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Abstract

Friction Stir welding has become an important method for welding of aluminium alloys. Excellent mechanical properties, economic benefits and environment friendly is just some of the advantages compared to ordinary fusion welding. However, large investments are needed as the workpiece need to be clamped properly against the worktable to resist any movement and the machine have to produce a large downforce. FSW can be performed using ordinary CNC- machines but force control or position control are suggested to make sound welds. This experiment used a Mazak VCN430a vertical milling centre and tools from Stirweld. The welding was conducted without any force control or force measuring system. To get a better control of the shoulder depth, the plates surface was measured using a measuring probe and the surface curvature was interpolated along the weld path. Friction stir welding was successfully performed on 300x150x3 mm plates of AA6082-T6 alloy using the Tagushi robust design approach. Optimal parameters for this particular machine and experiment was found to be 1200 rpm for the rotation speed, 150 mm/min for the welding speed, 2 seconds dwell time and a shoulder depth of 0.11 mm. The matrix experiment revealed almost the same value for the 0.07 mm shoulder depth which can be a prove of interaction among the parameters. Ultimate tensile strength test for the optimal weld parameters was 222.7 MPa. The predicted value was higher, but the measured value was inside the 2-standard confidence interval. Vickers hardness test showed that weakening of material had occurred throughout the specimen. The measured value 60 mm from the weld centre was approximately 75 Vickers HV. Developing the welding jig, clamping system and also simultaneously finding welding parameters without having any force control or position control proved itself to be very difficult. The clamping system seemed to be the most important factor to be able producing sound welds. For further friction welding experiment a welding jig and clamping system with the possibility of force control or position control need to be considered to eliminate defects.

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Table of Contest

Contents

List over Figures

List over Tables

List over Equations

1 Introduction

1.1 Background

Friction welding need massive and expensive equipment to be able to perform quality welds. A large downforce of the tool, clamping of the material to be welded and the need of controlling the welding process by force and temperature monitoring make this not achievable for most companies without making big investments. For small uniform parts and small welds, a CNC milling machine can be used to some extents if minor change and programming of the welding process is done for the specific CNC machine.

1.2 Problem Formulation

Can friction stir welding be performed using a Mazak VCN430a milling centre without expensive investment for equipment for force control or position control? Without any experience form friction stir welding, aluminium alloy is to be welded using the Tagushi robust design approach. The welding jig is to be made with a proper clamping system and the goal is to be able to achieve sound welds.

A pre-study where done to see if the Mazak could perform the friction welding process. Force measuring using 15 kN downwards pressure in Z-direction where applied to load cell. The value was compared with the Mazak machine internal power meter and measurement was found to be around 80 % of max capacity. The CNC machine should be able to produce the force and torque necessary for welding but factors like vibrations, constant downforce and other sources of noises to the process can't be known before welding is performed and results analysed. For this purpose, the Tagushi parameter design approach is used to find the optimal parameters. The goal is to develop a program to use with the Mazak to achieve defect free welds and highest possible tensile strength with the machine as is without expensive upgrade.

From the welded plates specimens is to be cut out for tensile strength testing and microscopic viewing. Vickers hardness measuring is performed on the confirmation experiment to find the HAZ/TMAZ.

1.3 Limitations

The budget is limited so equipment as load cells and other sensors to monitor the process is not available for this project. Access to the MAZAK machine is also limited to a few periods making the learn by doing process more difficult as knowledge about the process and solution to improve the welding jig, clamping system and weld parameters need to be done after each weld. Two aluminium plates with dimension of 1000x2000 is cut into smaller workpieces of dimension 100x300. This give a limitation to numbers of test weld that can be performed before the matrix experiment is conducted. For microstructure anodization only barker's reagent is available at the laboratory.

1.4 Structure of report

Chapter 2 will have the general theory used to complete this thesis. A general introduction to aluminium alloys and designation system for these alloys. Furthermore, a brief explanation of the Friction Stir Welding process and applications. Test methods used is also included in chapter two.

Chapter 3 is the experimental part and parameter studies.

Chapter 4 will present all results from this project and the Tagushi robust design approach using orthogonally arrows further explained when presenting the result, this to better understand the connections between the method and results.

Chapter 5 will have the conclusion and chapter 6 the discussion.

Appendix will have all things not included in the above structure but relevant for the thesis.

2 Theory

2.1 Friction Stir Welding

Friction welding is a new technology invented in 1991 by TWI and have significant advantages over traditional welding of aluminium alloys. Friction welding is a solid-state joining method where the welding process is performed below the materials melting point and problems that arises from traditional welding due to the physical properties of aluminium alloys, such as high solidification shrinkage, high coefficient of thermal expansion and conductivity, sensitive to oxide formation and high solubility of hydrogen in liquid state can give defects that with friction welding is not a problem. Defects from the high heat input and melting of the base material gives porosity, lack of fusion, hot cracking, residual stresses and soften in the heat affected zone known as HAZ (Texier et al., 2018).

FSW can be used for welding of materials like aluminium, copper, magnesium, titanium and dissimilar material such as copper and aluminium (Threadgill et al., 2009). Aluminium alloys like 2xxx and 7xxx which earlier was considered unweldable, can now be welded by friction stir welding. In Figure 2-1 a picture from friction welding of two plates being buttwelded using FSW ("Friction Stir Welding Expands Its Reach," n.d.).

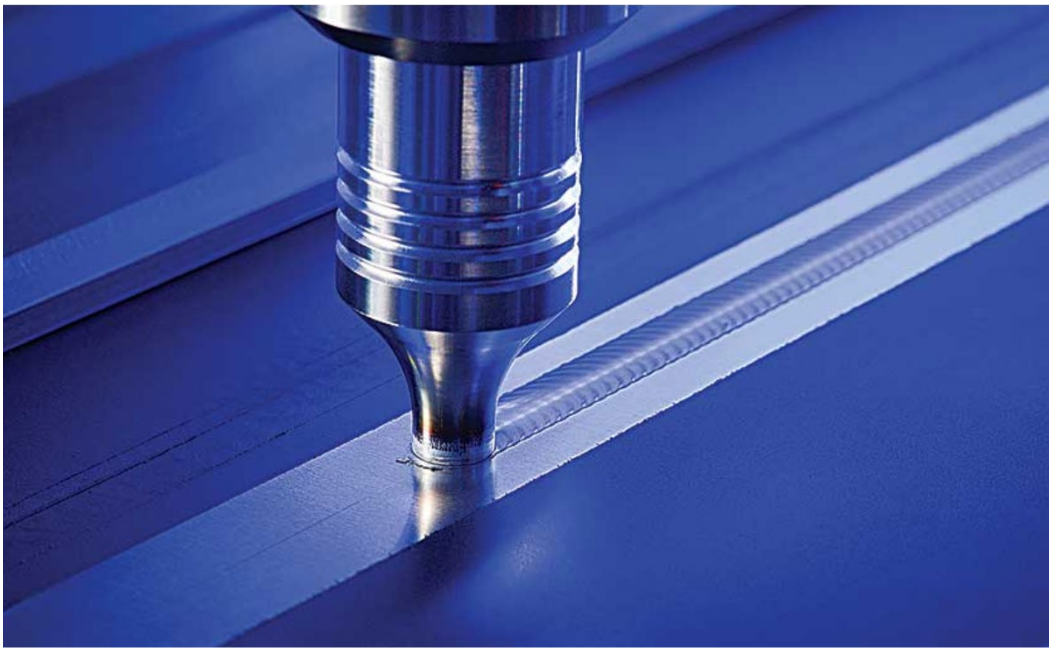


Figure 2-1 Picture of FSW Butt Weld

2.1.1 *The FSW Process*

The friction welding process for butt welding is illustrated in Figure 2-2 (Threadgill et al., 2009). The plates need to be rigidly clamped together, so they don't get apart during welding. The welding process starts as the special designed tool is plunged into the joint area between the plates. When the tool tip has penetrated the material and the tool shoulder touches the material friction is generated by the rotating tooltip and shoulder. The material is softened due to friction and pressure generated by the high downforce. Further friction is kept by keeping a constant downforce and the shoulder generates friction during the transverse weld. The material get into a plasticized state and the tool tip will now move the material close to the pin with boundaries from the backing plate, shoulder and the material that is not soften by the frictional heat. The advising side is the side where the flow is going in same direction as the traverse welding direction and the retracting side is when the flow is moving in the opposed direction to the welding directions. Friction stir welding can be seen as both a deformation and thermal process where the process generates very high strain rates and strains (Threadgill et al., 2009).

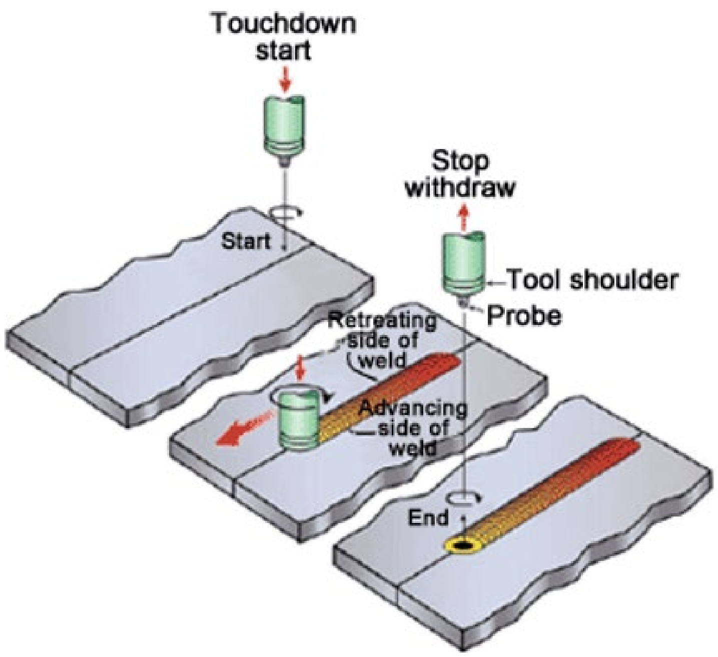


Figure 2-2 The Process for Butt-Butt Welding

2.1.2 *Process Parameters*

Threadgill et.al (2009) describes the process variables for the welding operator after the tool, alloy and thickness of plate is chosen as; downforce if it can be adjusted, tool, tilt angle, tool plunge, tool depth when position control is possible, rotation speed and transverse speed. From trials with aluminium alloys the optimal combination of this variables needs to be used to get defect free welds.

As seen in the below figure there are relationship between these variables for a 4 mm thick aluminium alloy. The process operating window is commonly described as being limited by “hot” or “cold” welds, where cold welds is when rotational speed is low and the traverse speed is high, and the hot weld can be described with high rotational speed and low traverse speed (Threadgill et al, 2009, p. 55). When the downforce is increasing, the process parameters tend to shift to higher welding speed and lower rotation speed as seen below in Figure 2-3 (Threadgill et al., 2009).

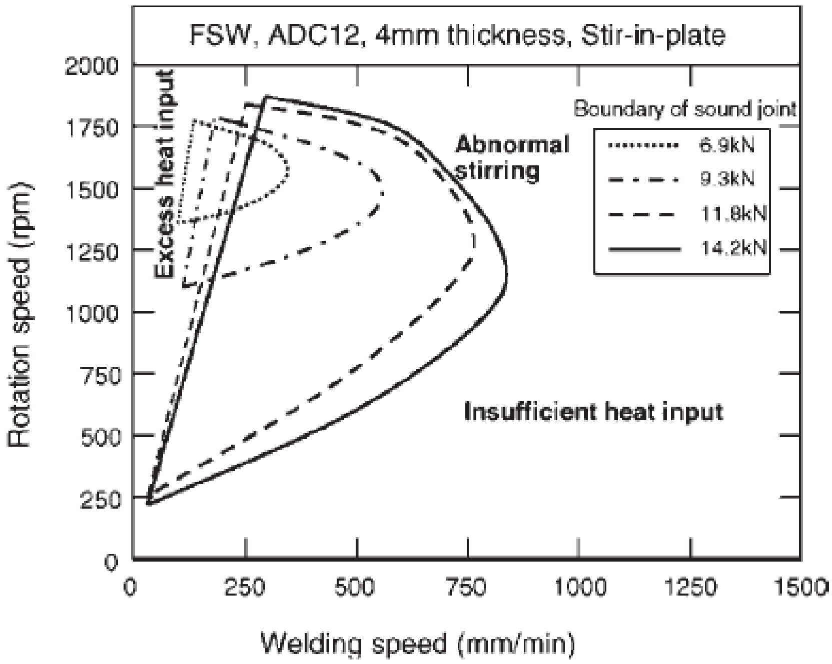


Figure 2-3 Range of optimum FSW conditions

2.1.3 *Microscopic Weld Zones*

The microstructure can be separated into four different zones A-D as shown in Figure 2-4 (Kallee and Nicholas, 2003; in Vilaça et al., 2005). The unaffected zone "A", the material has experienced no change in the microstructure and mechanical properties. Area marked "B" is the heat-affected zone known as "HAZ", here the material has been exposed to the thermal cycle generated from the weld and the microstructure and/or the mechanical properties has been modified but no plastic deformation has occurred. The thermo-mechanical zone "TMAZ" marked as "C" is where the material is plastically deformed in addition to the thermal effect. For aluminium this zone can have significant plastic strain and be without recrystallization. It's possible to distinguish between the boundaries between the recrystallised zone and the deform zone. Final the stir zone D, called nugget is the zone where recrystallization occurs (Kallee and Nicholas, 2003; Podržaj et al., 2015; Threadgill et al., 2009, p. 55).

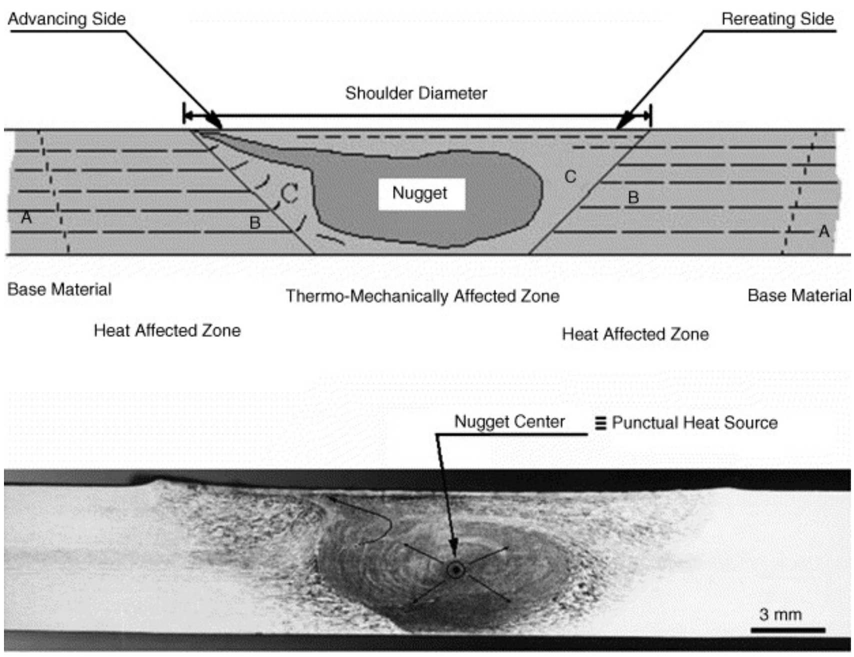


Figure 2-4 Picture of macrography scheme of FSW

2.1.4 *FSW Tool*

Tools have a significant influence on the friction welding process and it's important to choose the right tool to be sure they perform optimal to improve the welding process. Different design is made and their task is everything from breaking up the oxide layer, heat generation, improve the stirring and material flow and preventing weld defects such as weld flash, surface defects, wormhole, sheet thinning and hooking defects (Gibson et al., 2014). FSW uses a non-consumable tool and is made of a shoulder and a pin. The shoulder can have pattern to improve the stirring as seen in Figure 2-5 (Podržaj et al., 2015). The pin can consist of different shapes as seen in the lower part of the figure below. The length and type are decided by the material and thickness of weld.

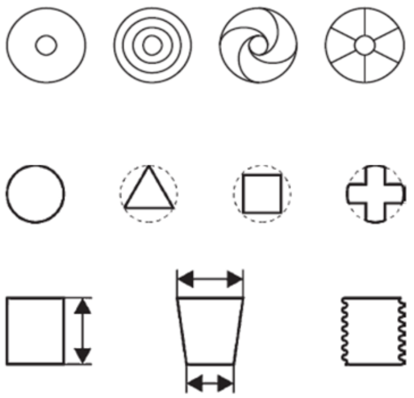


Figure 2-5 Top – Shoulder patterns, Middle – Pin patterns, Low – Pin Length

2.1.5 *Weld Defects*

FSW is a solid-state bonding method and the process is completely different from traditional welding methods thus other types of welding errors can occur during friction stir welding. Some of the most common errors for FSW butt weld is as follow; tunnel flash, kissing bond, void/wormhole, cavity/groove and crack defects (Soni et al., 2017, p. 121). Below are some experienced defects found during friction welding.

- ✓ Tunnel defects occurs due to insufficient heat input and metal flow of the material and can be eliminated by heat input and good flow pattern of the material Soni et al.,(2017).
- ✓ (Adamowski et al., 2007) experienced tunnel defects because of insufficient plasticization for the process not reaching the equilibrium and open surface tunnel defects as result of to low downforce pressure. Surface roughness was experienced using higher rotational speeds due to increased temperature. They reported excessive flash forming out from the shoulder. Problems with incorrect stirring of materials was found due to lack of downforce and position control system.
- ✓ In 2001 Colligan et al, (cited in Awang et al., 2011) reported that a high tool advancement per revolution lead to a tunnel defect at the advancing side of the weld line because of insufficient material transport around the pin. Awang found a similar defect

during welding of aluminium alloy and suggest this is occurring because of insufficient dwell time under the plunging phase giving the material to little heat input before the tool start the lateral travel (Awang et al., 2011).

- ✓ (Podržaj et al., 2015) described the most common errors found by a combination of rotational and traverse speed to be flash due to excessive heat input, cavity/groove defects due to insufficient heat input and cavity errors du to abnormal stirring. Defects can still occur even if optimal parameters are found due to inappropriate chosen parameters for tool tilt angle, tool geometry or an improper control algorithm.
- ✓ (Threadgill et al., 2009) mention that high rotation and low traverse speed (excessive heat input) leads to excessive flash production and low rotation and high traverse can lead to tool breakage. Tunnel voids where associated with insufficient heat input and abnormal stirring.
- ✓ In 2007 Annette wrote about the flaw formation, (cited in Kah et al., 2015) and described if using cold weld parameter's void formations and non-bonding could appear due to insufficient material flow. When welding using hot parameter's defects could occur due to excessive material flow leading to faults like flash formation, collapse of the nugget and deterioration of the strength properties of the joint.
- ✓ (Annette 2007; Wanjara et al. 2013; cited in Kah et al., 2015) found a connection for the strengthening mechanism; recovery and recrystallisation, dissolution and coarsening of precipitates by the position of the tool in relation to the weld line. This can occur because an imbalance in the material flow due to lack of joining when the tool is set in the wrong position.
- ✓ In Figure 2-6 (Arbegast, 2008) shows an overview of the characteristics defects and categorizes the defects as either flow or geometric related. As mentioned earlier the "cold weld" parameters are when the rotational speed is low and travel speed are high, leading to defects such as wormhole, scalloping, surface galling and lack of penetration. For the "hot weld" parameters; high rotational speed and low travel speed, will add more friction to the process and give heat time to build up in the process. Defects related to the hot welds is described as nugget collapse, root flow defect, surface lack of fill and lack of fusion (Arbegast, 2008).

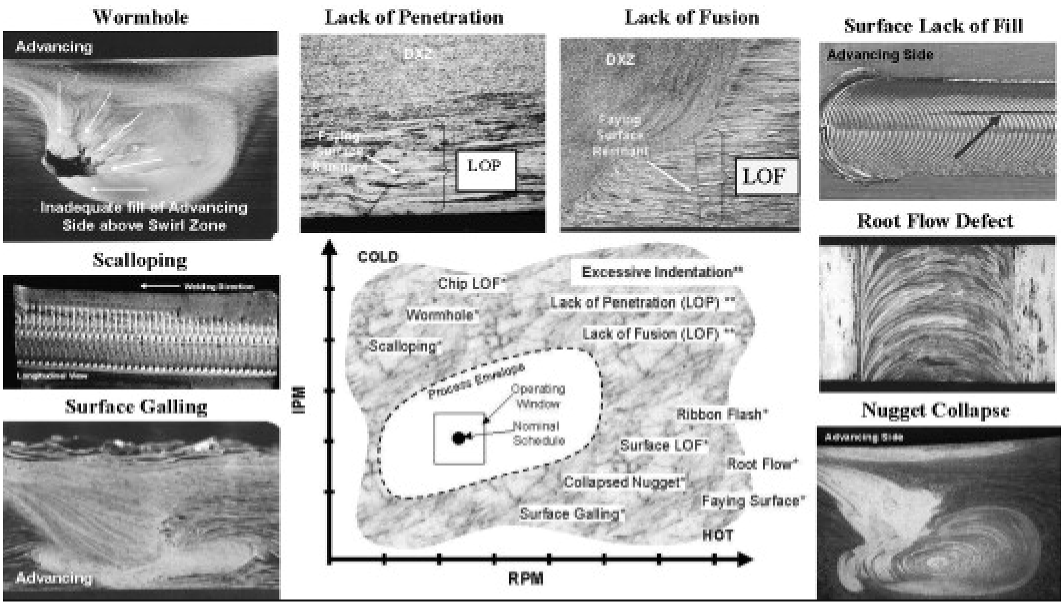


Figure 2-6 Processing Map and Correlating Weld Defects

2.1.6 *Welding Jig and Clamping*

For friction stir welding of butt joints, the configuration of the workpieces need to be placed against a rigid backing plate and clamped properly to prevent movement in any direction. The forces involved in friction welding of butt to butt joint will try to lift and pull the workpieces apart, therefore the main task for the welding jig and clamping is to hold them in position during the weld run so no movement of the workpiece is possible. The plates should be positioned as close to each other as possible; Annette O'Brien suggested a rot opening less than 10 % of the workpiece thickness for material up to 13 mm. Further he suggested that the clamping load should be reduced by having the clamps as near the weld area as possible (O'Brien and American Welding Society, 2007, p. 233). A study to learn more about different fixtures is done in chapter 3. In below Figure 2-7 (Suni,n.d.) is a fixture system used by SUNI to proper clamp the workpiece during welding.

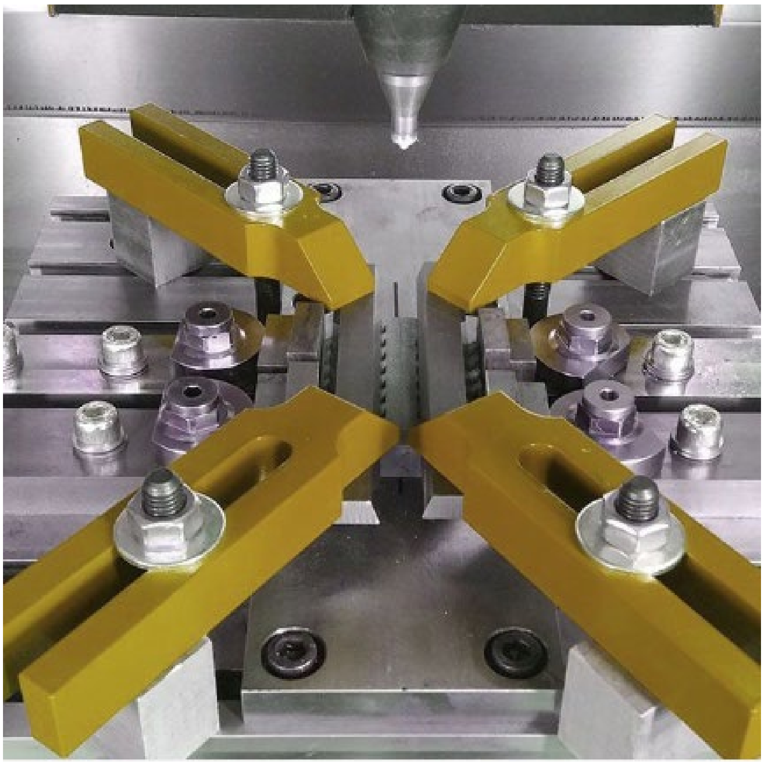


Figure 2-7 Clamping system from SUNI (Used with permission from Suni)

2.2 Taguchi Robust Design Approach

An introduction to robust design approach is given in this chapter, but a more detailed explanation based on chapter 3 "Matrix experiments using orthogonal arrays" in Phadke's book "Quality Engineering Using Robust Design" (Phadke, 1989) is presented in chapter 4. This to better understand the result found using this method.

The robust design approach is the most powerful method to reduce cost, improve quality and simultaneously reduce development interval (Phadke, 2019). The method was developed by Dr. Genichi Taguchi after world war II to improve the engineering productivity. This method can be used in many different industries such as electronics, automobiles, xerography, software development, healthcare and telecommunications and have saved companies hundreds of millions dollar (Phadke, 2019).

Robust design approach gives a method for systematically finding solutions that make our design less sensitive for different causes of variation described here as noise factors. This method can be used for optimizing product design and for different manufacturing process design. Phadke mentions that an OA matrix experiment can be used to study effects of control or noise factors, evaluate S/N ratios and find the best quality characteristics for an application (Phadke, 1989).

For an optimization of parameters using one factor at the time with the trial and error approach, a full factorial search would take 3^4=81 runs for 4 factors and three levels. With the same numbers of factors and levels using Tagushi L_9 orthogonal array only 9 runs is necessary to find the optimal parameters (Nourani et al., 2011).

In Figure 2-8 showing a block diagram with different factors having an impact on the product response. In this context the response of a process is the output or some other characteristics from the product/process we want to optimize. Tagushi refer to this as a *quality characteristic*.

Signal factors are parameters that have an impact on the process or product response. They are usually chosen based on engineering knowledge or experience.

The factors that cause quality loss for a process is been given the term *noise factors.* This is the parameters whose levels can't be controlled by the designer or for other reason is not consider economically or practical feasible. The noise factor's make the response deviate from the target specified by the signal factors (Phadke, 1989, p. 31).

Control factors are the parameters the engineer can choose and can be easily controlled.

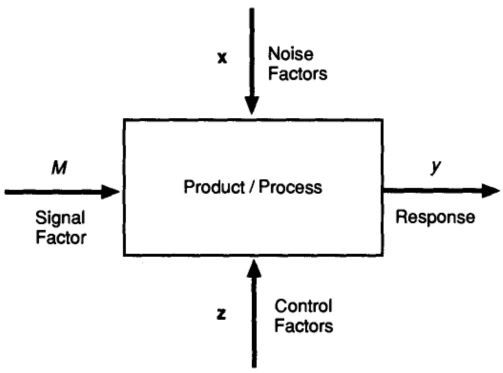


Figure 2-8 P-Diagram

Phadke separates the noise factors in to three categories. External noise such as humidity and temperature from the environment, voltage and vibration for machines and human errors when involved in production. The next step is the unit-to-unit variation for a product during a manufacturing process. It's difficult or even impossible to make precis product, some variation in quality due to variation in product parameters is expected. The third one is deterioration over time, the product will deteriorate, and the product performance will decrease over time

Ratnayake made a flow chart for the robust design approach for a process which is described in the flow diagram in Figure 2-9, (Ratnayake, 2015). As seen in the diagram, the identify performance characteristics to be observed can be of three types. Smaller-the-better, Nominal-the-best or Larger-the-better. The objective function to be optimized for this experiment is a larger-the-better type of function because the objective is to find optimal parameters to increase the tensile strength for the friction welds. This is equivalent to maximizing η. The summary statistic η is the signal to noise ratio (Phadke, 1989, p. 44). The method is further described in chapter 4 to better understand how the results are obtained.

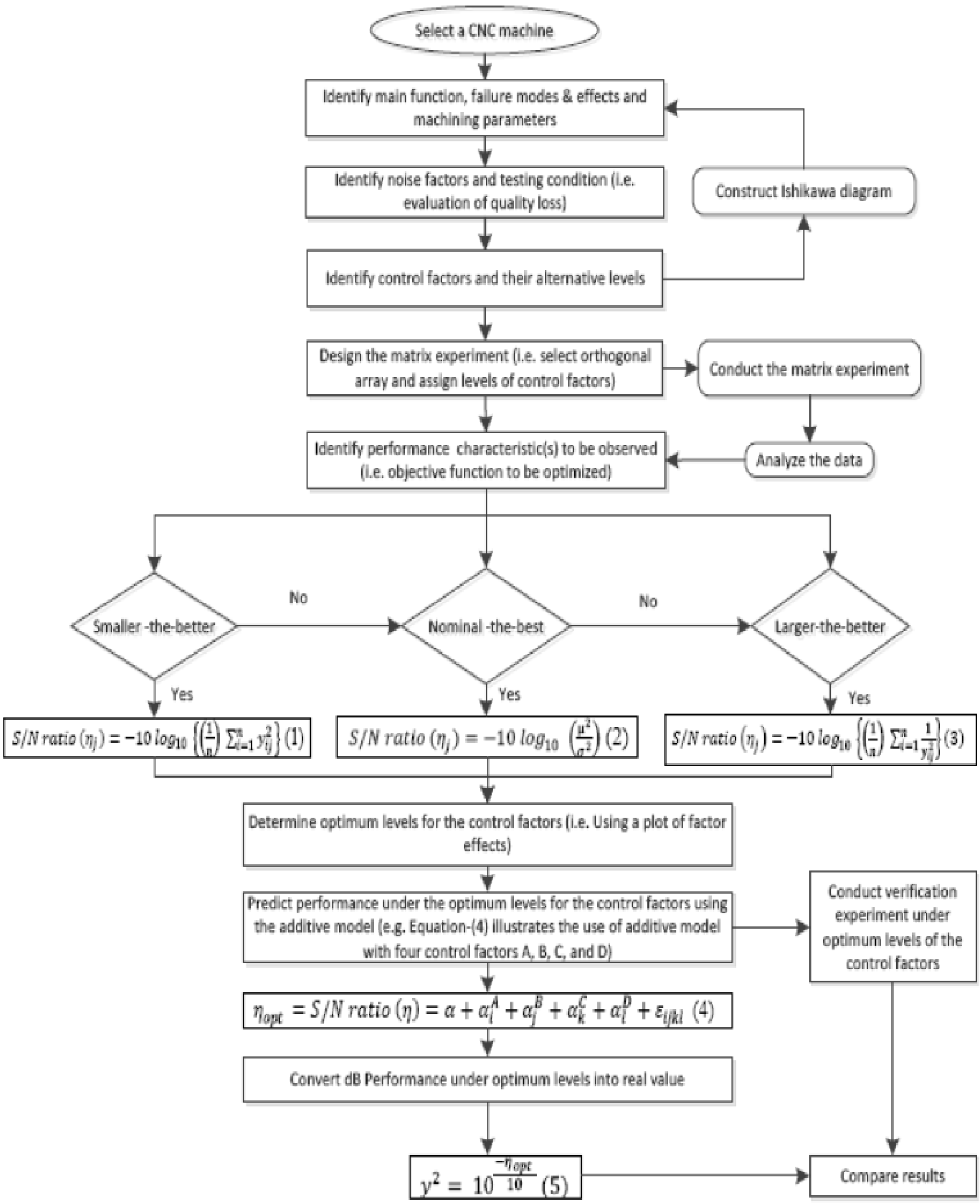


Figure 2-9 Mathematical Framework for Parameter Design Under the Noise

2.3 Aluminium and its Characteristic

Aluminium is one of the most common elements found in the earth crust. The earth crust consists of around 8% aluminium (AZom, 2005). The flexibility of aluminium makes it useful for a variety of areas and industries such as building, automotive, shipbuilding and aeroplane.

This light metal is resistant to corrosion, function as conductor for heat and electricity, non-magnetic and light weight versus strength (Hydro - Aluminium Alloys and Products," n.d.). In its pure form aluminium is soft and ductile and by adding other elements to the aluminium gives the alloy better properties which can be increased strength, workability, improved corrosion resistance, electrical and heat conductivity (Helmenstine et al., n.d.). The most common elements aluminium is alloyed with is zinc, copper, manganese, magnesium, silicon and lithium. There is also added small amount of nickel, chromium, titanium, lead and several other elements (AZom, 2005).

This give around 500 wrought alloys but only a minor part of them are for commercial use. To get an alloy with specific properties it depends on the alloying and the heat treatment. For sorting the aluminium alloys, a standardised designation system is made for the composition and tempering. In Table 2-1 a brief introduction to the aluminium alloy designation system where the alloys are categorized into several groups based on the alloys material characteristics. For the wrought aluminium alloy system, the first digit in this four-number series is for the principal alloying element added to the aluminium alloy. The second digit in the series ex. The 5174 series, the 1 indicates modifications or impurity limits and is going from 1 to 9 with 0 as no modification. The last two numbers 74 indicates the specific aluminium alloy and to identify the alloy in the 5xxx series (European Aluminium Association, n.d.). For 1xxx series the two last two digits is for describing the purity of the aluminium and 1350 alloy tells this is 99,50% pure aluminium ("Understanding the Aluminium Alloy Designation System," n.d.).

Table 2-1 Wrought Aluminium Alloy Designation System

Alloy Series	**Alloying Element**	**Heat Treatment**
1xxx-series	Pure aluminium > 99.00%	Non-Heat Treatable
2xxx-series	Copper	Heat Treatable
3xxx-series	Manganese	Non-Heat Treatable
4xxx-series	Silicon	Non-Heat Treatable and Heat Treatable
5xxx-series	Magnesium	Non-Heat Treatable
6xxx-series	Magnesium and Silicon	Heat Treatable

7xxx-series	Zinc	Heat Treatable
8xxx-series	Other elements	

Note: Table and date from Esab knowledge center ("Understanding the Aluminium Alloy Designation System," n.d.).

As seen in the above table there's two different types of aluminium in this identification system, the heat treatable and the non-heat treatable. The mechanical properties of heat treatable alloys can be changed whit thermal processes like solution heat treatment and artificial aging. The aluminium is heated to high temperatures so alloying elements and compounds can be mixed into the solution before quenching in a medium like water or oil. This make a supersaturated solution at room temperature and can be further changed by aging. The aging process is used for changing the properties of the alloy and is done by precipitation of elements or compounds from the supersaturated solution ("Understanding the Aluminium Alloy Designation System," n.d.). Natural aging is by room temperature and artificial aging is by selected temperatures. For the non-heat treatable aluminium alloys strain hardening is used to change properties like increased tensile strength. Below in Table 2-2 is the Temper Designation System. The system describes the conditions of the specific alloy using numbers and letters. After the four-digit number there will be letter and a number example for 6062-T6 alloy the T is for Temper- thermally treated designation and the number 6 that follows telling that the alloy is "Solution heat treated and artificially aged" as seen in table below. Another letter this system uses in this subdivision is the letter "H" and this letter means Temper -Strain Hardening.

Table 2-2 The Basic Temper Designations

Letter	Meaning
F	As fabricated – Applies to products of a forming process in which no special control over thermal or strain hardening conditions is employed
O	Annealed – Applies to product which has been heated to produce the lowest strength condition to improve ductility and dimensional stability
H	Strain Hardened – Applies to products which are strengthened through cold-working. The strain hardening may be followed by supplementary thermal treatment, which produces some reduction in strength. The "H" is always followed by two or more digits (see table below)

W	Solution Heat-Treated – An unstable temper applicable only to alloys which age spontaneously at room temperature after solution heat-treatment
T	Thermally Treated - To produce stable tempers other than F, O, or H. Applies to product which has been heat-treated, sometimes with supplementary strain-hardening, to produce a stable temper. The “T” is always followed by one or more digits (see table below)

Note: Table and date from Esab knowledge center (“Understanding the Aluminium Alloy Designation System,” n.d.).

Temper designation system for wrought aluminium alloys in Table 2-3 for “H” Temper-Strain Hardening.

Table 2-3 Subdivision of H Temper -Strain Hardening

First digit H”X”x describes a basic operation	
H1	Strain Hardened Only
H2	Strain Hardened and Partially Annealed
H3	Strain Hardened and Stabilized
H4	Strain Hardened and Lacquered or Painted
Second digit Hx”X” describes the degree of strain hardening	
HX2	Quarter Hard
HX4	Half Hard
HX6	Three-Quarters Hard
HX8	Full Hard
HX9	Extra Hard

Note: Table and date from Esab Knowledge Center (“Understanding the Aluminium Alloy Designation System,” n.d.).

Temper designation system for wrought aluminium alloys can be seen in Table 2-4 for “T” Temper- Thermally Treated Designation.

Table 2-4 Subdivision of T Temper -Thermally Treated

T1	**Naturally aged after cooling from an elevated temperature shaping process, such as extruding.**
T2	Cold worked after cooling from an elevated temperature shaping process and then naturally aged.
T3	Solution heat treated, cold worked and naturally aged.
T4	Solution Heat Treated and Naturally Aged
T5	Artificially aged after cooling from an elevated temperature shaping process.
T6	Solution Heat Treated and Artificially Aged
T7	Solution heat treated and stabilized (overaged).
T8	Solution Heat Treated, Cold Worked and Artificially
T9	Solution Heat Treated, Cold Worked and Artificially Aged
T10	Cold Worked After Colling From an Elevated Temperature Shaping Process Then Artificially Aged
Additional Digits Indicate Stress Relief	
TX(X)51	Stress relived by Stretching
TX(X)52	Stress Relived by Compressing

Note: Table and date from Esab knowledge center (“Understanding the Aluminium Alloy Designation System,” n.d.).

2.3.1 *Aluminium Alloys for FSW Welding*

The 6082 Alloy is used because of its excellent corrosion resistance and medium strength. The usage of 6082 is structural or machining and can be found in products like bridges, cranes , ore skips, beer barrels and high stress applications and is one of the strongest 6xxx alloy

("Aluminium Alloys - Aluminium 6082 Properties, Fabrication and Applications," 2005). Table 2-5 shows the composition for the AA6082.

Table 2-5 Chemical Composition of AA6082 Alloy

Element in alloy	**%Present**
Si	0.7-1.3
Fe	0.0-0.5
Cu	0.0-0.1
Mn	0.4-1.0
Mg	0.6-1.2
Zn	0.0-0.2
Ti	0.0-0.1
Cr	0.0-0.25
Al	Balance

Note: Data form AZO Materials ("Aluminium Alloys - Aluminium 6082 Properties, Fabrication and Applications," 2005)

From Table 2-6 below is some of the mechanical properties for AA6082 alloy

Table 2-6 Mechanical and Physical Properties of AA6082 Alloy (Sheet 0.4 to 6.0 mm)

Property	**Value**
Proof Stress	260 Min MPa
Tensile Strength	310 Min MPa
Hardness Brinell	94 HB
Modulus of Elasticity	70 GPa

Density	2700 kg/m^3
Melting Point	555°C
Thermal Conductivity	180 W/m.K

Note: Data form AZO Materials (“Aluminium Alloys - Aluminium 6082 Properties, Fabrication and Applications,” 2005).

The 5754 alloy is used because of its excellent corrosion resistance and can be used places with seawater and industrially pollution will have an impact. The usage for the 5754 alloy is in shipbuilding, flooring, treadplate, fishing and food processing industry (“Aluminium Alloys - Aluminium 5754 Properties, Fabrication and Applications,” n.d.). Table 2-7 shows the composition for the AA5754 alloy.

Table 2-7 Chemical composition of AA5754 Alloy

Element in alloy	**%Present**
Si	0.4
Fe	0.4
Mn	0.5
Mg	2.6-3.2
Al	Balance

Note: Data form AZO Materials industry (“Aluminium Alloys - Aluminium 5754 Properties, Fabrication and Applications,” n.d.).

Table 2-8 shows the mechanical properties for the AA5754 alloy.

Table 2-8 Mechanical and Physical Properties for Aluminium Alloy 5754 H22 Sheet Plate 0.2 to 40 mm

Property	**Value**
Proof Stress	130 Min MPa
Tensile Strength	220-270 MPa
Elongation A50 mm	7 Min %
Hardness Brinell	63 HB
Modulus of Elasticity	68 GPa
Density	2.66 kg/m^3
Melting Point	600°C
Thermal Conductivity	147 W/m.K

Note: Data form AZO Materials industry ("Aluminium Alloys - Aluminium 5754 Properties, Fabrication and Applications," n.d.).

2.4 G-Codes for Numerical Control

One of the numerical programming languages is G-Codes. This can be used to give the machine commands such as how to move the tool and cutting speed and spindle speed. The code is written line by line and the program is read by the machine from top to bottom. Below is some of the commands which can be used to control a CNC machine. The method is standardized and can be found in ISO 6983-1:2009 (International Organization for Standardization, 2009). Below is some of the g-codes used as explained from Autodesk Resource Center ("Getting Started with G-Code | CNC Programming | Autodesk," n.d.).

A line of code can be written like N01 G90 X10 Y10 Z2 F500 S1500 T04 M06

Where:

N: Line number
G: Motion

X: Horizontal position

Y: Vertical position

Z: Depth

F: Feed rate

S: Spindle speed

T: Tool selection

M: Miscellaneous functions

I and J: Incremental centre of an arc

R: Radius of an arc

Alpha numeric codes are used for programming as they are a simple way to:

Define motion and function (G##)

Declare a position (X## Y## Z##)

Set a value (F## and/or S##)

Select an item (T##)

Switch something on and off (M##), such as coolant, spindles, indexing motion, axes locks, etc.

2.5 Mazak VCN 430A and FSW

The Mazak VCN-430A vertical milling machine is a low-cost machine with an effective balance between speed and torque ("VCN-430A," n.d.). This machine is not designed for friction stir welding and to be sure it could perform as desired we turned to our Mazak vendor. After an email correspondence with Martin Forrest an applications development manager at Mazak UK, it was revealed that they had done a friction stir welding project with the same type of machine. They did some major modifications on their machine like changing the X axis motor, motor housing and cover. Some other modifications were done as well for the spindle flange and force control for Z-axis was turned on. This cost would be around 50K USD and with a limited budget wouldn't this be possible. He recommended 2-3 mm aluminium plates to be the best to start experimenting with (Martin Forrest, email correspondence, 2018). This email correspondence is presented in full in Appendix A.

Machine used for this project is installed with the Matrix Nexus II control system. The machine can be seen in below Figure 2-10.

Figure 2-10 MAZAK VCN430a

Highlights of the machine specification from Mazak brochure can be seen in Table 2-9.

Table 2-9 Standard Machine Specifications

Max. Spindle Output	**12000 rpm**			
Spindle Output	18.5 KW (5. min rating)	11 KW (40% ED)	7.5 KW (Cont. rating)	
Max Torque	95.5 Nm (10. Min rating)			
Feed rate	42 m/min			
Cutting Feed rate	1-42000 mm/min			

Note: Data from Mazak brochure ("MAZAK VCN series," 2000).

Before this project started a pre-study was done to check if the Mazak machine would be able to produce the process parameters needed to perform friction stir welds. The welding institute (TWI) presents a paper from the LOSTIR project where a low cost FSW process monitoring unit was made to fit ordinary CNC machines and during this study up to 100 CNC milling machines was tested to see if they fitted criteria they had based on knowledge from friction welding of 2-8 mm thick aluminium plates ("Development of a low cost Friction Stir Welding Monitoring System," n.d.). Data from this paper is presented in Table 2-10 and was used as another guideline to see if the Mazak would be able to perform FSW.

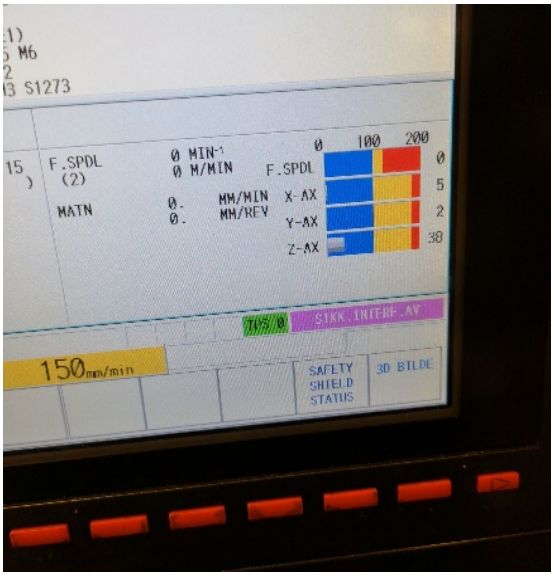
Table 2-10 Machine Specification FSW

Parameter	**Specified Range**
Spindle Speed Range	0-3000 rpm
Z axis traverse speed	0-1500 mm/min
X axis traverse speed	0-3000 mm/min
Z axis travel	500 mm
Z axis max workpiece size	750 mm
X axis travel	2000 mm
Y axis travel	2000 mm
Spindle tilt angle	0-5°
Z axis load	0-30 KN
X axis load	0-20 KN
Spindle torque	0-80 Nm

Note: Data found from TWI article referred to above.

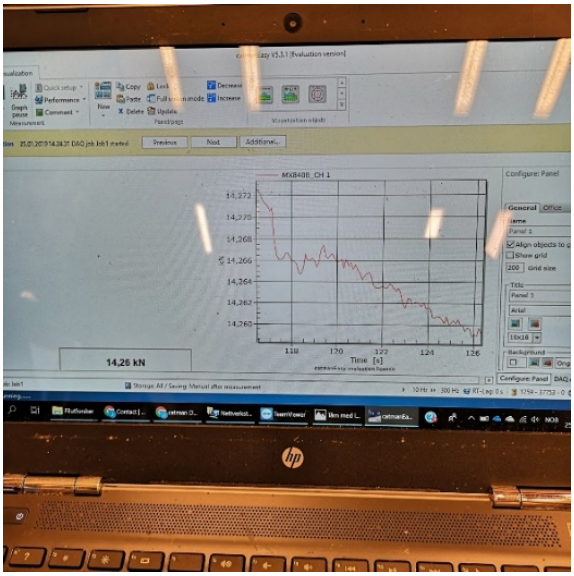
One major concern was the machines ability to produce enough downforce when performing friction welds. The Matrix Nexus software unit is installed with a power meter showing the load measured in percent and this feature were used to see how much downforce the Mazak machine could produce using an HBM 10 KN load cell. The load cell was connected to a Quantum X data acquisition system and data was read from a laptop installed with the Catman Easy software. For the safety of the machine an upper limit was set at 80% of max. When slowly driving the Z axis down towards the load cell a value of 14.22 KN was read from the screen. The measurement process can be seen in Figure 2-11.

a) Load cell 10 kN with Quantum X



b) Measuring from Mazak monitor

c) Downforce Z-axis



d) 14.26 kN read from data screen

Figure 2-11 Pictures from downforce measurement a-d)

2.6 Equipment and Methods for Material Properties Testing

2.6.1 Tensile Strength Testing

It's important to know the characteristics and mechanical properties of materials. Engineers need to choose suitable materials and use right dimensions when designing parts so they will have enough bearing capacity for loads, withstand stresses and the environment its exposed to during their service life. Materials can be exposed to different loads such as compressive, tensile and shear, but these loads can be constant or vary with time making fatigue a key factor for the materials life span. Some of the most important mechanical properties when designing parts are stiffness, strength, hardness, ductility and toughness(Callister and Rethwisch, 2015, p. 209).

Tensile testing is a method used to find several mechanical properties of a material and one of the most common stress-strain tests is done in tension (Callister and Rethwisch, 2015, p. 210). The specimen is prepared according to a standard for tensile testing and the specimen is fasten in a tensile machine as this below at the University of Stavanger.

Figure 2-12 Instron Tensile Test Machine at UIS

An increasing axial load is applied to the specimen by a crosshead moving slowly with a load cell attached for measuring the load applied. An extensometer is placed on sample to measure the elongation. The specimen is pulled until the point of breakage and a stress/strain curve can be obtained as seen in Figure 2-13 ("Effect of Specimen Geometry on Tensile Testing Results," 2017). Other important properties like the modulus of elasticity, yield strength and strain can be read out from tensile tests (“Tensile Testing - Instron,” n.d.).

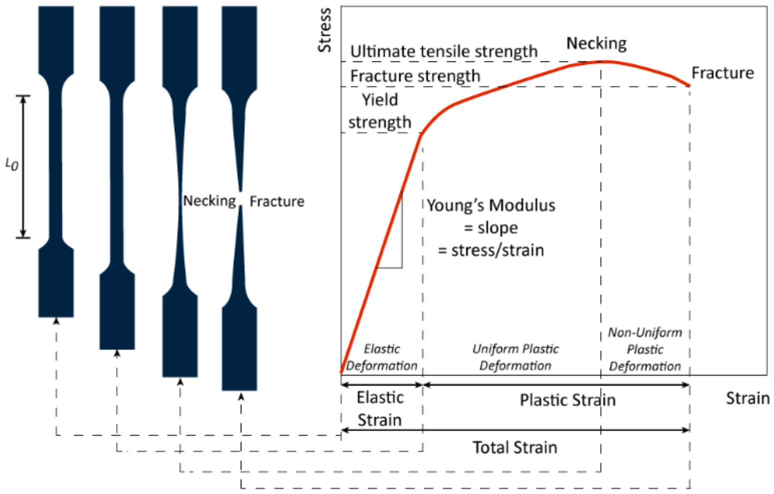


Figure 2-13 Tensile Strength Testing

2.6.2 *Vickers Hardness Testing*

Hardness testing is used to measure the hardness of a material by observing the ability to resist plastic deformation (“Vickers hardness test,” 2019). A diamond indenter is pushed into the test material leaving a squared mark. The square base having an angle of 136 degrees between opposite faces and this is held down for 10 to 15 seconds by a load of 1 to 100 kgf. The two diagonals formed by the diamond at the surface is then measured using a microscope and the average value of the diameters is used further to describe the area, as seen in Figure 2-14 a) (“Vickers Hardness Test,” n.d.). Figure b) shows the machine at the University of Stavanger.

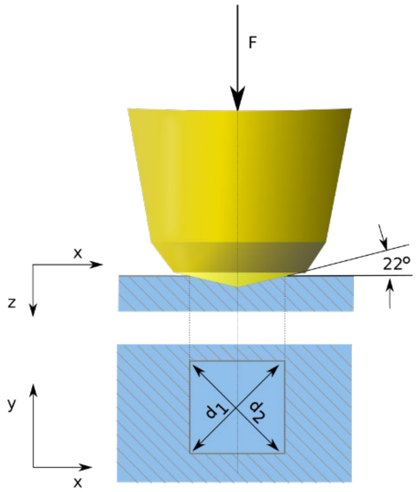


Figure 2-14 Vickers Hardness Test Indenter a) – Vickers machine by Innovatest b)

The area with the sloping surfaces is then used dividing the force by the area to give the Vickers Hardness. Using Equation 2-1 to find the surface area ("Vickers Hardness Test," n.d.).

Equation 2-1 Surface Area of the Vickers Hardness Test

$$A = \frac{d^2}{2 \cdot Sin\left(\frac{136°}{2}\right)} \approx \frac{d^2}{1.8544} \quad [mm^2]$$

Using Equation 2-2 to find the value of Vickers hardness ("Vickers Hardness Test," n.d.).

Equation 2-2 HV Hardness

$$HV = \frac{F}{A} = \frac{1.8544\mathrm{F}}{\mathrm{d}^2} \quad \left[\frac{kgf}{mm^2}\right]$$

3 Experimental

3.1 *Welding Parameters*

From chapter 2 process parameters, Threadgill described the parameters after tool and when the material was chosen to be; tilt angle, tool plunge, tool depth, rotation speed and traverse speed. To be sure choosing proper material and tools for this project friction welding company Stirweld were contacted to get information and help choosing material and tools. Furthermore, parameters as described above needs to be chosen wisely to assure sound welds. A fishbone diagram as seen in Figure 3-2 is used to get an overview over the process to more easily find the factor and their levels for the robust design approach as they should be chosen based on experience or knowledge. Stirweld provided helpful information and this had an impact on the starting parameters selected for this project (Laurent Dubourg, email correspondence, 2019). The email correspondence is attached in Appendix. Furthermore, some articles were found to try to solve which starting parameters to be used.

3.1.1 *Tool and Material Used for This Project*

Stirweld in France was chosen as the tool supplier due to their good service and helpful support in the early stages of this project. The lack of knowledge to understand the process and what our needs would be to perform welds made it necessary to ask for expert guidance to find the right tools and preferable alloys. After some mail exchange any 5xxx and 6xxx alloys was suggested to start with as they have good weldability when it comes to friction stir welding. For the 5xxx series plates with 2-3 mm thickness was suggested and for the 6xxx series plates of 3-4 mm thickness.

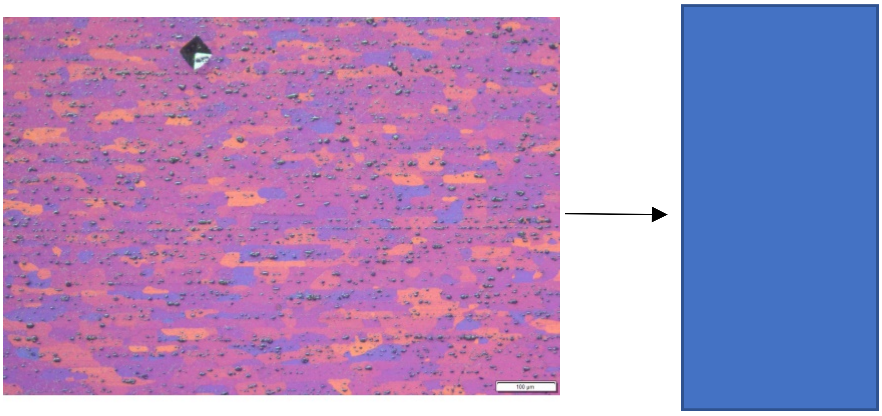
Two things were taken into consideration when selecting materials; availability at local steel suppliers and usage for the particular alloy in the industry. Material was ordered from Alunor Metall AS, as they had right dimension and could deliver on short notice both 6082-T6 and 5754-H22 alloy. The 6082-alloy was ordered as a plate with dimension of 2000x1000x 3 mm. The 5754-alloy was ordered having a dimension of 2000x1000x2 mm. Both plates were then sent to Smed.T. Kristiansen AS for waterjet cutting to get desired dimensions.

Friction welding tools was ordered from Stirweld given the above information regarding the alloys and plate thickness. The Al/Si tools F-AS-1-X/F-AS-2-X was suited to fit our project best and three tools each was sent from France. The tools were received directly from stock and as I didn’t know the pin length needed to be specified for each tool, the tools were delivered with 2- and 3-mm pin length. Stirweld was contacted about this matter and they sent new tools from their workshop with proper pin length machined free of charge. The new pin length was 1.8 mm for the F-AS-1-X tools and 2.8 mm for the F-AS-2-X tools and can be seen in below Figure 3-1. The scrolled shoulder is designed to improve the material stirring and with this feature tool tilt angle will be unnecessary. The triangular flat threaded after machined to the proper dimensions in below figure.

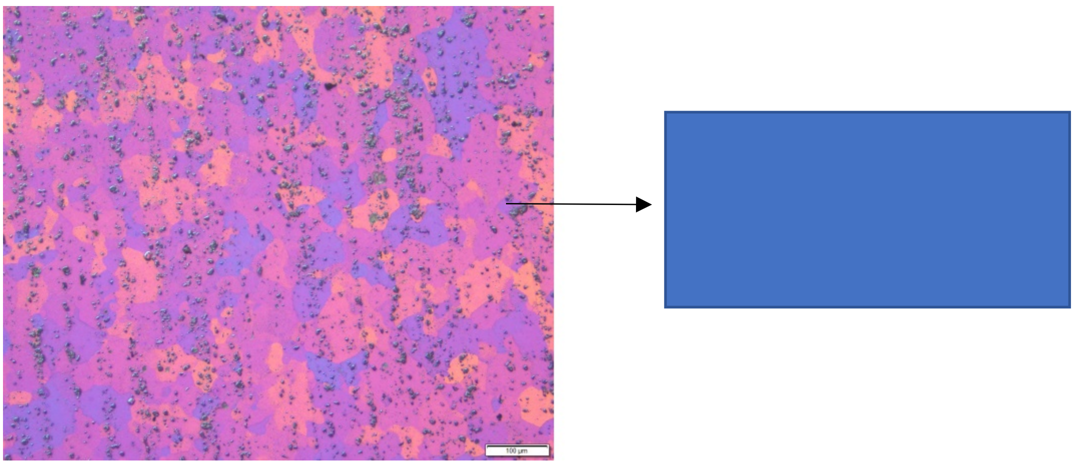
Figure 3-1 Tools from Stirweld

3.1.2 *Base Material 6082*

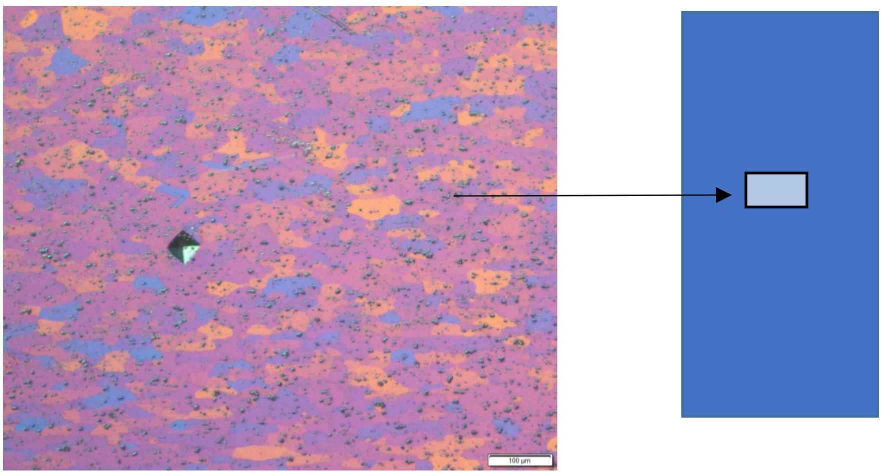
The base material was tested for Vickers hardness and tensile strength. Microstructure from the faying side can be seen in Figure 3-2 a). Next is the microstructure from the 100 mm side as seen in figure b). The microstructure in figure c) is from the top of the plate. The microstructure preparation follows the same procedure described for the welded specimens. For each sample below 4 point of Vickers hardness were performed and figure a) had an average hardness of 117.7 HV. The figure b) was found to be 116.7 HV and the top specimens in figure c) was measured to have a hardness of 115.5 HV. Ultimate tensile strength was found to be 347.6 MPa. The result from the tensile test can be seen in Table 4-9. The barker's solution used for anodization gave some impurities to the process.



a) Microstucture from the 300 mm side



b) Microstructure from the 100 mm side



c) Microstructure from the top

Figure 3-2 Microstructure of Base Material 6082 a-c)

3.1.3 *Fishbone Diagram*

In Figure 3-2 fishbone diagram is used to get an overview of the things having an impact on the welding process and the weld quality. The diagram is made using a brainstorming concept where every point is sorted in columns. Below the figure it’s a more detailed description from the points used in the diagram

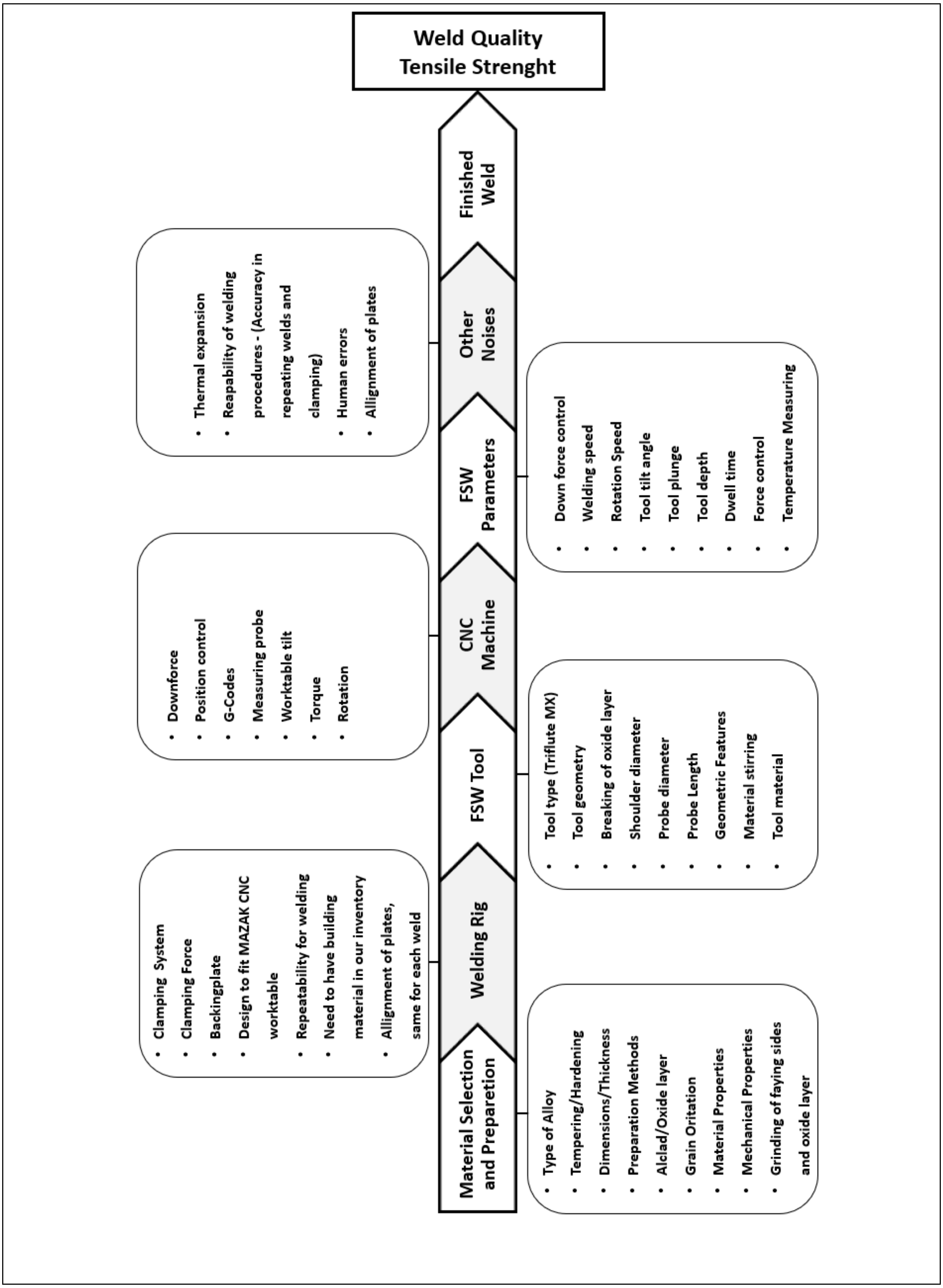


Figure 3-3 Fishbone Diagram

Material Selection and Preparation

From the material selection and preparation column in the fishbone diagram several things having an impact on the process and affecting the welds. After the alloy, tempering and thickness is decided there are still more things to be aware of such as the grain orientation, preparation before welding and removal of oxide layer. The plate is ordered to be cut in the same direction, so grain orientation is the same for every welded. Preparation of the workpieces is described in chapter 3.4.1.

Welding Jig

Welding jig development is described .in chapter 3.2.

FSW Tool

The FSW tool parameters and signals described in the fishbone diagram is now fixed parameters due to buying tools from Stirweld. The tools are from stock and only the pin length is chosen by the customer. The shoulder scrolls pattern used on Stirweld tools make the tool tilt parameters excess due to containment of softened workpiece material (O'Brien and American Welding Society, 2007). The pin length needs to be at least 10 % shorter than the plate thickness to avoid the pin touching the backing plate.

CNC Machine

CNC machine parameters and signals which can have an impact on the welding as noted in the fishbone is:

- ✓ Downforce - This is tested in an early pre-study as shown in chapter 2.5.
- ✓ Position control - The Mazak have built-in position control but not possible to measure and adapt during welding sessions.
- ✓ G-codes – The machine can be operated using g-codes. Program used for welding is described in chapter 3.4.3
- ✓ Measuring probe – Can be controlled and used in combination with g-codes programming using the Mazatrol Nexus control unit.
- ✓ Torque – the Mazak can provide enough torque.
- ✓ Rotation – the Mazak can provide the necessary rotation.

FSW Parameters

- ✓ Downforce control – Not possible due to lack of equipment

- ✓ Welding Speed – Traverse welding speed was suggested to be 400-1200 mm/min from asking Stirweld. From the early mail correspondence, a unit misunderstanding made the values used for welding speed in the early stages to be around 15-60 mm/min.
- ✓ Rotation speed – 1000 rpm to 1800 rpm
- ✓ Tool tilt angle – As described above the tool design with shoulder scrolls make this feature unnecessary.
- ✓ Tool plunge – Suggestion from Stirweld was around 1 mm/s.
- ✓ Tool depth (Shoulder depth) – Start with 0.03 mm doing a spot weld and increase to find where the tool makes a circle that have the same diameter as the tool shoulder. Important to not have zero shoulder depth as this can break the pin. To high shoulder depth can make the pin touch the backing plate.
- ✓ Dwell time – Suggestion is to use around 2-4 seconds.
- ✓ Force control – Not possible due to lack of equipment.
- ✓ Temperature measuring – Temperature datalogging during welds possible.

Other Noises

- ✓ Thermal expansion – Thermal expansion can have an impact on the shoulder depth and position control adding noise to the process leading to weld defects.
- ✓ Repeatability of welding procedures – It's important to get same condition and setup for every weld to avoid adding noise which will increase the variance.
- ✓ Human errors – As there are many parameters involved and difficult to be accurate preparing each experiment, risk for human errors is a source of noise.
- ✓ Alignment of plates – This fall under the human error and repeatability category. Clamping and welding jig need to be able to make each experiment setup as equal as possible.

3.1.4 *Parameter Study*

Similar projects performing friction welding using CNC machines and their choice regarding parameters is described below.

G.C. Jadhav and Dr.R.S. Dalu performed friction welding with a universal milling machine using AA6061-T6 alloy with thickness of 6.3 mm. The tools were made from D2 steel having several different design features. The experiment setup used Tagushi OA design L_{25} having five factors and five levels. The parameters were as follows; rotation speed in the interval of 500-1000 rpm, welding speed in the interval of 14-28 mm/min, axial force in the interval 5-9 kN, shoulder diameter 16-20 mm and tilt angle form 0-3 degree. They reported tensile strength up to 255 MPa using a square tool pin (G.C Jadhav and Dr.R.S Dalu, 2019).

Naimuddin et al., did a study using a conventional vertical milling machine on AA6082-T6 alloy having a thickness of 5 mm. A threaded welding tool were used having a shoulder diameter of 18 mm, pin diameter of 6 mm and pin length of 4.7 mm. Shoulder depth into the material was set to 0.15 mm. Welding speed used were 50 mm/min and rotational speed 1400 rpm. They reported tensile strength around 200 MPa and a successful bending test (Naimuddin et al., 2016).

J.Adamowski and M.Szkodo used a converted milling machine to perform friction stir welding on plates with AA6082-T6 alloy having a thickness of 5 mm. They used tools made from structural steel class 8.8 having a shoulder diameter of 19 mm and the pin consist of bolts size M6 with 4.8 mm pin length. Parameters used for welding were rotational speed in the interval 230-1700 rpm, travel speed in the interval 115-585 mm/min and 20 seconds preheat stage to soften the material. They concluded that the tensile strength is directly proportional to the travel and welding speed (Adamowski and Szkodo, 2007).

Z. Barlas and U. Ozsarac investigated the effect of FSW parameters on joint properties for AA5754-0 alloy having a thickness of 3 mm. They used a milling machine to perform FSW butt welds with constant parameters for tool geometry having a concave shoulder with diameter of 15 mm and a conical threaded pin with 3 mm length. Next parameters were welding speed set to 13 mm/min and the plunge depth at 2.9 mm. Variable parameters used were rotational speed in the interval 700-1100 rpm, tool tilt angle 0 and 2 degree. Dwell time was set to 15 seconds to soften the material. They also had tool rotation direction as a parameter. They reported tensile strengths in the interval 118-217 MPa. Best result was concluded to be after using 1100 rev/min and 2 degree tool tilt in CCW direction with a 86% tensile strength compared to the base material (Barlas and Ozsarac, 2012).

Abd Elnabi et al., studied and optimized the FSW process for AA5754-H111 alloy plates with a thickness of 6 mm. They used an ESAB Legio FSW machine with position control. Parameters used was welding speed of 200-300 mm/min, for the rotational speed values of 500-700 rpm was used. Dwell time were 15 seconds and plunging speed set to 0.5 cm/min. Tool shoulder was 22 mm and pin length 5.8 mm with a tilt angle of 1.2 degree. The downforce varied with the plunge depth but didn't exceed 20 kN. They reported tensile tests with 5% of the UTS in the base material (Abd Elnabi et al., 2019).

De Giorgi et al., studied the influence of three tool geometries on the joint performance for AA6082-T6 plates having a thickness of 1.5 mm. The tools made of 56NiCrMoV7-KU material had three different shoulders; scroll, shallow cavity and a flat shoulder. The pin used was 1.7 mm in diameter and the pin length ha a height of 1.2 mm. Other parameters used were rotational speed at 1810 rpm, welding speed at 460 mm/min, 2-degree tool tilt and 0.1 mm plunge depth. They reported successful welds having ultimate tensile strength between 252 and 254 MPa, around 76 % of the strength of the base material (De Giorgi et al., 2009).

From the parameter study above its difficult to find parameters that will work for every alloy and machine as there are many aspects that need to be considered to achieve sound welds. Starting parameters used in the experimental part below is therefore mostly based on the dialog with Stirweld. After each test weld adjustment is done to counter for the defects or the result experienced during testing. In Table 3-1 below are starting parameters used to find the appropriate factor levels used in Tagushi robust design approach.

Table 3-1 Starting parameters

Parameters	Units	Lower Value	Higher Value
Rotation Speed	rpm	800	1800
Welding Speed	mm/min	15	200
Shoulder depth	mm	0	0.15
Dwell time	seconds	2	6

3.2 Pre-Experimental and First Test Welding

This chapter is describing the process of producing the first weld and the first welding jig, towards finding the solution used in the Tagushi robust design approach. This is separated into two parts as several problems occurred during developing the jig and finding proper welding parameters. These problems are related to the nature of the friction stir welding process as this is a sensitive process involving a lot of parameters. As described in chapter 2 there is a small process window that will give sound welds and operating outside this window will most likely give faulty welds having defects. Improper clamping system or uneven clamping force distribution can affect the process and the same can be said for the lack of force control controlling the tool penetration along the weld. A lot of parameters affecting the welds made it hard to simultaneous develop the welding rig with a functional clamping system and finding the weld parameters to operate within the process window. All material disponible of the AA5754 alloy were used trying to solve the above-mentioned issues and therefor only the AA6082 alloy is used in the Tagushi experiment. As this project had limited amount of material available the need to adapt knowledge from every adjustment made during testing of the welding rig and parameters used. First the test weld done on the AA5754 is fully described and then a chapter describing how the rig was developed.

3.2.1 *Welding Jig and Pre-Experimental for Welding*

Before any friction weld could be done using the MAZAK CNC milling centre, a welding jig to support the clamping system and backing plate were needed. A study of clamping systems for friction welding using CNC machines and ordinary FSW machines was done the understand the basics. The information found in articles was then used to find ideas designing a system to be used for this project. Limitations for the clamping system before starting the design and machining was lack of knowledge for the welding process and understanding of the forces generated during welding. Other limitations such as time and budget had a great influence on this process.

The main constraints to consider before designing and building the rig and clamping system can be seen in below Table 3-2 Constraints for Welding Jig

Table 3-2 Constraints for Welding Jig

Constraint	Description of the constraint
Material	Need to have the build material in the workshop inventory
Welding jig dimensions	Need to fit our MAZAK 430A worktable, the jig needs to have place for two workpieces having dimensions of 150x300 mm and 2-3 mm thickness
Backing plate	Need to withstand the Z-axis downforce giving necessary backing and be able to produce defect free backside of the weld
Clamping system	Need to constraint the aluminium plates proper during welding so no movement is possible for the x-y-z forces and torque produced

Tool holder	Dimension of the tool and tool holder need to be considered when designing the system to avoid interference during machine operation
Repeatability	The weld setup most be repeatable after mounting/demounting the rig to the CNC worktable
Accuracy	The system needs to as accuracy as possible for each weld as this can have an impact on the result from Tagushi Robust Design Approach

3.2.2 *Short Study of Design for Clamping and Backing Plate*

Five welding jig and clamping concepts were found during an online article search and they are presented below.

Dawood et al, used a simple clamping system to weld two pieces of 1030 aluminium strips having 3 mm thickness as seen in Figure 3-3 (Dawood et al., 2014). The design was made of a backing plate unit with two steel bars mounted across the plate to give support against the welding forces.

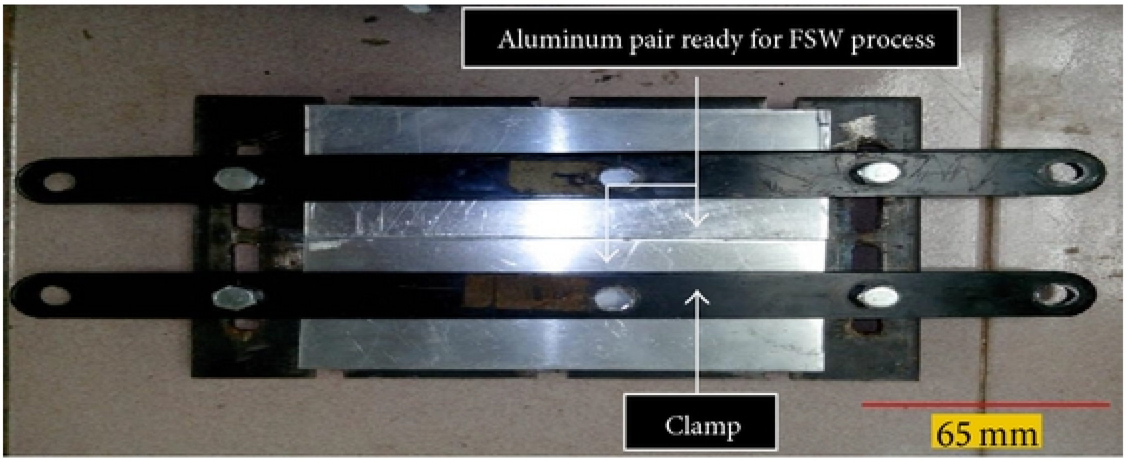


Figure 3-4 Simple Clamping for FSW

Asli Sicilan.T and S. Senthil presented an article describing FSW of AA6063 aluminium alloy using an ordinary CNC machine. Figure 3-4 (Asli Sicilan.T and S.Senthil, 2014) shows their fixture and setup restraining the plates having 6 mm thickness. They used two 3 bolts L-clamps to secure the workpiece against the backing plate and the force distribution can be adjusted with three tensioning screws at each side of these clamps. One end stopper is used to counter the force produced when the tool is travelling during welding. Further they have secured this system using 4 bolts connected to the worktable.

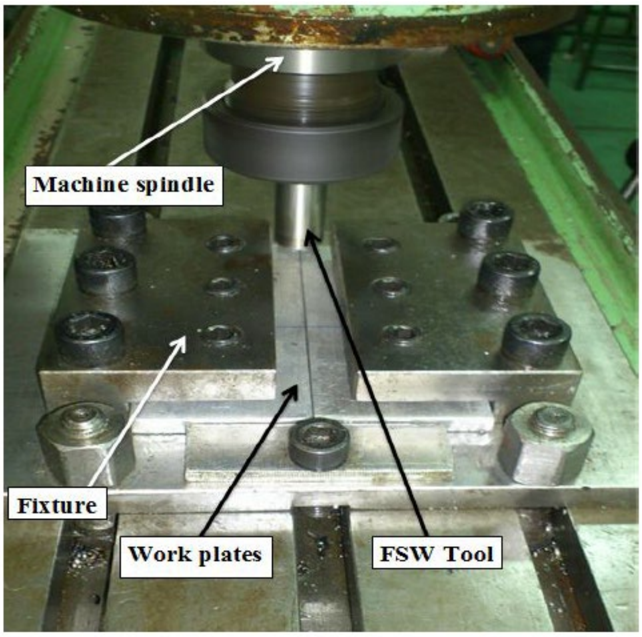


Figure 3-5 Fixture for CNC Machine Setup

In 2013 Pastor and Svoboda used the fixture seen below in Figure 3-5 (Pastor and Svoboda, 2013). They did FSW using a milling machine for welding of 7075 aluminium alloy, 4 mm thickness, 150 mm length and 75 mm width. The fixture was made by using edge guides and secondary supports to constraint the plates. For clamping the plates to the backing plate, four pieces of hold-down clamps was used. The end tip of the bolts used to press down the workpieces have small round plates attached to them probably to make a larger area for force distribution.

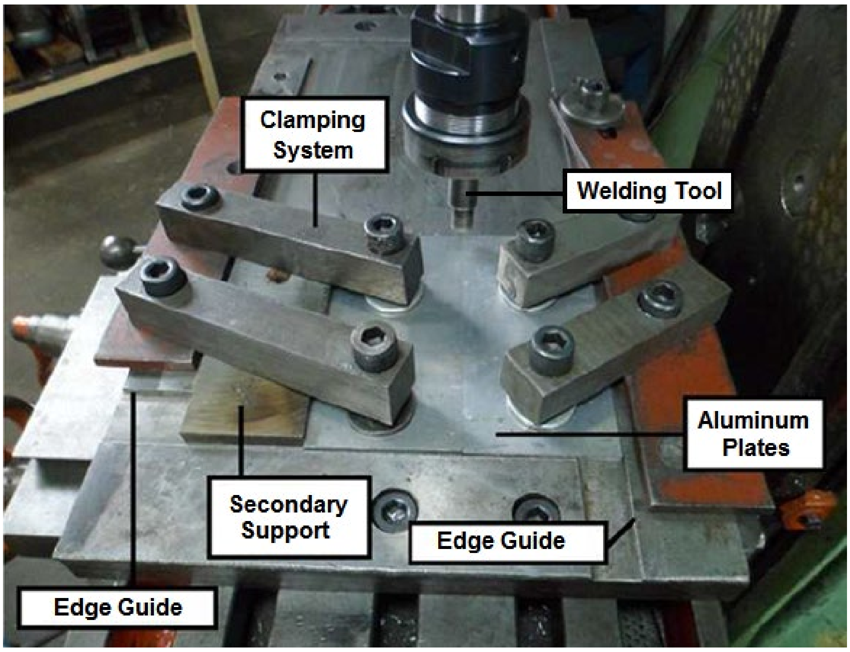


Figure 3-6 Welding Fixture for FSW

Hasan et al, made a simplified design for a clamping system to perform friction welding of aluminium alloy as seen in Figure 3-6 (Hasan et al., 2015). This design gives the possibility to adjust the clamping against the backing plate, but also pushes the two faying sides together by lateral pressure making the weld joint line gap free. The design is made using a backing plate, two angles connected by to bolts, two steel bars with two bolts each to secure the plate to the backing plate. The angles are then attached to the worktable with nuts and bolts. The purpose of this design was to prevent dispersal or lifting of the workpieces and ensure uniform temperature distribution along the weld line (Hasan et al., 2015).

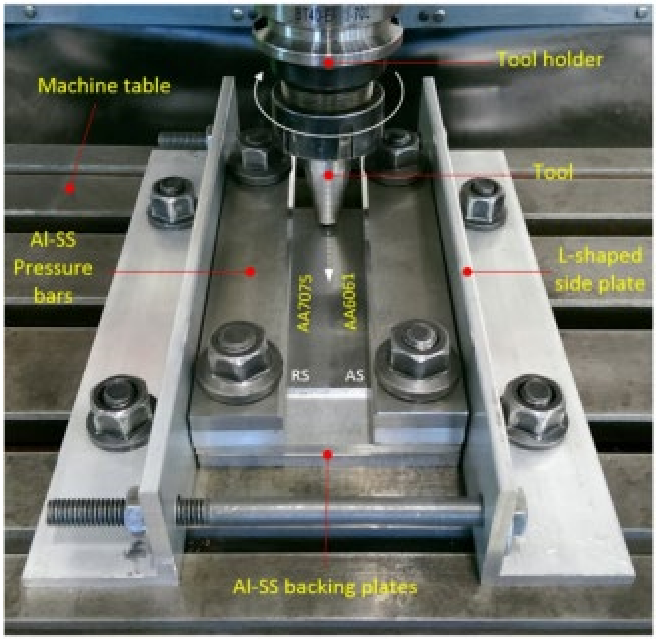


Figure 3-7 Welding Jig for Milling Machines

Daniel André Sequeira de Sousa used a FSW gantry system to complete welds for his master thesis. Dissimilar aluminium alloys of AA7050-T7451 with 8 mm thickness was friction welded and mechanical properties investigated. A presentation of the clamping system and backing plate from the FSW gantry system can be seen in Figure 3-7 (Daniel André Sequeira de Sousa, 2016). This system can provide clamping force in both vertical and horizontal directions. Several step clamps are evenly distributed across the workpieces making pressure distribution more controllable clamping the plate against the backing plate. Adjustable toe clamps are providing vertical force to the workpieces pushing them together to avoid gap between the faying sides or any movement during the welding process. Another benefit seen from this configuration is the removable backing plate which can be selected individually for each alloy giving better control of the temperature distribution.

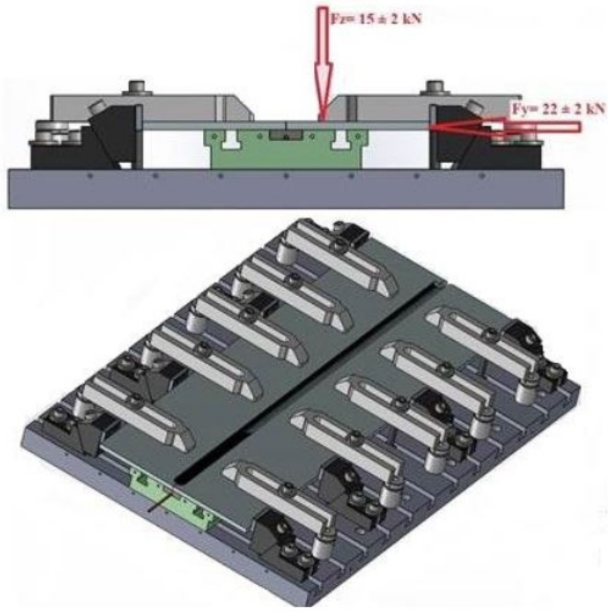


Figure 3-8 FSW Gantry System

Conclusion

There are several ways to clamp the workpieces to the backing plate as can be seen in the above figures. The fixture seen in Figure 3-6 seems like the best solution but as there was no material available at the workshops inventory this couldn’t be done. Furthermore, the worktable dimension limited the design options as the distance between the slots where the fixture would be attached to table was only 250 mm. This would not give an appropriate jig to support the 300x150 mm plates need to get proper tensile strength test specimens. The clamping system in Figure 3-7 is too advance to build at this point when it comes resources such as time, budget and manhours available for this project. For the clamping seen in Figure 3-4 the L-clamps is not in the workshop inventory, but this seems like a design worth to investigate further for easy clamping using milling machines.

After going through the material available from the inventory at our workshop a 12 mm carbon steel plate was selected to use as a backing plate. A combination of features from the clamping systems and backing plates seen in Figure 3-3, Figure 3-4 and Figure 3-5 was used as input designing the backing plate. The backing plate with aluminium plates inserted can be seen in the below Figure 3-8. The four corner bolts are for attaching the worktable using T-slot nuts, and grooves at the sides are for the step clamps.

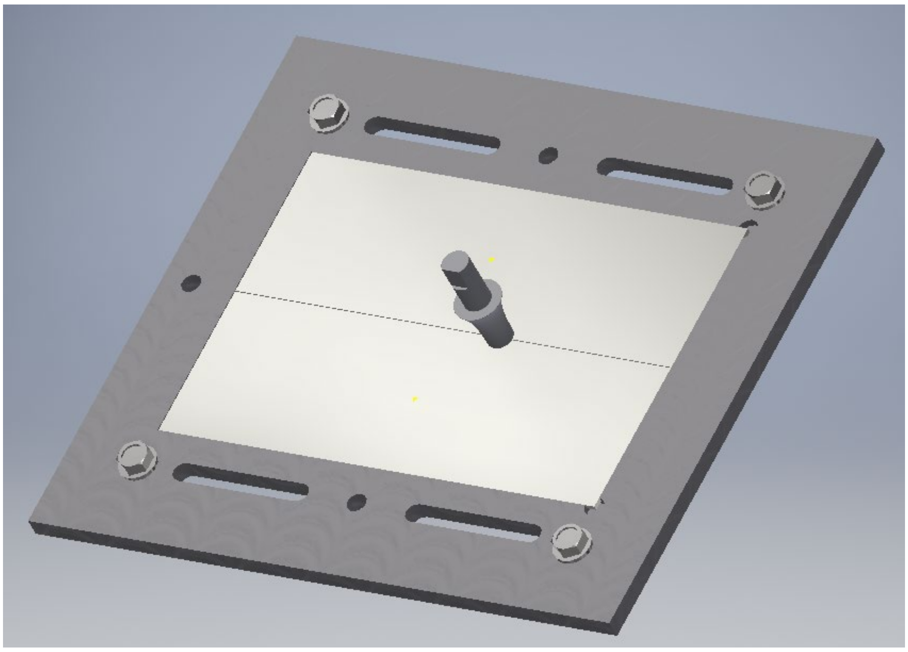


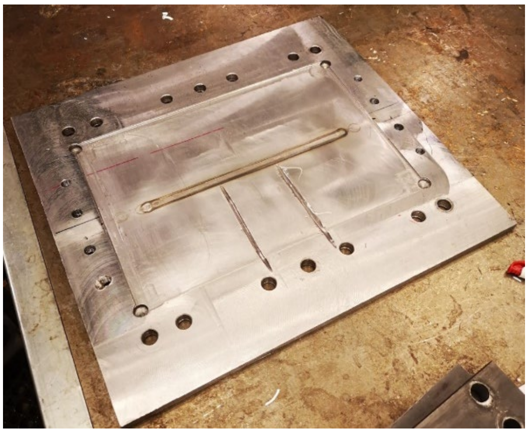
Figure 3-9 Design in Inventor

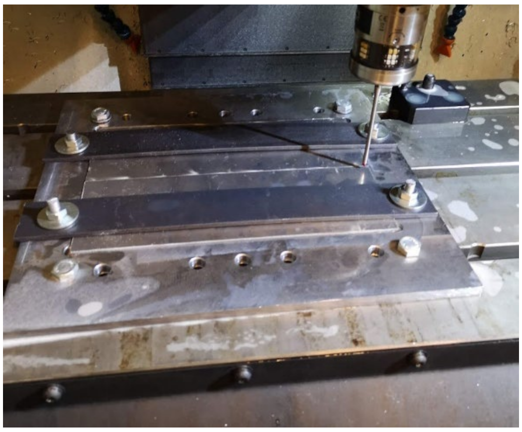
3.2.3 *Machining the Backing Plate*

The plate was cut out using a cutting torch and an automatic sawing machine was used to straighten the edges. The plate was then clamped to the milling machine worktable and the surface was flatten on both sides by face milling as seen in Figure 3-9 a) and b). Next phase in the process was end milling of a pocket feature making a square which the aluminium plates could fit into and the edges of this feature to function as guides that would hold the plates in place against lateral movement. A small curvature was detected on the surface of the pocket feature in the range of +/- 0,05 mm due to inaccuracy because the old machine used for milling. The below figure c) shows the finished backing plate with slots for thermoelement and holes to fit a clamping system onto the plate and fasten the plate to the worktable by T-slots nuts. In figure d) is the first clamping setup tested as described in the next chapter.

a) *12 mm plate fixed at worktable*

b) *Face milling of backing plate*





c) *Backing plate used for welding*

d) *First clamping system*

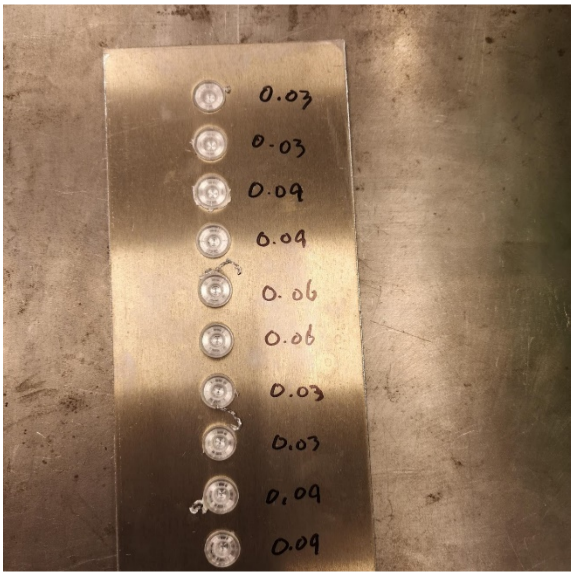
Figure 3-10 Machining the backing plate a-d)

3.2.4 *First Test Weld*

To test if the Mazak machine could perform friction welding some test welds where done using plates with aluminium 6082 alloy of 3 mm thickness. The first weld was with a tool designed for plates of 2 mm thickness; this was to avoid the tooltip touching the backing plate. Parameters used was 1500 rpm, 45 mm/min and 0.15 mm shoulder depth. The first test weld can be seen in Figure 3-10. Several welds were produced, and these first test welds had very good result using rotation of 1300-1500 rpm, travel speed of 30-45 mm/min and 0.05-0.15 mm shoulder depth. From a macroscopic point of view no defects except small areas of excessive flash. The backside of the plate seemed to have a solid weld but as figure b) shows there is a possible lack of penetration. In below figure c) testing of shoulder depths to find an appropriate shoulder depth.

a) Result after using 2 mm tool

b) Backside of weld



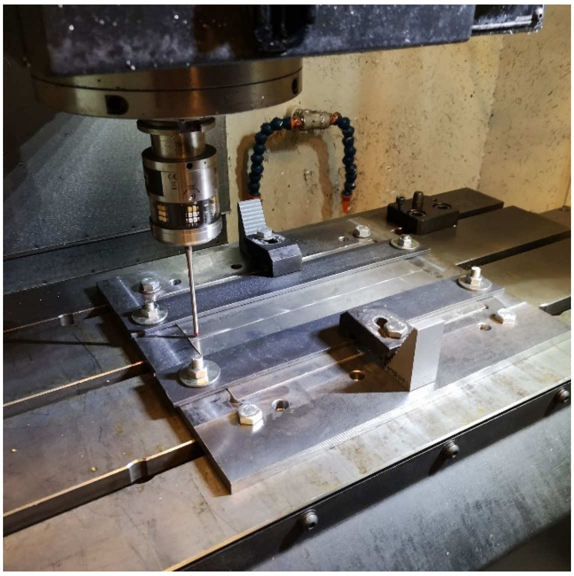
c) Backside after Tensile Testing

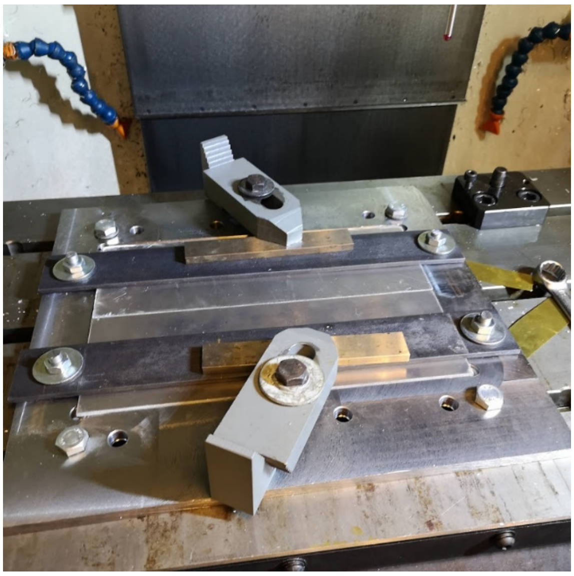
Figure 3-11 First test runs a-c)

3.2.5 *Test Runs Welding of AA5754*

After the successful test welds described above, the parameters and other experiences was adapted to try with the plate of AA5754 alloy having 2 mm thickness. This time using the correct tool for buttweld of two plates having dimension of 300 x150 mm. The tool bought from Stirweld can be seen in earlier shown Figure 3-1. The tool had a 1.8 mm pin length and 8.5 mm diameter shoulder. Several test welds where produced using parameters in the following range; rotational speed 1000-2000 rpm, travel speed 15-100 mm/min, dwell time 2-6 seconds and shoulder depths of 0-0.15 mm. Weld defects such as wormhole, excessive flash and lack of filling was found at almost every test weld but these defect was in different regions of the test weld making it hard to decide the impact each parameter had on the process. It seemed like a thermal expansion did occur when the heat input increased as the welding process went forward. After some test welds and adjusting the cold and hot welding parameters trying to deal with the defects it became clear something else was the source to the defects as they didn't disappear or improve as supposed by changing the parameters. A small groove like edge was found at the backside of most and there was also lack of surface filling when this error occurred. Simultaneously during this process of finding proper parameters to use for our experiment developing of the welding jig and clamping system took place. The process how the clamping system was developed is described below.

The first attempt to make a clamping system were made using a flat bar of 4x60x500 mm carbon steel as seen in below Figure 3-11 a) and b). First step was to use a measuring probe to get the plates mounted as evenly as possible in the horizontal direction. The main reason to align the plates using this method is because of the lack of force control during welding. Without any position or force control the tool would travel in a straight line over the plates without any concern to the height differences or thermal expansion when temperature is increasing during welding. The difference in measured height over the weld line was adjusted by changing the force distribution adding more torque over the clamping system bolts. With this method the tool travel path experienced a height difference from one side to the other, to be around +/- 0,15 mm for the worst case. This setup didn't work well, and weld defects were found on every test run. Defects such as surface breaking wormholes, excessive flash and improper stirring could be seen and adjusting parameters to counter for these defects weren't successful. The backside seemed to have full penetration but a small edge along the weld joint could be seen.





a) *First clamping system using step clamps*

b) *Testing different step clamps and force distribution*

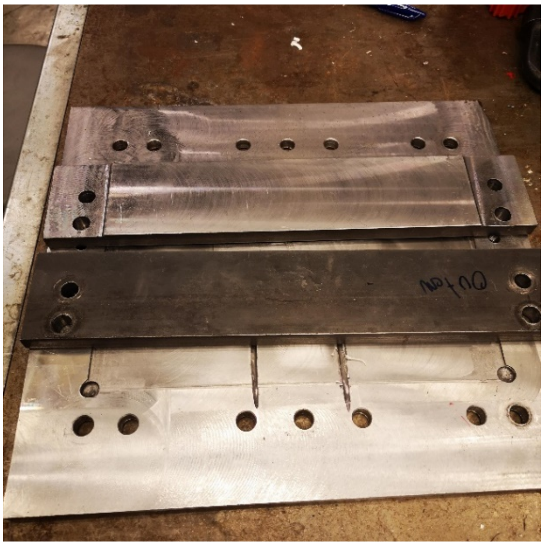
Figure 3-12 First clamping system a-b)

The next step in further developing the clamping system was to add more stiffness to the clamps using thicker steel bars. This was intended to get better control over the differences found when measuring the height at the weld travel line due to more uniform downforce distribution. A plate with a uniform thickness of 20 mm was cut into desired dimensions using a bandsaw and further machined using a milling machine to get a flat surface. The Parts can be seen in Figure 3-12 a). There was little improvement when using only step clamps as seen in figure b). The height difference was still unacceptable.

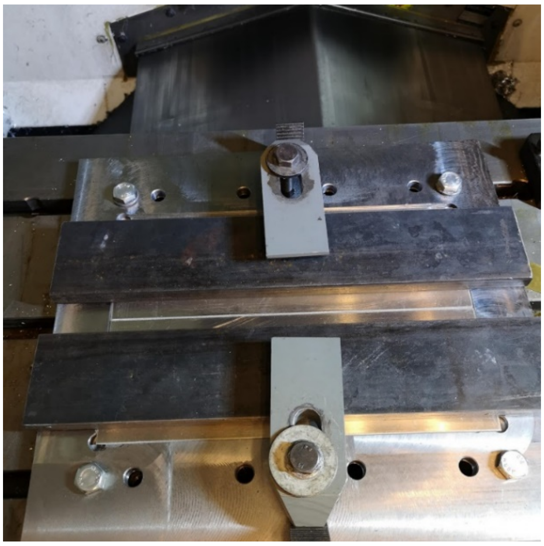
Next improvement was to drill holes at both ends to fasten the clamping to the backing plate using bolts and nuts in addition to the step clamps in the middle. Additional holes were drilled on the backing plate as well and threaded. Several setups using step clamps in different position was done to see if the welding process did improve but as the workshop at the university had limited set of these step clamps, it was difficult to make an even force distribution during clamping.

A measuring probe was used to find the curvature and adjustment was done by adding more force to the clamping by tightening the bolts with a torque wrench to get an even force distribution. The goal was to make the surface align to the tool shoulder when traveling. The measured height difference was between +/- 0.1 mm. Still the wormhole defect was detected and irregular surfaces defects and when adjusting the welding parameters welds didn't improve and it seemed randomly when a weld had areas without defects.

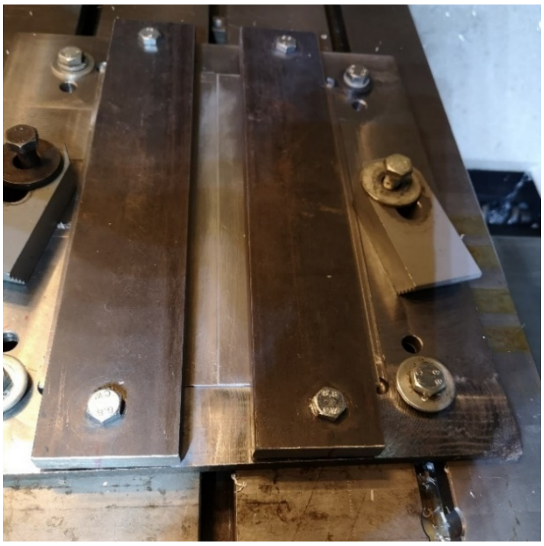
In figure c) below, a test run using bolts at both ends trying to get uniform clamping pressure, but still the measured height differences were not acceptable in the +/- 0.1 mm range. It seemed like the curvature found over the welding path was impossible to adjust by clamping force and force distribution, so the next step was to use a milling tool to flatten the surface to avoid any curvature. After some test welds it was clear that defects were still present and something else was affecting the welding process leading to defects. Excessive flash seemed to increase with the welding length and at the end of the weld. For some of the welds, the tool shoulder seems to have plunged deeper into the aluminium sheets.



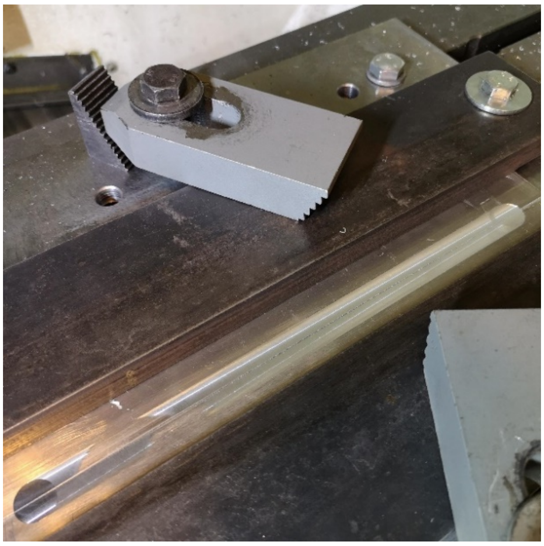
a) Second set of clamping



b) Setup using step clamps



c) Bolted ends



d) Flatten surface before welding

Figure 3-13 Second Attempt of Clamping a-d)

At this point it was difficult to understand if wrong welding parameters was the reason for the defects or if there were problems with the clamping and thermal expansion that lead to defects. A new strategy was now tested adjusting the tool shoulder height every 70 mm to counter for the thermal expansion. This gave some improvement but still defects such as excessive flash, lack of surface filling mostly at the advancing side and a small edge along the backside of the weld could be seen at some locations. After failing making the plates align in the horizontal direction a new strategy was tested. This time the measuring probe were used, and the height was measured for every 20 mm along the joint line. The values were then plotted into a excel script which calculated points for the tool to follow so the tool shoulder had a constant depth along the plate's curvature. Shoulder depths in the range of 0-0.15 mm was tested. Some parts of the welded joint were sound in the beginning and then defects start to arise as the heat or weld developed. Combination of parameters and clamping was tested without finding a clear connection or possibility to draw a conclusion. It seemed like it wasn't possible to do friction welding with the range of parameters and fixture. A last attempt was done without the step clamps holding down the steel bars in the middle. The steel bars were only looked in both ends using the bolt and nuts. The welding speed was increased to 100 mm/min. The result were defects such as surface lack of filling, excessive flash and a large edge along the backside weld. This can be seen in Figure 3-13.This was an eureka moment for this project after struggling for a long time not finding a proper setup giving sound welds. The edge defect origin appeared to be along the tool pin edge at the advancing side. It seems like the plate is pulled upwards during the welding session due to the extensive temperature and force generated. When the temperature is at a maximum and the tool spin are trailing along the weld line the easiest way for the energy created is to pull the plate up along the heat affected zone where the tool pin has softened the material.

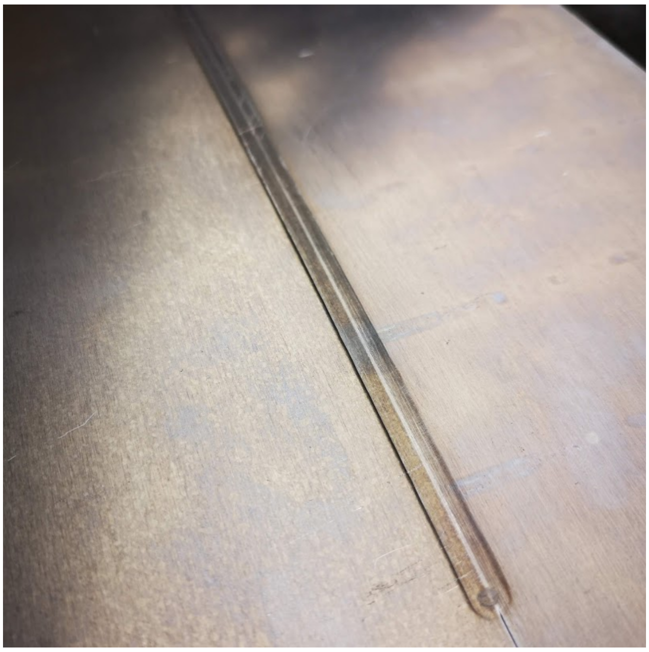


Figure 3-14 Defect found at the backside

In Figure 3-14 below is the lack of filling defect found at the surface due to the poor welding jig and clamping system used.

Figure 3-15 Defect at the frontside

3.3 Experimental for the Robust Design Approach

3.3.1 *Planning of experiment*

The parameter design starts with selections of the orthogonal array with selecting number of levels for each of the process parameter, Equation 3-1gives the minimum of trials in an orthogonal array (Gaitonde and Karnik, 2012).

Equation 3-1 Minimum Number of Experiment Equation

$$N_{min} = (L - 1)k + 1$$

L= number of levels => 3; k= number of parameters => 4; N_{min} =9

This will give us a L_9 orthogonally array according to Taguchi quality design concept (Phadke, 1989). Orthogonally array is mutually orthogonal and for every pair of columns the factor levels will appear an equal set of times. This can be arranged in a table and if we look at factor A and B in their respectively columns there are nine set of combinations if they only appears one time each (1,1),(1,2),(1,3),(2,1),(2,2),(2,3),(3,1),(3,2) and (3,3). Same can be done for factor C and D and every pair of columns. Table 3-3 shows the setup for a L_9 experiment.

Table 3-3 L_9 *orthogonal Array Setup for Process Parameters*

Experiment	**Levels of process parameters**			
	A	B	C	D
1	1	1	1	1
2	1	2	2	2
3	1	3	3	3
4	2	1	2	3
5	2	2	3	1
6	2	3	1	2
7	3	1	3	2
8	3	2	1	3
9	3	3	2	1

Four factors that can be controlled is chosen based on the fishbone diagram, parameter study and email correspondence with Stirweld. Rotational speed, welding speed (feed rate), dwell time and shoulder depth. The levels are chosen based on the suggestions form Stirweld and experience gained during testing and building the welding jig. There were limited plates available of the

6082 alloy to perform test welds to check the interval for factors and their levels. Based on the test weld used to solve the clamping issues the interwall was chosen as seen in Table 3-4.

Table 3-4 Factors and Their Levels

Factors	Levels			Units
	1	2	3	
Rotational Speed	1200	1400	1600	[rpm]
Travel Speed	100	150	200	[mm/min]
Dwell time	2	4	6	[sec]
Shoulder Depth	0.07	0.09	0.11	[mm]

In Table 3-5 is the L_9 orthogonal Array Setup with factors and their respectively levels.

Table 3-5 Experiment, Factors and Levels

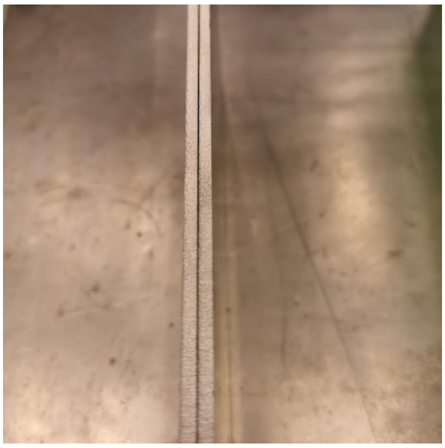
Experiment Number	A Rotation [Rpm]	B Travel Speed [mm/min]	C Dwell Time [sec]	D Shoulder Depth [mm]
1	1200	100	2	0.07
2	1200	150	4	0.09
3	1200	200	6	0.11
4	1400	100	4	0.11
5	1400	150	6	0.07
6	1400	200	2	0.09
7	1600	100	6	0.09
8	1600	150	2	0.11
9	1600	200	4	0.07

3.4 *Welding Procedure*

Before each weld experiment in the robust design approach a setup procedure was performed for the plates and insertion to the welding jig. This to increase the repeatability and accuracy for each weld experiment and reduce the noise to the process.

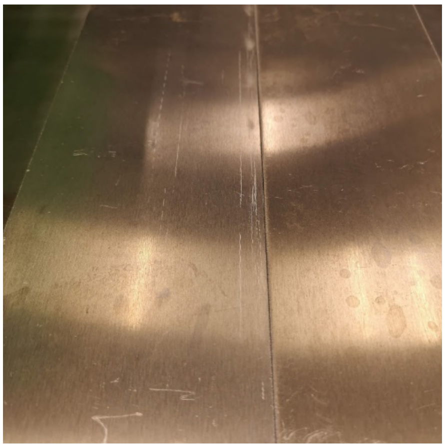
3.4.1 *Preparation of the plates*

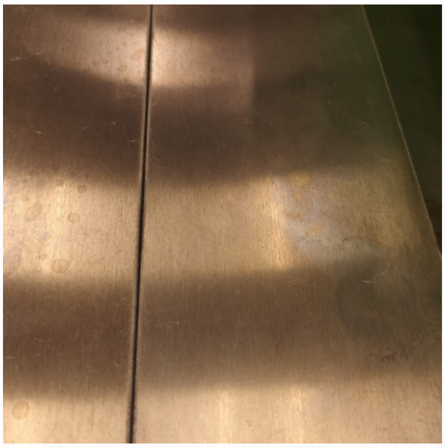
The welding material was cut from a plate of AA6082-T6 alloy with the dimension of 2000x1000x3mm. Smed.T.Kristiansen performed the water-jet cutting and even if this is a very accurate method making approximately the same pattern of 150x300x3 mm, small edge irregularities and inclined edges as seen in Figure 3-15 made the need for grinding before welding. Figure 3-15 d) showing the gap between plates and therefore the weld was done having the inclined angle facing each other as seen in Figure 3-15 e). Grinding of the oxide layer were done before each weld as seen in Figure 3-15 f). Red spirit on a cloth was used to remove grease and dirt at the surface.



a) Unprepared after cutting

b) Grinded edge before welding





c) Butt-Butt backside unprepared

d) Butt-Butt front unprepared, small gap

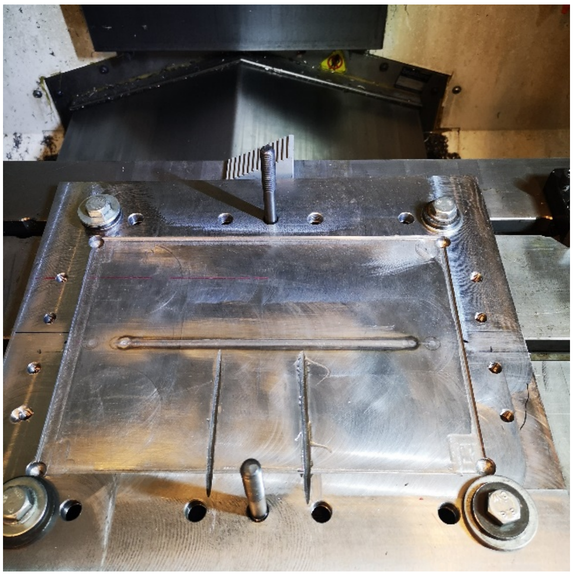
e) Alignment of plate during welding

f) Grinding of oxide layer

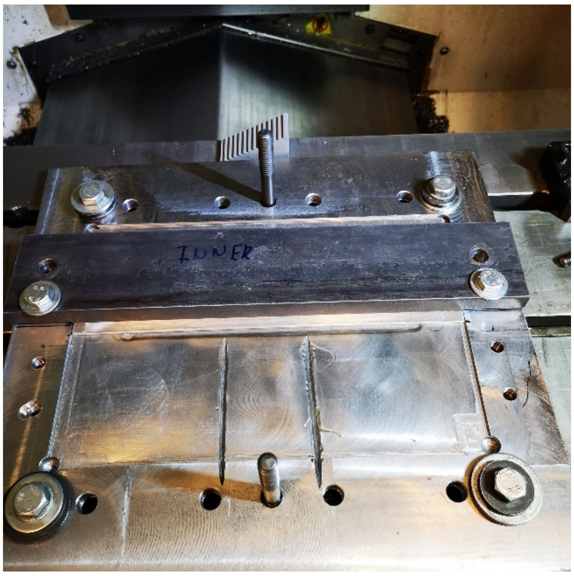
Figure 3-16 Pictures showing Preparation of welds a-f)

3.4.2 *Alignment of Plates in the Welding Jig*

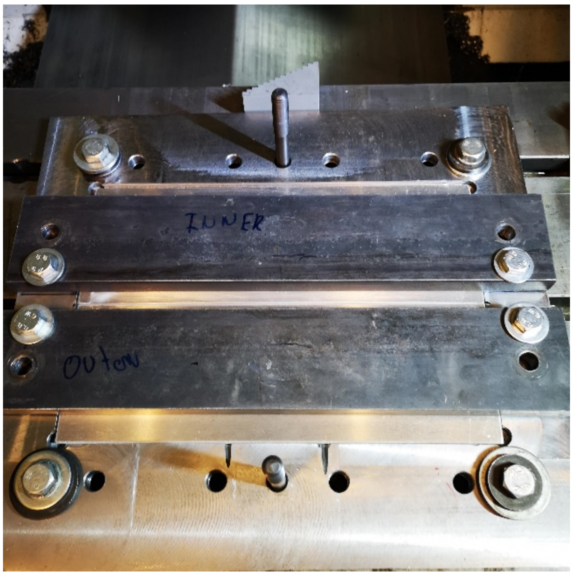
The workpiece setup in the final welding jig was performed in the same manner to ensure repeatability for each weld and less noise to the experiments. Below in Figure 3-16 is the steps used for every weld experiment. The welding jig was mounted to the worktable using bolts and with aligned using the measuring probe. This was to get the inner square where the plate is put to be as parallel as possible to the x-axis. After the jig was secured both aluminium plates were inserted into the jig and pushed against the edge. As this edge was aligned with the x-axis every plate got position at the same location using this solution. Next step was to secure one of the plates with the steel bar used for clamping as seen in figure b). Now the one plate was secured, and the weld line was aligned in parallel with the x-axis. As seen in figure c), the second plate was put into the jig and pushed against the other plate as the bolt was tightened. Finally, the step clamps and washer were placed an tighten to get a more even force distribution



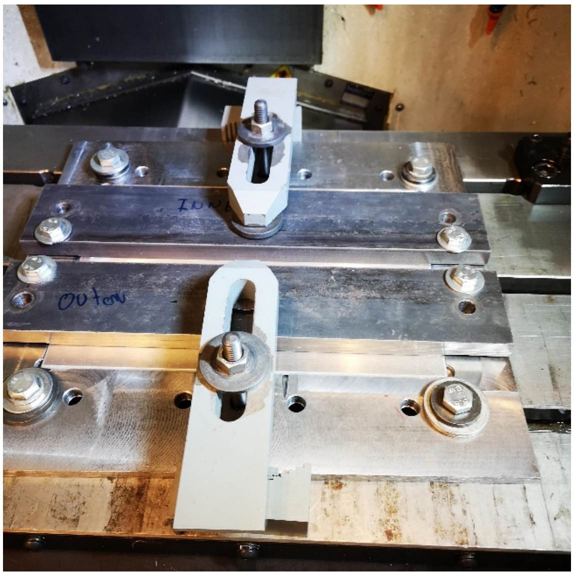
a) Alignment of the welding jig



b) Alignment against the x-axis



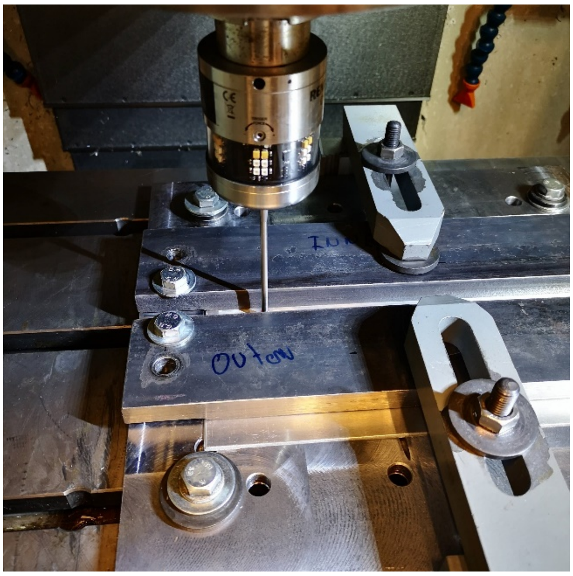
c) Clamping of the second plate

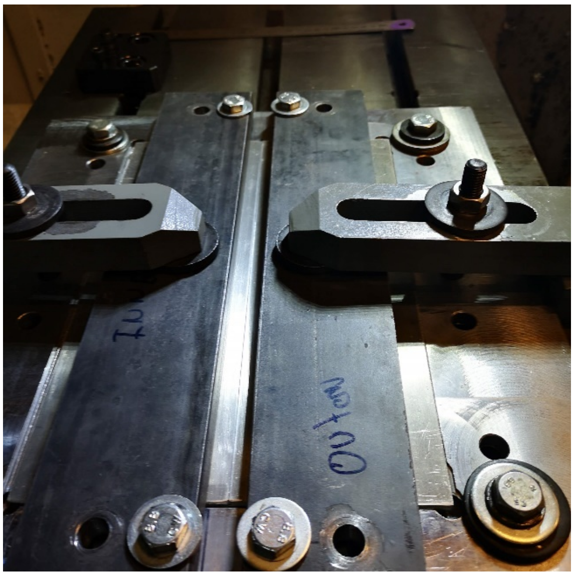


d) Step clamps to improve force distribution

Figure 3-17 Positioning of the Plates in the Welding Jig a-d)

After this sequence was performed the ready to be welded plates had no gaps between the faying sides. The measuring probe was used to measure the curvature of the weld line for every 20 mm as seen in Figure 3-17. The height difference across the plates weld line was interpolated using an excel worksheet which calculated the shoulder depth needed to follow the curvature more precise.





a) Measuring of the curvature

b) Ready to be welded plates

Figure 3-18 Finding the Curvature a-b)

3.4.3 *G-Code Program Used for Welding*

The welding session was performed using a small program with G-codes. Below in Table 3-6 is the final program used for the experiments with a short description of each code.

Table 3-6 G-codes Used to Perform Welds

Line	**Code**	**Description**
N01	G21 G90	Programming in mm / Absolute programming
N02	T14 M06	Select tool #14 / Tool change
N03	M03 F150 S1200	Spindle CW / Feed rate in mm/min. / Spindle speed in rpm.
N04	G17	X-Y Plane
N05	G0 X45 Y180.3 Z120	Rapid positioning / Linear motion to coordinates X/Y/Z

N06	X85	Linear motion in X direction
N07	Z5	Linear motion in Z direction
N08	G01 Z-2.91	Linear interpolation using feed speed
N09	G04 P2000	Dwell time in where P is the time given in milliseconds
N10	X105 Z-2.9211	Start of the welding session where Z-2.9211 is the interpolated value used to control the shoulder depth
N11-N19	The interpolated coordinates	Shoulder depth is changed for every 20 mm to follow the plates curvature using linear interpolation
N20	X305 Z-3.0466	End point of the weld
N21	G4 P2000	Dwell time for the endpoint at 2 seconds hold time
Z3	G0 Z300	Rapid positioning / move to Z300 away from the weld
End		

3.5 Material Test Specimen Preparation

The welded plates were sent to a local company named Sveiseservice AS for waterjet cutting of tensile test specimens. The cut-out pieces were kept using for microscopic viewing and Vickers hardness test. The tensile specimens were numbered with experiment number 1-9, OPT and prefix I-IV. The cut-out pieces were marked with experiment number and I-III as shown in Figure 3-18 The pieces at the start of weld and end of weld were scrapped. The main reason for an external supplier to cut the specimens was due to vacation time at the University making the Mazak machine unavailable for a period of two weeks. Second reason was the distortion and curvature found in some of the plates making the assembling and clamping to the worktable more challenging which could lead to poor dimensions for the specimens.

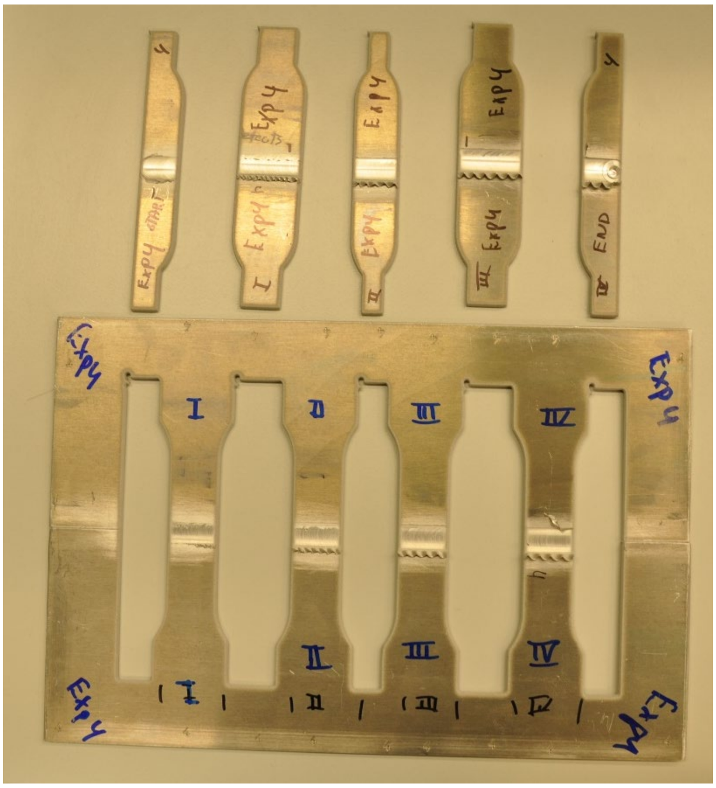
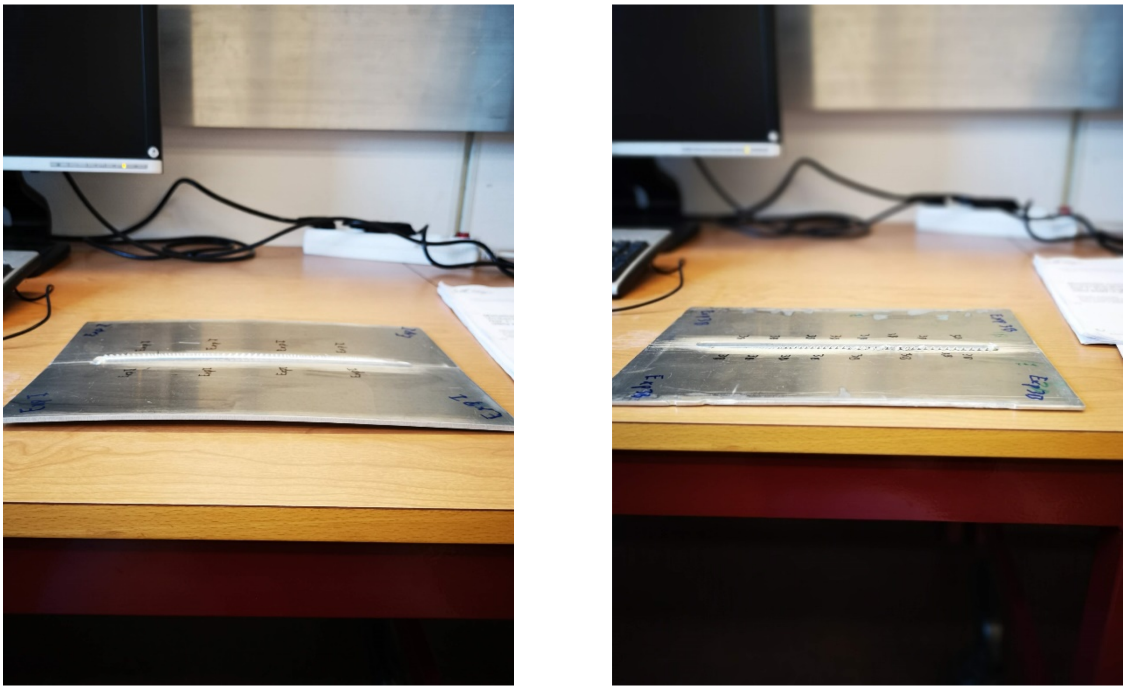


Figure 3-19 Marking of the Specimens

The shape that were most common was a saddle formed distortion with curvature in longitude direction and concave bending as seen in Figure 3-19 a). Some of the experiments did have low distortion as seen to the right figure below. After cutting the curvature and distortion almost disappeared from the specimens. The reason seems to be residual stress relief, but this is not confirmed, and the experiment continues without a deeper understanding of this phenomena experienced as every specimen have been exposed to the same treatment.



a) Curvature from Exp 1

b) Curvature seen from Exp 3B

Figure 3-20 Distortion After Welding a-b)

3.5.1 *Waterjet Cutting and Preparation of Specimens for Testing*

The tensile specimens were designed to have a width of the parallel length around 25 mm and the shoulder were designed to have a width of 37 mm, as described in ISO4136 (International Organization for Standardization, 2012). The waterjet did cut approximately 0.5 mm into each side of the specimens. This made the samples narrower than the design shown in the Figure 3-20. New measurements showed them to be around 24 mm and 35 mm respectively.

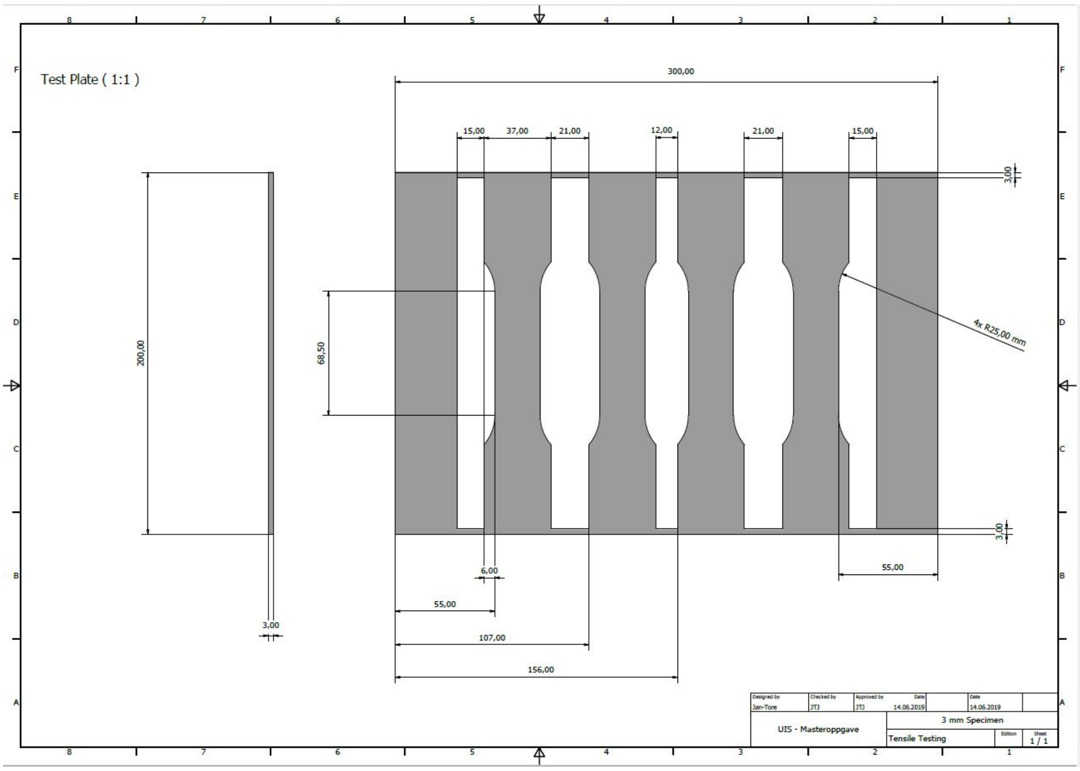
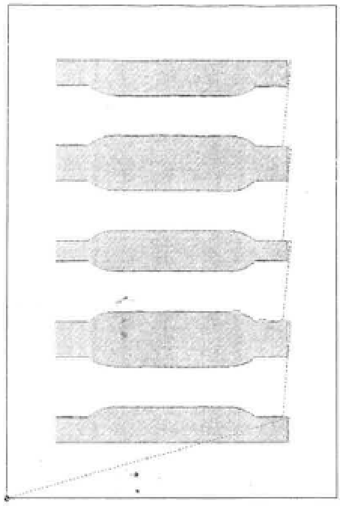


Figure 3-21 Drawings of tensile specimens

The test specimens were cut using a Kimtech-Bosch waterjet in accordance to the job report and DAK drawing seen in Figure 3-21.

JOB Report
20.06.2019



Files

CNC file	Z:\7449.NPG	Date	20.06.2019	Time	13.33
Drawing	Z:\20196645 UIS Masteroppgave.dig				

Material

Material	Aluminium/Standard	Thickness	3.000 mm
Name			
Size X	0.0 mm	Size Y	0.0 mm

Machine

Machine	KIMTECH-BOSCH	Pressure	3800 bar	Orifice diameter	0.330 (13)
Abrasive quality	GMA Garnet 80 (0.92)	Nozzle diameter	1.016 (40)	Abrasive flow	400.0 g/min

Length

Rapid length	1369.2 mm	Marking length	0.0 mm	**Cutting length**	1596.2 mm

Speeds

Max	1555.5 mm/min	Min	1032.2 mm/min		

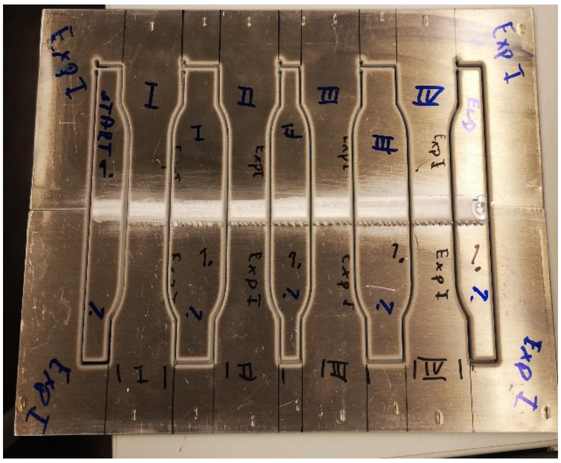
Tool setup

Time

Rapid time	00:00:22	Piercing time	00:00:10
Marking time	00:00:00	Various	00:00:00
Cutting time	00:01:07	**Total time**	**00:01:40**

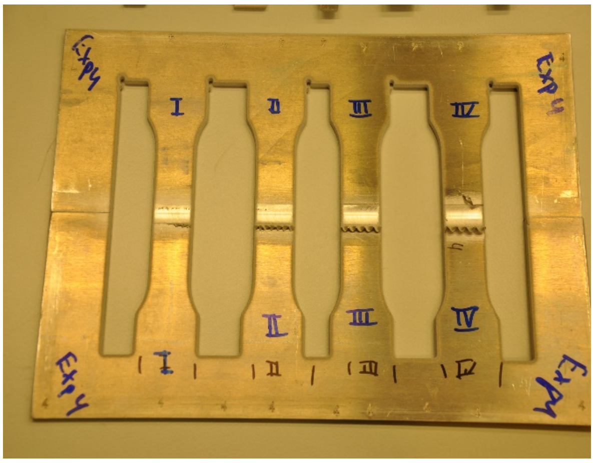
Figure 3-22 Job Report from SveiseService AS

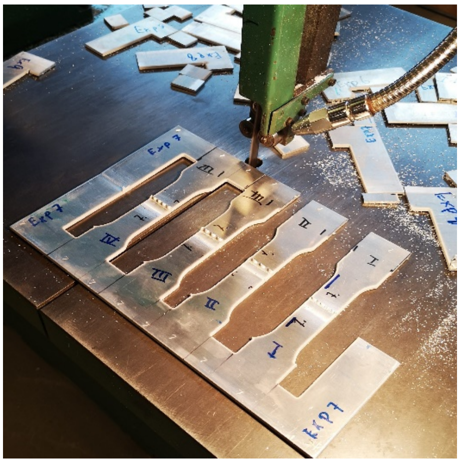
The plate after cutting can be seen in Figure 3-22 b) and because the machine needed to secure the thin plate against forces and movement during cutting the design were changed so clamping could be done at the shoulder part of the samples as seen in Figure 3-22 a). Furthermore, the samples needed to be separated from the frame and for this purpose a bandsaw were used so no heat input should affect the samples as seen in Figure 3-22 d). The specimens were separated and because of the waterjet cutter using small particles, a coarse edge is left on every sample as seen in Figure 3-22 e). The parts between each tensile specimen as seen in Figure 3-22 f) are used for Vickers hardness testing and microscopic viewing described later in this chapter.



a) Waterjet cutting in progress

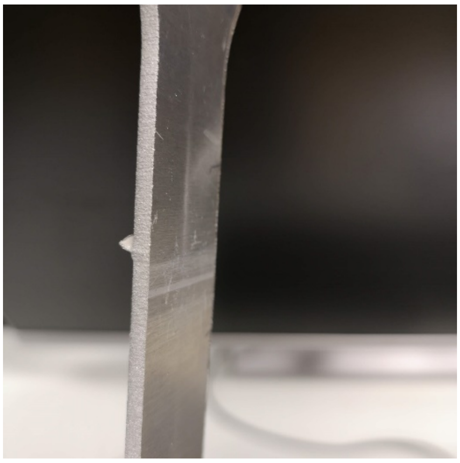
b) Waterjet cut plate





c) Tensile specimens

d) Bandsaw cutting



e) Coarse edges after water cutting

f) Pieces to use for other types of tests

Figure 3-23 Waterjet Cutting and Test Specimens a-f)

After receiving the specimens back from the cut job, a small program was made using the Mazak CNC milling centre to machine away the rough edge. A fixed jig was used to hold the specimens at the same location using a measuring probe to get identical specimens. This can be seen in Figure 3-23.

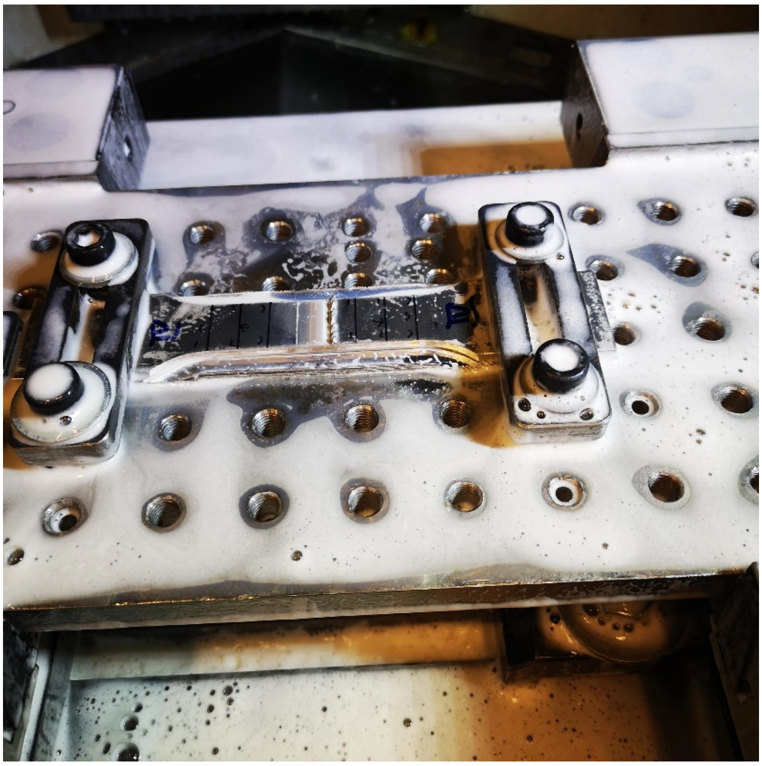


Figure 3-24 Machining of the edges

Marking of the original gauge length as seen in Figure 3-24.

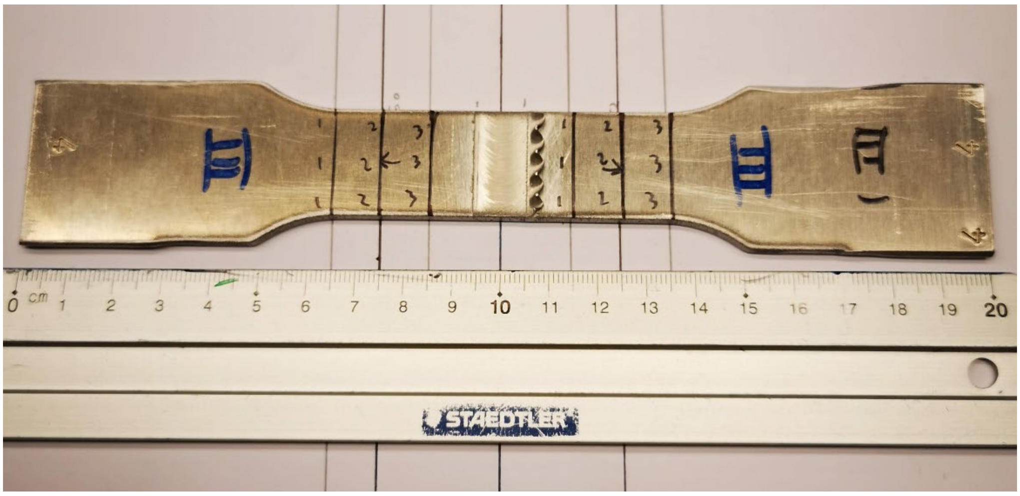


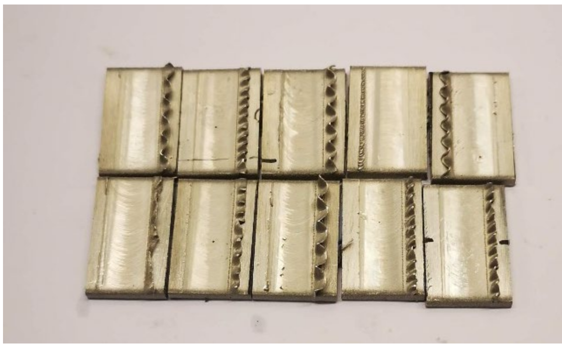
Figure 3-25 Marking of the original gauge length

The finished tensile specimen with approximately 21 mm parallel width as seen in Figure 3-25.

Figure 3-26 Finished Tensile Specimen

3.5.2 *Microstructure Specimens Preparation*

The piece marked with III was taken from between tensile specimen III and IV for every experiment and prepared for microstructure viewing as seen in Figure 3-26 a). The specimen was cut into two pieces and from each piece a 20mm sample was cut out using a Struers laboratory abrasive saw with coolant. The sample was placed into a Struers Citopress-30 to encase the samples into mounting resin using Multifast, Condufast and Clarofast. The Struers Citopress-30 can be seen in Figure 3-26 b). A Product data sheet for all resins can be seen in the Appendix. During the hot compressive mounting, there was a problem with the samples standing 90 degrees perpendicular to the surface using the Struers Citopress-30, two of the trials can be seen in Figure 3-26 c and d). Several attempts to solve this issue was conducted such as using different types of support, using electrical type to hold the samples aligned, one, two, three samples at the time and so on but nothing worked to our satisfaction. After discussion with the workshop crew a solution was proposed of drilling a hole through each sample and connect the samples using a bolt, washers and nuts. Every samples were tightened, and an aluminium piece was fastened as well in between the samples to be sure it would be conductive during later etching. The samples were now encased in homemade moulds using laminating epoxy bought from a local vendor named Biltema. The final solution can be seen in Figure 3-26 e and f). The threaded bolt with specimens fastens with nuts and washer between every sample and the mould used for epoxy.

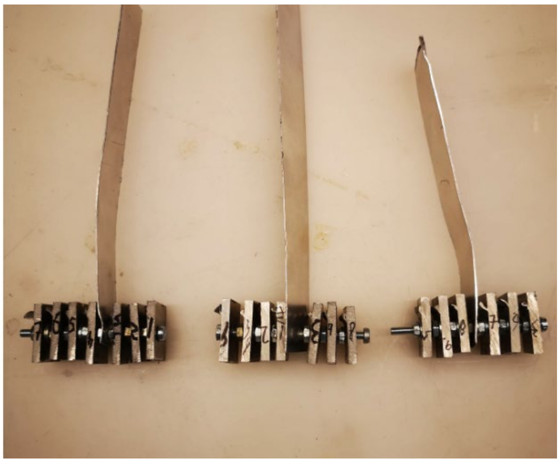


a) Samples made with abrasive saw

b) Struers CitoPress-30

c) Inclined sample with one support

d) Using two supports



e) Samples drilled and fasten with a bolt

f) Inside the mould ready for epoxy

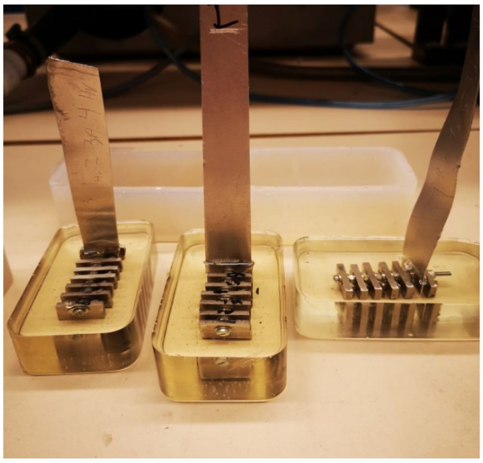
Figure 3-27 Preparation of Microstructure Specimens Part 1 a-f)

The samples were marked with experiment number and as the cut-out piece was cut in two smaller pieces, there was a total of twenty specimens distributed in three bolts named I-III. Distribution and usage of specimens can be seen in Table 3-7. For the bolt marked I, sample 1-7 is used for microstructure viewing. For bolt number II sample 8-9 are used for microstructure viewing. This is highlighted using bold writing. The specimens marked with red number and italic font is spare samples. For the last bolt marked III the second sample number 8 is used for Vickers hardness testing. ALU in the table is where the conducting aluminium bar is placed at each bolted structure used to perform the anodization.

Table 3-7 Samples for Microstructure Testing

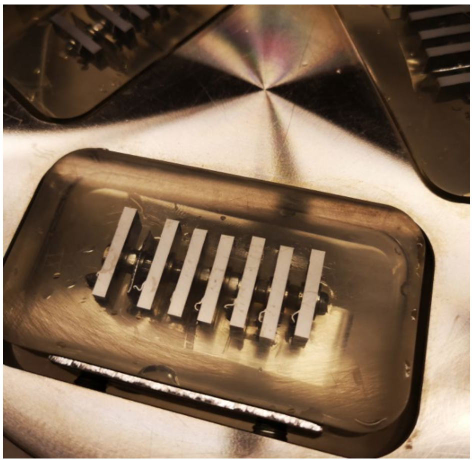
Bolt number	**Specimens for microstructure and Vickers**							
I	***1***	***2***	***3A***	***4***	***5***	***6***	ALU	***7***
II	***8***	***9***	*3*	*1*	*2*	*3A*	ALU	*4*
III	*9*	*8HV*	*7*	*6*	*5*	ALU	*3*	EMPTY

The epoxy was poured over the samples in three separate moulds and left to harden overnight. The result can be seen in Figure 3-27 a). The samples were secured into the sample holder with an accuracy to ensure that every specimen would be grinded equal and perpendicular to the surface. Three pieces of aluminium with a uniform thickness of 2 mm were used to adjust the sample holder and the moulded epoxy as seen in Figure 3-27 b). After the epoxy sample holders was adjusted for all three position, a thin steel bar with approximately dimension 2x15x60 mm was used to make the two bolts push against it for a uniform force distribution to ensure the epoxy parts to be in same position during grinding. This can be seen in Figure 3-27 c). The complete mounted sample holder ready for grinding and polishing can be seen in Figure 3-27 d). In Figure 3-27 e) is the Struers TigraForce-5 grinding/polishing machine used for the sample preparation. In the last Figure 3-27 f), a ready setup for Vickers hardness testing is shown.



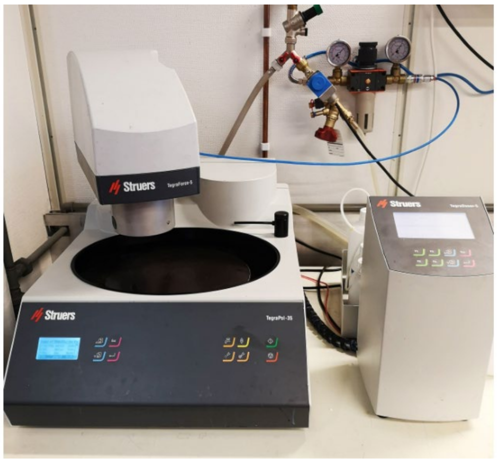
a) Embedded specimens in epoxy

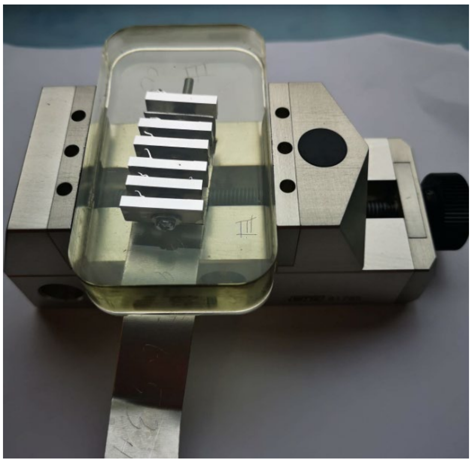
b) Samples mounted



c) A steel plate to distribute force

d) Ready to be grinded and polished





e) Struers TegraForce-5

f) Polished sample ready for Vickers

Figure 3-28Preparation of Microstructure Specimens Part 2 a-f)

3.5.3 *Mechanical Preparation of Microscopic Specimens*

In Table 3-7 is the procedure for grinding and polishing that was used to make the specimens for microscopic examination and Vickers hardness test. The samples are washed with a spray soap to resolve the grease and oil from the samples. Before and after each step in the grinding procedure below, a cleaning sequence was conducted using tap water and ethanol (CH_3CH_2OH). This to ensure that all excess particles, embedded grains and other kind of contamination's are removed before the next step in the procedure is performed. Hot dry air is used to blow away ethanol. The Struers TigraForce-5 is cleaned properly in between every step to make sure no particles are added from the machine itself. Barker's etchant solution is used as described in ISO/TR16060 (International Organization for Standardization, 2003, pp. 24–25). 940 ml water (H_2O) and 60 ml fluoroboric acid (HBF_4) is inserted with the Struers LectroPol-5 unit as seen in Figure 3-28 a). For some steps below additional grinding and polishing were done when needed.

Table 3-8 Grinding and Polishing

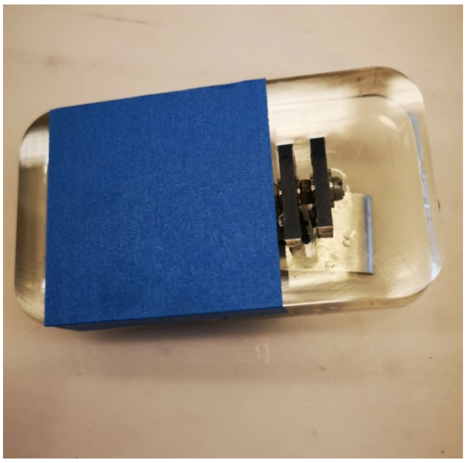
Surface	**Suspension**	**Lubricant**	**Process Time**	**Force**	**Disc Rotation Speed**	**Sample Holder Direction**
SIC-Paper #320	-	Water	1m1os	20N	300 rpm	CCW
SIC-Paper #500	-	Water	1m00s	25N	300 rpm	CCW
SIC-Paper #4000	-	Water	2m00s	20N	300 rpm	CCW
MD-MOL 9µm	DiaPro All/Lar Level 4/1	*DP-Lubricant	5m00s	25N	150 rpm	CCW
MD-MOL 3 µm	DiaPro Dac Level 3/2	*DP-Lubricant	10m00s	25N	150 rpm	CCW

MD-MOL 1 µm	DiaPro Nap-B Level 3/2	*DP-Lubricant	10m00s	25N	150 rpm	CCW

*DP-Lubricant used only when needed.

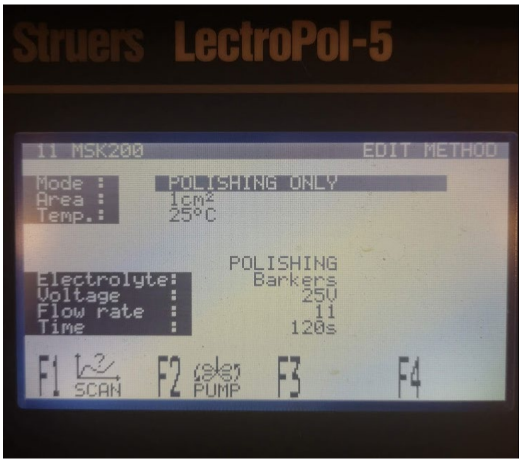
The Lectropol could only take two specimens at once because the largest mask available at the laboratory was the 5 cm^2 one. To protect the rest of the specimen's during the process a painters' tape with easy removal was used to cover up the items not being anodized as seen in Figure 3-28 b). This was possible only for the un-anodized surfaces because when using the tape to cover already anodized surfaces the clue stuck onto the surfaces and was impossible to remove without regrinding from the start of the procedure mentioned in above table. Solution to this was to do the process without the mask for all specimens at once as the picture are showing in Figure 3-28 c). Initial values can be seen in Figure 3-28 d), area was set to 1 cm^2, temperature to 25° Celsius, voltage 25 volt, flow rate 11 and time set to 120 seconds. As seen in Figure 3-28 the specimens have good conductivity even with this method used.

a) Inserting the Barker's solution

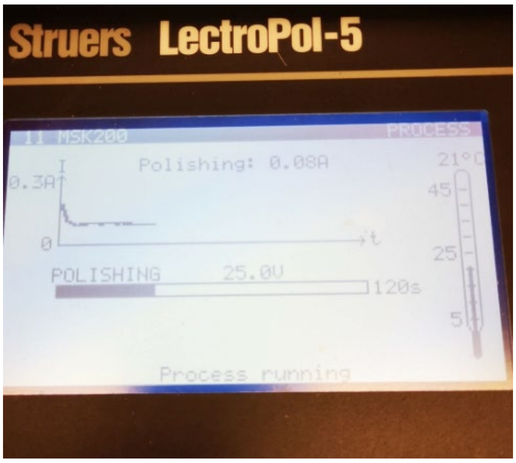


b) Covering of specimens

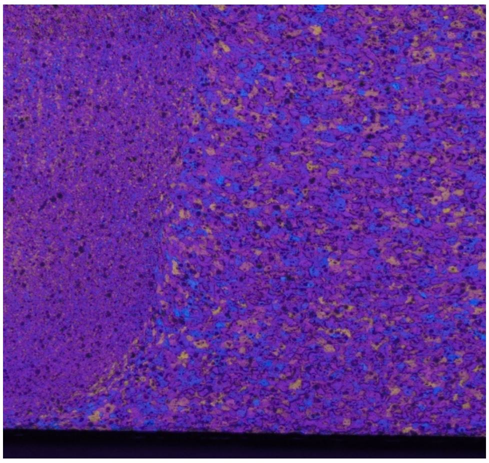
c) Anodizing of specimens



d) Initial values used for anodizing



e) Parameters during the process



f) Microstructure from experiment 5

Figure 3-29 Anodizing of Specimens a-f)

3.5.4 *Microscopy LOM*

For each experiment the microstructure was examined, and picture mapped using an Olympus GX53 Inverted system metallurgical light optical microscope Sn:7G50075 as seen in Figure 3-29. The microscope is delivered with a BX3M-CB/FM control box and several filters including a gout analyser U-GAN, polarizer slider GX-PO. The microscope has 2,5-100x lenses.

The microstructure picture was made using the Olympus Stream Essentials Software. The results can be seen in Chapter 4.2

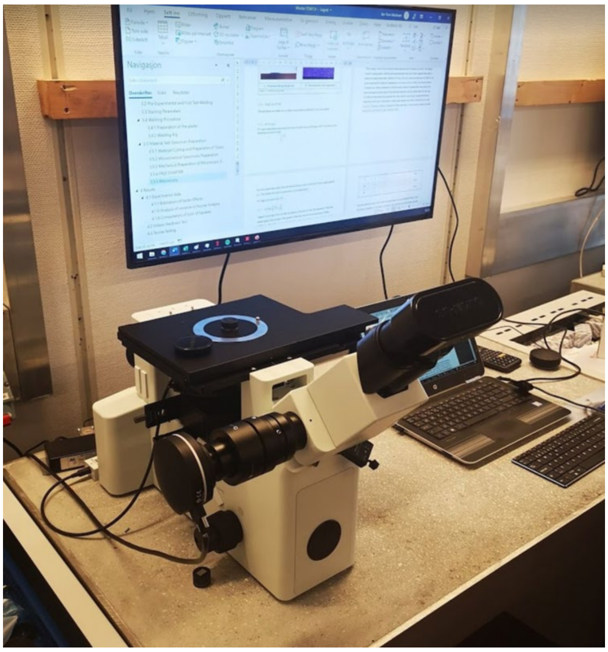


Figure 3-30 Olympus Light Optical Microscope

3.5.5 *Bending Test*

A 3-point bending test is performed using a 20 kN Zwick Roell Z020 tensile machine as seen in the below Figure 3-30. Test speed used was 20 mm/min and pre-load 0.1 MPa. A flexure test found in Zwick software following standard DIN-EN-ISO 178 was used for this test. The speed was set at a higher value as only the ductility was of interest performing this test.

Figure 3-31 Zwick Roell Tensile Machine

4 Results

4.1 Experimental Data

This chapter is dived into four parts. First part is the robust design approach and how the results are obtained using orthogonal arrays with the ANOVA and variance analysis. Second part is the material testing section with microstructure for all experiments. The Optimum weld has been subjected to extended testing using x-ray, Vickers and bending test as well to confirm the state of the weld. Result from the tensile strength testing is found in the last part.

4.1.1 *Matrix Experiment*

Tagushi Robust Design Approach (RDA) is used to find the parameters for the friction welding control factors giving the best quality characteristics. For this experiment the best quality characteristics are defined as ultimate tensile strength.

Three samples were cut out from each experiment and tensile strength was tested. The optimal would be making three welds for each experiment and made use of three samples from each to make an average mean value to find the S/N ratio. This isn't practical as the time and effort to set up the experiment for each set of parameters is to excessive. Ross (1988) wrote about selection of sample size, where a minimum of one test result is needed to maintain the orthogonality for each experiment but more tests will increase the sensitivity and Ross further describes the case for different experiments showing that one to four samples sizes can give enough information depending on the type of experiment. Adding higher sample sizes doesn't add much more to the sensitivity. Expensive testing or impractical testing can make us choose smaller sample sizes and this must be considered for each case (Ross, 1988).

For each experiment values from the tensile testing is used to find the S/N ratio using Equation 4-1. This defines the signal to noise ratio, η_j, for experiment *i:*

Equation 4-1 Signal to noise ratio S/N

$$\eta_j = -10\log_{10}\left[\frac{1}{n}\sum_{i=1}^{n}\frac{1}{X_{ji}^2}\right]$$

Signal to noise ratio S/N is for the calculations of the ratio for the j-th experiment. Where the mean square is the average of the squares of the nine observation in experiment (Phadke,1989).

We refer to the η_j calculated using above formula as the observed η_j . We use this average value as the observed η_j, for the nine experiments as shown in Table 4-1.

Table 4-1 S/N Ratios and Matrix Setup

Experiment number	Column Number and Factor Assigned				Observation η (dB)
	1 Rotation A	**2 Travel Speed B**	**3 Dwell Time C**	**4 Shoulder Depth D**	
1	1	1	1	1	44.96
2	1	2	2	2	46.67
3A	1	3	3	3	46.69
4	2	1	2	3	44.28
5	2	2	3	1	46.79
6	2	3	1	2	45.24
7	3	1	3	2	38.30
8	3	2	1	3	46.69
9	3	3	2	1	45.83

From the observed values of η from the nine experiments we can calculate the effects of the four factors. Equation 4-2 gives the overall mean value of η from each experiment using the process parameters in Table 4-2. The three levels and factors are equally balanced in all nine experiments and m is a balanced overall mean over the experimental region (Phadke, 1989, p. 45).

Equation 4-2 Overall Mean Value

$$m = \frac{1}{9}\sum_{i=1}^{9}\eta_i = \frac{1}{9}\left(\eta_1 + \eta_2 + \cdots + \eta_9\right)$$

Summing the observed η to find the overall mean to be **45.05 (dB).** Results from tensile strength testing and calculations can be seen in below table.

Table 4-2 Process Parameters, Results from Tensile Testing and Calculations

	Process Parameters for Experiments				**Tensile Test Results from Experiments**			**Calculations**		
Exp No	**A**	**B**	**C**	**D**	**I**	**III**	**IV**	**Mean**	**S/N Ratio (dB)**	**Overall Mean (dB)**
1	1200	100	2	0.07	145.8	192.1	215.5	184.5	44.96	45.05
2	1200	150	4	0.09	208.6	219.9	218.7	215.7	46.67	45.05
3A	1200	200	6	0.11	214.4	219.1	214.3	215.9	46.69	45.05
4	1400	100	4	0.11	132.6	173.9	212.8	173.1	44.28	45.05
5	1400	150	6	0.07	219.8	218.1	217.7	218.5	46.79	45.05
6	1400	200	2	0.09	147.6	212.4	214.5	191.5	45.24	45.05
7	1600	100	6	0.09	104.4	55.1	212.7	124.1	38.30	45.05
8	1600	150	2	0.11	218.5	213.5	216.4	216.1	46.69	45.05
9	1600	200	4	0.07	165.3	221.1	216.3	200.9	45.83	45.05

4.1.2 *Estimation of Factor Effects*

The effect of a factor is defined as the deviation it causes from the overall mean (Phadke, 1989, p. 45). Using equation 4-3, the average S/N ratio can be calculated for each factor and their correspondingly levels.

Equation 4-3 The Average S/N ratio

$$m_{A_2} = \frac{1}{3}\left(\eta_4 + \eta_5 + \eta_6\right)$$

For factor A_2 it can be seen from Table 4-3 that for level 2 we need the average data from experiment $\eta_4 + \eta_5 + \eta_6$ and for the level 3 the experiments data from $\eta_7 + \eta_8 + \eta_9$ is used. Same can be done for factor two and level 2 will have the average values from experiment $\eta_2 + \eta_5 + \eta_8$. For factor two at level 3 the average from experiment $\eta_3 + \eta_6 + \eta_9$ is needed. This is done for every factors and levels Table 4-3 show how the average is calculated for each factor and their level. The effect of rotation at level A_2 is thus given by $(m_{A_2} - m)$.

Table 4-3 Effect of a Factor Level

Factor and levels	**Average from experiment**
A_1	$\eta_1 + \eta_2 + \eta_3$
A_2	$\eta_4 + \eta_5 + \eta_6$
A_3	$\eta_7 + \eta_8 + \eta_9$
B_1	$\eta_1 + \eta_4 + \eta_7$
B_2	$\eta_2 + \eta_5 + \eta_8$
B_3	$\eta_3 + \eta_6 + \eta_9$
C_1	$\eta_1 + \eta_6 + \eta_8$
C_2	$\eta_2 + \eta_4 + \eta_9$
C_3	$\eta_3 + \eta_5 + \eta_7$
D_1	$\eta_1 + \eta_5 + \eta_9$
D_2	$\eta_2 + \eta_6 + \eta_7$
D_3	$\eta_3 + \eta_4 + \eta_8$

Because the balancing properties from the orthogonally array, every factor and levels have equal contributions of averages. After the numerical values from tensile testing was entered in Table 4-2, the average S/N ratios was calculated for all factors at their levels as seen in Table 4-4.

Table 4-4 Average S/N Ratios at Their Levels

Factor	Process Parameters	LEVEL		
		1	**2**	**3**
A	**Rotation**	46.106	45.436	43.606
B	**Welding Speed**	42.513	46.718	45.917
C	**Dwell Time**	45.632	45.592	43.925
D	**Shoulder Depth**	45.860	43.403	45.885

A plot was made to visualize the effect from each factor as seen in Figure 4-1. This is known as the *main effects* and Phadke is referring to this as an *analysis of mean(ANOM)* (Phadke, 1989, p. 46).

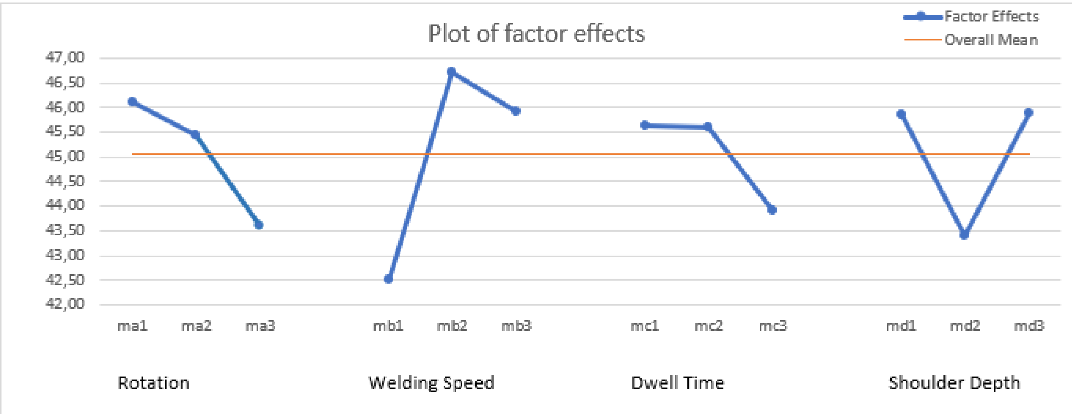


Figure 4-1 Plot of Factor Effects

The effect from rotation give the highest η for the lowest rotation at 1200 rpm, further increasing the rotation for this setup gave less tensile strength. For the traverse welding speed levels, the best effect on the process was given by 150 mm/min as seen above for factor b2. The welding speed had decreasing effect on both lower and higher values by a very poor result for the lower welding speed at 100 mm/min. Dwell time showed approximately same values for 2 and 4 seconds but decreasing for the 6 seconds level. Shoulder depth had some strange result showing both 0.07 mm and 0.11 mm contributing to greater tensile strength while 0.09 mm doesn't.

4.1.3 *Finding the optimum level*

One of the point by doing a matrix experiment is to optimize the product or process (Phadke, 1989, p. 48). For the FSW project the goal is to find the optimal process parameters from the estimated main effects. The highest value of η for each factor in the given range of parameters are found. As seen in below Table 4-5. The optimum factors are made bold and as we can see from below table- factors and levels A1, B2, C1 and D3 having the highest value of η.

Table 4-5 Finding the Optimum Factors

Factor	Level			Overall Mean	Optimum Level
	1	2	3		
A- Rotation	**46.106**	45.436	43.606	45.05	$\mathbf{A_1}$
B- Welding Speed	42.513	**46.718**	45.917	45.05	$\mathbf{B_2}$
C- Dwell Time	**45.632**	45.592	43.925	45.05	$\mathbf{C_1}$
D- Shoulder Depth	45.860	43.403	**45.885**	45.05	$\mathbf{D_3}$

From the parameter table this is equivalent to using these parameters for the optimum weld: 1200 rpm rotation, 150 mm/min welding speed, 2 seconds dwell time and 0.11 mm shoulder depth. This set of parameters can't be found in the matrix setup as described in Table 4-1 but a similar experiment setup can be found in experiment 8 where only factor A "rotation" and its level are dissimilar. Experiment 8 is using 1600 rpm for rotational speed, and the predicted optimal experiment only 1200 rpm. Welding speed for both was 150 mm/min, dwell time 2 seconds and shoulder depth 0.11 mm. The observed η for experiment 8 was 46.693. This was the second highest value for the overall experimental region with experiment 5 as the highest at 46.790 dB. Experiment 2 and 3 was close to the observed values found in experiment 5 and 8 with an observed η found to be 46.671 dB for experiment 2 and 46,685 dB for experiment 3. These values are almost identical in terms of the average mean values for tensile testing, Table 4-2 shows that the range for these 4 experiment described above are all between 215.73 MPa to 218,53 MPa, and as little as 0,2 MPa in difference for the mean values of experiment 2-3 and experiment 3-8. The optimum observed S/N ratio η was found to be 46,875 dB which is below the predicted η at 47,775 dB. The ANVOA showed that the variance was quite high with two standard deviation confidence limits for this predicted error to be ± 5.681 dB. In terms of the model used this is successful as long the value is in between the predicted value and its confidence interval. The optimum experiment did also give the highest observed value among all experiments. The optimum experiment did have the highest tensile strength found to be 222.7 MPa for tensile specimen Spec-OPT-I. Spec-OPT-III was measured to be 220.1 MPa and the Spec-OPT-IV specimen 219.3 MPA. These results gave an overall mean at 220.7 MPa. From the effect factors table another combination that would give high predicted tensile strength is A1, B2, C2 and D1. This combination of parameters is neither found in the matrix setup but experiment 2 have almost same setup except the shoulder depth.

Table 4-6 Result from The Optimum Parameters

Optimum Parameters from Experiments				**Result from Verification Experiment**			**Calculations**		
A_1	**B_2**	**C_1**	**D_3**	**I**	**III**	**IV**	**Average Mean**	**S/N Ratio dB**	**η Predicted**
1200	100	2	0.07	222.7	220.1	219.3	220.70	46.875	47.775

4.1.4 *The Additive Model and its Factors*

From before the factor effects was found by simple averaging of the nine η observations and then the effects were calculated separately to find the optimum parameter combinations. The validation of the experiment is related to the additive model as an approximation and the use of the orthogonal array to setup the experiment. *The relationship between η and the process parameter A, B, C and D can be quite complicated. Empirical determination of this relationship can, therefore, turn out to be quite expensive* (Phadke, 1989, p. 48). This relationship can be approximated by the following additive model shown in equation 4-4.

Equation 4-4 Additive Model

$$\eta(A_i, B_i, C_i, D_i) = \mu + a_i + b_j + c_k + d_l + e$$

Where μ is the overall mean value of η from experiments and the deviation from the mean value caused by factor A at level A_i is a_i and the b, c and d terms on right side is for similar deviations from the overall mean caused by the B, C and D factor on left side of equation. The error term e is by definitions from Phadke; *Note that by error we imply the error of the additive approximation plus the error in the repeatability of measuring η for a given experiment*. From engineering literature the additive model can be seen as a superposition model where the total effect from several factors is equal to the sum of the individual factor effects (Phadke, 1989, p. 48), further by definitions a_1, a_2 and a_3 are the deviations from μ caused by the three levels of factor A as seen in Equation 4-5.

Equation 4-5 Three Levels of Factors

$$a_1 + a_2 + a_3 = 0$$

The same can be done for deviations from μ caused by the levels of factor B, C and D.

Phadke mentions that when using the orthogonal array to plan the experiment it can be shown that the averaging procedure from earlier is the same as fitting the additive model and the least square method. Example below shows how to calculate the effect for the factor A at level 2 using equation 4-3. The experiment 4, 5 and 6 from Table 4-3 is used here and similar calculations can be done for every factor at their levels fitting the additive model.

Equation 4-6 Effects Drop Out

$$mA_2 = \frac{1}{3}(\eta_4 + \eta_5 + \eta_6)$$

$$= \frac{1}{3}[(\mu + a_2 + b_1 + c_2 + d_3 + e_4) + (\mu + a_2 + b_2 + c_3 + d_1 + e_5) + (\mu + a_2 + b_3 + c_1 + d_2 + e_6)]$$

$$= \frac{1}{3}(3\mu + 3a_2) + \frac{1}{3}(b_1 + b_2 + b_3) + \frac{1}{3}(c_1 + c_2 + c_3) + \frac{1}{3}(d_1 + d_2 + d_3)$$
$$+ \frac{1}{3}(e_4 + e_5 + e_6) = (\mu + a_2) + \frac{1}{3}(e_4 + e_5 + e_6)$$

From Equation 4-4 the effect from factor B, C and Drop out and mA_2 is calculated from $\mu + A_2$ with error variance $\frac{1}{3}\sigma_e^2$. For this to be valid every experiment need to be done to preserve the balancing property and the orthogonality (Phadke, 1989, p. 50).

4.1.5 *Analysis of variance vs Fourier Analysis*

From Table 4-5 we can see how the factors will affect the process by the average η. To get a better understanding for the relative effect each factor, a decomposition of variance was done. Phadke referring to the analysis of variance (ANOVA) as a tool for estimating the error variance for the factor effects and variance of the prediction error. Furthermore, Phadke make an analogy of the ANOVA with a Fourier analysis of an electrical signal where the relative importance of the different harmonics can be judged by the power of the signal (Phadke, 1989, p. 51). From Table 4-7, a comparison is made to see the analogy of decomposition of an electrical signal into different harmonics. The greater the power of the signal is from the harmonic's amplitude, the more important the harmonic is to describe the signal.

Table 4-7 ANOVA vs Decomposition of Electrical Signal

ANOVA	Electrical Signal
The nine observed values of η	Observed signal
The sum of squared values of η	Power of the signal
The overall mean η	The dc part of the signal
The four factors	Four harmonics

This is visualized using the orthogonal decomposition of the observed S/N ratio as can be seen in Figure 4-2 (Phadke, 1989, p. 52), where the Observed S/N ratio for each experiment is the sum of the overall mean plus the sum of the deviation from the overall mean for the factors represented in each experiment. The way this is linked to the Fourier analysis of the power of a signal is the experiments is along the x- axis like time, the overall mean is a straight line as a dc component and each factor from Table 4-4 is arranged as a harmonic. Using the matrix setup in Table 4-1 to see that the level of a factor is related to the position for the experiments described in the matrix setup. The level of factor B_1 is found in experiment 1,4 and 7 and therefore the values from the average S/N given in the table above at the value 42.513 is used for B_1. Similar can be done for the level factor B_2 here we can see from the matrix setup that experiment 2,5 and 8 has the value 46.718 as found in Table 4-5.

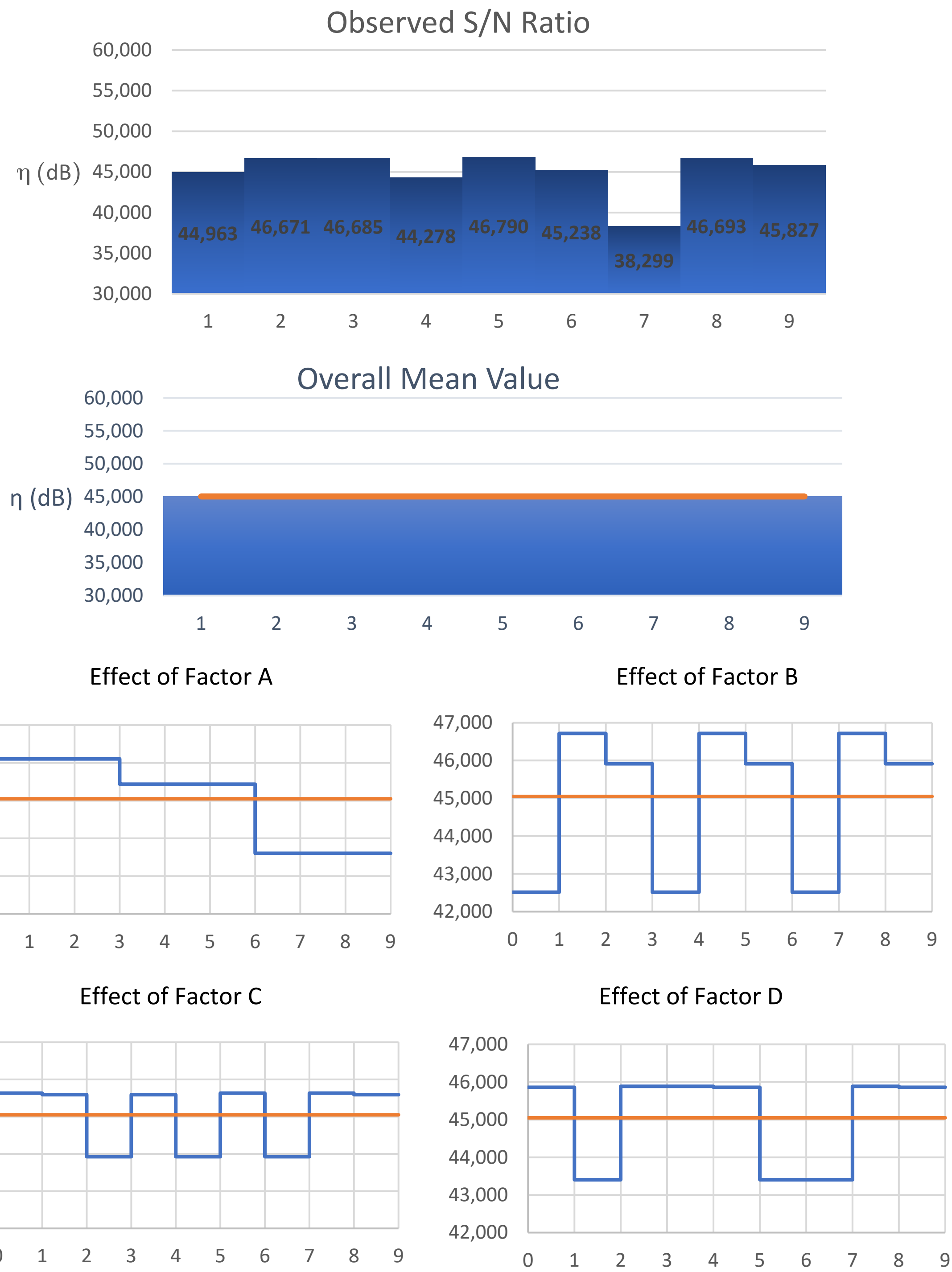


Figure 4-2 Orthogonal Decomposition of the Observed S/N Ratio

4.1.6 *Computation of Sum of Squares*

The total signal power in Fourier analysis is comparable to the grand total sum of squares given in Equation 4-7 (Phadke, 1989, p. 53).

Equation 4-7 Grand total sum of squares

$$Grand\ total\ sum\ of\ squares = \sum_{i=1}^{9} \eta_i^2$$

The squared values of the nine η is calculated to be **18322.89 (dB)^2.**

The grand total sum of squares consists of two parts, Equation 4-8 the sum of squares due to mean and Equation 4-9 total sum of squares (Phadke, 1989, p. 53).

Equation 4-8 The Sum of Squares due to Mean

$$Sum\ of\ squares\ due\ to\ mean = (number\ of\ experiments) * m^2$$

The sum of squares due to mean is calculated to be **18264,71 (dB)^2.**

Equation 4-9 Total Sum of Squares

$$Total\ sum\ of\ squares = \sum_{i=1}^{9} (\eta_i - m)^2$$

The total sum of squares is calculated to be **57,85 (dB)^2.**

Phadke is comparing this with the Fourier analysis which describing the sum of squares due to mean as the dc power signal found in the Fourier analysis, and the total sum of squares as the ac power signal. The ac power is equal to the difference between total power and the dc power of the signal as seen in Equation 4-10 (Phadke, 1989, p. 54).

Equation 4-10 Total Sum of Squares as the Analogues to Fourier Analysis

Total sum of squares = (grand total sum of squares)- (sum of squares due to mean)

Calculating using above equation - 18322.89 (dB)^2-18264,71 (dB)^2=**57,85 (dB)^2.**

Equation 4-11 (Phadke, 1989, p. 54) sum of squares due to factor A, is calculated by using the overall mean and how the three levels for factor A is deviating from the mean. This is then squared to get the sum of squares due to factor A. The same is done for factor B, C, and D at their respectively levels. Result from the below calculations can be seen in Table 4-8. This is analogues to the power in various harmonics, and a measure of the relative importance of the factors in changing the values of η (Phadke, 1989, p. 54).

Equation 4-11 Sum of Squares due to Factor A

$$Sum\ of\ Squares\ due\ to\ Factor\ A = 3(m_{A_1} - m)^2 + 3(m_{A_2} - m)^2 + 3(m_{A_3} - m)^2$$

Variation in η for a factor is found by dividing the sum of squares for a factor by the total sum of squares as seen in Equation 4-12. The values for the variation given in percent is given in the Table 4-8 further below.

Equation 4-12 Variation in η for a Factor

$$\frac{Sum\ of\ Squares\ due\ to\ a\ Factor}{Total\ Sum\ of\ Squares} x100$$

Estimation of the error terms by the additive model gives no information as the number of experiment is equal to the number of parameters in the model minus the number of constraint defined by the Equation 4-4 and Equation 4-5. Estimation for the pooled error sum of squares is added together using the two factors contributing to the lowest values for the sum of squares. Factor "A" and "C" added together gives a pooled error of **15.74 (dB)^2**. The pooled error consists of four parameters giving a total of 4 degree of freedom. By dividing the error term by the degrees of freedom the mean square error term is found to be **3.94 (dB)^2**. Same is done for each factor to find the mean square for a factor using 2 degree of freedom for each factor.

The F-ratio below can be calculated using the mean square for a factor and divide by the pooled error mean square. Results is presented in below table.

Table 4-8 ANOVA Table for η

Factor	***Degree of freedom***	***Sum of Squares***	***Mean Square***	***F-Ratio***	***Variation in η for Factor %***
A - Rotation	*2*	*10.05*	*5.02*	*1.28*	*17.37*
B - Welding Speed	*2*	*29.90*	*14.95*	*3.80*	*51.70*
C - Dwell Time	*2*	*5.69*	*2.85*	*0.72*	*9.84*
D - Shoulder Depth	*2*	*12.20*	*6.10*	*1.55*	*21.09*
Error	*0*	*0*			
Total	*8*	*57.84*			*100*
Pooled Error	*4*	*15.74*	*3.94*		

The welding speed contributes to over 50% of the variation of η, the shoulder depth contributes to around 21 %, the rotation to around 17 % and the dwell time to approximately 10 % of the total variation.

As seen in Equation 4-13 (Phadke, 1989, p. 55), there exist a relationship between the various sums of square due to the orthogonality from matrix experiment. This is like the decomposition of the power of a signal into different harmonics.

Equation 4-13 Total sum of squares

$$Total\ sum\ of\ squares =$$

$$(sum\ of\ squares\ due\ to\ factors\ (A, B, C\ and\ D)\ ) + (sum\ of\ squares\ due\ to\ error)$$

4.1.7 *Degrees of Freedom*

A Degree of freedom in a statistical sense is associated with each piece of information that is estimated from the data (Ross, 1988, p. 28). For this purpose a degree of freedom is the number of independent parameters found in a matrix experiment, factor or sum of squares (Phadke, 1989, p. 56). From this matrix experiment we had nine rows of information which then give us nine degree of freedom, this is the true also for the grand total of squares found in Equation 4-7. From the data collected for all nine experiments we calculated the overall mean and the sum of squares due to a mean, they both having one degree of freedom. Recall Equation 4-9, total sum of squares is equal to the grand total of sum of squares minus the sums of square due to a mean. This give eight degree of freedoms.

Ross mentions a way to think of degree of freedoms is to have one degree for each independent comparison that can be made from your data. The four factors used in the matrix experiment and the three levels give one degree of freedom each as the effect of the three levels only add one piece of information, furthermore they must satisfy the constraint given by the Equation 4-5 where the three levels are equal zero, adding a piece of information. The total independent information given from the factors is two which give a total of eight degree of freedom for the four factors.

By using the degree of freedom found above we can find the mean square for a factor by dividing the sum of squares for each factor by its degree of freedom as seen in above Table 4-8.

4.1.8 *Estimation of Variance*

For this matrix experiment the error variance from the mean square due to error is zero as the degree of freedoms is used to gain as much information as possible for the welding parameters and process. There is no degree of freedoms left to calculate the error terms found in our additive model. An approximation is therefore used to gain information about the error variance. The pooling of the sum of squares is explained in above chapter 4.1.6.

Confidence interval for factor effects is calculated using the mean square value from the pooled error. The mean square pooled error is divided by three to give the variance of the effect from each factor as seen in Equation 4-14 (Phadke, 1989, p. 58).

Equation 4-14 Variance for factor effects

$$\left(\frac{1}{3}\right)\sigma_e^2 = \frac{1}{3}\,(3.94) = 1.31\ (\mathrm{dB})^2$$

Thus, the variance for the factor effects is **1.31 (dB)^2**. Calculating the two-standard deviation confidence interval for each factor effects using above number in Equation 4-15 (Phadke, 1989, p. 58)

Equation 4-15 Confidence interval for factor effects

$$\pm 2\sqrt{1.31} = \pm 2.29\ dB$$

The width of two standard deviation confidence interval is about the same as a 95 % confidence interval of **±2.29 dB** for each factor effects.

Phadke mentioned that using the F-ratio seen in Table 4-8 is for a qualitative understanding of the relative factor effects. Each mean square factor is divided by the error mean square and this will give information how the factor is influencing the process response η. The larger the F-ratio is, the larger the factor effect is compared to the error variance.

F-ratios less than one is smaller than the error form the additive model. Larger than two tells that the factor is not quite small. F-Ratios larger than four is quite large (Phadke, 1989, p. 58).

4.1.9 *Prediction and Variance for the Prediction Error*

In chapter 4.1.3 the Optimum parameters were found by using the additive model to find the highest values of η from each level. The factors and their levels which gave the highest value was; A_1, B_2, C_1, D_3. The two factor levels giving the highest values is now used to find the predicted value η_{opt}. Remember that the two factor effects having the lowest sum of squares was used for the pooled error terms earlier and when finding the optimum the smallest values isn't used. If the lowest values are used situations where the predicted value exceeds the improvement can occur, the prediction would bias on the higher side (Phadke, 1989, p. 59). In Equation 4-16 the overall mean is denoted by m. The values found from the additive model for factor and levels A_1 and B_2 is now used to predict η under optimum conditions.

Equation 4-16 Prediction of η under optimum conditions

$$\eta_{opt} = m + (m_{A_1} - m) + (m_{B_2} - m) = 45.05 + (46.106-45.05) + (46.718-45.05)$$

η_{opt} is calculated to be **47.77 dB.**

The value found from η_{opt} is now used in Equation 4-17 to finding the predicted ultimate tensile strength using the optimum values.

Equation 4-17 Finding the predicted UTS

$$\sqrt{y} = \sqrt{10^{\frac{\eta opt}{10}}} = \sqrt{10^{\frac{47.77}{10}}}$$

The predicted UTS is **244.62 MPa.**

The variance for the prediction error is calculated using Equation 4-19 below. This equation consists of two parts where the first is the error in prediction of η_{opt} from estimation of m, m_{B_2} and m_{A_1}. The other part is from the repetition error from an experiment. As both parts are independent we can sum their variances (Phadke, 1989, p. 61).

The equivalent sample size found below is calculated using n=9 for the number of rows used in this matrix experiment, $n_{A_1}= n_{B_2}$=3 is the number of times the factor level appeared in the matrix experiment.

Equation 4-18 Equivalent sample size

$$\frac{1}{n_0} = \frac{1}{n} + \left(\frac{1}{n_{A_1}} - \frac{1}{n}\right) + \left(\frac{1}{n_{B_2}} - \frac{1}{n}\right) = \frac{1}{9} + \left(\frac{1}{3} - \frac{1}{9}\right) + \left(\frac{1}{3} - \frac{1}{9}\right) = \frac{5}{9}$$

The equivalent sample size $1/n_0$ is **5/9.**

To find the variance of the prediction error, the error variance from Table 4-8 is used, denoted (σ_e^2) having the value of 3.94. The number of tests performed using optimum parameters is denoted n_r. The observed η_{opt} is then the average η from these tests. The number of tests for the verification experiment was $n_r = 3$.

Equation 4-19 Variance of the prediction error

$$\sigma_{pred}^2 = \left(\frac{1}{n_0}\right)\sigma_e^2 + \left(\frac{1}{n_r}\right)\sigma_e^2 = \left(\frac{5}{9}\right)3.94 + \left(\frac{1}{3}\right)3.94 = 3.50$$

Variance of the prediction error is **3.5 (dB)^2.**

The two-standard deviation confidence interval for the predicted error was calculated using Equation 4-20 below.

Equation 4-20 Two-standard deviation confidence interval

$$2 * SD = 2 * \sqrt{\sigma_{pred}^2} = 2 * \sqrt{3.50} = \pm 3.74$$

The 2*SD interval for the predicted error was $\pm\mathbf{3.74}$ **dB.**

All values found form estimation of variance is collected in below table. Excel sheets used for the Tagushi experiment can be found in Appendix.

Equation 4-21 Overview of values found

Type of value	Equation	Values
Variance for factor effects	Equation 4-14	1.31 $(dB)^2$
Two-Standard confidence interval for factor effects	Equation 4-15	$\pm$2.29 dB
Prediction of η under optimum conditions	Equation 4-16	47,77 $(dB)^2$
Finding the predicted UTS	Equation 4-17	244.62 MPa
Equivalent sample size	Equation 4-18	5/9
Variance of the prediction error	Equation 4-19	3.5 $(dB)^2$
Two-standard deviation confidence interval	Equation 4-20	$\pm$3.74 dB.

4.2 Microstructure and Picture of Welds and Test Specimens

This section is divided into ten sub chapters, one for each of the ten experiment. Each experiment is divided into sections, where the images of the microstructure, the weld and the tensile test are put together to more easily see how they are connected. The weld from experiment 3 is not a part of the experimental region and its replaced with weld EXP3A and for some of the testing this same experiment is also marked with 3B. Extended testing is done for the optimum experiment EXP-OPT.

The weld is buttwelded using aluminium plates with dimension of 300x150x3 mm. The distance from the edge to where the weld starting, and ending is 50 mm. The weld itself is 200 mm. The weld from experiment 1 to 9 can be seen in the below Figure 4-3.

The microscopic sample used is taken from the cut-out between tensile specimen III and IV and prepared as described in Chapter 3.5.3. This is repeated for all welds.

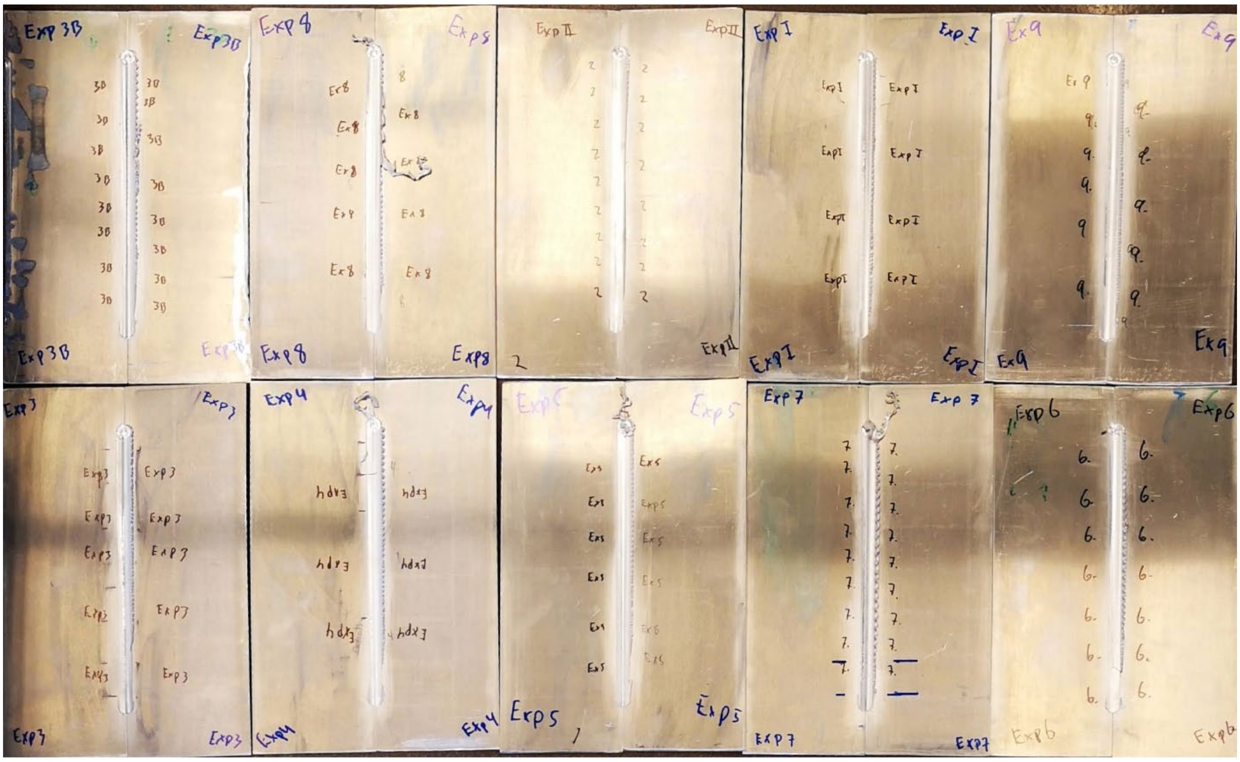


Figure 4-3 Finished FSW

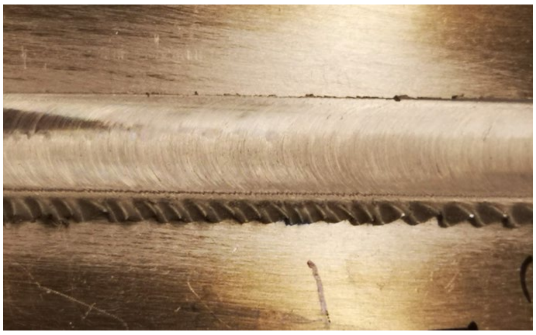
4.2.1 *Experiment 1*

Parameters used for welding of experiment 1 was 1200 rpm, 100 mm/min, 2 seconds dwell time and 0.07 mm shoulder depth relative to the measured curvature of the plate. The full length of the weld viewed from both sides can be seen in Figure 4-4 a) and b). The backside has no sign of macroscopic defects and seems to have complete penetration. The weld is aligned with the joint and the start/end point is in centre with the joint line as seen in below Figure b). There are some surface irregularities throughout the length of the weld with a close-up view in figure c) but this is not present in the last 50 mm of the weld. As seen in figure d) flash can be found on the retracting side.

a) Frontside of Experiment 1

b) Backside of Experiment 1

c) Irregular surface and excess flash RS.



d) Flash only at the last 50 mm

Figure 4-4 Picture of Weld from Exp1 a-d.

Microstructure for Experiment 1

The microstructure of the weld can be seen in Figure 4-5. The upper part is mapped using the 5x lens and the lower part is mapped using 10x lens. It can be seen from the image that an internal cavity defect like a wormhole is present in the lateral direction of the weld and some toe flash at the retracting side of the weld. Complete penetration from a micro/macroscopic point of view. The microstructure reveals the stir zone (SZ) with an onion ring like structure. The small grain can be seen from the dynamic recrystallization taken place in the stir zone.

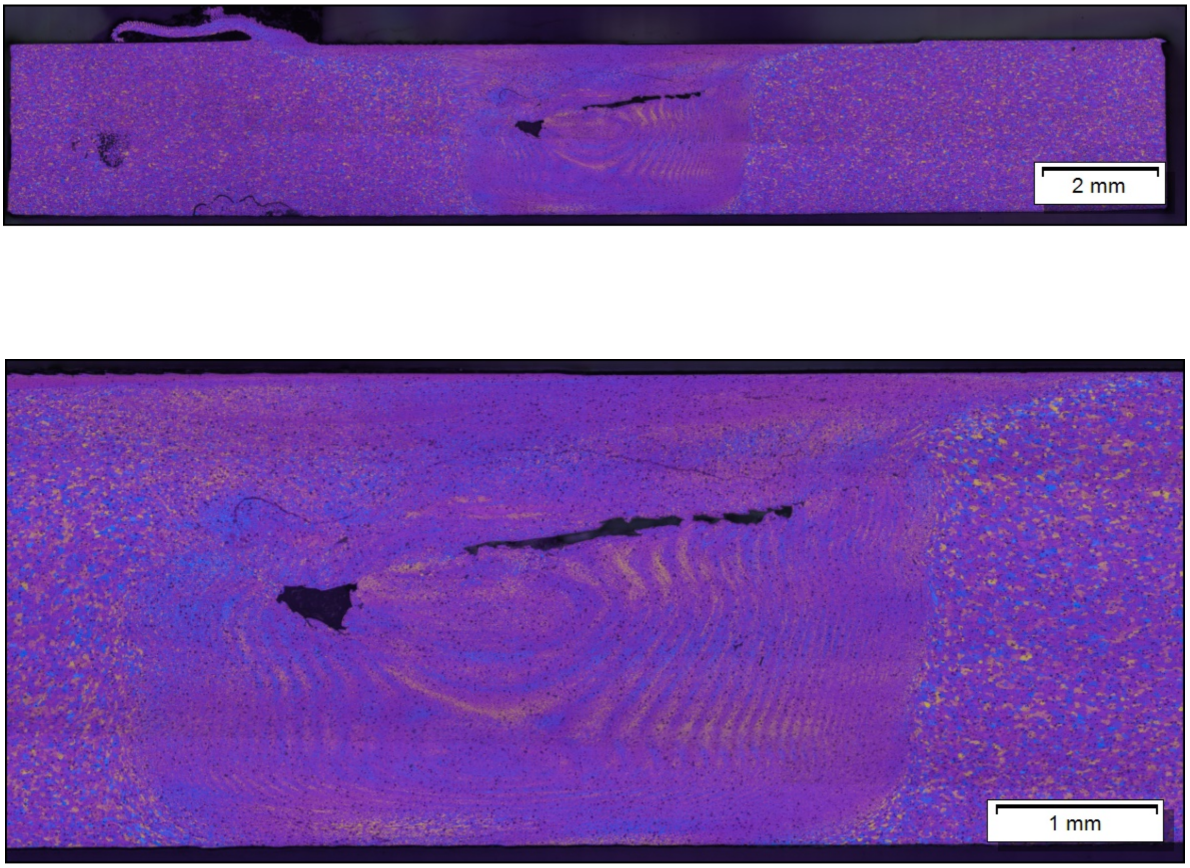
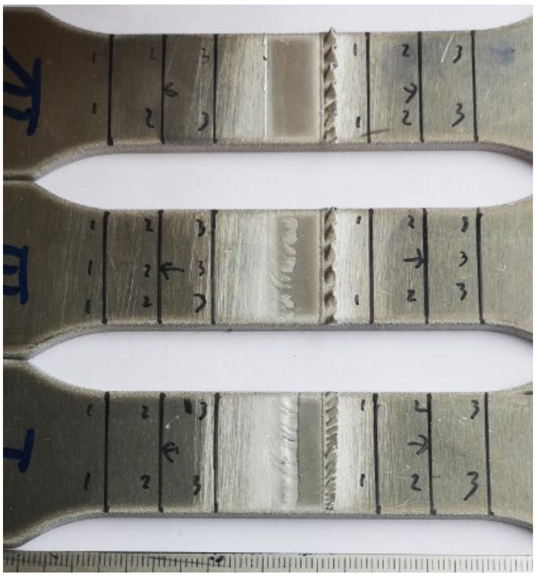


Figure 4-5 Microstructure from Experiment 1

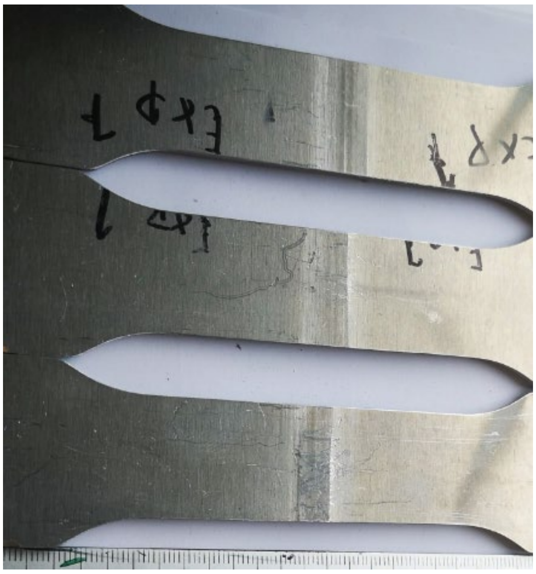
Tensile Specimen and Place of Fracture for Experiment 1

Figure 4-6 a-d) showing the front and backside of tensile test specimens before and after testing. The tensile test from specimen I, III and IV had values of 145.8 MPa, 192.1 MPa and 215.5 MPa. All specimens failed in the weld at the advising side between SZ and HAZ.

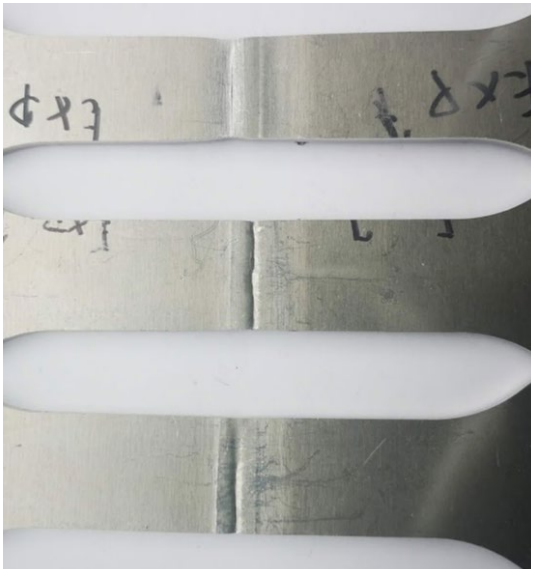


a) *Tensile Specimen I-III-IV from below*

b) *Specimen after testing I-III-IV from below*



c) *Backside of Specimens*



d) *Backside after Tensile Testing*

Figure 4-6 Exp 1- Tensile Specimen a-d).

4.2.2 *Experiment 2*

Parameters used for welding of experiment 2 was 1200 rpm, 150 mm/min, 4 seconds dwell time and 0.09 mm shoulder depth relative to the measured curvature of the aligned plates. The full length of the weld viewed from both sides can be seen in Figure 4-7 a) and b). The backside has no sign of macroscopic defects and seems to have complete penetration. The weld is aligned with the joint and the start/end point is in centre with the joint line as seen in Figure b). The notable macroscopic features are shown in Figure 4-7 c) and d). The weld didn't have deep enough shoulder depth the first 50 mm and from around 50 to 130 mm a visible surface irregularity can be seen with only minor flash presented at the retracting side. The end of the weld did only have minor flash present.

a) Frontside-

b) Backside- No macroscopic defects found

c) Irregular surface and some flash

d) Weld at last 50 mm having some flash

Figure 4-7 Picture of Weld from Exp 2 a-d).

Microstructure for Experiment 2

Pictures from microstructure of the weld in Figure 4-8. The upper part is mapped using the 5x lens and the lower part is mapped using 10x lens. It can be seen from the image that an internal cavity defects like a wormhole is present in the lateral direction of the weld and some toe flash at the retracting side of the weld. Complete penetration from a micro/macroscopic point of view. The stir zone and the nugget with onion rings. Advising side right and retracting side to the left of the nugget. TMAZ/HAZ.

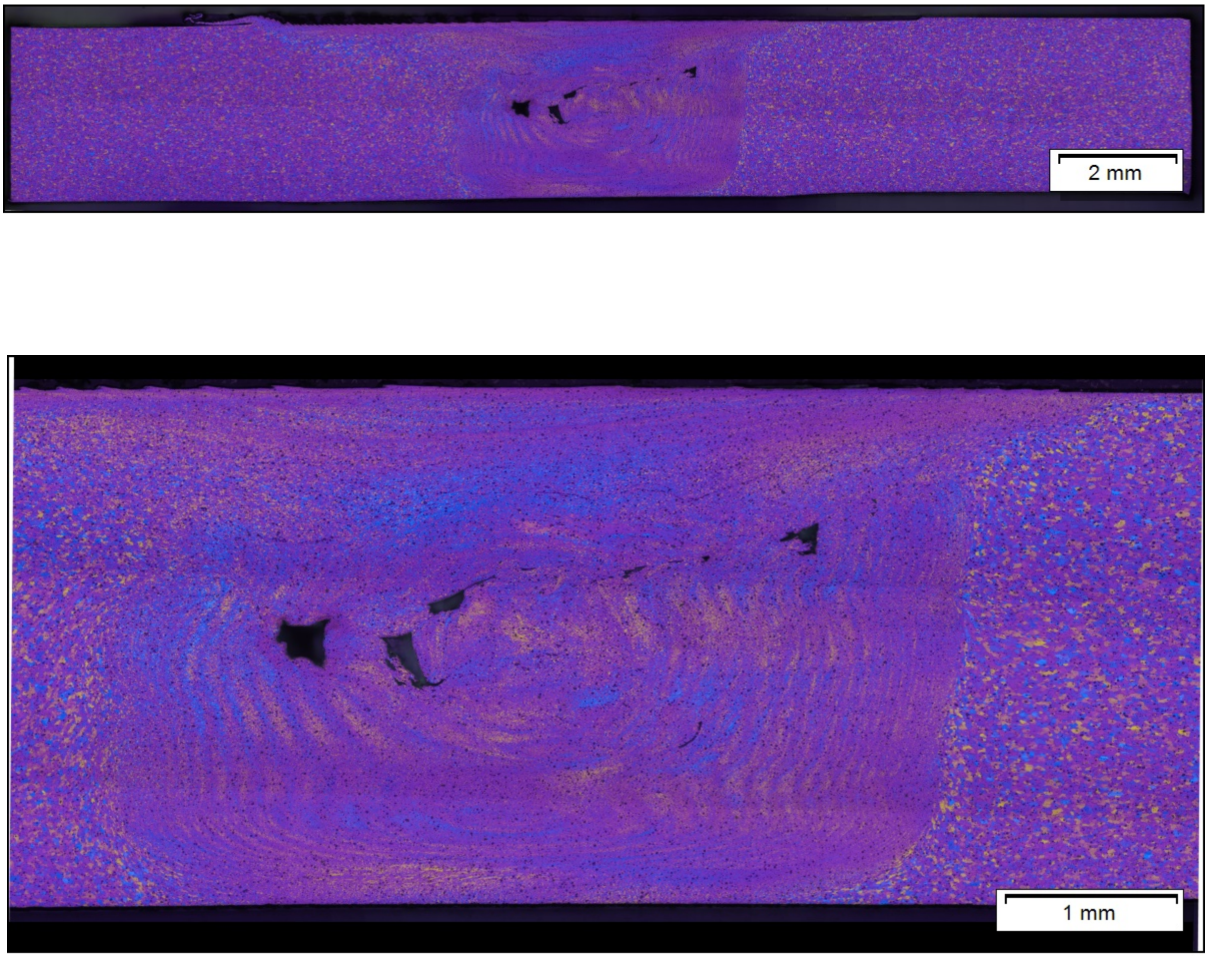


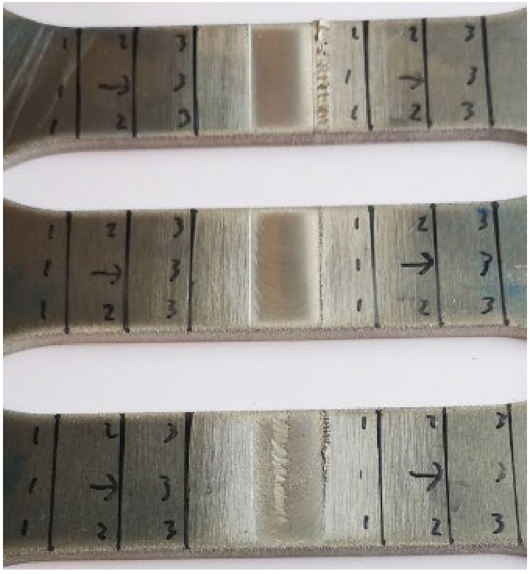
Figure 4-8 Microstructure from Experiment 2

Tensile Specimen and Place of Fracture for Experiment 2

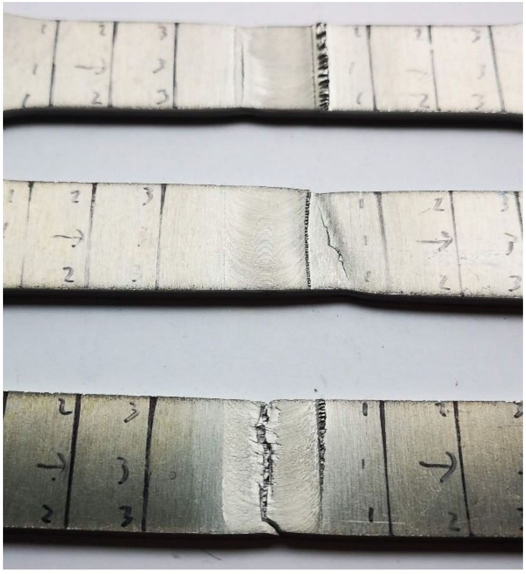
Figure 4-9 a-d) showing the front and backside of tensile test specimens before and after testing. The tensile test from specimen I, III and IV had values of 208.6 MPa, 219.9 MPa and 218.7MPa.

Specimens failed in different regions as shown in

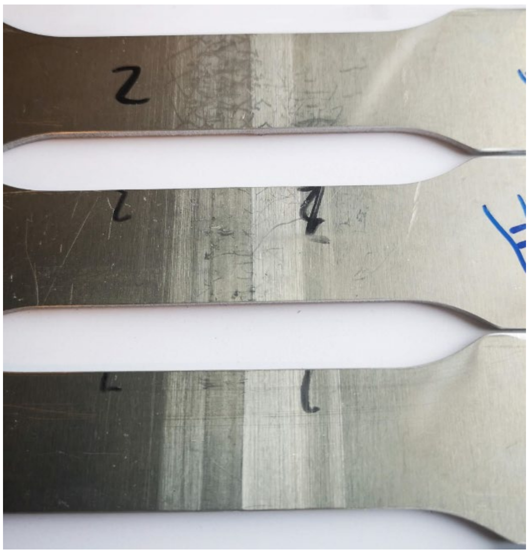
Figure 4-9 b). Specimen I failed in the SZ due to a wormhole while specimen III failed in the HAZ outside the weld area. Specimen IV failed in TMAZ/HAZ.



a) Tensile Specimen I-III-IV from below



b) Specimen after testing I-III-IV from below



c) Backside of Specimens

d) Backside after failure

Figure 4-9 Exp 1- Tensile Specimen a-d)

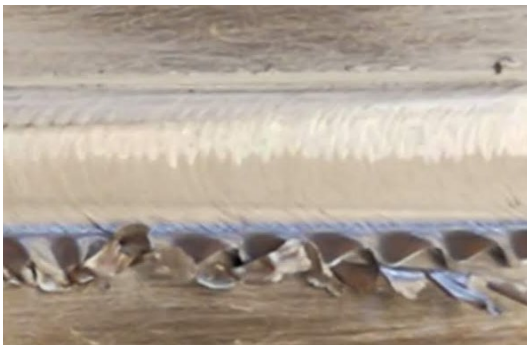
4.2.3 *Experiment 3A*

Parameters used for welding of experiment 3A was 1200 rpm, 200 mm/min, 4 seconds dwell time and 0.11 mm shoulder depth relative to the measured curvature of the aligned plates. The full length of the weld viewed from both sides can be seen in Figure 4-10 a) and b). The backside has no sign of macroscopic defects and seems to have complete penetration. The weld is aligned with the joint and the start/end point is in centre with the joint line as seen in Figure b). The notable macroscopic features are shown in Figure 4-10 c) and d). Beginning of the weld had low shoulder depth at advising side and after 50 mm flash developed at retrieving side. The surface had some irregularities due to two shades of “grey” reflecting. The surface had a smooth finish.

a) Frontside of weld with visible flash at retracting side

b) Backside had no visible quality loss

c) Start of the weld with low shoulder



d) Excessive flash and surface having two shades of grey

Figure 4-10 Picture of Weld from Exp 3A, a-d)

Microstructure for Experiment 3A

The microstructure of the weld can be seen in Figure 4-11. The upper part is mapped using the 5x lens and the lower part is mapped using 10x lens. It can be seen from the image that an internal cavity defects like a wormhole is present in the lateral direction of the weld and some toe flash at the retracting side of the weld to the left in below picture. Complete penetration from a micro/macroscopic point of view.

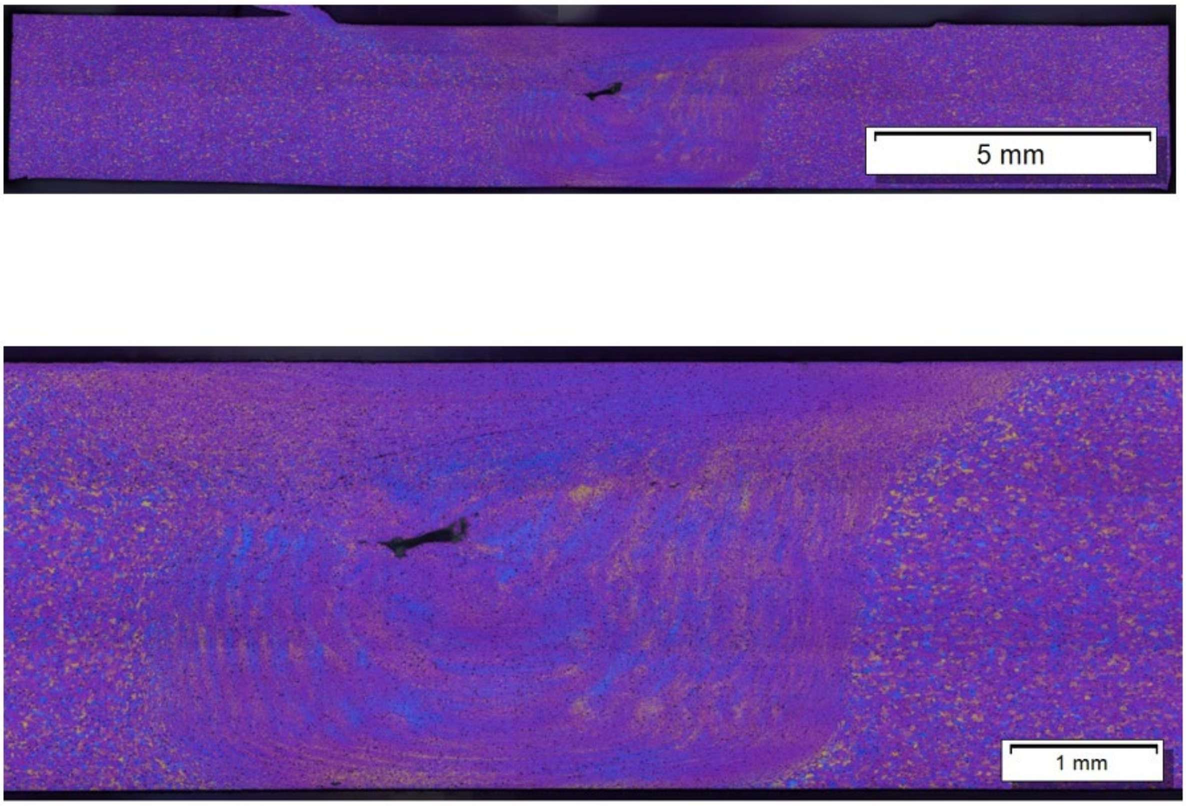


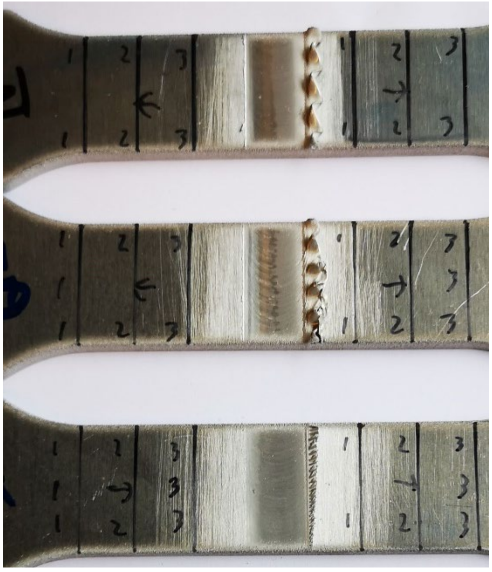
Figure 4-11 Microstructure from Experiment 3A

Stir zone with onion rings and small grains because of the dynamic recrystallization in the nugget. The advancing side is on the right in the above picture and the process shifting to this side as the process itself is asymmetric in nature.

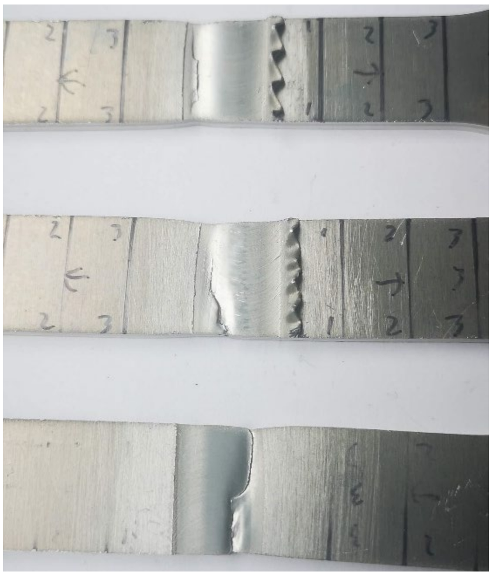
Tensile Specimen and Place of Fracture for Experiment 1

Figure 4-12 a-d) showing the front and backside of tensile test specimens before and after testing. The tensile test from specimen I, III and IV had values of 132.6, 173.9 and 212.8 MPa. Specimens failed in different regions as shown in

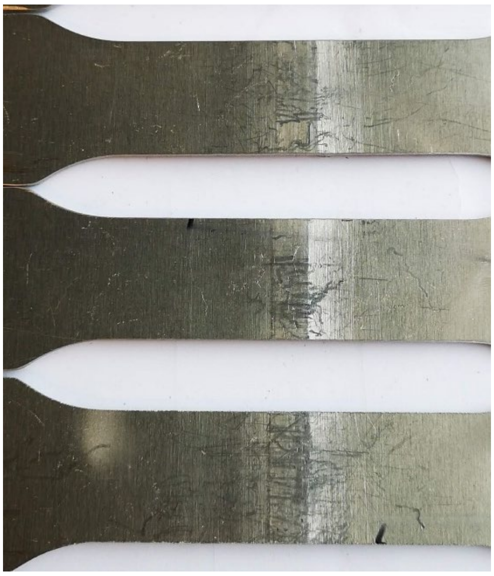
Figure 4-12 b). Lower specimen “I” in figure b) is rotated 180 degree having the retracting side at the left. The failure after tensile test for the specimen I is in the TMAZ/HAZ, the failure is partly inside the weld area and goes to the edge of the weld. Specimen III, IV both failed in the weld area.



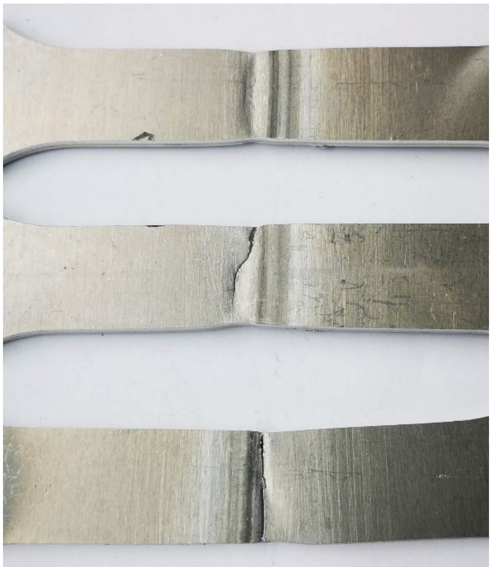
a) Tensile Specimen I-III-IV from below



b) Specimen after testing I-III-IV from below



c) Backside of Specimens



d) Backside after Tensile Testing

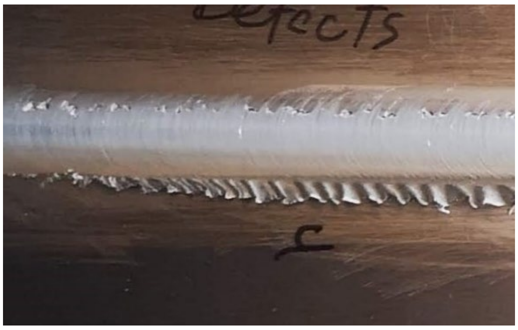
Figure 4-12 Exp 3A - Tensile Specimen a-d)

4.2.4 *Experiment 4*

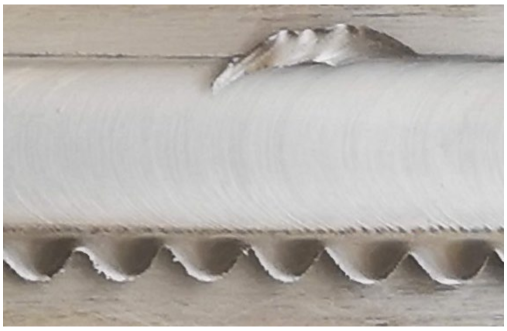
Parameters used for welding of experiment 4 was 1400 rpm, 100 mm/min, 6 seconds dwell time and 0.11 mm shoulder depth relative to the measured curvature of the aligned plates. The full length of the weld viewed from both sides can be seen in Figure 4-13 a) and b). The backside has no sign of macroscopic defects and seems to have complete penetration. The weld is aligned with the joint and the start/end point is in centre with the joint line as seen in Figure b). The notable macroscopic features are shown in Figure 4-7 c) and d). From below one can see that the weld has many defects and it varies along the weld. The weld doesn't seem to have proper contact with the shoulder and the advising side have lack of filling and a wormhole structure for the first 120-150 mm of weld. The flash is increasing along the length and the good surface properties is found at the end of the weld as seen in figure d).

a) Frontside of Experiment 4, wormholes, lack of filling and flash.

b) Backside of Experiment 1



c) Wormhole and lack of filling



d) End of weld having a sound surface

Figure 4-13 Picture of Weld from Exp 4 a-d).

Microstructure Experiment 4

Pictures from microstructure of the weld in Figure 4-14. The upper part is mapped using the 5x lens and the lower part is mapped using 10x lens. Advising side to the right in below figure. Wormhole/pores can be spotted at the edge of the nugget, excessive flash at the retracting side seen in the left part of upper image. One can also see that the shoulder has gone deep and the cross section has been reduced. Complete penetration from a micro/macroscopic point of view.

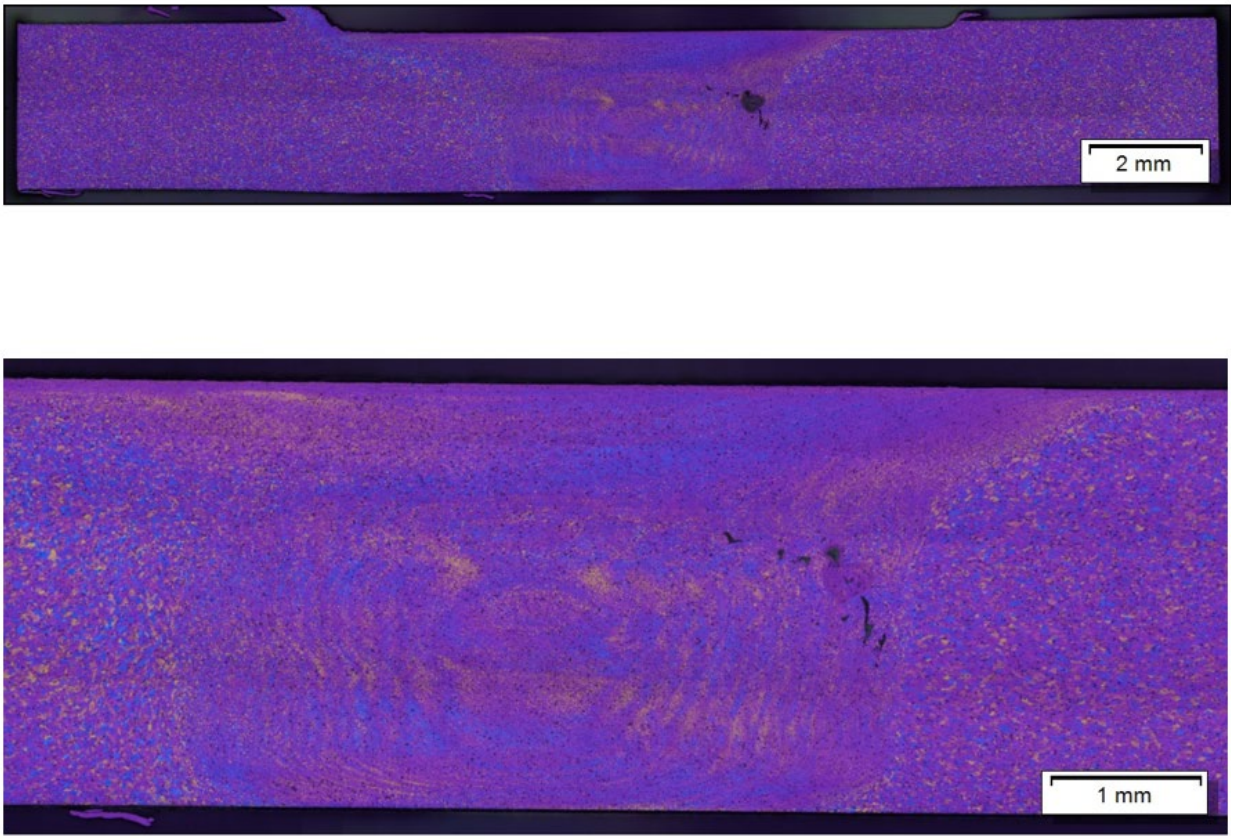
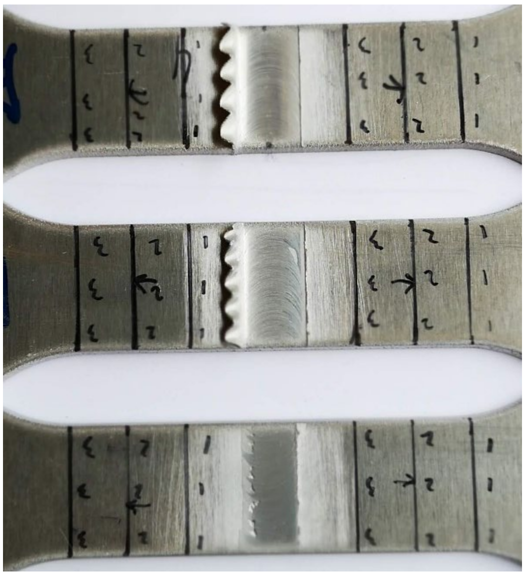


Figure 4-14 Microstructure of Exp 4

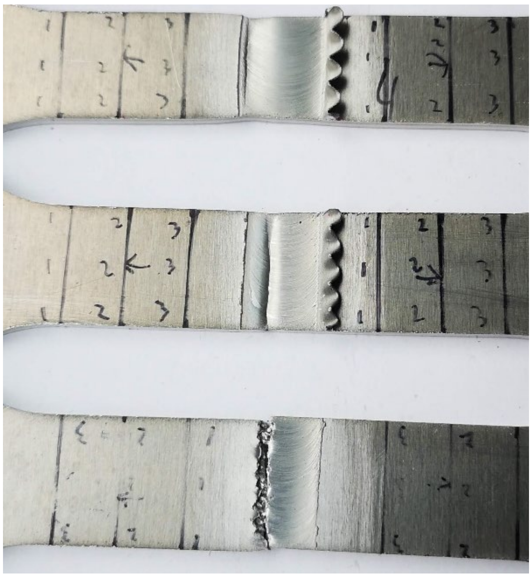
Tensile Specimen and Place of Fracture for Experiment 4

Figure 4-15 a-d) showing the front and backside of tensile test specimens before and after testing. The tensile test from specimen I, III and IV had values of 132.6 MPa, 173.9 MPa and 212.8MPa. The

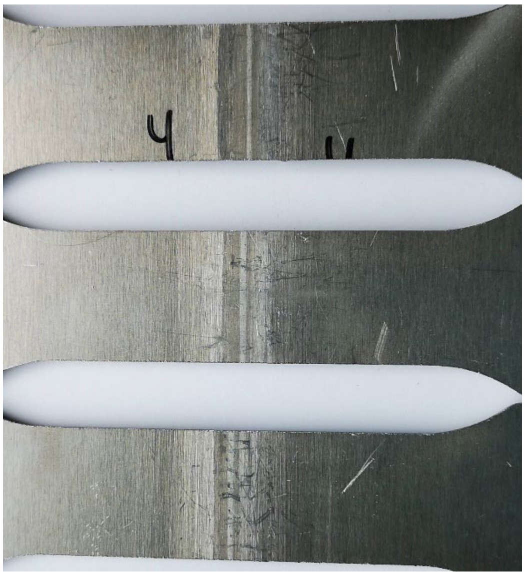
Figure 4-15 b) showing the failure area from tensile testing. Specimen I failed in the wormhole/pore like defect due to lack of filling and incomplete shoulder depth. Specimen III and IV failed in the weld area in between the TMAZ/HAZ.



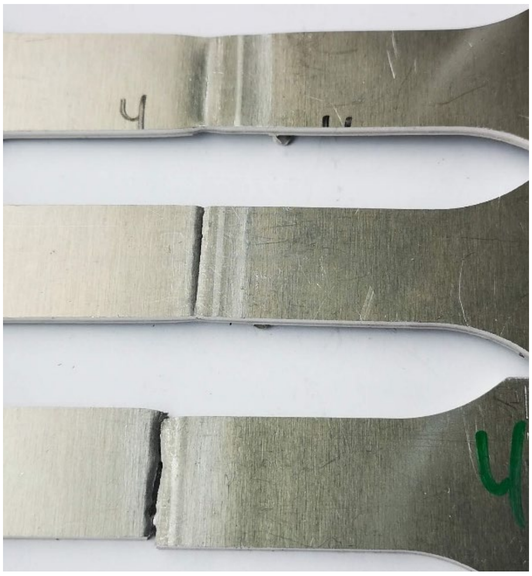
a) Tensile Specimen I-III-IV from below. Retracting to the left side



b) Specimen after testing I-III-IV from below



c) Backside of Specimens



d) Backside after Tensile Testing

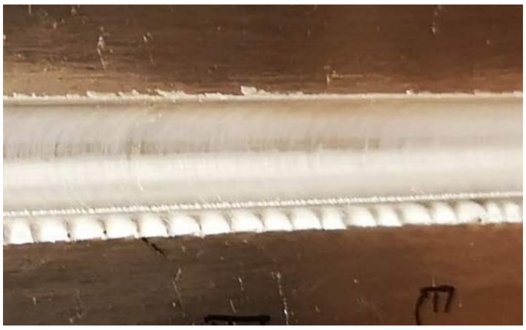
Figure 4-15 Exp 4 - Tensile Specimen a-d).

4.2.5 *Experiment 5*

Parameters used for welding of experiment 5 was 1400 rpm, 150 mm/min, 6 seconds dwell time and 0.07 mm shoulder depth relative to the measured curvature of the aligned plates. The full length of the weld viewed from both sides can be seen in Figure 4-16 a) and b). The backside has no sign of macroscopic defects and seems to have complete penetration. The weld is aligned with the joint and the start/end point is in centre with the joint line as seen in Figure b). The notable macroscopic features are shown in Figure 4-16 c) and d). The weld is good throughout the full length, at the start an area with little shoulder depth and then some flash at the retracting side.

a) Frontside of weld with visible flash at retracting side

b) Backside of weld showing good quality



c) Start of the weld with low shoulder depth

d) Good visible surface

Figure 4-16 Picture of Weld from Exp 5 a-d).

Microstructure for Experiment 5

Pictures from microstructure of the weld can be seen in Figure 4-17. The upper part is mapped using the 5x lens and the lower part is mapped using 10x lens. Complete penetration from a micro/macroscopic point of view. The retracting side is to the left side in below images. Nonvisible defects with a complete weld nugget, the stirring process seems to be shifted to the advising side.

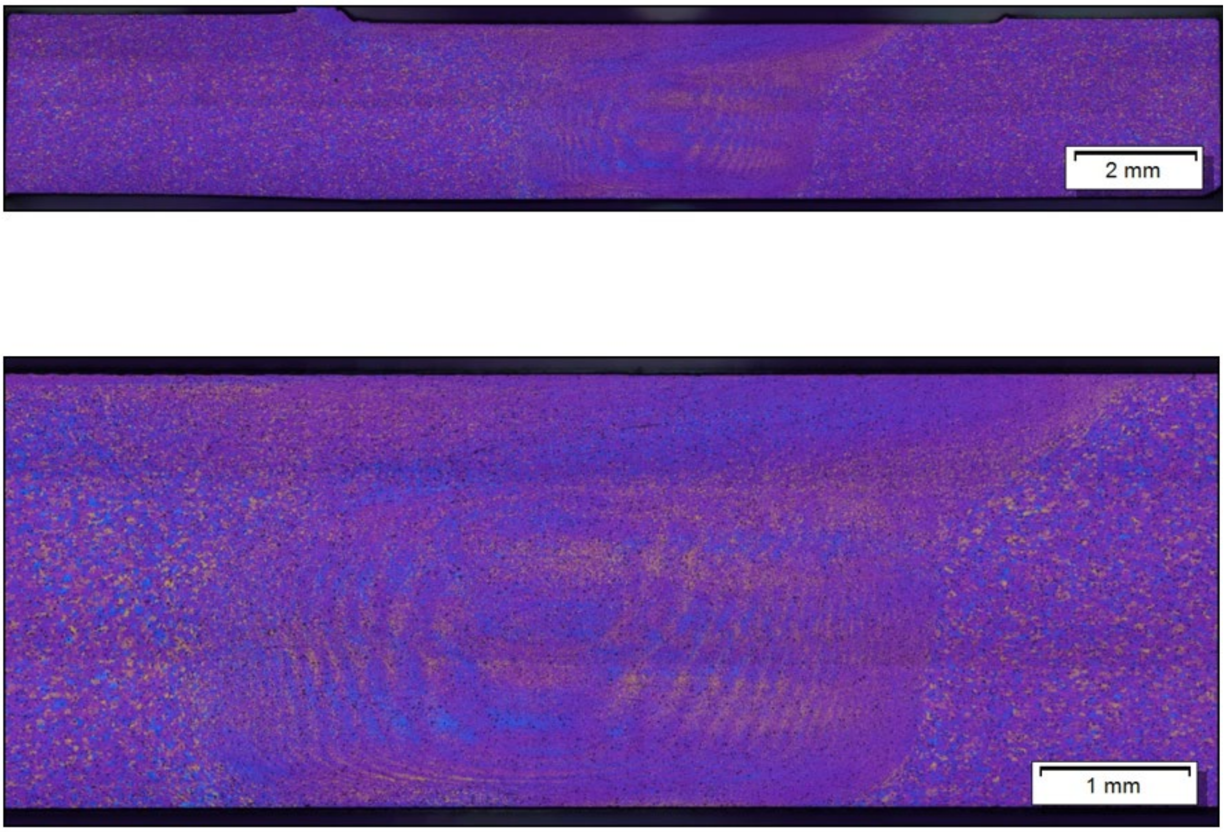
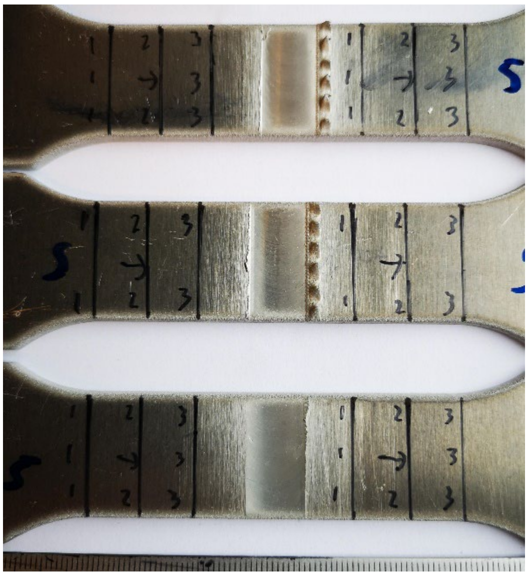


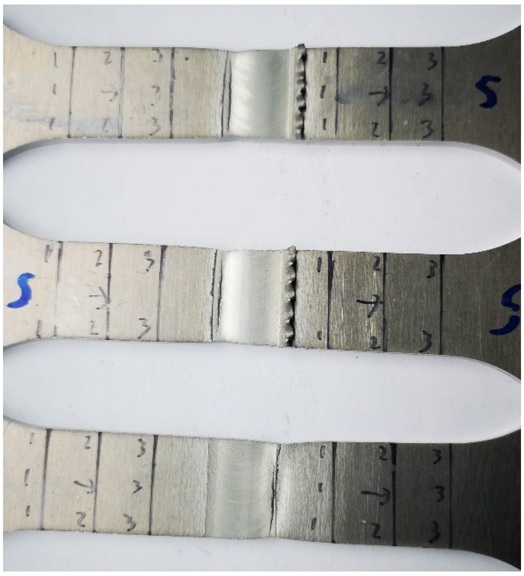
Figure 4-17 Microstructure for Exp 5

Tensile Specimen and Place of Fracture for Experiment 5

Figure 4-18 a-d) showing the front and backside of tensile test specimens before and after testing. The tensile test from specimen I, III and IV had values of 219.8 MPa, 218,1 MPa and 217.7 MPa. The Figure 4-18 b) showing the failure area from the tensile testing. Specimen I failed in the HAZ at the retracting side of the weld at the outer edge of the weld face. For specimen III and IV, the failure region was in the HAZ at the advancing side near the edge of the weld face.

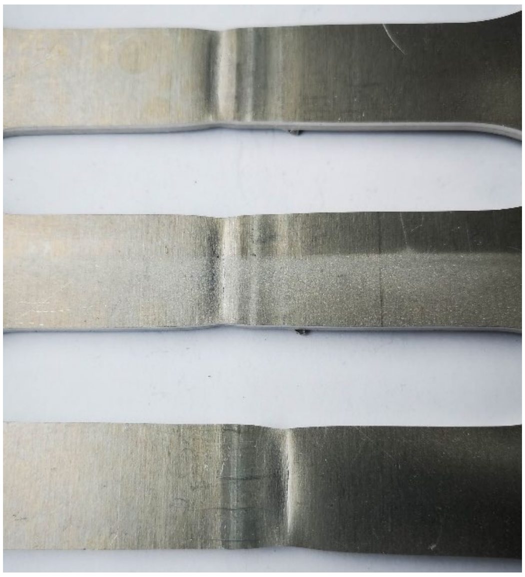


a) *Tensile Specimen I-III-IV from below. Retracting to the left*



b) *Specimen after testing I-III-IV from below*

c) *Backside of Specimens I-III-IV from below*



d) *Backside after Tensile Testing*

Figure 4-18 Exp 5 - Tensile Specimen a-d)

4.2.6 *Experiment 6*

Parameters used during welding for experiment 6 was 1400 rpm, 200 mm/min, 2 seconds dwell time and 0.09 mm shoulder depth relative to the measured curvature of the aligned plates. The full length of the weld viewed from both sides can be seen in

Figure 4-19 a) and b). The backside has no sign of macroscopic defects and seems to have complete penetration. There is no lateral offset and the start/end point is in centre with the joint line as seen in Figure b). The notable macroscopic features are shown in figure c) and d). The weld didn't have proper shoulder the first 30 mm and then an irregular surface was present with flash building up. The surface improved at the end of the weld as seen below.

a) Frontside of Experiment 6

b) Backside of Experiment 6

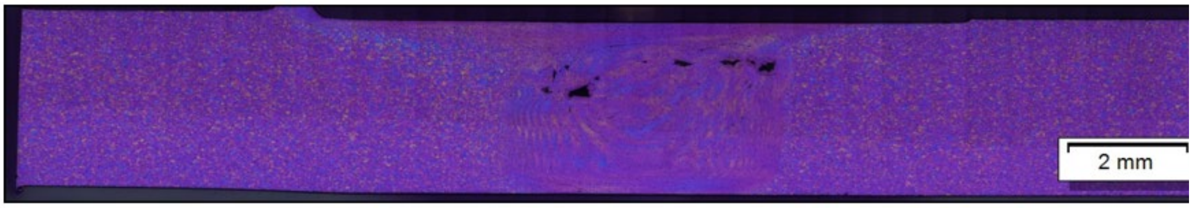
c) Irregular Surface and flash

d) End having better surface

Figure 4-19 Picture of Weld from Exp 6 a-d).

Microstructure for Experiment 6

Pictures from microstructure of the weld in Figure 4-20. The upper part is mapped using the 5x lens and the lower part is mapped using 10x lens. Complete penetration from a micro/macroscopic point of view. The retracting side is to the left side in below images. From the images in figure below several wormholes/pores was detected.



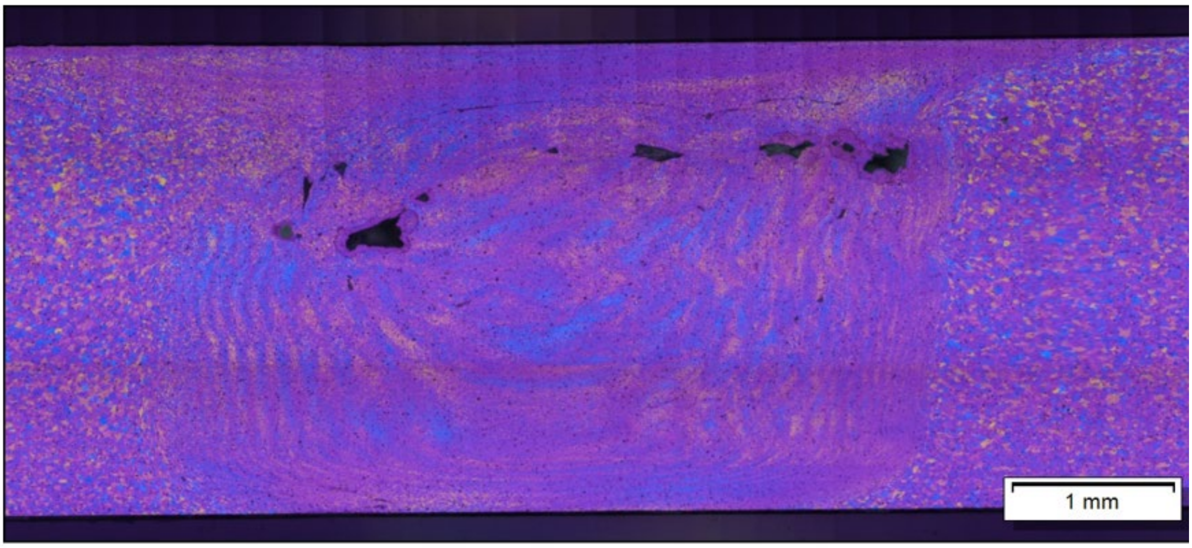
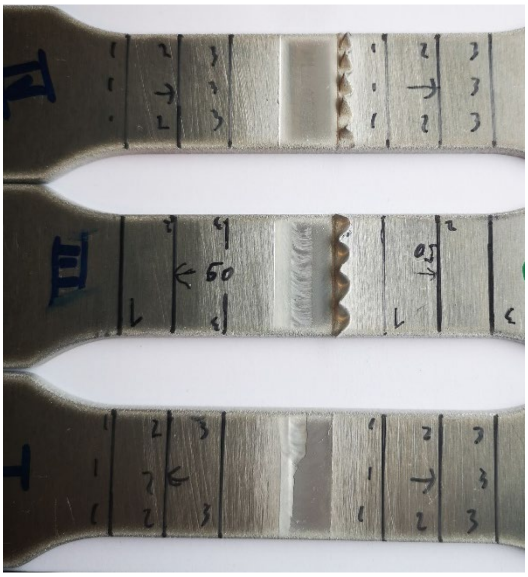


Figure 4-20 Microstructure for Exp 6

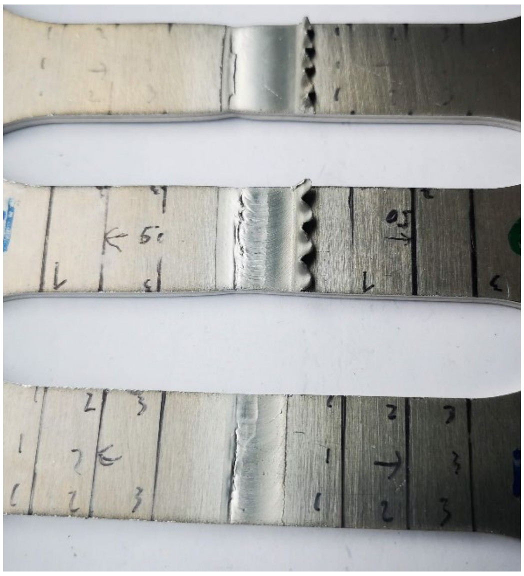
Tensile Specimen and Place of Fracture for Experiment 6

Figure 4-21a-d) showing the front and backside of tensile test specimens before and after testing. The tensile test from specimen I, III and IV had values of 219.8 MPa, 218.1 MPa and 217.7 MPa. The

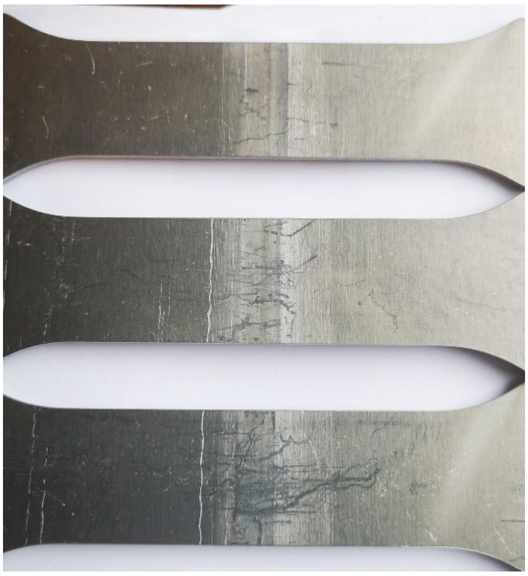
Figure 4-21 b) showing the failure area from the tensile testing. Specimen I failed in the HAZ at the retracting side of the weld at the outer edge of the weld face. For specimen III and IV, the failure region was in the HAZ at the advancing side near the edge of the weld face.



a) *Tensile Specimen I-III-IV from below. Retracting to the left*



b) *Specimen after testing I-III-IV from below*



c) *Backside of Specimens I-III-IV from below*

d) *Backside after Tensile Testing*

Figure 4-21 Exp 6 - Tensile Specimen a-d)

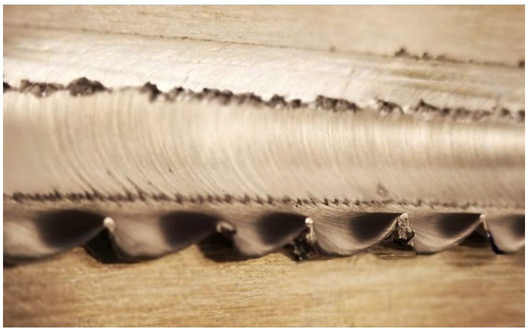
4.2.7 *Experiment 7*

Parameters used for welding of experiment 7 was 1600 rpm, 100 mm/min, 6 seconds dwell time and 0.09 mm shoulder depth relative to the measured curvature of the aligned plates. The full length of the weld viewed from both sides can be seen in

Figure 4-22 a) and b). The backside has no sign of macroscopic defects and seems to have complete penetration. There is no lateral offset and the start/end point is in centre with the joint line as seen in Figure b).

a) Frontside of Experiment 7

b) Backside of Experiment 7



c) Several defects present

d) End having good quality

Figure 4-22 Pictures of Weld Exp 7

Microstructure for Experiment 7

Pictures from microstructure of the weld in Figure 4-20. The upper part is mapped using the 5x lens and the lower part is mapped using 10x lens. Complete penetration from a macroscopic point of view. The retracting side is to the left side in below images. From the figure below several wormholes/pores at the advancing side given a defect nugget.

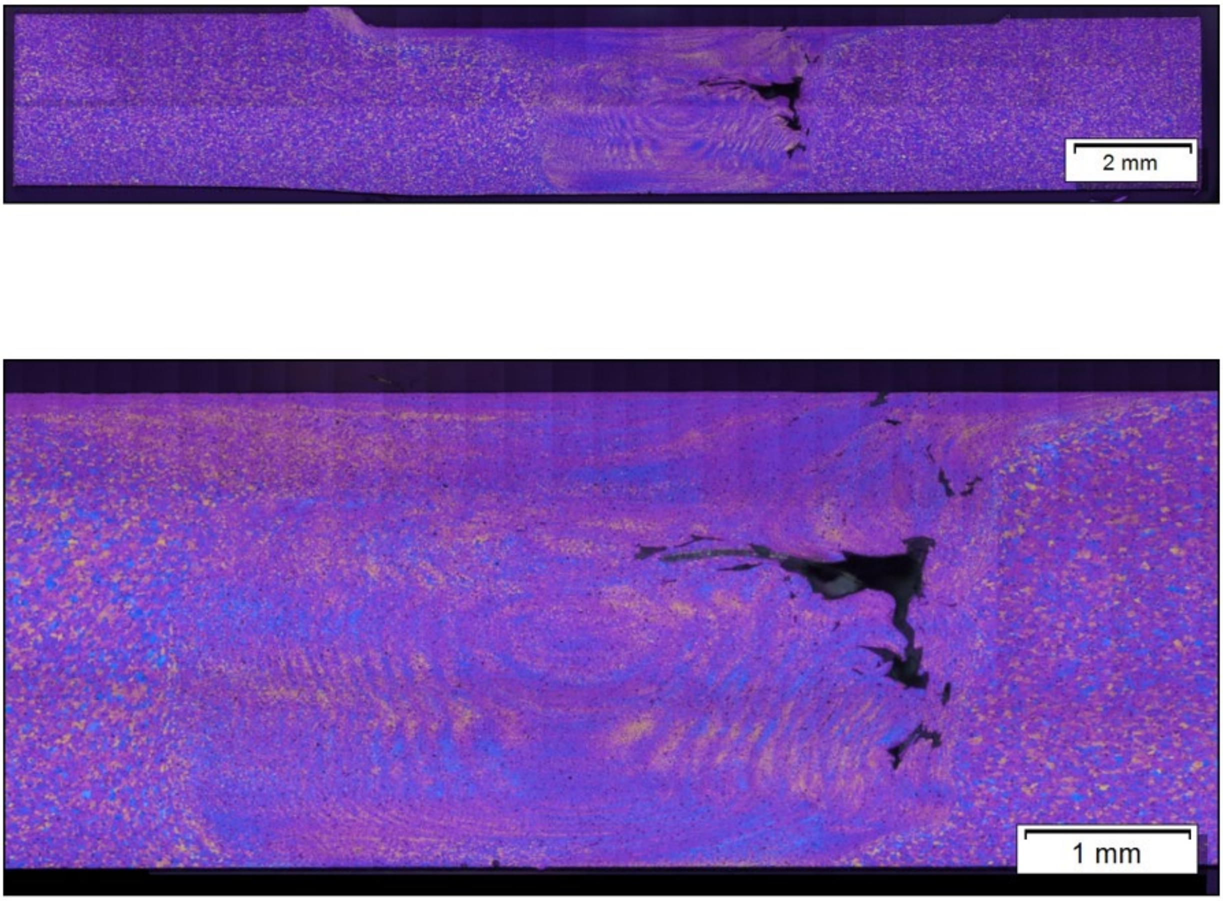
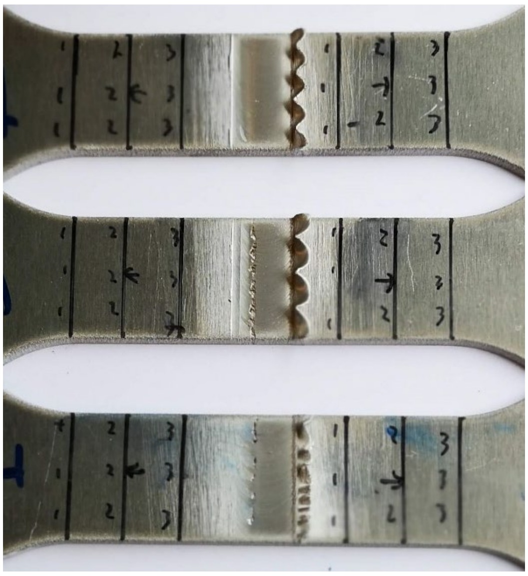


Figure 4-23 Microstructure Experiment 7

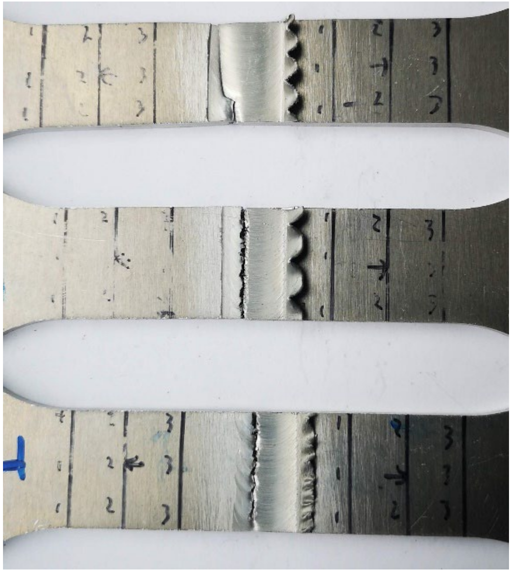
Tensile Specimen and Place of Fracture for Experiment 7

Figure 4-24 a-d) showing the front and backside of tensile test specimens before and after testing. The tensile test from specimen I, III and IV had values of 104.4 MPa, 55.1 MPa and 212.7 MPa. The

Figure 4-24 b) showing the failure area after tensile testing where specimens I and III failed due to the wormhole and specimen IV failed along the TMAZ/HAZ.

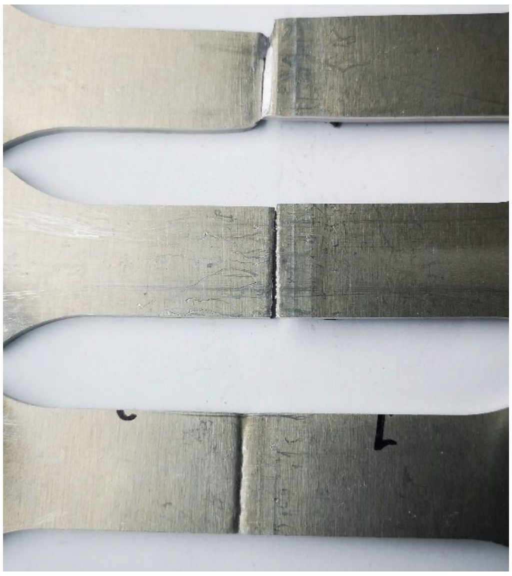


a) Tensile Specimen I-III-IV from below. Retracting to the left



b) Specimen after testing I-III-IV from below

c) Backside of Specimens I-III-IV from below



d) Backside after Tensile Testing

Figure 4-24 Exp 7- Tensile Specimens a-d).

4.2.8 *Experiment 8*

Parameters used for welding of experiment 8 was 1600 rpm, 150 mm/min, 2 seconds dwell time and 0.11 mm shoulder depth relative to the measured curvature of the aligned plates. The full length of the weld viewed from both sides can be seen in

Figure 4-25 a) and b). The backside has no sign of macroscopic defects and seems to have complete penetration. There is no lateral offset and the start/end point is in centre with the joint line as seen in Figure b).

a) Frontside of Experiment 8

b) Backside of Experiment 8

c) Good weld properties

d) Excessive flash

Figure 4-25 Pictures from Weld Exp 8

Microstructure for Experiment 8

The microstructure of the weld in experiment 8 can be seen in Figure 4-20. The upper part is mapped using the 5x lens and the lower part is mapped using 10x lens. Complete penetration from a micro/macroscopic point of view. The retracting side is to the left side in below images. No defects observed, complete nugget and some area reduction because of the shoulder depth used.

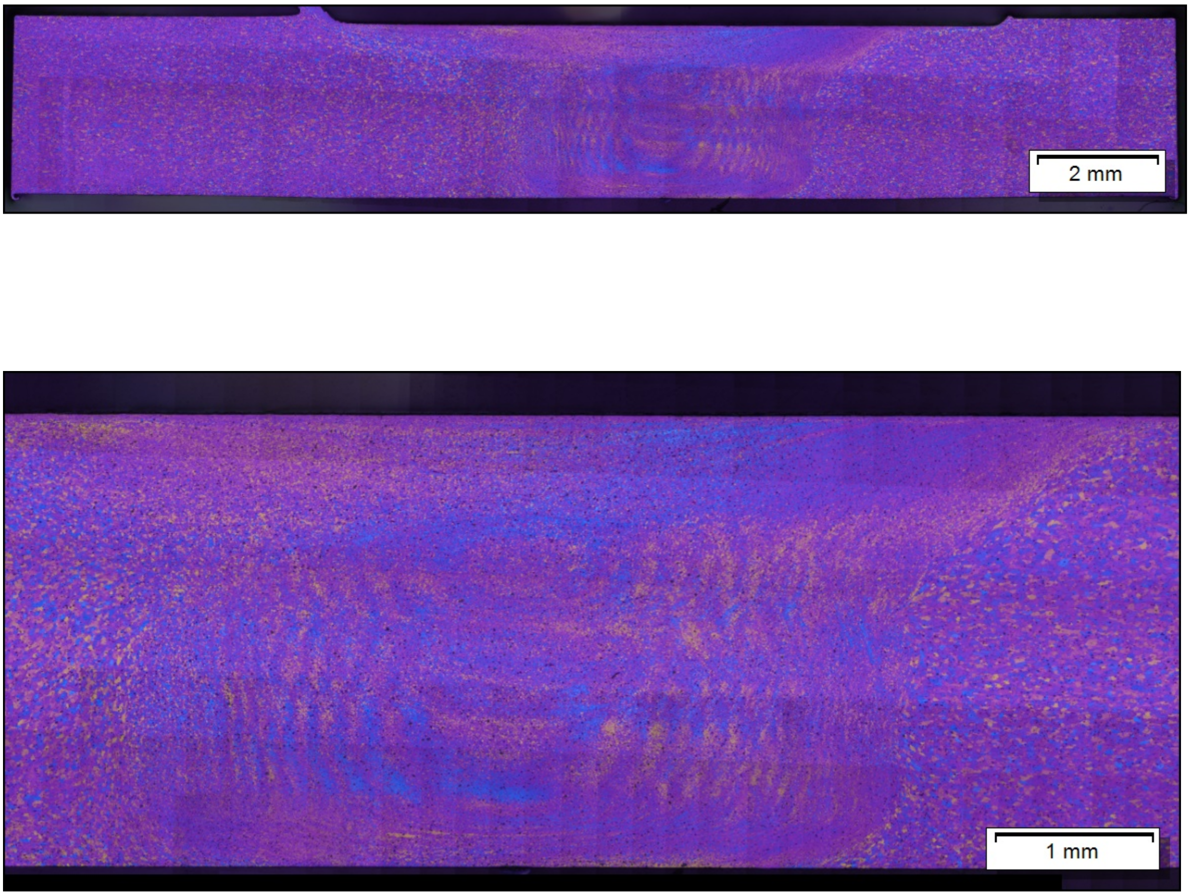
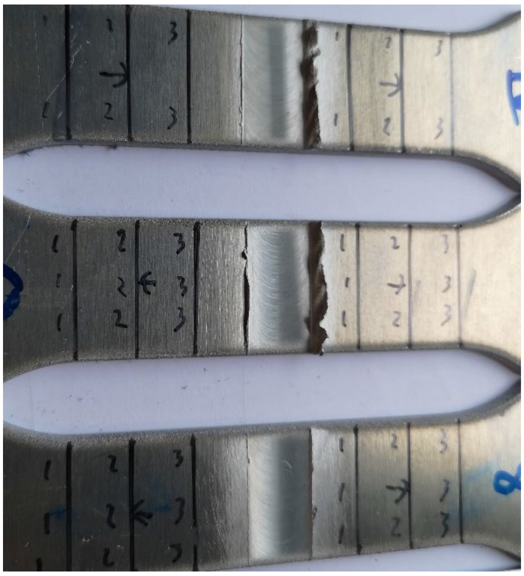


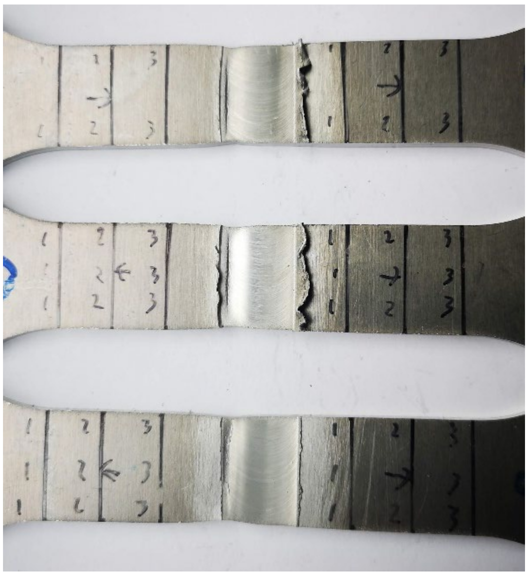
Figure 4-26 Microstructure Exp 8

Tensile Specimen and Place of Fracture for Experiment 8

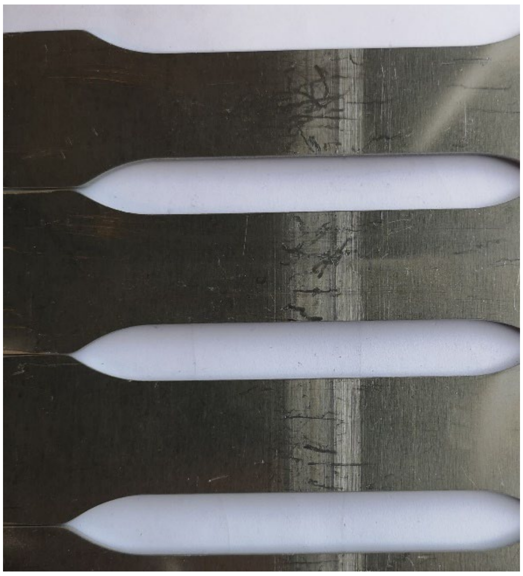
Figure 4-27 a-d) showing the front and backside of tensile test specimens before and after testing. The tensile test from specimen I, III and IV had values of 218.5 MPa, 213.5 MPa and 216.4 MPa. The figures b) and d) are showing the failure area from the tensile testing. All specimens failed in the TMAZ/HAZ regions at the advancing side.



a) Tensile Specimen I-III-IV from below. Retracting to the left



b) Specimen after testing I-III-IV from below



c) Backside of Specimens I-III-IV from below

d) Backside after Tensile Testing

Figure 4-27 Exp 8 - Tensile Specimens a-d).

4.2.9 *Experiment 9*

Parameters used for welding of experiment 9 was 1600 rpm, 200 mm/min, 4 seconds dwell time and 0.07 mm shoulder depth relative to the measured curvature of the aligned plates. The full length of the weld viewed from both sides can be seen in

Figure 4-28 a) and b). The backside has no sign of macroscopic defects and seems to have complete penetration. There is no lateral offset and the start/end point is in centre with the joint line as seen in Figure b).

a) Frontside of Experiment 9

b) Backside of Experiment 9

c) Irregular Surface and flash

d) End having better surface

Figure 4-28 Pictures of Welds Exp 9

Microstructure for Experiment 9

Light optical microscopic pictures showing the microstructure of the weld in Figure 4-29. The upper part is mapped using the 5x lens and the lower part is mapped using 10x lens. Complete penetration from a micro/macroscopic point of view. The retracting side is to the left side in below images. No defects observed and the nugget seems to be shifting to the advancing side. The classic onion rings due to the rotation of the tool and traverse movement can be seen.

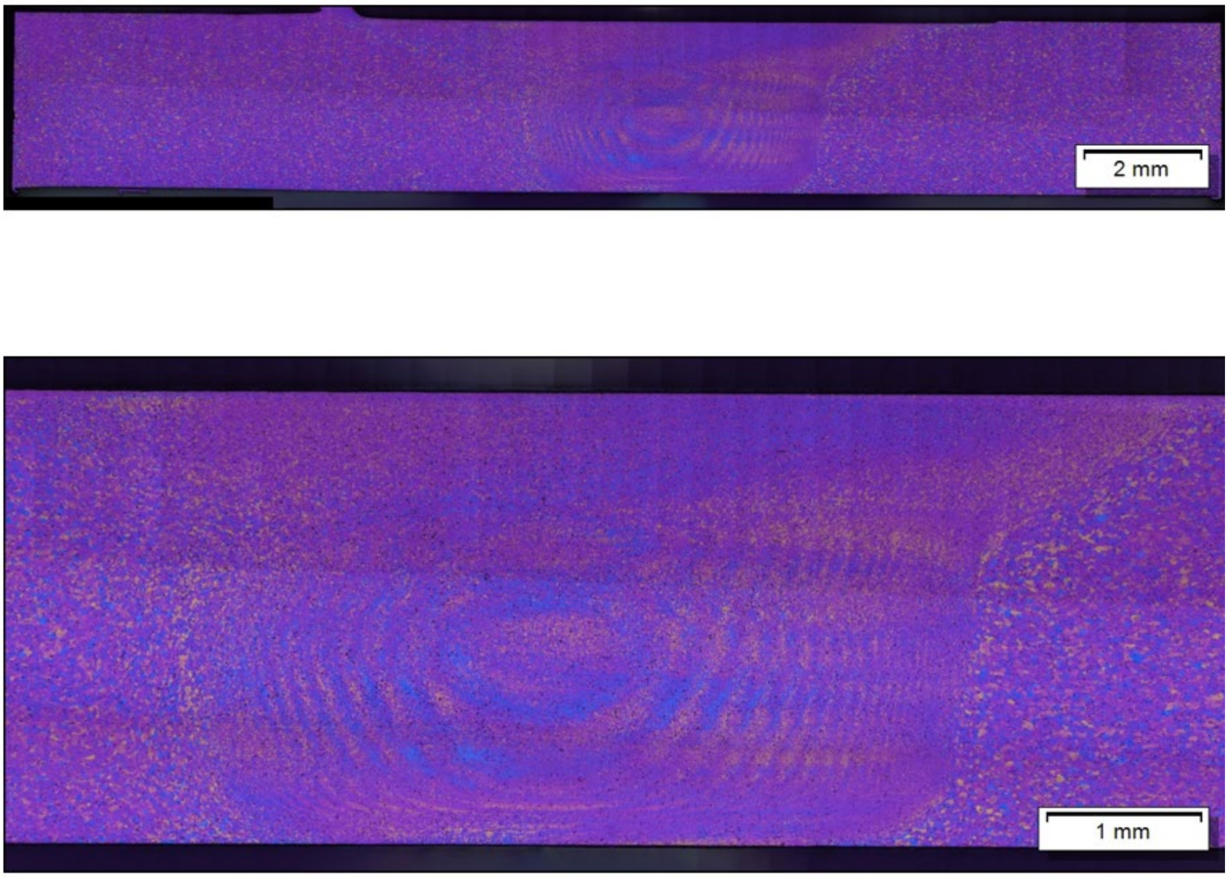
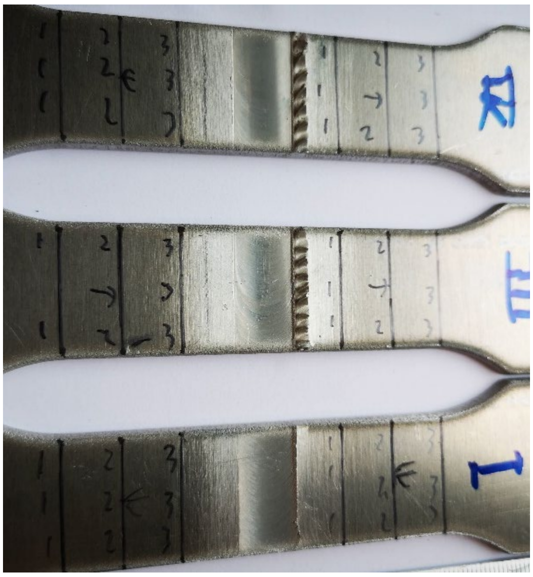


Figure 4-29 Microstructure for Exp 9

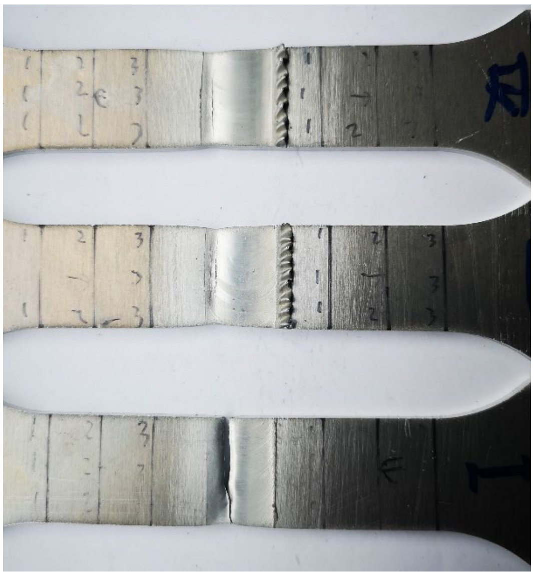
Tensile Specimen and Place of Fracture for Experiment 7

Figure 4-30 a-d) showing the front and backside of tensile test specimens before and after testing. The tensile test from specimen I, III and IV had values of 165.3 MPa, 221.1 MPa and 216.3 MPa. The

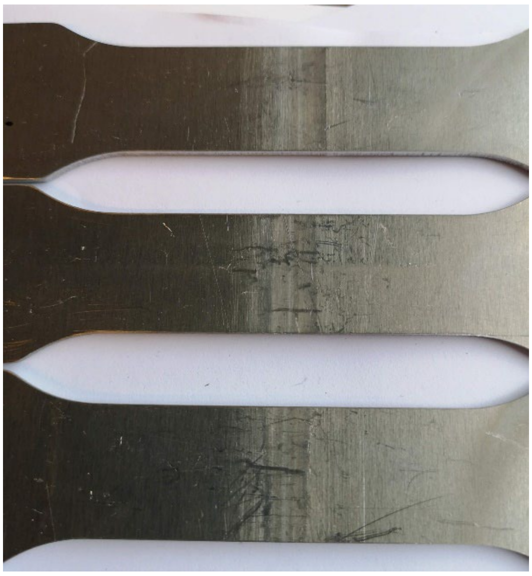
Figure 4-21 b) showing the failure area after tensile testing where Specimen I failed in the TMAZ/SZ. Specimens III and IV failed in the TMAZ/HAZ on the advancing side.



d) Tensile Specimen I-III-IV from below.



e) Specimen after testing I-III-IV from below



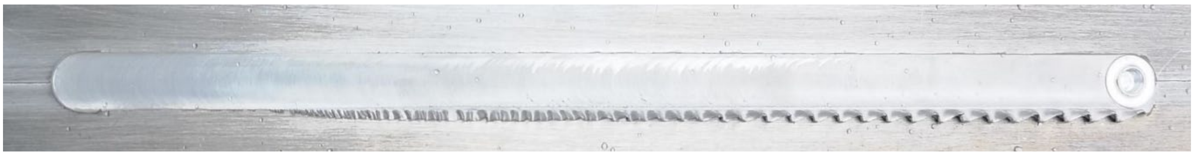
f) Backside of Specimens I-III-IV from below

g) Backside after Tensile Testing

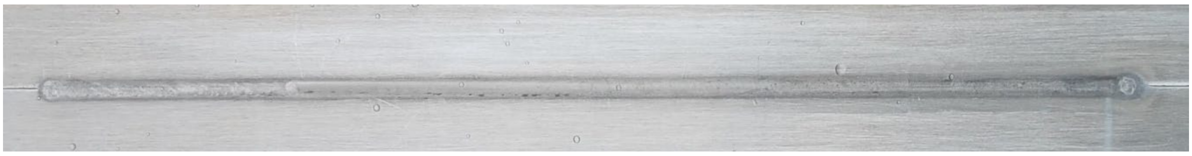
Figure 4-30 Exp 9 - Tensile Specimens a-d).

4.2.10 *Experiment OPT - Conformation Experiment*

The optimum parameters found by Taguchi's Robust Design Approach described in Table 4-5 was as follow; 1200 rpm rotation, 150 mm/min welding speed, 2 seconds dwell time and 0.11 mm shoulder depth. The full length of the weld viewed from both sides can be seen in Figure 4-31 a) and b). The backside has no sign of macroscopic defects and seems to have complete penetration. There is no lateral offset and the start/end point is in centre with the joint line as seen in Figure b).



a) Frontside of Optimum Weld advancing side at the top. Flash at retracting side



b) Backside of Optimum Weld

c) Sound weld

d) Flash and 2 shades of grey

Figure 4-31 Pictures of welds EXP OPT

X-ray confirmation weld EXP OPT

IKM Inspections AS performed x-ray in accordance to procedure/standard BPI-01. Radiographic Examination ISO 17636-1. No defects were detected. The radiographic film can be seen in below Figure 4-32. Full report is attached in appendix.

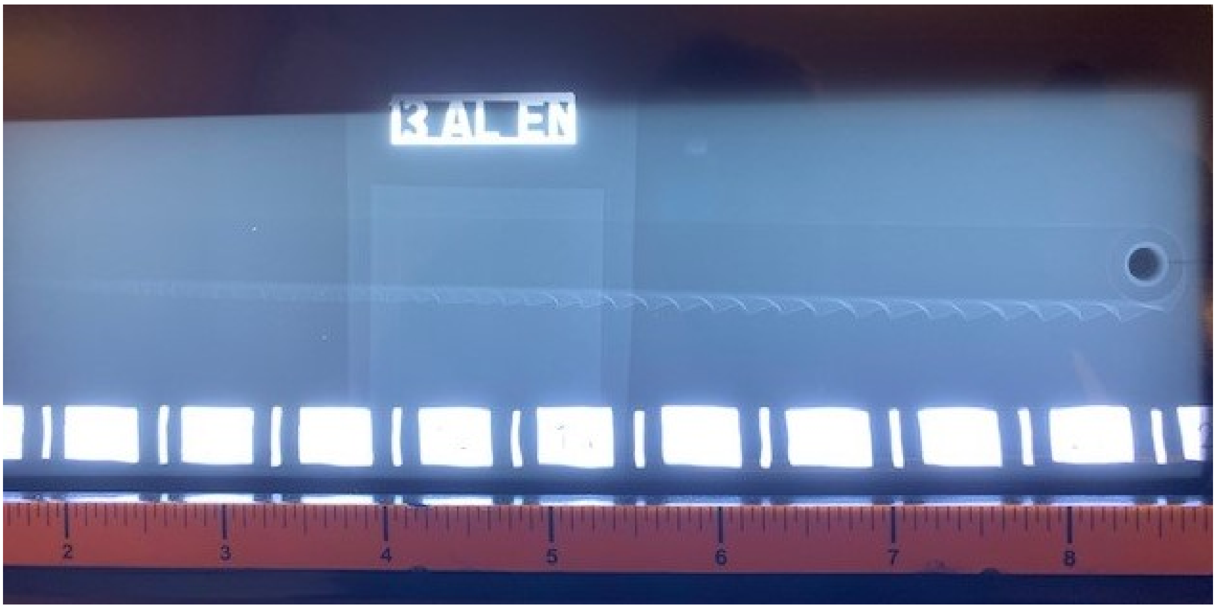


Figure 4-32 X-Ray of Optimum Weld

Scanning electron microscopy (SEM)

In below Figure 4-33 is a picture from the SEM. Nothing of interest was found and result and pictures is attached in the appendix.

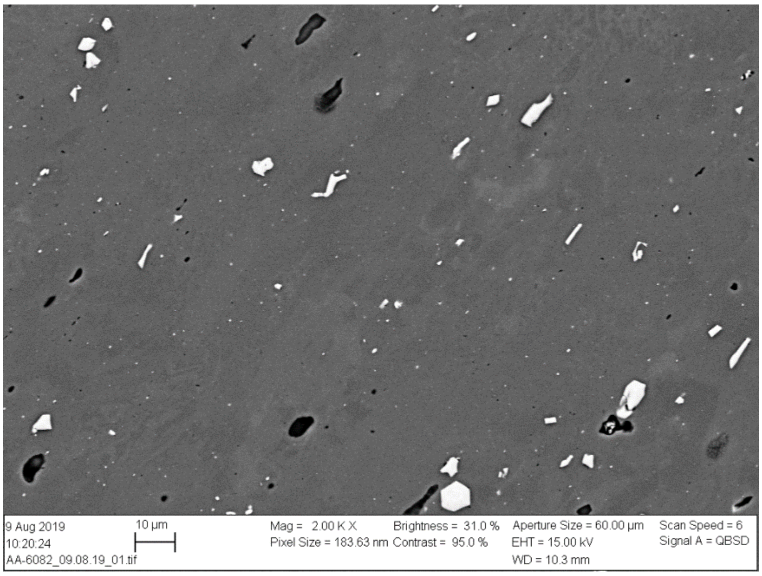
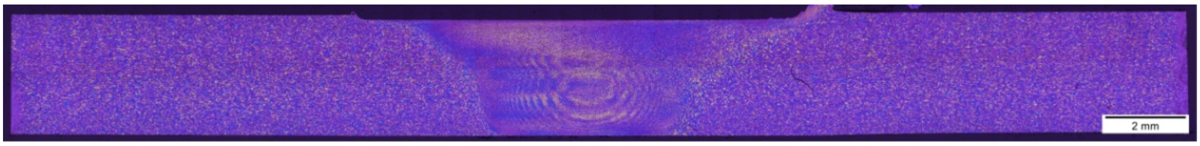


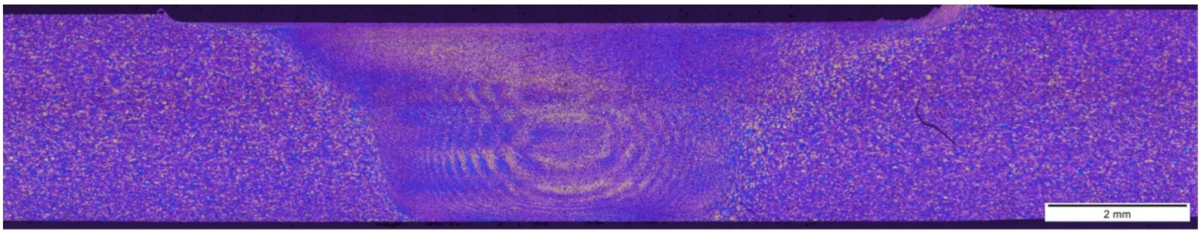
Figure 4-33 Picture using SEM

Microstructure for Experiment OPT

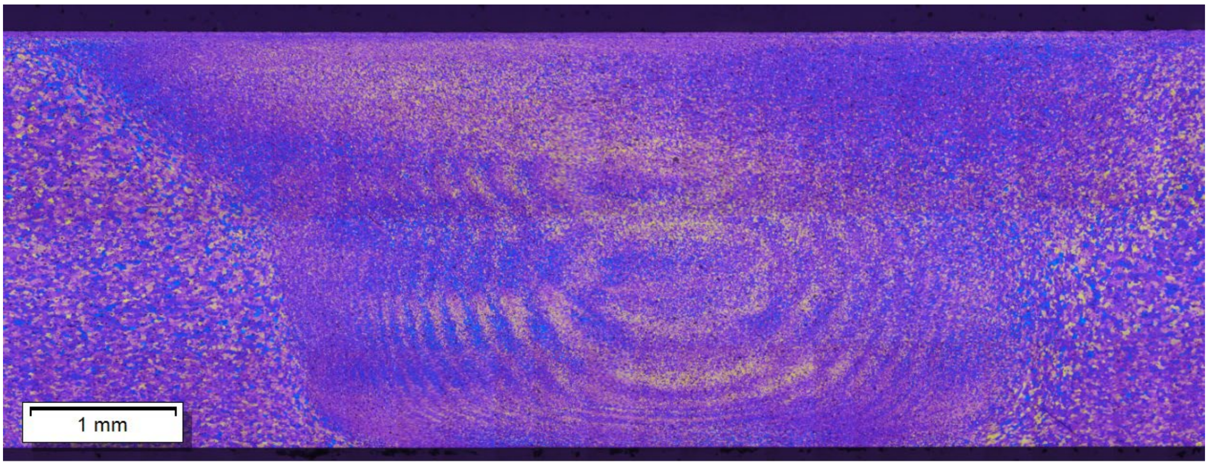
Below in Figure 4-34 is the LOM pictures revealing the microstructure for the weld using optimal parameters. Advancing side to the left in below images. The nugget is ok having the classic onion rings. The TMAZ can be seen next to the nugget and the HAZ occupies rest of the area with no possibility to separate the HAZ from the base material. Vickers hardness test is performed in the next chapter to identify and separate the different zones.



a) Mapping with 5x lens. Advancing side to the left



b) Zoom of stirzone using the 5x lens

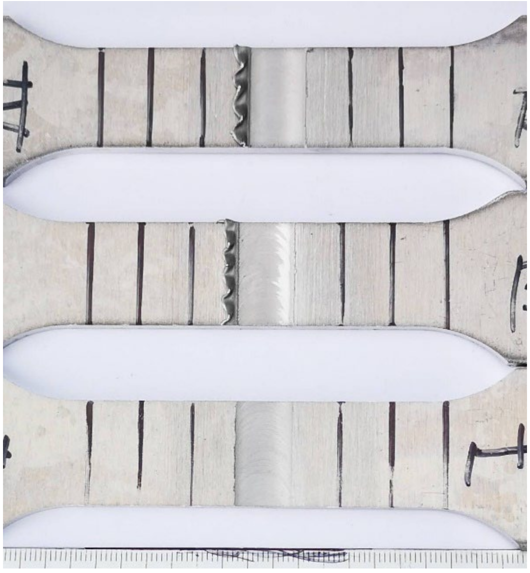


c) Mapping with 10x lens. Advancing side to the left

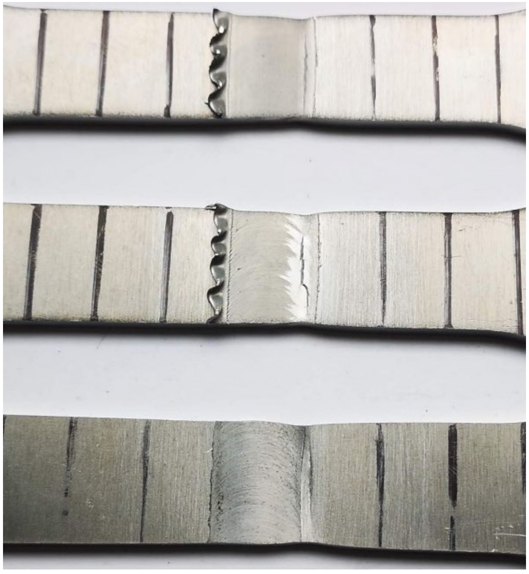
Figure 4-34 Microstructure for Optimum Welding

Tensile Specimen and Place of Fracture for Experiment OPT

Figure 4-35 a-d) showing the front and backside of tensile test specimens before and after testing. The tensile test from specimen I, III and IV had values of 222.7 MPa, 220.1 MPa and 219.3 MPa. The figure b) showing the failure area after tensile testing where Specimen all specimens failed at the advancing side in the TMAZ/HAZ

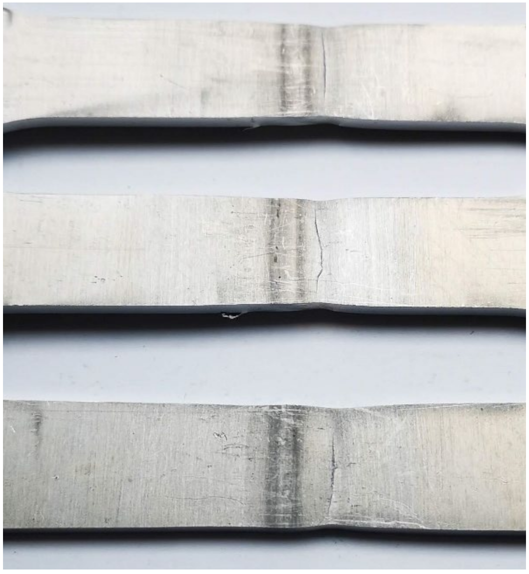


a) *Tensile Specimen I-III-IV from below. ADV side to the right*



b) *Specimen after testing I-III-IV from below*

c) *Backside of Specimens I-III-IV from below*



d) *Backside after Tensile Testing*

Figure 4-35 Tensile Specimen Optimum Welding

Bending Test

Bending test were performed to check the ductility of the optimal weld. Below in Figure 4-36 are the cut-out sample I and II without any defects after the 3-point bending test. Sample-II was bent from the frontside and sample-I from the backside of the weld. No defects or crack propagation were seen. Full report from the test attached in the Appendix. Where sample-I is numbered specimen 6 in the report and sample-II number 5.

Figure 4-36 Bending Test

4.3 Vickers Hardness Test

Vickers Hardness Testing were conducted in accordance with ISO6507-1(International Organization for Standardization, 2005). Samples is taken from the material in between tensile specimens III and IV that was cut from the plates described in figure 3-2. HV0.5 with a nominal value of the test force set at 4,9025N for 10 seconds. Magnification of 40x is used for all tests. For indentations near the edge of the specimens a distance from the centre of the indentation to the edge should be at least 3x the mean diagonal length and between any two adjacent points a distance from the centres should be at least 6x the mean diagonal length of the largest point. The arithmetical mean of the diagonals is taken, and these two values is used to calculate the Vickers hardness. If two diagonals measured on a flat surface have a difference greater than 5% it should be mentioned in the test report. The error measurement is done using a excel sheet calculating each point, this can be seen in the Appendix. Result for the Optimum weld can be seen in

Figure 4-37 below. The data point is plotted, and the anodized sample is marked with number to locate each point. The upper line is the blue line I and the lower line is the red line II. For the lower line the point with lowest hardness was point 13with a value of 58.2 HV. This point was in the HAZ right under the shoulder edge at the retracting side. At the advancing side the points with lowest hardness was found in the HAZ near the TMAZ. The HAZ seems to continue out over the rest of the specimen as the base material was found to have a value around 115 HV.

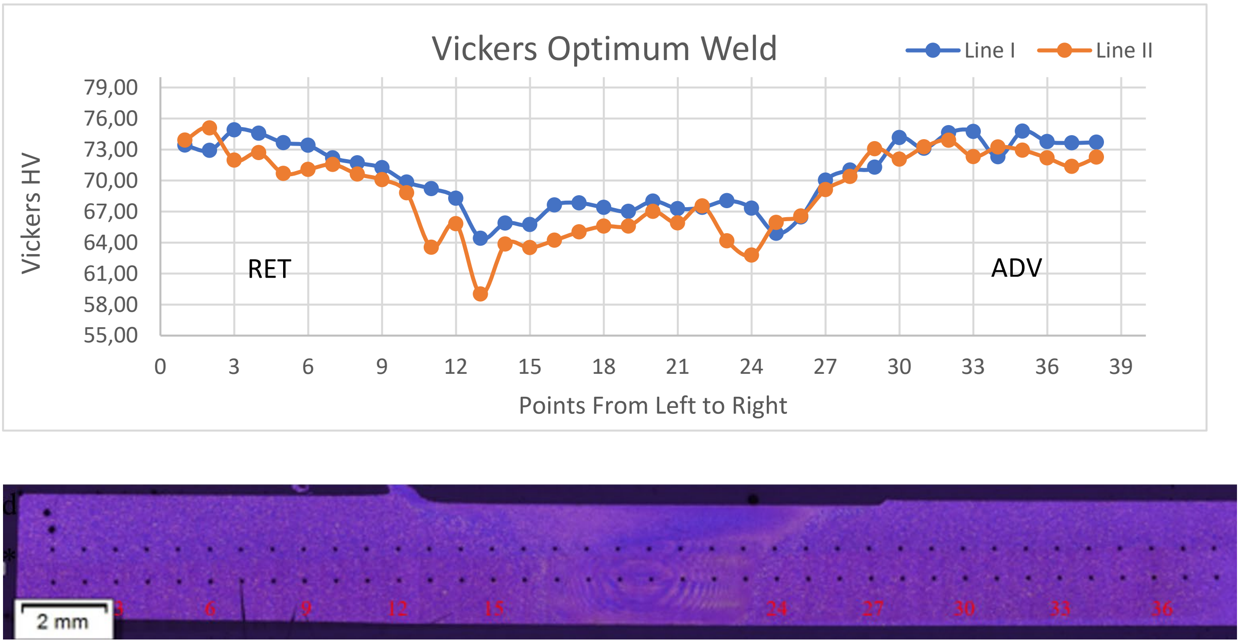
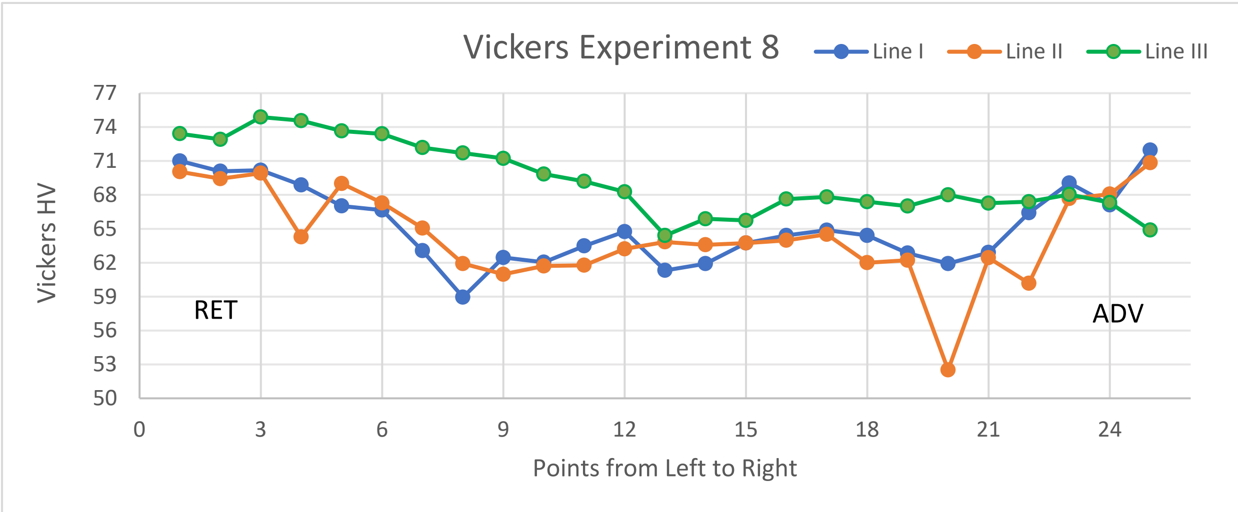


Figure 4-37 Vickers HV for the Optimum Weld

As the HAZ and base material wasn't detectable using the small specimens the cut-out piece from experiment 8 -9was mounted in epoxy using the same methods described earlier as seen in below figure. First five points using the same method as above was taken at approximately 65 mm from weld line. The result revealed a reduction in the hardness to be around 75 HV. More control point was also taken and had the same values. The material hardness has decreased over the hole specimen leaving no unchanged base material left.

Figure 4-38 Vickers Test 65 mm

Vickers hardness profile from experiment 8 can be seen in below figure. For line II and point 20 a value of 52.5 HV was found. The anodized sample can be seen in figure b) with the retracting side to the left in the image. Blue line I is the upper line, the red line II the middle and the green line III is the lower line. Point two in line I is removed as it was an error when doing the series.



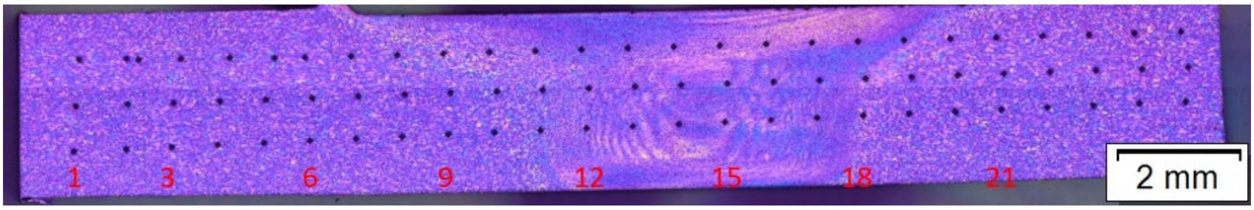


Figure 4-39 Vickers HV for Experiment 8

4.4 Tensile Testing

Tensile Specimens is partly made after specifications in ISO6507 (International Organization for Standardization, 2016). During waterjet cutting some loss of materials made the width over the cross section decreasing around 1 mm. Area is measured over the cross section at three positions and an average mean is used for input during the tests and these new dimensions are used when calculating the tensile strength. Preparation of the specimens is done to make every specimen as similar as possible with grinding to remove the cutting edges. In Figure 4-40 is a graph from the Instron tensile testing machine for specimens 13-16. Elongation measurement failed for some tests as the elongation continued after the specimens reached the UTS. As elongation is not a part of the quality characteristics for the matrix experiment the interpolation is not carried out. The bending test shows that the welds are ductile. The tensile are in accordance to ISO6507. Full report included in Appendix for all specimens. The test result is presented below in Table 4-9.

Tensile extension [mm]

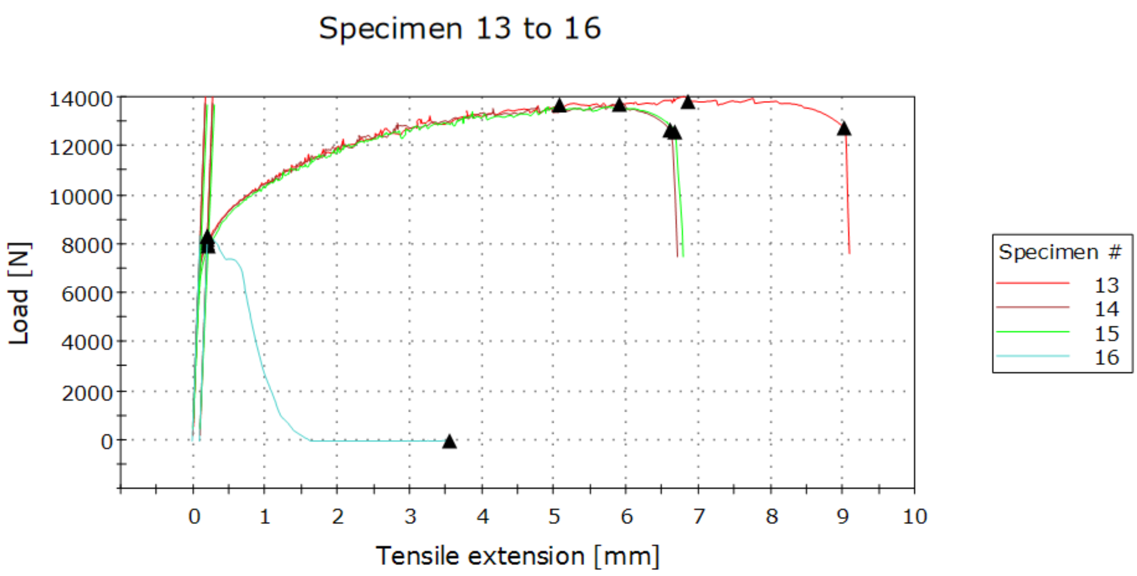


Figure 4-40 Tensile Test Graph

Table 4-9 Results for Tensile Testing

Test	Specimens name	E-Modul [MPa]	Rp0.2% [MPa]	UTS [MPa]	Extension [mm/mm]	Remarks
1	Spec 9-IV	64230	129.4	216.3|	0.11	
2	Spec 9-III	6500	130.3	221.1	0.13	
3	Spec 9-I	67610	133.1	165.3	-*	* Error in specified value
4	Spec 8-I	51940	123.7	218.5	0.14	
5	Spec 8-III	53160	127.5	213.5	0.11	
6	Spec 8-IV	61120	128.9	216.4	0.13	
7	Spec 7-I	55660	104.0	104.4	0.01	
8	Spec 7-III	48140	53.79	55.05	0.00	
9	Spec 7-IV	59610	126.6	212.7	-*	* Error in specified value
10	Spec 6-I	60710	137.1	147.7	0.01	
11	Spec 6-III	64530	133.9	212.4	0.11	
12	Spec 6-IV	62780	129.1	214.5	0.13	
13	Spec 5-I	63510	130.6	219.8	0.18	
14	Spec 5-III	60850	128.5	218.1	0.13	
15	Spec 5-IV	52850	126.3	217.7	0.13	
16	Spec 4-I	60730	132.5	132.6	-*	* Error in specified value
17	Spec 4-III	50600	126.4	173.9	0.04	
18	Spec 4-IV	57660	125.2	212.8	0.13	* Error in specified value

19	Spec 3-I [1]	53590	141.6	189.1	-*	* Error in specified value
20	Spec 3-III [1]	56510	135.8	206.2	-*	* Error in specified value
21	Spec 3-IV [1]	71420	129.8	208.5	-*	* Error in specified value
22	Spec 3A-I	61060	132.1	214.4	-*	* Error in specified value
23	Spec 3A-III	95340	135.0	219.1	0.12	
24	Spec 3A-IV	78520	128.9	214.3	0.12	
25	Spec 2-I	59340	143.2	208.6	-*	* Error in specified value
26	Spec 2-III	67080	140.3	219.9	0.16	
27	Spec 2-IV	59280	132.9	218.7	0.14	
28	Spec 1-I	61810	134.5	145.8	0.01	
29	Spec 1-III	64840	136.1	192.1	0.05	
30	Spec 1-IV	63990	132.5	215.5	0.13	
32	Spec OPT-II-TEST	-	-	-	-	Test of machine to check parameters
33	Spec OPT-I	63670	134.6	222.7	0.19	
34	Spec OPT-III	59360	134.0	220.1	0.13	
35	Spec OPT-IV	80380	28.9	219.3	0.15	
36	Base Material	62250	295.3	347.5	0.17	
37	Base Material	68110	299.7	347.6	0.16	
38	Base Material	75310	302.2	347.6	0.16	

5 Discussion

The friction stir welding is a delicate process with a lot of parameters involved that have an impact on the welding. By using force or position control the process parameters can be adjusted as the weld is produced leading to less defects. This project didn't use force control to monitor the downforce during welding. The position of the tool was controlled by the Mazak's integrated control system where the curvature of the plates was measured before welding started. These values were added or subtracted from the intended shoulder depth and programmed in the g-codes as linear interpolation at every 20 mm of weld line to get the tool shoulder travel at a constant depth across the hole length of the weld. Furthermore, the project did start from scratch with no experience from friction stir welding or running the Mazak milling centre. The welding jig and clamping system needed also to be designed and produced before any welding could be performed. This proved to be a challenging task due to having no knowledge about the linking between the welding jig, clamping system and welding parameters. Several test welds were performed using the first designed welding system and adjustment of weld parameters was done to counter for the defects found. This didn't work as welds with a groove like defect and with a trailing edge on the backside of the workpiece was found on almost every weld. The welding rig and clamping was further developed while searching for welding parameters that would make sound welds. After countless attempts without making good welds the cause to the problem were found and a better clamping system were made.

The reason for the edge defect seems to be the 2 mm plates try push it self-upwards during the welding session. The material thickness under the tool tip during welding is less than 0.2 and the material is also softened and in a plasticized state around the tooltip. The thermal expansion of the material seems to find this soften and thin area to be the easiest place to distort and release energy build up as the plate expands due to the temperature rise. The solution was to put the clamping bars as close to each other as possible and get an even force distribution holding the plates down against the backing plate. This fix solved the edge and groove defects found in the early welds. Temperature measurements was intended but as this also was found challenging to set up without spending a lot of time and effort using a datalogger with thermoelement, this was discharged from further exploration. Without the temperature measuring it's not easy to understand how the temperature distribution changed in the area around the weld due to the nearer clamping. As the plates are rigid supported and fixed under the clamping bar, a shorter distance from this clamping bar edge to the tool could lead to less thermal stress from the expansion of the material between both clamps.

Now as the welding jig and clamping system produced welds that was found acceptable the robust design approach could start. For the RDA a minimum of 10 welds is needed, 9 experiments and 1 confirmation weld. The process finding proper starting parameters and the clamping system acquired a lot of test welds and therefore less than 20 plates of the AA5754 alloy was available. From having 56 plates of AA6082 alloy only 20 of those with dimension 100x300 was left to do the matrix experiment. This issue didn't allow further investigation of the factor and their levels and they were chosen based on the test welds performed and email correspondence with Stirweld. Rotational speed that was used was 1400 rpm ± 200 rpm. The travel weld speed level interval was 150 mm/min and ±50 mm/min. This was because too much heat was added to the weld with lower welding speeds. For the dwell time 4 seconds ±2 seconds. For shoulder depth 0.9 mm ±0.02 mm was chosen.

Results from the robust design revealed the optimal parameters to be as follows; 1200 rpm rotational speed, 150 mm/min welding speed, 2 seconds of dwell time and a shoulder depth of 0.11 mm. Other combinations were also possible as the main effects calculated almost had identical values for some of the effects. This was not tested and simply the largest value for each main effect was identified as the optimal factor level. From the optimal parameters the lower levels for the dwell time and rotational speed is found to be the best option which can be a hint of need to weld using colder parameters. The main factor for the 0.07 mm shoulder and 0.11 mm shoulder depth have almost the exact same values, but the 0.09 mm shoulder depth seems to have poor influence on the tensile strength. This can't be explained and seems to be a strange result, but it can be due to interactions of factors.

The ANOVA analyse showed that the welding speed had most influence on the process contributing to 52% of the variation of η. Shoulder depth contributing to around 21%, rotational speed 17% and dwell time with only around 10 %.

The predicted tensile strength for the optimum weld was 244.7 MPa. The average value from the confirmation weld was 220.7 MPa with the highest measured ultimate tensile strength found to be 222.7 MPa. The value was lower than the predicted tensile strength but within the predicted error variance and confidence interval. The optimal weld gave the highest UTS value of all experiments. The x-ray testing found non defects, so the matrix experiment was successful. The Vickers however showed that all base material was heat affected with a reduction in hardness around 35% HV. This is not understood as temperature measurements is not performed and investigation using the Transmission Electron Microscope (TEM) would be needed to check the GP-zones or if the thermal exposure had led to precipitate coarsening or dissolution but this is not further discussed as it not part of the thesis to investigate such issues. Some microstructural change can be the reason the UTS was found to be around 222 MPa, 9 % lower than the predicted value as there can be an upper limit for what's possible to achieve using the experimental setup described. It's possible the heat input is too high by using hot welding parameters and the clamping method may keep the heat giving these processes time to evolve. The two-standard confidence interval for the predicted value showed a high value at ± 5.7 dB. This may be because the average tensile strength was found from using three specimens from the same weld experiment, knowing that there was a large variation in strength and quality for most of the experiments. But from an economical and time point of view, it would be impossible to perform three complete welds for each experiment to get the average mean value. Instead three tensile test specimens were cut out from each experiment and used for calculating the signal to noise ratio (S/N). Experiment 7 is an example of the variance added as the highest tensile strength for this experiment was found to be 212.7 MPa and the lowest value 55.1MPa this is a reduction around 74 % within the same weld using same parameters. By using 3 welds for each experiment this this is believed to decrease a lot as the repeatability from one weld to another would be the main source to increasing the variance.

The test specimen preparation for microscopic viewing was difficult as UIS didn't have equipment to properly mould the specimens in epoxy. The Struers CitoPress-30 mounting machine have only 25 mm cylinders and couldn't make perpendicular samples. Several attempts using different methods was explored but all samples were moulded with an inclined angle. More than a week of work was needed to develop a method to get the specimens proper moulded before grinding and polishing could be done.

Late in the project new knowledge about the Mazak machine having force control was given after mail correspondence with Ravema. The tool menu has an option in where thrust control is possible, this feature was used by Mazak on a similar project performing friction stir welds with a rebuild Mazak 530a machine. This was not tested but if the parameters adjust to keep a constant downforce excessive flash should in theory be easier to avoid.

6 Conclusion

Is it possible to perform friction stir welding using a CNC-machine without investing in expensive equipment to monitor the process? Yes indeed, but as this project have showed it takes a lot of effort and time to manage to get a sound weld. The Taguchi robust design approach did find the best combination of parameters, using the knowledge and experience gained from this project another matrix experiment should be conducted. Interaction among parameters can be tested to check which factors should be explored further. The thrust control feature in the tool menu could be interesting to test and maybe use as a factor. Monitoring the weld process using force control and/or position control would give a better control and understanding when finding the process window for sound welds.

The welding jig and clamping system seemed to be the main source to defects and problems encountered in the early stages of the project. This should be further explored and developing a welding jig and clamping system could be a thesis on its own.

It will be easier to understand the parameters used when welding having a proper welding jig and clamping system. The backing plate can be made as an inlay that could be inserted into the anvil depending on what material the user wants use as a backing plate. This can help with the temperature distribution during welds. If above issues are addressed the possibility of welding dissimilar alloys, and even other alloy such as magnesium and copper in future thesis would be there.

Microscopic testing using the transmission electron microscope (TEM) to investigate the reason for the hardness drop over the whole material.

One of the first things that should be tested doing a new friction stir weld project with the Mazak would be the thrust control feature in the machine tool menu as Mazak did a similar project and they used this feature to produce sound welds.

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8 Appendix

Excel Sheet

Experiment number	Welding Experiment Setup: Factors for welding experiment: A	B	C	D	Result: Input from tensile testing (Values from this table is used in worksheets): I	III	IV
	Rotation	Travel Speed	Dwell time	Shoulder depth	I	III	IV
1	1200	100	2	0,07	145,8	192,1	215,5
2	1200	150	4	0,09	208,6	219,9	218,7
3*	1200	200	6	0,11	214,4	219,1	214,3
4	1400	100	4	0,11	132,6	173,9	212,8
5	1400	150	6	0,07	219,8	218,1	217,7
6	1400	200	2	0,09	147,6	212,4	214,5
7	1600	100	6	0,09	104,4	55,05	212,7
8	1600	150	2	0,11	218,5	213,5	216,4
9	1600	200	4	0,07	165,3	221,1	216,3
OPT	1200	150	2	0,11	222,7	220,1	219,3

Hot Parameters	High Rotation	1400	rpm
	Low Travel speed	5	mm/min
Cold Parameters	Low Rotation	1000	rpm
	High Travel	15	mm/min
Shoulder depth	Critical values 0 mm and 0,15 mm Values in the range of 0.01 to 0.11		

utkli

Plunging speed 1-3 mm/s

Welding Parameters and Factors

Experiment	Prosess parameters for experiments: A	B	C	D
1	1200	100	2	0,07
2	1200	150	4	0,09
3	1200	200	6	0,11
4	1400	100	4	0,11
5	1400	150	6	0,07
6	1400	200	2	0,09
7	1600	100	6	0,09
8	1600	150	2	0,11
9	1600	200	4	0,07

Factor	Levels*: 1	2	3	Units
Roatation	1200	1400	1600	rpm
Travel Speed	100	150	200	mm/min
Dwell time	2	4	6	sec
Shoulder depth	0.07	0,09	0,11	mm

exp no	Start	Midt	slutt			
1	2349,00	2713	3263	647.0495	3152	3889
	2252	3815	3062	647.1307	2117	3687
2	1888	2602	3239	V		
	2193	3767	3423	h		
3	1626	3369	3569	V		
	2380	3700	3587	h		
4	1557	3078	2923	V		
	2617	3604	2887	h		
5	2065	3109	3561	V		
	2372	3243	2423	h		
6	1717	2911	3165	V		
	2145	3184	2834	h		
7	2645	3426	3447	V		
	3087	3895	3449	h		
8	2445	3103	2820	V		
	1867	2970	1894	h		
9	2334	3380	3284	V		
	2489	3783	3356	h		

Appendix Excel 1 - Robust Design Approach

FSW Experiment Result Tensile Testing

Experiment	Prosess parameters for experiments: A	B	C	D	Tensile test from welding experiments: I	II	III	Calculations: Mean	S/N ratio db	Trend	
1	1200	100	2	0,07	145,8	192,1	215,5	184,47	44,963		46,8
2	1200	150	4	0,09	208,6	219,9	218,7	215,73	46,671		46,7
3	1200	200	6	0,11	214,4	219,1	214,3	215,93	46,685		46,7
4	1400	100	4	0,11	132,6	173,9	212,8	173,10	44,278		46,7
5	1400	150	6	0,07	219,8	218,1	217,7	218,53	46,790		
6	1400	200	2	0,09	147,6	212,4	214,5	191,50	45,238		
7	1600	100	6	0,09	104,4	55,1	212,7	124,05	38,299		
8	1600	150	2	0,11	218,5	213,5	216,4	216,13	46,693		
9	1600	200	4	0,07	165,3	221,1	216,3	200,90	45,827		

Level 1
Level 2
Level 3

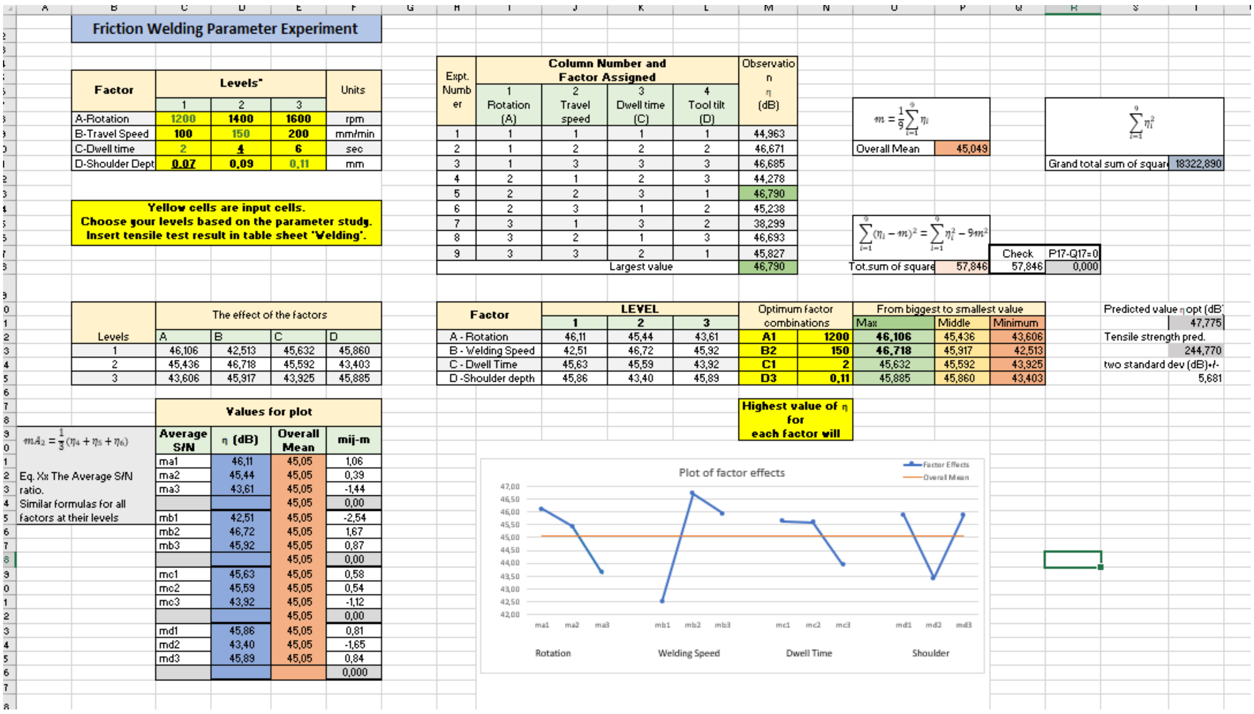
Input from tensile strenght testing
3 tensile test for each experiment

Verification Run With Optimum Parameters

Optimum parameters from experiments: A	B	C	D	Result from verification experiment: I	III	IV	Mean	Calculations: S/N ratio db	Trend	ηpred
1200	150	2	0.11	222,7	220,1	219,3	220,70	46,875		47,775

Insert values from tensile testing

Appendix Excel 2 - Robust Design Approach 2



Friction Welding Parameter Experiment

Factor	Levels* 1	2	3	Units
A-Rotation	1200	1400	1600	rpm
B-Travel Speed	100	150	200	mm/min
C-Dwell time	2	4	6	sec
D-Shoulder Dept	0,07	0,09	0,11	mm

Yellow cells are input cells. Choose your levels based on the parameter study. Insert tensile test result in table sheet "Welding".

Expt. Number	1 Rotation (A)	2 Travel speed	3 Dwell time (C)	4 Tool tilt (D)	Observation η (dB)
1	1	1	1	1	44,963
2	1	2	2	2	46,671
3	1	3	3	3	46,685
4	2	1	2	3	44,278
5	2	2	3	1	46,790
6	2	3	1	2	45,238
7	3	1	3	2	38,299
8	3	2	1	3	46,693
9	3	3	2	1	45,827
			Largest value		46,790

$m = \frac{1}{9}\sum_{i=1}^{9} \eta_i$ Overall Mean 45,049

$\sum_{i=1}^{9} \eta_i^2$ Grand total sum of squares 18322,890

$\sum_{i=1}^{9}(\eta_i - m)^2 = \sum_{i=1}^{9} \eta_i^2 - 9m^2$ Tot.sum of square 57,846 | Check 57,846 | P17-Q17=0 0,000

Levels	A	B	C	D
1	46,106	42,513	45,632	45,860
2	45,436	46,718	45,592	43,403
3	43,606	45,917	43,925	45,885

Factor	LEVEL 1	2	3	Optimum factor combinations		Max	Middle	Minimum
A - Rotation	46,11	45,44	43,61	A1	1200	46,106	45,436	43,606
B - Welding Speed	42,51	46,72	45,92	B2	150	46,718	45,917	42,513
C - Dwell Time	45,63	45,59	43,92	C1	2	45,632	45,592	43,925
D -Shoulder depth	45,86	43,40	45,89	D3	0,11	45,885	45,860	43,403

Highest value of η for each factor will

Predicted value η opt (dB) 47,775
Tensile strength pred. 244,770
two standard dev (dB)+/- 5,681

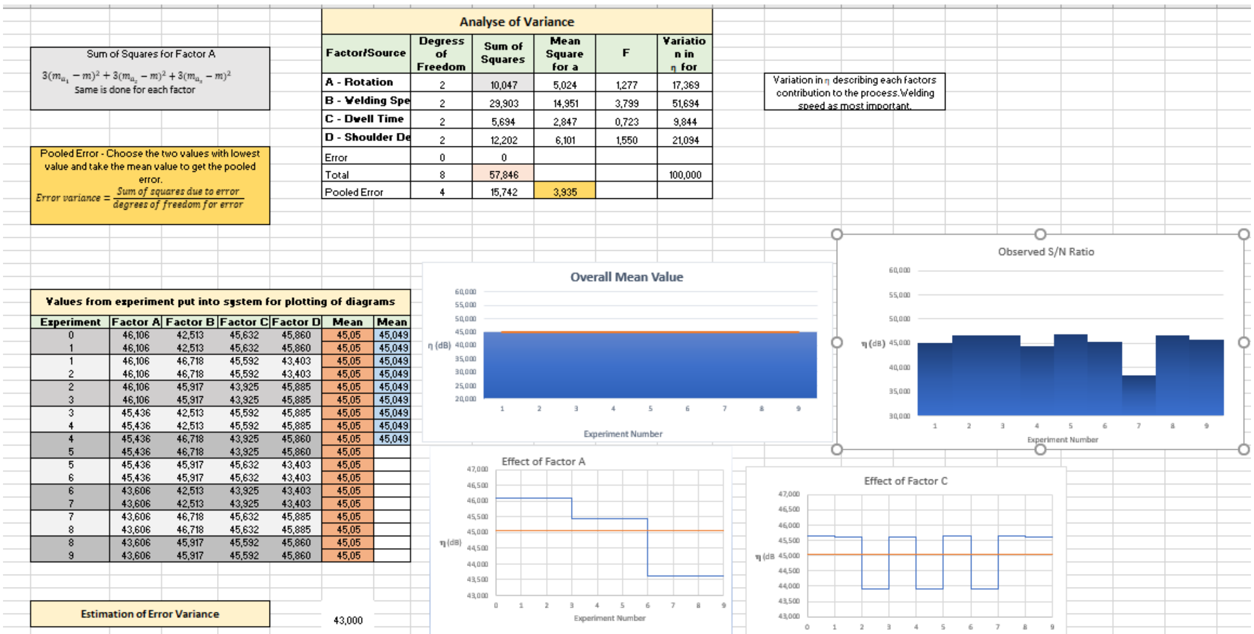
$m_{A_2} = \frac{1}{3}(\eta_4 + \eta_5 + \eta_6)$

Eq. X: The Average S/N ratio. Similar formulas for all factors at their levels

Values for plot

Average S/N	η (dB)	Overall Mean	mij-m
ma1	46,11	45,05	1,06
ma2	45,44	45,05	0,39
ma3	43,61	45,05	-1,44
		45,05	0,00
mb1	42,51	45,05	-2,54
mb2	46,72	45,05	1,67
mb3	45,92	45,05	0,87
		45,05	0,00
mc1	45,63	45,05	0,58
mc2	45,59	45,05	0,54
mc3	43,92	45,05	-1,12
		45,05	0,00
md1	45,86	45,05	0,81
md2	43,40	45,05	-1,65
md3	45,89	45,05	0,84
			0,000

Appendix Excel 3 - Robust Design Approach 3



Sum of Squares for Factor A

$3(m_{a_1} - m)^2 + 3(m_{a_2} - m)^2 + 3(m_{a_3} - m)^2$

Same is done for each factor

Analyse of Variance

Factor/Source	Degress of Freedom	Sum of Squares	Mean Square for a	F	Variation in η for
A - Rotation	2	10,047	5,024	1,277	17,369
B - Welding Spe	2	29,903	14,951	3,799	51,694
C - Dwell Time	2	5,694	2,847	0,723	9,844
D - Shoulder De	2	12,202	6,101	1,550	21,094
Error	0	0			
Total	8	57,846			100,000
Pooled Error	4	15,742	3,935		

Variation in η describing each factors contribution to the process.Welding speed as most important.

Pooled Error - Choose the two values with lowest value and take the mean value to get the pooled error.

$\text{Error variance} = \frac{\text{Sum of squares due to error}}{\text{degrees of freedom for error}}$

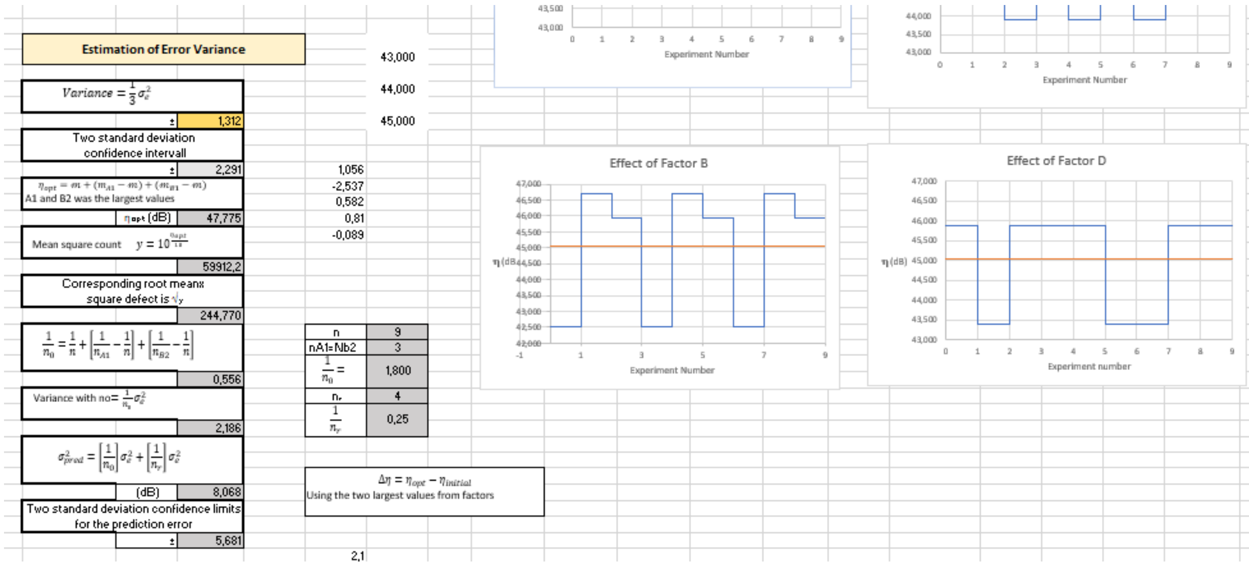
Values from experiment put into system for plotting of diagrams

Experiment	Factor A	Factor B	Factor C	Factor D	Mean	Mean
0	46,106	42,513	45,632	45,860	45,05	45,049
1	46,106	42,513	45,632	45,860	45,05	45,049
1	46,106	46,718	45,592	43,403	45,05	45,049
2	46,106	46,718	45,592	43,403	45,05	45,049
2	46,106	45,917	43,925	45,885	45,05	45,049
3	46,106	45,917	43,925	45,885	45,05	45,049
3	45,436	42,513	45,592	45,885	45,05	45,049
4	45,436	42,513	45,592	45,885	45,05	45,049
4	45,436	46,718	43,925	45,860	45,05	45,049
5	45,436	46,718	43,925	45,860	45,05	
5	45,436	45,917	45,632	43,403	45,05	
6	45,436	45,917	45,632	43,403	45,05	
6	43,606	42,513	43,925	43,403	45,05	
7	43,606	42,513	43,925	43,403	45,05	
7	43,606	46,718	45,632	45,885	45,05	
8	43,606	46,718	45,632	45,885	45,05	
8	43,606	45,917	45,592	45,860	45,05	
9	43,606	45,917	45,592	45,860	45,05	

Estimation of Error Variance

43,000

Appendix Excel 4 - Robust Design Approach 4



Appendix Excel 5 - Robust Design Approach 5

Appendix A

Universitetet
i Stavanger

Org.nr. 971564679

Bestilling

Dato:
24.04.2019

Bestillingsnummer:
UH1921157

Vår kontaktperson:
JØRGEN GRØNSUND
Telefon:
Epost: JORGEN.GRONSUND@UIS.NO

Leverandør
Smed T Kristiansen

Fakturaadresse
eFaktura - 9908:971564679
PDF-format - einvoices.uis@bscs.basware.com
Universitetet i Stavanger | Postboks 384, Alnabru
0614 Oslo

Leveringsadresse
Universitetet i Stavanger
UIS Postmottak
Rennebergstien 30
Kitty Kiellands Hus
4036 Stavanger

Melding til leverandør

Faktura og pakkseddel skal merkes med bestillingsnummer.
Vi forbeholder oss retten til å returnere fakturaer som ikke er korrekt merket.
Vennligst alltid send ordrebekreftelse per epost til vår kontaktperson!
Vennligst også påfør serienummer på faktura dersom varene har dette.

#	Artikkelnr.	Produktnavn	Ant.	Enh.	Lev. dato	Pris	Rab%	MVA%	Netto beløp	Brutto beløp
1		Kapping ihht spesifikasjoner fra Jan-Tore Jakobsen (UiS). 1 alu plate 2000x1000x2mm. 1 Alu plate 2000x1000x3mm.	1	EA		2 000,00	0	25	2 000,00	2 500,00

Total netto sum: **2 000,00 NOK**

Appendix A 1 - Order Smed.T.Kristiansen

Hei Svein

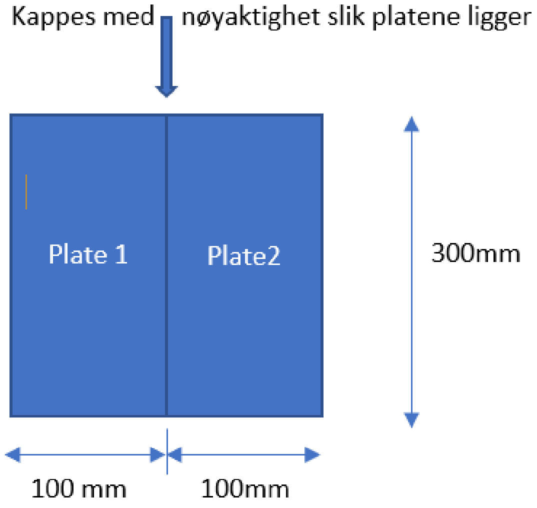
Her er en oversikt over hvordan kappingen skal gjøres.

Platene klippes i 100x300mm deler hvor ekstruderingsretningene må være lik for alle deler og det r merkes da dette er av stor betydning for med tanke på korn struktur i platen. Kappes med beste metode slik at korn struktur påvirkes minst mulig.

Kutt gjerne med ytre avvik på +/1 mm for å få maksimal utnyttelse av platen.

Platene skal butt sveises med friksjon så nøyaktighet med tanke på kapping er svært viktig. Kan ikke være mellomrom når 2 plater legges inntil hverandre før sveising

Kappes med nøyaktighet slik platene ligger tett.



Appendix A 2 Order Instructions to Smed.T.Kristiansen

Universitetet i Stavanger

Org.nr. 971564679

Bestilling

Dato:
27.06.2019

Bestillingsnummer:
UH1927961

Vår kontaktperson:
JØRGEN GRØNSUND
Telefon:
Epost: JORGEN.GRONSUND@UIS.NO

Leverandør
Sveiseservice AS

Fakturaadresse
eFaktura - 9908:971564679
PDF-format - einvoices.uis@bscs.basware.com
Universitetet i Stavanger | Postboks 384, Alnabru
0614 Oslo

Leveringsadresse
Universitetet i Stavanger, Teknisk Naturvitenskapelig Fakultet
Verkstedhall i bygg D ved inngang vest
Att: Jan-Tore Jakobsen
Kjølv Egelands Hus
4021 Stavanger

Melding til leverandør

Faktura og pakkseddel skal merkes med bestillingsnummer.
Vi forbeholder oss retten til å returnere fakturaer som ikke er korrekt merket.
Vennligst alltid send ordrebekreftelse per epost til vår kontaktperson!
Vennligst også påfør serienummer på faktura dersom varene har dette.

#	Artikkelnr.	Produktnavn	Ant.	Enh.	Lev. dato	Pris	Rab%	MVA%	Netto beløp	Brutto beløp
1	100003	Vannskjæring	1	EA		2 600,00	0	25	2 600,00	3 250,00

Total netto sum: **2 600,00 NOK**

Side 1/1

Appendix A 3 - Order Sveise Service AS

Universitetet i Stavanger

Org.nr. 971564679

Bestilling

Dato:
27.06.2019

Bestillingsnummer:
UH1927959

Vår kontaktperson:
JØRGEN GRØNSUND
Telefon:
Epost: JORGEN.GRONSUND@UIS.NO

Leverandør
Alunor metall AS

Fakturaadresse
eFaktura - 9908:971564679
PDF-format - einvoices.uis@bscs.basware.com
Universitetet i Stavanger | Postboks 384, Alnabru
0614 Oslo

Leveringsadresse
Universitetet i Stavanger
UIS Postmottak
Att: Jan-Tore Jakobsen
Rennebergstien 30
Kitty Kiellands Hus
4036 Stavanger

Melding til leverandør
Merk:
Sendes til
Sveiseservice AS
Arabergveien 2
4055 Sola

Faktura og pakkseddel skal merkes med bestillingsnummer.
Vi forbeholder oss retten til å returnere fakturaer som ikke er korrekt merket.
Vennligst alltid send ordrebekreftelse per epost til vår kontaktperson!
Vennligst også påfør serienummer på faktura dersom varene har dette.

#	Artikkelnr.	Produktnavn	Ant.	Enh.	Lev. dato	Pris	Rab%	MVA%	Netto beløp	Brutto beløp
1	1005	Aluminium plater. 3x1000x2000mm 1 plate(r) A IMgSi1 (Gul) EN-AW 6082 - T6 - AlSi1MgMn Leveringstid 5-7 dager	1	EA		3 000,00	0	25	3 000,00	3 750,00
2	20000	Emballasje	1	EA		230,00	0	25	230,00	287,50
3	10000	Frakt og fortolling	1	EA		2 950,00	0	25	2 950,00	3 687,50

Total netto sum: **6 180,00 NOK**

Side 1/1

Appendix A 4 - Order Alunor Metall

ALUNOR METALL AS

Vollsveien 13H
1366 Lysaker, Norge
Foretaksregisteret: NO 991 415 742 MVA
Telefon: 23 00 65 80
E-post: alunor@alunor.no
www.alunor.no

Universitetet I Stavanger
Postboks 8600 Forus
4036 STAVANGER
Attn.: Jan-Tore Jakobsen

Ordrebekreftelse

Ordrenummer:	3641	Ordredato:	2019-06-27
Vår kontakt:	Morten Askildt	Deres kontakt:	Jan-Tore Jakobsen
Referanse:	Jan-Tore - UIS-IHT 3395	Betalingsbetingelser:	14 dager
Leveransested:	SveiseService AS Arabergveien 2 4055 Sola		

Hei, og takk for forespørsel. Vi har gleden av å tilby følgende:
Tilbudet er gyldig i 3 uker fra dags dato.
Utgangspunkt for tilbudet er dagens valutakurs NOK/Euro.
En kursendring ut over 2% på fakturadato utløser en prisjustering.
Alunor Metall AS har generelle kredittgrenser, som må avtales ved større bestillinger.

•Tilbudet er uforbindtlig.Ved salg fra lager er det forbehold om mellomsalg. •Priser oppgitt er for det totale kvantum, ekskl. mva. •Vekt oppgitt er teoretisk, reell vekt kan avvike. •Kostnad for emballasje og evt. sertifikat kan komme i tillegg.

For våre salgs og leveringsbetingelser, se våre nettsider: http://www.alunormetall.no/om-oss/ for mer informasjon.
Hei, og takk for bestiling. Vi har gleden av å bekrefte følgende:

Utgangspunkt for ordren er dagens valutakurs NOK/Euro.
En kursendring ut over 2% på fakturadato utløser en prisjustering.
Alunor Metall AS har generelle kredittgrenser, som må avtales ved større bestillinger.

•Priser oppgitt er for det totale kvantum, ekskl. mva. •Vekt oppgitt er teoretisk, reell vekt kan avvike. •Kostnad for emballasje og evt. sertifikat kan komme i tillegg.

Se våre fyldige hjemmesider www.alunormetall.no
for ytterligere informasjon.

Beskrivelse	*Antall*	*Enh.pris (eks. mva)*	*Beløp (eks. mva)*	*Mva (25%)*	*Beløp (inkl. mva)*
1005 Aluminium plater. 3x1000x2000mm 1 plate(r) A lMgSi1 (Gul) EN-AW 6082 - T6 - AlSi1MgMn Leveringstid 5-7 dager	1 stk	3 000,00	3 000,00	750,00	3 750,00
20000 Emballasje	1	230,00	230,00	57,50	287,50
10000 Frakt og fortolling. Frakt etter regning ca pris	1	2 950,00	2 950,00	737,50	3 687,50
Sum (NOK)			**6 180,00**		**7 725,00**

Appendix A 5- Order Confirmation

Universitetet i Stavanger

Org.nr. 971564679

Bestilling

Dato:
18.03.2019

Bestillingsnummer:
UH1917920

Vår kontaktperson:
JØRGEN GRØNSUND
Telefon:
Epost: JORGEN.GRONSUND@UIS.NO

Leverandør
Alunor

Fakturaadresse
eFaktura - 9908:971564679
PDF-format - einvoices.uis@bscs.basware.com
Universitetet i Stavanger | Postboks 384, Alnabru
0614 Oslo

Leveringsadresse
Universitetet i Stavanger
UIS Postmottak
Att: Jan-Tore Jakobsen
Rennebergstien 30
Kitty Kiellands Hus
4036 Stavanger

Melding til leverandør
Kappes i hht vedlegg.

Faktura og pakkseddel skal merkes med bestillingsnummer.
Vi forbeholder oss retten til å returnere fakturaer som ikke er korrekt merket.
Vennligst alltid send ordrebekreftelse per epost til vår kontaktperson!
Vennligst også påfør serienummer på faktura dersom varene har dette.

#	Artikkelnr.	Produktnavn	Ant.	Enh.	Lev. dato	Pris	Rab%	MVA%	Netto beløp	Brutto beløp
1		AL Plate 3x1000x2000 1 stk 1 plate(r) AlMgSi1 (Gul) EN-AW 6082 - T6 - AlSi1MgMn. Kappes ihht vedlegg	1	EA		3 550,00	0	25	3 550,00	4 437,50
2		AL Plate 2x1000x2000 1 stk 1 plate(r) AlMg3 (Grøn) EN-AW 5754 - H12/H22 - AlMg3. Kappes ihht vedlegg	1	EA		2 950,00	0	25	2 950,00	3 687,50
3		Emballasje	1	EA		230,00	0	25	230,00	287,50
4		Frakt	1	EA		1 000,00	0	25	1 000,00	1 250,00

Total netto sum: 7 730,00 NOK

Appendix A 6- Order Alunor Metall 2

Universitetet i Stavanger

Org.nr. 971564679

Bestilling

Dato:
26.04.2019

Bestillingsnummer:
UH1921525

Vår kontaktperson:
JØRGEN GRØNSUND
Telefon:
Epost: JORGEN.GRONSUND@UIS.NO

Leverandør
IKM Instrutek

Fakturaadresse
eFaktura - 9908:971564679
PDF-format - einvoices.uis@bscs.basware.com
Universitetet i Stavanger | Postboks 384, Alnabru
0614 Oslo

Leveringsadresse
Universitetet i Stavanger
UIS Postmottak
Att: Jan-Tore Jakobsen
Rennebergstien 30
Kitty Kiellands Hus
4036 Stavanger

Melding til leverandør

Faktura og pakkseddel skal merkes med bestillingsnummer.
Vi forbeholder oss retten til å returnere fakturaer som ikke er korrekt merket.
Vennligst alltid send ordrebekreftelse per epost til vår kontaktperson!
Vennligst også påfør serienummer på faktura dersom varene har dette.

#	Artikkelnr.	Produktnavn	Ant.	Enh.	Lev. dato	Pris	Rab%	MVA%	Netto beløp	Brutto beløp
1	HILR843120IN	LR843120 Prosesslogger 10 kanaler	1	EA		11 287,00	0	25	11 287,00	14 108,75
2	MILJØ	Miljøavgift	1	EA		67,72	0	25	67,72	84,65

Total netto sum: **11 354,72 NOK**

Side 1/1

Appendix A 7 - Order IKM INSTRUTEK

Bestilling

Bestillingsnummer:
UH1917725

Dato:
15.03.2019

Org.nr. 971564679

Vår kontaktperson:
JØRGEN GRØNSUND
Telefon:
Epost: JORGEN.GRONSUND@UIS.NO

Leverandør
Stirweld

Fakturaadresse
eFaktura - 9908:971564679
PDF-format - einvoices.uis@bscs.basware.com
Universitetet i Stavanger | Postboks 384, Alnabru
0614 Oslo

Leveringsadresse
Universitetet i Stavanger
UIS Postmottak
Att: Jan-Tore Jakobsen
Rennebergstien 30
Kitty Kiellands Hus
4036 Stavanger

Melding til leverandør

Faktura og pakkseddel skal merkes med bestillingsnummer.
Vi forbeholder oss retten til å returnere fakturaer som ikke er korrekt merket.
Vennligst alltid send ordrebekreftelse per epost til vår kontaktperson!
Vennligst også påfør serienummer på faktura dersom varene har dette.

#	Artikkelnr.	Produktnavn	Ant.	Enh.	Lev. dato	Pris	Rab%	MVA%	Netto beløp	Brutto beløp
1		3ea F-AA1 Tool	1	EA		997,00	0	25	997,00	1 246,25
2		3ea F-AA2 Tool	1	EA		997,00	0	25	997,00	1 246,25
3		Transportation and handling	1	EA		200,00	0	25	200,00	250,00

Total netto sum: **2 194,00 EUR**

Side 1/1

Appendix A 8- Order Stirweld

Appendix B

X-Ray / Radiography of Optimum Weld Report

IKM Inspection AS

Radiographic Testing

CLIENT / KUNDE	CLIENT O.NO / KUNDE O.NR	DATE OF TESTING / KONTROLLDATO	REPORT NO. / RAPPORT NR.	PAGE / SIDE
UIS Stavanger	UH1928772	2019-07-29	180-8273-19-RT-1	1 of/av 1

DRAWING NO. / TEGNING NO.	PLACE OF WORK / KONTROLLSTED	OPERATOR / OPERATØR	ATTACHMENT / VEDLEGG
N/A	IKM Inspection AS	Sorin Erdei	0

OBJECT / KONTROLL AV
Test.
Welded Plate
Aluminium 3 mm WT

PROCEDURE / PROSEDYRE	REV	EXTENT OF TESTING / KONTROLLOMFANG	ACCEPTANCE STANDARD / AKSEPTSTANDARD
BPI-01.Radiographic Examination ISO 17636-1	00	100%	i

MATERIAL TYPE / MATERIALTYPE	HEAT TREATED / VARMEBEHANDLET	SURFACE / OVERFLATE	GROOVE / FUGEGEOMETRI	WELDING PROCESS / SVEISEPROSESS
Aluminium	No / Nei	Ground / Flushed	BW	141

EQUIPMENT / UTSTYR X-RAY TUBE / RØNTGENRØR	EQUIPMENT / UTSTYR ISOTOPE / ISOTOP
Smart 220	☐ Ir 192 ☐ Co 60 ☐ Se 75 ☐ Yt 169 ☐ Ingen

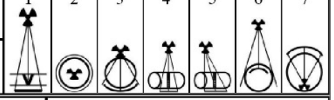
FOCAL SPOT SIZE / BRENNFLEKK	ACTIVITY / AKTIVITET
3	Gbq,Ci

EXP. DATA / EKS. DATA	A	B	C	D
TUBE/RØR VOLT kV	100			
FILMFOCUS DISTANCE FILMFOKUS AVSTAND mm	600			
EXP.TIME/ EKSP. TIME mAmin. Cimin.	0,7			

I.Q.I SOURCE SIDE/KILDE SIDE
☑ SOURCE SIDE/KILDESIDE
☐ FILM SIDE /FILMSIDE

TYPE OF I.Q.I. / I.Q.I. TYPE
W 13 AL

RADIATION SOURCE POSITION / KILDEPOSISJON
TECHNIQUE / TEKNIKK
1 2 3 4 5 6 7



DENSITY / SVERTNING	Ug	INTENSIFYING SCREENS / FOILER	FILM TYPE / FILMTYPE
2,3 - 3,5	0,1	Pb	D4

WELD NO SVEIS NR	DATE AND TIME DATO KL.	DIA. PIPE DIA RØR	FILM LOCATION FILM PLASSERING	SENSITIVITY FØLSOMHET % WIRE NR	WELDER SVEISER	MATERIAL THICKNESS TYKKELSE mm	EVALUATION BEDØMMELSE	DEFECT LOCATION FEILENS PLASSERING	REMARKS BEMERKNINGER	EXP. DATA A-D	TECH. TEGN. 1-7
Test	29-07-2019	Plate	0 - 240	W 15	--	3	Accepted	--	--	A	1

NS-EN ISO 6520-1:2007
Kolonne gir et tresifret referansenummer for hovedgruppen av uregelmessigheten og et firesifret referansenummer for undergrupper. Colum gives a three – figure reference number for the main group of the imperfection and a four–figure reference number for sub–terms.
Referanse no: - Reference No:
100/1000=Sprekk - Crack **200/2000**=Hulrom - Cavity **300/3000**=Fast inneslutting - Solid inclusion **400/4000**=Bindefeil og manglende gjennomsveising - Lack of fusion and penetration
500/5000=Uregelmessig form - Imperfect shape **600/6000**=Andre uregelmessigheter - Miscellaneous imperfection.

COMMENTS / KOMMENTARER

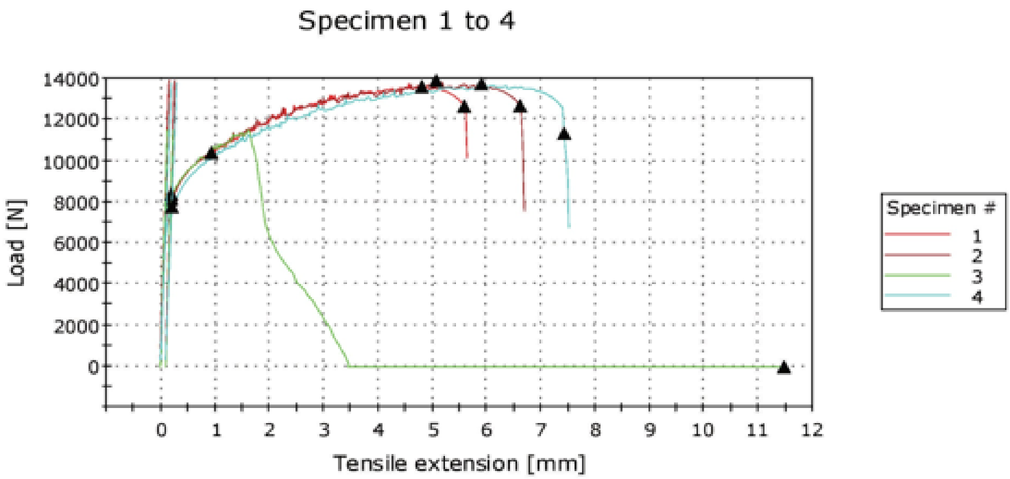
Result: Accepted.

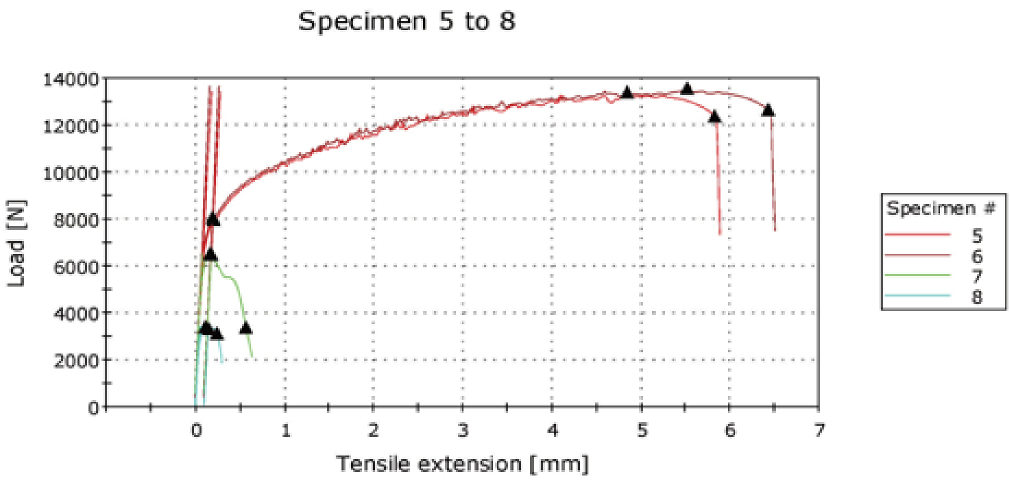
REPAIRS MARKED ON / REPARASJONER AVMERKET PÅ
☐ OBJECT / OBJEKT ☐ SKETCH / SKISSE

N3 NAME CERT. NO. / N3 NAVN SERT. NR.	N2 NAME CERT. NO. / N2 NAVN SERT. NR.	OPERATOR NAME CERT. NO. / OPERATØR NAVN SERT. NR.
()	Sorin Erdei (0816)	Sorin Erdei (0816)
APPROVED / GODKJENT DATO:	APPROVED / FILMLESER DATO:2019-07-29 **Approved /Godkjent** IKM Inspection AS	OPERATOR / OPERATØR DATO:2019-07-29 IKM Inspection AS

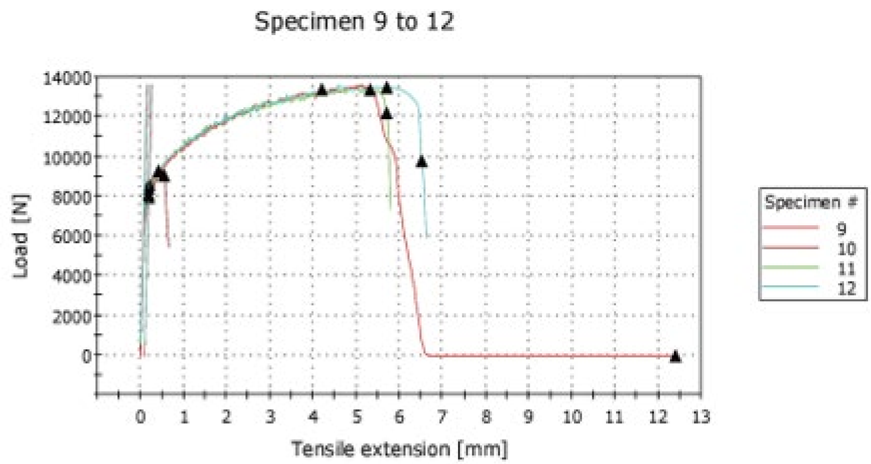
Appendix B 1 - Test Report IKM Inspection AS

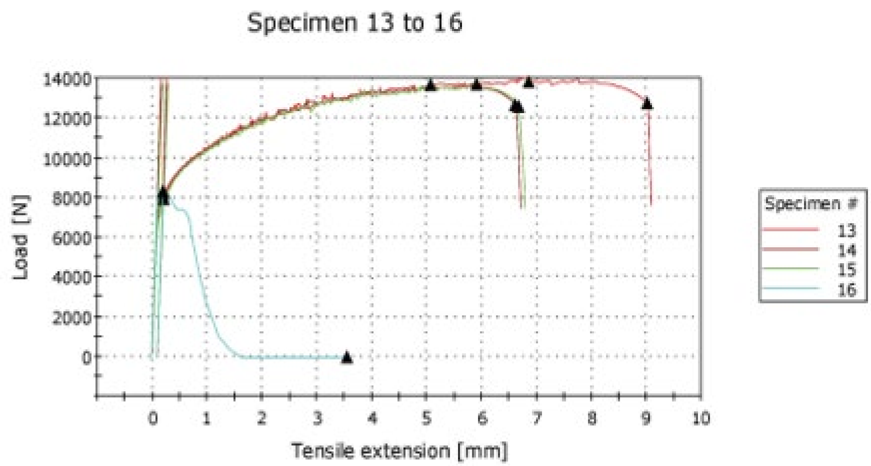
Tensile Test



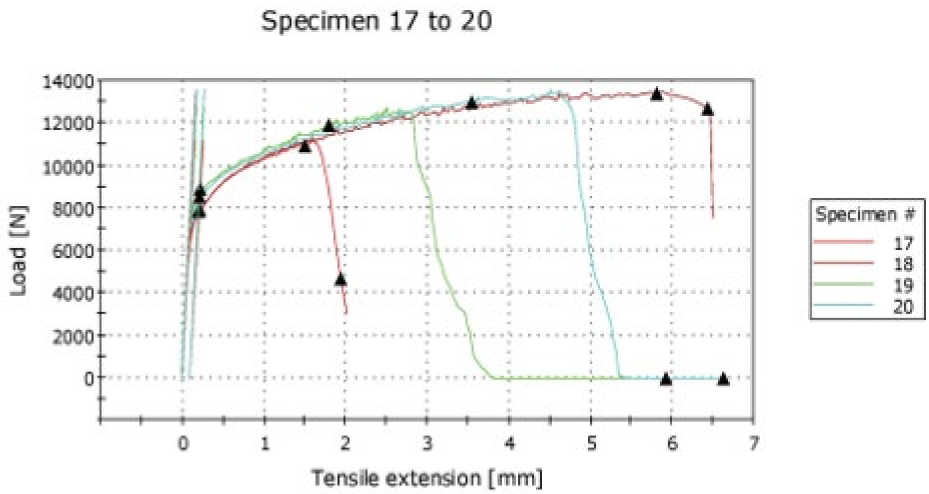


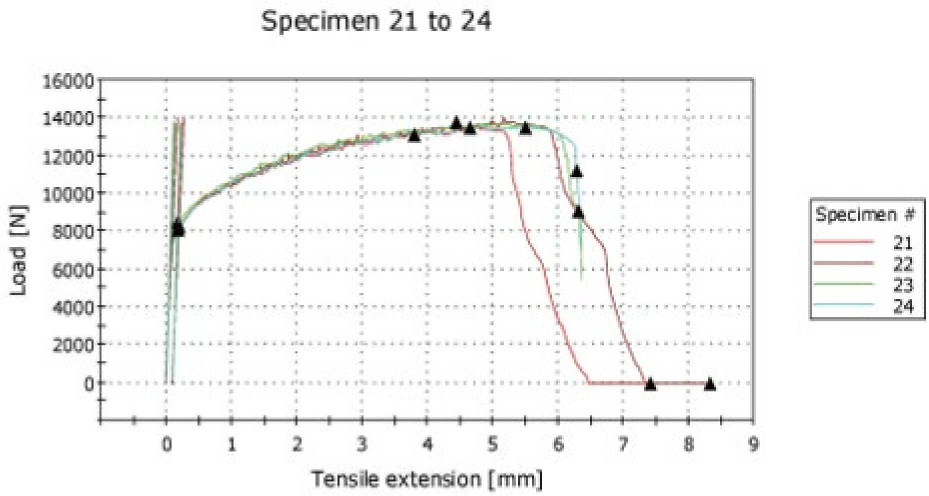
Appendix B 2 – Tensile Test for Specimen 1-8



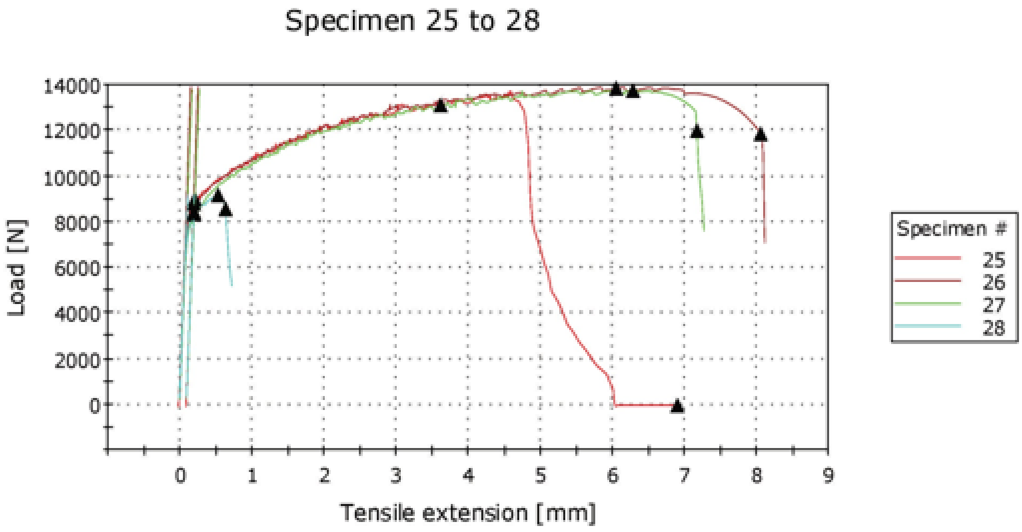


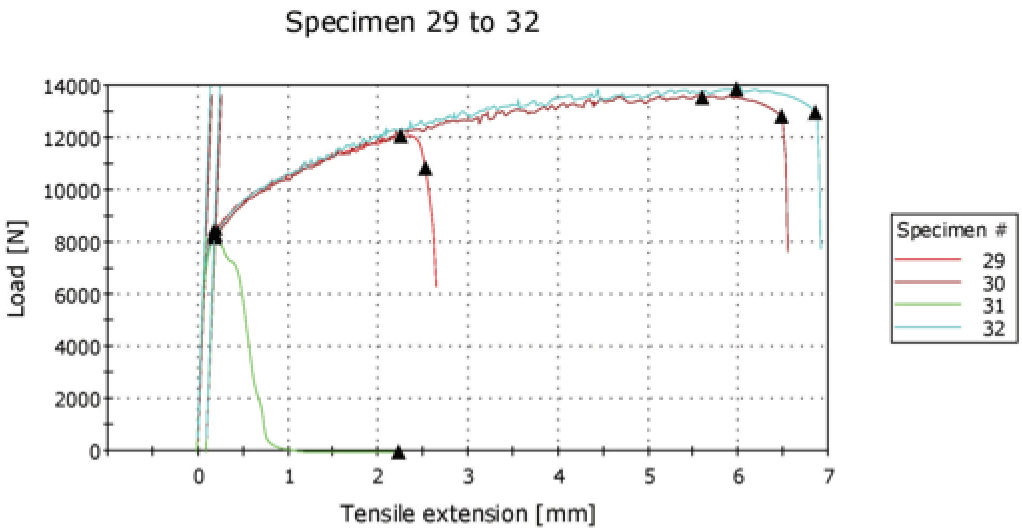
Appendix B 3- Tensile Test for Specimen 9-16



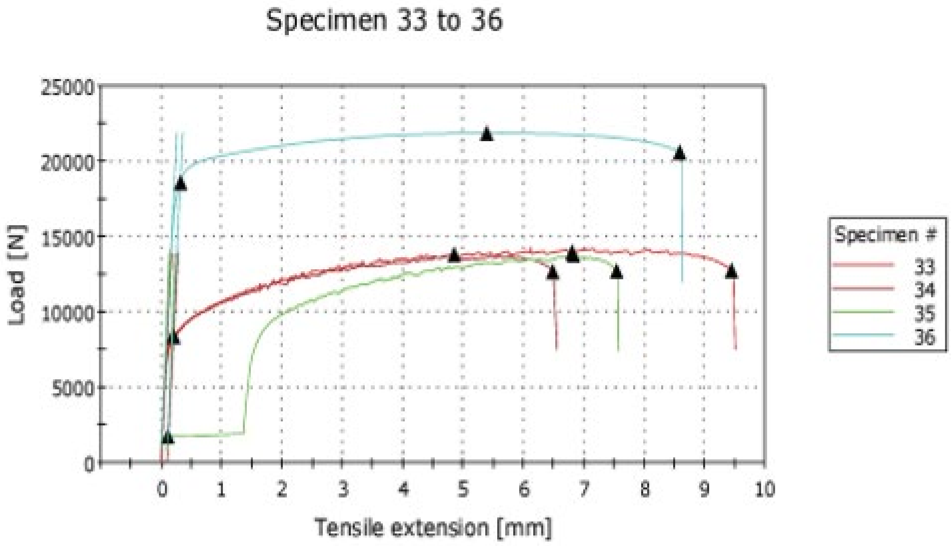


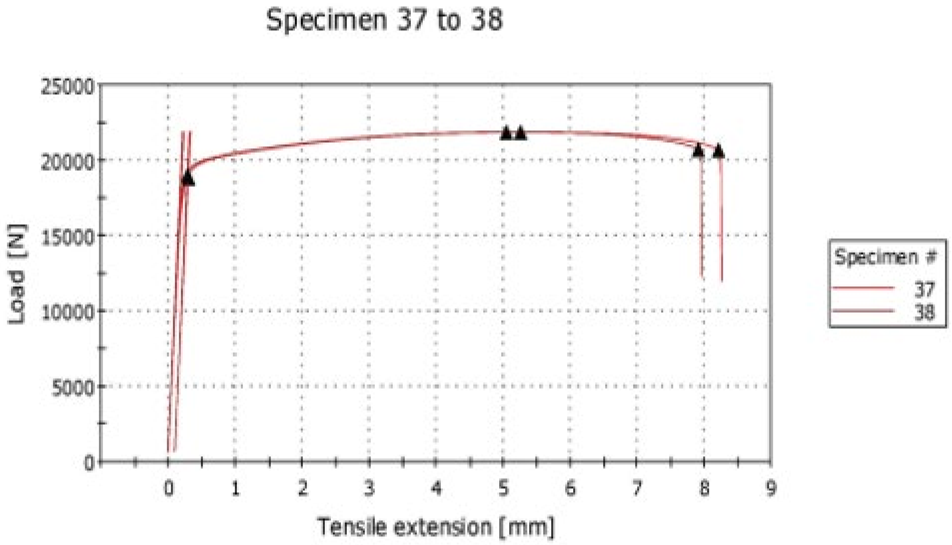
Appendix B 4 - Tensile Test for Specimen 17-24





Appendix B 5 - Tensile Test for Specimen 25-32





Appendix B 6 - Tensile Test for Specimen 33-38

	Prøve navn	E-modul [MPa]	Rp0.2% [MPa]	Rm [MPa]	A (forlengelse ved brudd) [mm/mm]
1	Spec 9-IV	64230	129.4	216.3	0.10919
2	Spec 9-III	65000	130.3	221.1	0.12927
3	Spec 9-I	67610	133.1	165.3	0.22932
4	Spec 8-I	51940	123.7	218.5	0.14476
5	Spec 8-III	53160	127.5	213.5	0.11263
6	Spec 8-IV	61120	128.9	216.4	0.12509
7	Spec 7-I	55660	104.0	104.4	0.01036
8	Spec 7-III	48140	53.79	55.05	0.00374
9	Spec 7-IV	59610	126.6	212.7	0.24810
10	Spec 6-I	60710	137.1	147.7	0.00855
11	Spec 6-III	64530	133.9	212.4	0.11147
12	Spec 6-IV	62780	129.1	214.5	0.12738
13	Spec 5-I	63510	130.6	219.8	0.17753
14	Spec 5-III	60850	128.5	218.1	0.12896
15	Spec 5-IV	52850	126.3	217.7	0.13098
16	Spec 4-I	60730	132.5	132.6	0.07112
17	Spec 4-III	50600	126.4	173.9	0.03740
18	Spec 4-IV	57660	125.2	212.8	0.12519
19	Spec 3-I	53590	141.6	189.1	0.11850

Page 5 of 6

Appendix B 7 - Tensile Test for Tensile Tables

	Prøve navn	E-modul [MPa]	Rp0.2% [MPa]	Rm [MPa]	A (forlengelse ved brudd) [mm/mm]
20	Spec 3-III	56510	135.8	206.2	0.13203
21	Spec 3-IV	71420	129.8	208.5	0.14835
22	Spec 3A-I	61060	132.1	214.4	0.16674
23	Spec 3A-III	95340	135.0	219.1	0.12414
24	Spec 3A-IV	78520	128.9	214.3	0.12355
25	Spec 2-I	59340	143.2	208.6	0.13861
26	Spec 2-III	67080	140.3	219.9	0.15803
27	Spec 2-IV	59280	132.9	218.7	0.14007
28	Spec 1-I	61810	134.5	145.8	0.01060
29	Spec 1-III	64840	136.1	192.1	0.04780
30	Spec 1-IV	63990	132.5	215.5	0.12674
31	TEST 1.august	66400	130.7	130.7	0.04464
32	Spec OPT-II-Test	71150	132.8	220.5	0.13426
33	Spec OPT-I	63670	134.6	222.7	0.18571
34	Spec OPT-III	59360	134.0	220.1	0.12606
35	Spec OPT-IV	80380	28.93	219.3	0.14765
36	Base	62250	295.3	347.5	0.16610
37	Base	68110	299.7	347.6	0.15897
38	Base	75310	302.2	347.6	0.15459

	Area [mm^2]
1	62.79000
2	62.76900
3	62.79000
4	62.79510
5	62.78490
6	62.79000
7	62.80500
8	62.78490
9	62.79000
10	62.79000
11	62.79000
12	62.80500
13	62.80500
14	62.79000
15	62.80500
16	62.80500
17	62.80500
18	62.82999
19	62.80500
20	62.80500
21	62.80500
22	62.80500
23	62.80500
24	62.80500
25	62.81499
26	62.80500
27	62.80500
28	62.80500
29	62.80500
30	62.80500
31	62.82000
32	62.88999
33	62.88999
34	62.88000
35	62.89000
36	62.88999
37	62.88999
38	62.88999

Appendix B 8- Tensile Test for Tensile Tables

Bending Test

Zwick / Roell

30.08.19

Test report

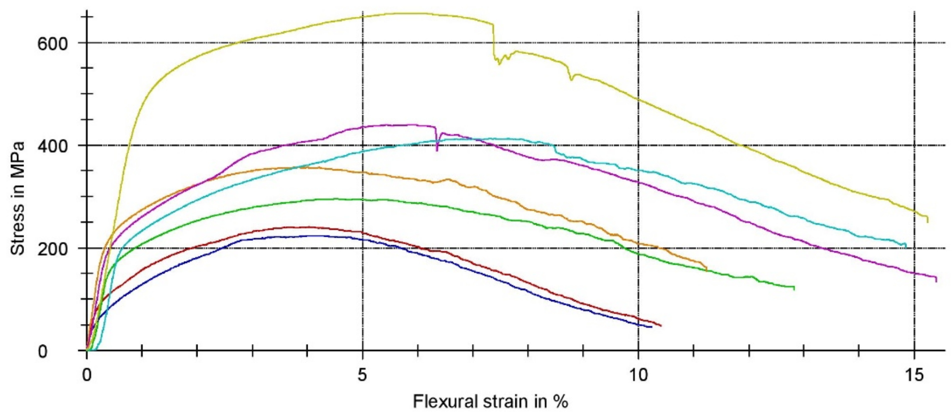
Customer	:		Specimen type	:	
Job no.	:		Pre-treatment	:	
Test standard	:	DIN EN ISO 178	Tester	:	
Type and designation of	:		Note	:	
Material	:		Machine data	:	
Specimen removal	:				

Pre-load : 0,1 MPa
Test speed : 20 mm/min

Test results:

Nr	Specimen no.	Date/Clock time	σ_{fC} MPa	σ_{fM} MPa	ε_{fM} %	σ_{fB} MPa	ε_{fB} %	Lv mm	h mm	b mm
1	1	30.08.2019 13:24:32	142	241	4,0	48,1	10	100	3	23,7
2	2	30.08.2019 13:30:13	195	296	4,5	-	-	100	3	21
3	3	30.08.2019 13:36:34	115	224	4,2	44,8	10	100	3	21
4	4	30.08.2019 13:42:25	260	357	3,8	-	-	80	3	22,5
5	5	30.08.2019 13:48:45	279	440	6,0	-	-	80	3	21
6	6	30.08.2019 13:52:57	251	413	7,3	-	-	80	3	31,3
7	7	30.08.2019 13:56:54	519	657	5,8	-	-	80	3	22,5

Series graph:



xcf052_01.zp2

Page 1/2

Appendix B 9 - Bending Tests

30.08.19

Zwick Roell

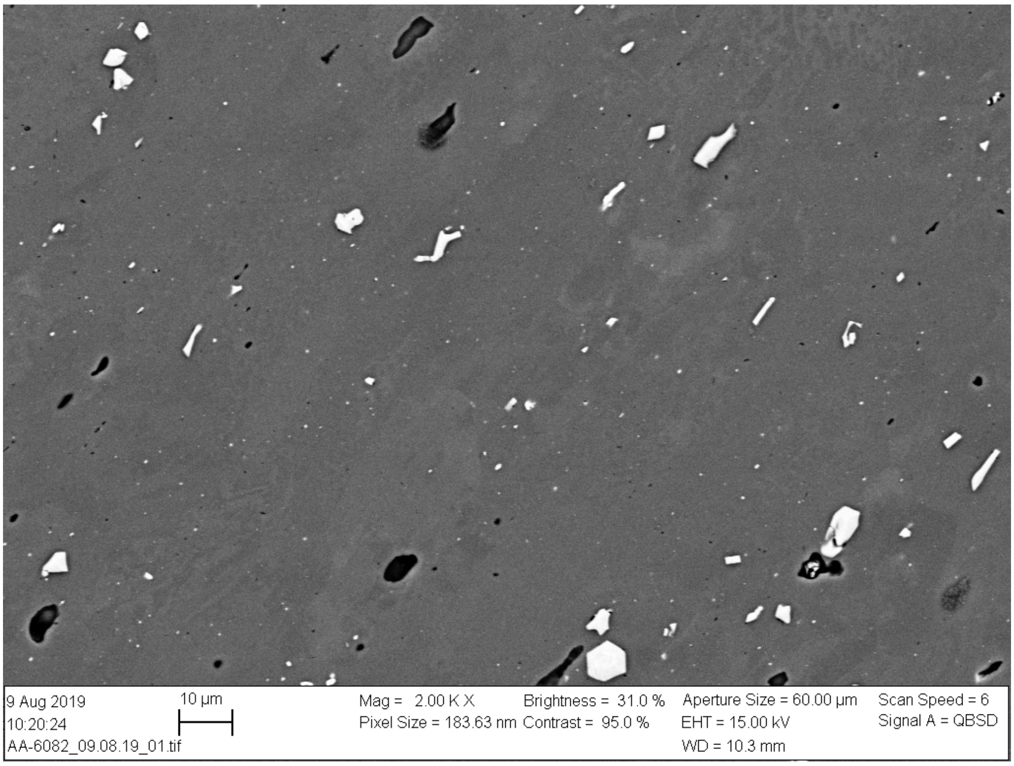
Statistics:

Series	Specimen no.	σ_{fC}	σ_{fM}	ε_{fM}	σ_{fB}	ε_{fB}	Lv	h	b
n = 7		MPa	MPa	%	MPa	%	mm	mm	mm
$\bar{x}$	4	252	375	5,1	46,4	10	88,57	3	23,29
s	2	133	149	1,3	2,32	0,12	10,69	0,000	3,681
ν	54,01	52,89	39,61	25,53	5,00	1,15	12,07	0,00	15,81

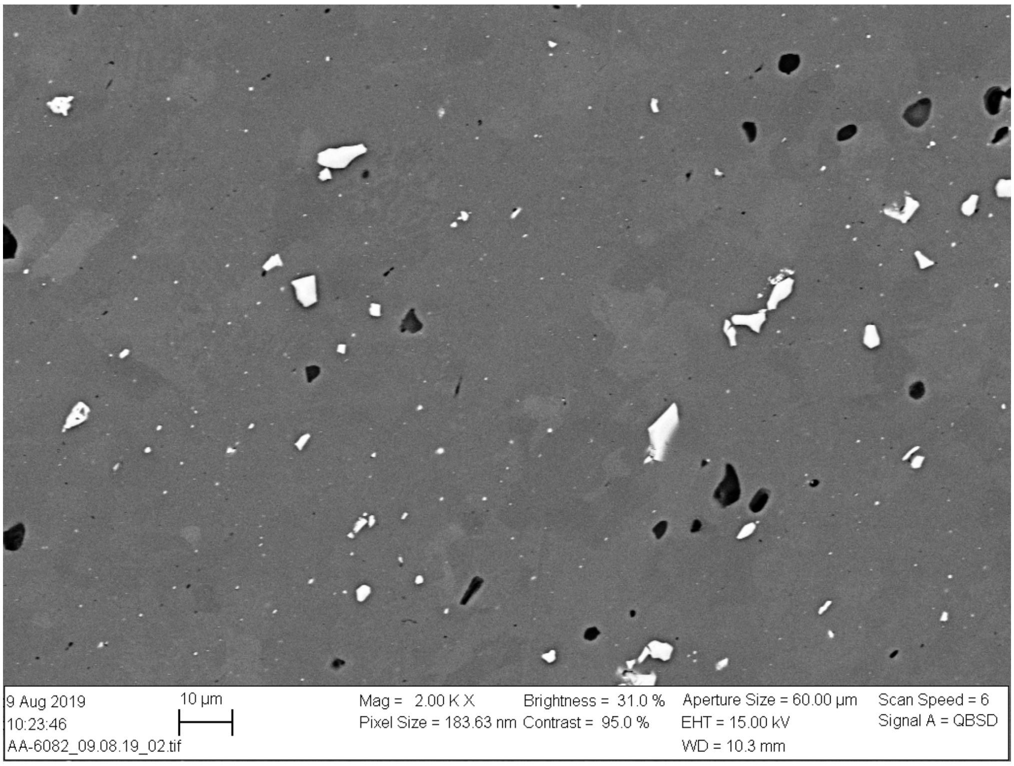
xcf052_01.zp2 **Page 2/2**

Appendix B 10 - Bending Tests

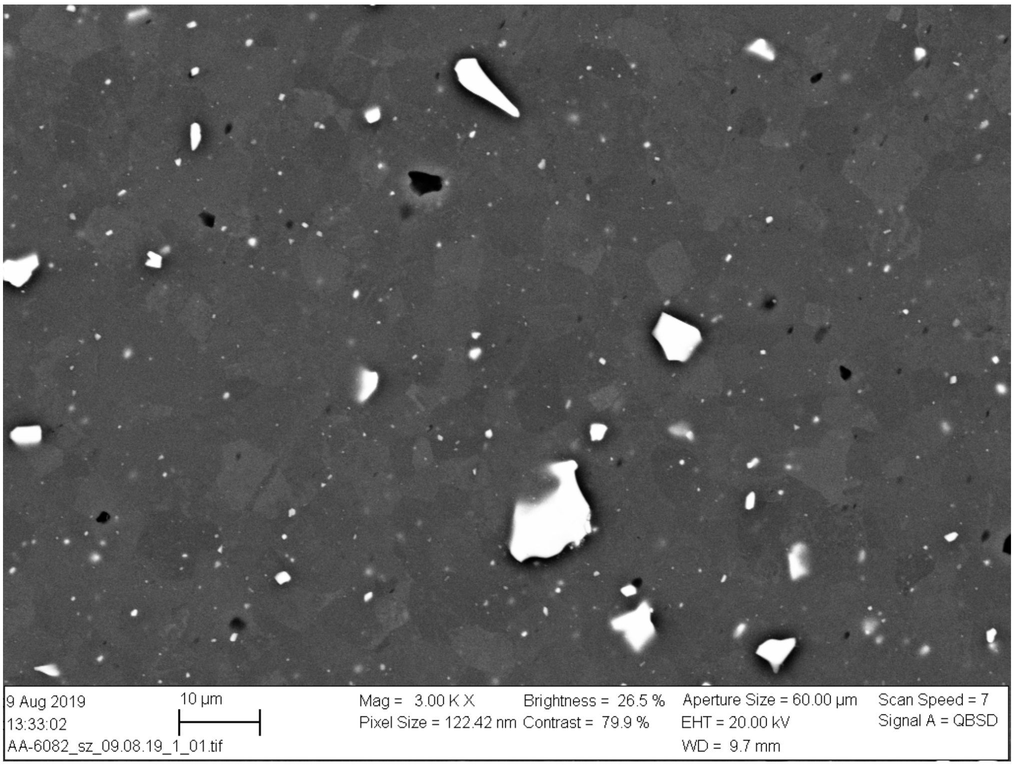
Scanning Electron Microscopy



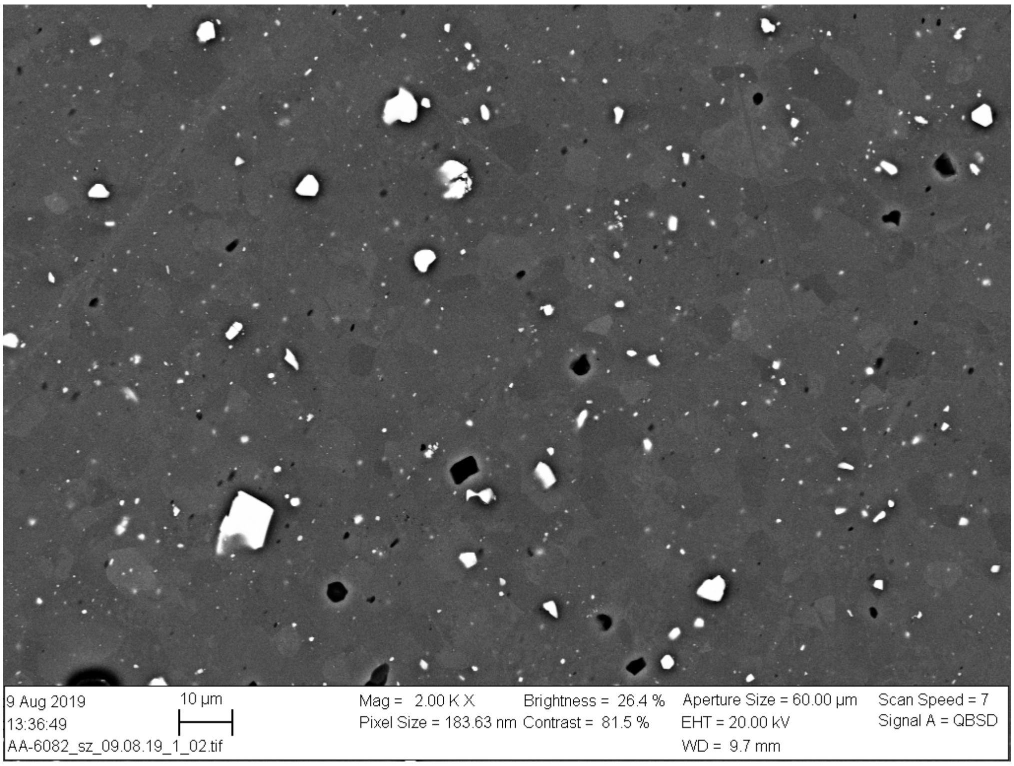
Appendix B 11 - 15kV Stir Zone



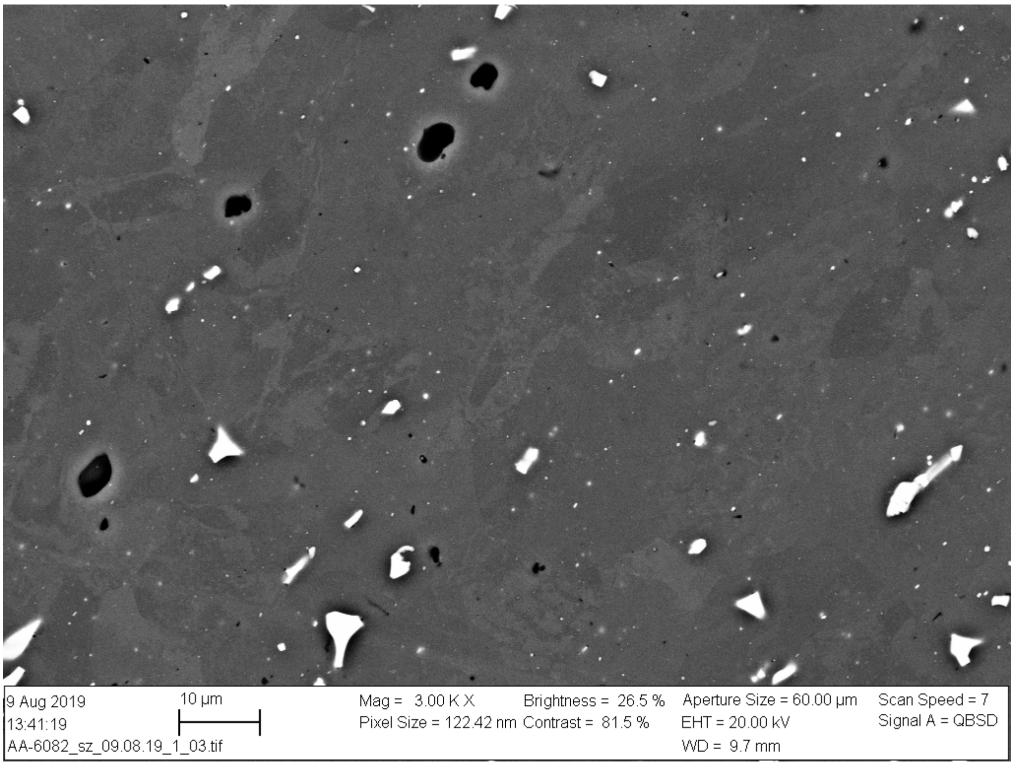
Appendix B 12 - 15 kV Stir Zone



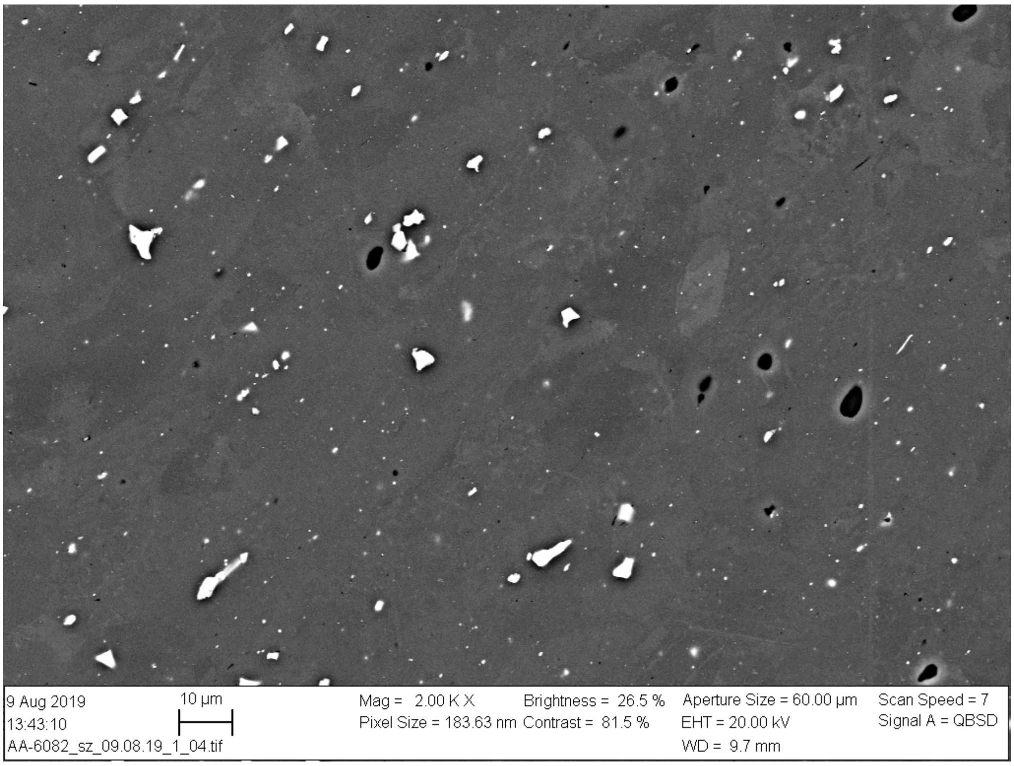
Appendix B 13- 20 kV Stir Zone



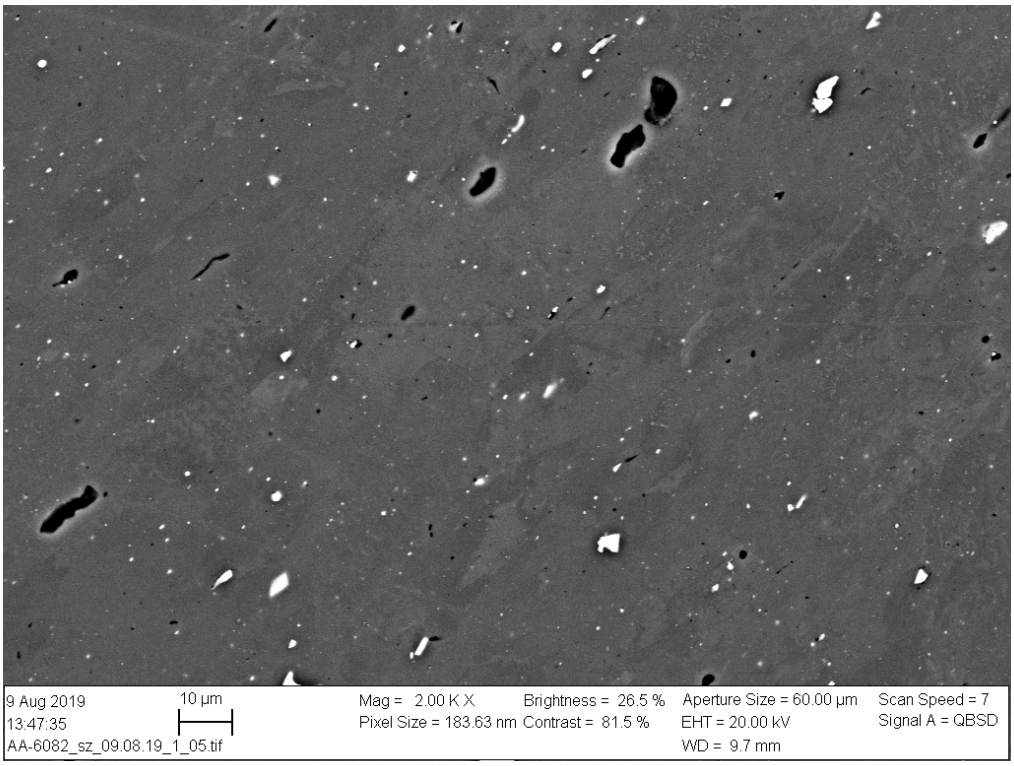
Appendix B 14- 20 kV Stir Zone



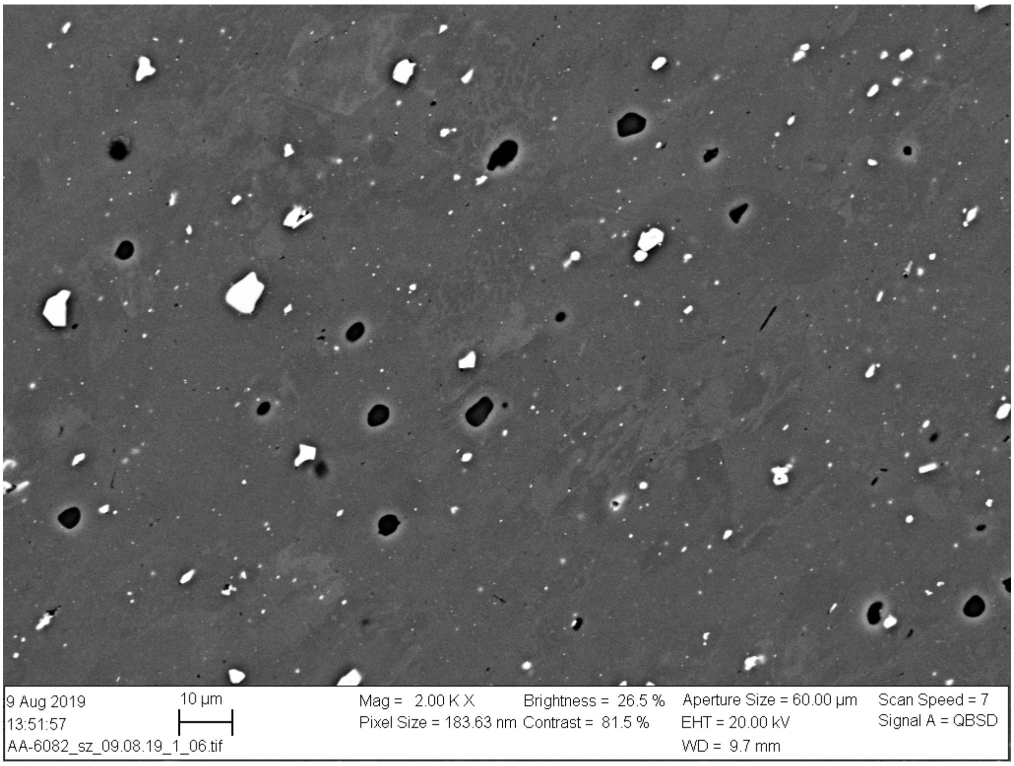
Appendix B 15 - 20 kV HAZ Near SZ



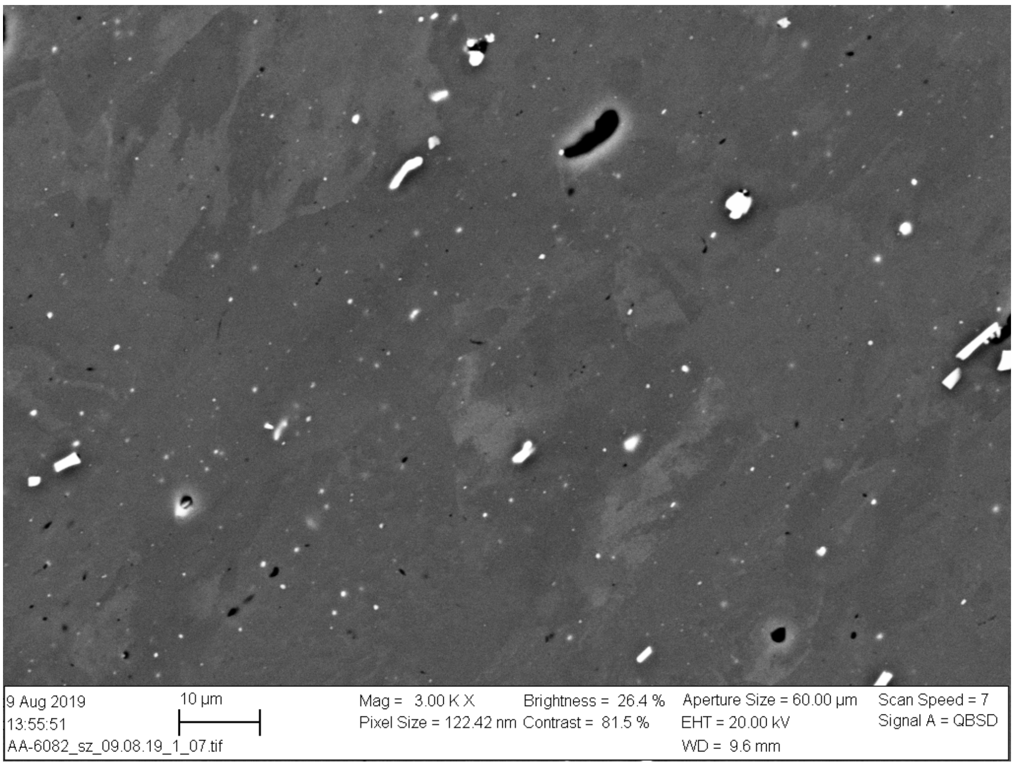
Appendix B 16 - 20kV HAZ Near SZ



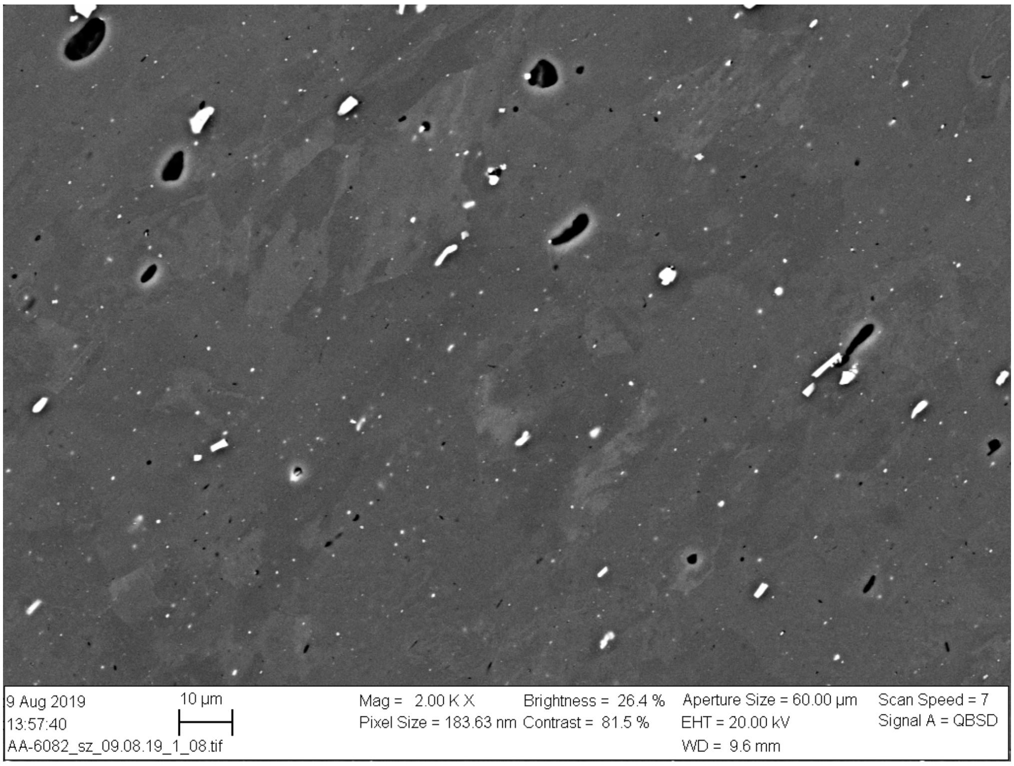
Appendix B 17 – 20kV Far away from the Stir Zone (10 mm)



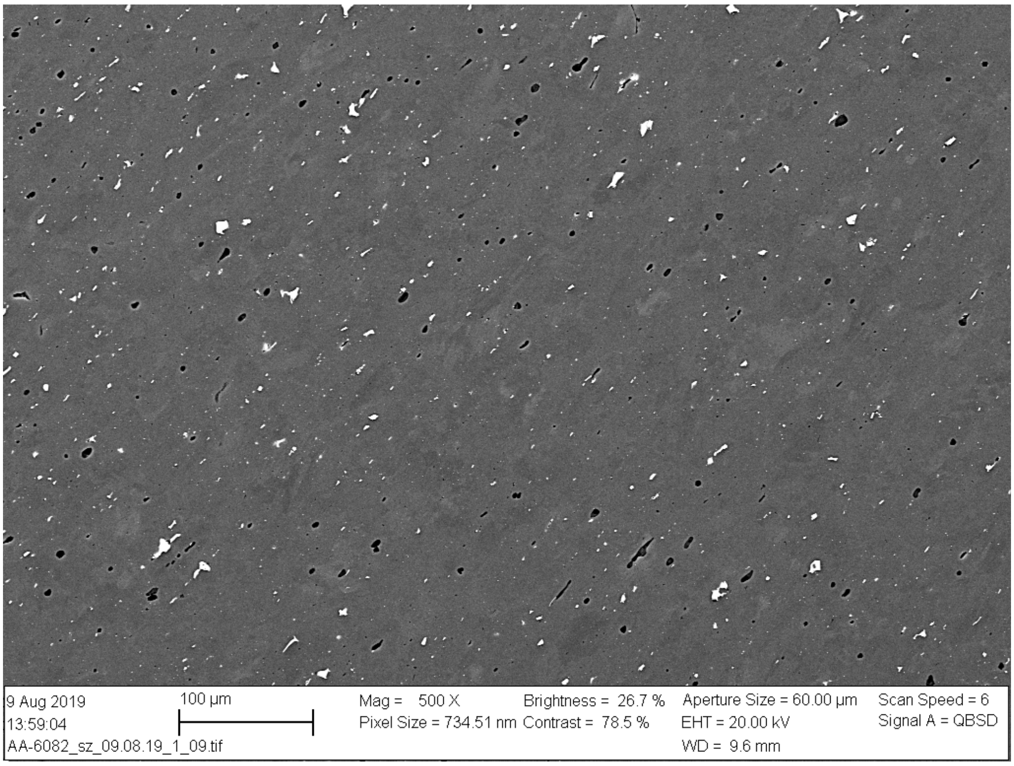
Appendix B 18 - 20 kV HAZ



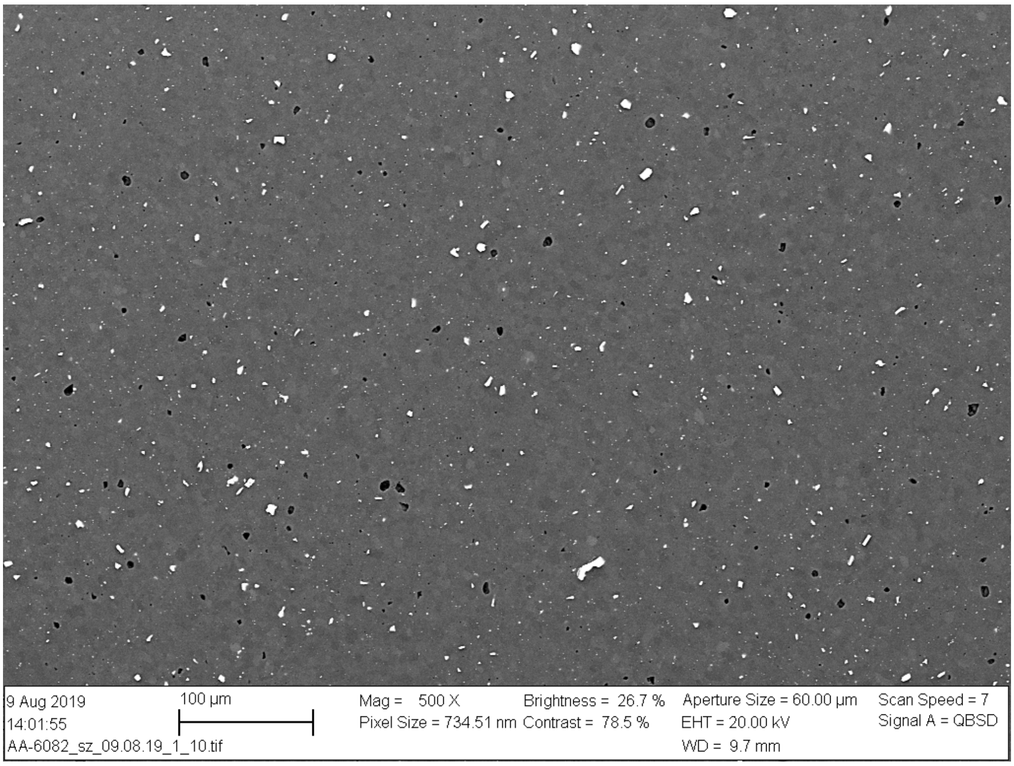
Appendix B 19 - Unknown Location



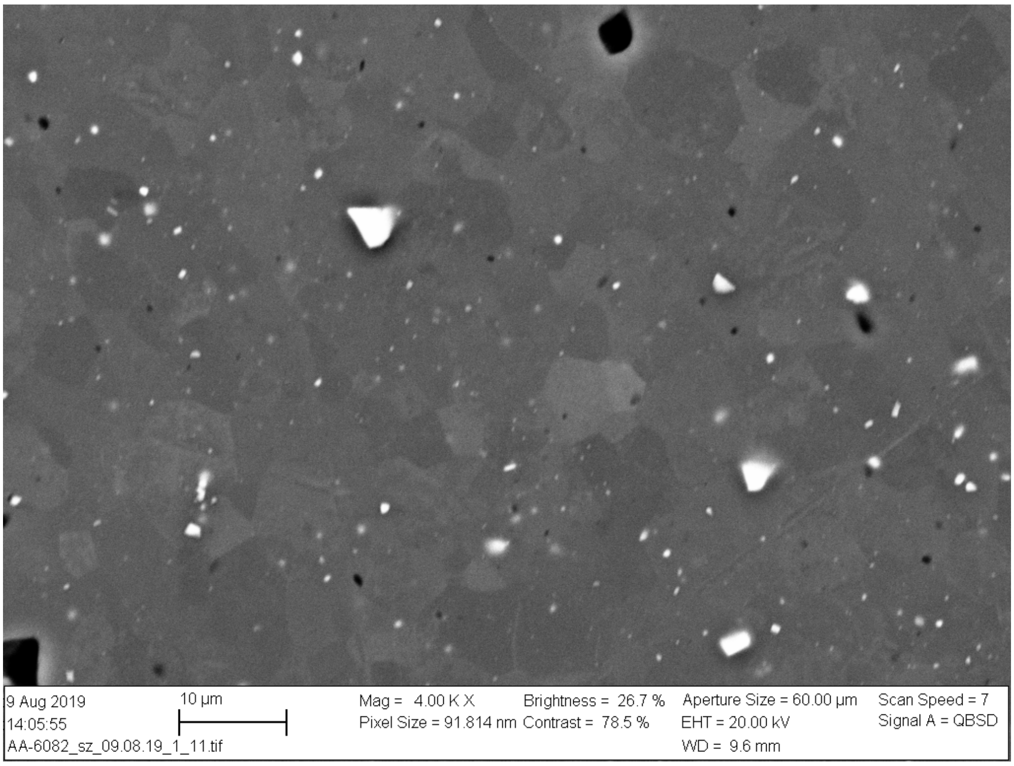
Appendix B 20 - Unknown Location II (HAZ)



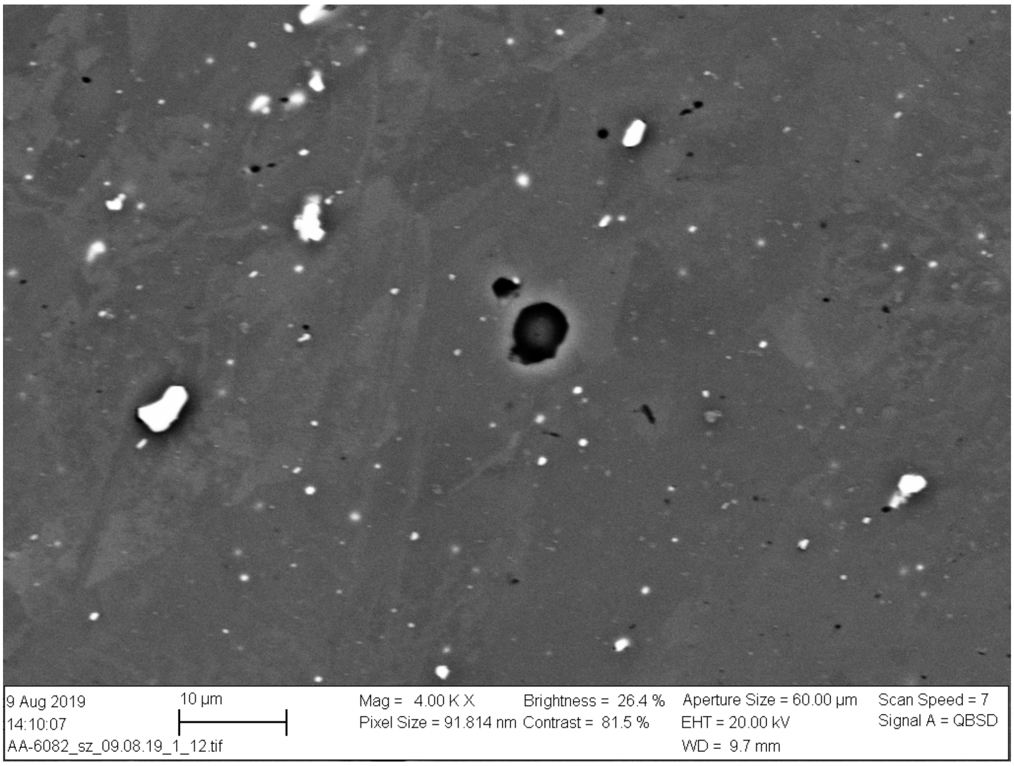
Appendix B 21 - 20 kV HAZ Far to the left (10 mm)



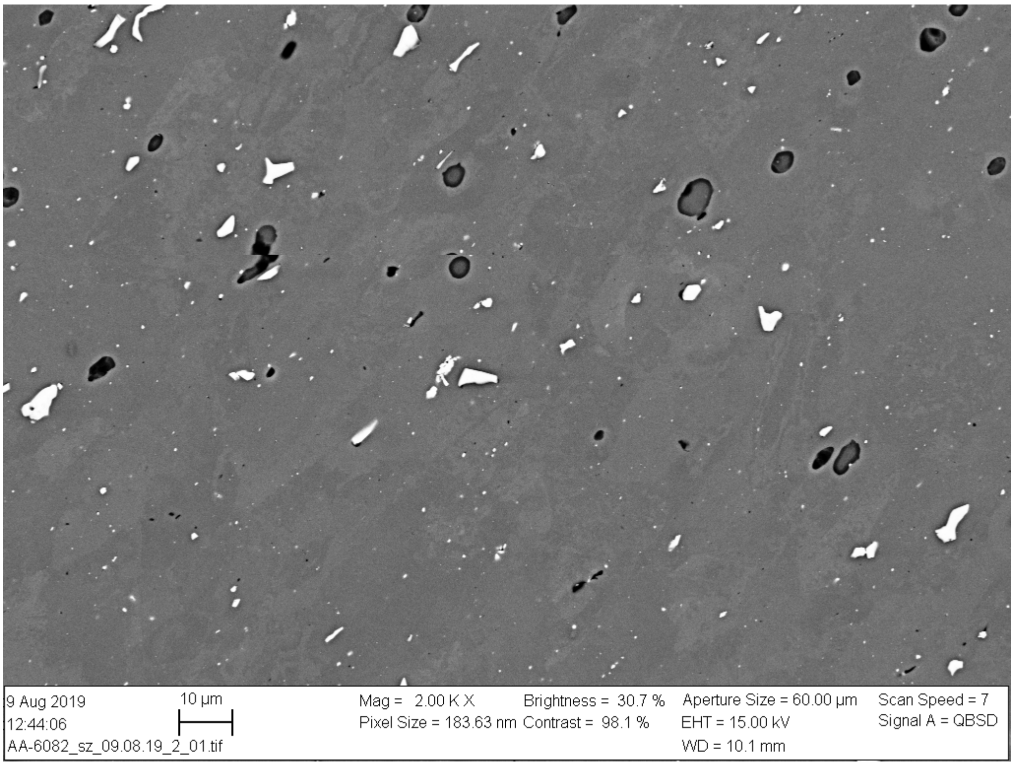
Appendix B 22 - 20 kV Stir Zone 100 ym



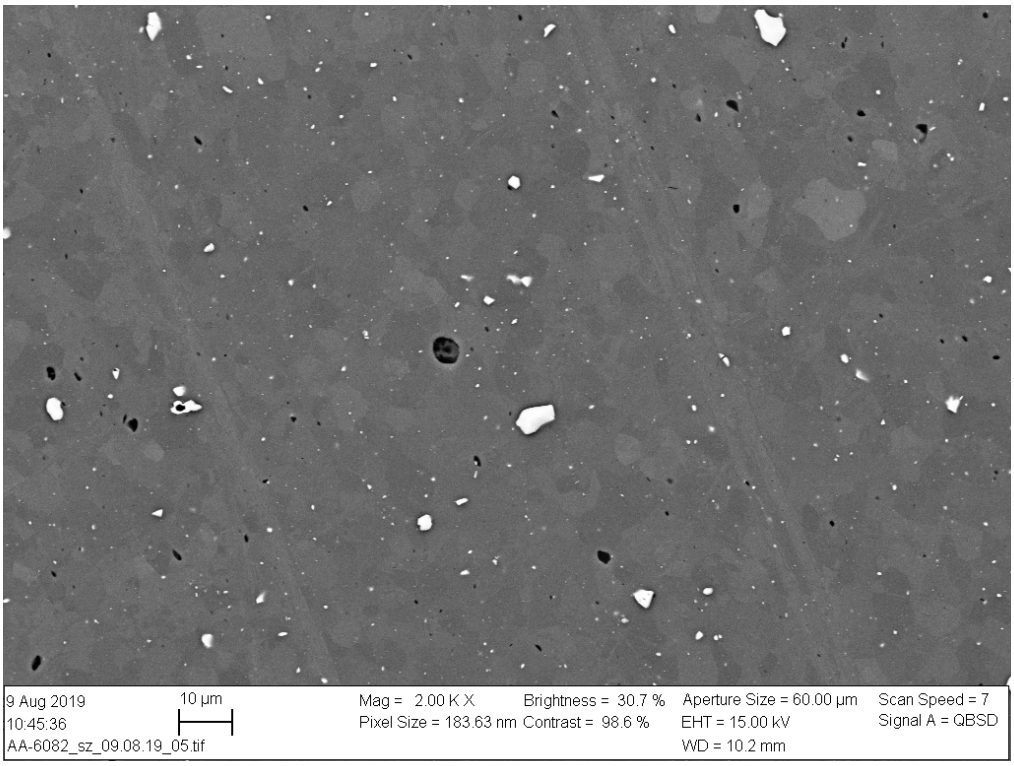
Appendix B 23 - 20 kV Stir Zone 10 ym



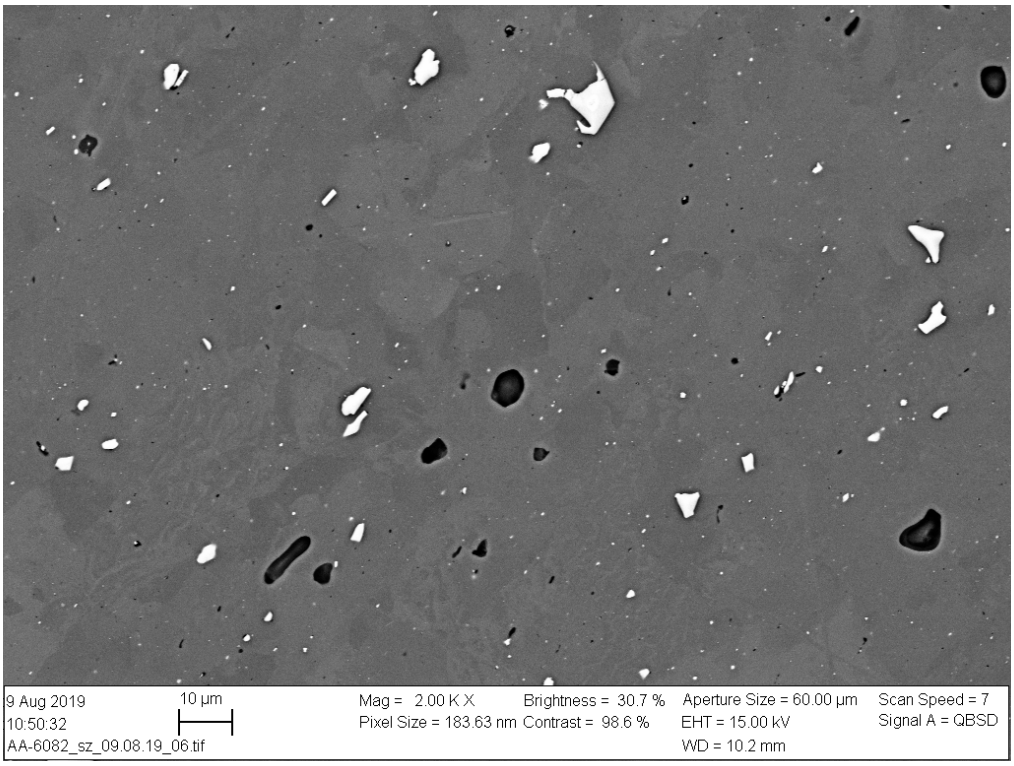
Appendix B 24 – Particle



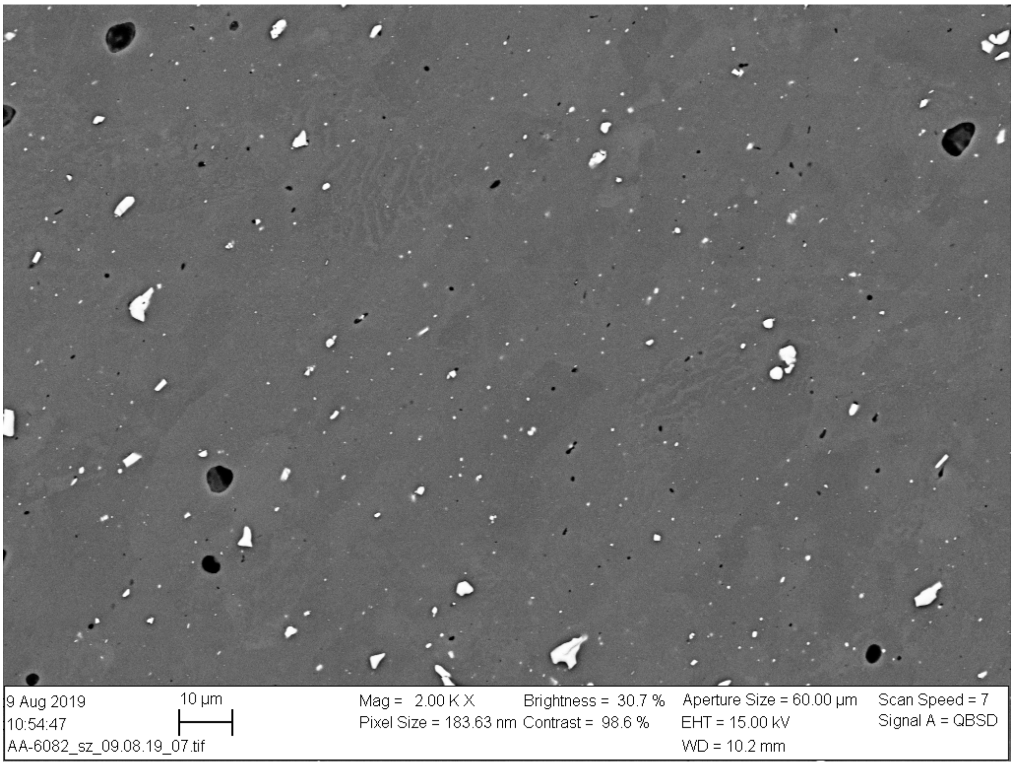
Appendix B 25 - 15 kV



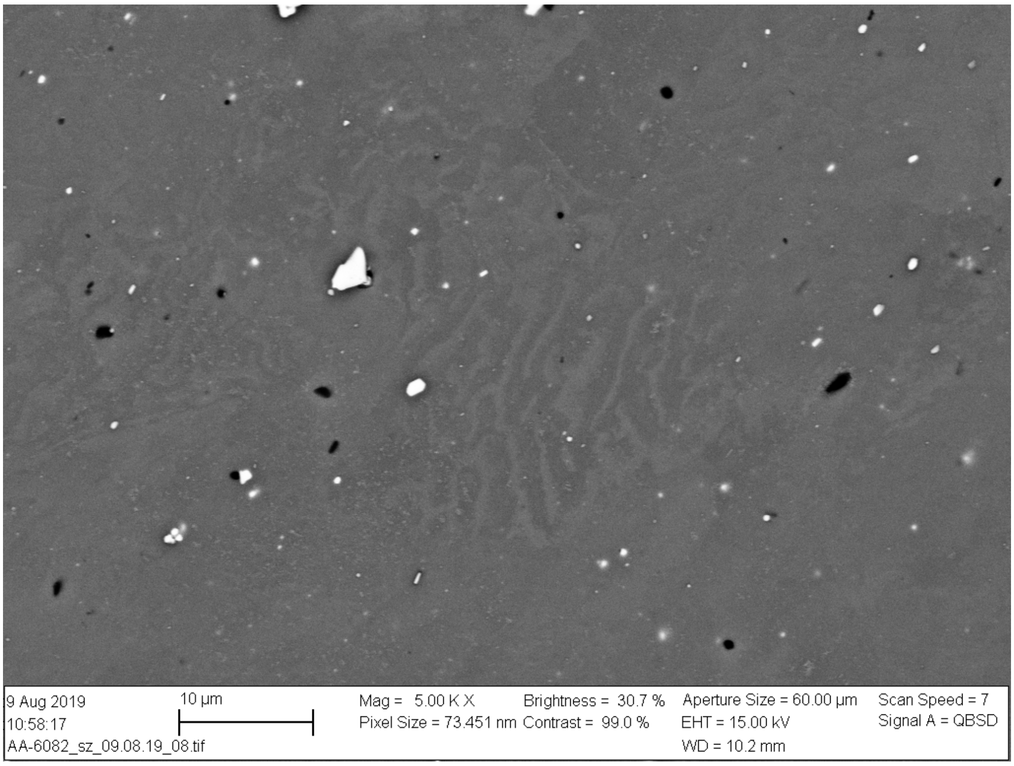
Appendix B 26 - 15kV Stir Zone



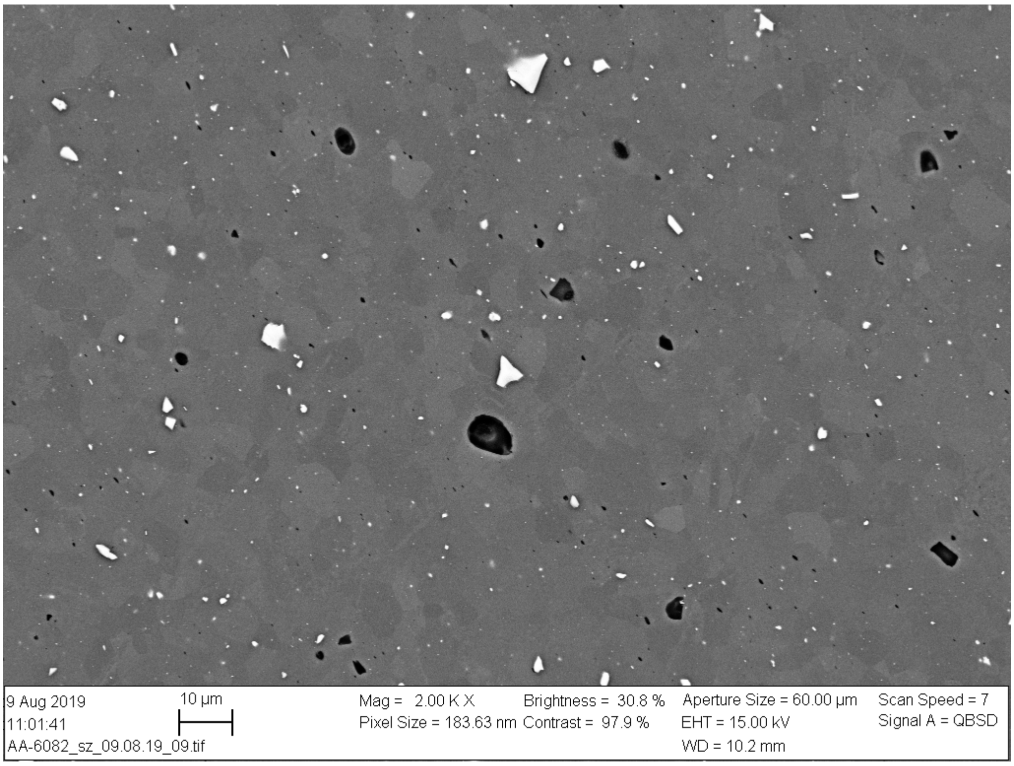
Appendix B 27 - 15 kV TMAZ/SZ



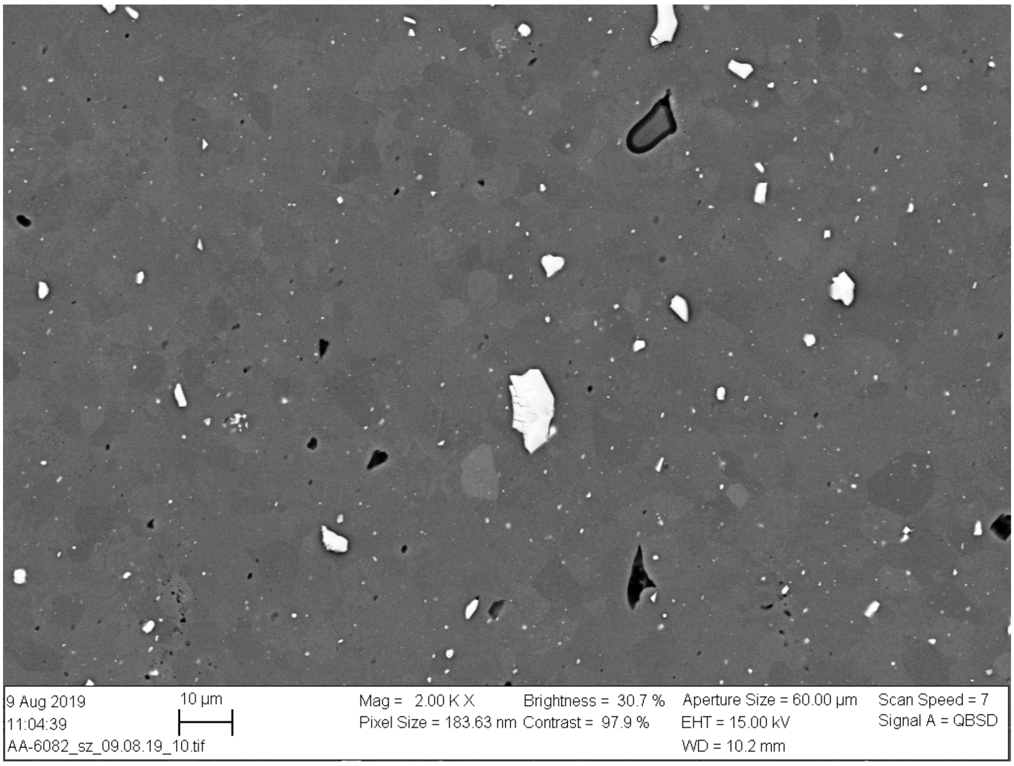
Appendix B 28 - TMAZ/HAZ



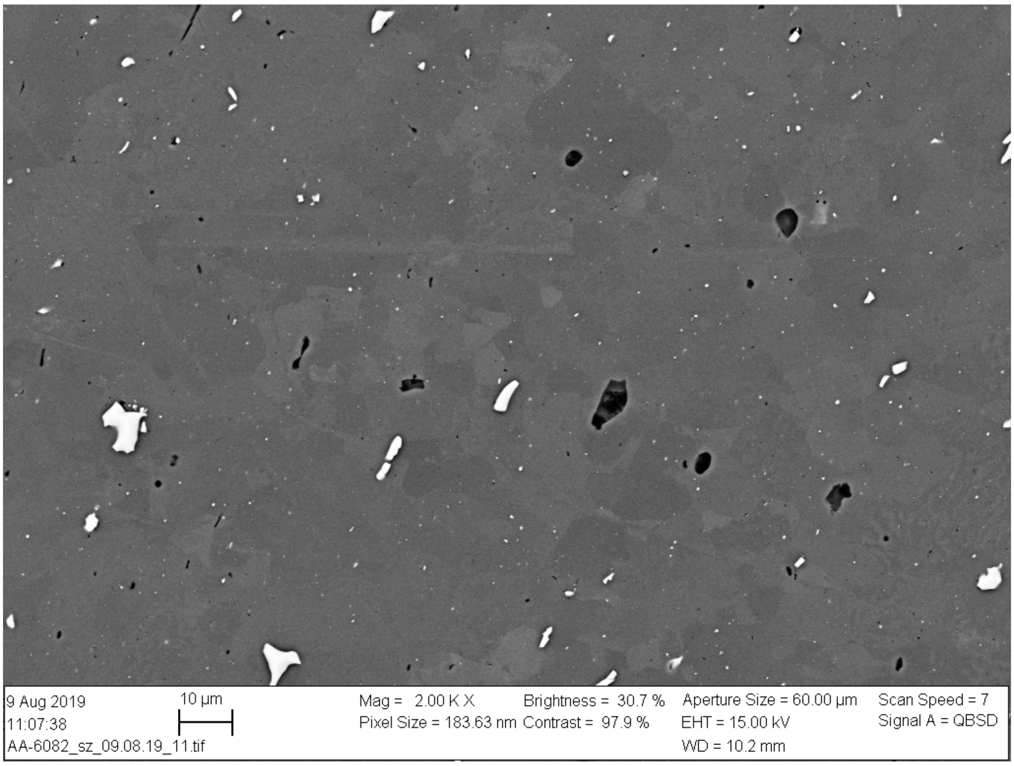
Appendix B 29 - 15kV TMAZ/HAZ Region



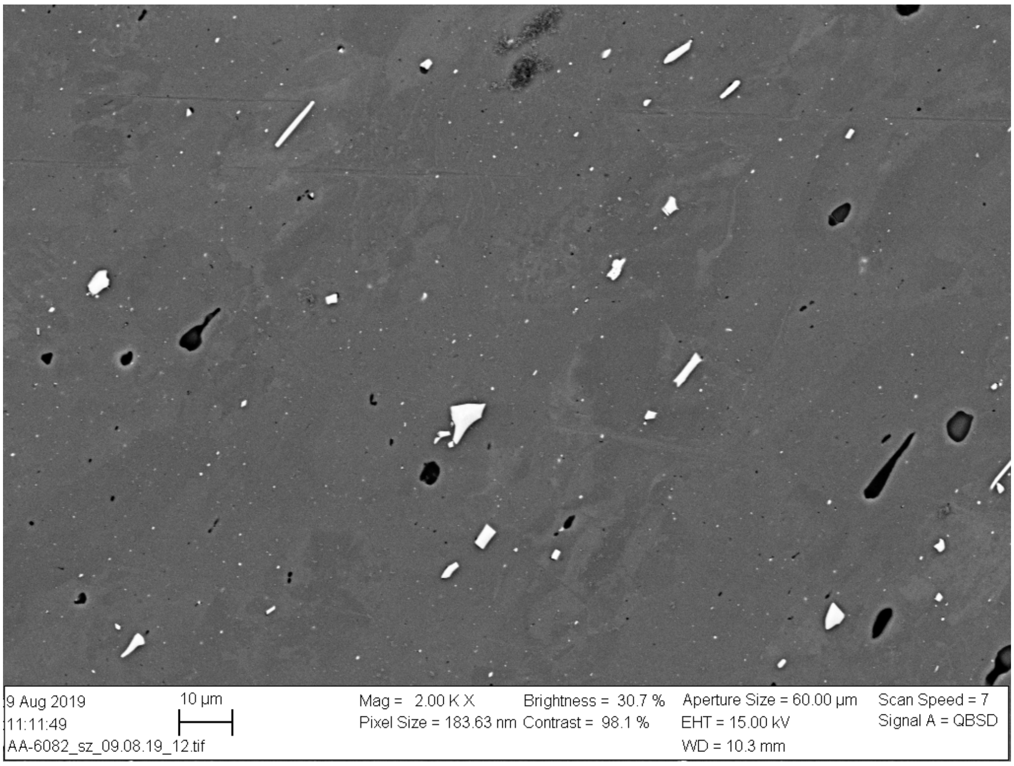
Appendix B 30 - 15 kV Stir Zone/TMAZ



Appendix B 31 - 15 kV HAZ



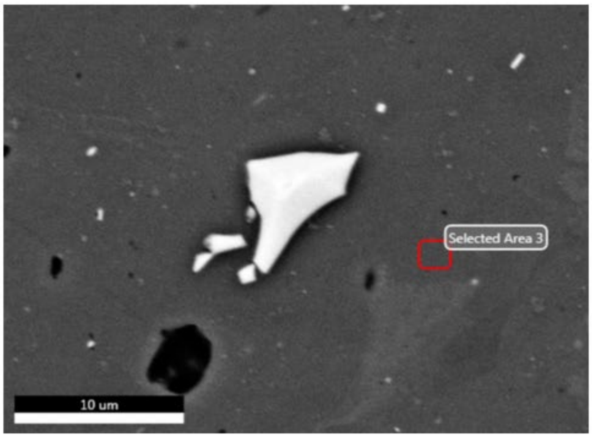
Appendix B 32 - 15 kV 5 mm away from SZ in HAZ



Appendix B 33 - Outer edge of sample HAZ jan2re

Author: student
Creation: 08/09/2019 11:30:28 AM
Sample Name: AA6082exp10

Area 2

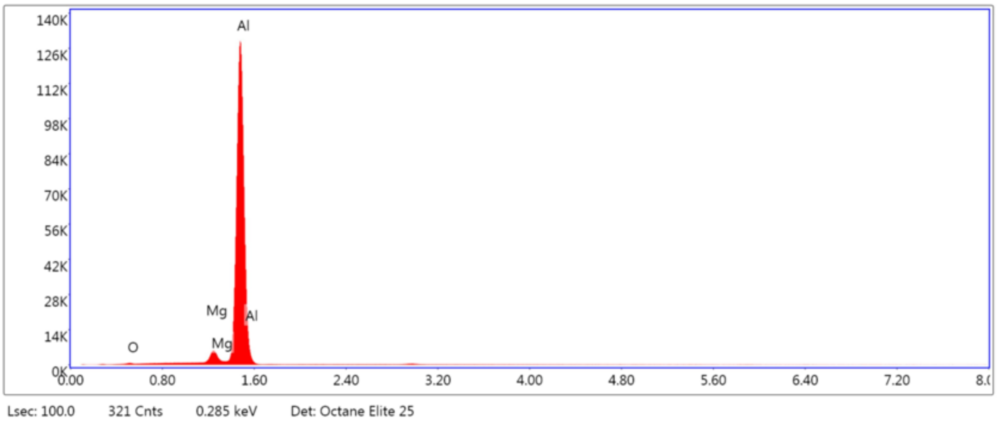


Notes:

Selected Area 3

kV: 15	Mag:10338	Takeoff: 37.4	Live Time(s): 100	Amp Time(µs):7.68	Resolution:(eV)125.8

Selected Area 3 - Det 1



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %	Kratio	Z	A	F
O K	0.11	0.19	8.61	39.21	0.0004	1.1295	0.3470	1.0000
MgK	4.05	4.47	902.02	2.23	0.0406	1.0378	0.9541	1.0110
AlK	95.84	95.34	19780.72	1.82	0.9132	0.9982	0.9546	1.0000

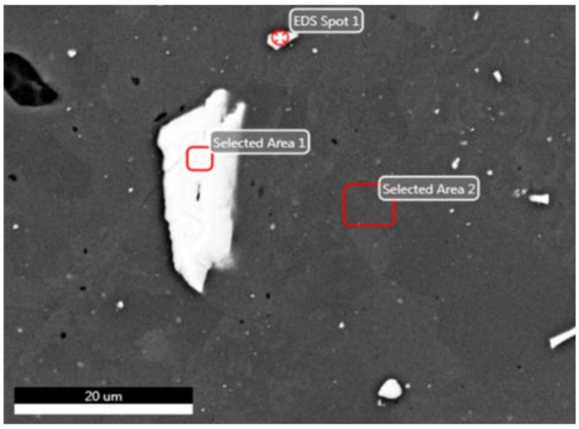
Appendix B 34 - EDS matrix

EDAX TEAM

jan2re

Author: student
Creation: 08/09/2019 11:43:52 AM
Sample Name: AA6082exp10

Area 3



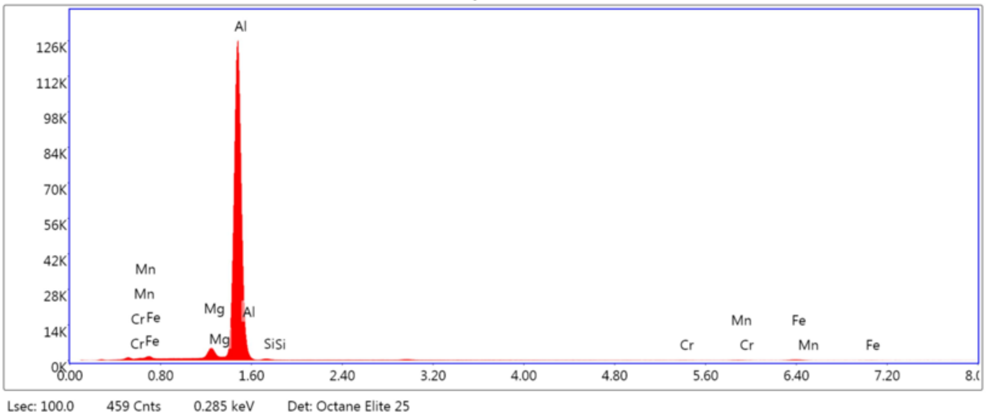
Notes:

Appendix B 35 - EDS - Optimum experiement

EDS Spot 1

kV: 15	Mag:5567	Takeoff: 37.2	Live Time(s): 100	Amp Time(µs):7.68	Resolution:(eV)125.8

EDS Spot 1 - Det 1



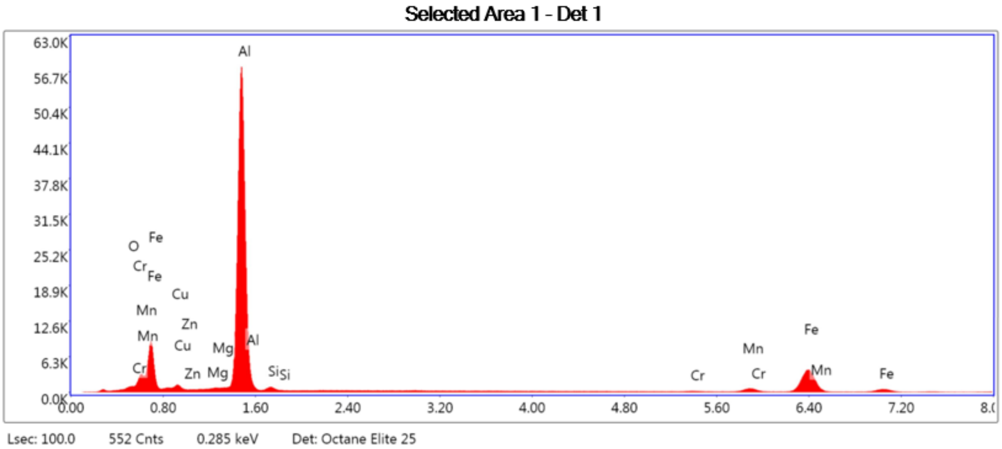
eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %	Kratio	Z	A	F
MgK	3.57	4.01	789.23	2.65	0.0343	1.0427	0.9136	1.0091
AlK	92.53	93.73	19396.90	2.04	0.8658	1.0030	0.9327	1.0002
SiK	0.68	0.66	73.12	11.98	0.0034	1.0239	0.4893	1.0005
CrK	0.22	0.11	10.78	34.99	0.0019	0.8569	0.9852	1.0512
MnK	0.70	0.35	28.97	17.63	0.0061	0.8370	0.9915	1.0557
FeK	2.31	1.13	81.95	7.37	0.0206	0.8479	0.9955	1.0567

Appendix B 36 - EDS Spot1

Selected Area 1

kV: 15	Mag:5567	Takeoff: 37.2	Live Time(s): 100	Amp Time(µs):7.68	Resolution:(eV)125.8



eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %	Kratio	Z	A	F
O K	0.47	0.99	41.85	11.98	0.0023	1.1906	0.4151	1.0000
MgK	0.48	0.66	63.21	10.10	0.0031	1.0971	0.5895	1.0027
AlK	59.63	74.16	8857.90	4.30	0.4482	1.0559	0.7113	1.0008
SiK	0.85	1.02	91.43	11.72	0.0048	1.0785	0.5269	1.0015
CrK	0.41	0.27	20.19	21.99	0.0041	0.9076	0.9881	1.1020
MnK	3.59	2.19	142.49	6.08	0.0340	0.8871	0.9935	1.0723
FeK	33.79	20.30	1077.53	2.78	0.3070	0.8995	0.9964	1.0136
CuK	0.76	0.40	12.31	34.75	0.0066	0.8554	0.9829	1.0322
ZnK	0.00	0.00	0.04	99.99	0.0000	0.8500	0.9878	1.0422

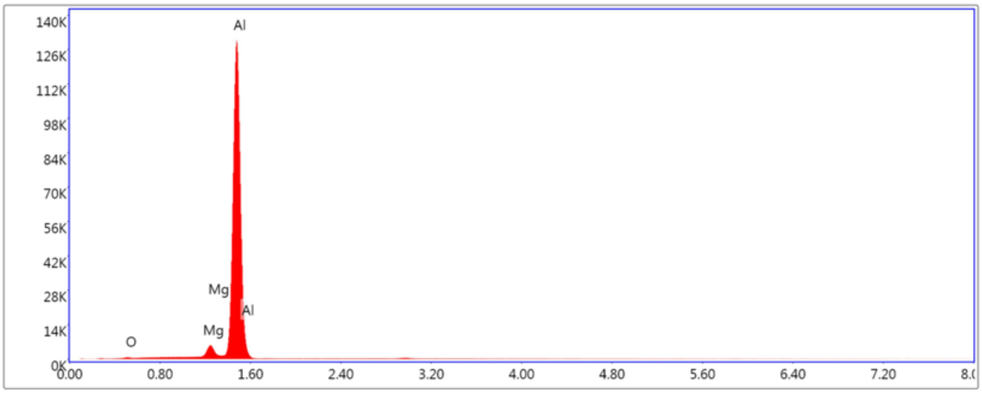
Appendix B 37 - EDS Spot 2

EDAX TEAM Page4

Selected Area 2

kV: 15	Mag:5567	Takeoff: 37.2	Live Time(s): 100	Amp Time(µs):7.68	Resolution:(eV)125.8

Selected Area 2 - Det 1



Lsec: 100.0 343 Cnts 0.285 keV Det: Octane Elite 25

eZAF Smart Quant Results

Element	Weight %	Atomic %	Net Int.	Error %	Kratio	Z	A	F
O K	0.11	0.19	8.80	39.10	0.0004	1.1296	0.3462	1.0000
MgK	4.02	4.44	901.33	2.23	0.0402	1.0378	0.9540	1.0110
AlK	95.87	95.37	19942.56	1.82	0.9137	0.9982	0.9548	1.0000

Appendix B 38 - EDS Spot 3

Appendix C

SIKKERHETSDATABLAD

Produktnavn:	CLAROFAST	Side:	1/10
Revidert:	2018-11-26	Printdato:	2018-11-26
Dokument nr.:	M0155	SDS-ID:	NO-NO/15.0

AVSNITT 1: IDENTIFIKASJON AV STOFFET/STOFFBLANDINGEN OG AV SELSKAPET/FORETAKET

1.1. Produktidentifikator

Produktnavn: CLAROFAST

Cat. No. 40100053, 40100054, 40100055

PRN-nr.: Ennå ikke tildelt

Emballasjestørrelse: 1; 7.5; 25 kg

1.2. Identifiserte relevante bruksområder for stoffet eller stoffblandingen som det advares mot

Anvendelse: Til innstøping av materialografiske emner

1.3. Opplysninger om leverandøren av sikkerhetsdatabladet

Leverandør: Struers ApS
Pederstrupvej 84
DK-2750 Ballerup
Tel:+45 44 600 800

Ansvarlig for utarbeidelse av sikkerhetsdatabladet: Ansvarlig for utarbeidelse av sikkerhetsdatabladet: DHI
Spørsmål til innholdet i dette sikkerhetsdatabladet kan sendes til:
struers@struers.dk

1.4. Nødtelefonnummer

Telefonnummer til giftinformasjonen: +4722591300.

+45 44 600 800
(Kun i åpningstiden)

AVSNITT 2: FAREIDENTIFIKASJON

2.1. Klassifisering av stoffet eller stoffblandingen

CLP: Produktet er ikke klassifisert.

2.2. Merkingselementer

Stoffet/blandingen oppfyller ikke kriteriene for klassifisering, men det er krav om følgende merking:

Inneholder Metylmetakrylat, Dibenzoylperoksid. Kan gi en allergisk reaksjon. Sikkerhetsdatablad er tilgjengelig på anmodning.

2.3. Andre farer

Finpartikler kan danne eksplosive damp-/luftblandinger. Kan irritere øynene og huden. Innånding av støv kan forårsake irritasjon av luftveiene.

PBT/vPvB: Ikke klassifisert som PBT/vPvB ifølge gjeldende EU kriterier.

AVSNITT 3: SAMMENSETNING/OPPLYSNINGER OM BESTANDDELER

3.2. Stoffblandinger

Produktet inneholder: akrylharpiks.

Appendix C 1 - Clarofast Datasheet

26.11.2018

VERNEBLAD

CLAROFAST

Vis sikkerhetsdatablad

Generelt

Artikkelnr.	Cat. No. 40100053, 40100054, 40100055
Kjemikaliets bruksområde	Til innstøping av materialografiske emner

Førstehjelpstiltak

Innånding	Gå ut i frisk luft og forbli i ro.
Hudkontakt	Ta straks av tilsølte klær og vask huden med såpe og vann. Ved eksem eller andre hudplager: Kontakt lege og ta med sikkerhetsdatabladet.
Øyekontakt	Skyll straks med rikelige mengder vann i minst 15 minutter. Fjern evt. kontaktlinser og åpne øyet godt opp.
Svelging	Skyll straks munnen og drikk rikelige mengder vann. Hold personen under oppsyn. Ved ubehag transporteres personen til sykehus. Ta med sikkerhetsdatabladet.
Generelle symptomer og virkninger	Se avsnitt 11 for ytterligere informasjon om helsefare og symptomer.

Verneutstyr

Egnede tekniske tiltak	Sørg for tilstrekkelig ventilasjon. Administrativ norm for eksponering skal overholdes, og faren for innånding av støv skal gjøres minst mulig. Punktavsug anbefales.
Egnet øyebeskyttelse	Ved risiko for kontakt: Bruk vernebriller/ansiktsskjerm.
Egnede materialer	Ved fare for kontakt: Bruk vernehansker. Best egnet er laminathansker (PE/EVOH). Hanske må velges i samarbeid med hanskeleverandøren, som kan opplyse om hanskematerialets gjennomtrengningstid.
Anbefalt utstyrstype	Ved utilstrekkelig ventilasjon må det brukes egnet åndedrettsvern. Bruk egnet åndedrettsvern med partikkelfilter, type P3. (*)

Tiltak ved brannslukking

Egnede slokkingsmidler	Ved brannslukking benyttes skum, karbondioksid, pulver eller vanntåke. (*)
Uegnede slokkingsmidler	Ikke egnede slukkingsmidler: Ikke bruk vannstråle ved brannslukking da dette vil spre brannen. (*)
Brann- og eksplosjonsfarer	Ved brann kan det dannes giftige og irriterende gasser. (*)
Personlig verneutstyr	Valg av åndedrettsvern ved brann: Følg bedriftens generelle forholdsregler.

Tiltak ved utslipp

Sikkerhetstiltak for å beskytte personell	Unngå innånding av støv og kontakt med hud og øyne. Hvis du ønsker mer informasjon om personlig beskyttelse, kan du se avsnitt 8. (*)
Sikkerhetstiltak for å beskytte ytre miljø	Unngå utslipp i avløp, jord og vannløp.
Opprydding	Søl fuktes med vann. Søl samles opp med skuffe, kost eller lignende.
Andre anvisninger	Hvis du ønsker mer informasjon om personlig beskyttelse, kan du se avsnitt 8. Hvis du ønsker mer informasjon om avhending, kan du se avsnitt 13.

Ansvarlig firma

Firmanavn	Struers ApS
Postadresse	Pederstrupvej 84
	DK-2750 Ballerup
Land	Denmark
Telefon	+45 44 600 800

Appendix C 2 - Clarofast Safety Sheet

AVSNITT 1: IDENTIFIKASJON AV STOFFET/STOFFBLANDINGEN OG AV SELSKAPET/FORETAKET

1.1. Produktidentifikator

Produktnavn: CONDUFAST

Cat. No. 40100039

Emballasjestørrelse: 1 kg

1.2. Identifiserte relevante bruksområder for stoffet eller stoffblandingen som det advares mot

Anvendelse: Til innstøping av materialografiske emner

1.3. Opplysninger om leverandøren av sikkerhetsdatabladet

Leverandør: Struers ApS
Pederstrupvej 84
DK-2750 Ballerup
Tel:+45 44 600 800

Ansvarlig for utarbeidelse av sikkerhetsdatabladet: Ansvarlig for utarbeidelse av sikkerhetsdatabladet: DHI
Spørsmål til innholdet i dette sikkerhetsdatabladet kan sendes til:
struers@struers.dk

1.4. Nødtelefonnummer

Telefonnummer til giftinformasjonen: +4722591300.

+45 44 600 800
(Kun i åpningstiden)

AVSNITT 2: FAREIDENTIFIKASJON

2.1. Klassifisering av stoffet eller stoffblandingen

CLP: Produktet er ikke klassifisert.

2.2. Merkingselementer

Stoffet/blandingen oppfyller ikke kriteriene for klassifisering, men det er krav om følgende merking:

Inneholder Metylmetakrylat, Dibenzoylperoksid. Kan gi en allergisk reaksjon.
Sikkerhetsdatablad er tilgjengelig på anmodning.

2.3. Andre farer

Støv kan irritere øyne og luftveier. Finpartikler kan danne eksplosive damp-/luftblandinger.

PBT/vPvB: Ikke opplyst.

AVSNITT 3: SAMMENSETNING/OPPLYSNINGER OM BESTANDDELER

3.2. Stoffblandinger

Produktet inneholder: polymer og fyllstoffer.

Appendix C 3 - Condufast Data Sheet

27.11.2018

VERNEBLAD

CONDUFAST

Vis sikkerhetsdatablad

Generelt

Artikkelnr.	40100039
Kjemikaliets bruksområde	Til innstøping av materialografiske emner

Førstehjelpstiltak

Innånding	Gå ut i frisk luft og forbli i ro.
Hudkontakt	Ta straks av tilsølte klær og vask huden med såpe og vann. Ved eksem eller andre hudplager: Kontakt lege og ta med sikkerhetsdatabladet.
Øyekontakt	Skyll straks med rikelige mengder vann i minst 15 minutter. Fjern evt. kontaktlinser og åpne øyet godt opp. Ved fortsatt irritasjon: transport til sykehus. Ta med sikkerhetsdatabladet.
Svelging	Skyll straks munnen og drikk rikelige mengder vann. Hold personen under oppsyn. Ved ubehag transporteres personen til sykehus. Ta med sikkerhetsdatabladet.
Generelle symptomer og virkninger	Symptomer/virkninger: Se avsnitt 11 for ytterligere informasjon om helsefare og symptomer.

Verneutstyr

Nødvendige egenskaper	Ved risiko for kontakt: Bruk vernebriller/ansiktsskjerm.
Egnede materialer	Ved fare for kontakt: Bruk vernehansker.
Egnede hansker	Best egnet er butylgummihansker. (*)
Anbefalt åndedrettsvern	Ved støvende arbeid: Bruk egnet åndedrettsvern med partikkelfilter, type P2.

Tiltak ved brannslukking

Egnede slokkingsmidler	Ved brannslukking benyttes skum, karbondioksid, pulver eller vanntåke.
Uegnede slokkingsmidler	Ingen spesielle forholdsregler.
Brann- og eksplosjonsfarer	Ved oppvarming og brann kan det dannes irriterende damper/gasser.
Personlig verneutstyr	Valg av åndedrettsvern ved brann: Følg bedriftens generelle forholdsregler.

Tiltak ved utslipp

Sikkerhetstiltak for å beskytte personell	Unngå støvdannelse og spredning av støv. Unngå hudkontakt/innånding av spill/støv/damp. Unngå kontakt med øynene. Hvis du ønsker mer informasjon om personlig beskyttelse, kan du se avsnitt 8. (*)
Sikkerhetstiltak for å beskytte ytre miljø	Unngå utslipp i jord og vannløp.
Opprydding	Søl fuktes med vann. Søl suges opp med absorberende materiale.
Andre anvisninger	Hvis du ønsker mer informasjon om personlig beskyttelse, kan du se avsnitt 8. Hvis du ønsker mer informasjon om avhending, kan du se avsnitt 13.

Ansvarlig firma

Firmanavn	Struers ApS
Postadresse	Pederstrupvej 84
	DK-2750 Ballerup
Land	Denmark
Telefon	+45 44 600 800
Nødtelefon	+4722591300. Telefonnummer til giftinformasjonen

Appendix C 4 - Condufast Safety

Appendix D

SV: VS: Friction stir welding with our MAZAK 430A

Reidar Kverneland <reidar@ravema.no>

ti. 18.12.2018 14:52

Til: CHANDIMA RATNAYAKE RATNAYAKE MUDIYANSELAGE <chandima.ratnayake@uis.no>
Kopi: Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>; Jan-Tore Jakobsen <jantore.jakobsen@gmail.com>

Hi Chandima
I have just received an email from Mazak. They confirm that they still have some Machin parts from their testing.
My contact are no checking out if it´s necessary to change the x axis motor.
When we have sorted that out, we can give you a proposal.

Best regards

Reidar Kverneland
Area Sales Manager
Mazak Machine Tools

Ravema AS
Orstadveien 134
NO-4353 Klepp St, Norway
Phone +47 916 011 71
reidar@ravema.no

Mazak

Fra: CHANDIMA RATNAYAKE RATNAYAKE MUDIYANSELAGE [mailto:chandima.ratnayake@uis.no]
Sendt: 30. november 2018 20:54
Til: Reidar Kverneland
Kopi: Jan-Tore Jakobsen; Jan-Tore Jakobsen
Emne: RE: VS: Friction stir welding with our MAZAK 430A

Hi Reidar,

We need to talk about this a bit detail. Prices etc.

Sincerely,

R.M. Chandima Ratnayake, Dr.,
Professor,
Department of Mechanical and Structural Engineering and Materials Science,
University of Stavanger,
PO. Box 8600 Forus
N-4036, STAVANGER, NORWAY.

Appendix D 1 - Email Correspondence with MAZAK

http://www.uis.no/

E-mail: chandima.ratnayake@uis.no
Office: +47 518 31 938; Mobile: +47 486 00 616; Home: +47 966 76 186;
Fax: +47 518 31 750

Visiting Professor: Department of Process Engineering, Memorial University, St. John's NL Canada, and University of Petronas, Malaysia.

Associate Editor: ASME -Journal of Offshore Mechanics and Arctic Engineering
Editor: Central European Journal of Engineering

Integrity Management Technical - Senior Advisor
Wood Group Kenny
E-mail: chandima.ratnayake@woodgroupkenny.com
www.woodgroupkenny.com

From: Jan-Tore Jakobsen <jantore.jakobsen@gmail.com>
Sent: Thursday, November 15, 2018 6:06 PM
To: CHANDIMA RATNAYAKE RATNAYAKE MUDIYANSELAGE <chandima.ratnayake@uis.no>
Cc: Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>
Subject: Fwd: VS: Friction stir welding with our MAZAK 430A

Hello
You will have my report later tomorrow but as you can see MAZAK have done this experiment on a similar machine, but they did some modifications to the motor and spindle. It seems like we can perform FSW but only for 2-3 mm plates and then take the experince from this and see if the machine can perform at a higher level. Im interested in what you learned about FSW when you were abborad last summer ? Which plate thickness and material did the people you visited perform weld on?
Can have a brief presentation of the result from my study next week and maybe we need to deicde what kind of experiment to do.

have a nice evening
Jan-Tore

---------- Forwarded message ---------
From: **Reidar Kverneland** <reidar@ravema.no>
Date: tir. 13. nov. 2018 kl. 18:01
Subject: VS: VS: Friction stir welding with our MAZAK 430A
To: jantore.jakobsen@gmail.com <jantore.jakobsen@gmail.com>
Cc: Martin Forrest <mforrest@mazak.co.uk>, Per Selskog <pese@ravema.se>, Sean Pritlove <SPritlove@mazak.co.uk>

Hi Jan-Tore !

I have received some information from Mr. Martin Forrest at Mazak UK.

If this is interesting for you, we can take a closer look at the price etc. I´m afraid that the budget you are estimating is a bit low.

Appendix D 2 - Page 2

Best regards

Reidar Kverneland
Area Sales Manager
Mazak Machine Tools

Ravema AS
Orstadveien 134
NO-4353 Klepp St, Norway
Phone +47 916 011 71
reidar@ravema.no

Mazak

RAVEMA expo
11.-12. DESEMBER

www.ravemaexpo.se

Fra: Martin Forrest [mailto:mforrest@mazak.co.uk]
Sendt: 13. november 2018 10:17
Til: Reidar Kverneland
Kopi: Sean Pritlove; Per Selskog
Emne: Re: VS: Friction stir welding with our MAZAK 430A

Hi Reidar,

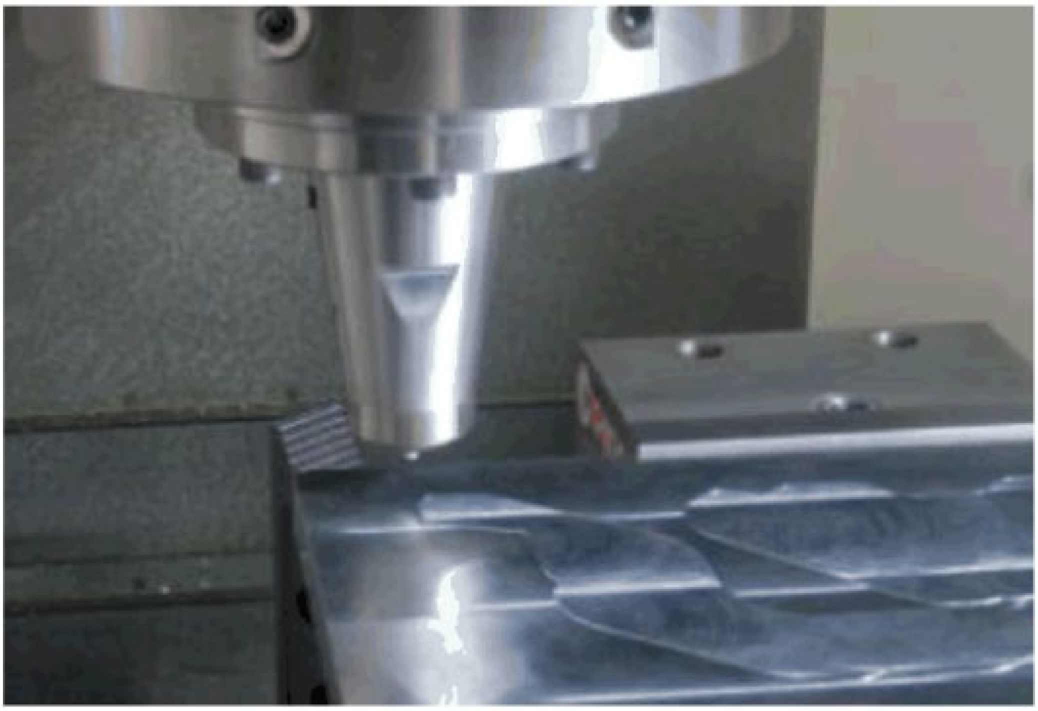
We fitted FSW to a VCS430A 3.5 years ago for testing. It worked very well.
The machine was since put back to standard and then sold.

To enable FSW, we had to do a few things:

1) Change the X axis motor, motor housing and cover.
2) Change spindle flange
3) Set parameters
4) Load FSW tool / pin to the spindle
5) Manually bolt on the fixed shoulder to the spindle face.

In order for the function to work, force control for the Z axis was turned on. Apart from that, it was just a case of making a simple program.

Appendix D 3 - Page 3



I don't know the answers to many of the technical questions that Jan-Tore has as this would be a one-off machine that hasn't had any testing.
2mm to 3mm aluminium plate would be OK, but I suspect that anything thicker would present an issue for this quite small machine.
A larger pin will require more thrust force.

Answers to his other questions:

Is it possible just to use the current toolholders we already have with FSW tools to perform welds on aluminium?
Is there a special designed tool holder for the mazak 430A with regrads to FSW?
The toolholders are standard side lock type. We would have the specification and may also even have some.

Is there a need for a unit for controlling the downforce and other parameters?
The Mazak unit will do this.

Do MAZAK deliver a software which we can integrate with the Matrix Nexus 2 unit regarding these above questions?
Basically yes. We set the Mazak control to use downward force control.

Do Mazak deliver FSW tools?
The actual FSW pin can be bought from several suppliers such as OSG.

Can you please send over a suggestion for what you think we will need for using our MAZAK 430A to perform FSW.
Both the simplest solution and also the best solution.

We would have to put together a kit based on our previous testing. Price ?
Mazak Japan also make specific Hybrid FSW machines - Maybe you know this?

Best Regards,

Martin Forrest
Applications Development Manager
Yamazaki Mazak UK Ltd

Badgeworth Drive, Worcester, WR4 9NF, United Kingdom
T: +44 (0) 1905 752099 | M: +44 7747 100537
E: mforrest@mazak.co.uk | W: www.mazakeu.com

From: Reidar Kverneland <reidar@ravema.no>
To: "Martin Forrest" <mforrest@mazak.co.uk>,
Date: 13/11/2018 07:46
Subject: VS: Friction stir welding with our MAZAK 430A

Good morning Martin !
I have got this request from a student at UiS that have a Mazak VCN.
Can you take a look at it, can they do steer welding in this machine ?

Best regards

Reidar Kverneland
Area Sales Manager
Mazak Machine Tools
[cid:image001.jpg@01D20A13.23F27730]
Ravema AS
Orstadveien 134
NO-4353 Klepp St, Norway
Phone +47 916 011 71
reidar@ravema.no<mailto:reidar@ravema.no>

[Mazak EMO 2017 logo]

[RavemaExpo jul 2018]

www.ravemaexpo.se<http://www.ravemaexpo.se>

Fra: Jan-Tore Jakobsen [mailto:jantore.jakobsen@gmail.com]
Sendt: 12. november 2018 21:44
Til: Reidar Kverneland
Emne: Re: Friction stir welding with our MAZAK 430A

Hello

The machine is the Vertical Center Smart 430A ,UiS did purchase in 2014- serial no: 257584
The machine is installed with Matrix Nexus 2 control system.

What we are interested in is to do Friction stir welding for research purposes, primarily buttwelding of aluminium plates 2-8 mm and then maybe later on we will extend this to do experiment with disimilar materials and magnesium and copper as well.

Budget for project: I will make a report based on a case study for the MAZAK 430A machine to perform FSW. I will present this for my advisor professor R.Chandima next week.
After the best solutions is presented, it will be possible to apply for funding in the range 10K to 250K. NOK.

Some question about parameters?
What is the max downforce the 430A can perform during FSW of aluminium plates ?
What is the max lateral force the 430A can withstand during FSW of plates aluminium plates 2-8 mm?

What my concern is after reading articles about FSW on CNC machines is what kind of toolholder we would need when we want to use the 430A machine to perform friction welding for researching purpose. On a yearly basis the MAZAK machine is mostly spent on ordinary CNC machining
but we want to be able to perform some studies on FSW welds occasionally.

Is it possible just to use the current toolholders we already have with FSW tools to perform welds on aluminium?
Is there a special designed tool holder for the mazak 430A with regrads to FSW?
Is there a need for a unit for controlling the downforce and other parameters?
Do MAZAK deliver a software which we can integrate with the Matrix Nexus 2 unit regarding these above questions?
Do Mazak deliver FSW tools?
Can you please send over a suggestion for what you think we will need for using our MAZAK 430A to perform FSW.
Both the simplest solution and also the best solution.

If something is missing from this request please dont hesitate to contact me.

best regards
Jan-Tore Jakobsen
M.Sc student University of Stavanger
+47 4721 9000

Den fre. 9. nov. 2018 kl. 19:46 skrev Reidar Kverneland
<reidar@ravema.no<mailto:reidar@ravema.no>>:
Hi Jan Tore !

Referring to your e-mail about stir welding in your Mazak machine.
As you maybe know, Ravema are representing Mazak in Norway, and we are more than happy to help you with questions about this.
Can you please support us with machine serial number and CNC controller and software version.

Appendix D 6 - Page 6

Hello.
I read an article about Friction Stir welding with a MAZAK 430A CNC machine posted at MAZAK web pages.

I want to do a project with Friction stir welding with our MAZAK 430A machine and im currently doing a case study at this topic.

Have MAZAK developed FSW tools or toolholders which are compatible with the 430A CNC milling machine? And if so can you provide me with details where to buy or get more information regarding this subject?

Thanks

Best regards

Reidar Kverneland
Area Sales Manager
Mazak Machine Tools
[cid:image001.jpg@01D20A13.23F27730]
Ravema AS
Orstadveien 134
NO-4353 Klepp St, Norway
Phone +47 916 011 71
reidar@ravema.no<mailto:reidar@ravema.no>

[Mazak EMO 2017 logo]

[RavemaExpo jul 2018]

www.ravemaexpo.no<http://www.ravemaexpo.no>

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(",)--Jan-Tore Jakobsen --(,")

[attachment "image001.jpg" deleted by Martin Forrest/EuroEng/ymuk/MazakEuro]
[attachment "image002.png" deleted by Martin Forrest/EuroEng/ymuk/MazakEuro]
[attachment "image003.png" deleted by Martin Forrest/EuroEng/ymuk/MazakEuro]
[attachment "image003.002.png" deleted by Martin Forrest/EuroEng/ymuk/MazakEuro]
[attachment "image001.002.jpg" deleted by Martin Forrest/EuroEng/ymuk/MazakEuro]
[attachment "image002.002.png" deleted by Martin Forrest/EuroEng/ymuk/MazakEuro]
[attachment "image003.003.png" deleted by Martin Forrest/EuroEng/ymuk/MazakEuro]

Appendix D 7 - Page 7 of the Email Corr.

Vs: SV: Spørsmål om MAZAK 430

Jan-Tore Jakobsen
on. 22.05.2019 23:05
Til: Emil Surnevik Kristiansen <emil.kristiansen@uis.no>

Hei Emil

Kan du se om du har denne instillingen som vist her ?

Jt

Fra: Reidar Kverneland <reidar@ravema.no>
Sendt: onsdag 22. mai 2019 16.03
Til: Jan-Tore Jakobsen
Emne: VS: SV: Spørsmål om MAZAK 430

FYI

Best regards

Reidar Kverneland
Area Sales Manager
Mazak Machine Tools

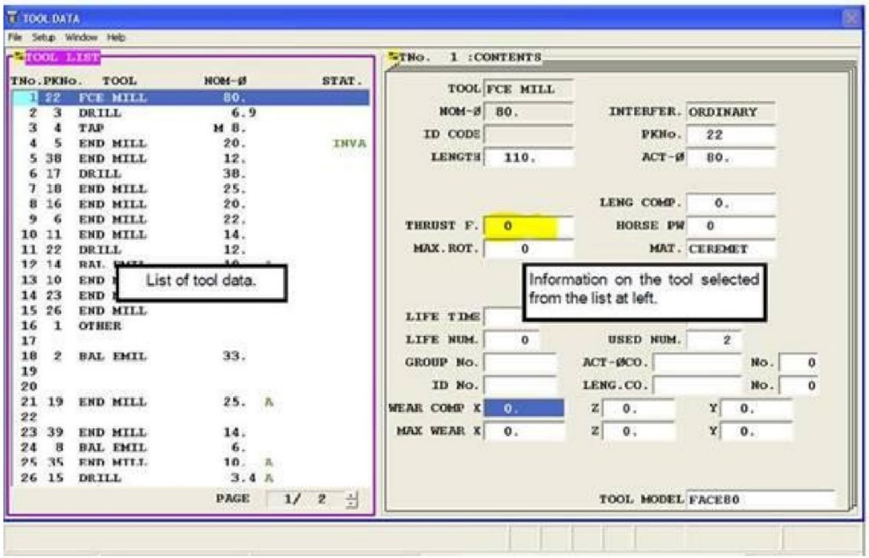
Ravema AS
Demosenter
Pauline Wiigs veg 4
NO-4344 BRYNE
Norway
Phone +47 916 011 71
reidar@ravema.no

Mazak

Hei

Se bilde nedenfor Trust F markert i gult (kan være annen rekkefølge på knappene på kundens maskin)

Appendix D 8 - Mail about force control



Hei Reidar

Har ett spørsmål angående MAZAK VCN430A maskinen.

Lurer på hvordan man setter på " force control på z axis"

Nedenfor er ett utdrag fra tidligere mail fra dere angående friksjonssveising. Jeg skal starte å sveise på mandag og trenger å sette opp maskinen.

Hi Reidar,

We fitted FSW to a VCS430A 3.5 years ago for testing. It worked very well.
The machine was since put back to standard and then sold.

To enable FSW, we had to do a few things:

1) Change the X axis motor, motor housing and cover.
2) Change spindle flange
3) Set parameters
4) Load FSW tool / pin to the spindle
5) Manually bolt on the fixed shoulder to the spindle face.

In order for the function to work, force control for the Z axis was turned on. Apart from that, it was just a case of making a simple program.

Mvh Jan-Tore

Appendix D 9 - Page 2

Note 1: If the load on the Z-axis servomotor exceeds the percentage value that has been input to the **THRUST F.** item, then the cutting feedrate will automatically decrease and the load will be controlled to within its permissible limits.

Note 2: This item is valid only for machine models provided with an AFC function. This operation does not need to be performed for the machine models of the standard specifications.

10. Horse power (HORSE PW)

To control the load current of the milling spindle drive motor, specify the horse power of the milling tool using the appropriate alphanumeric data keys, and press the INPUT key.

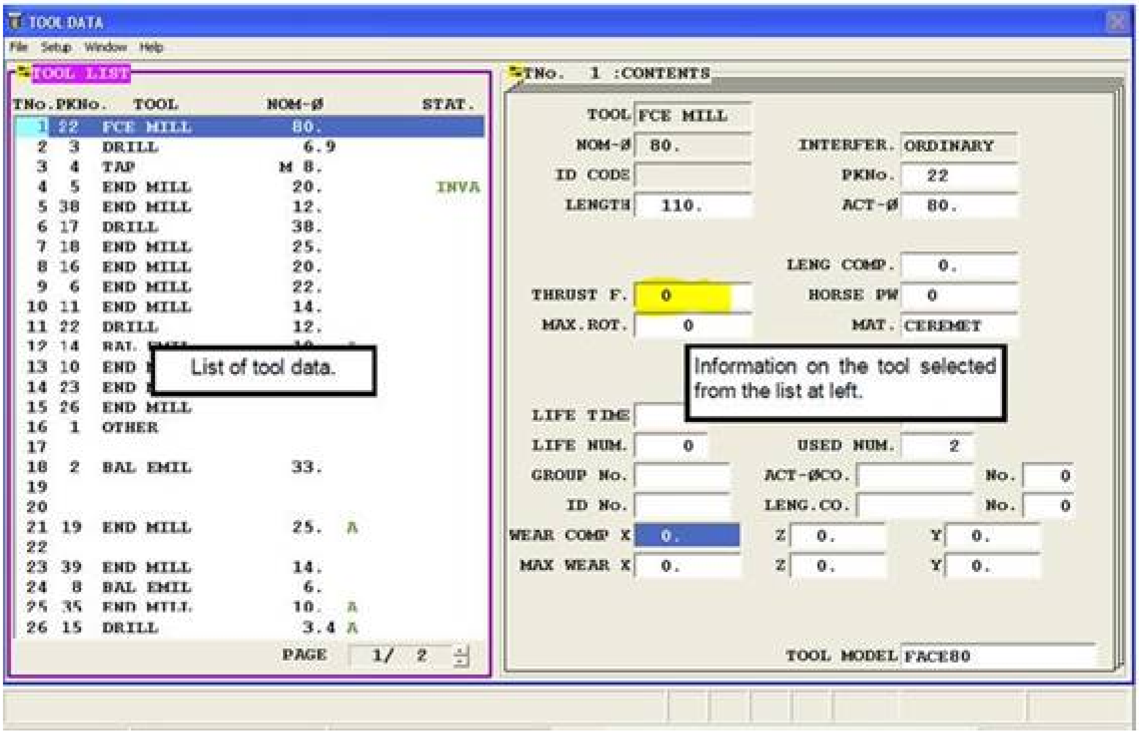
- When the **[AUTO SET]** menu key is pressed, the NC equipment will calculate the maximum permissible load value of the spindle drive motor and automatically set the adequate horse power coefficient (%).

Note 1: If the load on the milling spindle drive motor exceeds the percentage value that has been input to the **HORSE PW** item, then the cutting feedrate will automatically decrease and the load will be controlled to within its permissible limits.

Note 2: Input of data to the **HORSE PW** item becomes necessary only for face-mills, end-mills, boring bars, drills, backspot-facing tools, backboring bars or chamfering cutters.

Note 3: This item is valid only for machine models provided with an AFC function. This operation does not need to be performed for the machine models of the standard specifications.

Appendix D 10 - Force Control MAZAK



Appendix D 11 - Force Control MAZAK Menu

The Files containing the mails form Stirweld are merged together as a pdf file.

Appendix D 12 - Email Correspondence with Stirweld

Sv: FYI

Jan-Tore Jakobsen
on. 20.03.2019 14:14
Til: SW <laurent.dubourg@stirweld.com>

Sorry for the norwegian document.

Heres is my shipping adress and invoice adress:

Universitetet i Stavanger
UIS Postmottak
Att: Jan-Tore Jakobsen
Rennebergstien 30
Kitty Kiellands Hus
N-4036 Stavanger

Invoice adress -
eFaktura (*e-invoicing)*- 9908:971564679
PDF-format - einvoices.uis@bscs.basware.com
Universitetet i Stavanger| Postboks 384, Alnabru
N-0614 Oslo

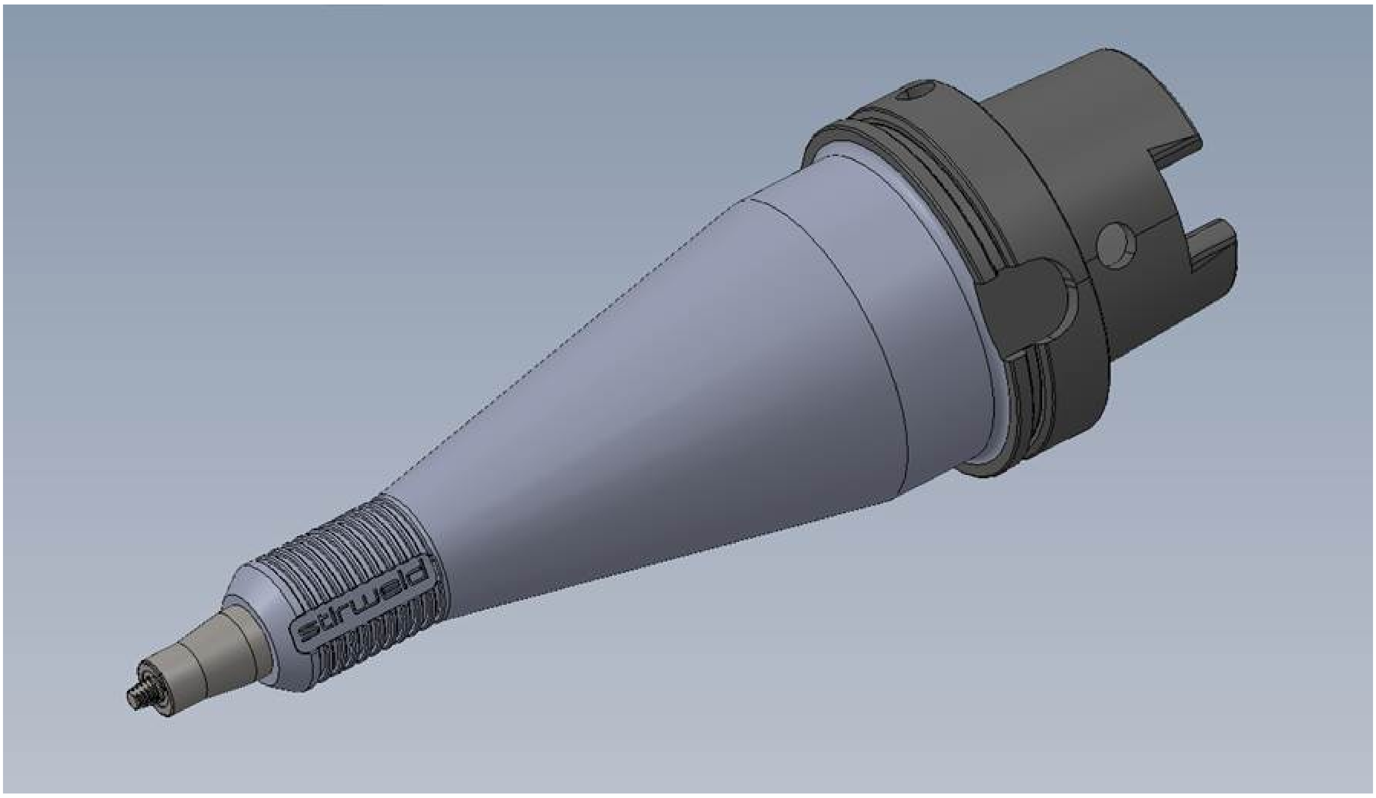
Sorry about that ☺
Jan-Tore

Fra: SW <laurent.dubourg@stirweld.com>
Sendt: lørdag 16. mars 2019 13.40
Til: Jan-Tore Jakobsen
Kopi: 'Sylvie DAGNET'
Emne: RE: FYI

Dear Jan,

Thank you for your PO. Sylvie will proceed the shipping and billing (affaire P50).
Could you send us your shipping address ? The PO is from Norway ?

About your question:
- We recommend to use a Stiweld tool holder to attach our tool (see below). This industrial tool holder guarantees the tool position, temperature management and mechanical resistance. The normal cost is 1290 €. We can give you a discount for student (price of 990 €).



- For R&D test (and lower cost), you can use a classic tool CNC holder (see below). You need a classic diameter 14 mm grip.

Cordialement,

Laurent Dubourg
CEO StirWeld
+33 (0)6 47 49 74 19
Envie de mieux nous connaître : www.stirweld.com

-----Message d'origine-----
De : Sylvie DAGNET <sylvie.dagnet@stirweld.com>
Envoyé : vendredi 15 mars 2019 17:43
À : Laurent Dubourg <laurent.dubourg@stirweld.com>
Objet : FYI

-------- Courriel original --------

Objet: Sv: Re: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices
Date: 15.03.2019 13:00
De: Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>
À: Sylvie DAGNET <sylvie.dagnet@stirweld.com>

Hello Sylvie
Finally i got the PO approved from our sales department. i will be in Finland from 24th -31th of Mars. So if the tools could be here in early April it would be great.

I didnt ask about how the tools is designed regarding to fit the CNC spindle but i guess the tools should fit standard spindles for CNC machines.

Thanks for your support.

bests
Jan-Tore Jakobsen

FRA: Jan-Tore Jakobsen
SENDT: tirsdag 12. mars 2019 18.21
TIL: Sylvie DAGNET
EMNE: Sv: Re: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices

Yes i am. I have sent this to our sales department and Im waiting to get a valid PO number to process this order. So you Will have it in one Day or two. And sure i Will talk nice about stirweld and mention your in my papers. We used megastir earlier but you folks have very good service so i Will recommend your company as future supplies for us.

Have a nice day.

Jt

Jan-Tore Jakobsen

-------- Opprinnelig melding --------
Emne: Fwd: Re: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices
Fra: Sylvie DAGNET
Til: Jan-Tore Jakobsen
Kopi:

Dear Jan,

Please let me know if you are interested in FSW tools?

Wishing you a pleasant afternoon

Sylvie Dagnet
+33 6 47 49 73 96

-------- Courriel original --------
Objet: Re: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices
Date: 07.03.2019 14:07
De: Sylvie DAGNET <sylvie.dagnet@stirweld.com>
À: 'Jan-Tore Jakobsen' <jan.jakobsen@stud.uis.no>
Cc: Laurent Dubourg <laurent.dubourg@stirweld.com>

Dear Jan,

Please excuse me for the delay. Here are the prices.

3 tools for aluminium AA6082 - 3mm plates
3 F-AA1 normal price 1494EUR for express delivery => your price 997 EUR

3 tools for aluminium AA5754 - 2 mm plates
3 F-AA2 normal price 1494EUR for express delivery => your price 997 EUR

The tools are on stock and ready for sending on Monday.

As you can see, we offer you more than 30% discount to help you with your research project.
Would you agree to name Stirweld on your paper in return and promote Stirweld when meeting people interested in FSW?
It would very nice and appreciated.

Have a very nice day

--

Regards

Sylvie Dagnet
Business Development Manager Stirweld
06.47.49.73.96

www.stirweld.com [1] [2]

Le 07.03.2019 13:32, SW a écrit :

> Sylvie,
>
> Could you proceed the Jan's request ?
>
> Thanks you
>
> Cordialement,
>
> Laurent Dubourg
>
> CEO StirWeld
>
> +33 (0)6 47 49 74 19
>
> Envie de mieux nous connaître : www.stirweld.com [1] [1]
>
> DE : Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no> ENVOYÉ : jeudi 7
> mars 2019 12:46 À : SW <laurent.dubourg@stirweld.com> OBJET : Sv: Sv:
> StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices
>
> Hello.
>
> Could you send me an update with prices and delivery time for the
> tools mentiod below
>
> 3 tools for aluminium AA6082 - 3mm plates
>
> 3 tools for aluminium AA5754 - 2 mm plates
>
> I Will try to send the purchase order tommorow.
>
> Thank you
>

> Jan-Tore Jakobsen
>
> -------- Opprinnelig melding --------
> Emne: RE: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices
> Fra: SW
> Til: 'Sylvie DAGNET' ,Jan-Tore Jakobsen
> Kopi:
>
> Dear Jan,
>
> The same tool could be used for welding 5xxx or 6xxx. Only the tool
> size is different for 2 or 3 mm thick
> F-AA-1 tool is OK for 2 mm thick.
> F-AA-2 tool is OK for 3 mm thick.
>
> Yes, 3 tools is enough for first trials. If you follow the process
> below, you should damage one tool, max 2.
>
> Cordialement,
>
> Laurent Dubourg
> CEO StirWeld
> +33 (0)6 47 49 74 19
> Envie de mieux nous connaître : www.stirweld.com [1] [2]
>
> -----Message d'origine-----
> De : Sylvie DAGNET <sylvie.dagnet@stirweld.com> Envoyé : lundi 4 mars
> 2019 11:36 À : Laurent Dubourg <laurent.dubourg@stirweld.com> Objet :
> Fwd: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices
>
> Laurent,
>
> can you please answer on the technical side?
>
> Thx
> -------- Courriel original --------
> Objet: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices
> Date: 04.03.2019 11:33
> De: Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>
> À: Sylvie DAGNET <sylvie.dagnet@stirweld.com>
>
> Hello
>
> Can i ask if there are different tools for different aluminium alloys?
> Im gonna buttweld 3 mm 6xxx series (6082-T3 or T6) and maybe 2-3 mm
> 5xxx series (5083 or 5754). can i use same tool for both series?
>
> Can you give me your best prices and delivery times for
>
> 3 tools for 3 mm - 6000 series
> 3 tools for 2 mm - 5000 series
>
> What are the chances for tool getting damaged during start up and
> initial phase when finding correct welding parameters? Do you think 3
> tools will do?
>
> Best regards
> Jan-Tore Jakobsen
>
> University of Stavanger

> +47 4721 9000
>
> ------------------------
>
> FRA: Sylvie DAGNET <sylvie.dagnet@stirweld.com>
> SENDT: mandag 11. februar 2019 14.34
> TIL: Jan-Tore Jakobsen
> KOPI: Laurent Dubourg
> EMNE: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices
>
> Dear Jan,
>
> please find our tools prices for standard aluminium alloys in
> attachment.
>
> You said that delivery time has to be short.
> If you choose express delivery, as you are starting a project with a
> limited budget, give us your requirements and the number of tools you
> need and we will do our best to make a helpful discount on the total
> amount.
>
> --
>
> Best regards
>
> Sylvie Dagnet
> Business Development Manager Stirweld
> 06.47.49.73.96
>
> Want to know us better : www.stirweld.com [1] [2] [1]
>
> On Mon, Feb 11, 2019 at 11:58 AM +0100, "Jan-Tore Jakobsen"
> <jan.jakobsen@stud.uis.no> wrote:
>
> Thank you for very helpful description for my FSW project.
> Can i ask how much one tool (plunger..) cost , lets say for welding
> 3 or 4 mm Al6082 alloy?
>
> i will make a request later when i have asked or steel supplier which
> alloy is available in their store. I want to purchase several tools
> just need to know your prices so i dont exceed my budget.
>
> Do you sell force measuring equipment and termo element for mesuring
> during welding?
> Im going to use taguchi parameter design method, so need to choose
> which parameters im going to optimize.
>
> Bests
> Jan-Tore
>
> ------------------------
>
> FRA: SW <laurent.dubourg@stirweld.com>
> SENDT: torsdag 7. februar 2019 22.47
> TIL: Jan-Tore Jakobsen; 'Sylvie DAGNET'
> EMNE: RE: StirWeld "Tool holder for MAZAK VCN 430A CNC machine"
>
> Dear Jan,
>
> I'm the FSW expert 😊 I could help you on the technical side.

>
> Normally, consider 1kN per 1 mm (for 5xxx and 6xxx). Of course, this
> is depending on the welding parameters (it's possible to weld 10-mm
> thick
> AA6061 with 7kN with low welding speed of 140 mm/min).
>
> Our FSW tools are specially designed to reduce the Z force.
>
> To reduce the plunging force, you can use a higher rotational speed
> during plunging. Then, reduce it to the nominal rotational speed 3
> seconds after the shoulder touch.
>
> To start, I recommend :
>
> * Any 6xxx alloys - thickness of 3 or 4 mm - flat extrusions
> (300 mm long, 50 mm wide). Start by placing a second sample under the
> first one for the first tests. This avoids to touch the backing plate
> and damage it for the first trials. Once you are confident with the
> welding parameters, we can remove the second "protecting" sample. Buy
> flat extrusions. It's cheap and the dimensions are interesting.
> * Any 5xxx alloys - thickness of 2 or 3 mm- laser cut sheets
> (300 mm long, 50 mm wide, 100 mm wide for tensile testing). Buy laser
> cut sheets. It's cheap and the cutting quality is OK for FSW.
> * I recommend butt welding as lap welding is more difficult due to
> specific defects (hooking).
>
> What do you mean by plunger ?
>
> Our FSW tools are in stock. The delivery time is under one week.
>
> Best regards,
>
> Laurent Dubourg
>
> CEO StirWeld
>
> +33 (0)6 47 49 74 19
>
> Envie de mieux nous connaître : www.stirweld.com [1] [2] [2]
>
> DE : Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no> ENVOYÉ : jeudi 7
> février 2019 21:57 À : Sylvie DAGNET <sylvie.dagnet@stirweld.com> CC
> : Laurent Dubourg <laurent.dubourg@stirweld.com> OBJET : Sv: StirWeld
> "Tool holder for MAZAK VCN 430A CNC machine"
>
> Thank you.
>
> Im about to start my project soon and yes iam currently looking for a
> supplier for my project.
>
> I will make a request next week because i have not decide which
> aluminium alloy to weld or thickness. I did measure the downforce in
> my mazak milling centre with a load gauge and just by driving down
> spindle in z-direction. When applying 80% downforce the load gauge
> measured 14kN . From this number i guess 3 mm plates would do maybe
> 6062 alloy. The FSW process i estimate would need around 6-8 kN and
> peaks of around 14kN to keep downforce constant.
>
> This is a startup project to get familiar with FSW with mazak machine.
> Do you have any suggestion about which aluminium alloy would be

> easiest to weld and with use of this forces.
>
> Im also interesting in maybe doing a double weld (2 sided).
>
> This is just for researching and master/phd subjects so not to big
> investment at this point beside plungers and maybe load cells and
> termo element.
>
> Any comments is appreciated. Let us see if we can find plungers and
> tools for this project.
>
> Delivery time have to be short - couple of weeks.
>
> Bests
>
> Jan-Tore Jakobsen
>
> ------------------------
>
> FRA: Sylvie DAGNET <sylvie.dagnet@stirweld.com>
> SENDT: torsdag 7. februar 2019 21.17
> TIL: Jan-Tore Jakobsen
> KOPI: Laurent Dubourg
> EMNE: StirWeld "Tool holder for MAZAK VCN 430A CNC machine"
>
> Dear Mr Jakobsen,
>
> When you got in touch with us you were interested in a tool holder for
> a
>
> MAZAK VCN 430A CNC Machine.
> We sent you informations about our FSW head, did we answer your
> questions or do you want to plan a conf-call to discuss your FSW
> projects?
>
> Perhaps did you want a tool holder but not a FSW head?
> If it is just the tool holder for your MAZAK that you need, of course
> we
>
> can provide it to you.
>
> We will be happy to help, if needed.
>
> PS: Please find in attachment our FSW Tools collection.
> --
> Best regards
>
> Sylvie Dagnet
> Business Development Manager Stirweld
> +33(0)6.47.49.73.96
>
> want to know us better : www.stirweld.com [1] [2] [1]
>
> -------- Courriel original --------
> Objet: RE: StirWeld "Tool holder for MAZAK VCN 430A CNC machine"
> Date: 18.11.2018 20:57
> De: "SW" <laurent.dubourg@stirweld.com>
> À: <jan.jakobsen@stud.uis.no>
> Cc: "'Sylvie DAGNET'" <sylvie.dagnet@stirweld.com>
>

> Dear Mr Jakobsen,
>
> Do you need additional data ?
>
> Could you tell me more about your needs ?
>
> Cordialement,
>
> Laurent Dubourg
>
> CEO StirWeld
>
> Envie de mieux nous connaître : www.stirweld.com [1] [2] [1] [1]
>
> DE : SW <laurent.dubourg@stirweld.com> ENVOYÉ : dimanche 11 novembre
> 2018 11:57 À :
> jan.jakobsen@stud.uis.no CC : 'Sylvie DAGNET'
> <sylvie.dagnet@stirweld.com> OBJET : TR: StirWeld "Tool holder for
> MAZAK VCN 430A CNC machine"
>
> Dear Mr Jakobsen,
>
> Yes, our FSW head for CNC is for sale 😊 and can be mounted on any CNC
> machine (see the attached PDF, our custumer CAP PROFILE produces
> 2000 parts / week using a mazak + our FSW head).
>
> Here is also additional specifications about the FSW head.
>
> Could you tell me more about your needs ?
>
> Best regards,
>
> Laurent Dubourg PhD-Eng.
>
> CEO StirWeld
>
> Envie de mieux nous connaître : www.stirweld.com [1] [2] [1] [1]
>
>>
>
> De : jan-tore jakobsen <jan.jakobsen@stud.uis.no> Sujet : Tool holder
> for MAZAK VCN 430A CNC machine
>
> Corps du message :
> Hello. Im interested in the tool holder. Is it for sale, and can i use
> it on a ordinary CNC machine? Do you have specifications for the tool
> holder? Please send information and contact information to get in
> touch with you. Bests JT
>
> Links:
> ------
> [1] http://www.stirweld.com/ [2]
>
> Links:
> ------
> [1] http://www.stirweld.com
> [2] http://www.stirweld.com/

Links:
------

[1] http://www.stirweld.com/
[2] http://www.stirweld.com

Links:
------
[1] http://www.stirweld.com

--
Cordialement

Sylvie Dagnet
Business Development Manager Stirweld
06.47.49.73.96

Envie de mieux nous connaître : www.stirweld.com

Sv: Re: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices

Jan-Tore Jakobsen
ma. 01.04.2019 14:59
Til: Sylvie DAGNET <sylvie.dagnet@stirweld.com>

2 vedlegg (3 MB)
IMG_20190401_145133.jpg; IMG_20190401_145243.jpg;

Hello Sylvie
I did recive the tools today and i think one of the items is for 4 mm plates because the tool tip is 4 mm when i measure it.

So i have recived :

3 times about - 3 mm tool tip
3 times about - 4 mm tool tip

Can you deliver the drawings with length of tool tip?
Is it suppose to be 0.1 or 0.2 mm less then plate thickness to be welded?

Best Regards
Jan-Tore

Fra: Jan-Tore Jakobsen
Sendt: tirsdag 12. mars 2019 18.21
Til: Sylvie DAGNET
Emne: Sv: Re: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices

Yes i am. I have sent this to our sales department and Im waiting to get a valid PO number to process this order. So you Will have it in one Day or two. And sure i Will talk nice about stirweld and mention your in my papers. We used megastir earlier but you folks have very good service so i Will recommend your company as future supplies for us.

Have a nice day.

Jt

Jan-Tore Jakobsen

-------- Opprinnelig melding --------
Emne: Fwd: Re: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices
Fra: Sylvie DAGNET
Til: Jan-Tore Jakobsen
Kopi:

Dear Jan,

Please let me know if you are interested in FSW tools?

Wishing you a pleasant afternoon

Sylvie Dagnet
+33 6 47 49 73 96

-------- Courriel original --------
Objet: Re: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices
Date: 07.03.2019 14:07
De: Sylvie DAGNET <sylvie.dagnet@stirweld.com>
À: 'Jan-Tore Jakobsen' <jan.jakobsen@stud.uis.no>
Cc: Laurent Dubourg <laurent.dubourg@stirweld.com>

Dear Jan,

Please excuse me for the delay. Here are the prices.

3 tools for aluminium AA6082 - 3mm plates
3 F-AA1 normal price 1494EUR for express delivery => your price 997 EUR

3 tools for aluminium AA5754 - 2 mm plates
3 F-AA2 normal price 1494EUR for express delivery => your price 997 EUR

The tools are on stock and ready for sending on Monday.

As you can see, we offer you more than 30% discount to help you with your research project.
Would you agree to name Stirweld on your paper in return and promote Stirweld when meeting people interested in FSW?
It would very nice and appreciated.

Have a very nice day

--

Regards

Sylvie Dagnet
Business Development Manager Stirweld
06.47.49.73.96

www.stirweld.com [2]

Le 07.03.2019 13:32, SW a écrit :

> Sylvie,
>
> Could you proceed the Jan's request ?
>
> Thanks you
>
> Cordialement,

>
> Laurent Dubourg
>
> CEO StirWeld
>
> +33 (0)6 47 49 74 19
>
> Envie de mieux nous connaître : www.stirweld.com [1]
>
> DE : Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>
> ENVOYÉ : jeudi 7 mars 2019 12:46
> À : SW <laurent.dubourg@stirweld.com>
> OBJET : Sv: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" /
> prices
>
> Hello.
>
> Could you send me an update with prices and delivery time for the
> tools mentiod below
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> 3 tools for aluminium AA6082 - 3mm plates
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> 3 tools for aluminium AA5754 - 2 mm plates
>
> I Will try to send the purchase order tommorow.
>
> Thank you
>
> Jan-Tore Jakobsen
>
> -------- Opprinnelig melding --------
> Emne: RE: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices
> Fra: SW
> Til: 'Sylvie DAGNET' ,Jan-Tore Jakobsen
> Kopi:
>
> Dear Jan,
>
> The same tool could be used for welding 5xxx or 6xxx. Only the tool
> size is different for 2 or 3 mm thick
> F-AA-1 tool is OK for 2 mm thick.
> F-AA-2 tool is OK for 3 mm thick.
>
> Yes, 3 tools is enough for first trials. If you follow the process
> below, you should damage one tool, max 2.
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>
> Laurent Dubourg
> CEO StirWeld
> +33 (0)6 47 49 74 19
> Envie de mieux nous connaître : www.stirweld.com [2]

>
> -----Message d'origine-----
> De : Sylvie DAGNET <sylvie.dagnet@stirweld.com>
> Envoyé : lundi 4 mars 2019 11:36
> À : Laurent Dubourg <laurent.dubourg@stirweld.com>
> Objet : Fwd: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" /
> prices
>
> Laurent,
>
> can you please answer on the technical side?
>
> Thx
> -------- Courriel original --------
> Objet: Sv: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices
> Date: 04.03.2019 11:33
> De: Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>
> À: Sylvie DAGNET <sylvie.dagnet@stirweld.com>
>
> Hello
>
> Can i ask if there are different tools for different aluminium
> alloys?
> Im gonna buttweld 3 mm 6xxx series (6082-T3 or T6) and maybe 2-3 mm
> 5xxx series (5083 or 5754). can i use same tool for both series?
>
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>
> 3 tools for 3 mm - 6000 series
> 3 tools for 2 mm - 5000 series
>
> What are the chances for tool getting damaged during start up and
> initial phase when finding correct welding parameters? Do you think 3
> tools will do?
>
> Best regards
> Jan-Tore Jakobsen
>
> University of Stavanger
> +47 4721 9000
>
> ------------------------
>
> FRA: Sylvie DAGNET <sylvie.dagnet@stirweld.com>
> SENDT: mandag 11. februar 2019 14.34
> TIL: Jan-Tore Jakobsen
> KOPI: Laurent Dubourg
> EMNE: StirWeld "Tools for MAZAK VCN 430A CNC machine" / prices
>
> Dear Jan,
>
> please find our tools prices for standard aluminium alloys in

> attachment.
>
> You said that delivery time has to be short.
> If you choose express delivery, as you are starting a project with a
> limited budget, give us your requirements and the number of tools you
> need and we will do our best to make a helpful discount on the total
> amount.
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> --
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> Best regards
>
> Sylvie Dagnet
> Business Development Manager Stirweld
> 06.47.49.73.96
>
> Want to know us better : www.stirweld.com [2] [1]
>
> On Mon, Feb 11, 2019 at 11:58 AM +0100, "Jan-Tore Jakobsen"
> <jan.jakobsen@stud.uis.no> wrote:
>
> Thank you for very helpful description for my FSW project.
> Can i ask how much one tool (plunger..) cost , lets say for welding
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>
> i will make a request later when i have asked or steel supplier
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> Do you sell force measuring equipment and termo element for mesuring
> during welding?
> Im going to use taguchi parameter design method, so need to choose
> which parameters im going to optimize.
>
> Bests
> Jan-Tore
>
> -------------------------
>
> FRA: SW <laurent.dubourg@stirweld.com>
> SENDT: torsdag 7. februar 2019 22.47
> TIL: Jan-Tore Jakobsen; 'Sylvie DAGNET'
> EMNE: RE: StirWeld "Tool holder for MAZAK VCN 430A CNC machine"
>
> Dear Jan,
>
> I'm the FSW expert 😊 I could help you on the technical side.
>
> Normally, consider 1kN per 1 mm (for 5xxx and 6xxx). Of course, this
> is depending on the welding parameters (it's possible to weld 10-mm
> thick
> AA6061 with 7kN with low welding speed of 140 mm/min).

>
> Our FSW tools are specially designed to reduce the Z force.
>
> To reduce the plunging force, you can use a higher rotational speed
> during plunging. Then, reduce it to the nominal rotational speed 3
> seconds after the shoulder touch.
>
> To start, I recommend :
>
> * Any 6xxx alloys - thickness of 3 or 4 mm - flat extrusions
> (300 mm long, 50 mm wide). Start by placing a second sample under the
> first one for the first tests. This avoids to touch the backing plate
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> welding parameters, we can remove the second "protecting" sample. Buy
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> cut sheets. It's cheap and the cutting quality is OK for FSW.
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> due to specific defects (hooking).
>
> What do you mean by plunger ?
>
> Our FSW tools are in stock. The delivery time is under one week.
>
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>
> Laurent Dubourg
>
> CEO StirWeld
>
> +33 (0)6 47 49 74 19
>
> Envie de mieux nous connaître : www.stirweld.com [2] [2]
>
> DE : Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no> ENVOYÉ : jeudi 7
> février 2019 21:57 À : Sylvie DAGNET <sylvie.dagnet@stirweld.com> CC
> : Laurent Dubourg <laurent.dubourg@stirweld.com> OBJET : Sv: StirWeld
> "Tool holder for MAZAK VCN 430A CNC machine"
>
> Thank you.
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> aluminium alloy to weld or thickness. I did measure the downforce in
> my mazak milling centre with a load gauge and just by driving down
> spindle in z-direction. When applying 80% downforce the load gauge
> measured 14kN . From this number i guess 3 mm plates would do maybe
> 6062 alloy. The FSW process i estimate would need around 6-8 kN and
> peaks of around 14kN to keep downforce constant.

>
> This is a startup project to get familiar with FSW with mazak machine.
> Do you have any suggestion about which aluminium alloy would be
> easiest to weld and with use of this forces.
>
> Im also interesting in maybe doing a double weld (2 sided).
>
> This is just for researching and master/phd subjects so not to big
> investment at this point beside plungers and maybe load cells and
> termo element.
>
> Any comments is appreciated. Let us see if we can find plungers and
> tools for this project.
>
> Delivery time have to be short - couple of weeks.
>
> Bests
>
> Jan-Tore Jakobsen
>
> ------------------------
>
> FRA: Sylvie DAGNET <sylvie.dagnet@stirweld.com>
> SENDT: torsdag 7. februar 2019 21.17
> TIL: Jan-Tore Jakobsen
> KOPI: Laurent Dubourg
> EMNE: StirWeld "Tool holder for MAZAK VCN 430A CNC machine"
>
> Dear Mr Jakobsen,
>
> When you got in touch with us you were interested in a tool holder for
> a
>
> MAZAK VCN 430A CNC Machine.
> We sent you informations about our FSW head, did we answer your
> questions or do you want to plan a conf-call to discuss your FSW
> projects?
>
> Perhaps did you want a tool holder but not a FSW head?
> If it is just the tool holder for your MAZAK that you need, of course
> we
>
> can provide it to you.
>
> We will be happy to help, if needed.
>
> PS: Please find in attachment our FSW Tools collection.
> --
> Best regards
>
> Sylvie Dagnet
> Business Development Manager Stirweld

> +33(0)6.47.49.73.96
>
> want to know us better : www.stirweld.com [2] [1]
>
> -------- Courriel original --------
> Objet: RE: StirWeld "Tool holder for MAZAK VCN 430A CNC machine"
> Date: 18.11.2018 20:57
> De: "SW" <laurent.dubourg@stirweld.com>
> À: <jan.jakobsen@stud.uis.no>
> Cc: "'Sylvie DAGNET'" <sylvie.dagnet@stirweld.com>
>
> Dear Mr Jakobsen,
>
> Do you need additional data ?
>
> Could you tell me more about your needs ?
>
> Cordialement,
>
> Laurent Dubourg
>
> CEO StirWeld
>
> Envie de mieux nous connaître : www.stirweld.com [2] [1] [1]
>
> DE : SW <laurent.dubourg@stirweld.com>
> ENVOYÉ : dimanche 11 novembre 2018 11:57 À :
> jan.jakobsen@stud.uis.no CC : 'Sylvie DAGNET'
> <sylvie.dagnet@stirweld.com> OBJET : TR: StirWeld "Tool holder for
> MAZAK VCN 430A CNC machine"
>
> Dear Mr Jakobsen,
>
> Yes, our FSW head for CNC is for sale 😉 and can be mounted on any
> CNC machine (see the attached PDF, our custumer CAP PROFILE produces
> 2000 parts / week using a mazak + our FSW head).
>
> Here is also additional specifications about the FSW head.
>
> Could you tell me more about your needs ?
>
> Best regards,
>
> Laurent Dubourg PhD-Eng.
>
> CEO StirWeld
>
> Envie de mieux nous connaître : www.stirweld.com [2] [1] [1]
>
> >
>
> De : jan-tore jakobsen <jan.jakobsen@stud.uis.no> Sujet : Tool holder

> for MAZAK VCN 430A CNC machine
>
> Corps du message :
> Hello. Im interested in the tool holder. Is it for sale, and can i use
> it on a ordinary CNC machine? Do you have specifications for the tool
> holder? Please send information and contact information to get in
> touch with you. Bests JT
>
> Links:
> ------
> [1] http://www.stirweld.com/ [2]
>
> Links:
> ------
> [1] http://www.stirweld.com
> [2] http://www.stirweld.com/

Links:
------
[1] http://www.stirweld.com/
[2] http://www.stirweld.com

RE: Question about parameters before welding

Laurent Dubourg <laurent.dubourg@stirweld.com>
to. 06.06.2019 21:39
Til: Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>

You’re right.

And my apologizes about the unit mistake….

Cordialement,

Laurent Dubourg
CEO StirWeld
+33 (0)6 47 49 74 19
Envie de mieux nous connaître : www.stirweld.com

De : Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>
Envoyé : jeudi 6 juin 2019 20:48
À : Laurent Dubourg <laurent.dubourg@stirweld.com>
Objet : Sv: Question about parameters before welding

This is the thrust control option. Not sure if this will help us, but we can try some values and see if this will improve the welding. The interpolating can be the best option though. For research purpose this can be ok, but as you mentiod earlier the force control unit is needed to make perfect welds without spending a lot of time programming every few mm for the weld path and try to manipulate the machine performing the process. I dont think we will be able to perform welds as specified in the standard without your force unit.

Anyway, i will let you know later how this option did affect the weld process. The Mazak company did some major changes to their Mazak 430a CNC machine to be able to do FSW. We asked them at the beginning at this project what they suggested we would need and the quote was 50k Euro for rebuilding of the machine to fit FSW. So i dont think this thrust control will fix the problems.

JT

Fra: Laurent Dubourg <laurent.dubourg@stirweld.com>
Sendt: torsdag 6. juni 2019 19.26
Til: Jan-Tore Jakobsen
Emne: RE: Question about parameters before welding

Hi jan,

Thank you for your helpfull feedbacks.

Your welds seems sound !

Im about to start welding the 3 mm plates with 6082 Alloy.

I will set the force control on for my MAZAK machine , i finally found the thrust control from the menu.
What do you mean by force control for my MAZAK machine ?
Native CNC does not have force control 😉 Are you sure about that ?

I know this was done by Mazak with the same type of machine earlier during FSW but im not sure if this will have any effect for our experiments.

I will also interpolate the welding route for every 5-10 mm and check the termal effect as well.

For the 2 mmm plates we did get problems with increased disturtion, i guess this is mainly due to overheating as we got excessive flash as well.
Traverse welding speed was between 30 and 60 mm/min and 1000-1500 rpm- with traverse speed at 5 mm/min our machine needed 50 minutes to weld 200 mm...

My apologizes :

- Classic welding speeds for this weld are between 400 to 1200 mm / min. Therefore, 0,6 to 20 mm/s .....
- I didn't notice your units in our previous discussions

I posted some picture for you to see , i did try the 1.8 mm tool on my 3 mm 6082 plates and this weld seems perfect.

Can we use the 1.8 mm for 3mm plates or are this limited by standards or wps?

Yes, you can use. However, we will get 1-mm lack of penetration defect.

I will check these welds for defects and microscopy later when the equipment is available. The backside looks ok from a macroscope point of view.

Your equipment for force control seems perfect to have at this moment though ☺

Have a nice day
Jan-Tore

Fra: Laurent Dubourg <laurent.dubourg@stirweld.com>
Sendt: mandag 20. mai 2019 22.39
Til: Jan-Tore Jakobsen
Kopi: 'Sylvie Dagnet'
Emne: RE: Question about parameters before welding

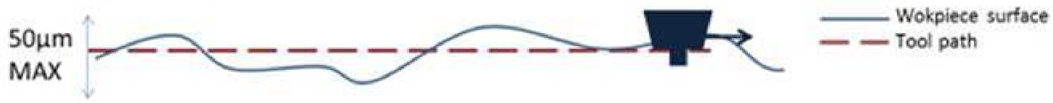
Hi Jan,

The large chip on the retreating side (called flash) is due a deeper shoulder plunge. The flash is also important on the advancing side of your weld. When the shoulder plunge is too deep, this creates also a void on the advancing side (called wormhole).

stirweld — FSW head

- To secure the weld quality, tool penetration into the workpiece must be constant.
- FSW requires a Z tool position of **+/- 50 µm** to avoid defects.
- However, the part thickness is not accurate (**extrusion/rolling ~ 0,1 mm, casting ~ 0,5 mm**) + inaccuracy of part positioning (**part positioning ~ 1 mm, thermal distortion during welding ~ 0,5 - 2 mm**).

Welding without force control



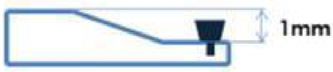
- The force control solves this problem on CNC machine (1 to 18 kN).

Welding with force control

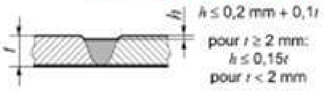
www.stirweld.com

stirweld — FSW head

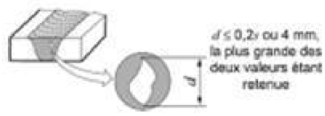
- Demonstration of force control on 1-mm step defect

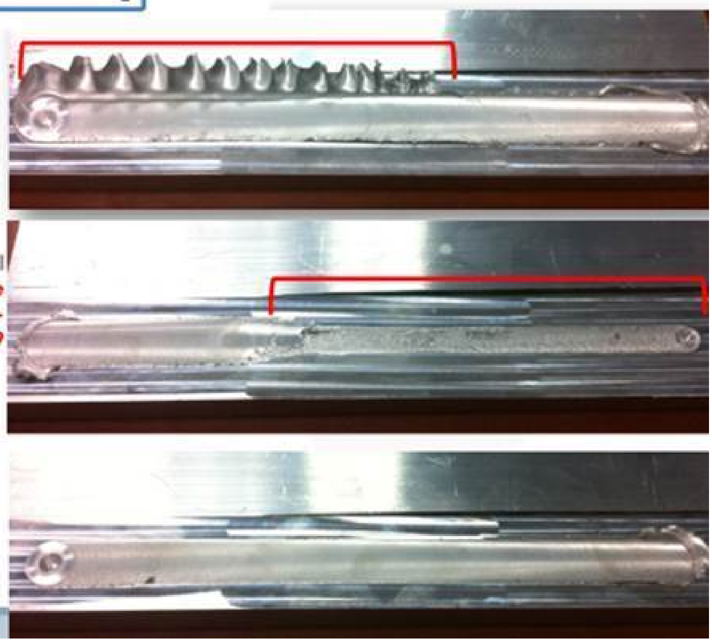


Welding without force control (positive step) : **excessive flash – controlled by ISO25239**

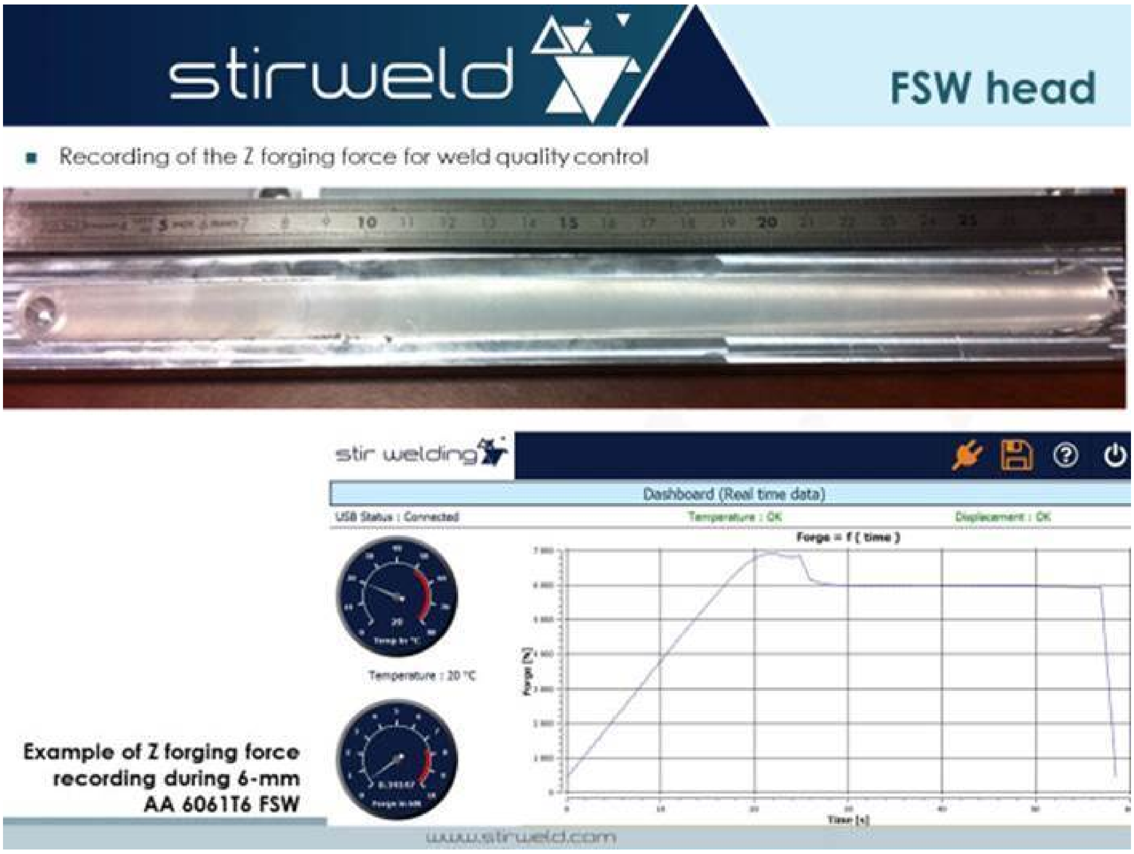


Welding without force control (negative step) : **porosities / wormhole due to the lack of compactness - controlled by ISO25239**





Welding with force control: **no defect**



Reduce the shoulder plunge to about 0,05 - 0,1 mm.

However, your experiment in position control is very tricky as :

- FSW requires a Z tool position of +/- 50 µm to avoid defects.
- However, the sheet thickness is not accurate (rolling accuracy is 0,1 mm) + inaccuracy of part positioning (part positioning + thermal distortion during welding = 0,5 mm).
- Then it is difficult to get repeatable weld without force control

A tip : measure the Z position on each sample before each weld (at the weld beginning and end) and adjust it in the CNC program before each weld. You should improve the repeatability.

Another, do you measure the gap bridging before FSW ? The gap must lower than 0,2 mm for 2 mm welding.

Be careful also to clamping problem. Check the stiffness of your jig to avoid any gap during FSW

Cordialement,

Laurent Dubourg
CEO StirWeld
+33 (0)6 47 49 74 19
Envie de mieux nous connaître : www.stirweld.com

De : Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>
Envoyé : lundi 20 mai 2019 15:47
À : SW <laurent.dubourg@stirweld.com>
Objet : Sv: Question about parameters before welding

Hello

Now i have started to weld but got this problem on advancing side. As you can see one of the weld were good but the other have this chip a long the side. Im using different parameters and this is for 2 mm 5754 alloy.

Any suggestion?

Jan-Tore Jakobsen

-------- Opprinnelig melding --------
Emne: RE: Question about parameters before welding
Fra: SW
Til: Jan-Tore Jakobsen
Kopi:

Hi

Select the spot on the right in the attached picture.

This difference of 0,05-0,1 mm is on the same sheet or between 2 sheets ?

We developed a FSW head for CNC including force control to avoid all the problems associated with the difference of thickness, Z position, plate distortions and so on. 😉

Cordialement,

Laurent Dubourg
CEO StirWeld
+33 (0)6 47 49 74 19
Envie de mieux nous connaître : www.stirweld.com

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@LaFrenchFab #FrenchFab

De : Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>
Envoyé : mercredi 15 mai 2019 11:12
À : SW <laurent.dubourg@stirweld.com>
Objet : Sv: Question about parameters before welding

Today we manage to do some welds. But we have a difference in the hight for the plates with 0.05 mm to 0. 1 mm this affects the shoulder depth so we Need to solve this issue. The long weld is with different tranverse speeds. Can you tell which one of the 6 spot welds you think have the best shoulder depth by this picture?

Best
Jt

Jan-Tore Jakobsen

-------- Opprinnelig melding --------
Emne: RE: Question about parameters before welding
Fra: SW
Til: Jan-Tore Jakobsen
Kopi:

Hi Jan,

Clearly the shoulder does not touch the surface. Are you sure about the 0,1-mm shoulder depth?
This tool has a 8,5-mm shoulder diameter. We must see the footprint of the shoulder on the coupons.
This is maybe a distortion into the CNC machine ?

A tip to clarify that:

- Carry out a spot weld (just plunge into the material)
- Increase the tool plunge using 0,05-mm step and remove the tool (for example, carry out a plunge with 0,05mm depth and exit the tool. Perform another spot with 0,1-mm **on the other position** and exit the tool. And so on).
- Perform this test until having a clear 8,5-mm spot weld and note the Z position of the machine (see page 6 in the attached document).
- This Z position gives you the correct Z position for FSW

Please perform this test and send me the results to see if you have another problem

Cordialement,

Laurent Dubourg
CEO StirWeld
+33 (0)6 47 49 74 19
Envie de mieux nous connaître : www.stirweld.com

De : Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>
Envoyé : mardi 14 mai 2019 20:53
À : SW <laurent.dubourg@stirweld.com>
Objet : Sv: Question about parameters before welding

Hello Laurent
Today i started to test the parameters. I did use a welding rig as you can see in the picture and paramters as we discussed
earlier spindle speed 1500 rpm, around 5 mm/min feed rate. I used a 3mm 6082-T6 plate and the 1.8 mm tool just to be sure not to touch the backing plate.

First test weld is with 3 seconds dwell time (worst) , the second on the plate is with 5 seconds dwell time and shoulder depth around 0.1 mm. (the middle weld)
Run 2 is the best weld , here i used 8 second dwell time and around 0.1-0.15 mm shoulder depth. as you can see the tool have experienced some heat exchange from the process. As you can see from the picture something is not quite right with my parameters or settings . Can you see from the picture what i should try to improve ?

Best regards
Jan-Tore

Fra: SW <laurent.dubourg@stirweld.com>
Sendt: mandag 29. april 2019 18.41
Til: Jan-Tore Jakobsen
Emne: RE: Question about parameters before welding

Thank you for your helpfull answer. Interesting reading about the method used for your project. So if i have understood you i will use 0 degree tilt and the shoulder is to hit parallel onto the plates?
Yes 😉

i did send the tools back with DHL and tracking number:4217060385
OK thank you

I will start the welding at the end of this week and next week . You will get an update on the progress and results.
Bests
Jan-Tore

Fra: SW <laurent.dubourg@stirweld.com>
Sendt: søndag 28. april 2019 15.43
Til: Jan-Tore Jakobsen
Kopi: 'Sylvie DAGNET'
Emne: RE: Question about parameters before welding

Dear Jan

Hello
Im about to start welding and need some help with finding paramters. Tagushi parameter design approch is choosen to find optimal parameters with 4 factors and 3 levels

I used a similar approach. Please find the paper in attachment.

Factor	Levels*			Units
	1	2	3	
Roatation	**1000**	**1200**	**1400**	rpm
Travel Speed	**5**	**10**	**15**	mm/min
Dwell time	**25**	**30**	**35**	sec
Tool Tilt	**1**	**2**	**3**	Angle
*Underline for starting level of parameter				
Yellow cells are input cells. Choose your levels based on the parameter study. Insert tensile test result in table sheet 'Welding'.				

Above figure is from my Tagushi excel sheet--Attached below if you need to understand more about my project- password is : jtj777

Alloys to weld is:

AA5754-H22- 2mm
AA6082-T6- 3mm Plates butt welding-

From before you suggestion was 1200 rpm , 5mm/min and forging force at 4000N

I cant monitor force with this MAZAK VCN430 milling centre but i have a data logger to monitor temperature during welding.

I will start with your suggestion and try to increase values to find the range where defects free welds are performed but can i ask about dwell time and shoulder depth? i was thinking of having one of this parameters for my Tagushi modell. Can i use shoulder depth of 0-0,025-0,5 ?

Yes this is a good idea without force control (while force control is an extremely safer for the pin lifetime !).
Use the following shoulder depth of 0,1-0,2-0,3
0 is too dangerous for the pin !
0,5 is also too dangerous for the pin !

Have you any suggestion for dwell time? Thermoelements is used about 2 mm from the weld outern diameter.
A good dwell time is between 2 to 5 s. Your values are too high.
Prefer a small plunging speed : 1 mm /s for example.

Don't use a tilt angle. Our tools are designed to avoid a tilt angle (due the scroll shape onto the shoulder). Tilt angle is required with old tool design.

Can i ask you about what you think may be the maximum values for tranverse speed and spindle speed for thin plates ? Dont need to be precise but tranverse speed of 5-200-500 etc..

Your values are correct :

Roatation	**1000**	**1200**	**1400**	rpm
Travel Speed	**5**	**10**	**15**	mm/min

However, start your taguchi experiments with the hottest parameters (High RPM, Low travel). This will reduce the forging force and reduces the risk of pin breakage in case of colder parameters (1000 RPM and 15 m/min).

Normally, the pin can handle the colder parameters (1000 RPM and 15 m/min). However, I cannot guaranteed this … as it depends also of other factors : plunging phase, clamping quality, etc….

as i understand the process so will higher spindle speed produce more heat-
and if i want to minimize the Z downforce i need high spindle speed and low tranverse speed.
Yes

Hope you can provide me with some answers before i start finding above levels for my factors (parameters).
I hope that I can help you.

Last point : have you shipped back the other tools to sylvie ?

Thanks

best regards

Jan-Tore Jakobsen
master student
University of Stavanger

Universitetet
i Stavanger

RE: Question about parameters before welding

Laurent Dubourg <laurent.dubourg@stirweld.com>
to. 06.06.2019 21:39
Til: Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>

You're right.

And my apologizes about the unit mistake….

Cordialement,

Laurent Dubourg
CEO StirWeld
+33 (0)6 47 49 74 19
Envie de mieux nous connaître : www.stirweld.com

De : Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>
Envoyé : jeudi 6 juin 2019 20:48
À : Laurent Dubourg <laurent.dubourg@stirweld.com>
Objet : Sv: Question about parameters before welding

This is the thrust control option. Not sure if this will help us, but we can try some values and see if this will improve the welding. The interpolating can be the best option though. For research purpose this can be ok, but as you mentiod earlier the force control unit is needed to make perfect welds without spending a lot of time programming every few mm for the weld path and try to manipulate the machine performing the process. I dont think we will be able to perform welds as specified in the standard without your force unit.

Anyway, i will let you know later how this option did affect the weld process. The Mazak company did some major changes to their Mazak 430a CNC machine to be able to do FSW. We asked them at the beginning at this project what they suggested we would need and the quote was 50k Euro for rebuilding of the machine to fit FSW. So i dont think this thrust control will fix the problems.

JT

Fra: Laurent Dubourg <laurent.dubourg@stirweld.com>
Sendt: torsdag 6. juni 2019 19.26
Til: Jan-Tore Jakobsen
Emne: RE: Question about parameters before welding

Hi jan,

Thank you for your helpfull feedbacks.

Your welds seems sound !

Im about to start welding the 3 mm plates with 6082 Alloy.

I will set the force control on for my MAZAK machine , i finally found the thrust control from the menu.
What do you mean by force control for my MAZAK machine ?
Native CNC does not have force control 😉 Are you sure about that ?

I know this was done by Mazak with the same type of machine earlier during FSW but im not sure if this will have any effect for our experiments.

I will also interpolate the welding route for every 5-10 mm and check the termal effect as well.

For the 2 mmm plates we did get problems with increased disturtion, i guess this is mainly due to overheating as we got excessive flash as well.
Traverse welding speed was between 30 and 60 mm/min and 1000-1500 rpm- with traverse speed at 5 mm/min our machine needed 50 minutes to weld 200 mm...

My apologizes :

- Classic welding speeds for this weld are between 400 to 1200 mm / min. Therefore, 0,6 to 20 mm/s .....
- I didn't notice your units in our previous discussions

I posted some picture for you to see , i did try the 1.8 mm tool on my 3 mm 6082 plates and this weld seems perfect.

Can we use the 1.8 mm for 3mm plates or are this limited by standards or wps?

Yes, you can use. However, we will get 1-mm lack of penetration defect.

I will check these welds for defects and microscopy later when the equipment is available. The backside looks ok from a macroscope point of view.

Your equipment for force control seems perfect to have at this moment though 🙂

Have a nice day
Jan-Tore

Fra: Laurent Dubourg <laurent.dubourg@stirweld.com>
Sendt: mandag 20. mai 2019 22.39
Til: Jan-Tore Jakobsen
Kopi: 'Sylvie Dagnet'
Emne: RE: Question about parameters before welding

Hi Jan,

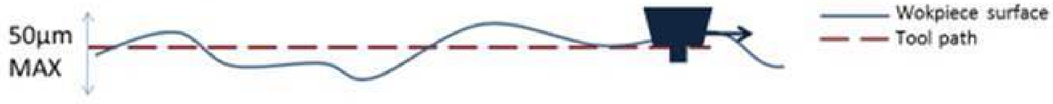
The large chip on the retreating side (called flash) is due a deeper shoulder plunge. The flash is also important on the advancing side of your weld. When the shoulder plunge is too deep, this creates also a void on the advancing side (called wormhole).

stirweld

FSW head

- To secure the weld quality, tool penetration into the workpiece must be constant.
- FSW requires a Z tool position of **+/- 50 µm** to avoid defects.
- However, the part thickness is not accurate (**extrusion/rolling ~ 0,1 mm, casting ~ 0,5 mm**) + inaccuracy of part positioning (**part positioning ~ 1 mm, thermal distortion during welding ~ 0,5 - 2 mm**).

Welding without force control



- The force control solves this problem on CNC machine (1 to 18 kN).

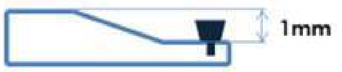
Welding with force control

www.stirweld.com

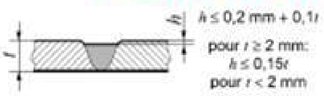
stirweld

FSW head

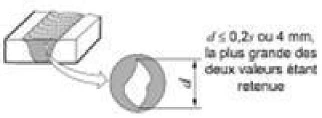
- Demonstration of force control on 1-mm step defect



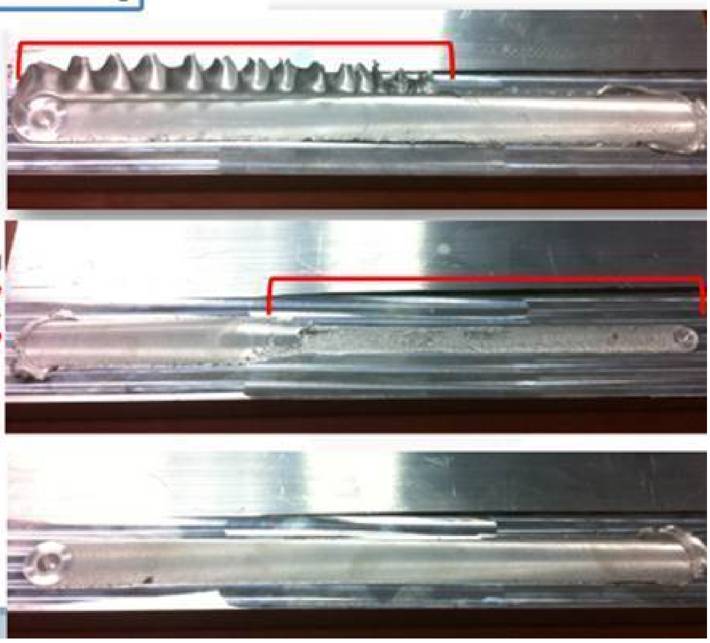
Welding without force control (positive step) : **excessive flash – controlled by ISO25239**

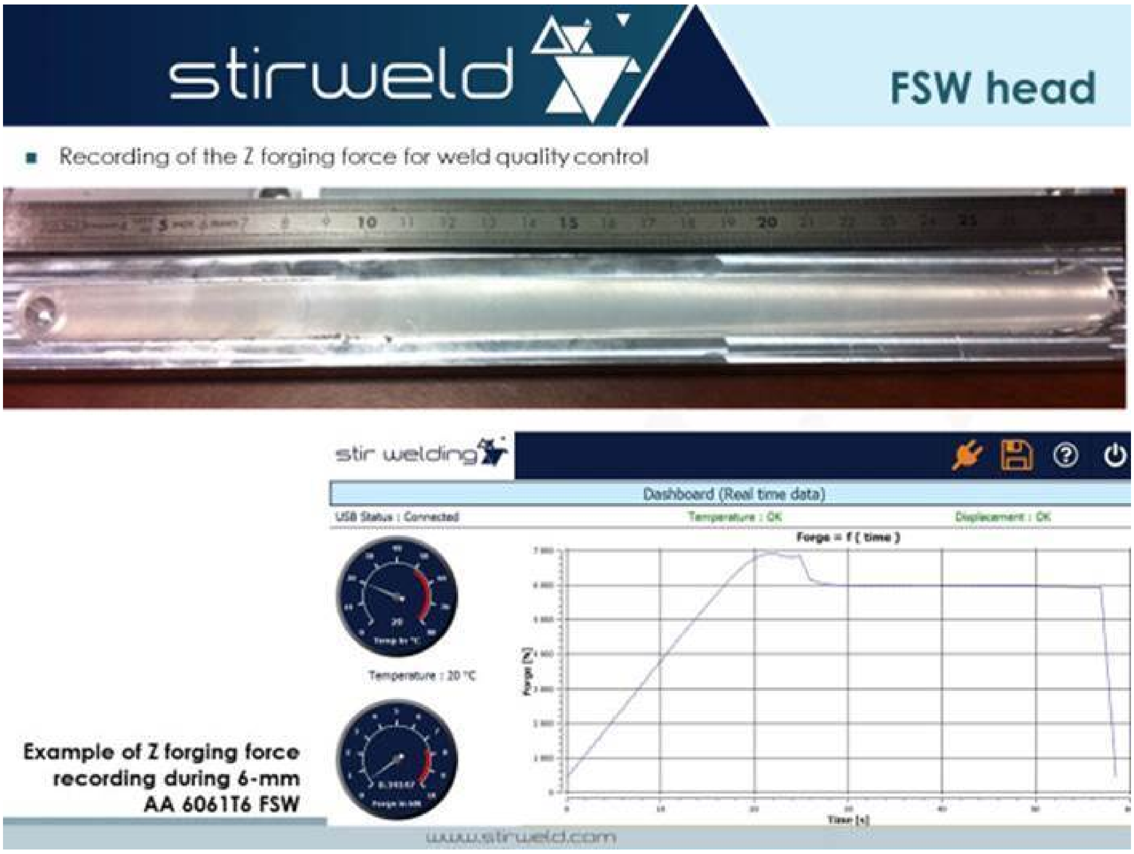


Welding without force control (negative step) : **porosities / wormhole due to the lack of compactness - controlled by ISO25239**



Welding with force control: **no defect**





Reduce the shoulder plunge to about 0,05 - 0,1 mm.

However, your experiment in position control is very tricky as :

- FSW requires a Z tool position of +/- 50 µm to avoid defects.
- However, the sheet thickness is not accurate (rolling accuracy is 0,1 mm) + inaccuracy of part positioning (part positioning + thermal distortion during welding = 0,5 mm).
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A tip : measure the Z position on each sample before each weld (at the weld beginning and end) and adjust it in the CNC program before each weld. You should improve the repeatability.

Another, do you measure the gap bridging before FSW ? The gap must lower than 0,2 mm for 2 mm welding.

Be careful also to clamping problem. Check the stiffness of your jig to avoid any gap during FSW

Cordialement,

Laurent Dubourg
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+33 (0)6 47 49 74 19
Envie de mieux nous connaître : www.stirweld.com

La FRENCH FAB
LES INDUSTRIELS EN MOUVEMENT
@LaFrenchFab #FrenchFab

De : Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>
Envoyé : lundi 20 mai 2019 15:47
À : SW <laurent.dubourg@stirweld.com>
Objet : Sv: Question about parameters before welding

Hello

Now i have started to weld but got this problem on advancing side. As you can see one of the weld were good but the other have this chip a long the side. Im using different parameters and this is for 2 mm 5754 alloy.

Any suggestion?

Jan-Tore Jakobsen

-------- Opprinnelig melding --------
Emne: RE: Question about parameters before welding
Fra: SW
Til: Jan-Tore Jakobsen
Kopi:

Hi

Select the spot on the right in the attached picture.

This difference of 0,05-0,1 mm is on the same sheet or between 2 sheets ?

We developed a FSW head for CNC including force control to avoid all the problems associated with the difference of thickness, Z position, plate distortions and so on. 😉

Cordialement,

Laurent Dubourg
CEO StirWeld
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Envie de mieux nous connaître : www.stirweld.com

De : Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>
Envoyé : mercredi 15 mai 2019 11:12
À : SW <laurent.dubourg@stirweld.com>
Objet : Sv: Question about parameters before welding

Today we manage to do some welds. But we have a difference in the hight for the plates with 0.05 mm to 0. 1 mm this affects the shoulder depth so we Need to solve this issue. The long weld is with different tranverse speeds. Can you tell which one of the 6 spot welds you think have the best shoulder depth by this picture?

Best
Jt

Jan-Tore Jakobsen

-------- Opprinnelig melding --------
Emne: RE: Question about parameters before welding
Fra: SW
Til: Jan-Tore Jakobsen
Kopi:

Hi Jan,

Clearly the shoulder does not touch the surface. Are you sure about the 0,1-mm shoulder depth?
This tool has a 8,5-mm shoulder diameter. We must see the footprint of the shoulder on the coupons.
This is maybe a distortion into the CNC machine ?

A tip to clarify that:

- Carry out a spot weld (just plunge into the material)
- Increase the tool plunge using 0,05-mm step and remove the tool (for example, carry out a plunge with 0,05mm depth and exit the tool. Perform another spot with 0,1-mm **on the other position** and exit the tool. And so on).
- Perform this test until having a clear 8,5-mm spot weld and note the Z position of the machine (see page 6 in the attached document).
- This Z position gives you the correct Z position for FSW

Please perform this test and send me the results to see if you have another problem

Cordialement,

Laurent Dubourg
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De : Jan-Tore Jakobsen <jan.jakobsen@stud.uis.no>
Envoyé : mardi 14 mai 2019 20:53
À : SW <laurent.dubourg@stirweld.com>
Objet : Sv: Question about parameters before welding

Hello Laurent
Today i started to test the parameters. I did use a welding rig as you can see in the picture and paramters as we discussed
earlier spindle speed 1500 rpm, around 5 mm/min feed rate. I used a 3mm 6082-T6 plate and the 1.8 mm tool just to be sure not to touch the backing plate.

First test weld is with 3 seconds dwell time (worst) , the second on the plate is with 5 seconds dwell time and shoulder depth around 0.1 mm. (the middle weld)
Run 2 is the best weld , here i used 8 second dwell time and around 0.1-0.15 mm shoulder depth. as you can see the tool have experienced some heat exchange from the process. As you can see from the picture something is not quite right with my parameters or settings . Can you see from the picture what i should try to improve ?

Best regards
Jan-Tore

Fra: SW <laurent.dubourg@stirweld.com>
Sendt: mandag 29. april 2019 18.41
Til: Jan-Tore Jakobsen
Emne: RE: Question about parameters before welding

Thank you for your helpfull answer. Interesting reading about the method used for your project. So if i have understood you i will use 0 degree tilt and the shoulder is to hit parallel onto the plates?
Yes 😉

i did send the tools back with DHL and tracking number:4217060385
OK thank you

I will start the welding at the end of this week and next week . You will get an update on the progress and results.
Bests
Jan-Tore

Fra: SW <laurent.dubourg@stirweld.com>
Sendt: søndag 28. april 2019 15.43
Til: Jan-Tore Jakobsen
Kopi: 'Sylvie DAGNET'
Emne: RE: Question about parameters before welding

Dear Jan

Hello
Im about to start welding and need some help with finding paramters. Tagushi parameter design approch is choosen to find optimal parameters with 4 factors and 3 levels

I used a similar approach. Please find the paper in attachment.

Factor	Levels*			Units
	1	2	3	
Roatation	**1000**	**1200**	**1400**	rpm
Travel Speed	**5**	**10**	**15**	mm/min
Dwell time	**25**	**30**	**35**	sec
Tool Tilt	**1**	**2**	**3**	Angle
*Underline for starting level of parameter				
Yellow cells are input cells. Choose your levels based on the parameter study. Insert tensile test result in table sheet 'Welding'.				

Above figure is from my Tagushi excel sheet--Attached below if you need to understand more about my project- password is : jtj777

Alloys to weld is:

AA5754-H22- 2mm
AA6082-T6- 3mm Plates butt welding-

From before you suggestion was 1200 rpm , 5mm/min and forging force at 4000N

I cant monitor force with this MAZAK VCN430 milling centre but i have a data logger to monitor temperature during welding.

I will start with your suggestion and try to increase values to find the range where defects free welds are performed but can i ask about dwell time and shoulder depth? i was thinking of having one of this parameters for my Tagushi modell. Can i use shoulder depth of 0-0,025-0,5 ?

Yes this is a good idea without force control (while force control is an extremely safer for the pin lifetime !).
Use the following shoulder depth of 0,1-0,2-0,3
0 is too dangerous for the pin !
0,5 is also too dangerous for the pin !

Have you any suggestion for dwell time? Thermoelements is used about 2 mm from the weld outern diameter.
A good dwell time is between 2 to 5 s. Your values are too high.
Prefer a small plunging speed : 1 mm /s for example.

Don't use a tilt angle. Our tools are designed to avoid a tilt angle (due the scroll shape onto the shoulder). Tilt angle is required with old tool design.

Can i ask you about what you think may be the maximum values for tranverse speed and spindle speed for thin plates ? Dont need to be precise but tranverse speed of 5-200-500 etc..

Your values are correct :

Roatation	**1000**	**1200**	**1400**	rpm
Travel Speed	**5**	**10**	**15**	mm/min

However, start your taguchi experiments with the hottest parameters (High RPM, Low travel). This will reduce the forging force and reduces the risk of pin breakage in case of colder parameters (1000 RPM and 15 m/min).

Normally, the pin can handle the colder parameters (1000 RPM and 15 m/min). However, I cannot guaranteed this … as it depends also of other factors : plunging phase, clamping quality, etc….

as i understand the process so will higher spindle speed produce more heat-
and if i want to minimize the Z downforce i need high spindle speed and low tranverse speed.
Yes

Hope you can provide me with some answers before i start finding above levels for my factors (parameters).
I hope that I can help you.

Last point : have you shipped back the other tools to sylvie ?

Thanks

best regards

Jan-Tore Jakobsen
master student
University of Stavanger

Universitetet
i Stavanger