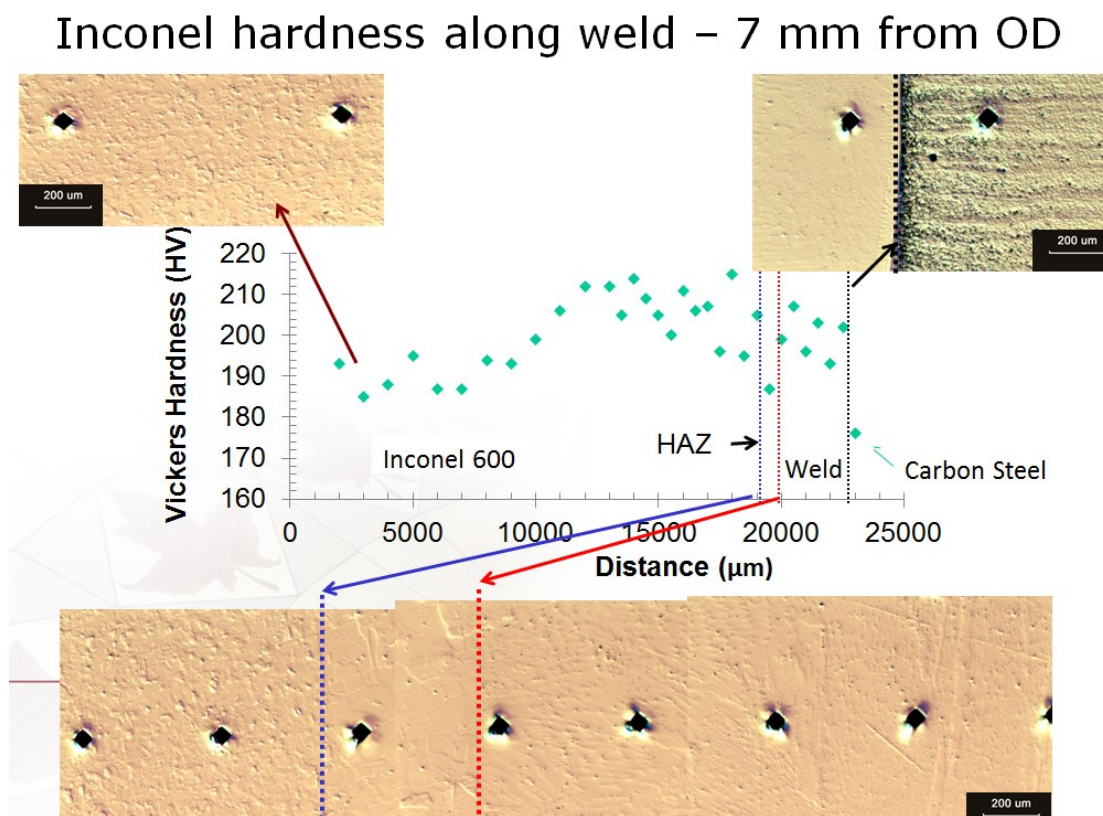


Figure 105: Inconel, Weld, and Carbon Steel hardness as compared to the microstructure

The Inconel pipe saw little to no cold working near the inner edge of the pipe. As such, the trend of decreasing hardness does not occur. The region of grain growth only contains 1 indent as seen in Figure 105. This indent has a hardness of around 180 HV. This agrees with the hardness seen in the areas of grain growth in the outer and middle of the pipe. There is a plateau of elevated hardness of around 200 HV between 0.25 and 6 mm away from the weld. This hardness corresponds to the same hardness seen in the recrystallized areas in the outer and middle weld. As such it is predicted that the area between 0.25 and 6 mm undergoes recrystallization.

Unlike elsewhere in the weld, the bottom saw some composition changes. But these changes did not make it into the Inconel region (or the Inconel heat affected zone). The carbon steel interface has a partially mixed zone, where a region of carbon steel composition can be seen within the weld matrix. The iron from the carbon steel region had also migrated throughout the first weld pass, all the way to the Inconel interface. The amount of iron was 38% (by weight) in the weld near the bottom which is significantly higher than the 8-9% observed elsewhere (and 3% in literature). The increase in iron caused a relative decrease in nickel (70%+ elsewhere down to 48%).

6.3 Miniature Stress vs. Strain Compared to Hardness and DIC

The miniature tensile tests that were adjusted using DIC show a good fit with the curves that were extracted by region from the large DIC tests as seen in Figure 106, Figure 107, and Figure 108. At all three thicknesses, the mini weld sample yielded before the large DIC one. Even though they yielded earlier they saw a significant increase in strength with a high failure stress. The lower yield stress but high failure stress is due to relationships with the adjoining grains and material (constraining effect). The mini carbon steel curves see a higher yield point than the large DIC curves. The mini carbon samples were taken close to the weld and were actually in the heat affected zone of carbon. The large DIC results were extracted from the bulk of the carbon.

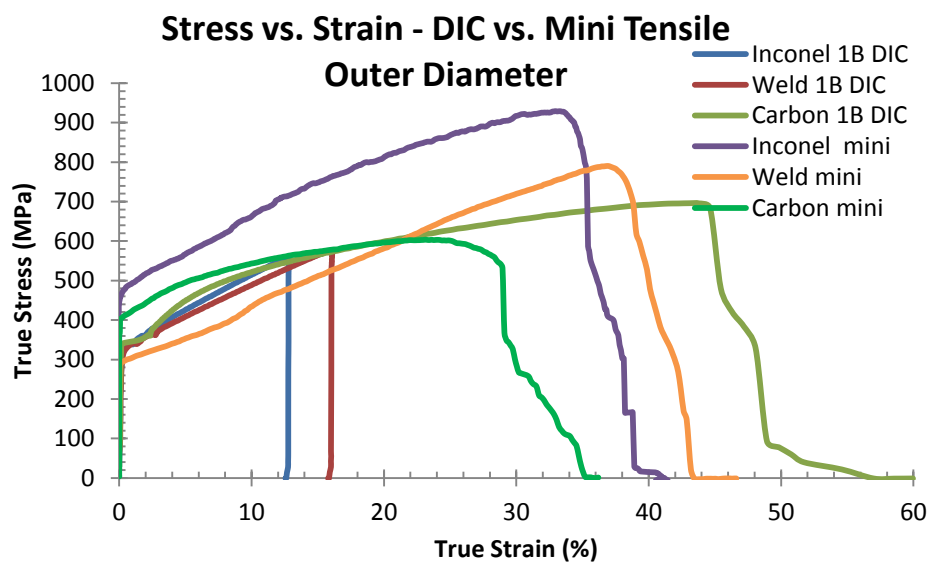


Figure 106: True Stress vs. True Strain for the outer diameter of the pipe. Comparing small curves as extracted from large DIC samples and small curves as extracted from mini samples with DIC.

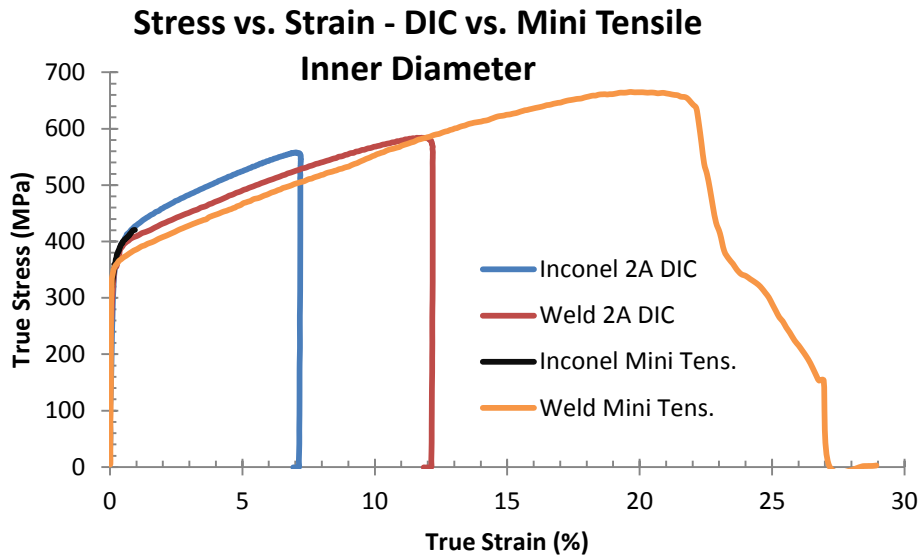


Figure 107: True Stress vs. True Strain for the inner diameter of the pipe by region. It compares the small curves as extracted from the large DIC versus the small curves as extracted from the mini samples with DIC

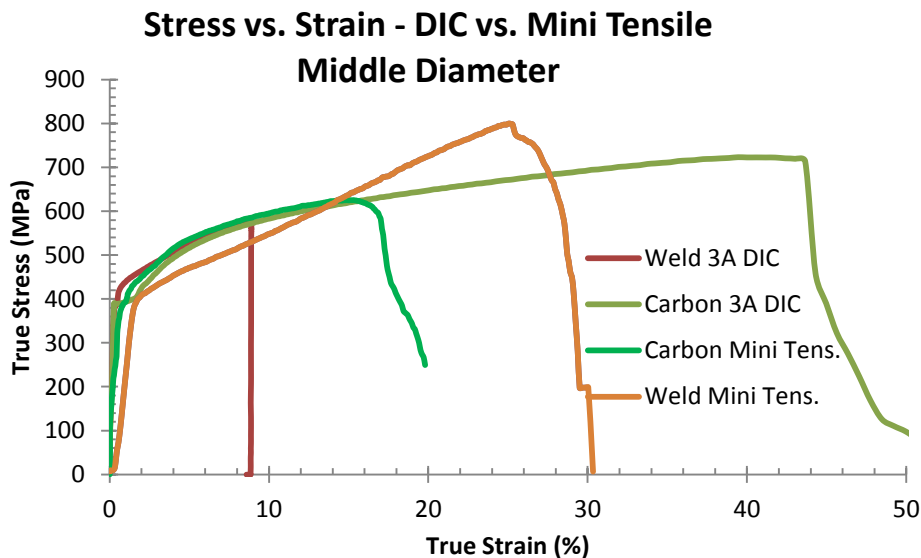


Figure 108: True Stress vs. True Strain of middle of the pipe. Comparing small curves as extracted from large DIC to small curves as extracted from the mini samples.

The weld region had properties that differ from literature. There are two reasons the weld region deforms more than the Inconel region even though in literature they have similar properties. The first one is the large grains in the weld orient themselves in the direction of strain. Since the grain size is so large the rotation causes significant strain. The other reason is dislocation motion. The dislocations in

the Inconel pipe are locked due to the original cold working. The dislocations in the weld are more free to move due to the large grain size. In addition the bottom of the weld, specifically the root pass, saw a large increase in iron content with a decrease in nickel content. The increase in iron causes the weld near the bottom to have a higher yield stress and a lower failure strain.

6.4 Large Stress vs. Strain Compared to Finite Element Analysis

The finite element model fit well with the large tensile samples. The failure strains of the middle and outer samples match with the experimental data. The failure strain of the inner FEA model was much higher than expected. Looking at the experimental data and the models it is observed that the failure strain is proportional to the width of the weld region. Meaning the larger the weld width the larger the failure strains. Although the FEA model for sample 2A-inner does not agree with this, every experimental test agrees with this trend. The yielding stress for the outer sample in the FEA model was lower than the experimental data. The weld region curve used in the FEA for the middle model was lower than the other weld regions. Although all the mini weld tests were below the DIC data, the outer samples weld curve was much lower. In this case, the model is deemed to be less accurate and the miniature tensile test should be repeated from the outer weld region. The FEA models were able to show the Luder band propagation and the maximum strain transitioning between the weld and the carbon steel. All the models failed in the carbon steel zone which agrees with the experiments. Overall, the large tensile samples and the FEA model matched.

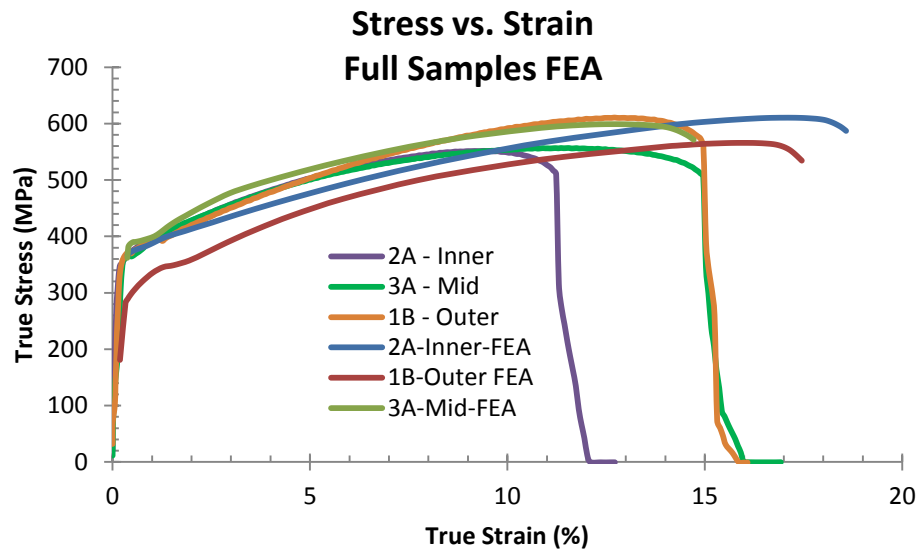


Figure 109: True Stress vs. True Strain comparing large tensile samples as extracted from DIC and the FEA models.

7. Conclusions and Future Work

7.1 Conclusions

This thesis successfully achieved its goals of determining the mechanical properties and creating a model of the Inconel dissimilar metal weld. It partially met the goal of observing fracture mechanisms as it was able to observe fracture in tensile samples but was not able to successfully track crack growth.

From the analysis of the weld region at various length-scales using optical microscopy, micro-hardness testing, small and large scale tensile testing and digital image correlation (DIC) the following conclusions can be made:

1. It was found that large grains were observed in the weld region and HAZ of Inconel. The large grains in the Inconel region were found to be between 0.2 and 0.75 mm in width. Recrystallization and tempering were found to have an effect up to 10 mm away from the weld. Smaller grains were observed in the Inconel and carbon steel base metals. Very small grains were observed in the heat affected zone of carbon steel.
2. Micro-hardness profiles showed variations across the weld and through the weld thickness. This research confirmed variations in stress-strain curves across the weld and through the thickness which emphasized the need for obtaining a complete map of the mechanical properties in the weld region for predictive models to be accurate. These changes were justified in terms of temperature effects from welding and compositional changes in the weld.
3. Large tensile samples were extracted from three different through thickness locations of the welded pipe and were used to observe the properties of the weld as a whole. Luder bands were observed in the carbon region. Significant deformation was observed in the weld region before fracture eventually occurred in the Carbon region.
4. Using digital image correlation, the local strains were observed. A competition for maximum strain was observed between the weld and the Carbon region before failure. Significant deformation was observed in the HAZ on Inconel. Little to no deformation occurred in the HAZ of carbon. The DIC also confirmed the Luder band propagation.
5. Local stress-strain curves were built from the DIC data and compared to stress-strain curves obtained from miniature tensile samples extracted from 9 regions (inner, outer, and middle

thickness of the carbon steel, Inconel and weld regions). The miniature samples confirmed the results from the DIC and extended the Inconel and Weld curves.

6. The stress strain curves by material were inputted in an FEA model of the large scale tensile samples. The FEA model matched with the experimental results. These results confirm that the local-stress strain curves can be used in more complex models.
7. Finally, the local DIC curves are a better representation of what happens in the large sample than the miniature ones. But the miniature tensile tests are better inputs for an FEA model as they consist of the entire stress-strain curve rather than the partial curves from the zones that don't reach failure.

7.2 Future Work

The 4-point bend test was not successful after many modifications of the test (See Appendix D). As such future work should include these samples that are already prepared. The most obvious solution would be using these samples under tensile loading. For this to be done it is recommended that the grips be hinged to allow the samples crack to open. If the grips are fixed the crack would not be allowed to open as much.

Another piece of future work directly related to this thesis would be to repeat some of the miniature tensile tests. Some of the miniature samples were destroyed during machining and others encountered technical difficulties during test. Having more repeatability would add to the credibility of the testing.

Overall, the recommended future work for Inconel dissimilar metal welds is:

1. Using the FEA models from the outer, middle, and inner diameters of the pipe in this thesis, extrapolate between them to create a model of the full pipe.
2. Add a damage model into the FEA so that crack nucleation and growth can be tracked.

Finally, this thesis shows that the heat affected zones are present and affect the materials mechanical properties. As such a better model of the weld would include the three different material regions and the two heat affected zones.

Bibliography

- [1] H. Ragheb, "GNG4128: Introduction to Nuclear Engineering Class Notes." .
- [2] H. Naffakh, M. Shamanian, and F. Ashrafizadeh, "Dissimilar welding of AISI 310 austenitic stainless steel to nickel-based alloy Inconel 657," *Journal of Materials Processing Technology*, vol. 209, no. 7, pp. 3628–3639, Apr. 2009.
- [3] M. Sireesha, S. K. Albert, V. Shankar, and S. Sundaresan, "A comparative evaluation of welding consumables for dissimilar welds between 316LN austenitic stainless steel and Alloy 800," *Journal of Nuclear Materials*, vol. 279, no. 1, pp. 65–76, Mar. 2000.
- [4] M. Sireesha, V. Shankar, S. K. Albert, and S. Sundaresan, "Microstructural features of dissimilar welds between 316LN austenitic stainless steel and alloy 800," *Materials Science and Engineering: A*, vol. 292, no. 1, pp. 74–82, Nov. 2000.
- [5] C. Jang, J. Lee, J. Sung Kim, and T. Eun Jin, "Mechanical property variation within Inconel 82/182 dissimilar metal weld between low alloy steel and 316 stainless steel," *International Journal of Pressure Vessels and Piping*, vol. 85, no. 9, pp. 635–646, Sep. 2008.
- [6] Special Metals, "INCONEL alloy 600 - Specifications Sheet."
- [7] American Piping Products, "A106 Pipe Specifications."
- [8] H. Shah Hosseini, M. Shamanian, and A. Kermanpur, "Characterization of microstructures and mechanical properties of Inconel 617/310 stainless steel dissimilar welds," *Materials Characterization*, vol. 62, no. 4, pp. 425–431, Apr. 2011.
- [9] F. Iwamatsu, K. Miyazaki, and K. Saito, "Estimation of Maximum Load for Pipes with Multiple Circumferential Flaws by Limit Load Analysis," *ASME 2011 Pressure Vessels & Piping Division Conference*, vol. PVP2011, no. 57876, Jul. 2011.
- [10] H. Machida, T. Hamanaka, and Y. Takahashi, "Fracture Assessment of Pipe Having Multiple Flaws Based on Ramberg-Osgood-Type Stress-Strain Relationships," *ASME 2011 Pressure Vessels & Piping Division Conference*, vol. PVP2011, no. 57859, Jul. 2011.
- [11] K. Suga, K. Miyazaki, R. Senda, and M. Kikuchi, "Ductile Fracture Simulation of Multiple Surface Flaws," *ASME 2011 Pressure Vessels & Piping Division Conference*, vol. PVP2011, no. 57147, Jul. 2011.
- [12] K. Suga, S. Kawasaki, K. Miyazaki, and Y. Arai, "Study of The Interaction of Multiple Flaws in Ductile Fracture Process," *ASME 2011 Pressure Vessels & Piping Division Conference*, vol. PVP2011, no. 57188, Jul. 2011.

- [13] K. Miyazaki, K. Hasegawa, and K. Saito, "Effect of Flaw Dimensions on Ductile Fracture Behavior of Non-Aligned Multiple Flaws in a Plate," *ASME 2011 Pressure Vessels & Piping Division Conference*, vol. PVP2011, no. 57559, Jul. 2011.
- [14] K. Hasegawa, K. Miyazaki, and K. Saito, "Plastic Collapse Loads for Flat Plate with Dissimilar Non-Aligned Through Wall Cracks," *ASME 2011 Pressure Vessels & Piping Division Conference*, vol. PVP2011, no. 57841, Jul. 2011.
- [15] Z. Jianping and W. Wang, "Numerical Simulation and Experiment of Interaction and Influence on Two Colinear and Offset Cracks by FRANC2D Software," *ASME 2011 Pressure Vessels & Piping Division Conference*, vol. PVP2011, no. 57448, Jul. 2011.
- [16] W. J. Mills and C. M. Brown, "Fracture Toughness of Alloy 600 and an EN82H Weld in Air and Water," *Metallurgical and Materials Transactions*, vol. 32A, May 2001.
- [17] C. Leitão, I. Galvão, R. M. Leal, and D. M. Rodrigues, "Determination of local constitutive properties of aluminium friction stir welds using digital image correlation," *Materials & Design*, vol. 33, no. 0, pp. 69–74, Jan. 2012.
- [18] H. Song, Y. Kang, and X. Xiao, "Experimental analysis of crack tip fields in rubber materials by 3D Digital Image Method," *Procedia Engineering*, vol. 10, no. 0, pp. 3369–3374, 2011.
- [19] A. Joseph, A. Ramesh, T. Jayakumar, and N. Murugan, "Failure analysis of a dissimilar weld joint in steam generator," *Pract Metallogr*, 2001.
- [20] C. Lundin, "Dissimilar metal welds—transition joints literature review," *Weld J*, 1982.
- [21] R. Klueh, J. King, and J. Griffith, "A simple test for dissimilar-metal welds," *Weld J*, 1983.
- [22] Internal Report No. IGC/DPEND/NDTES/FA1/1998., "Failure Analysis of Thermowell Boss of Fast Breeder Test Reactor (FBTR) Steam Generator," *Unpublished*, Sep. 1998.
- [23] S. Davis, "Hard facing, weld cladding and dissimilar metal joining, welding brazing and soldering," *ASM Handbook*, vol. 6, no. Ohio: ASM International, pp. 789–829, 1993.
- [24] American Welding Society, "Dissimilar metals," *Welding Handbook, 7th Edition*, vol. 4, pp. 514–47, 1992.
- [25] W. Jones, "Heat treatment effect on 2CR Mo joints welded with a nickel-based electrode," *Weld J*, 1974.
- [26] H. Thielsch, "Stainless steel weld deposit on mild steel and alloy steels," *Weld J*, 1952.
- [27] J. Rutherford, "Welding stainless steel to carbon or ferritic steel," *Weld J*, 1959.
- [28] J. Eckel, "Diffusion across dissimilar metal joints," *Weld J*, 1964.

- [29] T. Rowley, T. Rowberry, and C. Alldrige, "Problems associated with the design, inspection and use of large diameter ferritic/austenitic joints in power plate, proceedings or international conference welding dissimilar metals," *Met Constr BR Weld J*, 1969.
- [30] R. Christoffel and R. Curran, "Carbon migration in welded joints at elevated temeprature," *Weld J*, 1956.
- [31] L. Wyatt, "Dissimilar metal joints used in the steam circuit of electrical generating plates, proceeding of internation conference welding dissimilar metals," *Met Constr BR Weld J*, 1969.
- [32] R. Klueh, "The effect of carbon on 2.25Cr-1Mo steel (I) microstructure and tensile properties," *J Nucl Mater*, 1974.
- [33] R. Klueh, "The effect of carbon on 2.25Cr-1Mo steel (II) creep- rupture properties," *J Nucl Mater*, 1974.
- [34] R. Klueh and J. King, "Austenitic-ferritic weld joint failures'," *Weld J*, 1982.
- [35] R. Emerson and W. Hutchinson, "Welded joints between dissimilar metals in high temperature service," *Weld J*, 1952.
- [36] V. Roschin, "Residual stresses in pipe joints between dissimilar steels," *Weld Prodn*, 1969.
- [37] J. Williams, "Residual stresses in austentic-ferritic transition joints fabricated with austenitic weld metal," *High Temp Technol*, 1984.
- [38] A. Joseph, S. K. Rai, T. Jayakumar, and N. Murugan, "Evaluation of residual stresses in dissimilar weld joints," *International Journal of Pressure Vessels and Piping*, vol. 82, no. 9, pp. 700–705, Sep. 2005.
- [39] R. Singh Raman, "Role of microstructural degradation in the heat affected zone of 2.25Cr-1Mo steel weldments and sub scale features during steam oxidation and their role in weld failures," *Metal Mater Trans A*, 1998.
- [40] J. Tucker and F. Eberle, "Development of ferritic-austentic weld joint for steam plant application," *Weld J*, 1956.
- [41] R. Bruscato, "Temper embrittlement and creep embrittlement of 2.25Cr-1Mo shielded metal arc weld deposits," *Weld J*, 1970.
- [42] R. Swift and J. Gulya, "Temper embrittlement of pressure vessel steels," *Weld J*, 1973.
- [43] R. Swift and H. Rogers, "Embrittlement of 2.25Cr-1Mo steel weld metal by post weld heat treatment," *Weld J*, 1973.
- [44] J. Hou, Q. Peng, Y. Takeda, J. Kuniya, and T. Shoji, "Microstructure and stress corrosion cracking of the fusion boundary region in an alloy 182-A533B low alloy steel dissimilar weld joint," *Corrosion Science*, vol. 52, no. 12, pp. 3949–3954, Dec. 2010.

- [45] K. Tohgo, H. Suzuki, Y. Shimamura, G. Nakayama, and T. Hirano, "Monte Carlo simulation of stress corrosion cracking on a smooth surface of sensitized stainless steel type 304," *Corrosion Science*, vol. 51, no. 9, pp. 2208–2217, Sep. 2009.
- [46] H. P. Seifert, S. Ritter, T. Shoji, Q. J. Peng, Y. Takeda, and Z. P. Lu, "Environmentally-assisted cracking behaviour in the transition region of an Alloy182/SA 508 Cl.2 dissimilar metal weld joint in simulated boiling water reactor normal water chemistry environment," *Journal of Nuclear Materials*, vol. 378, no. 2, pp. 197–210, Aug. 2008.
- [47] M. Kikuchi, K. Suga, Y. Wada, and C. Ohdama, "Numerical Simulation of Coalescence Behavior of Multiple Surface Cracks," *ASME 2011 Pressure Vessels & Piping Division Conference*, vol. PVP2011, no. 57155, Jul. 2011.
- [48] ASME B&PV Code Section XI, "Rules for In-service Inspection of Nuclear Power Plant Components," 2007.
- [49] American Petroleum Institute, "Recommended Practice for Fitness-for-Service, Second Edition," *API 579-1/ASME FFS-1*, no. Second Edition, Jun. 2007.
- [50] The Japan Society of Mechanical Engineers, "Rules on Fitness-for-Service for Nuclear Power Plants (in Japanese)," *JSME S NA1*, Dec. 2008.
- [51] British Standard Institution, "Guide to Method for assessing the Acceptability of Flaws in Metallic Structures," *BS 7910*, Jul. 2005.
- [52] French Association for Design, Construction and, In-Service Inspection Rules for Nuclear Island, and Components, "In-Service Inspection Rules for the Mechanical Components of PWR Nuclear Islands," *RSE-M*, no. 3rd Addendum, 2005.
- [53] Forschungskuratorium Maschinenbau, "Fracture Mechanics Proof of Strength for Engineering Components," *FKM Guideline*, no. 2nd Revised Edition, 2004.
- [54] Commission of Energy Atomic, "Guide for Defect Assessment and Leak Before Break Analysis," *A16*, 1995.
- [55] Chinese Standard Committee, "Safety Assessment for In-service Pressure Vessels containing Defects (in Chinese)," *GB/T 19624-2004*, Dec. 2004.
- [56] M. Kocak, H. Hadley, I. Szavai, T. Tkach, and N. Taylor, "FITNET fitness-for-service procedures," *Vol. II*, Jan. 2008.
- [57] The Japan Welding Engineering Society, "Method of Assessment for Flaws in Fusion Welded Joints with Respect to Brittle Fracture and Fatigue Crack Growth (in Japanese)," *WES 2805*, 2008.

- [58] K. Miyazaki, K. Saito, K. Hasegawa, and B. Bezensek, "Experimental study of ductile fracture for non-aligned multiple flaws in a plate," *2009 ASME Pressure Vessels and Piping Division Conference*, no. PVP2009-77103, 2009.
- [59] D.-J. Shim, G. M. Wilkowski, and D. L. Rudland, "Determination of the elastic-plastic fracture mechanics Z-factor for alloy 182 weld metal flaws," *International Journal of Pressure Vessels and Piping*, vol. 88, no. 5-7, pp. 231-238, May.
- [60] G. M. Wilkowski, U. S. N. R. C. O. of N. R. R. D. of E. Safety, and B. M. I. C. Laboratories, *Analysis of experiments on stainless steel flux welds*. Division of Engineering Safety, Office of Nuclear Regulatory Research, U.S. Nuclear Regulatory Commission, 1987.
- [61] H. Richard, M. Fulland, and M. Sander, "Theoretical crack path prediction," *Fatigue & Fracture Engineering Materials & Structures*, vol. 28, pp. 3-12, 2005.
- [62] D. dell' Erba and M. Aliabadi, "On the solution of three-dimensional thermo-elastic mixed-mode edge crack problems by the dual boundary element method," *Engineering Fracture Mechanics*, vol. 66, pp. 269-285, 2000.
- [63] R. Citarella and F. Buchholz, "Comparison of crack growth simulation by DBEM and FEM for SEN-specimens undergoing torsion or bending loading," *Engineering*, vol. 75, pp. 489-509, 2008.
- [64] J. Fish, S. Markolefas, R. Guttal, and P. Nayak, "On adaptive multilevel superposition of finite element meshes," *Applied Numerical Mathematics*, vol. 14, pp. 135-164, 1994.
- [65] M. Maitireyimu, M. Kikuchi, and M. Geni, "Comparison of Experimental and Numerically Simulated Fatigue Crack Propagation," *Journal of Solid Mechanics and Materials Engineering*, vol. 3, no. 7, pp. 952-967, 2009.
- [66] Metallographic.com, "Common Etchants," *Metallographic Etchants*.
- [67] R. Wojes, "Metallographic Etching," *metals.about.com*.
- [68] K. Sindo, *Welding Metallurgy*. Wiley-Interscience, 2002.
- [69] ThyssenKrupp VDM, "VDM Data Sheet 6020 hMo - alloy 625," *Material Data Sheet No. 4018*, Aug. 2007.
- [70] A. Capriccioli and P. Frosi, "Multipurpose ANSYS FE procedure for welding processes simulation," *Fusion Engineerion and Design*, 2009.

Appendix A: Welding Techniques

MIG Welding

Metal Inert Gas (MIG) welding is a welding process an electric circuit that consists of a DC constant potential power supply, welding gun, wire drive mechanism, controller and shielding gas supply, and consumable wire. The once the trigger is pulled the power supply sends current to the gun, the wire is fed, and the shielding gas is supplied. As the wire is consumed the machine continues to feed the gun, making this process semi-automatic.

Oxy-Acetylene Welding (OAW)

Oxy-Acetylene Welding (OAW) can be a welding, heating and cutting process; although different torches are used for each process. The process uses a torch that completed the process by combusting acetylene with oxygen. Flame temperatures reach approximately 5600 °F.

TIG Welding (GTAW) [Used for Dissimilar Metal Weld]

Tungsten Inert Gas (TIG) welding uses an electric arc to melt the work piece and move the molten metal around. The arc is caused by the completion of the circuit between the Tungsten electrode and the work piece. TIG can use a filler rod of similar composition to add to the molten metal. In the case of a dissimilar metal weld there is a filler material. The metal is protected by a shielding gas during the welding process and a short post flow protects the weld after welding. Unlike many other welding techniques TIG can be used to weld very thin materials. TIG welding uses a constant current power supply which can be adjusted by a controller, such as a foot pedal.

Stick Welding (SMAW)

Stick Welding (SMAW) is a welding process that uses the completion of an electric circuit to weld. The circuit consists of heavy gauge electric cables, electrode holder, consumable electrode, and the piece being welded. An arc is formed between the electrode and the piece being welded which melts both the electrode and the work piece. The electrode is covered in a flux that releases shielding gases to protect the weld from atmospheric gases. The flux also forms a “slag” over the weld which further protects the weld as it cools. The slag is later chipped off. The power supply used is a constant current (CC) type.

Spot Resistance Welding (RSP)

Spot Resistance (RSP) welding or spot welding is a process used to weld sheet metal. The two surfaces must be cleaned in order to create a circuit. The two pieces are clamped together creating pressure and high amperage current is passed through the pieces. The electrical resistance between the two pieces creates heat which then joins the two materials together. This process requires no shielding gas, flux, or filler material. Usually the two pieces consist of the same material but in some cases spot welding can be used with dissimilar metals.

Appendix B: Detailed Polishing Procedure

The following section describes the standard polishing procedure used in our lab. Every sample type requires different steps, loads, time, etc. In the following sections, the polishing information won't be repeated but the variations from the procedure below will be noted.

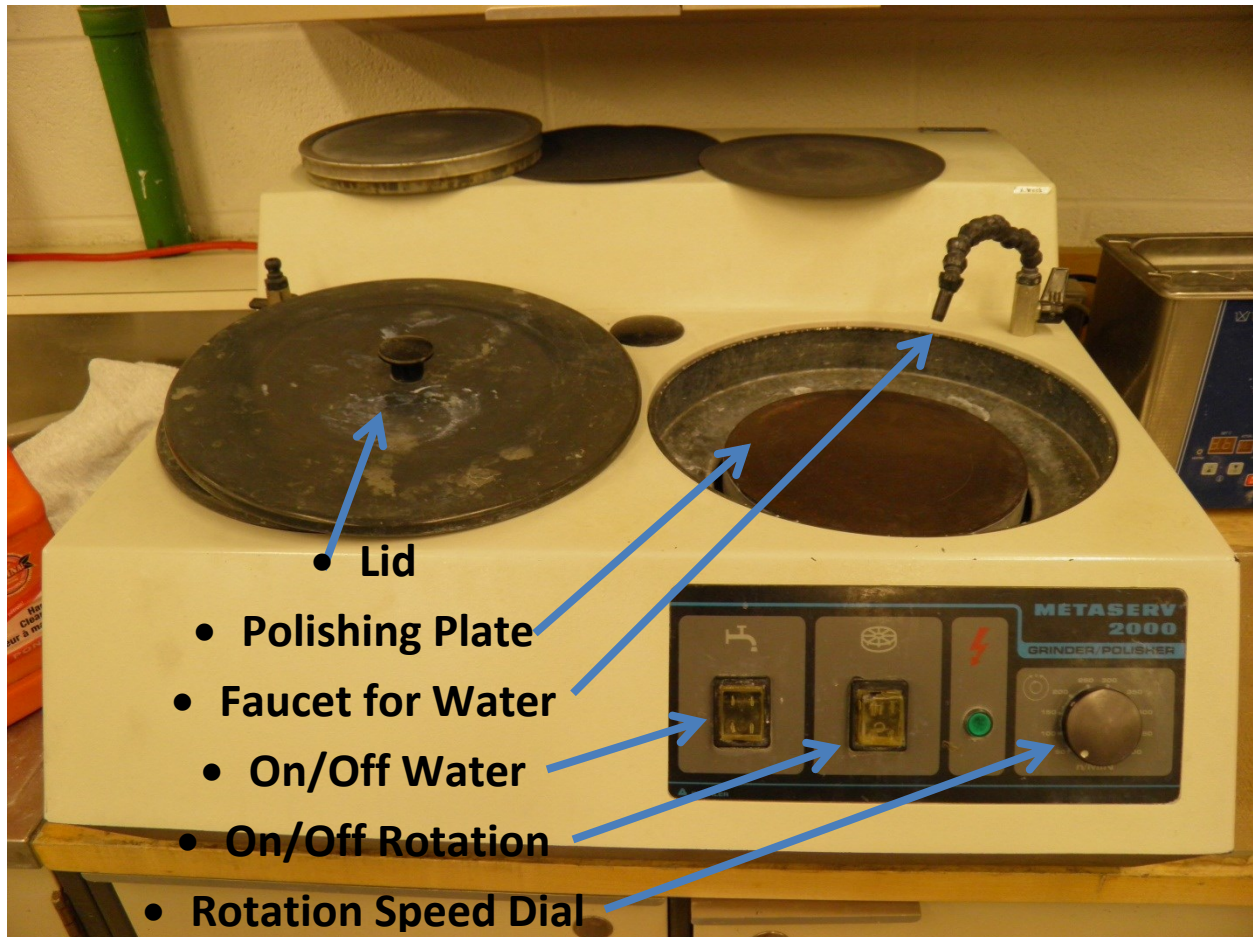


Figure 110: Metaserv 2000 Polishing Machine

Polishing Procedure when using Silicon Carbide Paper:

1. Mounting the Paper: The paper is placed on the polishing plate with the gritty face up. A metal ring is placed over the paper and the plate to hold the paper in place. The ring isn't holding the paper to the plate with much force and in some instances the ring can become loose and the paper can move relative to the plate. This is to be avoided, the machine stopped, and the ring pressed down. This often occurs if there is water on the plate before the paper is attached or the grit of the Silicon Paper is high and is binding with the sample.

2. Turning Machine On: The next step is to turn on the machine using the power switch at the back.
3. Turning the Water On: Now that the machine has power the next step is to turn on the water. The water is controlled in three places. At the faucet where the machine is attached, the switch on the machine, and the faucet of the machine. Turn the water on at the faucet and flip the switch at the machine to turn the water on. The water should be coming out of the faucet onto the paper. To adjust the amount of water coming out of the machine's faucet turn the lever on the machine's faucet. A slow but even flow should be coming out of the faucet. Since you will be rotating the sample around the plate, angle the faucet so that the faucet isn't directly in the path of your hands.
 - a. Note: that the purpose of the water is to lubricate the sample. Using less water will increase the effectiveness of the abrasive but risk non-uniform polishing and heat damage. Using more water can lead to the sample Hydroplaning, meaning the sample is basically floating on the water and not being polished.
 - b. Note: In our specific case, the room D05 at the University of Ottawa, the cold water is under higher pressure than the warm water. And as such if the faucet connected to the machine is left on and the machine is not in use the cold water can flush the hot water from pipes all over the building. This means only cold water should be used which helps cool down the sample during the polishing process anyways. If the water is too cold for your hands, try wearing plastic gloves or turn the hot water on slightly but be sure to turn it off after polishing is complete.
4. Mounting the Sample: Place the sample face down, near the outside edge of the paper. Be sure to avoid hitting the metal ring that holds the paper down with your sample as it could damage the surface.
5. Turn on the Rotating Plate: Flip the switch at the front of the machine to begin the plate's rotation. When the plate begins to rotate hold the sample in place and let the paper slide underneath it. When the plate has reached a uniform speed begin rotating the sample around the outer circumference of the plate in the opposite direction of the rotation.
 - a. Why Rotate the Sample: If the sample is held in place the surface will always meet the abrasive in the same way/direction creating scratches in one direction. If the sample is constantly rotated, the sample will always meet the abrasive in a slightly different way creating scratches in differing directions leading to a uniform surface finish.

- b. **Pressure:** The more pressure that is place on the sample the more deformation that occurs. This deformation causes cold working and can manipulate the surface conditions of your samples. For this reason the least amount of pressure to keep the sample in place should be applied.
- 6. **Controlling the Rotations Speed:** The rotation speed is controlled by the knob on the right of the machine. The faster the speed the more material will be removed when polishing. Keep in mind that the faster speed will be more difficult to control in terms of holding onto the sample and ensuring uniform polishing.
 - a. **Note:** The very rough grit papers (below 500), the process is more grinding than polishing. As such the high level abrasion makes it difficult to control the sample. The faster speeds are not recommended as the sample is already very hard to control.
- 7. **How Long Per Step:** The purpose of each step is to create a surface finish that is uniform. Meaning that the surface has scratches that are uniform in depth and comparable to the abrasives size. This is up to the polisher discretion. This can be tested by obverting the sample's surface and re-polishing for 10 seconds. If any of the pre-polishing scratches remain then the sample should continue to be polished at that step (or go back to a previous step depending on the depth of scratches).
- 8. **Between Steps:** The Sample should be cleaned between steps by rinsing with water and placing into an ultrasonic bath. The ultrasonic bath will remove that majority of particles that are stuck to the sample. It is critical that the abrasives used in each step are consistent and no contamination occurs. If a particle larger than the abrasive being used, scratches the surface it will create an imperfection that will be difficult to remove. The best way to remove this imperfection would be to return to a step that has a similar size abrasive as the particle that scratched the sample.



Figure 111: Digital Ultrasonic Bath/Cleaner – Eumax UD100SH-3L

Polishing with Suspended Particles and [Oxide Polishing Suspension (OPS)]

1. Mount the Cloth: The back of the cloth is magnetic and sticks to the polishing plate (The plate is different from the one used with the Silicon Carbide paper). [Same as above]
2. Adding the Suspended Polishing particle: Spray the surface of the cloth with the suspension approximately three times. The suspension is very expensive and not much is needed. [A teaspoon of OPS is poured onto the cloth to start]
3. Mounting the Sample: Place the sample face down on the cloth and move the sample around to spread the suspension. [Same as above]
4. Turning on the Rotating Plate: Rotate the sample opposite in direction to that of the plate rotation. Be sure not to let any part of the sample move over the edge of the cloth (since there is no barrier) as this can causes unwanted scratches.[Same as above, the OPS has an etchant in it, rotating the sample at a slower speed can increase the effectiveness of the etchant.]
5. Adding Lubricant: At approximately 30 second intervals add one spray of lubrication. More lubrication can be added if the sample is not rotating smoothly. [Add a couple drops of OPS when required, lubricant is not used].
6. Polishing Complete: When sample has a uniform finish. After 1 μm the sample should have nearly no visible scratches but the appearance can be cloudy. [After OPS the sample will have a

mirror like finish with no scratches. The etchant in the OPS can further reveal the grains. When held under light, if the sample is observed at different angles, grains can visually “pop” out of the surface.]

7. Cleaning Polishing Cloth: The polishing clothes must be cleaned with water after its use. A credit card type card can be used to scrape the cloth clean. If the cloth is not properly cleaned and stored after use it can become contaminated with particles that can scratch the surface of the next sample.

The polishing procedure using the vibratory polisher is:

- 1) Remove the screws in the outer ring of the vibratory polisher.
- 2) Remove the ring
- 3) Place the polishing cloth on the plate.
- 4) Place the ring on the plate and tighten the screws at equal intervals.
- 5) Pour the polishing solution onto the plate (the ring holds the liquid in). The plate must be completely covered on the solution.
- 6) Place the sample on the plate face down and turn on the machine.
- 7) The machine will vibrate the sample around the outside edge of the polishing plate. During polishing the sample can be unattended.
 - a. In the case of our sample, it wasn't quite heavy enough for the vibratory polishing so the sample would get stuck or stop moving every once in a while. For this reason I had to watch the sample and nudge it, if it stopped moving.

Appendix C: Detailed Microscopy Procedure and Grain Size Using Line Method

Microscopy Procedure:

1. Turn on the microscope, set the microscope to the 5x magnification.
2. Lower the stage of the microscope.
3. Spray the sample with Ethanol and gently wipe it off with a KimTeck Wipe (or use a blow dryer).
The Ethanol cleans any final debris of the sample.
4. Place the sample on the center of the stage. Point the light of the microscope at the center of the weld.
5. Using the x-y controllers for the stage of the microscope, center the light on the edge of the sample. Use the focus controls, to focus on the samples edge. (It is easier to focus on the edge of the sample than the center).
6. Once focused, inspection can begin and images can be captured using the computer software hooked-up to the computer. Once the image is captured a scale should be added immediately.

Grain Size Using Line Method

1. Select an image with at least 20 grains (more grains creates a better estimate it makes the grains harder to count).
2. Draw one line vertically on the image and measure the length of the line using the scale. (Specialty software can display length immediately).
3. Count the number of times the line crosses a grain boundary.
4. Divide the length of the line (determined by using the scale) by the number of intersections. The calculated number will be the estimated grain size in that direction.
5. Repeat steps 2-4, 3 more times except draw the line in a different orientation. Typically lines are drawn vertically, horizontally, at 45 degrees (1:30 to 7:30 on a Clock), and at 135 degrees (4:30 to 10:30 on a Clock).
6. If the grains are equiaxial (same size in all directions), average the grain size across all the directions. If the grain size varies across the different directions, determine the image orientation relative to the sample, which will give the line orientations relative to the sample. Record the grain size relative to the orientation.

Appendix D: 4-Point Bend Test

The four point bend test was chosen to demonstrate a crack propagating through the thickness of the pipe. It is also one of the few tests when the sample can still be evenly loaded with a crack in place during the test. Four point bending was chosen rather than three- point bending so that a region around the crack could have an equal amount of applied stress. This allows the crack to propagate in more directions based on the materials properties rather than just the loading conditions.

Experimental and Sample Design

The testing machine should be small enough to fit under the microscope so that crack propagation can be recorded as it happens (in-situ testing). The lab currently had a tensile machine that was capable of applying compressive loads. The 4-point bend testing apparatus was designed to work with the current tensile machine. The machine size would be the limiting factor for the sample size. The machine's load cell capability was the limiting factor for sample thickness. Finally, the width was to be equal to the pipe thickness. The pipe thickness direction would have to be ground down to remove the major surface imperfections caused by welding. This would allow for repeatability between samples.

ABAQUS Finite Element Analysis was completed on the four point bend sample to determine sample thickness and ensure the test would be successful. The model was made using the material properties of Inconel 600. This was a conservative estimate as Inconel is the strongest of the materials, so if the model deformed then the dissimilar metal sample would deform too. The boundary conditions are that the large span does not move and the narrow span moves at constant displacement. The model was run while varying the sample thicknesses until significant deformation occurred below 1000 lbs of load (the maximum load of the load cell in the test set-up). A course mesh was used in the models with no crack and a finer mesh was used on the samples with the crack (see Figure 112, Figure 113, Figure 114, Figure 115)

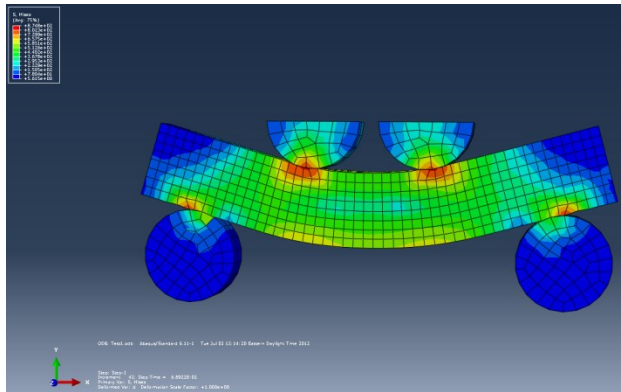


Figure 112: Model #1 - Basic Bending 1 mm thick sample

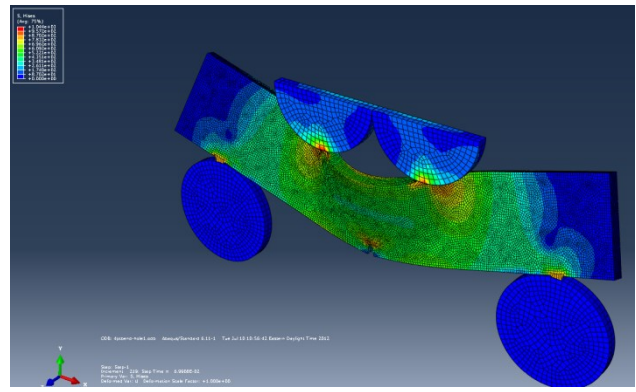


Figure 113: Model #2 - Bending with Crack (1 mm thick)

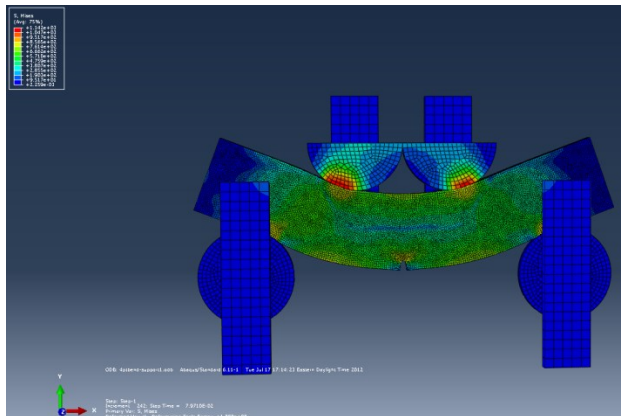


Figure 114: Model #3 - Bending with Crack and Supports (1 mm thick)

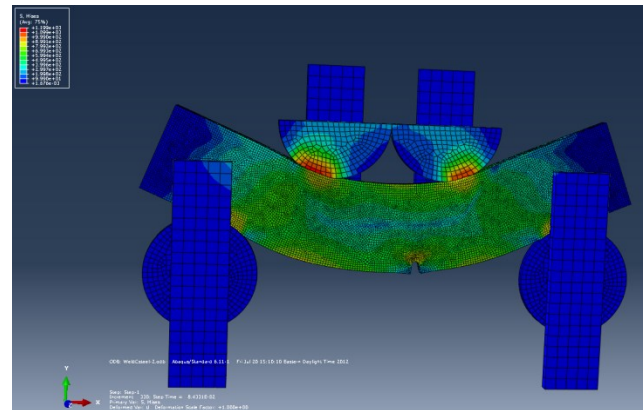


Figure 115: Model #4 - Bending with Off-Center crack and supports (1 mm thick)

Figure 116 shows the design of the 4 point bend grips. The holes with radius of 2.38 mm have hardened dowel pins inserted into them and are the contact points with the samples. The figure shows one design for the small span which is the smallest possible span where the two dowel pins were touching. Another design for the small span included a gap between the dowel pins. The first prototype was very similar to the initial design but the sample bent perpendicular to the loading direction. The final design is shown in Figure 117. The small grips have notches in them (1.2 and 1 mm in height) to help stop the bending in the wrong directions. Small holes were drilled in the bottom of the holder to allow air to be released with the dowel pins are put into place.

Experimental Set-Up

The two grips are inserted into the tensile machine. The bottom support is attached to the large span after the large span is installed into the machine. Next the sample is placed on the bottom supports and slid into the mouth of the small span. The top supports are then screwed onto the large span trapping the sample in the middle.

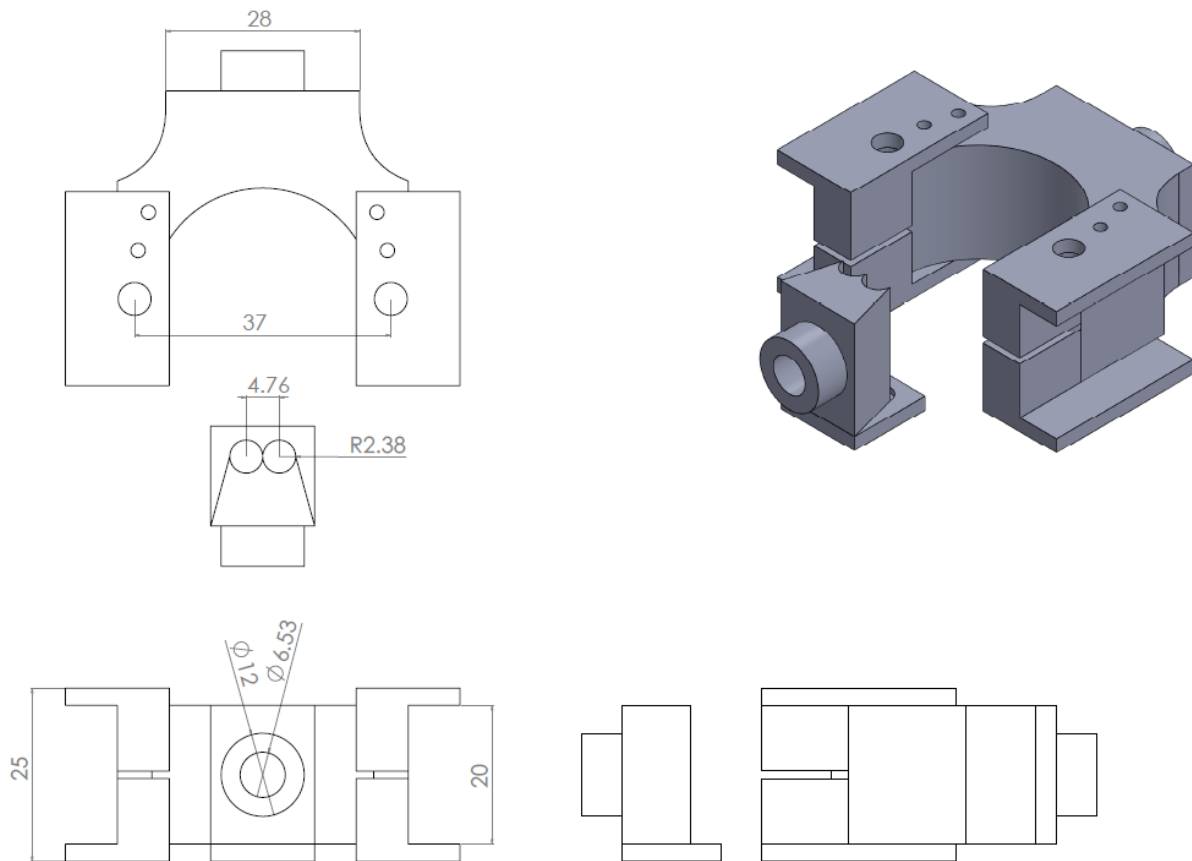


Figure 116: 4-Point Bend Grip Design (Dimensions in mm)

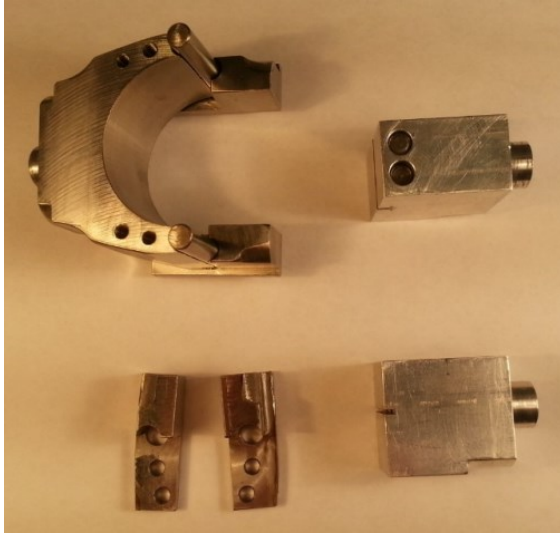


Figure 117: 4-Point Bend Grips (as tested).

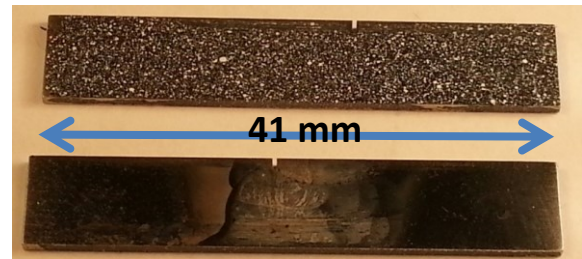


Figure 118: 4 Point Bend Samples (Top: Side #1 DIC Paint Speckle, Bottom: Side #2 Etched (Carbon on right))

Sample Preparation

A third party machine shop extracted the samples out of the pipe using electrical discharge machining (EDM). They also completed the first step of polishing using 600 grit silicon carbide paper.

4	0.04 μm OPS	90 sec	Adding OPS, rinse with water
---	------------------------	--------	------------------------------

Experimental Procedure

The sample is placed under the 5x lens of the microscope. A camera records images as seen through the microscope. The stage of the microscope is moved to follow the crack tip growth.

The majority of samples are to be tested using DIC which uses a different procedure, as described in the sections above.

Results for Four Point Bend Test

The tests under the original design bent significantly in the unloaded direction. The supports were design to stop this bending and it did help but after some deformation in the desired direction, the sample began to bend again in the unloaded direction. In addition the local deformation around the crack tip was very high which caused the microscope to lose focus. Direction of the crack tip could not be tracked using this method. The samples were painted with DIC speckle paint, in order to follow the strains around the crack tip. After reviewing the previous test further it was determined that there was not enough crack growth before the unwanted bending started to occur. The test was modified several times to battle the unwanted bending but eventually the test was abandoned. Figure 120 shows a four point bend sample that has been tested. The bottom edge has the crack in it and the top edge has the unwanted bending. Figure 121 shows the deformation at the crack tip during the test.



Figure 120: 4-Point Bend Sample (with trimmed edges and crack)

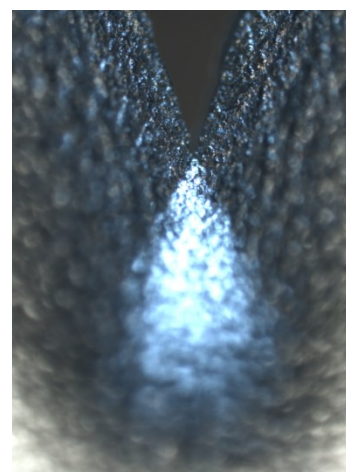


Figure 121: Crack Tip as seen through the Microscope (4 point bend sample)