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OPTIMIZATION OF SPRAY ARC PULSE PARAMETERS IN GAS METAL ARC WELDING OF UNALLOYED STEEL

Examiners:	Docent Harri Eskelinen
	D.Sc. (Tech.) Tuomas Skriko

ABSTRACT

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Optimization of spray arc pulse parameters in gas metal arc welding of unalloyed steel

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Keywords: GMAW, pulsed gas metal arc welding, pulse parameters, weld bead formation, pulsed spray arc, weld fusion depth

The main objective of this research was to find best possible pulse parameters for Kemppi’s WiseSteel process, in order to obtain deep weld fusion. In addition to that, level of voltage, which leads to maximum fusion depth was also looked for. The aim of this research was to find the answer for the following research questions: Why and how pulse parameters of spray arc mode in GMAW affect on weld bead formation? What are the optimal spray arc pulse parameters in GMAW when aiming for deep fusion of weld? Why and how arc voltage affects weld bead formation in GMAW? What is the optimal arc voltage of GMAW spray arc mode when aiming for deep weld fusion?

This research was implemented as a combination of qualitative and quantitative research. Literature review, previously implemented test results and knowledge about the topic inside the company were used as a supportive part for welding tests. Based on them, the most promising parameters were selected under further investigation, which was done by welding tests. Wide variety of parameter set ups were welded, and the test specimen were macroscopic examined in order to get results to analyze.

Results of the research show, that all the analyzed parameters, pulse amplitude, pulse frequency and voltage, have effect on a weld bead formation. By adjusting them and keeping other parameters constant, narrower and deeper weld fusion can be obtained without having effect on throat thickness. Depth of fusion was increased 8 % comparing to WiseSteel spray arc’s default parameter settings and around 15 % comparing to conventional MIG/MAG. Based on the results, comprehensive analysis about pulse parameters and arc voltages effect on weld depth fusion was made and parameter recommendation for WiseSteel spray arc mode was given.

TIIVISTELMÄ

Lappeenrannan-Lahden teknillinen yliopisto
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Kuumakaaripulssiparametrien optimointi seostamattoman teräksen MAG-hitsauksessa

Diplomityö

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Hakusanat: MIG/MAG, pulssiparametrit, hitsipalon muodostuminen, hitsin sulautumissyvyys

Tämän tutkimuksen tavoitteena oli löytää parhaat mahdolliset pulssiparametrit Kempin WiseSteel-prosessiin, joilla saavutettaisiin hitsille syvä sulautumissyvyys. Tämän lisäksi etsittiin suurimpaan sulautumissyvyyteen johtava kaarijännitettä. Tutkimuksessa etsittiin vastauksia seuraaviin tutkimuskysymyksiin: Miksi ja miten kuumakaaripulssiparametrit MAG-hitsauksessa vaikuttavat hitsipalon muodostumiseen? Mitkä ovat optimaaliset kuumakaaripulssiparametrit MAG-hitsauksessa, kun tavoitellaan syvää hitsin sulautumissyvyyttä? Miksi ja miten kaarijännite kuumakaari-MAG-hitsauksessa vaikuttaa hitsipalon muodostumiseen? Mikä on optimaalinen kaarijännite kuumakaari-MAG-hitsauksessa, kun tavoitellaan syvää hitsin sulautumissyvyyttä?

Tämä tutkimus toteutettiin kvalitatiivisen ja kvantitatiivisen tutkimuksen yhdistelmänä. Kirjallisuuskatsaus, aiemmin suoritettujen testien tulokset ja tietämys kohdeyrityksen sisällä toimivat tutkimuksessa tukevana osana käytännön hitsauskokeille. Niiden tietojen perusteella valittiin lupaavimmat parametrit tarkempaan tutkimukseen, joka suoritettiin hitsauskokeilla. Laaja otos eri parametriyhdistelmiä testattiin hitsauskokeilla, jonka jälkeen testikappaleista otettiin makrohiekuvat tulosten analysointia varten.

Tulokset osoittivat, että kaikilla tutkituilla parametreillä, pulssiamplitudilla pulssitaajuudella ja kaarijännitteellä on vaikutusta hitsipalon muodostumiseen. Säätämällä parametrejä, saatiin aikaan kapeampi ja syvempi hitsin sulautuminen, a-mitan pysyessä samana. Hitsin sulautumissyvyys kasvoi 8 % verrattuna WiseSteelin oletusarvoparametreillä hitsattuna, ja verrattuna normaaliin MIG/MIG-hitsausprosessiin syvyys kasvoi noin 15 %. Tutkimuksen perusteella annettiin kattava analyysi pulssiparametrien ja kaarijännitteen vaikutuksesta hitsin sulautumissyvyyteen ja suositusarvot WiseSteel-prosessille.

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Joonas Karhunen

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LIST OF SYMBOLS AND ABBREVIATIONS

A_p	Pulse amplitude [A]
Ar	Argon
CO_2	Carbon diokside
CV	Constant voltage [V]
f	Pulse frequency [Hz]
I_m	Mean current [A]
PB	Fillet weld
V_s	Welding speed [mm/min]
wfs	Wire Feed Speed [m/s]

GMAW	Gas Metal Arc Welding
HAZ	Heat-affected zone
MAG	Metal Active Gas Welding
MIG	Metal Inert Gas Welding
ODPP	One drop per pulse
P-GMAW	Pulsed Gas Metal Arc Welding

1 INTRODUCTION

Nowadays there are lots of different variations for welding processes developed to find optimal solutions for customers. Gas metal arc welding (GMAW), also known as MIG/MAG-welding, which includes metal inert gas welding (MIG) and metal active gas welding (MAG) is one of the most used welding processes in different industries. Development in MIG/MAG-welding has been intensive since it was found 1948, and its process variations seems to be one of the most interesting development areas in welding. (Grill 2019).

Productivity is one of the most important aspects nowadays in welding industry, as well as in any other industries. It is a key driver for ever-increasing process developments. Basically, every welding process variation development is aiming to increase of productivity somehow. Before aiming for a maximal productivity of the welding process, certain level of weld quality has to be met and maintained through productivity developments. There are lots of different ways to improve productivity of welding, which are improving e.g. deposition rate and arc time of the welding process.

The strength of a weld joint is influenced by geometry, microstructure and residual stresses of a weld bead. Geometry of the weld bead is dictated by process parameters like welding current, voltage, welding speed, shielding gas and welding consumables. By the selection of suitable welding parameters, weld bead formation can be affected, and advantages can be achieved, effecting quality of the weld and productivity of the welding process.

1.1 Background of the research

Kemppi have multiple special processes in their product portfolio to improve their welding equipment’s’ functionality. In their Wise process family, there are five different products. One of those is WiseSteel. WiseSteel process software can be integrated with Kemppi’s welding equipment. By optimizing arc characteristics, multiple benefits can be achieved on a structural steel MAG-welding with WiseSteel process. WiseSteel can be used in a different transfer modes. Short arc, globular arc and spray arc mode. In spray arc area, WiseSteel process combines two different arc types: Spray arc and pulse arc. Average current is kept above a transition level, which makes metal transfer type to be similar than in spray arc. On top of that, micropulsing of current and voltage is added to process. (Kemppi Oy a, p.68-74.)

Less labor costs per unit of weld due to higher welding speed, less grinding costs due to low amount of spatters, less straightening costs due to low heat input. All of these are benefits that can be achieved by WiseSteel. These have major influence in productivity of the welding process. (Kemppi Oy a, p.68.)

Now in this research, WiseSteel's micropulsing in spray transfer mode is wanted to be researched more closely to find out if weld bead's fusion depth can be increased and higher welding speed can be obtained by adjusting pulse amplitude and frequency. In addition to pulse parameters, different voltage levels are also compared in order to get maximal fusion depth of the weld bead.

There is a need for this kind of research. Multiple theoretical and experimental researches have been made to investigate the influence of pulse parameters effect on weld bead formation, but no common understanding have been found (Ghosh 2017, p.111). On top of that, special characteristics of WiseSteel makes predictions based on theoretical information even harder and unreliable.

Because of complex nature of pulse parameters' influence on weld bead formation, integration of existing scientific information to this research is challenging. Most of the researches made pertaining the topic, those handles different amplitude range and frequency level comparing to this research's scope. Other reason for small amount of publicly shared suitable data is most likely this: Welding equipment manufacturers and process developers, who are most likely the ones who are doing the research about the topic, have naturally interest to keep the knowledge inside a company and not to share it, when competitors could get an advantage of it.

Multiple databases were used for information search. One of the databases that was used, is Scopus. One scopus-search was done by using following keywords: "P-GMAW" OR "pulsed gmaw" OR "pulsed mag" OR "pulsed mig" AND "weld bead" OR "weld geometry"

OR “weld penetration” OR “bead formation”. Number of found documents is 102. (Search done 4.2.2020) When Scopus-search was done by using otherwise same keywords but adding “pulse frequency” by operator “AND”, number of found documents decreased from 102 to 14. It indicates that pulse frequency’s influence on weld bead formation is not widely research.

As said, prediction of pulse parameters effect on weld bead formation is hard to do. Even though in this process variation current is pulsed, type of a metal transfer is really close to spray arc’s metal transfer instead of pulse arc’s metal transfer. Because of that, comparison to conventional pulse arc’s pulse parameters influence on weld bead formation may not be suitable. That’s why importance of practical welding tests with wide variety of parameter values is huge in this research, and applicability of existing scientific information may be relatively low.

1.2 Objective of the research

The goal of this work is to find correlations between pulse parameters of WiseSteel process in spray arc mode, and formation of weld bead geometry. Based on the found correlations, adjust pulse parameters optimal way in order to achieve maximum fusion depth of a weld bead without causing any disadvantages. Adjustable pulse parameters are pulse frequency and amplitude of pulse. In addition to pulse parameter adjustments, adjustment of arc voltage is done as a secondary objective of the work.

The goal is to improve existing process significantly enough, that it is worthwhile to utilize found process parameters in products in a future and productivity of WiseSteel process will be further increased. It’s known that depth of penetration increases along with welding speed up to certain point and starts to decrease after that. Those aspects need to be handled together, knowing that they are dependent on each other.

After the research is done and if improvement for existing process is achieved by parameter adjustments, decision have to be done, how to take maximum advantage of new findings. For instance, different welding positions and joint types, where benefits of deep fusion of a weld bead can be achieved, are looked for. In the case of robot welding, deep fusion of weld may be used to increase welding speed without risk of incomplete penetration or lack of fusion.

In this work, answers for following primary research questions will be researched:

- Why and how pulse parameters of spray arc mode in GMAW affect on weld bead formation?
- What are the optimal spray arc pulse parameters in GMAW when aiming for deep fusion of weld?

In addition to primary research questions following secondary research questions considering arc voltage are set:

- Why and how arc voltage affects weld bead formation in GMAW?
- What is the optimal arc voltage of GMAW spray arc mode when aiming for deep fusion of weld?

It is believed that after finding optimal values of pulse parameters and arc voltage, increase in weld depth fusion compared to current WiseSteel process can be achieved.

1.3 Research methods

The research is executed as a combination of qualitative and quantitative research. Qualitative literature search is made at the beginning, to find scientific explanation behind the happening phenomenon. Why and how welding parameter value changes effect on arc characteristics, fluid flow of molten pool and metal transfer, and why and how they effect on weld bead geometry? In addition to that, purpose of the literature review is to find studies made pertaining to the topic, which could be compared to results of this research. On top of the search of external sources of information, knowledge, experience and existing test result data inside the company pertaining the same topic are studied and considered when deciding pulse parameters for the practical welding tests.

Quantitative part of research is implemented as a practical welding tests in laboratory environment. Welding tests are done by using a mechanized weld torch carrier. After welding, welded specimens are macroscopy examined. Cross-sectional area of the weld bead geometry will be examined from a macroscopy images, and measures of fusion depth in different directions can be seen. During the welding tests, oscilloscope is used to measure signals of voltage and current levels, in order to obtain accurate values and notice differences in short-circuit occurrences. Finally, results of the macroscopy images are compared to parameter changes and conclusions are made based on them. In image 1, there is schematic presentation of the research methods.

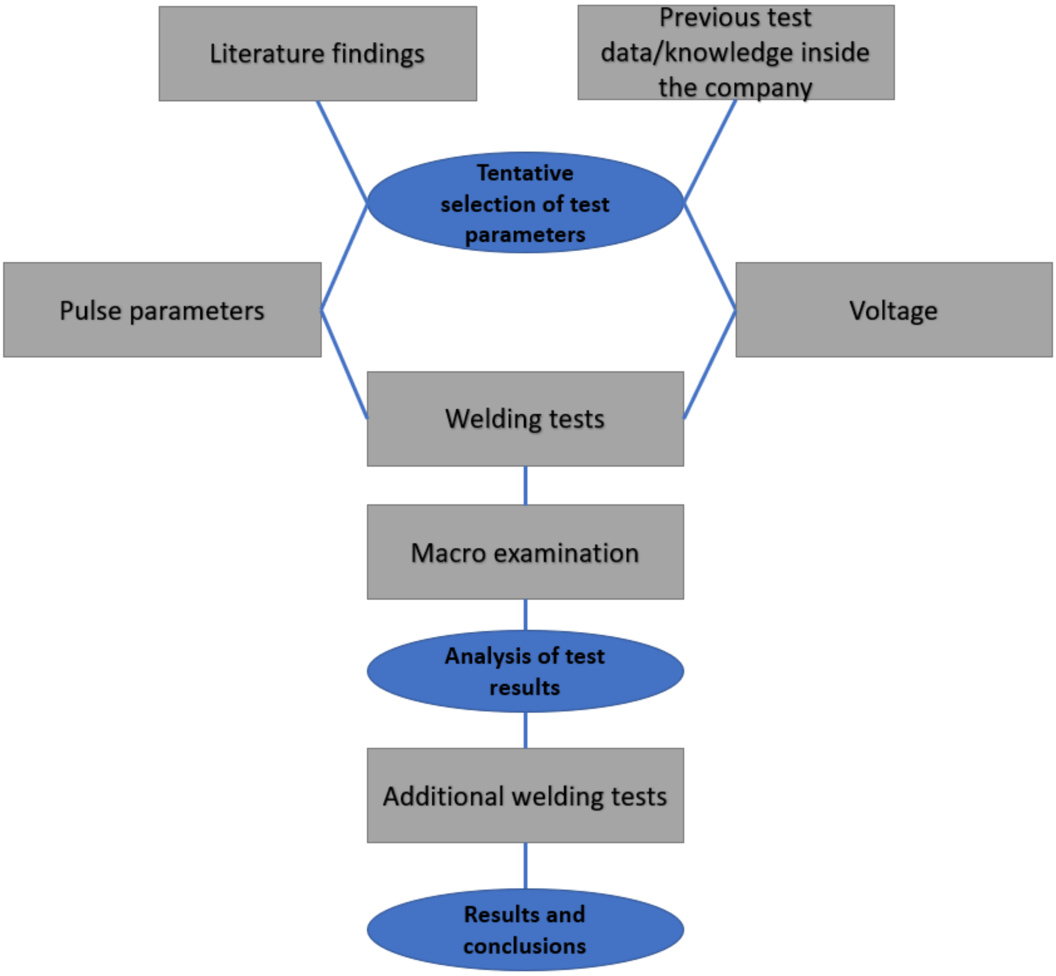

Image 1. Implementation of the research.

1.4 Reliability of the research

Due to simplicity of macro examination, reliability and validity aspects of research should not be concern. Reliability and validity analysis will be taken care of by macroscope, which is relatively easy to use and get accurate enough results about a weld bead shape dimension. One decimal of millimeters in the weld bead geometry will be measured and can be considered accurate enough. In addition to relatively simple and straight forward nature of macro examination, experience inside the company brings lots of reliability to this research.

As research is done in facilities of Kemppi, where help and opinions can be asked from experienced professionals of welding, risk of unreliable test implementation is low.

Saturation analysis of the research instead, have to be taken under closer focus. Wide variation range of parameter values are used. To tackle the concerns about insufficient amount of data, large number of tests will be done. Every parameter set up will be repeated twice, and average value of them will be used test result comparison.

In this research, used plate thickness will be 6 mm and joint type will be T-joint fillet weld. Welded material will be unalloyed structural steel S355. Because of the material selection, detrimental effects of welding heat input for material’s microstructure can be considered minor and will not be investigated. Welding tests will be done by using Kemppi’s X8 MIG welder welding machine. Results of the research have to be viewed critically, because applicability of test findings for other welding machines will not be tested and so on cannot be guaranteed. The research scope is set to focus on WiseSteel process’ functions in spray arc mode. Other arc modes, short and globular arc are scoped out of the research.

2 DEVELOPMENT OF GMAW PROCESSES

This chapter takes a look at few major productivity developments of GMAW. Mechanization/automation of welding, multi-wire processes and power source developments are handled briefly. Driver factors behind the development and things that are enabling them are put under the focus. At the end of the chapter, Kemppi's Wise products and their applications are introduced.

2.1 Major productivity developments of GMAW

Lots of different process variations have been developed to increase productivity of welding. Many of developed process variations are aiming for increase of productivity by increasing arc time and deposition rate. Three different development areas are discussed and introduced next. Those are mechanization/automation of the process, multi-wire processes and power source development.

2.1.1 Mechanization/automation of a welding process

Mechanization/automation can be applied to welding production in different levels. Highest level of automation is the use of robots with adaptive welding systems. Entire robot welding cell consist of not just robot but can also have for example trail for the robot and turning table for a workpiece to increase flexibility of the process. From economical point of view, relatively big number of welded units makes it profitable, because of the cost of programming and manufacturing of the jig. (Weman 2012, p.161-162.)

Benefits of robotization are very effective way to improve productivity by decreasing off-arc time, increasing welding speed, securing constant high quality, as well as decreasing labor costs. Duty cycle tells the ratio of arc time and total labor time in workday. Level of automation has the biggest influence on duty cycle, which increases along with level of automation. As a drawback can be mentioned, that lots of training for programming and service is needed and closer tolerances for workpieces are needed. (Weman 2012, p.161-162.)

2.1.2 Multi-wire processes

Different multi-wire variations in GMAW are developed in order to obtain higher deposition rate and speed of welding. That kind of process variations are for example twin-wire welding and tandem welding. Application, where both wires are connected and controlled by same power source, is called twin-wire welding. Same arc is melting both wires, which increases deposition rate comparing to conventional GMAW. Different than twin-wire, tandem welding uses two separate power sources. Even both wires have own power source, they are so close to each other, that there is only one weld pool. (Weman 2012, p.80.) In image 2, there is presentation of MIG/MAG tandem welding.

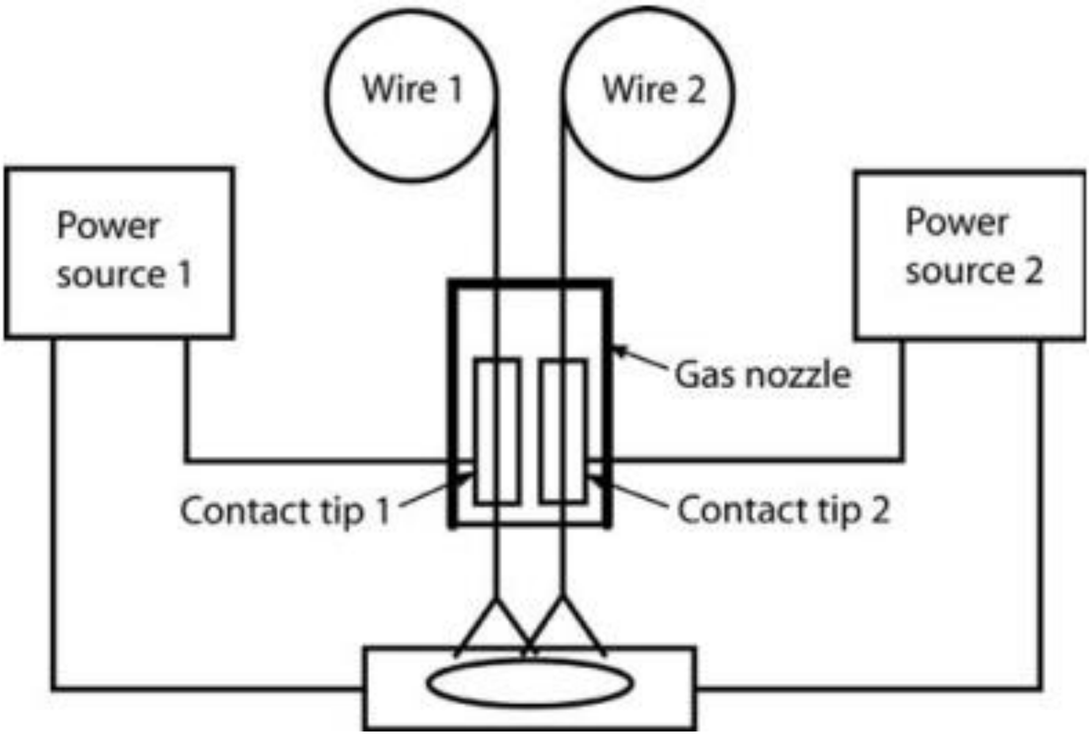

Image 2. Presentation of MIG/MAG tandem welding (Weman 2012, p.80.)

2.1.3 Development of power sources

In last decades, development of power sources has enabled progress of more versatile equipment in GMAW. Due to development of the power sources, tailored welding processes and functions are done to make welders' jobs easier and increase productivity of MIG/MAG-welding, as well as other welding processes. Software based programs can be integrated to welding machines. With a help of highly developed electronically controlled power sources, really accurate and specific parameter adjustments are possible to achieve and keep process steady. (Anderson 2010, p. 129-130.)

In pulsed arc welding, functionality of power source is really important. Power supply and wire feed unit are controlled by microprocessors keeping process stable. Different combinations of arc types, so called double processes can be done. For instance, pulse/short arc and pulse/spray arc, which combines constant current periods and pulse current periods into same welding program, are possible to create when aiming for optimal process for each application. (Anderson 2010, p. 129-130; Lukkari 2002, p.87.)

2.2 Kemppi Wise processes

As mentioned above, development of power sources and software programs have enabled more specific and versatile control of welding parameters, which is used in developments of welding process variations. In addition to WiseSteel process, there are four other Wise processes: WiseRoot+, WiseThin+, WisePenetration and WiseFusion. Following subchapters are introducing characteristics of Wise processes, and applications they are meant to be used in.

2.2.1 WiseSteel

Latest product variation of the Wise family is WiseSteel. When welding mild steels, improvement of efficiency and reduction of spatters can be obtained by using WiseSteel. WiseSteel can be applied to different transfer modes, short arc, globular arc and spray arc. (Kemppi Oy a, p.68.)

In short-circuit transfer mode, WiseSteel improves stability of the arc, which eases welding especially in out-of-position. Arc is controlled actively by voltage level, which controls length of the arc and short-circuit ratio in process. Adaptive arc ensures less spatters in process, better control of the weld pool and softer arc. In globular arc, welding power is pulsed between short arc and spray arc, averaging globular arc values. With the help of pulsing, spatters, which are disadvantage of traditional globular arc, can be reduced. Control of a weld pool is also improved by WiseSteel in globular arc. (Kemppi Oy a, p.69-73).

Spray arc mode, which is under the focus of this research, consist of micropulsing of the current and voltage. Micropulses are improving weld pool control and lowering welding power comparing to normal spray arc welding. Length of the arc is kept optimally short and focused, which creates higher intensity of the arc. Adaptive arc length is obtained by other Wise process, WiseFusion, which is integrated in WiseSteel. WiseFusion process is introduced in the next subchapter. In image 3, there is comparison of current and voltage curves of standard MIG/MAG and WiseSteel spray arc. (Kemppi Oy a, p.74).

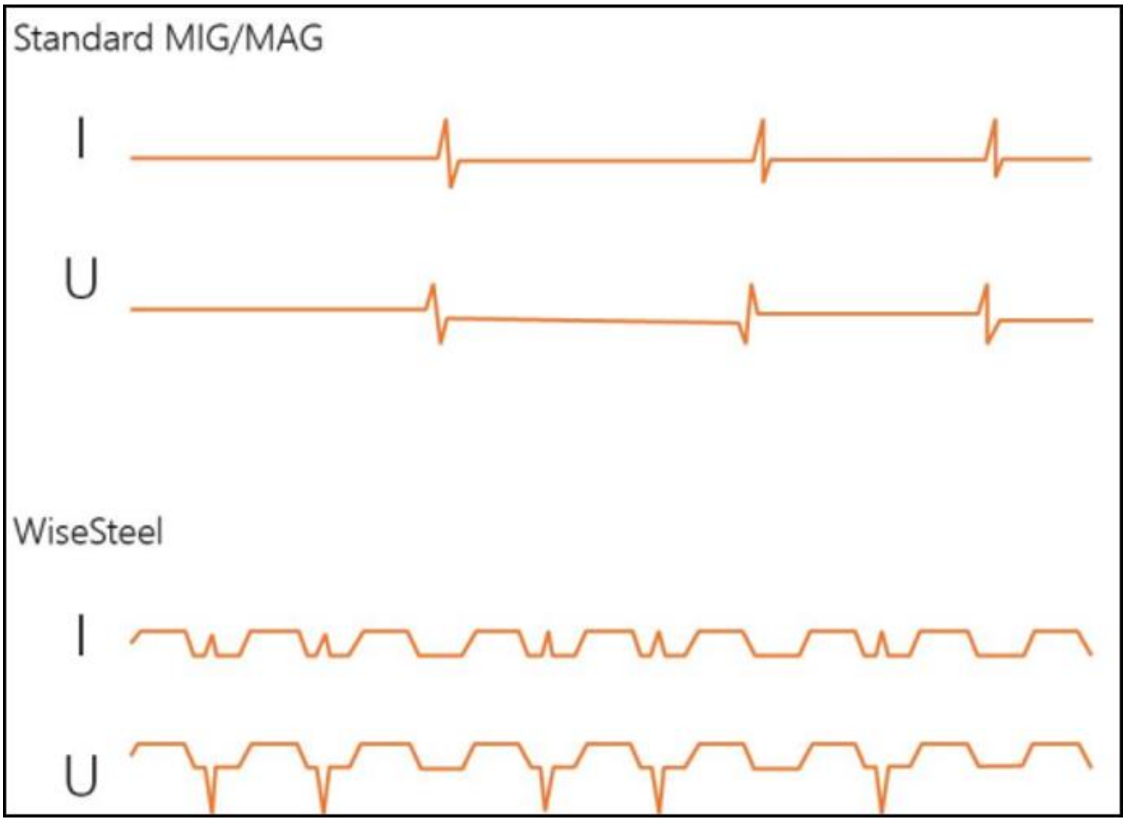

Image 3. Current and voltage curves of standard MIG/MAG and WiseSteel. (Kemppi Oy a, p.74).

WiseSteel in spray arc mode creates deep and narrow penetration with relatively low heat input. Because of that, higher welding speeds can be used without a risk of lack of fusion. On the other hand, more focused and narrower weld bead may require more accurate positioning of a weld torch.

2.2.2 WiseFusion

WiseFusion is process variation for pulse and synergic GMAW, which optimizes arc length.

With the help of WiseFusion, arc length stays short and concentrated due to adaptive control. System recognizes short-circuits and keeps arc level there. WiseFusion defines metal transfer type of the process. Some of the transfers happens by short-circuiting and some of them in open arc. Ratio of short-circuiting and open arc metal transfers can be adjusted by user by fine tuning. (Kemppi Oy a, p.60-62.)

WiseFusion is great process to ease welding in challenging positions. WiseFusion can be used in all arc types. Due to short and energy intense focused arc, deep and narrow penetration can be obtained. Because of that, also higher welding speed can be obtained with smaller risk of lack of fusion. Shorter arc also means lower voltage, which decreases heat input of the process. Due to lower heat input, residual stresses may be reduced. Residual stresses could decrease strength of the weld joint. Lower heat input may also prevent deflections of the welded structures. (Kemppi Oy a, p.61-63.) However, as mentioned in previous sub-chapter, narrower weld bead may require more accurate positioning of a weld torch.

2.2.3 WiseRoot+

WiseRoot+ is modified short-circuiting arc process, which is designed for root pass welding in GMAW. Digitally controlled voltage and current makes process stable and almost spatter free. It produces excellent quality of a weld and improves efficiency of the welding. (Kemppi Oy b, p.1-7.)

WiseRoot process is divided to two periods, short-circuit period and arc period. In the short-circuit period, when tip of a wire touches workpiece, current level is rapidly raised to level where pinch-power detaches droplet to weld pool. Detachment of a drop happens in lower current than in normal short-circuit process, which makes metal transfer smoother and creates less spatters. After that, current level is decreased before arc period. In arc period, current is raised up again, not to detach new drop, but to form a molten weld pool. Image 4 below presents principle of WiseRoot process. (Kemppi Oy b, p.4.)

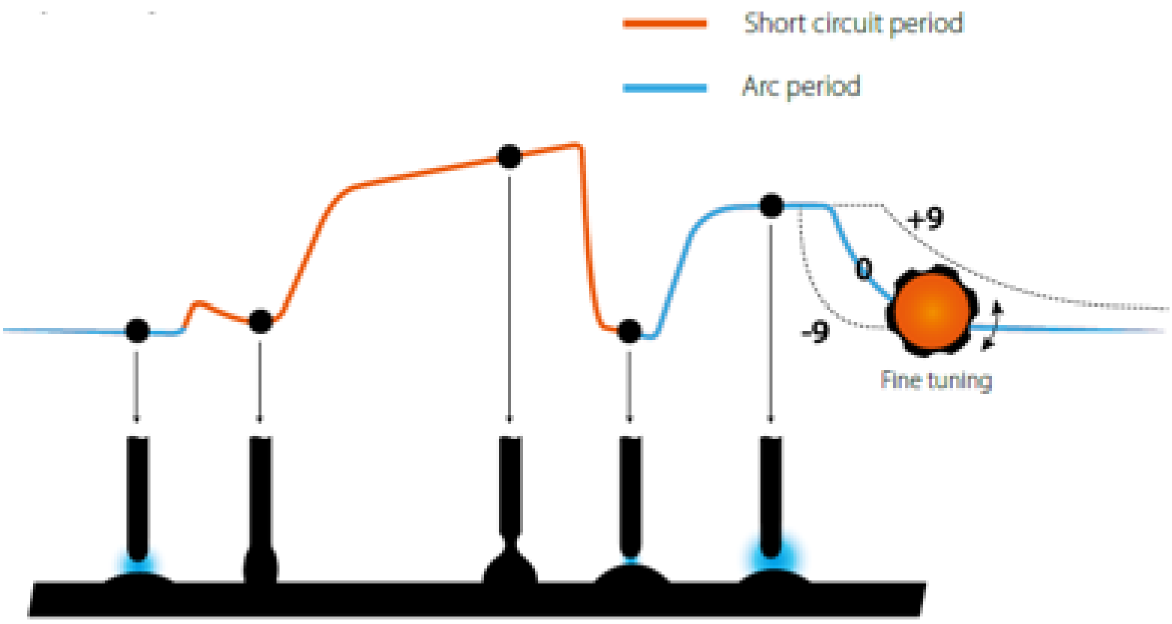

Image 4. WiseRoot+ process current curve (Kemppi Oy b, p.4).

In addition to less spattery process, WiseRoot+ has also other benefits. It is suitable for all positions, it is easy of learn and use and it allows the use of a wide root gap and makes possible to decrease groove volume. (Kemppi Oy b, p.5-6)

2.2.4 WiseThin+

Principle of WiseThin+ process is same as in WiseRoot+, but it is intended for thin material thicknesses. When welding thin materials, it is crucial to keep heat input of a process low enough. Comparing to conventional GMAW short arc process, heat input can be decreased by -5-15 % by using WiseThin process. Low heat input decreases deformation of welded parts which decreases need for after work. (Kemppi Oy c, p.3-7.)

Laser welding is widely used process for thin metal sheets due to its accurately focused laser beam and low heat input. However, relatively precise air gap tolerances for laser welding may cause some problems. Those tolerance areas are wider in GMAW, which makes GMAW with WiseThin+ function good alternative. WiseThin is fits for different position welding.

2.2.5 WisePenetration

Constant voltage (CV) is commonly used characteristic of GMAW processes. There is self-regulating arc, which means, that even stick-out length increases, voltage stays constant. However, increase of stick-out length decreases welding power because decrease of welding current. Decrease of current due to stick-out length increase most likely causes some severe welding defects, like lack of fusion and incomplete penetration. It may also cause more spatters in welding, as lower current decreases welding power, which may change arc type from spray arc to globular arc. (Kemppi Oy d, p.3-5.)

These problems can be avoided by using WisePenetration. WisePenetration recognizes changes in stick-out length and keeps current level constant by adjusting wire feed speed (wfs). Current level can be selected by user. WisePenetration process is useful especially in manual welding, when in some challenging cases keeping stick-out length constant is really hard even for skillful welder, but also in mechanized/automized welding processes may achieve benefits by using it. (Kemppi Oy d, p.8-10.)

2.3 Summary of productivity developments in GMAW

In this chapter, productivity developments in GMAW were introduced. Three main groups were selected, which are automatization/mechanization of a welding process, multi-wire processes and power sources. The topic of this research is closely to power source development. In WiseSteel, as well as other Wise processes, development of power sources have been enabled their development. With help of highly developed control from power source, arc characteristics can be modified to different applications.

3 METAL TRANSFER AND ARC TYPES OF GMAW

In gas metal arc welding, there are four basic arc types, which are determined by the type of metal transfer from consumable to workpiece. These arc types are short arc, globular arc, spray arc and pulsed arc. Arc type and its characteristics are mostly determined by welding current, arc voltage and shielding gas. Each arc type has its own advantages. Selection of an arc type in welding process depends on application. Things that effect on arc type selection can be material type, material thickness, welding position. (Tawfik 2012, p.5-6.)

On top of the basic arc types, lots of welding process variations are developed by combining and adjusting basic arc types during the past decades when power supplies have enabled that. This chapter introduces characteristics of basic arc types and compares them to characteristics of WiseSteel process in spray arc mode.

3.1 Short arc

In short arc, also known as short-circuiting arc, welding voltage and welding current are relatively low. Metal transfer happens with the help of short circuit. At the beginning, arc period, tip of the wire and base material are both melting. In next phase, tip of the filler wire dips into the weld pool, which creates short-circuit bridge and turns off the arc temporarily. Then current starts to increase due to short-circuit, and eventually detaches the droplet and re-ignites the arc. (Lukkari 2002, p.168.)

Excessive increase of the current is restricted by inductance. Otherwise it would raise too high, which would lead to creation of spatters. Short circuit cycle happens very rapidly, 30-200 times/second. Due to its low voltage and current, short arc has low heat input and weld pool is small and easily controllable. Therefore, short arc is applicable for welding sheet metals, root openings and different welding positions. (Lukkari 2002, p.169; Lepola & Ylikangas 2016, p.81.) Image 5 presents metal transfer steps in short arc welding.

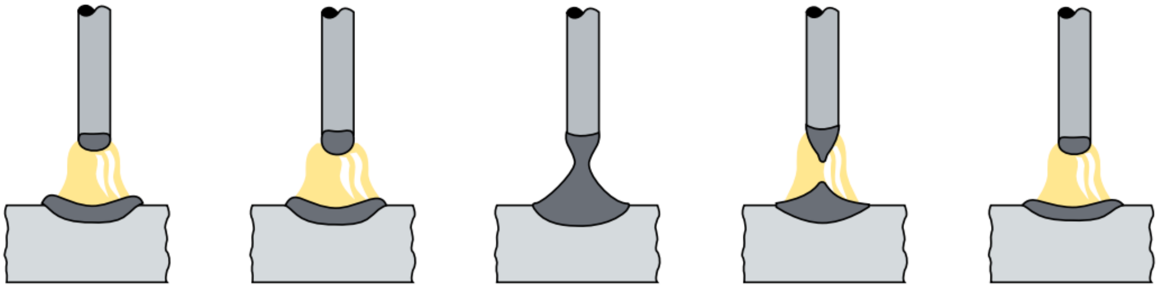

Image 5. Short arc metal transfer steps (Kuusisto 2014, p.16).

3.2 Globular arc

Globular arc is area of arc energy between low energy short arc and high energy spray arc. Metal transfer in globular arc is combination of short-circuit and spray arc. Short-circuits are not as controlled as in short arc, and they cause lots of spatters. Due to its great amount of spatters, globular arc welding should be avoided if possible. Sometimes, when short arc is not powerful enough and spray arc is too powerful for an application, globular arc is most suitable. Globular arc is mostly used in vertical down and horizontal welding. (Lukkari 2002, p.169; Lepola & Ylikangas 2016, p.81.)

3.3 Spray arc

In spray arc mode, arc power is great enough to keep arc burning continuously without short circuit periods. Spray arc has big welding power, which means high deposition rate and deep weld penetration. Due to its big weld pool, spray arc isn’t suitable for position welding. Spray arc mode welding is usually applied for thick materials. Electromagnetic power pinches droplets off from tip of an electrode before they are attached to workpiece and cause short-circuit. The greater the welding current is smaller are droplet sizes and transfer frequency is higher. (Lukkari 2002, p.169.) Image 6 shows the principle of metal transfer in spray arc mode.

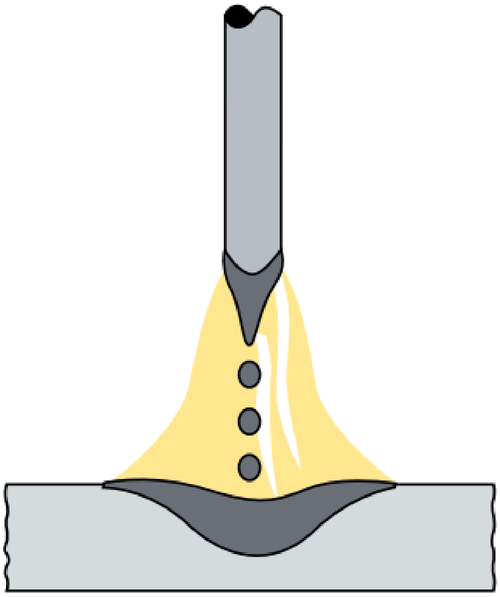

Image 6. Metal transfer of spray arc (Kuusisto 2014, p.17).

Transition current is important level of current in welding process. Exceeding transition current, droplet size decreases and droplet detachment frequency increase significantly. That is the point where arc type changes from globular to spray arc. Things that effect on level of transition current are consumable diameter, consumable material and shielding gas. For instance, when using in Ar+CO_2 -gas mixture, higher is CO_2 -content of the mixture, higher is the transition level. The bigger is diameter of wire, the bigger is transition current. Less alloyed material is, higher is transition current. For instance, unalloyed steel has higher transition current than stainless steel and stainless steel has higher transition current than aluminum. Anyways, transition current value is not precisely definable because also voltage, tip distance, welding speed and welding torch angle have minor effect on transition current. (Lukkari 2002, p.170.)

3.4 Pulsed arc

In pulsed arc, current level varies. There is constant base current, which keeps arc burning, a filler wire heated and weld pool molten but not great enough to detach a drop. Then high current pulse occurs, and melts preheated drop. Pinch-power grows due to current pulse and detaches a drop to molten weld pool. Pulsed arc welding requires special power source to supply different levels of current and changing between them. The first pulsing power source for welding was developed 1960s. After that development have brought markets more and more advanced power sources that enables variate pulsing programs. (Anderson 2010, p.190;

Lukkari 2002, p.171-172.) Image 7 shows the principle of current pulses and metal transfer of one drop per pulse (ODPP) pulsed arc welding, which detaches one drop in every peak current pulse.

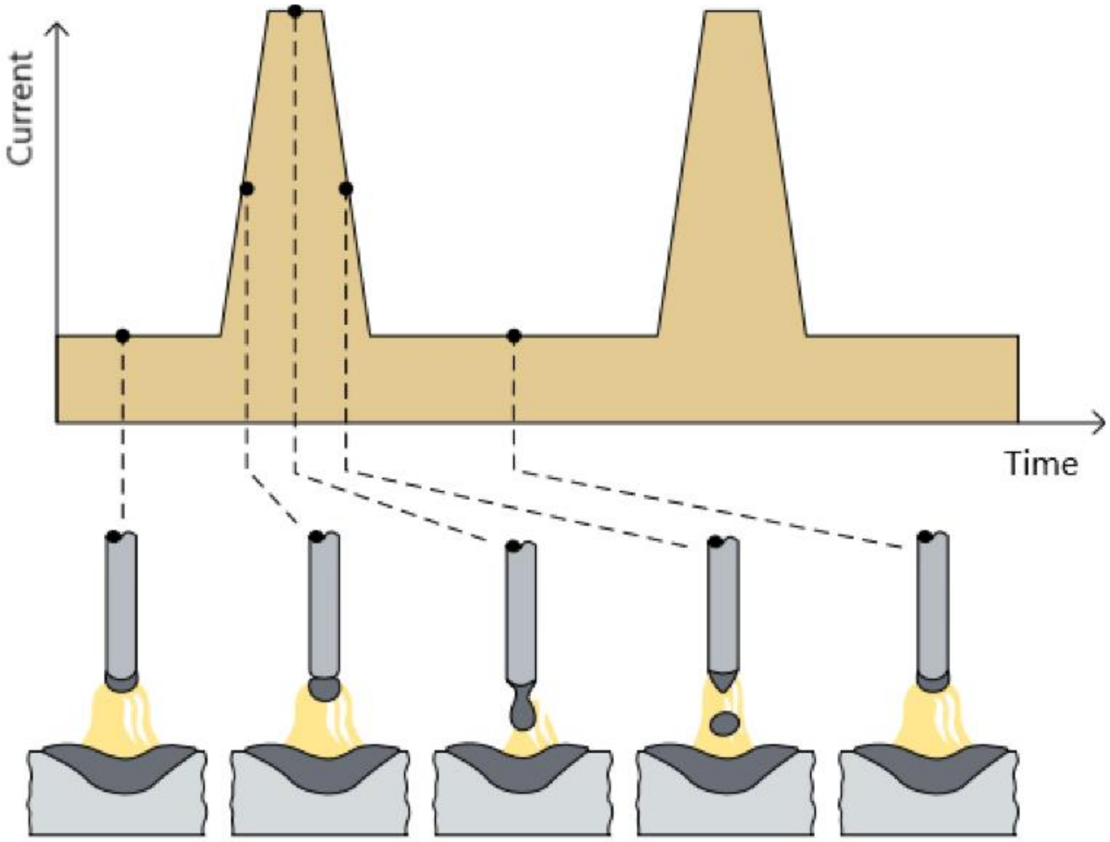

Image 7. Current curve and metal transfer of ODPP pulsed arc (Kuusisto 2014, p.18).

With help of peak current, peak time, base current and base time, pulse frequency and pulse amplitude can be calculated. Change of current between background level and peak level doesn't happen immediately but takes some time. It is depended on power sources capacity and settings. As well as speed of current change, also shape of the current curve it can be affected by dynamics of power source. By the shape current curve, shape of a bead and sound of arc can be affected.

By using pulsed arc, multiple advantages can be achieved over other arc types. In pulsed arc average current of welding process is below transition current. That means also heat input is relatively low in that process. Due to low heat input, welding stresses and distortions are lower. Regardless of relatively low heat input, deep weld bead penetration and high welding speed can be achieved due to current pulses, which is usually obtained by higher heat input. Other advantages of pulsed arc are good possibilities in different welding positions, low amount of spatters and visually good welds. (Lepola & Ylikangas 2016, p.30; Lukkari 2001, p.172.)

The most common application for Pulsed-MIG/MAG-welding is MIG-welding of aluminum, but advantages can be also achieved with different types of steels. With the help of solid-state devices and computers, pulse welding power supplies are designed the way that pulsing parameters can be varied over a wide range. By adjusting parameters independently, different pulse welding programs can be developed to achieve best possible settings for different applications. (Anderson 2010, p.129.)

3.5 Metal transfer and arc type of WiseSteel spray arc

As mentioned before, Spray arc mode of WiseSteel process is combining two basic arc types: Spray arc and pulse arc. Average current level is kept above the transition current in spray arc area and micropulsing of the current is added on that.

However, even conventional spray and pulse arc modes should be practically short-circuit free arc modes, there still are some short-circuits occurring in WiseSteel spray arc mode. That’s because WiseFusion function is integrated into WiseSteel process. WiseFusion, which adjusts arc length by adjusting voltage level low enough that short-circuits occur. With the help of shorter and better focused arc, intensity of arc’s power is more accurately focused to corner of a fillet weld.

Metal transfer type of WiseSteel spray arc is presumably very close to normal spray arc, which creates spraying flow of droplets. However, difference to conventional spray arc is made by controlled amount of short-circuits and micropulses, which may have some influence on metal transfer. Those things together have effect on weld bead formation.

3.6 Summary of metal transfer and arc types

Arc types in GMAW are defined by the type of metal transfer mode from filler wire to weld pool, which is mostly influenced by welding voltage, current and shielding gas.

Conventional arc types are short arc, globular arc, spray arc and pulsed arc. Different special welding processes can be combinations of conventional arc types. WiseSteel’s spray arc mode is that kind of process, which is combining characteristics of short-circuiting arc, pulsed arc and spray arc.

4 WELD BEAD FORMATION IN GMAW

Welding process parameters are affecting weld bead formation, each parameter different way. In addition to explain how some parameter change effects on weld bead formation, it is important to understand reasons behind phenomenon. This chapter introduces those effective the phenomenon. Conventional process parameters are introduced and discussed. Found example cases about pulse parameters' effects on weld bead formation are introduced and results of them are discussed. As mentioned in introduction chapter, multiple attempts have been made to predict a weld bead geometry in pulsed gas metal arc welding by mathematical models. However, due to high complexity of pulse parameters' effects on geometry, generally applicable model is not existing and that's why parameter adjustments have to be done case by case in order to find the best suitable parameters.

In GMAW, weld bead formation happens as a coalescence of melting filler wire droplets and melting workpiece. In conventional GMAW, it is generally understood, that geometry of the weld bead is primarily affected by following parameters: welding current, wire feed speed, welding voltage, welding speed, torch positioning and shielding gas because of their influence on arc characteristics, metal transfer and fluidity of a weld pool. However, in a case of P-GMAW, pulse parameters have their own effect on bead formation, partially because they are affecting basic parameters. (Ghosh, p.139-140.)

4.1 Welding current and wire feed speed

Welding current and wire feed speed, which are in connection to each other, have the biggest effect on bead formation. When wire feed speed is increased, welding current increases respectively. Deposition rate is and penetration are mostly affected by welding current and wire feed speed. With increase of them, increase in depth, width and height of the weld bead happens. The contact tip-to-work distance influences current and because of that also weld fusion. Increase in tip-to-work distance decreases current and heat input while keeping deposition rate constant. That leads to shallower penetration. (Weman 2012, p.92.)

4.2 Welding voltage

Adjustment of welding voltage and current are mostly connected to each other. That’s why synergic control of voltage and current is common in welding machines nowadays. It means, that in synergic control, both parameters are controlled by one control button. However, adjustments just for voltage, by keeping current constant, are possible to do in some limits without harming stability process**.** With increase of voltage, length of arc increases which makes focus area of arc cone wider and less energy intensive. That have effect on the weld bead width, but also may have effect on depth of fusion depth. (Weman 2012, p.91.) Image 8 presents voltages influence on arc length.

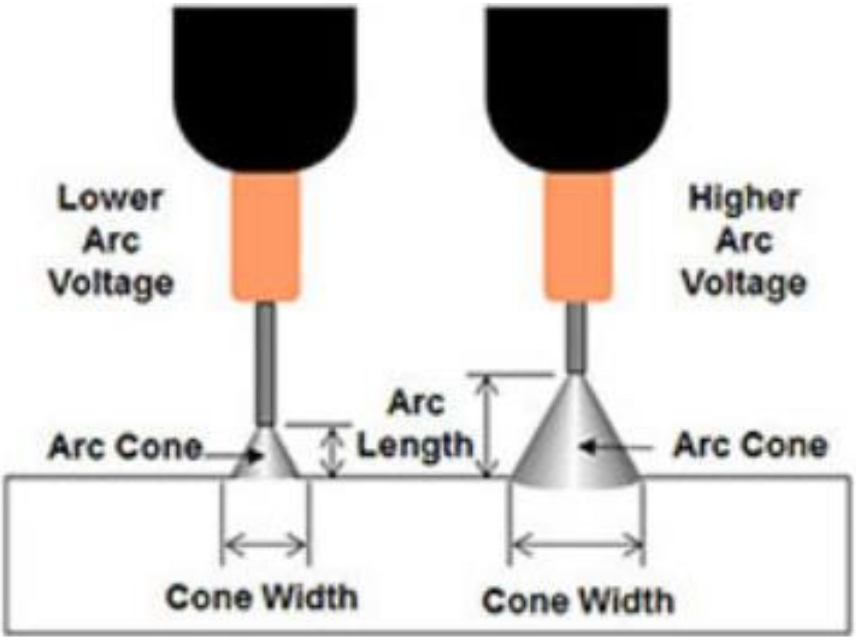

Image 8. Voltage’s effect on arc length (The Lincoln electric).

Decrease of welding voltage makes arc cone narrower. Further decrease of voltage leads to short-circuits in process. Even spray arc mode should be short-circuit free, some short-circuits may occur when wire feed speed is high and length of arc is decreased, and because of that arc is not able to melt wire every time before it reaches weld pool and that’s why some of the metal transfers happens by short-circuit. That is how for example Kemppi’s WiseFusion process works in order to get intensively focused arc.

4.3 Welding speed

Since welding speed and depth of fusion are closely related to each other, it is important to understand their relationship. Change in welding speed changes heat input the of arc. In general, higher heat input and higher intensity of arc means deeper fusion of weld. Maximum fusion by adjusting welding speed will be found by using average value of welding speed. Too slow welding speed creates large molten weld pool, which may cause problems by moving ahead of arc. Because of that, arc is burning on top of the molten metal and its ability to melt base material decreases. On the other hand, increase in welding speed decreases heat input per length unit, which decreases penetration. So, the depth of penetration increases along with welding speed until certain point and then starts to decrease. Unambiguous value for welding speed to obtain maximum fusion cannot be told, because it depends on different factors. (Lukkari 2002, p.207-208.)

4.4 Other effecting parameters

Shielding gas has also significant influence on weld bead formation. Pulse current arc requires inert shielding gas, argon or helium, or argon-based mixture. Argon + carbon dioxide-mixtures (Ar + CO_2) are the most common for welding of mild and low-alloyed steels. Amount of CO2 usually varies between 5-20 %. (Weman 2012, p.92.) Image 9 below shows principled effect of shielding gas' CO_2 content on a weld bead geometry and metal transfer on MAG-welding. Higher CO_2 content increases arc pressure which increases bead width and depth of penetration. (AGA 2013, p.5.)

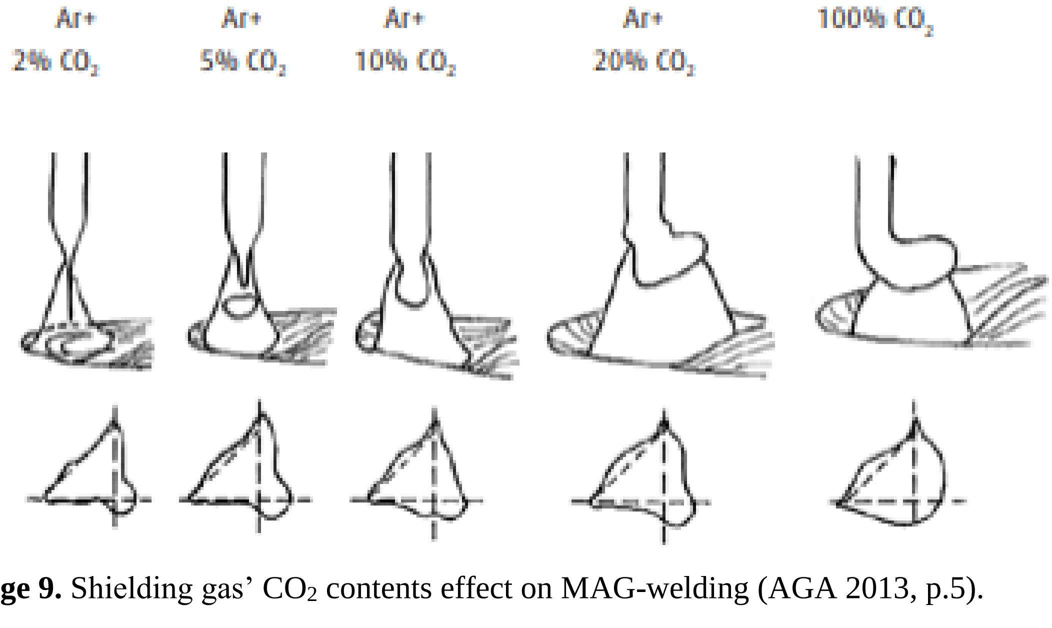

Image 9. Shielding gas' CO_2 contents effect on MAG-welding (AGA 2013, p.5).

A weld bead shape can be affected also by torch angle. By carving torch position, wide and shallow weld bead is obtained, when tracking torch leads to deeper and narrower penetration. The weld bead shape of neutral torch angle is between them. Image 10 below illustrates torch position's effect on weld bead shape. (Lepola & Ylikangas 2016, p.89.)

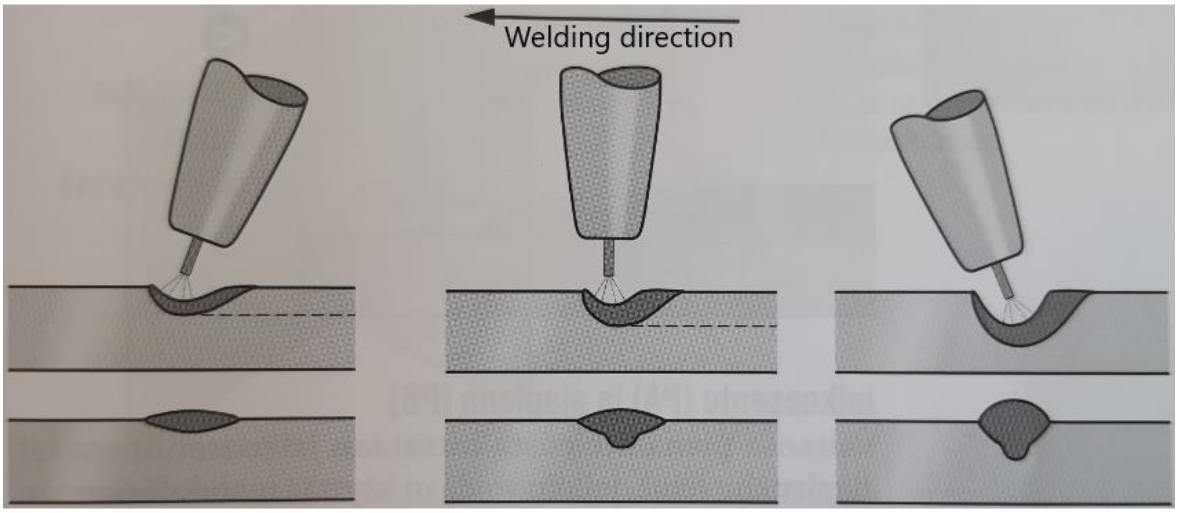

Image 10. Torch positions effect on a weld bead shape (Lepola & Ylikangas 2016, p.89).

4.5 Cases about pulse parameters' effect on depth of penetration

As already mentioned in introduction chapter, there is very limited amount of reliable and suitable information for this research about pulse parameters' effects on weld bead formation. In this chapter, few researches made about the topic are studied and pulse parameters' effects are evaluated. Results of these has to be looked from critical point of view because research frame of introduced researches don't match with this research.

Investigation of Pal & Pal was done by constant pulsed MIG/MAG welding machine. Welded material was 7.5mm thick low carbon steel and welding was done by using bead on plate method. Electrode wire thickness was 1.2mm and used shielding gas was pure argon. Variation in penetration is investigated by varying pulse frequency. Five different levels of frequency are used, which are 50, 100, 150, 200 and 250 Hz. Each frequency level was tested by varying also wire feed speed. Other process parameters were kept constant.

According the investigation, maximum penetration will be achieved when frequency level is at its lowest, which is 50 Hz in this case. Depth of penetration decreases when frequency increases and reaches its lowest point at frequency level 200Hz. However, after that when moving from 200 Hz to 250 Hz depth of penetration seems to start increase. (Pal & Pal 2011, p.690)

Further development of penetration depth would have provided valuable information, but unfortunately tests were not done with higher frequency levels. Other major differences between Pal & Pal's and this research are different shielding gas and wire feed speed. Even though the parameter values of Pal & Pal's research don't match completely to this research's, it may provide interesting comparison reference for pulse frequency's influence on penetration depth. Graph of the research results is shown in image 11.

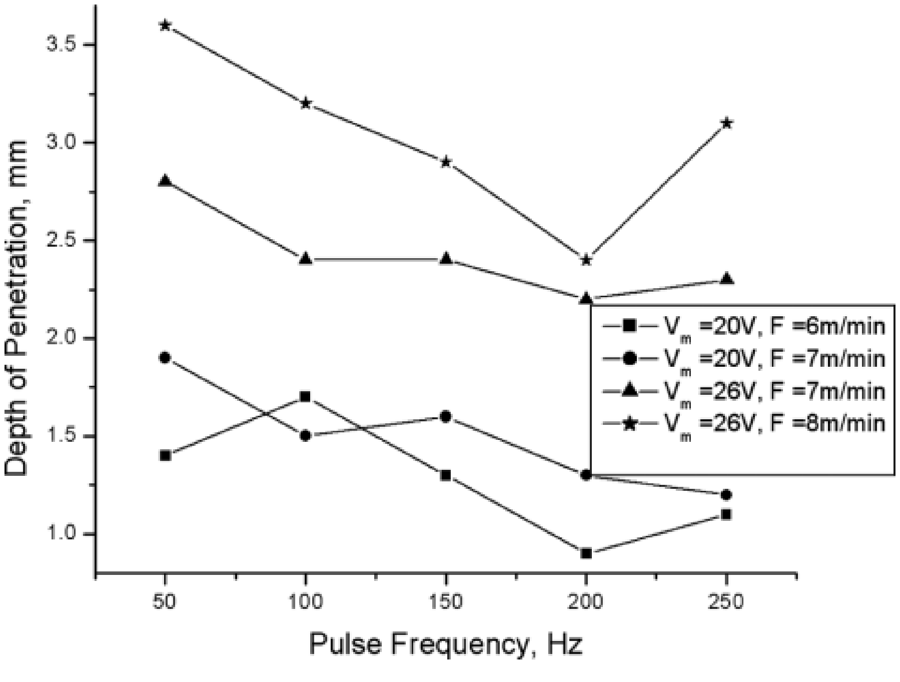

Image 11. Pulse frequency's effect on depth of penetration (Pal & Pal 2011, p.690).

Few different studies were found, where researcher have stated, that cross-sectional area of weld penetration is mostly affected by the heat content of transferring metal droplets, while the depth of penetration is determined by the impact of metal droplets to molten weld pool. It appears, that with increase of droplets' total impact per second, increase in depth penetration occurs. (Ghosh 2017, p.119-120; Esser & Walter 1986, p.40). In image 12 below, correlation between weld penetration and momentum and frequency of droplet is plotted.

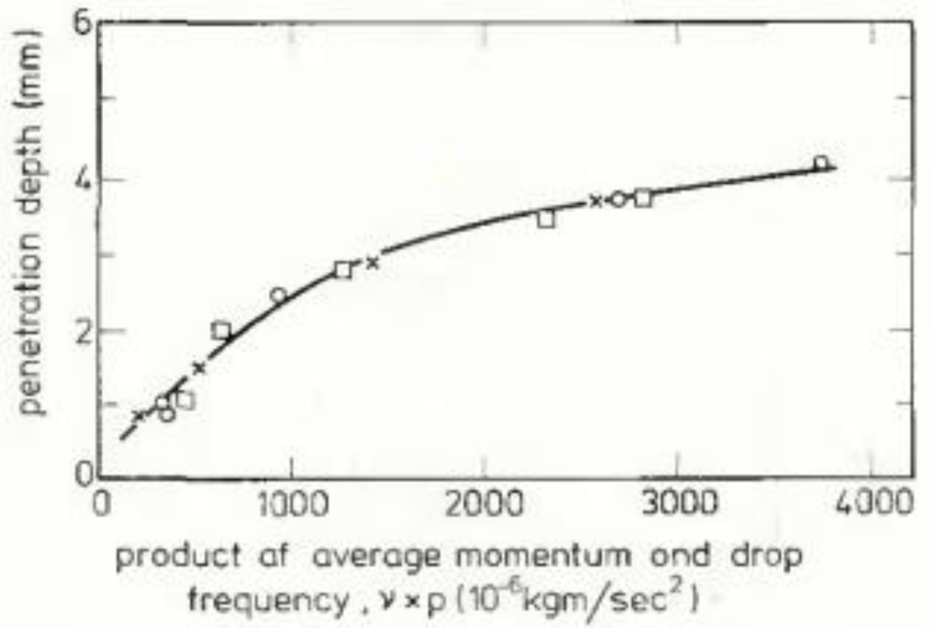

Image 12. Effect of droplet impact on penetration (Esser & Walter 1986, p.40)

As a droplet is detached from tip of a filler wire and flies to molten weld pool, its kinetic energy breaks the surface tension and creates a cavity. With increase of welding current, velocity of droplet increases, which increases kinetic energy. When frequency of detached droplets increases, surface tension has less time to recovery from previous hit of droplet. If the impact of the droplet hits the cavity of weld pool before it has filled and regained its shape, deeper fusion of weld pool can be achieved. (Ghosh 2017, p.119-120; Esser & Walter 1986, p.40.)

Dos Santos & al. 2017 (p.638) investigated pulse profiles' effect on metal transfer. One of the things that was under the investigation, was base and peak current ratio's effect on velocity of detached droplet. The conclusion of their research was that decrease in base and peak current ratio leads to increase in droplet velocity, which would increase depth of fusion. Practically decrease of base and peak current ratio means, that pulse amplitude increases. However, as in other found P-GMAW researches, parameter values are close to conventional P-GMAW values and, and metal transfer happened ODPP-way. Because of that results may not be applicable to this research.

4.6 Prediction of parameters effects on depth of penetration in this research

In conventional ODPP pulsed-GMAW every peak current pulse should detach one droplet. That would mean that by increasing pulse frequency, frequency of detached droplet would increase, which would possibly lead to deeper fusion of weld. However, in this process variation, which is under research, metal transfer mode is pretty much similar than in conventional spray arc, and pulse frequency may not have significant effect on metal transfer. If pulse frequency has an effect on drop detachment frequency in this process variation, that would mean high frequency level could be beneficial in order to achieve deep penetration.

Based on literature, few predictions can be made about pulse frequency's and amplitude's effect on depth of penetration. According found researches, it seems that increase of both, amplitude and frequency, could lead to deeper weld fusion, if they have effect on metal transfer. However, for example results of Pal&Pal's research, which is introduced earlier, about pulse frequency's effect on penetration depth are conflicting with that and makes predictions more unreliable. Pulse amplitudes effect on weld bead formation instead may be different between this research and research of Dos Santos et al., because of metal transfer type, which was ODPP in research of Dos Santos et al.

4.7 Summary of literature findings about parameters' effect on weld bead formation

In this part of literature review, welding parameters' effects on weld bead formation was looked for. At the beginning, basic parameters like current, voltage and welding speed were handled. Information was easy to find and lots of reliable references were existing.

Scientific information about pulse parameters' effects on weld bead formation was instead hard to find. Found references were mostly other researches, and clear and unambiguous information were not found. Special characteristics of WiseSteel spray arc made it even harder, since there is not any information available about exactly that kind of process variation. However, some predictions were made and those will be compared to results of welding tests.

5 WELDING TESTS PREPARATIONS AND IMPLEMENTATION

Welding tests and macro examination are implemented in laboratory conditions, facilities of Kemppi. This chapter introduces parameter selection steps, execution of welding tests and macro examination of test specimen. Sub-chapters 5.2.1 and 5.3 are done after initial welding test results are analyzed. Because of that, those chapters refer to chapter 6, which handles results of the welding tests. Welding tests will be done by using Kemppi's X8 MIG Welder-welding machine, which is shown in image 13 below.

Image 13. X8 MIG Welder (Kemppi Oy a, p.2).

Welding torch is attached to carrier and its movements are controlled by control panel. Work pieces are firmly clamped to the table, in order to avoid errors. Vertical and horizontal plates are tack welded from ends, in order to avoid deflection of the pieces due to heat. Image 14 shows the workstation presentation.

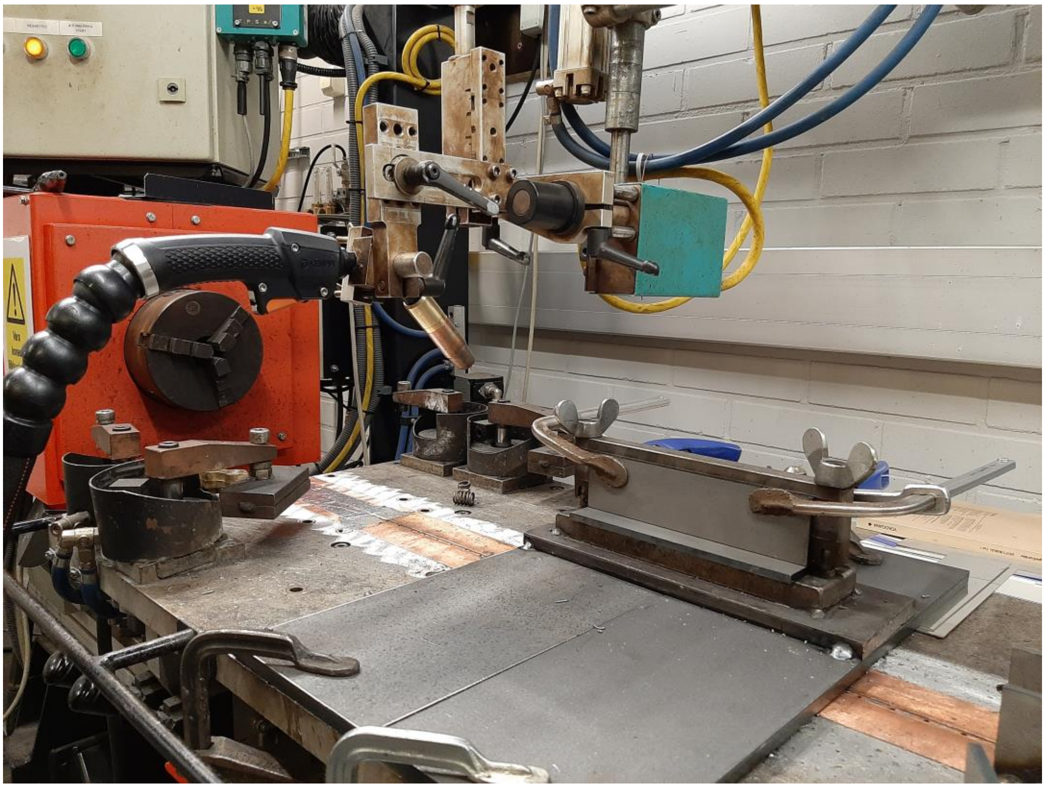

Image 14. Presentation of the workstation.

5.1 Selection of constant parameters

Welding parameters that are kept constant during the testing are selected based on previous tests made about spray arc pulse parameters. Keeping other parameters constant, comparison to previous research is easy and effect of parameter variations are easily noticeable. Ratio of peak current and base current time is held constant, in value 1, which means that time of peak and base currents are equal. Intended values for basic process parameters are shown on table 1.

Table 1. Constant kept welding parameters.

Mean current I_m [A]	~330
Welding speed V_s [mm/min]	600
Wire feed speed *wfs* [m/min]	11
Wire consumable	OK Autrod 12.51
Stick out length [mm]	20
Base material	S355
Material thickness [mm]	6

Table 1 continues. Constant kept welding parameters.

Welding position	PB
Travel angle of torch	Neutral, 0°
Tilt angle of torch	45°
Shielding gas	Argon + 18 % CO_2
Shielding gas flow [l/min]	20
Plate size [mm]	200x50x6
Air gap [mm]	0

5.1.1 Selection on arc length

Pre-selection of parameters consisted test, where welding voltage was selected for actual pulse parameter tests. The test set ups were welded with and without using WiseFusion function. WiseFusion function adjusts arc length the way, that short-circuits happen.

From these tests, it was found out that when welding voltage is at level where short-circuits occurs, depth of weld fusion is deeper than with an open arc. In addition to deeper penetration, shorter arc length also decreases heat input of the process and better shape of weld. In image 15 below, there is shown macro examination of short-circuiting arc on left (WiseFusion on) and open arc on right (WiseFusion off).

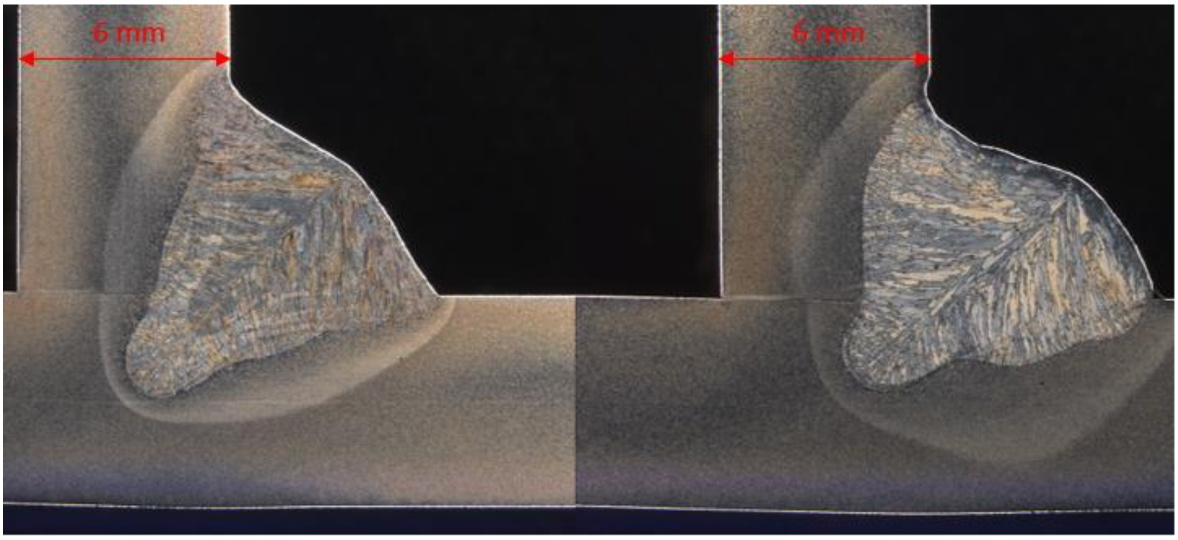

Image 15. Comparison of short-circuiting arc and open arc weld beads.

This pre-selection test clearly indicates that deeper fusion depth and better shape of the weld bead can be obtained by using WiseFusion function, and that's why it is used in actual welding tests.

5.2 Selection of test pulse parameters

In order to get big enough number of parameter settings from viewpoint of reliability of the research, it was decided to do at least 30 different parameter variations. Each amplitude level is tested with each frequency, which makes total number of parameter variations 32. Every variation is tested 2 times in order to tackle possible error of process. In table 2, there is 4x8 matrix of selected pulse parameter variations.

Table 2. Pulse parameter variations matrix.

	A_p(A)	1	2	3	4	5	6	7	8
f (Hz)		**200**	**250**	**300**	**350**	**400**	**450**	**500**	**600**
A	**60**	A1	A2	A3	A4	A5	A6	A7	A8
B	**90**	B1	B2	B3	B4	B5	B6	B7	B8
C	**120**	C1	C2	C3	C4	C5	C6	C7	C8
D	**150**	D1	D2	D3	D4	D5	D6	D7	D8

5.2.1 Expanded pulse frequency comparison

Expectations for pulse parameters' influence on weld fusion depth was, that increase of both pulse parameters would increase it. Based on that, pulse parameter variation range (table 2) was selected the way, that fusion depth would increase along with pulse parameters, and reach its maximum somewhere at high values. However, results didn't completely follow expectations and because of that, tested pulse frequency range was decided to be expanded. Expansion was done only for one amplitude level, 60A, and includes frequencies 50Hz, 100Hz and 150Hz.

5.3 Welding voltage and short-circuit tests

During the pulse parameter comparison tests, it was noticed that pulse parameters have effect on short-circuiting occurrence. When voltage is kept constant, increase of pulse parameters is decreasing amount of short-circuits. This raised interest to take a closer look into arc length's and short-circuits' effect on weld bead formation.

In this test, amplitude of the current was selected to be 60 amperages, which provided the deepest fusion depth in pulse parameter comparison welding tests described in previous chapter. Four levels of frequencies, 150Hz, 250Hz, 350Hz and 450Hz, were selected to be tested.

Levels of voltages were chosen the way, that in open arc, length of the arc was just above the short-circuiting limit. In short-circuiting arc, arc length was noticeably shorter and short-circuits were occurring clearly. In order to keep amount of short-circuits same, voltage level was decreased when frequency was increased.

Afterwards, when comparison of open arc and short-circuiting arc was done, additional test was done by reducing arc length further (Short-circuiting arc 2 and Short-circuitng arc 3). Those were tested only with two frequency levels, 150Hz and 450Hz. Complete test parameter values are presented in table 3. As in pulse parameter comparison tests, each parameter set up was tested two times, and average of the values was calculated.

Table 3. Open and short-circuiting arc voltage levels for pulse frequencies.

	Open arc
Pulse frequency (Hz)	**Voltage (V)**
150	32
250	31,8
350	31,3
450	30,9
	Short-circuiting arc
150	29,8
250	29,6
350	29,2
450	28,9
	Short-circuiting arc 2
150	29
450	28

Table 3 continues. Open and short-circuiting arc voltage levels for pulse frequencies.

	Short-circuiting arc 3
150	28
450	27,5

5.4 Comparison between WiseSteel and other processes

After pulse parameters' and welding voltage's effects on weld bead formation were tested and analyzed, results of WiseSteel with adjusted pulse parameters were compared to other processes. Comparison welding tests were done by conventional synergic MIG/MAG process, MIG/MAG process with WiseFusion on and WiseSteel process with default parameter settings.

5.5 Macro examination

Macro examination is destructive weld testing method, which is normally used for checking the quality or hardness of a weld. Different welding defects can be detected from macro images. From each welded specimen, only one sample is taken under macro examination. The sample is cut from the middle of specimen, in order to avoid discontinuities at the both ends of the weld. Cross section of the cut sample is polished and etched for examination.

After polishing and etching, macroscopic images are taken from each sample, and weld bead measurements are taken. Weld bead measurements are done by using Leica software. Lines are drawn as they are shown in image 16 below. Depth of fusion (4) is under the focus in this research and will be used later when doing comparison. As the image shows, fusion depth is measured from corner point of plates to tip of a weld fusion.

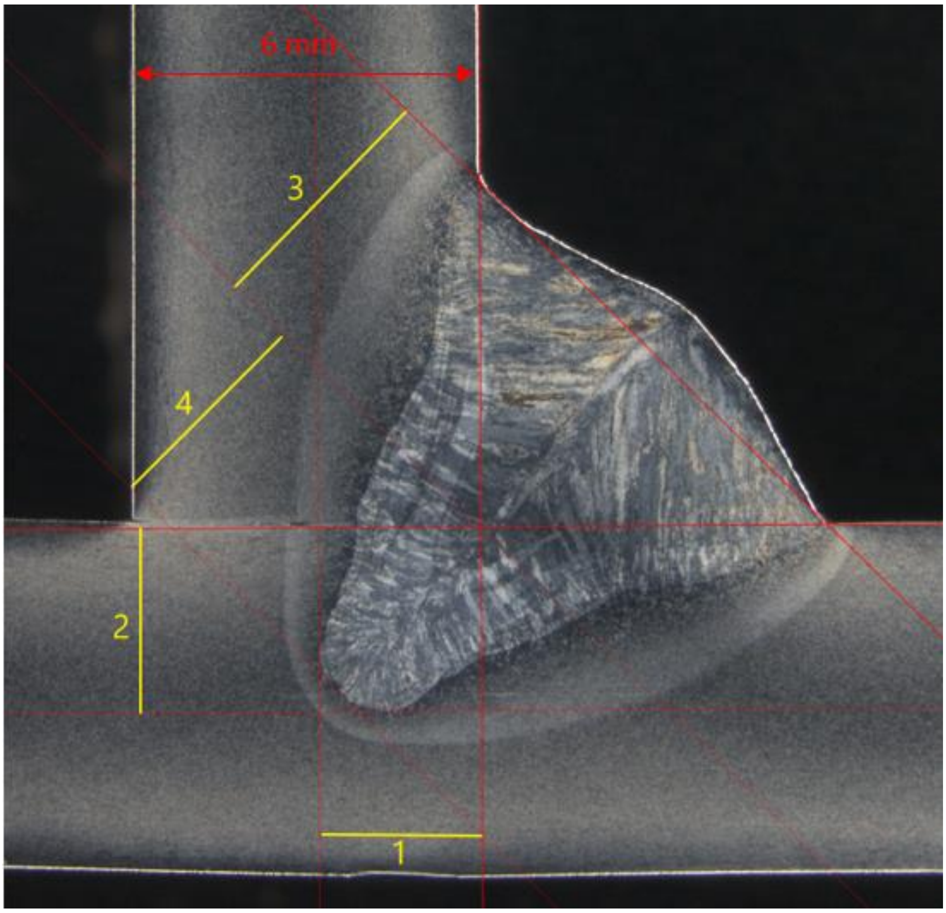

Image 16. The weld bead measurements from macroscopic image.

5.6 Summary of parameters' selection and test implementation

Test parameters' selection was started from parameters, that wanted to be kept constant. Selection was made based on previous tests considering WiseSteel process. Selection of welding voltage was exception from other constant parameters. There was made a pre-selection test for arc voltage level. Comparison was done between an open arc and short-circuiting arc. Short-circuiting arc, which was obtained by using WiseFusion process, turned out to be better alternative when seeking for deep fusion of the weld bead.

After selection of constant parameters, pulse parameters were selected. Range of pulse parameters was extensive, 32 different combinations, in order to get big enough number of tests for reliable results. After analyzing pulse parameter comparison welding test results, two different test expansions were decided to be implemented. The first expansion was considering range of tested pulse frequencies, which was widened. The second one was about arc voltage and short-circuits. During the initial welding tests, it was found out that pulse parameters have effect on how much short-circuits happens. Because of that, test set up was implemented, where arc voltage’s and short-circuits’ effect on weld depth fusion were tested. Eventually, when best parameter values were found, results of them were compared to other MIG/MAG processes, which were conventional MIG/MAG, MIG/MAG with WiseFusion and WiseSteel with default parameters.

6 RESULTS OF THE WELDING TESTS

In this chapter, results of welding tests are presented and analyzed. Test data is gathered up and analyzed numerically. Numerical data is made more illustrative by creating graphs. Some of the macroscopic images of weld beads are presented and used to support data analysis.

Pulse parameters’ influence on weld bead formation is analyzed. Fusion depth of a weld of each pulse amplitude is presented as a function of pulse frequency. Both pulse parameters, amplitude and frequency are also analyzed separately. Welding voltage’s and short-circuits’ effect on weld depth fusion is also discovered analyzed. At the end of the chapter, comparison of pulse parameter adjusted WiseSteel process is compared to other process variations of MIG/MAG-welding.

Test result data of the weld fusion depths is measured from macroscopic images by using Leica camera software. From Leica, depth measures are transferred to spreadsheet Microsoft Excel, which is used to calculate average values and form graphs.

6.1 Pulse parameters’ effect on fusion depth of weld

Pulse parameters’ effects on weld bead formation were researched by welding tests. These tests consisted of 32 different pulse parameter combinations. 4 levels of pulse amplitudes were tested with 8 levels of pulse frequencies. Every parameter combination was tested two times in order to reduce error in results. That led to total amount of welded test specimen 64.

Frequency and amplitude of the pulse both seems to have effect on depth of weld fusion. When it comes to amplitude of the pulse, lowest values of tested amplitudes are leading to the deepest fusions. Instead, frequency of the pulse seems to have different kind of effect on the weld bead. Deep weld fusion of lowest tested frequency (200Hz), is followed by reduction of fusion as frequency is increased to values 250-300Hz. After that, fusion depth starts to increase again until it reaches its maximum at levels of 450-500Hz and stays almost constant till 600Hz. Image 17 shows a graph of results of pulse parameters’ variation tests.

As each pulse parameter combination was tested twice, graph point shows average value of them.

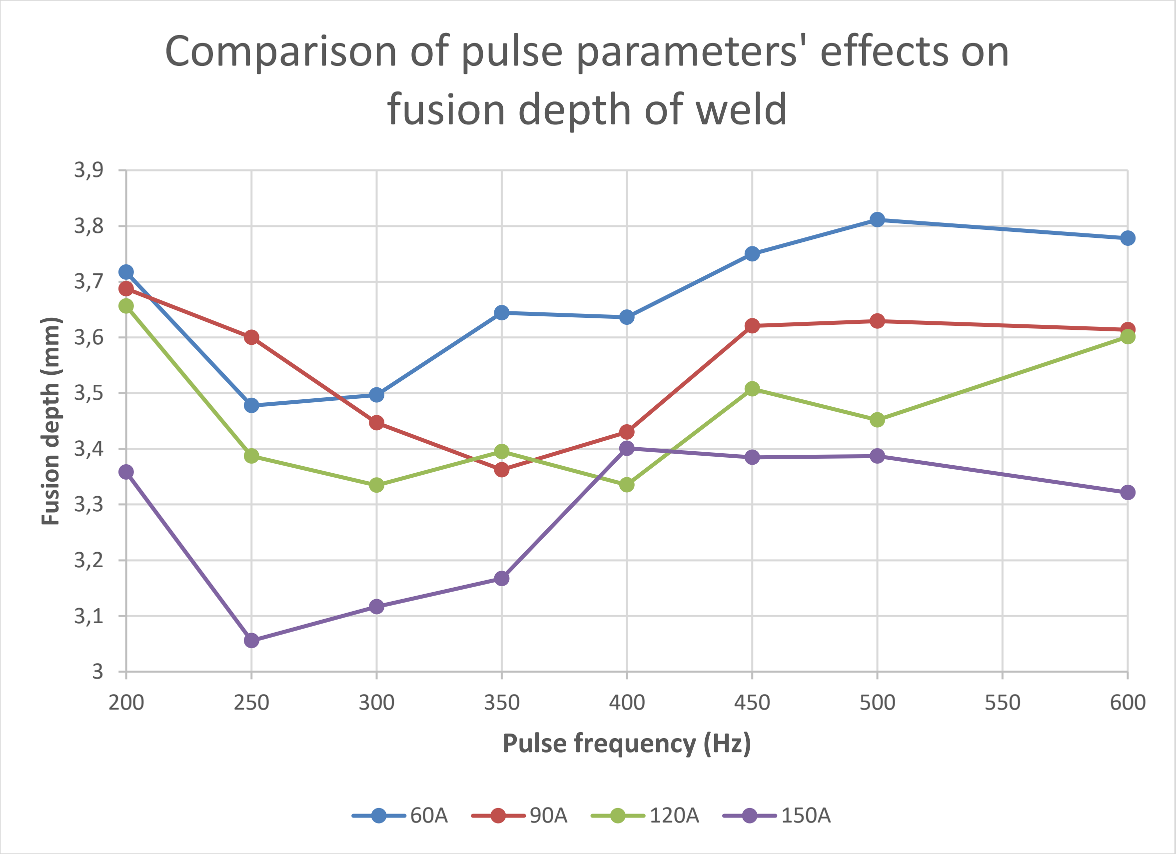

Image 17. Comparison of pulse parameter's effects on fusion depth of weld

Initial assumption was made, that depth of a weld fusion would increase along with increase of pulse frequency. Based on that, selection of pulse frequencies was made to start from 200Hz. However, results didn't completely match the expectations on pulse parameters' influence on weld fusion depth. Because of that, test range of lower levels of frequencies was expanded, and 150Hz, 100Hz and 50Hz were tested afterwards. Additional tests were impleneted only for amplitude level 60A. Results confirms, that as well as high frequencies (450-600Hz), also low frequencies (≤200Hz) lead to deep weld fusion. Image 18 below shows expanded test results of 60 amperages amplitude.

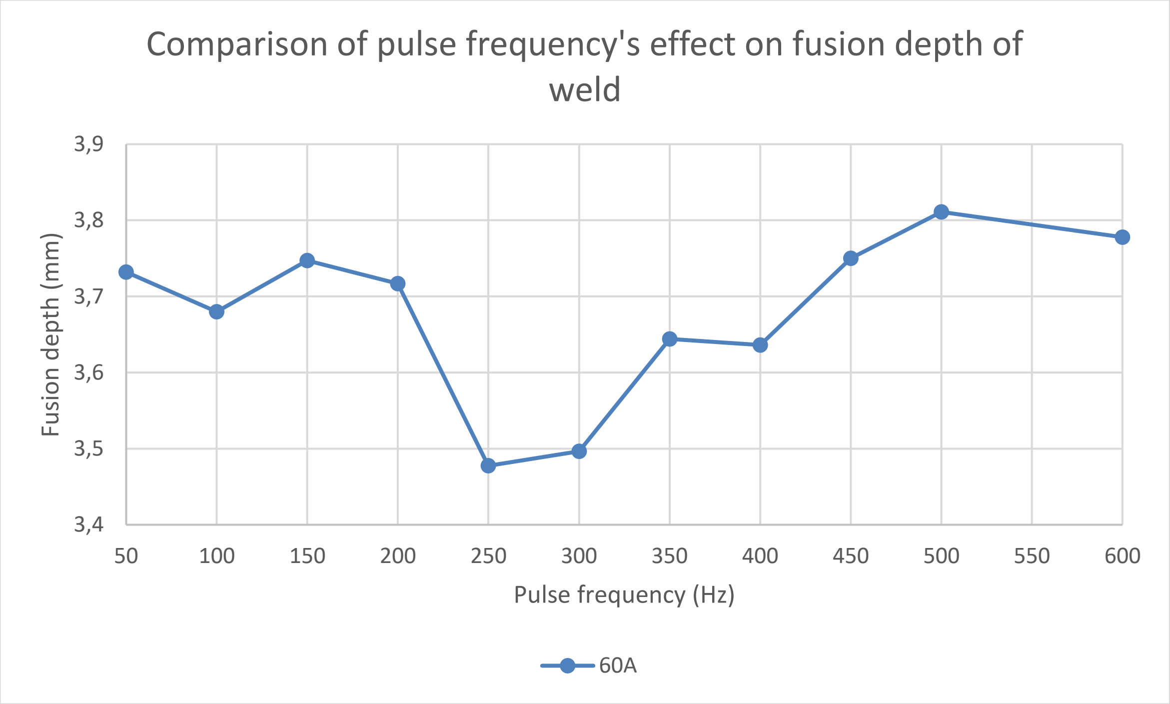

Image 18. Comparison of pulse frequency's effect on fusion depth of weld.

In image 19, there is comparison of two different marcoscopic images, which are welded by using different pulse parameter combinations. On left, there is used 60A/500Hz and on right 150A/250Hz, which are representing deepest and shallowest fusioon depths of tested parameters. As welding speed and wire feed speed are kept in same level in every set up, the size of molten weld area doesn’t vary much between test welds. In shape of the beads instead, differences can be clearly seen varies between set ups. Shape and size of the excess weld metal doesn’t vary much between different pulse parameter set ups, but difference in depth and width of the molten base material can be seen clearly form the marcoscopic image. As the width of 60A/500Hz bead is narrower, missing material in width is “replaced” by deeper penetrated tip of the weld bead.

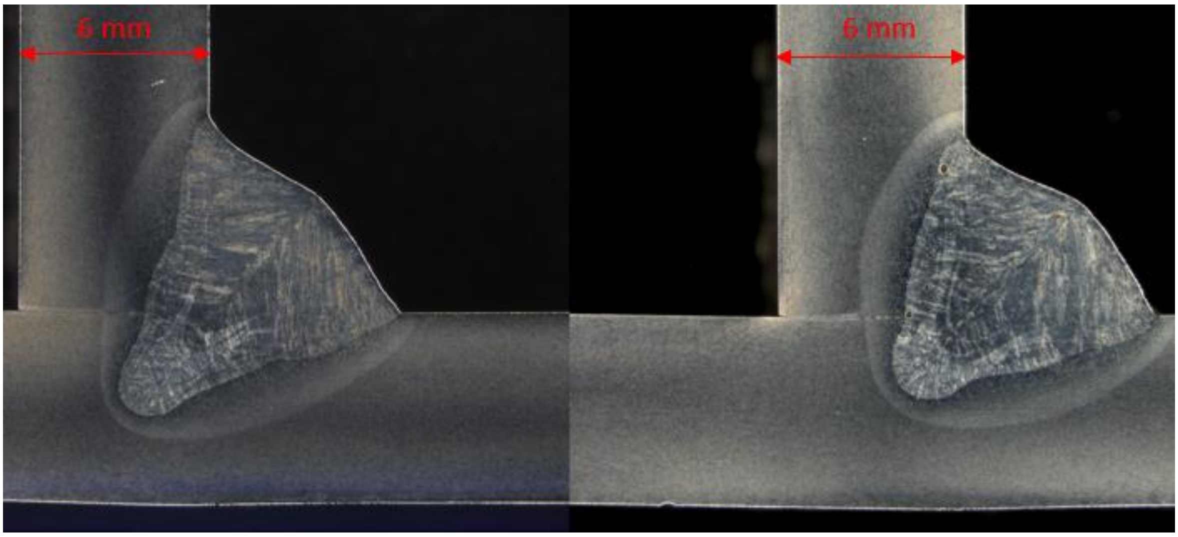

Image 19. Macro images of 60A/500Hz and 150A/250Hz weld beads.

Regardless of what set up of pulse parameters is chosen in WiseSteel process, depth of a weld fusion is relatively deep anyway. That’s why differences between them don’t seem to be significant. Every parameter set up leads to narrow and deep fusion due to arc which is short and well focused to the corner of the plates. That is obtained by WiseFusion process, which is adjusting arc length.

6.1.1 Pulse amplitude

In table 4, each pulse current amplitude level is separated, and average fusion depth of each amplitude level is calculated. Amplitude level 60 amperages is used as a reference point and other amplitudes are compared as difference in percentages. As table shows, lower the amplitude is, the deeper is weld fusion.

Table 4. Weld fusion depth average of each amplitude.

Amplitude (A)	Root penetration avg. (mm)	Difference (%)
60	3,66	0
90	3,55	-3
120	3,46	-5,5
150	3,27	-10,6

Values from table 4 are taken and converted into graph in image 20.

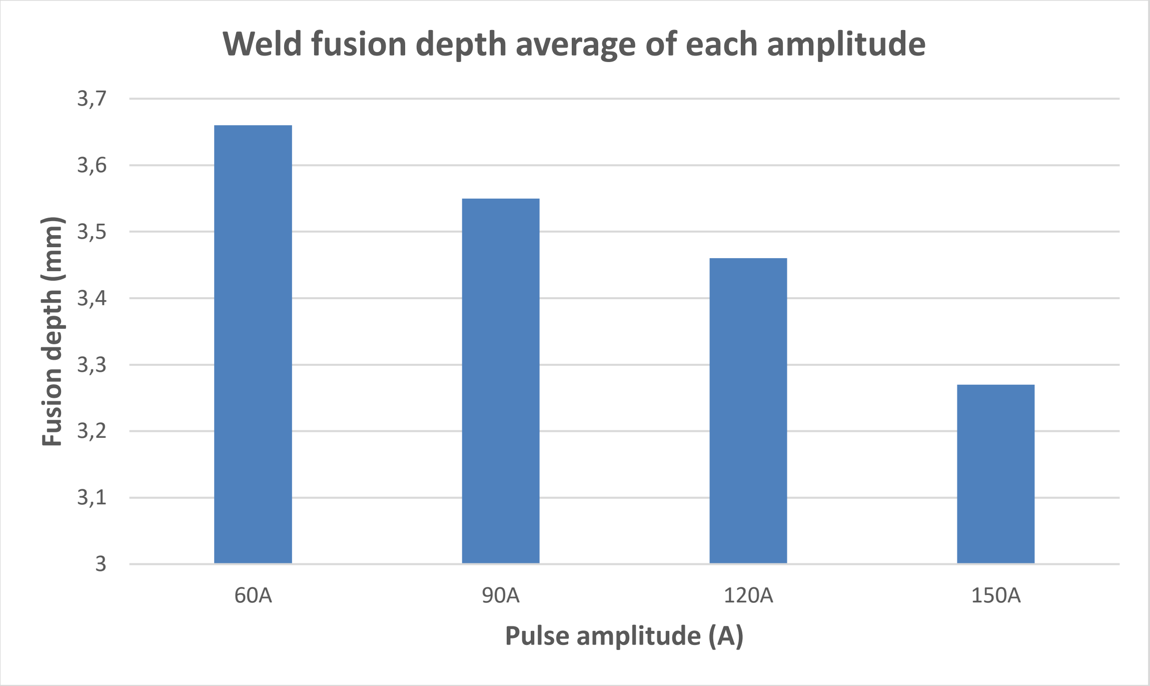

Image 20. Weld fusion depth average of each amplitude.

6.1.2 Pulse frequency

In table 5, each frequency level is separated, and average fusion depth of every frequency level is calculated. Fusion depth of 200Hz is used as a reference point and other frequencies are compared to it by the difference in percentages. As it can be seen, deepest fusions are obtained by lowest tested frequency, 200Hz, and again almost reaches that that depth at 450Hz. Further increase of frequency after 450Hz makes only small difference.

Table 5. Weld fusion depth average of each frequency.

Frequency (Hz)	Fusion depth avg. (mm)	Difference (%)
200	3,60	0
250	3,38	-6,11
300	3,35	-6,94
350	3,39	-5,83
400	3,46	-3,89
450	3,57	-0,83
500	3,57	-0,83
600	3,58	-0,56

Values from table 5 are taken and converted into graph in image 21.

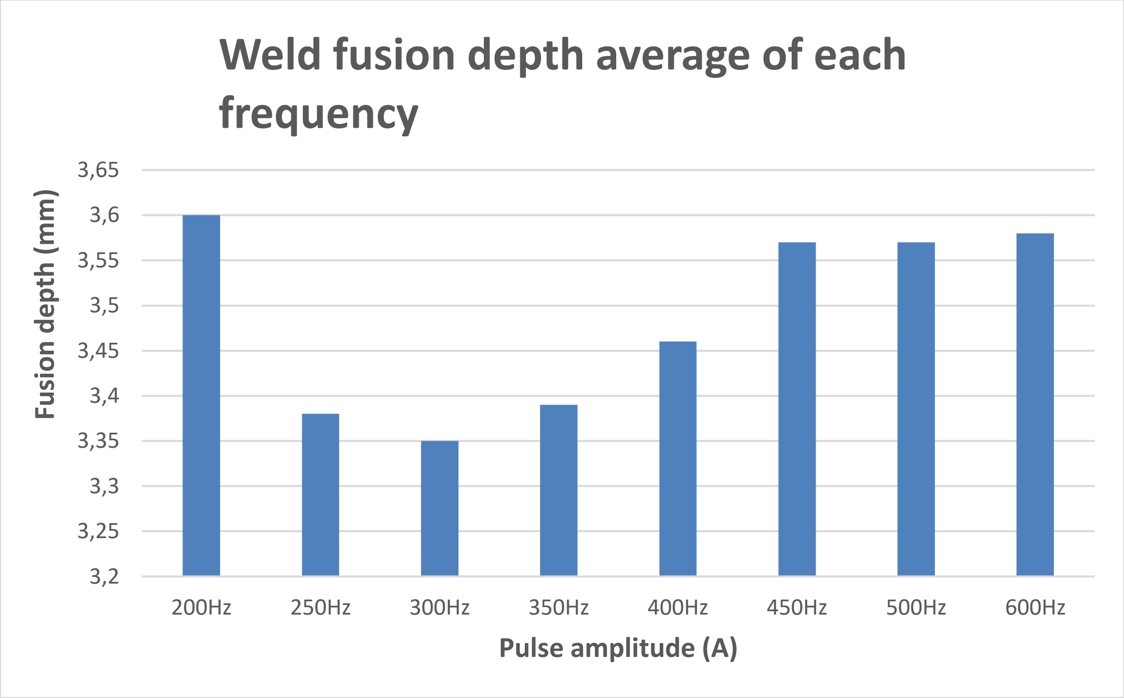

Image 21. Fusion depth average of each frequency

6.1.3 Pulse parameters' effects on short-circuit occurrence

One noticeable observation during the primary welding tests, was that pulse frequency and pulse amplitude have effect on short-circuiting occurrence. Below, there are presented two oscilloscope images with measured signals. Measured signals of voltage and current from welding machine are drawn on them. Red signal-curve represents current signal and green signal-curve voltage. Now the focus is on green voltage signal. Peaks in voltage signal are indicating short-circuits in a welding process. As it can be seen, in image 22 there are much more short-circuits indicating peaks in signal graph than in image 23.

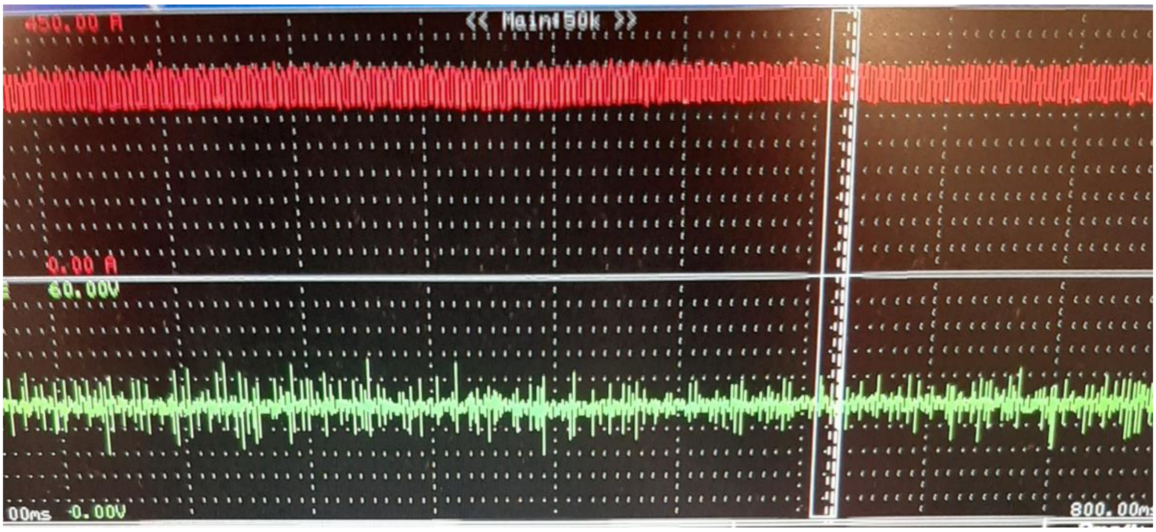

Image 23. Oscilloscope curves of pulse parameters 60A/200Hz.

Instead, with pulse parameters 150A/600Hz, short-circuits don’t occur as much as with set up 60A/200Hz. Amplitude of the pulse is bigger and short-circuits are occuring more rarely.

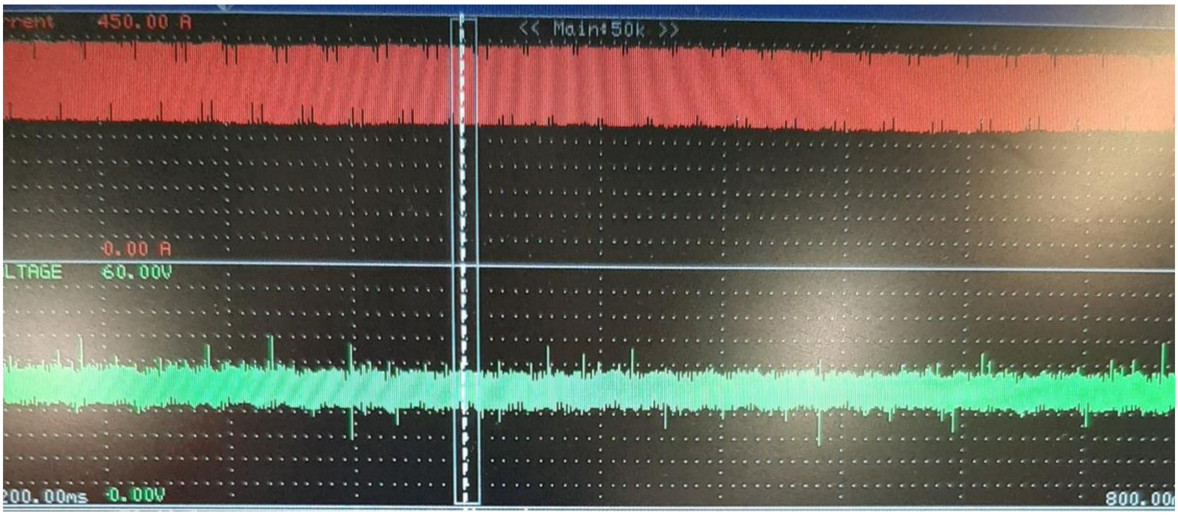

Image 23. Oscilloscope curves of pulse parameters 150A/600Hz.

Initially plan was to investigate only pulse parameter’s effects on weld penetration. However, due to above explained observations about short-circuit occurrence, effect of arc voltage and short-circuits on weld fusion depth wanted to be researched more closely. That is done in the next subchapter 6.2.

6.2 Welding voltage's and short-circuits' effect on weld penetration

As noticed previously, pulse parameters' have effect on short-circuit occurrence. When welding voltage is kept constant on the level where short-circuits happen, increase of both pulse parameters is decreasing amount of short-circuits. Due to that, question raised, if deep penetration of low frequencies (≤200) was caused by great amount of short-circuits. Following tests attempt to find out if there is a connection between amount of short-circuits and weld fusion depth.

As image 24 shows, short-circuiting arc leads to deeper penetration than longer open arc, which was already known after parameters pre-selection tests. Noticeable thing was, that even though voltage was adjusted the way, that amount of short-circuits don't vary between frequency levels, results are indicating the same thing that was seen in pulse parameter comparison test. Deepest fusion depths are obtained by low and high levels of frequency, when values between them there is decrease in fusion depth. Lower and higher levels of frequencies (150Hz and 450Hz) have deeper fusion and levels between them (250 and 350Hz) have shallower fusion.

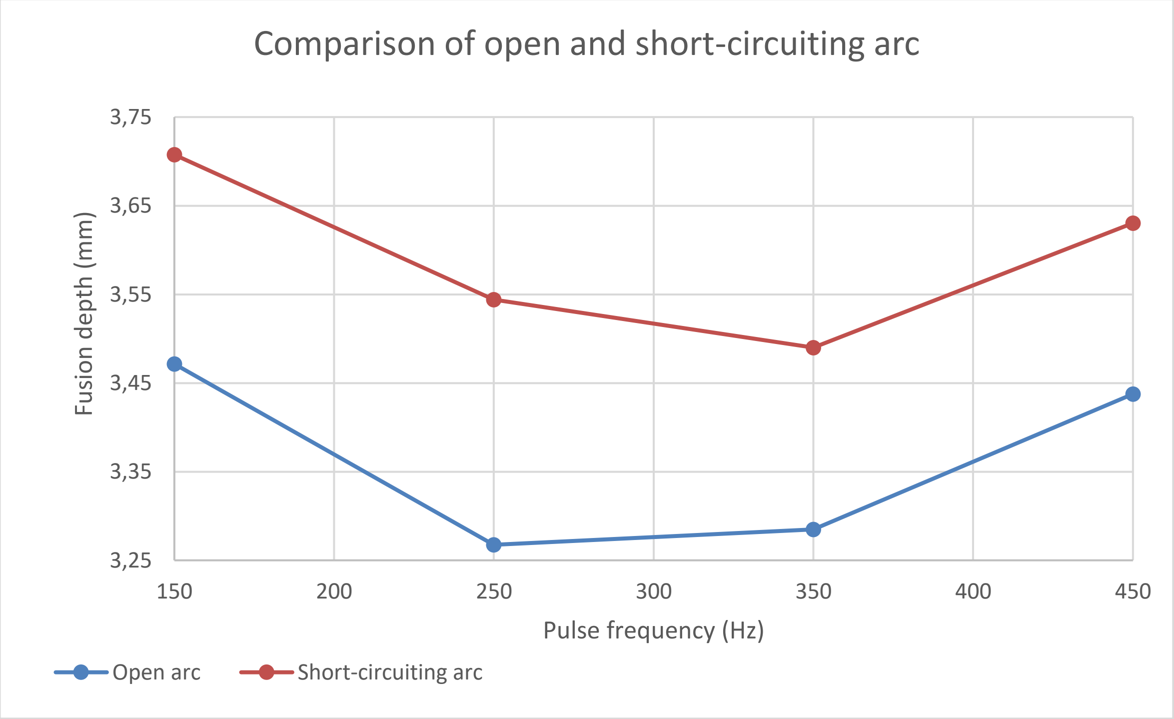

Image 24. Comparison of fusion depth of open and short-circuiting arc.

Values from image 24 above are converted to the table 6 below, where averages and difference in percentages is calculated.

Table 6. Comparison of fusion depth of open and short-circuiting arc

Arc type	Fusion depth (mm)	Difference (%)
Open arc	3,37	0
Short-circuiting arc	3,59	+6,53

After that, voltage level was reduced two steps further from short-circuiting arc. Idea was to find out, if even deeper fusion could be obtained by decreasing voltage level further. Reduction of voltage was done by two frequency levels, 150Hz and 450Hz. As image 25 shows, the first reduction of voltage (Short-circuiting arc 2) doesn't do significant difference, but further reduction of voltage (Short-circuiting arc 3) reduces weld fusion depth significantly. It was noticed during the welding, that in Short-circuiting arc 3, arc length was clearly too short. Because of that, significant amount of short-circuits occurred and made process unstable.

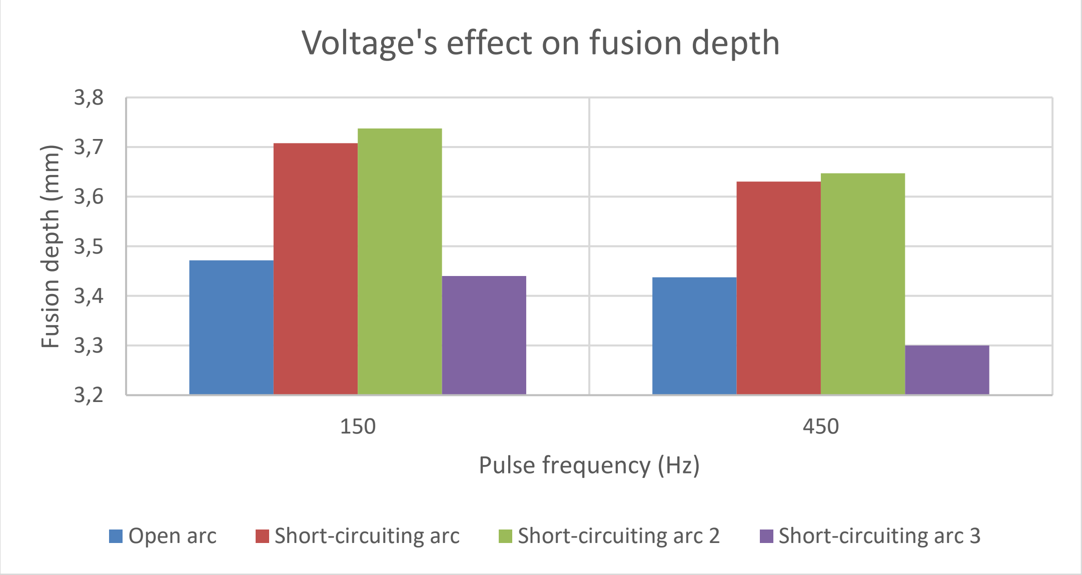

Image 25. Voltage's effect on fusion depth

6.3 Comparison of different processes

In addition to different variations of WiseSteel spray arc, comparison was done to other MIG/MAG-processes as well. Comparison was done with conventional synergic

MIG/MAG, MIG/MAG with WiseFusion and WiseSteel with default parameters. Other parameters than voltage and pulse parameters are kept constant between processes.

In image 26 below, there is shown the weld bead, which is welded with conventional synergic MIG/MAG. This is an example, where voltage is high enough that metal transfer happens without short-circuits. Because of that, shape of the weld bead is a bit wider and shallower, and connections to plates are steeper than in better focused processes. Higher voltage level, which leads to higher heat input, can be also noticed from wider area of heat-affected zone (HAZ), which have effect on metallurgy, and because of that may have effect on mechanical properties of the weld.

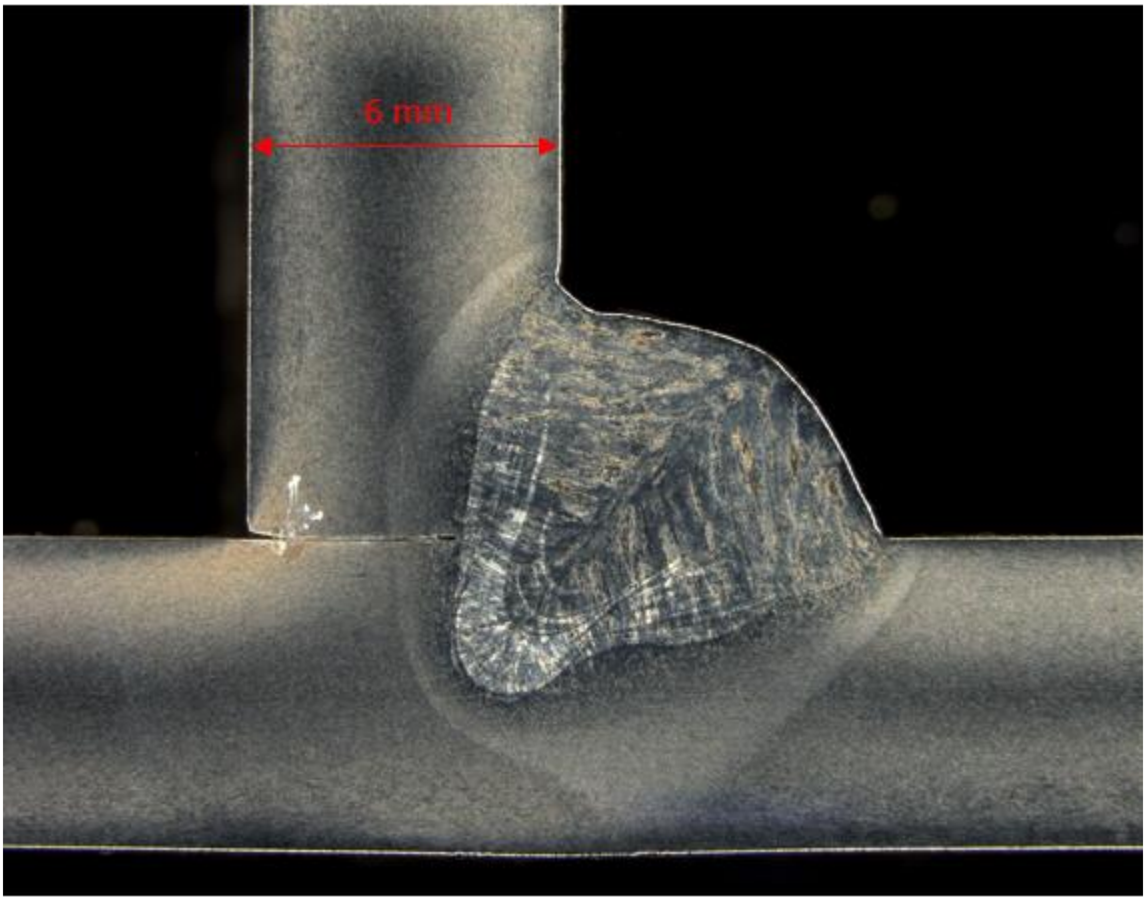

Image 26. Macro image of Conventional synergic MIG/MAG weld bead.

Weld bead of MIG/MAG with WiseFusion function on, is instead much closer to WiseSteel’s deep and narrow shape. On top of that, weld beads connections to plates are less steep than in conventional MIG/MAG, and HAZ is smaller. That is obtained by intensive arc, which is creating short-circuits. MIG/MAG with WiseFusion on is shown in image 27.

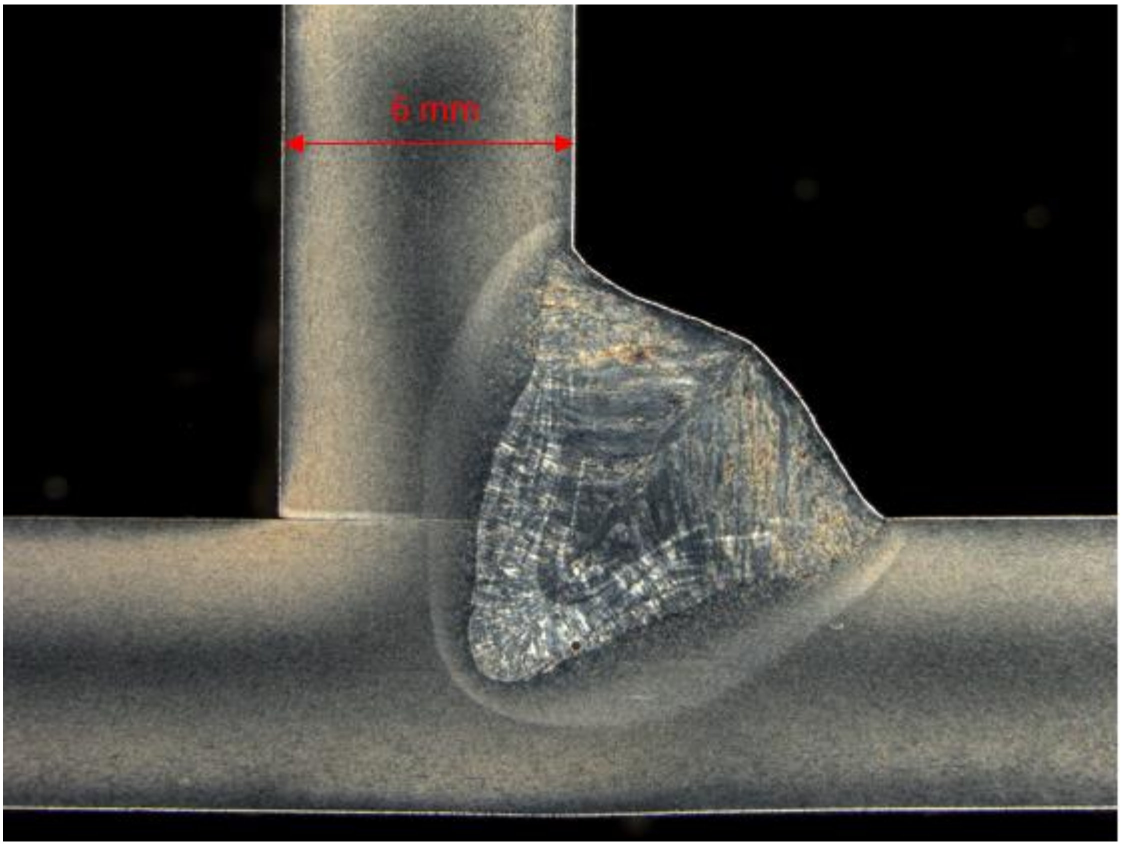

Image 27. Macro image of MIG/MAG with WiseFusion weld bead.

As well as MIG/MAG with WiseFusion, WiseSteel with default parameters, creates deeper and narrower fusion for weld bead than conventional MIG/MAG process. Shape of the weld bead is pretty much same as MIG/MAG WiseFusion’s. The weld bead of WiseSteel with default parameters is shown in image 28.

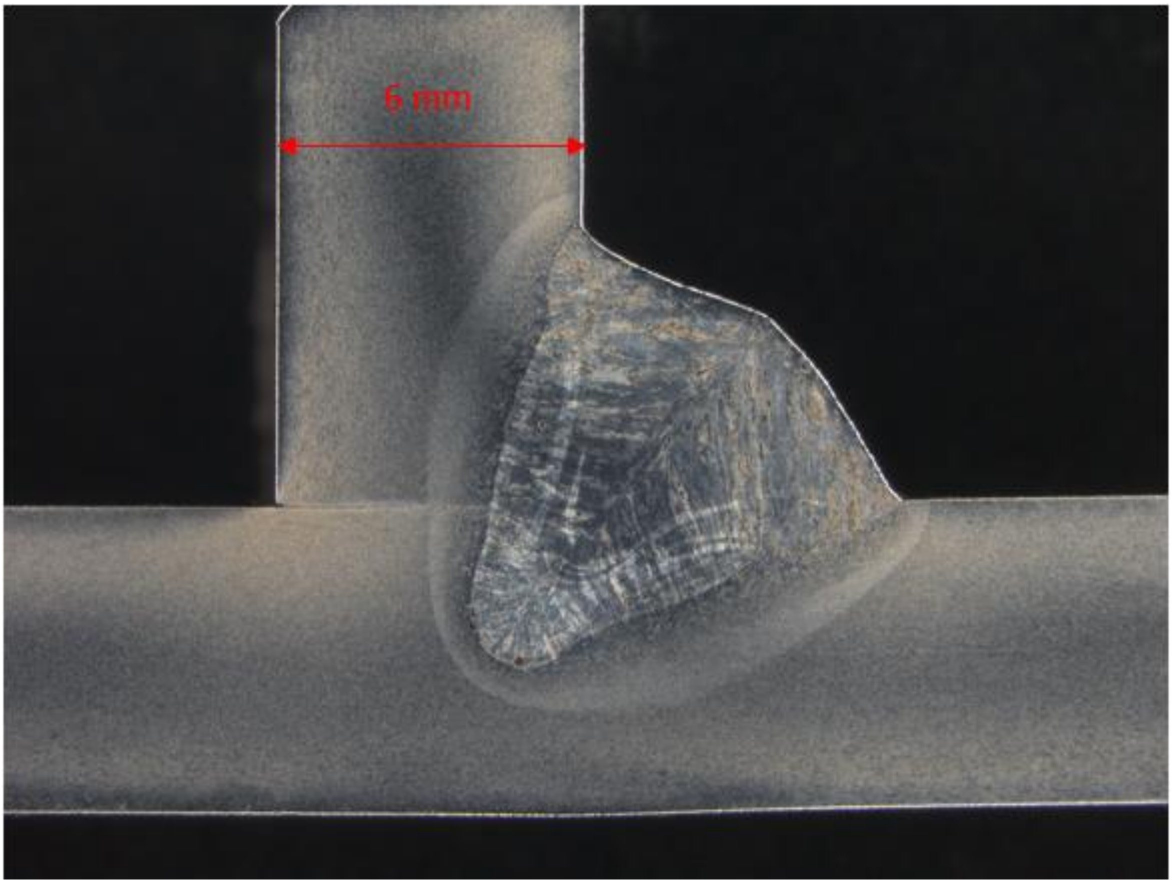

Image 28. Macro image of WiseSteel default parameters weld bead

As previous two examples, WiseSteel with adjusted pulse parameters, 60 amperages and 600 Hertz, leads to narrow and deep weld fusion with good connections to plates and narrow HAZ. In difference to two which were almost identically shaped, with adjusted pulse parameters even deeper tip is obtained to the weld bead. Macroscopic image of WiseSteel 60A/600Hz pulse parameters is shown in image 29.

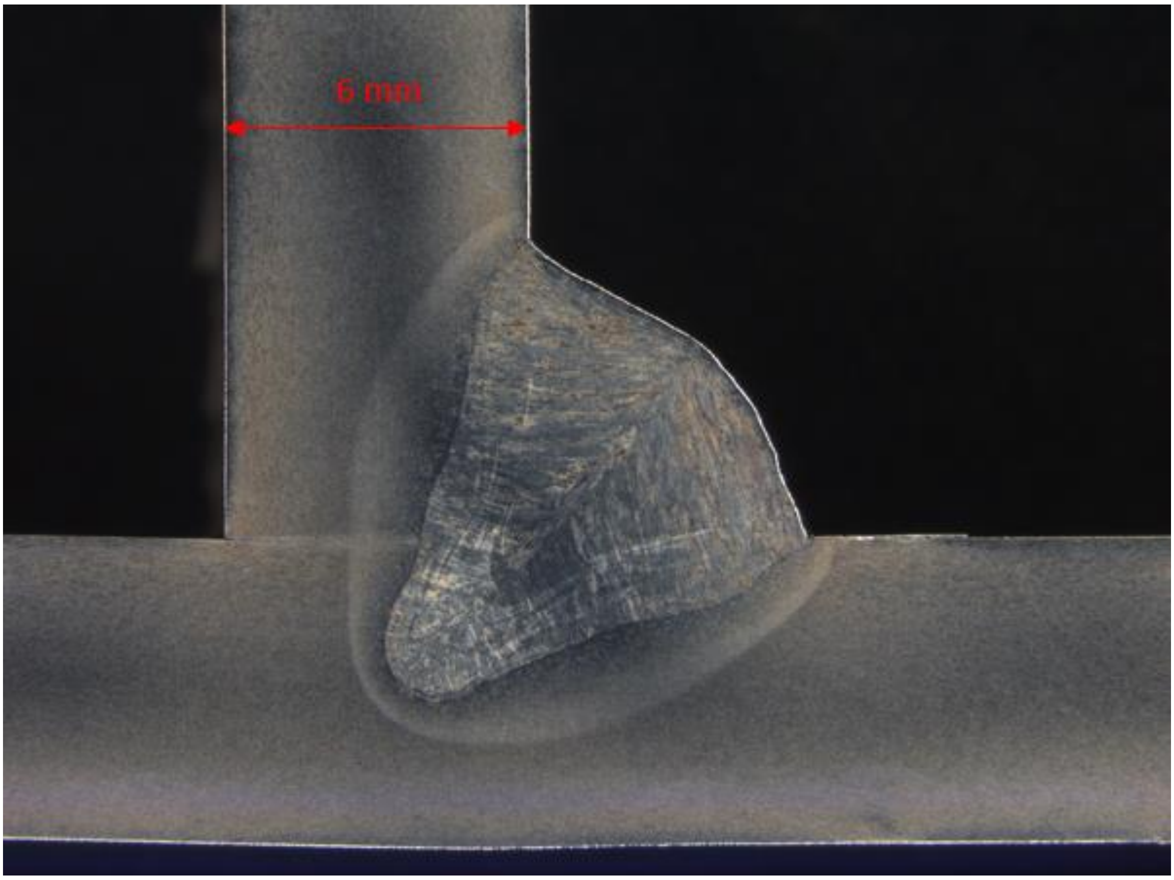

Image 29. Macro image of WiseSteel 60A/600Hz weld bead.

Weld bead shape comparison of different processes, that are introduced above, are measured and listed to the table 7 below. Fusion depth of weld beads are measured as in previous tests, and differences between them are calculated. Shallowest weld fusion is obtained with conventional MIG/MAG, followed by MIG/MAG with WiseFusion and WiseSteel with default parameters, which are practically identical. Deepest fusion is obtained by adjusted WiseSteel process.

Table 7. Fusion depth comparison of different processes

Process	Fusion depth (mm)	Difference (%)
MIG/MAG	3,31	0
MIG/MAG with WiseFusion	3,50	5,7
WiseSteel default	3,51	6,0
WiseSteel 60A/600A	3,78	14,2

6.4 Summary of the welding test results

Primary objective of welding tests was to gather comprehensive amount data, to be able to analyze reliably how pulse amplitude and frequency effect on weld fusion depth in WiseSteel spray arc. Based on analyzed data, best possible pulse parameter values in order to get deep fusion weld can be proposed later in this work. Secondary objective was to do same procedure for voltage's effect on weld fusion depth.

In welding tests, it was found out, that when it comes to effects of pulse amplitude, lower levels lead to deeper weld fusion. Penetration decreases gradually when moving in test range from 60A to 150A amplitude. Pulse frequency instead was found to have different kind of effect on weld fusion. Lower and higher levels of frequencies in test range, 50-200Hz and 450-600Hz, are leading to deeper fusions than range between them. Deepest weld fusions were achieved with pulse parameter combinations 60A and 500-600Hz.

During the pulse parameter combination tests, it was found out that pulse parameters effect on metal transfer of the process. Lower frequency and amplitude of the pulse leads to greater amount of short-circuits than higher levels. Because of that, short-circuits' and arc voltage's effect on fusion depth was tested. It was found out, that arc voltage decreases from open arc to short-circuiting arc increases fusion depth, but further decrease of voltage makes process unstable and decreases fusion depth.

At the end of the chapter, best found alternative of WiseSteel with adjusted parameters was compared to other MIG/MAG-welding processes. Those processes were conventional synergic MIG/MAG, MIG/MAG with WiseFusion and WiseSteel with default parameters. Results shows that improvement in fusion depth is obtained by focused arc and correctly selected pulse parameters.

7 DISCUSSION AND CONCLUSIONS OF RESEARCH

In this chapter, outcome of results of the research are discussed and concluded. Key findings from welding tests about pulse parameters’ and voltage’s effect on weld fusion depth are discussed. The test result findings are also compared to literature findings and discussion about differences between test results and expectations is made. Reliability of the test results are also discussed from a reliability point of view. At the end of the chapter, usability of the test result findings and further development ideas considering WiseSteel process are proposed.

7.1 Key results of the welding tests

It was found out, that all of the parameters that were under examination, have effect on depth of weld fusion. This chapter goes through those separately each parameter discussing results and tries to find reasons for them. There is also proposed the best combination of them.

By decrease of arc voltage from level of open arc to short-circuiting arc, depth of fusion increases approximately 7 %. It was noticed that increase in fusion depth was obtained right after arc was turned into short-circuiting mode. It seems, that occurrence of short-circuits have pretty significant effect on fusion depth, but amount of short-circuits doesn’t, until it reaches certain point where arc length is too small and too much short-circuits happens. Image 30 illustrates phenomena in simplified way.

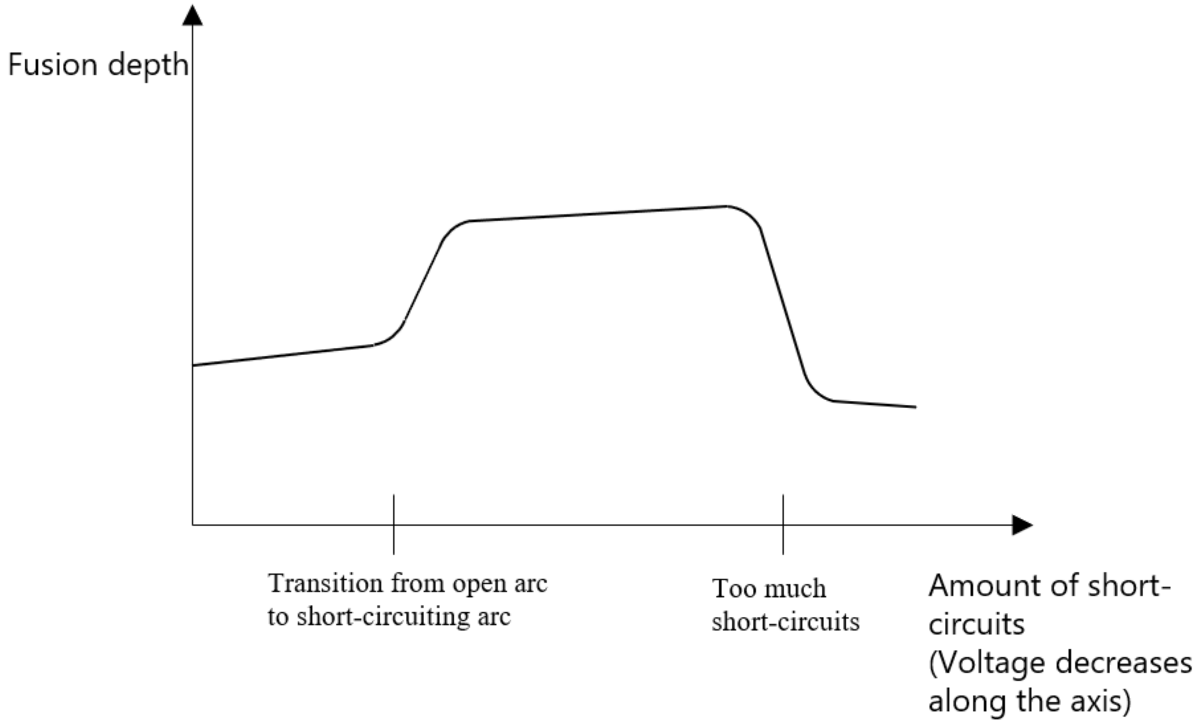

Image 30. Simplified presentation of arc length’s effect on fusion depth.

As results clearly showed, from tested range of pulse amplitudes (60-150A), 60A produced the deepest fusion depth, which decreases gradually when amplitude is increased. So it seems that smaller the amplitude is, the deeper is fusion depth. Because of the found trend, it could be questioned, if micropulses are beneficial at all for deep fusion. However, in welding comparison tests, there was tested MIG/MAG with WiseFusion, which is the same process than WiseSteel but without micropulses. Test results shows, that WiseSteel’s best pulse parameter combinations lead to approximately 8 % deeper fusion than MIG/MAG with WiseFusion and proves that by correct selection of micropulse parameters, deeper fusion can be achieved.

So after all, small decrease of lowest tested pulse amplitude, from 60A to 40-50A, could possibly increase fusion depth slightly. However, found and tested 60A is most likely really close to best alternative.

Expectations were that increase of pulse frequency would increase fusion depth of a weld. Welding tests indicated that deepest fusion depths are obtained by lower and upper ends of tested frequency range. Deepest fusion depths were found with values 150-200Hz and 500-

600Hz, when shallowest fusions were found at 250-300Hz. Difference between best and worst frequencies were found to be around 7 % in fusion depth.

As a conclusion, deep weld fusion of WiseSteel Spray arc is achieved by two differences comparing to conventional MIG/MAG spray arc process. The first one is short-circuiting and intensive arc, which is obtained by relatively low voltage level. The second is right selection of pulse parameters. Pulse amplitude around 60 amperages with pulse frequency of 500-600 Hertz lead to deepest fusion.

7.2 Comparison of test results and literature findings

The research questions set at introduction chapter can be mostly answered by the results of welding tests. However, answer for the research question; *Why and how pulse parameters of spray arc mode in GMAW effect on weld bead formation?* couldn't be given completely. "Why"-part of that question remained unsolved. That was intended to be answered by comparing information found from literature to welding test results. Reasons for the effects couldn't be explained completely and only some assumptions for it could be made.

As expected earlier based on literature findings, effects of pulse parameters on weld bead formation are hard to anticipate since they are not straight forward in nature. Thing that made anticipation even harder, is that WiseSteel process in spray arc mode is special GMAW process variation, which is not comparable to either spray arc or pulse arc mode. Even though clear reference point from literature to WiseSteel spray arc wasn't found, some estimations were made how pulse parameters would affect to weld bead formation.

According several found researches, fusion depth of a weld bead is highly related to total impact of droplets hitting weld pool. It was assumed, that if metal transfer of the process could be affected by pulse parameter variations, so would depth of a weld fusion. Based on that, assumption was made, that higher pulse frequency would increase droplet frequency and their total impact to weld pool and fusion depth. Pulse amplitude instead was expected to effect on velocity of the droplets. Higher amplitude would increase velocity, which would increase fusion depth.

Pulse amplitudes effect was found to be opposite that made assumption. Apparently metal transfer of conventional pulse arc is so different to WiseSteel spray arc, that found theory about pulse amplitudes effect on droplets velocity doesn't apply to WiseSteel process variation.

Outcome of pulse frequency's effect on fusion depth left partially unsolved. "V-shape" of fusion depth, which was at its lowest at 250Hz and increased to both directions, couldn't be explained by found information. The deepest fusions obtained by highest frequencies (500-600Hz) was probably caused by higher frequency and impact of droplets hitting the pool. But reasons why lowest levels of frequencies lead to deeper fusion than intermediate levels (250-300Hz) couldn't be justified by found scientific information. Image 31 below is the same as presented in results chapter but presented here again to ease understanding of conclusions.

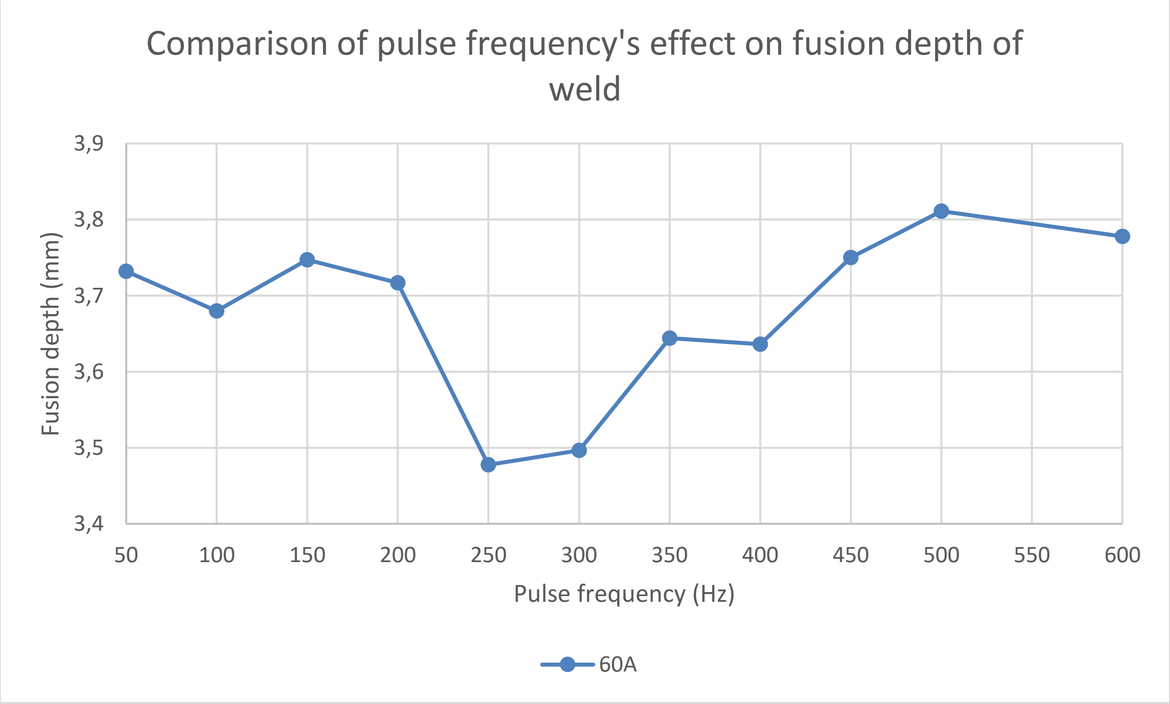

Image 31. Comparison of pulse frequency's effect on fusion depth of weld.

Same kind of phenomena considering pulse frequency was found in research of Pal&Pal, which was introduced in chapter 4.5. Penetration depth was decreased until certain level of frequency and started to increase after the level. That supports observation of this research, that penetration/fusion depth of weld doesn’t necessarily increase in accordance with pulse frequency.

More reliable explanations for pulse parameters’ effects on weld bead formation could be found by recording the process with a high-speed camera. With the help of the high-speed camera footage, parameters effects on metal transfer could have been seen and analyzed. Droplet size, velocity and detachment frequency would provide useful information about parameters effect on metal transfer, fusion depth of a weld bead.

7.3 Reliability of the test results

As mentioned in earlier chapters, each tested parameter combination was repeated two times. Welding procedure was done by using a mechanized torch carrier and specimen were clamped firmly to a table in order to avoid errors. Specimen were cut from midpoint of their length. In polishing and etching phase, same grinding materials and lubrication was used, and same pattern of actions was followed with every specimen.

Test results can be seen reliable enough to make conclusions about them. As each parameter combination was tested two times, and average deviation in fusion depth was calculated to be approximately 0.1 mm. The deviation would have been smaller if each test set-up would have been repeated multiple times, which would have eliminated some deviation in results. However, big picture of the test results trend can be seen clearly from the charts and they would have remained the same, even the bigger number of repetitions.

Welding tests were implemented by Kemppi’s X8 MIG Welder – welding machine. Since every welding machine has its own characteristics, there are no guarantees, that found parameter combinations would work exactly the same way when using other MIG/MAG welding machines of Kemppi, not to mention other manufacturers welding equipment. For instance, there can be differences in control of current curve. Shape and rise speed of pulse current curve may be different in other machines, which may have effect especially in high frequency levels.

In addition to individual differences between welding machines, other variables have to be taken into account when talking about applicability of the research results in other occasions.

Wire feed speed, welding speed, joint type etc. For instance, when wire feed speed is changed, arc voltage has to be adjusted as well, since welding current and voltage are closely related to each other. That’s why defining of the exact arc voltage is not reasonable.

7.4 Usability of deep fusion depth and further development of the research

In welding tests of this research, joint type was selected to be fillet weld T-joint and PB position was used. Wire was pointed to a corner, in 45° tilt angle. That kind of positioning leads to a weld bead, which is deeply penetrated into horizontal plate, as presented macroscopic images of weld beads shows. Depth of a weld fusion is easy to measure from that and so on parameters’ effect on a weld bead shape are easy to notice. However, in that kind of weld bead benefits of deep fusion of the WiseSteel are not taken advantage of completely.

Important thing considering strength of the weld joint is penetration depth instead of fusion depth. When determining the design resistance of fillet weld, effective throat thickness should be taken into account. In standard SFS-EN 1993-1-8 (p.42), effective throat thickness of fillet weld is defined to be length of a in image 31. Effective throat thickness consists of not just external part of the weld bead but also penetration (P) of the fillet weld. Penetration is measured to the point, where plates have coalescenced.

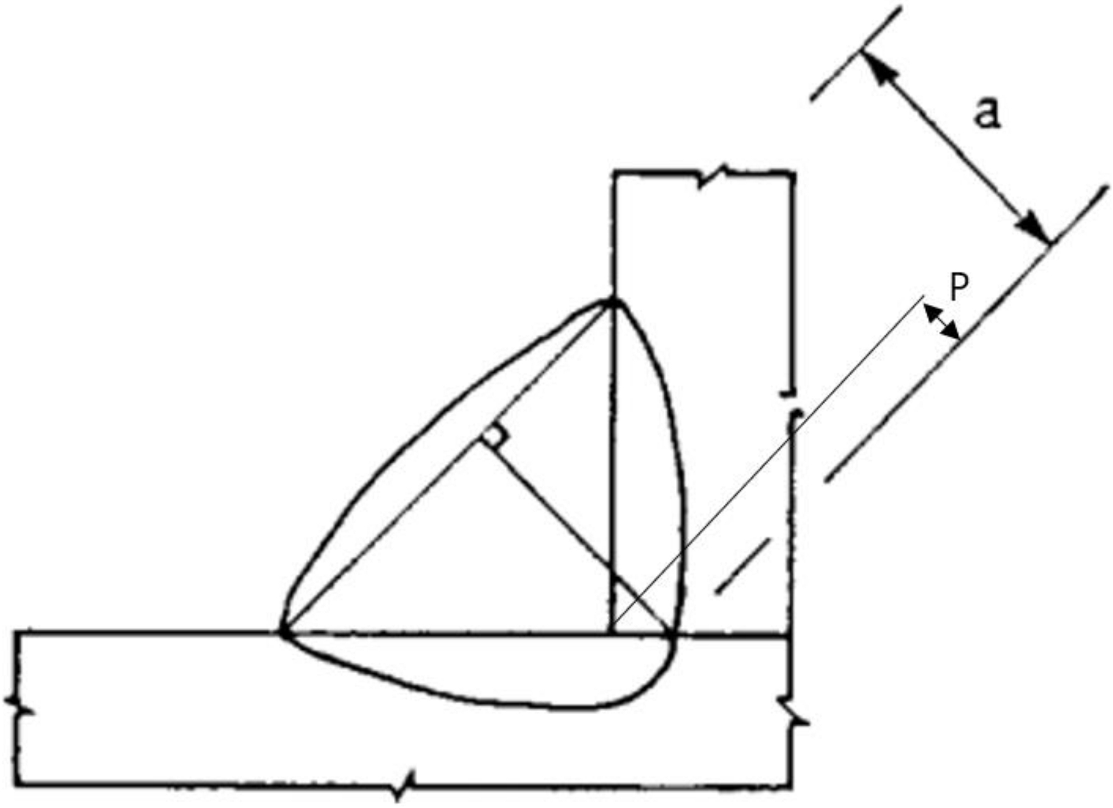

Image 32. Throat thickness of a deep penetration fillet weld (SFS-EN 1993-1-8 2005, p.42).

Now if welding test results and the weld bead shapes are looked from joint strength point of view, it can be noticed that there is no significant difference between parameter combinations. In image 32, earlier presented image of deep (60A/500Hz) and shallow (150A/250Hz) weld beads is presented again. Now instead of fusion depth from corner of plates to tip of the weld bead, lines are drawn to measure penetration depth of the weld bead. Yellow lines are drawn to illustrate, the length of coalescence between the plates. That length defines penetration depth, which is marked by letter P. As image shows, even fusion depth of 60A/500Hz weld bead is significantly deeper than 150A/250Hz, difference in penetration depth is almost insignificant.

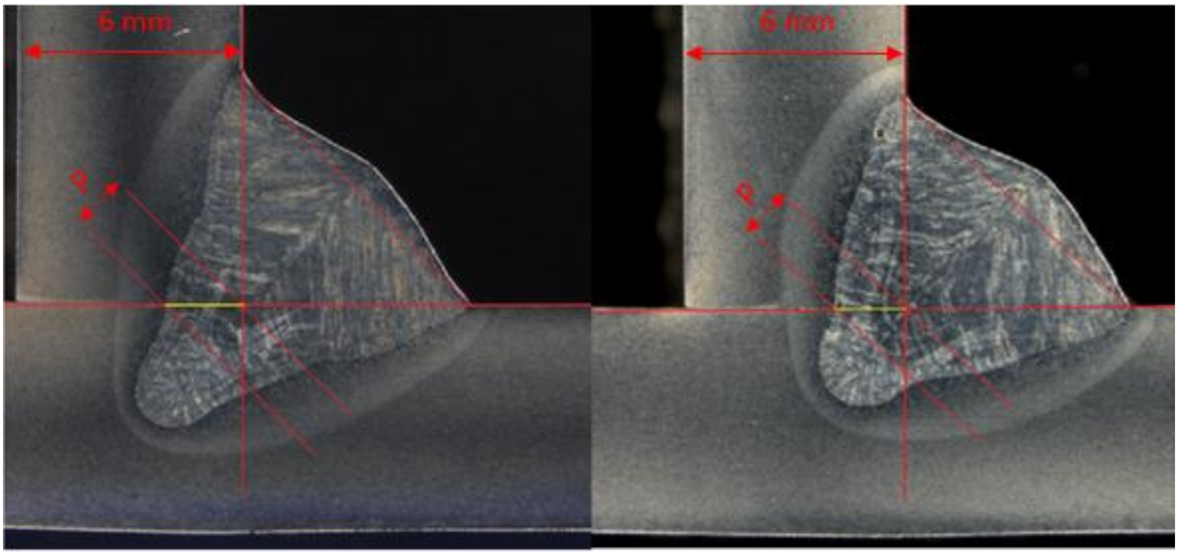

Image 33. Penetration depths of 60A/500Hz and 150A/250Hz weld beads.

So if welding torch would be positioned in different angle, for instance 30° angle to vertical plate, deep fusion depth could be used better for the strength of the joint, since the length of coalescence between plates would be longer. In image 33 represents idea of what would happen if weld torch is positioned in different angle. The red dotted lined shape doesn’t correspond realistic weld bead, but its idea is to illustrate how deep fusion of the WiseSteel could be possibly used more beneficially in case of T-joint fillet weld. That kind of positioning of weld torch could lead to excessive asymmetry of fillet weld, which means, that legs of a fillet weld are unequal length. That is defined as welding defect. However, that can be even beneficial for strength of the joint in right loading cases (Skriko 2020.)

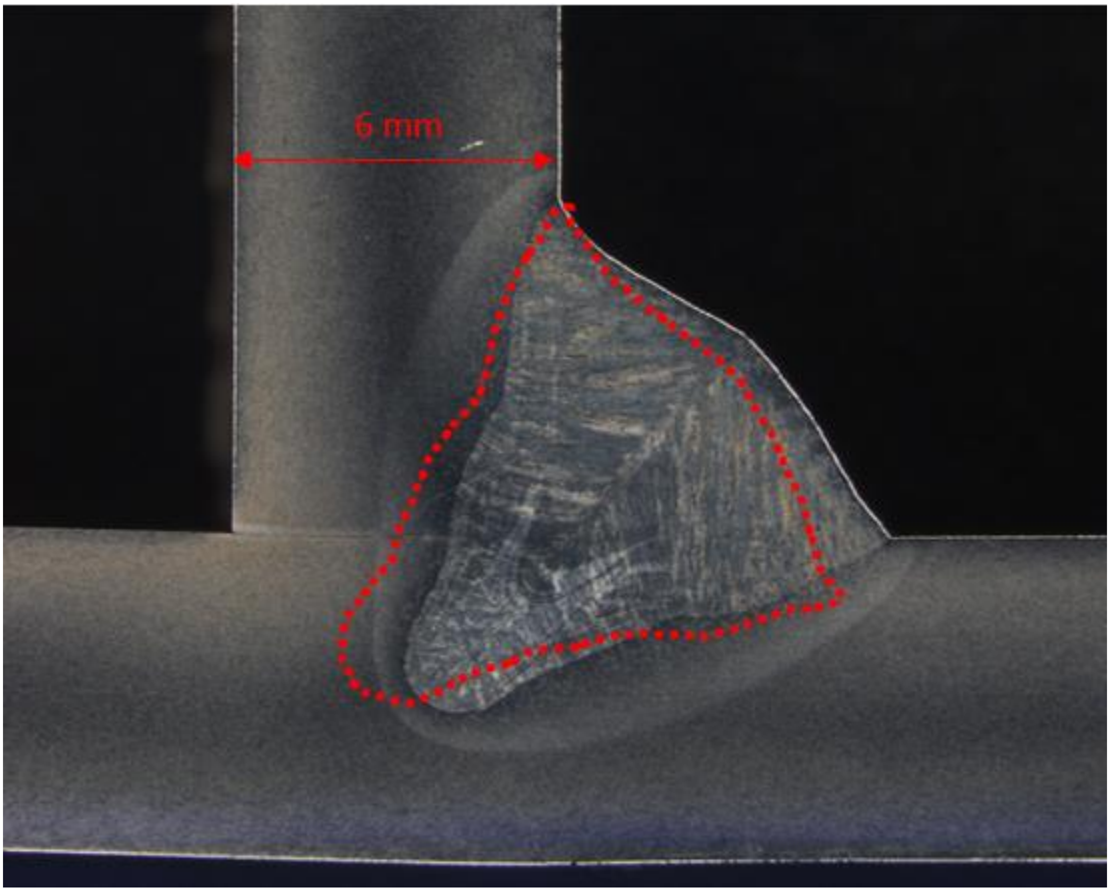

Image 34. Illustration of torch angle's effect on weld bead.

To keep scope of this research narrow enough, number of varied parameters had to be kept in few. To get more information about tested parameters influence on process, further development of research could be done. Variation of welding speed could be useful alternative considering usability of the test findings. If deeper fusion comparing to other processes and parameter set-ups could be maintained in higher welding speeds, found set-up could be beneficial in robot welding by increasing productivity.

As already discussed in reliability chapter, tests were implemented by using only one welding machine, Kemppi's X8 MIG Welder. Further development of the research could include testing with other MIG/MAG-welding machines.

8 SUMMARY

The objective of this research was to investigate Kemppi’s WiseSteel process in spray arc mode, and its parameters influence on weld bead formation. Research was scoped to be done by Kemppi’s X8 MIG Welder. Main research questions tried to be answered were*: Why and how pulse parameters of spray arc mode in GMAW affect on weld bead formation*, and *What are the optimal spray arc pulse parameters in GMAW when aiming for deep fusion depth of weld.*

Research was executed as a combination of qualitative and quantitative research. Qualitative research consisted of literature review and collection of previous test data and knowledge inside the company pertaining to the topic. From literature, theoretical information about pulse parameters’ effect on weld bead formation was looked for, as well as research pertaining to the topic. Based on literature findings and knowledge inside the company, range of pulse parameter values was selected for the welding tests.

Selected pulse parameter values were welded, and macro examination was done to each welded specimen. After analysis of the pulse parameter comparison test results, welding tests were decided to be expanded. Range of pulse frequency was widened, and on top of that, arc voltage’s effect on fusion depth of a weld was researched.

Based on welding test results, analysis of pulse parameters’ and arc voltage’s effect on weld bead formation was done. Arc voltage was found to be at optimal level, when arc was short and focused, and short-circuits occurs. The best pulse amplitude was found to be 60 amperages and best pulse frequency 500-600Hz, in order to get deep fusion of weld. Based on results, comprehensive analysis of pulse parameters’ and arc voltage’s effects on weld bead formation was given to the company, and suggestion of improvements for existing process.

Further development ideas and utilization of WiseSteel process were suggested, considering how found parameter set-ups would work with higher welding speed and different joint types. Found parameter combinations were suggested to be tried in practice in robotic welding if higher welding speed could be used without having a risk of incomplete fusion. Utilization of deep weld fusion was discussed considering positioning angle of the welding torch.

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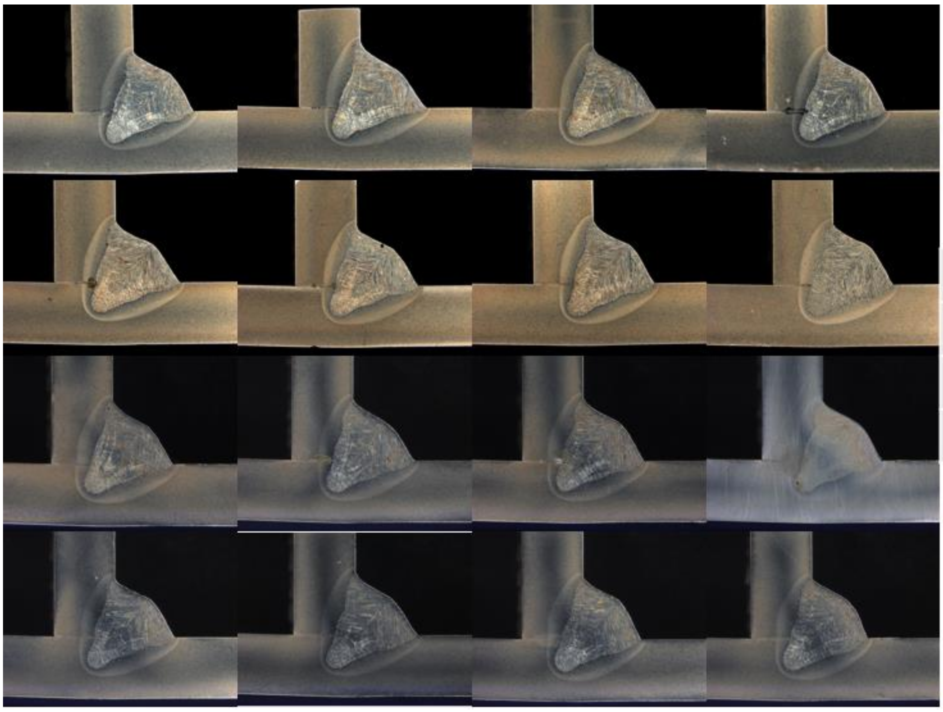
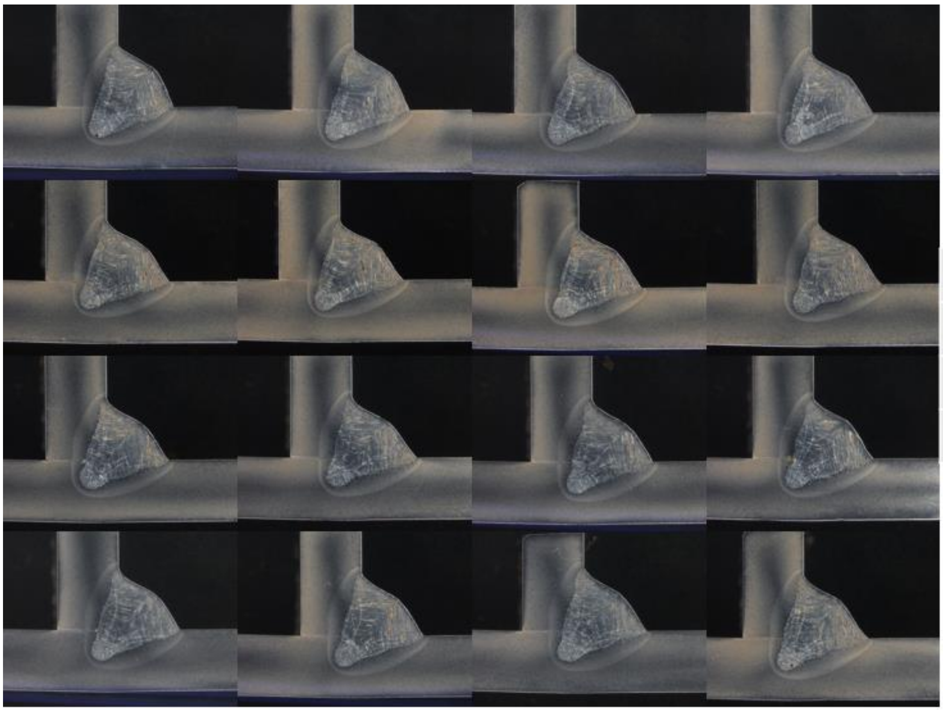
Appendice I,1

Macroscopic images of pulse parameter variation tests. Letter-number combination taken from table 2



A1	A1	A2	A2
A3	A3	A4	A4
A5	A5	A6	A6
A7	A7	A8	A8

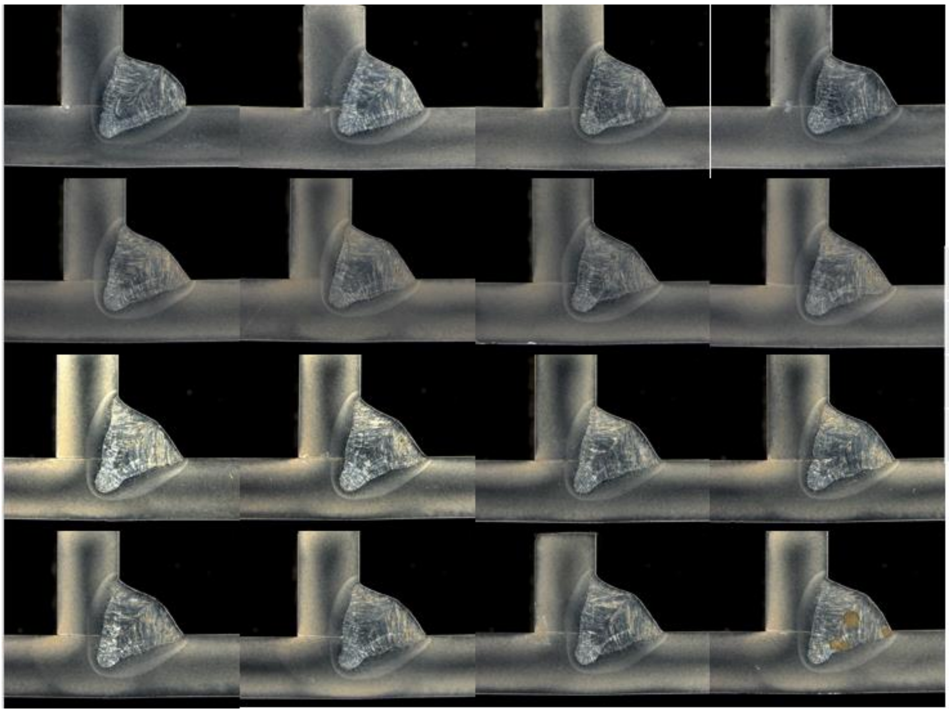


B1	B1	B2	B2
B3	B3	B4	B4
B5	B5	B6	B6
B7	B7	B8	B8

Appendice I,1

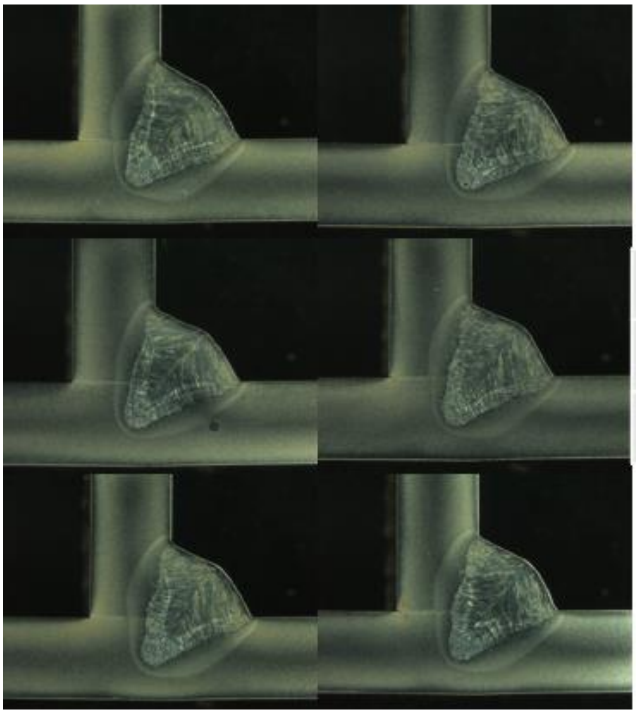
Macroscopic images of pulse parameter variation tests. Letter-number combination taken from table 2

C1	C1	C2	C2
C3	C3	C4	C4
C5	C5	C6	C6
C7	C7	C8	C8



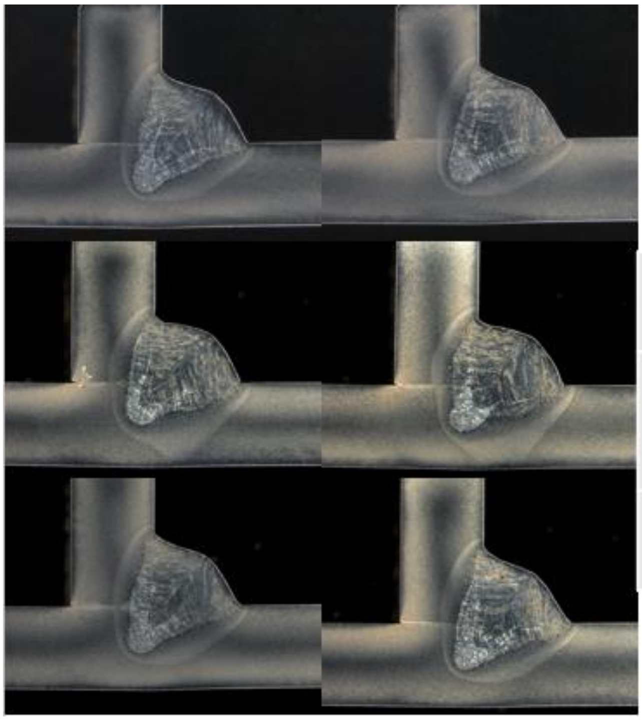
D1	D1	D2	D2
D3	D3	D4	D4
D5	D5	D6	D6
D7	D7	D8	D8

Macroscopic images of expanded pulse frequency comparison.



60A/50Hz	60A/50Hz
60A/100Hz	60A/100Hz
60A/150Hz	60A/150Hz

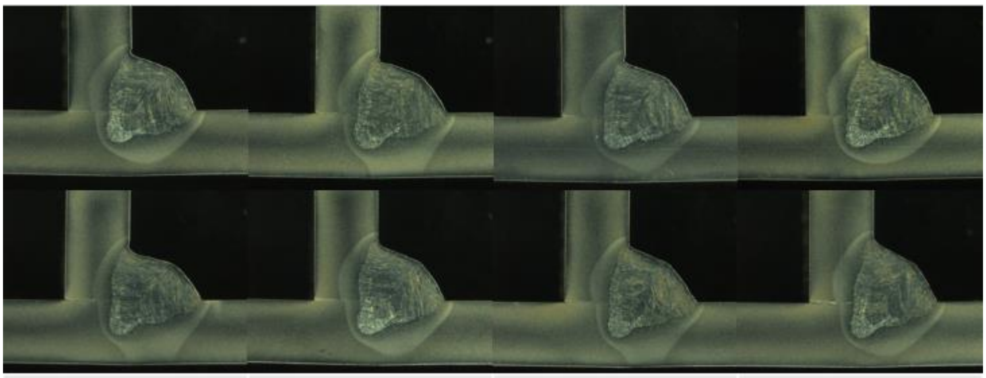
Macroscopic images of process comparisons.



WiseSteel default	WiseSteel default
Conventional MIG/MAG	Conventional MIG/MAG
MIG/MAG WiseFusion	MIG/MAG WiseFusion

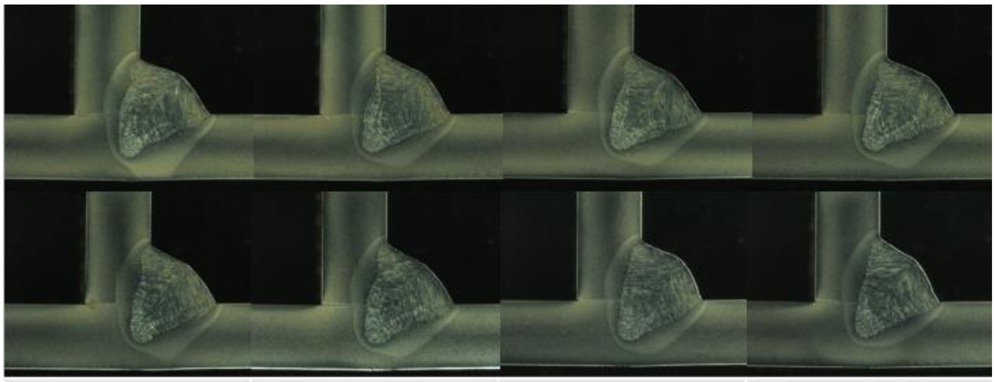
Macroscopic images of voltage tests.

Open arc



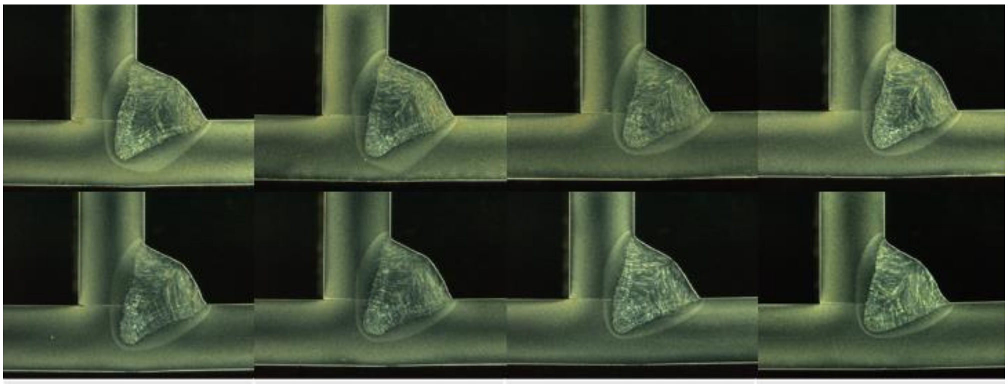
150Hz/32V	150Hz/32V	250Hz/31,8V	250Hz/31,8V
350Hz/31,3V	350Hz/31,3V	450Hz/30,9V	450Hz/30,9V

Short-circuiting arc



150Hz/29,8V	150Hz/29,8V	250Hz/29,6V	250Hz/29,6V
350Hz/29,2V	350Hz/29,2V	450Hz/28,9V	450Hz/28,9V

Short-circuiting arc 2 and 3

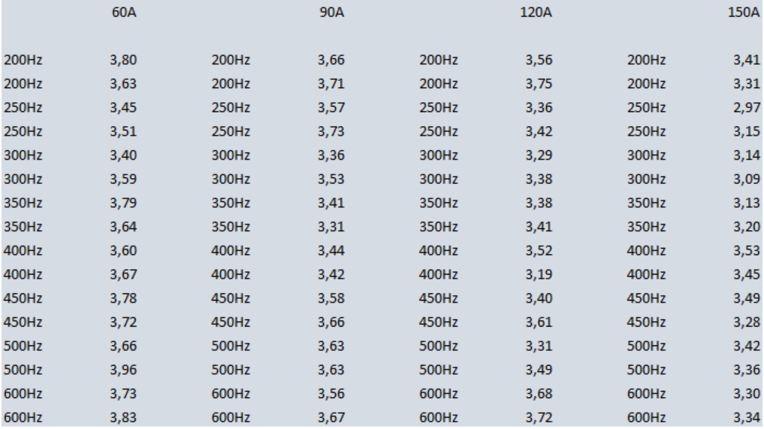


150Hz/29V	150Hz/29V	450Hz/28V	250Hz/28V
150Hz/28V	150Hz/28V	450Hz/27,5V	450Hz/27,5V

Fusion depth measures of test weld beads.

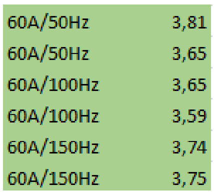
Appendice II,1

Pulse parameter comparison tests



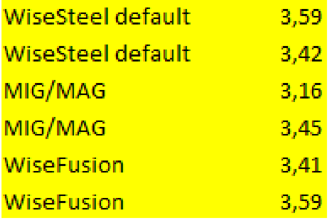
	60A		90A		120A		150A
200Hz	3,80	200Hz	3,66	200Hz	3,56	200Hz	3,41
200Hz	3,63	200Hz	3,71	200Hz	3,75	200Hz	3,31
250Hz	3,45	250Hz	3,57	250Hz	3,36	250Hz	2,97
250Hz	3,51	250Hz	3,73	250Hz	3,42	250Hz	3,15
300Hz	3,40	300Hz	3,36	300Hz	3,29	300Hz	3,14
300Hz	3,59	300Hz	3,53	300Hz	3,38	300Hz	3,09
350Hz	3,79	350Hz	3,41	350Hz	3,38	350Hz	3,13
350Hz	3,64	350Hz	3,31	350Hz	3,41	350Hz	3,20
400Hz	3,60	400Hz	3,44	400Hz	3,52	400Hz	3,53
400Hz	3,67	400Hz	3,42	400Hz	3,19	400Hz	3,45
450Hz	3,78	450Hz	3,58	450Hz	3,40	450Hz	3,49
450Hz	3,72	450Hz	3,66	450Hz	3,61	450Hz	3,28
500Hz	3,66	500Hz	3,63	500Hz	3,31	500Hz	3,42
500Hz	3,96	500Hz	3,63	500Hz	3,49	500Hz	3,36
600Hz	3,73	600Hz	3,56	600Hz	3,68	600Hz	3,30
600Hz	3,83	600Hz	3,67	600Hz	3,72	600Hz	3,34

Expanded pulse frequency tests



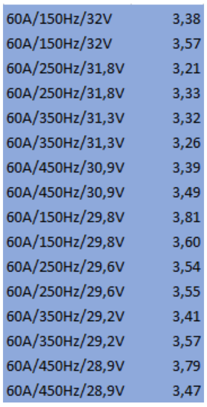
60A/50Hz	3,81
60A/50Hz	3,65
60A/100Hz	3,65
60A/100Hz	3,59
60A/150Hz	3,74
60A/150Hz	3,75

Process comparison tests



WiseSteel default	3,59
WiseSteel default	3,42
MIG/MAG	3,16
MIG/MAG	3,45
WiseFusion	3,41
WiseFusion	3,59

Welding voltage tests



60A/150Hz/32V	3,38
60A/150Hz/32V	3,57
60A/250Hz/31,8V	3,21
60A/250Hz/31,8V	3,33
60A/350Hz/31,3V	3,32
60A/350Hz/31,3V	3,26
60A/450Hz/30,9V	3,39
60A/450Hz/30,9V	3,49
60A/150Hz/29,8V	3,81
60A/150Hz/29,8V	3,60
60A/250Hz/29,6V	3,54
60A/250Hz/29,6V	3,55
60A/350Hz/29,2V	3,41
60A/350Hz/29,2V	3,57
60A/450Hz/28,9V	3,79
60A/450Hz/28,9V	3,47

60A/150Hz/29V	3,70
60A/150Hz/29V	3,78
60A/450Hz/28V	3,42
60A/450Hz/28V	3,46
60A/150Hz/28V	3,72
60A/150Hz/28V	3,57
60A/450Hz/27V	3,38
60A/450Hz/27V	3,22