LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
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TANDEM-MAG-WELDING OF HIGH STRENGTH STEELS FOR SHIPBUILDING APPLICATIONS

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TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
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Tandem-MAG-Welding of high strength steels used in shipbuilding

Diplomityö

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Keywords: Tandem MAG welding, Narrow gap welding, TMCP, High strength steels, Multipass welding, Heat input

Tämän työn tavoitteena oli hitsata tandem MAG –laitteistolla 25 mm paksua Ruukin E500 TMCP terästä. Työssä oli tarkoituksena vähentää railotilavuutta mahdollisimman paljon sekä suorittaa testihitsaukset 0.8 kJ/mm sekä 2.5 kJ/mm lämmöntuonneilla.
Teoriaosuudessa käsiteltiin Tandem MAG-hitsaukseen, sen tuottavuuteen ja laatukysymyksiin liittyviä asioita sekä siinä perehdyttiin suurlujuusteräksien käyttöön hitsauksessa sekä laivanrakennuksessa.

Kokeellisessa osuudessa perehdyttiin hitsauksessa huomattuihin etuihin, ongelmiin sekä ongelmien ratkaisumahdollisuuksiin. Hitsausliitoksen mekaaniset ominaisuudet tutkittiin rikkomattomin sekä rikkovin menetelmin. Alustavat hitsausohjeet luotiin kummallekin lämmöntuonnille.

Testaukset aloitettiin 30 º railokulmalla pienentäen kulmaa mahdollisuuksien mukaan. Testauksissa ei saatu hitsattua onnistuneesti alle 30 º railokulmalla. Hitsaustestien aikana huomattiin magneettisen puhalluksen vaikutus hitsaustapahtumaan. Kaasunvirtausnopeuden tuli olla tietyn suuruinen jotta palkokerrokset onnistuivat ilman huokoisuusongelmaa. Pienemmällä lämmöntuonnilla hitsattaessa kaasunvirtausnopeudet olivat tärkeämpiä hitsatessa ylempiä palkokerroksia. Kääntämällä hitsauspoltinta sivuttaissuunnassa 7-10 astetta auttoi ehkäisemään reunahaavan syntymistä. Rikkovista menetelmistä testitulokset olivat hyväksyttyjä kaikkien muiden paitsi päittäishitsin sivutaivutuskokeen osalta.

ABSTRACT

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Tandem-MAG-Welding of high strength steels used in shipbuilding

Master’s thesis

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92 pages, 62 figures, 12 tables and 10 appendices.

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Keywords: Tandem MAG welding, Narrow gap welding, TMCP, High strength steels, Multipass welding, Heat input

The aim of the study was to weld 25 mm thick Ruukki offshore steel E500 TCMP with tandem MAG. The air gap and volume of the single-V butt weld was as small as possible while using around 0.8kJ/mm and 2.5 kJ/mm heat input.

In theoretical part of this Master’s thesis tandem MAG welding, productivity of it and quality aspects in it were discussed. Also aspects of using high strength steels in welding and in shipbuilding were concentrated on.

The experimental part focused on benefits, problems and ways to lessen or counter these problems in welding procedure. Mechanical properties of welded joints were examined by non-destructive and destructive testing. Preliminary welding procedure specification (pWPS) was created.

The testing was started with groove angle of 30º and less. During testing welding was not successful for welds done with groove angle of less than 30º. Based on the results observed in welding tests, magnetic arc blow affects the quality on tandem MAG welding. Gas flow rate must be enough to prevent porosity on upper bead layers and it is of more importance while welding with lower heat input. By turning the tandem welding head on its axis by 7-10 degrees helps to prevent undercutting. All welds passed destructive testing, except for transverse bend test.

ALKUSANAT

Diplomityön löytämisen jälkeen taival näiden sanojen kirjoittamiseen on ollut antoisa. Tahdonkin kiittää alkusanoissa henkilöitä, jotka ovat olleet tärkeänä osana tämän työn valmistumisen kannalta.

Aluksi haluaisin kiittää yliopiston henkilökunnan jäseniä, jotka auttoivat suuresti erinäköisissä ongelmissa työn aikana. Kiitokset työn tarkastajille Jukka Martikaiselle ja Markku Piriselle neuvoista ja ohjauksesta työn aikana. Harri Rötkö, Esa Hiltunen sekä kaikki muut, jotka olivat mukana ratkomassa päivittäisiä pulmia hitsausarvojeni kanssa ansaitsevat erityiskiitokset.

Suuret kiitokset kuuluvat myös vanhemmilleni sekä siskolleni, jotka jaksoivat kuunnella selityksiäni kursseistani sekä pulteista ja muttereista näinkin monta vuotta. Erityiskiitokset Helille kun jaksoit kuunnella diplomityöasioitani gradusi ohessa. Kiitokset tiiviille kaveriporukalleni antoisista opiskeluvuosista.

Lappeenrannassa 20.4.2015

Ville Sandell

CONTENTS

SYMBOLS AND ABBREVIATIONS

ºC	Degree Celsius, unit of measurement for temperature
A	Elongation [%]
ABS	American Bureau of Shipping
Al	Aluminium
AR	Argon
B	Boron
BM	Base material
BV	Bureau Veritas
C	Carbon
CCS	Croatian Register of Shipping
CO_2	Carbon dioxide
Cr	Chromium
CTWD	Contact tip to work distance
Cu	Copper
DNV GL	Det Norske Veritas Germanischer Lloyd
DQ	Direct quenching
E	Heat input [kJ/mm]
E	Impact energy, [J]
E_{pr}	crack propagation energy, [J]
E_t	total impact energy, [J]
E_{in}	crack initiation energy, [J]
EWI	Edison Welding Institute
Fe	Yield load [kN]
Fm	Breaking load [kN]
HAZ	Heat-affected zone
I	Current [A]
IACS	International Association of Classification Societies
IRS	Indian Register of Shipping
ISO	International Organization for Standardization
k	Energy efficiency factor
kg	Kilogram, unit of measurement for weight

KR	Korean Register of Shipping
LR	Lloyd’s Register
MAG	metal active gas welding
mm	Millimeter, unit of measurement for length
Mn	Manganese
Mo	Molybdenum
MPa	megapascal
N	Nitrogen
Nb	Niobium
Ni	Nickel
NK	Nippon Kaiji Kyokai
NO	Nitric oxide
P	Phosphorus
PA	Flat position
PB	Horizontal vertical position
Pb	Lead
PC	Horizontal position
PE	Overhead position
PRS	Polish Register of Shipping
pWPS	preliminary Welding Procedure Specification
Q	Effective heat input
QT	Quenched and tempered
Re	Yield strength
RINA	Registro Italiale Navale
Rm	Ultimate tensile strength
RS	Russian Maritime Register of Shipping
s	Second, unit of measurement for time
S	Sulphur
SAW	Submerged arc welding
SBB	Transverse side bend test specimen for a butt weld
SFS	Suomen Standardisoimisliitto
Si	Silicon
Sn	Tin

So	Cross-sectional area [mm^2]
Ti	Titanium
TMCP	Thermo-mechanically Controlled Processed
TWM	Total Welding Management
U	voltage (V)
V	Vanadium
WPS	Welding Procedure Specification

1 INTRODUCTION

1.1 Background of the thesis

Shipbuilding industry nowadays is competitive and if companies wish to manufacture hulls and structures cost-efficiently new welding methods should be researched. The volume of the weld affect cost modifiers and by having a weld which has as little volume as possible it ensures better profit and time saving in manufacture.

Using multi-wire welding can be viewed as enhanced method for the conventional MAG welding and various arc modes and wires can be used at the same time. Tandem MAG welding in narrow groove has not been researched much. Problems and benefits with tandem MAG are different to traditional MAG, but overall the different arc mode and wire combinations provide the operator with many possibilities.

Ship registers give class descriptions to ships depending on the application. Standards as well as register rules must be followed to ensure quality and mechanical properties in the welding work to be corresponding both.

1.2 Aim of the study

The aim of the study was to weld 25 mm thick Ruukki offshore steel E500 TCMP with tandem MAG. The air gap and volume of the single-V butt weld was optimized while using 0.8kJ/mm and 2.5 kJ/mm heat input. The testing was started with groove angle of 30º and less. The aim is to reduce groove angle in steps of 5º.

Material to be welded in the research is Ruukki E500 TMCP, Extra high strength steel for ship structures. The plates will be 25 mm thick. Filler wire used mainly in the study is OK AristoRod 13.26 while the shielding gas will be M21 Mison 18.

The study is limited mainly to OK AristoRod 13.26 filler wire while some tests are done with other combinations. All of the arc modes are used to deduce best combinations. Root pass is not treated with same heat input values as the rest of the bead layers to ensure best root pass quality. Gas flow rates, mounting of the test piece and angles of the welding head are discussed further.

1.3 Arctic Development

This research has been done as a part of Arctic Materials Technologies Development or Arctic Development for short, ENPI Framework project. Priority in the project is the economic development in areas of South Karelia and St. Petersburg regions. The project is led by Lappeenranta University of Technology and Central Research Institute of Structural Materials, Prometey is a partner in the project. Overall objective is to improve cross border co-operation of companies and research centers in the area of materials and technologies in metal industries which operate across the borders. The main focus is to identify challenges in extreme temperature conditions for metal industry and offer possible development and solutions. Shipbuilding, offshore platforms, windmills and pipelines for the arctic region are main points of interest.

2 TANDEM MAG WELDING

Using multi-wire welding can be viewed as enhanced method for the conventional MAG welding. These multi-wire systems can be categorized to work for example by three different principles. (Goecke, et al., 2001, p. 24.)

- Twin welding with one feeding unit
- Twin welding with two feeding units
- Tandem welding

In the first one, the feeding unit feeds two wires; same power source is connected to both wires and the wires' potential is the same. The second one consists of two feeding units which each feed one wire but the wires still have the same power source and potential. The third i.e. Tandem welding consists of two power sources and two feeding units. In this case both feeding units feed one wire each and one power source is connected to one wire. The wires are electrically insulated in the welding head so that parameters for each wire can be adjusted as needed. There are also systems working on the principle that the wires are wider apart which will cause formation of two separate weld pools. This research focuses on tandem welding with both wires working in the same weld pool. (Goecke, et al., 2001, p. 24.)

2.1 Tandem MAG welding process

The best results and most efficiency in tandem welding can be achieved when the wires are working so near each other that they work in the same weld pool (Goecke, et al., 2001, p. 24). The other factor to successful tandem welding procedure is to control the wires simultaneously but individually i.e. the parameters are different for the both wires during the welding procedure. This allows using a combination of wires in the welding process i.e. solid wire and metal cored wire. This helps the designing of the weld and execution since consumable choice can be tailored according to the application. (Unosson & Persson, 2003, p. 28.)

In tandem MAG welding both welding heads can use different arc modes. These arc modes include spray arc, pulsed arc and short arc. These modes can be used on the welding head as any combination but it must be taken into account that arc processes affect each other and may cause disruptions. The first arc of the welding gun i.e. master arc must heat both the wire and create the molten pool in the work piece while the second one i.e. slave arc will then fill up the groove and take care of the weld's surface quality. These different tasks lead to the fact that the arcs have different purposes and need in turn different parameters for optimized performance. (Goecke, et al., 2001, p. 24-28.)

Figure 1 shows the welding pool in tandem MAG welding and also shows heat distribution and material flow. Because the slave arc works in the already molten pool the current for slave wire is can be less than for the master wire. While the master arc melts the base metal and the filler wire the trailing arc ensures diffusion of the wires and base metal in the weld pool for full change in microstructure. This leads to good quality weld seam and with relatively slow cooling rate the ductility of the weld will be increased. The angles of the nozzle which are discussed further in chapter 2.2 can help the weld pool diffusion to get even finer microstructure. E.g. Pulling angle on the lead wire and pushing angle with the trailing wire will have arc force and plasma flow force mixing the weld pool even more. This should lead to double peaks to thermal cycle during the weld, reduce the overall peak temperature in the weld pool and also make the HAZ (Heat-affected zone) narrow. (Fang et al., 2012, p. 83-84.)

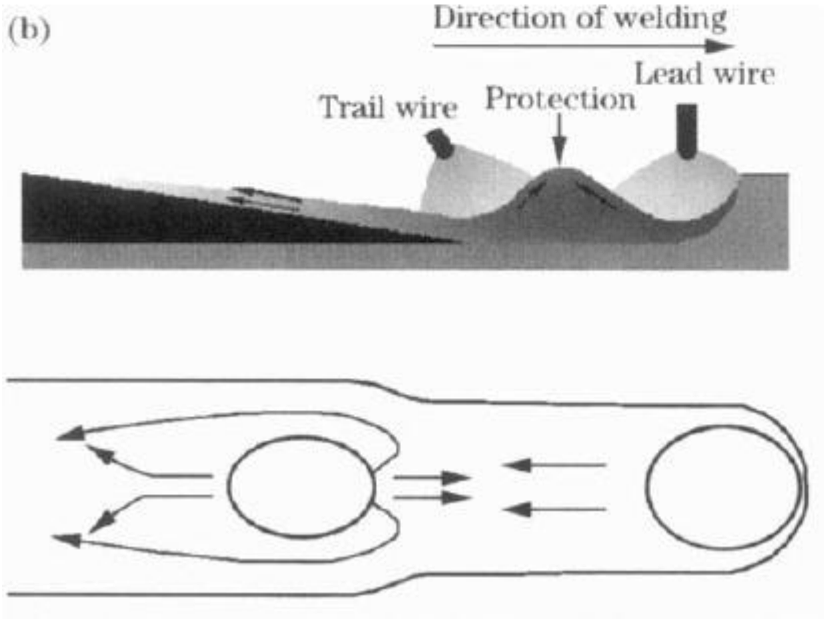

Figure 1. Material flow and Heat distribution in tandem MAG welding (Fang et al., 2012, p. 83.)

Like mentioned before, different arc modes can be used in both of the wires. Some of the possible combinations are (Uusitalo, 2011, p. 16.):

- Pulsed-pulsed
- Spray-pulsed
- Spray-spray
- Pulsed-spray

While using spray arc the droplet size is reduced drastically and short circuiting doesn't occur. In this case the rate of which droplets transfer is high and the wire will have a cone shaped tip. Well-adjusted spray arc results in nearly spatterless and smooth weld surface. Heat input can be high in spray arc welding (Lukkari, 2002, p. 169-170). Spray-spray arc mode combination can be used in tandem welding when deep penetration is needed in welding of heavy plates (Lincoln Electric, 2006a, p. 22).

The purpose for using constant voltage lead arc and pulsed trail arc as shown in Figure 2 is making both penetration and travel speed higher with lead arc while reducing heat input and electromagnetic arc interference with trail arc. (Lincoln Electric, 2006b, p.2.)

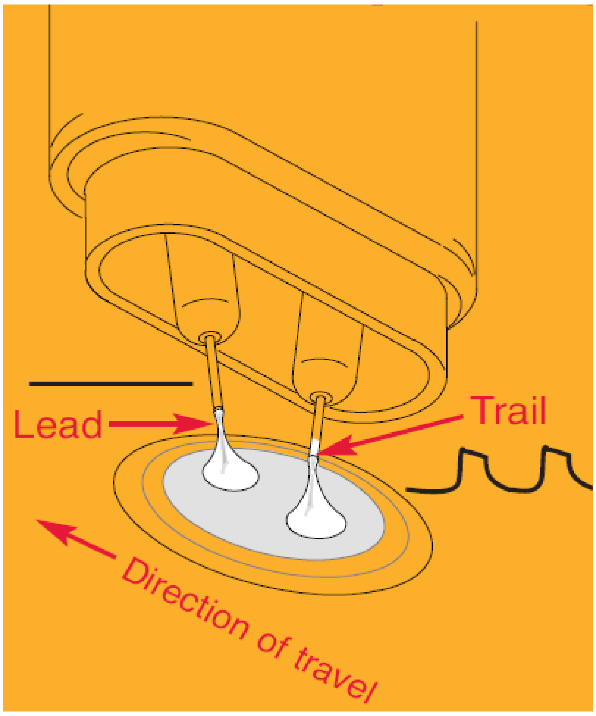

Figure 2. Lead arc with constant voltage mode and trail arc in pulsed mode (Lincoln Electric, 2006b, p. 2.)

Pulsed arc modes used on both wires is an appropriate solution for increased adaptability and optimization compared to other arc mode combinations (Goecke, et al., 2001, p. 26-28). Also Purslow (2012.) states that using pulsed arc mode in both wires with 180 degree phase shift between the power sources is a common practice. This makes Tandem MAG welding a stable process since only one of the electrodes peak at a time which leads to minimizing of the unwanted arc interaction and aforementioned disruptions.

When the arc modes are pulsed and have 180 degree phase difference the pulse cycle is following: at the start the lead wire has higher current and metal transfer takes place on the first wire while trailing arc maintains low current to keep the arc burning. On the second phase of the cycle lead wire is kept burning with low current and trailing wire produces the metal transfer. Peak current for the trailing wire is not as high as the peak current for lead wire. This results to the fact that lead wire arc will under normal conditions have high energy levels for penetration and the trailing arcs purpose with low energy level is to control the bead appearance. Example about pulse cycle, current level and droplet transfer in pulse cycle can be found in Figure 3. (Fang et al., 2012, p. 83.)

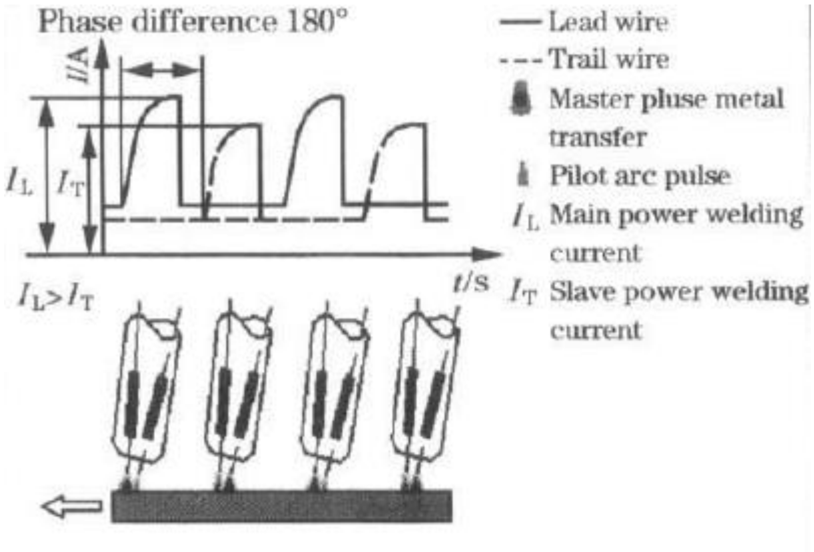

Figure 3. Tandem welding with pulsed arcs (Fang et al., 2012, p. 83.)

Tandem MAG welding requires more precise welding equipment installation due to the fact that process window with tandem MAG welding seems smaller than in traditional MAG welding. Some basic demands for optimal welding results are sturdy and vibration-free installation of the welding torches and reliable high performance feed units. Also joint tracking systems and large enough wire reels are needed to ensure optimal weld result. (Goecke, et al., 2001, p. 25.)

Figure 4 shows a comparison of welding speeds for single wire and tandem MAG on different weld types. Tandem MAG welding has higher welding speeds in the example cases around two times higher than single wire welding. Generally higher welding speeds and deposition rates can be achieved with tandem MAG welding than compared to traditional MAG welding depending on the weld type. (Goecke, et al., 2001, p. 26.)

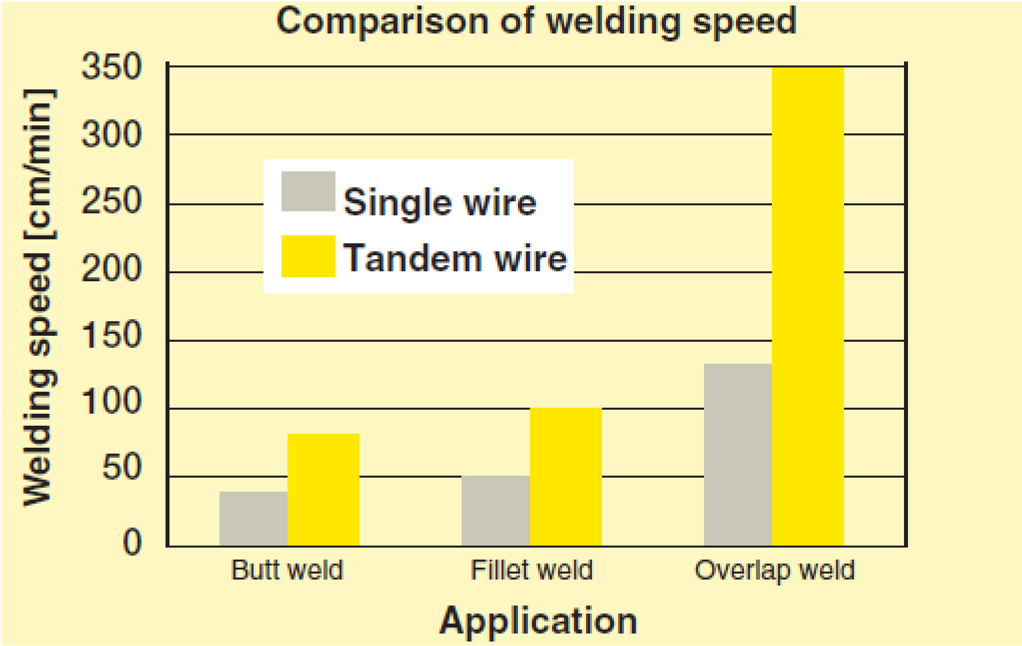

Figure 4. Comparison of the travel speeds for single-/ double-wire applications (Goecke, et al., 2001, p. 26.)

2.2 Welding equipment

Tandem MAG welding equipment consists from the following components (Purslow, 2012; Goecke et al., 2001, p. 26; Unosson & Persson, 2003, p. 28.):

- Two power sources
- Two MAG torches in a single welding head with common shielding gas nozzle
- Two feeding units
- Synchronised control system

Example of tandem MAG welding equipment installed for robot welding setup is shown in Figure 5.

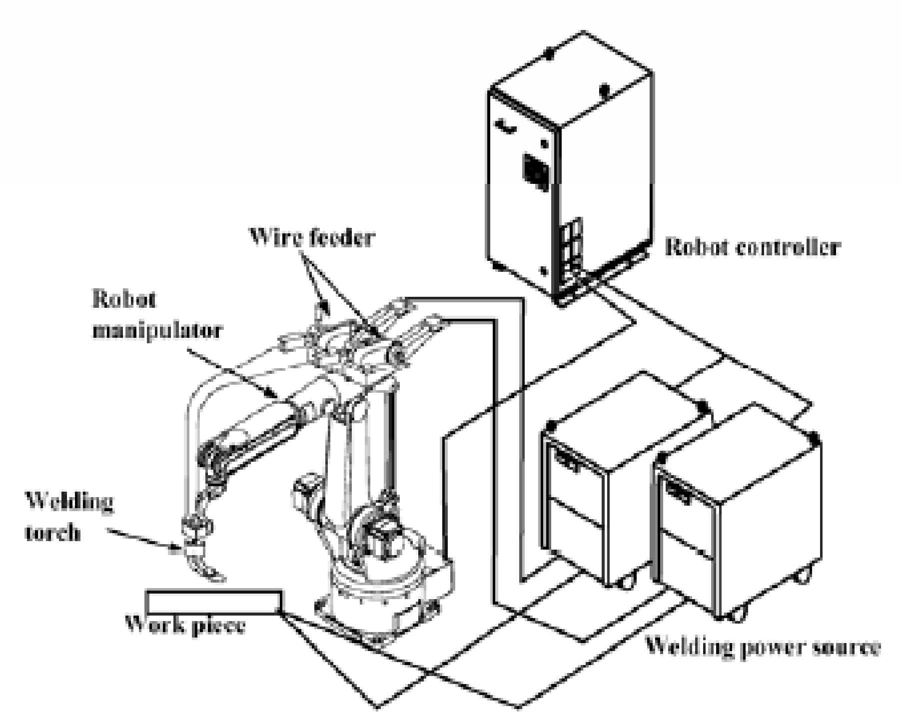

Figure 5. Tandem MAG welding equipment (Ueyama et al., 2005, p. 3.)

Special tandem welding heads are typically used in the welding configurations. These heads have both of the wires fed through them. The other option is to have two welding heads instead of one but the option is obsolete. Some possible torch configurations can be seen in Figure 6. (Unosson & Persson, 2003, p. 28.)

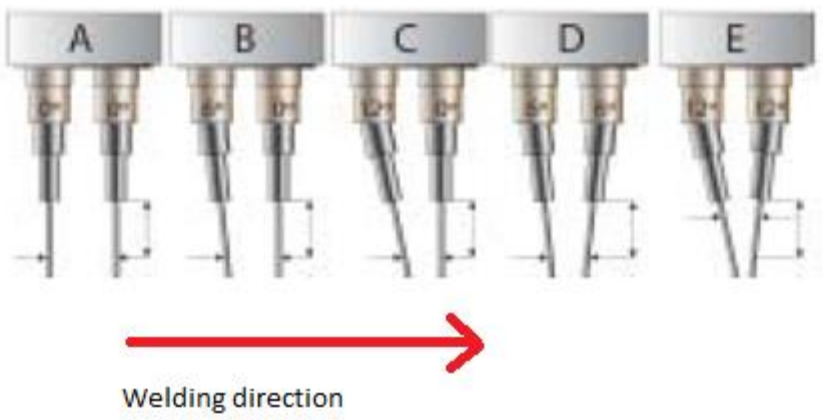

Figure 6. Possible torch configurations (Unosson & Persson, 2003, p. 29)

Tandem welding torches do have limitations compared to traditional MAG torches for example in accessibility of the welds. Because the welding torch is bigger in size it might be harder to use it in radial movement and in narrow gaps. The sheer amount of energy used in the welding process, fast welding speed and torch related reasons always makes the tandem MAG welding a mechanized or automatized process. (Uusitalo, 2011, p.17.)
Wire feeders used for tandem MAG welding purposes generally tend to have wire feed rates in the range on 2-20 m/min and are suitable for 0.6-1.6 mm diameter wire. Those can include optional features like timers for setting pre- and post-flow of the shielding gas, burn-back control, purge controls and methods for safely inching wire from the torch to the work piece surface. (Lincoln Electric, 2006a, p. 26.)

The power sources can be put into two main categories which are constant current and constant voltage power sources. In the first category, constant current power source, the arc length is determined by CTWD (contact tip to work distance). Increase in the CTWD causes the arc length to increase and in relation to that, decrease in CTWD leads to decrease in the arc length. Same CTWD is hard to maintain, so arc voltage controlled wire feeder can be used to counter the arc length changes. This type of power source is well suitable for large wire diameter and large weld puddle aluminum and carbon steel applications. Constant voltage power source uses specific wire feed rates which in turn determine specific arc voltage. CTWD increase leads to decrease in welding current and vice versa. (Lincoln Electric, 2006a, p. 25-26.)

2.3 Welding positions

Welding positions which are commonly used for tandem MAG welding are PA (Flat position) and PB (Horizontal vertical position) positions. (Goecke, et al., 2001, p. 25-26; Melton & Mulligan, 2001; Unosson & Persson, 2003, p. 28.; Lincoln Electric, 2005, p.4-6.)

Using PC (Horizontal position) and PE (Overhead position) positions with tandem MAG has been researched on high strength steel plates by EWI (Edison Welding Institute) for maritime applications. Examples of using tandem MAG in PE position can be seen in Figure 7 and in PC position in Figure 8. (English, 2012.)

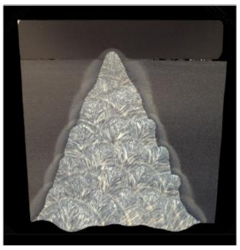

Figure 7. Tandem MAG overhead position (PE). (Harris, 2014, p.8.)

Figure 8. Tandem MAG horizontal position (PC). (Harris, 2014, p.7.)

2.3.1 Use in different positions

Spray arc is used in fill up and to do a final run while welding in flat position (PA). Flat fillet welds and horizontal fillet welds are also in the use range of spray arc mode MAG welding (Lukkari, 2002, p. 171). Nadzam (2002) describes spray arc as a possible choice to be used in case of flat and horizontal positions in tandem MAG welding which is also the case in single wire MAG welding as described by Lincoln Electric (2006a, p. 2).

Flat and horizontal lap welds in high speed applications are used for example in automotive component and tank fabrication. Typical use for flat and horizontal fillet welds with high welding speeds include but do not limit to railroad, shipbuilding and structural applications. In these the welding speeds vary from around 0.6 m/min to 2.55 m/min. J, U and V groove butt welds in PA position are commonly used to manufacture earth moving equipment. (Lincoln Electric, 2005, p.4-6.)

2.4 Groove shapes and gaps

J-,U- and V-shaped grooves are used while welding grooved butt welds along with bevel type grooves (Lincoln Electric, 2005, p.4-6). Narrow gap I-shaped joints have been welded with tandem MAG. (Coffey, 2012; Purslow, 2012.)

Example of narrow gap tandem MAG weld is shown in Figure 9. The joint is 127 mm (5 inches) thick and it was welded with a deposition rate around 9 kg/hour. (Purslow, 2012.)

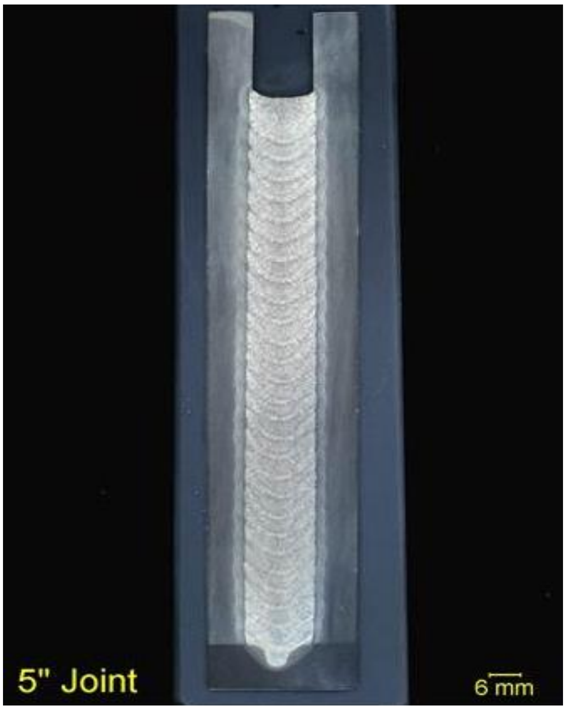

Figure 9. Narrow gap tandem MAG weld example (Purslow, 2012)

2.5 Materials and materials thicknesses

Lukkari (2002. p. 175) states that MAG welding can be used for stainless steel, low-alloy steel, non-alloy steel as well as non-ferrous materials. Tandem MAG basically enables the same materials to be welded and Binzel provides a list of materials which their welding head is designed for. These materials are (Abicor Binzel, 2014.):

- Construction steels
- Chrome –nickel steels
- Duplex steels
- Mixed compounds
- Nickel, magnesium, copper and special materials

MIG/MAG welding can be used for various material thicknesses starting from around 0.8 mm. Short arc mode is typically used for sheet metal applications (Lukkari, 2002. p. 176) while spray arc is used from around 6.4 mm thickness and up in the welding of stainless steel (Lincoln Electric, 2006a, p. 22). Unosson & Persson (2003, p.28) list stainless steel, aluminum and carbon steel as main materials for tandem MAG welding. Lincoln Electric (2006a, p.10) book about MAG welding describes different arc mode usage according to thickness of the material which is being welded. Figure 10 shows the material thicknesses to be ranging from 0.9 mm and upwards. Tandem welding can be described to have similar possibilities and Melton & Mulligan (2001) mention that tandem-MIG/MAG has been mostly used with steels and some Aluminium alloys, while the material thicknesses have been 1.5 mm – 25 mm for steels and 2 mm – 6 mm for Aluminium.

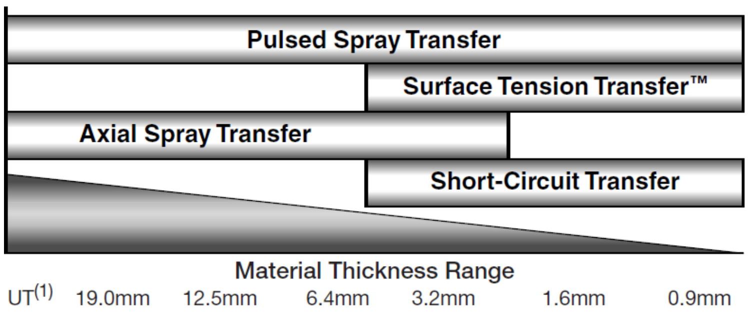

Figure 10. Steel material thicknesses weldable with tandem MAG (Lincoln Electric, 2006a, p. 10).

2.6 Heat input

Arc energy (E) and effective heat input (Q) can be calculated from equations 1 and 2 (Lukkari, 2002, p.54.):

$$E\left[\frac{kJ}{mm}\right] = \frac{I[A]*U[V]*60}{v\left[\frac{mm}{s}\right]*1000} \quad [1]$$

Where E = Arc energy

I = Current

U = Voltage

v = Welding speed

$$Q\ [kJ/mm] = k * E \qquad [2]$$

Where Q = heat input

k = Energy efficiency factor (0.8 for MAG)

E = Arc energy

The heat input concerning tandem welding can be calculated separately for both of the wires and added together. Overall heat input might not be higher than with typical single wire MAG welding as the welding equipment setup and parameters affect the outcome. In tandem MAG welding effective heat input can be calculated with the knowledge of separate effective heat inputs of both arcs as shown in equation 3. (Weman & Lindén, 2006, p.123)

$$Q\left[\frac{kJ}{mm}\right] = Q1 + Q2 \qquad [3]$$

Where Q = Heat input

Q1 = Heat input of the first arc

Q2 = Heat input of the second arc

To increase metal deposition rates with traditional single wire MAG, wire feed rate and wire diameter are usually increased, which leads to increase in the total current used and also in higher heat input. By using tandem MIG/MAG with the intent of having similar deposition rates of aforementioned case, the effect of having two wires of smaller diameter than in traditional MAG welding, user can have better weld pool control and lower heat input. Thus, heat input can be reduced around 30 – 50% by using two smaller wires compared to one larger diameter one. (Lincoln Electric, 2005, p. 7-8.)

Welding programs like Kemppi WiseFusion can be used for welding and the benefits include optimal arc length and energy density in the welding of narrow area. In the case of heat input using WiseFusion translates to smaller heat input and higher welding speed. (Uusitalo, 2011, p.17.)

Figure 11 shows heat input dependency from welding while using tandem MAG process for both leading and trailing arc.

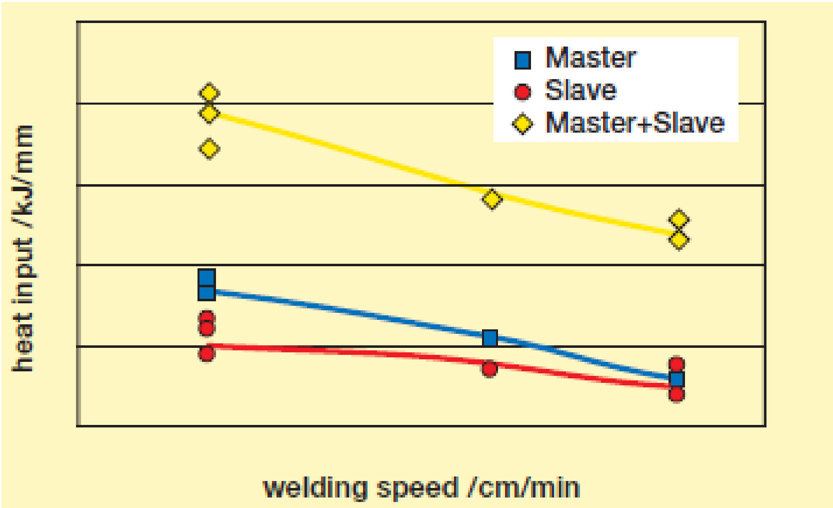

Figure 11. Heat input dependency on welding speed in tandem MAG Welding (Goecke, et al., 2001, p. 28.)

2.7 Welding mechanization and robotization

When welding with tandem MAG equipment mechanization and robotization must be used. One of the factors which limit the usability of tandem MAG only to mechanized or robotized welding, relate to the fact that tandem welding head is heavier and larger in size than traditional MAG welding head. Other factors which require mechanization and robotization to be used are high power and according to Berge (2002.) high deposition rates of the welding process. (Uusitalo, 2011, p.17.)

3 PRODUCTIVITY AND ECONOMIC ASPECTS OF TANDEM MAG WELDING

Tandem MAG welding has increased deposition rates and faster travel speeds than traditional MAG welding. Researches describe (Purslow, 2012; Goecke, et al., 2001, p. 26) that the travel speeds and deposition rates of tandem MAG are twice larger compared to traditional MAG welding. Tandem MAG welding also has similar deposition rate and lesser heat input compared to SAW (Submerged arc welding). (Purslow, 2012.)

3.1 Productivity of tandem MAG welding vs. conventional MAG welding

Wire feed rate with 1.2 mm solid wire for traditional MAG is from around 10 m/min and tandem MAG has wire feed rates totalling in around 25-30 m/min. In the case of metal cored wire with 1.8 mm width the welding speed varied from 7.7-12 m/min for traditional MAG and from 19.5-27 m/min for tandem MAG. Deposition rate of 20 kg/h was the maximum which was achieved in the before mentioned study. The deposition rates in the study for traditional MAG were ranging from 5.3 kg/h to 8 kg/h while the tandem MAG achieved from around 11 to 20 kg/h. It can be deduced from this data that tandem MAG roughly can have around 2.0-2.5 times the deposition rate of conventional MAG welding. This data is compiled from Figure 12.

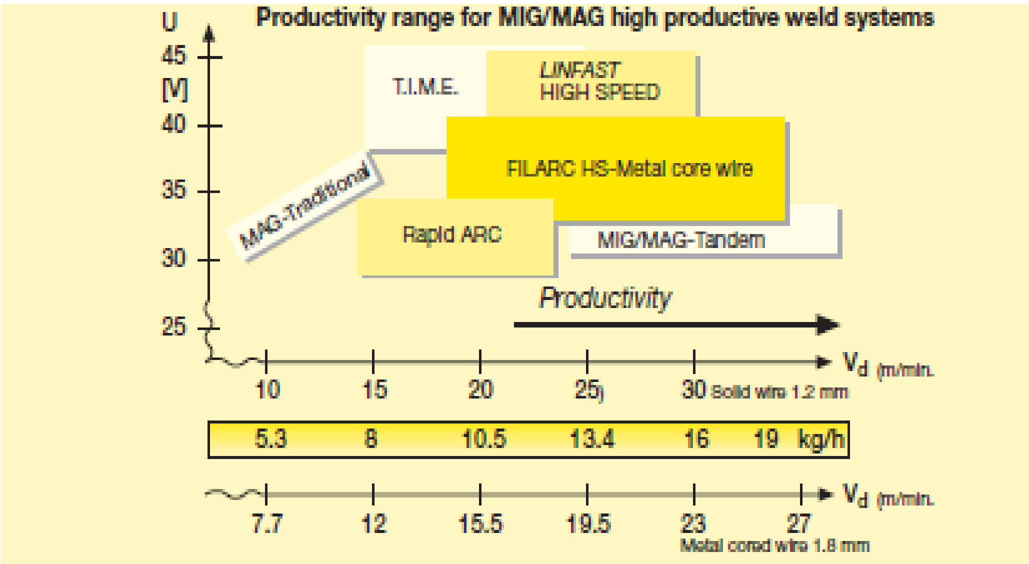

Figure 12. Productivity range for MIG/MAG high productive systems (Goecke, et al., 2001, p. 24.)

3.2 Costs of welding

Since tandem MAG welding has much faster welding speeds than single wire MAG welding, tandem welding can have in some cases significantly better cost efficiency compared to typical single wire MAG welding. This is demonstrated in Figure 13 with single and tandem MAG cost per meter and working cost per hour comparison. (Unosson & Persson, 2003, p. 28.)

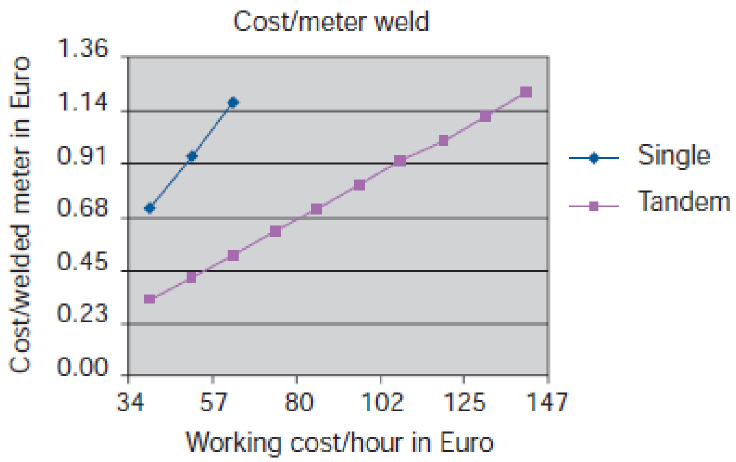

Figure 13. Cost comparison between single wire welding and tandem welding. (Unosson & Persson, 2003, p. 28.)

In the research, (Figueira, 2009) robotized tandem welding and mechanized traditional MAG welding were compared for welding high strength steel. As for the cost of welding one meter long fillet weld, tandem welding outperformed traditional MAG. The cost of welding with tandem resulted in 33 to 35% decrease in overall costs. In the data given, labour with overheads decreased while welding speed and efficiency increased. (Figueira, 2009, p. 9-11.)

3.3 Tandem MAG welding in shipbuilding

Important part of increasing productivity and reducing cost in shipbuilding welding is to manufacture high quality products with reduced time and cost (Uusitalo, 2011, p. 17). As stated before, the tandem MAG welding has faster welding speed and larger deposition rate than traditional MAG welding. If the amount of welding consumables consumption is reduced e.g. with narrow gap tandem MAG welding the effect would be beneficial for the industry (Stano & Matejec, 2010, p.47).

4 HIGH STRENGTH STEELS USED IN SHIPBUILDING

IACS (International Association of Classification Societies) is a non-governmental, non-commercial party, which consists of multiple classification societies from different parts of the world. These societies provide classification rules for shipbuilding e.g. standards for ship hull construction and strength, propulsion and steering system design and for many auxiliary systems. When a ship has been noted to be in conformity with specific IACS member society rules, ship can be assigned to a class designation. To remain in its class, the ship's seaworthiness must be inspected by periodic or non- periodic surveys. (IACS, 2011, p. 4-6; 15; 22; 25).

IACS members:

- American Bureau of Shipping (ABS)
- Bureau Veritas (BV)
- China Classification Society (CCS)
- Croatian Register of Shipping (CRS)
- Det Norske Veritas Germanischer Lloyd (DNV GL)
- Indian Register of Shipping (IRS)
- Korean Register of Shipping (KR)
- Lloyd's Register (LR)
- Nippon Kaiji Kyokai (NK)
- Polish Register of Shipping (PRS)
- Registro Italiale Navale (RINA)
- Russian Maritime Register of Shipping (RS)

Russian Maritime Register gives class descriptions to ships depending on the intended usage of the ship in question and few class descriptions are concentrated in this chapter. Polar class ships are intended for waters containing significant amount of ice in polar climate. The ships are to be constructed from steel. This class excludes icebreakers. Icebreaker in context of RS rules describes a ship intended for escorting other vessels through icy waters along with the ability to manipulate movement of the ice by adequate power supply and its weight.

In the later chapters RS rules concerning high strength steels are discussed further.

4.1 Properties requirements for steels

The Russian Maritime Register of Shipping includes documentation on materials, which contain standards and specifications, chemical, mechanical and technological properties and also test scope, procedures used with information on marking procedure and test results. (Russian Maritime Register of Shipping, 2015, p.104.)

RS rules apply to welded high strength steel structures made of steel plates up to 70 mm thick. If the steel plates used are thicker, the register may agree on using those. High strength steels are divided into six categories by yield strength. These categories are 420 MPa, 460 MPa, 500 MPa, 550 MPa, 620 MPa and 690 MPa. The categories are then marked with a grade depending of impact test temperatures. The grades are A, D, E and F. (Russian Maritime Register of Shipping, 2014b, p.430.)

RS rules state which materials are suitable for manufacturing of components and ship parts. For example in hull structures high strength steels can be used, but using high strength steel with upper yield stress of 420 MPa and above with steel grades D, E and F requires special consideration. (Russian Maritime Register of Shipping, 2014a, p.49.)

Manufacturer analysis certificate must be in accordance with registers table which shows the allowed chemical composition. The maximum percentage for content of elements can be seen in Figure 14. (Russian Maritime Register of Shipping, 2014b, p.430.)

Strength level of steel, in MPa	Steel grade	Content of elements, %, max					
		C	Si	Mn	P	S	N
420 — 690	A D, E F	0,21 0,20 0,18	0,55 0,55 0,55	1,70 1,70 1,60	0,035 0,030 0,025	0,035 0,030 0,025	0,020 0,020 0,020

Figure 14. Chemical composition according to steel grade and strength level of steel. (Russian Maritime Register of Shipping, 2014b, p.430).

4.1.1 Mechanical properties

Steel grade depends on the impact test temperature. RS has rules concerning tensile and impact test in welded work piece for approvable test outcomes and for minimal elongation of tensile test specimens. The mechanical properties which are required by RS are shown in Table 1 while minimal elongation values for test specimens are shown in Table 2.

- A – Test temperature 0 °C
- D - Test temperature -20 °C
- E - Test temperature -40 °C
- F - Test temperature -60 °C

Table 1. Mechanical properties required in tensile and impact tests for steel grades with plate thicknesses less than 70 mm. (Russian Maritime Register of Shipping, 2014b, p.431).

Steel grade	Tensile test			Impact test		
	Yield stress R_{eH} or $R_{p0,2}$, min, MPa	Tensile strength R_m, MPa	Elongation A_5, min, %	Test temperature, °C	Impact energy KV, min, J	
					longitudinal specimen	transverse specimen
A420 D420 E420 F420	420	530 — 680	18	0 −20 −40 −60	42	28
A460 D460 E460 F460	460	570 — 720	17	0 −20 −40 −60	46	31
A500 D500 E500 F500	500	610 — 770	16	0 −20 −40 −60	50	33
A550 D550 E550 F550	550	670 — 830	16	0 −20 −40 −60	55	37
A620 D620 E620 F620	620	720 — 890	15	0 −20 −40 −60	62	41
A690 D690 E690 F690	690	770 — 940	14	0 −20 −40 −60	69	46

Table 2. Minimal elongation percentage values for test specimens. (Russian Maritime Register of Shipping, 2014b, p.431).

Strength level of steel	Thickness t, mm						
	⩽10	>10 ⩽15	>15 ⩽20	>20 ⩽25	>25 ⩽40	>40 ⩽50	>50 ⩽70
420	11	13	14	15	16	17	18
460	11	12	13	14	15	16	17
500	10	11	12	13	14	15	16
550	10	11	12	13	14	15	16
620	9	11	12	12	13	14	15
690	9	10	11	11	12	13	14

4.1.2 Cold cracking and corrosion properties

According to RS, cold cracking tendency must be determined by calculating P_{CM} (Carbon equivalent). The equation for P_{cm} is the following (The National Shipbuilding Research Program, 2000, p. 3.)

:

$$\mathrm{Pcm}\ (\%) = \mathrm{C} + \frac{\mathrm{Si}}{30} + \frac{\mathrm{Mn+Cr+Cu}}{20} + \frac{\mathrm{Ni}}{60} + \frac{\mathrm{Mo}}{15} + \frac{\mathrm{V}}{10} + 5 \times \mathrm{B} \qquad [4]$$

P_{cm} carbon equivalent equation is commonly used for low carbon low alloy steels. If the HAZ contains much martensitic structure effect of carbon is more severe. In other words compared to other equations carbon content is more weighted in P_{cm} versus the alloying elements. Also Ni content is divided by 60 so in P_{cm} formula Ni content is not seen as harmful as in other carbon equivalent formulas. (The National Shipbuilding Research Program, 2000, p. 3.)

Properties of welding consumables, along with the measures taken by the welders should eliminate cold cracking tendencies. The technological measures to ensure this contain preheating and heat treatments.. (Russian Maritime Register of Shipping, 2014b, p.430; 521.)

Corrosion resistance tests can be done in order to ensure both the metal and welding consumable corrosion properties. Tests include e.g. testing pitting corrosion resistance initiated by chlorides and stress-corrosion cracking with hydrogen sulphide. (Russian Maritime Register of Shipping, 2014b, p.587.)

Corrosion resistance rules for hulls states that the manufacturer must calculate corrosion allowance for hull structures depending on the ships service life. The rules state different usage groups which in contrast are taken into account while calculating yearly thickness reduction. (Russian Maritime Register of Shipping, 2014a, p.42-44.)

4.2 Rules, Standards and Classifications

Manufacturer can apply for the Recognition Certificate for Manufacturer, which when granted by RS confirms the products and conditions of the manufacturing process as eligible to be entered in registry's list of recognized materials and manufacturers. Type Approval Certificate shows that the products are produced by the works according to the register rules. Manufacturer certificate is a document which certifies that a volume product meets the required rules and confirms that the manufacturing process is in compliance with correct production techniques. This document is given by the quality control personnel from the manufacturers' side. Register Certificate is in comparison issued for a similar, volumed product but issuer is a surveyor of the register. (Russian Maritime Register of Shipping, 2014b, p.370.)

Rules considering manufacturing of welded structures from high strength steels require the manufacturer to submit various data and documents. These must contain preheating temperature, linear power consumption during welding, temperatures between bead layers and data concerning post weld heat treatments. The welding conditions should be recorded while welding and records must be submitted to register if requested. Joints which are welded should always be welded with multiple passes without special agreement of the registry. Ignition of the arc should be done inside the groove edges. (Russian Maritime Register of Shipping, 2014b, p.524.)

5 WELDABILITY OF HIGH STRENGTH STEELS

High strength steels are considered to have yield strengths above the mild steel range of 235 - 420 MPa while steels with yield strengths of over 900 MPA are often described as ultra-high strength steels. There is no official definition for yield strengths of mild, high and ultra-high strength steels, so the categorization is not strict. Also necessary yield strength in high strength steels is achieved by well controlled manufacturing techniques and by micro alloying. These manufacturing techniques consist of quenching, forming and heat treatments in different combinations with alloying elements, for example of titanium and vanadium. (Pirinen & Martikainen, 2009. p.17.)

RS also states that high strength steel category to start from yield strengths of over 420 MPa. (Russian Maritime Register of Shipping, 2014b, p.431.)

While calculating P_{CM} to determine cold cracking tendency should be used (Russian Maritime Register of Shipping, 2014b, p.430.), it can be said that overall good weldability can be achieved by having small carbon and alloying element content and with only small impurity from sulphur and phosphor (Suomen Hitsausteknillinen Yhdistys r.y., 2014, p. 125).

5.1 Problems and benefits of high strength steels

Weldability of high strength steels nowadays can be considered to be good according to steel manufacturers. Typically high strength steels have low carbon content equivalent which relates to fewer problems in welding compared to high equivalent carbon content steels. While welding high strength steel, its tendency to harden due to high heat input should be kept in mind. There are differences in DQ (Direct quenching) high strength steels, TMCP steels and QT (Quenched and tempered) high strength steels. Typical quenched and tempered steel is manufactured so that the grain growth is prevented. DQ steel is manufactured so that it has bainitic-martensitic structure to provide wanted level of strength. Otherwise high strength steel is typically similar to weld as mild low carbon content steel. (Pirinen & Martikainen, 2009. p.17.)

High strength steels may have tendency to cold cracking. To avoid this effect the welder must use correct preheating and interpass temperatures. The cleanliness near the groove, lack of impurities near the groove and low hydrogen content welding consumables should be used to prevent it. Less than 3 mm root gap width along with correct weld sequence also help to reduce risk of hydrogen cracking. (Stridh, 2011.)

Furthermore using TMCP (Thermo-mechanically Controlled Processed) steel has benefits of high strength and toughness while mainly being less alloyed even in thicker plates. TMCP steels are considered to have good weldability and are used in offshore and shipbuilding structures. With high strength TMCP steels designers benefit from simpler and lighter constructions compared to ones designed from mild steels. With reduced volume of welding consumable used and reduced welding time and reduced amount of passes needed to complete the weld. Toughness of high strength steels permit using the material in lower temperatures. (Metalliteollisuuden Keskusliitto, 2001, p. 75.)

5.2 The effect of heat input

Heat input has an effect on the mechanical properties of the weld and typically heat input should be around 1-2 kJ/mm while ultra-high strength steel might have a recommendation heat input of 0.5 kJ/mm. Material thickness also affects proper heat input and other parameters used in welding. (Pirinen & Martikainen, 2009. p.17.)

High strength TMCP steels typically have a good weldability on wide heat input range. Heat treatment in over 700 ºC should be avoided because of TMCP steel microstructure. Even though during welding the temperatures are higher than this limiting HAZ width to less than half of the material thickness ensures structural integrity. (Metalliteollisuuden Keskusliitto, 2001, p. 76.)

5.3 Brittle fracture

Welding with high arc energy causes brittleness in HAZ, which can be taken into account by using multiple beads instead with less arc energy. One simplification for the matter says that if the weld needs to have 40 J energy to fracture in Impact test done in -40 °C, the amount of weld beads needed to fill the gap should be calculated by dividing the total material thickness by a factor of 5. Brittleness caused by tempering is not typically a problem for high strength steels since the alloying element content is rather low. (Suomen Hitsausteknillinen Yhdistys r.y., 2014, p. 131.)

Compared to mild steels high strength steels overall have to have better toughness or smaller critical crack length in order to ensure that brittle fracture probability is low. (Metalliteollisuuden Keskusliitto. 2001, p.70.)

Small grain size and some alloying elements are beneficial for preventing brittle fracture tendency. Alloying elements like titanium and niobium form nitrides and carbides while preventing austenitic grain growth. Prior and after welding, instructions about heat treatment of the material must be carefully followed since wrong heat treatment can harm ductility and cause problems due to brittle fracture mechanics. (Rautaruukki, 2000, p. 18)

5.4 Weld defects and weld classes

Standard SFS-EN ISO 5817 states that there are three weld quality levels to designate weld classes which are symbols B, C and D with B having the highest requirements for the finished weld. The standard also states that short imperfections in the weld are those that are not 25 mm in length for highest imperfection concentrated area or are not more than 25 percent in length of under 100 mm long welds. (SFS-EN ISO 5817, 2014, p.11; 13.)

Weld defects can be classified as two-dimensional and three-dimensional defects and the first category is considered to be more problematic for welded structure due to its sharp edges. These two-dimensional defects are for example different types of cracks, different kinds of lack of fusion and lack of penetration. Porosity, for example, is considered to be three-dimensional defect. (Lukkari, 2002, p.40) There are some weld defects that are not permitted in the weld for the weld classes at all and these can be found in Table 3.

Table 3. Not permitted weld defects for various weld classes. (Compiled from SFS-EN ISO 5817 p. 18-46; Lukkari, 2002, p.44-52.)

Weld class B	Weld class C	Weld class D
Burn through	Burn through	Burn through
Crack	Crack	Crack
Crater crack	Crater crack	
Crater pipe	Crater pipe	
Copper inclusions	Copper inclusions	Copper inclusions
End crater pipe		
Insufficient throat thickness		
Lack of fusion (any)	Lack of fusion (any)	Lack of fusion (reaching surface)
Lack of penetration	Lack of penetration (depends on joint type)	
Overlap	Overlap	
Poor restart	Poor restart	
Root porosity	Root porosity	Root porosity
Shrinkage cavity	Shrinkage cavity	
Stray arc	Stray arc	
Surface pore		

Since tandem MAG welding naturally makes the weld pool long, the gases leave the weld pool during cooling of the weld so the occurring of porosity is less likely. Despite of deposition rate being quite large the small energy output of tandem MAG ensures smaller deformations in the work piece. (Uusitalo, 2011, p.17.)

6 QUALITY AND QUALITY ASSURANCE OF TANDEM MAG WELDING

Quality and quality assurance overall in welding should be considered as part of competitiveness for a manufacturer. If quality of a product is not maintained, partners and customers can become unsatisfied with the product and even decide not to use the product anymore. In some instances it is easy to see direct results of poor quality. As for example these could be complaints and reclamations, accidents in the workplace or malfunctioning products. In other cases the relation between quality and effects of poor quality are harder to find out. These are for example the loss of customers or worse customer relations, process halts and poor workplace ergonomics. It is important to remember that quality, productivity and economical aspects should be considered to have a close relation between each other. (Martikainen, 2013, p.3)

6.1 Quality factors

Quality in welding can be categorized around two different topics. The first one being technical quality of a weld and second would be overall quality of the welding work. At least the technical quality of the weld can be designated with visual quality, good machine shop quality, weld class quality and metallurgical quality. The last two are more precise and standardized. (Martikainen, 2013, p.5)

The weld class quality is designated through standards, for example the main standards concerning this thesis are: EN ISO 6520-1 and EN ISO 5817. EN ISO 5817 describes permitted weld defects for different weld classes which were discussed in the earlier chapter. This weld class quality does not take part in the destructive testing results which are discussed further under metallurgical quality section. (Martikainen, 2013, p.5.)

Even if weld seems good in visual test it might not pass the destructive testing. Metallurgical quality must be ascertained by welding procedure test to ensure the needed properties from the work piece. Some main aspects to ensure metallurgical quality of the weld is that the microstructure of the material after welding is ductile enough, grain growth near the fusion line is not excess and hardness of the weld and HAZ is acceptable. Using

WPS (Welding Procedure Specification) is an important factor for ascertaining that weld quality remains production. (Martikainen, 2013, p.5-6.)

Overall quality of welding work can be considered as a wider subject with emphasis on work ethics and practises which help to improve and maintain quality of welding in general. Overall quality also contains aspects like productivity and economic efficiency. Standard EN ISO 9000, and standard set EN ISO 3834 contain tools for certifying that the manufacturing company produces welded products with certain level of documentation and with certain on quality levels. Quality aspects that can be used as examples in overall quality of the welding work are: safety and environmental safety subjects, networking, logistics, product markings and personnel training. (Martikainen, 2013, p.6-7.)

6.2 Effect of welding torch and wires

Factors like filler material type, heat input, base metal mixture degree, filler material type and post heat transfer to earlier welding beds from multipass welding have an effect on weld quality. (Popović, et al., 2010. p. 61-62.)

TTandem welding heads typically have pre-aligned torch configurations, and choosing a torch affects weld quality and characteristics of e.g. penetration and spatter. Each torch configuration will have different advantages and disadvantages. (Unosson & Persson, 2003, p. 29; Kobelco, 2011, p.27; Popović, et al., 2010. p. 61-62.)

Tandem MAG torches are versatile but need more focus on the parameters and angles from the operator to have an acceptable quality weld due to the fact that two different wires and even wire diameters can be used and while welding with e.g. torch variation C from Figure 6 operator can choose to use pulling or straight alignment as first, depending on the welding needs. (Goecke, et al., 2001, p. 26-28; Unosson & Persson, 2003, p. 28-29.)

Turning the welding torch around its axis so that the electrodes are parallel compared to typical one behind the other one may provide benefits to different situations while welding. In Figure 15 first case would be the typical tandem welding head orientation which provides maximum welding speed. The second case shows that turning the welding head several degrees will result more suitable profile for gap bridging. In the third case the electrodes are used in parallel the bead grows in size sideways and deposition increases.

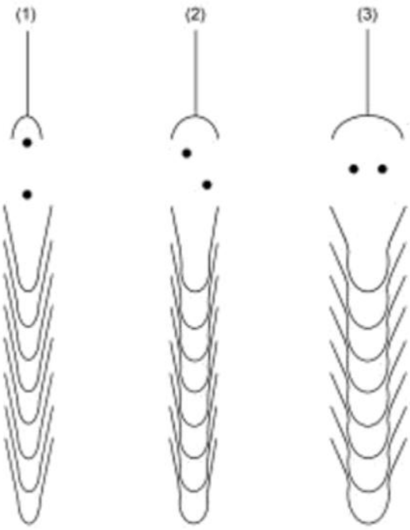

Figure 15. Different electrode orientations and resulting bead layer profile in the groove. Where in first case is typical one electrode behind the first one, second with small sideways orientation between the arcs and third parallel arcs for high deposition welding. (Weman & Lindén, 2006, p. 123.)

Using tandem welding torch can typically cause more problems with magnetic arc blow compared to the traditional MAG torch. Ways to reduce the arc disturbances are correct way of grounding the work piece and using different pieces for starting and ending the weld pass. Uusitalo, 2011, p. 16.)

6.3 Effect of heat input

Welding procedure test is done for the work pieces to ensure how heat input affects the piece in welding. (Martikainen, 2013, p.5.)

Since microstructure of the weld metal affects both mechanical properties and toughness of the weld and heat input affects cooling rate which determines the final metallurgical structure of the weld, the effect of heat input is important factor in weld quality (Kobelco, 2000; Popović, et al., 2010. p. 61-62.)

Relations between heat input and cooling rate can be found in Figure 16. With more heat input the HAZ grows larger and the weld bead grows. Size of the weld bead also influences the welded part toughness. During multiple passes some parts of the previous weld beads are refined and toughness of it improves since the earlier weld bead gets tempered. For comparison with multiple passes done with smaller heat input would lead to more grain refinement and better notch toughness and vice versa with higher heat input. Figure 17 shows example of how results of an impact test done at -40 ºC differ with test specimens welded with different heat input values. (Popović, et al., 2010. p. 61-62. 2010.)

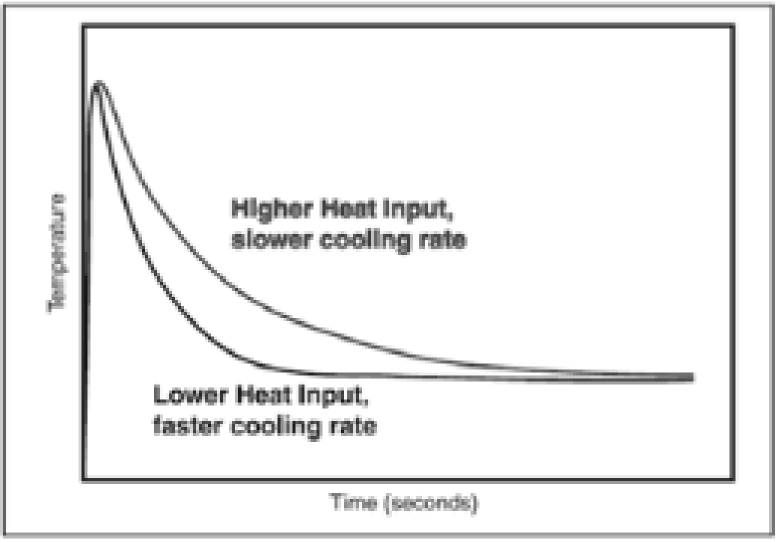

Figure 16. Heat input influence on cooling rate. (Popović, et al., 2010. p.61)

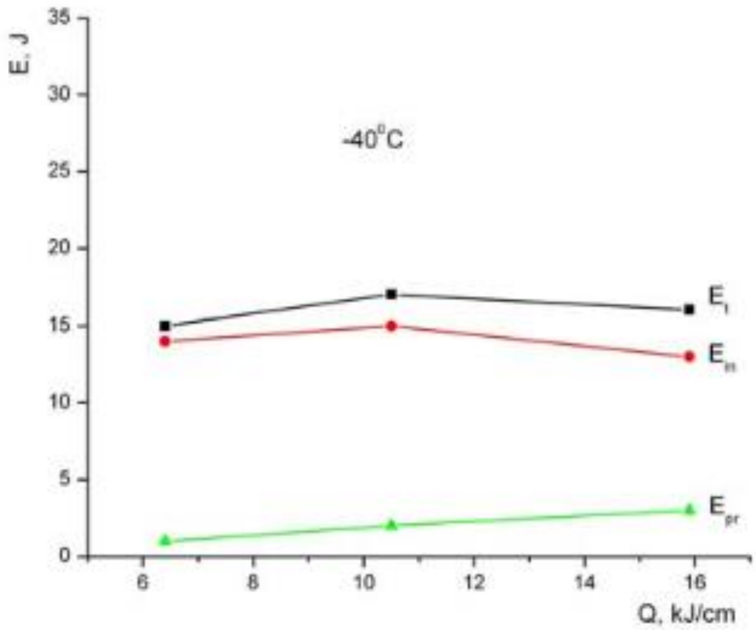

Figure 17. Dependence of heat input and impact energies in impact test. (Popović, et al., 2010. p.63) **(**E_{pr}=crack propagation energy, [J], E_t =total impact energy, [J], E_{in}=crack initiation energy, [J])

6.4 Effect of filler materials

In tandem MAG two different filler materials can be used even with different wire diameters e.g. solid wire and metal cored wire. (Unosson & Persson, 2003, p. 28)

Thus in tandem MAG welding filler wire diameter and differences in solid core and metal cored wires and chemical composition are factors which ensure the required quality. (Unosson & Persson, 2003, p. 28; Lincoln Electric, 2015.)

Filler wire with oversized diameter might be as harmful for the welding as undersized diameter. Undersized diameter causes erosion of the tip and oversized causes excessive feeding force, wire slippage, tip blockage and even downtime. (Lincoln Electric, 2015)

The major difference between solid and metal cored wire is, that solid wire provides deep penetration and metal cored wire provides larger, more round molten droplet which results in round shape penetration profile. Using either has advantages and disadvantages depending on the material being welded and required properties of the weld. (Miller, 2015)

6.5 Testing methods

WPS (Welding Procedure Specification) is needed to maintain quality even though there might be numerous materials and filler materials used constantly in the production (Martikainen, 2013, p.9). Welding procedure test is done to ascertain that quality control and welding design is done according to suitable practises. WPS ensures that the process of welding is corresponding to the requirements of the products in its purpose of use. NDT (non-destructive test) and DT (destructive test) testing are used to validate the quality. (SFS-EN ISO 15607, 2004, p. 7.)

The tests required, when using welding procedure test are visual, radiographic, surface crack detection, transverse tensile test, transverse bend test, impact test, hardness test and macroscopic examination. These tests and the specimens or percentage tested can be seen in Figure 18. **(**SFS-EN ISO 15614-1 + A1 + A2, 2012, p.21)

Test piece	Type of test	Extent of testing
Butt joint with full penetration –	Visual	100 %
Figure 1 and Figure 2	Radiographic or ultrasonic	100 %
	Surface crack detection	100 %
	Transverse tensile test	2 specimens
	Transverse bend test	4 specimens
	Impact test	2 sets
	Hardness test	required
	Macroscopic examination	1 specimen

Figure 18. Required tests in welding procedure test. (SFS-EN ISO 15614-1 + A1 + A2, 2012, p.21)

RS standards regulate requirements for shipbuilding and most importantly for this thesis, the properties required from the welds and materials used. These properties are then tested in welding procedure test. (Russian Maritime Register of Shipping, 2015, p.104.)

Important tools for overall quality management for ensuring and enhancing product and workshop quality contain tools such as: TWM (Total Welding Management), Lean production and Six Sigma. These can be used to test and reveal problems of a company’s production. (Martikainen, 2013, p.9.)

Standard set EN-ISO 3834 and EN-ISO 9000 are important for companies which want quality to correlate even in big international projects. EN-ISO 9000 is an international standard set which shows how to manage organizational functions both in quality and quality assurance aspects. EN-ISO 3834 regulates quality control aspects in welding and works with EN-ISO 9000 or as a standalone standard set. ISO-EN 3834 shows quality aspects for manufacturing and installing of products in which welding is used and shows the amount of documentation needed to fulfil requirements for different welding projects. (Martikainen, 2013, p.7-8.)

7 EXPERIMENTAL TESTING

Experimental testing was done in the welding laboratory of LUT with setup shown in Figure 19.

Welding machinery used for the experimental testing phase is:

- Two KempArc DT400 wire feeder units
- Two KempArc Pulse TCS power sources
- Kemp Cool 40 cooling unit
- Pemamek welding column
- Binzel welding head D15

Figure 19. Welding setup in the welding laboratory of LUT.

Four different arc modes were used to test which yielded the best possible results:

- Pulsed – Pulsed
- Synergic – Synergic
- Pulsed – Synergic
- Synergic – Pulsed

The main parameters used for controlling the welding procedure included the arc length and the welding speed. The power sources, in Figure 20, has synergic 1-MAG welding programs which were used and has parameters wire feed rate, dynamics and fine tuning.

Figure 20. KempArc Pulse TCS power sources and Kemp Cool 40.

Wire feeder unit can be seen in Figure 21 and welding column used can be seen in Figure 22. The tandem welding head from Binzel is shown in Figure 23.

Figure 21. KempArc DT400 Wire feeder units.

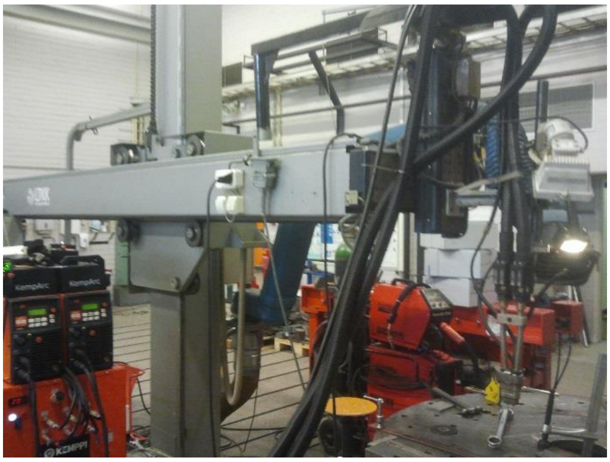

Figure 22. Power sources, cooling unit, welding column and torch.

Figure 23. Binzel D15 tandem welding head.

7.1 Experimental plan

Aim of the research is to weld offshore steel E500 TCMP from Ruukki with tandem MAG so, that the air gap and volume of the single-V butt weld is as small as possible while using around 0.8kJ/mm and 2.5 kJ/mm heat input. The testing will be done in flat position and it is started with groove angle of 30 degrees and the angle is decreased during tests by 5 degree increments. Air gap used in similar welding of thick plates is around 8 mm and at the first work pieces the air gap width possibilities will be examined. Welding class B is set as a goal for the welds. Pulsed and synergic programs will be tested to see which of the possible arrangements proves to produce the best results. The thickness of the material influences possible arc lengths because the air gap and groove diameter may affect how deep in the gap the welding torch can be aligned in. Initial tests will be done to find out penetration in correlation to welding speed. At the start of the research 1.2 mm OK AristoRod 12.50 filler wires will be used for defining better parameters and welding work pieces are made of S355K2+N Ruukki Multisteel. After this the material to be tested in this research, E500 TMCP will be used with two 1.2 mm OK AristoRod 13.26 filler wire reels. P_{cm} for E500 TMCP is 0.19. The shielding gas which is used is M21 Mison 18 (Ar + 18% CO_2 + 0.03% NO). Welding will be done with ceramic and copper backing. Ceramic backing used in the testing is PZ1500/81. Chemical composition of the base material E500

TMCP steel can be found in Table 4 along with filler wire compositions. OK Tubrod 14.02 composition which was used in one of the welding tests alongside OK AristoRod 13.26 can also be found in the table. Table 5 shows the mechanical properties of the aforementioned filler wires and base material. For further information Certificate, Mill sheet and test certificate, Test report and Analysis certificate can be found as whole in appendices 1-4.

Table 4. Chemical composition of base material and wires used in testing including metal cored filler wire used in one of the tests.

Chemical composition	Ruukki - E500 TMCP [%]	OK AristoRod 13.26 1.2 mm [%]	OK Tubrod 14.02 1.2mm [%]
C	0.070	0.11	0.07
Si	0.28	0.90	0.51
Mn	1.49	1.49	1.27
P	0.008	0.014	0.007
S	0.000	0.013	0.014
Al	0.041		
Nb	0.035		<0.01
V	0.011		0.01
Ti	0.015		
Cu	0.296	0.49	0.02
Cr	0.008	0.14	0.02
Ni	0.76	0.9	0.02
Mo	0.012	0.03	0.48
N	0.004		
B	0.0002		
Sn	0.001		
Pb	0.000		

Table 5. Mechanical properties of base material and the wires used in testing including metal cored filler wire.

Mechanical properties	Ruukki - E500 TMCP [%]	OK AristoRod 13.26 1.2 mm [%]	OK Tubrod 14.02 1.2mm [%]
Re [MPa]	574	540	588
Rm [MPa]	663	625	663
Elongation %	16-20	25	26
Impact energy and temperature	256 J/ -40 °C	50 J/ -60 °C	79 J/ -20 °C

Figure 24 shows the alignment of the wires as seen from the top compared to welding direction to emphasize the angles used in welding tests. In preliminary plans welding was planned to be done with the leftmost setup until widening groove presents the need to adjust the setting in order to successfully weld the upper bead layers. As later stated root pass would be done with the leftmost setup and depending on the heat input in second or third bead rightmost setup would be used.

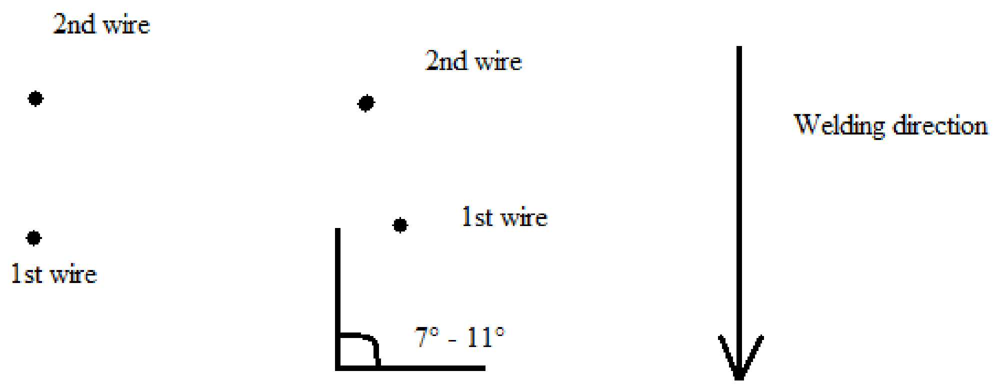

Figure 24. Alignment of wires in tandem welding torch as seen from top when welding direction is shown with arrow.

7.2 Testing materials and welding tests

Sawing was used in joint preparation with custom made backings to support the work piece at the correct angle. After this phase the work piece was deburred with belt grinding machine and angle grinder. This is shown in Figure 25 and Figure 26.

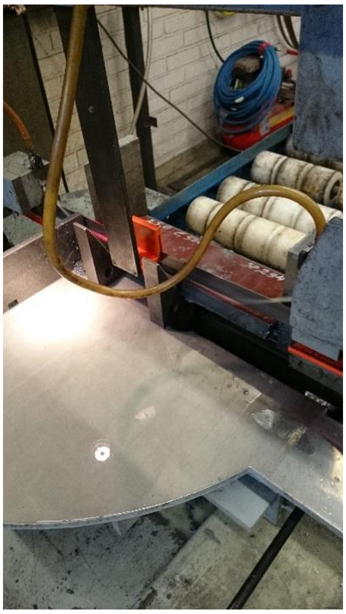

Figure 25. Work piece joint preparation

Figure 26. Sawing the joint to correct angle

Welding tests were started with emphasis of finding suitable welding parameters for narrow gap welding. Testing was started with welding of 25 mm thick S355K2+N Ruukki Multisteel plates and the filler wires used at first were both OK AristoRod 12.50.

The first welding test on 30º groove showed good results with air gap around 2 mm. In the aforementioned work piece the air gap was narrower at the start and wider at the end. This was taken as a starting point for air gap for next weld tests. The work piece preparations were done according to outcomes of the tests. Preparations were done by welding a plate at the end of the test piece while the test piece was clamped to the testing table and the air gap width was measured. This is shown in Figure 27 and Figure 28.

Figure 27. Preparation for welding and root gap measurement.

Figure 28. Work piece prior welding with 30º groove angle.

After the work piece preparations it was mounted on the table with adjustable clamping seen in Figure 29. The actual mounting of the work piece was done as seen in Figure 30. Different combinations of mounting were tried as seen in Figure 31.

Figure 29. Mounting system prior attaching the work piece.

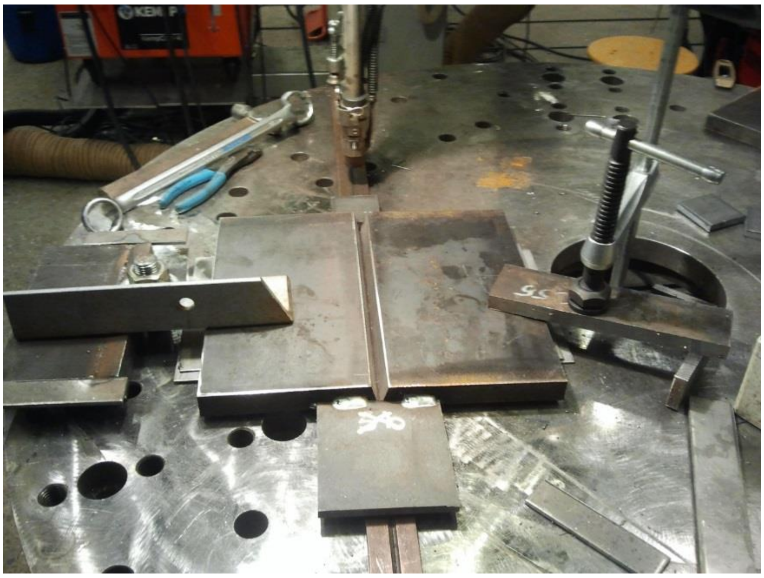

Figure 30. Work piece ready for welding.

Figure 31. Different style of mounting.

Preliminary tests were done by surface welding a test piece to find out behavior of the arcs and weld pool when the welding head is rotated so, that the first and second arc travel slightly different paths because of slight angle change. This would result in wider weld pool which is needed to fill the wider gap resulting from groove being filled.

Gas flow rate tests were performed by surface welding a test piece in order to prevent gas pore build-up. At first the pores would be present in the root pass when magnetic arc blow occurred and later the gas pore build up could be seen around the last bead layers. Gas flow rates and results from the test can be found in chapter 8.1.

In the root pass tests done, various kinds of grounding set-ups were used, however but it had no noticeable difference. Gas pores and close-up of pores can be found in Figure 32, Figure 33 and Figure 34.

Figure 32. Spatter and welding gas problems with 15 L/min + 15 L/min gas flow rates.

Figure 33. Gas pores near the end part of work piece due to gas problems and problems caused by magnetic arc blow while welding with 0.8 kJ/mm and gas flow rates of 20 L/min + 15 L/min.

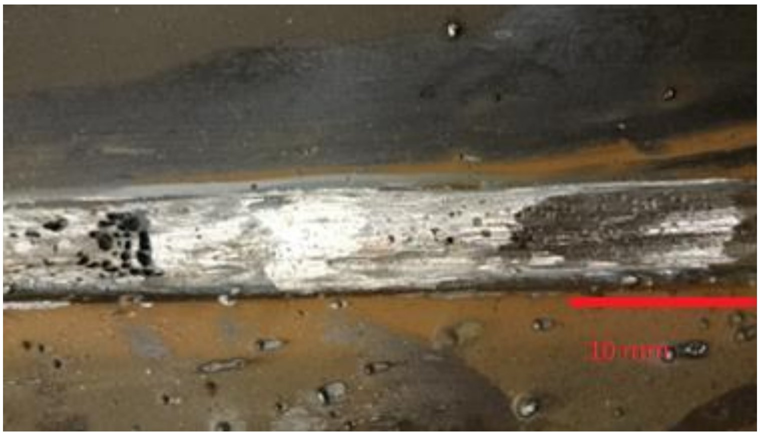

Figure 34. Close-up of gas pores beneath the weld surface after grinding while welding with 0.8 kJ/mm and gas flow rates of 20 L/min + 15 L/min.

Welding the root pass for 25 mm thick plate with narrow gap presented requirements for the possible arc lengths and placement of the welding head. The height setting was to have contact tip at the same height as work piece surface with arc length of 25 mm. Spatter due to poor torch placement can be found in Figure 35. While welding the upper bead layers shorter than 25 mm arc lengths were used to ensure better quality weld. At the same time the gas flow rates were increased. Difference in shielding gas diffusers which were used in testing was that the shorter version is 22 mm long and the longer version is 28 mm. Longer versions were used while welding the root pass and shorter for the rest of the beads.

Figure 35. Spatter due to wrong torch placement in the welding gap

Copper backing was used in the preliminary tests. On the later stages of testing ceramic backing was used and it was seen that overall spatter and effects of magnetic arc blow seemed to appear less. Ceramic backing which was used was of type PZ1500/81. Backing has rectangular groove for all position welding and had 25 mm long ceramic blocks in a tape.

Few of the first welding tests led to good penetration but resulted also in hot cracking in the root pass. The phenomenon is shown in Figure 36. This test piece had around 100 mm long crack and along with some other work pieces it was tested with penetrant fluid test.

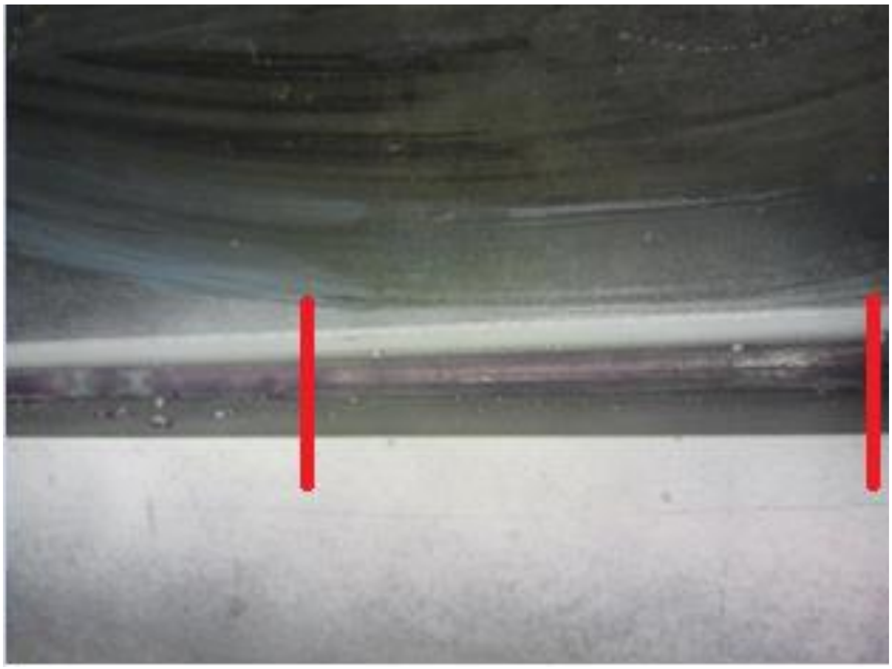

Figure 36. S355 root crack seen with penetrant fluid test between two red markers

The root run presented difficulties since many of the work pieces had good enough penetration in the midsection but too little penetration at the last third of the work piece and somewhat too much on the first third. Since there was variable results even with no significant changes in the welding parameters and setup, steps were taken to reduce the variance in the results. In the test phase this meant starting the welding on the fly or by igniting the arc before the movement of the welding head was started. Starting positions were varied and creep start levels were changed in the Kemppi power source. Creep start was used to smoothen the starting phase of the welding. Also the possibility to weld two plate pieces in an angle to the end pieces as a continuation for the groove was discussed but not tried out in the tests. Root pass welding problems can be seen in Figure 37.

Figure 37. Example of root bead problems where the first part of the weld showed excessive penetration on the right, middle section had stabilized and visually good root while the end part had too little penetration on the left.

A disturbance in the arc from magnetic arc blow or other reasons easily cascaded and resulted in even more disturbances. This can be found in Figure 38 where small disturbance in the arc resulted in few spatters which in turn resulted in stopping the welding run at the midsection of the work piece due to increased spatter.

Figure 38. Increased spatter due to magnetic arc blow and arc disturbances. Spatter started to affect the welding in the middle section of the weld so that the welding pass had to be stopped.

Tests were done using OK AristoRod 13.26 as the leading filler wire and using 1.2 mm metal cored filler wire OK Tubrod 14.02 as the trailing wire. Figure 39 and Figure 40 show the outcomes with welding S355. In the Figures OK AristoRod 13.26 filler wire was leading when welding from left to right and metal cored filler wire OK Tubrod 14.02 was leading with reversed parameters when welding from right to left. Noticeable differences were that at least with the parameters tested, leading with metal cored filler wire caused more spatter on the work piece and less penetration. With the parameters tested, penetration was larger while using OK AristoRod 13.26 as leading wire. These parameters for the wires were not tested except on this work piece.

Figure 39. Test with metal cored filler wire OK Tubrod 14.02 and OK Aristorod 13.26 – root leading with OK Aristorod 13.26 showed deeper and wider penetration. Both of the wires had diameter of 1.2 mm.

As Miller stated (2015) solid wire provides deep penetration and according to test shown in Figure 39 leading with solid wire with same parameters made the root bead penetration deeper.

Figure 40. Test with metal cored filler wire OK Tubrod 14.02 and OK Aristorod 13.26 – welding direction from right to left leading with metal cored filler wire resulted in more spatters.

Weld cooling time from 800 Celsius to 500 Celsius was measured by putting the measuring wire into the weld pool and results for this can be found in Figure 41 and how it was measured in Figure 42. Test was repeated twice with parameters resulting in 2.2 kJ/mm heat input by the means of deposition welding. Parameters can be found in Table 6. Parameters used in the weld beads concerning the cooling were:

Table 6. Parameters for cooling time test

Process	Synergic	Synergic
Arc length	23 mm	
Gas flow rate	25 L/min	20 L/min
Welding speed	0.47 m/min	
Wire feed rate	8.5 m/min	11.5 m/min
Fine tuning	-1	-0.5
Dynamics	-4	-3

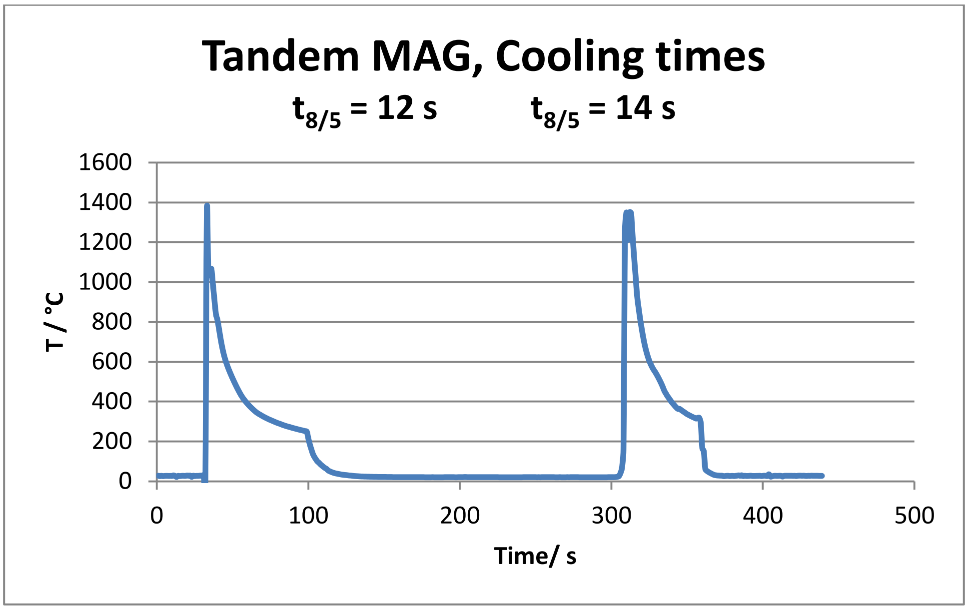

Figure 41. $t_{8/5}$ Cooling times for Tandem MAG welding with 2.2 kJ/mm heat input. The figure shows two tests recorded with same parameters on both welds.

Figure 42. Weld cooling time measurements from 800 Celsius to 500 Celsius.

In the preliminary tests Pulse – Pulse, Synergic – Synergic, Pulsed – Synergic and Synergic – Pulse program combinations were used. Synergic program in the first power source with pulse program in the second provided the best penetration and most reliable root pass. While defining the parameters rest of the beads the synergic program used in both of the power sources was seen as best option. In the root pass using Wise fusion in the first torch made the arc more stable. Longer gas shielding nozzle was used while welding root passes and shorter one was used in other weld beads.

In the research of Fang et al. (2012, p. 80-83) using pulsed arc modes on both of the wires led to minimization of the magnetic arc blow related problems, but during this testing process filling passes were done with synergic programs used in both arcs since the welds done with two pulsed arc modes did not provide good quality welds in the earliest tests.

Figures 47 to 53 show the welding procedure in full extent for work piece D35 and Figure 43 shows the root pass. The root pass was done with 25 mm contact tip to work distance with longer shielding gas nozzles in the tandem welding head. The root pass and the second pass were done without any changes in angles in the welding head. The second bead can be seen in Figure 44. The parameters used in welding the root pass and rest of the beads can be found in Table 7:

Table 7. Parameters for welding of test piece D35 for all of the bead layers.

	Process	Wire feed rate [m/min]	Current [A]	Fine tuning	Voltage [v]	Dynamics	Pulsed current percentage [%]	CTWD [mm]	Gas flow rate [L/min]	Air gap width [mm]	Welding speed [m/min]
Root Pass – D35.1											
Leading wire	Synergic	10.2	289	-1.5	28.9	-2		25	15	2	0.67
Trailing wire	Pulsed	8.2	236	-1	29.3	-5	5%		15		
2nd bead – D35.2											
Leading wire	Synergic	8.5	242	-1	30	-4	-	23	25	-	0.47
Trailing wire	Synergic	11.5	291	-0.5	32.3	-3	-		20		
3rd bead – D35.3											
Leading wire	Synergic	8.5	242	-1	30	-4	-	19	25	-	0.47
Trailing wire	Synergic	11.5	291	-0.5	32.3	-3	-		20		
4th bead – D35.4											
Leading wire	Synergic	8.5	242	-1	30	-4	-	19	25	-	0.47
Trailing wire	Synergic	11.5	291	-0.5	32.3	-3	-		20		
5th bead – D35.5											
Leading wire	Synergic	8.5	242	-1	30	-4	-	19	25	-	0.47
Trailing wire	Synergic	11.5	291	-0.5	32.3	-3	-		20		

Compared to the research of Fang et al. (2012, p. 80) wire feed rates, voltages and welding speed are similar. In the research air gap width was 3 mm. In their research gas flow rate of 30 L/min was used. The main difference in parameters is that leading wire had synergic mode and not pulsed as in their research.

Figure 43 Test weld D35.1 – Root pass after welding.

In the process of welding the second bead CTWD was reduced to 23 mm and parameters were changed. In this test piece only arc length and angle of the welding head was changed in the beads following the first one.

While in the research of Fang et al. (2012, p. 80-83) both the trailing and the leading wire were pulsed it was seen in the welding tests that synergic – synergic combination had the best outcome. Also noteworthy was that during the filling passes the leading wire had less wire feed rate than trailing wire. This was seen to lead with less spatter and better weld quality and weld bead shape.

Figure 44. Test weld D35.2 – Second pass after welding.

On the third bead the tandem welding head was turned 7° around its vertical axis, this can be seen in Figure 45. The leading wire is closer to the middle section of the groove and the trailing wire is 2 mm from the groove side to prevent undercutting which the first arc sometimes caused. Figure 46 shows the welded third bead with CTWD of 19 mm.

Ueyama et al. (2005, p. 1-2) mention undercutting as one of the problems which are caused by high welding currents and welding speeds which are typical to tandem MAG welding. In their research the undercutting was dealt with by using pulsed – pulsed arc modes and choosing the correct chemical composition for the filler wires.

Figure 45. Angle of the welding head before welding the third bead - D35.3 with 7 degree angle between the wires and the welding direction.

Figure 46. Test weld D35.3 – Third bead after welding.

Fourth weld bead was welded with same 7º turn of the torch but as mirror image of the earlier bead with arc length of 19 mm. The weld can be found in Figure 47.

Figure 47. Test weld D35.4 – fourth bead after welding.

While welding the fifth bead the angle used to turn the welding head in its travelling direction was 20º. While the CTWD remained 19 mm. The positioning of the welding torch can be found in Figure 48 and the final outlook of the work piece in Figure 49.

Figure 48. Angle of the welding head before welding the fifth bead - D35.5 with 20**º** angle between the wires and the welding direction.

Figure 49. Test weld D35.5 – fifth bead after welding.

Example of a good root pass done while igniting the arcs while welding speed was still stopped with first wire already slightly in the groove can be seen in Figure 50 with the parameters of Table 8.

Table 8. Parameters for root pass D37.

<table>
<tr><th></th><th>Process</th><th>Wire feed rate [m/min]</th><th>Current [A]</th><th>Fine tuning</th><th>Voltage [v]</th><th>Dynamics</th><th>Pulsed current percentage [%]</th><th>Arc length [mm]</th><th>Gas flow rate [L/min]</th><th>Air gap width [mm]</th><th>Welding speed [m/min]</th></tr>
<tr><td>Leading wire</td><td>Synergic</td><td>10.2</td><td>297</td><td>-1.5</td><td>29.5</td><td>-2</td><td rowspan="2">5%</td><td rowspan="2">25</td><td>15</td><td rowspan="2">2.6</td><td rowspan="2">0.67</td></tr>
<tr><td>Trailing wire</td><td>Pulsed</td><td>8.2</td><td>240</td><td>-1</td><td>28.8</td><td>-5</td><td>15</td></tr>
</table>

Figure 50. Example of succesful root pass quality

Figure 51 and Figure 52 the start and end points of the mentioned root pass. The figures show that upon visual inspection the root pass was successful. But however on the further tests, there were still problems with magnetic arc blow on the last 100 mm of the work pieces and some of the root passes done were not good enough. Thus repetition with the same parameters resulted in welds, which were unreliable in terms of quality control.

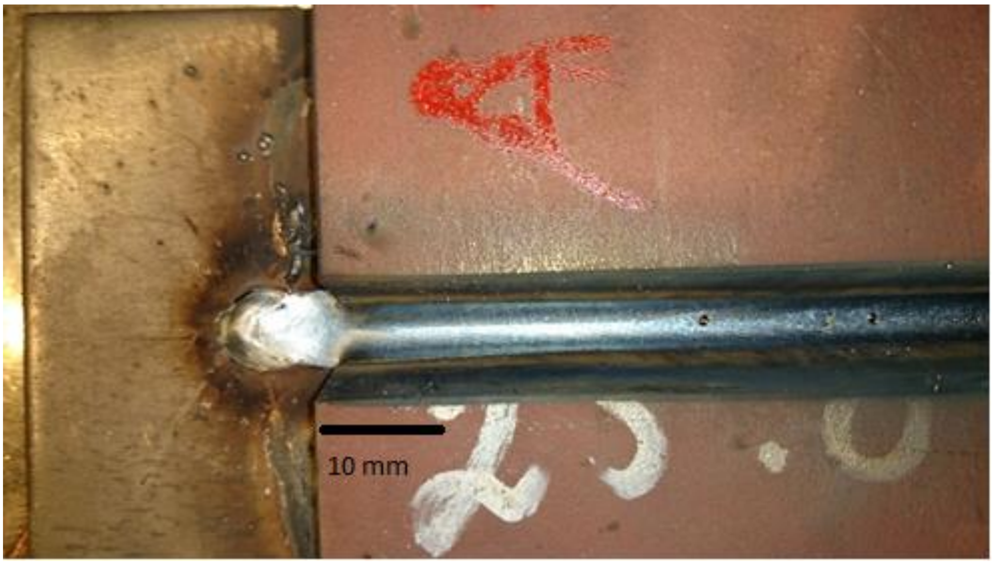

Figure 51. Close up of start section in root weld of D37.1 – smooth start without arc disturbances.

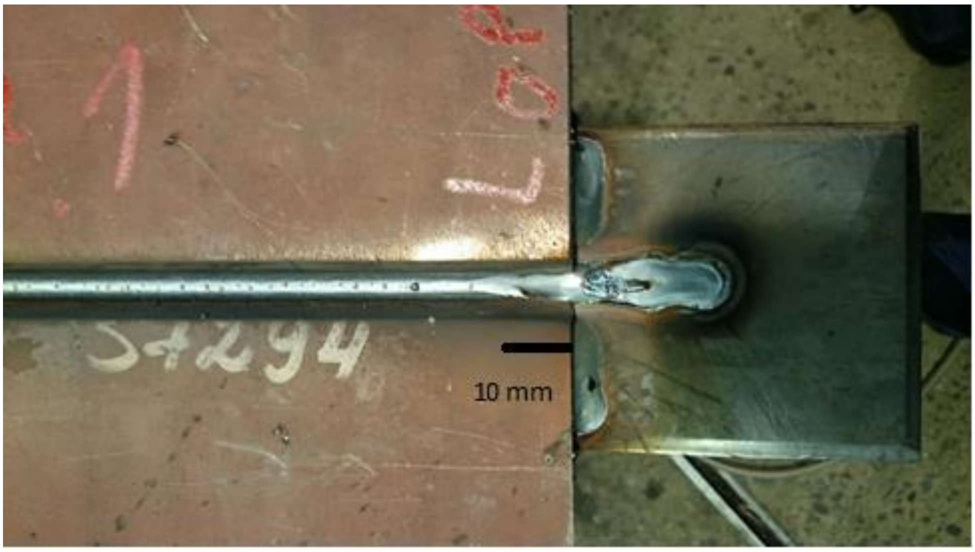

Figure 52. Close up of end section in root weld of D37.1 – smooth end of the weld because arc disturbances did not result in spatter and cascading impurities or gas problems.

7.3 Non-destructive and destructive testing

During welding tests non-destructive testing was done with visual and radiographic methods. Destructive tests were done with final testing pieces for both test pieces with heat input of 0.8 kJ/mm and 2.5 kJ/mm. These destructive tests contain transverse tensile test according to EN ISO 4136 and ISO 6892-1, transverse bend test according to EN ISO 5173 + A1, impact test according to EN ISO 148-1, EN ISO 9016 and also RS rules for impact test, hardness test according to EN ISO 9015-1 and macroscopic examination. Quality of the weld was not consistent during different test pieces e.g. due to disturbances in the arc. Thus, during testing, it was perceived that weld defects must be accepted in radiographic and visual testing in order to have enough test specimens for destructive testing. Selection was done to ensure testing of the best test pieces and manufacturing of test specimens.

Test specimens were machined from test pieces D32 and D41. D32 was welded with parameters which resulted in heat input of 2.5 kJ/mm and it was welded with 5 beads. D41 was welded with parameters which resulted in heat input of 0.8 kJ/mm and it was welded with 11 beads. In the tests A, B, C and D letters were used to describe arc modes used on root pass and consecutive numbering was marked for each test weld. A stands for Pulse – Pulse, B for Synergic – Synergic, C for Pulsed – Synergic and D for Synergic – Pulsed. Test specimens which were chosen for non-destructive tests and destructive tests had root passes welded with Synergic – Pulsed setup.

8 RESULTS AND DISCUSSION

In this chapter test results are analysed and discussed. All tests were done on LUT premises. Tests specimens were taken from test pieces D32 and D41. The parameters involved in welding of the work pieces can be found in pWPS figures 62 and 63.

8.1 Welding procedure related results

In this chapter results and problems found during welding tests are discussed with emphasis on results that were not straight connected to the destructive tests.

8.1.1 Grounding, gas flow rates and pores

As the testing ensued it was found out that better results in the case of spatter came with adjusting the clamps nearer the end of the work piece compared to middle or at the start of the work piece. The style of mounting may influence the magnetic blow and grounding of the work piece may work different because of it. All of the work pieces in the testing process had both start and end parts to help countering magnetic arc blow. Different grounding set-ups were used but without noticeable differences. This gas flow rate test can be seen in Figure 53. Tests were done with 2.5 kJ/mm heat input parameter set.

Gas flow rates for the Figure 53 where the leftmost one is test number 1 is shown in Table 9. Fifth and sixth beads were done with different torch alignment towards the direction of travel. Weld number 4 showed porosity towards the end of the test piece, otherwise notable differences in porosity between gas flow rates were not found. It was found out, that the gas flow rates which were used with parameters resulting in higher heat input were not suitable for welds done with 0.8 kJ/mm heat input. While welding fifth and sixth beads in the groove torch was turned along its’ axis and molten pool managed to slip out of position between the arcs. That resulted in wave like formation of the weld and pores in the places where molten pool moved suddenly out of position.

Table 9. Gas flow rates for first and second arc in the tandem welding torch

Weld No.	Gas flow rate for first arc [L/min]	Gas flow rate for second arc [L/min]
1	20	20
2	15	15
3	25	25
4	25	25-10 (changed manually during welding
5	20	20
6	25	20

Figure 53. Gas flow rate test with parameters of 2.5 kJ/mm heat input.

When testing the welding parameters which provided 0.8 kJ/mm heat input, it was noticed that gas pores began to emerge in the tests around seventh bead. Gas pores occurred near seventh or eighth bead and most of the times could not be seen during welding from the front, only from the behind and most notably between first and second arc. The pores emerged mostly on the latter half of the bead near the end of the work piece. Magnetic arc blow was suspected to be at least a partial reason. The porosity was corrected by increasing gas flow rate when welding beads near work piece surface. The amount of gas flow which gave the best results was 30 L/min for the first arc and 25 L/min for the second arc. Since magnetic arc blow and the resulting interference in the arc might have caused the porosity in the work piece, changing places of the grounding clamps and where those were situated might make a difference.

8.1.2 Torch alignment angle compared to travelling direction

The test results for discerning usable angles for the tandem torch can be seen in Figure 54. Turning the torch resulted in wider weld but also could cause material in the weld pool to move between the first and second arc which lead to wave like end result which can be seen on the second rightmost test in Figure 54. In this case the second arc would push the molten metal out of its way and the outcome would become unreliable. The parameters involved in 2.5 kJ/mm heat input allowed the torch to be turned more than the 0.8 kJ/mm parameters. The angle for the welding head compared to travelling direction used in the final test was around 7-10 degrees starting from third or fourth bead.

Figure 54. Test of usable angles of tandem MAG in surface welding.

8.1.3 Contact tip and torch vertical positioning

If the contact tip was situated lower than the work piece surface slight disturbance in the arc could easily cause spatter to stick on the nozzle and welding result would be poor and cause nozzle to be changed. The way to counteract this, longer shielding gas diffusers were used for welding the root run and then changed to shorter model for the rest of the bead layers. The gas shielding and vertical positioning of the nozzle had effect on each other since the gas flow may be different with contact tips moving deeper in the groove.

8.1.4 Heat input and parameter related problems

During welding testing it was seen that the process of welding sometimes had three distinct stages during welding of root pass of the test piece. The first 100 mm were susceptible to problems due overt penetration while the mid-section was seen as most reliable to weld concerning penetration. In the last 100 mm of the weld, disturbances in the arc were seen which caused spatter, insufficient penetration and visibly smaller, tightened arc near the end of the test piece. These may be a result from magnetic arc blow to some extent. In test pieces where this occurred the root was usually not good enough according to visual and radiographic testing.

0.8 kJ/mm heat input caused gas pores to begin to emerge when the amount of gas flow was incorrect. Welding with less heat input can be said to need more precise positioning of the welding torch and more gas flow than while welding with 2.5 kJ/mm heat input. Positioning of the welding torch was critical especially in the welding of bead layers closer to work piece surface to ensure that no undercutting or lack of sidewall fusion occurred.

Parameters for welding the root pass caused hot cracking at the start of the research but the cracking was solved by correcting weld bead height to width ratio.

8.1.5 Air gap, bead layers and geometry of the groove

Difficulties in welding of the root pass were lessened with the making the air gap smaller at the end part and wider at the start. The results were inconclusive and some test pieces which were welded had satisfying root bead and some, even with same parameters, had unacceptably poor outcomes. Best outcome was gotten through realization that after igniting the arc on the plate piece welded to work piece the molten pool could maybe collide with the edges along the groove facing towards the travelling direction and cause interference in the weld pool entering the groove. Some tests were done to confirm this by placing the first contact tip couple of millimeters in the groove so the first arc would start inside the groove before movement of the welding head started. This lead to good root beads on the test pieces.

In the tests performed less than 30º groove angles were not welded successfully. Factors which had an effect of this result related to the arc not being stable in the groove and initial gas flow problems connected to the values of gas flow rate or possibly geometry of the groove. While root pass was difficult to weld the narrower groove was, the more precise initial positioning of the tandem welding torch was required and still arc could jump to sidewall while welding. This would in turn result in insufficient penetration in the root.

8.1.6 Results from using 1.2mm diameter OK Tubrod 14.02 in conjunction with 1.2 mm diameter OK AristoRod 13.26

With the parameters tested, leading with OK AristoRod 13.26 wire caused fewer spatters on the work piece and deeper penetration. Even that the initial tests with metal cored filler wire with solid filler wire were not successful, further research might provide useful insight into matter. One possibility would be to weld the root bead with solid filler wire as the first wire and use metal cored wire as second, while reversing the movement direction for rest of the bead layers. This way time welder could exploit the benefit of leading with well penetrating solid wire for root pass welding purpose and having the benefit of larger, round molten droplet which results in round penetration profile while welding the rest of the bead layers. Using two OK AristoRod 13.26 filler wires was seen as more reliable than this setup but using metal cored filler wire as a second wire might be an interesting line of further research.

8.2 Welding procedure test

Transverse bend test according to 5173 + A1:

Transverse bend test was done in 20 ºC. Diameter for the former was 45 mm and distance between the rollers was 70 mm. The results can be seen in Table 10 and whole transverse bend test document in Appendix 5.

- D32.1 failed with bending angles (63°, 37°, 180°, 53°)
- D41.1 failed with bending angles (71°, 76°, 180°, 89°)

Table 10. Transverse bend test results.

Specimen	Type of test	Dimensions	Former diameter	Distance between rollers	Bend angle
No		mm	mm	mm	°
D32. 1	SBB	10X25	45	70	63
D32.2	"	"	"	"	37
D32.3	"	"	"	"	180 (passed)
D32.4	"	"	"	"	53
D41.1	SBB	20X25	45	70	71
D41.2	"	"	"	"	76
D41.3	"	"	"	"	180 (passed)
D41.4	"	"	"	"	89

It can be seen that with parameters involving test pieces welded with heat input of 0.8 kJ/mm two test pieces broke from between top bead layers. This could be caused by lack of sidewall diffusion since the torch positioning had to be more precise. One test piece broke from root side HAZ. Test piece which broke from the root side had minor imperfection in the root which might have caused the crack to propagate. In the test specimens with 2.5 kJ/mm heat input from D41.1 the cracks propagated from root side of the welded section. The test specimens used would not have passed visual and radiographic inspection since the weld specimen had significant insufficient penetration.

Nadzam (2002, p. 1) describes benefits of using pulsed arc mode and couple relating to this research would be that typically pulsing causes less spatter and issues incomplete fusion are not so likely. On that aspect, using pulsed arc modes during the filling passes could have related to better quality in the transverse bend tests.

<u>Transverse tensile test according to EN-ISO 4136 and ISO 6892-1:</u>

According to RS rules 16 percent elongation is the lowest elongation to be accepted in tensile test piece. All of the specimens had elongation values above this with lowest elongation percent of 16.6 in specimen D32.2. RS rules can be found in Table 1 and Table 2. All specimens broke from base material (BM). Thus it can be stated that specimens passed the transverse tensile test.

The results can be seen in Table 11 and whole transverse tensile test document in Appendix 6.

Table 11. Transverse tensile test results.

No		Cross-sectional area	Yield load	Yield strength	Breaking load	Ultimate tensile strength	Elongation	Location
	mm	So [mm^2]	Fe [kN]	Re [N/mm^2]	Fm [kN]	Rm [N/mm^2]	A [%]	
D32.1	9,7X25,6	248,61	135	543,0	157,2	632,3	21,5	BM
D32.2	10X25,5	255,3	137	536,6	160,8	629,8	16,6	BM
Mean				539,8		631,1	19,0	BM
D41.1	8,4X25,8	215,86	117	542,0	134,6	623,6	21,4	BM
D41.2	9,9X25,8	255,12	133	521,3	150	588,0	20,8	BM
Mean				531,7		605,8	21,1	BM

Transverse tensile test specimens were chosen from better quality area according to visual and radiographic inspection of the welding test pieces than transverse bend test specimens. Elongation percentages seem good with the exception of D32.2 test specimen which had lower elongation percentage compared to other specimens. The ultimate tensile strength varied from 588 N/mm^2 to 632.3 N/mm^2. The results can be said to be good and this is supported by the fact that fracture propagated in the base material.

<u>Impact test according to EN ISO 148-1 and RS rules:</u>

RS rules state that in -40 ºC E500 high strength steel should have impact energy over 33 J while using transverse impact test specimen. Limits can be found in Table 1 and test results in Table 12. This limit is exceeded and impact test was passed. The results can be seen in Table 12 and whole impact test document in Appendix 7. VWT describes Charpy V-notch with notch in the weld metal and the notch is positioned through the thickness. VHT means Charpy V-notch with notch in the HAZ while notch is positioned through the thickness. First number in the notch type describes the distance of the notch center from the centerline of the weld. Second number means the distance of the nearer test specimen face from the weld joint face.

Table 12. Impact test results

No	Type of notch	Test piece Size	Conditioning temperature of the test piece	Absorbed energy [J]	Broken from
D3211	VWT0/2	10X10X55	-40	65	W
D3212	"	"	"	51	"
D3213	"	"	"	48	"
Mean	VWT0/2	"	"	**55**	"
D3214	VHT1/2	10X10X55	"	178	HAZ
D3215	"	"	"	94	"
D3216	"	"	"	107	"
Mean	VHT1/2	"	"	**126**	"
D4111	VWT0/2	10X10X55	"	58	W
D4112	"	"	"	82	"
D4113	"	"	"	64	"
Mean	VWT0/2	"	"	**68**	"
D4114	VHT1/2	10X10X55	"	241	HAZ
D4115	"	"	"	276	"
D4116	"	"	"	211	"
Mean	VHT1/2	"	"	**243**	"

All of the specimens withstood impact energies over the limits mentioned in RS rules. Noteworthy aspect was that the lowest absorbed energy input was in test piece D32 with 48 J while in comparison the lowest absorbed energy in 0.8 kJ/mm test piece was 58 J. As expected, results varied more in the HAZ test specimens for both of the test sets. Test pieces which were welded with 0.8 kJ/mm heat input had better impact test results in both HAZ and weld area than their 2.5 kJ/mm heat input counterparts.

8.3 Hardness test and macrostructures

Hardness test was done according to EN ISO 9015-1. Figure 55, Figure 56, and Figure 57, Show hardness test results embedded in macrostructure pictures of test specimen welded with 0.8 kJ/mm. In Figure 57 the fourth measurement point does not show the correct hardness value due to movement of the test specimen during testing. Otherwise the hardness values in both test specimens behave as expected with highest hardness levels near HAZ on base material side with both test specimens. Appendices 8-10 show the exact hardness values in the tests for the following figures.

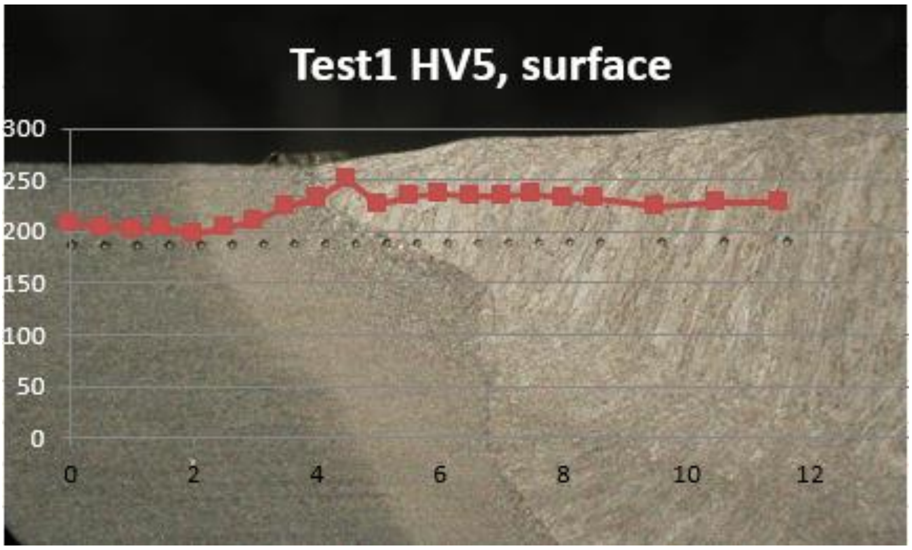

Figure 55. 0.8 kJ/mm hardness in surface.

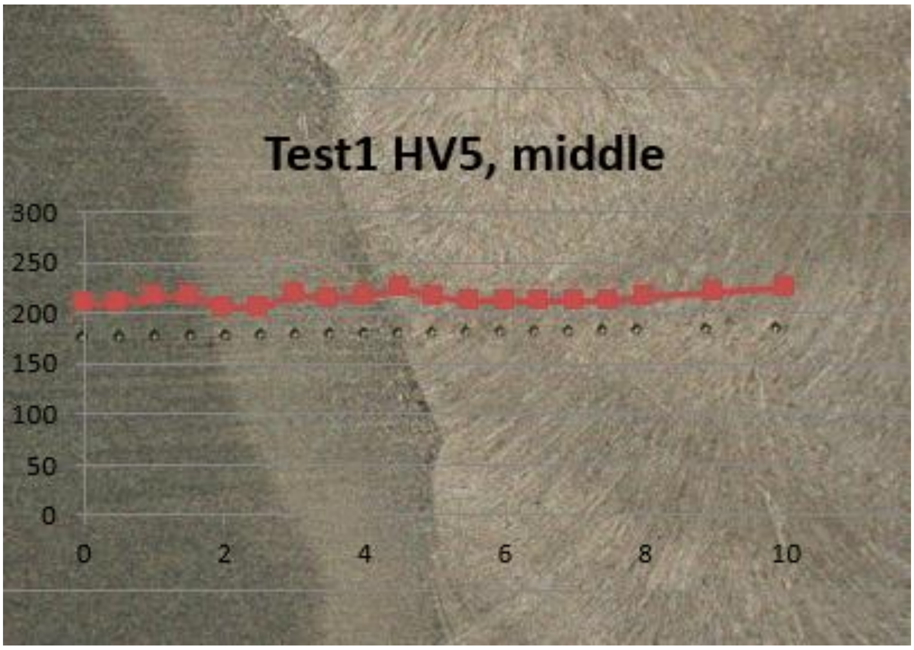

Figure 56. 0.8 kJ/mm hardness in middle section.

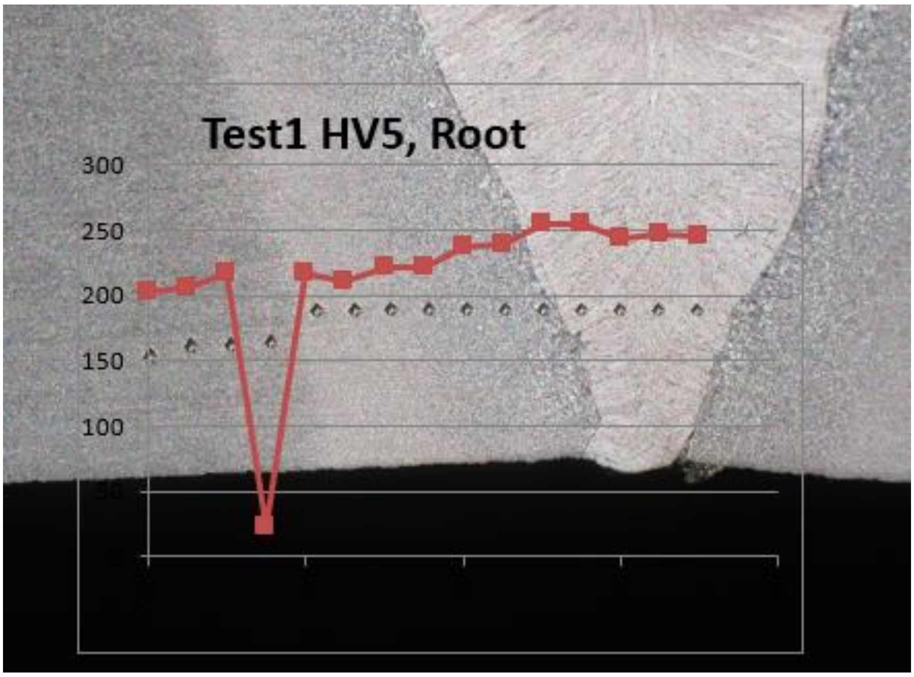

Figure 57. 0.8 kJ/mm hardness in root.

With 2.5 kJ/mm heat input the hardness values behave as expected and the hardness values range from 210 hv to 295 hv. Figure 58, Figure 59 and Figure 60 show embedded results of hardness test in macroscopic picture of base metal, HAZ and weld. In Figure 58 the first measurement point does not show the correct hardness value due to technical error.

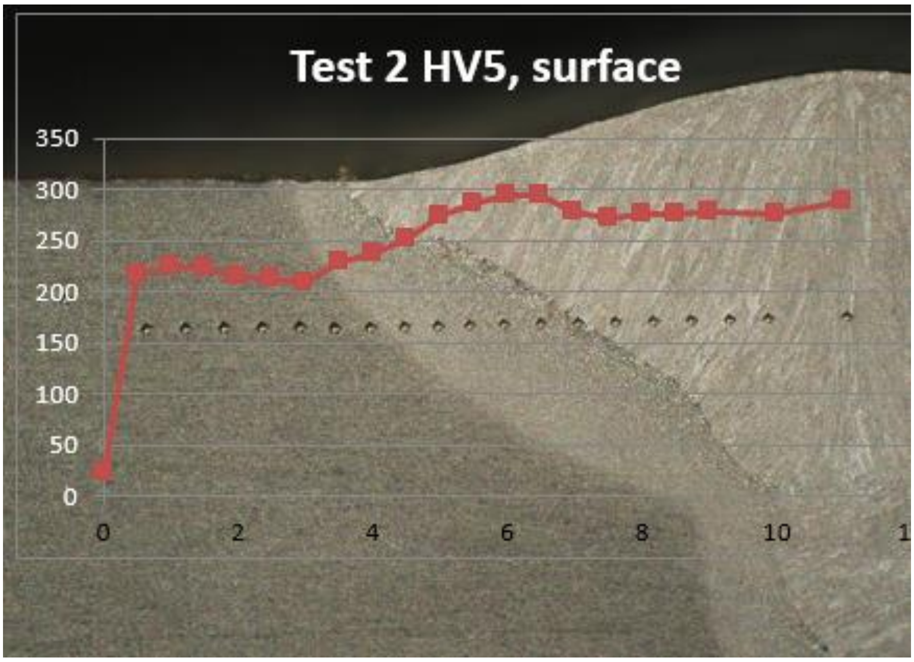

Figure 58. 2.5 kJ/mm hardness in surface.

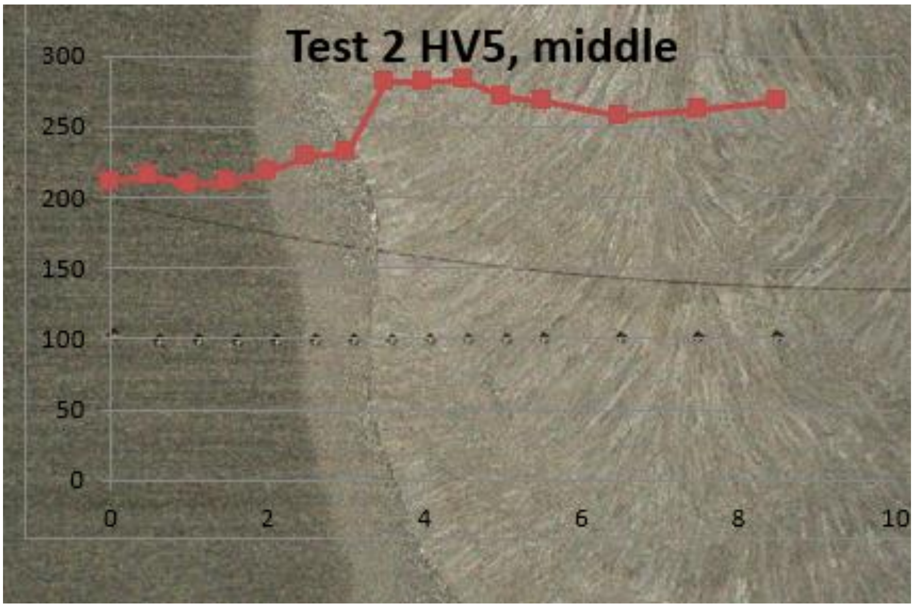

Figure 59. 2.5 kJ/mm hardness in middle section.

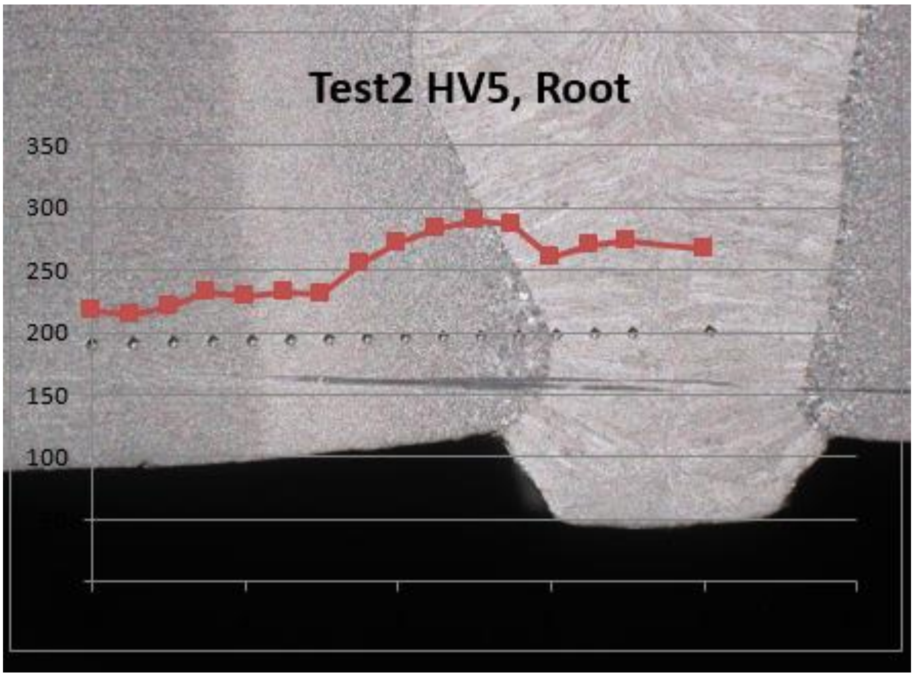

Figure 60. 2.5 kJ/mm hardness in root.

On the hardness test specimens welded with 2.5 kJ/mm heat input show higher variance in hardness in HAZ than the specimens welded with less heat input. As conclusion on hardness tests, higher heat input results in higher hardness values near HAZ but overall the results for both specimens are acceptable.

8.4 pWPS

pWPS was created for the test pieces D32 and D41, which can be found in Figure 61 and Figure 62. In these pieces, only angles which were changed during weld tests were the angles of the wires compared to the travelling direction. Gas flow rates which were used in the welding were 15 L/min + 15L/min for the D32 test piece and 15 L/min + 15 L/min for the D41 test piece root, 25 L/min + 20 L/min for D41 test piece beads 2-4 and 30 L/min + 25 L/min for D41 test piece beads 5-11. The welding test pieces which were machined for test specimens were chosen from the best test pieces.

Due to difficulties with welding of the root pass there were no test pieces which would have passed visual inspection and radiographic test for both the root bead and rest of the layers simultaneously. Surface crack detection was not done to these test pieces. Differences between welds were so high even with same parameters raises question if the pWPS’ can be seen as totally reliable. Also positioning of the torch and measuring of the angle of the wires compared to welding direction was done manually and may be affected by the measuring person. Welding with less heat input makes positioning more critical from several reasons. Some of these are possibility for lack of sidewall fusion, possibility of undercutting appearing and importance of using correct gas flow rates for the both arcs. Since the torch was manually turned to get it positioned in the correct angle the measurements have to be done by estimating the angle, measuring it and correcting as necessary, which may be time consuming.

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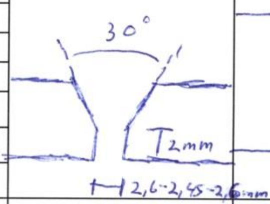
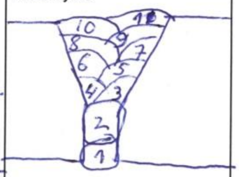
pWPS D41

Base Material	*Ruukki E500 TMCP*
Material Thickness	*25 mm*
Welding Process	*135* – MAG solid wire welding
Position	*PA*
Groove preparation	*Sawing*
Cleaning of the groove	*Grinding*
Mounting	*Clamps*
Tacking	*MAG*
Backing	*PZ1500/81*

Groove



Bead layers



Filler Metal and Welding Gas	
Filler metal specification	*EN USI 14341-A G0*
Filler wire market name	**OK AristoRod™ 13.26** ***Esab***
Shielding gas	**M21 Mison 18 (Ar + 18% CO_2 + 0,03% NO)**
Gas flow rates	***1. Arc 15-30 L/min*** ***2. Arc 15-25 L/min***

Notes: Angle between the wires compared to the travelling direction in joint details

Date and designer:
18.3 Ville Sandell

Bead	Process	Filler wire Ø	Current (A)	Voltage (V)	Travel speed (mm/s)	Wire feed speed (m/min)	Heat input (kJ/mm) CTWD (mm)	Joint details!
1	135	*1.2 mm*	*1. 317* *2. 243*	*1. 27,9* *2. 28,6*	*11,17*	*1. 10,2* *2. 8,2*	24	
2	135	*1.2 mm*	*1. 256* *2. 288*	*1. 30,7* *2. 31,9*	*18,3*	*1. 8,5* *2. 11,5*	23	
3	135	*1.2 mm*	*1. 246* *2. 282*	*1. 28,9* *2. 31,4*	*18,3*	*1. 8,5* *2. 11,5*	23	1 2 7°
4	135	*1.2 mm*	*1. 236* *2. 272*	*1. 28,6* *2. 31,5*	*18,3*	*1. 8,5* *2. 11,5*	23	2 1 7°
5	135	*1.2 mm*	*1. 246* *2..294*	*1. 28,8* *2. 31,5*	*18,3*	*1. 8,5* *2. 11,5*	19	1 2 8°
6	135	*1.2 mm*	*1. 248* *2. 287*	*1. 28,4* *2. 31,5*	*18,3*	*1. 8,5* *2. 11,5*	19	2 1 7°
7	135	*1.2 mm*	*1. 236* *2. 276*	*1. 28,3* *2. 31,5*	*18,3*	*1. 8,5* *2. 11,5*	19	1 2 9°
8	135	*1.2 mm*	*1. 240* *2. 293*	*1. 28,3* *2. 31,5*	*18,3*	*1. 8,5* *2. 11,5*	19	2 1 8°
9	135	*1.2 mm*	*1. 232* *2. 288*	*1. 28,9* *2. 31,5*	*18,3*	*1. 8,5* *2. 11,5*	19	1 2 8°
10	135	*1.2 mm*	*1. 230* *2. 287*	*1. 28,4* *2. 31,5*	*18,3*	*1. 8,5* *2. 11,5*	19	2 1 9°
11	135	*1.2 mm*	*1. 225* *2. 275*	*1. 28,4* *2. 31,5*	*18,3*	*1. 8,5* *2. 11,5*	19	1 2 8°

Customer	Accepted

Figure 61. pWPS for work piece D41. Welded with around 0.8 kJ/mm heat input with 11 beads and 7-9 degree angle of wires compared to travelling direction. The joint details – field shows the wire positioning so that the 1st wire is always closer to midsection of the weld.

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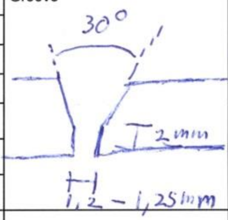
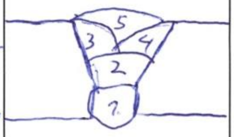
pWPS D32

Base Material	*Ruukki E500 TMCP*
Material Thickness	*25 mm*
Welding Process	*135* – MAG solid wire welding
Position	*PA*
Groove preparation	*Sawing*
Cleaning of the groove	*Grinding*
Mounting	*Clamps*
Tacking	*MAG*
Backing	*PZ1500/81*

Groove



Bead layers



Filler Metal and Welding Gas

Filler metal specification	*EN USI 14341-A G0*
Filler wire market name	**OK AristoRod™ 13.26**
	Esab
Shielding gas	**M21 Mison 18 (Ar + 18% CO_2 + 0,03% NO)**
Gas flow rates	*1. arc 15L/min* *2. arc 15L/min*

Notes: Angle between the wires compared to the travelling direction in joint details

Date and designer: *18.3 Ville Sandell*

Bead	Process	Filler wire Ø	Current (A)	Voltage (V)	Travel speed (mm/s)	Wire feed speed (m/min)	CTWD (mm)	Joint details!
1	*135*	*1.2mm*	*1. 313* *2. 242*	*1. 27,4* *2. 28,7*	11,17	1. 10,2 2. 8,2	25	
2	*135*	*1.2mm*	*1. 250* *2. 293*	*1. 30,1* *2. 32,2*	7,83	1. 8,5 2. 11,5	23	
3	*135*	*1.2mm*	*1. 240* *2. 309*	*1. 30,1* *2. 32,2*	7,83	1. 8,5 2. 11,5	19	2 1 8°
4	*135*	*1.2mm*	*1. 240* *2. 305*	*1. 30,1* *2. 32,3*	7,83	1. 8,5 2. 11,5	19	1 2 8°
5	*135*	*1.2mm*	*1. 211* *2. 297*	*1. 30,1* *2. 32,3*	7,83	1. 8,5 2. 11,5	19	2 1 12°

Customer	Accepted

Figure 62. pWPS for work piece D32. Welded with around 2.5 kJ/mm heat input with 5 beads and 7-9 degree angle of wires compared to travelling direction. The joint details –field shows the wire positioning so that the 1st wire is always closer to midsection of the weld.

9 SUMMARY

In theoretical part tandem MAG welding, productivity and quality aspects were discussed. Also aspects of using high strength steels in welding and in shipbuilding were concentrated on. Tandem MAG welding has faster welding speed and larger deposition rate than traditional MAG welding. If the amount of welding consumables consumption is reduced e.g. with narrow gap tandem MAG welding the effect would be beneficial for the industry. Welding positions typically used in tandem MAG narrow gap welding are PA and PB while welding in other positions have been studied but not to same extent.

The testing was started with groove angle of 30º and less. Destructive testing showed that bend tests were not passed, but others were. Less than 30º groove angles were not successfully welded during test in this thesis. Both 2.5 kJ/mm heat input and 0.8 kJ/mm heat input showed good results, while 0.8 kJ/mm heat input required more precise position of the welding torch. Air gap width was reduced to around 2mm successfully with 2mm root face. Best outcome in the research while welding root pass was done with using synergic arc mode with first arc and pulsed arc mode with second arc. Synergic arc modes were used in both arcs when welding rest of the bead layers.

The parameters involved in 2.5 kJ/mm heat input allowed the torch to be turned more than the 0.8 kJ/mm parameters. The angle for the welding head compared to travelling direction used in the final test was around 7-10 degrees starting from third or fourth bead.

For problems with porosity gas flow rates needed to be adjusted and increased while welding nearer surface of the test piece. Gas flow rates ascertained for best results were 25 L/min and 20 L/min for 2.5 kJ/mm while using 30 L/min and 25 L/min for 0.8 kJ/mm. Pores emerged mostly on the latter half of the bead near the end of the work piece and magnetic arc blow may have had an effect on amount of porosity.

The style of mounting may influence the magnetic blow and grounding of the work piece may work different because of it, but using different kind of grounding set-up and changing places of the grounding wires was not perceived to affect magnetic arc blow. Using ceramic backing instead of copper one however resulted in less arc disturbances in the latter half of the work piece. A disturbance in the arc from magnetic arc blow or other reasons easily cascaded and resulted in even more disturbances.

There was lack of sidewall fusion with 0.8 kJ/mm heat input and thus positioning of the wires in the groove became more precise than by welding with 2.5 kJ/mm heat input. Problems with undercutting were countered by slightly turning the welding head so that the first wire was close to mid-section of the weld and second wire would follow 2 mm from the groove sidewall. Since incomplete root penetration was problem at times, using traditional MAG with 1-MAG program instead of tandem MAG while welding root pass could provide better and more stable start point for filling up the narrow grooves with tandem MAG. 2 mm root opening with 2mm root face showed good results for root pass. When starting the root pass best results were gained by starting the movement of the welding head after arc ignition while the first wire was couple millimeters inside the groove.

10 FURTHER RESEARCH

Different tandem welding heads could be tried to ensure better and more consistent weld results. Binzel D15 was used in this research and also Binzel D8 was tried in the later stages of research. D8 showed promising results but other welding heads could be investigated as possibilities.

Using metal cored filler wire as a second wire could show interesting line of further research due to different characteristics of the filler wire.

Style of mounting may affect the amount of magnetic arc blow and might prove to be interesting topic for future research. Especially different positioning of grounding cables and also mounting styles. Meaning about mounting style is that the start piece could have a pieces welded in 45 degree angle to help smoothen the effects of the arc and molten pool entering the groove. Metal backing pieces could be used under the piece in welding to ensure that air gap does not differ in width during welding.

Different arc modes could be research to figure out if Pulsed – Synergic is the best option for root passes and Synergic – Synergic is the best for welding the rest of the bead layers.

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Appendix 1. Certificate of manufacture and testing in accordance of RMRS.

РОССИЙСКИЙ МОРСКОЙ РЕГИСТР СУДОХОДСТВА
RUSSIAN MARITIME REGISTER OF SHIPPING

6.5.31

СВИДЕТЕЛЬСТВО № 11.03545.260
CERTIFICATE No.

Город, страна / Place, country: RAAHE, FINLAND

Изготовитель / Manufacturer: RUUKKI METALS OY, RAAHE STEEL WORKS

Заказчик / Purchaser: ARCTECH HELSINKI SHIPYARD OY, 00150 HELSINKI, FINLAND

Заказ (контракт) № / Purchaser's order (contract) No. 525617

Заводской заказ № / Work's order No. 90296C-001

Настоящим удостоверяется, что нижеперечисленные изделия изготовлены и испытаны в соответствии с правилами и предписаниями Российского морского регистра судоходства.

This is to certify that the products listed below have been manufactured and tested in accordance with rules and regulations of Russian Maritime Register of Shipping.

Количество и единица измерения. Наименование, марка и технические данные изделий. Заводской(ие) (серийный(е)) номер(а). Ограничения. Оттиск клейма или запись «Изделие(я) имеет(ют) клеймо», если клеймение обязательно. Наименование и количество листов приложения, при необходимости.
Number and the unit of measure. Name, type and particulars of products. Manufacturer's (serial) No.(Nos). Limitations.
Imprint of stamp or record "Product(s) stamped", if stamping is necessary. Annex name and the number of sheets, if appropriate.

PCE/KG PC E 500TMCP PC PART XIII CH.3:2011

3/21600 25.00 X 3000 X 12000

PRODUCT(S) STAMPED
ENCLOSED: 90296C-001 / 3 SHEETS

Настоящее Свидетельство выдано изготовителем в соответствии с Соглашением об освидетельствовании № 05.04379.260
This Certificate is issued by the Manufacturer in accordance with the Agreement on Survey No.

От имени изготовителя / On behalf of Manufacturer: [signature] Minna Valkama 06.09.2011
М.П. / L.S. (подпись / signature) (фамилия, инициалы печатными буквами / name, in block letters) (дата / date)

Действие вышеупомянутого Соглашения об освидетельствовании подтверждается.
Validity of the above mentioned Agreement on Survey is hereby confirmed.

Инженер-инспектор / Surveyor: [signature] O. Miasnikov 06 09 2011
М.П. / L.S. (подпись / signature) (фамилия, инициалы / name) (дата / date)

260-9
10/2007
0631566

Appendix 2. Mill sheet and test certificate.

RUUKKI

MILL SHEET AND TEST CERTIFICATE

RUSSIAN MARITIME REGISTER OF SHIPPING

1/3
90296C-001
05.09.2011

Tilaaja Purchaser
ARCTECH HELSINKI SHIPYARD OY
00150, HELSINKI, FINLAND
Tilaus nro Order No.
525617

Tilausvahvistus Order Confirmation
90296C

Vastaanottaja Consignee
JSC "VYBORG SHIPYARD"
188800 VYBORG RUSSIA
Asiakkaan merkki Shipping mark
CONTRACT NO.A-525549/A-52550 FOR NB-506/NB-507

Päivämäärä Date
06.09.2011
11.03545.260
Valmistajan merkki
Mark of the Manufacturer

Todistus Certificate
PC

Laivaus Shipping
LAUGA

Laatuleimaus Quality Stamping
PC E500 TMCP

Tarkastajan leima
Stamp of work's Inspector

Vastaanottajan leima
Stamp of Surveyor

Muut leimaukset
Other Stamps

Toimitustyyppi Delivery type
TOTAL DELIVERY

Sulatus nro levy nro Cast No. Plate No.
XXXXX XXX XX XXX

Tuote Product
HEAVY PLATES

Toleranssit Tolerances
PC-2011/EN 10029:2010 CLASS B

Tekniset vaatimukset ja/tai viralliset määräykset Technical terms of Delivery and/or Official Regulations

Laji Grade
PC E 500TMCP PC PART XIII CH.3:2011

Laatuselvitys Quality Specifications
EXTRA HIGH STRENGTH STEEL FOR SHIP STRUCTURES

Positio Item	Mitat mm Dimensions mm	Merkki Marke	Kpl Pcs	Paino kg Weight kg	Sulatus levy nro Cast plate No		SP nro SP No	UT UT	MT MT
HOT ROLLED STEEL PLATES									
SURFACE CONDITION EN 10 163-2:2005 CLASS A3									
001	25.00 X 3000 X 12000		1	7200	37294	041	041		
001	25.00 X 3000 X 12000		1	7200	37294	042	042		
001	25.00 X 3000 X 12000		1	7200	37294	049	049		
		***	3	21600					

Raahe Steel Works

Testaus ja tarkastus Testing and Inspection

We hereby certify that the material described above has been made by the basic oxygen process approved by and in accordance with the Rules of the Russian Maritime Register of Shipping.

The products meet the requirements of the Russian Maritime Register of Shipping. Recognition Certificate for manufacturer 10.00148.260 is valid until 02.02.2015.

MINNA VALKAMA
Valtuutettu tarkastaja Authorized Inspector

RTX03

Yhtiön nimi Company Name: RUUKKI METALS OY
Kotipaikka Registered Office: HELSINKI
Osoite Address: PL 93, P.O Box 93 FIN-92101 RAAHE, FINLAND
Puhelin Telephone: 020 5911 +358 20 5911
Telekopio Telefax: 020 592 2736 +358 20 592 2736
Y-tunnus Business ID: 2389445-7

Appendix 3. Test report of PC E500 TMCP steel.

RUUKKI

AINESTODISTUS TEST REPORT

RUSSIAN MARITIME REGISTER OF SHIPPING

2/3
90296C-001
05.09.2011

Tilaaja Purchaser ARCTECH HELSINKI SHIPYARD OY	Vastaanottaja Consignee JSC "VYBORG SHIPYARD" LIC. NO 10206/200031	Päivämäärä Date 06.09.2011 TPE
Tilaus nro Order No. 525617	Asiakkaan merkki Shipping mark CONTRACT NO.A-525549/A-52550 FOR NB-506/NB-507	Valmistajan merkki Mark of the Manufacturer
Laji Grade PC E 500TMCP	Lisävaatimukset Additional requirements	Jatkuvavalettua happiterästä Oxygen steel, continuous casting
Laatuselvitys Quality Specifications EXTRA HIGH STRENGTH STEEL FOR SHIP STRUCTURES		Fully killed, Fine grain practiced

Pos. Item	Sulatus, k.erä nro Cast. test No	T-tila Cond	Vetokoe Tensile test K2	°C	RP02 MPa	RT05 MPa	REL MPa	REH MPa	RM MPa 1	RM MPa 2	RM MPa 3	A % 50	A % 80	A % 200	REH / RM	RM * A5	RAZ % 1	RAZ % 2	RAZ % 3	Keskiarvo Average	Taivutuskoe Bend test K5	D = X t	Huom Nb	Päästö Tempering °C
001	37294 041	TM	51					571	648			20												
001	37294 042	TM	51					601	674			17												
001	37294 049	TM	51		574				663			16												

K2: 51=BOTTOM,TRANSV.

TM=THERMOMECH. TREATED

Pos. Item	Sulatus k.erä nro Cast. test No	Iskukoe Impact test K3	°C	1	2	3	Keskiarvo Average	Sitkeämurtuma Ductile fracture 1	2	3	Keskiarvo Average	Erikoiskokeet Special tests K4	°C	1	2	Keskiarvo Average	Huom Nb	Päästö Tempering °C
001	37294 041	152	-040	297	303	294	298											
001	37294 042	152	-040	291	291	283	288											
001	37294 049	152	-040	257	263	248	256											

K3: 152=CH-V/ISO-V(J),10X10,BOTTOM,TRANSV,KV600

Raahe Steel Works

Täten todistamme, että toimitus on tilausvahvistuksen mukainen.
We hereby certify that the material described above has been tested and complies with the terms of the order confirmation.

Testaus ja tarkastus Testing and Inspection

MINNA VALKAMA
Valtuutettu tarkastaja Authorized Inspector

260-9

Yhtiön nimi Company Name: RUUKKI METALS OY
Kotipaikka Registered Office: HELSINKI
Osoite Address: PL 93, P.O Box 93, FIN-92101 RAAHE, FINLAND
Puhelin Telephone: 020 5911, +358 20 5911
Telekopio Telefax: 020 592 2736, +358 20 592 2736
Y-tunnus Business ID: 2389445-7

Appendix 4. Analysis certificate of PC E500 TMCP steel.

RUUKKI

ANALYYSITODISTUS ANALYSIS CERTIFICATE
ANALYSEBESCHEINIGUNG COMPOSITIO CHIMIQUE CERTIFICAT
СЕРТИФИКАТ АНАЛИЗА

3/3
9C296C·001
05.09.2011

Päivämäärä Date Datum Date Дата
06.09.2011 TPE

Analyysi % Chemical composition % Chemisch Zusammensetzung % Composition Chimique % Анализ плавки % (*=ppm)

Sulatus nro Cast No Schmelzen Nr No de coulén № Плавки	Koe nro Test No Prüf Nr. Essai No № Пробы	Positio Item Pos. Poste Поз.	PCM	C	SI	MN	P	S	AL	NB	V	TI	CU	CR	NI	MO	N	B	SN	PB
37294		001	.19	.070	.28	1.49	.008	.000	.041	.035	.011	.015	.296	0.08	0.76	.012	.004	.0002	.001	.000

PCM=C+(MN+CU+CR)/20+SI/30+NI/60+MO/15+V/10+5*B

Raahe Steel Works

Testaus ja tarkastus Prüfung und Kontrolle — Testing and Inspection Essais et Contrôle — Испытание и контроль качества

Steel manufactured and supplied by Rautaruukki is free from radiation.
Производимая на металлургическом комбинате «Rautaruukki» и поставляемая заказчику сталь не излучают радиации.

260-9

MINNA VALKAMA
Valtuutettu tarkastaja Wersachverständiger — Authorized Inspector Inspector autorisé — Уполномоченный инспектор

Yhtiön nimi Company Name: RUUKKI METALS OY
Kotipaikka Registered Office: HELSINKI
Osoite Address: PL 93, P.O Box 93 FIN-92101 RAAHE FINLAND
Puhelin Telephone: 020 5911 +358 20 5911
Telekopio Telefax: 020 592 2736 +358 20 592 2736
Y-tunnus Business ID: 2389445-7

Appendix 5. Transverse bend test sheet.

pWPS			
Sovellustandardi	***SFS-EN 5173***	Taivutintelan halkaisija	***d* = 4xt**
Asiakas / viite		Tukitelojen väli	***l* > (d+2xt)**
Perusaine	***E500 TMCP***		***t* = levynpaksuus**
Aineenpaksuus	***25 mm***		
Hitsityyppi	***BW***	**FBB**	*Päittäishitsin pintaivutuskoe*
Hitsausprosessi	***MAG-tandem***	**RBB**	*Päittäishitsin juuritaivutuskoe*
Hitsausaine		**SBB**	*Päittäishitsin sivutaivutuskoe*
Koelämpötila	***20 C***		
Huomautuksia			

Koesauva Nro / sijainti	Koemenetelmä	Mitat mm	Taivutintelan halkaisija/ mm	Tukitelojen väli / mm	Taivutuskulma /	Alkumittapituus / mm	Venymä %	Huom!
D32.11	***SBB***	***10X25***	***45***	***70***	***63***	-	-	
D32.12	"	"	"	"	***37***	-	-	
D32.13	"	"	"	"	***180***	-	-	
D32.14	"	"	"	"	***53***	-	-	
D41.11	***SBB***	***20X25***	***45***	***70***	***71***	-	-	
D41.12	"	"	"	"	***76***	-	-	
D41.13	"	"	"	"	***180***	-	-	
D41.14	"	"	"	"	***89***	-	-	

Taivutuskokeen koetulosten mukaisesti koetulos " ____________ ***hylätty***

Testauksen suorittaja

Päivämäärä	Allekirjoitus
26.11.2014	

Kokeen valvoja

Päivämäärä	Allekirjoitus

Appendix 6. Transverse tensile test sheet.

Open your mind. LUT.
Lappeenranta University of Technology

LUT Kone

HITSAUSLIITOKSEN POIKITTAINEN VETOKOE

Pöytäkirjan numero

pWPS		
Sovellustandardi	***SFS-EN 895***	Re = Fe / So
Asiakas / viite		
Perusaine	***E500TMCP***	Rm = Fm / So
Aineenpaksuus	***25 mm***	
Hitsityyppi	***BW***	Lo = 5,65 * sqrt (So)
Hitsausprosessi	***MAG-tandem***	
Hitsausaine		A =(Lu-Lo) / Lo
Koelämpötila	***20*** *°C*	
Huomautuksia		Z = (So-Su) / So

Koesauva Nro/sijainti	Mitat/halkaisija mm	Poikkipinta So / mm2	Myötövoima Fe / kN	Myötöraja Re / N/mm2	Murtovoima Fm / kN	Murtolujuus Rm / N/mm2	Alkumittapituus Lo / mm	Loppumittapit. Lu / mm	Murtovenymä A / %	Poikkip./murto Su / mm2	Murtokurouma Z / %	Murtuman sijainti	Huom!
D32.1	*9,7X25,6*	*248,61*	*135*	*543,0*	*157,2*	*632,3*	*89,4*	*108,6*	*21,5*	-	-	*BM*	
D32.2	*10X25,5*	*255,3*	*137*	*536,6*	*160,8*	*629,8*	*88,6*	*103,3*	*16,6*	-	-	*BM*	
KA				***539,8***		***631,1***			***19,0***	-	-	***BM***	
D41.1	*8,4X25,8*	*215,86*	*117*	*542,0*	*134,6*	*623,6*	*89,2*	*108,3*	*21,4*	-	-	*BM*	
D41.2	*9,9X25,8*	*255,12*	*133*	*521,3*	*150*	*588,0*	*89*	*107,5*	*20,8*	-	-	*BM*	
KA				***531,7***		***605,8***			***21,1***	-	-	***BM***	

Vetokokeen koetulosten mukaisesti koetulos " ______ ***hyväksytty***

Testauksen suorittaja		Kokeen valvoja	
Päivämäärä	Allekirjoitus	Päivämäärä	Allekirjoitus
27.11.2014	***Esa Hiltunen***		

Appendix 7. Impact test sheet .

Open your mind. LUT.
Lappeenranta University of Technology

LAPPEENRANNAN TEKNILLINEN YLIOPISTO
LUT Kone

Pöytäkirjan numero

ISKUKOE

pWPS		Nimikemerkintä:
Sovellustandardi	***SFS-EN ISO 9016, EN ISO 148-1***	*Muoto: 1 2 3 a/b*
Asiakas / viite		*1: sauvan tyyppi (V tai U)*
Perusaine	***E500 TMCP***	*2: loven paikka (W tai H)*
Aineenpaksuus	***25 mm***	*3: lovetun pinnan suunta (S tai T)*
Hitsityyppi	***BW***	*a: loven etäisyys vertailuviivasta*
Hitsausprosessi	***MAG-TANDEM***	*b: koekappaleen ja sauvan pinnan*
Hitsausaine		*välinen etäisyys*
Huomautuksia	***Koesarjat D321 ja D411.***	

Koesauva Nro	Nimike	Sauvan mitat / mm	Koelämpötila / °C	Vasaran energia/ J	Iskuenergia J	Murtuman sijainti	Murtuman tyyppi	Virheen tyyppi ja koko
D3211	*VWT0/2*	*10X10X55*	*-40*	*300*	*65*	*W*	-	-
D3212	"	"	"	"	*51*	"	-	-
D3213	"	"	"	"	*48*	"	-	-
Keskiarvo	***VWT0/2***	"	"	"	***55***	"	-	-
D3214	*VHT1/2*	*10X10X55*	"	"	*178*	*HAZ*	-	-
D3215	"	"	"	"	*94*	"	-	-
D3216	"	"	"	"	*107*	"	-	-
Keskiarvo	***VHT1/2***	"	"	"	***126***	"	-	-
D4111	*VWT0/2*	*10X10X55*	"	"	*58*	*W*	-	-
D4112	"	"	"	"	*82*	"	-	-
D4113	"	"	"	"	*64*	"	-	-
Keskiarvo	***VWT0/2***	"	"	"	***68***	"	-	-
D4114	*VHT1/2*	*10X10X55*	"	"	*241*	*HAZ*	-	-
D4115	"	"	"	"	*276*	"	-	-
D4116	"	"	"	"	*211*	"	-	-
Keskiarvo	***VHT1/2***	"	"	"	***243***	"	-	-

Iskukokeen koetulosten mukaisesti koetulos " __ ***hyväksytty***

Testauksen suorittaja

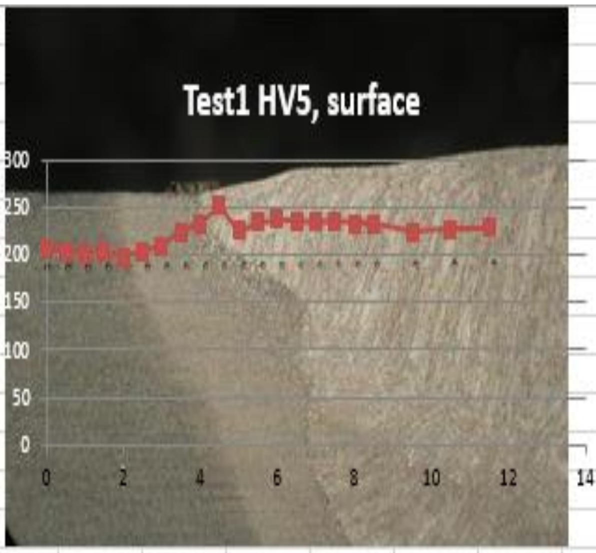
Päivämäärä	Allekirjoitus
2.12.2014	

Kokeen valvoja

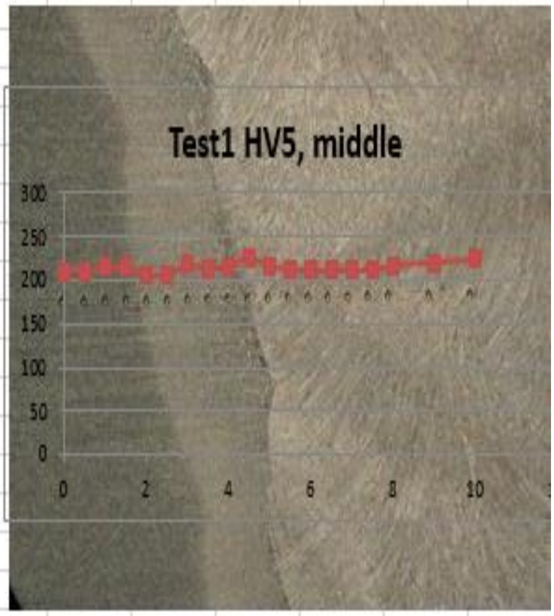
Päivämäärä	Allekirjoitus

Appendix 8. Hardness tests of D41.1 Surface and middle sections

Mittauspi	Meneteln	X-etäisyy	Kovuus
1	HV5	0	207
2	HV5	0,5	204
3	HV5	1	201
4	HV5	1,5	203
5	HV5	2	198
6	HV5	2,5	203
7	HV5	3	210
8	HV5	3,5	224
9	HV5	4	233
10	HV5	4,5	251
11	HV5	5	226
12	HV5	5,5	234
13	HV5	6	237
14	HV5	6,5	235
15	HV5	7	234
16	HV5	7,5	236
17	HV5	8	232
18	HV5	8,5	233
19	HV5	9,5	224
20	HV5	10,5	227
21	HV5	11,5	228

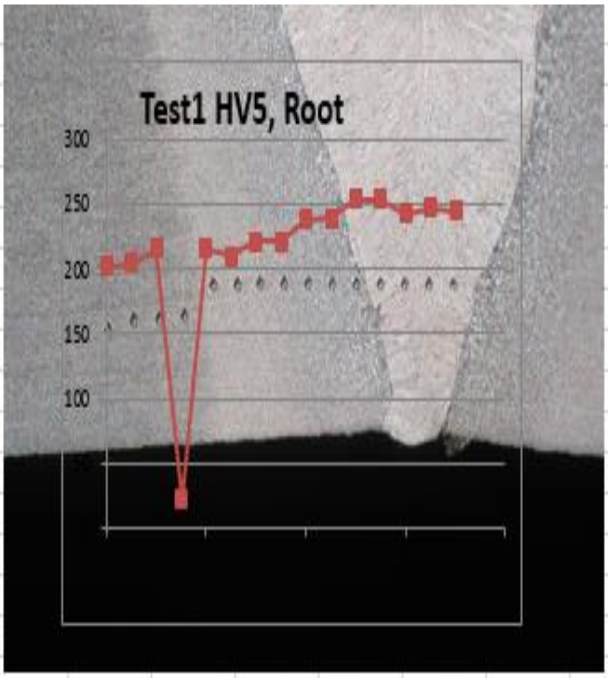


Mittauspi	Meneteln	X-etäisyy	Kovuus
1	HV5	0	210
2	HV5	0,5	210
3	HV5	1	216
4	HV5	1,5	216
5	HV5	2	206
6	HV5	2,5	206
7	HV5	3	218
8	HV5	3,5	214
9	HV5	4	216
10	HV5	4,5	226
11	HV5	5	217
12	HV5	5,5	212
13	HV5	6	212
14	HV5	6,5	212
15	HV5	7	212
16	HV5	7,5	212
17	HV5	8	217
18	HV5	9	220
19	HV5	10	225

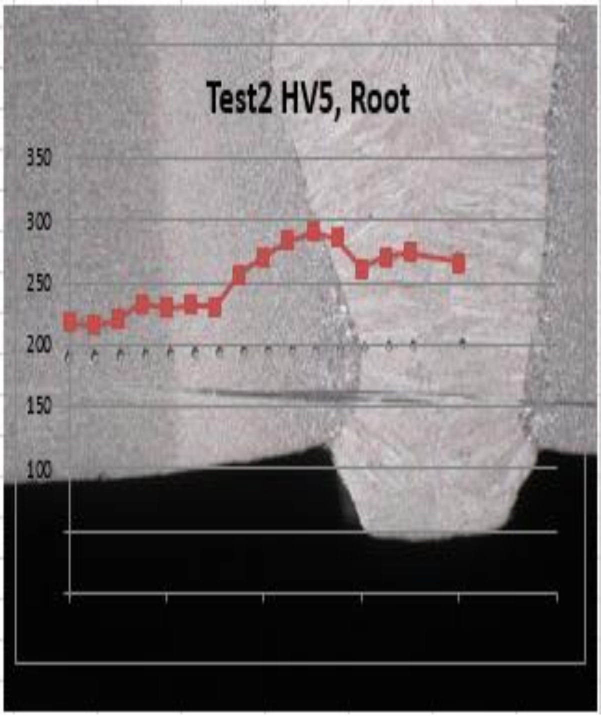


Appendix 9. Hardness tests of D41.1 root section and D32.1 root section

Mittauspi	Meneteln	X-etäisyy	Kovuus
1	HV 5	0	202
2	HV 5	0,5	205
3	HV 5	1	216
4	HV 5	1,5	22
5	HV 5	2	216
6	HV 5	2,5	210
7	HV 5	3	221
8	HV 5	3,5	221
9	HV 5	4	238
10	HV 5	4,5	239
11	HV 5	5	254
12	HV 5	5,5	254
13	HV 5	6	243
14	HV 5	6,5	247
15	HV 5	7	245

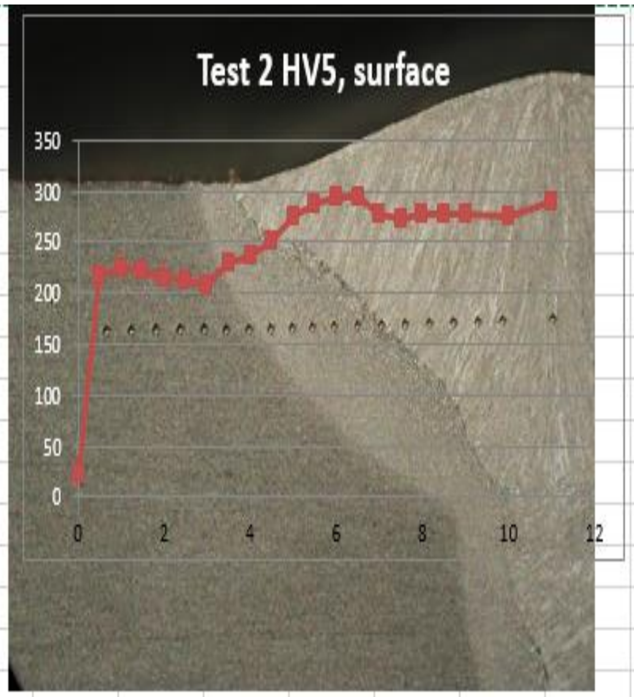


Mittauspi	Meneteln	X-etäisyy	Kovuus
1	HV 5	0	218
2	HV 5	0,5	215
3	HV 5	1	220
4	HV 5	1,5	233
5	HV 5	2	229
6	HV 5	2,5	232
7	HV 5	3	231
8	HV 5	3,5	256
9	HV 5	4	271
10	HV 5	4,5	284
11	HV 5	5	290
12	HV 5	5,5	286
13	HV 5	6	261
14	HV 5	6,5	270
15	HV 5	7	274
16	HV 5	8	266



Appendix 10. Hardness tests of D32.1 Surface and middle sections

Mittauspi	Meneteln	X-etäisyys	Kovuus
1	HV 5	0	22
2	HV 5	0,5	217
3	HV 5	1	224
4	HV 5	1,5	222
5	HV 5	2	215
6	HV 5	2,5	212
7	HV 5	3	209
8	HV 5	3,5	230
9	HV 5	4	237
10	HV 5	4,5	252
11	HV 5	5	275
12	HV 5	5,5	286
13	HV 5	6	294
14	HV 5	6,5	295
15	HV 5	7	278
16	HV 5	7,5	272
17	HV 5	8	277
18	HV 5	8,5	277
19	HV 5	9	278
20	HV 5	10	276
21	HV 5	11	289



1	HV 5	0	210
2	HV 5	0,5	215
3	HV 5	1	209
4	HV 5	1,5	211
5	HV 5	2	218
6	HV 5	2,5	229
7	HV 5	3	231
8	HV 5	3,5	282
9	HV 5	4	281
10	HV 5	4,5	283
11	HV 5	5	271
12	HV 5	5,5	267
13	HV 5	6,5	257
14	HV 5	7,5	261
15	HV5	8,5	268