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Abstract

This study aims to find the maximum, usable, feed limit at different arc-energies and use the findings in multi-pass welding planning for robotic welding, taking into consideration the high controllability of robot movements.

A combined studies using numerical analyses and practical experiments to calculate the feed limits for different arc energies. Each weld where analysed both mathematical, physical and thru observation. The combined results for one experiment will form the bases for the next set of experiments.

Two feed limits was discovered, one for room temperature metal and one for pre-heated metal. For welding on materials in room temperature, the arc was able to melt the filler, and make a complete fusion with the parent metal, when the energy requirement for melting the filler was under 20 per cent of the total arc energy. For welding on pre-heated metals the energy requirement for the filler was 23 – 24 per cent. The feed limits where tested and confirmed when welding with 2.6 kJ/s (300 A), 2.2 kJ/s (250 A) and 1.6 kJ/s (200 A). Welding at the feed limit, on pre heated metals, produced good welds at arc speed up to 5 millimetres per second. Part of the result is a preliminary welding procedure specification for a specific groove based on the findings in the experiments. It is recommended that the feed limits are tested when welding with filler of different thickness.

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Terminology

Description of mathematical symbols, with limits and max \ min values			
Symbol \ values	**Description**	**Unit**	**Limits \ constants**
Q	Heat input	[kJ]	-
Q_{mm}	Heat input per unit of travel	[kJ/mm]	-
Q_{filler}	Energy required to melt filler	[kJ/s]	-
$Q\%_{filler}$	Per cent energy to filler	-	0 – 100
η	Thermal efficiency of the arc	-	For GTAW: 0.6 [1]
U	Arc voltage	[V]	10.1 – 30
I	Arc current	[A]	3 – 400
v	Arc traveling speed	[mm/min]	-
60	Conversion factor for time	[sec to min]	-
1000	Conversion factor	[J to kJ]	-
A_w	Weld cross-area	[mm^2]	-
l	Weld length	[mm]	-
A_f	Filler cross-area	[mm^2]	-
f	Filler feed speed	[mm/min]	100 – 11000 mm/min
f_w	Filler total weight	[g]	-
f_{wmm}	Filler weight per mm	[g]	-
Tm_{iron}	Melting temperature, iron	[K]	1808 [2] (1535 °C)
Lh_{iron}	Heat of fusion, iron	[J/g]	For Fe: 272 [3]
Cp_{iron}	Specific heat, iron	[J/g x K]	For Fe: 0.449 [4]
ρ_{fe}	Density, iron	[g/cm^3]	7.874 [4]
ρ_c	Density, carbon	[g/cm^3]	2.26 [5]
ρ_{mn}	Density, manganese	[g/cm^3]	7.47 [6]
ρ_{si}	Density, silicone	[g/cm^3]	2.33 [7]
ρ_{filler}	Calculated density, filler	[g/cm^3]	7.8184

Table 1: Description of mathematical symbols, with limits and max \ min values

141:	Code for GTAW, used in iso – standards regarding welding
Arc:	In this paper, the electric arc between the electrode and work piece
AVHC:	Automatic Voltage Height Control
Cover beads:	Last pass / passes
DCEN:	Direct current electrode negative
Filler pass:	Subsequent passer
Filler:	The material added in the welding process
GMAW:	Gas Metal Arc Welding, also known as MIG/MAG
GTAW:	Gas tungsten arc welding
HAZ:	Heat Affected Zone, the area of the parent metal affected by the weld
IRM:	Industrial Robot Manipulator
Multi pass:	Making more than one weld seam to fill a groove
Parent metal:	The metal welded on
pWPS:	Preliminary Welding Procedure Specification
Root pass:	First pass (in a multi pass weld)
Slag:	Solidified unwanted materials in the weld
TIG:	Tungsten inert gas
Weld seam:	The area where the filler has melted and bonded with the parent metal
Work piece:	See parent metal

Introduction

The complexity of welding in modern production challenges the agility and physical limits of humans. Longer welds mean that human welders must start and stop welding in the middle of long grooves. Robotic welding is capable better movement control over longer distances. This thesis aims to quantify the relative energy distribution of the arc in GTAW, and investigate how high feed is possible to use at different energy settings.

Background

Since the first time a metalworker wanted to create a product that was too big for the forge or too complex to do in one piece, the hunt for good methods for fusing two metal objects together has been ongoing. The knowledge, methods and indeed the question itself has evolved. A new part of the problem is now the ability to weld together different metals, and ensuring that the weld is as solid as the weakest metal. In modern production, we also want to ensure that that the weld is of high quality and that the material use is at a minimum. However, at the core, the problem remains the same: How do we most efficiently fuse two pieces of metal together?

When replacing manual labour with robots, the work performed by the robot is only as good as the software controlling it. This is especially true for robot welding. Through years of practice a manual welder has learned to make a good weld based on the sound and appearance of the arc and weld pool. Since this is a practical and “hands on” process, little is written down and documented. Moreover, what is documented is considered somewhat secret. The different companies welding procedures is a big part of the competitive strategy. However, the growing competition from low-cost countries and the diminishing availability of highly skilled welders is accelerating the need for robots. Robotic welding can be a good supplement, and is able to replace humans on the heaviest and most repetitive tasks.

Much of the welding knowledge is based on the individual experiences of the welder. Different individuals have different arc speeds, heights and feed rates. Therefore, there is no straight forward way to go from manual welding to robotized welding. There exists little information on parameters that are written with the precise control of movement the robot represents in mind. Most of the guidelines in the available literature deals whit single pass welding, or the welding of straight and easy grooves. As previously mentioned, robots offer good control over their movements and in combination with the automatic feeder it is easy to calculate the size of the weld seam. Moreover, these calculations can be used to alter the size of the weld, either by adjusting the speed or the feed. The two unknown factors are the effectiveness of the arc and the how large feed the arc is able to melt.

The findings of a linear correlation for the arcs capability to melt the filler, will lay ground work for the possibility to have software generated preliminary welding procedure specifications (pWPS), taking into consideration the current, feed rate, robot speed and the parent materials heat capability.

Statement of the problem

There exists a gap in the knowledge regarding the portion of the arc energy that can be utilized to melt the filler. In other words: given an arbitrary energy input of the arc, how large feed can be tolerated, and still make a good fusion between the parent metal(s) and filler. And is it possible to estimate this limit for different energy levels.

Purpose of the Study

A mixed method study, combining experiments with numerical analyses and expert observations of the results. A set of test will be designed to test the impact on the weld seam when adjusting current, voltage, feed and arc speed. Based on these findings, maximum feed and arc speed will be found. Analyses and calculations of these tests will form the parameters for the next experiments.

Significance of the study

The most effective way to fill up a groove in a multi pass setup is to use the highest current the electrode is rated for, and the highest feed that can be successfully fused. Finding the threshold values for the maximum feed based on arc energy will help maximize the utilization of the robotic capabilities. Moreover, this knowledge can minimize the total cycle time. It can also assist weld supervisors to develop more optimized welding process procedures. It can also have a great impact if feed limits for various speeds can be found, this can make it easier to weld grooves with variating width in multiple continuous passes.

Primary Research Question

Is there a linear correlation between the arcs ability to melt the filler and the energy input, and is this limit affected by the robot speed?

Research Design

The first step is to research welding history and the selected welding technique to identify the strengths and weaknesses. Since the different parameters given in textbooks and other sources usually are guidelines, a set of experiments must be performed. The results from one experiment must be analysed and preferably form the basis for the next experiment. The findings and experience gained from the experiments will be documented and used to make a pWPS for a specific groove.

Limitations and scope

Due to the complex nature of metallurgy, the data and values found in this report is only directly transferable to welding on similar metals with the same filler. The melting point of different types of steel is relative constant, the thermal conductivity is not. This means that different steels need different heat treatment. In addition, different types of steel can tolerate different temperatures without losing their mechanical properties.

The scope of the thesis:

- Investigate multi-pass welding process planning
- Possibilities for automatic welding planning whit GTAW
- Test welding on plates at UiT – Campus Narvik
- Model and parameter table of a given welding test

Structure of the thesis

Chapter 1: Related research presents in the first part the history and working principals of TIG welding. Secondly a short description of the different software and hardware used in the experiments. Thirdly a description of the parent metal and the filler wire, with their chemicals composition and mechanical properties. And lastly an analyses of the different parameters in welding, and their impact in the weld seam.

Chapter 2: Experiments starts with a description of all the mathematics used in the analyses of the experiments, and also explains the entire excel sheet used. Secondly a description of all the experiments, tables for all the test and pictures documenting every test. Third part of the chapter describes the macro etch test and analyses from macro etching experiment 5 and 6. And lastly, a summary of the main findings from the experiments.

Chapter 3: Making a pWPS starts with describing the theory behind multi pass welding and the challenges with this method. Second part deals with the calculation and design of an effective and economic weld groove. The last part is a preliminary welding procedure specification using the knowledge gained from the experiments and the weld groove design.

Chapter 4: Conclusion gives the conclusion from all the experiments and the findings from the experiments. It also contains suggestions for further work.

Contents of the CD:

- A pdf of the thesis
- All hand written notes from the experiments
- Pictures of all the test welds and macro etching
- RSI logs from the test welds
- Original pictures taken and figures made
- Test report from the filler wire test
- Spreadsheet containing all the calculations

Related research

Short history of welding

The basic welding techniques are about as old as metalworking itself. Even before the Iron Age started, the ancient gold workers knew how to heat up two pieces of gold and hammer them together [8]. The early process of brazing is found in different gold objects in Egyptian tombs , and has been dated to go back as far as 3000 BC [9]. However, the earliest process that is similar to modern day welding where carried out by blacksmiths in the middle ages. The process then was to heat up the ends of two pieces of metal, stick them together and hammer it until the two ends had cooled down. The hammering had two functions: The first, and obvious one, was to forge the two ends together. The second function was to keep slag from forming. Slag is the solidification of unwanted materials, or pollutions, that can get trapped inside the weld and weakening it. The welding techniques remained more or less the same until the end of the 19th century [10].

In 1881, French scientist Auguste De Meritens succeeded in fusing lead plates by using the heat generated from an electrical arc [10]. This method is in some ways the bridge between blacksmithing and welding. Auguste used the arc to heat and fuse lead. However, he did not add any filler, so it was not a completely melted bond between the two plates. Later that same year the Russian inventor Benardos was the first to demonstrate the principle of arc welding [11]. He was able to form an electric arc between the work piece and a carbon electrode. When the arc had stabilized, a small metal rod where introduced. The metal rod melted in the arc and filled the gap in the work piece, thus completing the first electric arc weld. He had invented the first proses similar to TIG welding. He is therefore considered the “father of welding” In Russia. The drawback to his invention was the energy needed. The electric current required where generated by a steam engine, making the equipment needed for welding large and impractical. There did exist batteries capable of storing and delivering the needed current, but they did not last very long due to the short – circuiting [12]. The heavy equipment needed, combined with the accidental discovery of how to produces acetylene (1892), halted the development of arc welding.

In January 1941 [13], Russell Meredith working for Northrop Aircraft, filed a patent for the first practical and complete TIG system. The invention was driven by the need to weld magnesium, aluminium and other lightweight metals in the production of aircrafts. It was a complete system with voltage and current control and nozzle for an inert gas.

TIG / GTAW / 141 – Gas Tungsten Arc Welding

As the abbreviation implies, this is a gas shielded electrical welding process utilizing a non-consumable electrode. The gas is used to shield the weld pool from the oxygen in the atmosphere. Liquid iron is very reactive, and will make a bond with the oxygen in the atmosphere, this is known as oxidation and can weaken the weld. The gas protects the weld pool until the iron solidifies, making it far less likely to oxidase. The gas also increases the conductivity between the electrode and work piece, making it possible to strike an electric arc. The electrode is made of tungsten, which has a melting point of 3422 [14] degrees Celsius, this enables the electrode to remain solid during the weld. This allows a precise control of the electric arc, and there for the heat. The method is also known as TIG, tungsten inert gas. In welding standards and literature, it is often just referred to as “method 141”.

A GTAW system consist of a constant current power supply, typically operating from 3 to 300 A, and 10 to 35 V. Both direct and alternating current. The GTAW can be manual or semi-automatic. Meaning that the filler metal can be hand-fed into the arc when welding. Alternatively, it can be continually fed. It is possible to weld without a filler [15], then referred to as autogenous welding. This method is used on thin metals, edge joints and flange joints. This unit also contains a gas flow regulator and gas supply. The torches used are lightweight, compared to the other systems. It has a small gas nozzle, a tungsten electrode and a power switch. The only real weight comes from the cables attached to it. The torches come in four basic designs: for automatic welding, for manual welding, air cooled for low current welding and water-cooled for high current welding. A workpiece clamp is needed to complete the welding circuit. Differing from the other systems, the GTAW usually have a "throttle pedal" giving the operator direct control over the current, and in turn direct control over the arc and melting pool.

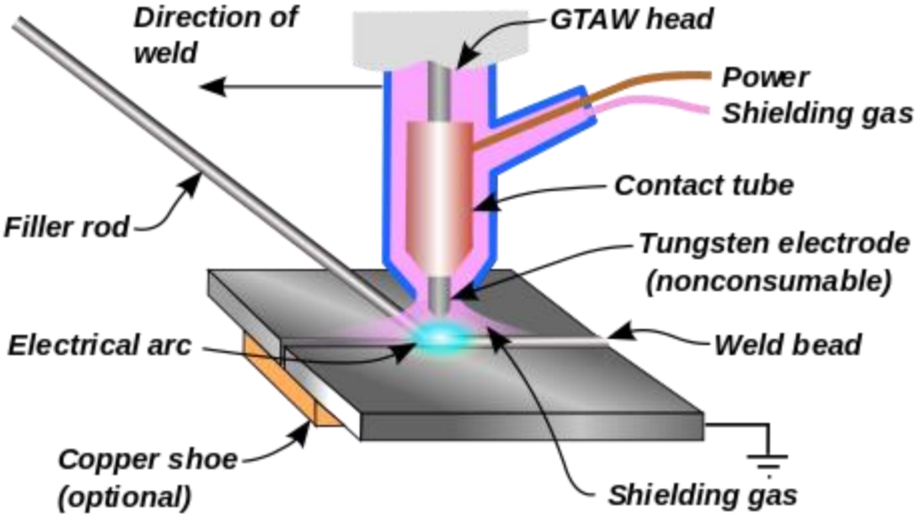


Figure 1: Principe GTAW. By Duk - Own Work This vector image includes elements that have been taken or adapted from this: GTAW.png., CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=455575

GTAW is the best method to use when welding together different metals. In addition, it creates a very smooth, uniformed surface. Therefore, needing little or none after work. When operating manually it requires a highly skilled worker, compared to the other methods. When welding manual GTAW the operator need one hand operating the torch, one hand to feed the filler and a foot to control the current. This is why manual GTAW is referred to as "three arm welding".

Advantages:

1. Makes high quality welds in almost all metals and alloys.
2. Almost none post weld clean up required.
3. The arc and weld pool are clearly visible to the welder.
4. The arc carries no filler, so there is little to none splatter.
5. GTAW consumes almost 1/3 of the gas compered to GMAW.
6. No slag produced that can be trapped in the weld.
7. Welding can be performed in all positions.

Disadvantages:

1. The GTAW is not a high production or high deposit-rate welding process.
2. Requires a highly skilled operator.
3. Prone to pollution due to unclean work area.
4. Hard to weld in difficult operator positions.

Multi-pass welding

When welding together thick pieces of metal, the amount of energy or filler required to make a complete fusion may be too large to do in one pass. This means that a multi pass technique must be applied.

The maximum depth of the groove before making the leap from single pass welding to multi pass is not a constant value. It all depends on what welding method is used and what metal is being welded on. Even when welding on different steels, the maximum energy input ranges from 0.8 to 3 kJ /mm.

If the temperature in the parent metal gets too high, it may crack under the cooling process. Hot cracks can occur if the temperature is above 0,5 x Tm, this is caused by the lack of ductility in the material when the metal is contracting when cooling down. Cold cracks can occur at lower temperatures, sometimes long after the weld is completed. Even as long as 48 hours if the weld is very deep.

Arc efficiency

Different studies have indicated values for the arc efficiency from 0.36 up to 0.9, a meta study from 2013 have analysed several articles from 1955 to 2011 and found that the value is likely to be 0.77 [16]. The effectiveness is regardless of the metal used. The study also indicated that the most effective arc-length is around 5 millimetres. The arc efficiency is reduced when the arc length is increased. On the other hand, the meta study found conflicting results in the literature as to the influence of arc current and travel speed.

The Norwegian standard NS-EN 1011-1:2009 recommends using 0.6 for the efficiency of the GTAW process. This is the governing standard for welding procedures, so their value will be used.

Software and hardware critical to the thesis

KUKA KR 30-3

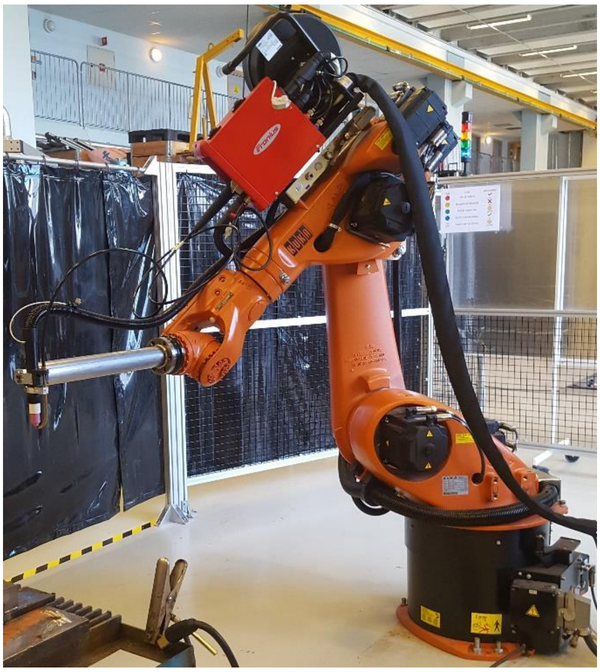


Figure 2: Kuka robot mounted with KD 4000 feeder and weld torch

The robot used is the KUKA KR 30-3 (HA) (K), robots working in industrial setups are often referred to as industrial robot manipulators (IRM). This is a 6-axis IRM in the medium payload category 30 – 60 kg. This IRM have a rated payload of 30 kg; in addition, it can carry an extra supplementary 35 kg of weight. This gives the IRM a total load capability of 65 kg. This is the HA (high accuracy) model, that means positioning repeatability is, according to the producer, <±0.05 mm [17]. The ability for the robot to accurate achieve the desired position is of great importance when welding tight grooves. This robot is also fitted with a 600 millimetre custom-made range-extender for the welding torch. In addition, an automatic feeder is mounted between the third and fourth axis.

KD 4000 D-11 wire feeder

An orbital wire feeder for mechanized TIG cold wire welding. In this case the feeder is mounded on the robot arm, as seen in Figure 2. It can deliver filler from 0.1 m/min to 11 m/min in 0.02 m/min intervals [18].

KR C 2

Figure 3: KUKA KR C 2 controller with teach pendent

KR C 2 is the controller used to control the robot, it includes a control PC, power unit, KCP (KUKA control panel) teach pendant and safety logic ESC. It can control up to eight axes, the robot in use has six. The controller uses Windows as operating system, making it familiar and easy to use. The KCP has all the control and display functions required for operating and programming the robot system. The welding path and speed is programmed via the teach pendent. All other hardware communicates with the controller; it is the hub in this welding system [19].

MagicWave 5000

Figure 4: Fronius MagicWave 5000 job

The welding machine used is the Fronius MagicWave 5000 job. This is a constant current generator that is capable of delivering 3 – 500 A when TIG welding. To maintain the arc, it can deliver 10 – 30 V. The machine is able to store 100 different job settings, making it easy to change between different parameter settings when welding. These can be automatically called upon by the controller (KR C 2). [20]

Tungsten + cerium 2% electrode

The electrode in use consists of 98 % tungsten and 2 % cerium, the used diameter is 3.2 mm. According to the producer the recommended current is 225 to 330 A, when welding in direct current electrode negative (DCEN) mode [21].

AVHC – Automatic Voltage Height Control

Since the MagicWave 5000 delivers a constant current, and the voltage will increase linearly with the distance between the torch and parent metal. This correlation is utilized by a software running on a separate computer. This software communicates with the robot controller and can adjust the z-axis, with in defined limits, to keep the right height above the parent metall. This is important to keep the efficiency of the arc constant. Higher voltage means longer and wider arc, reducing the portion of energy available for the welding operation. According to Magnus [22], the recommended height of the torch should be around 1.5 times the electrode diameter:

$$1.5 \times D_{electrode} \rightarrow 1.5 \times 3.2 = \underline{4.8\,mm}$$

Equation 1: Recommended arc length

RSI log

The AVHC software makes a log-file after every weld. The file contains information about the robots X, Y and Z movement, the Z correction from the software and the voltage of the arc. Together with the timestamp it is possible to plot this information in five different graphs. This gives great insight to the process if the test produces a bad weld.

AISI 1020 steel

AISI 1020 is a low hardenability and low tensile carbon steel with Brinell hardness of 119 – 235 and tensile strength of 410-790 MPa. It has high machinability, high strength, high ductility and good weldability. It is normally used in turned and polished or cold drawn condition. Due to its low carbon content, it is resistant to induction hardening or flame hardening. Due to lack of alloying elements, it will not respond to nitriding. However, carburization is possible in order to obtain case hardness more than Rc65 for smaller sections that reduces with an increase in section size. Core strength will remain as it has been supplied for all the sections. Alternatively, carbon nitrating can be performed, offering certain benefits over standard carburizing.

AISI 1020 steel can be largely utilized in all industrial sectors in order to enhance weldability or machinability properties. It is used in a variety of applications due to its cold drawn or turned and polished finish property. [23]

The chemical composition of AISI 1020 steel	
Element	Content
Iron, Fe	99.08 - 99.53 %
Carbon, C	0.17 - 0.230 %
Manganese, Mn	0.30 - 0.60 %
Phosphorous, P	≤ 0.040 %
Sulfur, S	≤ 0.050 %

Table 2: The chemical composition of AISI 1020 steel

AISI 1020 can be welded by performing the most common welding processes. In the cold drawn or turned and polished condition, it has better weldability. It has been suggested that the welding process should not be performed in heat-treated or carburized condition.

Thermal Properties AISI 1020 steel [24]	
CTE, linear	11.7 µm/m-°C @Temperature 0.000 - 100 °C
Coefficient of thermal expansion	12.8 µm/m-°C @Temperature 0.000 - 300 °C
	13.9 µm/m-°C @Temperature 0.000 - 500 °C
Specific Heat Capacity	0.486 J/g-°C @ temperaturs >=100 °C
	0.519 J/g-°C @ temperaturs 150 - 200 °C
	0.599 J/g-°C @ temperaturs 350 - 400 °C
Thermal Conductivity	51.9 W/m-K

Table 3: Thermal Properties AISI 1020 steel

Mechanical Properties ASIS 1020 steel		
Hardness, Brinell	121	
Hardness, Knoop	140	Converted from Brinell hardness
Hardness, Rockwell B	68	Converted from Brinell hardness
Hardness, Vickers	126	Converted from Brinell hardness
Tensile Strength, Ultimate	420 MPa	
Tensile Strength, Yield (0.2 %)	350 MPa	
Elongation at Break	15 %	In 50 mm
Reduction of Area	40 %	
Modulus of Elasticity	186 GPa	
Bulk Modulus	148 GPa	calculated from elastic modulus and Poisson's ratio
Poissons Ratio	0.29	
Machinability	65 %	Based on AISI 1212 steel. as 100% machinability
Shear Modulus	72 GPa	calculated from elastic modulus and Poisson's ratio

Table 4: Mechanical Properties ASIS 1020 steel

Böhler EMK 6 solid wire

The filler material used is Böhler EMK 6; this is a universally applicable copper-coated wire electrode. Because of its ability to withstand high currents, it offers ideal properties for thick sheet welding. The wire is used on a wide range of steels, up to a yield strength of 420 MPa [25]. The wire used in this setup is 1.0 mm in diameter. The specific wire used for this thesis was tested and analysed. The chemical composition is from the analyses by Voestalpine, the mechanical properties is a combination of data from the product data sheet and the analyses by Voestalpine.

The chemical composition of Böhler EMK 6 solid wire	
Element	Content
Iron, Fe	97.5 %
Carbon, C	0.07 %
Manganese, Mn	1.45 %
Silicon, Si	0.82 %
Other metals	0,155 %

Table 5: The chemical composition of Böhler EMK 6 solid wire

Mechanical Properties Böhler EMK 6 solid wire			
	Untreated	Stress relieved	Tested at 20 °C
Tensile Strength, Ultimate	560 MPa	490 MPa	≥ 420 MPa
Tensile Strength, Yield (0.2 %)	440 MPa	380 MPa	≥ 500 MPa
Elongation at Break	30 %	30 %	≥ 24 %

Table 6: Mechanical Properties Böhler EMK 6 solid wire

Welding parameters

The amount of energy the metal can tolerate before the mechanical properties get altered dictates to a large degree the amount of filler that can be added in every pass. It is therefore good to have guidelines, or a maximum value, for the amount of filler the arc can melt and fuse.

A good weld is a result of the correct relationship between current, arc speed and feed rate. In addition, when using the AVCH – software, voltage represents a fourth parameter that can be manually set. However, every welder has his own speed, movement and work height. When searching and inquiring for guidelines and/or approximate values for the different settings, one can get as many different answers as the number of sources. In addition, most of welders asked start with the sentence: “you just start the welding process, and you will see how it goes”. In accordance to the experts, several test welds will be made. Before testing can begin, analyses of the impact on the weld by the different parameters must be analysed.

The settings and parameters for the welding operation is one side of the problem, another regard is the amount of heat / energy the parent metal can handle. In other words, how easy is it to weld? Different metals and alloys have different thresholds for heat. One indicator for the weldability in carbon steel is the carbon equivalent. The carbon equivalent and the calculation is discussed in a later chapter.

The four dominating parameters

Current, voltage and arc speed are the three parameters that affect the energy input to the parent metal. Increasing current and voltage increases the energy input per mm, on the other hand increasing arc speed has the opposite effect. The fourth is the feed rate of the filler material.

Voltage: To compensate for the varying height of the weld torch, the voltage varies automatic. This information is in this case, used to keep the arc height constant. Too low voltage, and therefore arc, may cause the electrode to get into the weld pool. Too high and the efficiency of the arc will have a dramatic fall, and may cause the weld pool to cool down, or the arc can just extinguish. Experiments show that increasing the arc length, with constant current, typical will increase the voltage with 0.5 – 2 V per millimetre. This value is dependent of the gas, but is linear for the respective gas. The same happens when decreasing the arc length. The voltage has little effect on the penetration of the weld. However, it has an effect on the width, higher voltage means longer arc. This effect is due to the bell-shape of the arc [26].

Current: The dominating parameter regarding energy input. This the main parameter that is adjusted in manual GTAW, as previously stated the voltage will “self-adjust”. When altering the current the penetration of the weld, and therefor HAZ, will change. Higher current means deeper penetration.

Arc speed: Also called robot speed. The higher this movement is, the lower energy input per millimetre. This is one of the strength with robot welding; a robot can have a higher and more accurate arc speed, over longer distances than a human can.

Feed rate: The amount of filler added, this is controlled independently of the other parameters. The feed rate is adjusted according to the type of weld and the arc energy. A filler pass will have higher feed than a root / cover pass, while the other settings can remain the same.

Carbon equivalent

A good indicator for the weldability and need of pre-heat and post-heat is the carbon equivalent. The hardenability of a steel, is approximately, related to its carbon content, and the content of certain other alloying elements. The contribution to the hardenability of other alloys are known, and can be calculated as a percentage if all the alloys where carbon. There exist different formulas too calculating the carbon equivalent, all based on the different alloying metals on the steel.

The formula and limits of the formula is from the ESAB homepage [27] For AISI 1020 steel the following formula is used:

$$CE = \%C + \frac{\%Mn}{6} + \frac{\%Ni}{15} + \frac{\%Mo}{4} + \frac{\%Cr}{5} + \frac{\%Cu}{13}$$

Equation 2: Carbon equivalent

Limits for the formula		
Alloying metal	**Maximum weight %**	**Actual in AISI 1020**
C, Carbon	0.50	0.17 - 0.230 %
Mn, Manganese	1.60	0.30 - 0.60 %
Ni, Nickel	3.50	-
Mo, Molybdenum	0.60	-
Cr, Chromium	1.00	-
Cu, Copper	1.00	-

Table 7: Limits for the carbon equivalent formula

The percentage of carbon and manganese for AISI 1020 is given in weight intervals, the maximum values are chosen. This is to determine if pre-heat is necessary in a "worst case" scenario.

$$CE = 0.23 + \frac{0.6}{6} + \frac{0}{15} + \frac{0}{4} + \frac{0}{5} + \frac{0}{13} = 0.33$$

Equation 3: Carbon equivalent with AISI 1020 values

According to the ASME table of weldability [28], based on the carbon equivalent, AISI 1020 have excellent weldability. However, this is a relatively thick weld, and the finished weld needs inspection to see if pre-heat is necessary.

Carbon Equivalent (%)	Weldability
Up to 0.35	Excellent
0.36 to 0.40	Very good
0.41 to 0.45	Good
0.46 to 0.50	Fair
Over 0.50	Poor

Table 8: Weldability index

Experiments

In order to start the experiments, it is vital to establish a good baseline. This is a weld with relatively low energy input and feed. The material added and cross section of the welds will be measured to verify that the calculations and actual vales corresponds. The somewhat uneven nature of a weld means that some deviation of the actual values and the measured ones is to be expected. To control the material added, a weight from concrete lab (betong labben) at campus Narvik is used. The weight is yearly certified and have an accuracy of 0.1 g. This means that with two measurements the accuracy is ± 0.2 g. Height and width is measured manually, on the first ten welds, with callipers and Digimatic Height Gage 192-601. Each weld is measured at five random places; the average value is used in the calculations. To compensate for the variations in thickens on the test plates, the height gage is zeroed out in-between every individual height measurement. Magnus Aanstad has agreed to assess the different welds. Every set of parameters that produces a good weld will be retested to assure that the results can be reproduced. As far as possible only one of the parameters are adjusted at the time.

Welds 001 to 014 are performed on steel plates measuring 100 x 60 x 11 mm, this means that there are two seams of 90 mm length on each test piece. The last set of tests will use steel plates measuring 200 x 250±10 x 10 mm, allowing 240±10 mm long weld seams with 20 mm spacing. This is done to check that the selected parameters are stable in longer welds.

Calculations

To manage all the calculations, and holding the data, a spreadsheet made in Microsoft Excel is utilized. The sheet contains four “pages”; filler constants, parameters and calculations, post weld measurements and pWPS calculations. All the symbols used in this chapter is described in Table 1: Description of mathematical symbols, with limits and max \ min values.

Filler constants

This sheet contains values that are constant and will not change during the experiments.

Dimensions

Diameter is given from the datasheet, 1 mm, this gives the following cross section of the filler:

$$A_f = \pi \times \left(\frac{d}{2}\right)^2 \rightarrow \pi \times \left(\frac{1}{2}\right)^2 = \underline{0.785\ mm^2}$$

Equation 4: Cross section of filler

d - diameter of the filler [mm]

Energy requirements

This calculation is for the minimum energy required to heat up the filler and melt it. It is based on the specific energy required to heat iron (Cp), the temperature difference (ΔT) and the energy required to transform iron from solid to liquid state (Lh_{iron}). It does not take into account the additional heating after the filler is melted. It is based on a start temperature of 20 °C for the filler. It is assumed that the entire filler contains only iron.

$$Q = (Cp \times \Delta T \times kg) + (Lh_{iron} \times kg)$$

Equation 5: Energy requirement equation

Per gram:

$$Q = (0.449 \times 1515 \times 0.001) + (272 \times 0.001) = \underline{0.943 \ {}^{kJ}/_{g}}$$

Equation 6: Energy requirement per gram

Filler weight

To calculate the specific weight of the filler, the weight and distribution of the four dominating components is used. The formula is based on the density of the components (ρ) multiplied with their relative percentage. Iron is the most dominating component, both in fraction of the whole and in specific weight. Therefore, the weight of the filler will be close to the weight of iron.

$$\rho_{filler} = \frac{\rho_1 \times \%_1 + \rho_2 \times \%_2}{100}$$

Equation 7: Weight of filler without values

$$\rho_{filler} = \frac{7.874 \times 97.66 + 2.26 \times 0.07 + 7.47 \times 1.45 + 2.33 \times 0.82}{100} = \underline{7.819 \ {}^{g}/_{cm^3}}$$

Equation 8: Calculation of the filler weight

Parameters and calculations

This sheet contains input data and calculations based on these. To keep things orderly, the first two columns contain a test number and a short disceprtion. The current is somewhat constant. This is because AVHC uses this to regulate the height, the value varies between 13.5 and 15, and is kept constant at 14.5 for most parts of the tests. Current, arc speed and feed rate are set by the user, these are the main parameters manipulated to achieve different test goals in the first set of experiments. In the last experiments, the sequence of calculations is reversed.

Energy input

The heat input is based in the current [I], voltage [U] and the arc speed [v], and is calculated as follows [1]:

$$Q_{mm} = \eta \times \frac{U \times I \times 60}{1000 \times v} = \underline{kJ \ / \ mm}$$

Equation 9: Energy input per millimetre

Weld size

To calculate an approximate number off passes in multi pass welding, it is important to have some guidelines for the cross area of the weld seam, this can be done if the area of the feed line [A_f], the feed speed [f] and the arc speed [v] is known:

$$A_w = \frac{A_f \times f}{v} = \underline{mm^2}$$

Equation 10: Cross section weld seam

This value can be used to calculate the weight of the weld per mm:

$$f_{wmm} = \frac{A_w \times 1\ mm \times \rho_{filler}}{1000} = \underline{{}^{g}/_{mm}}$$

Equation 11: Weight added per millimetre weld seam

Filler energy requirement

Based on the specific energy requirement, the theoretic energy requirement per second can be calculated. Calculations are based on the cross-area of the weld, density of the filler and the specific energy required to melt the filler.

$$Q_{filler} = A_w \times \rho_{filler} \times Cp_{iron} = \underline{{}^{kJ}/_{s}}$$

Equation 12: Estimate energy requirement to melt filler per second

This energy estimate is compared to the total energy used in the proses. This is done to try to establish a correlation.

$$Q\%_{filler} = \frac{Q_{filler}}{U \times I \times \eta} \times 100\%$$

Equation 13: Filler energy compared to total energy

Weld seam weight

By combining the estimated weight per millimetre and the length of the weld, it is possible to estimate the weight of the seam. This estimated weight is compared to the actual weight. If the deviation between the values is large, it can be an indicator that the feed is unstable, and that the feed limit is reached.

$$f_w = f_{wmm} \times l = \underline{g}$$

Equation 14: Total weight of the weld seam

The difference between actual and estimated value is calculated in absolute weight and the relative difference.

Post weld measurements

To control the weight added, each sample is weighted between tests. On the first ten samples the height and width are also measured.

pWPS calculations

This sheet contains some of the same calculations as “parameters and calculations”. First to columns describe the number and purpose of the pas. The next three is manual input: voltage, current and arc speed. Energy input per millimetre is calculated the same way as in Equation 9. The filler speed columns are manually input as well. Cross section of the weld is calculated according to Equation 10, this area is multiplied with the number of passes to give the total area of multiple passes. Energy requirements are calculated in the same way as Equation 12 and Equation 13. To control if the numbers of passes is sufficient to fill up the groove, the total areal of the material added is compared to the area of the groove. The area added should be slightly higher than the area of the groove.

Experiment 0

The first experiment was done to get to know the equipment and how the different parameters influence the appearance of the weld.

Test 001

Parameter	Value	Parameter	Value
Voltage [V]	15	**Weight after weld [g]**	559.1
Current [A]	220	**Material added [g]**	13
Robot speed [mm/min]	60	**Average height [mm]**	N/A
Feed [mm/min]	1500	**Average width [mm]**	N/A
Weight before weld [g]	541.1		

Table 9: Test parameters weld 001

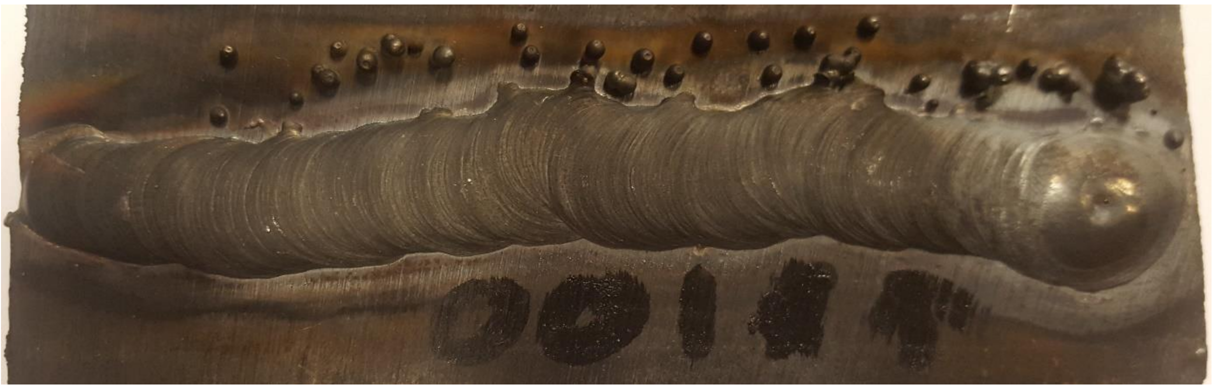


Figure 5: Test weld 001 - baseline test 01

Very uneven weld. The arc seams to “jump”, this may be due to height. Filler is also building up unevenly. Recommendations for the next run: lower height (voltage) and increase robot speed.

Test 002

Parameter	Value	Parameter	Value
Voltage [V]	13.5	**Weight after weld [g]**	568
Current [A]	220	**Material added [g]**	8.9
Robot speed [mm/min]	90	**Average height [mm]**	2.12
Feed [mm/min]	1500	**Average width [mm]**	9.72
Weight before weld [g]	559.1		

Table 10: Test parameters weld 002

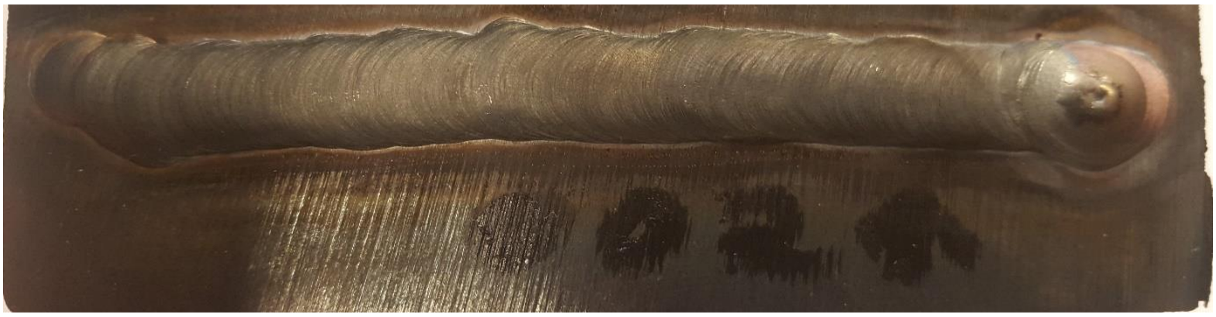


Figure 6: Test weld 002 - baseline 02

Weld looks good, will be a good baseline for further experiments. RSI log show that the arc may be a little below the recommended height. Increase voltage to 13.75.

Test 003

Parameter	Value	Parameter	Value
Voltage [V]	13.75	**Weight after weld [g]**	561.3
Current [A]	220	**Material added [g]**	10.8
Robot speed [mm/min]	90	**Average height [mm]**	2.3
Feed [mm/min]	1800	**Average width [mm]**	8.94
Weight before weld [g]	550.5		

Table 11: Test parameters weld 003

Figure 7: Test weld 003 - feed test 01

Before weld the feed is increased to 1800 and voltage to 13.75. Post weld inspection shows good melting, increase feed before next weld. Torch height is near the recommended point, test piece to uneven to conclude.

Test 004

Parameter	Value	Parameter	Value
Voltage [V]	13.75	**Weight after weld [g]**	572.9
Current [A]	220	**Material added [g]**	11.6
Robot speed [mm/min]	90	**Average height [mm]**	8.88
Feed [mm/min]	2000	**Average width [mm]**	2.54
Weight before weld [g]	561.3		

Table 12: Test parameters weld 004

Figure 8: Test weld 004 - feed test 02

Weld shows good melting of filler, feed to be increased before next weld.

Test 005

Parameter	Value	Parameter	Value
Voltage [V]	13.8	**Weight after weld [g]**	491.3
Current [A]	220	**Material added [g]**	13.2
Robot speed [mm/min]	90	**Average height [mm]**	2.76
Feed [mm/min]	2200	**Average width [mm]**	9.06
Weight before weld [g]	478.1		

Table 13: Test parameters weld 005

Figure 9: Test weld 005 - feed test 03

Voltage increased to 13.8, this parameter is now "looked". RSI log shows that the distance is at the recommended distance. Weld shows good melting of the filler, feed to be increased before next weld.

Test 006

Parameter	Value	Parameter	Value
Voltage [V]	13.8	**Weight after weld [g]**	506
Current [A]	220	**Material added [g]**	14.7
Robot speed [mm/min]	90	**Average height [mm]**	2.98
Feed [mm/min]	2500	**Average width [mm]**	8.7
Weight before weld [g]	491.3		

Table 14: Test parameters weld 006

Figure 10: Test weld 006 - feed test 04

The weld seam seems to be wondering of centre, this can be caused by the high feed. However, after the weld table has been grinded to improve electrical contact, these parameters need to be re-tested.

Test 007

Parameter	Value	Parameter	Value
Voltage [V]	13.8	**Weight after weld [g]**	490.8
Current [A]	240	**Material added [g]**	9
Robot speed [mm/min]	90	**Average height [mm]**	1.74
Feed [mm/min]	1500	**Average width [mm]**	11.42
Weight before weld [g]	481.8		

Table 15: Test parameters weld 007

Figure 11: Test weld 007 - current test 01

First test examining the impact of increasing current with constant feed. Weld looks good, increase current on next run.

Test 008

Parameter	Value	Parameter	Value
Voltage [V]	13.8	**Weight after weld [g]**	499.6
Current [A]	260	**Material added [g]**	8.8
Robot speed [mm/min]	90	**Average height [mm]**	1.36
Feed [mm/min]	1500	**Average width [mm]**	13
Weight before weld [g]	490.8		

Table 16: Test parameters weld 008

Figure 12: Test weld 008 - current test 02

Weld looks good, increase current.

Test 009

Parameter	Value	Parameter	Value
Voltage [V]	13.8	**Weight after weld [g]**	547.2
Current [A]	280	**Material added [g]**	9
Robot speed [mm/min]	90	**Average height [mm]**	1.2
Feed [mm/min]	1500	**Average width [mm]**	14.92
Weight before weld [g]	538.2		

Table 17: Test parameters weld 009

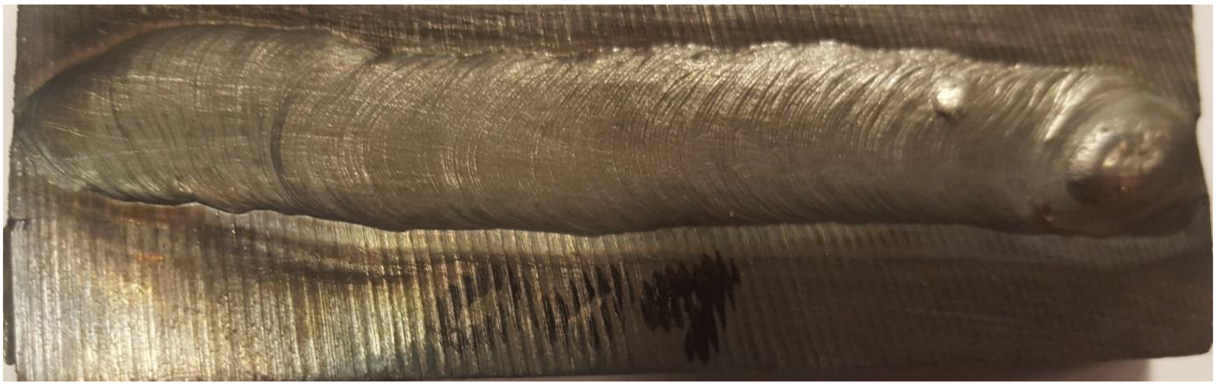


Figure 13: Test weld 009 - current test 03

Good melting of the filler, increase current on next test.

Test 010

Parameter	Value	Parameter	Value
Voltage [V]	13.8	**Weight after weld [g]**	556.1
Current [A]	300	**Material added [g]**	8.9
Robot speed [mm/min]	90	**Average height [mm]**	1.1
Feed [mm/min]	1500	**Average width [mm]**	15.9
Weight before weld [g]	538.2		

Table 18: Test parameters weld 010

Figure 14: Test weld 010 - current test 04

Good melting of the filler, increase current on next test.

Notes

The electrode in use is rated for currents over 300 A. However, the welding machine is limited to 300 A when using a 3.2 mm electrode. All the RSI logs indicated that the robot and arc where moving in a straight line, however the weld seam was not. This may be caused by the horizontal threads on the material made by the saw, during preparation of the material.

Re-testing to confirm findings

In the feed test, test number 005 was the best candidate for good parameters for a filler layer in the multi-pass setup. However, when testing the same parameters, the result failed to reproduce. To be able to reproduce the result the current had to be dropped with 20 A. After consulting with Ståle [29], and investigating what had changed on the hardware between test days. The most likely reason is the grinding on the welding table. This may have caused the electrical conductivity to improve, allowing a higher portion of the current to be utilized in the welding process itself. A new set of tests is conducted to find new parameters. Ståle also pointed out that the distortion in the welds (pulling left) could be caused by a magnetic field forming at the connection point between the earth clamps and the welding table. The clamps where moved so that a magnetic field will pull in the same direction as the welding is done.

Test 011

Parameter	Value	Parameter	Value
Voltage [V]	13.8	**Weight before weld [g]**	627.6
Current [A]	200	**Weight after weld [g]**	642.6
Robot speed [mm/min]	90	**Material added [g]**	15
Feed [mm/min]	2500		

Table 19: Test parameters weld 011

Figure 15: Test weld 011 - Feed retest 01

Test did not reproduce a good weld. Reduce feed for next test.

Test 012 1 - 4

Parameter	Value	Parameter	Value
Voltage [V]	13.8	Weight before weld [g]	N/A
Current [A]	200	**Weight after weld [g]**	N/A
Robot speed [mm/min]	90	**Material added [g]**	14.3
Feed [mm/min]	2400		

Table 20: Test parameters weld 012 1 - 4

Figure 16: Test weld 012 - 1 and 2

Figure 17: Test weld 012 - 3 and 4

These parameters give a good weld, it also reproduced four times. This will be the benchmark settings for a good filler weld.

Test 013

Parameter	Value	Parameter	Value
Voltage [V]	13.8	**Weight before weld [g]**	498.7
Current [A]	265	**Weight after weld [g]**	512.5
Robot speed [mm/min]	120	**Material added [g]**	13.8
Feed [mm/min]	3200		

Table 21: Test parameters weld 013

Figure 18: Test weld 013

Test to replicate the results from test 012 with higher current, robot speed and feed. Produced a good weld with good melting of the filler. Should tolerate higher feed.

Test 014

Parameter	Value	Parameter	Value
Voltage [V]	13.8	**Weight before weld [g]**	512.5
Current [A]	265	**Weight after weld [g]**	516.5
Robot speed [mm/min]	120	**Material added [g]**	4
Feed [mm/min]	4200		

Table 22: Test parameters weld 014

Figure 19: Test weld 014

High feed test. Test aborted when the filler where pushed thru the weld pool out on the other side of the arc.

Notes

Tests 013 and 014 were made to investigate whether there is a linear correlation between the energy of the arc and feed rate. According to the calculations, weld 014 has the same relative energy input per mm and feed as test number 012. Test 014 was aborted when the filler come out from the other side of the weld pool. The energy and feed rate estimates was based on the energy per millimetre, and not the absolute energy in the arc.

Experiment 1

These test where the first to run a 240 mm weld. When increasing the feed between the passes, the table and robot started to move. At first, it was just a little swing in the cables, so it where ignored. The movement continued to manifest 10 seconds after start, and increasing in strength. It was also observed that the weight of the welds where not increasing according to the calculations. The most likely source for this deviation was connected the feed unit. To control this, the spool containing the filler was observed directly. In the 96 seconds the run takes, the spool did 6.33 revolutions. Converting to rev/min: 6.33 x (60/96) = 3.95. With a circumference of 840 mm this gives an estimated feed of 3300 mm/min. These calculations are not extremely precise, but the results have a relatively large deviation from the desired 4500 mm/min. Multiple tests where done with the same settings, and the estimated feed and weight of the weld where not constant and / or according to the set parameters. This fact, combined with the observed uneven speed on the feed spool, led to the hypotheses that the feed mechanism caused the undesired movement. This movement, most likely, was due to the filler being feed through the arc and therefore it collided into solid metal on the other side. The feed mechanism reacted to this, and stopped the feed for a short while before trying again. This “pulse-feeding” causes the weld table and robot to oscillate. Therefore, the results from test 015 – 024 are not included in the report. However, the weld-reports and pictures are included in the CD.

Parameter	Value	Parameter	Value
Voltage [V]	13.8	**Weight added 1st pass [g]**	N/A
Current [A]	230 – 300	**Weight added 2nd pass [g]**	N/A
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	N/A
Feed [mm/min]	2500 – 4600	**Estimated weight added [g]**	N/A
Heat input [kJ/mm]	0.76 – 0.99	**Average error [g]**	N/A

Table 23: Test parameters welds 015 - 024

Experiment 2

The first two welds measure the correlation between calculated and measured weight added, and the height of the torch. This is to control that the distance is near the optimal point. After weight and arc length is controlled, the next objective is to find a feed limit when using a 300 A current.

Weight test 1

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	25.1
Current [A]	300	**Weight added 2nd pass [g]**	-
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	-
Feed [mm/min]	2500	**Estimated weight added [g]**	25.6
Heat input [kJ/mm]	1.04	**Error [g]**	0.5

Table 24: Test parameters weight test 1

AVCH failed to keep the correct height. The caused was identified as a programing error, the endpoint of the path was set to high. AVCH wanted the torch to go lower than the work envelope allowed. This did not affect the weight and appearance of the weld seam, produced a fine weld.

Weight test 2

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	30.4
Current [A]	300	**Weight added 2nd pass [g]**	-
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	-
Feed [mm/min]	3000	**Estimated weight added [g]**	30.7
Heat input [kJ/mm]	1.04	**Error [g]**	0.3

Table 25: Test parameters weight test 2

AVHC kept correct height; distance from torch to parent metal at welds end was 5 mm. 14.5 volt produces an arc of good length when welding at 300 amperes.

Notes

Taking into account the data and experience from tests 015 – 024, the lid of the feeder is open during welding and the rotation observed directly. Early indications of too high feed can also be detected by a small movement in the cables connected to the weld table. This visual information, combined with an unexpected large deviance in the actual and calculated weight added, will act as indicators of overfeeding. Testing for extremes, the first runs is single runs. The following tests will be repeated two or three times. Weld appearance, visual inspection during welding and stabile weld weight will be the observed.

Test 025

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	32.6
Current [A]	300	**Weight added 2nd pass [g]**	-
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	-
Feed [mm/min]	3200	**Estimated weight added [g]**	32.7
Heat input [kJ/mm]	1.04	**Average error [g]**	0.1

Table 26: Test parameters weld 025

Some small movement was detected in the feedline, may be near the maximum feed

Test 026

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	33.4
Current [A]	300	**Weight added 2nd pass [g]**	-
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	-
Feed [mm/min]	3500	**Estimated weight added [g]**	35.8
Heat input [kJ/mm]	1.04	**Average error [g]**	2.4

Table 27: Test parameters weld 026

Relative large movement detected in the feedline and “jerking” in the movement of the feed drum. The relative large difference between actual weight and estimated weight added also indicate that the feed is too high.

Test 027

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	31.1
Current [A]	300	**Weight added 2nd pass [g]**	30.8
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	-
Feed [mm/min]	3200	**Estimated weight added [g]**	32.7
Heat input [kJ/mm]	1.04	**Average error [g]**	1.75

Table 28: Test parameters weld 027

Observed movement is still present at this feed. Added weight is uneven in passes on similar settings.

Test 028

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	29.5
Current [A]	300	**Weight added 2nd pass [g]**	29.5
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	-
Feed [mm/min]	3000	**Estimated weight added [g]**	30.7
Heat input [kJ/mm]	1.04	**Average error [g]**	1.2

Table 29: Test parameters weld 028

Both passes have added the same amount of weight.

Test 029

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	27.7
Current [A]	300	**Weight added 2nd pass [g]**	27.6
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	-
Feed [mm/min]	2800	**Estimated weight added [g]**	28.7
Heat input [kJ/mm]	1.04	**Average error [g]**	1.05

Table 30: Test parameters weld 029

Test run at lower feed, to confirm that two “identical” welds produced. Both passes have added the same amount of weight. The tolerance of the scale is 0.1 g. The measurement is within excepted deviance.

Test 030

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	30.7
Current [A]	300	**Weight added 2nd pass [g]**	30.8
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	
Feed [mm/min]	3100	**Estimated weight added [g]**	31.7
Heat input [kJ/mm]	1.04	**Average error [g]**	0.95

Table 31: Test parameters weld 030

Both passes have added the same amount of weight.

Notes

The limit for producing even welds is around a feed of 3100 mm/min at 300 A.

Figure 20: Test weld 025 - 030, feed test 300 A

Experiment 3

Test to find out if the robot speed has impact on the fusion between filler and parent metal. The current, voltage and feed is constant.

Test 031

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	24.4
Current [A]	300	**Weight added 2nd pass [g]**	25.4
Robot speed [mm/min]	180	**Weight added 3rd pass [g]**	25.5
Feed [mm/min]	3100	**Estimated weight added [g]**	26.4
Heat input [kJ/mm]	0.87	**Average error [g]**	1.33

Table 32: Test parameters weld 031

Fist try produced an uneven and somewhat light weld, second and third produced straight and smooth welds. This is likely due to a pre-heat effect from the first weld.

Test 032

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	21.8
Current [A]	300	**Weight added 2nd pass [g]**	21.9
Robot speed [mm/min]	210	**Weight added 3rd pass [g]**	
Feed [mm/min]	3100	**Estimated weight added [g]**	22.7
Heat input [kJ/mm]	0.75	**Average error [g]**	0.85

Table 33: Test parameters weld 032

Both welds look good.

Test 033

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	19
Current [A]	300	**Weight added 2nd pass [g]**	19.4
Robot speed [mm/min]	240	**Weight added 3rd pass [g]**	
Feed [mm/min]	3100	**Estimated weight added [g]**	19.8
Heat input [kJ/mm]	0.65	**Average error [g]**	0.6

Table 34: Test parameters weld 033

Both welds look good.

Test 034

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	17
Current [A]	300	**Weight added 2nd pass [g]**	17.1
Robot speed [mm/min]	270	**Weight added 3rd pass [g]**	
Feed [mm/min]	3100	**Estimated weight added [g]**	17.6
Heat input [kJ/mm]	0.58	**Average error [g]**	0.55

Table 35: Test parameters weld 034

Both welds look good.

Test 035

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	15.4
Current [A]	300	**Weight added 2nd pass [g]**	15.4
Robot speed [mm/min]	300	**Weight added 3rd pass [g]**	15.4
Feed [mm/min]	3100	**Estimated weight added [g]**	15.9
Heat input [kJ/mm]	0.52	**Average error [g]**	0.5

Table 36: Test parameters weld 035

Notes

The speed test indicates that the speed of the robot and the arcs ability to melt the filler is unrelated at relative low feed and high current. This observation should be tested further, to investigate if it can be utilized for welding more complex grooves.

Figure 21: Test weld 031 - 036, speed test 180 - 300 mm/min

Experiment 4

036 – 048, before these tests the gas nozzle was changed from size 6 to a size 7, and the gas flow was decreased from 22 l/min to 9 l/min. Moreover, the tip of the electrode was re-grinded. This lead to a drastic change in in the test result. Before this was done, the approximate feed limit, at 300 A, was thought to be 3100 mm/min. After the adjustment the limit at 250 A is in excess of 6000 mm/min.

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	N/A
Current [A]	200 – 250	**Weight added 2nd pass [g]**	N/A
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	N/A
Feed [mm/min]	1800 – 5900	**Estimated weight added [g]**	N/A
Heat input [kJ/mm]	0.7 – 0.87	**Average error [g]**	N/A

Table 37: Test parameters welds 036 - 048

Notes

Figure 22: Test weld 036 – 042

Test 040 showed some signs that something was wrong, the cause was thought to be pollution on the electrode. Electrode was cleaned with a steel brush. Test 041 made it clear that something was not right, observation of the arc showed that it “jumped around” and made unusual sounds.

Figure 23: Test weld 043 – 048

Weld 043 is the first with newly grinded electrode. This had a large improvement in the arc stability and the welding process is now almost soundless.

From this experiment the impact of gas flow and electrode maintenance, has proven to be vital to the production of good welds.

Experiment 5

Feed test 250 A, adjusted gas nozzle and gas flow. This round of testing is to investigate if there is a linear correlation between the arc energy, mainly the current, and the feed rate. The first test will run at a low and safe feed. This is done to check calculation, heat up the work piece and establish that the system is able to produce a stable weld. Every set of parameters is tested three times. Second and third run will follow the edge of the first, this is to investigate if the three welds will fuse. Welding supervisor Hans Arne Mariåsen at rainpower Sørumsand, recommended to angle the torch towards the base of the first seam when welding multiple seams. Based on his descriptions, it was decided to angle the torch 15 degrees.

Test 049

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	35.4
Current [A]	250	**Weight added 2nd pass [g]**	36.5
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	36.2
Feed [mm/min]	4000	**Estimated weight added [g]**	37.7
Heat input [kJ/mm]	0.87	**Average error [g]**	1.6

Table 38: Test parameters weld 049

4th run added 36.6 grams. This test had two objectives: First to heat up the parent metal, and second to calculate the distance between seams. The distance is set to half the width of the weld plus two millimetres. Since the robot is not equipped with seam tracking this is a safe distance. The macro etch testing of the welds will give a better answer, see macro etch testing page 50.

Test 050

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	45.3
Current [A]	250	**Weight added 2nd pass [g]**	45.4
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	45.5
Feed [mm/min]	4000	**Estimated weight added [g]**	47.1
Heat input [kJ/mm]	0.87	**Average error [g]**	1.7

Table 39: Test parameters weld 050

Test 051

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	54.1
Current [A]	250	**Weight added 2nd pass [g]**	54.6
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	54.3
Feed [mm/min]	6000	**Estimated weight added [g]**	56.5
Heat input [kJ/mm]	0.87	**Average error [g]**	2.16

Table 40: Test parameters weld 051

Distance and overlap between seams looks good.

Test 052

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	63.4
Current [A]	250	**Weight added 2nd pass [g]**	60.6
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	63.8
Feed [mm/min]	7000	**Estimated weight added [g]**	65.9/63
Heat input [kJ/mm]	0.87	**Average error [g]**	2.33

Table 41: Test parameters weld 052

Due to a miscalculation the 2nd seam was 10 mm shorter than the other two. 2nd and 3rd run looked bad and uneven. May be near or over the feed limit.

Test 053

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	68.1
Current [A]	250	**Weight added 2nd pass [g]**	68.1
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	13.4 (a)
Feed [mm/min]	7500	**Estimated weight added [g]**	70.6
Heat input [kJ/mm]	0.87	**Average error [g]**	2.5

Table 42: Test parameters weld 053

3rd run aborted, started to produce an uneven and visually unappealing weld. Last good weld was at feed 6000. Next test will run at 6500.

Test 054

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	56.6 (a)
Current [A]	250	**Weight added 2nd pass [g]**	-
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	-
Feed [mm/min]	6500	**Estimated weight added [g]**	61.2
Heat input [kJ/mm]	0.87	**Average error [g]**	4.6

Table 43: Test parameters weld 054

Test aborted, bad result on first seam.

Test 055

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	-
Current [A]	300	**Weight added 2nd pass [g]**	59
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	59.3
Feed [mm/min]	6500	**Estimated weight added [g]**	61.2
Heat input [kJ/mm]	1.04	**Average error [g]**	2.05

Table 44: Test parameters weld 055

Error EFd 8.1 the first three attempts, this was caused by fault in the wire feed system (overcurrent in wire feeder drive). To remedy this problem, the hose pack was rearranged to straighten out the line as much as possible. The connections were checked, there are no kinks or dirt in the inner liner. The contact pressure on the 4-roller drive was also checked [30]. Due to this the weight of the first successful run is unknown.

Test 056

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	68.1
Current [A]	300	**Weight added 2nd pass [g]**	68.1
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	68.4
Feed [mm/min]	7500	**Estimated weight added [g]**	70.6
Heat input [kJ/mm]	1.04	**Average error [g]**	2.4

Table 45: Test parameters weld 056

2nd seam started bad, but ended good. Start-up time from arc strike to welding operation start increased from 0.6 to 1.0 seconds. 3rd seam looked good.

Test 057

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	76.8
Current [A]	300	**Weight added 2nd pass [g]**	10 (a)
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	-
Feed [mm/min]	8500	**Estimated weight added [g]**	80.0
Heat input [kJ/mm]	1.04	**Average error [g]**	3.2

Table 46: Test parameters weld 057

Aborted, build-up of filler close to the gas nozzle.

Test 058

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	72.2
Current [A]	300	**Weight added 2nd pass [g]**	72.8
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	70.3
Feed [mm/min]	8000	**Estimated weight added [g]**	75.3
Heat input [kJ/mm]	1.04	**Average error [g]**	3.53

Table 47: Test parameters weld 058

Produced three very bad welds. Last good weld was with feed 7500.

Notes

Figure 24: Test weld 049 – 054

Figure 25: Test weld 055 - 05

During this experiment there were several problems with the feeder. This was probably the first time it had been used at high speeds, so some things needed adjusting on the unit itself. This experiments also produced some of the least visual acceptable weld. The wire sometime come out from the weld pool at the start, this may have been remedied if the acceleration of the feeder was one of the parameters that could be adjusted.

Experiment 6

Experiment 6 is designed to recreate some of the test results. First for the feed limits on a cold plate, and the feed limits for 200, 250 and 300 A on a pre heated plate. The first four test will be replicated three times. The welds will be made as close as possible to try and get a complete fusion of the seams. The distance between seams is adjusted so that the torch will follow the last seam. They will therefore not be measured one by one. The last two tests are high speed test running at 300 A and 6000 mm/min feed, with arc speed at 360 and 300 mm/min. Both test will be done two times. In case of an error the welds will continue close to the brake off point.

Test 059

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	147.4
Current [A]	300	**Weight added 2nd pass [g]**	-
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	-
Feed [mm/min]	5400	**Estimated weight added [g]**	155.9
Heat input [kJ/mm]	1.04	**Average error [g]**	8.5

Table 48: Test parameters weld 059

The estimated energy requirements to melt the filler is 20 per cent, other experiments had showed that this is quit near the maximum. All three passes looked good.

Test 060

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	N/A
Current [A]	300	**Weight added 2nd pass [g]**	N/A
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	N/A
Feed [mm/min]	6400	**Estimated weight added [g]**	N/A
Heat input [kJ/mm]	1.04	**Average error [g]**	N/A

Table 49: Test parameters weld 060

First pass looked good. 2nd and 3rd aborted due to error EFd 8.1 from the freed unit, this has happened on several occasions when welding with high feed. 4th pass had a lowed feed, 6000 mm/min, and was successful. In the last pass the feed was adjusted up to 6400 mm/min again. In addition, the angle of the feed nozzle was adjusted so that the filler entered at a more optimal point of the arc. 5th pass produced a good weld. The required energy to melt the filler was estimated to 23.67 per cent of the total arc energy.

Test 061

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	144.9
Current [A]	250	**Weight added 2nd pass [g]**	-
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	-
Feed [mm/min]	5200	**Estimated weight added [g]**	150.1
Heat input [kJ/mm]	0.87	**Average error [g]**	5.2

Table 50: Test parameters weld 061

All three passes looked good. Estimated energy requirement for the filler is 23.08 per cent.

Test 062

Parameter	Value	Parameter	Value
Voltage [V]	14.5 – 13.5	**Weight added 1st pass [g]**	155.5
Current [A]	200	**Weight added 2nd pass [g]**	-
Robot speed [mm/min]	150	**Weight added 3rd pass [g]**	-
Feed [mm/min]	4160	**Estimated weight added [g]**	160.1
Heat input [kJ/mm]	0.7	**Average error [g]**	4.6

Table 51: Test parameters weld 062

1st pass looked a little "cold", adjusted the gas feed down to 7 l/min. 2nd and 3rd pass looked better, however the observed arc seamed to high, the voltage was adjusted down to 13.5 V. 4th pass looked good, and had a better arc. Estimated energy required to melt the filler is 23.08 per cent.

Test 063

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	44.2
Current [A]	300	**Weight added 2nd pass [g]**	-
Robot speed [mm/min]	360	**Weight added 3rd pass [g]**	-
Feed [mm/min]	6000	**Estimated weight added [g]**	48.1
Heat input [kJ/mm]	0.44	**Average error [g]**	4.3

Table 52: Test parameters weld 063

Two bad welds, speed is too high. The weld seam has air holes and is very uneven.

Test 064

Parameter	Value	Parameter	Value
Voltage [V]	14.5	**Weight added 1st pass [g]**	140
Current [A]	3000	**Weight added 2nd pass [g]**	-
Robot speed [mm/min]	300	**Weight added 3rd pass [g]**	-
Feed [mm/min]	6000	**Estimated weight added [g]**	144.3
Heat input [kJ/mm]	0.52	**Average error [g]**	4.3

Table 53: Test parameters weld 064

Five passes, variating result. Starts bad and evens out at the end. 300 mm/min (5 mm/s) may be a speed that is too high to start with.

Notes

After the welding operations the test plate where sandblasted, this was done to examine the outside of the weld seams. The perforations of the high speed test (063) where easy to examine after the blasting, and confirmed that 360 mm/min is to high speed. For the high feed tests, the sandblasting did not reveal anything new.

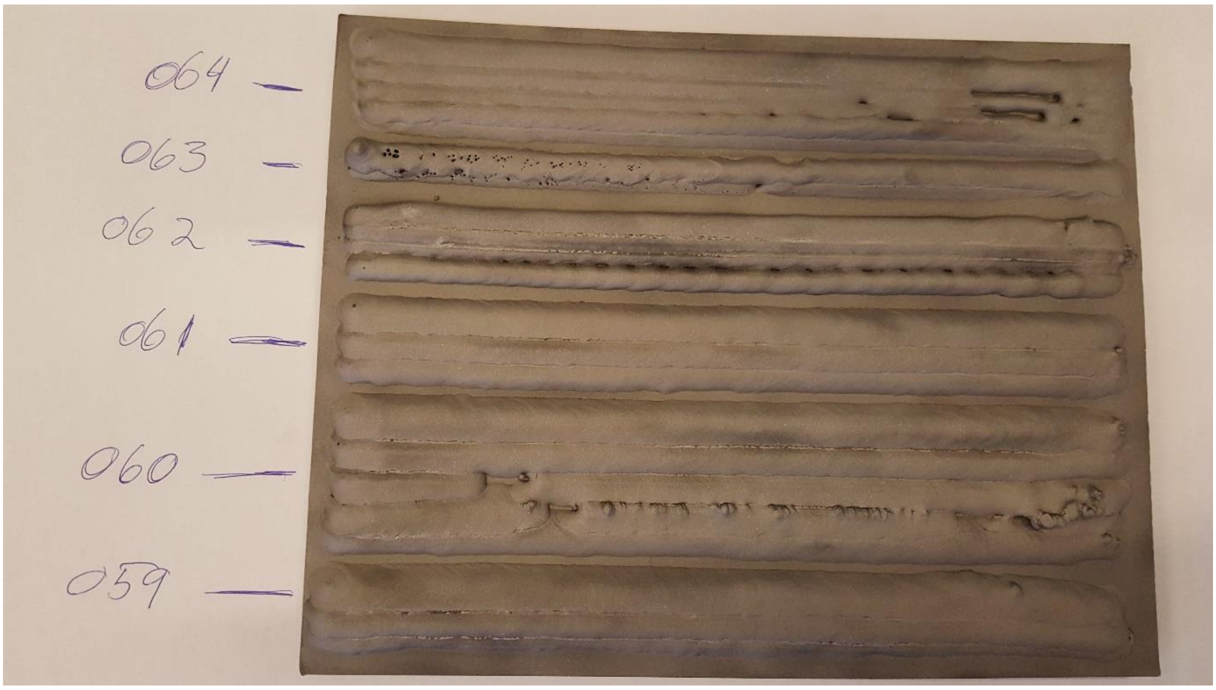


Figure 26:: Test weld 059 – 064

Macro etch testing

Macro etch testing allows the tester to see a cross section of the weld, and see the arrangement of the grains in the parent metal and the weld material. This is known as its macrostructure. It can also show defects such as porosity, inclusions and poor fusion. This test requires minimal equipment. Under the supervision of Magnus Aanstad the test plates where cut in smaller pieces, making the cuts perpendicular to the welds. These pieces will undergo macro inspection. The edge is grinded, first with a belt grinder, and after that with increasingly fine sand paper (180 – 320 – 800 – 2400 grid). After the last polish with 2400 grid sand paper, the surface is mirror like in appearance. After cleaning the surface, an acid solution is applied. The solution is 10% Nitric acid (HNO_3) and 90% water. Nitric acid is used because of its rapid oxidizing properties. After a short time, the parent metal and weld areas will begin to discolour [31].

This particular test was only done after experiment 5 and 6. These where the experiments that tested calculated parameters, and were done based on experience and data gathered from the other experiments.

Macro etch testing experiment 5

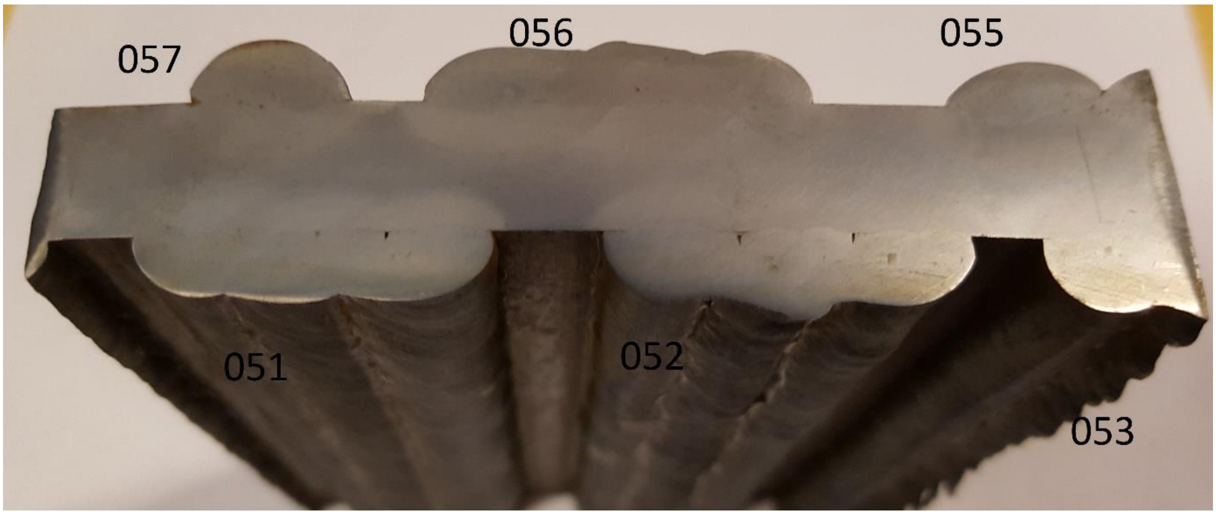


Figure 27: Inspection of welds 051, 052, 055, 056 and 057

Weld 051 had a feed of 6000 and 052 a feed of 7000, both running at 250 A and 150 mm/min. As the macro inspecting has revealed, there are black spots between the welds and parent metal. This is a small gap between the seams, this may be caused by a coating on the parent metal, low heat or wrong placement of the electrode on 2nd and 3rd pass. Because this is robot welding, it is reasonable to assume that the fault exists the whole weld length. Weld 057 was aborted due to over-feeding. The interesting thing is to note that there is complete fusion, indicating that a bad weld does not need to be completely removed. Weld 056 had the highest successful feed in the 300 A tests, it appears to have a better fusion between the seams. More investigation needed to be done to see if this is a result of better placement of the electrode or higher heat (current).

Macro etch testing experiment 6

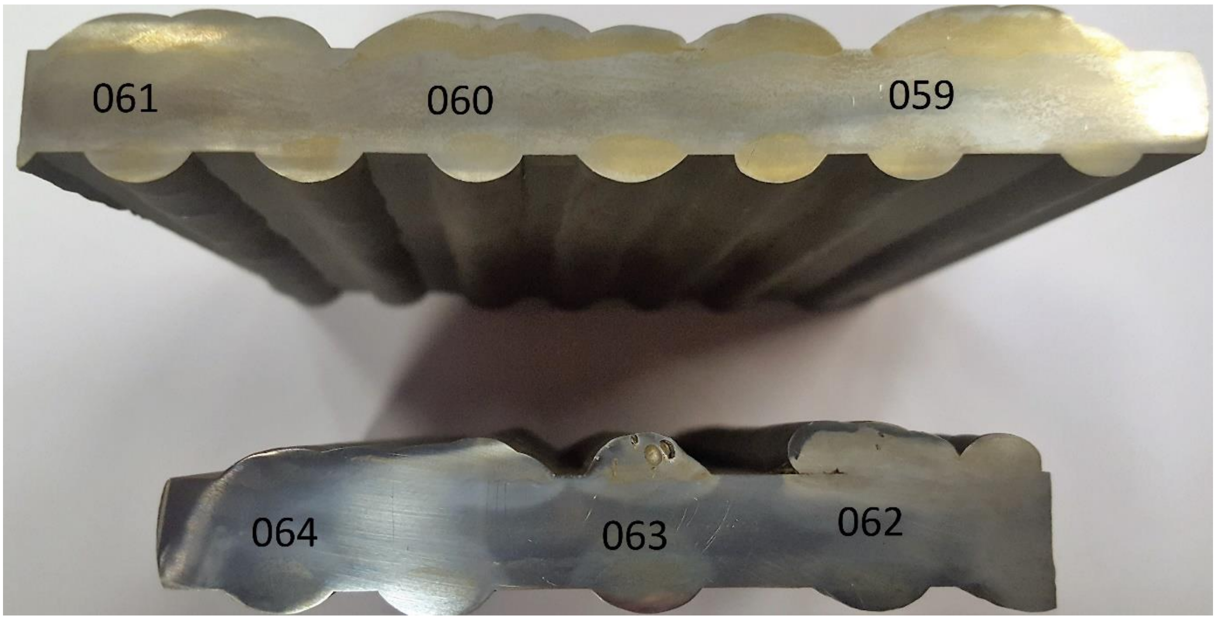


Figure 28: Inspection of welds 059 – 064

The discoloration on the welds is caused by oxidation, and does not reflect the quality of the welding. Welds 059 – 061 where the high feed tests. Inspection indicates that the problem with the missing fusion between welds was eliminated when the test plate was not weighted after every seam. Weld 062 had good fusion, but not a good appearance. The step down to 200 A needs more adjustment than just reduced feed. However, the filler melted so that part of the experiment is confirmed. Weld 063 and 064 where high speed. Inspection reveals relative big holes in weld number 063, this was running at the highest speed. As mentioned in the notes after the weld, the speed might have been too high. Weld 064 has good fusion to the parent metal, and between the seams. This confirms the findings from other experiments. The findings indicate that the highest speed that can produce a good weld, at maximum feed, is 300 mm/min (5 mm/sec).

Main findings in the experiments

Some of the experiments failed to unveil the planed results. However, the experience and knowledge from these tests helped in fine tuning the parameters from the successful experiments. The findings from most of the failed experiments are mentioned under the chapter "Lessons learned".

For a complete overview of all the calculations for the experiments, see the enclosed excel file. All the parameters and values has been calculated for every single pass.

Feed limit

In the first experiments one or more of the parameters was continually adjusted until the desired result was discovered, or a limit had been reached or found. All the calculations where done after the parameters where set. In experiment 5 and 6 the sequence of calculations was reversed. The assumed energy requirements found for welding with maximum feed 300 A where used as a benchmark. When testing to find a correlation, the current was set to 250 A and 200 A. The feed was then adjusted until the calculations gave the same relative energy requirements for the filler, and that became the feed-rate setting for the next test. Welding at 200 A was a little more challenging, and the voltage needed to be lowered to get an acceptable result.

The limits found in the experiments, 5 and 6 especially, indicates that there is a linear correlation between the maximum feed and the arc energy. In these experiments the main way of adjusting the arc energy has been the variation of the current. The arc voltage, and therefore the height, has been kept constant. According to the calculations, the negative energy requirement introduced by the filler has a limit around 20 per cent when welding on cold metals. When the metal has heated up, the limit seams to rise to around 23 – 24 per cent. The feed limit where tested and confirmed when welding with 2.6 kJ/s (300 A), 2.2 kJ/s (250 A) and 1.6 kJ/s (200 A) arc energy.

Arc speed

In experiment number 3 the main objective was to investigate if the speed of the arc had a large impact on the fusion between the filler and parent material. The experiment was run with a high current and relatively low feed. The destructive testing indicated that the parent metal and filler had good fusion up to 300 mm/min. Experiment 6 had similar results, and indicated that 300 mm/min is a threshold for "high speed" welding, at least at 6000 mm/min feed rate. The weld seams done at 420 mm/min did not give a good result. It is possible that they would had been better with lower feed / higher current.

Deviation between actually and calculated weight

After every test, the actual weight of the weld was found, there is a relative constant mismatch between the weight of 3.6 per cent on successful welds. The error between actual and calculated weight added can have four likely causes.

- It can be caused by the acceleration delay in the feed mechanism. The acceleration time of the feeder is a parameter that is unknown at this point.
- Evaporation of material from filler and parent metal.
- The speed of the feeder was not controlled, and the set speed of the feeder may not correspond with the actual speed.
- The assumed weight used in the calculations may be too heavy.

Lessons learned

Some of the findings were of a general nature, this information was not stated in any of the literature available. However, a routine welder would probably recognize these findings as everyday problems.

Electrode shape

There were several signs that could indicate that the electrode was in need of some maintenance. The first, and most direct, was the visual observation of the arc. The tip of the electrode decides the direction of the arc, it will to a large degree follow the direction of the tip and the gas flow. When the tip becomes too rounded of, or polluted with filler, it will start to jump and not follow a straight line. This can be observed directly by looking at the arc through the welding mask. Secondly, the sound of the arc: as the arc starts to "jump", it will make the same noise as under the first arc-strike at weld start. It will make this sound constantly. And lastly, the initial strike will have difficulties to start, or not start at all. This can happen early with the tungsten + cerium electrode, which has a low rating regarding striking the arc. When the electrode tip is sharp, the only sound from the welding is the sound of the gas flow.

Gas flow

In the initial testing the gas flow was assumed to be acceptable, that was a mistake. The gas flow was so high that it manages to cool the outer layer of the weld seam to the degree that is was unable to flow naturally. When the flow was reduced from 20+ litres per min to 10, and de nozzle increased from a size six to seven, the weld seam got wider with a more natural flow pattern.

Feed alinement

The alignment of the feedline into the arc also plays a part in making a good weld. The two welds in the picture below were made with identical settings, and should look somewhat similar. The one on the top was made first, upon inspecting the end of the feeder it was discovered that the wire did not go straight into the arc, but slightly to the side. As is evident by the picture, the second weld was successful.

Figure 29: Welding with feeder out of alinement with the arc

Feed nozzle angle

When welding with high feed, experience show, that the point in the arc the filler hits has a significate impact on the success rate of the weld. At this point that exact point is not known. However, the signs that something is wrong is clear. If the entry point is too close to the electrode, the filler tends to pass right through without melting. If the entry point is too close to the parent metal, the filler will not melt properly and give the weld a bad appearance. Moreover, this often causes error EFd 8.1.

Magnetic pull / arc blow

According to The Welding Institute, magnetic arc blow can occur when welding ferromagnetic steels and the magnetic field of the arc is distorted [32]. This can be caused by three factors:

- Residual magnetism if the metal has been handed with magnetic equipment
- Earth magnetic field, especially when welding on pipelines
- The position of the current return

Making a pWPS

A welding procedure specification is a document that gives a welder all the information that is needed to perform, or make, a specific weld. This includes, but is not limited to, groove dimensions, exact parent metal, cleaning of the parent metal, filler type, weld method, gas type, current, speed, heat input, number of passes etc. The WPS is somewhat a personal document, and is based on the personal experience from the person who wrote it. However, the required information is the same. The first step in developing a WPS is to make a preliminary welding procedure specification. A pWPS will follow a process similar to the flowsheet below and be adjusted so I can become the final and approved WPS.

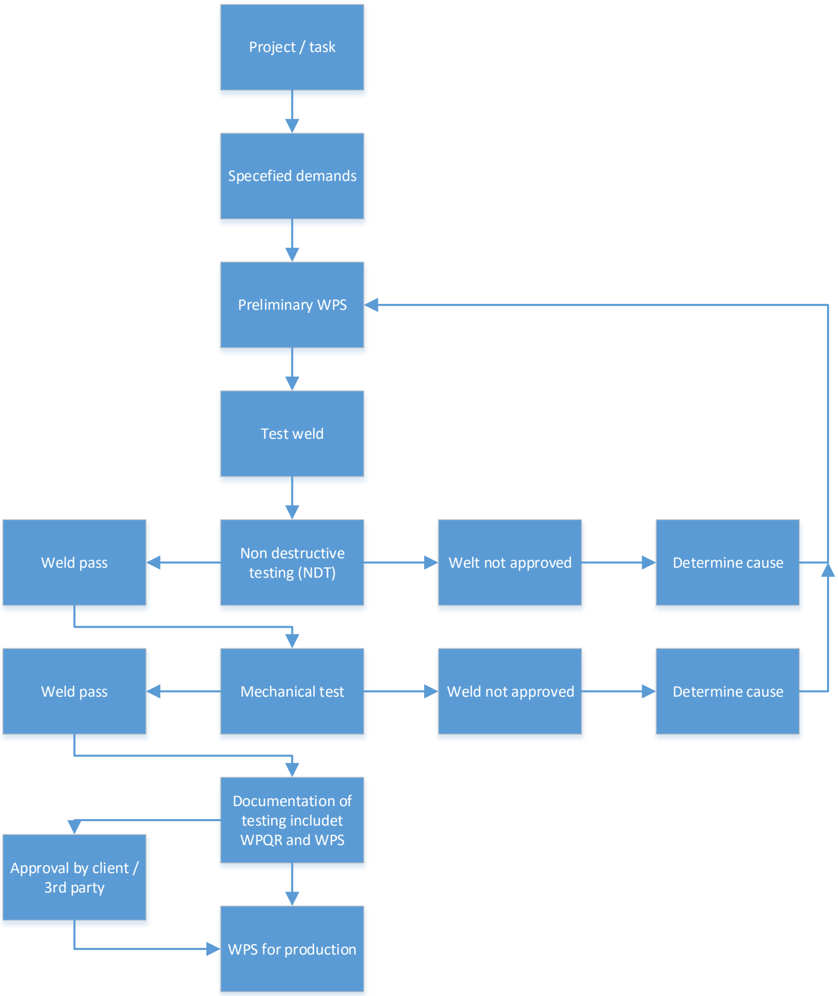


Figure 30: Flow diagram pWPS to WPS

Thermal distortion

Another side to the joint design is to minimise the tension put on the weld area. When a hot metal cools down it shirks, this shrinking will pull the metal, and can lead to distortions. It is therefore advised, if possible, to start welding the groove in an offset angle to compensate. The shrinkage of metals is known values, so calculating the extra width is relatively straight forward. The thermal expansion for iron is 0.0000118 K^{-1} [4]. The calculation will multiply the expansion factor with the temperature difference from melted iron and to room temperature (1515 K).

$$0.0000118 \times 1515 = 0.01788$$

Equation 15: Thermal expansion for iron from melting temperature to room temperature.

This value is called the expansion factor. However, this is calculated from melting point and to room temperature, so this is in fact a negative expansion.

Pre – heating and post – heating

Pre-heating and post-heating is a method used to reduce the risk of forming martensite in the heat affected zone while the metal is cooling down, this is a hard and brittle form of steel. Welds that contain a high amount of martensite will have extreme hardness and low ductility, and known to crack under cooling. The martensite is formed under the cooling process itself, to limit this the temperature difference between the weld area and the metal can be reduced by pre-heating. In some instances, it is also necessary to post-heat the metal after the welding

The calculations for the actual weld seams used in the suggested pWPS is described in the chapter pWPS calculations on page 24.

Weld joint design

The objective of the weld groove is to make enough space so that the welding electrode is able to reach the root face of the two pieces that is being fused. On the other side, the groove must not be so large that it takes an unreasonable large amount of filler, and therefore time and money, to fill up again. The simplest and smallest grooves is relative easy to design and cut manual. When using automatic welding systems, it is best if the weld groove is machined. This is because robots, and other automatic welding equipment, have a hard time following uneven surfaces. Ultimately this should be considered already in the design phase to ensure that a minimum of “on the spot” work is needed. The design of the weld can have any number of layouts and designs.

Modern Welding Technology list up eight different types of joints [33], some of them with several sub-types. Most of them have names after the appearance of the cross section, like V-groove, square-groove, X-groove, J-groove and so on. The most used joint type is the fillet weld, with all its sub-types.

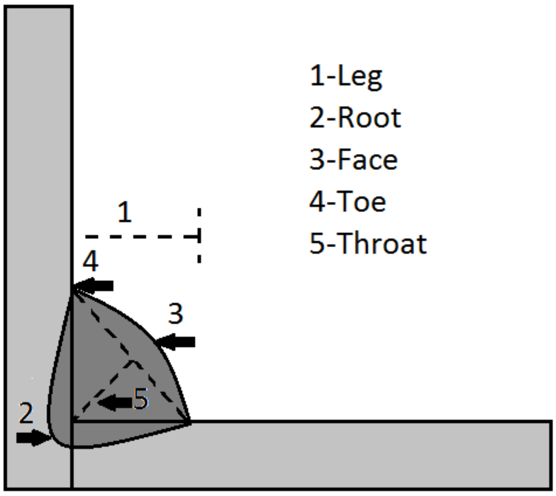


Figure 31: Fillet weld terminology By Powerstroker - Microsoft Paint, CC BY-SA 3.0, https://commons.wikimedia.org/w/index.php?curid=25942071

Based on the on the dimensions and weld position in this case, the best option is to start with the single – V weld.

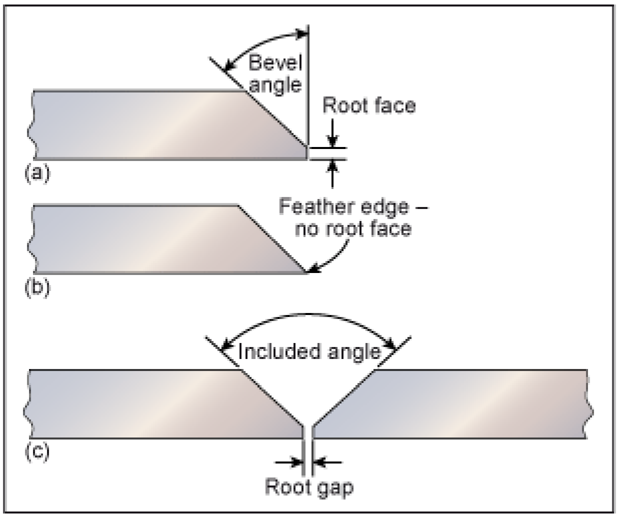


Figure 32: Single - V terminology By The Welding Institute http://www.twi-global.com/_resources/assets/inline/full/0/9842.gif

The information about the optimal construction or design of a weld groove is hard to find in books and articles. The information that is available is often of a very general nature, and is referred to as “existing knowledge based on experience”. It is all down to the preference of the welder, material, agility of the robot / automate and the orientation of the weld. With this knowledge I turned to the expertise of Asgeir Hakaas, senior engineer at Teknologisk Institutt AS [34]. When given the dimensions of the welding area he advised me to use something he referred to as “sparefuge”, with roughly translate to a “savers groove”. This is a variant of the V – groove, instead of one includes angle it has two.

Calculating the cross area

Calculating the cross area of the standard V-groove is relatively straightforward; the calculation consists of two parts:

1. Calculating the area of the groove: the high of the groove multiplied with the tangent of the bevel angle and the height
2. Compensation for the root gap

Usually when calculating the area of a triangle we divide by two; in this instance, it is the area of two identical triangles.

$$A = \left(\Delta height \ \times (\Delta height \times \tan(angle))\right) + (root\ gap \times total\ height) = mm^2$$

Equation 16: Cross area standard V - groove

Calculating the area of the savers groove is a little more work and is made up by four parts, however the mathematics are the same.

1. Calculating the area of the first part of the groove, the height of the first groove multiplied with the tangent of the bevel angle and the height
2. Calculating the area of the second groove: the height of the second groove multiplied with the tangent of the bevel angle and the height
3. Calculating the square area over the first angle of the groove: the height of the second groove multiplied with the tangent and height of the first part of the groove. This value is multiplied with two, since there is two of this areas
4. Compensation for the root gap

$$A = \left(\Delta height1 \ \times (\Delta height1 \times \tan(angle1))\right) + \left(\Delta height2 \ \times (\Delta height2 \times \tan(angle2))\right) + (\Delta height2 \ \times (\Delta height1 \times \tan(angle1)) \times 2) + (root\ gap \times total\ height) = mm^2$$

Equation 17: Cross area "savers grove"

The cross area, with the normal design parameters, for a V-groove is a root face at 2 mm, 2 mm root gap and a bevel angle of 30 ° for the remaining 58 mm [35].

Groove area:

$$A = \left(58 \times (58 \times \tan(30))\right) + (2 \times 60) = 2062.21\ mm^2$$

Equation 18: Calculated cross area V - groove

This will give a cross section of 2062 mm^2.

The "savers groove"

The design parameters for the savers groove version 1 is 2 mm root face, 60 ° included angle approx. 1/3 of the height and 5 – 10 ° included angle on the rest.

Savers groove version 1

Using these new guidelines, the following values where selected 2 mm root nose, 60 ° included angle to height 22 mm and 6 ° included angle to height 60 mm the groove is calculated.

The height from the base to point A is 2 mm. From point A to B there is a bevel angle of 30 °, and a different of height of 20 mm. From point B to C there is a bevel angle of 3 ° and a height difference of 38 mm.

Figure 33: "Savers groove" version 1

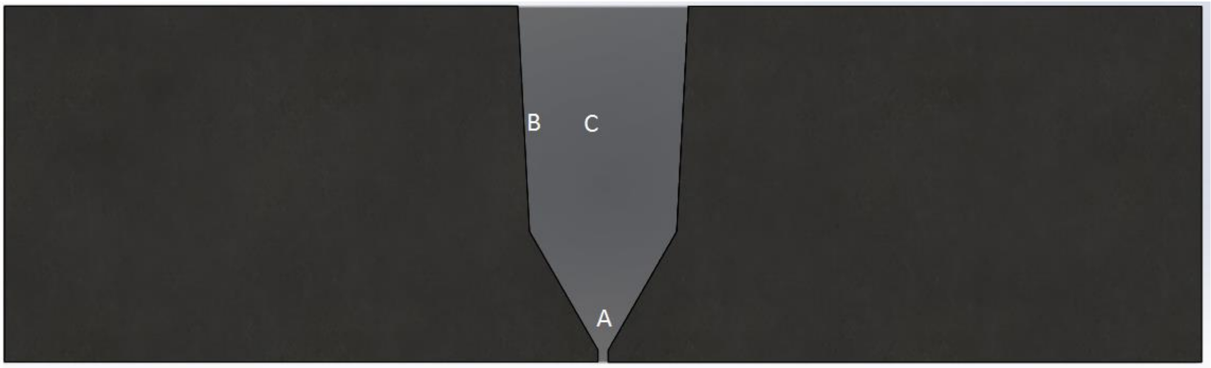


Figure 34: "Savers groove" version 1 assembled

The cross section of the groove is made up by 3 (4) different sections. Areas A and B are the areal covert by their respective triangles. C is the quadratic areal between the two B triangles. The fourth is the areal given by the width of the root gap.

Total areal is calculated:

$$A = \left(20 \times (20 \times \tan(30))\right) + \left(38 \times (38 \times \tan(3))\right) + (38 \times (20 \times \tan(30)) \times 2) + (2 \times 60)$$
$$= \ 1304.18\ mm^2$$

Equation 19: Actual cross areal "savers groove" version 1

Groove areal: 1304 mm^2

Testing version 1

As seen in the pictures below, it turns out that version 1 is too small to accommodate the weld torch. It is too narrow in the top, and the electrode is ca 15 mm above the optimal point.

Figure 35: Weld groove too small for the torch

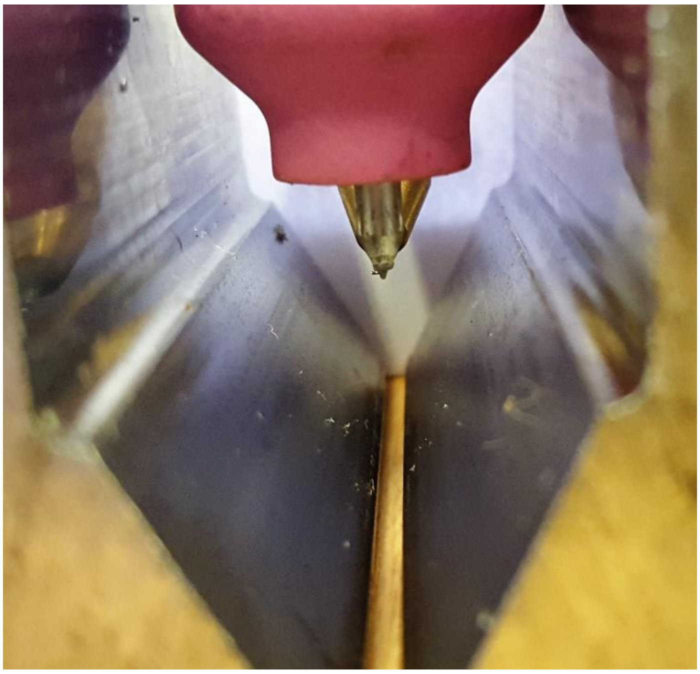
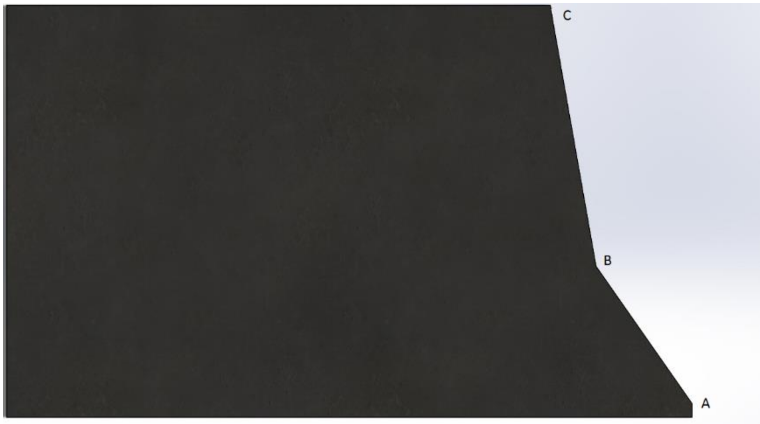


Figure 36: Torch unable to reach the maximum distance to the root of the weld

Both the bevel angles need to be increased to ensure an effective weld.

Savers groove version 2

Using the information obtained from the first test, the weld groove has been re-designed. The new values are 35 ° for the lowest bevel angle and 10 ° for the second. The heights are the same.



The height from the base to point A is 2 mm. From point A to B there is a bevel angle of 35 °, and a different of height of 20 mm. From point B to C there is a bevel angle of 10 ° and a height difference of 38 mm.

Figure 37: "Savers groove" version 2

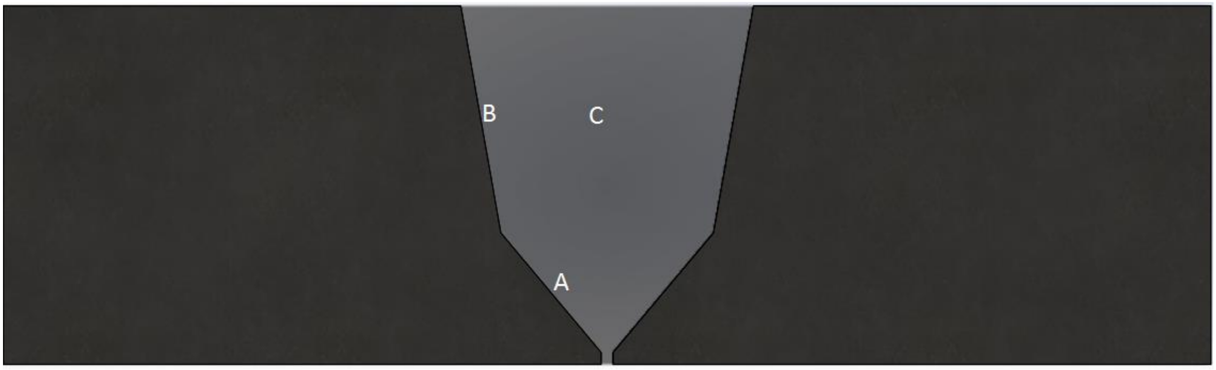


Figure 38: "Savers groove" version 1 assembled

Total areal is calculated:

$$A = \big(20 \times (20 \times \tan(35))\big) + \big(38 \times (38 \times \tan(10))\big) + (38 \times (20 \times \tan(35)) \times 2) + (2 \times 60) = 1719{,}01\ mm^2$$

Equation 20: Actual cross areal "savers groove" version 2

Groove areal: 1719 mm^2

Testing version 2

To avoid any further extra machining, the new parameters where tested using a cut out piece made up of cardboard. This simple test showed that this is a tight fit; however, there is enough room to manoeuvre the weld touch to satisfactory angles. It is decided to re-machine the old pieces with the new parameters.

Calculating the withe of the weld opening:

$$L = \left((20 \times \tan(35)) + (28 \times \tan(10))\right) \times 2 + 2 = 43.4\ mm$$

Equation 21: Maximum width of the groove

The widest part of the welding torch measures 29.5 mm.

Difference in cross area V – groove and "savers groove" version 2

Equation 18 gives us the area for the V – groove, and from Equation 20 the area of the "savers groove" version 2.

$$2062\ mm^2 - 1719\ mm^2 = 343\ mm^2$$

Equation 22: Absolute difference V – groove and "savers groove" version 2

$$\frac{1719\ mm^2}{2062\ mm^2} \times 100\ \% = 83.4\ \%$$

Equation 23: Relative difference V – groove and "savers groove" version 2

The two biggest advantages with the reduction in cross area is the need for machining, or material removal. And the reduction in number of passes needed to fill the groove with filler.

Width compensation "savers groove" version 2

Equation 15 gives the expansion factor for iron from melting point to room temperature. This information is used to calculate the opening at the top of the groove.

$$X \times (1 - 0.01788) = 43.3\ \rightarrow \frac{43.3}{0.9821} \approx 44.1$$

Equation 24: Offset in width when mounting the groove

This means that in a V shaped groove like this, the workpiece must be pre sett with a 44.1 mm gap at the top before welding starts, and it will shrink to 43.4 mm. This may not have a huge impact on the test sample. However, it can lead to distortion if the workpiece is wide.

Suggested pWPS

Preliminary Welding Procedure Specification

Version 1

Groove design sketch

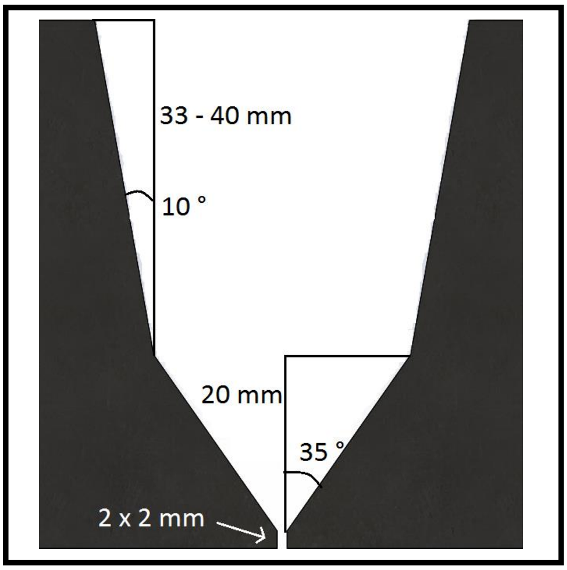


Figure 39: Weld sketch for pWPS

Backing

Type: None

Permanent:

Removed:

Other:

Base metal

Type: AISI 1020

Thickness: 55 – 62 mm

Other:

Filler metal

Type: Böhler EMK 6

Size: 1 mm

Other:

Shielding gas

Shielding gas(es): Argon

Percent composition: 100 %

Flow rate: 9 l/min

Other:

Preheat

Preheat temperature: room temperature

Interpass temperature: 250 °

Cleaning

Initial cleaning oxide: Grinding/machining

Initial cleaning oil and dirt:

Grinding/machining

Interpass cleaning: None

Post weld heat treatment

Original temperature: None needed

Process

Process: GTAW / 141

Type: Automatic / robotic

Electrode: 3.2 mm, 2 % cerium

Technique

Movement: String

Orifice or gas cup size: 7 w/ gas lens

Single or multi pass: multi

Welding parameters

Pass No.	[A]	[V]	Arc speed	Feed rate
1	200	14.5	60	3000
2 – 4	280	14.5	60	5000
Filler pass	300	14.5	60	6500
Cover beads x3	300	14.5	60	2000

Sketch of welding sequence

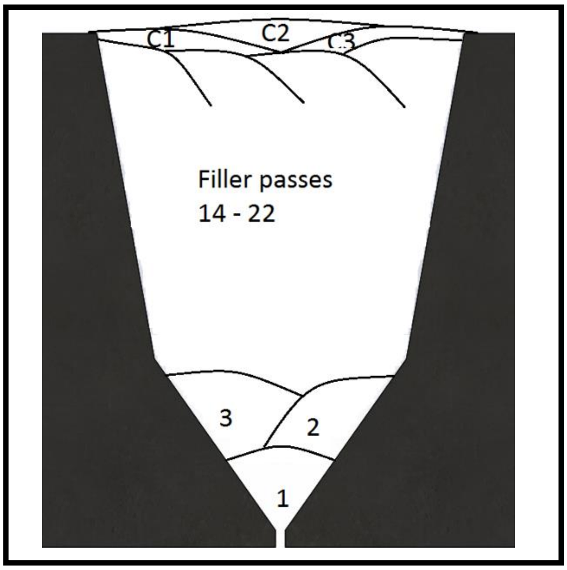


Figure 40: Numbered weld sequence pWPS

Conclusion

In the experiments to discover the different feed limits, the relative difference of 4 per cent points when welding on cold and pre heated does not look like a huge difference. However, looking at the calculations, the difference in the weld cross area indicates welding near the feed limit gives circa 20 per cent more filler per pass. This has an impact on the number of passes required to fill up a groove. And that, in turn, means a reduction of the time needed to complete the whole welding operation. It is also very interesting to note that it seems to be a linearly correlation between the arc energy and the maximum feed.

The experiments for finding the maximum speed may not have a huge impact on this particular setup. However, it can have an important role when welding on more complex grooves. If the grove has a variating width, or cross section, the normal way to weld is by using fewer passes in the “thin” sections. This means that some of the weld seams will stop, and / or start, in “the middle” of the groove. This again can lead to problems when the next seam passes over the start / stop point, causing impurities or weakened zones in the weld. The discoveries in experiment 4 and 6 indicate that the robots highly controllable speed can be utilized to make weld seams with variating width, thus keeping the number of seams constant throughout the whole weld. This has the potential to eliminate, or at least reduce, the number of start and stop points in the middle of the groove.

When utilizing the accuracy in the robot movement, in conjunction with good control over the arc and feed, it is possible to write a very effective WPS. The number of passes required for a specific groove can be calculated accurate, and the size of each individual weld seam can be controlled by manipulate either the feed rate or the arc speed.

Recommended further work

This thesis is limited to one type of steel and filler, as for further work the recommendation is to investigate if the calculated energy consumption by the filler is transferable to thinner and thicker filler wires. It is also advised to control the feed and speed limits against other steels, to investigate the impact from the difference in thermal conductivity. It is also recommended to test the pWPS.

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