# INVESTIGATION IN THE CHANGES IN METALIC MATERIALS AS A RESULT OF HEATING

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# Statement of Candidate

I, Steven Wang, declare that this report, submitted as part of the requirement for the award of Bachelor of Engineering in the Department of Engineering, Macquarie University, is entirely my own work unless otherwise referenced or acknowledged. This document has not been submitted for qualification or assessment at any other academic institution.

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Date: November $7^{th}$, 2016

# Abstract

Steels and aluminum are the two of the most commonly used metals, and are used in many industries. As the manufacturing processes involved with these metals often involve high temperatures, it is important to understand the consequences of exposing the metal to these temperatures. Steel welding and aluminum extruding are manufacturing processes which involve the heating of the metal. Steel welding involves high temperatures in order to fuse two pieces of metal together, however these high temperatures cause the properties and microstructure of the metal in a localized area to change. On the other hand aluminum extrusion requires the metal to be preheated before the process to reduce the forces required to shape the metal.

As undesirable properties occur as a result of the elevated temperatures during steel welding, heat treatments may be applied to optimize the final properties and microstructure. During the aluminum extrusion process imperfections may occur causing the final product to be flawed, this was the case at Capral with an extrusion of cladding, causing the part to be rejected by the architect. As a result an investigation on the cause of the imperfection was launched. In order to investigate the properties of both the welded steel joints and aluminum extrusion, specimens were created, cut, hot mounted, polished and chemical etched, so that Vickers hardness test and microscopy analysis could be performed.

The findings of this report suggest that annealing is the most appropriate heat treatment to optimize the properties of the welded steel joints. Further research should be conducted in the annealing conditions in order to optimize the properties and microstructure of the welded steel. Through testing it was found that the properties and microstructure of the aluminum extrusion were not the cause the imperfection, however through further testing of the profile of the extrusion, it was found that the flow rate in the extrusion die caused the imperfections. As a result it is suggested that modifications be made on design of the extrusion die to remove the imperfection.

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# Abbreviations

| | |
|---|---|
| HAZ | Heat Affected Zone |
| TIG welding | Tungsten Inert Gas welding |
| PPE | Personal Protective Equipment |
| S/S | Stainless Steel |
| C/S | Carbon Steel |
| $\alpha$-Fe | Ferrite |
| $\gamma$-Fe | Austenite |
| BCC | Body Centered Cubic |
| FCC | Face Centered Cubic |
| TTT Curve | Time temperature transformation curve |
| $HNO_3$ | Nitric acid |
| HCL | Hydrochloric acid |
| HF | Hydrofluoric acid |

# Chapter 1: Introduction

Steels and aluminum are common metals used in many industries such as construction, machinery and transport. The manufacturing techniques welding and extruding have been used to create large structures and parts from these metals. The metals stainless steel 304 grade, stainless steel 316 grade and carbon steel 1045 grade have been selected to study welding and the effect of heat treatment. In order to study extrusions, aluminum 6XXX series has been chosen.

Welding is a manufacturing technique used to permanently join two or more metals together with fusion to form a single piece. This process is achieved by melting the base metal and adding a filler material to form a weld pool that cools to form the welded joint. The high temperatures experienced by the metal due to welding causes the hardness and microstructure around the weld to change in the heat affected zone (HAZ) altering the properties of the welded joint [1].

Heat treatment can be used to affect the strength and toughness of a metal. Through the use of heat treatment on welded steel joints, the hardness and microstructure of the material in both the base material as well as around the HAZ of the steel can be altered [2]. By tailoring heat treatments applied to the welded steel the properties of the welded steel can be manipulated to suit the conditions in which the steel will be working under. To optimize the strength and microstructure of a welded steel joint the heat treatment used must be analyzed so that an optimal solution can be found.

To find the effect of heat treatment on welded steel, a variety of tests have been used to find the hardness and microstructure of the welded steel, before and after heat treatment has been applied. Through this testing, the optimal heat treatments to be applied to welded steel can be found.

Extrusion is a manufacturing technique where a hot billet of metal is forced through a die by a ram at high temperature and pressure to create a geometry on one surface that has been extended out. As the metal is forced through a die at high temperatures and force, the properties of the metal are important [3]. Aluminum is widely used in the extrusion process due to its ductility. Pressure lines can occur on extruded aluminum and can be visible on the surface of the extrusion. By investigating the properties and profile of extruded aluminum the cause of the pressure lines can be found.

## 1.1 Project Objective

The objective of this project is to investigate heat treatments on welded steel joints and pressure line on extruded aluminum. An experimental approach will be taken to find the optimal heat treatment for welded steel joints and to find the cause and possible solutions for pressure lines in extruded aluminum.

An investigation to find the effect of heat treatment on welded steel and to find the optimal heat treatment to be applied to welded steel will be conducted. To achieve this an experimental approach is taken to test and analyze the properties and microstructure of welded stainless steel 304 grade, stainless steel 316 grade and carbon steel 1045 grade before and after heat treatment is performed.

An investigation of the occurrence of pressure lines on an extruded aluminum sample will be conducted. This sample was provided by Capral and features a pressure line located on the top surface opposing a webbed support structure in the geometry of the extrusion. A sample without this pressure line and webbed support structure was also provided for comparison. An experimental approach will be taken to perform tests to investigate the properties of the pressure line, find the cause of the pressure line and to find possible solutions to the problem.

# Chapter 2: Background

## 2.1 Welded Steel

The investigation in the optimal heat treatment for welded steel is important because of the wide variations of microstructure and properties that is achievable in steel through the use of heat treatment. Heat treatments to optimize the microstructure and properties of steel have been established [2], [4] and [5]. The welding process creates undesirable outcomes in the microstructure and properties of the steel through the high heats experienced by the steel, causing phase transformations to occur. The microstructure and properties found in the HAZ of the steel differ from the microstructure and properties found in the base metal, therefore causing undesirable properties in the welded joint [1], [6] and [7]. In this paper the hardness and microstructure of welded steel joints under various heat treatments will be tested to find the optimal heat treatment for welded steel.

### 2.1.1 Properties of Welded Steel

The important properties of welded steel joints are microstructure, hardness, tensile strength and impact toughness, these properties determine the strength of the welded joint. The microstructure and properties of the steel around the welded joints are significantly different from that of the base steel. The microstructure of the steel around the welded joint exhibits larger sized grains than that of the base metal indicating that the properties around this area are also different [4]. As the microstructure and properties of the metal in this area are affected by the welding process, undesirable outcomes can occur as a result. The area around the welded joint experiences elevated heat during the welding process, causing this increase in grain size around the area as well as an increase in hardness in the surround areas of the welded joint [7]. The tensile and the yield strength of the steel around the welded joint are higher than the tensile and yield strength found at base metal and the impact toughness of welded steel is found to be less than that of base steel [8]. This is important as the variation in these properties are undesirable as they vary from the HAZ and base metal.

### 2.1.2 HAZ of Welded Steel

The HAZ of a welded joint is the region of the base metal that has undergone changes due to the elevated heat experienced during the welding process. The effects of the heat from the welding process causes grain growth to occur in the microstructure of the metal [9]. This causes the metal to experience changes in the microstructure and properties in a localized area, creating non-optimal properties in the welded joint.

The HAZ also undergoes phase transformation between $\alpha$-Fe (ferrite) and $\gamma$-Fe (austenite) during the heating process. The phase transformation affects the microstructure of the HAZ by creating new grains and causing growth in smaller grains [6]. The new grains created and grain growth around the HAZ of steel is shown in Figure 1 below. Large grains are found directly around the edge of the weld while further away from the weld smaller grains exist.

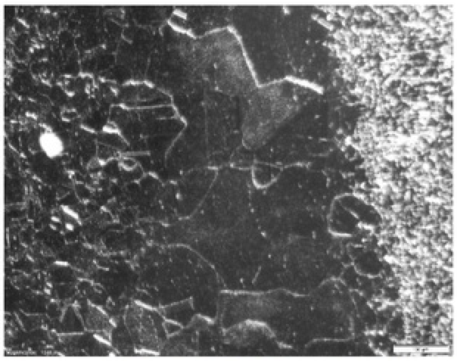


*Figure 1 - Micrograph of the HAZ of S/S 316 grade (weld is on the right)*

## 2.2 Heat treatment

### 2.2.1 Phase Transformations

Phase transformations can be represented through phase diagrams, where the effect of the composition of the alloy and temperature against the phase change in are illustrated. Phase diagrams show the phases present in the metal at a specific temperature and composition [10]. Phase diagrams can be used to determine the temperatures in which the one component or both components of the alloy become liquid, this is shown by the region marked by $\gamma + L$ and $L$ respectively in Figure 2 below. The $\gamma$ + L region represents the region where there is a combination of liquid and solid while the line marking the L region represents temperature where the alloy becomes liquid. Phase diagrams also show the temperatures required for phases to be present, this can be seen in the $\gamma$, $\alpha$ and $\alpha + \gamma$ regions in Figure 2. These regions represent where $\gamma$-Fe, $\alpha$-Fe and a combination of the two phases exist as solid.

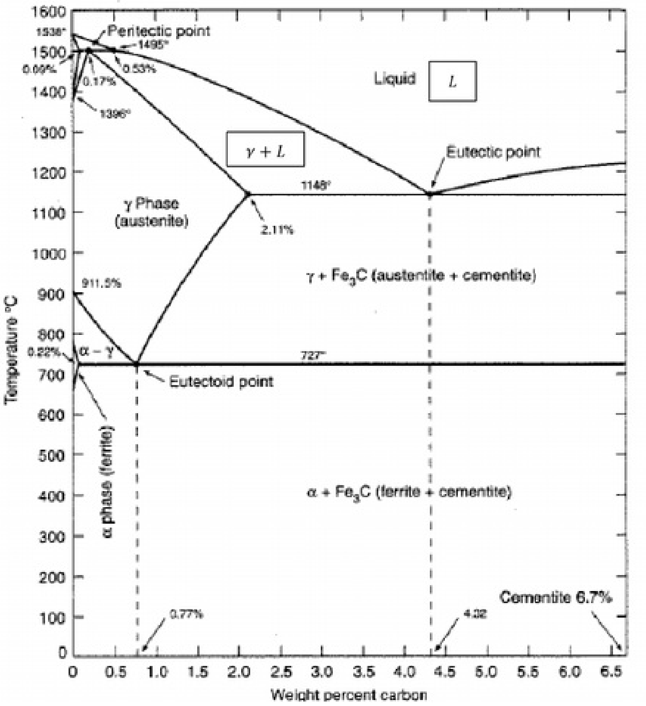



*Figure 2 - Iron-carbon phase diagram from Reed-Hill and Abbaschian [11]*

The phase transformation of steel also determines the lattice structure of the atoms. The $\alpha$-Fe phase in the steel consists of body centered cubic (BCC) structure, while the $\gamma$-Fe phase of the steel contains face centered cubic (FCC) structure [1]. The transformations between the various lattices structures present in the phase of the steel are responsible for the microstructure and properties of each phase transformation [12]. The BCC and FCC structures can be seem in Figure 3 below, these structures occur depending on the phase transformation of the steel.

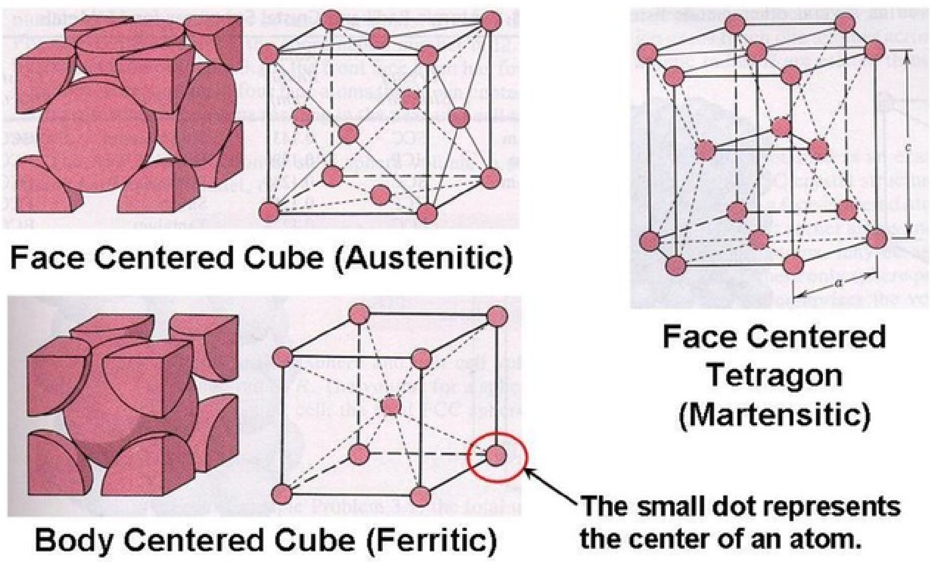



*Figure 3 - The difference between FCC and BCC lattice structure [13]*

In order to alter the mechanical properties of metals, heat treatments can be applied to the metal. By controlling the heating and cooling of the metal, we are able to control the phase transformations and create the desired effects on the metal [2]. The phase transformation of $\alpha$-Fe and $\gamma$-Fe alter the grain boundaries of the steel [14].

### 2.2.2 Annealing

Annealing is a heat treating process used to reduce deformations in steel to achieve the following goals:

- Relieve the internal stress inside the steel
- Improve the uniformity of grain structure within the steel
- Soften the steel

Annealing requires the steel to be heated to a pre-determined temperature and left to soak at this temperature for a predetermined time. The heated steel is them cooled down either in air at room temperature or quenched [2], [5].

This process causes the crystalline structures of the $\alpha$-Fe components in the steel to restructure, improving the microstructure of the steel. The annealing process reduces the dislocations in the steel by improving the uniformity of the grain size in the microstructure of steel [5]. As a result of annealing undesired effects from cold working process are removed from the steel.

### 2.2.3 Quenching

Quenching is a heat treatment that is used to strengthen and harden steels. The process involves heating the steel to high temperatures and allowing it to soak at this temperature before cooling the steel in fluid. The fluid used to cool the steel is important as this dictates the cooling rate and final properties of the steel. Quenching can be performed with water or oil as the quenching fluid to control the cooling rate of the steel.

Controlling the quenching temperature and medium determines the properties and microstructure of the steel [2], [14]. Through quenching the grain sizes in the microstructure of the steel can be reduced and the hardness of the steel increased. By rapidly cooling the steel a high thermal gradient can be produced and unwanted phase transformations can be reduced. This is because steel is rapidly cooled during the temperatures where phase transformations occur, reducing the time that undesirable phase transformations can occur.

Quenching can be used to create a new phase in the steel known as martensite, as the austenite component of the steel is suppressed and the $\alpha$- $\gamma$ Fe transform is unable to be completed. This new phase displays hard and brittle qualities due to its martensitic structure [15].

### 2.2.4 Tempering

Tempering is used increase the toughness of the steel as after quenching the steel is hard and brittle. Tempering is used to remove internal stress inside hardened steel, as the quenching process leaves the steel in a vulnerable state due to its brittleness, while in this brittle state a shock load can cause failure to the steel. Tempering involves heating the steel to a predetermined temperature below the critical temperature of the steel and leaving it to soak before allowing the steel to slowly cool in air.

The temperature at which the steel is tempered directly affects the result, as lower temperatures retain hardness while higher temperatures maximize toughness of the steel [2]. In order to optimize the hardness and toughness of steel a combination of quenching and tempering must be performed [5], [15]. A balance between the toughness and hardness of the steel can be found through tempering and quenching to suit the working condition of the steel.

## 2.3 Aluminum Extrusions

Aluminum is a widely used metal due to its favorable properties, including light weight, high strength, malleability and easy machining. As a result aluminum is commonly used in the extrusion process, during the extrusion process the aluminum is heated and forced through a die at high pressures using a ram. Extrusions are used to create long parts with the same geometry and can be used to create simple extruded shapes like pipes, I-beams and bars or complex shapes to be used for window frames and cladding.

### 2.3.1 Properties of Aluminum Alloy 6XXX Series

Aluminum is alloyed with small amount of alloying elements, aluminum 6XXX series has primarily been alloyed with magnesium and silicon. The content of pure aluminum in aluminum 6XXX series alloys is between 91.7% and 99.6% depending on the alloy [16]. The properties of aluminum 6XXX series varies depending on the alloy that is used, as aluminum 6XXX encompasses a wide range of aluminum alloys.

| Mechanical Properties | Metric |
|---|---|
| Hardness, Brinell | 25.0 - 130 |
| Hardness, Knoop | 73.0 - 163 |
| Hardness, Rockwell A | 35.5 - 49.5 |
| Hardness, Rockwell B | 49.0 - 80.0 |
| Hardness, Vickers | 35.0 - 149 |
| Tensile Strength, Ultimate | 89.6 - 478 MPa |
| Tensile Strength, Yield | 40.0 - 455 MPa |
| Elongation at Break | 2.00 - 35.0 % |
| Modulus of Elasticity | 67.0 - 70.0 GPa |
| Ultimate Bearing Strength | 228 - 607 MPa |
| Bearing Yield Strength | 103 - 386 MPa |
| Poissons Ratio | 0.330 |
| Fatigue Strength | 55.0 - 375 MPa |
| Machinability | 30.0 - 90.0 % |
| Shear Modulus | 25.8 - 26.0 GPa |
| Shear Strength | 60.0 - 269 MPa |

*Figure 4 - Table of properties of aluminum alloy 6XXX series [16]*

## 2.3.2 Extrusion Process

Extrusion is a manufacturing process used to create a continuous length of metal with a fixed cross-sectional geometry. Aluminum is a suitable metal to be used for extrusion due to the malleability of aluminum. The aluminum is heated up to reduce the hardness of the aluminum and reducing the force required during the extrusion process. If the aluminum is not heated excessive pressure is used, causing additional wear damage to the die [17]. In direct extrusion the billet of aluminum is feed through the die by a ram, compressing the aluminum through the geometry of the die [18]. The extrusion exiting the die can contain simple or complexed geometries depending on the geometry of the die. Extrusion can be performed for complex geometries, as long as there is no change in the geometry, by designing the die to produce the complex geometry.

The die used for aluminum extrusions consists of multiple parts to shape the aluminum. The die is designed to produce the cross-sectional geometry of the extrusion. The front piece of the die works to direct the flow of aluminum towards the necessary areas and the backing piece which shapes the aluminum. The die also contain bearings to control the flow of aluminum during the extrusion. The length of the bearing controls the flow rate of the aluminum through the die [19]. The bearings are raised edges on the die, slowing the flow of the aluminum as it is forced through the die.

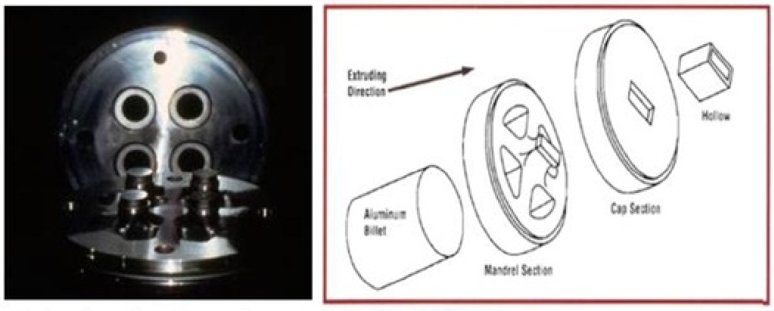



*Figure 5 - Extrusion die producing a shape containing voids [20]*

### 2.3.3 Pressure lines

Pressure line are deformities on the surface of the extrusion, creating a visible line on the extrusion. Pressure line can be caused by uneven flow of aluminum in the die, shrinkage in the extrusion or high friction between the container and billet. Deformations can be fixed by compensating for the deformation during the design of the die. In order to fix pressure lines the design of the die can be adjusted. To increase the flow rate of the aluminum at a certain area the bearings on the die can be shortened or chamfered [21].

The 'front end' of the extrusion can be used to assess deformations occurring in the extrusion that may cause problems in the resulting extrusion. The 'front end' of the extrusion is the first piece of the extrusion to be extruded. This piece of the extrusion is important it does not possess the constraints of the material already extruded, causing this piece to warp and deform.

*Figure 6 - Front end of an extrusion*

# Chapter 3: Method

This section will outline the preparation for the stainless steel, carbon steel and aluminum specimens in order to perform testing on the specimens. Before testing can be conducted, the specimens must be fully prepared. The preparation involves welding, precision cutting, hot mounting, polishing and chemical etching to ensure that accurate results are gathered.

## 3.1 Welding

To create the welded steel specimens, 304 grade and 316 grade stainless steel and 1045 grade high carbon steel were butt welded together using TIG welding. The steel specimen was first fully prepared by chamfering the welded edge to create a 'single v' geometry as seen in Figure 7 below. The specimens were then tacked together on each end before being welded together with TIG welding. As a flat surface is required for testing, the specimens were milled to create a flat surface on the top surface of the welded specimen.

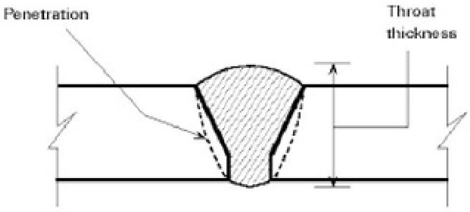



*Figure 7 - Example of a fully prepared specimen*

*Figure 8 - Fully prepared stailess steel specimen (S/S)*

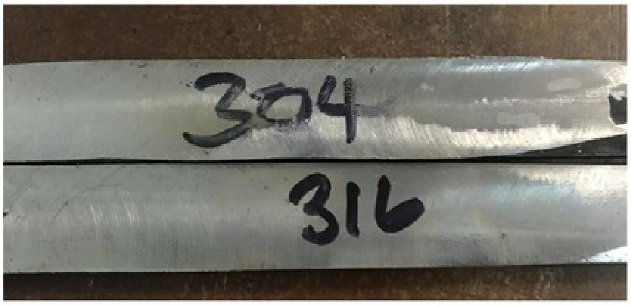



*Figure 9 - Welded S/S specimens after milling*

## 3.2 Precision Cutting

Precision cutting is required in the preparation of the specimens to prevent any damage from occurring while cutting the specimens to required sizes. Precision cutting uses lubricant to prevent the material from heating up during the cutting process. This prevents any deformations to occur due to the material heating up in the cutting process.

In order to cut the specimens to size the Struers' Secotom-50 precision cutting machine was used. This machine allows for the specimen to be accurately cut to a desired size without changing the properties of the material. The cutting method used can be seen in Table 1 below.

*Table 1 - Precision cutting method*

| **Cutting Wheel** | **Wheel Speed** | **Feed Speed** |
|---|---|---|
| 50A20 | 5000 rpm | 0.5 mm/s |
| **Cutting Length** | **Return Position** | **ExciCut** |
| 10mm | Start position | Z =46.1µm |

### 3.2.1 Precision Cutting Method

1. Create a the precision cutting method (see Table 1) in the Secotom-50
2. Move cutting table away from the cutting wheel by twisting the control knob
3. Clamp specimen to the table
4. Move table so that the specimen is almost touching the cutting wheel
5. Initiate the cutting method by pressing the green button
6. Once cutting is complete, remove specimen from the machine

## 3.3 Hot Mounting

In order to prepare the specimens for hardness testing and microscopy, the specimen is hot mounted in thermosetting resin. Mounting the specimen allows for ease of handling as well as protection for the specimen. During the hot mounting process, the resin is first heated to a high temperature of up to 180°C, softening the resin and then compressed with up to 250 bar of force before being cooled with water [22].

A Struers' Citopress-10 hot mounting press with MultiFast black resin was used in the preparation of the S/S 316 grade, S/S 304 grade and carbon steel specimens while PolyFast resin was used in the preparation of the aluminum specimens. The method required to produce a mounted specimen for both MultiFast black and PolyFast resins are shown in Table 2 below.

*Table 2 - Hot mounting method for MultiFast resin*

| **Heating** | | | **Cooling** | |
|---|---|---|---|---|
| **Temperature** | **Time** | **Pressure** | **Water** | **Time** |
| 150°C | 3.0 mins | 250 bar | High | 2.0 mins |

### 3.3.1 Hot Mounting Method

1. Raise the ram platform by pressing the up arrow button
2. Place specimen on the ram platform, with the testing surface face down
3. Lower the ram platform by pressing the down arrow button
4. Add 25mL (5 turns of the dispenser) of MultiFast into the mounting cylinder
5. Move the head unit over the ram and screw it down so that it is locked into place
6. Initiate the process by pressing the green button
7. Once the process is complete unscrew the head unit and raise the platform by pressing the up arrow button
8. Remove the specimen and clean the head unit and ran platform

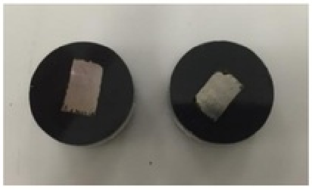


*Figure 10 – S/S Specimens mounted in MultiFast black*

## 3.4 Polishing

In order to prepare the specimens for hardness testing and microscopy the surface must be polished until the surface is flawless. Polishing involves two main steps, grinding and polishing, in order to remove all scratches and flaws in the specimen. The initial step in the polishing process is grinding, this uses coarser abrasive material such as Silicon carbide (SiC) foil, to eliminate larger scratches in the specimen. This process of removing larger scratches is repeated with finer abrasive material, typically 80 to 4000 grit, to reduce the scratches until the specimen is ready for polishing. Polishing uses fine abrasive material, typically 1-6 microns, to remove all fine scratches and provide a mirror finish.

Polishing a surface before testing is an important step as it removes all scratches and flaws in the specimen. This prevents errors occurring due to defects in the surface finish and prevents scratches from disturbing the collection of results. Polishing is especially important when performing microscopy tests as small scratches in the surface can create difficulty when collecting results.

The Struers' Tegramin-25 polishing machine was used to prepare the specimens and provide a clean flawless testing surface. In order to use this machine, the specimen must first be mounted. In order to polish the stainless steel specimens the Struers' 'High Alloyed, Heat Treated Steels' polishing method was used, the carbon steel specimens were polished using Struers' 'High Carbon Steel' polishing method and the aluminum specimens were polished using Struers' Pure aluminum' polishing manual. These polishing manuals can be found in appendix A. These manuals were used as a guide to the polishing process as a visual inspection between each step was conducted to ensure that quality of the polish was acceptable. If a specimen fails this visual inspection due to a larger than expected scratch or mark the polishing step is repeated until the specimen's surface has achieved a satisfactory level for its polishing step. The surface has reached a satisfactory level when only fine scratches remain and all larger scratches are removed.

### 3.4.1 Polishing Method

1. Set the method in the Tegramin-25 and ensure that all the suspensions are correctly setup in the machine
2. Place the specified abrasive disc onto the platform
3. Wet the disc with the lubricant solution by pressing the lubricant/water button

4. Lower the head piece by pressing the vertical arrows button and place specimens in the holding slots
5. Initiate the programed method by pressing the green button
6. Once the polishing is complete, raise the head piece by pressing the vertical arrows button and carefully clean each specimen taking care to not touch the specimens surface
7. Remove the headpiece and thoroughly clean
8. Remove the abrasive disc and place back on the holding rack
9. Clean the spinning platform by applying water using the water button and spinning the platform by pressing the rotation button at the same time, hold a paper towel against the spinning platform to clean the surface. Dry the platform by pressing and holding the rotation button
10. Repeat for each step in the polishing method (see appendix A)

Note: Ensure that all components are thoroughly cleaned between each method to prevent contaminating the abrasive discs.

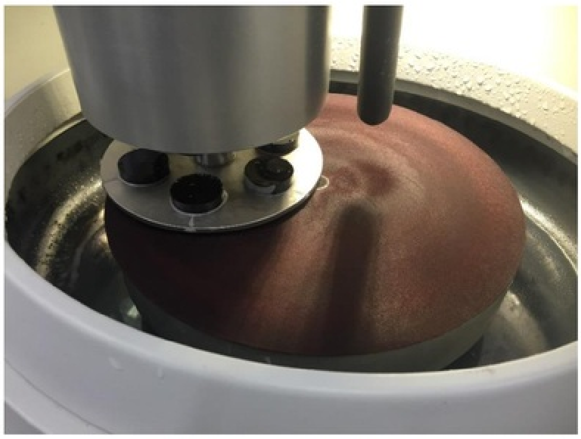


*Figure 11 - Specimens in the polishing process*

## 3.5 Chemical Etching

Chemical etching is essential in order to reveal the microstructure of the specimens, but first requires the specimen to be polished. After the microstructure of the stainless steel has been revealed, it can be examined using an optical microscope where the grain boundaries and phases within the stainless steel can be observed. Through observing the microstructure of the stainless steel the composition and mechanical properties of the metal can be found.

As potentially dangerous chemicals are used it is important for correct safety procedures to be followed. The use of a fume hood and having a partner are required when working with dangerous chemicals. Correct PPE including safety glasses, rubber gloves, tongs and protective clothing must also be used when dealing with dangerous chemicals.

The chemical etching process can be performed through swabbing or immersion. Swabbing is performed by holding the specimens with tongs and swabbing the surface of the specimen with surgical cotton that has been dipped in the etchant. This is repeated until the desired amount of chemical etching has be achieved. Immersion involves filling a beaker with the etchant and submerging the specimen, polished side up, in the etchant. The specimen is left submerged until the desired amount of etching has been achieved. Once the etching is complete the specimens are rinsed in water and then ethanol before being dried by warm air. When the specimen is exposed to the etchant, the etchant corrodes the surface of the specimen revealing the microstructural features of the specimen. This can be seen when the surface starts to experience coloration or dulling.

Through conducting research, it was found that the etchant Nital is suitable for use in chemical etching steel specimens as it is able to corrode the top surface and reveal the microstructure. Nital is composed of nitric acid and ethanol making it hazardous due to its explosive nature when mixed with concentrations of nitric acid above 10%. In order to chemical etch aluminum Keller's reagent was found to be the most suitable etchant. Keller's reagent contains water, nitric acid, hydrofluoric acid and hydrochloric acid. Although hydrofluoric acid is extremely hazardous, Keller's reagent contains a low percentage of the acid compared to other possible etchants and doesn't require any other extremely hazardous components.

### 3.5.1 Chemical Etching - Immersion Method

1. Carefully measure and mix the each component of the etchant
2. Pour the etchant into small beaker
3. Submerge the specimens in the etchant so that the testing surface is completely submerged and facing up
4. Stir the etchant with tongs to provide agitation
5. Remove the specimen from the etchant once the surface has experienced coloration or dulling and then rinse with water
6. Rinse specimen with ethanol and blow dry with warm air

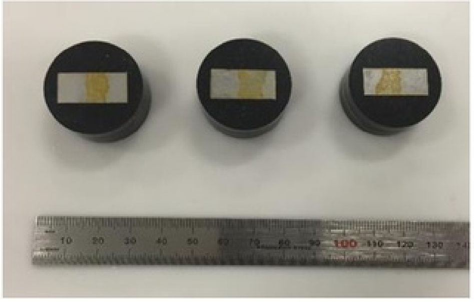


*Figure 12 – Carbon steel specimens etched with Aqua regia*

## 3.6 Hardness Testing

The hardness testing method chosen is the Vickers hardness test. The Vickers testing method uses a diamond shape indenter to apply a load and indent the surface of the specimen. A diamond indent is left on the specimen and diagonals of the indent are then visually measured and used in an equation to find the hardness measurement. As seen in Figure 13 below, the Vickers hardness test result comes in the form of 242 HV 5, where the 242 represents the hardness value, the HV represents the type of testing and the 5 represents the force in kilograms that was applied during the testing. Before a Vickers hardness test can be conducted the specimen must be prepared with mounting and polishing to ensure a flat flawless surface.

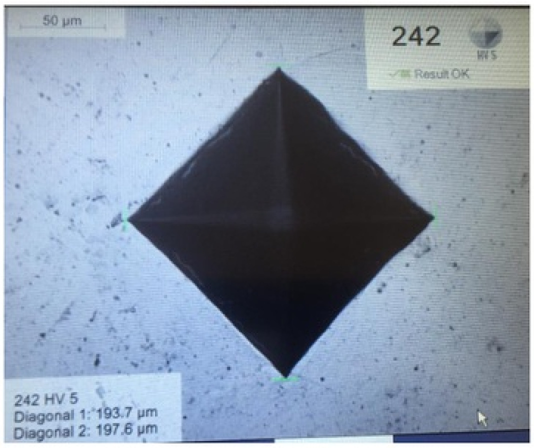



*Figure 13 - Hardness tester screen during hardness measurement*

The steel specimens were tested after welded, and again after heat treatment was applied. A control specimen without welding or heat treatment was created and tested in order to compare the results found. In order to find the change in hardness due to the heat experience during the welding process hardness indents were made across the specimen with 2mm spacing between. By indenting the specimen every 2mm the change in hardness in the specimen can be represented. For each point 5 values were taken, creating matrix like formation. Each column of results, was represented by 'Y' followed the corresponding number of the column.

To investigate the properties of the aluminum extrusions around the webbed section, an aluminum specimen using the section contain the webbing was used. A second specimen was created form the no webbing sample, from the same region that the webbed specimen came from. A 2mm spacing between indents was used to measure the hardness around and at the webbing and the corresponding area on the not webbed specimen.

In order to receive an accurate reading for the hardness multiple rows of hardness indents were made and the average was taken. The load applied onto the indenter was determined separately for each metal by gaining an idea of load through research and trails with different loads.

### 3.6.1 Vickers Hardness Testing Method

1. Turn on the hardness tester and ensure that the indenter is selected
2. Place mounted specimen in specimen holder
3. Place specimen underneath the indenter
4. Focus the hardness tester by selecting autofocus touch
5. Select the position tab and position the specimen so the indenter is at the corner of the specimen and the micrometer is set at 0
6. Create a series method with 1mm spacing in the Y-axis
7. Indent the specimen
8. Ensure that the diagonals are measured correctly, making adjustments if required
9. Return to the position tab and move the specimen 1mm up
10. Repeat steps 7 to 9 until 5 measurements are taken or specimen runs out of space
11. Return to the position tab and press complete row
12. Save the series row and move the indenter back to its original Y position
13. Move the indenter 2mm in the X-axis
14. Repeat steps 6 to 12 until you reach the edge of the specimen

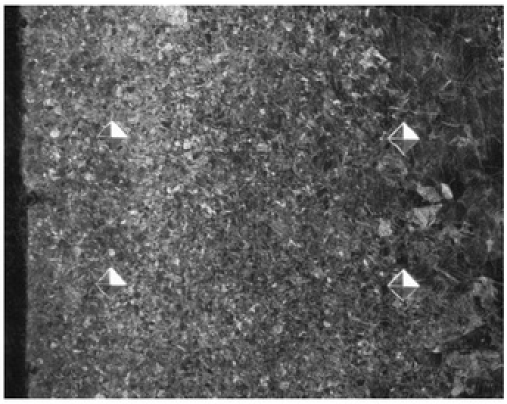


*Figure 14 - Set of Indents on heat treated S/S 304 grade specimen under a microscope*

## 3.7 Microscopy

Microscopy involves using an optical microscope to view areas of objects that are otherwise too small to inspect. This allows the microstructure of the welded stainless steel specimen to be inspected, giving us a greater understanding of the properties of the specimen. By using a microscope to observe the microstructure of the stainless steel specimens the grain boundaries can be seen and the properties of the steel can be determined.

Microscopy requires specimens to be carefully prepared so that it is mounted, polished and chemically etched to provide good results. A mirror finish polish is required as any imperfections or scratches will provide difficulty when looking under a microscope. The better quality of the polish the better the results collected will be. Chemical etching is an important preparation as this process will reveal the microstructure of the stainless steel. If the chemical etching is too strong or too weak the microstructure of the steel will not be clear and the specimen must be polished and etched again.

The microscope used was an Olympus SZX16 optical light microscope. The lens used was a 2x lens and a magnification of 8 times was used to observe and capture micrographs of the specimen.

### 3.7.1 Microscopy Method

#### *3.7.1.1 Operation of Microscope*

1. Turn on the microscope and light
2. Place the etched specimen under the microscope lens
3. Adjust the eyepiece and focus so that the specimen is clearly visible through the microscope
4. Move the specimen so that the desired area is in view
5. Select the magnification
6. Adjust the focus so that specimen is clearly visible
7. Adjust the lighting so that the details of the specimen are clear

#### *3.7.1.2 Microscopy Analysis*

1. Ensure that the lens and magnification used are selected on the computer
2. Set the working directory by clicking acquisition settings and selecting the file location. Note that the working directory can be changed at any time

3. Set the save name of the micrographs by clicking acquisition settings and changing the save name, the file will be save as $File\ name\_number$. Note that the name of the file can be changed at any time
4. Ensure that the image on the screen is focused and has adequate lighting
5. Press snapshot button on the computer to take a micrograph
6. Select the tab that the new micrograph is on
7. Add a scale bar by pressing image and then "burnininfo"
8. Save the micrograph

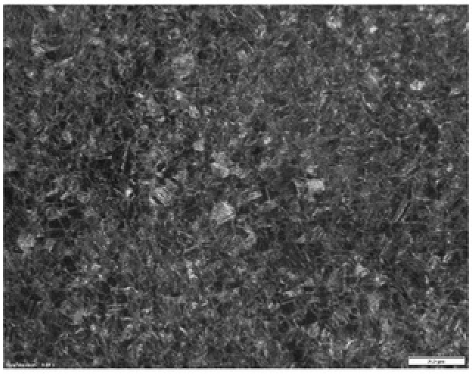


*Figure 15 - Micrograph of S/S 316 grade specimen*

## 3.8 Heat Treatment

Heat treatment involves heating the metal to high temperatures and controlling the cooling process from the elevated temperature. The temperatures required for heat treatment varies depending on the metal and heat treatment. High temperatures are required so that the metal undergoes phase changes, which causes the microstructure and properties of the metal to change.

The selected heat treatments for the steel specimens are quenching and annealing. A furnace was used to heat treat the specimens. To heat treat the specimens, they were heated up to a specific temperature and left to soak. After the specimens have been soaked for a sufficient time, they are taken out of the furnace and either quenched in water or left on a ceramic brick to cool down in room temperature. Due to the high temperatures involved in heat treating, the correct PPE was required. The PPE required were welding gloves, tongs and safety glasses.

To find the temperature required for the steels a time-temperature-transformation curve (TTT) curve was used. Using the TTT curve it was found that 880°C was a suitable temperature to heat treat both the stainless steel and carbon steel specimens. The stainless steel specimen were placed in the furnace at 880°C and left for 25 minute, while the carbon steel specimens were left in the furnace for 30 minutes. The specimens were then separated to be quenched or annealed, the quenching process was conducted by submerging the specimens in water and the annealing process was conducted by allowing the specimens to cool down in room temperature. The stainless steel specimens cooled down in 8 minutes with a room temperature of 15.6° C and the carbon steel specimens cooled down in 10 minutes with a room temperature of 23°C.

### 3.8.1 Heat Treatment Method

1. Turn on the furnace and set the temperature
2. Prepare a ceramic block to place specimens on for after furnace
3. Prepare the specimens on a silicon wafer
4. Place the wafer containing the specimens in the furnace
5. Close the furnace and leave for the required amount of time
6. Remove wafer containing the specimens from furnace
7. Quench a set of specimens by dropping them in water
8. Anneal a set of specimens by placing them on a ceramic block and allowing them to cool in room temperature, record the cooling time

## 3.9 Aluminum Extrusion Testing

In order to investigate the cause of the pressure line occurring at the webbed section of the aluminum extrusion the following tests were conducted. While hardness testing and microscopy performed on the aluminum extrusion specimens provided details of the properties and microstructure of the aluminum and the pressure lines, the physical dimensions and geometry of the aluminum extrusion can be used to isolate the cause of the pressure lines.

The profile of the aluminum extrusion was tested to determine if the webbed section created any discrepancies in the profile in the specimen which could cause visual imperfections in the surface of the extruded specimen. The profile of both the webbed and not webbed specimens were tested to compare the difference the webbing creates in the profile of the extruded specimen. A visual test was first conducted to determine any major profile changes between the two specimens. This was done by comparing the profile of the surface against a flat surface such as a ruler. This was followed by testing using a profilometer to find how the profile of the surface changes with the inclusion of the webbing. A profilometer measures the profile of a surface by running a stylus along the surface, measuring the vertical movements of the stylus. In order to use a profilometer the testing surface must be parallel to the testing apparatus. As the geometry of the aluminum extrusions did not allow for the top surface to sit parallel on a flat surface, the specimen was propped up on wood planks and a spirit level was used to level the surface. Although this did not give accurate data this set up allowed enough information to be gathered to determine whether testing using a profilometer was viable.

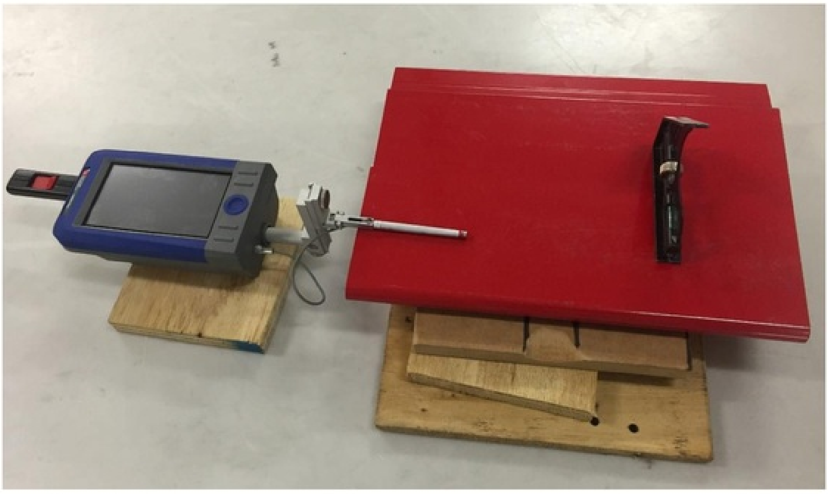


*Figure 16 - Profilometer setup for aluminum extrusion*

The thickness of the cross section along the top surface of the aluminum extrusion was tested to ensure that the aluminum across the specimen was uniform along the extruded piece. This was conducted using electronic vernier calipers to gather thickness values along geometry of both the webbed specimen and the non web specimen. This was done to investigate whether a correlation between thicknesses found in the geometry and the occurrence of the pressure lines. The thickness of the cross section was tested every 15mm of the top surface.

The thickness of the webbing of the aluminum extrusion was also tested to ensure that the aluminum in the webbing was consistent across the section. As only the webbed extruded aluminum specimen contained a webbing, only this specimen was tested. Electronic vernier calipers were used to measure the thickness of the webbed section. Thickness measurements were taken 5mm of the webbed section.

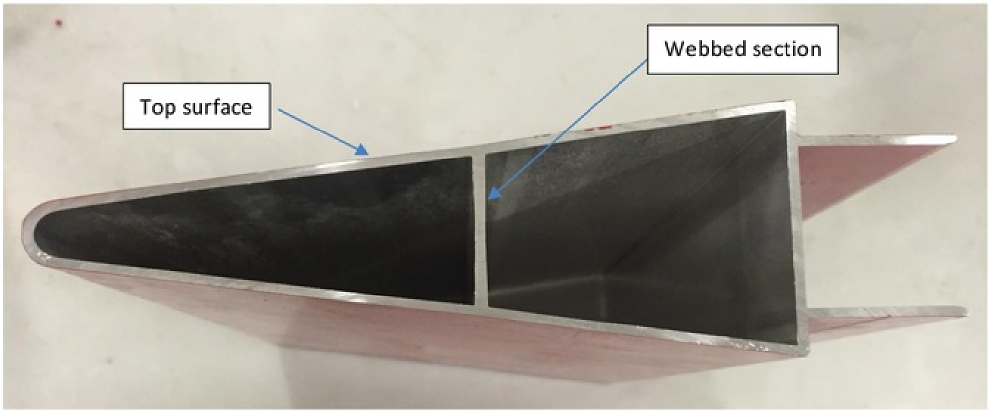



*Figure 17 - Cross section of the aluminum extrusion webbed specimen*

# Chapter 4: Results

## 4.1 Hardness Test

A control specimen was created for each of the welded steels, this control specimen was made from steel which had not been welded or heat treated. In order to test the control specimen 10 indents were made on the control specimen at random covering the entirety of the specimen.

To test the hardness of the specimens a series of indents were made across the specimen with a spacing of 2mm. For each point along the specimen 5 hardness measurements were taken 1mm apart to ensure the accuracy of the testing. As a result, a matrix was formed from the indents as seen in Figure 18 below. Each column of the matrix was labeled by 'Y' followed by a numbered representing the order of the columns. The data collected from hardness testing consisted of 2 indents in the HAZ on one side of the weld, 3 indents in the welded area and 2 indents of the other side of the weld. The data was then plotted on a graph using the mean value from each column. The welded area is marked on the graph by vertical lines and a textbox containing "weld" written in it.


*Figure 18 - Indents along S/S 316 grade quenched specimen*

### 4.1.1 Stainless Steel 304 Grade

To find the optimal heat treatment for welded stainless steel 304 grade, a variety of specimens under different heat treatment conditions were tested. The heat treatment conditions tested were no weld, weld, quenched in water from 880°C for 30 minutes and annealed in 15.6°C air from 880°C for 30 minutes.

#### *Control*

The hardness of the control specimen was found to be 198.8HV5.

*Table 3 - Hardness testing results for S/S 304 control specimen*

| NR. | Hardness | Method |
|---|---|---|
| 1 | 196 | HV 5 |
| 2 | 201 | HV 5 |
| 3 | 208 | HV 5 |
| 4 | 195 | HV 5 |
| 5 | 199 | HV 5 |
| 6 | 197 | HV 5 |
| 7 | 204 | HV 5 |
| 8 | 197 | HV 5 |
| 9 | 195 | HV 5 |
| 10 | 196 | HV 5 |
| Average | 198.8 | HV5 |

### *S/S 304 Grade No Heat Treatment*

The hardness results gathered from the stainless steel 304 grade no heat treatment specimen shows an increase in the hardness of the specimen with an average hardness in the weld of 248HV5. The hardness found in the HAZ of the specimen also increased from the 199HV5 found in the control specimen to 247HV5. The overall hardness of the welded specimen increased compared to the control specimen.

*Table 4 – Hardness results from 'S/S 304 grade - no heat treatment' specimen*

| | Y1 | Y2 | Y3 | Y4 | Y5 | Y6 | Y7 |
|---|---|---|---|---|---|---|---|
| | 260 | 248 | 242 | 230 | 242 | 241 | 237 |
| | 267 | 257 | 244 | 255 | 244 | 272 | 240 |
| | 260 | 248 | 242 | 254 | 254 | 248 | 221 |
| | 254 | 243 | 252 | 262 | 258 | 255 | 238 |
| | 259 | 235 | 247 | 245 | 256 | 231 | 230 |
| Mean | 260 | 246.2 | 245.4 | 249.2 | 250.8 | 249.4 | 233.2 |
| Standard Deviation | 4.636809 | 8.043631 | 4.219005 | 12.31666 | 7.293833 | 15.43697 | 7.79102 |
| Standard Error | 2.073644 | 3.597221 | 1.886796 | 5.508176 | 3.261901 | 6.903622 | 3.48425 |
| X Distance | 2 | 4 | 6 | 8 | 10 | 12 | 14 |

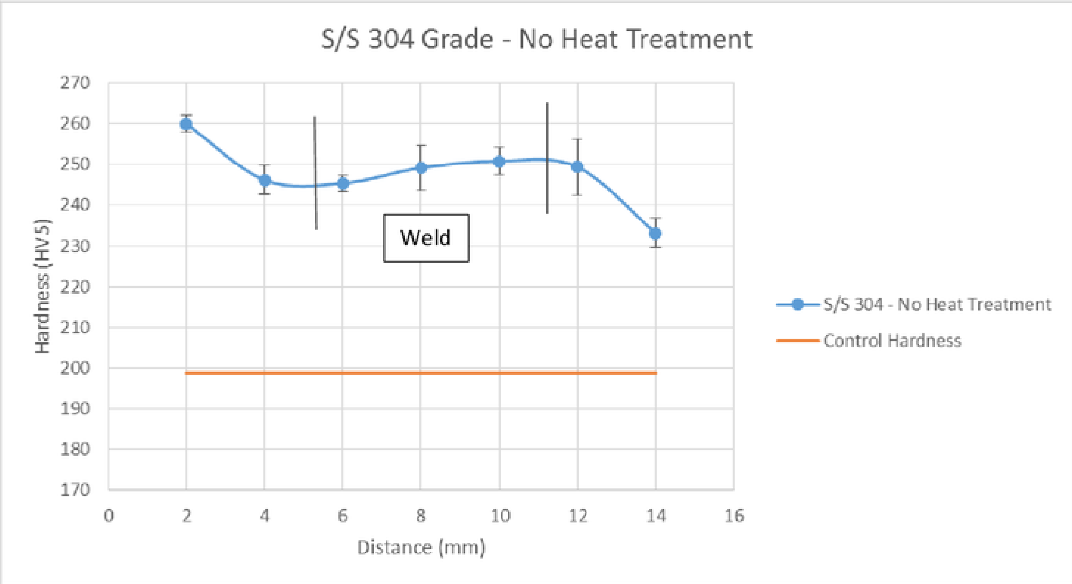



*Figure 19 - Hardness across 'S/S 304 grade - no heat treatment' specimen*

### *S/S 304 Grade Quenched*

The hardness of the stainless steel 304 grade quenched specimen shows that the hardness in the HAZ of the specimen has decreased from the no heat treatment specimen and averages 199HV5. The hardness of the weld in the specimen also experiences a drop in hardness but remains harder than the HAZ.

*Table 5 - Hardness results from S/S 304 grade specimen water quenched at 880°C for 30 minutes*

| | Y1 | Y2 | Y3 | Y4 | Y5 | Y6 | Y7 |
|---|---|---|---|---|---|---|---|
| | 201 | 208 | 221 | 234 | 197 | 205 | 190 |
| | 200 | 201 | 212 | 222 | 202 | 202 | 195 |
| | 201 | 208 | 207 | 216 | 212 | 193 | 192 |
| | 212 | 201 | 211 | 215 | 209 | 205 | 189 |
| | 197 | 189 | 197 | 213 | 199 | 194 | 196 |
| Mean | 202.2 | 201.4 | 209.6 | 220 | 203.8 | 199.8 | 192.4 |
| Standard Deviation | 5.718391 | 7.765307 | 8.70632 | 8.514693 | 6.457554 | 5.890671 | 3.04959 |
| Standard Error | 2.557342 | 3.472751 | 3.893584 | 3.807887 | 2.887906 | 2.634388 | 1.363818 |
| X Distance | 2 | 4 | 6 | 8 | 10 | 12 | 14 |

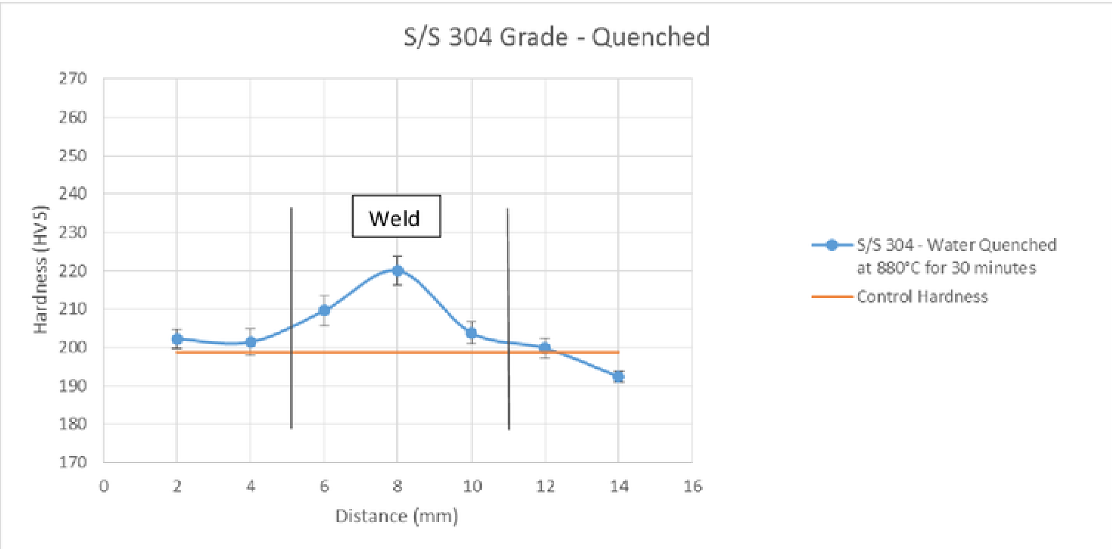



*Figure 20 - Hardness across S/S 304 grade specimen water quenched at 880°C for 30 minutes*

### *S/S 304 Grade Annealed*

The hardness of the stainless steel 304 grade annealed specimen was found to have decreased from the welded specimen without heat treatment. The hardness is inconsistent on either side of the weld with the hardness decreasing on one side. The overall hardness of the HAZ and weld of the annealed was less than the hardness found in the quenched and no heat treatment specimens.

*Table 6 - Hardness results across S/S 304 grade specimen annealed at 880°C for 30 minutes and cooled in 15.6°C air*

| | Y1 | Y2 | Y3 | Y4 | Y5 | Y6 | Y7 |
|---|---|---|---|---|---|---|---|
| | 204 | 190 | 196 | 202 | 185 | 168 | 174 |
| | 205 | 200 | 203 | 235 | 183 | 179 | 178 |
| | 199 | 193 | 206 | 206 | 190 | 179 | 182 |
| | 202 | 199 | 204 | 200 | 191 | 181 | 181 |
| | 214 | 197 | 219 | 198 | 191 | 180 | 181 |
| Mean | 204.8 | 195.8 | 205.6 | 208.2 | 188 | 177.4 | 179.2 |
| Standard Deviation | 5.630275 | 4.207137 | 8.38451 | 15.27089 | 3.741657 | 5.319774 | 3.271085 |
| Standard Error | 2.517936 | 1.881489 | 3.749667 | 6.829348 | 1.67332 | 2.379075 | 1.462874 |
| X Distance | 2 | 4 | 6 | 8 | 10 | 12 | 14 |

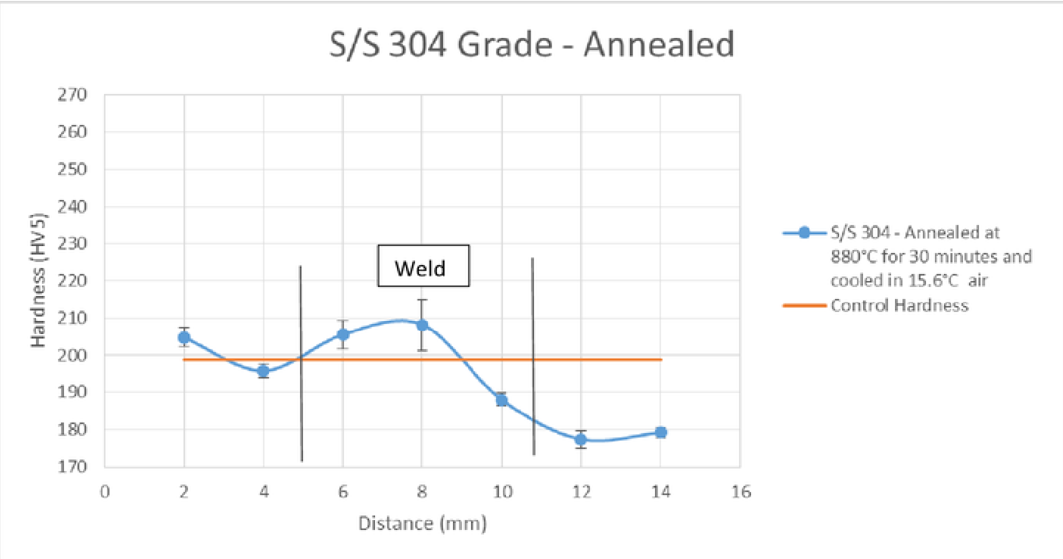



*Figure 21 - Hardness across S/S 304 grade specimen annealed at 880°C for 30 minutes and cooled in 15.6°C air*

### 4.1.2 Stainless Steel 316 Grade

To find the optimal heat treatment for welded stainless steel 316 grade, a variety of specimens under different heat treatment conditions were tested. The heat treatment conditions tested were no weld, weld, quenched in water from 880°C and annealed in 15.6°C air from 880°C.

#### *S/S 316 Grade Control*

The hardness of the stainless steel 316 grade control specimen was found to be 198.3HV5.

*Table 7 - Hardness testing results from S/S 316 grade control specimen*

| NR. | Hardness | Method |
|---|---|---|
| 1 | 199 | HV 5 |
| 2 | 199 | HV 5 |
| 3 | 199 | HV 5 |
| 4 | 194 | HV 5 |
| 1 | 199 | HV 5 |
| 2 | 199 | HV 5 |
| 3 | 199 | HV 5 |
| 4 | 194 | HV 5 |
| 5 | 201 | HV 5 |
| 6 | 200 | HV 5 |
| Average | 198.3 | HV5 |

### *S/S 316 No Heat treatment*

The hardness of the stainless steel 316 grade specimen without heat treatment was found to be lower than the hardness found in the control specimen. The hardness found in the HAZ of the specimen was found to be less than the hardness found in the control specimen.

*Table 8 - Hardness testing results from 'S/S 316 grade - no heat treatment' specimen*

| | Y1 | Y2 | Y3 | Y4 | Y5 | Y6 | Y7 |
|---|---|---|---|---|---|---|---|
| | 180 | 180 | 190 | 192 | 184 | 185 | 174 |
| | 181 | 170 | 192 | 193 | 179 | 182 | 178 |
| | 178 | 173 | 185 | 189 | 186 | 182 | 176 |
| | 170 | 178 | 189 | 178 | 176 | 174 | 165 |
| | 177 | 175 | 179 | 181 | 181 | 180 | 166 |
| Mean | 177.2 | 175.2 | 187 | 186.6 | 181.2 | 180.6 | 171.8 |
| Standard Deviation | 4.32435 | 3.962323 | 5.147815 | 6.730527 | 3.962323 | 4.09878 | 5.932959 |
| Standard Error | 1.933908 | 1.772005 | 2.302173 | 3.009983 | 1.772005 | 1.83303 | 2.6533 |
| X distance | 2 | 4 | 6 | 8 | 10 | 12 | 14 |

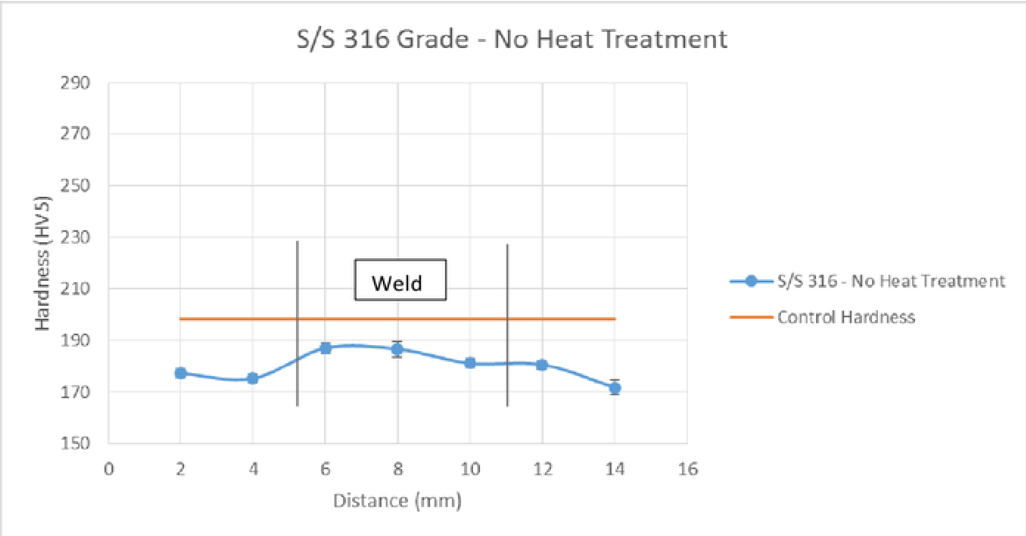



*Figure 22 - Hardness across 'S/S 316 grade - no heat treatment' specimen*

### *Quenched*

The hardness of the stainless steel 316 grade quenched specimens varies around the weld. The hardness in the HAZ of the specimen is inconsistent with one side of the weld exhibiting an average hardness of 257HV5, the other side has an average hardness of 244HV5. The harness of the specimen between the weld and edge also exhibit large variations, ranging from 260HV5 to 182HV5. The overall hardness of the specimen is higher than the hardness found in the control specimen.

*Table 9 - Hardness testing results from S/S 316 grade specimen water quenched at 880°C for 30 minutes*

| | Y1 | Y2 | Y3 | Y4 | Y5 | Y6 | Y7 |
|---|---|---|---|---|---|---|---|
| | 269 | 235 | 285 | 277 | 223 | 213 | 251 |
| | 260 | 242 | 276 | 275 | 219 | 218 | 262 |
| | 254 | 263 | 251 | 237 | 215 | 244 | 260 |
| | 242 | 268 | 265 | 245 | 248 | 237 | 263 |
| | 259 | 279 | 274 | 275 | 218 | 238 | 260 |
| Mean | 256.8 | 257.4 | 270.2 | 261.8 | 224.6 | 230 | 259.2 |
| Standard Deviation | 9.884331 | 18.36573 | 12.87245 | 19.21458 | 13.39029 | 13.61984 | 4.764452 |
| Standard Error | 4.420407 | 8.213404 | 7.431913 | 11.09354 | 5.988322 | 6.090977 | 2.130728 |
| X Distance | 2 | 4 | 6 | 8 | 10 | 12 | 14 |

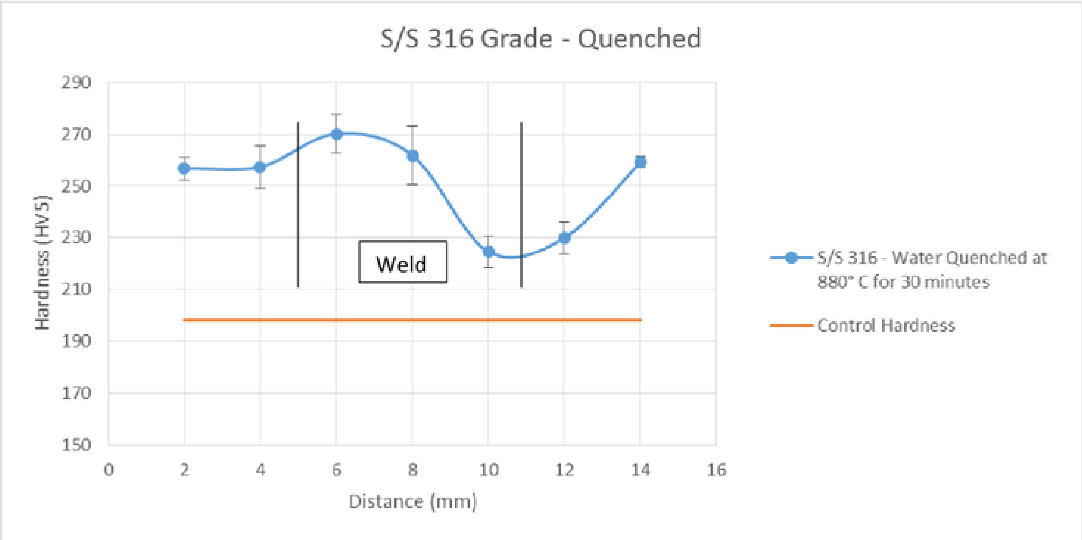



*Figure 23 - Hardness across 'S/S 316 grade - quenched' specimen water quenched at 880°C for 30 minutes*

### *Annealed*

Overall the hardness of the stainless steel 316 grade annealed specimen was found to be greater than the hardness of control specimen and no heat treatment specimen but less than the hardness of the quenched specimen. The hardness in the HAZ of the specimen was found to average 246HV5 with one side being harder than the other. The weld of the specimen was found to average 252HV5, higher than the HAZ.

*Table 10 - Hardness testing results from S/S 316 grade specimen annealed at 880°C for 30 minutes and cooled in 15.6°C air*

| | Y1 | Y2 | Y3 | Y4 | Y5 | Y6 | Y7 |
|---|---|---|---|---|---|---|---|
| | 229 | 235 | 235 | 260 | 221 | 219 | 261 |
| | 237 | 229 | 252 | 263 | 229 | 242 | 265 |
| | 245 | 235 | 264 | 265 | 251 | 260 | 264 |
| | 246 | 240 | 252 | 255 | 271 | 231 | 285 |
| | 241 | 221 | 256 | 268 | 240 | 254 | 284 |
| Mean | 239.6 | 232 | 251.8 | 262.2 | 242.4 | 241.2 | 271.8 |
| Standard Deviation | 6.913754 | 7.28011 | 10.59245 | 4.969909 | 19.59081 | 16.69431 | 11.69188 |
| Standard Error | 3.091925 | 3.255764 | 6.115554 | 3.514257 | 9.795407 | 7.465923 | 5.228767 |
| X Distance | 2 | 4 | 6 | 8 | 10 | 12 | 14 |

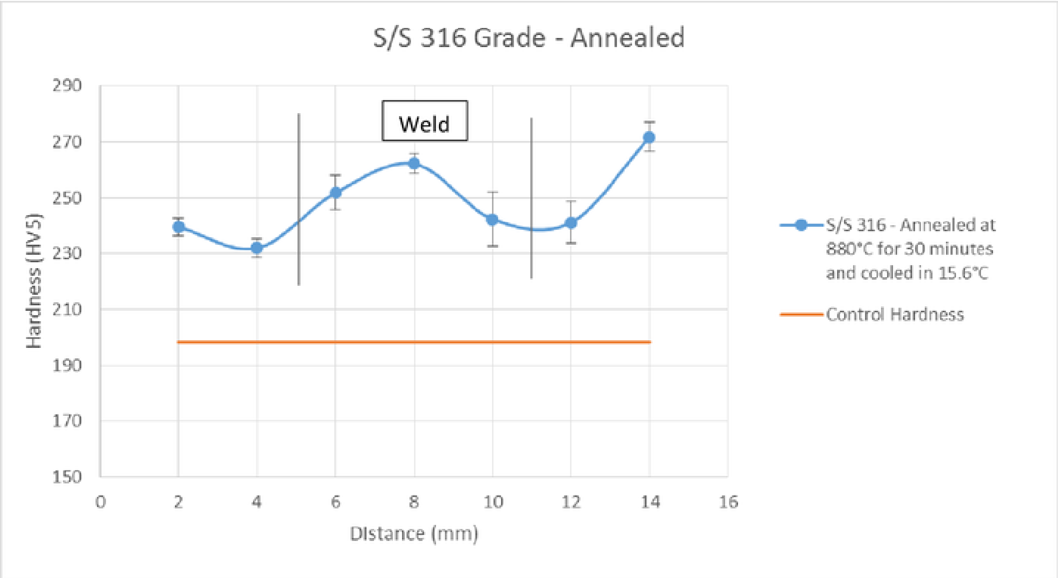



*Figure 24 - Hardness across S/S 316 grade specimen annealed at 880°C for 30 minutes and cooled in 15.6°C air*

### 4.1.3 Carbon Steel 1045 Grade

To find the optimal heat treatment for welded carbon steel 1045 grade, a variety of specimens under different heat treatment conditions were tested. The heat treatment conditions tested were no weld (control), welded without heat treatment (no heat treatment), quenched in water from 880°C and annealed in 23°C air from 880°C.

*Control*

The hardness of the carbon steel 1045 grade control specimen was found to be 121.9HV3.

*Table 11 - Hardness testing results from C/S 1045 grade control specimen*

| NR. | Hardness | Method |
|---|---|---|
| 1 | 120 | HV 3 |
| 2 | 120 | HV 3 |
| 3 | 121 | HV 3 |
| 4 | 122 | HV 3 |
| 5 | 124 | HV 3 |
| 6 | 122 | HV 3 |
| 7 | 124 | HV 3 |
| 8 | 121 | HV 3 |
| 9 | 121 | HV 3 |
| 10 | 124 | HV 3 |
| Average | 121.9 | HV 3 |

### *No Heat treatment*

The hardness of the carbon steel 1045 grade welded no heat treatment specimen was found to be greater than the control specimen. The hardness greatly increases in the weld of the specimen, increasing by up to 63HV3 from the control specimen. Around the HAZ of the specimen the hardness of the specimen also increases compared to the control value.

*Table 12 - Hardness testing results from 'C/S 1045 grade - no heat treatment' specimen*

| | Y1 | Y2 | Y3 | Y4 | Y5 | Y6 | Y7 |
|---|---|---|---|---|---|---|---|
| | 149 | 156 | 186 | 181 | 179 | 157 | 144 |
| | 151 | 155 | 183 | 169 | 179 | 153 | 141 |
| | 143 | 155 | 179 | 179 | 178 | 151 | 146 |
| | 145 | 162 | 187 | 175 | 175 | 152 | 150 |
| | 143 | 154 | 191 | 167 | 161 | 150 | 148 |
| Mean | 146.2 | 156.4 | 185.2 | 174.2 | 174.4 | 152.6 | 145.8 |
| Standard Deviation | 3.63318 | 3.209361 | 4.494441 | 6.09918 | 7.668116 | 2.701851 | 3.49285 |
| Standard Error | 1.624808 | 1.43527 | 2.009975 | 2.727636 | 3.429286 | 1.208305 | 1.56205 |
| X Distance | 2 | 4 | 6 | 8 | 10 | 12 | 14 |

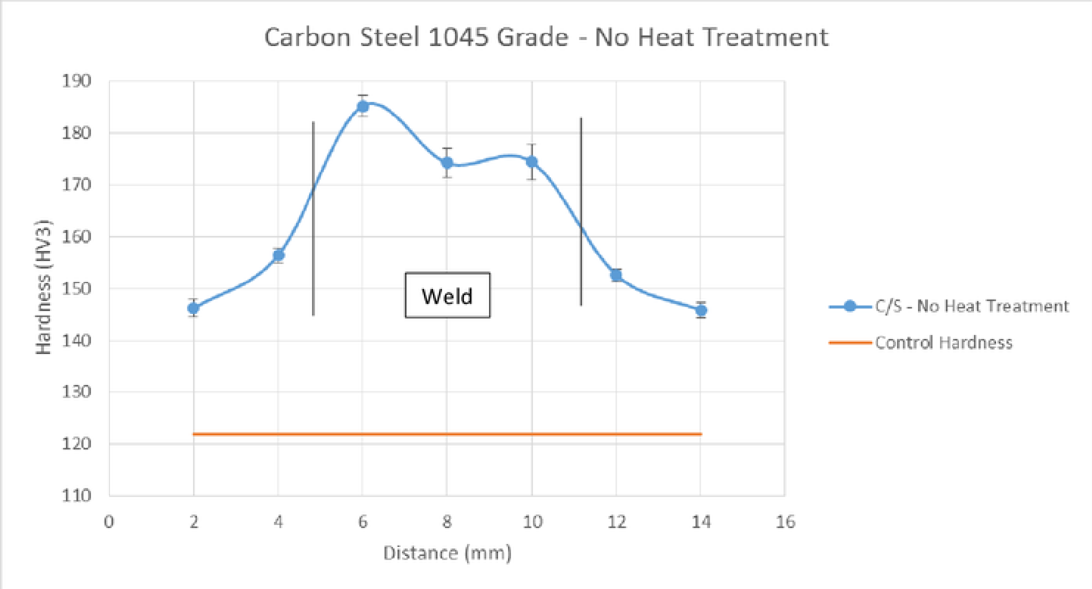



*Figure 25 - Hardness across 'C/S 1045 grade - no heat treatment' specimen*

### *Quenched*

The hardness of the carbon steel 1045 grade quenched specimen was found to be similar to the hardness of the carbon steel specimen without heat treatment. The hardness of the specimen increased closer to the weld, while staying consistent at the edges of the specimen. The hardness at the welded zone of the specimen decreased to approximately 148HV3, making it similar to the hardness of the rest of the specimen.

*Table 13 - Hardness testing results from C/S 1045 grade specimen water quenched at 880°C for 30 minutes*

| | Y1 | Y2 | Y3 | Y4 | Y5 | Y6 | Y7 |
|---|---|---|---|---|---|---|---|
| | 144 | 182 | 148 | 144 | 144 | 151 | 142 |
| | 143 | 180 | 143 | 151 | 146 | 148 | 146 |
| | 139 | 164 | 151 | 152 | 149 | 159 | 147 |
| | 149 | 138 | 150 | 152 | 154 | 151 | 143 |
| | 155 | 135 | 146 | 149 | 146 | 154 | 151 |
| Mean | 146 | 159.8 | 147.6 | 149.6 | 147.8 | 152.6 | 145.8 |
| Standard Deviation | 6.164414 | 22.40982 | 3.209361 | 3.361547 | 3.898718 | 4.159327 | 3.563706 |
| Standard Error | 2.75681 | 9.14877 | 1.852926 | 1.94079 | 1.949359 | 1.860108 | 1.593738 |
| X Distance | 2 | 4 | 6 | 8 | 10 | 12 | 14 |

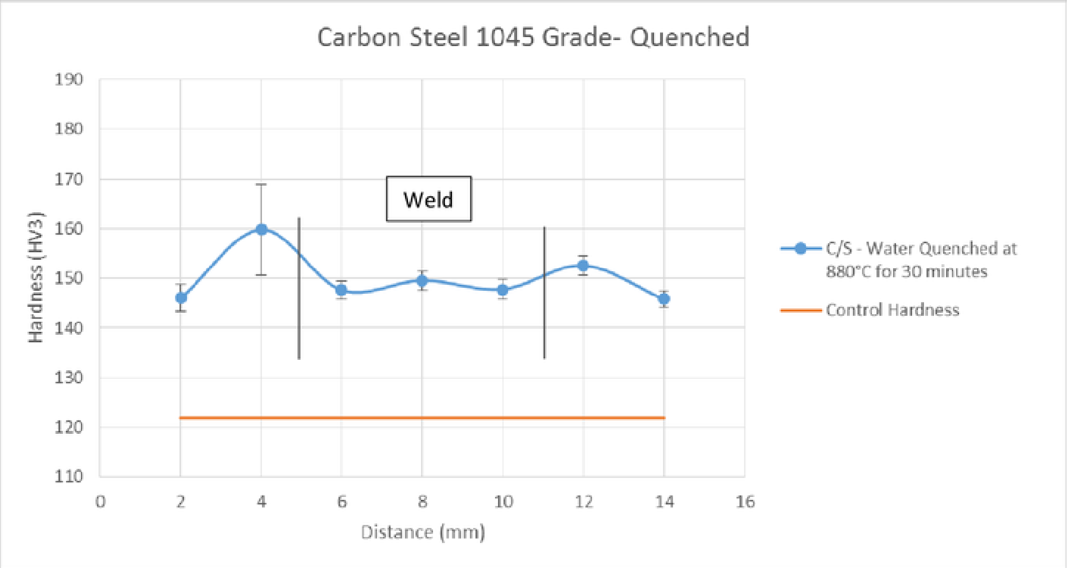



*Figure 26 - Hardness across 'C/S 1045 grade specimen water quenched at 880°C for 30 minutes*

### *Annealed*

The hardness of the carbon steel 1045 grade annealed specimen increases around the weld. The HAZ of the specimen was found to be lower than both the quenched and no heat treatment specimens. The hardness in the HAZ was found to be 150HV3 while the hardness in the weld was found to be 157HV3.

*Table 14 - Hardness testing results from 'C/S 1045 grade specimen annealed at 880°C for 30 minutes*

| | Y1 | Y2 | Y3 | Y4 | Y5 | Y6 | Y7 |
|---|---|---|---|---|---|---|---|
| | 147 | 158 | 161 | 166 | 152 | 152 | 149 |
| | 150 | 151 | 150 | 159 | 160 | 151 | 151 |
| | 151 | 152 | 153 | 160 | 152 | 153 | 147 |
| | 141 | 152 | 157 | 164 | 151 | 152 | 154 |
| | 140 | 149 | 163 | 158 | 154 | 152 | 142 |
| Mean | 145.8 | 152.4 | 156.8 | 161.4 | 153.8 | 152 | 148.6 |
| Standard Deviation | 5.069517 | 3.361547 | 5.403702 | 3.435113 | 3.63318 | 0.707107 | 4.505552 |
| Standard Error | 2.267157 | 1.50333 | 2.416609 | 1.536229 | 1.624808 | 0.316228 | 2.014944 |
| X Distance | 2 | 4 | 6 | 8 | 10 | 12 | 14 |

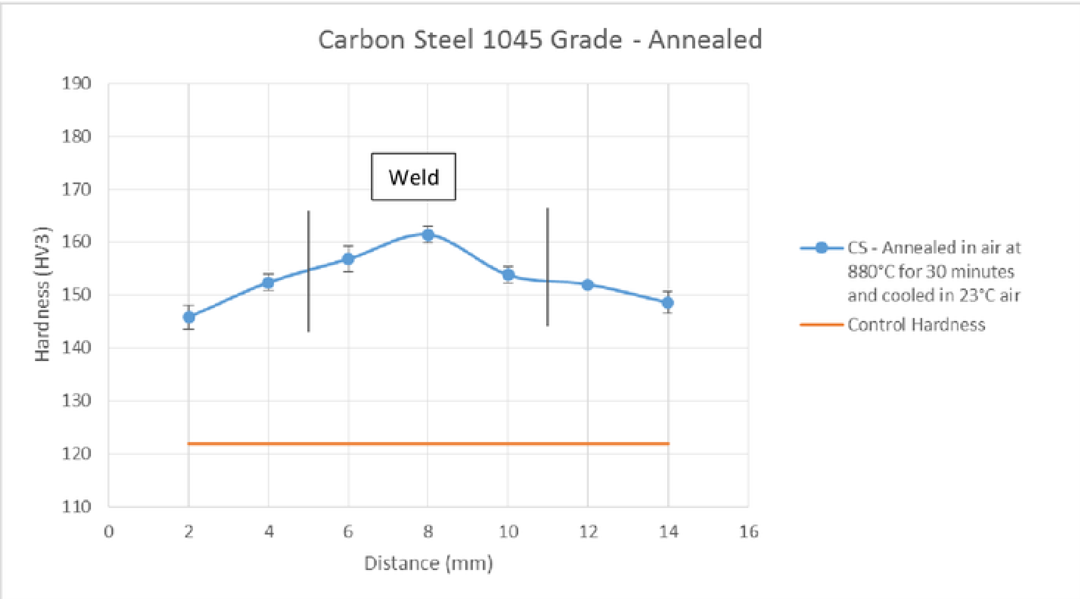



*Figure 27 - Hardness across 'C/S 1045 grade specimen annealed at 880°C for 30 minutes and cooled in 23°C air*

### 4.1.4 Aluminum

To investigate the properties of the aluminum extrusions with and without the webbing, hardness testing was performed on both specimens with and without the webbing in area containing the webbing and pressure line.

#### *Not Webbed*

The hardness of the 'aluminum not webbed' specimen was found to be 50.6HV1. The variation found in hardness found in this specimen is very small, with all the results along the specimen being between 49.1HV1 and 51.1HV1.

*Table 15 - Hardness testing results from 'aluminum – not webbed' specimen*

| | Y1 | Y2 | Y3 | Y4 | Y5 | Y6 | Y7 | Y8 |
|---|---|---|---|---|---|---|---|---|
| | 50.5 | 47.7 | 51.1 | 49.6 | 52.1 | 49.8 | 50.5 | 51.2 |
| | 51.2 | 50 | 51.4 | 50.1 | 54 | 51.6 | 50.5 | 49.3 |
| | 54.5 | 47.5 | 50.8 | 51.7 | 50 | 51.1 | 50.9 | 50.8 |
| | 48.4 | 50.9 | 49.1 | 50.6 | 51.1 | 51.4 | 50.4 | 50.4 |
| | 50.9 | 49.8 | 50.6 | 50 | 50.5 | 51 | 51 | 50.2 |
| Mean | 51.1 | 49.18 | 50.6 | 50.4 | 51.54 | 50.98 | 50.66 | 50.38 |
| Standard Deviation | 2.194311 | 1.502332 | 0.891628 | 0.809321 | 1.582087 | 0.701427 | 0.270185 | 0.715542 |
| Standard Error | 0.981326 | 0.671863 | 0.398748 | 0.361939 | 0.707531 | 0.404969 | 0.155991 | 0.413118 |
| X Distance | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 |

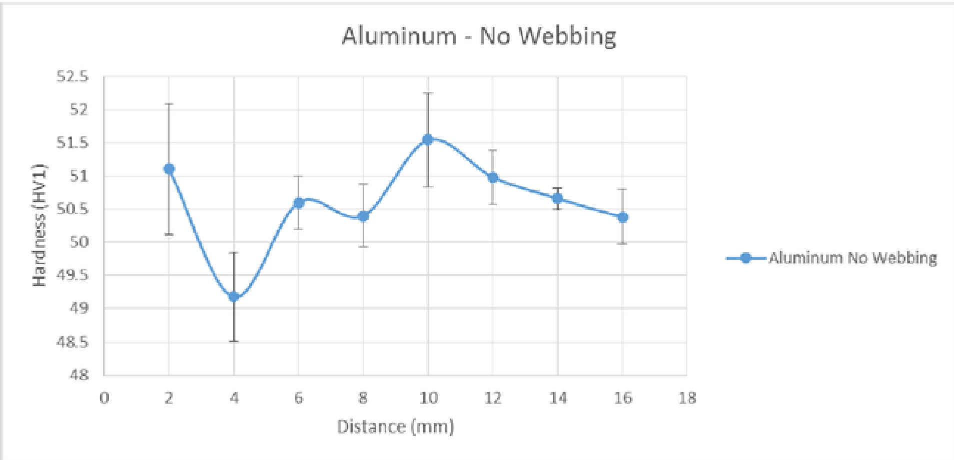



*Figure 28 - Hardness across 'aluminum - not webbed' specimen*

### *Webbed*

As the results gathered from the hardness testing contained very little variation only 3 data points were tested in each row as opposed to 5. The hardness of the general area in aluminum webbed specimen varies between 84HV1 and 87HV1. The hardness along the aluminum webbed specimen decreases to 81.26HV1 in the area containing the webbing.

*Table 16 - Hardness testing results from 'aluminum –webbed' specimen*

| | Y1 | Y2 | Y3 | Y4 | Y5 | Y6 | Y7 | Y8 |
|---|---|---|---|---|---|---|---|---|
| | 88.4 | 84 | 86.6 | 84.6 | 79.7 | 84.8 | 88.2 | 87.5 |
| | 85.8 | 84 | 85.2 | 84.9 | 81.7 | 86.2 | 85.4 | 85.8 |
| | 86.5 | 86.3 | 86.8 | 84.9 | 82.4 | 82.1 | 85.2 | 87.6 |
| Mean | 86.9 | 84.76667 | 86.2 | 84.8 | 81.26667 | 84.36667 | 86.26667 | 86.96667 |
| Standard deviation | 1.345362 | 1.327906 | 0.87178 | 0.173205 | 1.40119 | 2.084067 | 1.677299 | 1.011599 |
| Standard Error | 0.776745 | 0.766667 | 0.503322 | 0.1 | 0.808977 | 1.203236 | 0.968389 | 0.584047 |
| X Distance | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 |

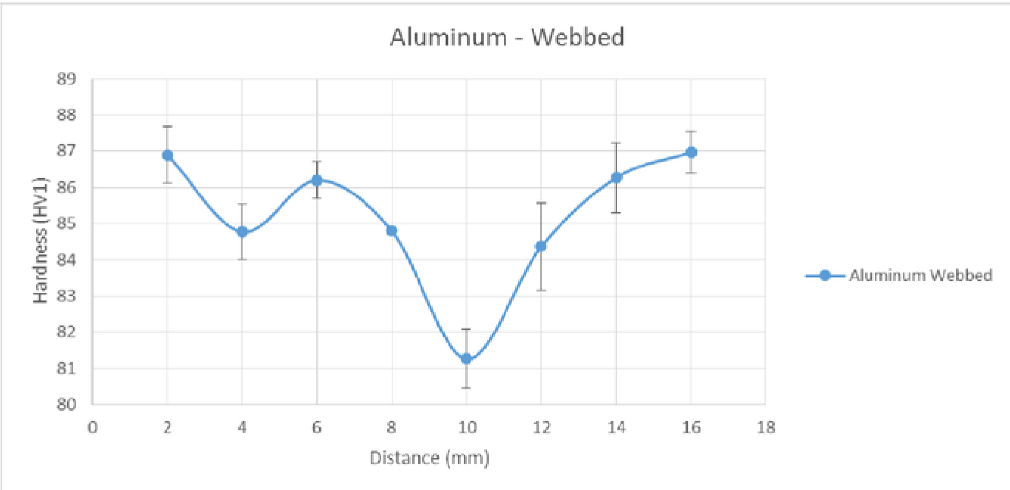



*Figure 29 - Hardness across 'aluminum - webbed' specimen*

## *Not Webbed*

The hardness of the 'aluminum not webbed' specimen was found to be 50.6HV1. The variation found in hardness found in this specimen is very small, with all the results along the specimen being between 49.1HV1 and 51.1HV1.

*Table 17 - Hardness testing results from 'aluminum – not webbed' specimen*

| | Y1 | Y2 | Y3 | Y4 | Y5 | Y6 | Y7 | Y8 |
|---|---|---|---|---|---|---|---|---|
| | 50.5 | 47.7 | 51.1 | 49.6 | 52.1 | 49.8 | 50.5 | 51.2 |
| | 51.2 | 50 | 51.4 | 50.1 | 54 | 51.6 | 50.5 | 49.3 |
| | 54.5 | 47.5 | 50.8 | 51.7 | 50 | 51.1 | 50.9 | 50.8 |
| | 48.4 | 50.9 | 49.1 | 50.6 | 51.1 | 51.4 | 50.4 | 50.4 |
| | 50.9 | 49.8 | 50.6 | 50 | 50.5 | 51 | 51 | 50.2 |
| Mean | 51.1 | 49.18 | 50.6 | 50.4 | 51.54 | 50.98 | 50.66 | 50.38 |
| Standard Deviation | 2.194311 | 1.502332 | 0.891628 | 0.809321 | 1.582087 | 0.701427 | 0.270185 | 0.715542 |
| Standard Error | 0.981326 | 0.671863 | 0.398748 | 0.361939 | 0.707531 | 0.404969 | 0.155991 | 0.413118 |
| X Distance | 2 | 4 | 6 | 8 | 10 | 12 | 14 | 16 |

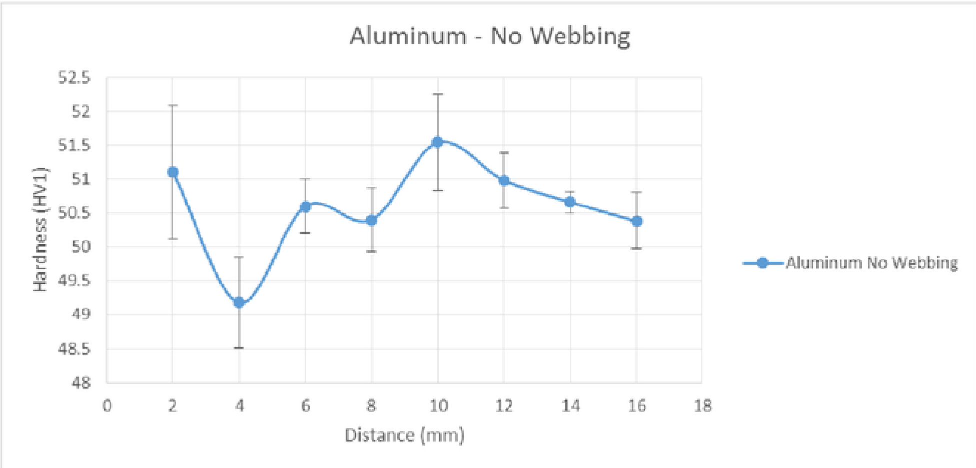



*Figure 30 - Hardness across 'aluminum - not webbed' specimen*

## 4.2 Microscopy

In order to represent the different heat treatments on the steels, the stainless steel 304 grade specimens were used. The micrographs of each heat treatment applied on this steel was analysis, the style of the analysis carried out on this specimen will be similar in the specimens that follow.

The microstructure of the stainless steel 304 grade without heat treatment specimen (Figure 31) show a large grain sizes, the sizes of the grains also varies considerably between each grain. The microstructure also shows that the grains are disorientated. The grains present in the microstructure of this specimen are over 60µm.

The stainless steel 304 grade quenched specimen (Figure 33) shows a finer grain size in the steel. The orientation of the grains are also better aligned and the sizes of the grains are more consistent. The size of the grains present in the microstructure is approximately 30µm in size.

The grain size present in the stainless steel 304 grade annealed specimen (Figure 35) were larger than the quenched specimen. The orientation of the grains were also more orientated than the no heat treatment specimen. The grain size found in the specimen is approximately 40µm.

## 4.4.1 Stainless Steel 304 Grade

*No Heat Treatment*

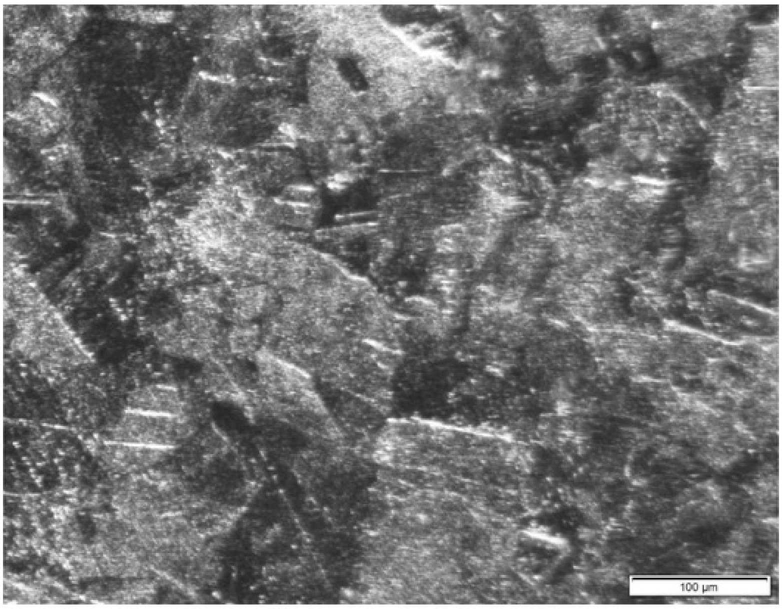



*Figure 31 – General area of S/S 304 grade without heat treatment*

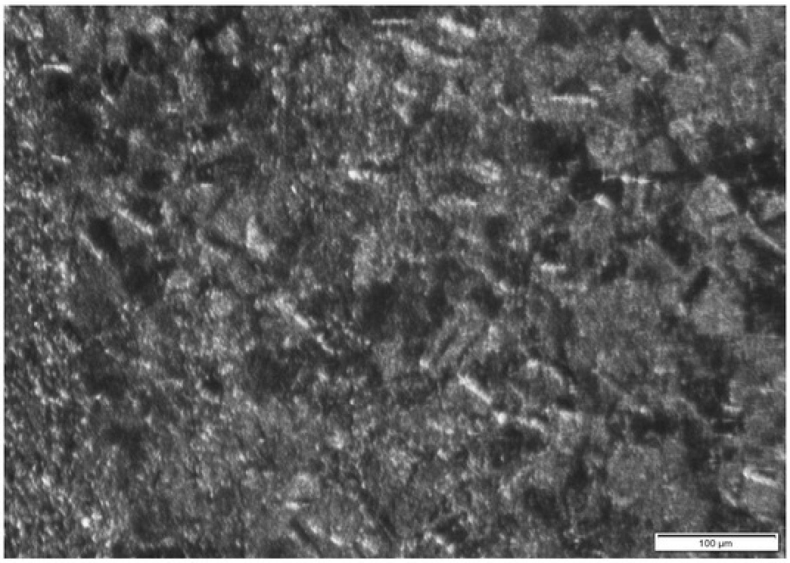



*Figure 32 - HAZ of S/S 304 grade without heat treatment*

### *Quenched in Water*

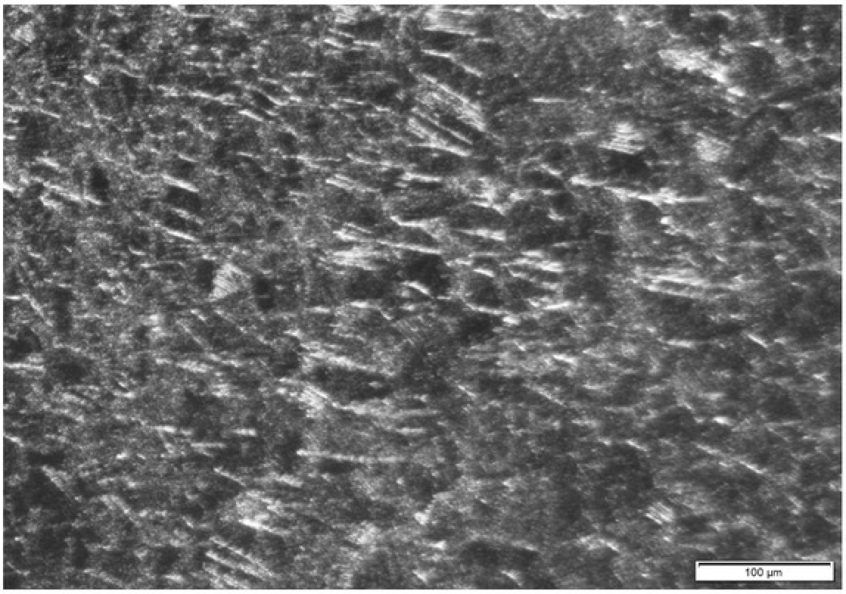



*Figure 33 –General area of S/S 304 grade quenched in water*

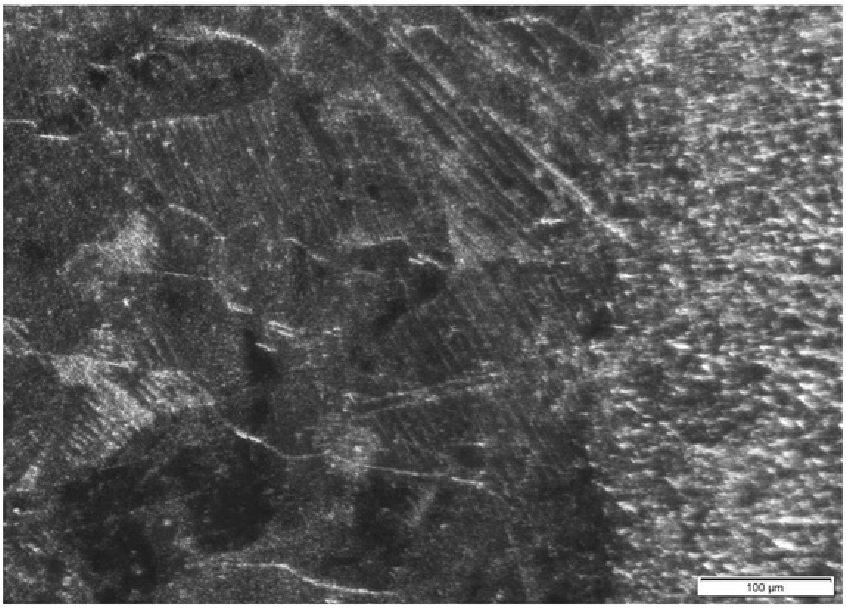



*Figure 34 - HAZ of S/S 304 grade quenched in water*

*Annealed*

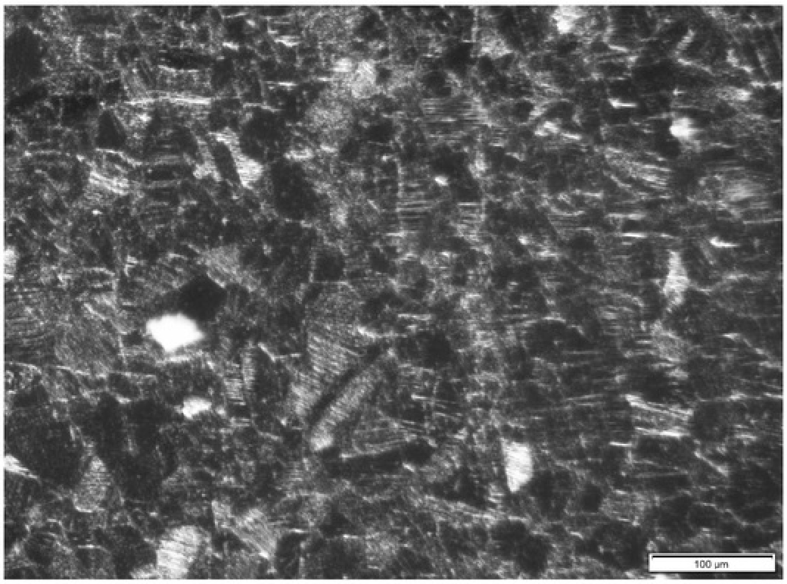



*Figure 35 - General area of S/S 304 annealed in room temperature*

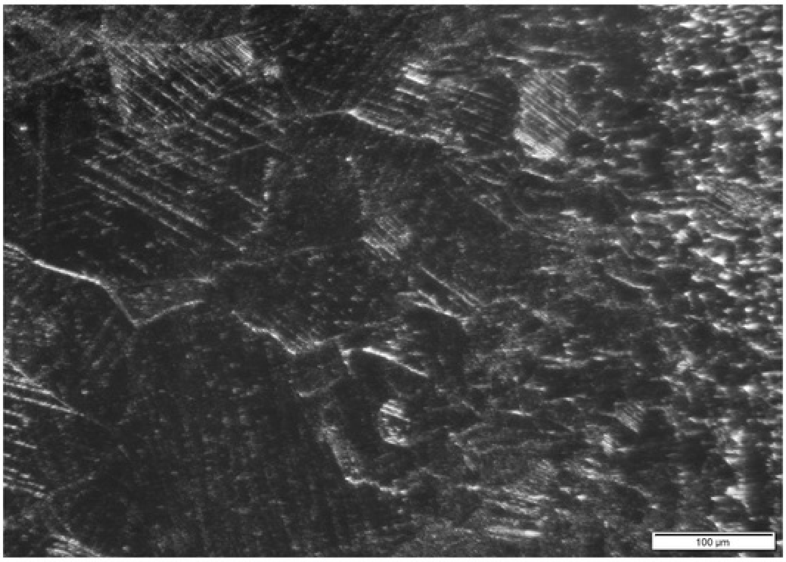



*Figure 36 - HAZ area of S/S 304 annealed in room temperature*

### 4.4.2 Stainless Steel 316 Grade

*No Heat treatment*

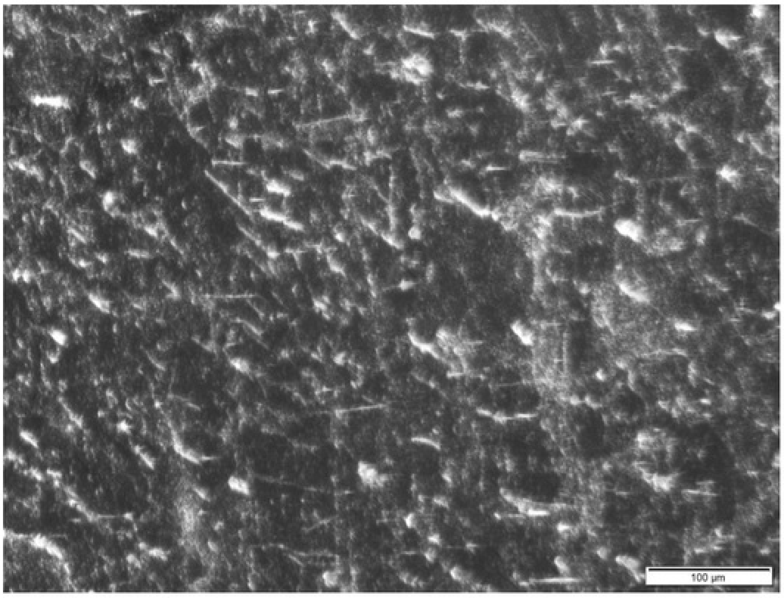



*Figure 37 - General area of S/S 316 grade without heat treatment*

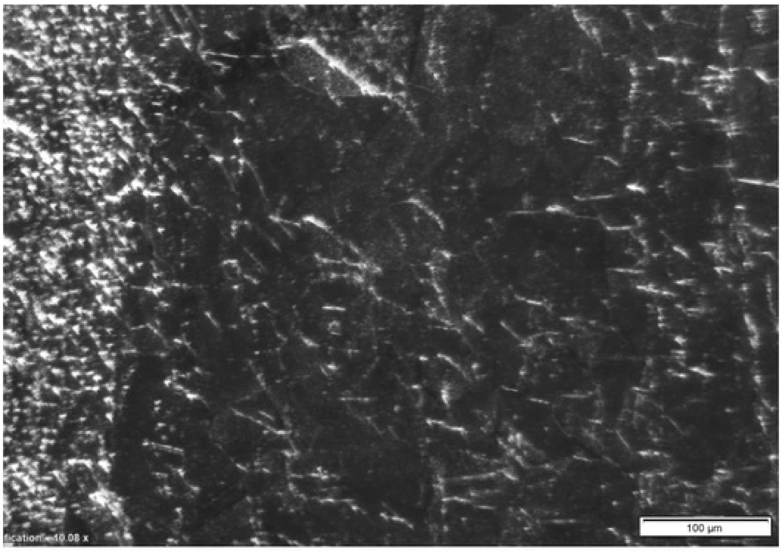



*Figure 38 - HAZ area of S/S 316 grade without heat treatment*

## *Quenched*

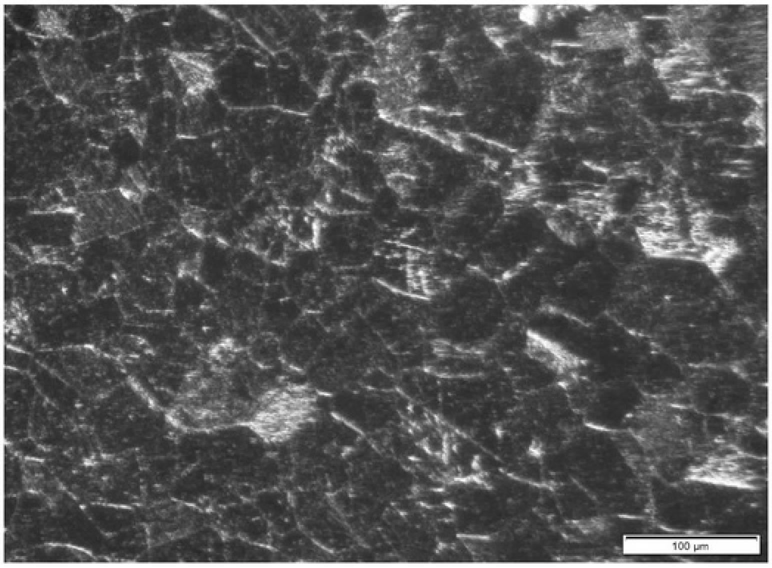



*Figure 39 - General area of S/S 316 grade quenched in water*

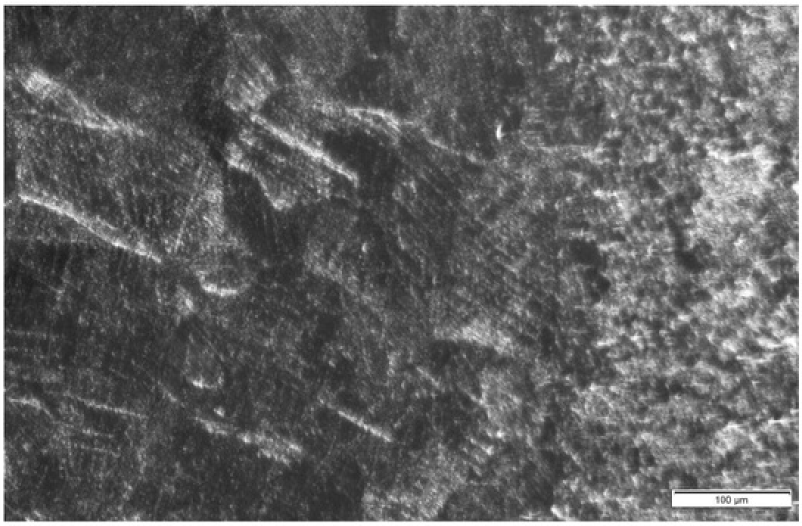



*Figure 40 - HAZ area of S/S 316 grade quenched in water*

*Annealed*

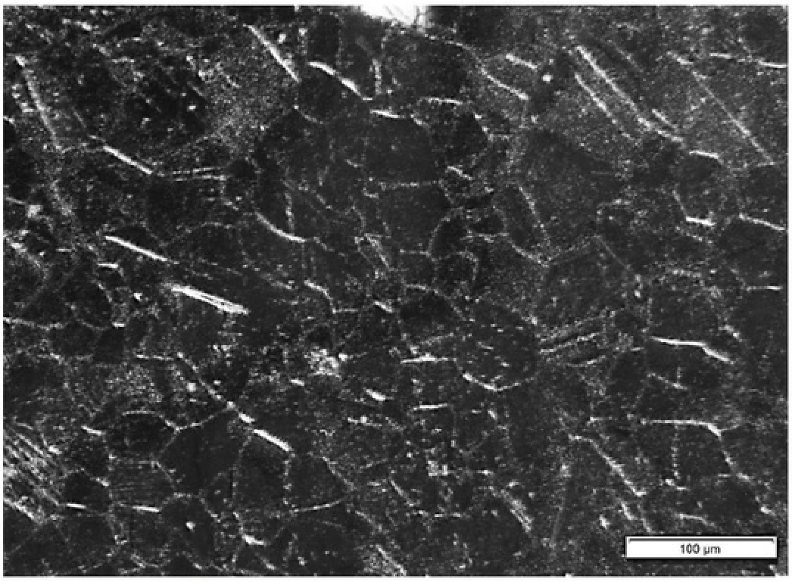



*Figure 41 - General area of S/S 316 annealed in room temperature*

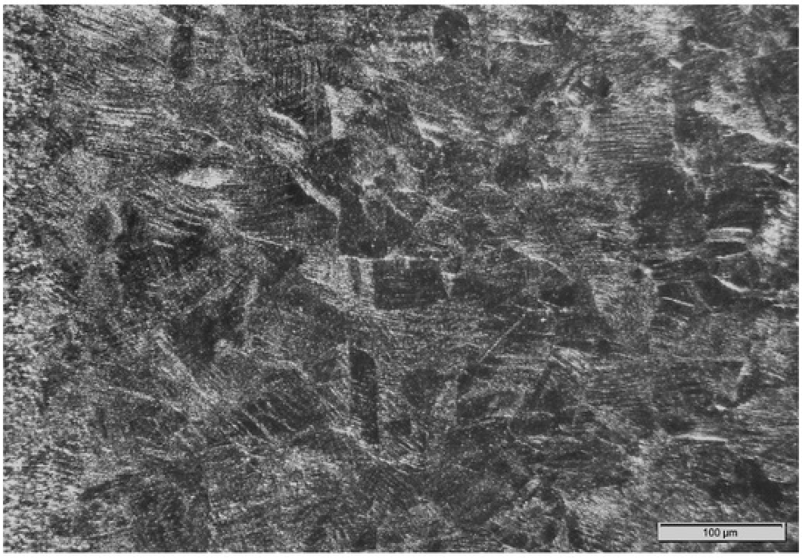



*Figure 42 - HAZ area of S/S 316 annealed in room temperature*

### 4.4.3 Carbon Steel 1045 Grade

*No Heat treatment*

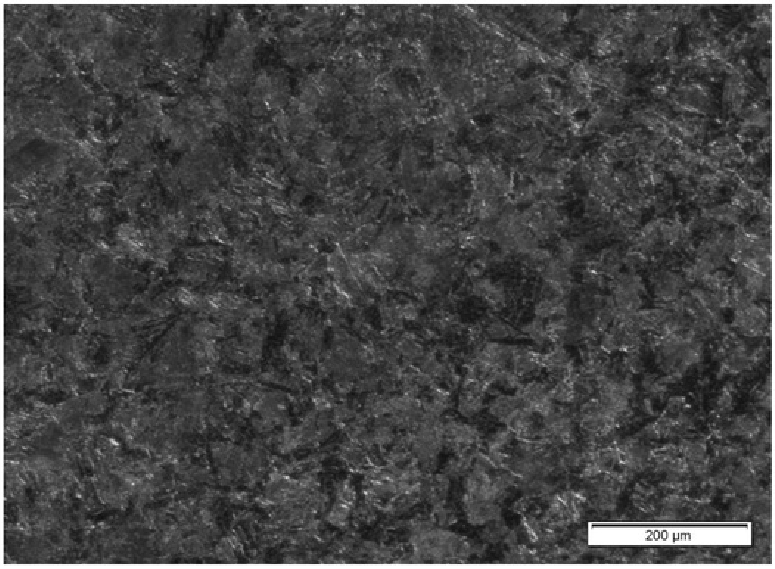



*Figure 43 - General area of carbon steel 1045 grade without heat treatment*

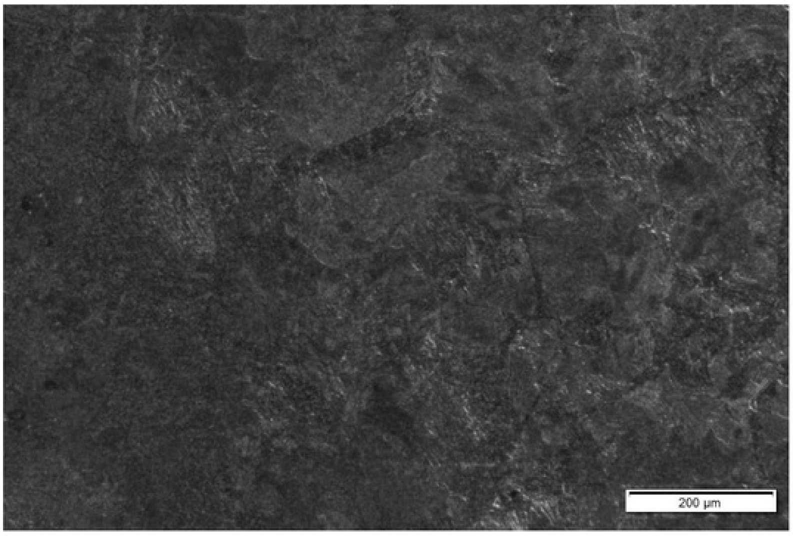



*Figure 44 - HAZ area of carbon steel 1045 grade without heat treatment*

*Quenched*

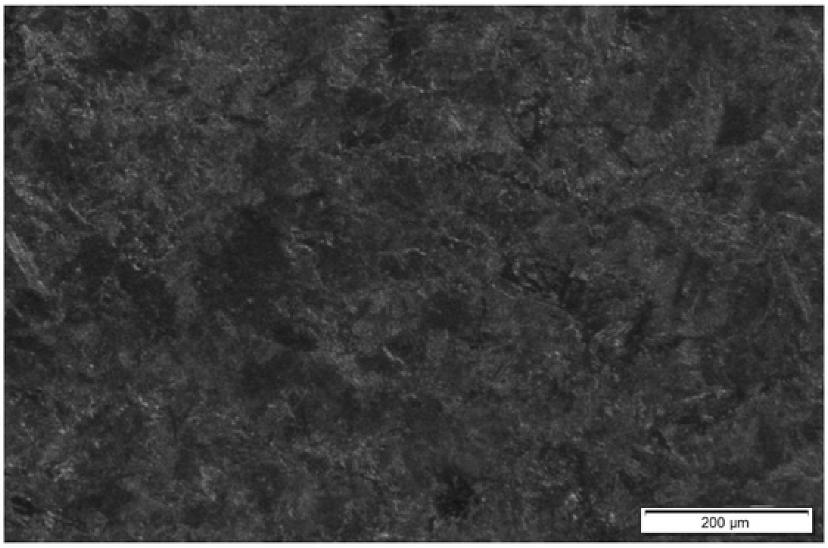



*Figure 45 - General area of carbon steel 1045 grade quenched in water*

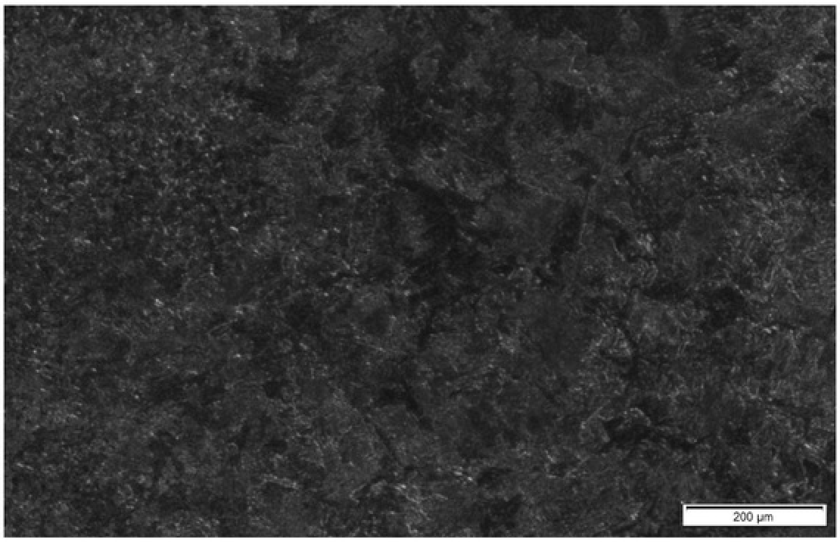



*Figure 46 - HAZ area of carbon steel 1045 grade quenched in water*

### *Annealed*

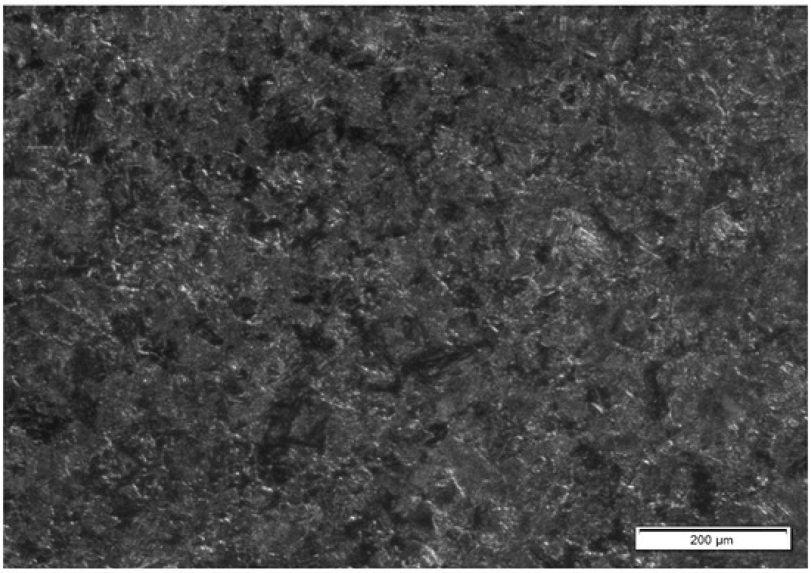



*Figure 47 - General area of carbon steel 1045 grade annealed in room temperature*

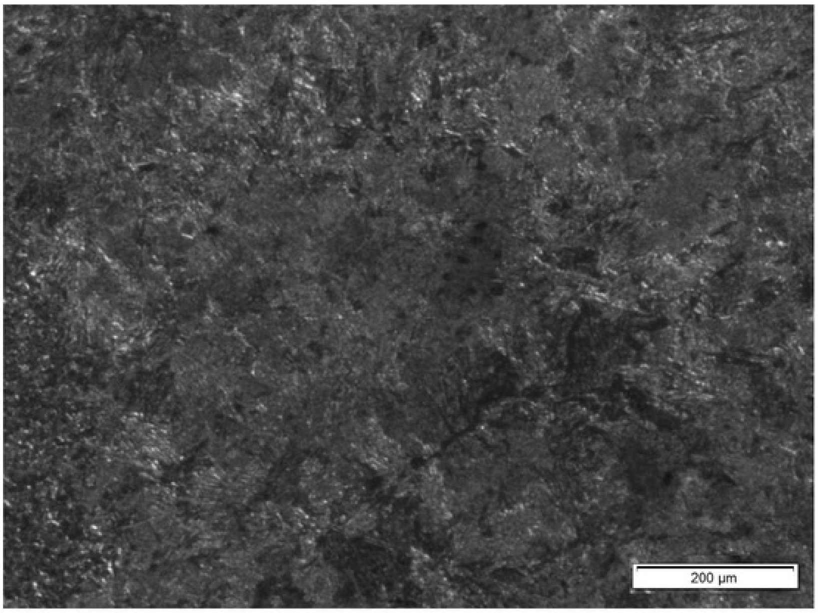



*Figure 48 - HAZ area of carbon steel 1045 grade annealed in room temperature*

### 4.4.4 Aluminum 6000 Series

#### *Webbed*

The figures below demonstrate the microstructure of the webbed aluminum sample in the general area and at the webbed section. The grain sizes of both areas, at the webbing and in the genera area were found to be similar.

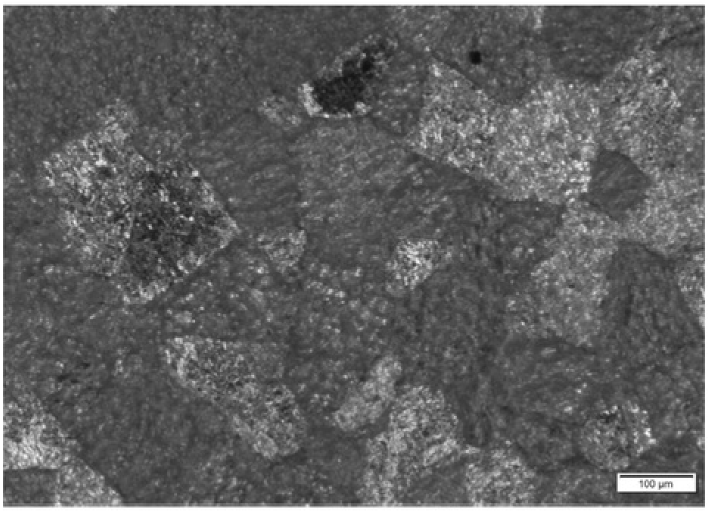



*Figure 49 - General area of aluminium specimen with webbing*

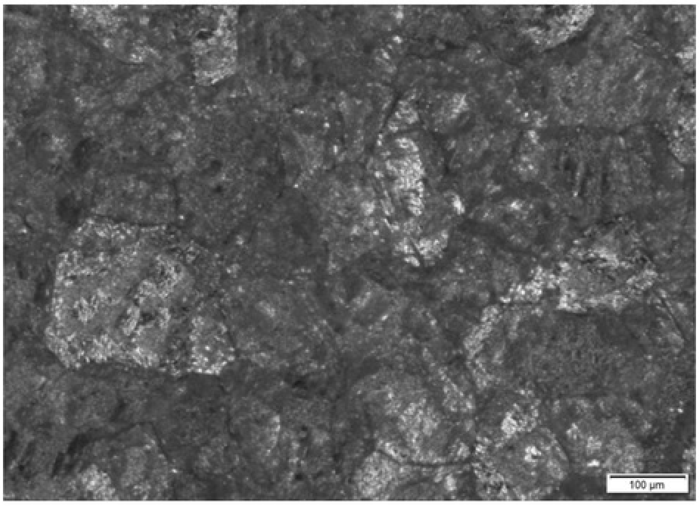



*Figure 50 - Webbed area of aluminium specimen with webbing*

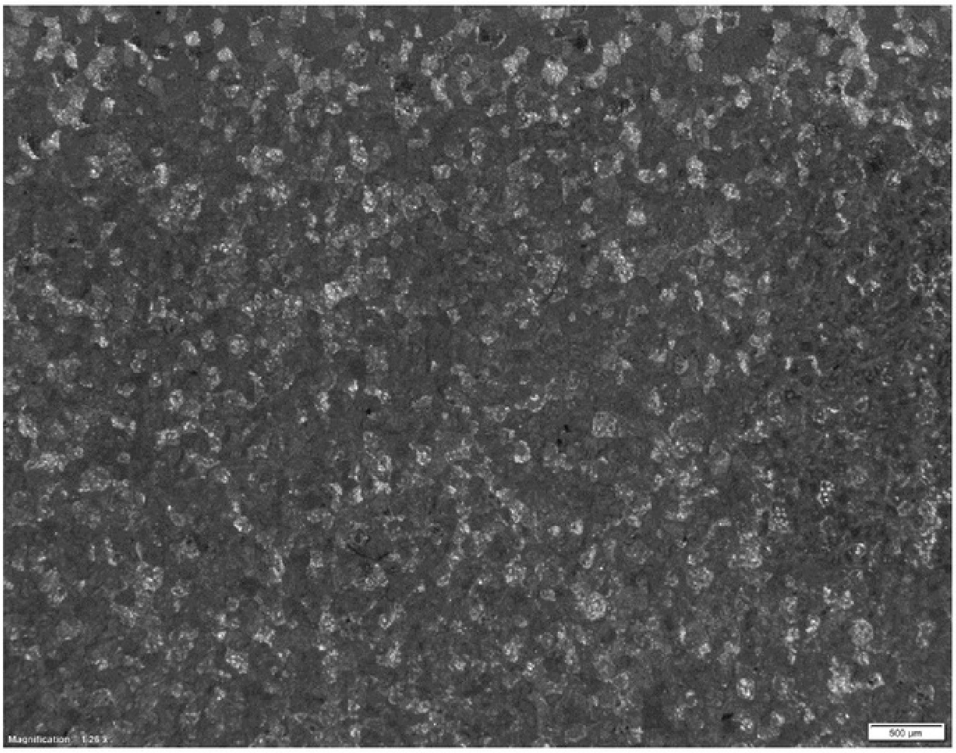



*Figure 51 - Macro view of aluminium specimen with webbing*

### *Not Webbed*

The figures below demonstrate the microstructure of the aluminum extrusion of similar areas in the sample without the webbing.

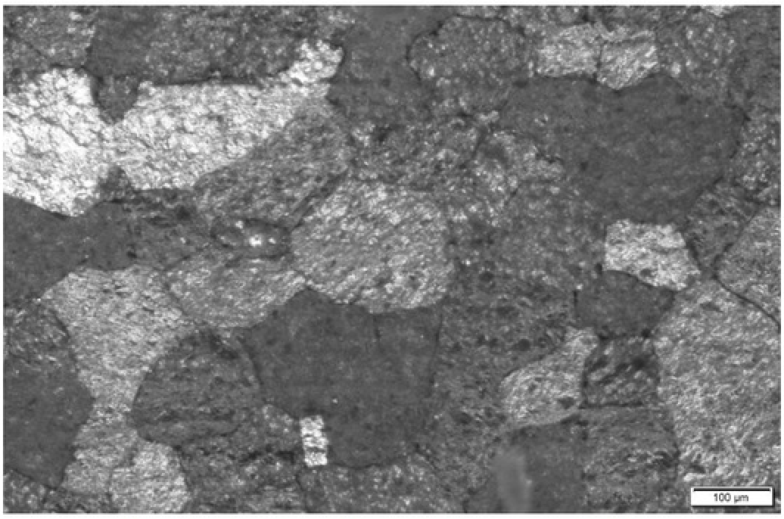



*Figure 52 - General area of aluminium specimen without webbing*

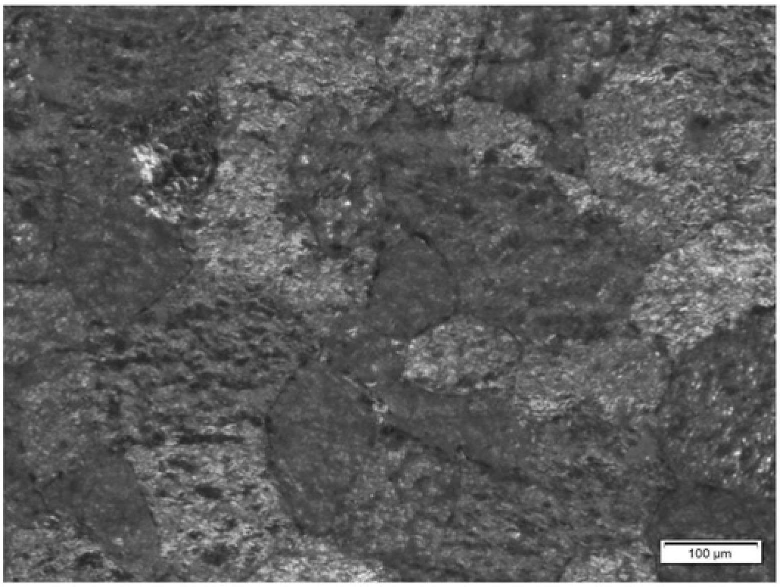



*Figure 53 - General area of aluminium specimen without webbing*

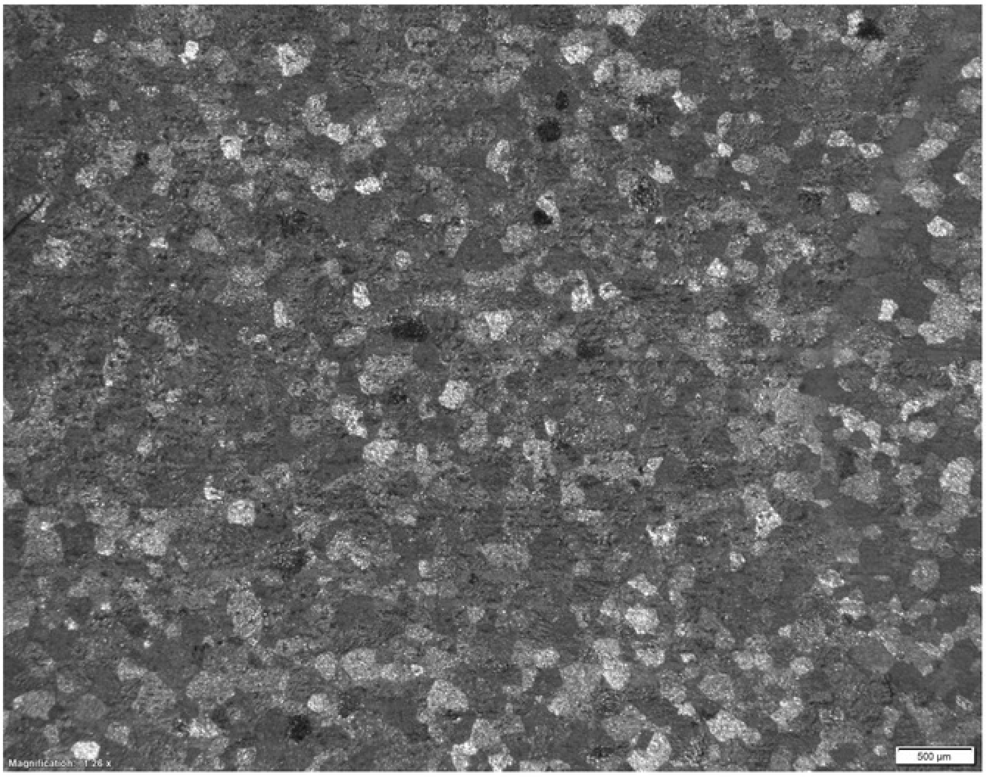



*Figure 54 - Macro view of aluminum specimen without webbing*

## 4.3 Aluminum Testing

The results gather from the profilometer test were not usable to determine the profile of the aluminum extrusions, this was due to the profilometer only being able to measure 4mm at a time. As only 4mm could be tested at a time the curvature of the profile was not represented in the results gathered. Instead the profile of the aluminum extrusion was examined by eye against a straight edge. From this it was determined that both samples were concaved inwards. The webbed sample had a concave profile at the webbing section of the sample while the not webbed sample contained a concave profile around the front of the sample. The profile of the not webbed sample also had a longer concave section than the webbed sample. The concave profile of the webbed sample also seems to be two separate concave geometries meeting at the webbing.

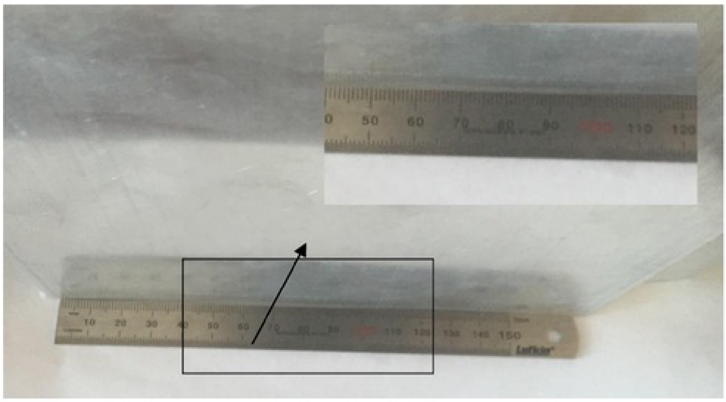


*Figure 55 - Profile of the not webbed aluminum extrusion*

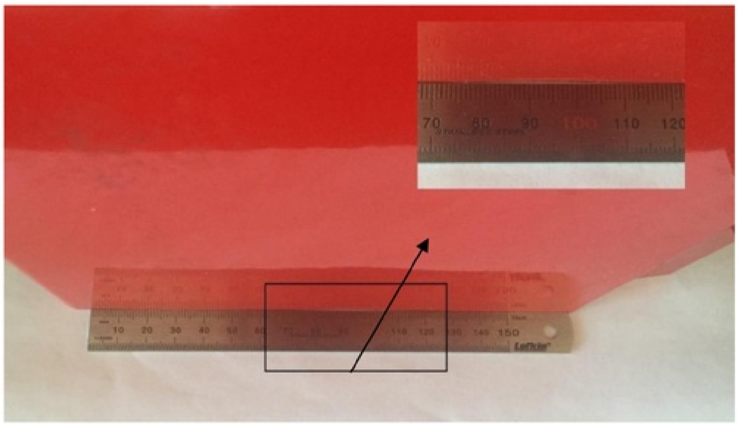


*Figure 56 - Profile of the webbed aluminum extrusion*

The thickness of the top surface of the extruded aluminum varied between the webbed and not webbed samples. This is caused by the layer of powder paint on the webbed sample, as only the webbed sample had gone through this process. The thickness around the webbed section of the sample decreased in the webbed sample. This decrease in thickness is also displayed on the not webbed sample.

*Table 18 - Thickness of the top surface of the webbed aluminum extrusion*

| Webbed | | |
|---|---|---|
| Number | Distance (mm) | Thickness (mm) |
| 1 | 15 | 2.47 |
| 2 | 30 | 2.53 |
| 3 | 45 | 2.54 |
| 4 | 60 | 2.44 |
| 5 | 75 | 2.47 |
| 6 | 90 | 2.38 |
| 7 | 105 | 2.47 |
| 8 | 120 | 2.46 |
| 9 | 135 | 2.58 |
| 10 | 150 | 2.51 |

*Table 19 - Thickness of the top surface of the not webbed aluminum extrusion*

| Not Webbed | | |
|---|---|---|
| Number | Distance (mm) | Thickness (mm) |
| 1 | 15 | 2.35 |
| 2 | 30 | 2.33 |
| 3 | 45 | 2.35 |
| 4 | 60 | 2.25 |
| 5 | 75 | 2.39 |
| 6 | 90 | 2.23 |
| 7 | 105 | 2.23 |
| 8 | 120 | 2.26 |
| 9 | 135 | 2.31 |
| 10 | 150 | 2.3 |

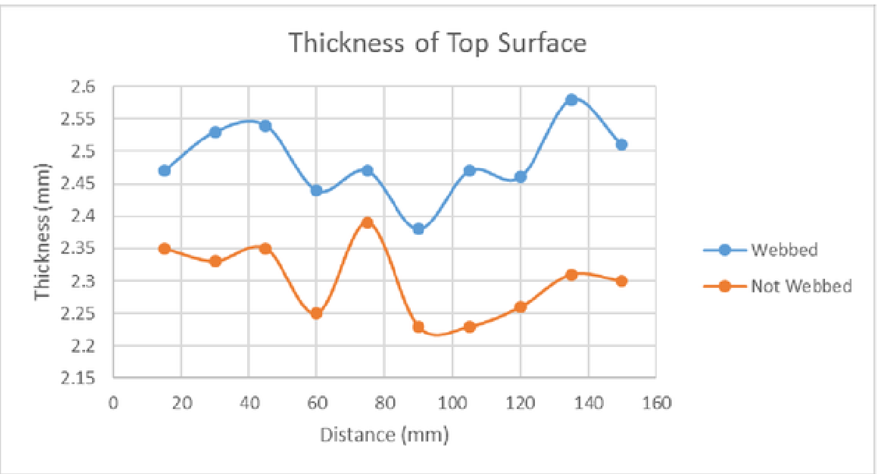



*Figure 57 – Thickness of the top surface of the webbed Vs not webbed aluminum extrusion*

The thickness of the webbed section decreases in the middle of the webbing. The thickness of the webbed section decrease gradually towards the middle of the section, starting at 3.16mm and decreasing to 2.56mm.

*Table 20 - Thickness of the webbed section in the aluminium extrusion*

| Webbed section | | |
|---|---|---|
| Number | Distance (mm) | Thickness (mm) |
| 1 | 5 | 3.16 |
| 2 | 10 | 2.91 |
| 3 | 15 | 2.6 |
| 4 | 20 | 2.56 |
| 5 | 25 | 2.64 |
| 6 | 30 | 2.91 |
| 7 | 35 | 3.12 |

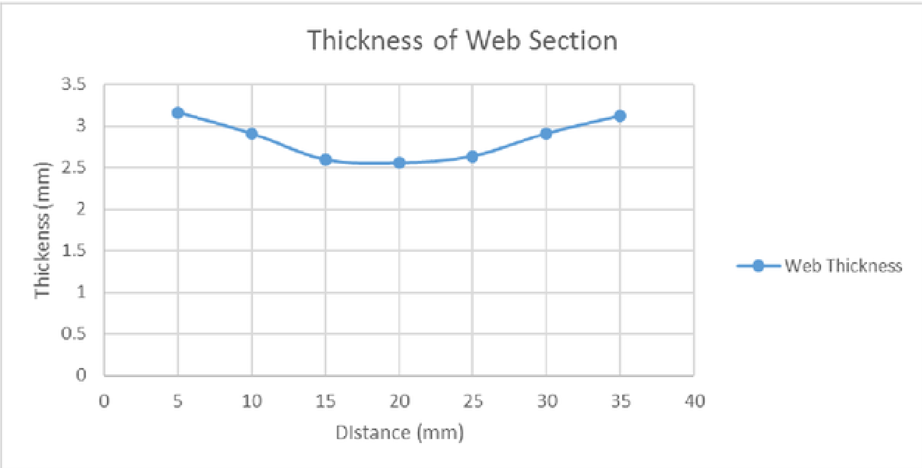



*Figure 58 - Thickness of the webbed section*

# Chapter 5: Discussion

## 5.1 Preparation

### 5.1.1 Precision Cutting

During the precision cutting process the length of the specimens being cut was inconsistent because of a lack of space to use measuring tools. As the length of the specimen was not an important factor these specimens were used, however for the next set of specimens the series cutting option was used to cut equal lengths. The series tool allows the user to initiate the first cut, which is used as an offcut, and then measures a specified length for the following cuts. Using this the following specimens were cut to 10mm length.

While cutting the carbon steel specimens, sparks were produced by the cutting wheel. This was an indication that rotation speed of the cutting wheel or the feed speed was too fast. To fix this problem the rotation speed was reduced from 5000 rpm to 3000 rpm and the feed speed was reduced from 0.5 mm/s to 0.3 mm/s. These corrections in the cutting method prevented sparks from being generated while cutting the carbon steel specimens.

*Table 21 – Precision cutting method for carbon steel specimens*

| **Cutting Wheel** | **Wheel Speed** | **Feed Speed** |
|---|---|---|
| 50A20 | 3000 rpm | 0.3 mm/s |
| **Cutting Length** | **Return Position** | **ExciCut** |
| 10mm | Start position | Z =46.1µm |

### 5.1.2 Chemical etching

The process chosen to apply the chemical etchant to the specimens was immersion. Immersion was chosen as the application method as Keller's reagent requires immersion, while the other etchants can be performed by both swabbing and immersion. The etch produced by immersion is more uniform throughout the specimen but risks being over etched or under etched due to the lack of control of amount of etchant applied to the specimen.

Each etchant was created fresh by carefully measuring and mixing the components together. Once the etchant was mixed it was poured into a small beaker so that the specimens could be submerged. Each specimen was then submerged for an amount of time depending on the etchant and specimen.

In order to etch both the stainless steel 304 and 316 grade specimens, the etchant 5% Nital was used and applied for 5 minutes. When handling Nitric acid it is important for the ratio between nitric acid and ethanol to be regulated as the solution becomes unstable with 5% nitric acid and explosive with 10% nitric acid. [23]

5% Nital contains:

$$5\%\ HN0_3\ (nitric\ acid)$$
$$95\%\ ethanol.$$

Initially 2% Nital was used, which contained 2% concentration of nitric acid, was used but provided no results. The concentration of nitric acid was increased in increments of 0.5% until 5% Nital was reached, due to safety concerns the concentration of nitric acid did not exceed 5%. However, this etchant failed to bring out the microstructure of the stainless steel specimens. As a result, a new chemical solution, aqua regia was found in order to etch the stainless steel specimens.

Aqua regia contains:

$$3\ parts\ Water$$
$$2\ parts\ HCL\ (hydrochloric\ acid)$$
$$1\ part\ HNO_3\ (nitric\ acid)$$

The aqua regia reagent was applied to the specimens until the microstructure of the steel was revealed, taking between 10-30 seconds. This new chemical solution revealed the microstructure of the stainless steel specimens as seen in Figure 59.

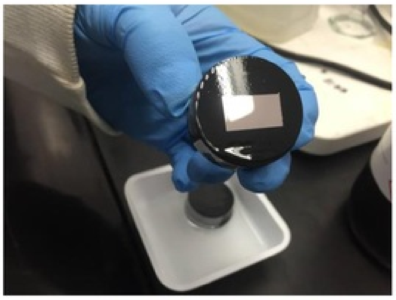


*Figure 59 – S/S 304 etched with 5% Nital*

As the Nital enchant was found ineffective when used to etch stainless steel, the aqua regia etchant was used to etch the carbon steel specimens. The aqua regia solution was used to immerse the carbon steel samples for 10-30 seconds.

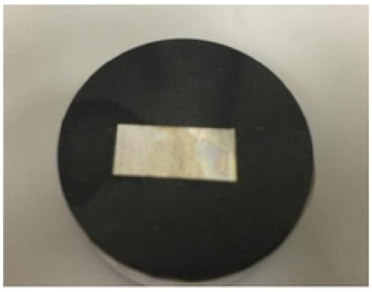


*Figure 60 - S/S 304 Specimen etched with Aqua Regia*

The resulting etched surface gained from the Aqua Regia etching was over-etched but still usable to gather results. Due to time constraints and availability of etching equipment due to safety this over-etched specimens were used.

Aluminum is a difficult metal to etch due to its corrosive resistant nature and requires anodizing or highly corrosive chemicals to reveal the microstructure. Through conducting research it was found that Keller's reagent is a suitable etchant to etch aluminum 6XXX series. Keller's reagent requires immersion for between 10-30 seconds to etch aluminum specimens.

Keller's reagent:

$$190ml\ Distilled\ water$$
$$5\ mL\ HNO_3\ (nitric\ acid)$$
$$3\ ml\ HCL\ (hydrochloric\ acid)$$
$$2\ ml\ HF\ (hydrofluroic\ acid)$$

As Keller's reagent contains hazardous chemicals, a clean room was required to handle the substance. As this etchant is harmful when in contact with skin additional PPE is required, this includes protective gloves, protective clothing, eye protection and face protection. The Keller's reagent etchant was used to immerse the aluminum specimens for 30 seconds. Keller's reagent failed to reveal the microstructure of the aluminum so the aqua regia etchant was used. The aqua regia etchant was used to immerse the aluminum specimens for 10-30 seconds. The aqua regia etchant was successful in chemical etching the aluminum specimen.

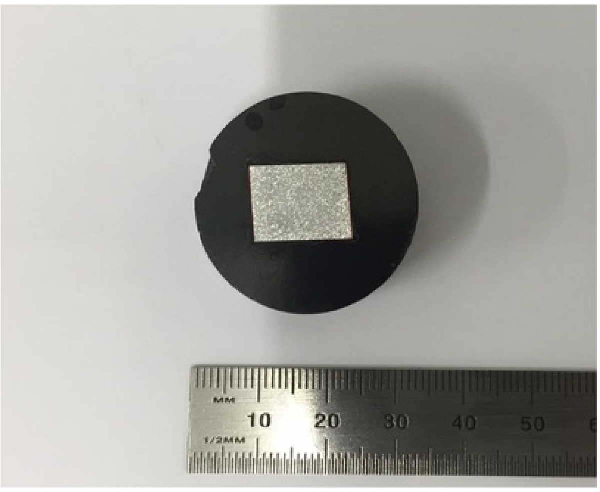



*Figure 61 - Alumnium etched with Keller's reagent*

### 5.1.3 Heat Treatment

The furnace used to heat treat the specimens contained an exhaust hole at the back of the furnace, which allowed heat to escape and causing the heat inside the furnace to become inconsistent. This may cause discrepancies as the location within the furnace can determine the heat experienced by the specimen. In order to overcome this issue a digital infrared thermometer was used to measure the temperature of the furnace, however the digital infrared thermometer could only read temperatures up to 650°C. Thus, the location of the specimens was decided as the furnace was heating up. To decide the best location in the furnace measurements were taken around the inside the furnace and compared to the temperature reading the furnace was displaying.

As the heat treatment for the stainless steel specimens and the carbon steel specimens was performed on separate days the temperature of the air used to anneal the specimens vary between the specimens. During the stainless steel 304 and 316 grade heat treatment the air temperature was 15.6°C and the air temperature for the carbon steel was 23°C. This change in air temperature means the cooling rate of the steel varies between the specimens.

## 5.2 Stainless Steel 304 Grade

The hardness of the stainless steel 304 grade 'no heat treatment' specimen was found to be significantly higher than both the control and heat treated specimens. The hardness found in the welded area of the 'no heat treatment' specimen was similar to the hardness found in the HAZ of the specimen. The hardness of the welded section and the HAZ of the specimen are similar, this may have been caused by the welding process. The high hardness found in the specimen may have been caused by a phase transformation during the welding process.

The hardness of the quenched and annealed specimen are lower than that of the no heat treatment specimen. The hardness of the HAZ of the heat treated specimens are around the control value, indicating that specimens underwent recovery during the heat treatment. As the temperature used for the heat treatment was higher than the recovery temperature of the steel, the steel recovered during the heat treatment. The hardness of the quenched specimen is higher than the hardness of the annealed specimen, as expected due to the cooling rate involved.

The micrograph of the no heat treatment specimen show a larger and disorientated grain structure. The microstructure of the quenched specimen show a fine grain size that is orientated, and the microstructure of the annealed specimen contain larger grains and is also orientated. The grain size in small grain size in the quenched specimen is expected as the hardness of the quenched specimen is high. This is because smaller grains sizes corresponds with higher hardness in the steel. The microstructure of the annealed specimen is larger than that of the quenched specimen. Around the welded area, the grain size increases on all three specimens.

The optimal heat treatment to be applied to stainless steel 304 grade was found to be annealing, due to the preferable hardness microstructural properties of the heat treatment.

*Table 22 - Hardness of S/S 304 grade specimen under different conditions*

| S/S 304 Grade | | | | |
|---|---|---|---|---|
| Type | HAZ 1 | HAZ 2 | HAZ Combined | Weld |
| No Heat Treatment | 253.1 | 241.3 | 247.2 | 248.4667 |
| Quenched | 201.8 | 196.1 | 198.95 | 211.1333 |
| Annealed | 200.3 | 178.3 | 189.3 | 200.6 |

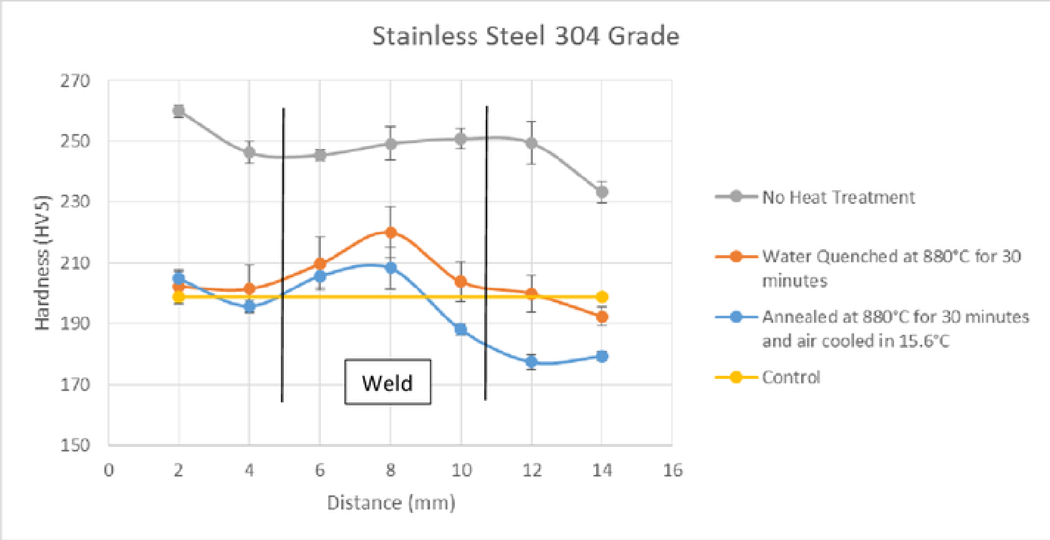



*Figure 62 - The effect of heat treatment on S/S 304 grade*

## 5.3 Stainless Steel 316 Grade

The stainless steel 316 grade 'no heat treatment' specimen was found to have a significantly low hardness, below the control value. This result is unusual and could have resulted from
The hardness found in the quenched and annealed specimens was found to be higher than the control and no heat treatment specimen. The average hardness of the quenched specimen in the HAZ was found to be higher than the annealed specimen. This is expected due to the cooling rate of the quenching process.

The microstructure of the no heat treatment specimen contains a mixture of both large and small grains. The quenched specimen shows a consistent fine grain size suggesting that the hardness of the specimen is higher. The annealed specimen shows a larger grain size, indicating that the hardness of the specimen is lower than the quenched specimen.

As both heat treatments have similar hardness and microstructural properties no conclusion could be drawn regarding the optimal heat treatment for welded stainless steel 304 grade joints.

*Table 23 - Hardness of S/S 316 grade specimen under different conditions*

| S/S 316 Grade | | | | |
|---|---|---|---|---|
| Type | HAZ 1 | HAZ 2 | HAZ Combined | Weld |
| No Heat Treatment | 176.2 | 176.2 | 176.2 | 184.9333 |
| Quenched | 257.1 | 244.6 | 250.85 | 252.2 |
| Annealed | 235.8 | 256.5 | 246.15 | 252.1333 |

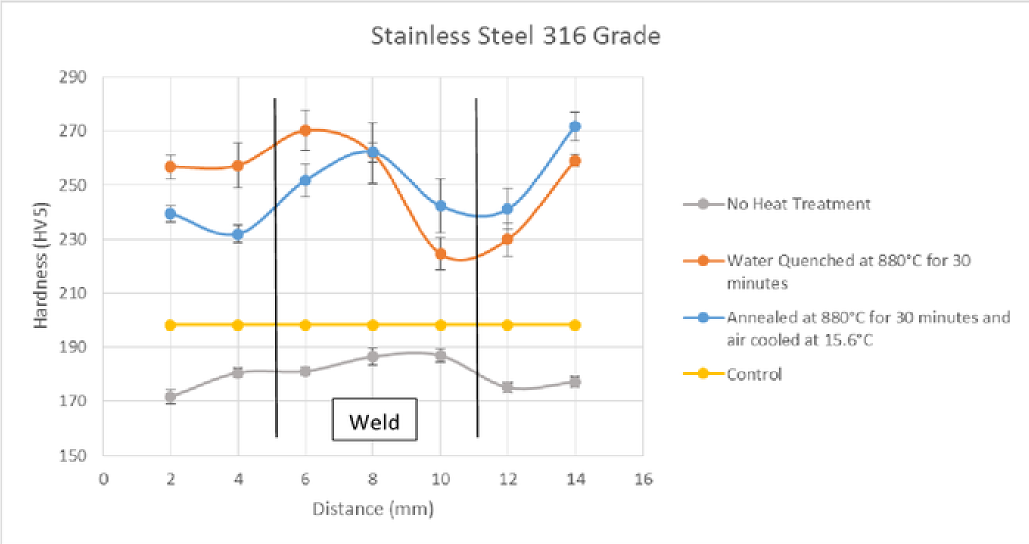



*Figure 63 - The effect of heat treatment on S/S 316 grade*

## 5.4 Carbon Steel 1045 Grade

The hardness found in the weld section of the carbon steel 1045 grade 'no heat treatment' specimen was found to be higher than the HAZ of the specimen. The welded section of the specimen was found to average 178HV3, while the HAZ was found to average 150HV. This is expected due to the heat experienced during the welding process. The HAZ of the specimen

The hardness found in the HAZ of the quenched and annealed specimens remain similar to the hardness found in the HAZ of the no heat treatment specimen. The HAZ of the quenched specimen was found to be higher than the other specimens by a small margin. The annealed specimen had the lowest hardness in the HAZ. The welded section of the specimens shows a greater variation in the results, with the no heat treatment specimen having the highest hardness and the quenched specimen having the lowest hardness.

The carbon steel 1045 grade 'no heat treatment' specimen contained small grain sizes. The quenched specimen contains smaller grain sizes than the annealed and no heat treatment specimens. As the specimens were over etched, the micrographs were hard to read, because of this the results may be inaccurate.

The optimal heat treatment for the carbon steel 1045 grade specimen was found to be annealing. As the hardness of the annealed specimen have a more constant hardness around the HAZ of the welded joint.

*Table 24 - Hardness of C/S 1045 grade specimen under different conditions*

| Carbon Steel 1045 Grade | | | | |
|---|---|---|---|---|
| Type | HAZ 1 | HAZ 2 | Total | Weld |
| No Heat Treatment | 151.3 | 149.2 | 150.25 | 177.9333 |
| Quenched | 152.9 | 149.2 | 151.05 | 148.3333 |
| Annealed | 149.1 | 150.3 | 149.7 | 157.3333 |

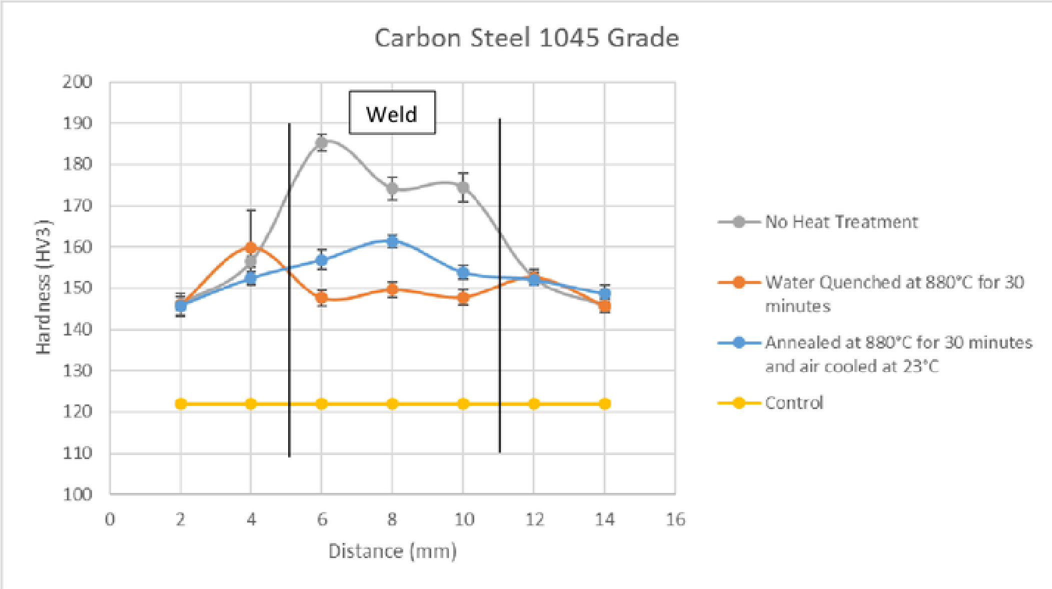



*Figure 64 - The effect of heat treatment on C/S 1045 grade*

## 5.5 Aluminum Extrusion

The hardness found in the webbed and not webbed specimen differ from each other, suggesting that the composition of the aluminum alloy used may be different. The heating involved with power coating may have also caused a change in hardness but is unlikely due to the low temperatures required to cure powder coating thermoplastic are relatively low.

The hardness of the webbed specimen shows a decrease in the hardness at the webbed area of the specimen, this area also corresponds with the pressure line found on the specimen. The average hardness found in the webbed specimen surrounding the webbed section was 85.75HV1, while the hardness found in the webbed section of the specimen was 80.85HV1. The hardness of the specimen drops by 5 Vickers, indicating that properties of the aluminum may be different due to the webbing.
The hardness found in the 'no webbing' specimen had little variations across the specimen indicating that the hardness across the specimen is consistent.

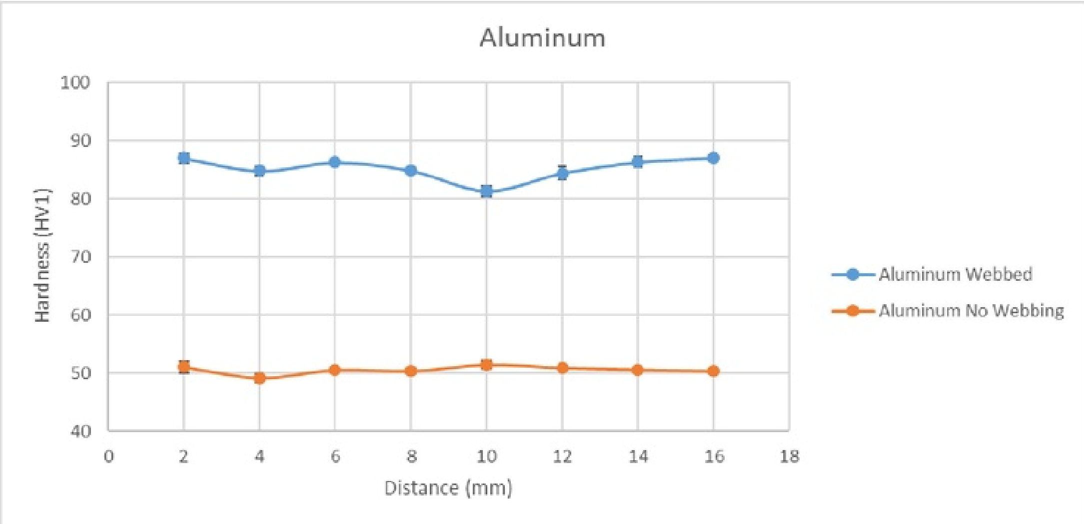



*Figure 65 - Hardness of webbed Vs not webbed aluminium extrusion specimens*

The micrographs obtained through the microscopy testing show similar grain sizes between the webbed area and the general microstructure of the sample. The grain sizes found in the webbed sample are approximately 200µm and are orientated in the extrusion direction. The sizes of the grains found in the not webbed sample are larger than the grain sizes found in the webbed sample. This is expected as the hardness of the webbed sample is also higher. As the microstructure of the webbed section is similar to the general area of the extrusion, there is no evidence that the pressure line is caused by the microstructural properties of the aluminum.

A concave profile was found at the webbed section of the webbed sample. While a concave profile was also found on the not webbed sample the position of the concave profile was found to closer to the front of the sample and extends for a longer area. As the profile of the webbed sample contains two separate concave geometries meeting at the webbed section, the gradient changes rapidly at webbed section. The not webbed specimen contains a concave profile as well but as it only contains a single concave profile there is no point with conflicting gradients. This rapid change in gradient between the two concave profiles could create the visible pressure line present on the webbed sample.

The two-concave profile found on the webbed sample are caused by the webbed section of the sample. As the webbed section creates a joint in the aluminum, addition constraints are present on the web sample. The aluminum surrounding the webbed area are pulled towards the joint, causing the shape of the profile of the aluminum on both sides of the joint to become concaved as it is pulled towards the joint.

The thickness found along the top surface of the aluminum extrusion in both the webbed and not webbed sample feature a decrease in the thickness around the center of the sample. As both samples display this change in thickness along the top surface, this suggests that the change in thickness of this surface is not the cause of the pressure line on the webbed sample. However this does indicate that there may be a lack of flow during the extrusion process to these areas, contributing the pressure line.

The thickness of the webbed section decreases towards the middle of the webbing, decreasing by almost 20% in the middle of the webbing. This drastic drop in thickness in the middle of the webbing suggests that the flow into the area during the extrusion process is limited. As the flow in the webbed area is not sufficient to create a uniform thickness, shrinkage occurs in the area. During the extrusion process the flow of aluminum into the webbing area is too little to fill the space in the die, causing the aluminum to be drawn in from the surrounding areas, causing the shrinkage to occur. As the thickness of this area is also thinner than the surrounding areas, as the aluminum cools following the extrusion process, the cooling rates of the extrusion will vary depending on the thickness. The thinner areas in the webbing will cool faster, causing the area around the webbing to be pulled towards the webbing.

In order to prevent the shrinkage and suffocation of the aluminum flow during the extrusion process the die used in the extrusion process can be modified. To improve the flow of aluminum into the webbed section the bearings on the die can be made smaller or chamfered, allowing more aluminum to flow into these areas. By increasing the flow of aluminum into the webbed section of the extrusion the shrinkage in the webbing will be reduced, preventing the webbed section from pulling material in and reducing the effect of the pressure line.

# Chapter 6: Summary

## 6.1 Welded steel

In order to find the optimal heat treatment for welded steel, testing was performed on welded steel before and after heat treatment. The steels selected to be tested were stainless steel 304 grade, stainless steel 316 grade and carbon steel 1045 grade. In order to test the steels a Vickers hardness test and microscopy analysis was conducted. The optimal heat treatment for welded steel was found to be annealing.

## 6.2 Aluminum extrusion

It was found that the properties in around the pressure line in the webbed aluminum extrusion had a slight change as a result of the pressure line, with no links that the properties of the aluminum are the cause of the pressure line. Instead it was found that the cause of the pressure line is likely a lack of aluminum flow to the webbing section during the extrusion process. This lack of flow causes shrinkage in the local area, causing a concave profile on either side of the webbing. The rapid change in gradient caused by the conflicting profiles causes the pressure line. To fix this the design of the die may be modified to allow for me flow into the area.

# Chapter 7: Future Work

Based on the results gathered the following suggestions for future investigate can be made:

- Additional heat treatment conditions can be tested. By varying the heating temperature, soaking time, cooling temperature and cooling time the results of the heat treatment will change. A further investigation on how these factors affect the final outcome of the heat treated welded steel could be conducted to provide additional information to find the optimal heat treatment.
- An investigate using different types and grades of steel can be conduct to provide a broader range of results. As only 3 different grades and types of steel were investigated in this report, an expansion of the type of steel could be done to provide a larger spectrum of results and to compare the effect of welding and heat treatment on different steels.
- Different types of testing could be performed to investigate other properties of the steel. Tensile testing could be performed to find the tensile strength of the steel before and after heat treatment. This will provide a greater insight on the effect of the heat treatment on the steel.
- An analysis of the design of the extrusion die and changes that will improve the flow of aluminum to areas suffocated of flow during the extrusion process can be conducted. Simulations to find the ideal modifications the design of the extrusion die can be performed.

# References

[1] J. Elmer, T. Palmer, W. Zhang, B. Wood and T. Debroy, "Kinetic modeling of phase transformations occuring in the HAZ of C-Mn steel welds based on direct observation," *Acta Materialia,* vol. 51, no. 12, pp. 3333-3349, 2003.

[2] B. Schlenker, "Heat Treatment of Steel," in *Introduction to Material Science*, Brisbane, John Wiley & Sons, 1974, pp. 229-245.

[3] T. Bjork, R. Westergard and S. Hogmark, "Wear of surface treated dies for aluminium extrusion — a case study," *Wear,* vol. 249, no. 3-4, pp. 316-323, 2001.

[4] D. Edmonds, K. He, F. Rizzo, B. D. Cooman, D. Matlock and J. Speer, "Quenching and partitioning martensite—A novel steel heat treatment," *Materials Science and Engineering: A,* Vols. 438-440, pp. 25-34, November 2006.

[5] B. Ferguson, Z. Li and A. Freborg, "Modeling heat treatment of steel parts," *Computational Materials Science,* vol. 34, no. 3, pp. 274-281, November 2005.

[6] B. Schlenker, "The Joining of Metals," in *Introdection to Material Science*, Brisbane, John Wiley & Sons, 1974, pp. 248-258.

[7] M. M. Attallah and H. G. Salem, "Friction stir welding parameters: a tool for controlling abnormal grani growth during subsequent heat treatment," *Materials Science and Engineering: A,* vol. 391, no. 1-2, pp. 51-59, 2004.

[8] H. Yan, H. Bi and Z. Xu, "Effect of two-step cold rolling and annealing on texture, grain boundary character distribution and r-value of Nb + Ti stabilized ferritic stainless steel," *Materials Characterization,* vol. 60, no. 1, pp. 65-68, January 2009.

[9] R. Song, D. Ponge, D. Raabe and R. Kaspar, "Microstructure and cystallographic texture of an ultrafine grained C-Mn steel and their evolution during warm deformation and annealing," *Acta Materialia,* vol. 53, no. 3, pp. 845-858, February 2005.

[10] B. Capudean, "Metallurgy Matters: Phase, structures, and the influences of temperature," 26 June 2003. [Online]. Available: http://www.thefabricator.com/article/metalsmaterials/phases-structures-and-the-influences-of-temperature. [Accessed 16 October 2016].

[11] R. E. Reed-Hill and R. Abbachian, Physical metallurgy principles, Boston: PWS Publishing Company, 1994.

[12] J. Childress, S. H. Liou and C. L. Chien, "Ferromagnetism in metastable 304 stainless steel with BCC structure," *Journal of Applied Physics,* vol. 64, pp. 6059-6061, 1988.

[13] "Thecoffeebrewers.com," [Online]. Available: http://www.thecoffeebrewers.com/de.html. [Accessed 6 11 2016].

[14] S. Lee, B. Kim and D.Kwon, "Fracture toughness analysis of heat-affected zones in high-strength low-alloy steel welds," *Metallurgical Transactions,* vol. 24, no. 5, pp. 1133-1141, May 1993.

[15] Y. Jun, G. Ming and Z. Xianyan, "Study on microstructure and mechanical properties of 304 stainless steel joints by TIG, laser and laser-TIG hybrid welding," *Optic and Lasers in Engineering,* vol. 48, no. 4, pp. 512-517, April 2010.

[16] "Overview of materials for 6000 Series Aluminum Alloy," MetWeb, [Online]. Available: http://www.matweb.com/search/DataSheet.aspx?MatGUID=26d19f2d20654a489aefc0d9c247cebf. [Accessed 4 11 2016].

[17] A. F. M. Arif, A. K. Sheikh and S. Z. Qamar, "A study of die failure mechanisms in aluminum extrusion," *Journal of Materials Processing Technology,* vol. 134, no. 3, pp. 318-328, 2003.

[18] P. K. Saha, "Thermodynamics and tribology in aluminum extrusion," *Wear,* vol. 218, no. 2, pp. 179-190, 1998.

[19] P. K. Saha, "Fundamentals of Extrusion," in *Aluminum Extrusion Technology*, ASM International, 2000, pp. 1-23.

[20] "Extrusion Design - Dies & Tooling - Aluminum Extruders Council," AEC, [Online]. Available: http://www.aec.org/?page=basics_dies. [Accessed 6 11 2016].

[21] D. Ponnudurai and K. Gao, *Personal communication,* Capral, 2016.

[22] "Hot Mounting," 2016. [Online]. Available: http://www.struers.com/en-GB/Knowledge/Mounting/Hot-mounting#.

[23] "Metallographic Etching," 2016. [Online]. Available: http://www.metallographic.com/Technical/Etching.htm.

[24] Z. Zhang, Z. Wang, Y. Jiang, H. Tan, D. Han, Y. Guo and J. Li, "Effect of post-weld heat treatment on microstructure evolution and pitting corrosion behavior of UNS S31803 duplex stainless steel welds," *Corrosion Science,* vol. 62, pp. 42-50, September 2012.

[25] A. Lakshminarayana and V. Balasubramanian, "An assessment of microstructure, hardness, tensile and impact strength of friction stir welded ferritic stainless steel joints," *Materials and Design,* vol. 31, no. 10, pp. 4592-4600, December 2010.

[26] A. Lambert-Perlade, A. Gourgues and A. Pineau, "Austenite to bainite phase transformation in the heat-affected zone of a high strength low alloy steel," *Acta Materialia,* vol. 52, no. 8, pp. 2337-2348, 2004.

# Appendix A – Polishing Methods

24/10/2016 e-shop.struers.com - Method Details

## High Alloyed, Heat Treated Steels (DiaPro)

Select equipment disc size 300 mm ▾

Method details

| | |
|---|---|
| Method number: | 1891 |
| Download documents: | Print method |

**These methods are meant as a guide**

All methods are generic methods. This means that the methods have been developed according to the following standard: 6 specimens of 30 mm diameter clamped in a specimen holder of 160 mm diameter (MAXCY).

Grinding

| Step | PG | FG |
|---|---|---|
| Surface | MD-Piano 220 | MD-Allegro |
| Abrasive Type | | DiaPro Allegro/Largo 9 µm |
| Lubricant Type | Water | |
| Speed (rpm) | 300 | 150 |
| Force (N) / Specimen | 40 | 30 |
| Holder direction | >> | >> |
| Time (min) | 01:00 | 03:00 |

Polishing

| Step | P 1 | P 2 |
|---|---|---|
| Surface | MD-Dac | MD-Nap |
| Abrasive Type | DiaPro Dac 3 µm | DiaPro Nap B 1 µm |
| Lubricant Type | | |
| Speed (rpm) | 150 | 150 |
| Force (N) / Specimen | 30 | 25 |
| Holder direction | >> | >> |
| Time (min) | 03:00 | 01:00 |

Method comments

PG Time: As needed. FG Step: MD-Plan with DiaPro Plan can also be used instead of MD-Allegro with DiaPro Allegro/Largo.

This method is developed to fit a standard equipment configuration.
For advice on how to adjust the method to fit your equipment, please take a look at Preparation Parameters.

https://e-shop.struers.com/SE/EN/methods/Ferrous_Metals/Heat_Treated_Steels/High_Alloyed_Heat_Treated_Steels_(DiaPro)(1891).aspx 1/2

*Figure 66 - Struers' High Alloyed, Heat Treated Steels Polishing Method; Struers E-Metalog*

24/10/2016 e-shop.struers.com - Method Details

## Pure Aluminium (Optimum edge retention, DiaPro)

Select equipment disc size 300 mm ▾

### Method details

Method number: 1477

Download documents: Print method

#### These methods are meant as a guide

All methods are generic methods. This means that the methods have been developed according to the following standard: 6 specimens of 30 mm diameter clamped in a specimen holder of 160 mm diameter (MAXCY).

### Grinding

| Step | PG | FG |
|---|---|---|
| Surface | SiC Foil #320 | MD-Largo |
| Abrasive Type | | DiaPro Allegro/Largo 9 µm |
| Lubricant Type | Water | |
| Speed (rpm) | 300 | 150 |
| Force (N) / Specimen | 20 | 30 |
| Holder direction | >> | >> |
| Time (min) | 01:00 | 04:00 |

### Polishing

| Step | P | OP |
|---|---|---|
| Surface | MD-Mol | MD-Chem |
| Abrasive Type | DiaPro Mol R 3 µm | OP-S, 0.04 µm |
| Lubricant Type | | |
| Speed (rpm) | 150 | 150 |
| Force (N) / Specimen | 25 | 15 |
| Holder direction | >> | >< |
| Time (min) | 03:00 | 02:00 |

### Method comments

PG Time: As needed. OP Time: 2-5 min.

This method is developed to fit a standard equipment configuration.
For advice on how to adjust the method to fit your equipment, please take a look at Preparation Parameters.

https://e-shop.struers.com/SE/EN/methods/Non-Ferrous_Metals/Aluminium_and_Al_Alloys/Pure_Aluminium_(Optimum_edge_retention_DiaPro)(1477).a... 1/2

*Figure 67 - Struers' Pure Aluminium Polishing Method; Struers E-Metalog*

24/10/2016 e-shop.struers.com - Method Details

## High Carbon Steels (DiaPro)

Select equipment disc size 300 mm ▾

Method details

| | |
|---|---|
| Method number: | 1874 |
| Download documents: | Print method |

**These methods are meant as a guide**

All methods are generic methods. This means that the methods have been developed according to the following standard: 6 specimens of 30 mm diameter clamped in a specimen holder of 160 mm diameter (MAXCY).

Grinding

| Step | PG | FG |
|---|---|---|
| Surface | MD-Piano 220 | MD-Allegro |
| Abrasive Type | | DiaPro Allegro/Largo 9 µm |
| Lubricant Type | Water | |
| Speed (rpm) | 300 | 150 |
| Force (N) / Specimen | 25 | 25 |
| Holder direction | >> | >> |
| Time (min) | 02:00 | 05:00 |

Polishing

| Step | P 1 | P 2 | OP |
|---|---|---|---|
| Surface | MD-Dur | MD-Nap | MD-Chem |
| Abrasive Type | DiaPro Dur 3 µm | DiaPro Nap B 1 µm | OP-U, 0.04 µm |
| Lubricant Type | | | |
| Speed (rpm) | 150 | 150 | 150 |
| Force (N) / Specimen | 20 | 20 | 10 |
| Holder direction | >> | >> | >< |
| Time (min) | 04:00 | 01:00 | 01:00 |

Method comments

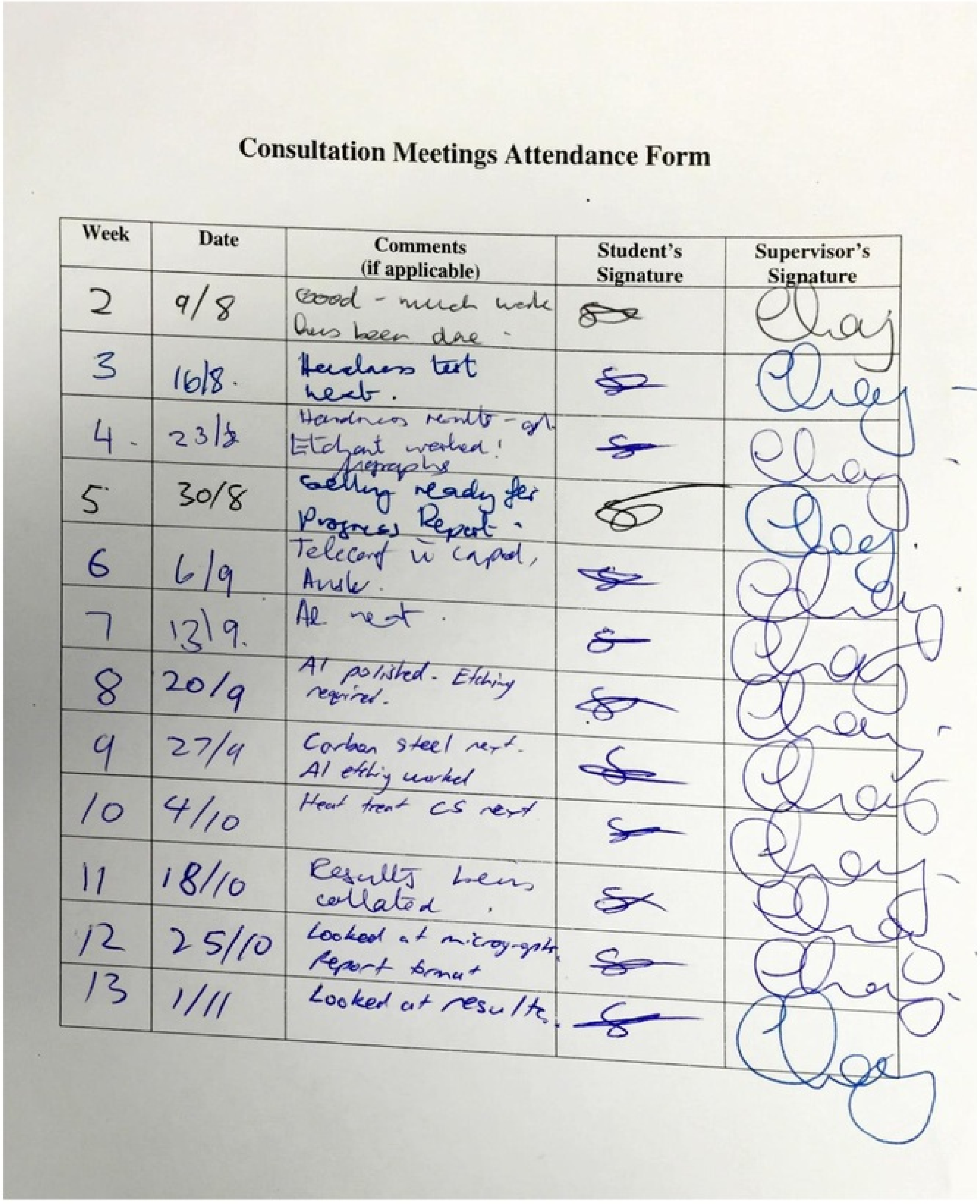
PG Time: As needed. OP Step: Is optional.

This method is developed to fit a standard equipment configuration.
For advice on how to adjust the method to fit your equipment, please take a look at Preparation Parameters.

https://e-shop.struers.com/SE/EN/methods/Ferrous_Metals/Carbon_Steels/High_Carbon_Steels_(DiaPro)(1874).aspx 1/2

*Figure 68 - Struers' High Carbon Steels Polishing Method; Struers E-Metalog*

# Appendix B – Consultation Meeting Attendance Form



**Consultation Meetings Attendance Form**

| Week | Date | Comments (if applicable) | Student's Signature | Supervisor's Signature |
|---|---|---|---|---|
| 2 | 9/8 | Good - much work has been done. | | |
| 3 | 16/8. | Hardness test next. | | |
| 4. | 23/8 | Hardness results - ok. Etchant worked! Micrographs | | |
| 5 | 30/8 | Getting ready for Progress Report. | | |
| 6 | 6/9 | Telecon in capsd, Arvde. | | |
| 7 | 13/9. | Al next. | | |
| 8 | 20/9 | Al polished. Etching required. | | |
| 9 | 27/9 | Carbon steel next. Al etching worked | | |
| 10 | 4/10 | Heat treat CS next | | |
| 11 | 18/10 | Results being collated. | | |
| 12 | 25/10 | Looked at micrographs. Report format | | |
| 13 | 1/11 | Looked at results. | | |

*Figure 69 - Consultation meeting attendance form*