Development of GMAW consumable test method

An analysis of I/U-characteristics and automated welding, regarding new quantifying measurables and stability

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ABSTRACT

This project investigates the possibility to find measurable values based on the current and voltage characteristics of the GMAW, Gas Metal Arc Welding, process that may be correlated to process parameters and/or geometrical measurements of weld beads. Such quantites may have the potential to replace or complement existing subjective and qualitative charcterisation and validation methods of the welding process. Existing characterisation methods of the performance of welding consumables consist, at least partly, of an experienced welder/engineer that uses his/her experience to evaluate the welding process. Finding other more objective and quantitative measures that correlates to aspects of the welding process may enable more systematic and efficient methods of development and validation of welding consumbles. Also, a replacement of manual welding with automated welding may further contribute to the efficiency of the methods.

This work will focus on two aspects during two experiments. The first experiment performed aimed on deriving possible quantitative measurables from the I/U characteristics from welds acquired with varying voltage and wire feed speed. An automated GMAW process were used. The I/U data was then analysed in a computer software to find possible characteristic measurables, which have the potential of correlating to the welding process. Examples of calculated characteristic quantities are; amount of short-circuiting, quantities from Fourier transformation analysis and deviation in current, voltage and power. A discussion are made about how these aspects of the I/U characteristic are linked to the process and different transfer modes. The I/U characteristics analysis revealed that some of the calculated characteristic quantities showed possible trends or indications of correlations to the weld process. The Fourier transformation showed a unexpected peak in the frequency span of 300-900 Hz, which could be of future interest but it needs further analysis to draw any conclusions.

In the second experiment, a number fillet welds were made in order to demonstrate the effectiveness and stabillity of the automated setup. These welds are also made with varying wire feed speed and voltage with an automated GMAW process. Geometry measurements were performed on the weld bead profile, in terms of throat thickness, leg length, penetration, etc. The result from the geometrical measurements and their correlation with the input parameters are shown to be in good agreement with theory and the automated setup being promising as a standard method for consumable characterisation.

Keywords: Automated GMAW, I/U characteristics, MIG/MAG Welding

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1. INTRODUCTION

This work is a step to improve the understanding of how the process parameters influence the welding characteristics. The project is performed at ESAB in Gothenburg at the research and development department, which have an aim to improve efficiency and to minimize the uncertainties in test welding and in procedure development.

The arc welding, as we know it today, was invented in the 19^{th} century after the innovation of the electric generator. The first stable electric arc was created 1810 between two terminals. In 1885 the first carbon arc electrode patent was filed in England, which became a popular process for joining and repairing. Five years later an arc welding process using a metal electrode that worked as filler material was invented. A problem was the weld quality, it was bad due to the reaction with surrounding atmosphere, which made it impossible to get an airtight weld, (Cary, 1998). In 1907 Oscar Kjellberg, ESAB Sweden, patented the covered electrode. The iron electrode was dipped in a thick mixture of carbonates and silicates that protected the melt from the gases in the atmosphere. This improvement made manual metal arc welding, MMA, useful in industrial applications, which was a breakthrough, (Weman, A History of Welding , 2004). A step to automate the welding process was to use a process with a continuous wire. The most successful method was submerged arc welding, SAW, that is also called under powder. The process was developed in the 1930's and is very similar to MMA except that the protecting cover is a powder that is applied around the weld. The deposit rate is increased a lot with this method compared to MMA.

During the Second World War the aircraft industry needed a method for welding magnesium and aluminium. An arc welding process in a shielded gas atmosphere is needed and by using a tungsten electrode and an inert gas flow, the arc could be struck without melting the electrode. This also made it possible to weld without a filler material. The new method was called TIG, Tungsten Inert Gas. Some years later, the MIG welding process (Metal Inert Gas) was developed using a continuously fed metal wire as the electrode, also called GMAW, Gas Metal Arc Welding. The inert gases used were Helium and Argon, (Weman, A History of Welding , 2004). The method had a high deposition rate, which led users to try the process on steel but the cost of inert gas was relatively high. In 1953 it was discovered that it was possible to use cheaper gas mixtures with carbon dioxide when welding in steel. The discover was revolutionary due to the better deposition rate, better penetration, less spatter (using certain mixtures of $Ar\text{-}CO_2$) and much cheaper gas. This method is called MAG welding, Metal Active Gas, due to the use of a gas that reacts with the arc and melt, (Cary, 1998).

GMAW is one of the most common welding methods today due to the high deposition rate, automation aspects and price. After more than 50 years of elaboration of GMAW, there are still areas within the technology that have potential of improvements. The complexity of the welding process, in terms of the sheer number of physical parameters that influence the process, along with lacking of good measurement technology, has forced the development of welding consumables to historically be of a trial-and-error type. However, the technological development in recent years allows a more knowledge based and scientific approach towards the welding process and the development of welding consumables.

The method of validation and verification of the welding performance of consumables is currently based on a rather subjective evaluation by experienced welders. The development of a more objective measurement method will allow a more accurate comparison of consumables. Furthermore, an increased use of automated welding in the validation and verification method could also improve comparisons and lower the risk of uncontrolled parameters influencing the outcome.

1.1 Problem definition

The performances of consumables are with current methods subjectively quantified. A welder grade the consumables properties (arc stability, wetting, spatter level etc.) based on experience. This type of subjective evaluation is difficult to work with during consumable development due to lack of objective responses. Welding is a craftsmanship and the exact welding techniques are varying from welder to welder. Welders get used to the properties of a certain consumable and master the difficulties. This is a problem when testing new consumables that have varying properties, some welders may like the properties and can adapt to the new consumable while others do not. Some new consumables may demand a change in welding technique for optimum performance, which can make the comparison between welders misleading or even invalid. The current testing method has problems with repeatability and reproducibility of test results.

1.2 Aim of the project

The aim of this project is to investigate the possibility of using quantities from the I/U-characteristic and an automated welding setup for testing, validation and development of welding consumables. Also to suggest such quantities that could be further analysed in future work.

1.3 Limitations

The primary goal is not to find correlations between the suggested quantities and welding parameters or the geometrical measurements. This will be the aim of possible future work. However, if such possible correlations would be found during the I/U characteristic analysis, these results can be presented.

2. METHODOLOGY

The methodology for this work is divided into two steps; the definition phase and the experimental phase. The definition phase consists of a literature study that worked as underlying information for the problem definition and the design of the experiments. The experimental phase describes how all the experiments are performed. The results from the experiment are then presented.

2.1 Definition phase

The first step in the methodology is the definition phase, where the literature study and the project planning are the two main parts. The purpose of the literature study is to gather sufficient amount of background information about and around the subject so that the problem can be defined, understood and later on solved.

The literature study is focusing on the GMAW process and how different input parameters influence the welding process. These are very important because they determine the quality and the geometry of the weld. There are many different input parameters that influence welding. Some are fixed during the process, such as consumable and shielding gas, and some are used for tuning the process, such as voltage and travel speed. The input parameters that are fixed during welding are termed as variables in this work. The ones that are used for tuning the process are defined as process parameters, (ASM International, 2011). Some parameters can be controlled by the choice of welding method, automatic or manual, such as travel speed, while some parameters are indirectly controlled. For example, an increase in voltage will result in an increase in arc length, (Weman, Karlebo Svetshandbok, 2013). This will be further discussed later on. The important thing is to know which input parameters that exist and what impact they have during welding and of its quality. All the defined variables and process parameters are stated in *Table 1*.

Table 1 - Variables that influences welding

Process parameters:	***Variables:***
Wire feed speed (Current)	Shielding gas mixture
Voltage (Arc length)	Consumable, composition/type/diameter
Travel speed	Base material
Travel angle	Base material thickness/pre-heating
Work angle	Cleanliness
Inductance	Rate of dilution
Gas flow	Welding position
Electrode extension	
Electric polarity	

All the process parameters will be described and discussed in the following literature study, as well as other important information about the GMAW process such as; shielding gas, consumables, modes of metal transfer and equipment.

2.1.1 Equipment

The equipment used for MIG/MAG welding consists of a power source, feeder, electrode nozzle and a shielding gas system. The basic principles of the process are that a power source is connected to the work piece and the wire. The wire is continuously feed onto the work piece producing an electric arc that melts the material. Welding current flows through the electrode causing resistive heating and the highest temperature is found where the resistivity is highest, at the arc. This is illustrated in *Figure 1*. Shielding gas protects the melt from the surrounding atmosphere, which otherwise reacts with the melt. The electrode nozzle transfers the current onto the wire close to the work piece for less resistive heating of the wire.

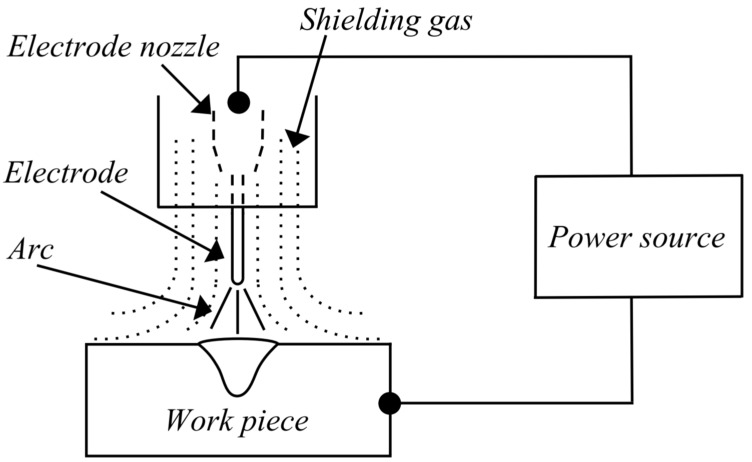

Figure 1 - A sketch over the basic principle of the GMAW process

The main purpose of *the power source* is to supply the system with the right amount of power. Its characteristics have a large influence on the ignition and stability of the arc. The static characteristic of a power source is how it responds to static load, resistance. At such a load a machine typically provides a current and voltage according to line “A” in *Figure 2*, where the voltage drops 2-5V/100A. The MIG/MAG power units have often a straight characteristic for better self-regulation of the arc, which gives a faster response. The voltage level is strongly connected to the arc length where a decrease in voltage decreases the arc length. If the arc length starts to decrease the voltage will drop, which will result in increased current. The increased current will increase the rate of melting of the electrode, and the arc length will be restored, (Weman K., 2006). The self-regulation of the arc length is illustrated in *Figure 2*.

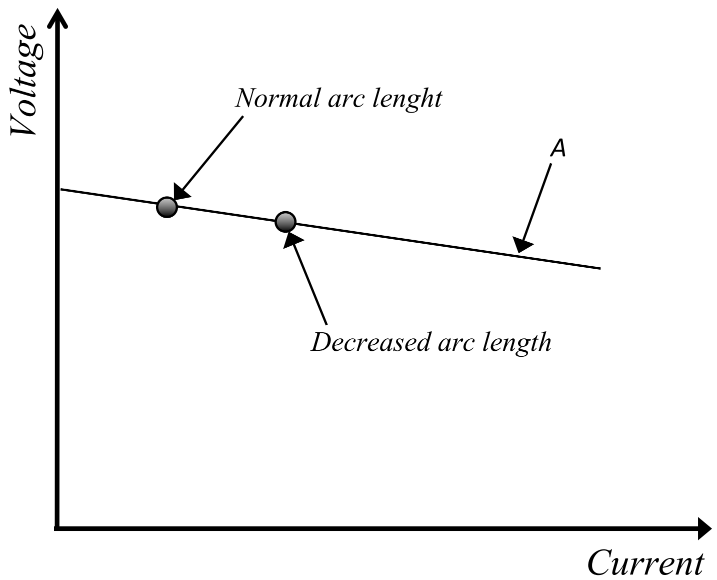

Figure 2 - Illustration of a static characteristic power source, showing the voltage and current relationship for a self-regulated arc length

The dynamic characteristics of a power source are of importance if rapid changes in current and voltage occur. The ability for the system to change parameter quickly is mainly depending on the inductance in the system. A low inductance is equal to rapid changes in the system and a high inductance leads to slower changes. The system needs a certain delay in the changes of current and voltage to be able to have a stable short-circuit metal transfer with low amount of spatter, (Weman, Karlebo Svetshandbok, 2013).

As the technology is developing the power sources get new features. The characteristics can be changed through software control and the system has less limitations. In a so-called synergic power source, the user friendliness is improved by automatic parameter adjustment. Another feature is pulsed welding where the current pulses between a high current level and a low background current. This increases the stability of the arc and also reduces the spatter. The heat input is also lower due to lower average power, (Weman K., 2006). A feature for short-circuit mode is ESABs QSet™, which automatically stabilises and controls the arc. For a conventional machine, the welder sets the voltage to a fixed value on the power source, but the real voltage over the arc can deviate due to voltage drop over the hose or the electrode extension. The QSet™ function is monitoring the amount of time the arc is short-circuited. The system is regulated through voltage control so that the amount of short-circuited time is optimized, (Weman, Karlebo Svetshandbok, 2013). The QSet™ function is adjusting the short-circuit time to be approximately 21% of the cycle for optimal performance. A power source that has QSet™ is very easy to manage due to the automatic voltage control. All the welder needs to do is select a wire feed speed and QSet™ will automatically set suitable welding parameters for the given gas/wire combination. A short circuit sequence is illustrated in four steps in *Figure 3*.

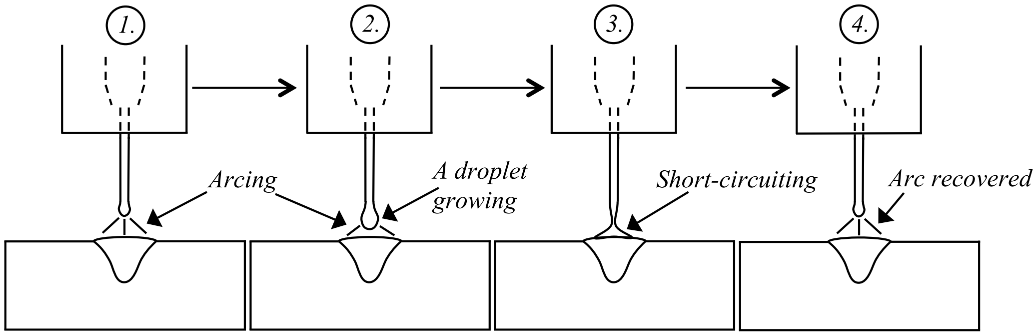

Figure 3 - Illustration over the short-circuiting sequence during welding.

Figure 4 shows an example of how the voltage and current curve looks like for a typical short-circuiting welding process. The current and voltage at each of the four short-circuiting steps is marked in the figure. Step 1 shows an arc that correlates to a high voltage with the air gap that hinders the current to flow. Step 2, a droplet grows due to the heat created by the resistivity. Step 3, the droplet reaches the work piece and metal is overlapping the air gap that creates short-circuiting. The resistivity is decreased and current can now flow more easily. The droplet surface tension drags the droplet down into the melt pool and the air gap is restored. Step 4, the arc is recovered and the pattern is repeating itself.

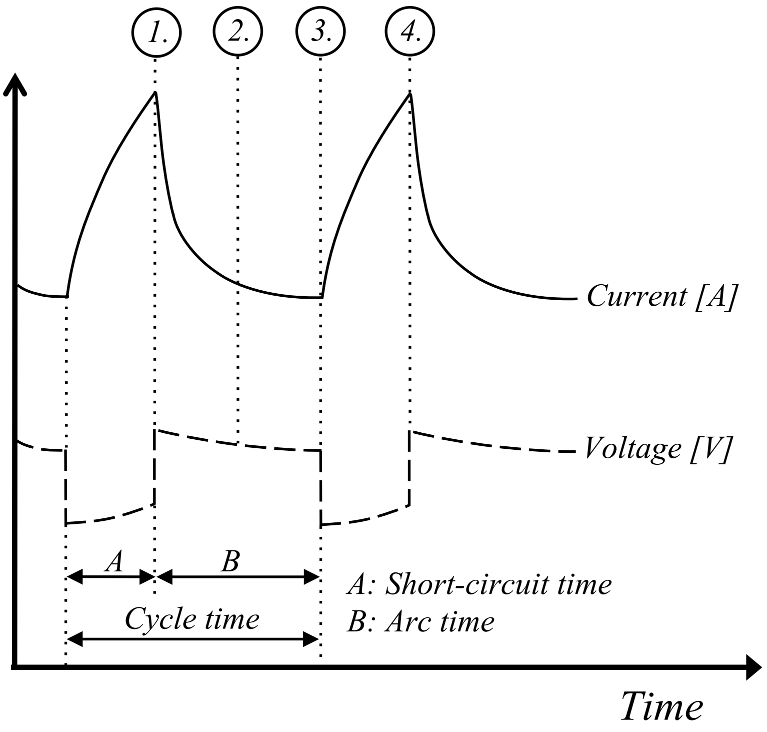

Figure 4 - I/U-characteristics for a short-circuit process

The Feeder has a direct influence on the quality of the weld. With an unstable feeder the speed of the wire will deviate from its stated value, which can lead to a bad weld quality. The feeding system is either a “push” or a “push-pull” system. The main difference between these two systems is that the “push-pull” system has an additional feeder in the welding gun, besides the regular one located close to the power source. This system is commonly used when welding with soft materials such as aluminium or when the hose is unusually long, (Weman K., 2006).

The gas supply system provides the welding gun with shielding gas that protects the weld and the arc from the atmosphere. The gas is provided either through a gas tube or by a central gas system, depending of what is available. A regulator is placed between the gas source and the weld gun to adjust the gas pressure and flow. At the weld gun where the gas flows, a gas nozzle is mounted. The nozzles size and shape also affect the flow.

The electrode nozzle is exposed to a lot of wear and needs therefore be changed regularly. The wire wears it down due to small arcs at the contact points in the nozzle and because the wire is bent. There are three main contact points in a normal nozzle and these are illustrated in *Figure 5*. The bent wire also affects the aim of the electrode and can be fixed by using specialised nozzles that straightening the wire. These nozzles are expensive and are not commonly used.

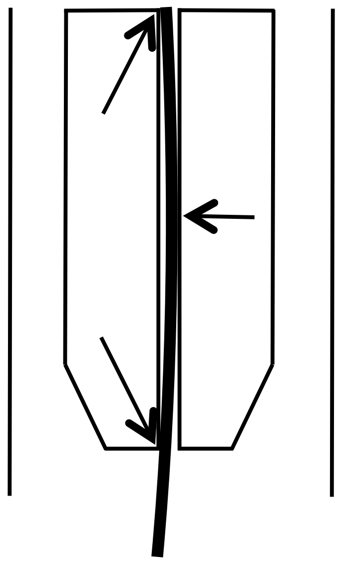

Figure 5 - Contact points in electrode nozzle

2.1.2 Consumables

There are two main types of consumables for GMAW, solid wires and cored wires. The cored wires are either filled with metal powder (MCAW, Metal Cored Arc Welding) or flux powder (FCAW, Flux Cored Arc Welding). The powder can be used to control the welding and material properties. Deoxidizing components such as manganese and silicon can be used to refine the weld. Additives can also stabilize the arc or create a protective layer of slag. When using a wire filled with flux that creates a slag layer the need of shielding gas is decreased. Some wires can be used without any shielding gas. Adding small amounts of additives to the powder mixture, e.g. Ni, Cr, Mn or Mo, can alloy the weld metal and enhance the mechanical properties. If productivity is of essence then it is common to add metal powder, MCAW, that increases the productivity significantly, (Weman, Karlebo Svetshandbok, 2013).

The electrode dimension is selected depending on the current range to be used for a given application. Typical wire diameters are 0.9 – 1.6 mm and the current ranges from 60 - 475 A. A larger electrode requires a higher minimum current than a smaller electrode for the same metal transfer characteristics. The smaller wire diameters use less current than the thicker wires which creates a smaller weld pool. This is commonly used in thin materials and in out-of-position welding. Larger electrodes that require higher currents are generally preferred for application where high deposition rate and deep penetration is of essence, (ASM International, 2011).

2.1.3 Shielding gases

GMAW is also called MIG/MAG that is short for Metal Inert/Active Gas, respectively. This implies that either an inert or active gas is used to shield the arc and weld pool. The shielding gas is crucial and affects the welding environment, the appearance of the weld surface, the weld metal microstructure, mechanical properties, weld geometry, material transfer and arc stability, (Suban M., 2001). To obtain a shielding gas that is suitable for a specific application, a mix of gases is generally needed. Each gas contributes with certain characteristics to the performance of the overall mixture. Some of the gases have relatively specific areas of application and are only used in a limited operation range; others can be used on many materials under a variety of welding conditions, (ASM International, 2011).

Argon is an inert gas, which does not react with the materials present in the welding electrode. The density of the shielding gas has an important influence of the shielding efficiency. It is of primary importance that the shielding gas has a high relative density compared to air for good shielding properties, (Suban M., 2001). Argon has a high relative density, which makes it suitable as a shielding gas. The properties of the electric arc, mainly ignition and arc stability, are strongly affected by the dissociation and ionization processes in the gas atmosphere. With its low ionization potential, argon promotes easy starting and a stable arc, (ASM International, 2011). The low ionization potential contributes to low heat transfer to the base material. This results in a thin penetration that easily misses the root, also called "argon finger". Pure argon is not favourable because of disturbances in the weld arc, resulting in an irregular weld pool formation, (Lancaster, 1999). The arc has an anode and cathode spot. During DC+ welding, which is the most common electric polarity used for GMAW, the anode is located at the electrode and cathode at the work piece. Movement in the cathode spot, especially at spray metal transfer mode, causes arc disturbances. Metal transfer modes will be discussed in the next section. By adding small amounts of oxidizing gas mixtures the movement of the cathode spot can be hindered, (Weman, Karlebo Svetshandbok, 2013).

Helium is another inert gas that is commonly used as a shielding gas. Unlike argon helium is lighter than air and ten times lighter than argon, (ASM International, 2011). When using a lighter shielding gas it is necessary to increase the gas flow to get the same shielding properties. This is a drawback due to the increased usage of shielding gas. Helium is also chemically inert and does not react with other elements. Because of its high thermal conductivity and high ionization potential, more heat can be transferred to the base material. Helium produces an intense and more contracted arc with a smaller cathode spot. The intense and contracted helium arc therefore results in greater penetration, mainly wider and not deeper, than for the argon shielding gas, (Jönsson P.G., 1995). The cost for helium is higher than for argon, which is a commercial disadvantage. Helium is therefore frequently combined with argon or argon mixtures to enhance the overall performance of the blend while minimize the cost, (ASM International, 2011).

Oxygen is a reactive gas and is often added in small amounts to some inert mixtures to improve the stability of the arc and also increase the fluidity of the melted metal. In the spray transfer mode oxygen reduces the spatter that may occur. The droplet size decreases and the number of drops per unit time increased as oxygen is added to the mixture, (ASM International, 2011).

Carbon dioxide is also a reactive gas that is added to argon blends to improve arc stability. A high thermal conductivity transfers more heat to the base material, which results in better penetration of the weld, (ASM International, 2011). Mixtures of argon with carbon dioxide or oxygen are used because a low amount of oxidizing gases is favourable to get low spatter, (Weman K., 2006). The process parameters are easier to control with an argon mixture than with pure carbon dioxide, typically up to 25% carbon dioxide is used. The heat input used is an important parameter when choosing amount of oxidizing gas. At high currents and voltages low amount of oxidizing gas is recommended or else the drop transfer will be irregular and a lot of spatter is emitted. A spray arc mode is not achieved in pure carbon dioxide. A high amount of oxidizing gas will get a wider and more penetrating weld with low amount of porosity. The lack of fusion is also lower with carbon dioxide due to the better heat transfer to the base material, (Weman K., 2006).

Small additions of nitrogen monoxide are often added to decrease the ozone level for health aspects. An example is Mison® 2, which is a commercial product and sales name from AGA. This gas contains 2% carbon dioxide, 0.03% nitrogen monoxide and is balanced with argon. Ozone is harmful even in very small dozes and by using Mison® gas the risk for exposure is minimized, (AGA, 2012).

Shielding gases are standardized according to EN ISO 14175:2008, which divide all shielding gases into groups depending on composition levels.

One aspect that also needs to be taken into account when choosing shielding gas is what kind of base material that is used. If the base material for example is stainless steel then oxidization is unwanted. Pure argon is not favourable due to the moveable cathode spot and it is therefore necessary to add small amounts of either oxygen or carbon dioxide, 2-3%. Carbon dioxide is better since the oxidization is lower, (Weman K., 2006). Oxidation might not be a problem for plain carbon steel and therefore, a mixture of typically 10-20% carbon dioxide with argon as balancing component is used due to lower price.

2.1.4 Modes of metal transfer

The electrode is continuously fed into the melt to maintain a constant arc length. In which way the metal is transferred from the end of the electrode to the work piece has considerable effect on the weld characteristics. These different ways of metal transfers are typically divided into three groups, or modes; Short-circuiting, globular and spray transfer, (ASM International, 2011). The mode that is obtained depends on several factors such as; shielding gas, current and voltage level. *Figure 6* shows the relationship between voltage and current levels and the different natural metal transfer modes, (Weman, Karlebo Svetshandbok, 2013).

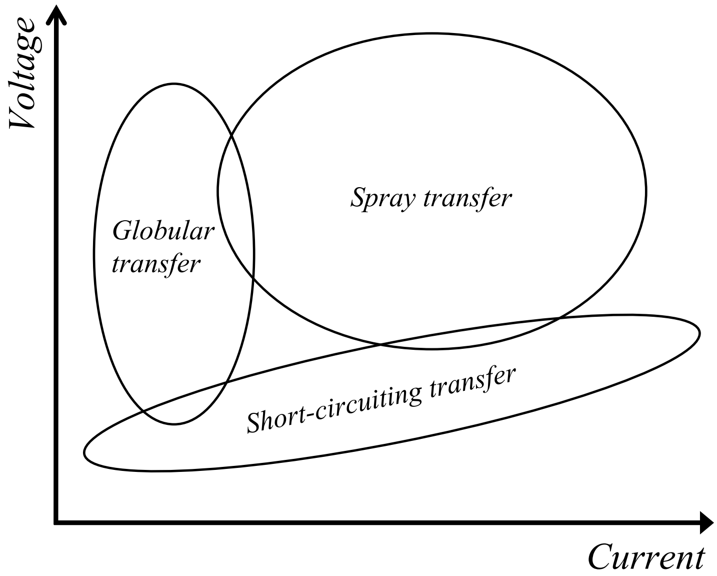

Figure 6 - Schematic map of the natural metal transfer modes

Spray and globular transfer mode is grouped as free-flight transfer due to the transfer characteristic while short-circuiting transfer is of the contact transfer type. If the three natural metal transfer modes are further analysed in a high-speed camera it will be seen that they can be divided into more specific groups, (Américo Scotti, 2012). The spray mode can be divided into three main sub-modes; projected spray, streaming spray and rotating spray. There is another spray mode called explosive and a globular mode called repelled globular, these are governed by choice of shielding gas and filler wire and are not seen as typical modes. The three main spray modes; projected spray, streaming spray and rotating spray are depending on voltage and current settings, as can be seen in *Figure 7*. An increase in voltage and current leads to a greater heat input that results in an increasing transfer rate with a decreasing droplet diameter, (Quintino, 2008). This is the main change when going from projected spray to streaming spray. When reaching very high voltage and current levels, that is required for rotating spray, the magnetic field starts to interfere with the metal transfer and displaces it from its straight line of flow and causes the rotation of the arc, (Américo Scotti, 2012).

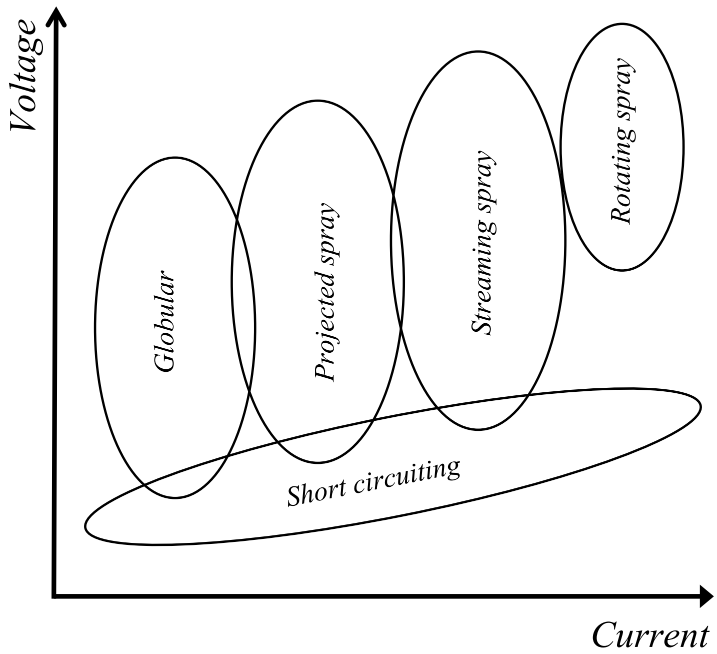

Figure 7 - Schematic map of the expanded spray modes

There are electromagnetic forces and plasma currents interfering with the different transfer modes. A combination of current and magnetic fields creates forces that act towards the centre of the wire. If the arc is narrow and has a small anode area, a force that is targeted upwards is created. This is common when using low currents. The force will make it possible for the drops to grow. The opposite relationship applies when welding with high current and voltage. The current intensity is higher at the tip of the electrode than at the work piece. This creates a pressure difference, which is called arc pressure. The arc pressure generates a plasma-current that forms a crater in the weld pool, (Weman, Karlebo Svetshandbok, 2013). The arc pressure is the dominant force when a spray arc is established. For the globular transfer mode the dominant force is the gravity. At short-circuit transfer the surface tension is more important, (Quintino, 2008).

In the 1980s during developments of new high production GMAW welding processes specialized arc modes where in focus. The special arc modes focused on were moderated spray, rotating spray and forced short arc, also called rapid arc. Mutual to all three is the usage of high wire feed speed and the potential to increase the deposition rate. The forced short arc is achieved by using a low voltage in combination with high wire feed speed that results in increased penetration. Moderated spray and rotation spray is commonly used with specialised gas mixtures to stabilize the arc, (Weman K., 2006).

2.1.5 Process parameters

The welding process is controlled by process parameters, which is tuned relatively to each other to achieve wanted weld quality. Some parameters interact with others when tuned, e.g. a change in wire feed speed or electrode extension will immediately change the current, which influences quality and geometry of the weld. To understand what effect the parameters have on the welding process, it is important to know the correlation between them. All the identified process parameters for GMAW are stated and described below.

Current is a parameter that has a high influence on the welding process. But a typical power source has a self-regulated arc-length that uses the current as a regulator. This makes it impossible to choose a specific current. The current is changed by changing other parameters, such as voltage, wire feed, wire diameter or electrode extension, and is therefore interdependent. The current has a direct influence on the weld penetration, the fusion characteristics, the weld shape and the metal transfer mode, (ASM International, 2011). The relationship between the current and weld shape is illustrated in *Figure 8*.

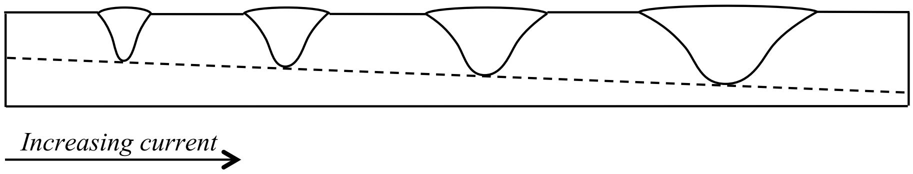

Figure 8 - Relationship between current and weld shape

Voltage and arc length are strongly connected. An increase in voltage correlates to an increase in arc length, which is the typical way to regulate the arc length. There are a number of other factors that affect the arc length as well, such as shielding gas and current. The current is regulated by wire feed and electrode extension. Voltage is one of the parameters that the welder can change during the welding process, (ASM International, 2011). When using lower voltage, the weld bead tends to be narrow with a high crown compared to a wider and flatter weld when using high voltage. The relationship between voltage level and weld shape is illustrated in *Figure 9*. If the voltage is too high or low during welding the arc will become unstable with a poor quality as a consequence. To high voltage may lead to a major increase in arc length, unstable arc, while a to low voltage may lead to a very short arc length that have problem to ignite, (ASM International, 2011).

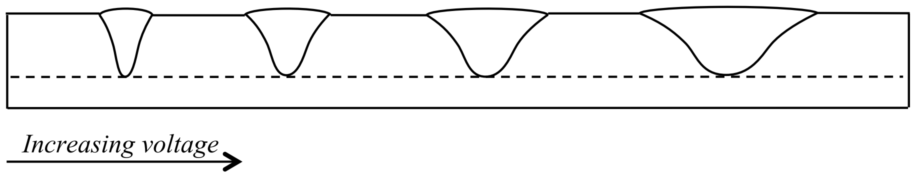

Figure 9 - Relationship between voltage levels and weld shapes

Wire feed speed, together with voltage and current, is one of the three main parameters that is used to tune the welding process and is monitored by the welding equipment for MIG/MAG welding. The continuous wire feed in the MIG/MAG process makes the welding equipment more complex, less portable and more vulnerable and therefore requires more maintenance, (ASM International, 2011). It's important to have a constant and smooth wire feed to obtain a stable arc and a weld with a uniform quality and geometry, (KOBE STEEL, LTD., 2011). As stated in the section *Current* above, the current is regulated by other parameters, such as wire feed speed for example. An increase in wire feed speed is directly related to an increase in current and a greater penetration, especially during lower wire feeds when the ratio of wire feed speed to current is linear, (Hoffman, Dahle, & Fisher, 2011). For higher feeding rates there is a chance that the ratio wire feed speed to current is increased, which causes an increase in deposition rate and a decelerating increase in penetration. This is due to the drop in current per unit volume in the welding process, (Duane K. Miller, 1997). The relationship between the wire feed speed and current is illustrated in *Figure 10*. Parameters such as wire diameter, shielding gas and electrode extension may affect and change the curve and are therefore held constant.

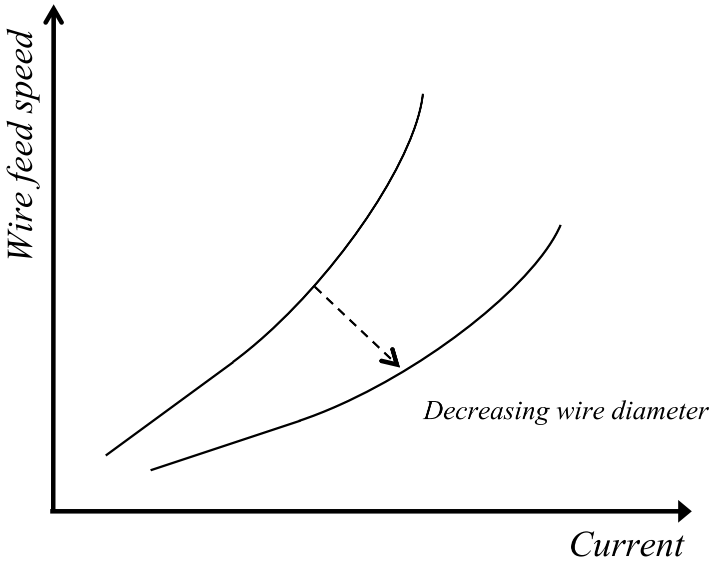

Figure 10 - Relationship between wire feed speed and current

Travel speed is one of the parameters that are controlled by the welder, assumed manual welding, and describes how fast the arc moves in relation to the work piece. The speed of the arc influences the efficiency of the heat transfer from the arc to the base-material. If the travel speed is too slow, the weld pool will flow ahead of the arc so that the arc heats the weld pool instead of the base-material. This results in a reduced penetration of the weld and a wide weld bead, (ASM International, 2011). The relationship between travel speed and bead width is shown in *Figure 11*.

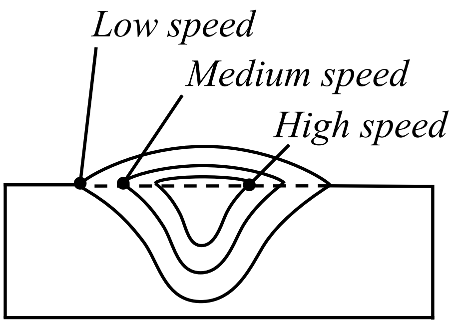

Figure 11 - Relationship between travel speed and bead geometry

A reduction in penetration can also be seen if the travel speed is very high, because the base-material does not have enough time to absorb the heat. A high travel speed increases the risk for undercutting, lack of fusion, pores and the weld bead becomes narrow, (Weman, Karlebo

Svetshandbok, 2013). The placement of the point of energy affects both heat transfer and penetration. Penetration and heat transfer is highest when the point is at the leading edge of the weld pool, (ASM International, 2011). Selecting suitable travel speed optimizes the placement of the point, assuming no changes in other process parameters such as voltage or wire feed speed. An illustration of this feature is shown in *Figure 12*.

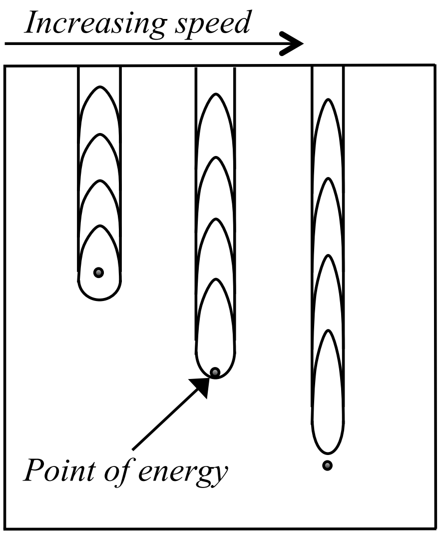

Figure 12 - Relationship between travel speed and energy point

The size and feed of the consumable are important for the welding process. They decide the deposition rate and together with the travel speed the dimension of the weld can be estimated. If the wire diameter and the wanted weld dimensions are known the wire feed speed indirectly sets the travel speed. A higher wire speed will correlate to a higher travel speed defined with *Equation 1* below where; v is the travel speed, WFS is the wire feed speed, A_{wire} is the area of the wire and A_{bead} is the area of the weld bead profile.

$$v = \frac{WFS * A_{wire}}{A_{bead}} \quad (Equation\ 1)$$

Travel angle is the parameter that describes the orientation of the weld gun in relation to the welding direction. The travel angles are divided into two groups; drag angle and push angle, illustration in *Figure 13*. When welding with a drag angle one reaches the best penetration of the weld and the bead becomes narrow with a convex surface. The push angle provides a wider weld bead width, a flatter surface and a better visibility for the welder, (ASM International, 2011). Push angle, within the range of 5 to 15°, is the most common travel angle. Mainly due to the better visibility for the welder, but it also allows higher travel speeds during welding, (Weman K., 2006). *Figure 13* shows an illustration of how the travel angle affects the bead shape.

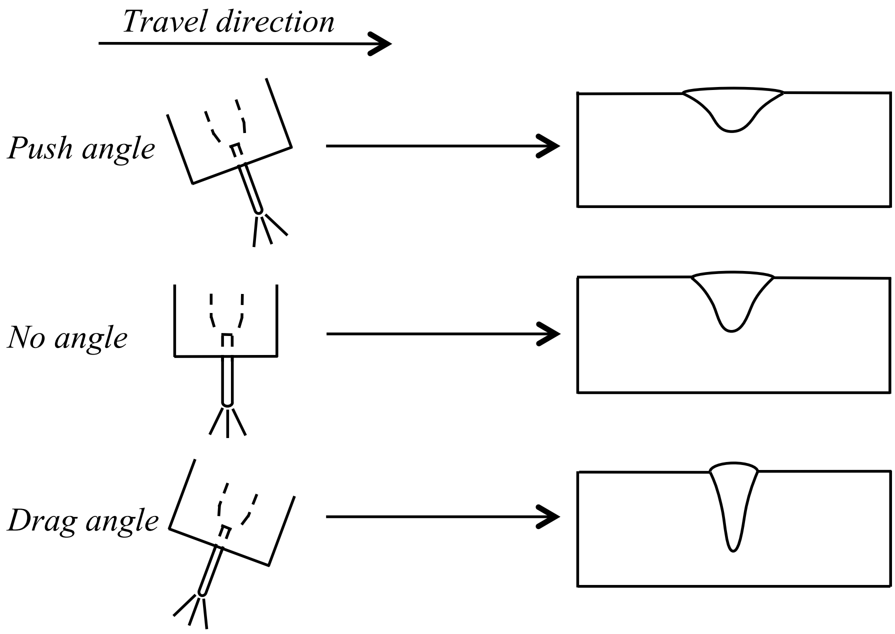

Figure 13 - Relationship between travel angles and weld shape

Electrode extension is the distance between the weld gun and the weld arc; this is illustrated in *Figure 14*. By increasing the electrode extension the electrical resistive heating in the electrode will increase while the current decreases. This makes it possible to maintain a constant melting rate, (Weman, Karlebo Svetshandbok, 2013). The drop in current decreases the heat input and results in a reduced penetration and produces a narrow crowned weld bead. By increasing the travel speed when increasing the electrode extension the current can be held at a constant level. Depending on the metal transfer mode, different electrode extensions are required to obtain an optimum welding condition, generally in the range of 6 to 13 mm for short-circuiting and 13 to 25 mm for spray, (ASM International, 2011). The electrode extension is a variable that is hard to control during the welding process. This is due to sudden changes in arc length and difficulties in measuring the arc length. The stick-out, which is the total length of the electrode extension and the arc length, is a parameter that is much easier to control due to independency of the uncontrolled arc length, and is therefore widely used by welders. *Figure 14* illustrates the correlation between stick-out, electrode extension and arc length.

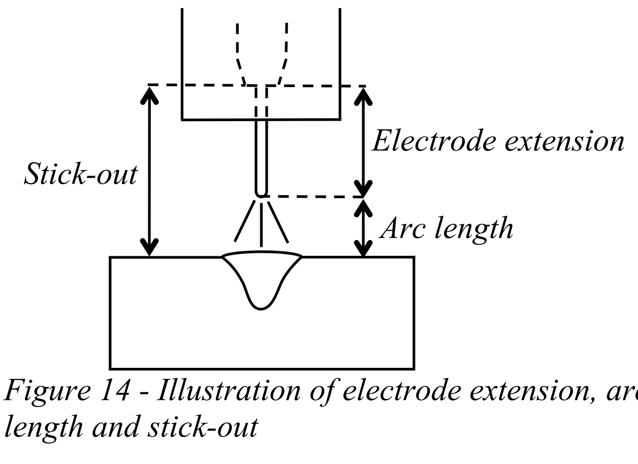

Figure 14 - Illustration of electrode extension, arc length and stick-out

Inductance is a parameter that can tune the welding process when other parameters, such as voltage, wire feed and wire diameter, are set. When a low inductance is used, the arc becomes sharp and concentrated but will also allow the current to increase rapidly after short circuit and may result in a higher spatter level. With increasing inductance the welding process feels smoother and the weld bead flows out more easily. If the inductance is set on a to high level the short circuit frequency is reduced, the arc becomes unstable and the start of the welding process can be a bit choppy, (Weman, Karlebo Svetshandbok, 2013).

Shielding gas flow is selected dependent on material and metal transfer. For example, welding in aluminium requires a slightly higher gas flow than for steel. With increasing process parameters, such as voltage and wire feed, the optimized gas flow rate is increased, (Weman, Karlebo Svetshandbok, 2013). Other important factors are the density of the shielding gas, size of the nozzle, the distance between nozzle and work piece, joint type and position and velocity of surrounding air. A typical gas flow for argon-based mixtures in short-circuiting arc welding is 10-15 l/min and for spray arc welding 15-25 l/min. If the nozzle size or distance to the work piece is increased then the gas flow also needs to be increased, (Weman K., 2006).

Electric polarity defines which way in the closed circuit the electricity flows. Depending on the polarity the anode, which has the greatest heat evolution due to the net flow of electrons from the cathode to the anode, (Weman, Karlebo Svetshandbok, 2013), will either be on the electrode or on the base-material. For GMAW it is most common to have the weld gun connected to the positive terminal, so that the anode is located on the electrode. This provides the welding process with a more stable arc, improved metal transfer, lower spatter level, improved bead geometry and better penetration, (ASM International, 2011). AC/DC is used for welding in aluminium and is not commonly used for GMAW of steel. The relationship between polarities and weld shape is illustrated in *Figure 15*.

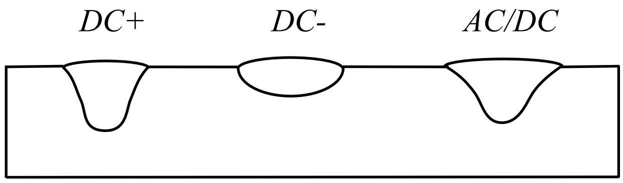

Figure 15 - Relationship between polarities and weld shape

Welding position is an important factor that affects the choice of process parameters. The welding positions are divided into seven groups that are illustrated in *Figure 16*. The names of the groups are different depending on which standard that is used. In the AWS standards they are termed with a number (1-6) and a letter for joint type: F for fillet weld and B for butt weld. ISO standards are using a two-letter composition, PA to PG, which only describe the position. There are also specific standards for special applications e.g. tube welding, (Weman, Karlebo Svetshandbok, 2013).

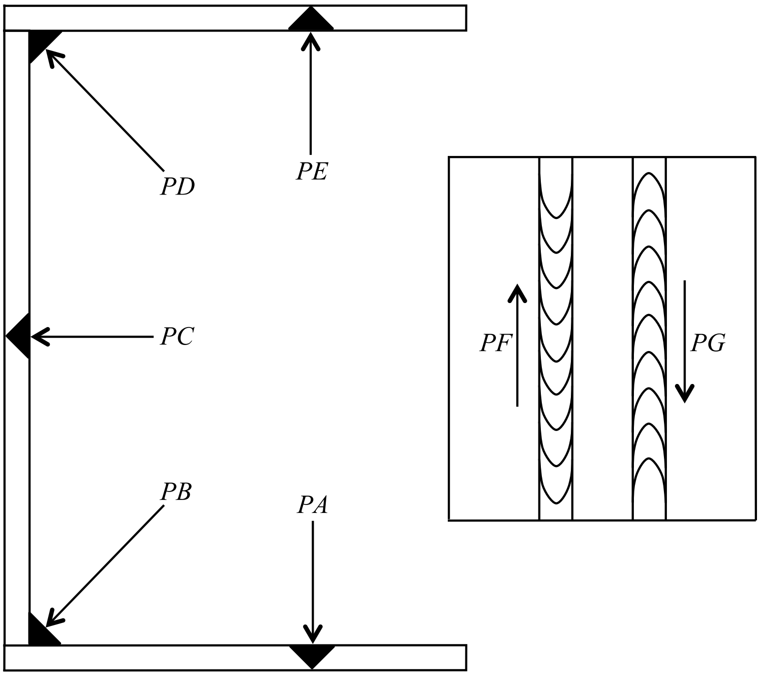

Figure 16 - Welding positions according to EN-ISO 6947

Work angle is defined as the relative angle between the weld gun and the joint. If welding in thick plates in PB position it is important to have the correct work angle and aim. The general recommended setup for fillet welds is a work angle of 45 degrees and an aim of the electrode 1-2 mm away from the joint if one of the plates have two cooling paths, as illustrated in *Figure 17*. The offset of the aim produces a more even penetration between the two plates due to a better distribution of heat among the plates. The work angle can be adjusted dependent on the consumable. A consumable with a high wetting that makes the melt sink down upon cooling may need a smaller work angle that pushes the melt upwards the vertical plate to be able to generate a homogenous weld bead geometry, (Weman, Karlebo Svetshandbok, 2013).

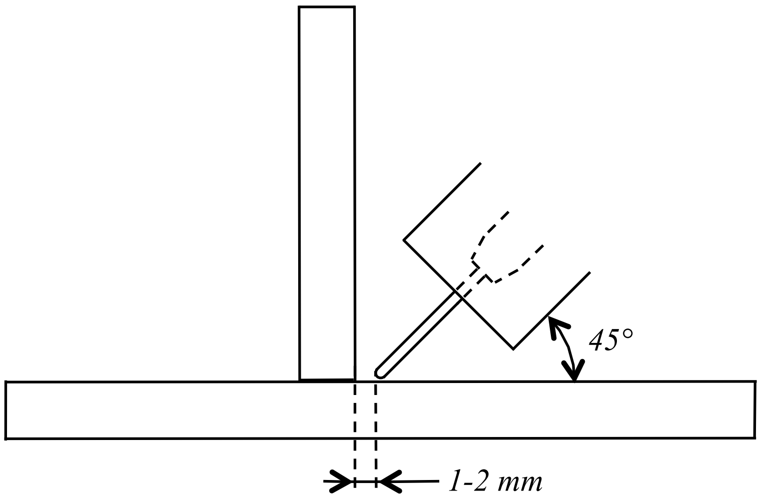

Figure 17 - Illustration of recommended work angle and aim point

2.1.6 Heat input

Heat input is the amount of energy supplied to the weld during the welding process per length unit. This energy can be calculated using *Equation 2*, where Q is the heat input, U is voltage, I is current, v is travel speed and k is the thermal efficiency of the process.

$$Q = \frac{U * I}{v} * k \left[\frac{KJ}{mm}\right] \quad (Equation\ 2)$$

For MIG/MAG welding the heat input, Q, is typically in between 0.8-3 KJ/mm, (Hannerz, 2002) and the thermal efficiency, k, is typically set to 0.8, (Weman, Karlebo Svetshandbok, 2013). It is good to know that the thermal efficiency is not a constant and can vary between 0.60-0.85 for MIG/MAG welding, (Hannerz, 2002).

The heat input is affecting the bead width, penetration depth, HAZ (heat affected zone) width, cooling rate and dilution rate, (PANDEY, 2013). A low heat input will result in a high cooling rate that increase the risk for hydrogen cracking due to the fact that the hydrogen gets shorter time to diffuse out from the work piece. High cooling rates also decrease the bead width, penetration depth, HAZ and dilution. Vice versa will a high heat input result in a low cooling rate, which increase the bead width, penetration, HAZ and dilution. The cooling rate are also affected by the thickness of the work piece, a large volume of material absorbs heat faster i.e. higher cooling rate. Fast cooling can lead to hot cracking if the material has a high hardenability. The carbon equivalent, CE, is an empirical value of how easy the material transforms into martensite. Different formulas are used to calculate the CE depending on the chemical composition, (Weman, Karlebo Svetshandbok, 2013). The CE can be calculated according to SS-EN-1011-2 Annex C (Method A) if the material is low alloyed steel, typical construction steel, by *Equation 3*.

$$CE = C + \frac{Mn}{6} + \frac{Cr + Mo + V}{5} + \frac{Ni + Cu}{15} [\%] \quad (Equation\ 3)$$

If CE is between 0.3 - 0.7, SS-EN-1011-2 Annex C (Method A) can be used to calculate if preheating is necessary. Hot cracking and hydrogen cracking can be avoided by using preheating. The elevated temperature decreases the cooling rate. The HAZ are increased with an increased heat input. A high heat input leads to grain growth that result in a low toughness, (Weman, Karlebo Svetshandbok, 2013). The most common way of measure cooling characteristics is to measure or calculate $\Delta t_{8/5}$, which is the time of cooling from 800°C to 500°C. The value of $\Delta t_{8/5}$ should typically be in the range of 3-20s to avoid martensite and grain growth for low alloyed steel, (Hannerz, 2002).

2.2 Experimental phase

The second step in the methodology is the experimental phase. It includes a definition on how the experiment is performed, which equipment that is used and how the results could be evaluated.

2.2.1 Experimental definition

The work has been divided into two separate experiments. Experiment 1 investigates the correlation between the process parameters and the current and voltage characteristics, while experiment 2 will demonstrate the efficiency with using automated welding for acquiring large data sets of quantified data regarding weld bead geometry. The procedure for the two experiments will be carried out in the same manner with the same consumable, base material, shielding gas, power source, logging equipment and welding robot. An austenitic stainless steel consumable, OK Autrod 16.95, is used due to its difficulties in reaching acceptable bead geometry. A suitable base material for this kind of a consumable and testing is regular 304L stainless steel with dimensions 200x50x10 mm. A weld length between 100 and 150 mm is assumed to be sufficiently long to achieve a stable welding process. The shielding gas that will be used for experiments is called Mison®2, which contains argon, 2% carbon dioxide and 0.03% nitrogen monoxide. The power source used has a maximum current output of 600 ampere with a high duty factor. A high duty factor makes it possible to use the maximum output over a longer time span. The sampling equipment, Vermaat Wave Viewer from Vermaat Technics, register current and voltage with a frequency of 10 kHz, a current range of 0-700 A and a voltage range of 0-60 V.

The consumable used in the project is OK Autrod 16.95 with a diameter of 1 mm, which is a corrosion resistance austenitic stainless steel with a high content of manganese. It is used in a broad field of welding applications such as for; work hardened steels, austenitic manganese steels as well as armour plate and heat resistance steels, (ESAB AB, 2003). The composition of the OK Autrod 16.95 is illustrated in *Table 2*.

Table 2 - The general composition of OK Autrod 16.95

Composition [%]	**C**	**Si**	**Mn**	**Cr**	**Ni**
OK Autrod 19.65	0.08	0.9	7.0	18.5	8

2.2.2 Experimental pre-study

The aim of the project is to investigate the welding process within a general process window for welders. It is known that the welding process can be modified and tuned by a number of process parameters, e.g. voltage, electrode extension, travel angle, etc. and that the choice of variable parameters is dependent on what is to be investigated. These two parts, the definition of the process window and the choice of process parameters, are discussed in this section starting with the process window.

The width of the process window should include both stable and unstable welding processes so that a comparison between sufficient and insufficient welds can be done. The placements of process windows for both experiments were set with help from preliminary testing using a synergy power source. The choice of gas composition, wire diameter and material type defines the synergic line, which is a function of voltage and wire feed. *Figure 18* shows the synergic line where the markers are the gathered values from the synergy power source. The sudden change in the line at wire feed 9-10 m/min corresponds to the globular transition zone where metal transfer mode goes from short circuit, at lower wire feeds, to spray mode, at higher wire feeds. The line illustrates the recommended parameter setup for a defined welding procedure, i.e. known shielding gas, wire diameter and base material, and is therefore not to be seen as the absolute optimum values for every welding scenario. It is therefore necessary to verify the estimated synergy line to see if the recommended values are performing as expected. A preliminary experiment was conducted using a setup with the same gas composition, material type and wire diameter as the final experiments. The experiment revealed that the synergic line worked as expected and that the welding process became unstable when the parameter setup deviated too much from the synergy line. The process window for the experiments where therefore designed based on the location of the synergy line to include as many interesting welding conditions as possible. How the experimental scheme is designed is illustrated and discussed in the later section about each experiment.

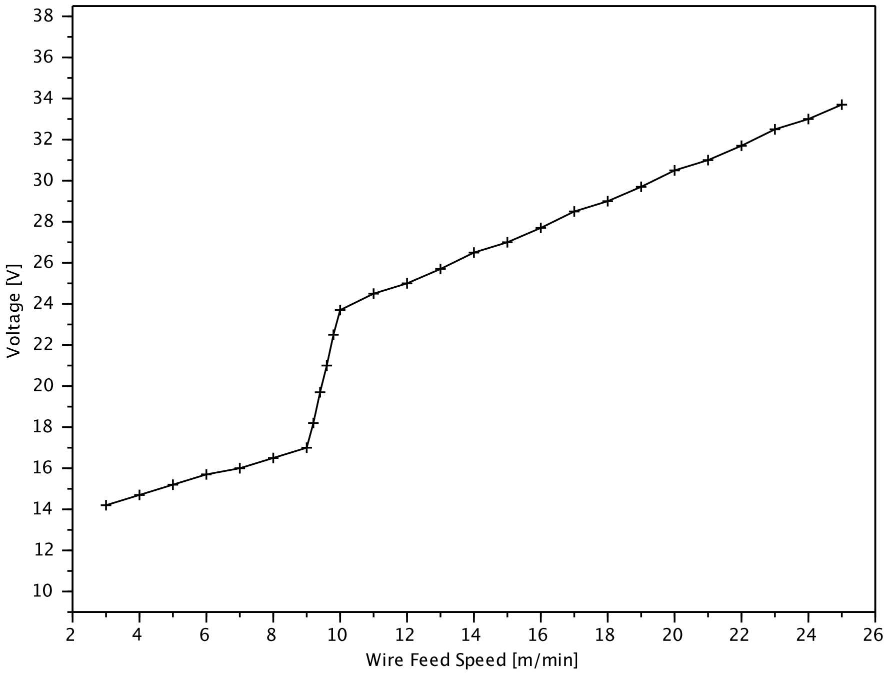

Figure 18 - Synergic line from a power source

The welding process is rather complex due to the dependence on a lot of variables that defines the process. To get a reasonable test scope with high resolution, the numbers of dependent variables for the experiment must be held on a low level. With increasing variables the number of tests will increase rapidly. Since the goal of the project was to investigate the weld bead geometry and I/U characteristics in general, the so-called process parameters were the interesting factors to take in consideration. So the variables that are connected to choice of material, weld machine and consumable are held constant through both the experiments. The identified process parameters for GMA welding, that welders normally use to monitor the process are; current, voltage, wire feed, travel speed, travel angle, work angle, stick-out, inductance, shielding gas flow and welding position. They are all described in the section 2.1.5. The process parameters influence the welding process in different ways and dependent on what to investigate different parameters may be of interest to vary, while others can be held constant. The following defined process parameters where evaluated and the following once were determined to be held constant through each experiment:

- *The welding position* was pre-determined by the choice of experimental set up, PA mode for experiment 1and PB mode for experiment 2, fillet welds.
- *The shielding gas flow* has no big influence on either weld bead geometry or I/U characteristics if a moderate gas flow is chosen. The gas flow is determined by looking at gas type, nozzle size and distance to work piece and since all of them are held constant, the gas flow was held constant as well at a level of 12 l/min.
- *The travel angel* has impact on the weld bead geometry. The most common travel angle is push angle in the range of 5-15° and within this range the impact of bead geometry is limited. These experiments are focusing on investigating typical welding setups and therefore a push angle of 10° is chosen.

- *The work angle* is dependent on factors such as welding position, travel speed and consumable. When welding in PA mode the work angle is more or less always perpendicular to the base material, but the work angle may deviate from the common angle of 45° for PB mode, dependent on the wetting of the consumable. A good wetting give rise to irregularities of the weld bead geometry, a sinking of the molten melt and can be adjusted by lowering the work angle. The work angle was held at 90° for I/U characteristic experiment and 40° for the weld bead measurement experiment.
- *The inductance* has an impact on the frequency in short circuit welding but is rarely changed in practice and is therefore held constant at 70% for both the experiments, which is a common value for the inductance.
- *The stick-out* and electrode extension is directly linked to the current. An increase in stick-out and electrode extension correlates to a decrease in current, due to that the extension works like a resistor. The resistor acts as a pre-heater for the wire, which lowers the current needed to melt the electrode. The lowered current will lead to a decrease in penetration, arc length, heat input and a narrower weld bead. The electrode extension is hard to control due to changes in arc length. To be able to control the process, the stick-out is held constant at 17 mm and the electrode extension varies with varying arc length. The difference between the stick-out and the electrode extension is illustrated in *Figure 14*.

The process parameters that are identified as the most important/interesting ones and that have the largest impact on the welding process are; voltage, current, wire feed and travel speed. In this case, when using a power source with self-regulated arc length, the current cannot be set due to the dependence on other parameters. Therefore the current cannot be varied in the experiments. In the weld bead measurement, when the weld bead geometry is to be analysed, it is convenient that all the samples have roughly the same bead area so a comparison between them can be done. The weld bead area correlates to the deposition rate per length unit, which is a function of wire feed speed and travel speed. By holding the deposition rate per length unit constant one can regulate either the wire feed speed or the travel speed, which indirectly determines the other parameter. The travel speed is an important parameter but is not regulated through the power source and is therefore decided to be the indirect parameter, just as the current. The travel speed will vary depending on the chosen bead area, wire diameter and apparent wire feed speed according to *Equation 1* in section 2.1.5. The bead area is estimated to be the throat thickness of the weld times itself; throat thickness is illustrated with notation "A" in *Figure 35* in upcoming section 2.2.4. A rule of thumb is that the throat thickness of a fillet weld should be around 50% of the thickness of the base material. Since the base material used in the experiment is 10 mm thick, the throat thickness should be roughly 5 mm. This is the value used when estimating the travel speed for the experiments. With the current and the travel speed set as indirect variables, the voltage and the wire feed are left as variables for the experiments. Variations within these two parameters will produce the sought scope with the desired resolution with arbitrarily number of samples.

2.2.3 Experiment 1 – I/U characteristic analysis

Experiment 1 is focusing on the I/U characteristics for the welding process. The aim is to define quantities that correlate the I/U characteristics to the process parameters. A secondary goal is to correlate the defined quantities to the stability and/or quality of the welding process. By collecting data from a wide process window the changes in metal transfer mode will be seen in the result as well as changes in arc stability. This investigation will give a better understanding of the cause and effect in welding and could be a future help in product development and for validation and verification of consumables. These quantities could work as subjective evaluation and a complement to the welder's objective evaluation of consumables.

EXPERIMENTAL SCHEME

The design for experiment 1, I/U characteristic analysis, consists of 101 tests points with varying voltage, wire feed speed and travel speed. The wire feed speed and the joint geometry determines the travel speed. The process window spans over a wide range of both voltages and wire feed speeds, see *Figure 19*. The wire feed speeds range from 3 to 25 m/min and the voltages from 10 to 37.5 V. With a large process window the test includes several metal transfer modes, which is schematically drawn in the figure. Short circuit mode at low wire feed speed, globular mode at the transition zone towards spray and rapid arc modes at high wire feed speed and low voltage. Rapid arc is a special type of short-circuiting due to the high wire feed speed and low voltage. Unlike normal spray the voltage is lowered, which causes a forced short arc. This is possible due to the higher current caused by the high wire feed speed.

The experimental scheme is established with help from a software program called MODDE that is based on DOE, design of experiments. The program randomizes the test order to prevent external noise from interfering with the results. In other words, MODDE makes the result statistically validated.

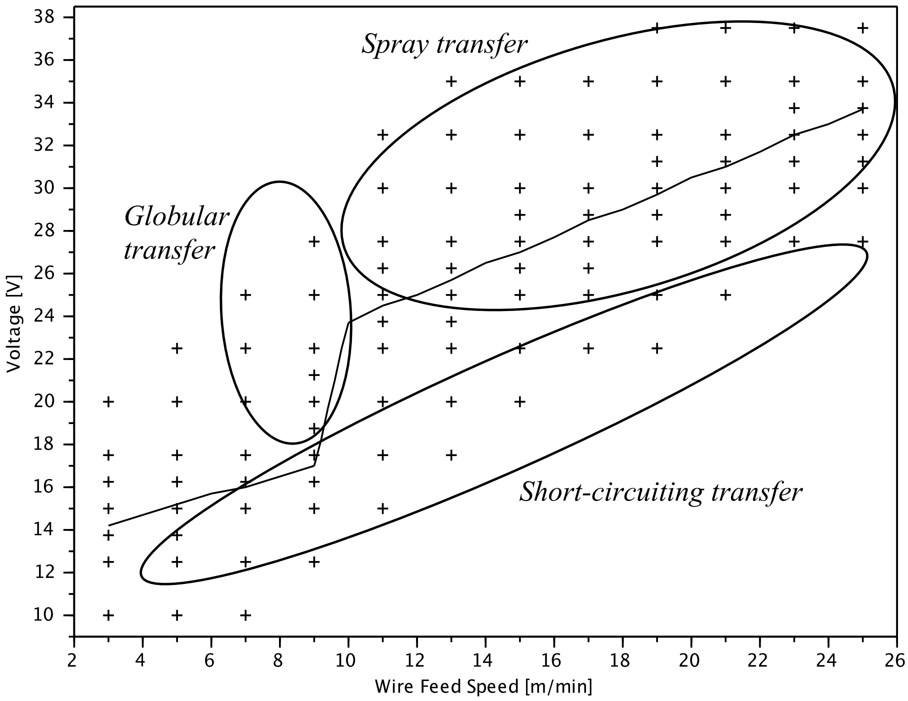

Figure 19 - Test scope for experiment 1, including a schematically placement of the general metal transfer modes

EXPERIMENTAL PROCEDURE

The procedure for experiment 1 is to weld bead on a plate in an automated welding operation, measure voltage and current, and analyse the I/U characteristics. The used equipment and variables, such as shielding gas and consumables, are stated in section 2.2.1, and is held constant for both experiments. The use of an automated welding process ensures a good repeatability and reproducibility. The welding position used during this experiment is PA on a regular plate, illustrated in *Figure 20*.

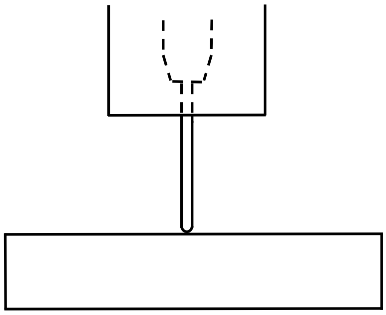

Figure 20 - Welding position, PA, for experiment 1

The following paragraphs in this subtitle describe how the voltage and current are measured and how the processing of the I/U characteristics is performed. The last part of this section is a definition of the experimental method, the Fourier transformation that is used for analysis of the I/U characteristics.

The voltage and current are measured by connecting a measurement device, I/U logger, with a high sample rate, ≈10kHz. The measured data is stored and analysed using computer software, Scilab. A measured weld sequence is shown in *Figure 21*. This sequence is welded with a wire feed speed of 19 m/min and the voltage set to 31V. This parameter setup will result in a spray mode. The spray mode is characterized by its low fluctuations in current and lack of short-circuiting during welding. The figure also shows that there is a peak at the weld start. This is caused by the power source that provides a higher current and voltage to ignite the arc. If using a very low voltage-current parameter setup, there can be a problem to get a stable arc. The power source will then try to stabilize the arc by increasing the voltage and current. The figure below shows a stable spray process.

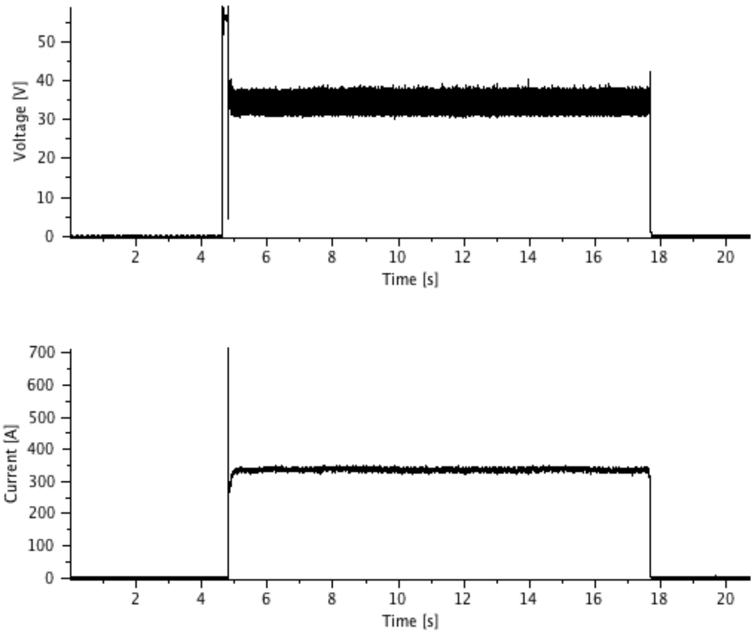

Figure 21 - An example of measured voltage (top) and current (bottom) during a welding sequence in spray mode

Another weld sequence is shown in *Figure 22* where the metal transfer mode is short-circuiting. Parameters used are 15 V and wire feed 7 m/min. The short-circuiting mode is characterized by large fluctuations in voltage and current. The voltage is very low, almost zero, when the wire is short-circuiting. This is illustrated in *Figure 4*. If comparing the spray sequence with the short-circuiting it is obvious that the spray process is more stable. It is also seen that the short-circuiting needs more help from the power source to get a stable arc.

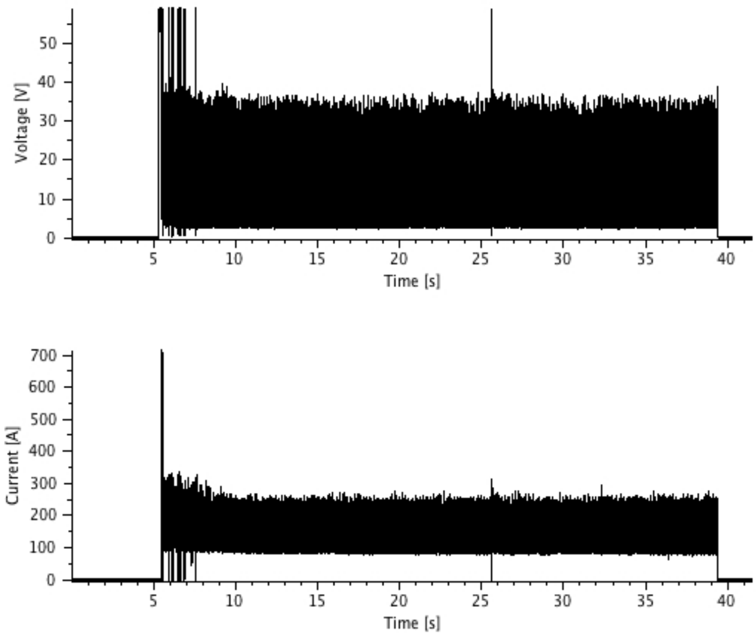

Figure 22 - An example of measured voltage (top) and current (bottom) during a welding sequence in short-circuiting mode

This information about the voltage and current can be analysed and calculations of quantifiable aspects of the weld characteristics are possible. The data logger is turned on a few seconds before the welding begins and turned off a few seconds after the welding stops. This can be seen in *Figure 21* and *Figure 22*. The voltage and current are zero when not welding. This is used to identify welding start and stop. The process is unstable at start and stop, which can be seen as large fluctuations in voltage and current. The logger has a maximum value in voltage and current that is 60 V and 700 A, respectively. Start and stop is not of importance in the data analysis and is therefore cut-off. It can be seen that it takes a few seconds for the process to stabilize and an unstable region at the end of the weld that is less than a second. These fluctuations are cut-off and the stable process is left. The stable process is to be analysed, referred to as the cut-off view. A cut-off view of the short-circuiting mode is shown in *Figure 23*.

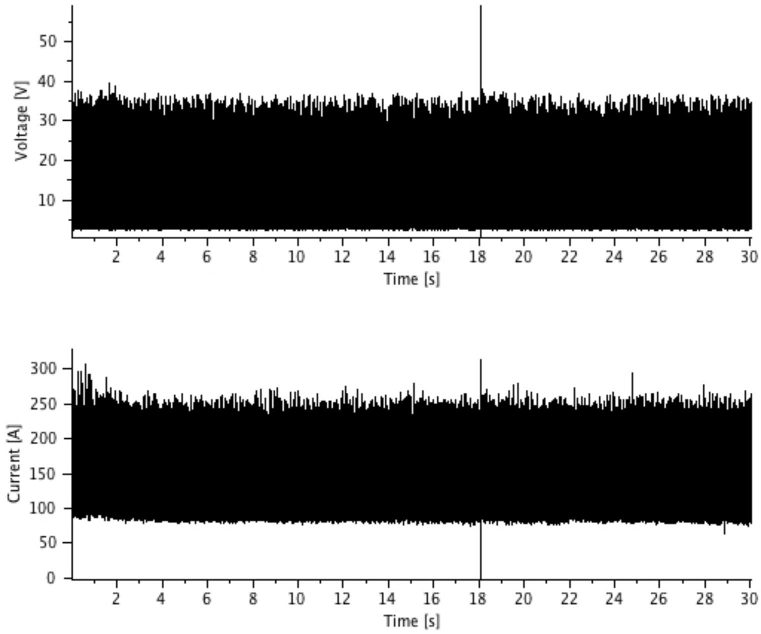

Figure 23 - An example of the cut-off view of a short-circuiting mode for voltage (top) and current (bottom)

The data from the cut-off view is used to calculate several quantities that in turn can be used to characterize the process. Obvious values such as mean voltage and mean current are calculated and compared to the set voltage value and expected current. Through voltage and current the power can be calculated, and by dividing the power with the travel speed the heat input of the process can be estimated. These two values are also analysed in the experiment.

Another variable that characterize the process is the ratio of short-circuiting, used in Qset that is described in section 2.1.1. The ratio of short-circuiting tells in percentage how much time the process spends in short-circuiting mode. This is only important for the short-circuiting metal transfer mode and will be zero for the spray mode. A zoomed in view of the cut-off view shown in *Figure 24* illustrates the short-circuiting behaviour.

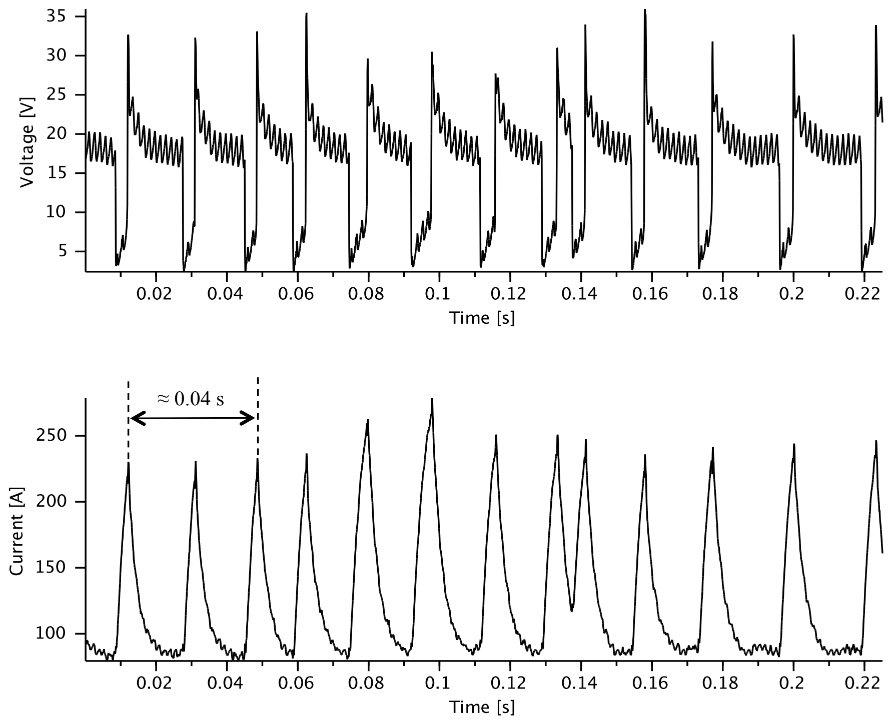

Figure 24 - An example of a zoomed view of the short-circuiting behaviour for voltage (top) and current (bottom)

The zoomed in view shows that the voltage is pending between having an arc and short-circuiting. By dividing the short-circuiting time with the total time of one period gives the short-circuiting ratio. This ratio can also be illustrated in a histogram, see *Figure 25*, where the two peaks show the difference in voltage at arc time and short-circuiting time. The data is divided into 150 segments in the histograms. The short-circuiting results in higher current levels due to lowered resistance, which is shown in the histogram for the current.

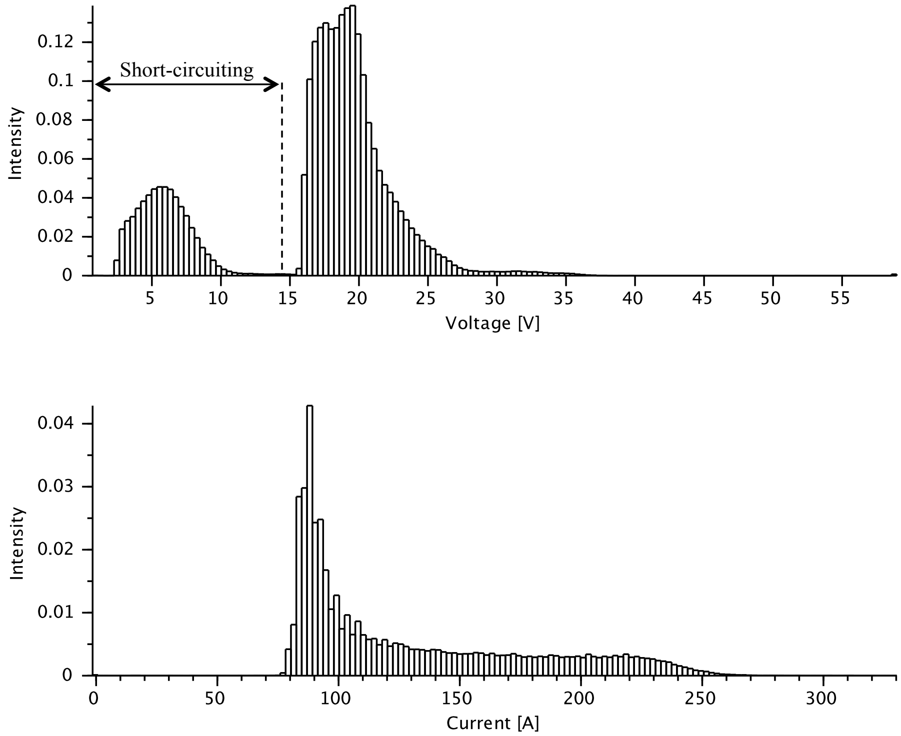

Figure 25 - An example of a histogram for the voltage (top) and current (bottom) for short-circuit transfer mode

Spray metal transfer mode, which has zero short-circuiting, have a different appearance than the short-circuiting. *Figure 26* shows a zoomed in view of the earlier shown spray mode.

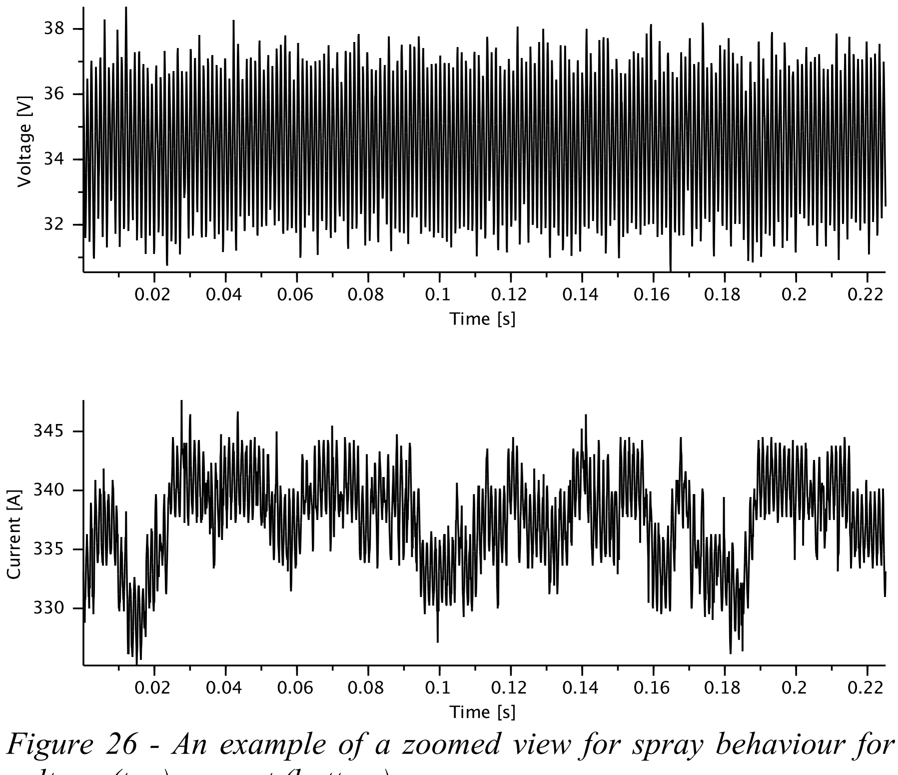

Figure 26 - An example of a zoomed view for spray behaviour for voltage (top) current (bottom)

A histogram of the spray mode is shown in *Figure 27* where the distribution of voltage and current is shown. 150 segments divide the histogram, which is the same as the short-circuiting histograms. The spray mode only has one peak in the voltage histogram due to no short-circuiting. A wave pattern is observed in the histogram for the current. This pattern is shown for every test and is a likely artefact from the power source, which explains the absence of correlation to the welding process. Further analysis of the wave pattern is therefore not of interest for the experiment.

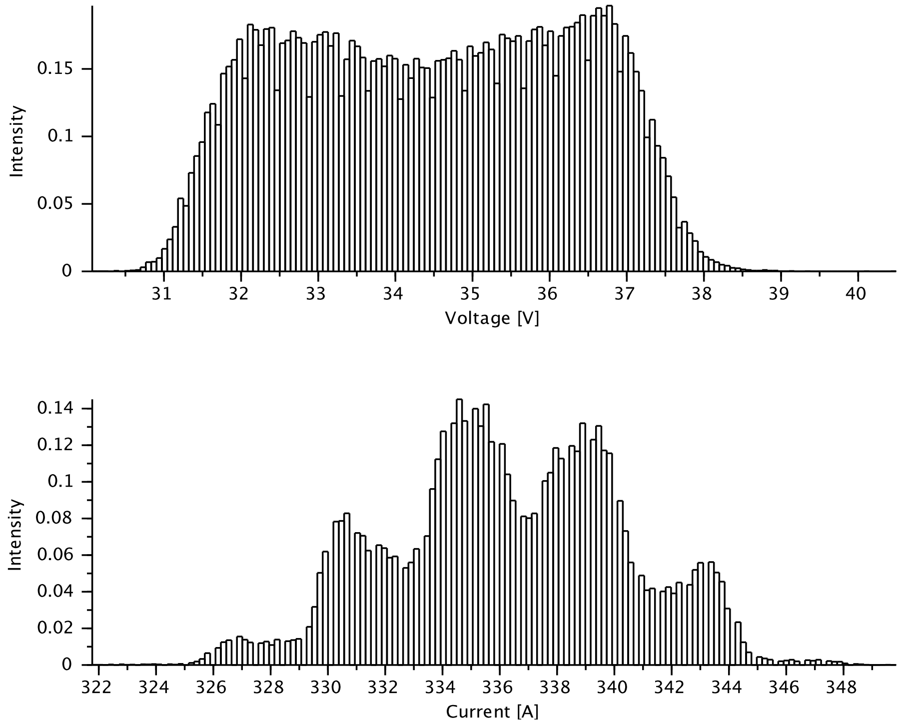

Figure 27 - An example of a histogram for the spray mode for voltage (top) and current (bottom)

To determine a quantifiable value of the stability of the process the noise levels are analysed in three different ways; mean deviation, number of peaks per second and amount of spikes. A cut-off view of the short-circuit mode is shown in *Figure 28* and the deviations and spikes is pointed out. The appearance of the cut-off view is spiky and a possible way to characterize the process is to count all peaks and divide it with the process time i.e. nr of peaks per second.

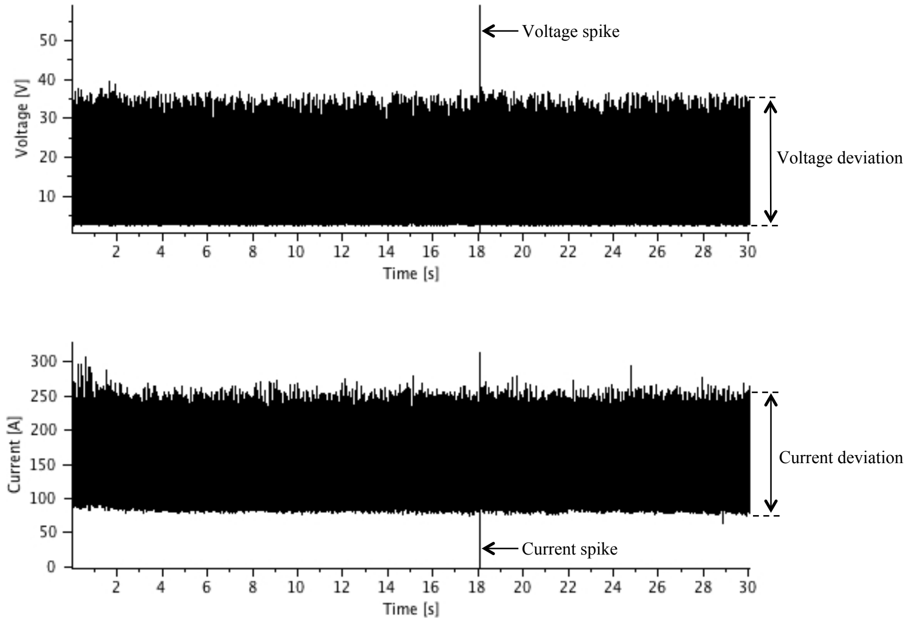

Figure 28 - An example of the cut-off view illustrating spikes and deviations for voltage (top) and current (bottom)

The amount of spikes, in percentage, is the fraction of time that the process is irregular. It can be a measurement that determines the stability of the spray or how the droplet size is varying. This can be used to characterize the process. Spikes are defined as values deviating too much from the mean value. The maximum deviation is set as a percentage of the mean value, 10% for voltage, 30% for current and 20% for power. Values above that limit are defined as spikes. To determine the deviation and amount of spikes the data is divided into small segments that are analysed. The deviation in each segment is the difference between maximum and minimum value. This is done for all segments and a mean value is calculated for each test run. *Figure 29* shows a histogram of the deviation for the spray arc. The deviation histograms are divided into 150 bins, the same as the other histograms. The mean deviation is calculated for voltage, current and power data. It can also be seen that peaks with higher difference exist. These peaks are counted and quantified as amount of spikes. The values outside the normal distribution is counted and presented as amount of spikes in percentage of weld time. The amount of spikes parameter is also calculated for voltage, current and power data. The amount of spikes is a measurement of the stability of the process.

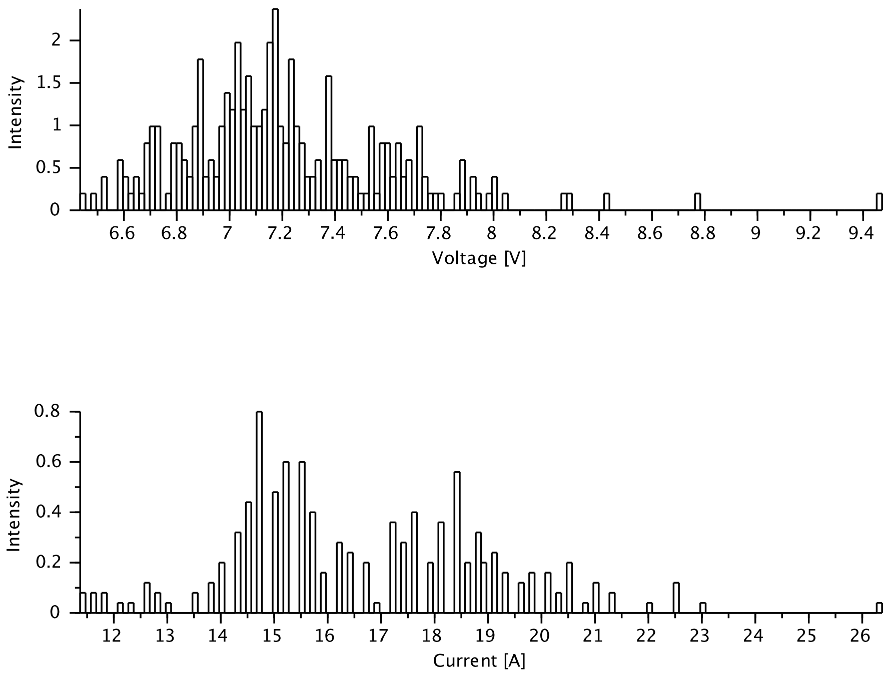

Figure 29 - An example of a histogram for the deviation in spray mode for voltage (top) and current (bottom)

EXPERIMENTAL METHODS

Fourier transformation analysis is a common method to analyse signals. It transforms the discrete values in the time plane into the frequency plane. The Fourier transformation is similar to the histogram process but is dividing the signal into different frequencies. A peak in a certain frequency responds to having a lot of reoccurring values with certain interval equivalent to the frequency.

A smoothened Fourier transformation of the voltage in short-circuiting mode is shown in *Figure 30* where it is cut-off from 1 to 900 Hz. It is smoothened in order to distinguish patterns and to take away background noise. The cut-off is necessary because the value at below one hertz is so big that the other values disappear in the figure. In the figure for the Fourier transformation of the voltage, three peaks are to be seen. Fourier transformations of the current and power give an almost identical pattern and are therefore shown in Appendix A.

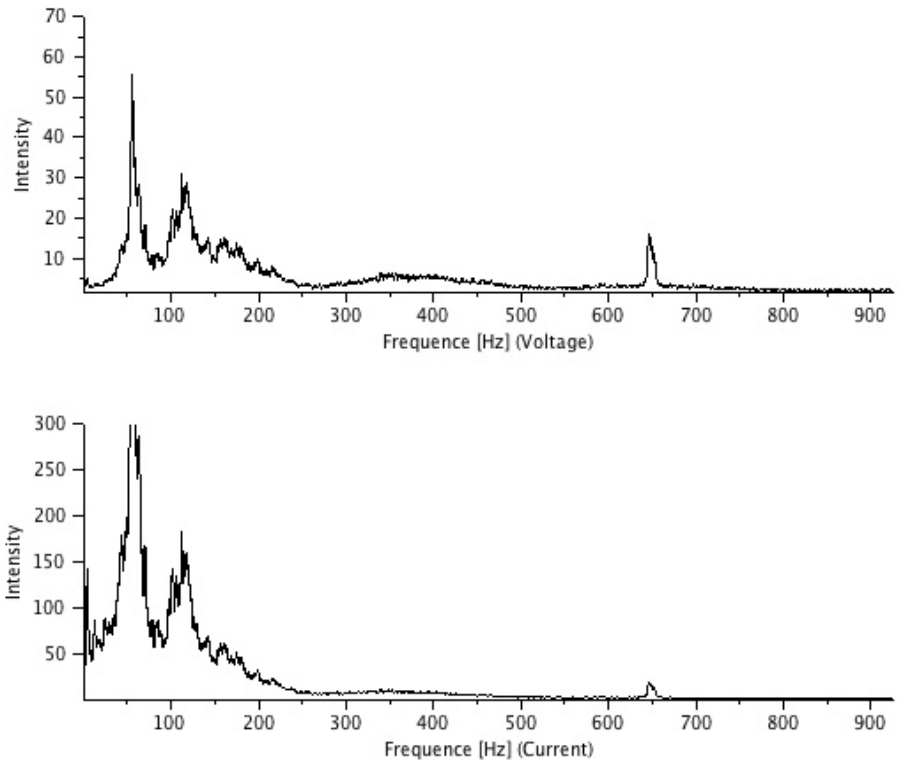

Figure 30 - An example of a smooth Fourier transformation for the voltage (top) and current (bottom)

By analysing the I/U characteristics a correlation of the peaks in the figure and the welding process can be made. *Figure 24* shows a zoomed in view of the same welding sequence that is Fourier transformed. It is known that a peak in short-circuiting is correlated to the droplet transfer, (SIEWERT, 1990). In the figure, two peaks take 0.04 seconds, this correlates to a droplet transfer rate of, 1/0.02, 50 Hz. This can be seen as a peak at 50Hz in *Figure 30*. The first peaks in the figure can be correlated to droplet transfer rate. The stability in the process can be seen in the sharpness of the first peak. A sharp peak means that the droplet transfer is very stable, while a wider peak corresponds to a more instable droplet transfer with varying frequency over time. There do not exist any peaks for spray metal transfer modes under 300Hz due to the fact that spray mode have a much higher droplet transfer rate.

There is another peak of interest, which was unexpected, located at higher frequencies. This peak is found in the range of 300 to 900 Hz for all types of metal transfer modes, which means that there is a repeating pattern at an interval of 1-3 milliseconds for all transfer modes. In the shown Fourier transformation there is a peak at 650Hz, this correlates to a repeating pattern of 1,5 milliseconds. A zoomed in view of the repeating pattern within the 1-3 millisecond interval can be seen *Figure 31*. The position in Hz and intensity may be used to characterize the process.

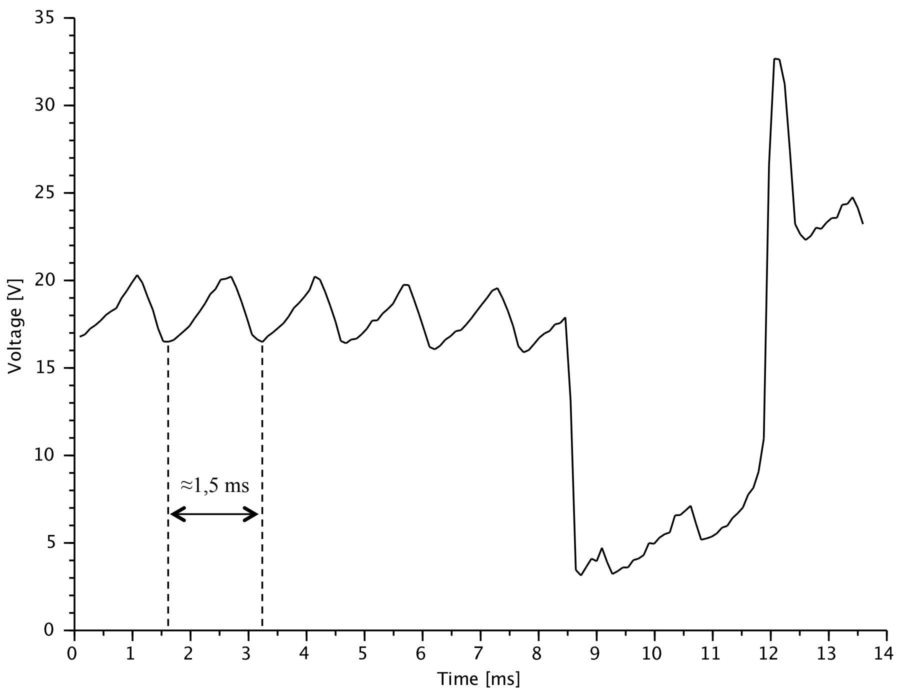

Figure 31 - An example of a zoomed in view over the repeating pattern within the 1-3 millisecond interval

2.2.4 Experiment 2 – Weld bead measurements

Experiment 2 will evaluate the stability and reliability of using automated welding as a method. It will demonstrate the efficiency for acquiring large data sets of quantified data regarding weld bead geometry. A fast and reliable method for collecting data of weld bead geometry could improve the validation and verification of new and already fabricated products through a more easy evaluation process of consumables. The result from the experiment, geometrical data of the weld, will be evaluated to see if it is consistent with the theory. The verification of the result will distinguish if the used method is reliable and stable or not, and if it can be used for data acquisition and validation.

EXPERIMENTAL SCHEME

Experiment 2, weld bead measurement, consists of 34 tests points with varying voltages and wire feed speeds. The test scheme is presented in *Figure 32*. All tests points are located in the metal transfer mode for spray and rapid arc. This is due to the thickness of the plate, which makes a normal short-circuiting mode insufficient to create the required fillet weld. The range of the wire feed speed goes from 10 to 25 m/min and voltage from 18 to 34 V. The experimental scheme for this experiment is established with help from the software program MODDE, in the same way as for experiment 1, to remove external noise and make the result statistically validated.

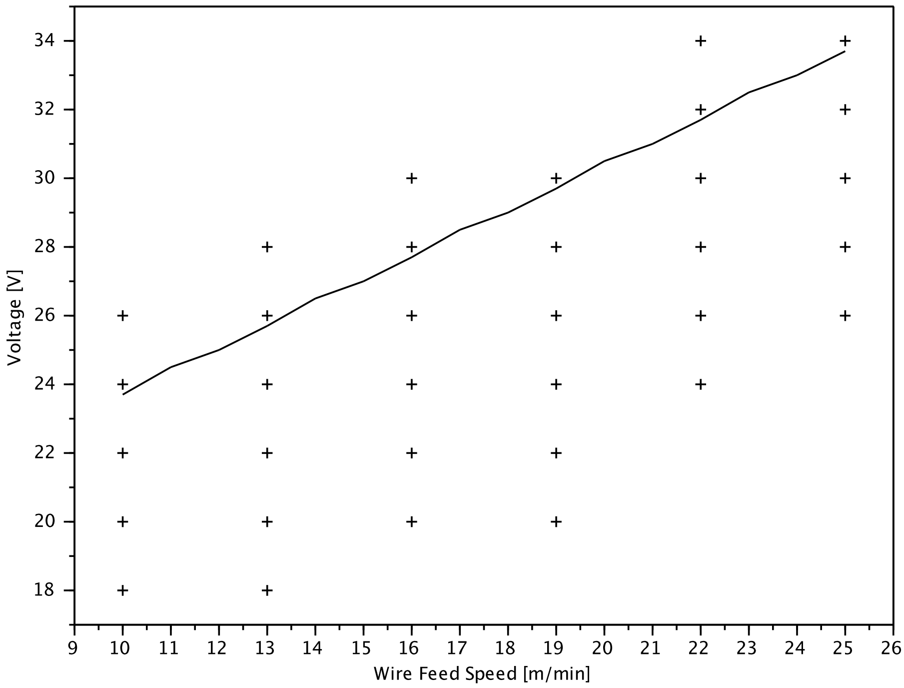

Figure 32 - Test scope for experiment 2

EXPERIMENTAL PROCEDURE

The procedure for experiment 2 is to weld fillet welds in an automated welding operation, cut and grind sample, etch the surface and measure the bead profile. The equipment used and variables, such as shielding gas and consumables, are stated in section 2.2.1. The repeatability and reproducibility of input variables are to be held at a high level, due to the use of an automated welding process. The cutting, grinding and etching of the samples are just necessary preparation stages for the optical measurement and are not vital for the actual experiment and will therefore not be discussed further. The welding position used is PB, which is illustrated in *Figure 33* together with the work piece placement of the fillet weld. The work angle for the weld bead measurement experiment was reduced from the standard angle of 45° to 40° to compensate the wetting and push the melt upwards the vertical plate to create a more homogenous weld bead geometry.

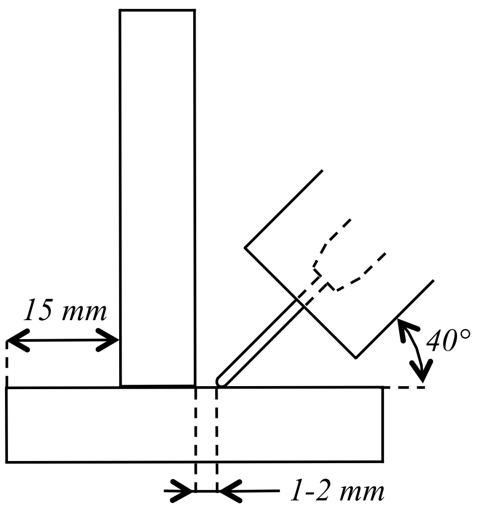

Figure 33 - Welding position and work piece placement for experiment 2

EXPERIMENTAL METHODS

The weld bead measurements for experiment 2 are performed with optical microscope, which captures a picture of the weld bead profile. Measurements are performed in a software program connected to the microscope that calculates the values of the geometrical measurements with respect to the magnification. The measurement and notations is from ISO 15792-3:2000, which is illustrated in *Figure 34.*

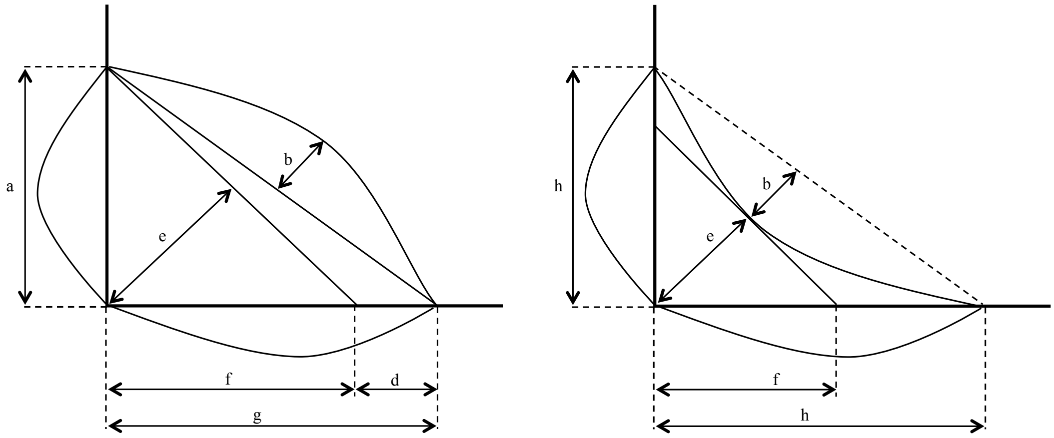

Figure 34 - Measurements for fillet welds according to ISO 15792-3:2000 for convex filled weld (left) and concave filled weld (right)

Since the aim of the measurements is to identify correlations between weld bead geometry and process parameters rather than evaluate the actual weld, some measurements describing the penetration are added, illustrated in *Figure 35*. The notations have been changed to distinguish the measurements more easily. The notations for both convex and concave fillet welds are the same for easier comparison.

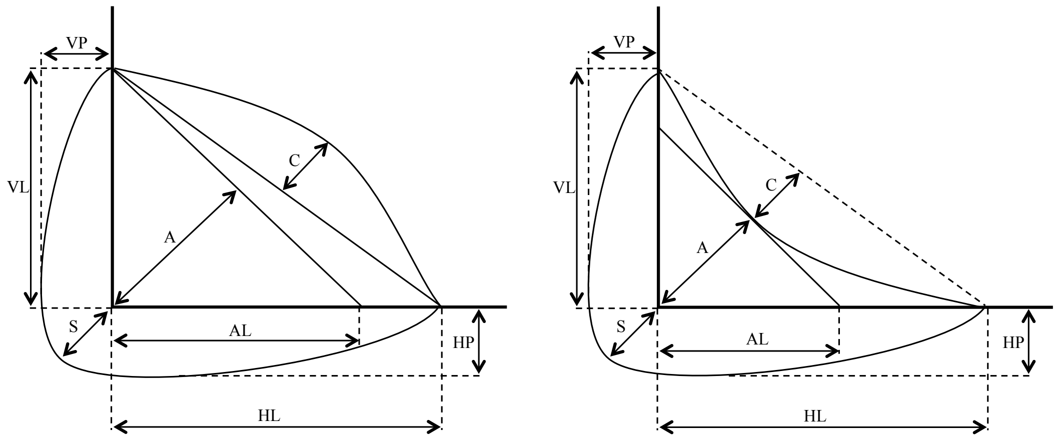

Figure 35 - Measurement system of fillet weld for experiment 1 for convex filled weld (left) and concave filled weld (right)

There are different requirements specified for type of weld, type of standard, application area, etc., that needs to be fulfilled to get an approved weld. One of the requirements listed in SS-EN ISO 5817:2014 is the maximum deviation in leg length difference. The standard for this requirement is divided into three different classifications, B, C and D, which are defined as the equations below, where the *h* is the deviation in leg length difference. By using this classification, the samples can be categories by which classification they fulfil or not fulfil.

B-classification: $h \leq 1.5\ mm + 0.15 * A$
C-classification: $h \leq 2\ mm + 0.15 * A$
D-classification: $h \leq 2\ mm + 0.2 * A$

3. RESULT

The result has been divided into two parts, one for each experiment. Experiment 1, I/U characteristic analysis, investigates objective characterising quantities, while experiment 2 evaluates the stability and reliability of using automated welding as a method for data acquisition and validation.

3.1 Experiment 1 – I/U characteristics analysis

Experiment 1, I/U characteristic analysis, resulted in several quantities. For comparison, the results from different test runs are plotted at the positions of the set values of within the process window for each tests, see *Figure 36*. All values that are calculated are listed in *Table 3*; the unit for each quantity is also stated.

Table 3 - Calculated quantities

Quantity:	**Unit:**
Voltage (mean value)	[V]
Current (mean value)	[A]
Power (mean value)	[kW]
Heat input	[KJ/mm]
Ratio of short-circuiting	[%]
Number of voltage peaks per second	[100*Nr/s]
Number of current peaks per second	[100*Nr/s]
Number of power peaks per second	[100*Nr/s]
Voltage deviation (mean value)	[V]
Current deviation (mean value)	[A]
Power deviation (mean value)	[kW]
Amount of voltage spikes	[%]
Amount of current spikes	[%]
Amount of power spikes	[%]
Voltage peak position (Fourier transformation)	[Hz]
Current peak position (Fourier transformation)	[Hz]
Power peak position (Fourier transformation)	[Hz]
Voltage peak amplitude (Fourier transformation)	[Relative peak intensity]
Current peak amplitude (Fourier transformation)	[Relative peak intensity]
Power peak amplitude (Fourier transformation)	[Relative peak intensity]

One of the process parameters is voltage. *Figure 36* shows the measured voltage. The figure shows that for low voltages and wire feed speeds the measured voltages are much higher than the set value. The wire feed speed does not affect the voltage except for the lowest voltages. This is caused by the power source that increases the voltage to keep the arc stable. This is not required at higher wire feed speed.

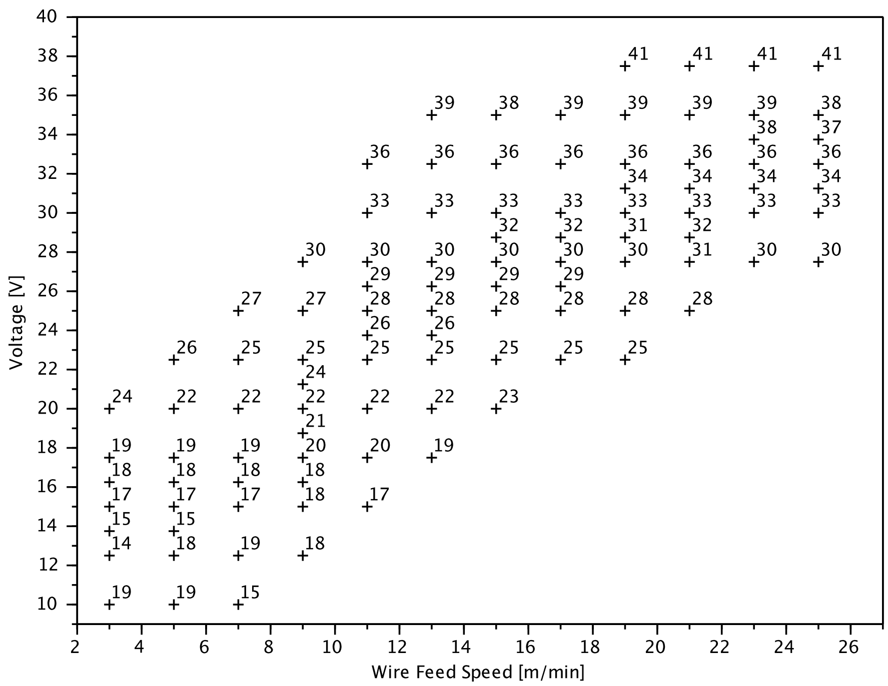

Figure 36 - Mean values of the voltage [V]

Figure 37 shows the mean current for all test runs. It is known that the wire feed speed is strongly connected to the current level but it can also be seen that the voltage is affecting the current considerably at higher wire feed speeds.

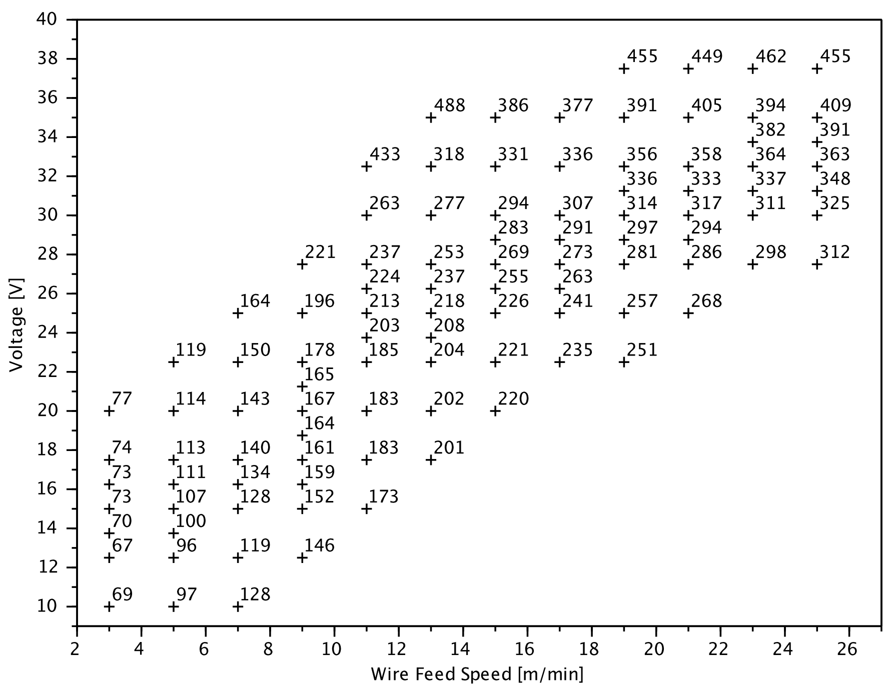

Figure 37 - Mean values of the current [A]

Figure 38 shows the heat input for all test runs. An increase in voltage corresponds to a decrease in heat input while the wire feed speed has the opposite relationship. The figure shows that high heat input correlates to spray modes while low correlates to short-circuiting modes.

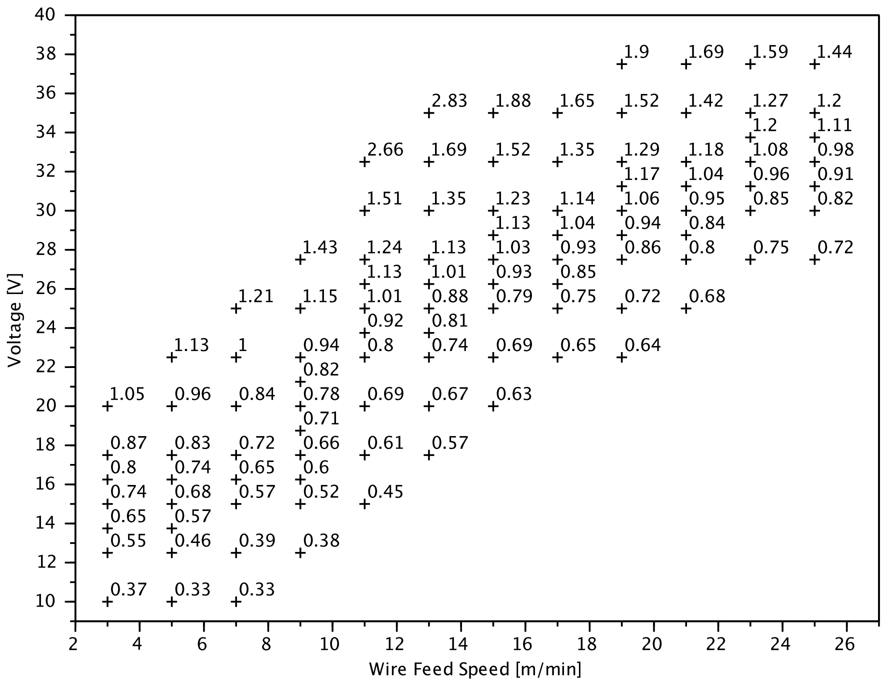

Figure 38 - Mean values of the heat input [kJ/mm]

Ratio of short-circuiting is shown in *Figure 39*. The figure states that a low voltage increases the amount of short-circuiting time. An increase in wire feed speed increases the amount of short-circuiting for a fixed voltage.

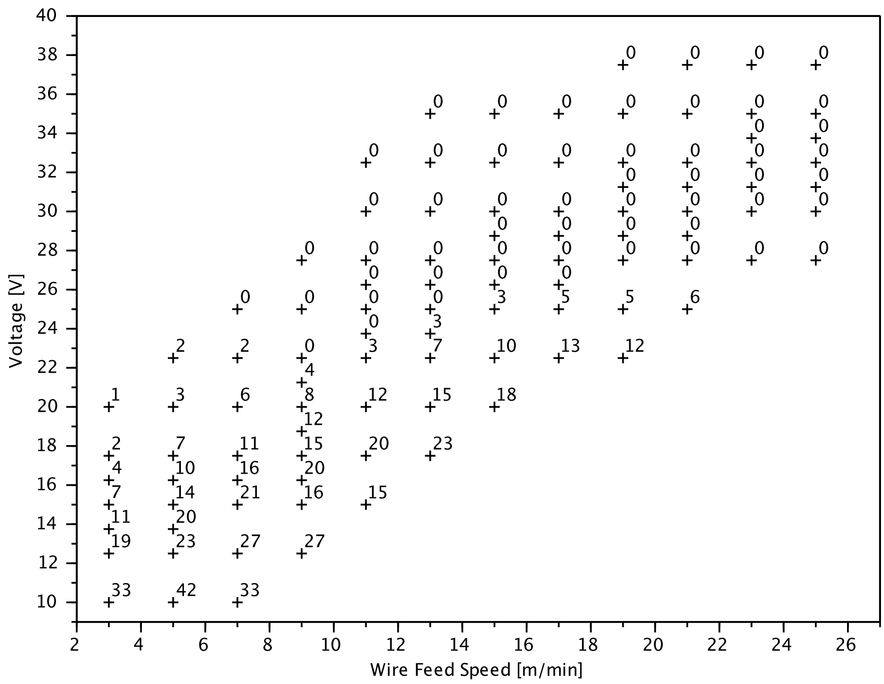

Figure 39 - Ratio of short-circuiting in percentage [%]

The number of voltage peaks per second is calculated. Result is presented in *Figure 40*, unit 100 peaks per second. The results of number of current and power peaks are very similar and are shown in Appendix A. It is mostly the voltage level that affects number of peaks where a low voltage leads to the highest amount of peaks while the lowest amount of peaks is in a medium voltage level. An increase in number of peaks can be seen at higher voltage levels.

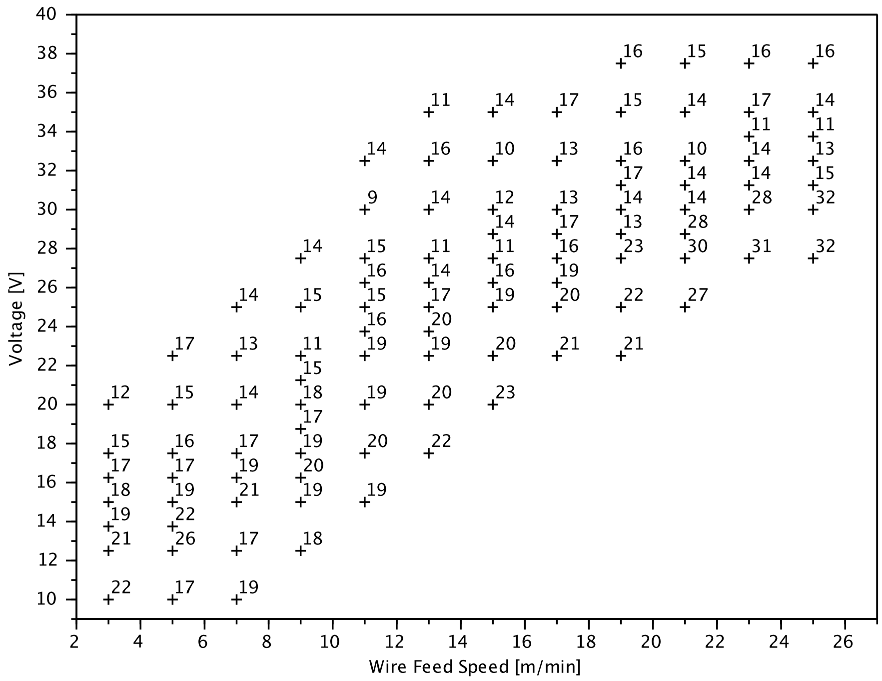

Figure 40 - Number of voltage peaks per 100 second

The mean voltage deviation is shown in *Figure 41*. Mean current and power deviation has a similar pattern and is shown in Appendix A. The figure shows that a decrease in voltage will increase the voltage deviation, which typically means an unstable weld. A spray metal transfer mode has by definition a low deviation and a short-circuiting mode a high deviation. It can also be used to characterize the short-circuiting mode. A high value can be correlated to a low short-circuiting voltage while a low deviation correlates to a higher short-circuiting voltage. A globular transfer mode can be characterized by using this method.

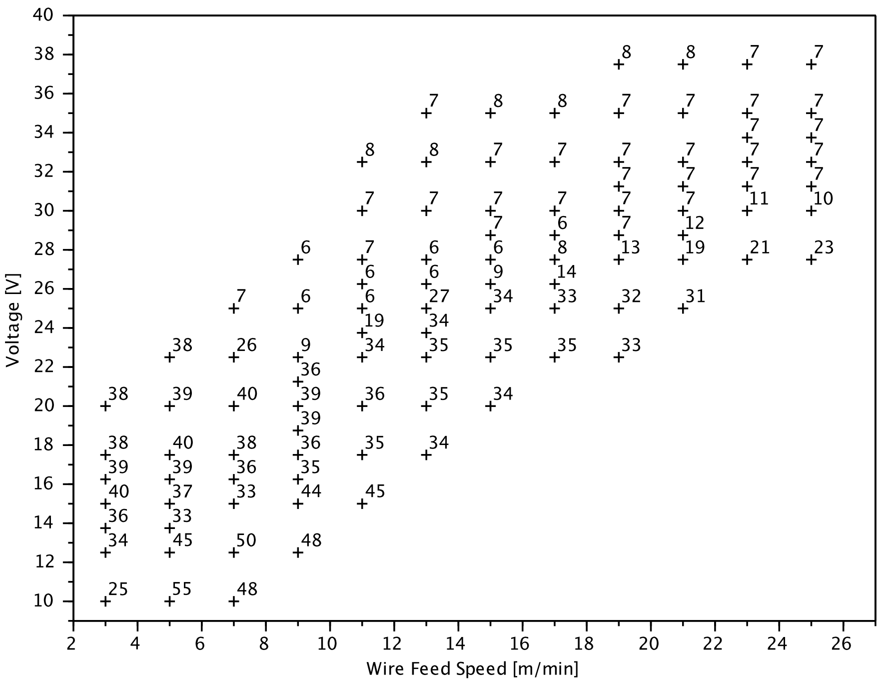

Figure 41 - Voltage mean deviation [V]

The amount of voltage spikes, fraction of spikes outside normal, is calculated for voltage, current and power and the amount voltage spikes is presented in *Figure 42*. An increase in the amount of spikes can be seen in the centre of the wire feed speed at voltages above 9 m/min, which is the transition zone between spray and forced arc mode. Spikes in current and power have the same pattern as the voltage spikes and is presented in Appendix A.

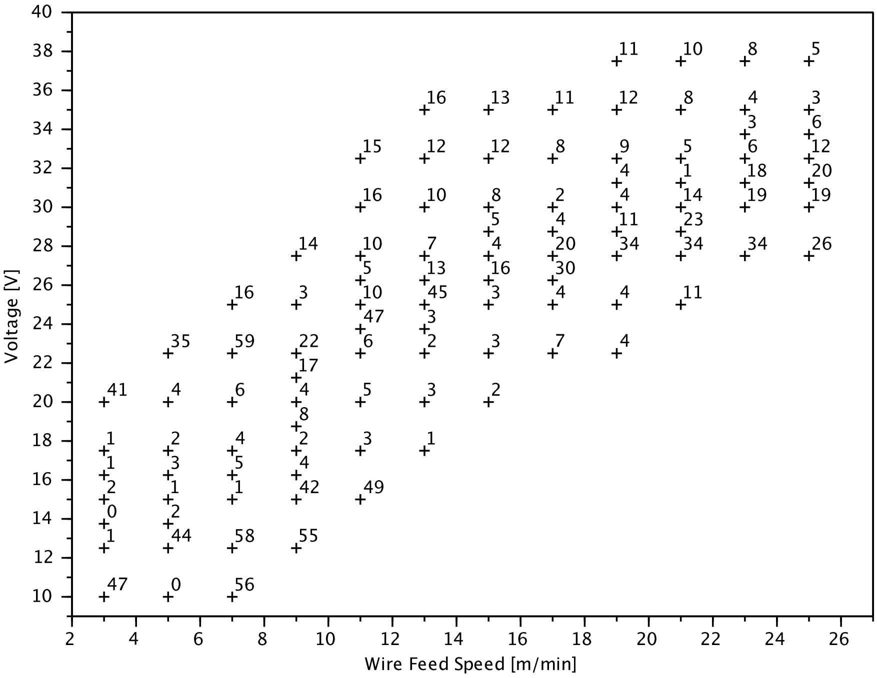

Figure 42 - Amount of voltage spikes in percentage [%]

The Fourier transformation resulted in two different quantifiable values that are collected for each test run. It is the peak position and amplitude, discussed in section 2.2.3. The peak position for the voltage is shown in *Figure 43* with unit Hz. Almost identical positions are found for the current, which is shown in Appendix A.

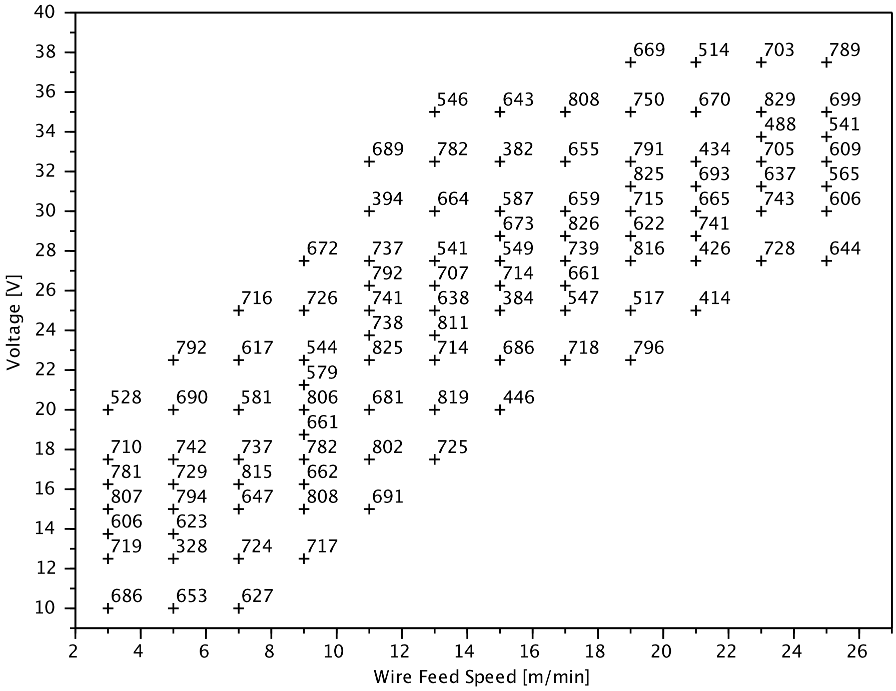

Figure 43 - Voltage peak position [Hz] from the Fourier Transformation

The amplitude, in relative peak intensity, for the peaks in the Fourier transformation for the voltage is shown in *Figure 44*. Similar result is seen from the current and power, which is presented in Appendix A.

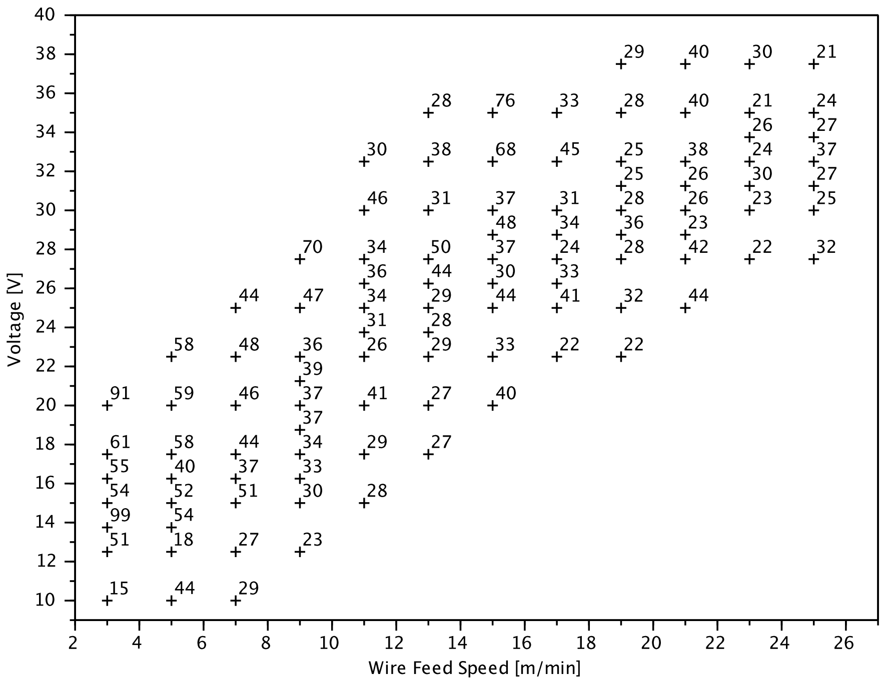

Figure 44 - Relative peak amplitude for the voltage curve from the Fourier Transformation

3.2 Experiment 2 – Weld bead measurement

The measurement of the weld bead geometry showed that the process parameters, voltage and wire feed speed, had great impact on the geometrical changes of the weld, as expected. Trends connecting the process parameters with the weld bead measurements can easily be seen and will be illustrated later in this section. The geometrical measurements, leg length deviation, penetration (S-dimension) and throat thickness, will be presented in the result below, the other measurements did not reveal any further information and is therefore shown in Appendix B. All the geometrical measurements performed on the weld bead profiles are stated in *Table 4*.

Table 4 - Geometrical measurements of the weld bead profile

Geometrical measurements:	**Unit:**
VP, vertical penetration	[mm]
VL, vertical leg length	[mm]
HP, horizontal penetration	[mm]
HL, horizontal leg length	[mm]
Leg length deviation	[mm]
AL, leg length of the equilateral triangle	[mm]
A, throat thickness	[mm]
S, S-dimension	[mm]
C (concavity)	[mm]
C (convexity)	[mm]

Figure 45 shows the geometrical changes for the different voltage and wire feed speed levels in an illustrative way. Expected trends of the leg length deviation, penetration and throat thickness can easily be seen. The leg length deviation increases at high parameter setups; high voltage and wire feed speed. The penetration increases with both increasing voltage and wire feed speed. The throat thickness reaches the largest value for the samples in the middle of the voltage range and decreases in both direction, where high voltage provides the lowest throat thickness.

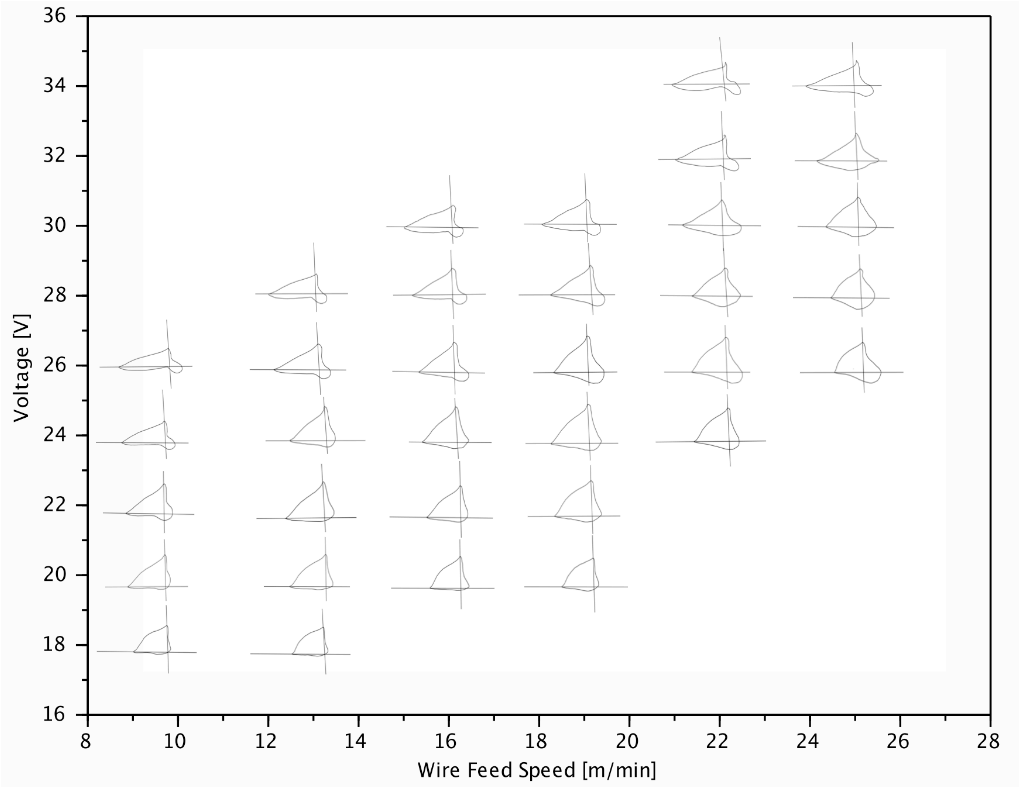

Figure 45 - The geometry change in the process window

The geometrical changes, in terms of leg length deviation, penetration and throat thickness, can be correlated to the heat input, which is commonly known. *Figure 46* shows the heat input dependence on leg length deviation, penetration and throat thickness. Both the leg length deviation and the penetration show an increasing trend with increasing heat input, while the throat thickness shows a decreasing trend.

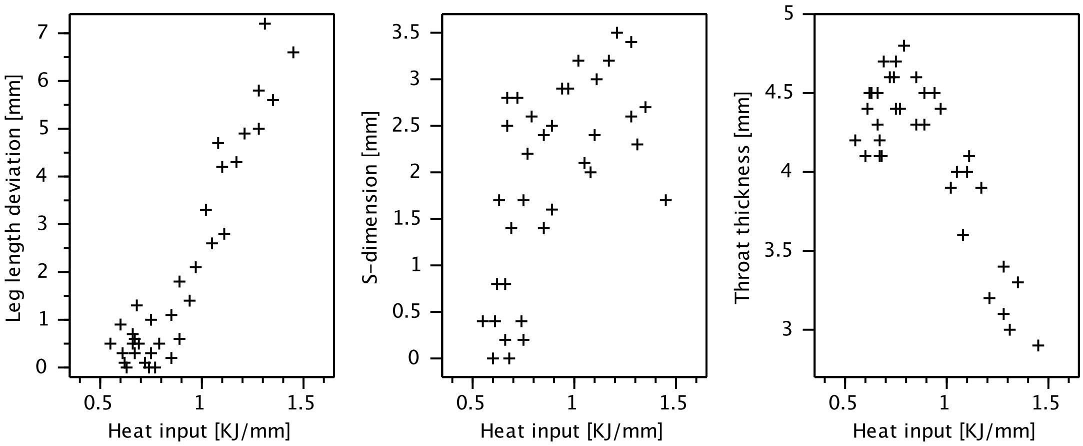

Figure 46 - Plots showing the relationship between heat input and leg length deviation (left), penetration/S-dimension (middle) and throat thickness (right)

Figure 47 shows the different heat input for all the samples. The heat input increases with increasing voltage and decreasing with increasing wire feed speed, when the voltage is held at a constant level. This is due to the correlation between wire feed speed and travel speed for the experiments, a higher wire feed speed leads to a higher travel speed, which decreases the heat input by definition. A low heat input corresponds to low wetting, short arc length and low leg length deviation, while a high heat input increase the wetting and arc length, and therefore also the leg length deviation, see *Figure 46*.

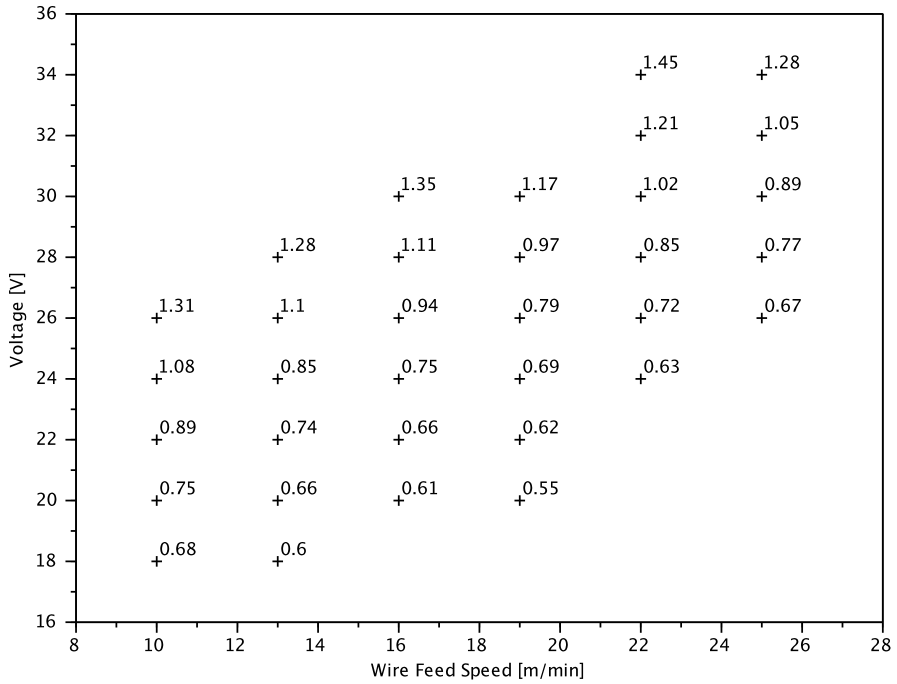

Figure 47 - Mean values of the heat input [kJ/mm] for experiment 2

The appearance of the penetration, depth and form, for the tests with a heat input below 0.9 kJ/mm, cannot be estimated by looking at the level of heat input, see *Figure 47*. The tests with the lowest heat input for each wire feed speed are roughly the same, but the penetration varies a lot, see *Figure 45*. The figure shows that the penetration increases with increasing wire feed speed, and this is due to the correlation between the wire feed speed and the current. A rise in wire feed speed corresponds to a rise in current when the voltage is held constant, which results in greater penetration of the weld. The mean current for each sample is shown in *Figure 48*.

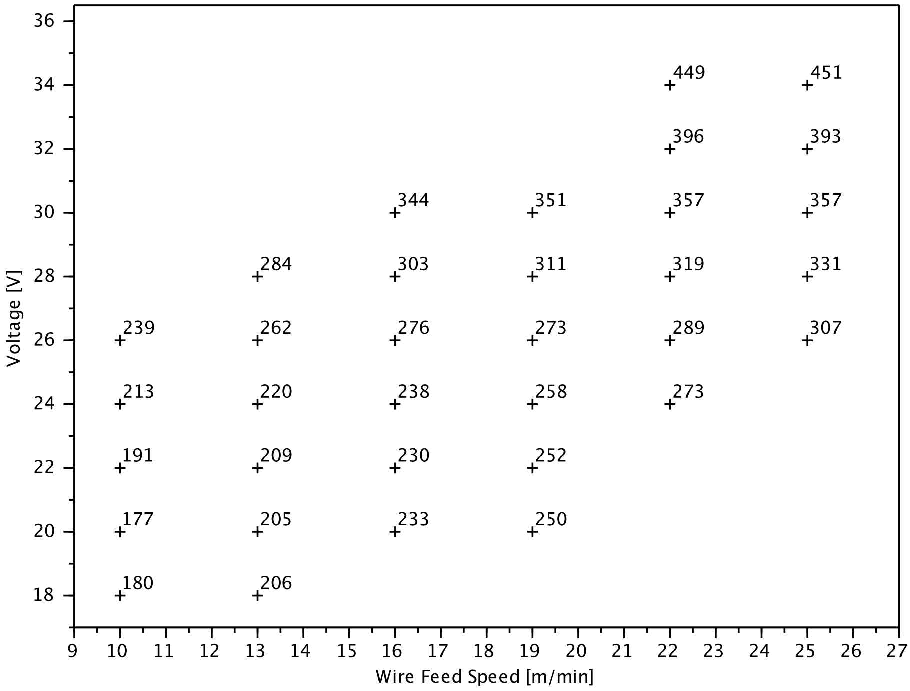

Figure 48 - Mean values of the current [A] for experiment 2

The leg lengths of the weld correlate to the width but also to the homogeneity of the weld. A large deviation in the vertical and horizontal leg lengths corresponds to a heterogeneous weld profile. The deviation of the vertical and horizontal leg lengths is illustrated in *Figure 49*. The figure shows that the leg length deviation increases with increasing voltage, which raises the temperature in the weld pool due to greater heat input. The solidification process of the weld pool will take longer time if the temperature rises. The delay in solidification enables the melt to flow more and together with the extended arc length create a large deviation in leg length. The flow of the melt is dependent on the weld position due to the involvement of the gravity. The increase in voltage also extends the arc length, which makes the current and the metal transfer flow more to the horizontal plate, due to the shorter arc. Higher metal transfer towards the horizontal plate will increase the leg length deviation and the heat input on that plate, with a greater penetration as a result. One way to compensate the flow of the weld is to decrease the work angle to push the melt up towards the vertical plate with help from the arc pressure. The arc pressure needs to reach a certain limit to have any affect.

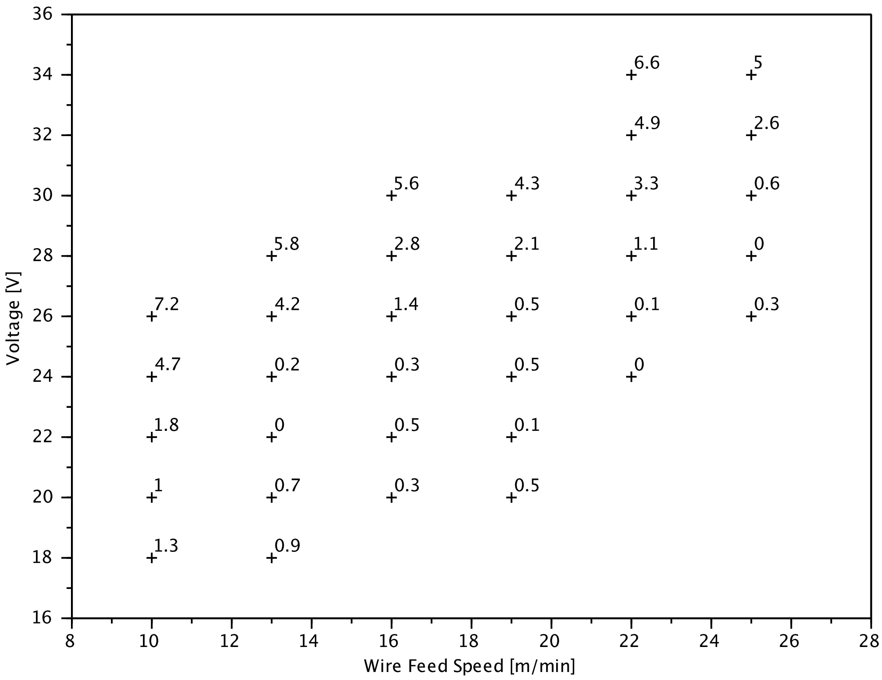

Figure 49 - Deviation in leg length [mm]

Depending on application area, different requirements may be specified for the measurement. The requirements can be divided into classifications where a smaller deviation from the theoretical value gives a higher classification. The definition of the classifications is stated in the section 2.2.4. The classification of the samples is presented in *Figure 50*, which clearly states that to high voltage leads unclassified welds due to too large leg length deviation.

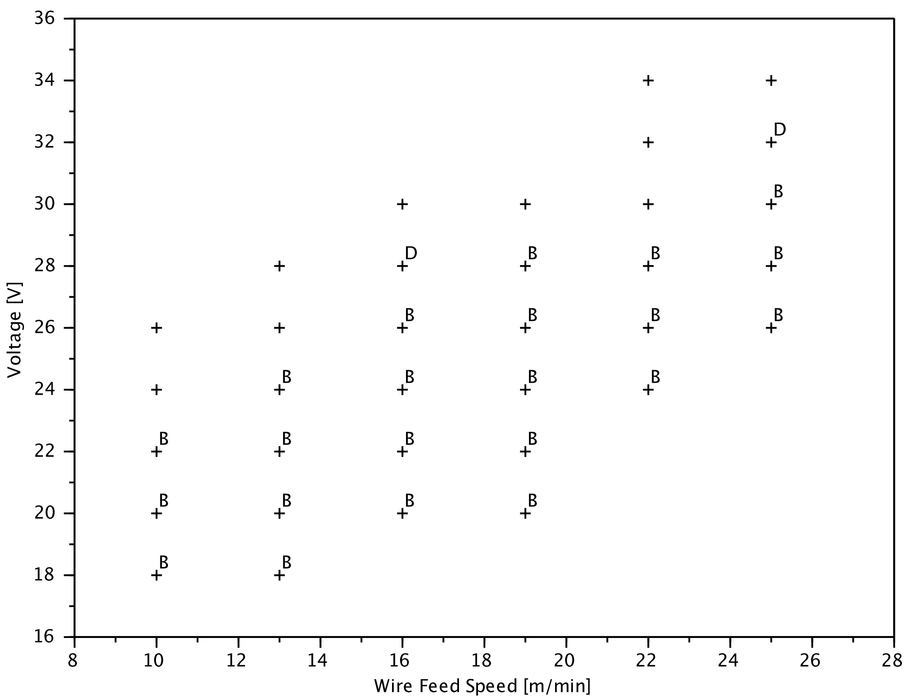

Figure 50 - Classification depending on deviation in leg length according to SS-EN ISO 5817:2014

The penetration measurement consists of three values; S-dimension, vertical penetration and horizontal penetration. The results from the vertical and horizontal penetration are very similar to the S-dimension and are therefore shown in Appendix B. The S-dimension is the penetration defined as extended throat thickness and is one of the measurements that are not included into the standard ISO 15792-3:2000, see *Figure 35* for definition. The values for the S-dimensions are illustrated in *Figure 51*.

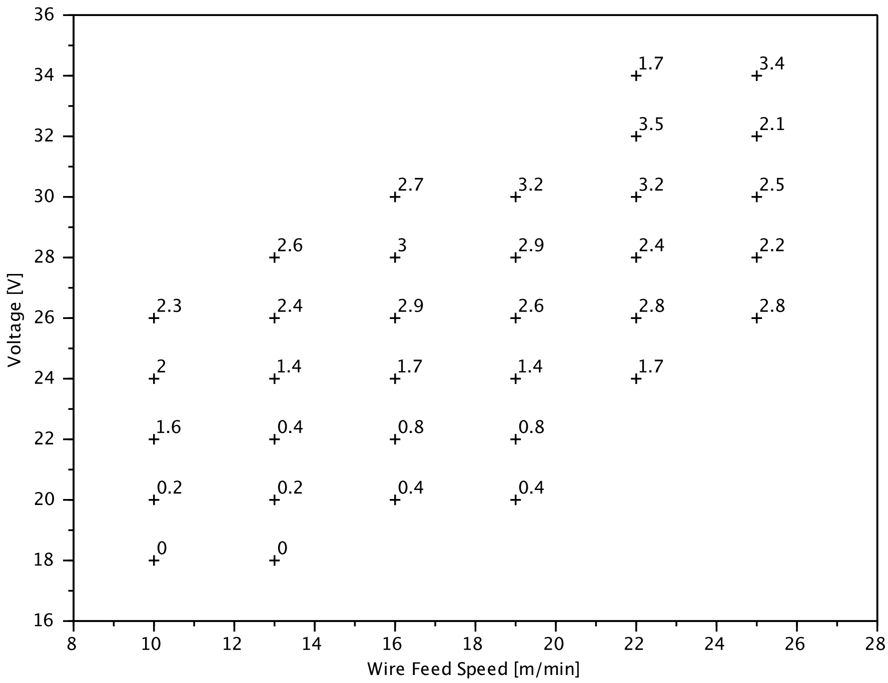

Figure 51 - S-dimension [mm]

The penetration of the weld can be seen in *Figure 45*, which shows that the depth of the penetration generally increases with increasing voltage and wire feed speed. The essential part of penetration is to join together more material and not to melt the base material. A greater joint can resist more mechanical load. The base material has generally lower alloy content and contains generally a higher amount of impurities than the consumable, which may result in a diluted weld with decreased quality and mechanical properties.

The shape of the penetration has a sudden change when the voltage reaches high values, as seen in *Figure 45*. The penetration becomes more tapered, focused at the midsection of the joint and looks like a finger, argon finger. This phenomenon occurs due to the low ionization potential of argon. The test that exhibit this phenomenon lies in the upper field in the voltage level for each wire feed speed that corresponds to a high heat input, see *Figure 47*. According to the figure, test with heat inputs of 0.9 kJ/mm or more cause the phenomenon of argon finger to occur, for this specific welding condition. A change in the consumable, base material or any other variable could likely exhibit deviations from this result.

Figure 52 illustrates the throat thickness in mm, for different combinations of voltages and wire feed speeds. According to previous calculations of the travel speed for the experimental phase, the approximated value for the throat thickness was set to 5mm. The travel speed is estimated for a fixed weld bead area with varying wire feed speed. The largest throat thicknesses, up to 4.8mm, are located at the centre points of the voltage values, and are slightly decreasing for lower voltage. This is due to a decrease in heat input that decreases the wetting, which results in a more convex weld with shorter leg lengths. The throat thickness is defined as the length, 45 degrees from the joint, in the largest isosceles triangle of the weld. That means that the largest throat thickness is achieved when the weld is flat, due to the fixed deposition rate. Convexity or concavity will therefore always reduce the throat thickness from its theoretical maximum value.

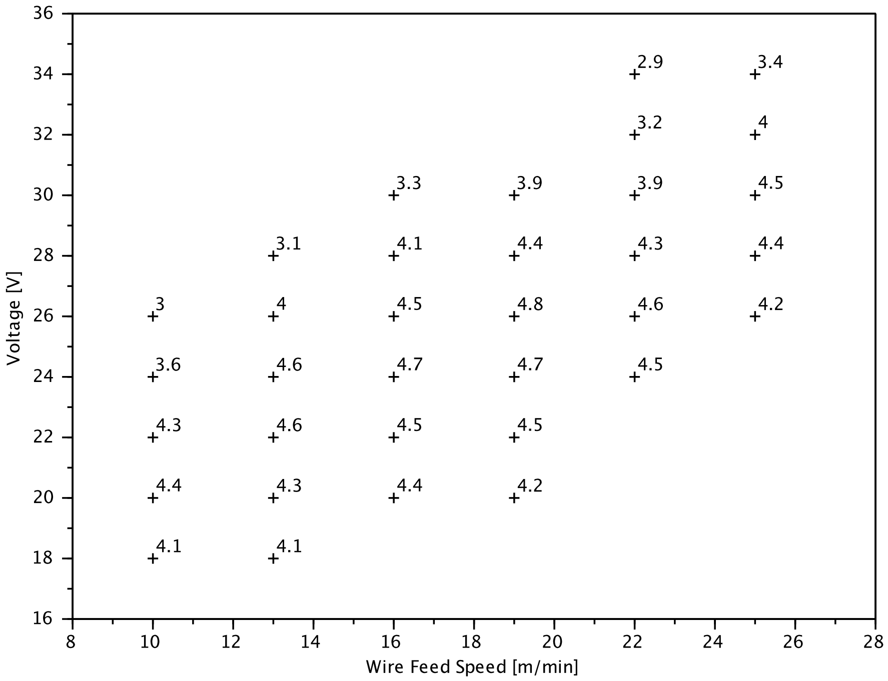

Figure 52 - The Throat thickness [mm]

Other remarks from experiment 2:

- Concavity/convexity was hard to identify due to the frequently appeared S-shaped welds, illustrated as A) in *Figure 53*. The samples with lower voltage had a convex weld bead and samples with higher had either S-shaped or concave weld beads.
- Pores have been identified in 6 samples randomly distributed within the process window, illustrated as B) in *Figure 53*. The most likely cause of the pores is contamination of the surface of the base material used for the specific samples that exhibited pores. That pores were observed in some samples does not have any impact of the rest of the result.
- Undercuts have been identified in 4 samples with high voltage, illustrated as C) in *Figure 53*. The cause of undercut is the increased heat input, above 1.2 kJ/mm, which makes the melt flow down to the base plate and creates a ditch.
- Argon finger was observed in samples welded with high voltage, illustrated as D) in *Figure 53*.

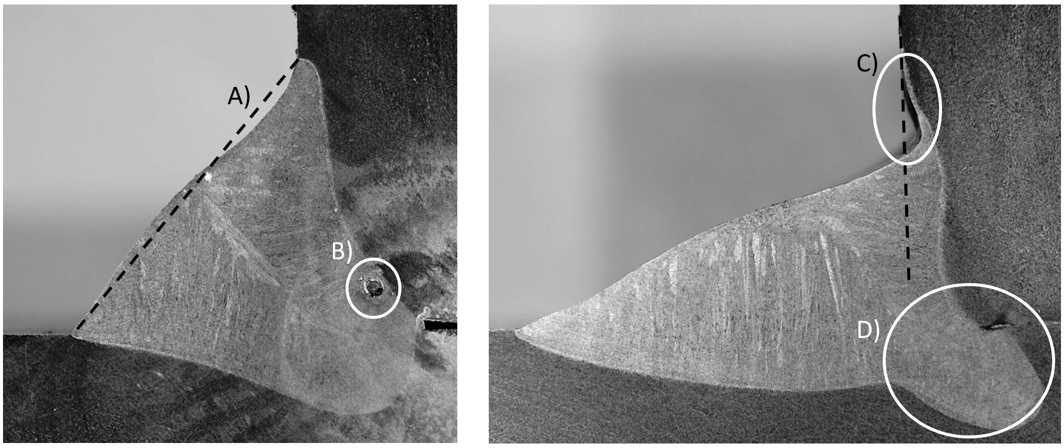

Figure 53 - Irregularities in fillet welds; A) S-shape weld bead, B) Pore, C) Undercut and D) Argon finger

4. DISCUSSION

The discussion has been divided into two parts. Experiment 1 addresses the discussion about the quantities established through the I/U characteristic analysis, while the discussion in experiment 2 is about the method used of applying automated welding for data acquisition and validation.

4.1 Experiment 1 – I/U characteristics analysis

The power source is affecting the result when choosing a low voltage and a low wire feed speed. The measured value deviate a lot from the set value on the power source. It is caused by the low parameters that is to low for keeping a stable arc. The power source increases the voltage, trying to maintain a stable arc. The deviation between set voltage and measured voltage is much less when choosing a higher voltage.

Current has a strong connection to the wire feed speed and it is known that an increase in wire feed speed will increase the current level, keeping all other parameters constant. The same goes for an increase in voltage that also will increase the current. It can also be seen that the increase in voltage has a low effect on the current at low wire feed speeds. At higher wire feed speeds the sensitivity from voltage changes are much higher.

The heat input is defined as power per length unit kJ/mm and it is stated that the power increases if the current or voltage is increased according to Ohms law (P=U*I). An increased power is often correlated to a decreased travel speed. This results in an almost unchanged heat input even if the voltage and current is increased, due to the increase in travel speed. In our case, the travel speed is calculated by the wire feed speed, so changes in heat input is mainly caused by the change in voltage. It can be seen that for all wire feed speeds the same level of heat input can be found. Changing stick out, which lowers the current for the same wire feed speed, could also alter the heat input. This is often used as method in industry to increase productivity due to the fact that the deposition rate is unchanged and heat input is lowered. The heat input is the most common and the most important parameter when deciding a welding procedure.

The ratio of short-circuiting is a useful quantity to characterize the metal transfer mode. The result shows that high ratio of the short-circuiting occurs at low voltage and low wire feed speed, while there is non short-circuiting above 25V. This quantity can be used to distinguish the metal transfer mode of short-circuiting, both usual short-circuiting and rapid arc, from other transfer modes. The quantity does not, however, say anything about the other metal transfer modes or the stability/quality of the short-circuit mode. It should be known that the definition of a short-circuiting is of essence when analysing the ratio of short-circuiting. At low parameters the short-circuiting are distinctive, almost zero in voltage, but at higher parameters when the current level is increased the definition of a short-circuiting is higher, up to a few voltage. They can be distinguished by listening to the process. These two types of short-circuiting is therefore called short-circuit and forced short-circuiting. The forced short-circuiting feels like it want to be in spray mode but is forced to short circuit and the sound level is much higher than for an ordinary short-circuiting process.

The number of peaks per second can be used to characterise the welding process. This value describes how many times per second the curves gradient changes. A high number of peaks are correlated to a large deviation, high instability, in the process, and it can possibly be connected to the metal transfer mode. No obvious correlations could be found between number of peaks and metal transfer modes with current analysis. Theoretically it could be possible to find potential correlations, but it requires further research to make a better assumption. It is also possible that the sample rate used was too low. The result shows that an increase in wire feed speed increases the number of peaks and at the same time an increase in voltage decreases the number of peaks. The correlation between number of peaks and voltage seems to be the same independently of wire feed speed. The number of peaks cannot be used as a single characterising quantity due to the uncertainties in the correlations. It can be used as a complement to other characterising quantities, though.

The voltage deviation is changing a lot, due to reasons such as unstable process or different metal transfer modes. The result shows that the deviation in voltage, current and power decreases with an increase in voltage. The increase in deviation is mainly due to a change in metal transfer mode. Spray mode has typically a deviation of less than 10 V and the other modes, short-circuiting, forced arc and globular, have a deviation around 30 V. A drawback with the quantity is that it can only be used for classifying if it is a spray mode or not, and not the characterisation of the actual transfer mode. Another complementary quantity is needed to extract that information. The short-circuit mode has typically a deviation of more than 10 V. Traditional short-circuit mode and rapid arc can be distinguished, rapid arc have a lower deviation, less than 30 V.

The amount of spikes is a value that characterizes the stability of the process. It shows the fraction of time outside normal in the process. A stable process has the value zero and the result shows that the unstable processes can occur at different regions. It can be caused by change in metal transfer mode or by other irregularities. This quantity can be used to characterize the transition zones between the different metal transfer modes and stability. It can be used to see where the transfer zone between short-circuiting and spray mode. This parameter is the best parameter to use to describe the stability in the process but it should be mentioned that the calculations could be misleading in some cases where a test run gets a lot of spikes. The definition of a spike is that it should be an irregularity in the process and if they occur a lot then this definition states that the values that typically are seen as an irregularity are regular. A very unstable welding process, with a high amount of spikes, can therefore be characterised incorrectly as stable when it is in fact very unstable, and that is a limitation for this quantity. Normally welding will not be this unstable and it is therefore a minor limitation.

The Fourier transformation makes it possible to analyse the voltage and current signals even further. Two values were calculated that characterize the welding process. One is the position of a determined peak and the other one is the amplitude of this peak. The peak for the short-circuiting modes at 50 Hz was expected but the peak between 300-900 Hz where not. The peak found at 50 Hz is very useful to identify the droplet transfer rate for short-circuiting metal transfer modes. The peak at the higher frequency existed in almost all cases, independently of metal transfer mode. More peaks at higher frequencies were observed for short-circuiting and globular transfer mode, which possibly can be used to determine the characteristics in the other metal transfer modes or show an irregular droplet transfer rate. The amplitude and position of the peak at higher frequencies was very similar for current and voltage data. It is unknown why the peak is moving but the fact that it is moving makes it less chance that it is an artefact from the power source. It could have something to do with the metal transfer mode and the droplet transfer rate and this could be further analysed using a high-speed camera. It could also be that the cathode spot is moving during arcing and that it creates variations in the arc. Changing shielding gas to another with different electrical properties could test this theory. The Fourier transformation analysis is one of the most interesting for further analysis due to the big potential of characterising process.

4.2 Experiment 2 – Weld bead measurements

The method used for the experiment 2, the automated welding process, turned out to be a reliable and stable method for acquiring large data sets of quantified data regarding weld bead geometry. The trends of the geometrical measurements were as expected and consistent to the theory, which states the accuracy of the method. The intended time for both experiments where set to 2-3 weeks, but it took less than 2 working days to perform the approximately 150 tests and run the calculations of the I/U data on the computer. By using this method a large database could be established in a short period of time and then be used for future research and development. Automated welding has high repeatability and reproducibility compared to manual welding where process parameters, such as; travel speed, work angle, travel angel and electrode extension, are hard to hold absolutely constant during a test, between tests and between welders. The accuracy in the setting of the process parameters makes automated welding beneficial when it comes to evaluation of different parameters setups for a specific consumable or evaluation between different consumables with the same parameters setup. It is important that all tests is performed during the same circumstances to be able to objectively compute characteristic quantities that could be correlated to the welding process, such as stability and quality.

5. CONCLUSION

Following conclusions are made:

- Several characteristic quantities showed possible trends or indications of correlations towards the welding process. An interesting discovery was the unexpected peak in the Fourier transformation analysis located between 300-900 Hz. No correlations to the welding process could be made and further research is necessary.

- The quantity *amount of spikes* showed promising correlations with the welding process. It can be used for characterising the stability of the process as well as locating the transition zone between metal transfer modes between short-circuiting and spray mode.

- The automated welding process used showed great reproducibility, repeatability and time efficiency. A large process window was covered with around 150 samples, which were performed in less than 2 working days. This shows a great potential that a large amount of quantified data can be acquired in a short period of time, which later can simplify the validation process of consumables.

6. RECOMMENDATION

This project has investigated the possibility of using measurable values from the process voltage and current data to characterise the welding process. Several measurable values have been identified and analysed, unfortunate no correlations were found between all values and process. Further research is necessary to correlate these values to the process. Following recommendations for future work are considered relevant:

- A database with typical values of the specified quantities should be established for different materials, power sources, logging device etc. Many quantities are not absolute, they need to be compared relatively to other tests to reveal any information.

- If the welding process, arc and weld pool, can be observed with a high-speed camera, correlations between I/U characteristics and metal transfer mode could be made. This could used to correlate values such as number of peaks and peak position to the welding process e.g. droplet transfer rate.

- The geometrical measurement is made after the experiment by cutting, grinding and measure in an optical microscope. This is only possible to do as an experiment and is not suitable for production. In production a laser scanner can be used to calculate leg length, throat thickness, amount of spatter etc., and no destructive testing in needed. The penetration may be determined by looking at I/U characteristics, validation is of course necessary.

- Sound from the welding process might be interesting to analyse. The sound may be used to detect irregularities in the process or find frequencies similar to them shown in the Fourier transformed data.

- Light is emitted from the arc and might be very useful to study. Changes in the arc will affect the emitted light, which can be used to characterise the process. An advantage with this method is that specific elements in the material can be observed due to the huge amount of information that can be derived from light emission.

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APPENDIX A – Results from experiment 1 – I/U characteristics analysis

This appendix presents results from the experiment that is has similar patterns as the result presented in the result section. The result is a vital part of the experiment and is of essence for the project. The number of current and power peaks per second is presented in *Figure 54* and *Figure 55* respectively. Unit is hundred peaks per second.

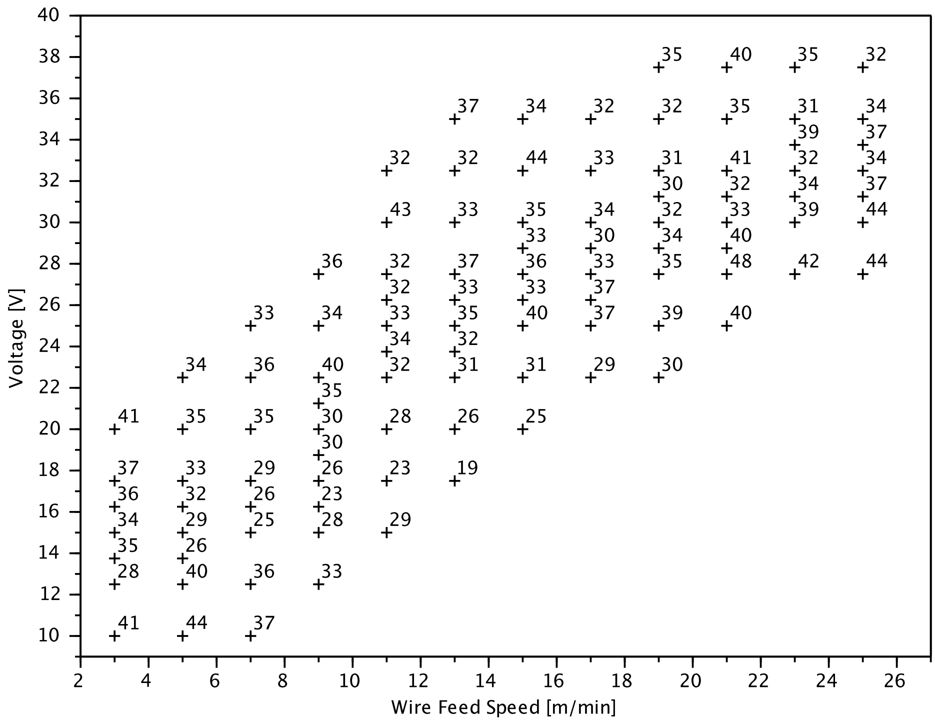

Figure 54 - Number of current peaks per second [100peaks/second]

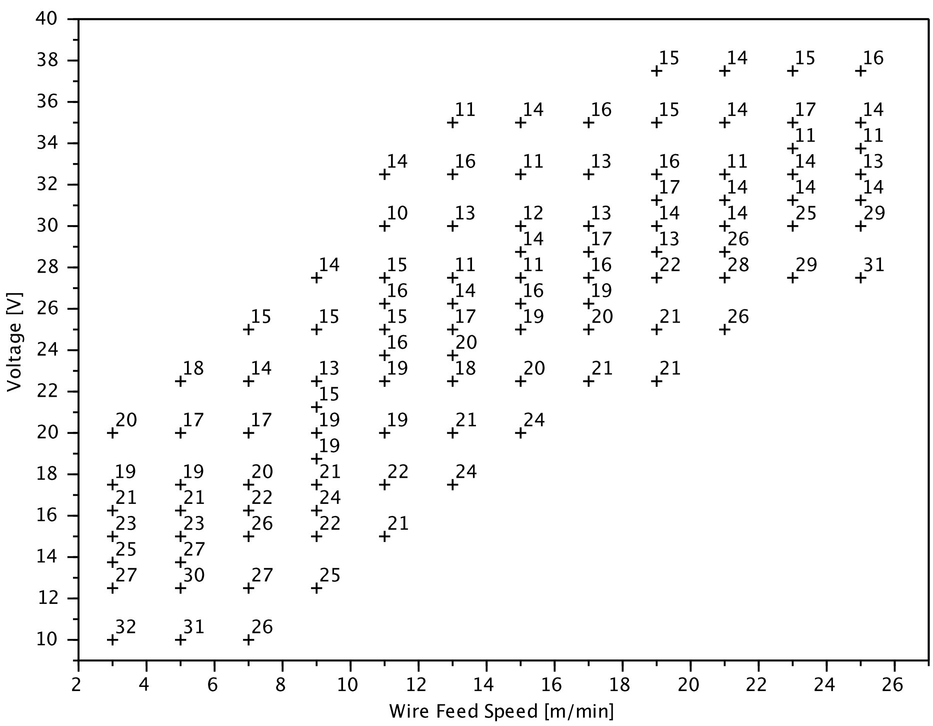

Figure 55 - Number of power peaks per second [100peaks/second]

The mean deviation in current and power is presented in *Figure 56* and *Figure 57*.

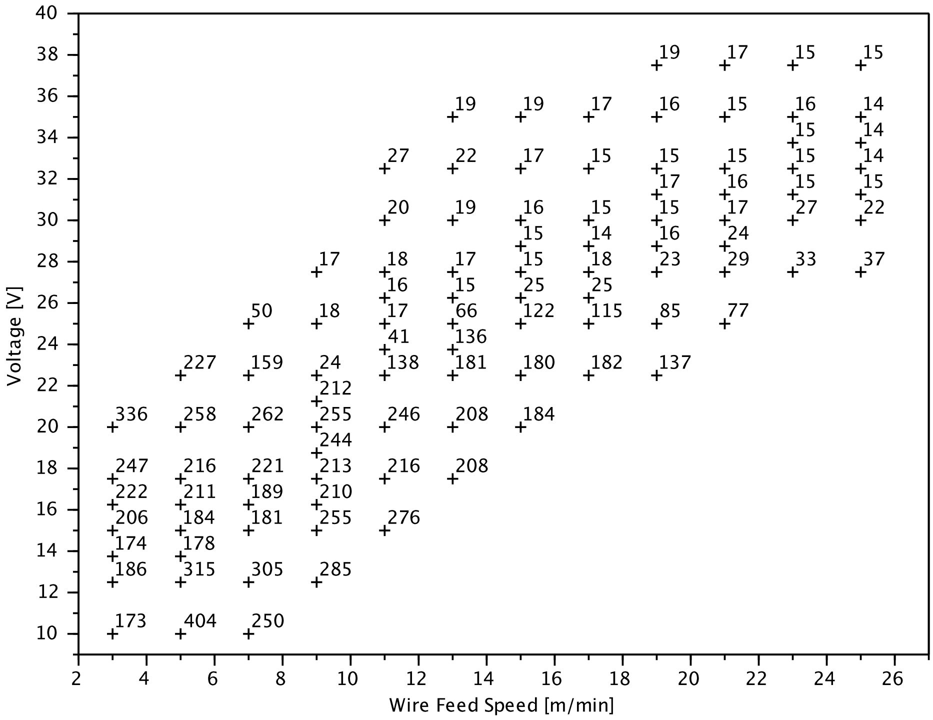

Figure 56 - Mean current deviation [A]

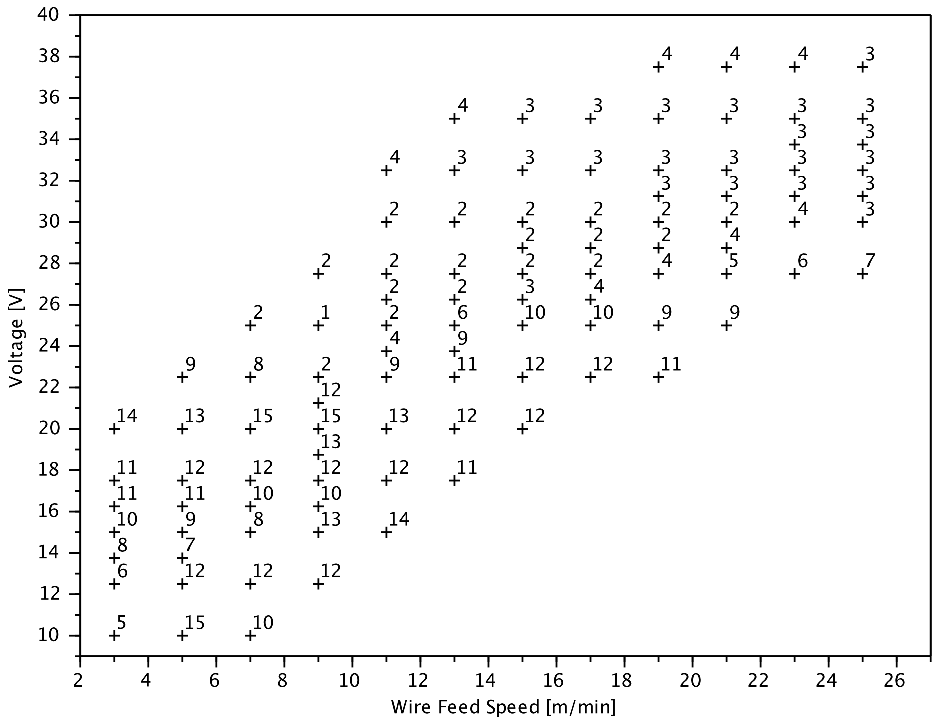

Figure 57 - Mean power deviation [kW]

The amount of current and power spikes in percentage is presented in *Figure 58* and *Figure 59*.

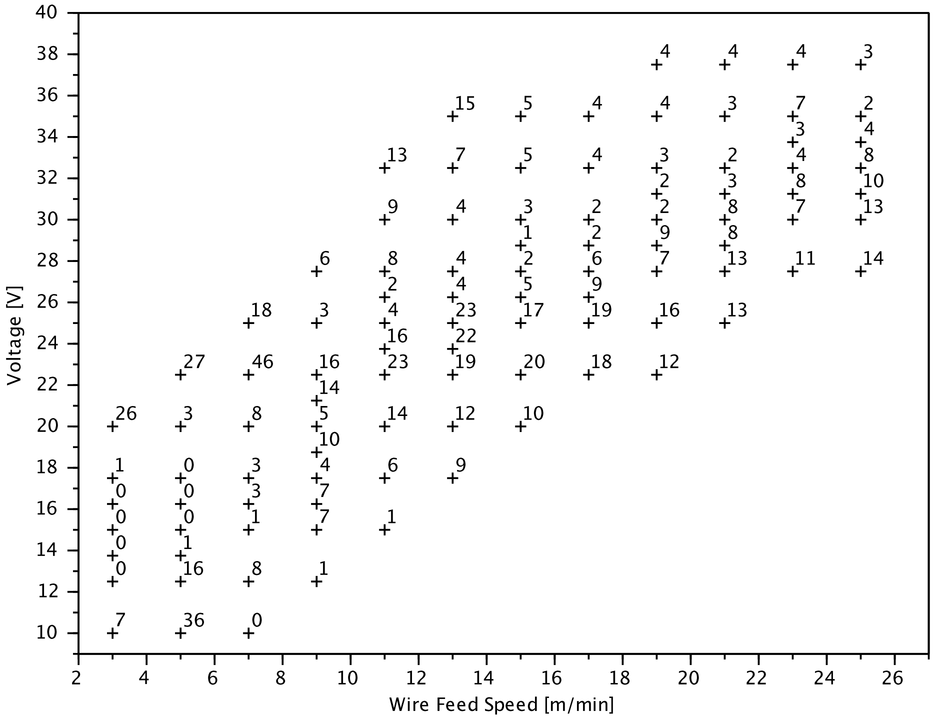

Figure 58 - Amount of current spikes [%]

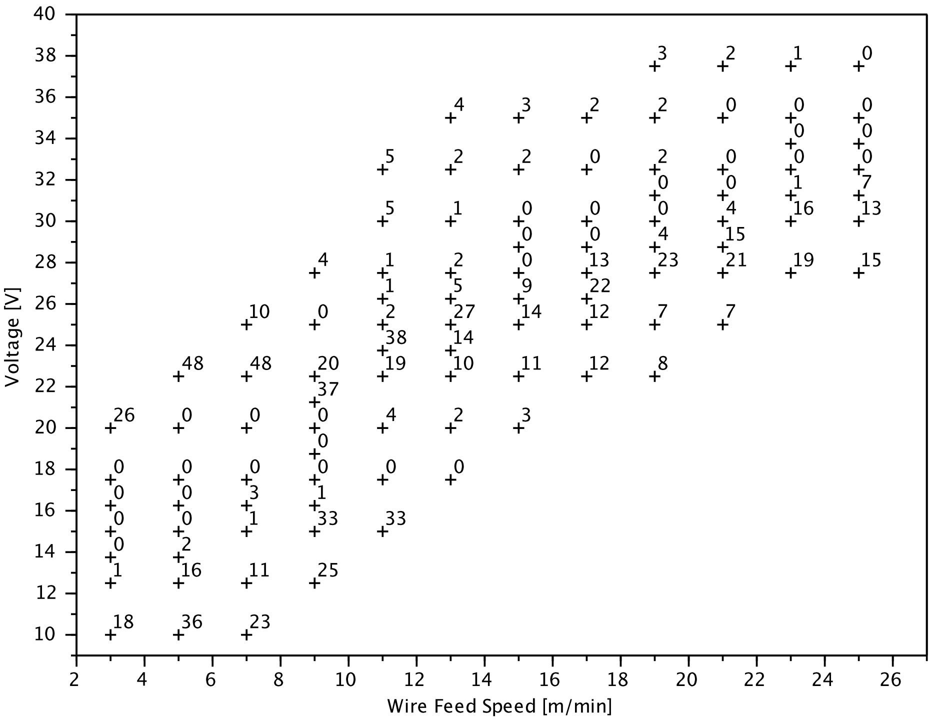

Figure 59 - Amount of power spikes [%]

The peak position for the Fourier transformed current and power data is presented in *Figure 60* and *Figure 61*.

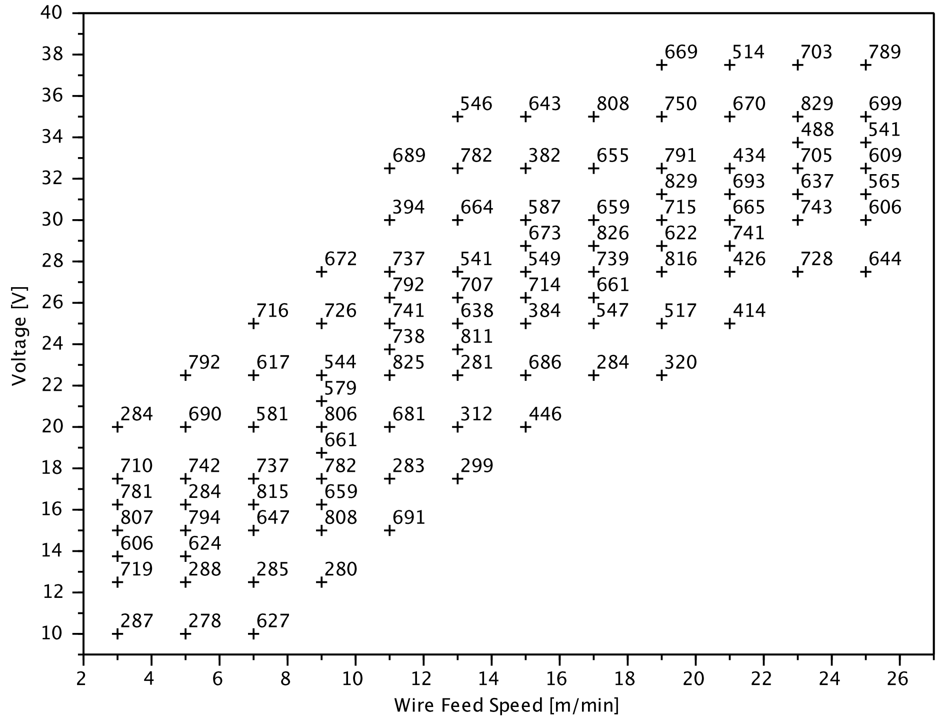

Figure 60 - Peak position of the Fourier transformed current

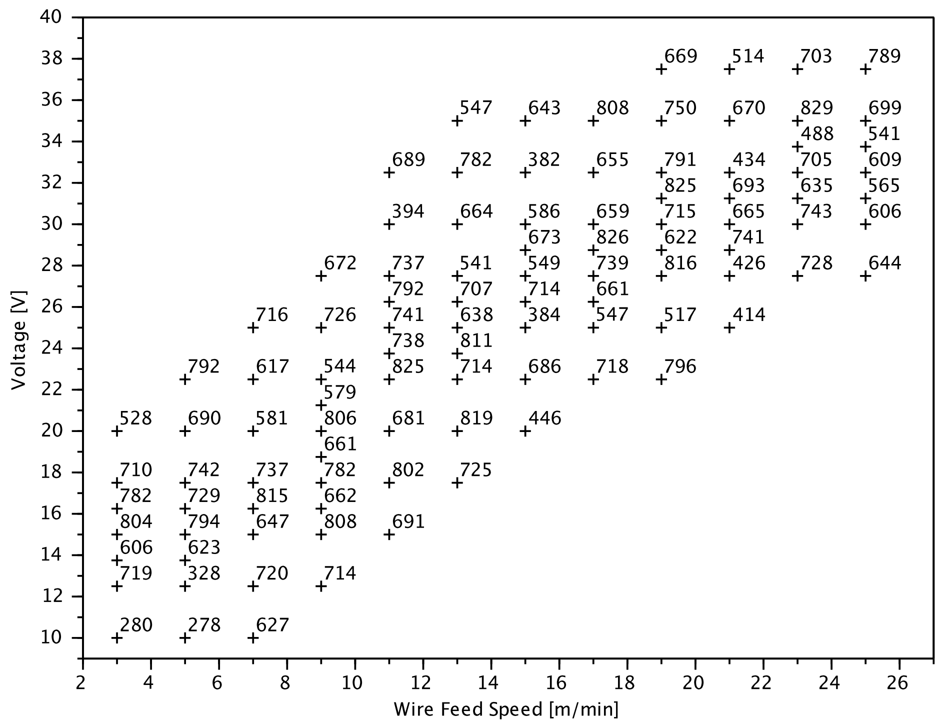

Figure 61 - Peak position of the Fourier transformed power

The amplitude of the peak in the Fourier transformed current and power data is presented in *Figure 62* and *Figure 63*.

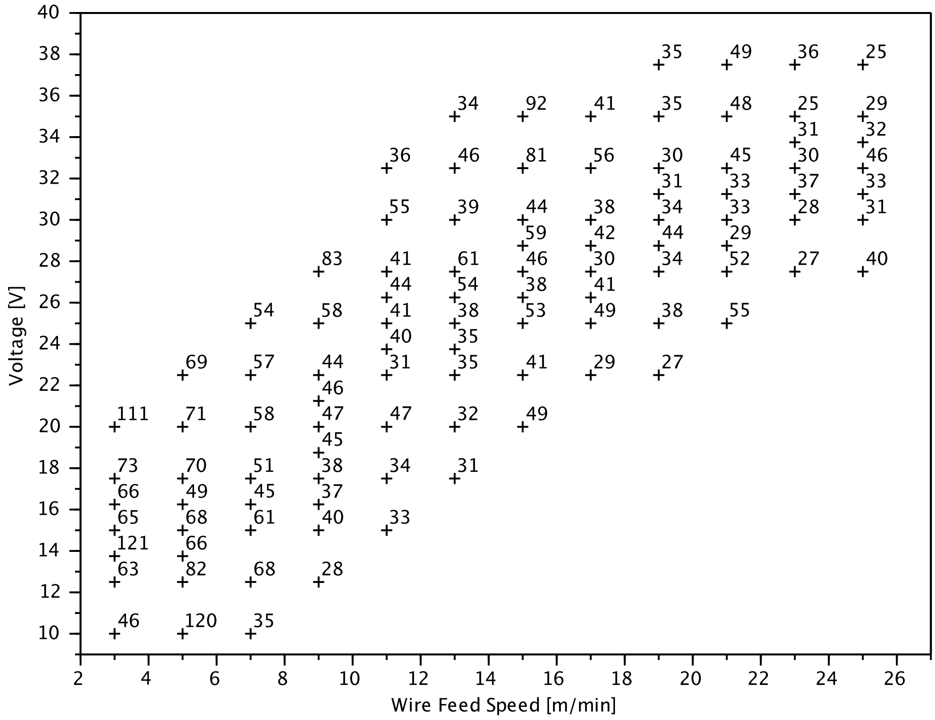

Figure 62 - Peak amplitude of the Fourier transformed current

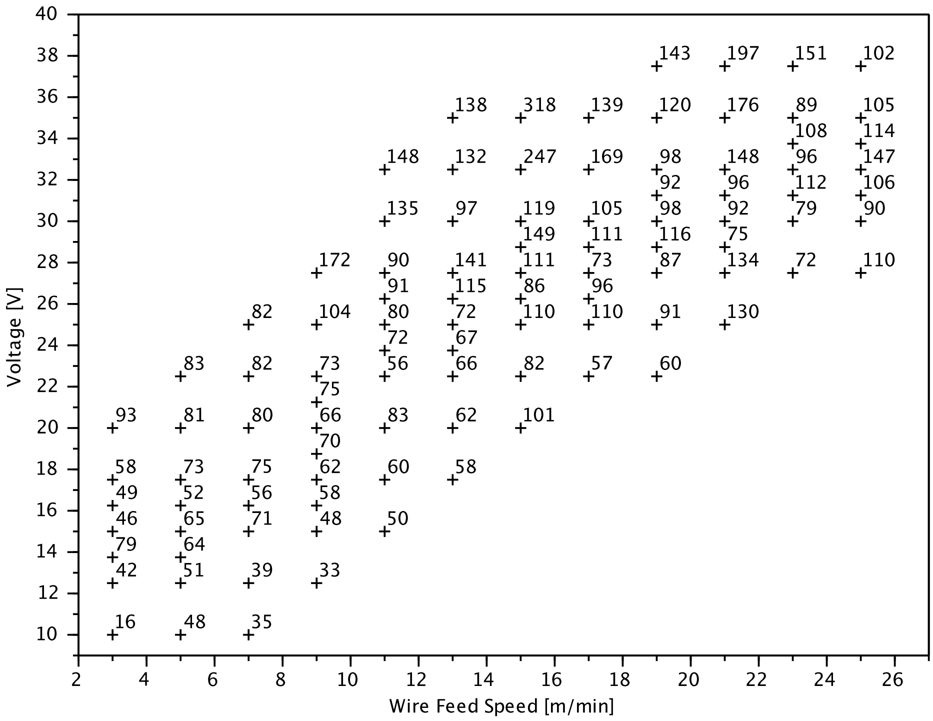

Figure 63 - Peak amplitude of the Fourier transformed power

APPENDIX B – Results from experiment 2 – weld bead measurement

This appendix presents results of the geometrical measurements from experiment 2 that not was shown in the result section. *Figure 64* shows the vertical penetration, *Figure 65* shows the horizontal penetration, *Figure 66* shows the Leg length of the equilateral triangle, *Figure 68* shows the vertical leg length and *Figure 67* shows the horizontal leg length.

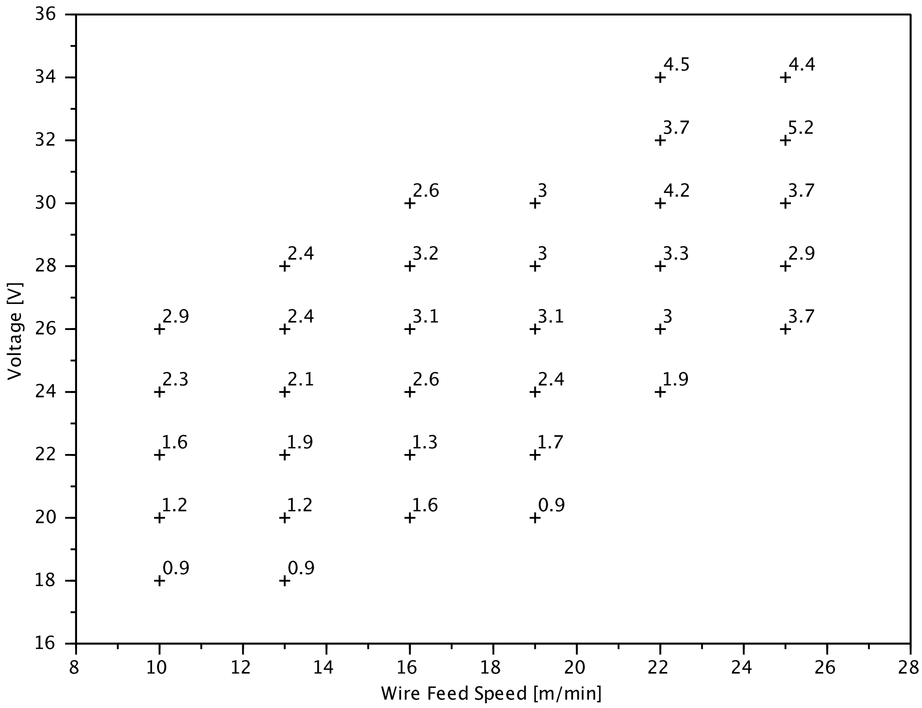

Figure 64 - Vertical penetration [mm]

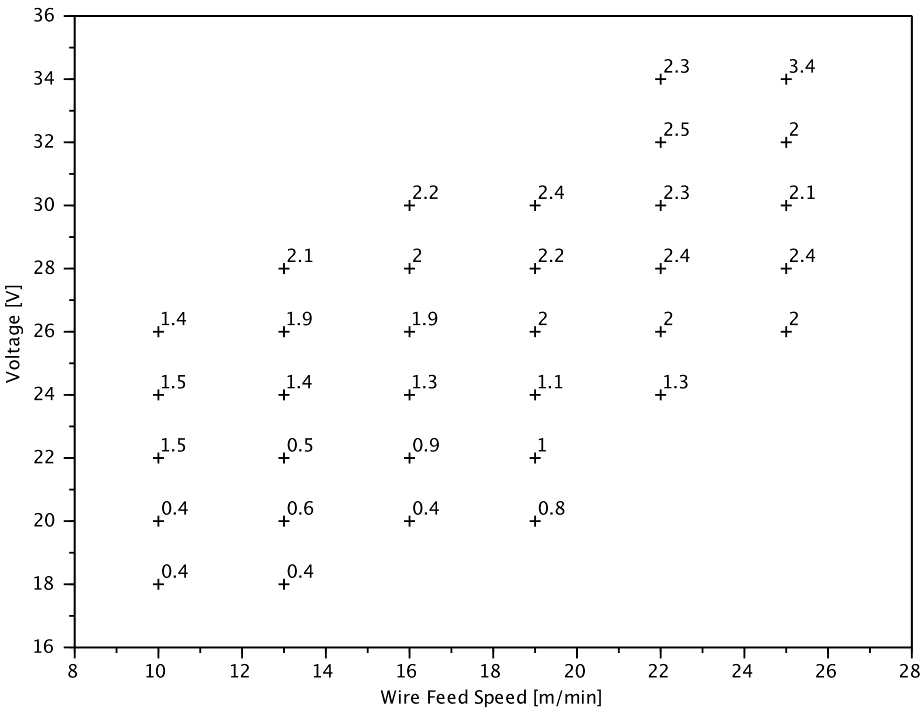

Figure 65 - Horizontal penetration [mm]

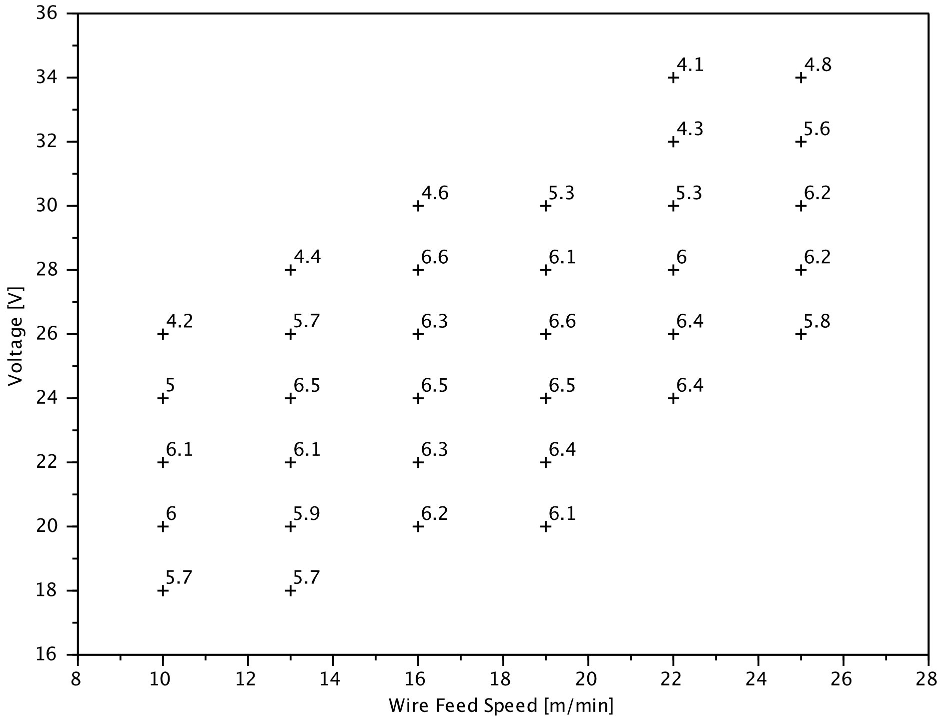

Figure 66 - Leg length of the equilateral triangle [mm]

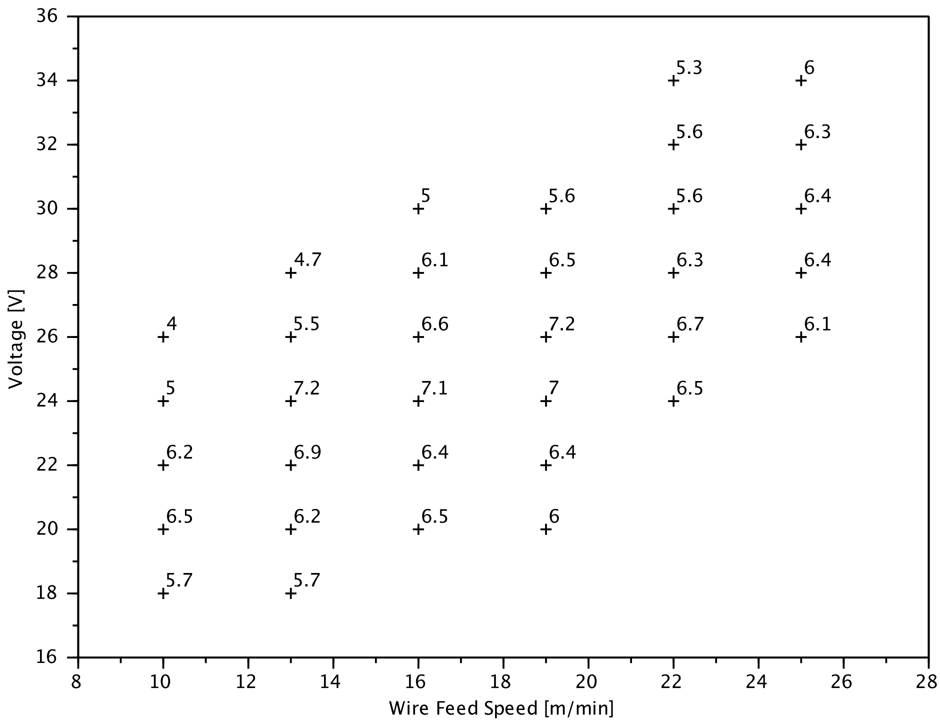

Figure 67 - Vertical leg length [mm]

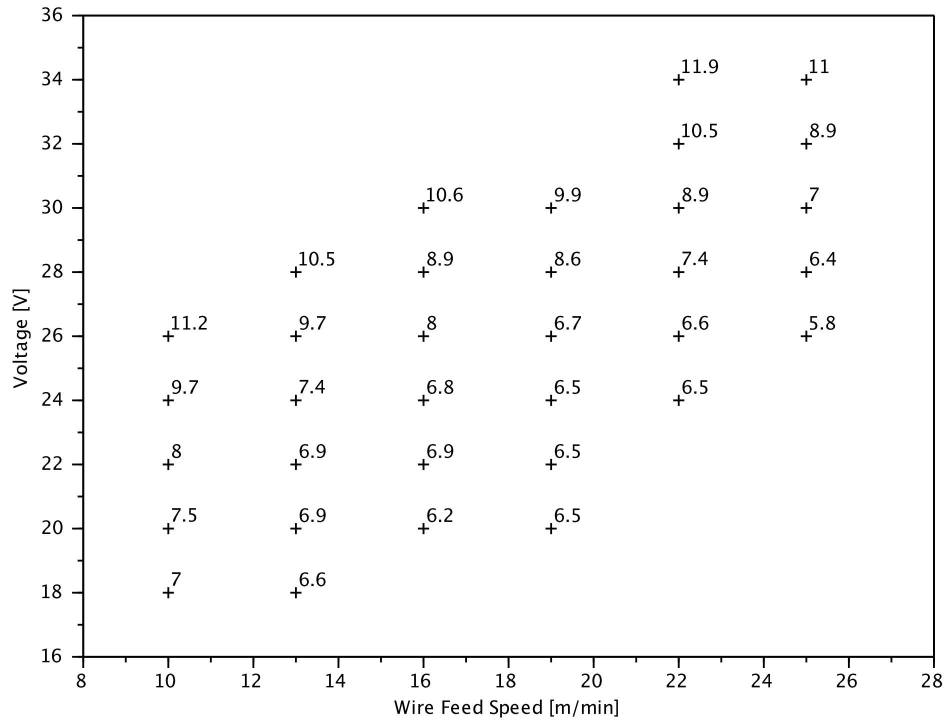

Figure 68 - Horizontal leg length [mm]