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POSSIBILITIES OF ADVANCED MAG-WELDING PROCESSES IN SHIPBUILDING

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ABSTRACT

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Possibilities of advanced MAG-welding processes in shipbuilding

Master's thesis

2016

110 pages, 36 figures, 38 tables and 8 appendices

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Keywords: Solid wire welding, Metal transfer modes, Pulse, Double pulse, FCAW, MCAW, GMAW, ForceArc, RapidArc, Shop Primer, Jotun Muki Z 2001, Tack welding, 135, 136, 138

In shipbuilding industry welding of primer coated and tack welded steel products cause different issues. Primer coated steel products are commonly used at shipyards to ensure corrosion free storage of products in outdoor conditions. However usage of primer can cause imperfections to welds. To prevent porosity primed steel products are usually welded with tubular welding wires. Tack welds cause commonly interferences in mechanized welding when over welded, which increases costs related to welding due to increased need of preparing and repairing. The aim of this study is to research possibilities of advanced solid wire MAG-welding processes to deal with these two previously mentioned problems. This study concentrates to examine possibilities of MAG-welding, pulse MAG-welding, double pulse MAG-welding, RapidArc and ForceArc processes. Large amount of experiments were made to find out the produced porosity and the ability to over weld tack welds with each process in different circumstances.

In welding of primed steel products porosity is caused mainly by hydrogen, CO, CO_2, nitrous gases and zinc fumes. It was found in experiments that porosity of MAG-welding can be greatly decreased by using pulse MAG-welding instead. Also reduction of welding speed, usage of air gap and usage of solid wire product with higher amount of alloying elements reduces porosity. Researched advanced MAG-welding processes did not have an improvement into over welding of tack welds. With studied throat thicknesses and welding positions conventional MAG-welding managed better over welding of tack welds than the four studied advanced MAG-welding processes. Studied solid wire MAG-welding processes would be best suited at shipyard for mechanized welding in welding position PB. In welding positions PD and PG tubular welding wires are clearly more productive.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
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Kehittyneiden MAG-hitsausprosessien mahdollisuudet laivanrakennuksessa

Diplomityö

2016

110 sivua, 36 kuvaa, 38 taulukkoa ja 8 liitettä

Tarkastajat: Professori Jukka Martikainen
DI Antti Itävuo
Ohjaaja: DI Antti Itävuo

Hakusanat: Umpilankahitsaus, Aineensiirtyminen, Pulssi, Tuplapulssi, FCAW, MCAW, GMAW, ForceArc, RapidArc, Konepajapohjamaali, Jotun Muki Z 2001, Silloitushitsaus, 135, 136, 138

Telakkateollisuudessa hitsattavien terästuotteiden pohjamaalaus ja silloitushitsaus aiheuttaa hitsauksen kannalta erilaisia ongelmia. Pohjamaalattuja terästuotteita käytetään yleisesti telakkateollisuudessa, koska osia ja lohkoja säilytetään pitkiä aikoja ulkotiloissa. Pohjamaalattujen terästuotteiden hitsauksessa esiintyy kuitenkin huokoisuusongelmia. Ongelmien välttämiseksi pohjamaalattujen terästuotteiden pienaliitosten hitsauksessa käytetään usein täytelankoja. Mekanisoidussa hitsauksessa hitsin muodosta tulee usein huono silloitushitsien kohdalla, mikä lisää tarvetta silloitushitseihin kohdistuvalle esityöstölle ja hitsien korjaamiselle. Tämän tutkimuksen tavoitteena on tutkia kehittyneiden MAG-hitsausprosessien mahdollisuuksia vähentää pohjamaalista ja silloitushitseistä aiheutuvia ongelmia. Tämä tutkimus keskittyy tutkimaan MAG-hitsauksen, pulssi-MAG-hitsauksen, tuplapulssi-MAG-hitsauksen sekä RapidArc- ja ForceArc-prosessien mahdollisuuksia. Tutkimus koostui hitsauskokeista, joiden avulla tutkittiin huokoisuutta ja silloitushitsien ylityksiä erilaisissa olosuhteissa.

Pohjamaalattujen terästuotteiden hitsauksessa huokoisuus aiheutuu pääasiassa vedystä, CO:sta, CO_2:sta, typpikaasuista ja sinkkihuuruista. Työssä havaittiin, että MAG-hitsauksen huokoisuutta voidaan merkittävästi vähentää käyttämällä pulssi-MAG-hitsausta tavallisen MAG-hitsauksen sijaan. Myös hitsausnopeuden hidastamisella, ilmaraon ja seostetumman hitsauslangan käytöllä voidaan vähentää huokoisuutta. Tutkittujen kehittyneiden MAG-hitsausprosessien ei havaittu helpottavan silloitushitsien ylitse hitsaamista. Tavallinen MAG-hitsaus suoriutui silloitushitsien ylityksistä paremmin kuin tutkimuksen kohteena olleet kehittyneet MAG-hitsausprosessit tutkituissa olosuhteissa. Tutkitut MAG-hitsausprosessit soveltuvat telakan tuotannossa parhaiten mekanisoituun hitsaukseen PB-hitsausasennossa. PD- ja PG-hitsausasennoissa täytelangat ovat selvästi tuottavampia.

ACKNOWLEDGEMENTS

This Master's Thesis has been carried out for Meyer Turku Oy as a part of renewals of the shipyard.

I would like to thank my advisor welding engineer IWE Antti Itävuo and head of hull production IWE Kari Laiho of this opportunity to do my Master's Thesis from such an interesting topic. I would also like to thank my examiner professor Jukka Martikainen of advices and comments. I would like to especially thank welding coordinator Jukka Hahko of all support and guidance which he gave me during my Master's Thesis.

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Turku
1st of June 2016

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LIST OF SYMBOLS AND ABBREVIATIONS

a	Throat thickness	[mm]
f	Pulse frequency	[Hz]
F	Pinch force	[N]
I	Welding current	[A]
I_{ave}	Average welding current of pulse welding	[A]
I_b	Base current	[A]
I_p	Peak current	[A]
k	Thermal efficiency	
Q	Heat input	[kJ/mm]
t	Material thickness	[mm]
b	Width of the convex of weld	[mm]
T_b	Base time	[ms]
T_p	Peak time	[ms]
U	Voltage	[V]
v	Travel speed	[cm/min]

2-Pulse	Double pulse MAG-welding
AWS	American welding society
BV	Classification society Bureau Veritas
C	Carbon
CO	Carbon monoxide
CO_2	Carbon dioxide
Cr	Chromium
CTWD	Contact tip to work distance
Cu	Copper
DNV GL AS	The result of merger between classification societies Det Norske Veritas and Germanischer Lloyd
EN	European standard
F	Fluorine
Fe	Iron

FCAW	Flux cored arc welding
GMAW	Gas metal arc welding
HAZ	Heat affected zone
HV10	Hardness Vickers (load 10 kgf)
IACS	International association of classification societies LTD
ISO	International organization for standardization
MAG	Metal active gas
MIG	Metal inert gas
MMA	Manual metal arc welding
M21	Marking of shielding gas which contains argon and carbon dioxide from 15 % to 25 %
MCAW	Metal cored arc welding
Mn	Manganese
Mo	Molybdenum
Ni	Nickel
P	Phosphorus
PA	Flat welding position
Pb	Lead
PB	Horizontal vertical welding position
PC	Horizontal welding position
PD	Horizontal overhead welding position
PE	Overhead welding position
PG	Vertical down welding position
S	Sulfur
SFS	Finnish standards association
Si	Silicon
SWOT	Analysis of strengths, weaknesses, opportunities and threats
Ti	Titanium
VL	DNV GL material certificate
Zr	Zirconium

1 INTRODUCTION

Welding wires can be divided into two categories: solid welding wires and tubular wires. MIG/MAG (Metal Inert Gas/Metal Active Gas) processes are originally used with solid wires, but tubular wires have few advantages over solid wires. For example metal cored wire has higher productivity than solid wire. Rutile wires have better features than solid wires when welding in horizontal, vertical and overhead positions. At this moment Meyer Turku is using mainly metal cored and rutile wires. Approximately 65 % of used wire products are rutile type flux cored wires and 20 % are metal cored wires. Rests of the wire products are submerged arc welding wires and also small quantities of MAG solid wires are used. However the shipyard is increasing its capacity, decreasing lead times and improving cost-efficiency. Solid welding wire draws attention as a cheaper wire choice, but also its effective use in mechanized welding interests.

Generally in shipbuilding industry steel plates are primed to keep parts and blocks free of rust when stored outside. Primer causes few problems while welding. For example gases and vapors can cause porosity and primer can reduce travel speed. Tubular wires have higher tolerance to deal with impurities, which is why they are extensively used in shipbuilding. However it has been researched that pulse MAG-welding can improve usability of solid wires.

Another problem which is not only related to shipbuilding is over welding of tack welds. Especially for mechanized welding it is important that the used welding process is capable to pass tack welds smoothly, so that the weld does not need repairing afterwards. One possibility to handle tack welds is to use a welding process with high penetration. Modern productive MAG-welding processes are based on to pulsing of welding current, focusing electric arc to small area or to using both of the previous mentioned methods as the same time. These methods enable higher penetration than conventional MAG-welding, why it is reasonable to study their potential to handle tack welds.

1.1 Objectives

The aim of this study is to investigate utilization of solid welding wire in Meyer Turku shipyard. This study focuses to research possibilities to increase productivity and decrease wire costs by changing tubular welding wires to solid wires in possible targets. The main research topic is porosity which forms when primed steel products are over welded and also interferences which forms when tack welds are over welded. Interest is also in mechanized MAG-welding and in modern MAG-welding processes.

1.2 Limitations

This study concentrates to examine usage of solid wire MAG-welding in part manufacturing and block assembly of Meyer Turku shipyard. The Main interest will be in fillet welds. In studied cases throat thicknesses are from 3 mm to 6 mm. Parent metals are limited to shipbuilding steels A-E36.

1.3 Research methods

This study consists of theoretical part which deals essential things of different kind of wire types. Also used MAG-welding processes, shipyards special conditions, quality requirements and quality assurance are explained shortly. The second part of this study is an experimental part which consists of two different experiments: preselection and additional experiments. In preselection experiments different MAG-welding processes ability to handle tack welds and primed plates is researched. The most suitable process will be used in additional experiments. In additional experiments effect of different variables to porosity is studied. Productivity, costs and overall work time will be researched and compared to the current way of working.

1.4 Meyer Turku Shipyard

The shipyard was originally founded in 1737. After several owners, the shipyard is today owned by Meyer Werft and the managing director is Dr. Jan Meyer. Over the years products have developed from wooden crafts to large cruise ships, car-passenger ferries and special vessels. The shipyard has built over 1300 ships during its history and today it has approximately 1400 employees. (Meyer Turku, 2016a; Meyer Turku, 2016b.)

When the ownership of shipyard transferred to Meyer Werft, the order book expanded so that the shipyard has orders until year 2020. In order to that the shipyard is able to deliver all ordered ships in time, current production needs renewals and productivity needs to be increased. The aim of this study is to find ways to increase productivity and to improve cost-effectiveness by reconsidering alternatives for used wire types and working methods. In figure 1 is shown Meyer Turku shipyard and Mein Schiff 4.

Figure 1. Meyer Turku shipyard (Meyer Turku, 2016a).

2 MAG-WELDING

Gas-shielded metal-arc welding (GMAW) is a welding process in which electric arc forms between welding wire and work piece. Depending of used shielding gas welding is called either MIG-welding (Metal-arc inert gas welding) or MAG-welding (Metal-arc active gas welding). Active gas is a mixture of argon and other gas which is either carbon dioxide (CO_2) or oxygen. It can as well be a mixture of all three previous mentioned. Also pure CO_2 is used as active shielding gas. Inert gas is pure argon, helium or their mixture. Inert gas does not react with weld pool and it is used with non-ferrous metals. Non-alloyed steels and stainless steels are usually welded with active gas. (Lukkari, 1997, p. 159.)

MAG-welding is semi-automatic welding where welding wire is fed automatically by wire feed unit and welder travels welding torch. MAG-welding can also be automatized and robotized with various equipment. Used current type is direct current, but polarity varies depending of the used wire type. In most cases with solid wire +polarity is used. With tubular wires –polarity is sometimes used, depending of the welding wire type. In MAG-welding used power sources are constant voltage power sources which enable self-adjusting electric arc. Length of the arc stays constant although the distance between contact nozzle and work piece would change. Generally MAG-welding equipment consists of a power source, wire feed unit, welding hose, work cable, welding torch and gas cylinder. (Lukkari, 1997, p. 160–177.)

2.1 Welding with solid wire

Originally MAG-welding was performed with solid welding wires (TWI, 2015). Solid wires can be used in all positions as long as welder has chosen right welding parameters to ensure the correct metal transfer mode. Solid wire welding is common in all kind of welding industry. The minimum weldable plate thickness is 0.8 mm and there is no upper limit. As previously mentioned, solid wire MAG-welding is suitable for non-alloyed steels and stainless steels. (Lukkari, 1997, p. 159, 173–176.)

2.2 Welding with tubular wires

Tubular wire welding can be performed with gas shielding or with self-shielded flux cored wires which do not need shielding gas. When shielding gas is used, it is active gas which is usually pure CO_2 or mixture of argon and CO_2. Commonly there is 25 % of CO_2 and 75 % of argon. (The Fabricator, 2003; Lukkari, 1997, p. 228.) The largest user base of tubular wires is shipyard and offshore industry (Lukkari, 1997, p. 230). With tubular wires arc types differ depending on the used wire type. In general it can be said that there are the same arc types in tubular wire MAG-welding and in solid wire MAG-welding. With metal cored wires short arc is used in position welding and in welding of sealing runs. Spray arc is used in fill up runs when welding takes its place in flat position. With rutile type flux cored wires arc type is mostly spray arc. (Lukkari, 1997, p. 229.) While writing this study majority of welding wires at Meyer Turku shipyard are either metal cored tubular wires or rutile type flux cored tubular wires.

2.3 Welding parameters

Despite is it talk about MAG solid wire welding or MAG-welding with tubular wires, both processes have four common parameters which welder can control: travel speed, wire feed rate, voltage and stickout. The used power source adjusts right welding current to wire feed rate. Relationship between wire feed rate and voltage can be either adjusted separately or with synergic control which means adjusting both wire feed rate and voltage from the same knobs. By adjusting stickout, welder can affect to welding current and penetration. Effect of stickout to welding current is less remarkable in short arc welding than it is in spray arc welding. In general it can be said that changes in stickout can cause ± 40 A changes in welding current. (Lukkari, 1997, p. 164–165, 210–211.)

Important issue in welding is heat input Q which describes the amount of thermal energy put into weld (Lukkari, 1997, p. 54). Heat input together with plate thickness, joint form and working temperature sets cooling rate for weld. Cooling rate has large effect to properties of the weld joint. If the cooling rate is too fast, microstructure of heat affected zone (HAZ) starts to get more martensitic, which also means that hardness of this area increases. Increased hardness can cause cold cracking. On the other hand too slow cooling rate weakens impact strength of the weld, because the grain size in HAZ increases. (Lukkari, 2007, p. 9–10; TWI, 2016a.) Classification society DNV GL AS (Det Norske

Veritas and Germanischer Lloyd) requires that the maximum hardness of the HAZ-area should not exceed 380 HV10 (Hardness Vickers) in case of single pass fillet welds. The maximum hardness of HAZ-area can be estimated with different kind of formulas which takes in account the effect of chemical composition of parent metal and the cooling rate of weld. (DNV GL AS, 2015a, p. 48; Nolan, Sterjovski & Dunne, 2012, p. 6.)

Welder can achieve the desired heat input by using correct welding parameters. Heat input Q can be calculated with following formula:

$$Q = k \frac{UI}{1000v} \tag{1}$$

In formula 1 U is voltage, I is welding current, k is thermal efficiency and v is travel speed. For MAG-welding with solid wire and MAG-welding with tubular wire factor of thermal efficiency is 0.8. (Lukkari, 2007, p. 8.)

In addition to heat input welded structures usually also have specifications for throat thicknesses to ensure sufficient heat input and designed strength of joint. Too small throat thicknesses can lead to fast cooling rates and thus to unwanted microstructure of HAZ-area. On the other hand relatively small increase in throat thickness will have a large impact into cross section of fillet weld and thus it will increase the amount of consumed filler material. Meaning of throat thickness appears from figure 2. (TWI, 2016a, TWI, 2016b.) Oversized throat thicknesses cause also unnecessary deformations to welded plates. Above a certain heat input level buckling of welded plates increases remarkably, why it is important not to exceed the required throat thickness. (Kolodziejczak, 1987, p. 82.)

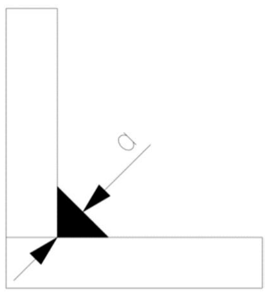

Figure 2. Throat thickness *a* of fillet weld.

2.4 Arc types and metal transfer modes

Besides of heat input and throat thickness, welder can also affect to type of the electric arc when choosing welding parameters. Different kind of arc types can be divided into a short arc, globular arc, spray arc, long arc and pulsed arc. Arc types have different metal transfer modes, which affects to behavior of weld pool, appearance of weld and amount of spatters. The pulsed arc appears only in pulse MAG-welding. Appearance of other arc types depends for example of thickness of the used welding wire, type of the wire and used shielding gas (Lukkari, 1997, p. 174). Each arc type has its own range of use. Different features can be utilized for example in position welding. Also sealing run and fill up runs can be welded with different arc types. Current regions of each arc type for 1.2 mm solid welding wire and shielding gas which contains argon and carbon dioxide from 15 % to 25 % (M21) are shown in table 1. (Lukkari, 1997, p. 167–173; SFS EN-ISO 14175, 2008, p. 18.)

Table 1. Current regions of each arc type when using 1.2 mm solid welding wire and shielding gas M21 (Lukkari, 1997, p. 174).

Parameters/Arc	Min.Current[A]	Min.Voltage[V]	Max.Current[A]	Max.Voltage[V]
Short arc	80	16	195	20
Globular arc	180	23	257	28
Spray arc	247	30	350	36

Pinch-effect is important physical phenomenon which has great effect to characteristics of different arc types. Magnetic pinch force squeezes in radial direction molten tip of welding wire, which causes detachment of a droplet. After the detachment plasma jet accelerates the droplet to weld pool. (Linnert, 1994, p. 456–458.) Pinch force *F* can be calculated with the following formula:

$$F = \frac{I^2}{2} \qquad (2)$$

In formula 2 *I* is welding current. If the welding current *I* is doubled, the magnetic pinch force *F* will be quadruple. (Lukkari, 1997, p. 170.)

Short arc appears when welding is performed with low voltage and current values. Welding wire transfers to parent metal with short circuits. Short circuiting frequency is 20-200 Hz. (ESAB, 2015a.) Frequency of short circuiting depends of the used wire feed rate, voltage, inductance and used shielding gas. Inductance affects to smoothness of the arc and temperature of the arc. In every short circuit a drop of molten wire transfers to the weld pool. After the drop has transferred, arc ignites again and a new drop starts to form from the head of the welding wire. Changes in welding current and voltage values in different phases of short arc cycle appears from figure 3. In short arc welding size of the weld pool stays relatively small, which makes it usable arc type for sealing runs and for position welding. (Lukkari, 1997, p. 168–169.)

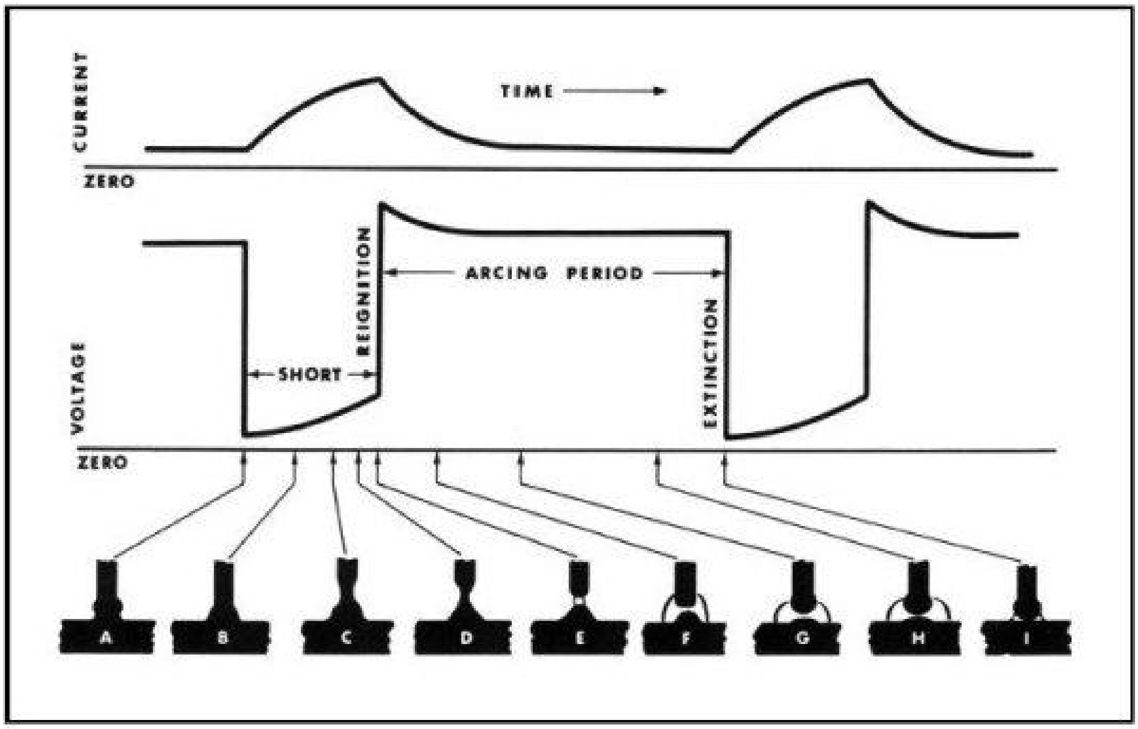

Figure 3. Short circuiting cycle in short arc welding (ESAB, 2015a).

When current and voltage values come high enough, short arc changes to globular arc. In globular arc molten welding wire transfer both with short circuits and with spray transfer. Diameter of the molten drop is larger than diameter of the used welding wire, which causes a lot of spatters (Weglowski, Huang & Zhang, 2008, p. 50). Nevertheless globular arc can be used in horizontal position PC and vertical down position PG. (Lukkari, 1997, p. 169.)

Spray arc appears when welding current passes transition current. Transition current is a current value after which droplet size of the molten welding wire decreases significantly. Transition current depends of the used diameter of welding wire, type of welding wire, shielding gas, travel speed, torch angle, stick out, cleanness of welded object and parent material itself. Following things lowers transition current (Lukkari, 1997, p. 169–170):

- decrease in wire diameter
- inert shielding gas
- high travel speed
- greater torch angle
- decrease in stick out (electrode extension)
- cleanness of welded object
- noble material.

In spray arc welding droplet size of the molten welding wire is small. Short circuits do not exist, which makes electric arc smooth and metal transfer mode almost spatter free. Increase in welding current increases pinch force and thus makes the droplet size smaller and transfer rate higher. (Lukkari, 1997, p. 169–171.) For example if welding current is increased from 178 A to 246 A, transfer rate increases from 16 to 414 drops per second and diameter of the droplet decreases from 1.29 mm to 0.51 mm when using argon as shielding gas (Weglowski et al., 2008, p. 55). It was investigated by Rhee & Kannatey-Asibu (1992) that for high transfer rates optimum shielding gas contains 95 % argon and 5 % CO_2. With pure argon or with greater amount of CO_2, transfer rate decreases and thus droplet size increases as the wire feed rate remains constant. Rhee & Kannatey-Asibu (1992) also found that optimum electrode extension for high transfer rate is 19 mm. Transfer rate decreased when 14 mm or 24 mm were used as electrode extension instead of 19 mm. (Rhee & Kannatey-Asibu, 1992, p. 383–384.) Disadvantage of spray arc is large weld pool which makes it suitable only for welding fill up runs in flat position (PA) or welding in horizontal vertical position (PB) (Lukkari, 1997, p. 169–171).

Long arc exists instead of spray arc when welding is performed with high current value and CO_2 is used as shielding gas. In long arc welding considerably amount of spatters occurs and surface of the weld remains harsh. Long arc welding can be used for welding of fill up runs in flat position PA or welding in horizontal vertical position PB. (Lukkari, 1997, p. 171.)

2.4.1 Pulsed arc

With pulsed electric arc spray transfer mode can be achieved with lower wire feed rate than with conventional direct current. Short arc and globular arc can be thus avoided. Short circuiting does not exist in pulsed arc welding, which makes it almost spatter free welding process. Pulsing of the welding current makes also heat input smaller and thus causes smaller deformations to welded objects. Travel speed and deposition rate are higher and visual look of the weld is better than in conventional direct current welding. To achieve spray transfer in pulsed arc welding, shielding gas cannot be CO_2 and it should be as inert as possible. Pulsed current is rarely used with tubular welding wires (Lukkari, 1997, p. 172, 229).

2.5 Welding positions

Standard SFS-EN ISO 6947 divides welding positions into flat, horizontal, vertical and overhead positions. Welding position markings do not specify is the joint form fillet, butt or other joint form. For example flat position PA can be fillet or butt weld. Welding position PA is shown in figure 4. (SFS-EN ISO 6947, 2011, p. 9.)

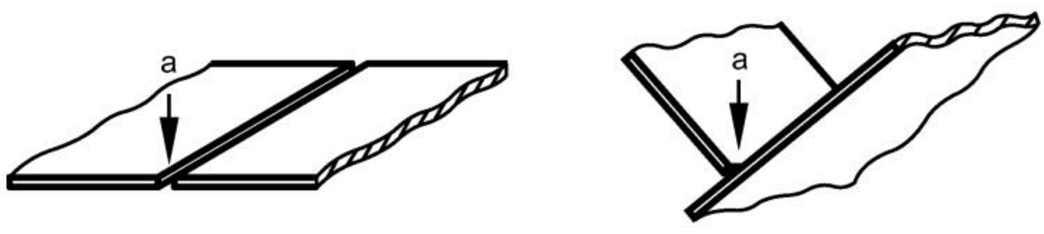

Figure 4. Flat position PA (modified from: SFS-EN ISO 6947, 2011, p. 13).

According to SFS-EN ISO 6947 (2011) there are five main positions: flat position (PA), horizontal vertical position (PB), horizontal position (PC), horizontal overhead position (PD) and overhead position (PE). In addition to previous there are also markings PF for vertical up and PG for vertical down positions. This study concentrates to investigate fillet welds in positions PB, PG and PD. Five main positions are shown in figure 5. (SFS-EN ISO 6947, 2011, p. 13-17.)

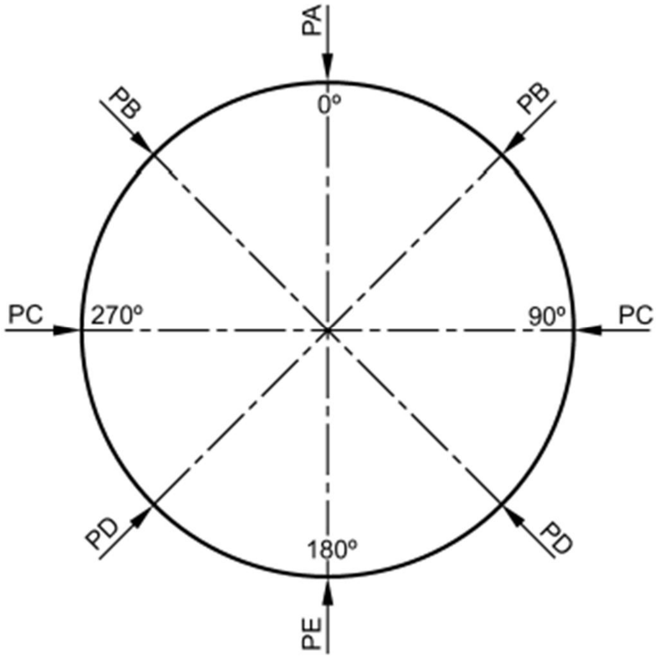

Figure 5. Main positions (modified from: SFS-EN ISO 6947, 2011, p. 12).

Welding positions PH, PJ and PK are for welding upwards, downwards and for orbital welding of pipes. Pipes with inclined axels have markings depending of the welding direction and angle of the pipe. Also basic positions can be marked more precisely if there is either slope or rotation in welded object. (SFS-EN ISO 6947, 2011, p. 17–21.)

2.6 Mechanized MAG-welding in shipyard

In light mechanization of MAG-welding a tractor or a carrier is used to travel the welding torch. These equipment make possible to mechanize welding with existing wire feeders, power sources and welding torches. Mechanized welding enables higher productivity which can be achieved by possibility to use higher travel speed and higher wire feed rate. In addition to higher productivity, light mechanization also improves working ergonomics of the welder and thus decreases physical stress. Light mechanization improves quality of welds, appearance and allows quality to be more consistent. It is also possible to weld longer welds, which decreases the amount of starts and stops. However the usage of mechanized welding in shipbuilding is disturbed by large tolerances and variation between parts and grooves. (Lukkari, 2005, p. 7; Kolodziejczak, 1987, p. 63.)

Meyer Turku shipyard has different kind of light mechanization devices for mechanized MAG-welding. Devices are different kind of tractors which move forward on wheels or carriers which move on rails. Hull production of Meyer Turku shipyard can be divided into four stages: part manufacturing, block assembly, grand block assembly and erection stage. In part manufacturing for example different kind of stiffeners, brackets and bulkheads are made. In block assembly parts are combined to blocks and later in grand block assembly blocks are combined to grand blocks which consist of blocks with different shapes. Finally in erection stage grand blocks are combined to hull of the ship.

In the part manufacturing tractors are more common because most of the welds which are reasonable to mechanize are fillet welds in welding position PB. When moving further in production the amount of rail carriers increases. Mechanization of MAG-welding has same basic advantages in different stages of the production of Meyer Turku shipyard:

- more uniform quality
- healthier working position for welder
- increase in productivity
- decrease in post-repairing.

In the part manufacturing fillet weld tractors are used for welding bulbs (a profile shape which is widely used in shipbuilding and also known as Holland profile) and flat bars of bulkheads, longitudinal stiffeners of decks and boards and T- and L-beams in welding position PB. In figure 6 is shown one of the fillet weld tractors which is in use at the part manufacturing.

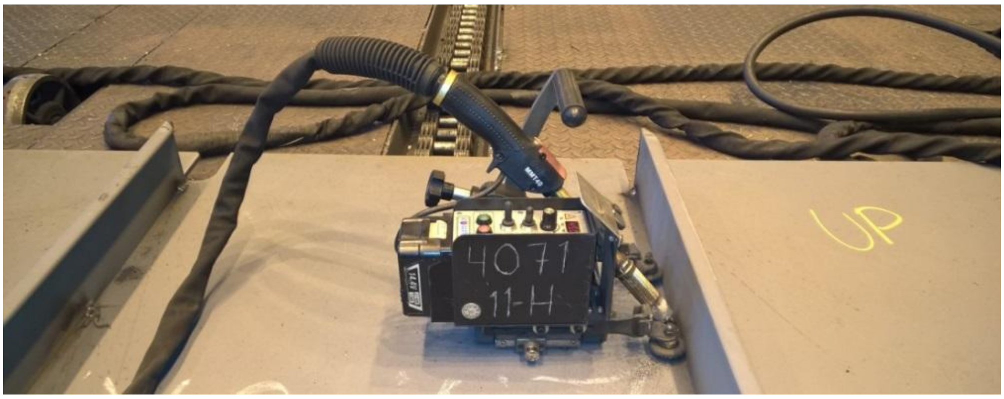

Figure 6. For example Koweld CS-B71 is used for welding fillet welds in welding position PB.

In the block assembly fillet weld tractors are used for welding longitudinal stiffeners, bulbs, flat bars and fillet welds between bulkheads and boards in welding position PB. Both, tractors and rail carriers, are also used in welding position PD.

In the grand block assembly tractors and rail carriers are used for welding fillet welds of bulkheads and butt welds of block boundaries in welding position PF with weave technique. Rail carriers are also used when welding horizontal welds of boards in welding position PC.

In the erection stage rail carriers are used for welding butt welds in some boundary areas of grand blocks in welding positions PE and PF with weave technique and horizontal grand block boundaries in welding position PC. In figure 7 is shown one of the rail carriages of the shipyard, ESAB Railtrac, which is capable to different weaving techniques.

Figure 7. Mechanized flux cored arc welding (FCAW) with ESAB Railtrac in welding position PF.

3 DIFFERENT TYPES OF WELDING WIRES

MAG-welding wires can be divided into two main categories: solid wires and tubular wires. Tubular wires are either flux cored wires or metal cored wires. Type of the flux cored wire can be either rutile or basic. Each wire type has its own use, advantages and disadvantages. Advantage of solid wire is clearly its low price compared to other wire types. Tubular wires have high productivity and especially rutile type flux cored wires have great position welding features. (Lukkari, 1997, p. 160, 228–229, 232.)

3.1 Effect of shielding gas in MAG-welding

In MAG-welding processes oxidizing feature of shielding gases leads to forming of carbon monoxide (CO) which can cause porosity into weld. Porosity can be prevented by alloying the welding wire with deoxidizing agents for example with silicon, manganese, titanium, zirconium or aluminum. The usage of deoxidizing agents leads to forming of slag instead of harmful gases. When the oxidizing feature of shielding gas increases, strongly reacting metals, for example manganese and silicon, reacts with shielding gas and their concentration in weld metal decreases. Decreased composition in weld can lead to reduced strength and impact strength. Also decrease in manganese composition can affect to behavior of weld pool and to metal transfer. (Lukkari, 1997, p. 193–194.)

3.2 Solid welding wires

Solid welding wires are hot rolled and drawn from a blank. After drawn process wires are in most cases coppered to give them corrosion protection, better conductivity and better motion features in welding hose. Percentage of copper in solid wire has to be low enough which is approximately 0.2 %. Higher percentages of copper can lead to brittleness phenomenon. Wires can be also coated with tin bronze instead of copper or completely without coating. General diameters for solid wires are 0.8, 1.0 and 1.2 mm. (Lukkari, 1997, p. 192.) MAG-welding with solid wire has numerical code 135 (SFS-EN ISO 4063, 2011, p. 12).

3.2.1 Classification of solid welding wires according to SFS-EN ISO 14341-A

SFS-EN ISO 14341 (2008) classifies solid welding wires and weld deposits for non-alloy and fine grain steels. Welding wires are classified by their chemical composition. Weld deposits are classified by mechanical properties of all-weld metal with a certain shielding gas. Standard SFS-EN ISO 14341 (2008) has two systems: A and B. In system A classification is made based on yield strength and 47 J average impact energy. In system B it is based on tensile strength and average impact energy of 27 J. System A divides solid MAG-welding wires into 11 different qualities by their chemical composition: 2Si, 3Si1, 3Si2, 4Si1, 2Ti, 2Al, 3Ni1, 2Ni2, 2Mo, 4Mo and Z. In table 2 is shown only essential chemical elements of which percentage differs clearly between different qualities. The particular standard defines more accurately chemical composition of different qualities. The last quality Z stands for solid wires of which chemical composition does not correspond to any other quality. System B divides solid MAG-welding wires into 38 qualities by their chemical compositions. (SFS-EN ISO 14341, 2008, p. 11–23.)

Table 2. Classification of solid MAG-welding wires by chemical composition according to SFS-EN ISO 14341-A (modified from: SFS-EN ISO 14341, 2008, p. 19).

Wire	Si [%]	Mn [%]	Ni [%]	Mo [%]	Al [%]	Ti+Zr [%]
2Si	0.5-0.8	0.9-1.3	0.15	0.15	0.2	0.15
3Si1	0.7-1.0	1.3-1.6	0.15	0.15	0.2	0.15
3Si2	1.0-1.3	1.3-1.6	0.15	0.15	0.2	0.15
4Si1	0.8-1.2	1.6-1.9	0.15	0.15	0.2	0.15
2Ti	0.4-0.8	0.9-1.4	0.15	0.15	0.05-0.2	0.05-0.25
2Al	0.3-0.5	0.9-1.3	0.15	0.15	0.35-0.75	0.15
3Ni1	0.5-0.9	1.0-1.6	0.8-1.5	0.15	0.2	0.15
2Ni2	0.4-0.8	0.8-1.4	2.1-2.7	0.15	0.2	0.15
2Mo	0.3-0.7	0.9-1.3	0.15	0.4-0.6	0.2	0.15
4Mo	0.5-0.8	1.7-2.1	0.15	0.4-0.6	0.2	0.15
Z	?	?	?	?	?	?

For example if solid wire is classified with the system A and its quality is 2Si, it can be marked as: ISO 14341-A-2Si. Marking of weld deposit consist of strength, elongation, impact energy, used shielding gas and chemical composition of the welding wire. For example marking: ISO 14341-A-G 35 4 M21 2Si implies that weld deposit is classified with the system A. *G* stands for MAG-welding, *35* for minimum yield strength of 355 MPa and elongation of 22 %, *4* for impact energy of 47 J in temperature -40 °C, *M21* for shielding gas ISO 14175-M21 and *2Si* for chemical composition of welding wire. (SFS-EN ISO 14341, 2008, p. 15–31.)

The most common solid wire quality is 3Si1. Quality 2Ti differs from other solid wire qualities by its alloying elements: aluminum, titanium and zirconium, which make this quality suitable for welding plates with rust and primer. Qualities 2Si1 and 2Ti have low percentage of silicon and manganese, which is why they are not suitable for welding with CO_2. (Lukkari, 1997, p. 194–195.)

3.2.2 Classification according to DNV GL

In shipbuilding DNV GL divides welding consumables into four groups according to strength of the welding wire: normal strength steels, high strength steels, extra high strength steels and austenitic stainless steels. These four groups are divided into grades with roman numerals I-V. The impact test temperature of the welding wire specifies into which grade it belongs. Roman numeral specifies impact test temperatures as follows (DNV GL AS, 2015a, p. 22):

- I: 20 °C
- II: 0 °C
- III: -20 °C
- IV: -40 °C
- V: -60 °C.

Normal steels are marked only with a roman numeral. High strength steels are marked with a roman numeral following Y or Y40. Marking of extra high strength steels differ only by the number following Y, which can have value 42, 46, 50, 55, 62 or 69. The number always describes the yield strength of weld deposit when it is multiplied with 10. Austenitic stainless steels are marked according to specifications of American welding society (AWS). In table 3 is shown classifications for welding wires which suits for steel grades A-E36 as long as the used plate thickness is under 50 mm. Welding wires with classification marking Y40 can be used also for steel grades A-E in some cases with agreement of DNV GL. In steel grade markings VL stands for the material certificate of DNV GL. (DNV GL AS, 2015a, p. 22-26; DNV GL AS, 2015b, p. 59.)

Table 3. Suitable welding wires for shipbuilding steels A-E36 according to DNV GL (DNV GL AS, 2015a, p. 23).

Grade	I	I Y	II	II Y	II Y40	III	III Y	III Y40	IV Y	V Y	IV Y40	V Y40
VL A	x	x	x	x		x	x		x	x		
VL B			x	x		x	x		x	x		
VL D			x	x		x	x		x	x		
VL E						x	x		x	x		
VL A27S		x		x	x		x	x	x	x	x	x
VL D27S				x	x		x	x	x	x	x	x
VL E27S							x	x	x	x	x	x
VL A36		x		x	x		x	x	x	x	x	x
VL D36				x	x		x	x	x	x	x	x
VL E36							x	x	x	x	x	x

3.2.3 Classification according to Bureau Veritas

Bureau Veritas (BV) classifies welding consumables into different grades depending on the chemical composition and mechanical properties of filler metal. Depending on the suitable materials to be welded, welding consumables can be divided into 5 main groups. Consumables for (Bureau Veritas, 2014, p. 184–185):

- C, C-Mn and Q-T steels
- Mo and Cr-Mo steels
- Ni steels
- austenitic and duplex stainless steels
- aluminium alloys.

Consumables for carbon-manganese (C-Mn) steels are divided into groups depending of minimum yield strength of the steel and further into grades by the impact test temperature.

In table 4 is shown classification of welding wires for C-Mn steels. (Bureau Veritas, 2014, p. 184.)

Table 4. Classification of applicable welding wires for C-Mn steels according to BV (Bureau Veritas, 2014, p. 184).

Yield strength of the steel (MPa)	Grade of the welding wire				
<315	1	2	3	4	-
≥315, <360	1Y	2Y	3Y	4Y	5Y
≥360, <400	-	2Y40	3Y40	4Y40	5Y40
≥400	-	-	3Y42, 3Y46, 3Y50, 3Y55, 3Y62, 3Y69	4Y42, 4Y46, 4Y50, 4Y55, 4Y62, 4Y69	5Y42, 5Y46, 5Y50, 5Y55, 5Y62, 5Y69

Classification marking consists of a number relating to impact test temperature of the weld metal and information about the yield strength of the weld metal. Impact test temperatures are +20 °C, 0 °C, -20 °C, -40 °C and -60 °C and they are marked with numbers 1, 2, 3, 4 and 5. Marking of welding wires which are suitable for high strength steels and extra high strength steels contains the letter Y which can be followed with a number describing the minimum yield strength of the weld metal. For example marking 2Y40 indicates that the impact test temperature of the weld metal is 0 °C and it is suitable for welding of C-Mn steels with yield strength equal or greater than 360 MPa but lesser than 400 MPa. (Bureau Veritas, 2014, p. 184.)

3.3 Tubular welding wires

Tubular welding wires can be divided into two categories: wires which need shielding gas and shelf-shielded tubular wires which produce shielding gas itself. These shelf-shielded tubular wires are not in use at Meyer Turku shipyard, which is the reason why they are not dealt in this study. The reason not to use shelf-shielded tubular wires is that gas lines of shipyard supplies shielding gas into every target where welding takes its place. Gas shielded tubular wires are divide into metal cored and flux cored wires. MAG-welding with metal cored wire has numerical code 138 and MAG-welding with flux cored wire has numerical code 136 (SFS-EN ISO 4063, 2011, p. 12). There are two types of flux cored wires: rutile and basic. Basic type flux cored wires have advantage over rutile type flux cored wires and metal cored wires when high requirements are set for the quality of weld metal. Disadvantage of basic type flux cored wires is relatively high amount of produced spatters. Basic type flux cored wires are not used in Meyer Turku shipyard because of high spatter levels and the fact that this kind of quality features are not demanded from products. Basic type flux cored wires are not dealt in this study more widely. (Lukkari, 1997, p. 228–229, 238.)

Tubular wire consists of a wire tube and filling material. Cross section of the wire varies depending how the wire is manufactured. The filling of tubular wire deoxidizes weld pool, alloys weld metal, affects to arc and welding features and produces slag in case of rutile type flux cored wire. By varying the chemical composition of the filling, type of shielding gas and filling ratio (ratio between wall thickness of wire tube and thickness of filling) it is possible to affect for example to amount of spatters, mechanical features of weld metal and appearance of weld. (Lukkari, 1997, p. 234–236.)

Tubular wires are usually welded with pure CO_2 or mixture of argon and CO_2 as shielding gas. Type of the welding current is direct current and polarity can be either plus or minus. When tubular wire is used, current density is higher compared to welding with solid wire of the same diameter and with the same welding current. This is due to a smaller current carrying cross section which is caused by the fact that electric conductivity of the flux is smaller than electric conductivity of the wire. Less energy is spent to molten wire kilogram. For example energy consumption in solid wire MAG-welding is approximately 1.8 kJ/kg and in MAG-welding with metal cored wire 1.6 kJ/kg. This causes weld pool to be cooler, which is an advantage in position welding. Filling rate of tubular wire has important effect to productivity. Increase in thickness of the filling and decrease in the tube wall thickness raises current density, which makes the wire melt faster and thus also increases deposition rate. (Lukkari, 1997, p. 228–229, 235.)

3.3.1 Metal cored wire

Metal cored wires are slag-free wires of which filling consist of metal powder, deoxidizing and ionizing agents. Metal cored tubular wires are suitable for mechanized and robotized welding because no slag is produced. Unlike with rutile type flux cored wires, short arc exists and it is used in position welding and in sealing runs. If compared to solid welding wire, the spray arc region of metal cored tubular wire, with the same diameter, starts at lower wire feed rate. The main advantages of metal cored tubular wires are high deposition rate and high productivity in welding positions PA and PB. (Lukkari, 1997, p. 236–238.) An example of metal cored wire, which is in use at Meyer Turku shipyard, is ESAB OK Tubrod 14.12. OK Tubrod 14.12 is designed to be used with minus polarity and it is also suitable for welding in welding position PG. (ESAB, 2015b.)

3.3.2 Rutile wire

Type of the electric arc is always spray arc with rutile type flux cored wires. Possibility to use spray arc also in position welding makes usage of rutile wires efficient. Usually the amount of produced spatters is low and electric arc is smooth and stable. Formation of slag has its advantages and disadvantages. Slag enables efficient position welding with high wire feed rate, but it can also sometimes prevent hydrogen to become gasified from the weld. Problems with hydrogen can be decreased by choosing correct welding parameters and by using CO_2 instead of mixture gas as shielding gas. In addition to good position welding features rutile wire also has its advantages when good impact strength is needed. Good impact strength originates from nickel, boron and titanium alloy. (Lukkari, 1997, p. 237.) An example of rutile type flux cored wire which is in use at Meyer Turku shipyard is Filarc PZ6113.

3.3.3 Classification of tubular wires

SFS-EN ISO 17632 (2008) classifies tubular welding wires for non-alloy and fine grain steels. As well as standard SFS-EN ISO 14341 (2008) also this standard has two systems: A and B. In system A classification is based on yield strength and 47 J average impact energy. In system B it is based on tensile strength and 27 J average impact energy of all-weld metal. (SFS-EN ISO 17632, 2008, p. 1–13.) According to SFS-EN ISO 17632-A the classification marking consists of compulsory and optional parts. Yield strength, elongation, impact energy, chemical composition, type of core and used shielding gas are in the compulsory part. The optional part contains suitable welding positions and hydrogen content of the welding wire. Depending is the wire suitable for multi-run welding or only for single-run welding the marking of yield strength varies. According to system A marking could be for example: ISO 17632-A – T 38 2 2Ni R C 3 H5. In this marking *T* means tubular wire, *38* means that minimum yield strength of the all-weld metal is 380 MPa, minimum elongation is 20 % and the wire is suitable for multi-run welding. *2* means that impact energy 47 J is measured in -20 °C, *2Ni* is chemical composition of all-weld metal, *R* means that type of the core of the wire is slow freezing slag, *C* means that previously mentioned mechanical properties of the all-weld metal are achieved with CO_2 as shielding gas and *3* means that the welding wire is suitable for welding in welding positions PA and PB. *H5* means that maximum hydrogen content is 5 ml/100 g of deposited metal. (SFS-EN ISO 17632, 2008, p. 14–41.)

Classification rules of Bureau Veritas and Det Norske Veritas does not separate classification of tubular wire electrodes in any way of classification of solid wire electrodes. Thus the same rules that were above mentioned in case of solid wire go also for tubular wires. (Bureau Veritas, 2014, p. 184; DNV GL AS, 2015a, p. 22–26.)

3.4 Comparison between solid, metal cored and rutile wires

Different welding wire types differ greatly for example by their productivity, prices, hydrogen content and by the recommended welding technique that should be used. Solid wires are cheaper wire choices than tubular wires, they produces less fumes than tubular wires and are in general able to produce weld metal with lower hydrogen content than tubular wires. Tubular wires have advantage when unclean plates and primed plates are welded. Solid wires are less tolerant for impurity, which is the reason why plates need to be often cleaned before welding. (Lukkari, 1997, p. 220, 232–245; The Fabricator, 2010; Lincoln Electric, 2016.) With flux cored wires it is also possible to achieve deeper penetration than with solid wires. Most of the tubular wires are also less susceptible to cold laps than solid wires. (Widgery, 1994, p. 5–6.)

3.4.1 Productivity

When comparing different welding processes, in this case GMAW, metal cored arc welding (MCAW) and flux cored arc welding (FCAW), it is useful to use a few characteristic to describe productivity and efficiency of the processes. For example burn-off rate, deposition efficiency and deposition rate. Burn-off rate describes how much welding wire is spent in one hour. Unit of burn-off rate is *kg/h*. Deposition efficiency describes the proportion of the spent welding wire which can be obtained into weld. Small portion of the welding wire goes wasted uselessly for example into formation of welding fumes, slag or spatters. Unit of deposition efficiency is either decimal number or percentage. Deposition rate describes the amount of produced weld metal in one hour. Deposition rate can be calculated when burn-off rate and deposition efficiency is known. Unit of deposition rate is *kg/h*. (Stenbacka, 2011, p. 68–69.)

In table 5 is shown deposition rates for three welding wires with 1.2 mm diameter: ESAB Aristorod 12.50 solid wire, Filarc PZ6113 rutile type flux cored wire and ESAB OK Tubrod 14.12 metal cored wire. Previous mentioned wires are in use at Meyer Turku shipyard. Like it was earlier mentioned the ratio between wall thickness of the wire tube and thickness of the filling affects to deposition rate of tubular wires. In addition to this, also wire diameter, used shielding gas and additive wire length has effect to deposition rate. Based on data in table 5, solid wire has 20-30 % lower deposition rate than metal cored wire in this individual case. (ESAB, 2015c; Lukkari, 2007, p. 5.)

Table 5. Deposition rates for ESAB Aristorod 12.50, ESAB OK Tubrod 14.12 and Filarc PZ6113 with different welding currents (ESAB, 2015c; Lukkari, 2007, p. 7).

Wire product	Deposition rate [Kg/h]	Welding current [A]
Aristorod 12.50	1.59	150
OK Tubrod 14.12	2.0	150
Filarc PZ6113	2.4	150
Aristorod 12.50	3.45	250
OK Tubrod 14.12	4.5	250
Filarc PZ6113	4.4	250
Aristorod 12.50	4.53	300
OK Tubrod 14.12	6.5	300
Filarc PZ6113	6.25	300

The used welding position has great impact to the deposition rate in which certain wire type is capable. Especially some tubular wires are designed to work efficiently in position welding or in certain position. For example rutile type flux cored wire Filarc PZ6113 can be welded in welding position PF with wire feed speeds 6-12 m/min. As opposed to this solid wire with the same diameter can be welded approximately with wire feed speed 4 m/min in welding position PF. Compared to rutile type flux cored wire and solid wire, metal cored tubular wire ESAB OK Tubrod 14.12 can be used more safely in welding position PG. Suitable wire feed speed for Tubrod 14.12 in this position is between 6.5-8 m/min. Usage of rutile type flux cored wire or solid wire is unsafe in this position because of possible defects. When solid wire is used in welding position PG there is a possibility to lack of fusion and when flux-cored wire is used slag may cause problems. In figure 8 is shown deposition rates for ESAB OK Tubrod 14.12, Filarc PZ6113 and solid wire in four welding positions. All three welding wires has the same 1.2 mm diameter. (Lukkari, 1997, p. 224; Industriacenter, 2008; Lukkari, 2007, p. 7; ESAB, 2012, p. 2; Tessin, 2003, p. 26.)

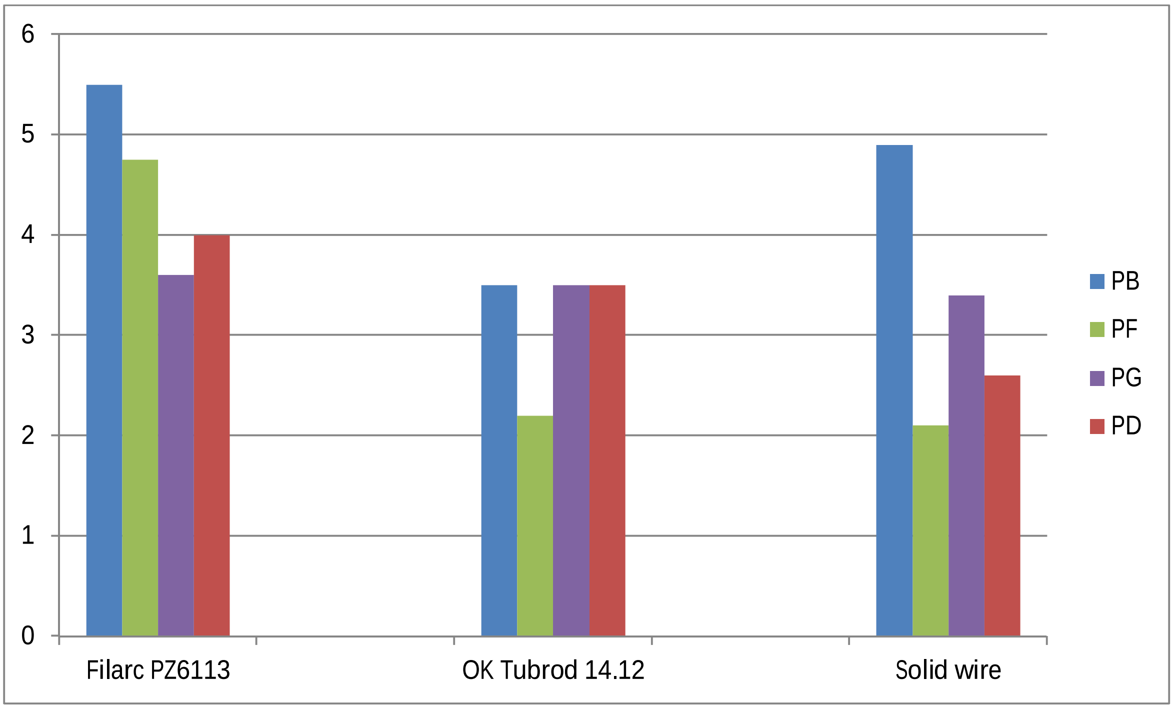

Figure 8. Maximum deposition rates *(kg/h)* for three different welding wires in welding positions PB, PF, PG and PD. (Industriacenter, 2008; Lukkari, 2007, p. 7; ESAB, 2012, p. 2; Lukkari, 1997, p. 222–224).

As it can be seen from figure 5, rutile type flux cored wire PZ6113 has clearly higher deposition rate in welding position PF than other two wire types. In position PG all three wires have almost equal deposition rates. However, like it was mentioned above, metal cored wire OK Tubrod 14.12 is more safety to use in this position. Important characteristic in OK Tubrod 14.12 is that it can be welded in all welding positions with the same parameters excluded welding position PF. In welding positions PB and PD Filarc PZ6113 has higher deposition rates than OK Tubrod 14.12 and solid wire. Deposition rate for solid wire in welding position PD is based on the welding test that was performed in Meyer Turku shipyard because literary resources for the deposition rate in this position were not found. At Meyer Turku shipyard ESAB OK Tubrod 14.12 is used with relatively high wire feed rates, which causes the fact that deposition rates for this wire are higher at shipyard than what is shown in figure 8. (Industriacenter, 2008; ESAB, 2012, p. 2; Tessin, 2003, p. 26.)

3.4.2 Wire costs

Prices for welding consumables depend on contracts between wire supplier and customer. Because of this prices between solid and tubular welding wires cannot be compared in general. In table 6 is shown price ratio for three different welding wires in case of Meyer Turku shipyard.

Table 6. Price ratio between different tubular wire and solid wire products.

Wire product	Type of the wire	Price ratio
Filarc PZ6113	Rutile type flux cored wire	1.37
ESAB OK Tubrod 14.12	Metal cored wire	1.61
ESAB OK Aristorod 12.50	Solid wire	1.0

As can be seen from table 6 at least in this case tubular welding wires are clearly more expensive than solid wire. The price difference is emphasized in case of metal cored wire ESAB OK Tubrod 14.12.

In figure 9 is shown an example of cost distribution in semi-automatic MAG-welding for a fillet weld with throat thickness of 4 mm. As can be seen percentage of welding wire costs in overall welding costs is relatively low. Most of the costs are due to high labor costs. Prime costs of the welding equipment are not represented, because they are highly case sensitive. The information in the figure 9 is mainly based on following baselines (Stenbacka, 2011, p. 92–93):

- deposition rate: 3.8 kg/h
- duty cycle: 0.2

- labor costs: 30 euro/h
- consumption of the shielding gas: 18 l/min
- price of the shielding gas: 3 euro/m^3
- price of the welding wire: 1.5 euro/kg

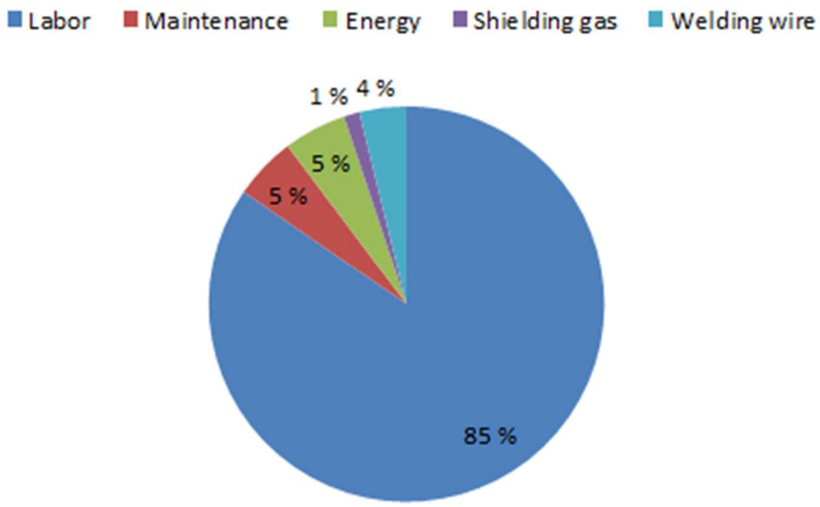

Figure 9. Cost distribution between welding wire, shielding gas, energy, maintenance and labor in semi-automatic MAG-welding (modified from: Stenbacka, 2011, p. 93).

In Meyer Turku shipyard percentage of welding wire costs in overall costs of the ship is approximately 0.2 % depending on situation. It can be also roughly said that percentage of shielding gas costs in Meyer Turku shipyard is approximately 30 % of the welding consumable costs, which is a bit higher than what is shown in figure 9.

3.4.3 Hydrogen content and storage

Hydrogen content of weld deposit informs how many milliliter hydrogen 100 g of weld deposit contains. In solid wire MAG-welding hydrogen content is under 5 ml/100g. Hydrogen content of tubular wires varies depending of wire product between less than 5 ml/100 g and over 15 ml/100 g. For example weld deposit of ESAB OK Tubrod 14.12 contains less than 10 ml/100 g and weld deposit of Filarc PZ6113 contains less than 10 ml/100 g with mixed gas and less than 5 ml/100 g with carbon dioxide. (ESAB, 2008, p. 37, 54, 57, 501.) Storage of welding wire, welding current, stickout and also temperature and humidity circumstances of the location where welding takes its place have influence to the hydrogen content of weld deposit (Lukkari, 1997, p. 239). High hydrogen content in weld deposit can cause cold cracking, which can lead to failure of welded structure (EWF, 2008).

Storage instructions for solid wires and tubular wires are almost the same. With both wire types storage must be carried out in unopened original packages. With tubular wires storage times should be kept short. However it is a common habit in industry to store solid welding wires in vicinity of workstations without any special actions. (ESAB, 2010, p. 13–16; Itävuo, 2016.)

3.4.4 Torch travelling technique

Welding technique differs between different kinds of wire types. In case of solid wire welding torch can be pushed or pulled depending what is desired. Pulling technique forms narrower and higher weld bead while pushing technique forms smoother weld bead, but penetration remains less deep. In MCAW pulling technique is used for fillet and butt welds. Pushing technique can be used in fillet welds, if welding speed is fast enough. In FCAW pulling technique is mostly used to prevent imperfections. (Lukkari, 1997, p. 210, 243–244.)

3.4.5 Welding fumes and radiation.

The amount of produced welding fumes depends on several matters. To the forming of welding fumes affects for example (OSHA, 2013, p. 1; TWI, 2006; Lukkari, 2006, p. 7):

- welding process
- welding parameters
- base metal
- composition of welding wire
- shielding gas
- ventilation of workplace
- composition of the plate coating.

In general flux cored wires produces more welding fumes than solid wires and even more fumes than manual metal arc welding (MMA). Composition of flux cored wire has a great effect to the amount of produced fumes. In MAG-welding the amount of produced fumes depends on used process, shielding gas, chemical composition of the welding wire and used arc type. Short arc welding produces low amount of fumes. Fume generation in spray arc mode depends on used welding voltage. Usage of high or low voltage values increases fume generation and thus the minimum fume generation can be achieved between these critical points. It can be also said that increase in wire diameter or in welding current increases fume generation. Pure argon produces least welding fumes and the fume generation increases while the proportion of CO_2 in shielding gas is increased. In case of copper coated wires copper can also produce harmful fumes. In table 7 is shown typical chemical compositions for fumes of Filarc PZ6113 and ESAB OK Autrod 12.50. With flux cored wire PZ6113 5-15 g/kg fumes are generated. With solid wire OK Autrod 12.50 the amount of generated fumes is between 5-10 g/kg. (Lincoln Electric, 2016; TWI, 2006; ESAB, 2000; Lukkari, 2006, p. 7.)

Table 7. Typical chemical compositions of generated fumes (represented as weight percentage) with ESAB OK Autorod 12.50 and Filarc PZ6113 (Truflame, 2015; Etra, 2009).

Product	Fe [%]	Mn [%]	Si [%]	F [%]	Pb [%]	Cu [%]	Ni [%]	Cr [%]
PZ6113	45	15	-	5	0.1	0.1	0.1	0.1
12.50	65	5	5	-	0.1	1	0.1	0.1

As it was in case of fume generation also many things affects to the intensity of emitted ultraviolet radiation in MAG-welding (Ylianttila et al., 2009, p. 237):

- base metal
- welding parameters
- welding wire
- shielding gas
- arc type
- reflects from different surfaces.

Usage of pulse in MAG-welding does not significantly increase ultraviolet radiation (Ylianttila et al., 2009, p. 238). Okuno, Ojima & Saito (2001) researched ultraviolet radiation emitted by MAG-welding with CO_2 shielding gas. They found that effective irradiance is higher with solid wire than with flux cored wire. In figure 10 is shown relationship between welding wire type, welding current and measuring distance. The measurements were made at 30° angle from surface where welding took its place. (Okuno, Ojima & Saito, 2001, p. 597–599.)

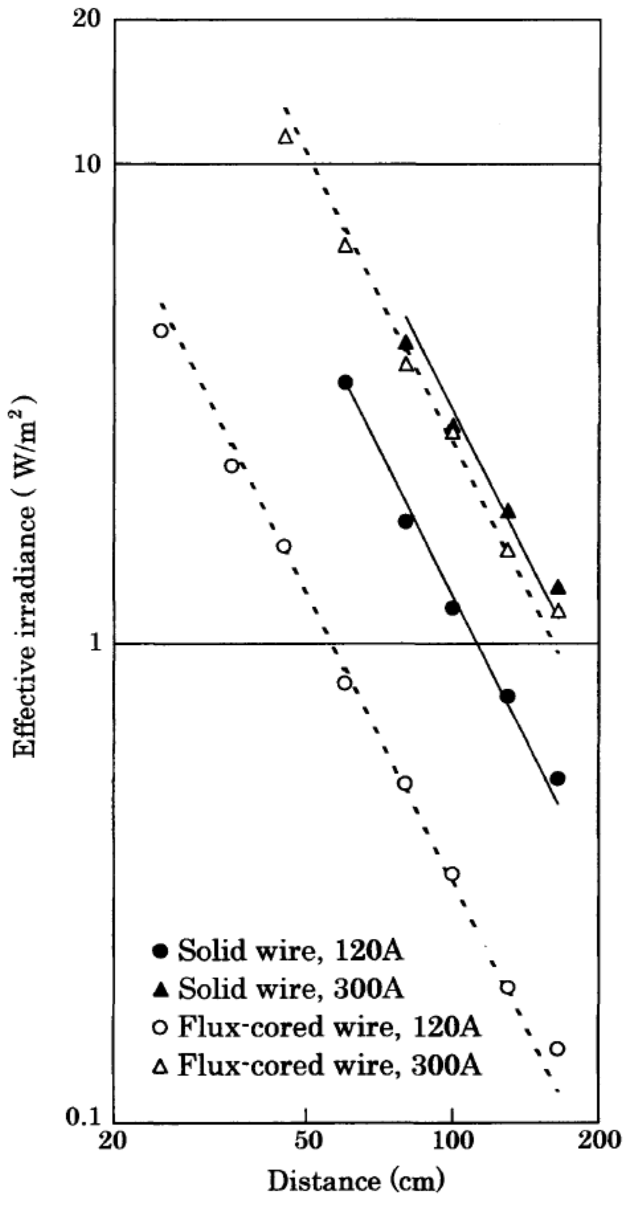

Figure 10. Effective irradiance in MAG-welding with solid wire and rutile type flux cored wire (Okuno et al., 2001, p. 599).

3.4.6 Shielding gas and welding wire combination

The chosen shielding gas affects for example to chemical and mechanical features of weld metal, metal transfer modes, amount of spatters, shape of weld, penetration and welding fumes. Higher percentage of argon in shielding gas enables better mechanical features of weld metal. With CO_2 higher amount of spatters and fumes are produced. With solid wire usage of CO_2 is possible but long arc will appear instead of spray arc. CO_2 is not suitable for pulse MAG-welding. In case of tubular wires suitable shielding gas depends of the used wire product. Metal cored wires are usually welded with mixed gas M21. Rutile type flux cored wire products are designed to be used with pure CO_2, mixed gas or with these both type of gases. With rutile type flux cored wires CO_2 is used mostly in outdoor conditions. (Lukkari, 1997, p. 171–172, 196–202, 241.)

4 ADVANCED MAG-WELDING PROCESSES

This chapter deals with the MAG-processes which are used in welding tests of this study. In addition to traditional MAG-welding manufacturers have brought to market more sophisticated MAG-welding processes which enables new type of arcs. These new arc types can be divided for example to controlled short circuiting arc, controlled globular arc, controlled spray arc and high-power arc (Kah et al., 2014, p. 9). In this study possibilities of pulse MAG-welding, double-pulse MAG-welding and two different controlled spray arc processes are researched. The aim is to find out if any of these processes is capable to increase deposition rate and welding speed over values in which traditional MAG-welding is capable when welded plates are primed and tack-welded. The possible benefit of these controlled spray arc processes is higher penetration which can improve the over welding of tack welds. RapidArc and ForceArc have narrow electric arc which is less susceptible to undercuts, has lower heat input and produces less spatters (Builtconstructions, 2016). In general also pulse MAG-welding has higher penetration, but it can also be more tolerant process to primer than MAG-welding. In this study welding processes are chosen from three different manufacturers: Kemppi, Lincoln Electrics and EWM. The main principles of RapidArc process from Lincoln and ForceArc process from EWM are explained in this chapter. Also pulse and position pulse MAG-welding processes are explained shortly.

4.1 Pulse MAG-welding

Pulse MAG-welding is based on to pulsing of welding current which allows achieving spray transfer mode with lower wire feed rate than in MAG-welding. At its simplest pulsed MAG-welding has several parameters in addition to basic MAG-welding parameters such as wire feed rate, travel speed and voltage. For simple cases these four parameters are sufficient to define the current waveform: peak current I_p, base current I_b, peak time T_p and base time T_b (Praveen, Kang & Yarlagadda, 2009, p. 197). The base current melts the head of the welding wire, keeps weld pool molten and keeps the electric arc ignited. High peak current detaches one droplet and accelerates it into weld pool. (Lukkari, 1997, p. 172.) Of these four parameters most affect to metal transfer has peak current and peak time (Kolodziejczak, 1987, p. 96). Simple pulse cycle is shown in figure 11.

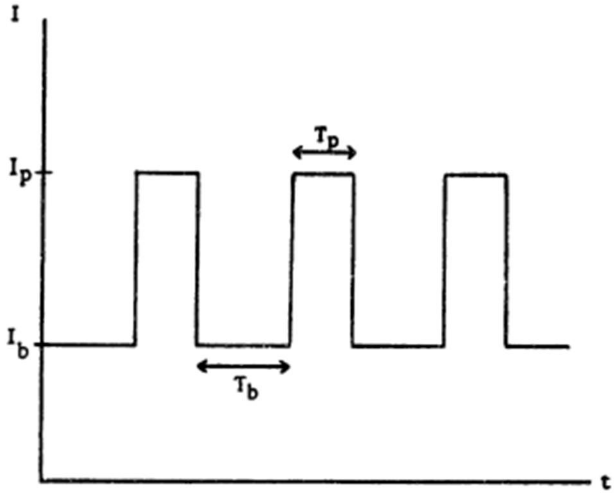

Figure 11. Changes in current as a function of time (Kolodziejczak, 1987, p.93).

In addition to previously mentioned basic parameters also pulse frequency *f* and average current I_{ave} are used although these two parameters together cannot completely define the shape of the waveform. Both of these parameters are derived from the four basic parameters. Average current is used when determining the heat input pulse MAG-welding. (Kolodziejczak, 1987, p. 93–100.)

The effect of pulse MAG-welding parameters to amount of spatters and porosity was studied by Takeuchi (1984). He found that when Ar + 20% CO_2 is used as shielding gas the amount of spatters decreases continuously when pulse frequency is increased from 0 Hz to 200 Hz. Correlation between the peak current and the amount of spatters was less clear. For the minimum porosity optimum pulse frequency is between 150 Hz and 300 Hz. It seemed that the used peak current had minimal effect to porosity. In figure 12 is shown that optimal pulse frequency for minimum amount of spatters is 200-250 Hz and peak current is 500 A. Correlation between pulse frequency, peak current and porosity is shown in figure 13. (Takeuchi, 1984, p. 23.)

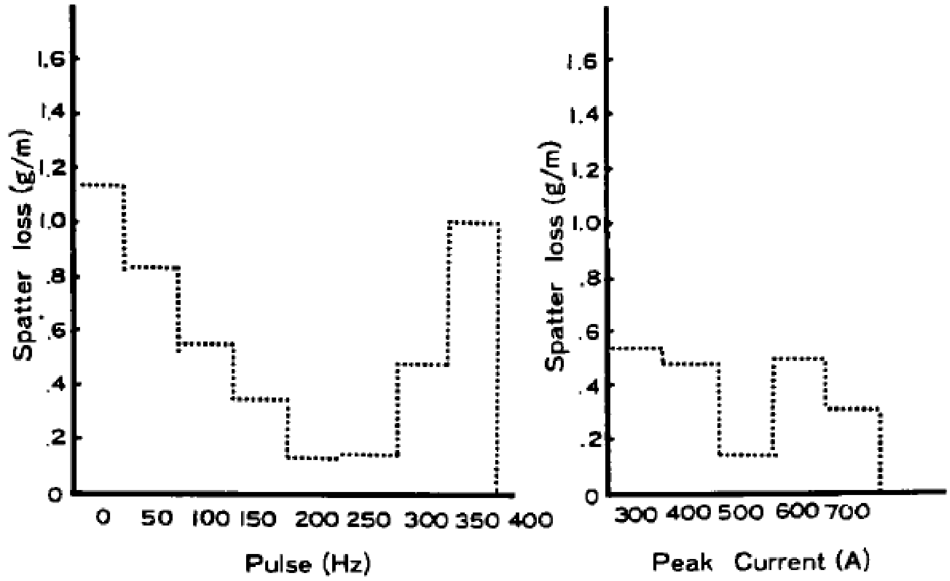

Figure 12. Effect of pulse frequency and peak current to amount of spatters when shielding gas Ar+20% CO_2 is used (Takeuchi, 1984, p. 23).

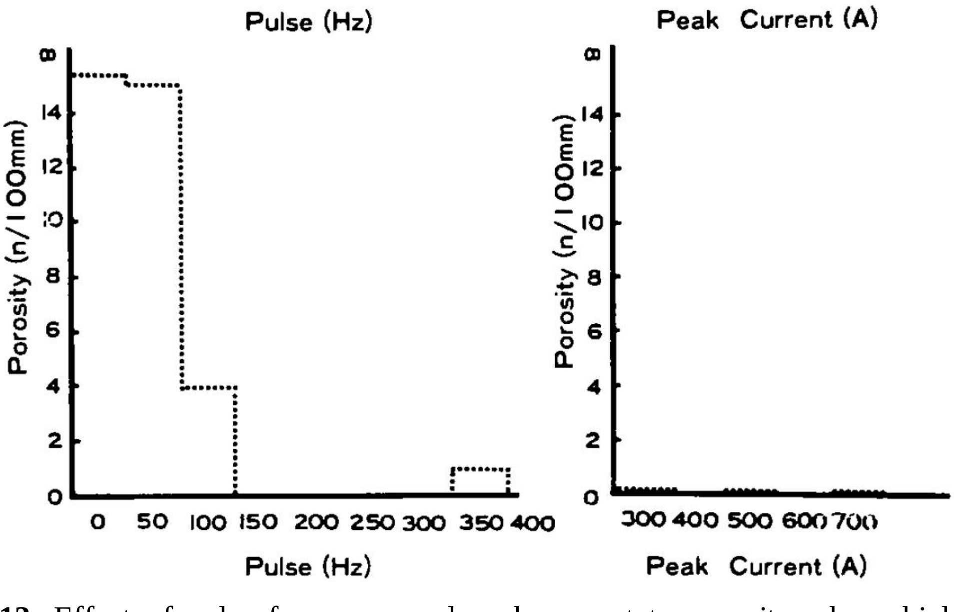

Figure 13. Effect of pulse frequency and peak current to porosity when shielding gas Ar+20% CO_2 is used (Takeuchi, 1984, p. 23).

Usage of pulse in MAG-welding improves welding features and makes primed plates less vulnerable to porosity. Kaputska & Blomquist (2015) found that usage of pulse can increase travel speed 38 % in mechanized welding of fillet welds when welded plates were primed. (Kaputska & Blomquist, 2015, p. 47.) Johnson et al. (1998) mentioned in their study: “Welding over paint primer” pulsed MAG-welding of primed plates as area for further research (Johnson, Liu & Olson, 1998, p. 215). Also Takeuchi (1984) found in his study that in pulse MAG-welding welding wire melting rate can be raised to 1.5 times higher compared to MAG-welding without pulse (Takeuchi, 1984, p. 18).

There are also pulse processes which are optimized for position welding for example Kemppi Double pulse and Lincoln Precision Pulse. In double pulse process of Kemppi welding current and wire feed speed are both pulsed. Double pulse makes easier to control penetration, heat input, welds look and to control weld pool in position welding. Lincoln Precision Pulse has focused and short arc which makes controlling of weld pool easier. Focused and short arc is achieved with fixed pulse frequency which ensures stable metal transfer. (Kemppi, 2013; Lincoln Electric, 2008, p. 1.)

4.2 RapidArc

Lincoln RapidArc is a pulsed MAG-welding process. In RapidArc process length of the electric arc is shorter than in conventional pulse MAG-welding, which makes possible to use higher travel speeds. Shorter and more focused arc can be achieved with lower welding voltage, which causes metal transfer mode to be combination of pulsed spray transfer and short circuiting transfer. Short circuiting occurs in a controlled manner. Shorter arc length provides fewer spatters than in pulse MAG-welding and low heat input. RapidArc suites for both solid wire and metal cored wire welding and it is possible to use RapidArc in all welding positions. (Lincoln Electric, 2005, p. 1–3.)

The waveform of RapidArc consists of four segments: pulse, puddle rise, short and puddle repulsion. Pulse forms droplet into head of the welding wire. In puddle rise –segment the decrease of current causes weld puddle to move towards to droplet. In short-segment short circuit occurs when droplet touches weld puddle. In puddle repulsion welding wire is separated from weld puddle and arc ignites again. In figure 14 is shown four segments of RapidArc waveform. (Lincoln Electric, 2005, p. 2.)

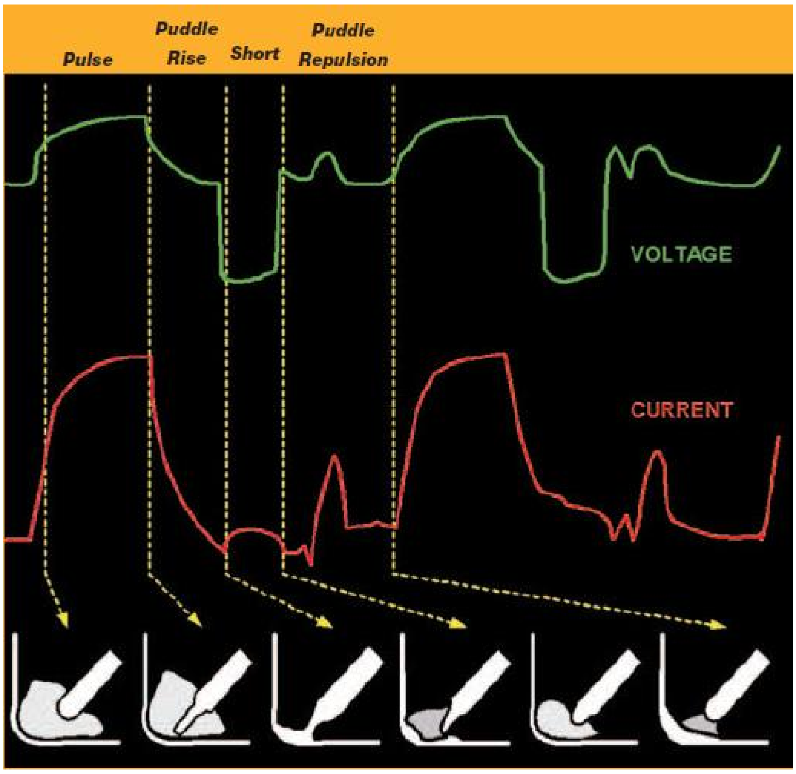

Figure 14. Pulse waveform of RapidArc process (Lincoln Electric, 2005, p. 2).

4.3 ForceArc

Also EWM ForceArc is forced short spray arc process, but unlike RapidArc welding current is not pulsed. Shortness of the arc causes arc voltage to be lower than in conventional spray arc MAG-welding. This causes droplet size to be larger than in spray arc. Due to shorter arc and lower arc voltage, short circuiting exists. Short circuits do not add spattering because raise of current is prevented with dynamic control. ForceArc has several advantages over spray arc. Shortness of the electric arc makes it stable and penetration is deep. Undercuts are less expected than with spray arc. ForceArc also increases welding speed and decreases heat input. (Lihavainen, 2010, p. 44–45.)

5 PRIMER

Primers are widely used in shipbuilding to protect plates, profiles, parts and blocks when stored outdoors or when fabrication takes its place outdoors. Ability to over weld primed plates has large impact to productivity and costs. If the used combination of primer and welding consumables does not allow passably over welding of the primed products, abrasive blasting, grinding and repairing will increase manufacturing costs. (Johnson et al., 1998, p. 1.)

5.1 Types of primers

Primers can be divided into four main groups by their chemical composition (Volpone & Mueller, 2006, p. 943):

- poly-vinyl-butyric-iron oxide resins
- epoxy resin
- zinc-epoxy
- zinc-silicate.

Zinc-silicate primers can be divided further into three subgroups based on zinc content: low, average and high. The most common type of primers is zinc-silicate due to good welding and thermal cutting features. (Volpone & Mueller, 2006, p. 943.)

5.2 Problems related to over welding of primers

When primed plates are welded, few problems may occur (Johnson et al., 1998, p. 1, 81):

- porosity
- increase in hydrogen content
- changes in fluidity of slag and weld metal
- changes in weld metal ductility
- instable arc
- loss of carbon and alloying elements in weld metal
- cold cracking.

In case of welding primed plates porosity is mainly caused by hydrogen, CO_2, CO, water and nitrous gases (Boniszewski, 1992, p. 39). These gases remain in the weld after it has solified. In case of primers containing zinc, can gasified zinc cause porosity and also arc instability. (Johnson et al., 1998, p. 2, 84.) Arc instability is caused by fumes which invades into arc and disturbs metal transfer. With MAG-processes arc instability can cause 18 % decrease in welding speed. (Volpone & Mueller, 2006, p. 946.) In the welding of primed plates several variables have effect to the porosity level: pigments and binders of the primer, thickness of coating, plate thickness, joint geometry, welding position and welding parameters. It has been found that as the thickness of coating increases also hydrogen content of weld metal increases (Johnson et al., 1998, p. 149). When taking concern the joint form, fillet welds are more prone to porosity than butt welds. The usage of primer can force to decrease travel speed because risk to porosity increases while travel speeds increases. (Johnson et al., 1998, p. 86.) With higher travel speeds gases have less time to escape from the weld pool (Volpone & Mueller, 2006, p. 945).

5.3 Minimization of welding problems related to primers

Problems that occur when welding primed plates can be approached at least from three different aspects: chemical composition of primer, chemical composition of welding consumables and the used welding process (Johnson et al., 1998, p. 215). If the subject is approached from the welding consumables point of view it has been found that if oxygen content of weld metal is increased with way or another, hydrogen content will decrease. This dependence is shown in figure 15. However it must take in concern that increase in oxygen content will affect to microstructure of weld metal. With high oxygen content large grain-boundary ferrite forms, which has negative effect to mechanical properties of weld metal. High oxygen content has also negative effect to amount of deoxidizing elements like it was earlier told in chapter 3.1. (Johnson et al., 1998, p. 11–136.) Because of problems which high oxygen content causes also fluoride compounds can be used to reduce diffusible hydrogen content (Johnson et al., 1998, p. 213). For example rutile type flux cored wires are alloyed with oxides and fluorides to eliminate porosity. Without alloying rutile type flux cored wires would have considerable amount of porosity because of the sluggish slag. Also colder weld pool makes tubular wires per se more vulnerable to porosity which has however been eliminated with alloying. (Volpone & Mueller, 2006, p. 945.) Instead of chemical composition of primer and welding consumables this study concentrates to research possibilities to prevent primer-related difficulties by using more sophisticated welding processes.

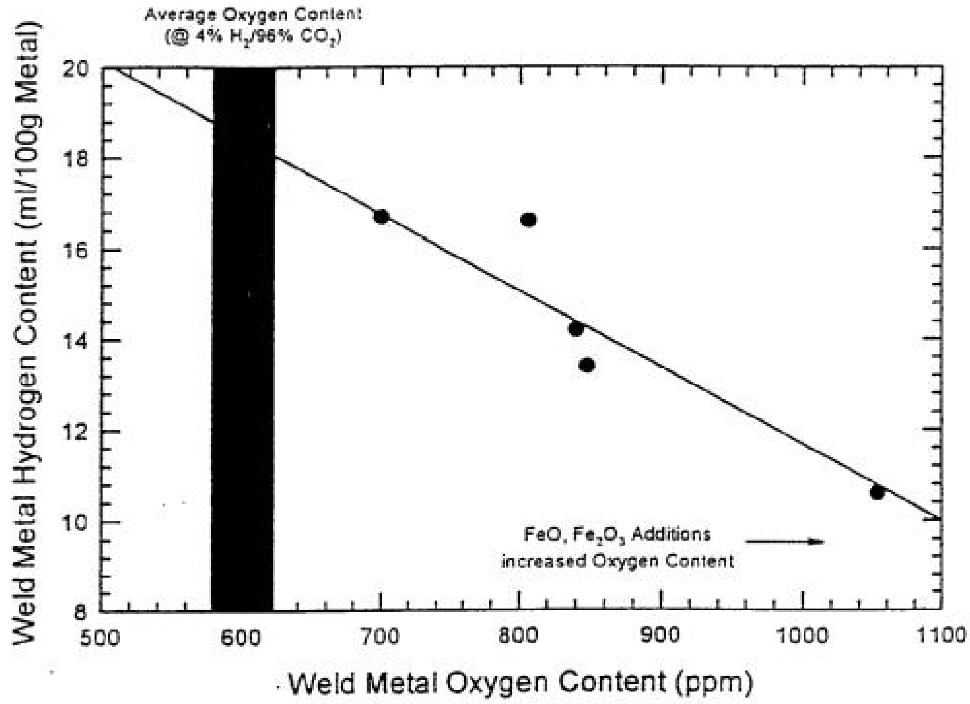

Figure 15. Relationship between oxygen and hydrogen contents of weld metal (Johnson et al., 1998, p. 137).

5.4 Fumes generated in welding of primed steel products

Primer coating increases amount of generated fumes in welding. When the steel which is to be welded is coated with primer containing zinc produced fumes contain zinc oxide. With high primer coating thicknesses also more fumes are generated. (NPL, 2014, p. 5.) Depending of the chemical composition of the primer also cadmium and lead fumes can be produced (MSHA, 2014).

6 TACK WELDING

Tack welding is a technique to attach parts, which later are to be welded, with short welds together. Despite of the temporary nature of tack welds they must be performed correctly so that the quality of final weld would not be weak. (Levi, 2006.)

6.1 Problems related to tack welds

Problems related to tack welds are for example rise in the hardness of HAZ-area, which is caused by the fast cooling of short tack weld. Increased hardness of HAZ-area also indicates of brittleness of the tack welded area and the increased possibility to cracking. Critical parts of tack welds are starting and stopping points which usually contain imperfections. (Levi, 2006.) Tack welds have also often poor penetration, why tack weld can be a starting point for a fatigue crack (Kolodziejczak, 1987, p. 82).

6.2 Minimization of interferences caused by tack welds

In ideal situation tack welds are dealt so that they can be melted into part of the final weld. Two different welding techniques are used when manually welded over tack weld. Travel speed can be increased or it can be decreased. By decreasing the travel speed, it is possible to melt the tack weld, but in this case the contour of weld surface becomes undesired. On the contrary increased travel speed gives smoother weld contour but the tack weld may remain without melting. (Kolodziejczak, 1987, p. 80.) The problem of melting the tack welds is caused because of the fact that in MAG-welding wire feed rate and welding current are dependent of each other. If tack weld is melted by increasing the heat input, also throat thickness will increase momentarily. This problem would be solved if heat input could be increased without the increase in deposition rate. This kind of ideal way to handle tack welds is shown in figure 16. (Kolodziejczak, 1987, p. 86.)

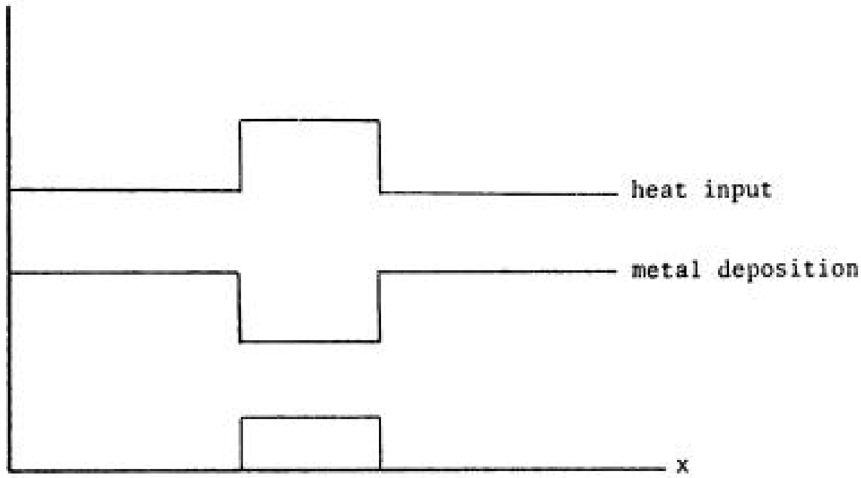

Figure 16. Ideal strategy for over welding of tack welds (Kolodziejczak, 1987, p. 86).

Kolodziejczak (1987) studied the possibilities to handle tack welds with higher penetration achieved by pulse MAG-welding. He made an assumption that by pulsing the welding current high penetration and proper heat input would be achieved at the same time. He studied the effects of different pulse parameters to the achieved penetration. Kolodziejczak found that to important features for high penetration, for example arc pressure, droplet momentum and convection, can be affected in pulse MAG-welding separately from heat input. Kolodziejczak found that with high peak current values higher arc pressure increases penetration. With low frequencies weld pool oscillation caused the increased penetration. However, he made conclusion that the achieved increase in penetration is not sufficient to completely handle tack welds. Because of this Kolodziejczak proposed that pulse MAG-welding should be used with other techniques such as varying the electrode stickout, increasing the wire feed speed and travel speed or chancing the shielding gas momentarily to helium while welding over the tack weld. Last mentioned technique is based on increase in the heat input, which is caused by the fact that usage of helium results higher arc voltage than argon. (Kolodziejczak, 1987, p. 153, 303, 305–307, 312, 315.)

7 WELDING ON SHIPYARD

This chapter deals with the basic things of welding on Meyer Turku shipyard. Used materials, material thicknesses, most common welding wires, shielding gases, used primer and basic information of tack welding is told shortly.

7.1 Used materials and thicknesses

Used materials at Meyer Turku shipyard are mainly shipbuilding steels of grades A-E36. Also different stainless steels and cast steels are used in specific targets. Used steel plates and profiles are blasted with abrasive and painted with primer in shipyards pretreatment line. Used material thickness varies greatly depending of the use. In general it can be said that minimum plate thickness in hull structures is 4 mm and in ships bottom parts at least 16 mm.

7.2 Welding wires

Most of the MAG-welding wires of the shipyard are either metal cored wires or rutile type flux cored wires. The most common metal cored wire product in shipyard is ESAB OK Tubrod 14.12 with a diameter of 1.2 mm. Primarily this product is used in the beginning of the production. It is mostly used in positions PB, PD and PG. The most used rutile type flux cored wire is Filarc PZ6113 with a diameter of 1.2 mm. It is used for fillet welds and butt welds in all positions except vertical-down position PG. The usage of this product increases when moving forward in the production. In the dry dock most of the welding is carried out with this wire. Also very small quantities of solid wire ESAB OK Aristorod 12.50 is used into two different targets. It is used as a second wire of the tandem portal of 22 m panel line and in some special applications for welding root passes of pipe joints.

7.3 Shielding gases

There are mainly two different shielding gases used on Meyer Turku shipyard: mixed gas M21 and pure carbon dioxide. Shielding gas M21 is mixed in shipyards gas mixing station and it contains 75 % of argon and 25 % of CO_2. M21 shielding gas is used in steel fabrication halls and CO_2 is used on dry dock and grand block halls.

7.4 Used primer

Plates and profiles, used on Meyer Turku shipyard, are primed to prevent corrosion when parts and blocks are stored outdoors. Abrasive blasting and priming process of plates and profiles takes its place in shipyards pretreatment line. Equipment are calibrated regularly to ensure the desired primer coating thickness. Used primer at Meyer Turku shipyard is inorganic weldable zinc ethyl silicate shop primer Jotun Muki Z 2001 which is type approved by Det Norske Veritas. Desirable dry thickness of coating is 15-20 µm. Monthly average values of primer coating thicknesses, which were measured in pretreatment lines of shipyard, are represented in appendix I. (Jotun, 2014, p. 1–2.)

7.5 Tack welding

At Meyer Turku shipyard fillet weld joints must be tack welded according to welding instructions to ensure that the quality of tack welds fulfills the mechanical and metallurgical requirements. Tack welding is performed by plate fitters. The used welding process in tack welding is tubular wire MAG-welding with metal cored wire or with rutile type flux cored wire. In butt joints tack welding is prohibited and strongbacks must be used instead.

8 QUALITY REQUIREMENTS AND QUALITY ASSURANCE

In this chapter the focus is in the quality of welding which is in Meyer Turku shipyard guided by standard SFS-EN ISO 5817 – Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded) – Quality levels for imperfections and International association of classification societies (IACS) No. 47 Shipbuilding and repair quality standard. In addition to welds quality itself also the quality of surface preparation of welded structures for painting is followed by standard SFS 8145. Quality of welding is assured by confirmed welding procedure specifications (WPS), qualification of welders, welding coordinators, spot checks and by the continuous quality assurance, which is carried out by welders and visual inspectors.

Det Norske Veritas demands that in case of other than container vessels visual testing of welds should be carried out according to instructions of IACS No.47 Shipbuilding and Repair Quality Standard or alternatively according to ISO 5817 quality level C. Those imperfections that are not dealt in IACS No.47 must be dealt according to ISO 5817 quality level C. SFS-EN ISO 5817 (2014) divides welding imperfections into three quality levels B, C and D. Of these three levels, B has the highest demands for quality of welds. IACS No. 47 handles more generally the overall quality in shipbuilding. Sections related directly to quality of welds handle surface imperfections and joint geometry imperfections. (SFS-EN ISO 5817, 2014, p. 10; IACS, 2013, p. 1–31; DNV GL AS, 2015a, p. 84.)

SFS-EN ISO 5817 (2014, p. 18-45) groups different welding imperfections to surface imperfections, internal imperfections and imperfections in joint geometry. In Meyer Turku shipyard quality level C is used in most of the structures. Also quality levels B and D are used in some targets. For example quality level B is used in demanding pipelines and quality level D is used in some outfitting targets. Requirements according to SFS-EN ISO 5817 for quality level C in surface imperfections, when material thickness is over 3 mm and joint type is fillet weld, are shown in table 8 and requirements for internal imperfections are shown in table 9. In both tables *a* means throat thickness of fillet weld, *t* means thickness of the material and *b* means width of the convex of weld (SFS-EN ISO 5817, 2014, p. 15). Imperfections in joint geometry are not dealt in this study.

Table 8. Requirements for quality level C (surface imperfections) in case of fillet welds and material thicknesses over 3 mm (SFS-EN ISO 5817, 2014, p. 18–31).

Type of the imperfection	Limits
Crack	Not permitted.
Crater crack	Not permitted.
Surface pore	Max. diameter: ≤ 0.2a, max 2 mm.
End crater pipe	Depth of crater: ≤ 0.1t, max. 1 mm.
Lack of fusion	Not permitted.
Micro Lack of fusion	Permitted.
Undercut	Depth of undercut: ≤ 0.1t, max 0.5 mm.
Excessive convexity	The excess height: ≤ 1 mm +0.15b, max 4 mm.
Incorrect weld toe	α ≥ 100°.
Excessive asymmetry of fillet weld	Deviation of leg length: ≤ 2 mm + 0.15a.
Poor restart	Not permitted.
Insufficient throat thickness	For short imperfection max. undersize: 0.3 mm + 0.1a, max. 1 mm.
Excessive throat thickness	Max. oversize: 1 mm + 0.2a, max 4 mm.
Stray arc	Not permitted.
Spatter	On occasion.

Table 9. Requirements for quality level C (internal imperfections) in case of fillet welds and material thicknesses over 3 mm (SFS-EN ISO 5817, 2014, p. 30–41).

Type of the imperfection	Limits
Crack	Not permitted.
Microcrack	Depends of parent metal.
Gas pore, Uniformly distributed porosity	Cross section area of imperfections related to fracture area: ≤ 1.5 %. Diameter for a pore: ≤ 0.3a, max 4 mm.
Clustered porosity	Summation of imperfection areas related to evaluation area: ≤ 8 %. Diameter for a pore: ≤ 0.3a, max 3 mm.

Table 9 continues. Requirements for quality level C (internal imperfections) in case of fillet welds and material thicknesses over 3 mm (SFS-EN ISO 5817, 2014, p. 30–41).

Type of the imperfection	Limits
Linear porosity	Cross section area related to fracture area: ≤ 4 %. Diameter for a pore: ≤ 0.3a, max 3 mm.
Elognated cavity, Wormhole	Height: ≤ 0.3a, max 3 mm. Length: ≤ a, max. 50 mm.
Shrinkage cavity	Not permitted.
Crater pipe	Not permitted.
Solid-, slag-, flux- and oxide-inclusions	Height: ≤ 0.3a, max 3 mm. Length: ≤ a, max. 50 mm.
Metallic inclusions	≤ 0.3a, max 3 mm.
Copper inclusions	Not permitted.
Lack of fusion	Not permitted.
Lack of penetration	Not permitted.

Guidance of IACS No.47 is more limited compared to guidance of SFS-EN ISO 5817. Unlike SFS-EN ISO 5817, IACS No.47 does not deal internal imperfections. Limits for welds surface imperfections in case of fillet welds are shown in table 10. In addition to imperfections shown in table 10 IACS No. 47 guides also that loose weld spatters should be removed from following targets if painting requires: shell plating, visible decks and tanks for fresh water, oil and chemical cargoes. In IACS No. 47 the used toe angle is a complementary angle of that which is used in SFS-EN ISO 5817. (IACS, 2013, p. 1–6.)

Table 10. Limits for surface imperfections in case of fillet welds according to IACS No. 47 (IACS No. 47, 2013, p. 28).

Type of imperfection	Limits
Wrong measurement in leg length (s) or throat thickness (a)	s ≥ 0.9 x designed s, a ≥ 0.9 x designed a.
Toe angle (θ)	θ ≤ 90°.
Undercut	depth of undercut ≤ 0.8 mm.

Standard SFS 8145 (2001) divides quality of surface preparation into six different grades. Of these grades 06 have the highest demands for quality of surface which is to be painted. At Meyer Turku shipyard quality grade 05 is used for surfaces which are visible for passengers of the ship. Quality grade 03 stands for an overall good quality and quality grade 01 is for surfaces which are not visible in any case for passengers. In table 11 is shown the actions for quality grades 01, 03 and 05. (SFS 8145, 2001, p. 2–4.)

Table 11. Actions, related to welding, for quality grades 01, 03 and 05 (modified from SFS, 2001, 8145, p. 4).

Action	01	03	05
Removing of slag	x	x	x
Removing of wire electrode pieces		x	x
Removing of spatters which can be removed with a scrapper		x	
Removing of all spatters			x
Repairing of pores			x
Repairing of undercuts			x
Smoothening of sharp peaks			x

Quality assurance can be divided into actions before welding, which are made to prevent defects, and to control which takes place afterwards. At Meyer Turku shipyard all welders are qualified according to standard SFS-EN ISO 9606-1 and welding procedure specifications, which have been drawn up to all welding work, are qualified according to standard SFS-EN ISO 15614-1. Welding engineer is the main welding coordinator of the shipyard and there are also several other welding coordinators. Spot checks are used to control welding parameters and the visual quality of weld. In some critical areas constant visual inspections are made. Also radiographic testing, ultrasonic testing, magnetic particle testing and liquid penetrant testing are performed according to project-specific NDT plan.

9 WELDING EXPERIMENTS

Welding experiments consisted of preselection welding tests, destructive tests, examination of macro sections and additional experiments. In preselection welding tests potential of different solid wire MAG-welding processes to weld primed and tack welded plates in welding positions PB, PD and PG was researched. The focus was in porosity, processes ability to handle tack welds and in productivity. Destructive testing was carried out to expose the inner quality of welds. In destructive testing the goal was to study the amount of produced pores with different welding processes and to ensure that the welding parameters were chosen so that the root penetration was sufficient. In additional experiments the most appropriate welding process from the preselection welding tests was used to study which issues affects to porosity most. Overall worktime and costs between tubular wire MAG-welding and chosen solid wire MAG-welding process was calculated.

9.1 Used materials and welding consumables

In each section of the welding experiments the used materials were shipbuilding steels of grade A and A36. Used plates and profiles were primed in pretreatment line of shipyard with Jotun Muki Z 2001 primer to ensure that welding test circumstances correspond to reality. The chemical composition of the used steel grade A is shown in table 12 and the chemical composition of grade A36 is shown in table 13. Yield strength of grade A is 235 MPa and tensile strength varies between 400 and 520 MPa (DNV GL AS, 2015c, p. 33). Yield strength of grade A36 is 355 MPa and tensile strength varies between 490 and 630 MPa. In table 12, as opposite to other elements, manganese content is the minimum content of steel and in table 13 aluminum content is the minimum content of the steel. (DNV GL AS, 2015c, p. 34–36.)

Table 12. Maximum limits for the chemical composition of shipbuilding steel grade A (DNV GL AS, 2015c, p. 31–32).

C [%]	Si [%]	Mn [%]	P [%]	S [%]	Cu [%]	Cr [%]	Ni [%]	Mo [%]
0.21	0.5	0.525	0.035	0.035	0.35	0.2	0.4	0.08

Table 13. Maximum limits for the chemical composition of shipbuilding steel grade A36 (DNV GL AS, 2015c, p. 34).

C [%]	Si [%]	Mn [%]	P [%]	S [%]	Cu [%]	Cr [%]	Ni [%]	Mo [%]	Al [%]	Nb [%]	V [%]	Ti [%]
0.18	0.5	1.6	0.035	0.035	0.35	0.2	0.4	0.08	0.02	0.05	0.1	0.02

The used solid wire product was ESAB OK AristoRod 12.50 and the diameter of used wire product was 1.2 mm. AristoRod 12.50 is a non-coppered and non-alloyed solid wire and it is suitable for welding of fine grain and structural steels. SFS-EN ISO 14341-A classifications of AristoRod 12.50 are: G 3Si, G 38 3 C1 3Si and G 42 4 M21 3Si and it is approved for example by DNV GL AS, Bureau Veritas and Lloyd's Register. From the SFS-EN ISO 14341-A classification can be seen that if AristoRod 12.50 is welded with M21 shielding gas yield strength of weld deposit is 420 MPa. The chemical composition of weld metal as a result of welding with shielding gas M21 is shown in table 14. (ESAB, 2015d; ESAB, 2015c; SFS-EN ISO 14341, 2008, p. 15, 31.)

Table 14. Chemical composition of weld metal when solid wire ESAB OK AristoRod 12.50 and shielding gas: 75% Ar and 25% CO_2 are used (ESAB, 2015c).

C [%]	Mn [%]	Si [%]	P [%]	S [%]	Cu [%]
0.08	1.19	0.68	0.012	0.012	0.02

In all experiments classification of the used shielding gas was SFS-EN ISO 14175-M21. Shielding gas was supplied from the gas mixing station of shipyard. The desired mixing ratio with this shielding gas is 75 % of argon and 25 % of CO_2. The assumption was that mixing ratio of the gas remains sufficiently constant in order to obtain reliable results from the welding tests. During the preselection welding tests moisture content of shielding gas was measured to ensure that obtained results were reliable and that shielding gas cannot contaminate weld metal with hydrogen addition. (SFS-EN ISO 14175, 2008, p. 18.)

9.2 Experimental setup of preselection welding tests

In the preselection welding tests ability of five different MAG-welding processes to weld primed and tack welded fillet weld joints were researched. With each welding process, nine tests were made: throat thicknesses 3 mm, 4 mm and 6 mm were welded in welding positions PB, PG and PD. Throat thickness 6 mm was carried out in multi pass welding with three passes. Combination of used power sources, wire feed units and examined processes are shown in table 15. As a reference throat thicknesses 3 mm and 4 mm were welded also with metal cored wire ESAB OK Tubrod 14.12 and throat thickness 4 mm was welded with Filarc PZ6113 in welding position PB. These tubular wire references were welded according to WPS' of shipyard.

Table 15. Welding equipment and processes used in preselection tests.

Process no.	Manufacturer	Power source	Wire feed unit	Process
1	Kemppi	FastMig Pulse 450	MXF 65	135
2	Lincoln	s 500 CE Power Wave	PF 46	135 (pulse)
3	Kemppi	FastMig Pulse 450	MXF 65	135 (double pulse)
4	Lincoln	s 500 CE Power Wave	PF 46	135 (RapidArc)
5	EWM	Phoenix 505 puls	drive 4X	135 (ForceArc)
6	Kemppi	FastMig Pulse 450	MXF 65	138
7	Kemppi	FastMig Pulse 450	MXF 65	136

9.2.1 Test specimens and preparation

Preselection welding test specimens were T-beams. Webs of T-beams were fully primed flat bars of steel grade A and they were cut to length with guillotine. Flanges of T-beams were manufactured from primed plate of steel grade A36 and also cut to length with guillotine. In table 16 is shown measurements of test specimens. Reason to use fully primed flat bar in the web of the T-beams was to ensure that welding processes are exposed fully to negative effects of primer.

Table 16. Measurements of preselection welding test specimens.

Part	Length [mm]	Width [mm]	Thickness [mm]
Web	1200	100	10
Flange	1200	200	9

Three test welds of equal lengths were welded in one T-beam. The same welding test was performed to the both opposite sides of the beams. Each test weld was designed to be 300 mm long. T-beams were tack welded so that every test weld had to pass over two tack welds on the both sides of the T-beams. Tack welds were welded with MAG-welding and with same shielding gas and welding wire as the actual welding test. The used wire feed speed in tack welding was 6 m/min. Feeler gauge was used to measure air gaps between tack welds. In appendix II is shown drawing of test specimen which indicates the position of welds, tack welds and locations of air gap measurements. Results of tack weld measurements are shown in appendix III and IV. Based on the measurement results, air gaps did not exist in preselection welding test specimen.

9.2.2 Test welds

Test welds were marked with numerical codes to describe the used welding position, process and throat thickness. First part of the marking indicates the used welding position, second part the welding process and third part indicates the desired throat thickness. In welding positions, number 1 means PB, 2 means PD and 3 means PG. Numbering of welding processes is shown in table 15. In throat thickness values number 1 means 3 mm, 2 means 4 mm and 3 means 6 mm. The formation of numerical code is shown in figure 17.

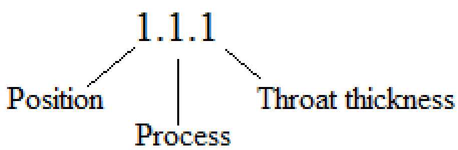

Figure 17. Formation of numerical codes which were used in preselection tests.

9.2.3 Welding setups

From each welding test welding parameters as wire feed speed, welding current, voltage, travel speed and pulse parameters, in case of pulse MAG-welding, were marked-up. Lincoln Power Wave Manager -software was used to record the pulse parameters from pulse MAG-welding and RapidArc process. In case of Kemppi double pulse MAG-welding, pulse parameters were enquired from welding engineer of Kemppi. The used pulse parameters are shown in appendix V. With constant voltage processes, MAG-welding and ForceArc, digital clamp meter Hioki 3285 was used to measure welding current *I* and voltage *U*. With pulsed processes welding current and voltage did not remain constant, which is the reason why it was more reasonable to record the parameters from wire feeders. Gas flow rate was adjusted to 20 l/min in each welding test with rotameter. Contact tube to work distance (CTWD) varies depending of used process and welding positions as well as torch travelling technique. More detailed information about CTWD and torch travelling is spoken out in the following sections. Throat thicknesses were measured from the middle of each weld and also on all tack welds to find out how different processes managed tack welds in different welding positions.

In welding positions PB and PD welding was performed with Koweld CS-B71 trackless fillet weld tractor. In these two positions welding torch was attached so that the torch angle was 25° pushing except in RapidArc test weld for 4 mm throat thickness and in MCAW and FCAW reference tests in welding positon PB. In RapidArc welding test 1.4.2 the torch angle was increased to 29° to reduce convexity of the weld. Torch angles for MCAW and FCAW reference tests were determined by WPS of shipyard. In all welding test except FCAW reference test, torch angle was pushing. In table 17 is shown the used CTWDs, gas nozzle diameters and torch angles for welding tests in welding positions PB and PD except previously mentioned exception in case of RapidArc process.

Table 17. Torch angles, CTWDs and gas nozzle diameters for welding tests in welding positions PB and PD.

Process	Position	CTWD [mm]	Gas nozzle diameter [mm]	Angle [°]
135	PB & PD	19	16.6	25
135 (pulse)	PB & PD	22	16.4	25
135 (double pulse)	PB & PD	19	16.6	25
135 (RapidArc)	PB & PD	22	16.4	25
135 (ForceArc)	PB & PD	19	17.7	25
138	PB	19	16.6	10
136	PB	22	16.6	5

Test specimens were attached to the test chassis with clamps. In figure 18 is shown the setups of welding position PB and welding position PD.

Figure 18. Setups for welding positions PB (left) and PD (right).

In welding position PG test welds were welded with rail carriage ESAB Railtrac. The used torch angle was 26° pulling in each test. Test specimens were attached to the test chassis in the same way as in positions PB and PD. The used CTWDs were shorter than in welding positions PB and PD. In table 18 is shown the used CTWDs, gas nozzle diameters and torch angles for welding tests in welding position PG. In figure 19 is shown welding setup of this position.

Table 18. Torch angles, CTWDs and gas nozzle diameters for welding tests in welding position PG.

Process	Position	CTWD [mm]	Gas nozzle diameter [mm]	Angle [°]
135	PG	16	16.6	26
135 (pulse)	PG	15	16.4	26
135 (double pulse)	PG	16	16.6	26
135 (RapidArc)	PG	15	16.4	26
135 (ForceArc)	PG	11	17.7	26

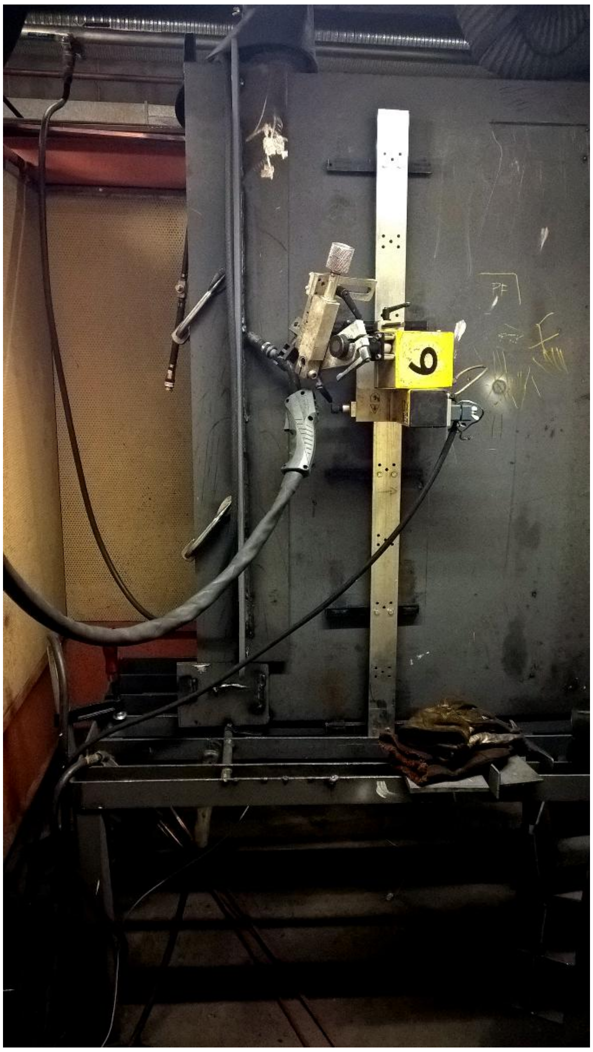

Figure 19. Setup for welding position PG and ESAB Railtrac torch carriage.

9.3 Visual inspection

Visual inspections were carried out to finished test specimen. Each test weld was inspected against surface imperfections which are mentioned in standard SFS-EN ISO 5817 (2014). Inspections were carried out according to acceptance levels of SFS-EN ISO 15614-1 which sets the acceptance levels for qualification of welding procedures specifications. SFS-EN ISO 15614-1 requires that test specimen full fills the requirements of quality level B except as regards of excessive convexity, throat thickness, penetration and in case of incorrect weld toe. In these cases test specimen must only full fill the requirements of quality level C. In visual inspections special attention was given to weld toe angle, amount of spatters and to possible undercuts. In addition to this, spots where weld passed tack weld were inspected carefully. (SFS-EN ISO 15614, 2012, p. 1, 33.)

9.4 Destructive testing and preparation of macro sections

After visual inspections welding test specimens were cut to pieces with Thomas SAR 230 band saw. The aim was to cut approximately 150 mm long piece from each weld for destructive testing and 50 mm long piece for macro section. In figure 20 are shown cut pieces.

Figure 20. Test pieces cut to 150 mm length and ready for Carbon-arc gouging and breaking.

After the cutting step first side weld was removed with carbon-arc gouging from each test piece. Used electrode size in carbon-arc gouging process was 8 mm. The reason to remove weld from another side of the test specimen was to minimize the force which was required to break the test specimen. In figure 21 is shown carbon-arc gouged test specimen.

Figure 21. Carbon-arc gouged test specimen.

After carbon-arc gouging second side welds of test pieces were broken with Sicmi hydraulic press. The used hydraulic press and positioning of test piece are shown in figure 22.

Figure 22. Breaking of the test specimen with hydraulic press.

The porosity percentage and diameter of largest pore were defined from the fracture surfaces after the second side welds were broken. A sliding caliper was used to define the diameters of pores. In figure 23 is shown fractured surface of test weld which is ready for the determination of porosity. Macro sections were prepared in DEKRA Industrial Oy from welds which had 4 mm throat thickness and which were welded in welding positions PB and PG. Hardness surveys were made with a single line of measurements from each macro section. Macrographs were taken from each macro section.

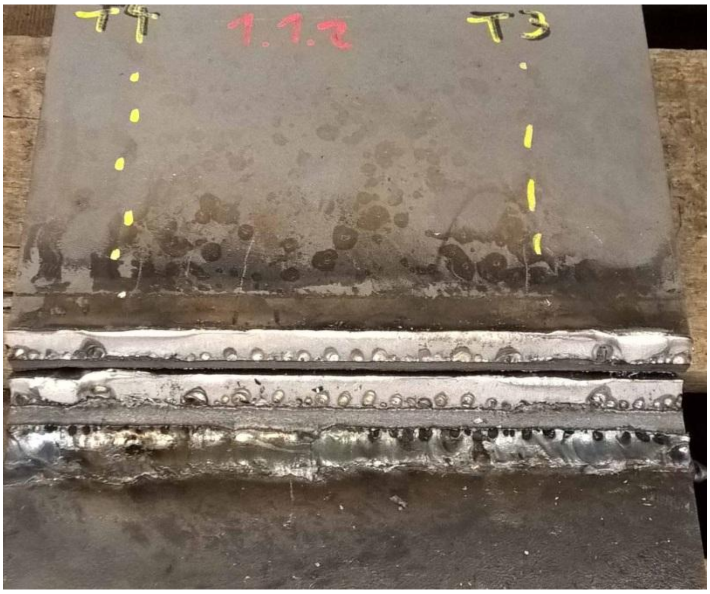

Figure 23. Example of broken weld (1.1.2) which is ready for the determination of porosity.

9.5 Setup of additional experiments

In addition to preselection welding experiments of which goal was to determine reasonable but productive travel speeds, correct welding parameters, burn-off rates, processes abilities to over weld tack welds and tendencies to porosity, additional experiments were made to find ways to minimize porosity. Over welding of tack welds was not studied in additional experiments. In additional experiments objects of study were:

- reduction of travel speed
- removing of primer
- increase of air gap
- usage of CO_2 instead of mixture gas
- usage of more alloyed solid wire qualities G4Si1 and 2Ti.

The additional experiments were made with the best suited process found in preselection. The used welding position in all of these experiments was PB and the desired throat thickness was 4 mm. These experiments were welded with equipment of Lincoln Electric.

The used CTWD was 22 mm, diameter of gas nozzle was 16.4 mm and torch angle was 25° pushing. The changes in the wire product, travel speed and shielding gas required also searching of new welding parameters which are shown in appendix VI.

The reduction of travel speed was carried out with travel speeds 60 cm/min and 40 cm/min. The idea was to maintain the 4 mm throat thickness despite of the decrease in travel speed. The used welding wire product was ESAB OK AristoRod 12.50 and used shielding gas was mixed gas M21.

Three experiments were made to define the sufficient level of primer removal to ensure porosity free welds. The first experiment was carried out by removing the primer from the flange of test specimen. In second test primer was removed from the web and in third experiment from all surfaces which were to be welded. Primer removal was done with angle grinder and flap disk. The used welding wire product was ESAB OK AristoRod 12.50 and used shielding gas was mixed gas M21.

To study the effects of air gap one test specimen was tack welded so that size of air gap was 1.2 mm. The air gap was made by setting pieces of solid welding wire with thickness of 1.2 mm between web and flange before tack welding. This ensured that the air gap remained constant in the whole length of the test specimen. The used welding wire product in this welding test was ESAB OK AristoRod 12.50 and used shielding gas was mixed gas M21.

Effects of CO_2 shielding gas were studied with MAG-welding. As well as M21 shielding gas in the other welding experiments also CO_2 shielding gas was supplied from the gas mixing station of shipyard. As well as in the previous cases also in this case the used wire product was ESAB OK AristoRod 12.50.

The last additional experiments were made with solid wire qualities 4Si1 and 2Ti. The aim was to study if porosity can be reduced by using more alloyed solid wire qualities. Product name of used 4Si1 quality was ESAB OK Autrod 12.64 and the product name of 2Ti quality was ESAB OK AristoRod 12.62. The quality 2Ti was not available on the European market and it was only possible to receive it from a special request. It was also only possible to get the 12.62 product with a diameter of 1.0 mm. The chemical composition of weld metal as a result of welding with ESAB OK Autrod 12.64 and shielding gas Ar 80 % and CO_2 20 % is shown in table 19. Corresponding information of the composition of ESAB OK AristoRod 12.62 is not available.

Table 19. Nominal chemical composition of weld metal when solid wire ESAB OK Autrod 12.64 and shielding gas Ar 80 % and CO_2 20 % are used (Engweld, 2015, p. 1).

C [%]	Mn [%]	Si [%]	P [%]	S [%]
0.1	1.28	0.8	0.013	0.013

10 RESULTS AND DISCUSSION

The first section of this chapter presents the results of preselection welding tests. The goal is to represent the used welding parameters and observations which were made of different welding processes in different welding positions. The second section is about analysis of strengths, weaknesses, opportunities and threats (SWOT) which is made to find out the most appropriate welding process for production of shipyard. In third section the results of additional experiments are represented and discussed.

10.1 Results and discussion of preselection welding tests

This section presents the used parameters, results of porosity and results of over welding of tack welds. Also heat inputs, macrographs, hardness values and observations from welding tests are presented.

10.1.1 Parameters

In preselection welding tests welding parameters were searched so that shapes of the weld beads were satisfying and no visual defects occurred. The goal was to find parameters which would ensure productive welding but which would also be easy to apply into production of shipyard. In appendix VII is shown all the parameters from preselection welding tests. For each welding process welding data is divided into tables by the used throat thickness and welding position. Used wire feed speeds, welding currents, voltages, travel speeds and average throat thicknesses are represented. Current and voltage values are shown separately for the both first and second side of the welded test specimen. In tables green color is used to mark the most productive values and red color to mark the least productive. The used travel speeds and achieved burn-off rates are shown in tables 20-22. Burn-off rates were calculated based on the used wire feed rates and density of steel which is 7850 kg/m^3 (The Engineering toolbox, 2016). Travel speeds and burn-off rates of multipass welds are average values which are calculated from the three welded passes.

Used travel speeds in welding position PB for throat thicknesses 3 mm and 4 mm and also average travel speeds for multi pass welds with 6 mm throat thicknesses are shown in table 20. As it can be seen the fastest travel speed for 3 mm throat thickness was achieved with pulse MAG-welding and RapidArc process. The slowest travel speed was obtained with ForceArc process. In 4 mm throat thickness the fastest process was clearly pulse MAG welding. The slowest travel speed of five solid wire processes was in this case with MAG-welding. It can be seen from table 20 that in cases where parameter searching is only based on the visual look of the weld, it is easy to achieve higher travel speeds than what the current WPSs of shipyard allows for metal cored wire and rutile type flux cored wire in this welding position. If the travel speeds of multi pass welds are compared, highest average travel speed is achieved with pulse MAG-welding and slowest average travel speed is achieved with ForceArc process.

The highest burn-off rates in welding position PB were achieved with pulse MAG-welding and RapidArc process. The lowest burn-off rates were achieved with MAG-welding and double pulse MAG-welding. It can be seen from table 20 that it was possible to achieve higher burn-off rates with pulse MAG-welding and RapidArc process than with MCAW when MCAW was carried out in accordance with WPSs of shipyard.

Table 20. Productivity values with studied welding processes in welding position PB.

Process	Throat thickness [mm]	Travel speed [cm/min]	Burn-off rate [kg/h]
135	3	75	4.69
135	4	60	4.79
135	6	70	4.69
135 (pulse)	3	80	5.33
135 (pulse)	4	80	6.92
135 (pulse)	6	77	5.33
135 (double pulse)	3	72	4.26
135 (double pulse)	4	72	5.86
135 (double pulse)	6	68	4.26
135 (RapidArc)	3	80	5.33
135 (RapidArc)	4	65	6.12
135 (RapidArc)	6	76	5.33
135 (ForceArc)	3	65	4.69
135 (ForceArc)	4	70	5.86
135 (ForceArc)	6	62	4.69
138	4	55	5.86
136	4	39	5.59

In table 21 is shown travel speeds of preselection welding tests in welding position PD for throat thicknesses 3 mm, 4 mm and 6 mm. The highest travel speed for 3 mm throat thickness was achieved with double-pulse MAG-welding and the slowest travel speed with pulse MAG-welding. In throat thicknesses 4 mm and 6 mm the highest travel speeds were achieved with RapidArc process and the slowest with MAG-welding. In this welding position the highest burn-off rates were achieved with RapidArc process and the lowest burn-off rates were result of pulse MAG-welding and MAG-welding.

Table 21. Productivity values with studied welding processes in welding position PD.

Process	Throat thickness [mm]	Travel speed [cm/min]	Burn-off rate [kg/h]
135	3	41	2.66
135	4	29	2.66
135	6	37	2.66
135 (pulse)	3	40	2.40
135 (pulse)	4	40	3.46
135 (pulse)	6	40	2.61
135 (double pulse)	3	50	2.66
135 (double pulse)	4	40	3.46
135 (double pulse)	6	47	2.93
135 (RapidArc)	3	48	3.20
135 (RapidArc)	4	42	3.73
135 (RapidArc)	6	51	3.55
135 (ForceArc)	3	48	3.20
135 (ForceArc)	4	34	3.66
135 (ForceArc)	6	43	3.25

In table 22 is shown travel speeds of preselection welding tests in welding position PG for throat thicknesses 3 mm, 4 mm and 6 mm. It can be seen from table 22 that the highest travel speeds for 3 mm, 4 mm and 6 mm throat thicknesses in welding position PG were achieved with RapidArc process and the slowest travel speeds with ForceArc process and MAG-welding. As well as in welding position PD also in position PG the highest burn-off rates were result of RapidArc process. The lowest burn-off rates in each throat thicknesses were result of double pulse MAG-welding.

Table 22. Productivity values with studied welding processes in welding position PG.

Process	Throat thickness [mm]	Travel speed [cm/min]	Burn-off rate [kg/h]
135	3	43	3.20
135	4	43	4.26
135	6	37	3.55
135 (pulse)	3	40	3.46
135 (pulse)	4	40	4.26
135 (pulse)	6	40	3.73
135 (double pulse)	3	45	2.93
135 (double pulse)	4	40	3.73
135 (double pulse)	6	47	3.2
135 (RapidArc)	3	55	4.26
135 (RapidArc)	4	48	4.79
135 (RapidArc)	6	51	4.44
135 (ForceArc)	3	35	3.46
135 (ForceArc)	4	35	4.79
135 (ForceArc)	6	43	3.91

In summary it can be said that it was possible to achieve high travel speeds with pulse MAG-welding in welding position PB. In other two positions RapidArc was the fastest process. The slowest processes were MAG-welding and ForceArc process. RapidArc process was capable to produce high burn-off rates in all three welding positions. Pulse MAG-welding was also capable to produce high burn-off rates in welding position PB, but it managed other positions worse. The lowest burn-off rates were mainly result of double pulse MAG-welding. In welding position PB it was possible to achieve higher burn-off rates with pulse MAG-welding and RapidArc process than with MCAW and FCAW. In welding positions PD and PG tubular wire processes are clearly more productive than studied solid wire processes. In these welding positions it is possible to achieve burn-off rates which are over 5 kg/h when welding is carried out accordance to WPSs of shipyard with metal cored wire ESAB OK Tubrod 14.12.

10.1.2 Heat input in preselection welding tests

Heat input values were calculated with formula 1 which is shown on page 16. In case of double pulse MAG, pulse MAG and RapidArc processes heat input values are calculated with average current and voltage values. As it was earlier told these values were taken directly from the view panels of wire feeders. Heat input values for MAG-welding and ForceArc processes are calculated with current and voltage values which are measured with digital clamp multi meter. All welding parameters which were used in the heat input calculations are shown in appendix VII. In case of multi pass welds shown heat input values are average values from three welded passes. Following tables 23-25 represent calculated heat input values. The smallest heat input value is marked with green color and the largest with red color for each position and throat thickness combination. Heat input values shown in figures 23-25 are average values which are calculated from parameters of first side welds and second side welds.

In table 23 is shown calculated heat input values for welding position PB. As it can be seen RapidArc process achieved the smallest heat input values in all three throat thicknesses. The highest heat input values were result of MAG-welding in all three throat thicknesses. The heat input value of FCAW is not simply comparable to other results because of the larger throat thickness of the weld which was 4.6 mm. Also heat input value of MCAW is slightly disparate because of the 4.3 mm throat thickness.

Table 23. Heat inputs in welding position PB.

Process	Throat thickness [mm]	Heat input [kJ/mm]
135	3	0.62
135	4	0.74
135	6	0.59
135 (pulse)	3	0.48
135 (pulse)	4	0.63
135 (pulse)	6	0.5
135 (double pulse)	3	0.39
135 (double pulse)	4	0.58
135 (double pulse)	6	0.43
135 (RapidArc)	3	0.37
135 (RapidArc)	4	0.53
135 (RapidArc)	6	0.37
135 (ForceArc)	3	0.46
135 (ForceArc)	4	0.63
135 (ForceArc)	6	0.46
138	4	0.77
136	4	0.81

Heat input values for welding position PD are shown in table 24. In case of the welds with 3 mm throat thickness the smallest heat input was achieved with double pulse MAG-welding. In case of 4 mm and 6 mm throat thicknesses the smallest heat input values were achieved with RapidArc process. Largest heat input values for 3 mm and 4 mm throat thicknesses were result of ForceArc process and in 6 mm throat thickness result of MAG-welding.

Table 24. Heat inputs in welding position PD.

Process	Throat thickness [mm]	Heat input [kJ/mm]
135	3	0.52
135	4	0.72
135	6	0.58
135 (pulse)	3	0.36
135 (pulse)	4	0.57
135 (pulse)	6	0.4
135 (double pulse)	3	0.31
135 (double pulse)	4	0.58
135 (double pulse)	6	0.42
135 (RapidArc)	3	0.35
135 (RapidArc)	4	0.51
135 (RapidArc)	6	0.36
135 (ForceArc)	3	0.6
135 (ForceArc)	4	0.75
135 (ForceArc)	6	0.56

Heat input values in welding position PG are shown in table 25. Like it was case in welding position PB also in this position RapidArc process achieves the smallest heat input values in all throat thicknesses. Largest heat input values for throat thicknesses 3 mm and 6 mm were result of ForceArc process. Largest heat input in case of 4 mm throat thickness was result of MAG-welding.

Table 25. Heat inputs in welding position PG.

Process	Throat thickness [mm]	Heat input [kJ/mm]
135	3	0.47
135	4	0.73
135	6	0.57
135 (pulse)	3	0.5
135 (pulse)	4	0.68
135 (pulse)	6	0.56
135 (double pulse)	3	0.43
135 (double pulse)	4	0.61

Table 25 continues. Heat inputs in welding position PG.

Process	Throat thickness [mm]	Heat input [kJ/mm]
135 (double pulse)	6	0.49
135 (RapidArc)	3	0.41
135 (RapidArc)	4	0.55
135 (RapidArc)	6	0.48
135 (ForceArc)	3	0.56
135 (ForceArc)	4	0.71
135 (ForceArc)	6	0.65

From tables 23-25 can be seen that RapidArc process has clearly lower heat input than other solid wire processes. For example heat input of RapidArc was 45.6 % lower than what it was with MAG-welding in welding position PB with 3 mm throat thickness. Also double pulse MAG-welding has low heat input. In each position and throat thickness MAG-welding or ForceArc process had the highest heat inputs.

10.1.3 Observations from preselection welding tests

In welding position PB MAG-welding produced considerably amount of spatters and soot. Spatters were produced also in welding position PD and due to low wire feed rate arc instability occurred if targeting of welding wire was not precise enough. The wrong targeting caused the electric arc to go out in welding positions PD and PG. It turned out that it was almost impossible to produce 3 mm throat thickness with MAG-welding in welding position PG.

It was possible to use high travel speeds with pulse MAG-welding in welding position PB. However with high travel speeds pulse MAG-welding was prone to undercuts. Decrease in arc voltage reduced vulnerability to undercuts but also made shape of the weld less satisfying. It was possible to achieve satisfying look of the weld with 80 cm/min travel speed but to achieve high visual quality travel speed had to be less than 60 cm/min. In few welds worm holes occurred. Specific reason to this could not be found and later exactly same experiments were repeated and no worm holes occurred. In welding position PD low arc voltage had to be used to ensure satisfying look of the weld. However low arc voltage increased amount of spatters, which caused that wheels of fillet weld tractor filled with spatters. As well as the case was with MAG-welding, also in pulse MAG-welding targeting of welding wire had to be precise enough. Pulse MAG-welding performed well in welding position PG.

As well as MAG-welding and pulse MAG-welding also double pulse MAG-welding was vulnerable to undercuts. Double pulse MAG-welding was the easiest process to operate in multi pass welding. With other studied processes it was important to wait until earlier passes had cooled down enough. With double pulse MAG-welding cool down time was not needed. In right circumstances it was possible to achieve visually excellent welds. In welding position PD double pulse MAG-welding was unstable process and also few worm holes occurred. In welding position PG no special observations were made.

Convex weld shape is characteristic for RapidArc process. Convexity can be reduced by increasing pushing angle of welding torch. In welding position PB with 3 mm throat thickness it was possible to use same 25° pushing torch angle than with other processes. If the same travel speed would have been maintained also with 4 mm throat thickness, torch angle should have been a lot more pushing. Because of the used equipment it was possible to achieve only 29° pushing torch angle. Usage of this angle restricted the travel speed to 65 cm/min. RapidArc process managed well welding position PD and no special observations were made in this welding position. In welding position PG RapidArc formed few worm holes.

ForceArc process managed preselection welding test considerably worse than other processes. In welding position PB a large amount of spatters were produced and welding was uncomfortable. Unlike with other processes arc instability occurred also in welding position PB. The high amount of spatters caused problems especially in welding position PD. Because of the arc instability electric arc went out easily if targeting of welding wire was not precise enough. ForceArc process failed completely welding tests in welding position PG. Each of these welds was full of worm holes and also weld toes were incorrect in each of these welds.

It can be said that with all processes arc instability occurred in some extents. It was clearly seen that non pulsed processes, MAG-welding and ForceArc, were clearly more vulnerable to arc instability. The arc instability was problematic especially in welding positions PD and PG because in these positions low wire feed rates were used. As it was said on page 45, arc instability can be caused by zinc fumes which invade into electric arc. Arc instability occurred also with pulsed processes. However in these cases instability did not cause electric arc to go out. Pulsed processes were clearly more stable and immune to primer.

The usage of pulse MAG, double pulse MAG or RapidArc processes has a great advantage in hand-held welding. In regular MAG-welding great amount of spatters are produced when welding is performed in current region of globular arc. In spray arc region controlling of weld pool comes more difficult and undercuts may be formed. Pulsed MAG-welding processes allow spray type metal transfer with lower wire feed rates. This reduces amount of spatters and also makes the controlling of weld pool easier because heat input is lower compared to MAG-welding. Lower heat input makes weld pool colder and stiffer. It can be said that with pulsed processes welding features of solid wires begins to resemble welding features of tubular wires.

With all processes great amount of spatters were produced. The largest amounts of spatters occurred with MAG-welding and ForceArc process. Pulse MAG-welding and RapidArc process produced less spatters, although the amount of spatters was highly dependent for example of the right targeting of welding wire. It was also found that the amount of produced spatters was greater in welding positions PD and PG than in PB. In some cases amount of spatters was so high that wheels of fillet weld tractor filled with spatters. This caused that the wheels had to be cleaned almost after each weld. In figure 24 is shown fillet weld tractor which was used in welding tests of this study. In the beginning of welding tests tractor was nearly unused. At the time when image was captured tractor was used for welding of approximately 250 m with studied solid wire processes. The high amounts of spatters are probably resulting from the used primer. Pulse MAG-welding and MAG-welding was also tested with unprimed steel plates. In these tests amount of spatters was clearly lower.

After welding tests it was found from macrographs, which are shown in appendix VIII, that convexity of welds in welding position PG caused effective throat thickness to be less than desired 4 mm. In these welds the effective throat thickness varies between 3.1 mm and 3.5 mm instead of 4 mm.

Figure 24. Spatter damages of fillet weld tractor which was used in welding tests.

RapidArc and ForceArc processes were clearly more tolerant to undercuts than other processes. At least with RapidArc process it could be possible to achieve relatively high travel speeds without a risk of undercuts. In pulse MAG-welding the shape of the weld bead and propensity to undercuts restricts welding speed. Characteristic features of RapidArc and ForceArc processes are also more solid weld pool and slightly rougher surface of the weld bead.

10.1.4 Macro sections

This chapter represents the observations which were made from macro sections. In figure 25 is shown macrographs of the welds which had 4 mm throat thickness and which were welded in welding position PB. It can be seen from the macrographs that pulse MAG-welding and ForceArc process have deeper penetrations than other processes although penetrations are narrow. In macrographs of double pulse MAG-welding and ForceArc process can be seen pore which are in the both cases in the root of the welds. The macrographs of this section can be seen larger in appendix VIII. Macrographs in appendix are completed with information of fusion depth and throat thickness.

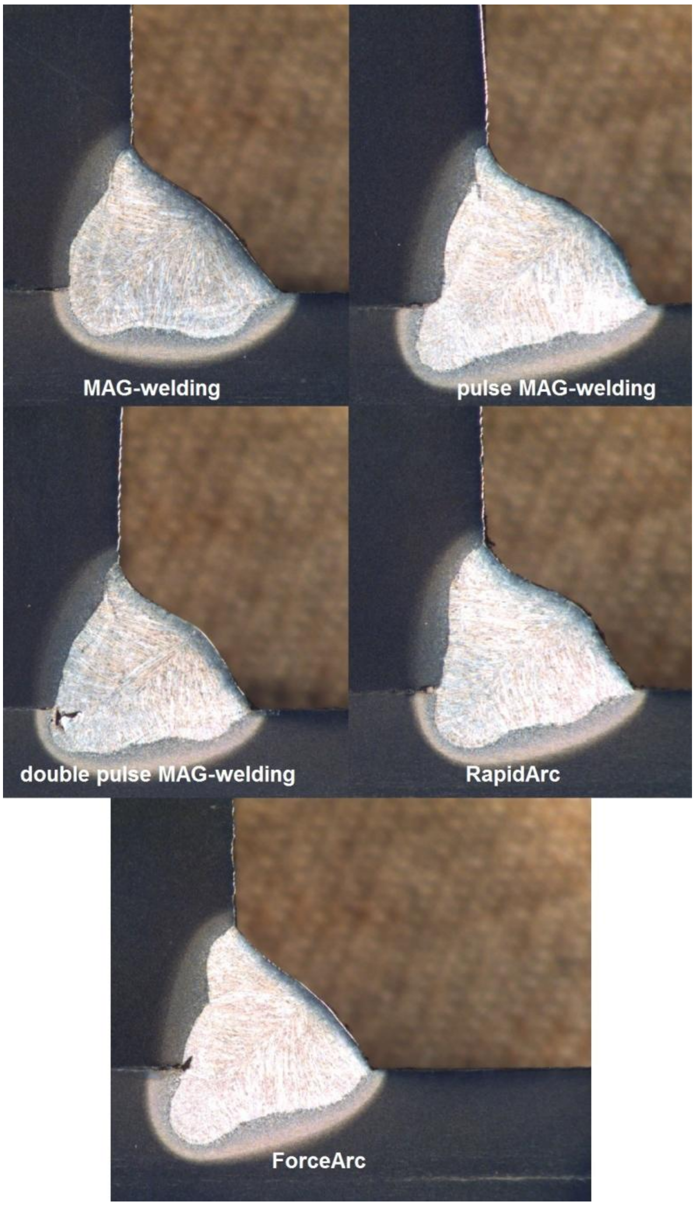

Figure 25. Macrographs of welds in welding position PB with throat thickness of 4 mm.

In figure 26 is shown macrographs of welds which were welded in welding position PG and which had 4 mm throat thickness. Like it was earlier told all the welds which were welded in PG welding position with ForceArc process failed, which explains the strange bead shape of ForceArc weld. Unlike in position PB penetrations of pulse MAG-welding and RapidArc are relatively wide and they do not differ greatly from penetration of MAG-welding. The welds of RapidArc and ForceArc processes contain pores.

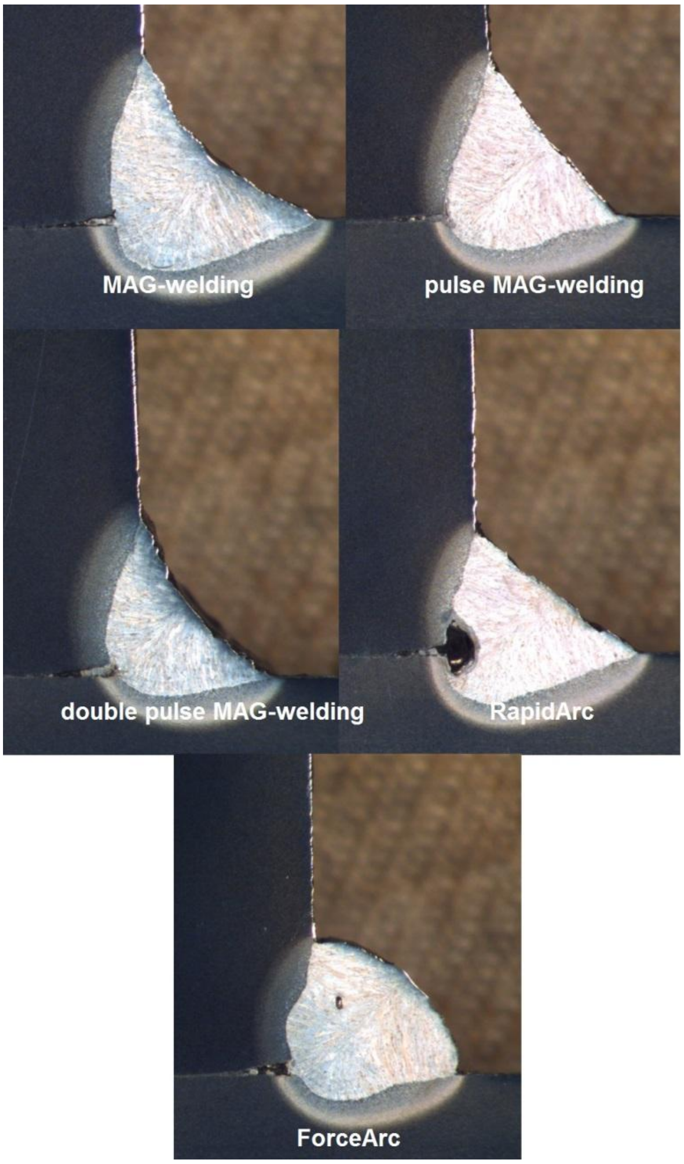

Figure 26. Macrographs of welds in welding position PG with throat thickness of 4 mm.

In figure 27 is shown macrographs of welds which have been welded with tubular wires Filarc PZ6113 and ESAB OK Tubrod 14.12. Macrographs are from old welding procedure tests of shipyard. The first macrograph on the left has 4 mm throat thickness and it is welded in position PB with Filarc PZ6113. Other two macrographs are welded with ESAB OK Tubrod 14.12. The macrograph in the middle is welded in welding position PB and it has 4 mm throat thickness. The last macrograph on the right is welded in welding position PG and it has throat thickness of 3.5 mm. If the macrographs in figures 25-27 are compared, it can be seen that welds which have been welded with tubular wires have lower but wider penetration than welds which have been welded with solid wire processes.

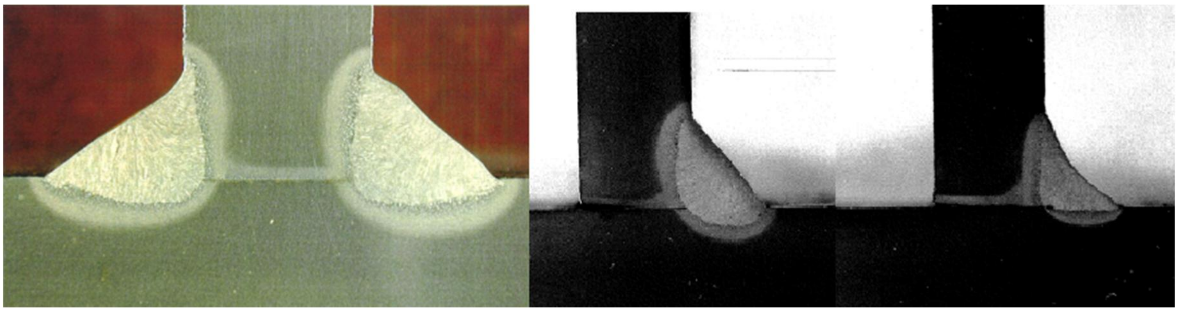

Figure 27. Penetrations with tubular wires Filarc PZ6113 (PB) on the left, ESAB OK Tubrod 14.12 (PB) in the middle and ESAB OK Tubrod 14.12 (PG) on the right.

In table 26 is shown hardness test results of welds which were shown in figure 25. The reported value is maximum hardness value which was found in hardness test. In all cases the highest value was found from the HAZ-area of the flange. This is due to the fact that the material of flanges was shipbuilding steel of grade A36 and the material of webs was shipbuilding steel of grade A. As it can be seen from table 26 the hardness results of pulse MAG-welding and RapidArc process are close to the limit 380 HV10 which DNV GL has set to the maximum hardness for single pass fillet welds (DNV GL AS, 2015a, p. 48). It can be also assumed that hardness in welds with 3 mm throat thickness would exceed the hardness limit. Hardness of pulse MAG-welding in table 26 was achieved with heat input 0.63 kJ/mm and hardness of RapidArc process was achieved with heat input 0.53 kJ/mm. In case of 3 mm throat thicknesses heat input for pulse MAG-welding was 0.48 kJ/mm and for RapidArc process 0.37 kJ/mm, which sets the hardness of welds with 3 mm throat thickness questionable.

Table 26. Results of HV10 hardness tests for welds which were welded in welding position PB with 4 mm throat thickness.

Process	Max. hardness [HV10]
135	358
135 (pulse)	369
135 (double pulse)	353
135 (RapidArc)	371
135 (ForceArc)	359

In table 27 is shown the results of hardness tests of the welds which were shown in figure 26. As it can be seen each of these test welds exceeds the hardness limit 380 HV10. The calculated heat input were in these cases between 0.55-0.73 kJ/mm. These results are contradictory to the results in table 26. In welding position PG hardnesses of HAZ-areas have increased higher than in welding position PB although the heat inputs were higher in position PG. Reason to this can be different duty cycles in welding which have given less time for test specimens of welding position PB to cool down. Higher working temperatures may have caused slower cooling of welds in position PB and thus lower hardness values. It is likely that these hardness measurements are not completely valid but they can give a direction of hardness values which could be reached in welding procedure tests. Due to the fact that material certificates of used steel products were not available it must be taken into concern that probably the concentration of alloying elements in A36 shipbuilding steel product, which was used in welding experiments, was not the maximum allowed content which is shown in table 13. The increase in the alloying elements of this particular steel could probably raise hardness of HAZ-area even higher.

Table 27. Results of HV10 hardness tests for welds which were welded in welding position PG with 4 mm throat thickness.

Process	Max. hardness [HV10]
135	383
135 (pulse)	398
135 (double pulse)	398
135 (RapidArc)	393
135 (ForceArc)	398

10.1.5 Porosity

The porosity examination was done to fractured surfaces of test welds as it was explained in chapter 9.4. SFS-EN ISO 5817 (2014) sets the limits for uniformly distributed porosity in fillet welds as it was told on page 52. The maximum limit for uniformly distributed porosity is 1.5 % and maximum dimensions for a single pore are 0.9 mm for 3 mm throat thickness, 1.2 mm for 4 mm throat thickness and 1.8 mm for 6 mm throat thickness. In figure 28 is shown defined porosity values in welding position PB. As it can be seen the largest amount of pores was produced in MAG-welding and double pulse MAG-welding. It can be said that with all processes measured porosity percentage was highest in 4 mm throat thickness. It can be also said that pulse MAG-welding, RapidArc and ForceArc processes decrease porosity greatly when compared to MAG-welding. The test welds of rutile type flux cored wire Filarc PZ6113 and metal cored wire ESAB OK Tubrod 14.12 have significantly lower porosity than tested solid wire processes. It must be also taken into account that these different processes are not fully comparable with each other because of the different travel speeds. (SFS-EN ISO 5817, 2014, p. 31.)

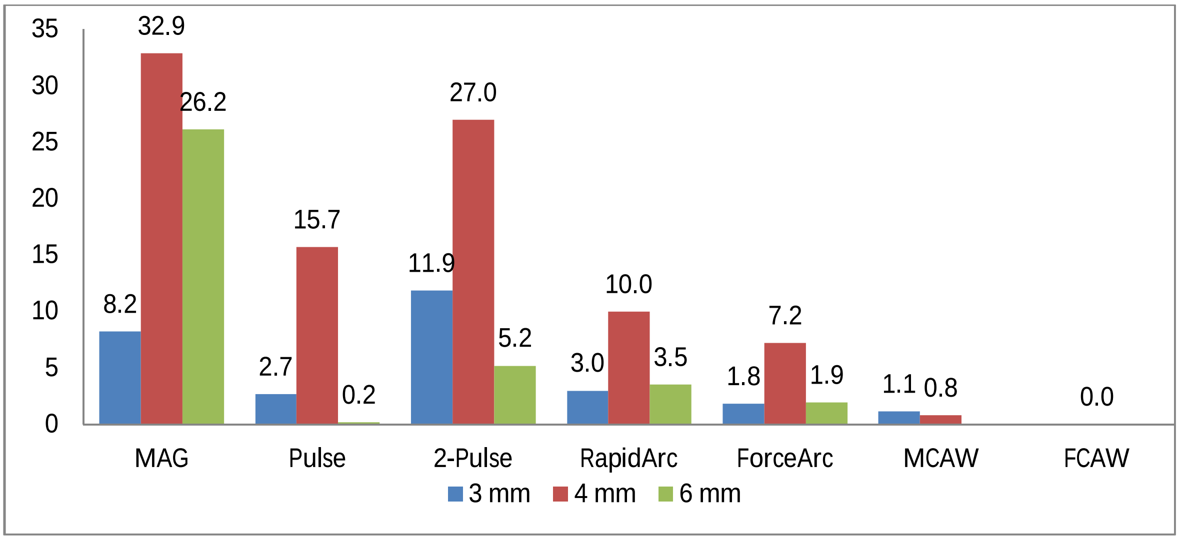

Figure 28. Porosity percentages in welding position PB according to results of preselection tests.

In figure 29 is shown porosity values in welding position PD. It can be seen from the results that the largest porosity values in this position were in 3 mm throat thickness, except in pulse MAG-welding. Unlike in welding position PB, ForceArc produced relatively high and double pulse relatively low porosity values. All in all it can be said that the porosity values were lower in welding position PD than in PB and the highest porosity values were result of MAG-welding.

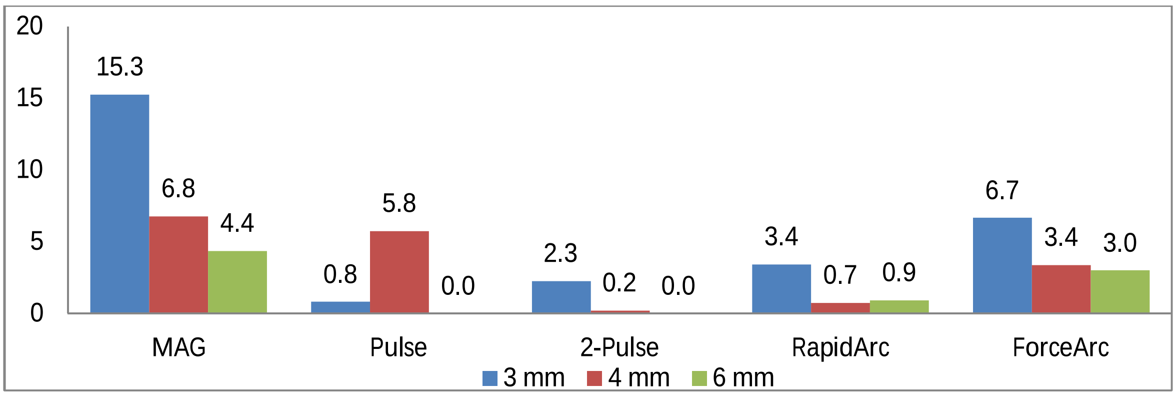

Figure 29. Porosity percentages in welding position PD according to results of preselection tests.

In figure 30 is shown porosity values of welding position PG. It can be seen that the highest porosity values were obtained in welds with 3 mm throat thickness except in case of ForceArc process. On contrary to results of welding positions PB and PD, in welding position PG MAG-welding produced relatively low porosity values. As well as in position PB, double pulse MAG-welding produced relatively high porosity values.

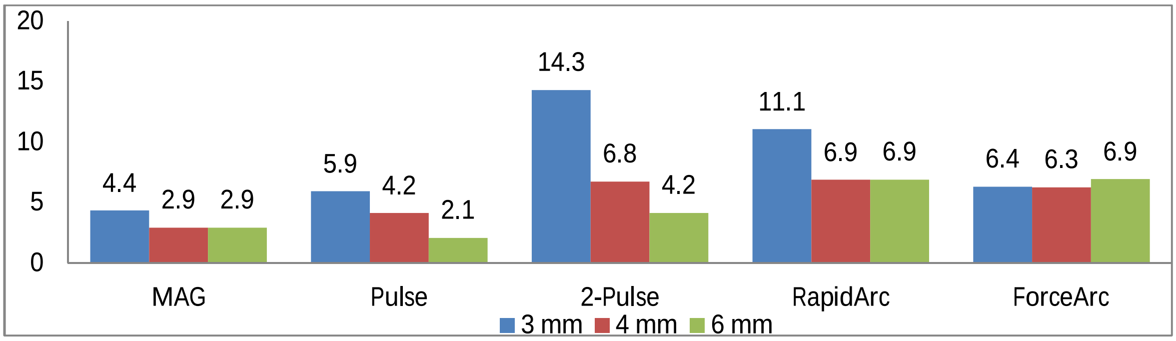

Figure 30. Porosity percentages in welding position PG according to results of preselection tests.

As it can be seen from figures 28, 29 and 30 it cannot be said clearly which of the used processes is able to produce welds with lowest porosity values in general. If a comparison is made with the travel speed information in tables 19-21, heat input information in tables 22-24 and porosity values in figures 28-30, it is impossible to make a clear statement which are the effects of welding position, welding process, throat thickness, heat input and travel speed to porosity. Only statement which can be made from these results is that usage of pulse-MAG, RapidArc or ForceArc processes instead of MAG-welding has probably positive effect to porosity. It can be also said that in most cases multi pass welds had relatively low porosity percentage.

The following tables 28-30 represent results of measurements which were made to define the diameter of largest pore from each weld. In table 28 is shown diameters of largest pores in welding position PB. It can be seen that the largest pore in welds with 3 mm throat thickness formed with double pulse MAG-welding. In welds with 4 mm throat thickness largest pore was result of MAG-welding and in welds with 6 mm throat thickness result of RapidArc process. In tables 28-30 red color is used to mark the largest pores from each welding position and throat thickness group and green color is used to mark pores which pass requirements of SFS-EN ISO 5817 quality level C.

Table 28. Diameters of largest pores in welding position PB.

Process	Throat thickness [mm]	Diameter [mm]
135	3	3
135	4	5.5
135	6	4.5
135 (pulse)	3	2.5
135 (pulse)	4	4
135 (pulse)	6	1
135 (double pulse)	3	4
135 (double pulse)	4	2.5
135 (double pulse)	6	4
135 (RapidArc)	3	2
135 (RapidArc)	4	3
135 (RapidArc)	6	5
135 (ForceArc)	3	2
135 (ForceArc)	4	3
135 (ForceArc)	6	1.5
138	3	1
138	4	2
136	4	0

As it can be seen from table 29 in welding position PD the largest pores in 3 mm throat thickness were results of MAG-welding, RapidArc process and ForceArc process. In 4 mm throat thickness the largest pores were results of pulse MAG-welding and ForceArc process. In 6 mm throat thickness largest pore was result of MAG-welding.

Table 29. Diameters of largest pores in welding position PD.

Process	Throat thickness [mm]	Diameter [mm]
135	3	3
135	4	2.5
135	6	5
135 (pulse)	3	1.3
135 (pulse)	4	3
135 (pulse)	6	0
135 (double pulse)	3	2
135 (double pulse)	4	0.5
135 (double pulse)	6	0
135 (RapidArc)	3	3
135 (RapidArc)	4	1

Table 29 continues. Diameters of largest pores in welding position PD.

Process	Throat thickness [mm]	Diameter [mm]
135 (RapidArc)	6	1
135 (ForceArc)	3	3
135 (ForceArc)	4	3
135 (ForceArc)	6	2

In welding position PG the largest pore in 3 mm throat thickness was result of double pulse MAG-welding. In 4 mm throat thickness RapidArc produced pore with largest diameter and in 6 mm throat thickness RapidArc and ForceArc produced largest pores as it can be seen from table 30.

Table 30. Diameters of largest pores in welding position PG.

Process	Throat thickness [mm]	Diameter [mm]
135	3	2
135	4	1.5
135	6	1.5
135 (pulse)	3	1
135 (pulse)	4	2
135 (pulse)	6	1.45
135 (double pulse)	3	4
135 (double pulse)	4	3
135 (double pulse)	6	3
135 (RapidArc)	3	2.5
135 (RapidArc)	4	5
135 (RapidArc)	6	4
135 (ForceArc)	3	2
135 (ForceArc)	4	3
135 (ForceArc)	6	4

In each position RapidArc process produced largest pore at least with one throat thickness. Also MAG-welding, pulse MAG-welding and ForceArc produced largest pores in two welding positions. Pulse MAG-welding produced largest pore only in position PD with 4 mm throat thickness. If the average diameter of largest pore for each process is calculated, results are as follows:

- MAG-welding: 3.2 mm
- pulse MAG-welding: 1.8 mm
- double pulse MAG-welding: 2.6 mm

- RapidArc: 2.9 mm
- ForceArc: 2.6 mm
- MCAW: 1.5 mm.

As it can be seen, on average the pore diameter in pulse MAG-welding is smallest and in MAG-welding it is largest. The average sizes of largest produced pores with other three solid wire processes are almost the same. In summary of porosity percentages and maximum pore sizes it can be said that only following solid wire welds fulfills the requirements of SFS-EN ISO 5817 (2014) quality level C:

- PB, pulse MAG-welding, throat thickness: 6 mm
- PD, pulse MAG-welding, throat thickness 6 mm
- PD, double pulse MAG-welding, throat thickness 4 mm
- PD, double pulse MAG-welding, throat thickness 6 mm
- PD, RapidArc, throat thickness 4 mm
- PD, RapidArc, throat thickness 6 mm.

10.1.6 Over welding of tack welds

This chapter represents the results of processes ability to over weld tack welds and also visual observations which were made of the over welding of tack welds. Formula 3 was used to create a comparison factor *x* for each test weld which enables comparing of different processes ability to handle tack welds. Formula 3 takes in concern throat thickness of tack weld $a_{Tack\ weld}$, throat thickness of weld a_{Weld} and throat thickness of over welded tack weld $a_{Over\ welded}$:

$$x = \frac{a_{Over\ welded}}{a_{Tack\ weld} + a_{Weld}} \tag{3}$$

In practical situations comparison factor *x* can have values between 0.5 and 1.0. The closer the comparison factor *x* is value 0.5 the better the process is to handle tack welds. When the comparison factor approaches 1.0 processes ability to handle tack welds decreases. Throat thickness measurements, which were performed to tack welds before and after over welding, are shown in appendix III.

In figure 31 is shown results of over welding of tack welds in welding position PB. As it can be seen studied solid wire processes cannot deal tack welds as well as tubular wire processes MCAW and FCAW. In 3 mm throat thickness MAG-welding was able to handle tack welds significantly better than other solid wire processes. In 4 mm throat thickness all processes handled tack welds almost equally well except RapidArc process. In 6 mm throat thickness double pulse MAG-welding performed over welding of tack welds considerably better than other solid wire processes. Unlike it was case in 3 mm throat thicknesses MAG-welding performed 6 mm throat thickness badly and RapidArc relatively better.

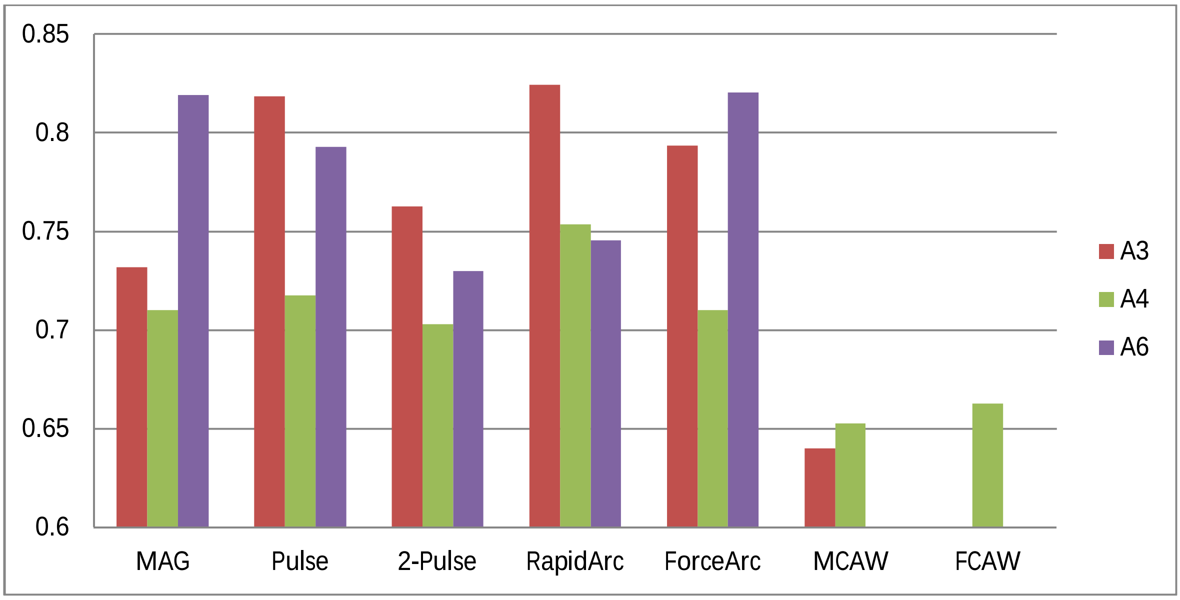

Figure 31. Processes ability to over weld tack welds in welding position PB presented using comparison factor *x* which is shown on the vertical axis.

In figure 32 is shown results of over welding of tack welds in welding position PD. As it can be seen in this welding position processes have succeeded over welding of tack welds worse than in welding position PB. ForceArc process managed over welding of tack welds clearly better than other processes in 3 mm throat thickness. In 4 mm throat thickness MAG-welding was the most successful process and in 6 mm throat thickness the most successful process was pulse MAG-welding. As well as in position PB RapidArc performed poorly in throat thicknesses 3 mm and 4 mm.

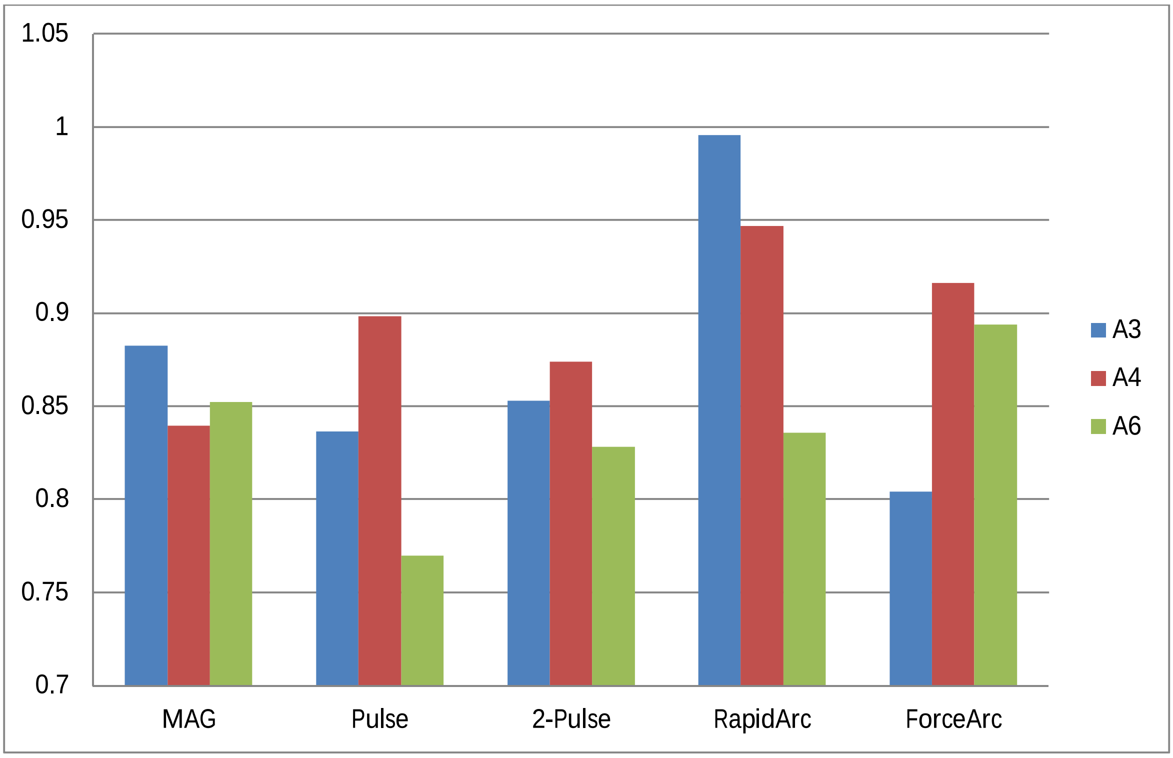

Figure 32. Processes ability to over weld tack welds in welding position PD presented using comparison factor *x* which is shown on the vertical axis.

In figure 33 is shown results of over welding of tack welds in welding position PG. Results of ForceArc process are not represented because it failed each of the welding tests in welding position PG as it was told previously. The result of MAG-welding in 3 mm throat thickness should be also treated with a caution. Particular welding test was not successful which has probably caused relatively high comparison factor *x*. In 3 mm throat thickness pulse MAG-welding was most successful in over welding of tack welds and in 4 mm throat thickness the most successful was MAG-welding. In 6 mm throat thickness RapidArc was the most successful process.

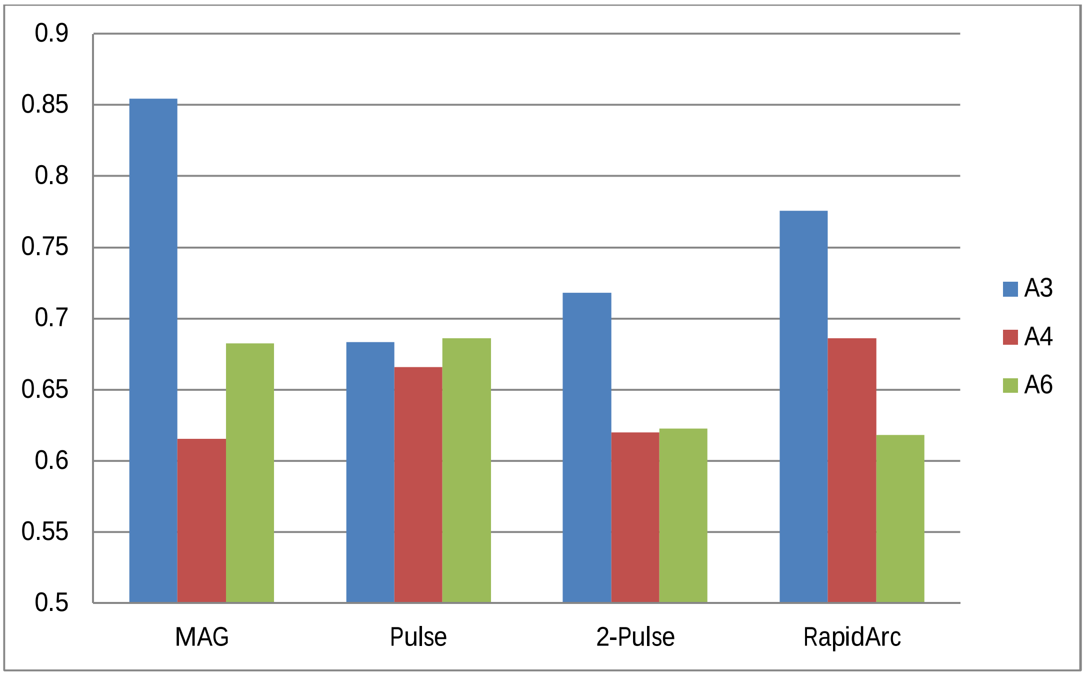

Figure 33. Processes ability to over weld tack welds in welding position PG presented using comparison factor *x* which is shown on the vertical axis.

Comparison factors do not correspond fully to observations which were made in visual examination. Welds which were welded with RapidArc and ForceArc had a convex shape, which caused welds to rise over tack welds. In MAG-welding and pulse MAG-welding welds spread more over tack welds, which decreased the propensity to form incorrect weld toe. In 6 mm throat thickness the alignment of passes had a great effect to the comparison factor *x*. Because of this it is more reasonable to compare welding processes ability to over weld tack welds with single pass welds. Based on the data in appendix III the average throat thickness of tack welds was 3.1 mm. In this case the difference in welding processes was more clearly recognizable in welds with 3 mm throat thicknesses than in welds with 4 mm throat thicknesses.

The over welding of tack welds succeeded with all welds in welding position PB. In welding position PD almost all welds had convex shape which caused incorrect weld toes on tack welds. Only following welds performed over welding of tack welds acceptably in welding position PD:

- 2.1.1: MAG-welding: 3 mm throat thickness
- 2.1.3: MAG-welding: 6 mm throat thickness
- 2.3.3: double pulse MAG-welding: 6 mm throat thickness.

As opposed to previous, in welding position PG all welds had more or less concave shape, which was a favorable feature in terms of over welding of tack welds. The welds spread smoothly over tack welds and incorrect weld toes formed only in following welds:

- 3.3.3: double pulse MAG-welding: 6 mm throat thickness
- 3.4.1: RapidArc: 3 mm throat thickness
- 3.4.2: RapidArc: 4 mm throat thickness
- 3.5.1: ForceArc: 3 mm throat thickness.

Based on figures 31, 32 and 33 it cannot be said clearly which one of these solid wire processes was most successful in over welding of tack welds. However visual examination supports the fact that RapidArc was less successful in all positions with 3 mm and 4 mm throat thicknesses. It must be taken in concern that used parameters, shape of tack welds and alignment of weld has great impact to the results. It must be also recognized that formula 3 does not take into concern length of the tack welds. Thus it can be said that the results of visual examination are more reliable when comparing the processes ability to weld over tack welds.

10.1.7 SWOT analyzes

SWOT analyzes were used to outline strengths, weaknesses, opportunities and threats of each studied MAG-welding process. In tables 31-35 are represented SWOT analysis of each welding process. The observations and results from the preselection welding test are collected to following analyzes so that the most suitable welding process for the production of shipyard could be chosen.

Table 31. SWOT analysis of MAG-welding.

Strengths	Opportunities
1. Existing welding equipment can be used. 2. Smooth passing of tack welds.	1. Low cost initialization.
Weaknesses	**Threats**
1. High porosity welds 2. Slow travel speeds 3. High spatter levels 4. Unstable arc at low wire feed rates 5. Vulnerable to undercuts 6. Relatively high heat input 7. Requires removing of primer.	1. Impurities may cause porosity 2. Usage of solid wire MAG-processes may cause dissatisfaction among the welders.

Table 32. SWOT analysis of pulse MAG-welding.

Strengths	Opportunities
1. High travel speeds 2. Deep penetration 3. Low porosity 4. Different equipment manufacturers 5. Easy to adjust parameters 6. Suitable equipment for shipyard is available.	1. Possibility to use relatively high travel speeds. 2. Possibility to use equipment from various manufacturers.
Weaknesses	**Threats**
1. Vulnerable to undercuts 2. Requires removing of primer.	1. Usage of solid wire MAG-processes may cause dissatisfaction among the welders 2. The bead shape may not be satisfying with high travel speeds.

Table 33. SWOT analysis of double pulse MAG-welding.

Strengths	Opportunities
1. Good position welding features 2.Easy multi pass welding 3. Suitable equipment for shipyard is available.	1. Easier position welding and multi pass welding than with MAG-welding and pulse MAG-welding.
Weaknesses	**Threats**
1. High porosity levels 2. Vulnerable to undercuts 3. Requires removing of primer.	1. The bead shape may not be satisfying with high travel speeds 2. Usage of solid wire MAG-processes may cause dissatisfaction among the welders 3. Impurities may cause porosity.

Table 34. SWOT analysis of RapidArc process.

Strengths	Opportunities
1. High travel speeds 2. High tolerance for undercuts.	1. Possibility to use relatively high travel speeds without a risk to undercuts.
Weaknesses	**Threats**
1. Welding equipment of Lincoln Electric fit to shipyard poorly due to fact that they are mainly relatively large and heavy. 2. Requires accurate adjustments of torch angles 3. Convex weld shape 4. Poor over welding of tack welds 5. Requires removing of primer.	1. The Precise control of torch angle may be a problem 2. Usage of solid wire MAG-processes may cause dissatisfaction among the welders 3. The hardness of the HAZ-area may exceed the set limits at small throat thicknesses.

Table 35. SWOT analysis of ForceArc process.

Strengths	Opportunities
1. High tolerance for undercuts 2. Low porosity 3. Deep penetration.	1. Possibility to achieve deep penetration 2. Possibility to use moderate welding speeds without a risk to undercuts.
Weaknesses	**Threats**
1. High spatter levels 2. Slow travel speeds 3. Unstable with small wire feed rates 4. Works poorly in welding position PG 5. Relatively high heat input 6. Requires removing of primer 7. Equipment does not fit to shipyard.	1.Welders' may feel that working conditions are unpleasant because of the spatters and unstable electric arc 2. Usage of solid wire MAG-processes may cause dissatisfaction among the welders.

Great advantage in MAG-welding is that it can be deployed with existing power sources. MAG-welding also performed well in over welding of tack welds. The disadvantages of MAG-welding are for example high porosity and slow travel speeds. From these five SWOT analyzes in tables 31-35 can be seen that pulse MAG-welding has greater number of strengths and also less weaknesses than any other process. Important feature in pulse MAG-welding is capability to be able to produce low porosity welds with relatively high travel speeds. The most important thing from shipyard´s point of view is that there are many manufacturers which sell power sources for pulse MAG-welding, although each manufacturer has its own pulse program. The usage of RapidArc or ForceArc process would commit shipyard to use welding machines only from a single manufacturer in solid wire applications. In any case usage of pulse MAG-processes and other MAG-processes require compilation of WPSs for each used process. A good feature in RapidArc and ForceArc processes is high tolerance for undercuts. RapidArc process is capable to high travel speeds although the precise adjustment of torch angle complicates the use of this process. The strengths of double pulse MAG-welding is easy multi pass welding and good position welding features. As it was previously said pulse MAG-welding has by far the most suitable features for production of shipyard, which is the reason why it is used in the additional experiments of this study. The main reasons which support the use of pulse MAG-welding is a possibility to achieve low porosity welds with relatively high travel speeds and the wide range of existing equipment manufacturers.

10.2 Results and discussion of additional experiments

In every part of additional experiments porosity could be reduced a lot from the starting point. In preselection welding tests porosity of pulse MAG-welding, in welding position PB with 4 mm throat thickness, was 15.7 % and with MAG-welding it was 32.9 % as it can be seen from figure 28. In figure 34 is shown effects of each improvement that was made to decrease porosity. Each of the additional experiments was carried out with pulse MAG-welding, except the CO_2 welding test which was carried out with MAG-welding. The used welding parameters are shown in appendix VI.

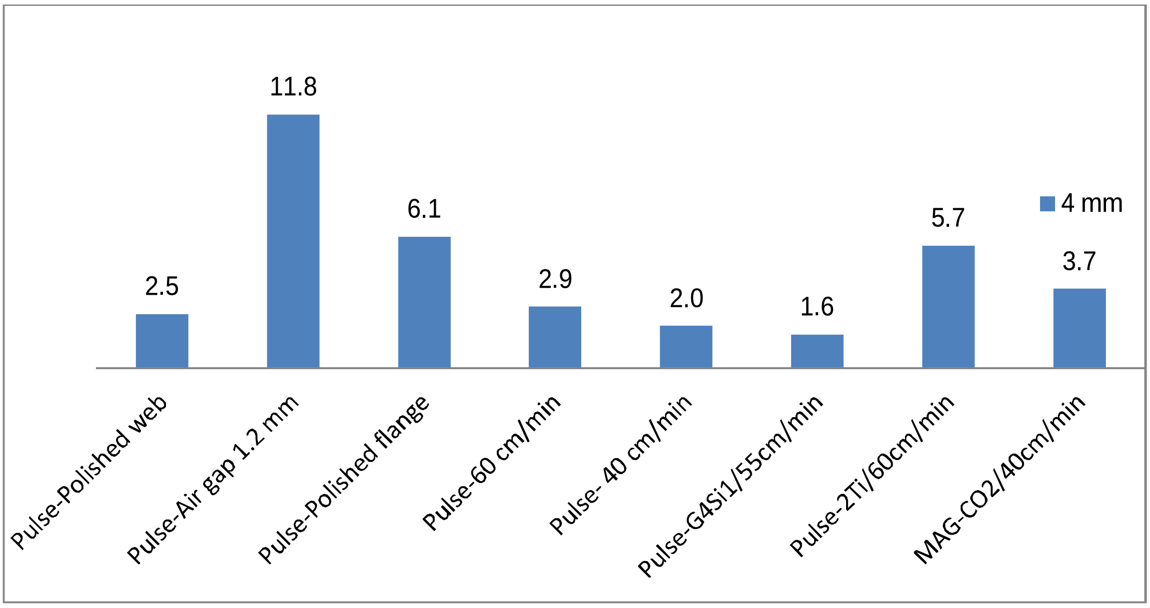

Figure 34. Porosity percentages (%) which were defined from test specimen which were welded in additional experiments.

It can be seen from figure 34 that none of the experiments could reduce porosity to the level which would allow to use the process in production of shipyard. In each case porosity remains over the limits of SFS-EN ISO 5817 quality level C. The lowest porosity value was achieved by using solid wire quality G4Si1 with 55 cm/min travel speed. This experiment decreased the porosity 89.8 % compared to obtained results from preselection welding tests. However end crater cracking existed few times with this wire product. It was also more difficult to achieve satisfying visual look of the weld with solid wire quality G4Si1 than it was with quality G3Si1. Low porosity welds were also achieved by using 40 cm/min and 60 cm/min travel speeds and solid wire quality G3Si1. If the results from these three welding test are compared, it can be seen that the usage of solid wire quality G4Si1 clearly reduces porosity. Also the decrease in travel speed reduces porosity.

The effect of paint removal can be seen from the results of welding tests which were made to test specimen with polished web and to test specimen with polished flange. It can be seen that polishing of web reduced porosity more than polishing of the flange. It was also tested that if both web and flange are polished no porosity will form regardless is the used process MAG-welding or pulse MAG-welding.

Contrary to expectations solid wire quality 2Ti managed porosity test worse than solid wire quality 3Si1. This may have been caused by the fact that there can be differences in the thickness of the primer layer. Also the results from air gap experiment were poor. The usage of air gap reduced porosity only 24.8 % which is the least significant improvement in additional experiments.

The MAG-welding test which was performed with CO_2 shielding gas had lower porosity percentage than what was achieved in preselection welding test. However these results cannot be compared because the CO_2 welding test was performed with 40 cm/min travel speed and preselection MAG-welding test for 4 mm throat thickness in welding position PB with 60 cm/min travel speed. However it can be assumed that the decrease in porosity is not entirely caused by the slower travel speed.

The porosity results in preselection welding tests were not fully comparable between different processes because used travel speeds were different. As the used travel speed in preselection test for MAG-welding with 4 mm throat thickness in position PB was 60 cm/min, comparison between pulse MAG-welding and MAG-welding can be made. Based on the fact that in the above mentioned situation porosity percentage was 32.9 % for MAG-welding and for pulse MAG-welding with 60 cm/min travel speed 2.9 %, it can be said that usage of pulse can decrease porosity 91 %. In table 36 are shown percentage changes of each improvement which were shown in figure 34.

Table 36. The effect of each change in additional experiments to porosity.

Experiment	Percentage change in porosity [%]
135 (pulse), G4Si1 solid wire, 55 cm/min	89.8
135 (pulse), 40 cm/min	87.3
135 (pulse), Polished web, 80 cm/min	84.1
135 (pulse), 60 cm/min	81.5
135 (pulse), 2Ti solid wire, 60 cm/min	63.7
135 (pulse), Polished flange	61.1
135 (pulse), Air gap 1.2 mm, 80 cm/min	24.8
135, CO_2, 40 cm/min	88.8 (Compared to MAG-welding with M21 shielding gas.)

In addition to porosity percentages, also diameters of the largest pores in each welding test of additional experiments were defined. The results of these measurements are shown in table 37. It can be seen from the results that the largest pore was result of the air gap test. As the porosity was also highest in air gap test, it can be assumed that high porosity and large pore diameter are dependent of each other. The smallest pores were result of the test with polished web and test with wire type G4Si1. The porosity was relatively low in these experiments, which supports the previously made statement of the relation between porosity and maximum pore diameter. Other five experiments produced pores with almost the same size.

Table 37. Diameters of largest pores in additional experiments.

Experiment	Diameter [mm]
135 (pulse), Polished web, 80 cm/min	1
135 (pulse), Air gap 1.2 mm, 80 cm/min	4.1
135 (pulse), Polished flange, 80 cm/min	2
135 (pulse), 60 cm/min	2.2
135 (pulse), 40 cm/min	2
135 (pulse), G4Si1 solid wire, 55 cm/min	1.5
135 (pulse), 2Ti solid wire, 60 cm/min	2
135, CO_2, 40 cm/min	2

10.3 Evaluation of costs and productivity with chosen method

In this chapter is represented evaluation of the productivity and costs with the chosen solid wire MAG-process compared to tubular wire process used at the Meyer Turku shipyard. As it was earlier shown pulse MAG-welding is capable to achieve high travel speeds and deposition rates in welding position PB. In this chapter pulse MAG-welding and metal cored arc welding are compared in case where used welding position is PB and throat thickness is 4 mm. As it was told earlier usage of solid wire processes in current production of shipyard would demand primer removal from surfaces which are to be welded. In this situation productivity and cost-efficiency of pulse MAG-welding compared to metal cored arc welding depends on time and costs which are caused by primer removal. In table 38 is shown the initial data which is used for comparison of the processes. In following evaluations duty cycle of welding is 100 % in both cases. In addition to information in table 38 labor costs are calculated based on labor cost of an hour which is typical for Meyer Turku shipyard. The same labor costs are used for both welding processes. In case of pulse MAG-welding milling costs and abrasive blasting costs are estimated to meet the cost level which would be realistic in Meyer Turku shipyard.

Table 38. Initial data for process comparison in welding position PB and with 4 mm throat thickness.

Variable	Pulse MAG-welding	MCAW
Shielding gas consumption	18 l/min	18 l/min
Welding wire cost factor	1	1.61
Travel speed	80 cm/min	55 cm/min
Burn-off rate	6.92 kg/h	5.33 kg/h

If the process comparison is made based on the data in table 38 the total estimated costs of pulse MAG-welding are 22.2 % lower than costs of metal cored arc welding in this individual situation. The total manufacturing time is 18.9 % lower in pulse MAG-welding than in metal cored arc welding. This comparison is based on the costs and time factors which are formed to describe total costs and total working time resulting from manufacturing of one meter of finished weld. In metal cored arc welding manufacturing time consists of welding time and manufacturing costs consists of labor costs of welder, shielding gas costs and welding wire costs. In pulse MAG-welding manufacturing time consists of machining time, abrasive blasting time and welding time. Manufacturing costs in pulse MAG-welding consists of labor costs, welding wire costs, shielding gas costs and milling costs. Labor costs in pulse MAG-welding consists of machinist's, abrasive blasting operator's and welder's labor costs. Milling costs consists only from price of milling cutters and abrasive blasting costs consists only of labor costs of operator. This evaluation gives very rough estimate of costs and productivity differences between pulse MAG-welding and metal cored arc welding. However it can be said that if the product which is to be welded contains many long fillet welds which are easy to mechanize and primer removal can be performed effectively enough, usage of pulse MAG-welding in shipyard for fillet welds in welding position PB can be cost efficient and productive. In figures 35 and 36 are shown the estimated cost distribution between these two processes.

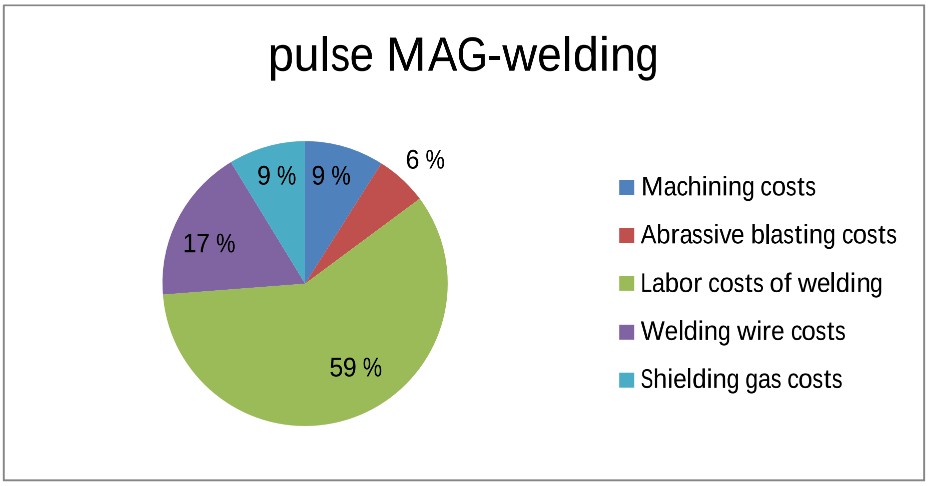

Figure 35. Evaluated costs distribution in pulse MAG-welding.

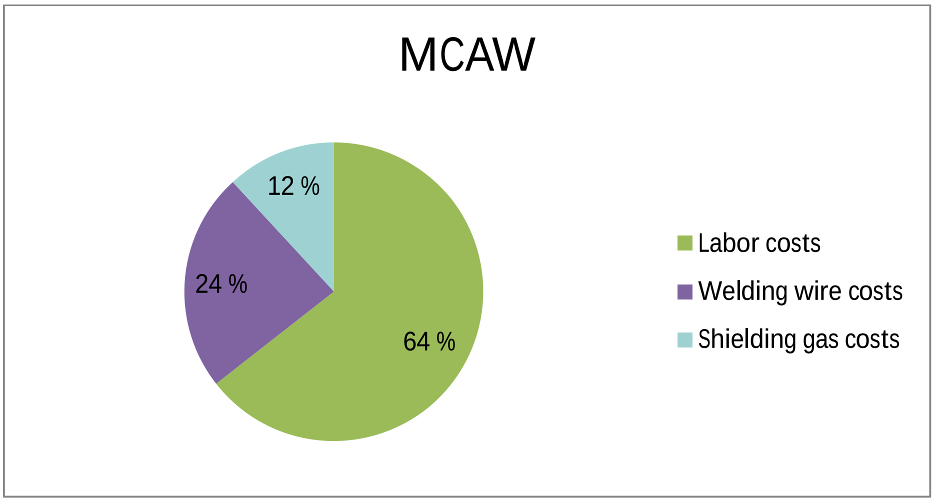

Figure 36. Evaluated costs distribution in metal cored arc welding.

11 CONCLUSIONS

This study concentrated to examine possibilities to use solid welding wire productively for fillet welds in production of Meyer Turku shipyard. Welding tests were made with five different solid wire welding processes to primed and tack welded steel products. Based on the results following conclusions can be made.

It was found that none of the examined processes could produce porosity free welds in all studied welding positions and with all studied throat thicknesses. Porosity percentages varied a lot depending of used welding position and throat thickness. As it has been earlier studied, it was also shown in this study that usage of pulse decreases porosity in MAG-welding. Results of this study showed that by decreasing the used travel speed, increasing alloying elements of welding wire and by partial removal of primer porosity can be greatly decreased. However the usage of solid wire MAG-processes, with currently at the shipyard used primer product and layer thickness, would demand complete primer removal from welded surfaces to ensure demanded quality of welds.

Each of the examined welding processes was able to over weld tack welds acceptably in welding positions PB and PG. Imperfections occurred in welding position PD with each of the studied processes. Differences between different processes were more clearly visible with 3 mm throat thickness than they were with 4 mm and 6 mm throat thicknesses. With 4 mm and 6 mm throat thicknesses each of the processes managed to over weld tack welds acceptably in welding position PB and PG. As the case was in porosity results, also high variance occurred in the results of over welding of tack welds. It was not possible to make clear conclusions of the superiority between the examined processes based on measurements. The difference in the superiority between processes was easier to define by visual inspections. By the visual inspections MAG-welding and pulse MAG-welding were the most successful processes in over welding of tack welds. RapidArc and ForceArc processes, which have narrow electric arc, managed over welding of tack welds worst with throat thicknesses used in this study.

The studied advanced solid wire MAG-welding processes are capable to achieve higher deposition rates than conventional MAG-welding. Pulse MAG, double pulse MAG and RapidArc processes are also capable to higher burn-off rates and travel speeds in welding position PB than what is the current way of working at shipyard with tubular wires. Despite the fact that usage of solid wire MAG-processes requires removing of primer, the usage of these processes in welding position PB can be still economical and productive depending on how effectively primer removal can be performed. In welding positions PD and PG deposition rates of solid wire processes are significantly lower than deposition rates of tubular wire processes of the shipyard and there for the usage of current tubular wire processes is appropriate. It can be stated briefly that solid welding wire can be used productively and cost efficiently for fillet welds in welding position PB in production of Meyer Turku shipyard if surfaces which are to be welded can be cleaned efficiently from primer before welding.

12 FURTHER STUDIES

During this study several issues arose which would require a more detailed examination. Based on the observations and results made in this study following topics can be mentioned as area of further research:

1. Effect of Pulse parameters to welding of primed steel products.

2. Effect of different primer types to porosity.

3. Relation between porosity and size of the air gap.

4. Effective methods to remove primer from surfaces which are to be welded.

13 SUMMARY

This master's thesis was carried out for Meyer Turku shipyard to investigate utilization of solid welding wire in production of the shipyard. Possibilities of five different solid wire MAG-welding processes were studied in welding experiments of this study. Studied processes were MAG-welding, pulse MAG-welding, double pulse MAG-welding, RapidArc and ForceArc. The aim was to find out if it is possible to increase productivity and to achieve demanded quality with these solid wire processes when steel products, which are to be welded, are primed and tack welded.

For this study large number of welding experiments was carried out to find out the produced porosity levels with five above mentioned MAG-welding processes and also abilities of studied processes to over weld tack welds. Processes were studied in welding positions PB, PD and PG with throat thicknesses 3 mm, 4 mm and 6 mm. The best suited process for production of the shipyard was chosen and additional experiments were performed with this process to find out ways to reduce porosity.

Based on this study it can be said that none of the studied MAG-welding processes fulfils the requirements, in all studied welding positions and throat thicknesses, which are set for porosity in quality level C. Usage of studied processes is possible at Meyer Turku shipyard if primer is removed from surfaces which are to be welded. Reasonable use of studied MAG-welding processes would be mechanized welding of fillet welds in welding position PB. In itself double pulse MAG-welding, pulse MAG-welding and RapidArc processes are more productive with searched parameters in welding position PB than currently at the shipyard used tubular wire processes. Cost-efficiency and productivity of usage of the studied processes in shipyard depends on how efficiently primer removal can be performed. Studied advanced MAG-welding processes are not able to reduce interferences which are caused by over welding of tack welds. However all studied processes managed over welding of tack welds in welding position PB and only few tests welds failed in welding position PG. Pulse MAG-welding turned out to be the best suited process for production of the shipyard.

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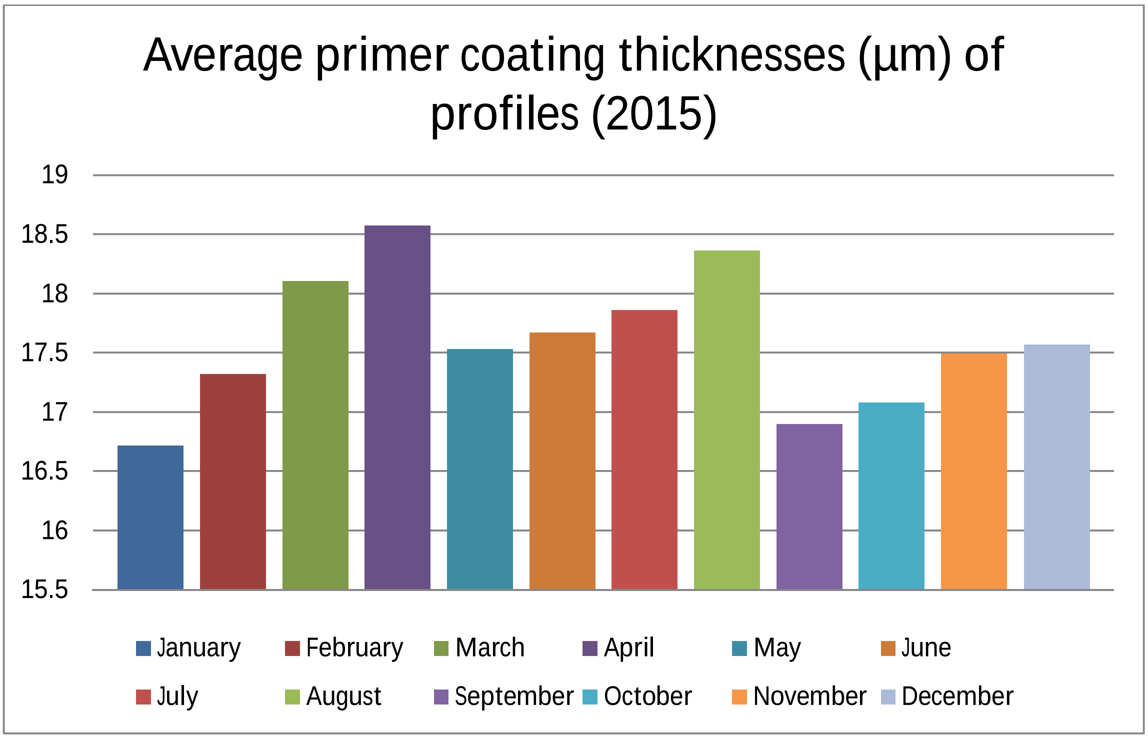
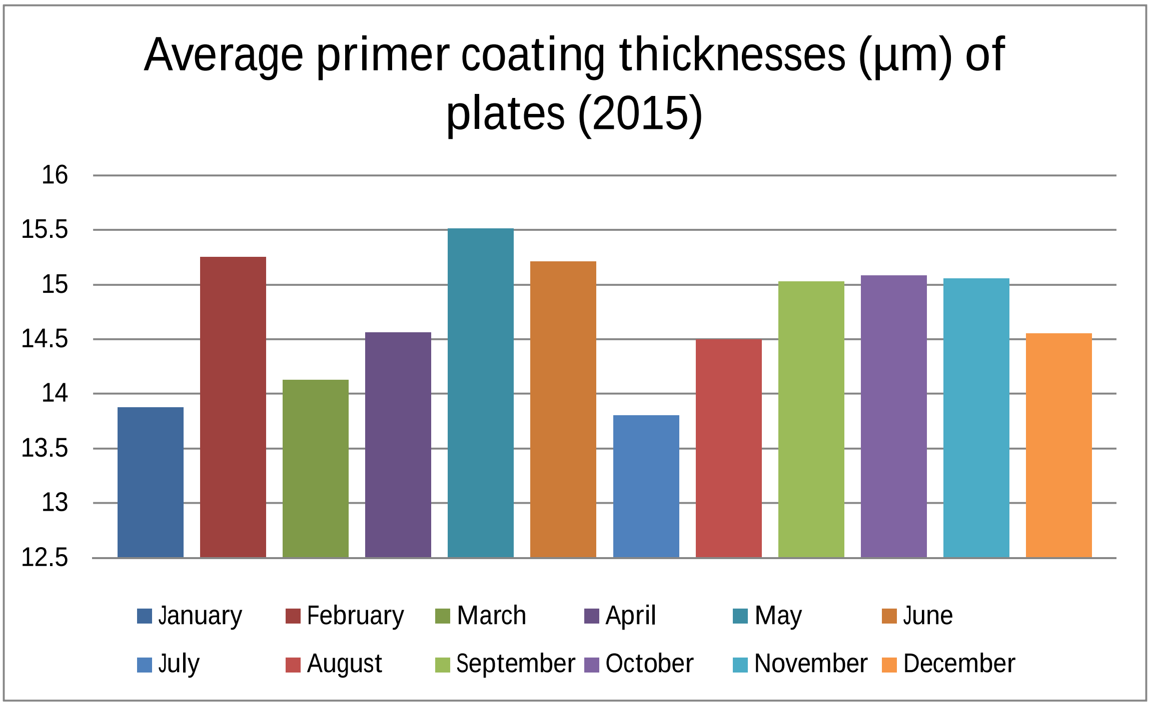
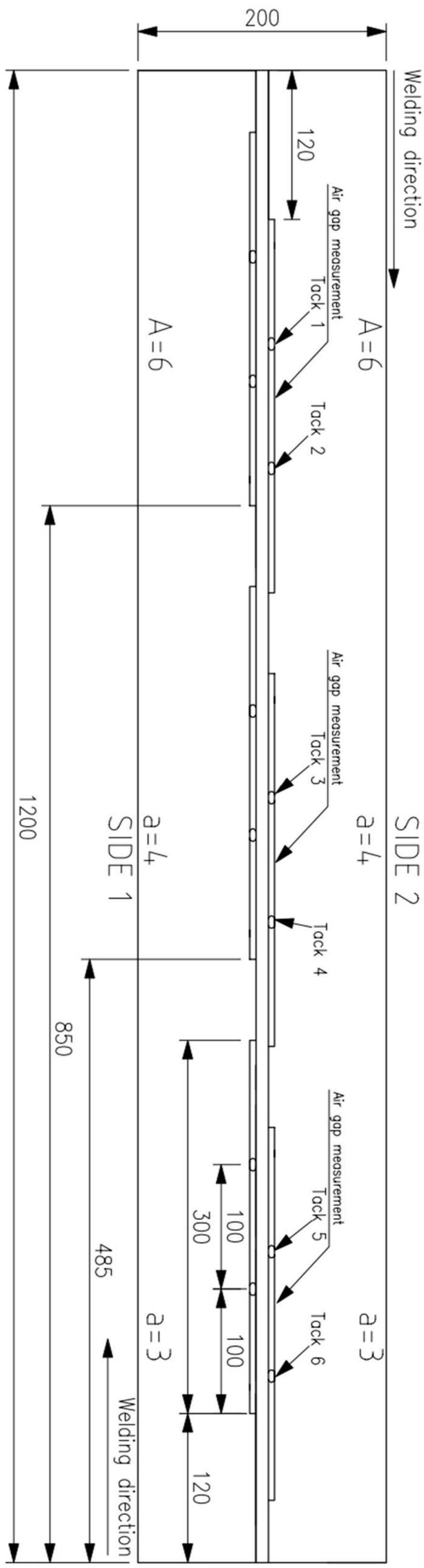
Primer coating thickness statistics.





Drawing of test specimen.



Throat thicknesses of tack welds.

PB					
Throat thickness	Process number	Side 1 [mm]		Side 2 [mm]	
3	1	3.1	3	2.2	2.9
3	2	3	3	2.9	2.5
3	3	2.8	2.6	3	2.3
3	4	2.9	3.1	2.5	2.9
3	5	3	2.9	3.1	2.9
4	1	4	3	2.9	2.5
4	2	2.9	2.9	2.9	2.9
4	3	3	3	3.3	3
4	4	3	3	3	3
4	5	3	4	2.9	2.4
6	1	3.2	3.5	3	2.9
6	2	2.9	2.8	3	3
6	3	3	3.8	3.5	2.9
6	4	3.1	2.9	2.5	3
6	5	3	3.1	3	2.9

Throat thicknesses of tack welds.

PD					
Throat thickness	Process number	Side 1 [mm]		Side 2 [mm]	
3	1	3	3	3.6	3.1
3	2	3.9	3.2	3.2	3.1
3	3	2.6	2.2	3	3
3	4	2.9	3.1	3.1	3
3	5	3	2.9	3.5	3.5
4	1	3.5	3	3.2	2.9
4	2	3.4	2.9	3.1	3.4
4	3	2.1	3	3	3
4	4	4.1	2.5	3.1	3.1
4	5	2.5	3.1	3.9	3.1
6	1	2.5	3	3.1	3.5
6	2	3.5	2.6	3.9	3.5
6	3	2.9	2.9	3.1	3.9
6	4	2.1	3	3	3.5
6	5	3	2.5	3.2	3.1

Throat thicknesses of tack welds.

PG					
Throat thickness	Process number	Side 1 [mm]		Side 2 [mm]	
3	1	3	2.5	2.5	2.5
3	2	3.1	3	2.1	5
3	3	3.5	3	3.1	3.5
3	4	3	3.5	3	3.6
3	5	3	3.1	3	3.1
4	1	2.5	3.9	3.1	3.1
4	2	3.5	3.5	3.5	3
4	3	3.1	3	3.1	3.1
4	4	3.5	4	3	3.1
4	5	3	3.1	3.1	3.1
6	1	2	3.6	2	3.9
6	2	4.1	3	3.6	3.1
6	3	3.6	3.8	3	3.5
6	4	3	3	3	3.5
6	5	3.6	3.6	2.5	3.1

Lengths of tack welds.

PB					
Throat thickness	Process number	Side 1 [mm]		Side 2 [mm]	
3	1	19	17	20	19
3	2	18	21.5	19.2	19
3	3	17	20	12	18.5
3	4	17	17	19.2	24.2
3	5	21	20	16	25
4	1	24	23	21	17.5
4	2	19	15.5	19.1	18
4	3	21.6	18	19	17
4	4	20.5	18	20.2	19.2
4	5	22	18	21	13
6	1	23.5	25	15	17
6	2	18.1	22	20.9	22
6	3	24.8	16	18.9	15
6	4	16.5	19.1	18.5	18.2
6	5	18	17.9	18	24

Lengths of tack welds.

PD					
Throat thickness	Process number	Side 1 [mm]		Side 2 [mm]	
3	1	16.3	21.8	21.8	21.3
3	2	22.7	29.7	15.5	15.6
3	3	16.7	19.4	20.5	26.8
3	4	19.7	19.1	15.6	15.5
3	5	17.9	21.2	19	21.6
4	1	24.5	26	21.9	28.4
4	2	18.7	16.8	19.4	16.6
4	3	20.3	18.5	22.1	24.7
4	4	25.6	24	19.9	22.3
4	5	23	20.8	20.6	23.2
6	1	20	22.3	21.5	25
6	2	16.7	21.8	26.9	25.4
6	3	21.7	20.3	29.8	17.7
6	4	19.6	21.4	25.4	20.2
6	5	17.5	23.7	19.5	22.1

Lengths of tack welds.

PG					
Throat thickness	Process number	Side 1 [mm]		Side 2 [mm]	
3	1	15	16.5	20.3	17.15
3	2	18	22.7	20.8	19.3
3	3	14,2	12.2	22.3	21.7
3	4	17,6	15.5	16.7	18.1
3	5	24	14.7	18	19.4
4	1	17,3	14	15.7	18.1
4	2	15,6	17	17.5	20.4
4	3	17,6	19.7	16.6	22.5
4	4	15,2	16.5	14.7	16.2
4	5	14,9	13.8	17.4	20.3
6	1	21,8	21.5	18.6	18.9
6	2	20,8	17	20	21.6
6	3	16,1	20	17.5	18
6	4	21,3	22.5	20.6	19.4
6	5	13,3	20.8	19.7	14.5

Pulse parameters.

Preselection					
Process number	Position	Throat [mm]	Frequency [Hz]	Ip [A]	Ib [A]
2	PB	3	211	450	150
2	PB	4	267	450	200
2	PB	6	211	450	150
2	PB	6	211	450	150
2	PB	6	211	450	150
3	PB	3	175	445	130
3	PB	4	220	480	165
3	PB	6	175	445	130
3	PB	6	175	445	130
3	PB	6	175	445	130
4	PB	3	200	540	60
4	PB	4	250	540	80
4	PB	6	200	540	60
4	PB	6	200	540	60
4	PB	6	200	540	60

Preselection					
Process number	Position	Throat [mm]	Frequency [Hz]	Ip [A]	Ib [A]
2	PD	3	84	430	50
2	PD	4	138	450	100
2	PD	6	84	430	50
2	PD	6	84	430	50
2	PD	6	106	430	100
3	PD	3	110	425	110
3	PD	4	140	434	100
3	PD	6	110	425	110
3	PD	6	110	425	110
3	PD	6	140	434	100
4	PD	3	127	480	20
4	PD	4	133	480	20
4	PD	6	127	480	20
4	PD	6	133	480	20
4	PD	6	133	480	20

Pulse parameters.

Preselection					
Process	Position	Throat [mm]	Frequency [Hz]	Ip [A]	Ib [A]
2	PG	3	100	420	75
2	PG	4	116	410	75
2	PG	6	100	420	75
2	PG	6	100	420	75
2	PG	6	116	410	75
3	PG	3	119	428	79
3	PG	4	152	438	110
3	PG	6	119	428	79
3	PG	6	119	428	79
3	PG	6	152	438	110
4	PG	3	166	510	20
4	PG	4	145	500	20
4	PG	6	166	510	20
4	PG	6	166	510	20
4	PG	6	145	500	20

Additional experiments					
Experiment	Position	Throat [mm]	Frequency [Hz]	Ip [A]	Ib [A]
60 cm/min	PB	4	-	-	-
40 cm/min	PB	4	-	-	-
G4Si1-wire	PB	4	-	-	-
polished flange	PB	4	267 Hz	450	200
polished web	PB	4	267 Hz	450	200
air gap 1,2mm	PB	4	267 Hz	450	200
2Ti-wire	PB	4	-	-	-

Welding parameters of additional tests.

Additional experiment	Wire feed [m/min]	Current [A]	Voltage [V]	Travel speed [cm/min]
Polished web (pulse MAG-welding)	13	-	-	80
Air gap 1.2 mm (pulse MAG-welding)	13	-	-	80
Polished flange (pulse MAG-welding)	13	-	-	80
60 cm/min (pulse MAG-welding)	9	263	27.7	60
40 cm/min (pulse MAG-welding)	6.5	189	27.2	40
G4Si1-wire (pulse MAG-welding)	9	-	-	55
2Ti-wire (pulse MAG-welding)	17	283	32.2	60
CO_2 (MAG-welding)	9	266	28.5	40

Welding parameters of preselection tests.

3 mm Throat thickness, welding position PB							
Process number	Side 1				Side 2		Avg.throat [mm]
	Wire feed [m/min]	Current [A]	Voltage [V]	Speed [cm/min]	Current [A]	Voltage [V]	
1	8.8	338	31.3	75	305	29.1	3
2	10	268	29.7	80	275	29.5	3.4
3	8	239.3	24.4	72	237.3	24.5	3.1
4	10	239	26.1	80	228	26.5	3.2
5	8.8	271	25.2	65	254	22.1	3.4

4 mm Throat thickness, welding position PB							
Process number	Side 1				Side 2		Avg.throat [mm]
	Wire feed [m/min]	Current [A]	Voltage [V]	Speed [cm/min]	Current [A]	Voltage [V]	
1	9	325	30.2	60	290	30.1	4
2	13	331	31.7	80	329	32	4.1
3	11	312.3	27.7	72	311	27.9	4
4	11.5	270	26.8	65	269	26.9	4
5	11	325	28.5	70	320	28.5	4
6	11	307	28.6	55	309	28.6	4.3
7	10.5	243	26.6	39	249	26.7	4.6

Welding parameters of preselection tests.

6 mm Throat thickness, welding position PB							
Process number/pass	Side 1				Side 2		Avg.throat [mm]
	Wire feed [m/min]	Current [A]	Voltage [V]	Speed [cm/min]	Current [A]	Voltage [V]	
1/ 1.pass	8.8	310	24.8	75	305	27.9	
1/ 2.pass	8.8	305	29.1	69	302	27.7	
1/ 3.pass	8.8	307	31	65	290	27.7	6
2/ 1.pass	10	266	39.7	80	289	29.9	
2/ 2.pass	10	258	30	79	253	29.9	
2/ 3.pass	10	225	30.1	72	226	29.8	6.1
3/ 1.pass	8	255	28.7	72	233	25.3	
3/ 2.pass	8	233.9	25.1	66	246	23.5	
3/ 3.pass	8	234	25	66	243	23.9	6.0
4/ 1.pass	10	235	24.9	80	238	26.1	
4/ 2.pass	10	224	26.3	74	218	26.5	
4/ 3.pass	10	194	29.4	74	229	26.4	6.0
5/ 1.pass	8.8	270	25.2	67	263	21.6	
5/ 2.pass	8.8	280	21	62	260	22.8	
5/ 3.pass	8.8	265	22.1	58	265	21.9	6.1

Welding parameters of preselection tests.

3 mm Throat thickness, welding position PD						
Process number	Side 1				Side 2	
	Wire feed [m/min]	Current [A]	Voltage [V]	Speed [cm/min]	Current [A]	Voltage [V]
1	5	196	22.7	41	188	23.24
2	4.5	135	22.1	40	133	22.3
3	5	150	23.3	50	136	22.5
4	6	152	23.7	48	146	23.2
5	6	234	28.8	48	208	24.9

4 mm Throat thickness, welding position PD						
Process number	Side 1				Side 2	
	Wire feed [m/min]	Current [A]	Voltage [V]	Speed [cm/min]	Current [A]	Voltage [V]
1	5	196	22.7	29	187	22.7
2	6.5	189	25.2	40	192	25.1
3	6.5	196	24.5	40	200	24.2
4	7	179	25.1	42	180	24.9
5	6.3	215	24.6	34	213.3	24.8

Welding parameters of preselection tests.

6 mm Throat thickness, welding position PD							
	Side 1				Side 2		Avg.throat [mm]
Process number/pass	Wire feed [m/min]	Current [A]	Voltage [V]	Speed [cm/min]	Current [A]	Voltage [V]	
1/ 1.pass	5	204	22.7	41	194	22.7	
1/ 2.pass	5	193.7	22.6	41	184	22.8	
1/ 3.pass	5	191.6	22.6	29	188	22.7	6.3
2/ 1.pass	4.5	138	22.1	40	137	22.2	
2/ 2.pass	4.5	131	22.4	40	132	22.3	
2/ 3.pass	5.7	164	23.8	40	162	24	6.0
3/ 1.pass	5	150	23	50	147	23.4	
3/ 2.pass	5	151	22.8	50	156	22.3	
3/ 3.pass	6.5	200	24.5	40	193	24.9	5.8
4/ 1.pass	6	151	23.4	48	148	23.6	
4/ 2.pass	7	169	24	55	169	23.7	
4/ 3.pass	7	162	23.8	50	167	24	6.0
5/ 1.pass	6	209	24.8	48	210	23.9	
5/ 2.pass	6	206	23.6	48	208	22.8	
5/ 3.pass	6.3	202	24.2	34	211.5	23.3	6.2

Welding parameters of preselection tests.

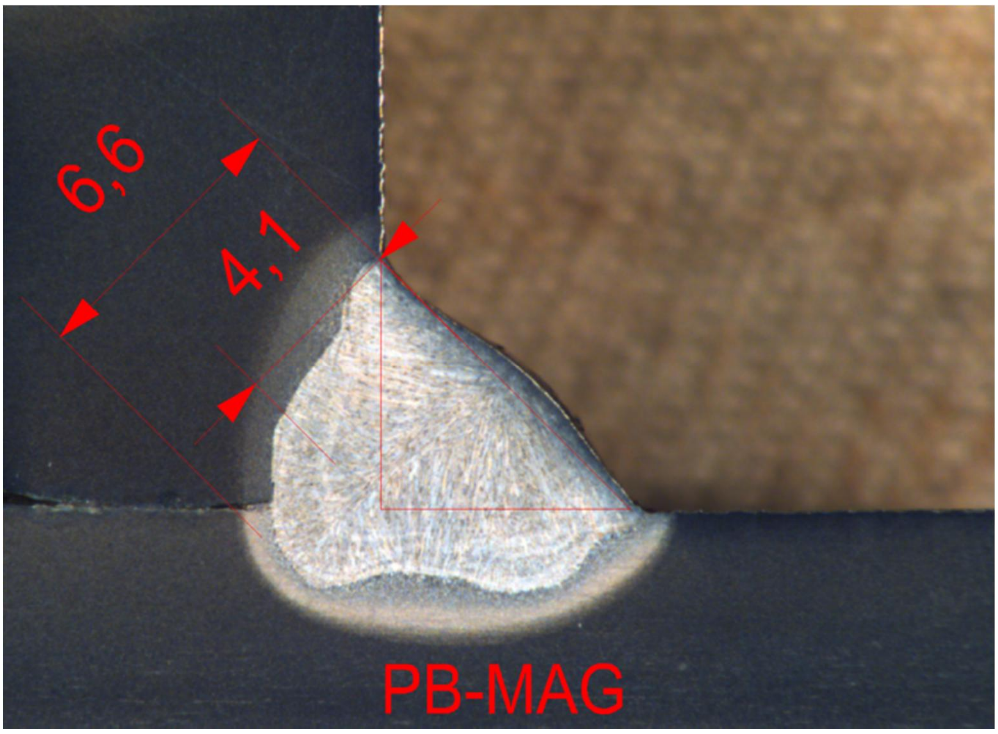
3 mm Throat thickness, welding position PG							
Process number	Side 1				Side 2		Avg.throat [mm]
	Wire feed [m/min]	Current [A]	Voltage [V]	Speed [cm/min]	Current [A]	Voltage [V]	
1	6	198	21.2	43	204	21.1	2.8
2	6.5	190	21.7	40	201	21.3	3
3	5.5	190	21	45	183	21.8	3.5
4	8	207	21.7	55	220	22	3
5	6.5	225	17.8	35	245	17	3.3

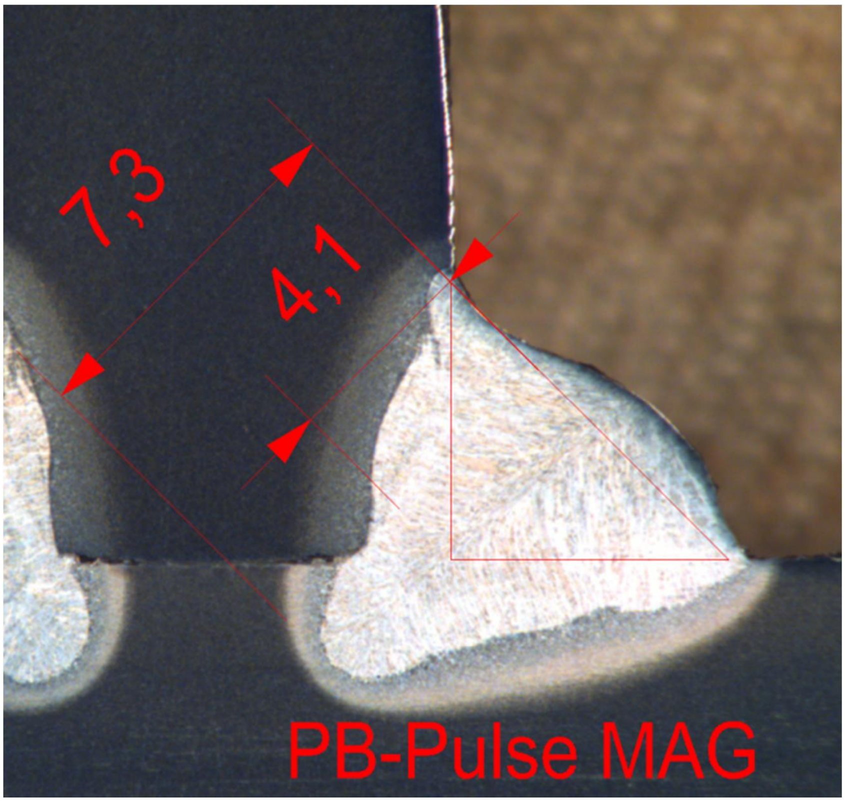
4 mm Throat thickness, welding position PG							
Process number	Side 1				Side 2		Avg.throat [mm]
	Wire feed [m/min]	Current [A]	Voltage [V]	Speed [cm/min]	Current [A]	Voltage [V]	
1	8	252	26.1	43	252	25.5	4
2	8	258	21.8	40	247	22.8	4
3	7	226	22.5	40	230	22.1	4.1
4	9	238	22.1	48	237	23.9	3.4
5	9	330	15.4	35	319	16.5	3.9

Welding parameters of preselection tests.

6 mm Throat thickness, welding position PG							
	Side 1				Side 2		Avg.throat [mm]
Process number/pass	Wire feed [m/min]	Current [A]	Voltage [V]	Speed [cm/min]	Current [A]	Voltage [V]	
1/ 1.pass	6	206	21.2	43	205	21.1	
1/ 2.pass	6	226	21.2	43	186	21.5	
1/ 3.pass	8	272	25.4	43	245	25.7	6.5
2/ 1.pass	6.5	189	21.6	40	207	22	
2/ 2.pass	6.5	190	21.6	40	202	21.9	
2/ 3.pass	8	258	21.8	40	239	22.8	6.5
3/ 1.pass	5.5	191	20.9	45	181	21.5	
3/ 2.pass	5.5	187	21.3	45	182	21.6	
3/ 3.pass	7	227	22.3	40	235	21.9	6.3
4/ 1.pass	8	219	23.8	55	215	21.7	
4/ 2.pass	8	230	22.1	55	225	22	
4/ 3.pass	9	238	22.1	48	258	23.4	6.1
5/ 1.pass	6.5	251	16.8	35	230	17.5	
5/ 2.pass	6.5	240	17	35	260	16	
5/ 3.pass	9	281	22.5	35	337	16.2	6.6

Macrographs.





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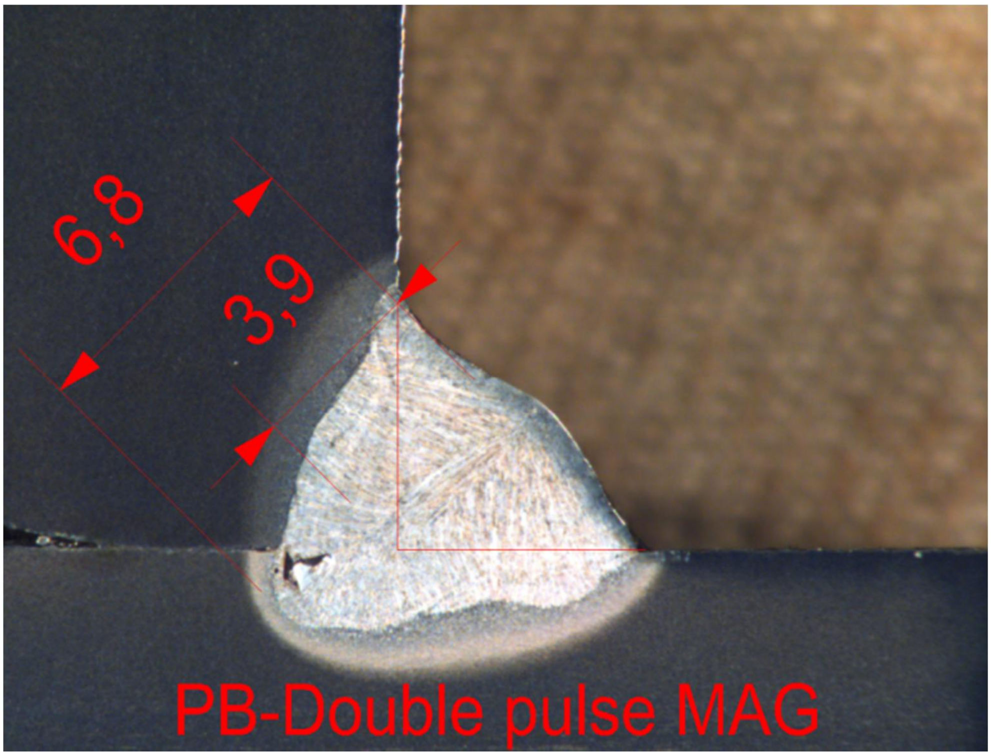

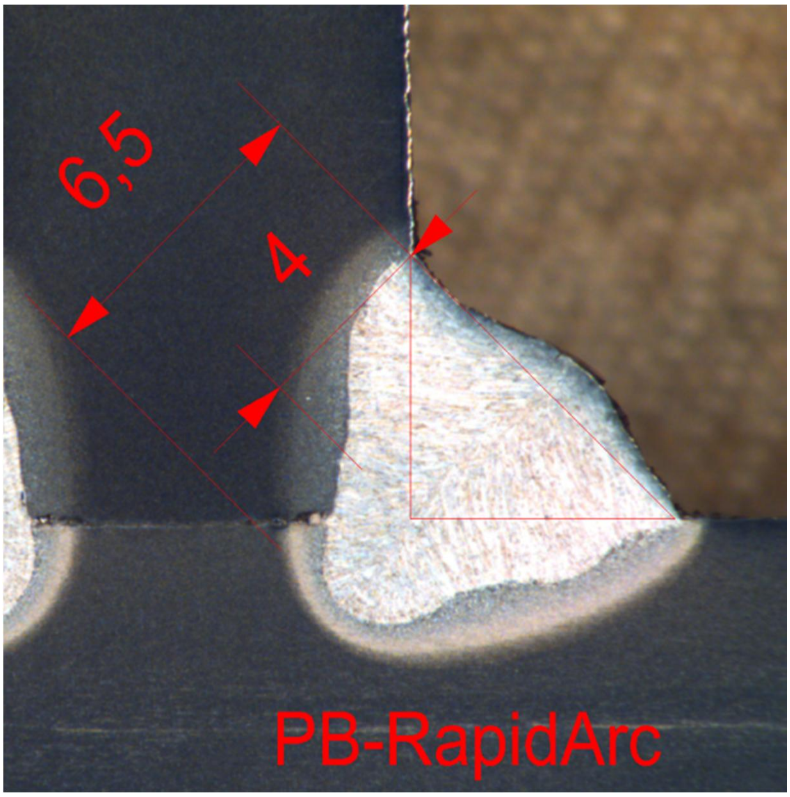

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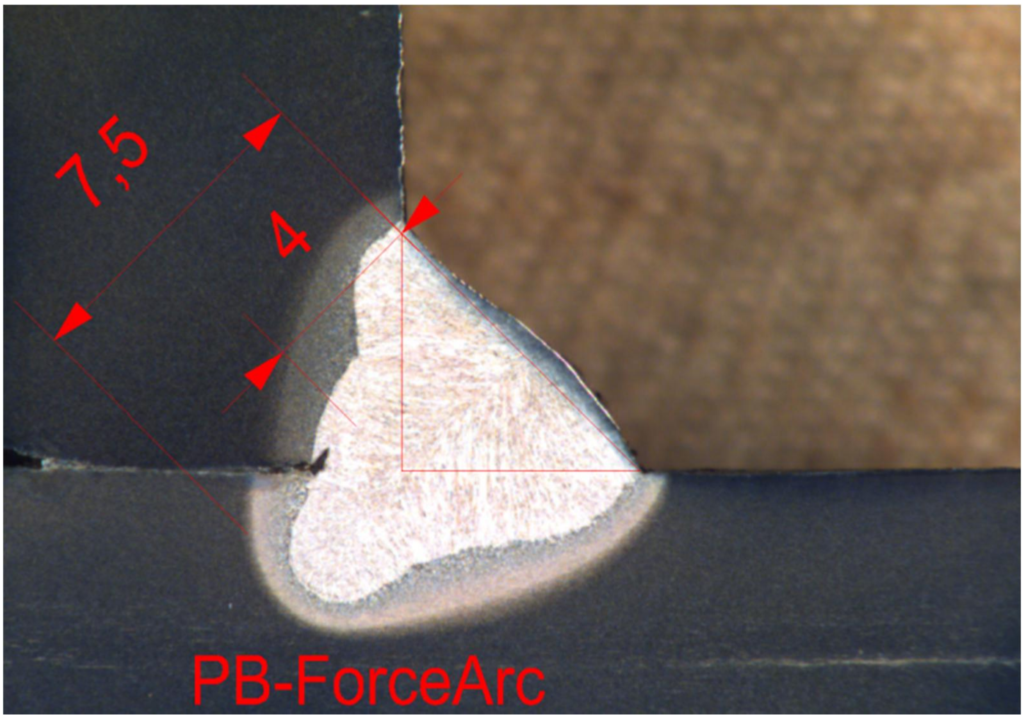

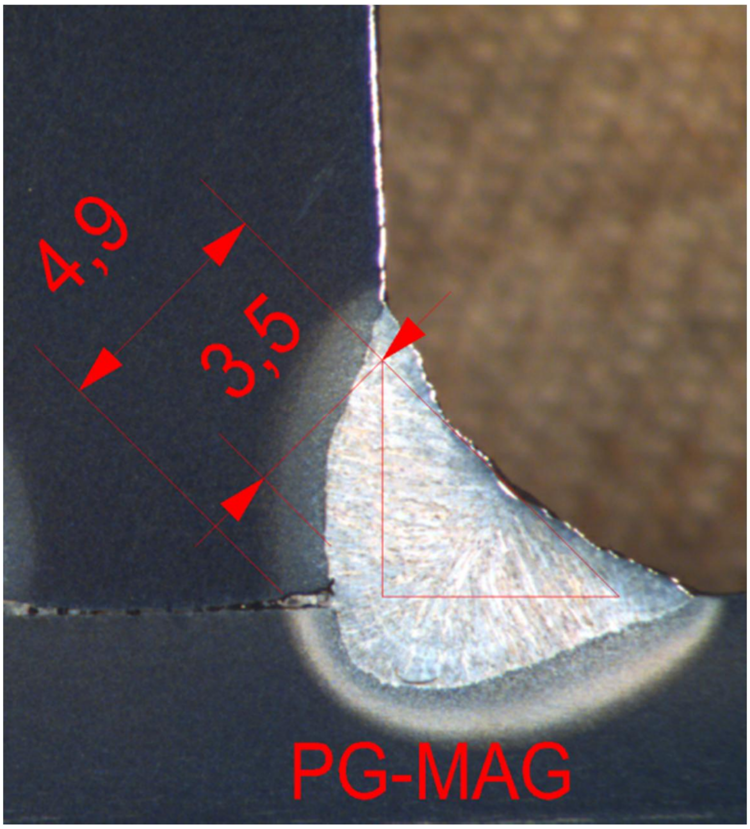

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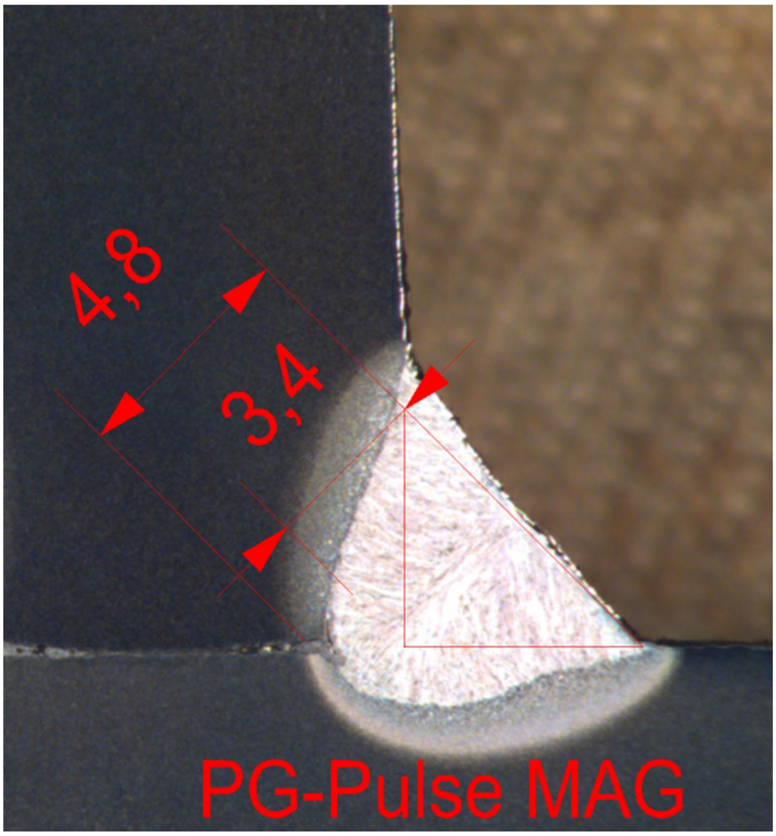

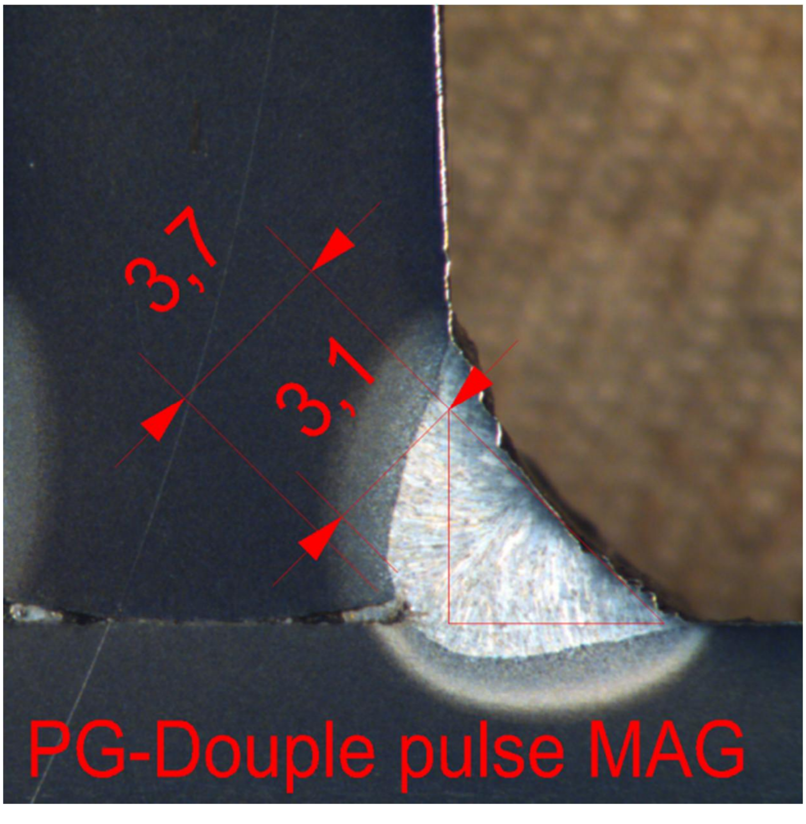

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