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Masters´s Thesis

Juha-Pekka Keltanen

NARROW GAP FLUX-CORED ARC WELDING OF HIGH STRENGTH SHIPBUILDING STEELS

Examiners: Prof. Jukka Martikainen
Lic.Sc. Matti Nallikari

ABSTRACT

Lappeenranta University of Technology
Department of Mechanical Engineering

Juha-Pekka Keltanen

Narrow Gap flux-cored arc welding of high strength shipbuilding steels

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This thesis is part of the Arctic Materials Technologies Development –project. The research of the thesis was done in cooperation with Arctech Helsinki Shipyard, Lappeenranta University of Technology and Kemppi Oy. Focus of the thesis was to study narrow gap flux-cored arc welding of two high strength steels with three different groove angles of 20°, 10° and 5°. Welding of the 25 mm thick E500 TMCP and 10 mm thick EH36 steels was mechanized and Kemppi WisePenetration and WiseFusion processes were tested with E500 TMCP steel. EH36 steel test pieces were welded without Wise processes. Shielding gases chosen were carbon dioxide and a mixture of argon and carbon dioxide. Welds were tested with non-destructive and destructive testing methods. Radiographic, visual, magnetic particle and liquid penetrant testing proved that welds were free from imperfections. After non-destructive testing, welds were tested with various destructive testing methods. Impact strength, bending, tensile strength and hardess tests proved that mechanized welding and Wise processes produced quality welds with narrower gap. More inconsistent results were achieved with test pieces welded without Wise processes. Impact test results of E500 TMCP exceeded the 50 J limit on weld, set by Russian Maritime Register of Shipping. EH36 impact test results were much closer to the limiting values of 34 J on weld and 47 on HAZ. Hardness values of all test specimens were below the limiting values. Bend testing and tensile testing results fulfilled the the Register requirements. No cracking or failing occurred on bend test specimens and tensile test results exceeded the Register limits of 610 MPa for E500 TMCP and 490 MPa for EH36.

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
Konetekniikan koulutusohjelma

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Tämä työ on osa Arctic Materials Technologies Development -projektia. Diplomityö tehtiin yhteistyössä Arctech Helsingin telakan, Lappeenrannan teknillisen yliopiston ja Kemppi Oy:n kanssa. Työn tavoitteena oli tutkia lujien terästen mekanisoitua MAG-täytelankakapearailohitsausta. Kahdesta eri lujuusluokan ja paksuuden teräksistä hitsattiin 20, 10 ja 5 asteen railokulmilla koekappaleita. 25 mm paksun E500 TMCP ja 10 mm paksun EH36 teräksen hitsaus oli mekanisoitua. Kemppi Oy:n kehittämiä WisePenetration ja WiseFusion -prosesseja käytettiin E500 TMCP teräksen hitsauksessa, kun taas EH36 teräksen koekappaleet hitsattiin ilman Wise-prosesseja. Suojakaasuiksi valittiin hiilidioksidi ja argonin sekä hiilidioksidin seoskaasu. Hitsejä tutkittiin sekä ainetta rikkomattomilla että ainetta rikkovilla menetelmillä. Radiografinen, magneettijauhe-, visuaalinen ja tunkeumanestetarkastus osoittivat, ettei hitseissä ollut hitsausvirheitä. Ainetta rikkovat isku-, taivutus-, veto- ja kovuuskokeet osoittivat, että mekanisoitu kapearailohitsaus yhdessä Wise-prosessien kanssa tuottaa laadukkaita hitsejä. Ilman Wise-prosesseja hitsattujen koekappaleiden tuloksissa esiintyi enemmän vaihtelua. E500 TMCP iskukoetulokset ylittivät Venäjän laivaliikenteen merirekisterin rajan 50 Joulea hitsiaineessa. EH36 iskukoetulokset olivat Rekisterin asettamilla rajoilla, 34 Joulea hitsiaineessa ja 47 Joulea HAZ:ssa. Hitsien kovuusarvot pysyivät alle vaatimusten, eikä taivutuskoesauvoissa esiintynyt halkeamia. Myös vetokoetulokset ylittivät Rekisterin vaatimukset, 610 MPa E500 TMCP teräksellä ja 490 MPa EH36 teräksellä.

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SYMBOLS AND ABBREVIATIONS

°C	Celsius
ABS	American Bureau of Shipping
Al	Aluminium
B	Boron
BV	Bureau Veritas
C	Carbon
CCS	China Classification Society
CEN	European committee for standardization
CEV	Carbon equivalent by International Institute of Welding
ClassNK	Nippon Kaiji Kuokai
Co	Cobalt
CO_2	Carbon dioxide
Cr	Chrome
CRS	Croatian Register of Shipping
CTOA	Crack tip opening angle
CTOD	Crack tip opening displacement
Cu	Copper
CVN	Charpy V-notch
d	Material thickness
DNV GL	Det Norske Veritas Germanischer Lloyd
DQ	Direct quenching
DT	Destructive testing
DWTT	Drop-weight tear test
EN	European standard
ENPI	European Neighborhood and Partnership Instrument
F_2	Shape factor for two-dimensional heat flow
F_3	Shape factor for three-dimensional heat flow
FCAW	Flux-cored arc welding
GMAW	Gas metal arc welding
GTAW	Gas tungsten arc welding
HAZ	Heat-affected zone

HSS	High strength steel
HV5	Vickers hardness test with 5kg weight
HV10	Vickers hardness test with 10kg weight
I	Welding current
IACS	International Association of Classification Societies
IIW	International Institute of Welding
IRS	Indian Register of Shipping
ISO	International Organization for Standardization
J	Joule
k	Thermal efficiency factor
KRS	Korean Register of Shipping
KV_L	Impact energy on longitudinal specimens
KV_T	Impact energy on transverse specimens
LR	Lloyd’s Register of Shipping
M21	Shielding gas mixture of argon and carbon dioxide
MAG	Metal active gas
MHz	Megahertz, one million hertz
MIG	Metal inert gas
Mn	Manganese
Mo	Molybdenum
MPa	Megapascal, one million pascal
N	Nitrogen
Nb	Niobium
NDT	Non-destructive testing
NGW	Narrow gap welding
Ni	Nickel
P	Phosphorus
P_{cm}	Cold cracking susceptibility
Pb	Lead
PRS	Polski Rejestr Statkow
pWPS	Preliminary welding procedure specification
Q	Heat input
QT	Quenched and tempered

RINA	Registro Italiano Navale
RMRS	Russian Maritime Register of Shipping
S	Sulphure
SAW	Submerged arc welding
SFS	Finnish Standard Association
Si	Silicon
Sn	Tin
T_0	Working temperature
$t_{8/5}$	Cooling time from 800 °C to 500 °C
T_{tr}	Transition temperature
Ti	Titanium
TMCP	Thermomechanically controlled process
TQM	Total Quality Management
TWI	The Welding Institute
U	Voltage
UCS	Unit of Crack Susceptibility
V	Vanadium
VT	Visual testing
WPQR	Welding procedure qualification record
WPS	Welding procedure specificatio

1 INTRODUCTION

This master´s thesis is part of an Arctic Materials Technologies Development –project, which relates to ENPI (European Neighborhood and Partnership Instrument, Cross border cooperation) program. There are three parties closely involved in this thesis: Arctech Helsinki Shipyard, Lappeenranta University of Technology and Kemppi Oy.

1.1 Background of the thesis

This thesis was encouraged by an earlier made master´s thesis in cooperation with Arctech Helsinki Shipyard, where the goal was to research welding with narrower groove angles in conjuction with new kind of welding software solutions. Results of the study were inspiring and further research was decided to carry out with even smaller groove angles. Arctech Helsinki Shipyard experimented welding with minimal groove angles, very close to square butt preparation. The results were promising and it was decided that more comprehensive research was needed.

Welding is playing a key role in construction of ships and need for weight, cost and construction time reduction is continuous in shipbuilding industry. Icebreakers have welding seams totaling in about hundred kilometers, new kind of narrower groove preparation can be used in more than ten of the kilometers. High strength steels and new kind of welding techniques and software solutions such as Kemppi Wise products are helping to provide a solution to these objectives. By replacing conventional steel grades with higher strength steels, ship structures can be made lighter without sacrificing the strength or weldability.

1.2 Aim of the study

This thesis examines mechanized flux-cored MAG narrow gap welding of two different steels with different welding variables. Welding tests were performed to find out, if narrower groove and Kemppi Wise products would deliver good quality welds. Preliminary welding plan was done with three different groove angle setups for both steels. The benefits of new kind of welding software solutions was also examined during the welding. The main goal was to accomplish a pWPS which could later be used to achieve approved welding procedure specification for tested materials and welding processes.

1.3 Arctech Helsinki Shipyard

Helsinki Shipyard has a long tradition in shipbuilding. The shipyard was established in 1865 and ships have been built in the same location for 150 years. About 60 percent of the world’s operational icebreakers have been built in Helsinki shipyard. Arctech Helsinki Shipyard is owned by United Shipbuilding Corporation and has specialized in building icebreakers, arctic offshore and special vessels. Icebreaking multipurpose vessel Baltika is shown in figure 1. (Arctech, 2014)

Figure 1. Drydock and icebreaker "Baltika" (Arctech, 2014)

2 NARROW GAP FLUX-CORED ARC WELDING (FC-NGAW)

Narrow gap welding (NGW), also called narrow groove welding is a term referring to a welding technique which can be applied with many of the conventional arc welding processes. The technique aims to reduce the weld joint volume as well as welding time. (Koivula & Gröger, 1984, p. 5)

If conventional V-shaped joint is used, the joint volume and weld completion time increases as thickness increases. When reduced angle of preparation is used, the weld metal volume and joint completion rate decreases, particularly if a narrow parallel-sided gap is used as shown in figures 2 and 3. In addition to improved welding economics, narrow gap technique has also other benefits such as reduced distortion and more uniform joint properties. Mechanical properties of narrow gap joints are better due to lower heat input and progressive refinement of the weld bead by multipass runs. (Norrish, 2006, p. 166).

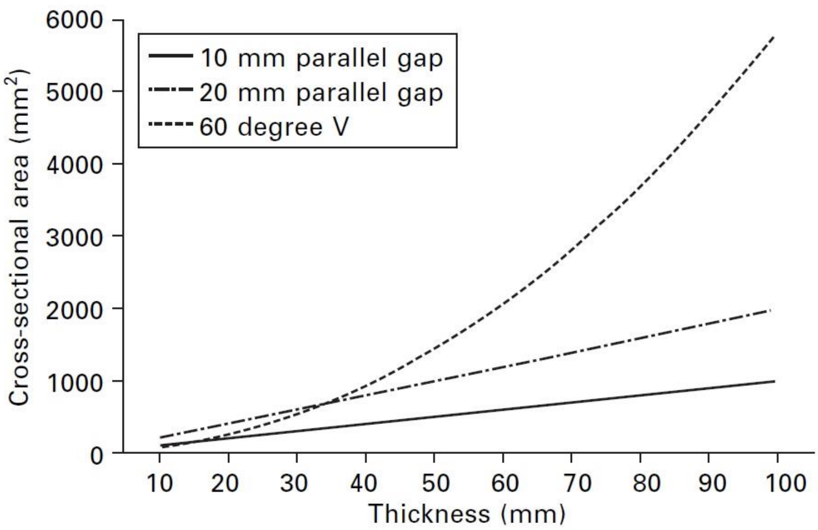


Figure 2. The effect of joint preparation on weld cross-sectional area (Norrish, 2006, p. 166)

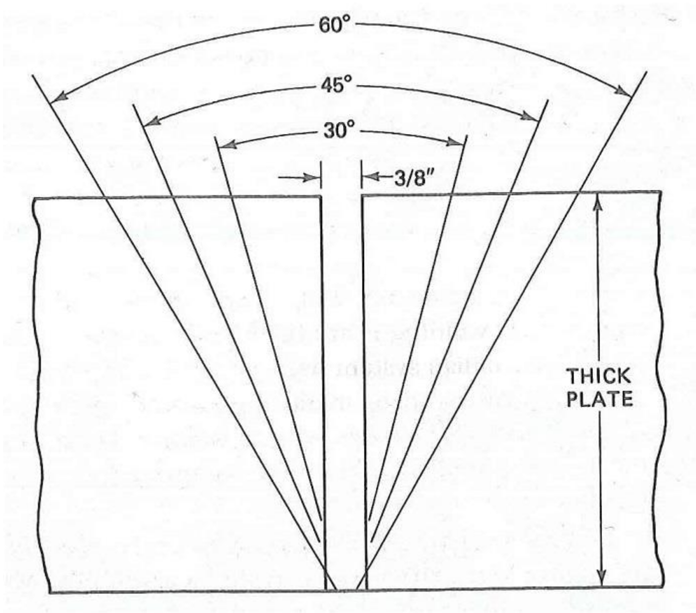


Figure 3. Comparison of cross-sectional area (Cary & Helzer, 2005, p. 676)

Conventional narrow gap welding is used for joining thick sections (up to 300 mm) more economically. The process is designed to reduce weld metal volume in butt welds. Some welding processes such as laser, electro beam, plasma keyhole, friction and flash butt have narrow parallel sided gaps or square butt preparations inherent in them. With arc welding, narrow gap welding has been mostly used with gas metal arc welding (GMAW), submerged arc welding (SAW), gas tungsten arc welding (GTAW) and flux-cored arc welding (FCAW) processes. Usually narrow gap welding requires specialised equipment to access the root of the preparation. Not much research is found on using narrower groove with normal plate thicknesses, which do not necessarily require special welding equipment. (Cary & Helzer, 2005, p. 676, Norrish, 2006, p. 165; Weman, 2003, p. 114)

Narrow gap welding processes share some common features (Norrish, 2006, p. 166):

- A use of special joint configuration
- Special welding head or equipment may be required
- Arc length control and seam tracking may be required
- Modified consumables may be required

Narrow gap welding can be separated by various techniques developed. Adequate sidewall penetration is ensured by electrode or arc manipulation such as directing electrodes towards the sidewall and oscillating or rotating the arc. Another technique to control sidewall penetration is mere tuning of welding parameters. In addition to welding current, voltage and travel speed, the oscillating parameters such as dwell time and oscillating amplitude influence the weld profile. The fusion can also be controlled by weld bead placement as illustrated in figure 4. One or two weld beads per layer are commonly used, the torch is re-positioned after each run or two separate torches can be used simultaneously. (Norrish, 2006, p. 171; Cary & Helzer, 2005, p. 676-677; Xu et al., 2014, p. 3)

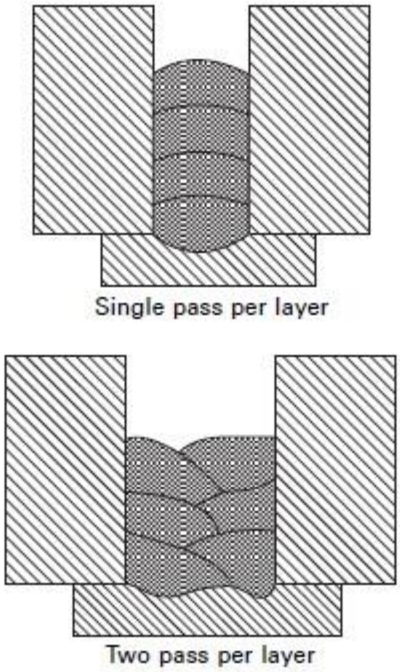


Figure 4. Weld bead placement (Norrish, 2006, p. 172)

Primary use of narrow gap gas metal arc welding (NG-GMAW) is the construction of large metal structures, such as ships, pressure vessels, power plants etc. Due to difficulties changing position with such large structures, all-position welding capabilities are very important. (Xu et al., 2015, p. 1) Numerous joint configurations can be used based on the welding process and the nature of the application. The simplest example is a straight parallel-sided gap with a backing strip. The gap width also varies depending on welding process and equipment used. In many cases standard power sources and wire feed systems can be used. (Norrish, 2006, p. 167)

The advantages of narrow gap welding are as follows (Cary & Helzer, 2005, p. 676; Koivula & Gröger, 1984, p. 7-8; Norrish, 2006, p. 165-166):

- High productivity resulting from smaller cross section of the weld
- All-position and one side welding capability
- Lower residual stresses and distortions, due to reduced volume of molten weld metal and consecutive tempering of subsequent weld beads
- High quality welds and excellent mechanical properties of the weld joint
- Economically viable, due to less weld metal and labour is needed

The disadvantages of narrow gap welding are as follows (Cary & Helzer, 2005, p. 676-676; Norrish, 2006, p. 166, 170, 178):

- The special welding heads and control gear are more expensive and complex
- The technology is more demanding and requires well trained operators
- Joint fit up must be accurately made to ensure consistent results the entire length of the joint
- Magnetic arc blow can be a problem
- Possibility of lack of fusion
- Special filler metals may be required which are more expensive

2.1 Flux-cored arc process

Flux-cored arc welding (FCAW) is a variation of gas metal arc welding. Flux-cored arc welding uses an electrode which is a tube instead of solid wire. Shielding from atmosphere can be achieved with so called self-shielded electrodes which rely solely on shielding gas generated by the disintegration of ingredients within the electrode or by supplying external shielding gas. Ingredients within the electrode are multi-purposed, instead of just producing the shielding gas they also provide deoxidizers, ionizers and purifying agents. The glasslike slag which these ingredients form floats on the surface of the weld and acts as a protective cover. (Cary & Helzer, 2005, p. 126-127) The principle of the process is shown in figure 5.

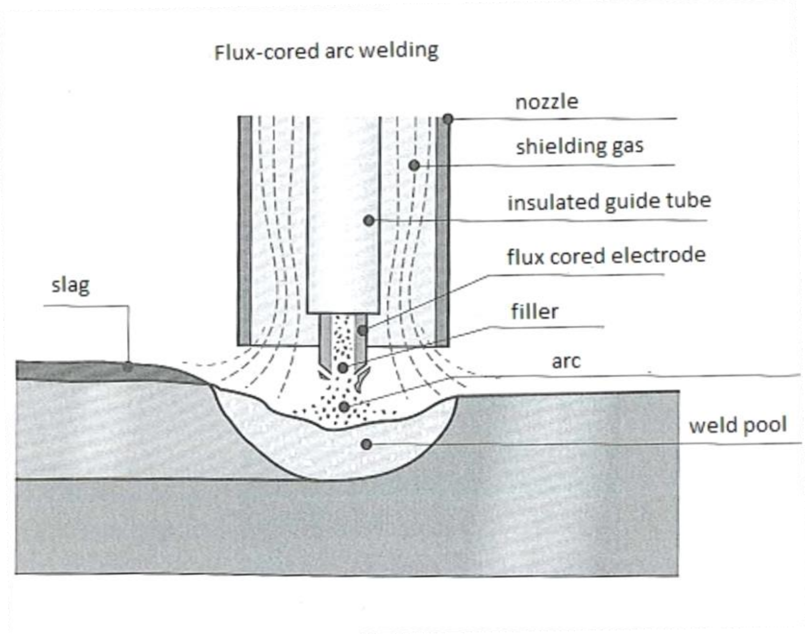


Figure 5. The principle of flux-cored arc welding (Lepola & Makkonen, 2005, p. 138)

The equipment used for flux-cored arc welding is very similar to ordinary MIG/MAG welding equipment. Mainly same equipment can be used for both processes. However the power source needs to have good load capacity and the wire feeding unit need to cooperate with more fragile and thicker wire structure, also the welding torch needs to be adequately cooled. (Lukkari, 2002, p. 232-233) Usually direct current is used with electrode in positive pole. The characteristic of the power source is slightly drooping, which gives a self-regulating arc. (Weman, 2003, p. 52)

The advantages of flux-cored arc welding are as follows (Cary & Helzer, 2005, p. 127; Lukkari, 2002, p. 232; Weman, 2003, p. 54):

- High deposition as a result of the high current density
- Relatively high travel speeds
- Can be used in all-position
- Good mechanical properties of weld joint
- Wide material thickness range
- Easily mechanized
- Good penetration
- Less spatter

The disadvantages of flux-cored arc welding are as follows (Weman, 2003, p. 54; Cary & Helzer, 2005, p. 134; Lukkari, 2002, p. 232):

- Fume and smoke generation especially with high welding currents
- Slag covering must be removed after welding
- Cored electrode wire is more expensive compared to solid electrode wires

2.1.1 Kemppi Wise products

Welding equipment evolve, but also better welding software solutions are being developed. Kemppi Wise products are welding software solutions which are developed to provide useful benefits for different welding cases. Kemppi Wise product family consists of four different solutions: WiseRoot, WiseThin, WisePenetration and WiseFusion. These Wise products can be loaded to Kemppi welding equipment prior to delivery or added later as a software updates. (Kemppi Oy, 2014, p. 3)

WiseRoot is a tailored short arc process for automated and manual root pass welding. It is also designed to take into consideration gap tolerances caused by poor joint fit-up. WiseThin is a cold arc process designed for manual and automated thin sheet welding and brazing. (Kemppi Oy, 2014, p. 4-7)

WisePenetration is designed to deliver consistent power to the weld pool in cases when welding gun orientation or distance between welding gun and work piece changes as seen in figure 6. These changes can cause quality issues such as lack of fusion, incomplete penetration and welding spatter. WiseFusion is designed to keep optimal arc length and ensure consistent weld quality in pulsed MIG/MAG and spray-arc welding applications. WiseFusion automatically regulates and produces narrow and energy dence arc. (Kemppi Oy, 2014, p. 8-11)

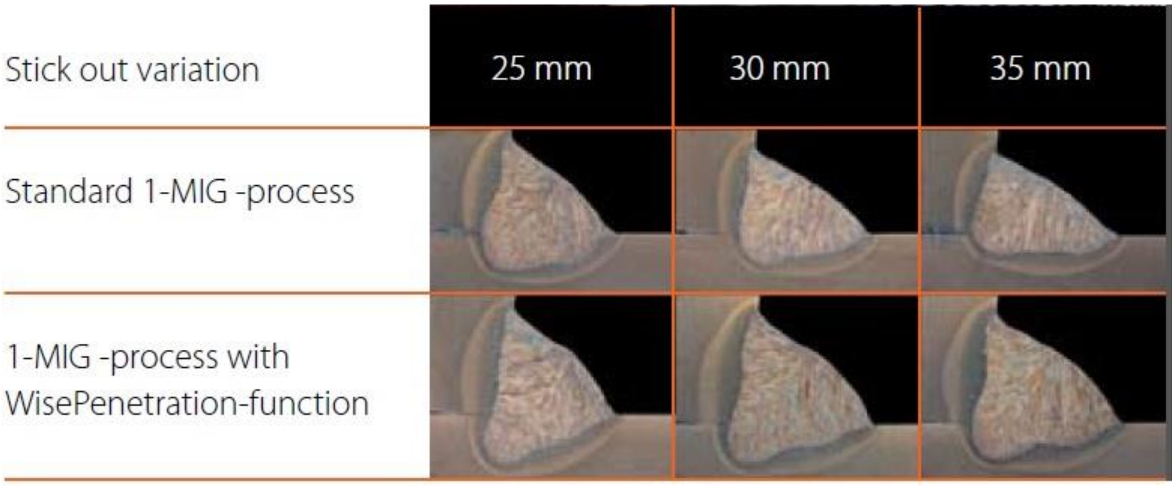


Figure 6. Comparison of standard 1-MIG-process and 1-MIG-process with WisePenetration (Kemppi Oy, 2014, p. 8)

2.2 Welding positions & flux-cored wires

Flux-cored arc welding process is suitable for all-position welding depending on the chosen flux-cored wire and welding parameters. Different kind of flux-cored wires have different kind of welding position capabilities. The composition of the flux can be designed depending on the desired welding position. Flux-cored wires suitable for position welding form slag that solidify quicker and give support to molten weld pool. Some flux-cored wires are suitable only for flat position welding because the slag they form is more fluid. (Lukkari, 2002, p. 231 & 236)

The flux-cored electrode wires have fluxing and alloying components inside the tube structure instead of outside, that’s why they are sometimes called inside-outside electrodes. Flux-cored electrodes have a metal sheath which surrounds the core of chemicals. Two kind of electrode wires exist: the self-shielding and gas-shielding electrode wires. The self-shielding electrodes have core materials that form additional gas which is necessary to prevent oxygen and nitrogen of the air from contaminating the welding process. In addition they also include deoxidizing and denitriding elements. (Cary & Helzer, 2005, p. 128)

Mainly two different kind of fluxes are used, rutile and lime based. Rutile-based flux-cored electrodes produce a smooth and stable arc, easily removable slag and good shaped weld bead. This combined to fine drop transfer and low spatter and fume production makes them well suitable for out-of-position welding. The weld metal properties of some rutile-based flux-cored electrodes are comparable to lime-based flux-cored electrodes. The impact strength values are good still at -60° C and they produce low-hydrogen content weld metal. These qualities have made rutile-based flux-cored electrodes very popular in offshore and shipyard industry. (Lukkari, 2002, p.237)

Lime-based flux electrodes are good at removing impurities from the weld metal and their weld metal properties are considered to be the best of the flux-cored electrodes. The slag they form is more fluid, which makes it more difficult to use them for out-of-position welding. They also produce more spatter and fume. (Lukkari, 2002, p. 238)

2.3 Groove shapes and gaps

In general all the basic groove shapes are also suitable for flux-cored arc welding. The groove angle can be a bit smaller because of the deeper penetration and smaller diameter electrodes when compared to manual metal arc welding. General groove angle is 45-55° with tight root opening. (Lukkari, 2002, p. 242) Usually square groove or a V-groove weld joint with groove angle of 2-10° or less is used with narrow gap welding. Typical root opening can be 4–9 mm wide but it varies greatly depending on which welding process and equipment is used. (Cary & Helzer, 2005, p. 675; TWI, 2014). A backing strip is needed if straight parallel-sided gap is used. There are also a number of other narrow joint preparation designs which vary based on the process and the application used as seen in figure 7. (Norrish, 2006, p. 166)

In this thesis, term “narrow gap welding” is used to describe grooves, which aren’t fully eligible to conventional narrow gap welding. A term “narrowed gap welding” would be more suitable for two of the three groove angles chosen for testing. In any case, the term “narrow gap welding” is used to keep things simple.

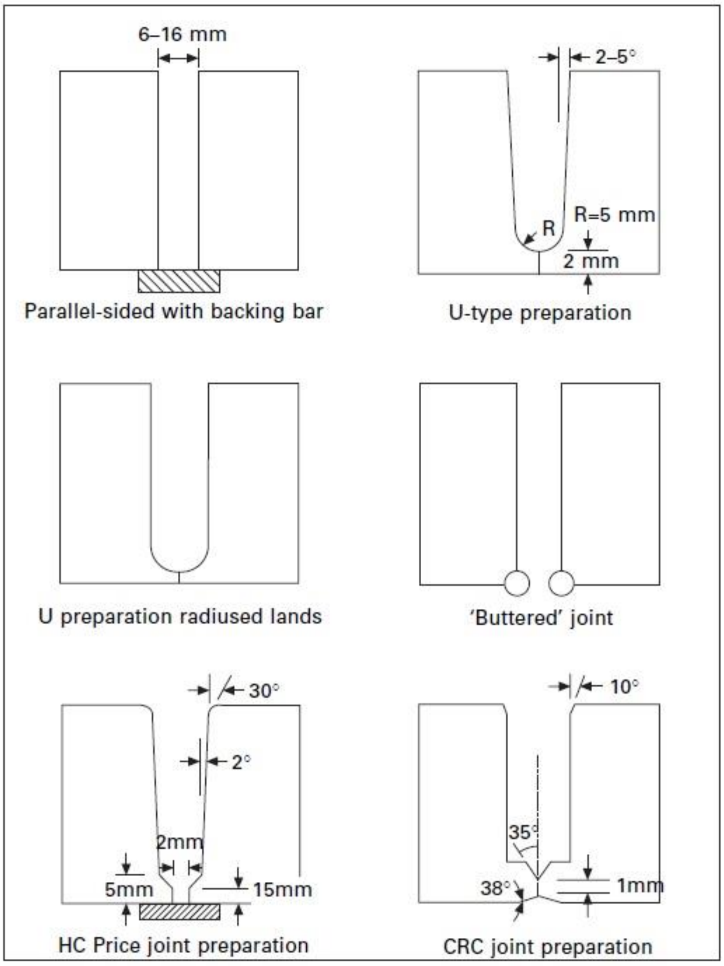


Figure 7. Typical narrow gap joint preparations (Norrish, 2006, p. 167)

In reality, the welds cross-sectional area is not constant. The parameters affecting the joint design, aren't precisely the same in every joint preparation. This is the case especially, if the joint preparation is done manually. Root gap and bevel angle can vary throughout the length of the joint preparation, at the same time affecting the shape. If not done carefully, joint preparation can be wedge shaped, where the root gap is narrower at the other end. This combined to variation in bevel angle can make unique joint preparations. The effect of different root gap to cross-sectional area can be seen in figure 8. Figure 9 illustrates the new narrower joint design. As seen in the figure 9 the weld mass of the original 45° groove setup is more than double if compared to the 5° groove setup.

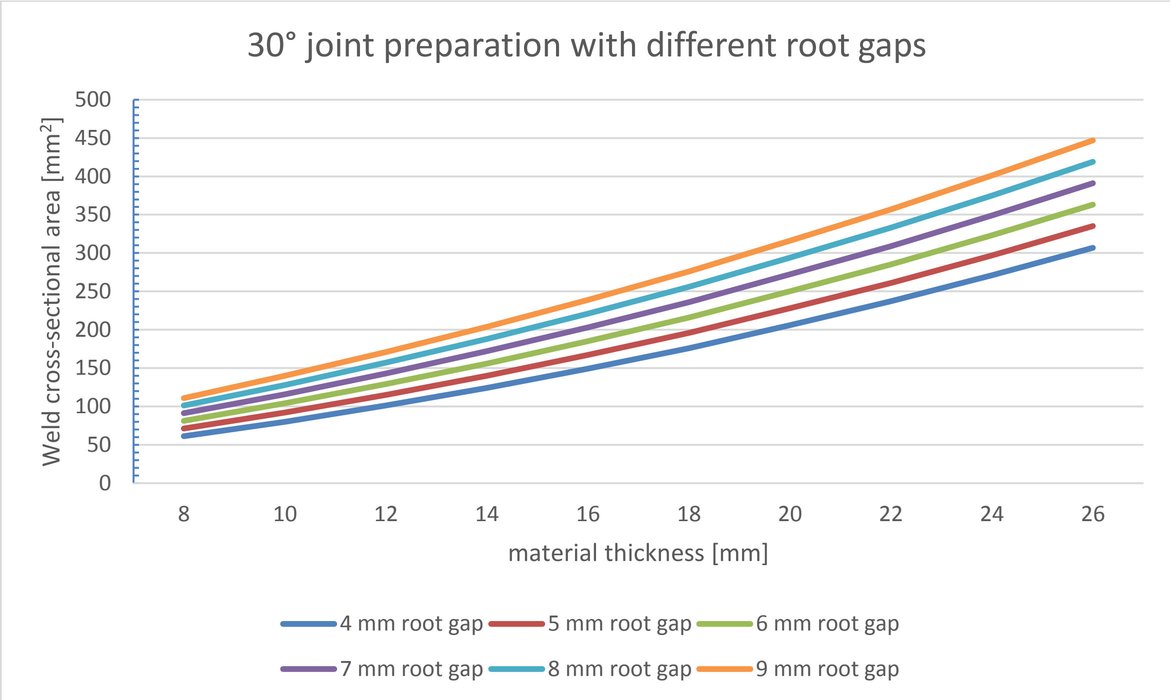
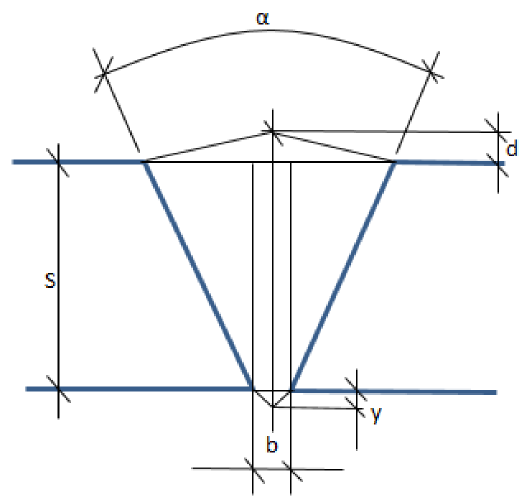


Figure 8. The effect of root gap to cross-sectional area

Joint preparation



Groove measurements	Current 45° groove			New 20° groove			New 5° groove		
thickness	S=	25	mm	S=	25	mm	S=	25	mm
bevel angle	α/2=	22,5	°	α/2=	10	°	α/2=	2,5	°
gap	b=	6	mm	b=	6	mm	b=	6	mm
root reinforcement	y=	2	mm	y=	2	mm	y=	2	mm
reinforcement	d=	2	mm	d=	2	mm	d=	2	mm
groove area	A=	442	mm2	A=	281	mm2	A=	191	mm2
Weld mass	G=	3,5	kg/m	G=	2,2	kg/m	G=	1,5	kg/m

Figure 9. Comparison of current and new narrow groove joint preparation (Nykänen, 2014)

2.4 Welding mechanization

Welding mechanization can be applied in a number of levels for arc welding processes. Manual welding with equipment that controls one or more of the welding conditions is called semiautomatic welding. In mechanized welding, the welding equipment needs to be adjusted manually and monitored visually. The welding torch, welding gun or electrode holder is held by a mechanical device. Automated welding requires only occasional or no observation and adjusting. Robotic welding is welding performed and controlled by robotic equipment. Adaptive control welding is welding with sophisticated process control system that makes changes in welding conditions automatically and adjusts the equipment to take appropriate action. (Cary & Helzer, 2005, p.291)

Flux-cored arc welding can be mechanized rather easily and many kind of arc motion devices for example welding tractors and carriages can be used (Lukkari, 2002, p. 231). Mechanization frees the welding person to be in an operator role, the machine moves the arc, welding torch and welding head along the joint. When the person is partially removed from the welding area, higher welding parameters such as current and traveling speed can be used. The person fatigue factor is also eliminated. This increases productivity and reduces welding cost. (Cary & Helzer, 2005, p. 292) Narrow gap welding is often mechanized so all the benefits of the process can be achieved. Narrower preparation widths cause access and fusion problems with manual welding, these problems can be prevented with mechanization which allows improved control of the process. (Norrish, 2006, p. 170)

Light mechanization can be an easy and cost-efficient way of mechanization. Light mechanization involves a use of small, easy to use and relatively low-priced equipment, usually small tractors and carriers on rails, to move the welding gun. Higher productivity is just one of the advantages achieved with light mechanization. It can also improve work conditions and safety, the quality and consistency of the welds and weld appearance. Mechanization is easier to carry out if it has been taken into consideration already at the construction design stage. The longer and straighter the welds, the easier and more suitable it is for mechanization. Fillet welds are more preferable than butt welds from the mechanization point of view. (Lukkari, 2005b, p. 7)

Although mechanization frees the welding person to be in supervision role, he must be experienced and have expert knowledge to be able to set the suitable welding parameters and adjust them when needed. Light mechanization of MIG/MAG welding is usually carried out with cored wires. Welding position and required impact strength affect which kind of wire is selected. Welding tractors are typically used with horizontal fillet welds and carriages on rails are suitable for both fillet and butt welding vertically. Ceramical weld metal support is used on roots of butt welds. (Lukkari, 2005b, p. 8)

2.5 Productivity and economy of FC-NGAW

Welding process economy can be improved by many different ways. Many process developments are aimed to decrease joint completion time, hence reducing labour costs by increasing deposition rates or mechanization and automation. On the other hand also weld size or joint volume reduction gives benefits to welding economy, and process control optimization can reduce needs of post-weld inspections and repair. (Norrish, 2006, p. 165)

Welding costs are made of labour costs, welding consumable costs, machine costs and energy costs. The labour cost is usually the single greatest factor in the total cost of welding. Welding consumable costs vary depending on the welding process. With FCAW they are a bit higher than with GMAW, because flux-cored electrodes cost about double compared to GMAW electrodes and flux-cored electrodes have also smaller deposition efficiency. Naturally mechanization and especially automation elevate the machine costs, if expensive new equipment has to be bought. (Lukkari, 2011, p. 20-22)

Deposition rate means the amount of welding material supplied to the joint per unit of time, it is often used as an indicator of productivity among other things. Deposition rate depends on welding process, chosen welding consumables and its diameter, welding current and nozzle distance. (Lukkari, 2008, p. 11) Table 1 illustrates different deposition rates of commonly used Filarc PZ6113 all position rutile based flux-cored wire.

Table 1. Deposition rate of PZ6113 all position rutile flux-cored wire with different variables (Lukkari, 2008, p. 12)

Electrode diameter	∅ 1,2 mm (7,2 g/m)	∅ 1,2 mm (7,2 g/m)	∅ 1,2 mm (7,2 g/m)	∅ 1,4 mm (10,0 g/m)	∅ 1,4 mm (10,0 g/m)	∅ 1,4 mm (10,0 g/m)	∅ 1,6 mm (12,5 g/m)	∅ 1,6 mm (12,5 g/m)	∅ 1,6 mm (12,5 g/m)
Welding current (A)	Arc voltage (V)	Wire feed rate (m/min)	Deposition rate (kg/h)	Arc voltage (V)	Wire feed rate (m/min)	Deposition rate (kg/h)	Arc voltage (V)	Wire feed rate (m/min)	Deposition rate (kg/h)
150	22,0	5,8	2,3	23,0	3,3	1,8	23,0	2,8	1,9
200	26,0	8,0	3,1	25,5	5,0	2,7	25,5	3,5	2,4
250	28,0	11,6	4,5	27,5	6,6	3,6	28,0	5,0	3,4
300	32,0	16,2	6,3	30,0	9,0	4,9	31,0	7,0	4,7
350	34,0	20,7	8,0	32,5	11,6	6,3	33,0	8,3	5,6
400							35,0	11,0	7,4
450							37,0	12,4	8,4

As mentioned earlier when the material thickness increases, the amount of weld metal in the joint increases as well. Cary and Helzer (2005) mention that the economic advantage of conventional narrow gap welding is obtained when material thickness is 38 mm and above, their assumtion is based on using less weld metal to produce the joint. Norrish (2006) however states that the minimum economic thickness for narrow gap technology varies with the welding process and the operating mode. Narrow gap GMAW configurations have been utilized in thicknesses from 15-22 mm upwards.

3 HIGH STRENGTH STEELS USED IN SHIPBUILDING

Shipbuilding industry has recently been focused on weight reduction and increasing energy efficiency. Ship structures and components become lighter and their size is increasing in order to reduce fuel consumption, increase transport volume and in general improve the general efficiency of ships. At the same time construction cost and time reduction are increasingly required. To achieve these objectives, new materials with improved properties such as high strength steels have been used. Steel plates produced by thermo-mechanical control process (TMCP) offer strength and toughness without losing weldability. The properties of these steels has also made it possible to utilize high speed and high heat input welding techniques. (Heinz et al., 2000, p. 407; Komizo, 2007, p. 1) Normal strength structural steel is still the bulk material in shipbuilding and in addition to TMCP it can also be delivered in normalized condition. Normalizing consists of heating the steel above its critical temperature range and air cooling. This kind of heat treatment is used to achieve uniform grain refinement and improved mechanical properties. (Ruukki, 2014b; Karhula, 2008)

Russian Maritime Register of Shipping (RMRS) has been the classification society for many of the recent ships built in Helsinki shipyard. RMRS divides steels used in ship hull structures into three categories. Normal strength steels have a minimum yield stress of 235 MPa, higher strength steels, which are further divided into three subcategories of steels with minimum yield stresses of 315, 355 and 390 MPa. Steels with minimum yield stress of 420 MPa and over are considered high strength steels. High strength steels are subdivided into six strength levels by minimum yield stress guaranteed: 420, 460, 500, 550, 620 and 690 MPa. Each strength level has a steel grade A, B, D, E or F in relation to impact test temperature: where A = +20 °C, B = 0 °C, D = -20 °C, E = -40 °C and F = -60 °C. (Russian Maritime Register of Shipping, 2014a, p. 392 & p.428)

The application of grade 620 and 690 high strength steels for hull structures is subject to special consideration by the Register (Russian Maritime Register of Shipping, 2014a, p. 406)

3.1 Properties requirements for steels

Nowadays steel is produced with many different properties and choosing the appropriate grade for wanted application is the key. Strength and toughness properties are important but also the fabrication aspects such as weldability and performance aspects like corrosion resistance and fatigue must be taken into account. Prevention of brittle fracture and satisfactory crack arrestability are one of the key design requirements for ship design. (Heinz et al., 2000, p. 408)

Heinz et al. (2000) list major criteria of ships for material selection as follows:

- Permissible stresses
- Buckling strength
- Fatigue strength
- Corrosion resistance
- Fabrication properties

In addition Oryshchenko and Khlusova have listed requirements for high strength steels as follows (Oryshchenko & Khlusova, 2011, p. 59):

- Wide strength characteristic interval (355-690 MPa) and high plasticity and viscosity with thickness up to 70 mm
- High resistance to brittle fracture in freezing operation temperatures up to -50 °C
- High resistance to static, dynamic and cyclic loads
- Good weldability at ambient temperature
- Resistance to laminary fracture of welded connections
- High crack resistance
- Corrosion resistance and mechanical strength in sea water
- Even mechanical properties

3.1.1 Mechanical properties

The chemical composition of the steel must be in accordance with the specification approved by the Register. Limiting values of the chemical compostion are shown in table 2. The manufacturer of the steel will determine the chemical composition of each cast or ladle and this should be verified by adequately equipped laboratory with competent staff.

The steel shall be fully killed and fine grain treated. (Russian Maritime Register of Shipping, 2014a, p. 428)

Table 2. Limiting values of chemical composition for steel grades (Russian Maritime Register of Shipping, 2014a, p. 428)

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

Steels need to be Q&T but for steels up to 50 mm thick, TMCP manufacturing can be permitted by the Register. Mechanical properties of high strength steels for the purpose of tensile and impact testing are shown in Appendices 1 and 2.

3.1.2 Cold resistant

The low environment temperature has a major effect on the mechanical properties as well as the engineering properties of steel. It can affect the weldability, corrosion resistance and fatigue behavior of steel and an important thing to take into consideration is the possibility of brittle fracture. (Eranti & Lee, 1986, p. 343) Steels are prone to brittle fracture at low temperatures hence it is important to know their transition temperature at which their properties change from ductile to brittle.

3.2 Rules, Standards and Classification

Maritime industry is regulated by different classification societies of whom majority are members of International Association of Classification Societies (IACS). The role of IACS is to unite and regulate guidance and rules for its members. The rules and regulations of the societies are based on international and national standards. Over 90 % of the world’s cargo carrying tonnage involved in international trade is covered by members of IACS. The classification societies monitor that ships are build according to rules and regulations. The purpose of the societies is to support maritime safety and pollution prevention. (International Association of Classification Societies, 2011, p. 4–6) The members of IACS are shown in table 3.

Table 3. The members of IACS (International Association of Classification Societies, 2011, p. 25).

Europe	**Asia**	**Russia**	**America**
Bureau Veritas (BV)	China Classification Society (CCS)	Russian Maritime Register of Shipping (RMRS)	American Bureau of Shipping (ABS)
Croatian Register of Shipping (CRS)	Korean Register of Shipping (KR)		
Det Norske Veritas Germanischer Lloyd (DNV GL)	Nippon Kaiji Kyokai (ClassNK)		
Lloyd's Register (LR)	Indian Register of Shipping (IRS)		
Polish Register of Shipping (PRS)			
Registro Italiano Navale (RINA)			

ISO (International Organization for Standardization) is the world’s largest developer of international standards. ISO is an independent and non-governmental organization made up of 165 member countries. ISO is divided into great number of different technical committees, subcommittees and working groups, which lead standard development. (International Organization for Standardization, 2014) CEN stands for European Committee for Standardization and it’s a provider of European standards, technical specifications and technical reports. CEN consists of 33 European countries working together to develop and define voluntary European standards known as ENs, which automatically becomes national standards in each member countries. CEN cooperate closely with ISO and standard projects are jointly planned when possible. (European Committee for Standardization, 2014)

SFS (Finnish Standards Association) is the central standardization organization in Finland. SFS consists of professional, industrial and commercial organizations as well as the state of Finland. SFS is a member of ISO and CEN and majority of the SFS standards are based on international or European standards. (Finnish Standards Association SFS, 2014)

4 WELDABILITY OF HIGH STRENGTH STEELS

Weldability as a concept can refer to the weldability of the base material or broader to the weldability of a component. Weldability of the component consists of the following factors: base material, the structure and the manufacture. Weldability of the base material is considered to be good, if a satisfactory welded joint can be made without any special needs. (Martikainen & Niemi, 1993, p. 121; Vähäkainu, 2003, p. 16)

Weldability of steel can be predicted with different kind of equations. The most used are different variations of carbon equivalent. The carbon equivalent is calculated on the basis of the chemical composition of steel and it estimates the hardenability and susceptibility for cold cracking. Carbon equivalent is often used to estimate weldability because it indirectly can be used to estimate steels hydrogen cracking through the hardenability value. The most common is the CEV equation by the International Institute of Welding (IIW). Under 0,40 % results are considered as good weldability. (Lukkari, 2007, p. 20)

$$CEV = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Cu+Ni}{15}\ [\%] \qquad (1)$$

Another commonly used carbon equivalent equation is the Japanese Ito-Bessyo P_{cm}. It is especially suitable for high strength low carbon steels. (Lukkari, 2007, p. 23)

$$P_{cm} = C + \frac{Si}{30} + \frac{Mn+Cr+Cu}{20} + \frac{Ni}{60} + \frac{Mo}{15} + \frac{V}{10} + 5B\ [\%] \qquad (2)$$

The Russian Maritime Register of Shipping instructs the use of P_{cm} equation to estimate the cold cracking resistance of steel. The maximum value of P_{cm} shall be agreed with the Register and included in the Register approved specification. (Russian Maritime Register of Shipping, 2014a, p. 428) Both CEV and P_{cm} equations are important factors but weldability is much more than just carbon equivalent equations. Many other factors such as stress state, hydrogen content and processing route of the steel need to be taken into account too.

4.1 Chemical composition

The chemical composition of steel defines what kind of base properties the steel has. Alloying elements also have effect to the weldability of steel as can be seen in table 4. (Vähäkainu, 2003, p. 17)

Table 4. The effects of alloying elements to weldability (Vähäkainu, 2003, p. 17)

Alloying element	C	Si	Mn	P	S	Mo	Cr	Ni	Al	Nb	V
Weldability	--	+	+	---	--	-	-	+	+	+	+
Markings: + affects positively, - affects negatively, the more markings the more effect											

Carbon even though the basic alloying element in steel, actually affects negatively to weldability of steel when its content is risen. It causes hardenability and formation of carbides to the weld seam and heat affected zone. Carbon will also lower the impact strength and cause the risk of cold cracking. (Vähäkainu, 2003, p. 17; Vartiainen, 2005, p. 3)

Silicon and manganese are also basic alloying elements in steel. Manganese is alloyed in all steels to adsorb harmful free sulfur and oxygen. It will also raise hardness and impact strength of steel. Manganese also lowers the transition temperature (T_{tr}) and widens the austenite zone. In addition it will boost austenite grain size and can cause blue brittleness. Manganese is still considered to benefit weldability more than weaken it. Silicon is mainly used to adsorb oxygen, it also makes the weld pool more fluid and forms slag with impurities. Silicon is considered almost neutral alloying element when weldability is considered. (Vähäkainu, 2003, p. 17; Vartiainen, 2005, p. 3)

Niobium, vanadium, titanium and aluminium are used as micro alloying elements, small amounts of them are alloyed into steel to form small precipitations with carbon and nitrogen. They prevent grain size growth in high temperatures and so improve toughness and impact strength. Aluminium adsorbs nitrogen and oxygen thus improving impact strength and preventing age brittleness. Vanadium even in small quantaties prevents grain size growth but also increases hardenability. Titanium adsorbs many kind of impurities and prevents grain size growth. It affects positively to weldability. Niobium is also considered to benefit weldability. It forms carbides with carbon and prevents grain size growth. (Vähäkainu, 2003, p.17; Vartiainen, 2005, p. 3-5)

Chromium, copper, molybdenum and nickel are not usually used as alloying elements in low-alloy steels, they appear as residue content. All of them are involved in carbon equivalent calculation. (Vähäkainu, 2003, p. 17; Vartiainen, 2005, p. 4-5) Sulfur and phosphor appear in steel as impurities and their concentrations are aimed to be minimized. Sulfur and phosphor are also impurities that affect the forming of hotcracks. In addition dissolved gases such as nitrogen, oxygen and hydrogen appear in steel. They have negative effects to various properties. (Vähäkainu, 2003, p. 17)

4.2 Prosessing routes of high strength steels

High strength steels (HSS) are produced with three different processes. Quenhing and tempering (QT), thermomechanically controlled process (TMCP) and direct quenching (DQ). Required yield strengths can be achieved with all the processes but steels have different microstructures depending on which manufacturing method has been used. (Porter, 2006, p. 2-8)

Quenching and tempering process is used to produce steels with very high strength up to 1100 MPa. This level of strength is achieved with higher amounts of alloying elements which tend to result with higher hardenalibility. This can lead to higher risk for brittle fracture and hydrogen induced cracking in welded structures especially if wrong process parameters for welding are used. Up to 690 MPa yield strength steel grades can be reasonably used for special elements. (Willms, 2009, p. 597) Quenching and tempering aims to produce mainly martensite microstructure with some amounts of lower bainite is also acceptable. Quenching is performed at temperatures of 900-960 °C. Accelerated cooling is necessary to suppress the formation of softer microstructure. The fastest way of cooling the plate surface below 300 °C within few seconds is achieved by using rapid water stream. A suitable tempering of the martensitic microstructure is needed after quenching in order to achieve the wanted tensile and toughness properties. (Hanus et al., 2005, p. 4-5)

Steels with higher strength but excellent weldability are often chosen for the overall efficiency. These properties can be achieved with thermomechanically controlled process. TMCP steels have higher strength and better toughness but also lower hardenability. They are less likely to suffer cold cracking and can be welded with higher heat input processes. TMCP was developed in Japan early 1980’s and TMCP steels soon became common in Japanese shipbuilding. (Imai, 2002, p. 1) Carbon contents of the TMCP steels are very low, in the range of about 0,07-0,14 % and their carbon equivalent are no higher than those of normalized fine grain-steel with a yield strength of 355 MPa. Yield strength of 500-700 MPa can be produced by reducing the grain size. This is achieved by rolling the steel below its recrystallization temperature in combination with accelerated cooling. Very fine and uniform microstructure of TMCP steels is a mixture of ferrite and bainite (Porter, 2006, p. 5; Imai, 2002, p. 2)

Direct Quenching process offers more possibilities for microstructural control than conventional reheat quenching. Rolling and quenching are combined into a single process reducing delivery times. Higher hardness with same chemistry is achieved which can be converted into products with lower carbon equivalents and better weldability. Finer microstructures with improved toughness is possible by using thermomechanical rolling. (Porter, 2006, p. 9)

There are also more ways to estimate weldability such as (Martikainen & Niemi, 1993, p. 121; Martikainen, 2011)

- Exposure to hot cracking UCS
- Composition and processing route of steel
- Hardness values inspection
- Microstructure inspection
- Phase diagrams
- Continous cooling transformation phase diagrams
- Welding procedure test and weldability test

4.3 Problems and benefits of high strentgh steels

The principal benefit of high strength steels is their increased strength to weigth ratio and the resulting savings in materials costs and welding times (Komizo, 2007, p. 1; Lämsä & Kiuru, 2012, p. 7). High strength steels are used in structures where higher static strength is needed. They can also be used in dynamically loaded structures, if the number of cycles during the life span of structure is under 10^7 or the critical point of fatigue is outside the welded joint. When high strength steels are used instead of conventional structural steels, the design aspect must be taken into account. Important factors that need to be assessed are the geometry, joint form and rigidity of the structure and location and shape of the weld. (Silvennoinen, 2001, p. 81)

Benefits of using high strength steels instead of conventional structural steels include (Silvennoinen, 2001, p.81; Lämsä & Kiuru, 2012, p. 7):

- Higher permitted design stresses
- Smaller material thicknesses
- Weight reduction of the structure
- Simple structure designs
- Less welding and filler metals needed
- Increase in payload
- Increase in service life of the structure

The properties and microstructure of high strength steel will change during welding due to the effect of heat. Processing route of steel determine partly what kind of effects can occur but high enough heat input and cooling time will produce undesired microstructures and lower the mechanical properties of the weld joint. Steel producing companies recommend limiting heat input usually to 1-2 kJ/mm when welding high strength steels. (Pirinen & Martikainen, 2009, p. 15) As the strength of the steel increases the need for pre-heating becomes greater because such steels are usually more alloyed (Ruukki, 2014a, p. 4-5).

Limiting factors when using high strength steels (Silvennoinen, 2001, p. 82; Xu et al., 2014, p.1):

- Higher residual stresses after welding can affect the creation of brittle fracture, fatigue and stress corrosion cracking

- Stricter requirements of welding imperfections
- The weight reduction of structure can affect the stiffness negatively
- Welding of high strength steels is more demanding
- Softening and hardening of HAZ with incorrect welding parameters

4.4 Heat input and cooling rate

Weld joint properties are depended on the cooling rate. Things that affect the cooling rate are: heat input, plate thickness, joint type and working temperature. The most critical microstructural changes of weld metal and HAZ take place when they cool from 800 °C to 500 °C and cooling rate is often given as a value of this time ($t_{8/5}$). Figure 10 estimates the effect of cooling rate on the hardness and ductility transition temperature of HAZ with non-alloy and low-alloy steels. When cooling rate is very fast, the hardness value of HAZ rises because of the hardening of steel. Nonetheless the ductility properties of the joint are good. In proportion if cooling rate is very slow, the hardness value stays low but ductility properties will decline because of transition temperature value rises. The optimal results can be achieved at area II. (Ruukki, 2014a, p. 6)

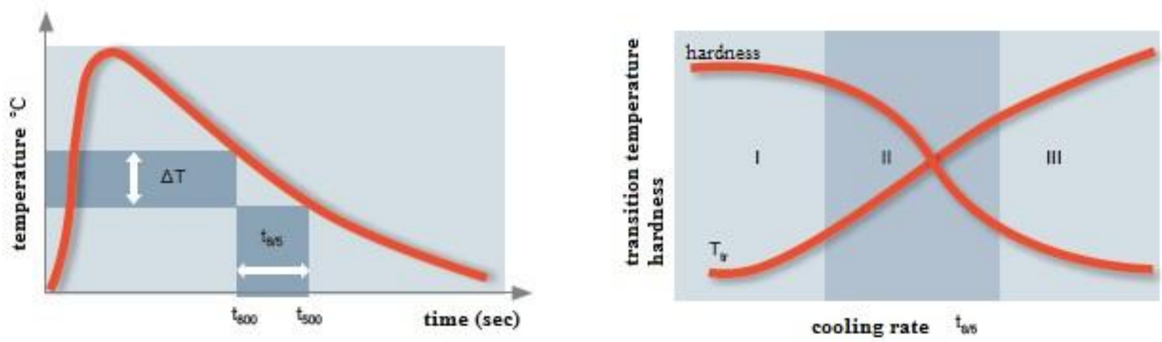


Figure 10. The effect of cooling rate on the properties of HAZ (Ruukki, 2014a, p. 7)

Heat input value Q, which tells how much of the actual arc energy reaches the work piece, can be calculated as follows (SFS-EN 1011-1:en, p.12):

$$Q = k \frac{U \, x \, I}{v \, x \, 1000} \left({}^{kJ}/_{mm} \right) \tag{3}$$

Where Q is the heat input, k is the thermal efficiency, U is the arc voltage, I is the welding current and v is the travel speed in mm/s. (SFS-EN 1011-1:en, p. 11) Thermal efficiency factor is depended on welding process, they can be seen in table 5.

Table 5. Thermal efficiency factor k values (SFS-EN 1011-1:en, p. 12)

Process No	Welding process	*k*
12	Submerged arc welding	1,0
111	Manual metal-arc welding	0,8
131	MIG welding	0,8
135	MAG welding	0,8
114	Self-shielded tubular-cored arc welding	0,8
136	Tubular-cored wire metal-arc welding with active gas shield	0,8
137	Tubular-cored wire metal-arc welding with inert gas shield	0,8
141	TIG welding	0,6
15	Plasma arc welding	0,6

Cooling rate for two-dimensional heat flow can be calculated as follows (SFS-EN 1011-2:en, p. 41):

$$t_{8/5} = (4300 - 4{,}3\,T_0)\;x\;10^5 x\;\frac{Q^2}{d^2}\;x\;[(\frac{1}{500-T_0})^2 - (\frac{1}{800-T_0})^2]\;xF_2 \tag{4}$$

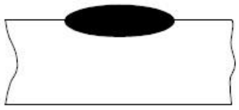
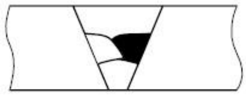
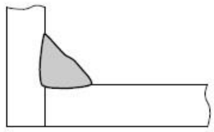
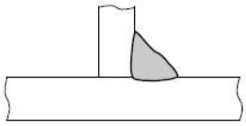
Where $t_{8/5}$ is cooling rate from 800 °C to 500 °C, T_0 is working temperature, Q is heat input, d is material thickness and F_2 is appropriate shape factor for two-dimensional heat flow found in table 6.

Cooling rate for three-dimensional heat flow can be calculated as follows (SFS-EN 1011-2:en p. 41):

$$t_{8/5} = (6700 - 5T_0)\;x\;Q\;x\;(\frac{1}{500-T_0} - \frac{1}{800-T_0})\;xF_3 \tag{5}$$

F_3 is appropriate shape factor for three-dimensional heat flow.

Table 6. Shape factor values (SFS-EN 1011-2:en, p. 45)

Form of weld		Shape factor F_2 two-dimensional heat flow	 F_3 three-dimensional heat flow
Run on plate		1	1
Between runs in butt welds		0,9	0,9
Single run fillet weld on a corner-joint		0,9 to 0,67	0,67
Single run fillet weld on a T-joint		0,45 to 0,67	0,67

4.5 Transition temperature & Brittle fracture

Non-alloyed and low-alloyed steels have microstructures that are mostly ferritic. Their fracture behavior changes from ductile to brittle on certain temperature area, this is called transition temperature. With low-alloyed steels this often occurs between temperatures of +20 °C and -100 °C. (Huhdankoski, 2000, p. 8) At higher temperatures the absorbed energy is relatively large with a ductile mode of fracture. As the temperature is lowered the energy absorbtion drops over a relative narrow temperature range, below which the energy has a small constant value and fracture mode is brittle. (Callister & Rethwisch, 2011, p. 251) Typical transition temperature curve of low-alloyed steel can be seen in figure 11.

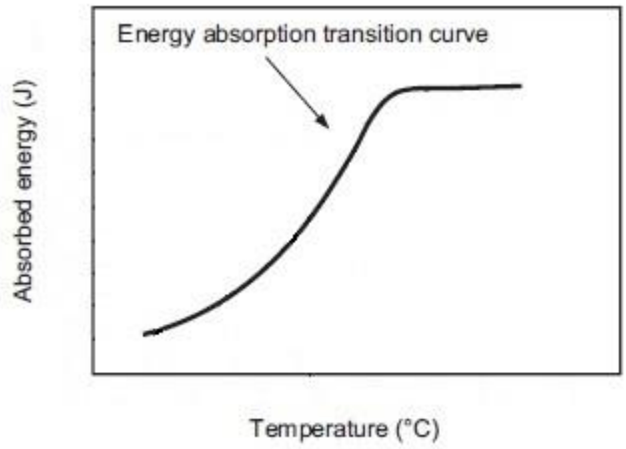


Figure 11. Energy absorption transition curve of low-alloyed steel (replotted from Kobelco, 2008, p. 8)

As mentioned, two kind of fractures can occur for metals, ductile and brittle. Classification is based on the materials ability to experience plastic deformation. Fracture process has two steps, crack formation and propagation. Typical characteristic for ductile fracture is extensive plastic deformation in the vicinity of an advancing crack. The fracture process proceeds relatively slowly as the crack length is extended. It resists further extension unless the stress is increased. This kind of fracture process is often called stable. In comparison brittle fracture may spread very rapidly with very little plastic deformation. No applied stress is needed once the crack propagation will occurs, it will continue spontaneously. (Callister & Rethwisch, 2011, p. 236)

Brittle fracture can occur as a grain boundary fracture or as a cleavage fracture. On cleavage fracture, crack propagation happens with successive and repeated breaking of atomic bonds along specific crystallographic planes. The fracture cracks pass through the grains. On grain boundary fracture the crack propagation happens along the grain boundaries. (Huhdankoski, 2000, p. 8; Callister & Rethwisch, 2011, p. 240-241)

Steels and weld metals resistance to brittle fracture can be evaluated by several fracture toughness tests. Maybe the most common of these methods is Charpy-V notch impact test (CVN). Other alternative methods include the crack-tip opening angle (CTOA), the crack-tip opening displacement (CTOD), the drop-weight tear test (DWTT), the stress intensity factor K, the elastic energy release rate G and the J-integral. (Callister & Rethwisch, 2011, p. 250; Zhu & Joyce, 2012, p. 3; Huhdankoski, 2000, p. 12)

4.6 Weld imperfections and quality level

According to SFS-EN 6520-1 term imperfection means a discontinuity in the weld or a deviation from the intended geometry. Weld defects are unacceptable imperfections. Typical imperfections are for example cracks, cavities, solid inclusions, lack of fusion, incomplete penetration and porosity. Some imperfections are allowed depended on welding quality level. Three quality levels are given: B, C and D, where quality level B corresponds to the highest requirement on the finished weld. (SFS-EN 6520-1, p. 8; SFS-EN 5817, p. 11) Welding imperfections affect negatively to the joint properties and their existence is always tried to minimize. Decision of quality level need to be done with relation to application, expences and production time tend to rise with better quality level. (Lukkari, 2001, p. 2)

4.6.1 Hydrogen cracking

Weld hydrogen cracking, also known as cold cracking, can occur to hardened microstructure after welding. Hydrogen cracking usually occurs when the weld cools down to temperature around 150 °C or sometimes even days after the welding is completed. Non-alloyed steels, fine-grain steels, high strength steels, quenched and tempered steels and heat resisting steels can all suffer hydrogen cracking but three causal factors need to exist for hydrogen cracking to occur (Lukkari, 2001, p. 8):

- Sufficient amount of hydrogen absorbed in weld
- Hardened (martensitic) microstructure sensitive to cracking
- Elevated stress

Steel development has reduced the problem of hydrogen cracking in the HAZ and with high strength steels the cracking is more of a problem in the weld metal. How the cracking mechanism work is still under research but it is thought to relate to the diffused hydrogen movement in the steel and its accumulation to the stress concentrations in the weld metal. Hydrogen affects negatively to forces binding atoms and grains together and helps crack formation. Main sources of dissolved hydrogen are atmospheric and welding consumable moisture, impurities and hydrogen compounds in welding consumable and in base metal. (Lukkari, 2005c, p. 44-46) Hydrogen scale of weld metal can be seen in table 7.

Table 7. Hydrogen scale of weld metal (SFS-EN 1011-2, p. 29)

Diffusable hydrogen content ml/100 g of deposited metal	Hydrogen scale
> 15	A
10 ≤ 15	B
5 ≤ 10	C
3 ≤ 5	D
≤ 3	E

The amount of hydrogen ending up in the weld metal differs creatly based on chosen welding process and welding consumable as well as heat input. Higher heat input means longer cooling time and more hydrogen can escape the weld pool by diffusion. (Lukkari, 2005c, p.49) Flux-cored consumables have normally hydrogen scales of B-D (SFS-EN 1011-2, p. 29)

Hydrogen cracking can be preventent by (Lukkari, 2005c, p. 44-45):

- Using a steel with low carbon content and carbon equivalent
- Using a TMCP steel
- Using a low hydrogen scale welding consumable
- Proper storage of welding consumables and base metals
- Cleansing the fusion face
- Using recommended heat input, given by steel manufacturer or standards
- Preheating

4.6.2 Hot cracking

Hot cracking, or solidification cracking, may occur on high temperatures during the solidification of the weld metal. Such cracking is intergranular along the grain boundaries of the weld. Solidification cracks are most commonly longitudinal centerline cracks but they can appear on many locations and orientations. The cracks do not necessarily open to the surface, they can also be buried. (Lukkari, 2001, p.6; Kou, 2003, p. 263)

Following factors affect the forming of hot cracking (Lukkari, 2001, p. 6):

- Shape of the weld bead
- Metallurgical factors such as chemical composition, the amount of impurities and the extent of weld metal solidification area
- Strain factors

A concave shaped weld bead is more prone to suffer solidification cracking than a convex shaped. The outer surface of a concave shaped weld bead is stressed in tension when the weld cools and shrinks. The outer surface of the weld is being pulled towards the toes and the root as seen in figure 12. If the weld is convex shaped, pulling towards the root compresses the outer surface and offsets the tension caused by pulling towards the toes. The tensile stresses are reduced along the outer surface and so is the tendency to solidification cracking. Excessive convexity can however produce stress concentrations and other forms of cracking. (Kou, 2003, p. 294)

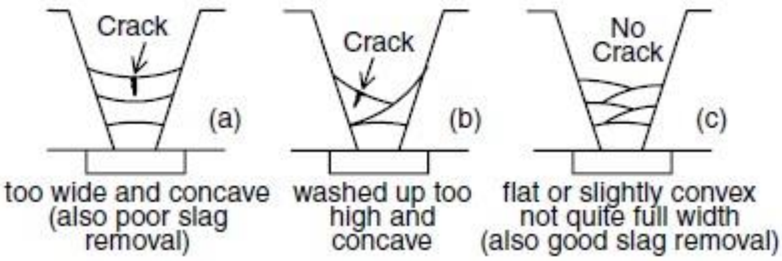


Figure 12. The effect of weld bead shape (Kou, 2003, p. 294)

Weld width to depth ratio can also effect the solidification cracking. If the weld bead shape is deep and narrow, as seen in figure 13, it can be susceptible to centerline cracking. This is because the angle of the abutment between the columnar grains growing from opposite sides of the weld pool is too steep. This will also help the impurities to segregate in the center of the weld pool in the final stages of solidification and form low melting point compounds. Cracks will occur easier in the centerline of weld when the tensile stresses start to develop, if there are still partly liquid films at grain boundaries. (Lukkari, 2001, p. 6; Kou, 2003, p. 268, p.294) Some research has also proven that narrower gap is more prone to suffer solidification cracking. It was also observed that these cracks were healed by remelting of the following overlapping passes. (Karhu & Kujanpää, 2011, p. 173-174)

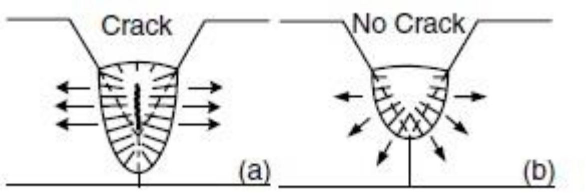


Figure 13. Effect of weld depth-width ratio on centerline cracking (Kou, 2003, p. 295)

Tendency to hot cracking can be estimated with the unit of crack susceptibility (UCS) formula developed by The Welding Institute (TWI). It was originally developed for submerged arc welding but can also be used with other welding processes. UCS is calculated in relation to composition of the weld metal as follows. (Lukkari, 2001, p.8; Vähäkainu, 2003, p. 45)

$$UCS = 230C + 190S + 75P + 45Nb - 12{,}3Si - 5{,}4Mn - 1 \qquad (6)$$

The formula is valid for weld metal containing following concentrations seen in table 8 and table 9.

Table 8. Validity of the UCS formula (SFS-EN 1011-2, p. 93)

Element	Content in %
C	0,03[a] to 0,23
S	0,010 to 0,050
P	0,010 to 0,045
Si	0,15 to 0,65
Mn	0,45 to 1,6
Nb	0 to 0,07
[a] Contents of less than 0,08 % to be taken as equal to 0,08 %.	

Table 9. Limits of alloying elements and impurities (SFS-EN 1011-2, p. 95)

Element	Content max. in %
Ni	1
Cr	0,5
Mo	0,4
V	0,07
Cu	0,3
Ti	0,02
Al	0,03
B	0,002
Pb	0,01
Co	0,03

As the UCS formula is calculated results can be estimated as follows (Lukkari, 2001, p. 8; Vähäkainu, 2003, p.45):

UCS = <10 High resistance to cracking

UCS = 10-30 A risk of cracking with low weld bead width/depth ratio

UCS = >30 Low resistance to cracking

Hot cracking can be prevented by (Vähäkainu, 2003, p. 44; Lukkari, 2001, p. 7; Kou, 2003, p. 294; SFS-EN 1011-2, p. 93):

- Adjusting welding parameters so that weld width to depth ratio is 1:1 or more
- Designing the weld joint so that strains will be minimal
- Cleaning the impurities and slag from welding faces
- Choosing steel with low carbon content
- Avoiding base materials with over 0,04 % sulphur and phosphorus content
- Reducing penetration and welding speed
- Avoiding concave shaped welds

5 QUALITY ASSURANCE OF FC-NGAW

Quality requirements for welded structures are set out in different directives, regulations, standards or customer specification. Quality systems standard such as ISO 9001 defines welding as special process or as process requiring validation that must be properly controlled to ensure that the necessary quality requirements are achieved. (Weman, 2003, p. 171) Actual quality requirements for welding are presented in ISO 3834 standards. This standard can be used as a quideline to provide assurance of welding competence. ISO 3834 consists of six parts. Different quality requirement levels: comprehensive quality requirements, standard quality requirements and elementary quality requirements are found on parts 2-4. (Martikainen, 2013, p. 7) All the quality requirement levels have some common demands (Martikainen, 2013, p. 7; Martikainen, 2010, p. 181):

- Welding coordination must be defined
- The welders and welding operators must have been tested and approved
- The NDT personnel need to be qualified and approved
- The welding need to ne carried out in accordance to welding procedure specifications (WPS)
- The consumables need to be stored and handled properly
- Identification and traceability of welding consumables and products

The differences between quality requirements of ISO 3834-2 and ISO 3834-3 are slight and mostly related to documentation, which is stricter on ISO 3834-2. (Martikainen, 2013, p. 7) Table 10 shows the relationship between demands of different quality requirement levels.

Table 10. The relationship of requirements between different quality requirement levels (SFS-EN ISO 3834-1, p. 15)

No.	Element	ISO 3834-2	ISO 3834-3	ISO 3834-4
1	Review of requirements	review required		
		record is required	record may be required	record is not required
2	Technical review	review required		
		record is required	record may be required	record is not required
3	Sub-contracting	treat like a manufacturer for the specific subcontracted product, services and/or activities, however final responsibility for quality remains with the manufacturer		
4	Welders and welding operators	qualification is required		
5	Welding co-ordination personnel	required		no specific requirement
6	Inspection and testing personnel	qualification is required		
7	Production and testing equipment	suitable and available as required for preparation, process execution, testing, transport, lifting in combination with safety equipment and protective clothes		
8	Equipment maintenance	required to provide, maintain and achieve product conformity		no specific requirement
		documented plans and records are required	records are recommended	
9	Description of equipment	list is required		no specific requirement
10	Production planning	required		no specific requirement
		documented plans and records are required	documented plans and records are recommended	
11	Welding procedure specifications	required		no specific requirement
12	Qualification of the welding procedures	required		no specific requirement
13	Batch testing of consumables	if required	no specific requirement	
14	Storage and handling of welding consumables	a procedure is required in accordance with supplier recommendations		in accordance with supplier recommendations
15	Storage of parent material	protection required from influence by environment; identification shall be maintained through storage		no specific requirement
16	Post-weld heat treatment	confirmation that the requirements according to product standard or specifications are fulfilled		no specific requirement
		procedure, record and traceability of the record to the product are required	procedure and record are required	
17	Inspection and testing before, during and after welding	required		if required
18	Non-conformance and corrective actions	measures of control are implemented		measures of control are implemented
		procedures for repair and/or rectification are required		
19	Calibration or validation of measuring, inspection and testing equipment	required	if required	no specific requirement
20	Identification during process	if required		no specific requirement
21	Traceability	if required		no specific requirement
22	Quality records	if required		

5.1 Quality factors

Welding quality factors can be divided into two very different scale aspects: technical quality of a weld and operational welding quality. Technical quality of a weld is considered sound when it meets the given requirements. Usually the customer is the party who sets these requirements but sometimes the welded product can define the requirements on its own. Such products could be off-shore structures, nuclear power plant structures, pressure vessels, bridges, cranes and so on. The authorities and classification societies can also set requirements and nowadays it is common that even the producer can set requirements by itself. (Martikainen, 2013, p. 5)

Technical quality of a weld can be presented as follows (Martikainen, 2013, p. 5):

- Visual quality
- Basic workshop quality
- Weld class quality
- Metallurgical quality

Visual quality and basic workshop quality as a concepts do not define the quality level very strictly. Still the importance of the visual quality of the weld has been emphasized lately. Surface of the weld has to be smooth and flawless and without restart points. In simple terms it needs to look good. Basic workshop quality can be achieved with competent personnel and equipment. It can be compared to quality level C or IIW (International Institute of Welding) 3 without incomplete penetration. (Martikainen, 2013, p. 5)

Weld classes are defined more clearly and weld in such level will have to meet the certain welding imperfection requirements. Welding imperfections are described in EN ISO 6520-1 and related quality levels B, C and D for steels in EN ISO 5817. New quality level designed as B+, which has additional requirements is described in EN 1090. Different weld classes do not in anyway define the metallurgical factors or properties of the welded joint. The joint can have no welding imperfections but still be unusable in its application. The microstructure needs to be tough enough, grain size next to the fusion line cannot be too large, too hard or too soft zones are not permitted and so on. These kind of factors cannot be detected with ordinary NDT. Welding procedure test must be done to be able to verify these factors and WPS is a great aid for quality control. (Martikainen, 2013, p. 5-6)

By focusing solely on technical quality it's hard to see the big picture. Operational welding quality takes widely into account factors affecting to quality before, during and after welding. When productivity and economy related things are also included, a TQM (Total Quality Management) model is the result. It's a comprehensive way where all the things form a solid base for action. (Martikainen, 2013, p. 6-7)

5.2 Welding procedure test

Welding procedure test is the most common method to gain approval for the WPS. A standardized test piece is made representing the welded joint in relation to production. The shape and dimensions of the test piece need to be sufficient for allowing all the required tests to be carried out. Testing includes both non-destructive testing (NDT) and destructive testing (DT), testing is summarized in table 11. (SFS-EN ISO 15614-1, p. 13 & 19)

Table 11. Examination and testing of the welded test pieces (SFS-EN ISO 15614-1, p. 21)

Test piece	Type of test	Extent of testing	Footnote
Butt joint with full penetration –	Visual	100 %	–
Figure 1 and Figure 2	Radiographic or ultrasonic	100 %	a
	Surface crack detection	100 %	b
	Transverse tensile test	2 specimens	–
	Transverse bend test	4 specimens	c
	Impact test	2 sets	d
	Hardness test	required	e
	Macroscopic examination	1 specimen	–
T-joint with full penetration –	Visual	100 %	f
Figure 3	Surface crack detection	100 %	b and f
Branch connection with full penetration – Figure 4	Ultrasonic or radiographic	100 %	a, f and g
	Hardness test	required	e and f
	Macroscopic examination	2 specimens	f
Fillet welds –	Visual	100 %	f
Figure 3 and Figure 4	Surface crack detection	100 %	b and f
	Hardness test	required	e and f
	Macroscopic examination	2 specimens	f

[a] Ultrasonic testing shall not be used for $t < 8$ mm and not for material groups 8, 10, 41 to 48.
[b] Penetrant testing or magnetic particle testing. For non-magnetic materials, penetrant testing.
[c] For bend tests, see 7.4.3.
[d] 1 set in the weld metal and 1 set in the HAZ for materials ≥ 12 mm thick and having specified impact properties. Application standards may require impact testing below 12 mm thick. The testing temperature shall be chosen by the manufacturer with regard to the application or application standard but need not be lower than the parent metal specification. For additional tests see 7.4.5.
[e] Not required for parent metals: -sub-group 1.1, and groups 8, 41 to 48.
[f] Tests as detailed do not provide information on the mechanical properties of the joint. Where these properties are relevant to the application an additional qualification shall also be held e.g. a butt weld qualification.
[g] For outside diameter ≤ 50 mm no ultrasonic test is required.
For outside diameter > 50 mm and where it is not technically possible to carry out ultrasonic examination, a radiographic examination shall be carried out provided that the joint configuration will allow meaningful results.

Test specimen shall be taken after the NDT is carried out. It is also acceptable to take the specimen from locations avoiding welding imperfections located by NDT. (SFS-EN ISO 15614-1, p. 21) Test specimen locations for butt joint in plate can be seen in figure 14.

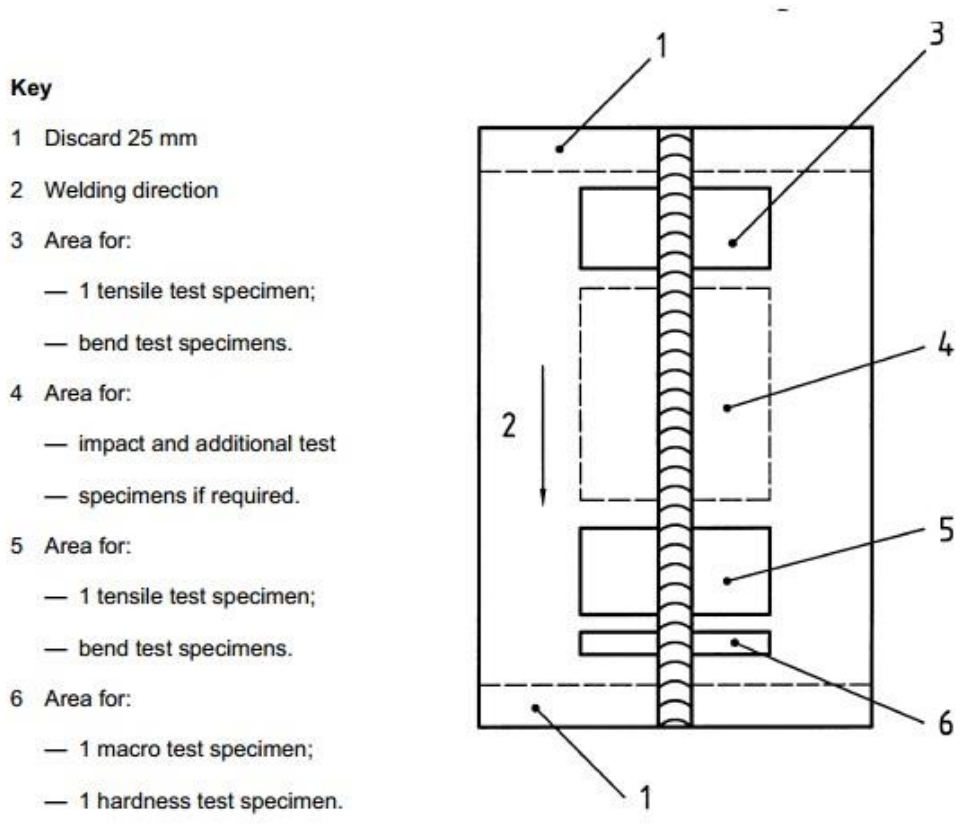


Figure 14. Test specimen locations of butt joint in plate (replotted from SFS-EN ISO 15614-1, p. 23)

5.3 Testing methods

Testing methods can be separated into non-destructive testing and to destructive testing methods. Non-destructive testing is used to check if the quality demands are being met. NDT methods cause no damage to the test piece and can find many kind of welding imperfections. Destructive testing is used when mechanical properties and metallurgical quality of the test piece are needed to found out.

5.3.1 Non-destructive testing

The most common way of NDT is visual testing (VT). Human eye can detect line shaped imperfection about 0,05 mm in width and circular imperfection about 0,10 mm in diameter. Optical instruments such as magnifying glasses and macroscopes can be used. Even though the method is simple to use, rules, guide books, contrasting items and clear limits for approval are needed to make this method reliable. (Martikainen & Niemi, 1993, p. 27-30)

Liquid penetrant testing is a surface testing method, used to detect discontinuities in the surface of non-porous materials. It is suitable also for non-magnetic materials. The test piece is carefully cleaned after which a colored or fluoroscent liquid is poured on the surface, a capillary force helps the liquid to penetrate the discontinuities. After certain amount of time the liquid is washed away and a developer is introduced. Some of the still present penetrant liquid is absorbed into the developer and information is obtained about the discontinuity. (Martikainen & Niemi, 1993, p. 30)

Magnetic particle testing is also a surface testing method, used to reveal discontinuities in or in the immediate vicinity of the surface of ferromagnetic materials. Fine ferrous iron particles are set on the surface of the piece and the piece is then magnetized. The magnetic field introduced is composed of magnetic lines of force. Flaws and imperfections interrupt the flow of the magnetic lines and the ferrous particles gather around these points exposing the flaws. If the discontinuity is presicely same way oriented as the magnetic lines of force, it cannot be discovered. Magnetic particle testing should always be done twice in downright directions. (Martikainen & Niemi, 1993, p.32)

Radiographic testing covers all the photographic methods using ionizing radiation and it can be used to reveal many kind of internal flaws. An appropriate measuring instrument, usually film is placed behind the test piece. The test piece is then exposed to radiation and the intensity of the rays penetrating is stored on the measuring instrument. Radiograph of the piece is then processed and interpreted to discover information about the present flaws. Three-dimensional flaws such as porosity, slag inclusions and defects in form can be found, if their size is at least 1-2 % of the material thickness. (Martikainen & Niemi, 1993, p. 35)

Radiographic testing with X-rays is very usable method up to 50 mm material thicknesses. The sensibility of the equipment is commonly 2-3 % of the material thickness. Over 50 mm thick materials need to be tested with different radiation sources. (Martikainen & Niemi, 1993, p. 35)

Ultrasonic testing is a method which utilizes high frequency sound waves usually between 0,5 and 20 MHz range. The sound waves travel through the material and their intensity is measured after reflection. The presence and location of the flaw can be determined from the reflection. The higher the frequency used the smaller the flaws that can be detected. The penetrating ability suffer the higher the frequency used though. (Martikainen & Niemi, 1993, p. 36)

5.3.2 Destructive testing

Hardness test provides information about the metallurgical changes caused by welding. Three different commonly used hardness tests are the Brinell, Rockwell and Vickers. (Connor, 1987, p. 394) The Brinell test uses a steel ball of known diameter as identer which is forced into material by specified force. The diameter of the impression is then measured and converted to Brinell hardness number, so the hardness value is calculated as a load per area. The Vickers test is similar but uses smaller inverted pyramid as identer which is ideal for measuring different zones of microstructure. The Rockwell test measures hardness through depth of penetration which the identer causes on set force. (Bruce et al., 2004, p. 36-37) The hardness identations can be done at regular intervals or as a single indentations (SFS-EN ISO 9015-1, p. 9).

Impact test measures the impact strength of a test piece. The test shall be carried out in specified temperature because the impact values of metallic materials can vary with temperature. The most common impact test method is the Charpy V-notch impact test. A standard sized notched test piece is hit by a swinging pendulum and the amount of energy absorbed is measured. Specimen for Charpy impact test is usually 55 mm long and 10 mm and of square section with 10 mm sides with V- or U-shaped notch in the center of the length as seen in figure 15. (SFS-EN ISO 148-1, p. 11)

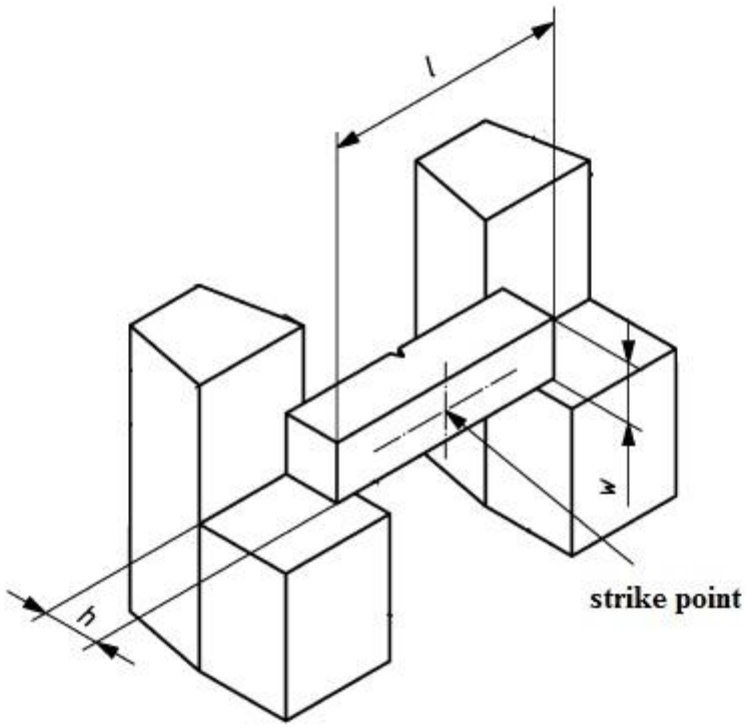


Figure 15. Charpy impact test princible (Adapted from SFS-EN ISO 148-1, p. 19)

Tensile test is performed to stress the test specimen to the breaking point. An increasing tensile load is applied to the test specimen on a machine until the rupture occurs. The result is stress-strain diagram which can be interpreted to discover the yield strength, tensile strength and percent elongation. (Bruce et al., 2004, p. 32-35; SFS-EN ISO 4136, p. 9) Tensile test can be transversal or longitudal. The purpose of the transversal tensile test is to verify that certain design strength requirements are met. (Connor, 1987, p. 389)

Various types of bend tests are used to evaluate the ductility of a welded joint. Transversely or longitudinally taken test specimen from the welded joint is submitted to plastic deformation by bending it, without reversing the bending direction. (SFS-EN ISO 5173/A1, p. 11) Either the weld surface area or the weld cross section is made under tension in order to expose flaws (Connor, 1987, p. 395).

5.4 WPQR and WPS

Welding procedure specification (WPS) is a formal written document that specifies the details of the required variables for a specific application in order to assure repeatability. It must contain all important information relating to the welding work and with indication whether such factors can affect the metallurgy, mechanical properties or geometry of the welded joint. WPS forms a sound base for planning, execution and quality assurance of welding. (Weman, 2003, p. 176; Lukkari, 2002, p. 55; SFS-EN 15609-1, p. 7) At least following information is required in WPS (Lukkari, 2002, p. 55):

- Identification of the manufacturer
- Identification of the WPS
- Reference to the welding procedure qualification record (WPQR)
- Designation of the material
- Thickness ranges of the joint
- Welding process
- A sketch of the joint design
- Weld run sequence (given on the sketch if essential)
- Applicable welding positions
- Joint preparation methods
- Welding parameters
- Welding consumables
- Heat input and preheating
- Interpass temperature

SFS-EN ISO 15609 gives all the required information needed in WPS. New welding processes or materials usually aren’t applicable with old welding procedure specification and need to be tested with some of the methods listed in SFS-EN ISO 15607. Until the WPS is proven that way it is considered pWPS or preliminary welding procedure specification. (Weman, 2003, p. 176; Lukkari, 2002, p. 55; SFS-EN 15609-1, p. 7) If the results are satisfactory and proven, welding procedure qualification record (WPQR) is made. WPQR is a document specifying all the needed information about the welding and the results of the testing performed for the weld. (SFS-EN ISO 15614-1, p. 47)

5.5 Comparison of RMRS procedures of testing to EN

The test piece for butt welded joint in plate according to RMRS is shown in figure 16. Symbols a and b are dimensions depending on a welding process. These rules apply for manual and semi-automatic welding: a ≥ 150 mm but not less than 3 times material thickness, b ≥ 350 mm but not less than 6 times material thickness. For automatic welding, a ≥ 200 mm and b ≥ 1000 mm. Number 1 is orientation of rolling direction for plates impact tested in the longitudinal direction KV_L and number 2 is orientation of rolling direction for plates impact tested in the transverse direction KV_T.

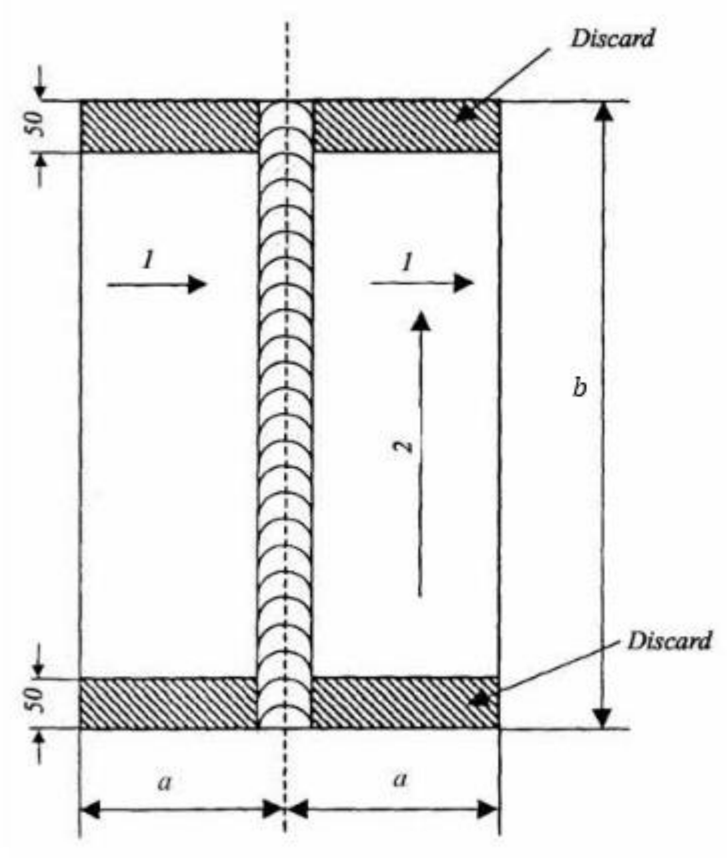


Figure 16. Test piece for butt welded joint in plates according to RMRS (Russian Maritime Register of Shipping, 2014b, p. 126)

Corresponding test piece according to SFS-EN ISO 15614-1 is shown in figure 17. Minimum value for a is 150 mm and minimum value for b is 350 mm, t being the material thickness and number 1 referring to joint preparation and fit-up as detailed in pWPS. EN rules do not specify different dimensions for automatic welding.

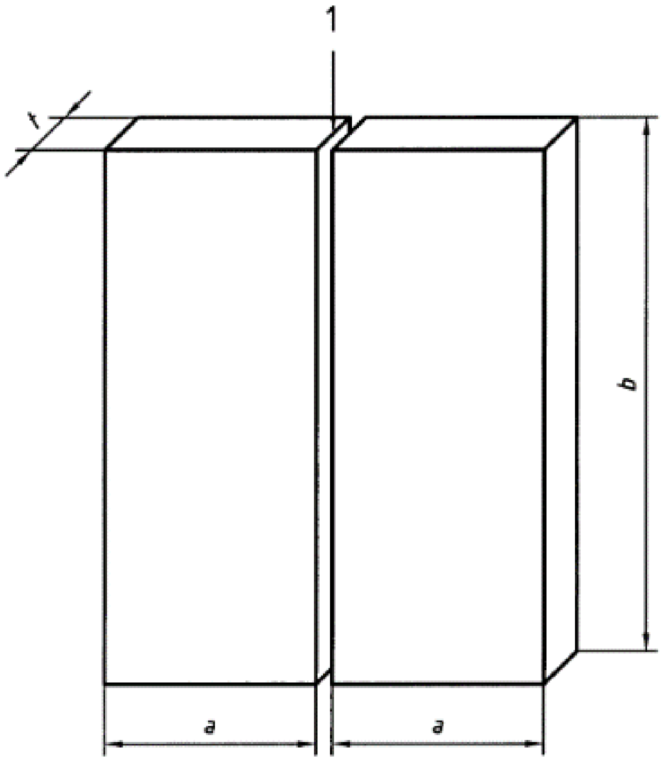


Figure 17. Test piece for a butt welded joint in plate with full penetration according to EN rules (SFS-EN ISO 15614-1, p. 15)

Required testing methods according to RMRS are shown in table 12. The EN requirements are similar except only 2 series of impact test specimens are needed. The extent of impact testing according to RMRS depends on thickness of the test piece, the heat input of welding and grade of the base material. Charpy-V notches need to be in weld metal, on fusion line and in HAZ, 2 mm from fusion line. Additional notches may be required in HAZ, 5 and 10 mm from fusion line.

Table 12. Requirements of testing for butt joints according to RMRS (Russian Maritime Register of Shipping, 2014b, p. 128)

Type of test	**Extent of testing**
Visual testing	100 %
Radiographic or ultrasonic testing	100 %
Surface crack detection	100 %
Transverse tensile test	2 specimens
Transverse bend test	4 specimens
Impact test	Minimum 3 series of 3 specimens
Hardness test	Required
Macro examination	1 specimen

RMRS impact strength requirements are shown in table 13.

Table 13. Impact strength requirements of different steel grades welded on vertical position for butt joints according to RMRS (Russian Maritime Register of Shipping, 2014b, p. 136)

Steel grade	**Impact energy in J (min.)**		
		HAZ and FL	
	Weld	Longitudinal	Transverse
A32-F32	34	47	-
A36-F36	34	47	-
A40-F40	39	47	-
A420-F420	42	42	28
A460-F460	46	46	31
A500-F500	50	50	33
A550-F550	55	55	37
A620-F620	62	62	41
A690-F690	69	69	46

Hardness requirements for higher and high strength steels also differ a bit from EN as seen in table 14. Heat treatment of high strength steels must be consulted with Register.

Table 14. Limiting hardness values for high strength steels (SFS-EN ISO 15614-1, 2012, p. 33; Russian Maritime Register of Shipping, 2014b, p. 135)

Rules	Non-heat treated	Heat treated
SFS-EN 15614-1	380 (HV10)	320 (HV10)
RMRS	420 (HV10)	-

There is also some deviation between RMRS and EN in range of approval for butt welds material thickness. Comparison of qualification ranges is shown in table 15.

Table 15. RMRS and EN comparison of qualification ranges for butt welds material thicknesses (SFS-EN ISO 15614-1, 2012, p. 41; Russian Maritime Register of Shipping, 2014b, p. 141)

		Range of qualification	
Rules	**Test piece thickness (mm)**	**Single run**	**Multi run**
EN	t ≤ 3	0,7t - 1,3t	0,7t - 2t
	3 < t ≤ 12	0,5t (min. 3) - 1,3t	3 - 2t
	12 < t ≤ 100	0,5t - 1,1t	0,5t - 2t
	t > 100	not applicable	50 -2t
RMRS	t ≤ 3	t - 1,1t	t - 1,5t
	3 < t ≤ 12	0,7t - 1,1t	3 - 2t
	12< t ≤ 100	0,7t - 1,1t	0,5t - 2t (max. 150)
	t > 100	-	0,5t - 2t

6 EXPERIMENTAL TESTING

The experimental part of the thesis aims to clarify, if narrowed gap welding with mechanized flux-cored arc welding and further reducing groove angles is qualitative possible. Certain factors have to be taken into account when welding high strength steels to achieve good mechanical properties of the welded joint. In this case the limiting factor was heat input, which was limited to value 2 kJ/mm that the steel producer and Russian Maritime Register of Shipping recommend.

Twelve different test pieces were welded on vertical upwards position (PF) during the testing period and their weld joint qualities were tested with NDT and DT methods. These test results are used as a foundation for an official welding procedure test performed later on in supervision of Maritime Register of Shipping.

6.1 Experimental plan

Arctech Helsinki Shipyard has earlier done welding tests with 30° groove angle and the results were succesful. Preliminary testing plan was made at the beginning of the experimental testing period, it can be found in Appendices 3 and 4. Three different groove angles were chosen to be tested, these were 20, 10 and 5 degrees. Some test pieces were also welded with identical groove angle, but with different root opening. Finally one test piece was welded without mechanization to provide some comparison. The idea was to use two different shielding gases, pure CO_2, a mixture of argon and CO_2 (M21) and appropriate filler materials. The availability of Wise welding software solutions was also utilized with E500 TMCP steel.

The goal was to find optimal welding parameters and to achieve clean quality weld pieces, which were later tested with destructive testing methods at Lappeenranta University of Technology Welding laboratory. The main goal of the experimental testing was to achieve welding procedure qualification record (WPQR) and preliminary welding prodecure specification (pWPS) for the tested steels.

6.2 Testing materials and welding tests

Two shipbuilding steels were chosen to be tested, they were Ruukkis's E500 TM and EH36. They are commonly used at the Shipyard and both are E grade steels, meaning that their impact strength test temperature is -40°C. E500 TM was delivered 25 mm thick where EH36 was delivered 10 mm thick. E500 TM is thermomechanically treated and EH36 is normalized. Chemical composition and mechanical properties of the steels are shown in tables 16 and 17.

Table 16. Chemical compostion of the steels (Test certificates, Appendix 5 & 6)

Chemical composition %											
Steel	Thickness	Pcm	C	Si	Mn	P	S	Al	Nb	V	Ti
E500 TM	25 mm	0,18	0,068	0,26	1,50	0,011	0,001	0,047	0,036	0,008	0,015
EH36	10 mm	0,27	0,169	0,39	1,44	0,022	0,003	0,026	0,001	0,032	0,003
Steel	Thickness	Cu	Cr	Ni	Mo	N	B	Sn	Pb	-	-
E500 TM	25 mm	0,271	0,05	0,75	0,008	0,004	0,003	0,002	-	-	-
EH36	10 mm	0,07	0,08	0,03	0,006	0,005	-	-	-	-	-

Table 17. Mechanical properties of the steels (Test certificates, Appendix 5 & 6)

Mechanical properties				
Steel	Yield strength (Mpa)	Tensile strenght (Mpa)	Elongation (%)	Impact test (J)
E500 TM	575	657	17	309 (-40°C)
EH36	409	574	23,5	74 (-40°C)

Welding consumables selected were Filarc PZ6113, Filarc PZ6115 and Dual Shield II 91-LT. PZ6113 was chosen because it is commonly used and it is also suitable for both pure CO_2 as well as M21 shielding gas. EH36 steel welding tests were performed with PZ6113. Filarc PZ6115 was used for welding E500 TM steel with M21 shielding gas and Dual Shield II 91-LT was a new welding consumable, delivered specifically to be used with E500 TM steel and CO_2 shielding gas. All consumables are rutile cored wires and 1,2 mm in diameter. PZ6113 and PZ6115 are both designed to be used with positional welding. PZ6113 produces softer arc than PZ6115, further information about the consumables is shown in tables 18 and 19. Shielding gases were M21 80% Ar + 20% CO_2 and pure CO_2. Kerback FS 271412 T flat ceramic backing was also used.

Table 18. Chemical composition of the welding wires (Test certificates, Appendix 7)

Chemical composition [%]											
Wire	C	Mn	Si	S	P	Cr	Ni	Mo	Nb	Cu	V
DS II 91 LT	0,05	1,06	0,35	0,008	0,014	0,02	2,23	-	-	-	-
PZ6115	0,05	1,00	0,37	0,017	0,017	-	2,50	-	-	-	-
PZ6113-1*	0,05	1,20	0,49	0,020	0,011	<0,1	<0,1	<0,1	0,01	0,02	0,02
PZ6113-2*	0,05	1,20	0,50	0,021	0,014	<0,1	<0,1	<0,1	0,01	0,01	0,02
* two different manufacturing batches of PZ6113 were used											

Table 19. Typical mechanical properties of the welding wires (Test certificates, Appendix 7; Esab, 2014, p. 2; Lukkari, 2005a, p. 6)

Typical mechanical properties				
Wire	Yield strength (Mpa)	Tensile strength (Mpa)	Elongation (%)	Impact test (J)
DS II 91 LT	568	643	24	89 (-40°C)
PZ6115	560	620	24	60 (-50°C)
PZ6113	505–535	571–601	25	128 (-20°C)

The butt welded test pieces were made of two plasma cutted 40 by 20 cm sized steel plates. Material thicknesses were 25 mm for E500 TM steel and 10 mm for EH36 steel. 20° and 10° groove angles were machined at shipyards own machine tooling shop and 5° groove angle was achieved with the plasma cutting, no machining was necessary. Before welding, fusion faces were grinded to clean them from impurities. The cutted and machined test pieces were tack welded with planned root openings and ceramic backing strip was fastened. Finally the test piece was fastened to a custom made rack where the welding carriage and rails were located. The welding was done by highly skilled Arctech Helsinki Shipyard welder.

Welding tests were started by acquiring proper welding parameters for each test configuration. Shielding gas flow was measured and set to 18 litre per minute. The root pass of all test pieces was welded with slightly pushing torch angle and with short stopping time in oscillation motion to achieve good fusion. Short stopping time was also used in final run to assure a good weld bead shape. Both WisePenetration and WiseFusion processes were used with E500 TM steel test pieces, except with the 20° groove angle where WiseFusion was only used in the root pass. EH36 steel test pieces were welded without the Wise processes. Welding parameters for each test piece were documented and the records can be found in Appendix 8.

6.2.1 Welding tests with E500 TM steel

No major problems occurred during welding the E500 TM test pieces with M21 shielding gas. WisePenetration and WiseFusion software solutions were active during the welding, except when welding the 20° groove angle test piece, where WiseFusion was only used in root pass. Welding the following beads without WiseFusion was done in experimental purpose. WiseFusion keeps the arc length optimally short and makes the arc alignment easier in narrower groove. It was noticed during the welding tests that, the narrower the groove, the more the arc started to wander closer the groove faces, if WiseFusion was not active. It was, however, possible to weld the subsequent weld beads of the 20° groove angle test piece without WiseFusion. With narrower groove angles the benefits of Wise processes was emphasized. More precision was needed and careful adjusting of oscillating width, but in general the welding was successful. It must be mentioned though that highly skilled operator is needed to achieve good results with narrower groove angles.

Welding with the CO_2 shielding gas and Dual Shield II 91-LT flux-cored wire was problematic. The root pass was extremely good, but welding the following weld beads resulted in excess penetration and inadequate fusion with the groove faces. These problems were not able to be solved during the testing period, although welding parameter tuning and other factors were tested. The penetrative nature of the wire was so dominant, that successful test piece could not be achieved and the testing was decided to postpone.

6.2.2 Welding tests with EH36 steel

All in all the welding tests with EH36 steel and both shielding gases were successful. The material thickness of the steel plates was 10 mm, so welding parameters were a bit lower and not that many welding beads were needed to fill the joint. Wise processes were not used to have some comparison on welding quality.

The welding of test pieces with 20° and 10° groove angles and M21 shielding gas was successful eventhough more adjusting was needed by the welding operator during the welding. The narrowest groove with 5° groove angle and 6 mm root opening caused problems. The result was incomplete fusion with groove faces and eventually the wire pushed the ceramic backing strip out of its position. Next test piece was made with larger, 9 mm root opening and that solved the problem. The failure of the first test piece may have been a result of distortions, to be precise, bending of the test piece during the welding. The bending might have caused the joint geometry to change, so that the groove got even narrower than it supposed to be.

Welding with CO_2 shielding gas proved no difficulties. Same Filarc PZ6113 flux-cored wire was used, it has good welding properties and it is suitable for both shielding gases. The test piece with the narrowest groove angle was again prepared with 9 mm root opening and suffered no shortcomings during welding. Because of the welding tests with CO_2 shielding gas and E500 TMCP steel were unsuccessful an extra test piece of EH36 steel was welded without mechanization.

6.3 Non-destructive and destructive testing

Non-destructive testing was done at the Arctech Shipyard's premise. Visual testing was performed after welding to make certain that welds are good quality. After the visual testing all test pieces were tested with magnetic particle testing. This test was performed by personel from Dekra Industrial. Finally test pieces were sent to radiographic testing, where X-ray photos were taken. The photos were taken and analyzed by Dekra personnel. More information of the non-destructive testing is found on the results section of the thesis.

After non-destructive testing was approved, the test pieces were shipped to Lappeenranta University of Technology welding laboratory, where test specimens were produced for destructive testing. Test pieces were first cut with bench saw to proper blanks. Tensile test specimens were machined to proper dimension according to SFS-EN ISO 4136. Three series of impact test specimens were machined per test piece according to SFS-EN ISO 148-1. E500 TMCP steel impact test specimens dimensions were standard 10x10x55 mm but EH36 steel test specimens had to be made subsidiary with dimensions of 7,5x7,5x55 mm. Impact test temperature was -40°C for the E500 TMCP steel test specimens and -20°C for the EH36 steel test specimens.

Final runs of the bend test specimens were grinded to same level with the base material and then tested with side bend test according to SFS-EN ISO 5173. Macro test specimens were grinded, polished and then etched before examination and photography. Hardness tests were performed with automatic Struers DuraScan 70 hardness testing machine. E500 TMCP test specimens' surface, middle and root were measured with rows of identations, where EH36 test specimens' surface and middle was measured.

7 EQUIPMENT

All welding equipment and necessary materials were provided by Arctech Helsinki Shipyard. All the test welding was done in Shipyard´s premise. Welding equipment which was used was Kemppi Fastmig X 450 power source and FastMig MXP 37 Pipe wire feeding unit. The power source was equipped with latest editions of Kemppi's WisePenetration and WiseFusion welding software solutions. WisePenetration and WiseFusion can be adjusted in one of the submenus of the power source control panel. Power source and wire feeding unit can be seen in figure 18.

Figure 18. Kemppi wire feeding unit and power source

Welding was mechanized with the aid of Esab railtrac welding carriage and rails. A remote control unit was used to do necessary guidance correction during welding. Mechanization devices are shown in figures 19 and 20. Assembled welding setup is shown in figure 21.

Figure 19. Esab welding carriage on rail with mounted welding gun

Figure 20. Esab railtrack control unit and remote control

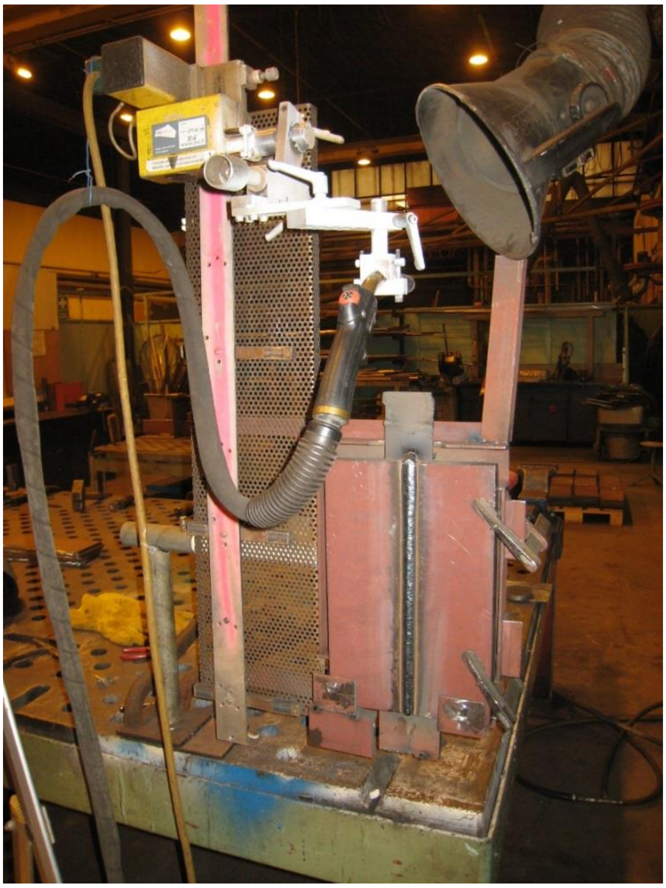


Figure 21. Welding setup with fastened and welded test piece

8 RESULTS AND DISCUSSION

A review of the results is shown in this chapter. Non-destructive testing results are examined before destructive testing and finally a preliminary welding procedure specification is presented based on the performed narrow gap welding tests. Test specimens identifier and legend is shown in table 20.

Table 20. Identifiers and legend of the different test specimens

Identifier	Steel	Groove angle (°)	Root opening (mm)	Shielding gas	Mechanization
B56M	E500 TM	5	6	M21	x
B59M	E500 TM	5	9	M21	x
B106M	E500 TM	10	6	M21	x
B109M	E500 TM	10	9	M21	x
B206M	E500 TM	20	6	M21	x
A59C	EH36	5	9	CO_2	x
A59M	EH36	5	9	M21	x
A59MK	EH36	5	9	M21	-
A106C	EH36	10	6	CO_2	x
A106M	EH36	10	6	M21	x
A206C	EH36	20	6	CO_2	x
A206M	EH36	20	6	M21	x

8.1 Non-destructive testing

Test pieces were visually inspected after welding by welder in adequate lighting. Visually welds looked great and had good shape on both sides. Some test pieces had low amount of spatter but no major flaws were detected. Magnetic particle testing was performed to all test pieces after visual testing. Testing was carried out by personnel from Dekra Industrial. No flaws were detected during testing and all the test pieces passed qualitative demands of EN rules. Ongoing magnetic particle testing is shown in figure 22.

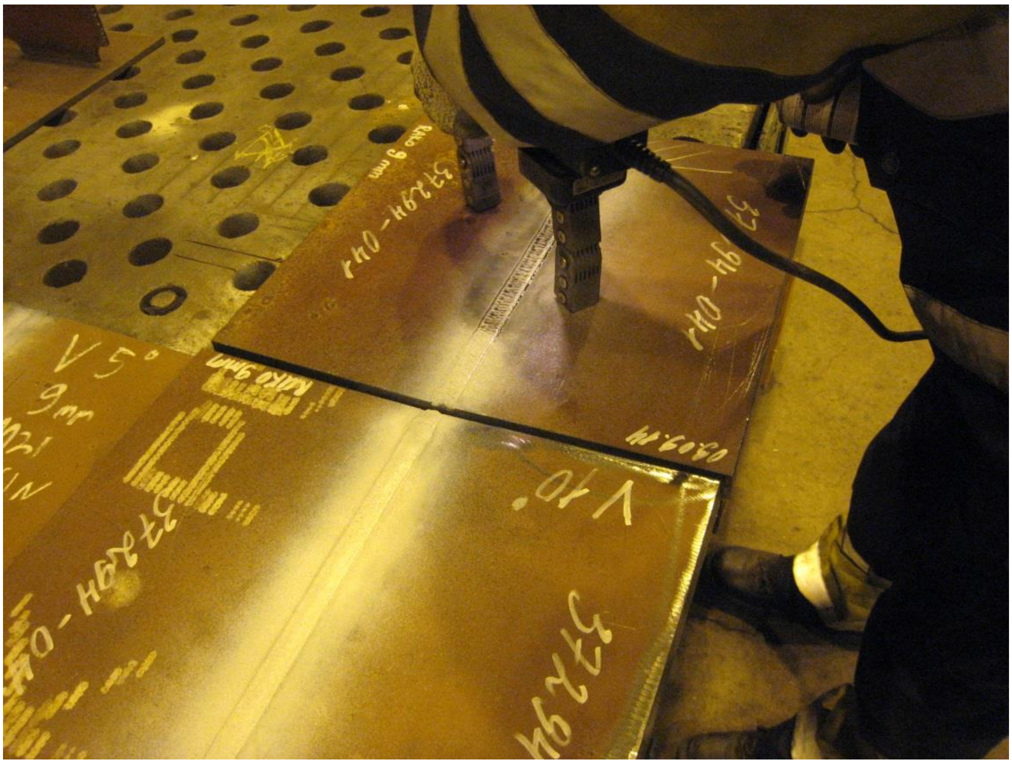


Figure 22. Ongoing magnetic particle testing

Finally test pieces were sent to radiographic testing. It was discovered, that the weld quality was excellent through the length of the welds. Only the test piece which was welded without mechanization had lack of fusion on a single point in the top of the test piece. An example photo of radiographic testing is shown in figure 23.

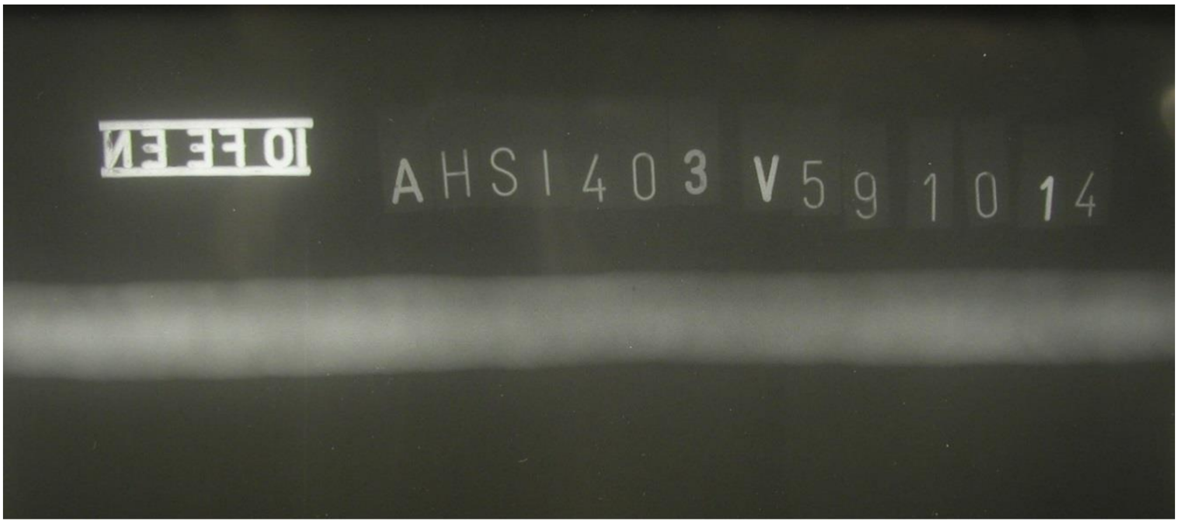


Figure 23. Radiographic photo of one of the test pieces

8.2 Bend testing

Bend testing was carried out using transverse side bend test for E500 TM and transverse root and face bend test for EH36 steel. All test specimens of both steels were bended to 180° angle. According to SFS-EN 15614-1, the test specimen shall not reveal any single flaw greater than 3 mm in any direction. No flaws occurred to any of the test specimens during testing and target bend angle was achieved with each test specimen. Test specimens proved to be very ductile and as expected free from imperfections. Full records of the bend testing are shown in Appendix 9.

8.3 Impact testing

Impact testing was considered to be one of the crucial test methods. Shipbuilding steels have strict rules for toughness to prevent failures in ship structures. Impact testing was carried out as Charpy-V test method. According to SFS-EN 15614 the absorbed energy shall be in accordance with appropriate parent material standard and for each notch location one individual value can be below the average value specified, but not less than 70 % of the specified value. Average values of impact testing are shown in figures 24 and 25. Groove angle (in degrees), root gap (in mm) and shielding gas (if varies) are marked on the figures. Complete impact test records are shown in Appendix 10.

Impact test results for E500 TM steel test specimens were really good. The results are pretty consistent on the weld metal which is due to similar welding parameters and mechanization were used. Better test results were achieved with 6 mm than with 9 mm groove gaps. All test specimens exceeded 50 J minimum value on weld metal set by RMRS. The lowest measured E500 TM impact strength value on weld metal was 52 J and the highest was 85 J. Deviation between single values on weld metal was below the 70 % average limiting value. However more deviation is noticeable in HAZ values, where a single test specimen of B206M fails to qualify to the 70 % rule.

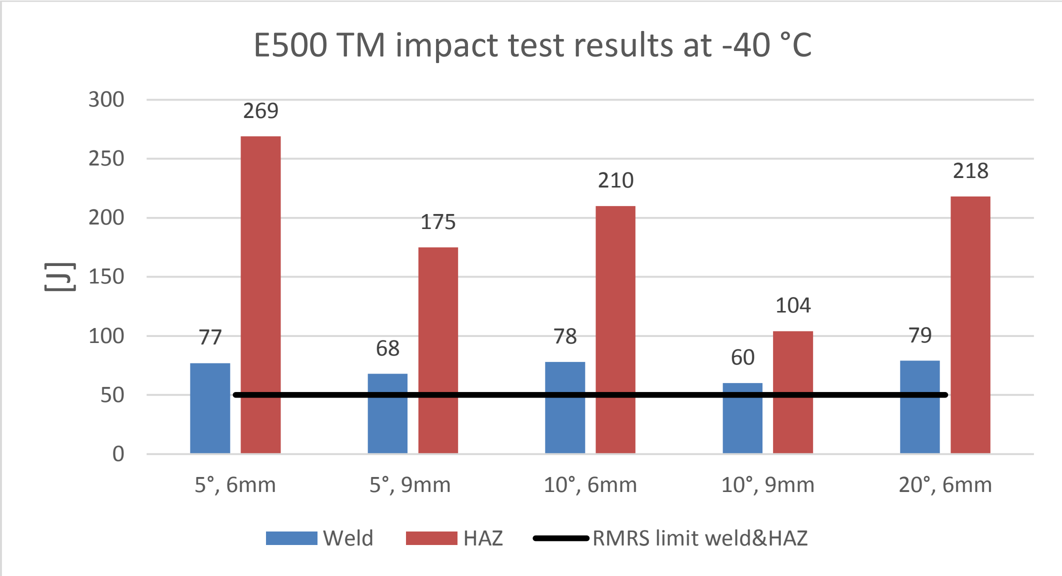


Figure 24. Average impact test results of E500 TM test specimens welded with M21 shielding gas

EH36 steel test results were surprisingly good considered that the testing of specimens was done at lower temperature, than what the filler metal is designed for. The limiting values according to RMRS for EH36 steel are 34 J on weld and 47 J in HAZ and on fusion line. As seen in figure 25, some of the results are close to the limiting values. Difference of manual welding and mechanization is clear. The manual welded test piece (A59MK) has lower average impact strength value and also the single specimen results were worse than those welded with mechanization. The average impact strength values do not show the whole truth, because there was much variation between single test specimens and many were under 70 % of the average impact strength value. The lowest measured impact strength value of EH36 was 37 J for test piece with mechanized welding and 20 J for manual welded test specimen.

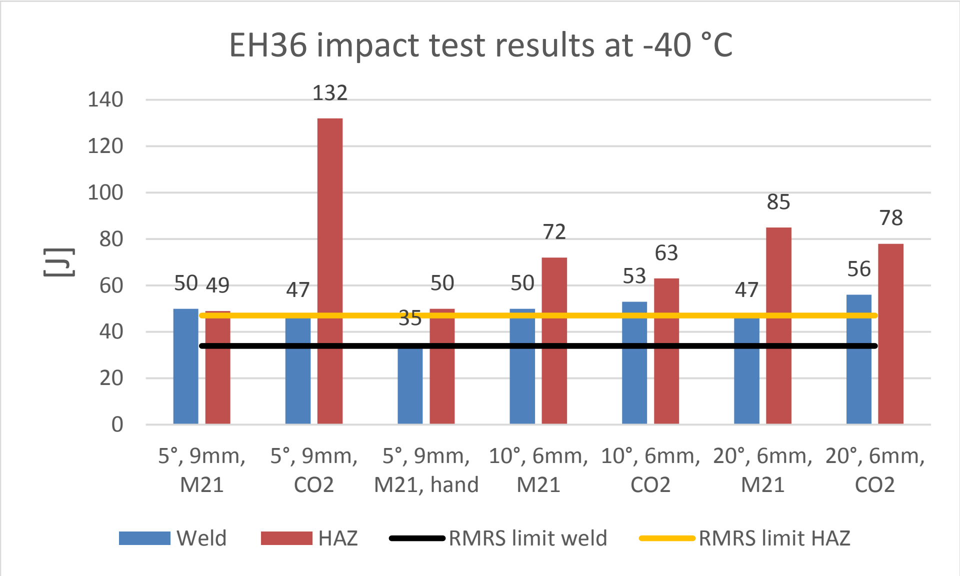


Figure 25. Average impact test results of EH36 test specimens (Manual welded test specimen marked with hand, the rest of the test pieces were welded with mechanization)

8.4 Tensile testing

Transversal tensile tests were done to find out yield strength, ultimate strength and percentage elongation of test specimens. According to SFS-EN ISO 15614 the tensile strength of the test specimen shall not be less than the corresponding specific minimum value for the parent metal. As seen in material certificates both steels had strength values above the minimum values set by the standard and also the measured strength values of the welded test specimens exceeded the minimum parent metal values. Also the tested elongation values of both steels test specimens were above the limiting values set by RMRS.

All of the EH36 test specimens broke from the base material, but there was some variation where the E500 TM test specimens fractured. Due to malfunction with the test setup, not all of the EH36 steel test specimens could be tested, but atleast one of each test specimen per test piece was tested. Average tensile test results are shown in figures 26 and 27. Groove angle (in degrees), root gap (in mm) and shielding gas (if varies) are marked on the figures. Test pieces that had only one tensile test specimen tested are marked with * in the figure. RMRS limits for ultimate strength were 610 MPa for E500 grade and 490 MPa for EH36 grade. Complete test records are shown in Appendix 11.

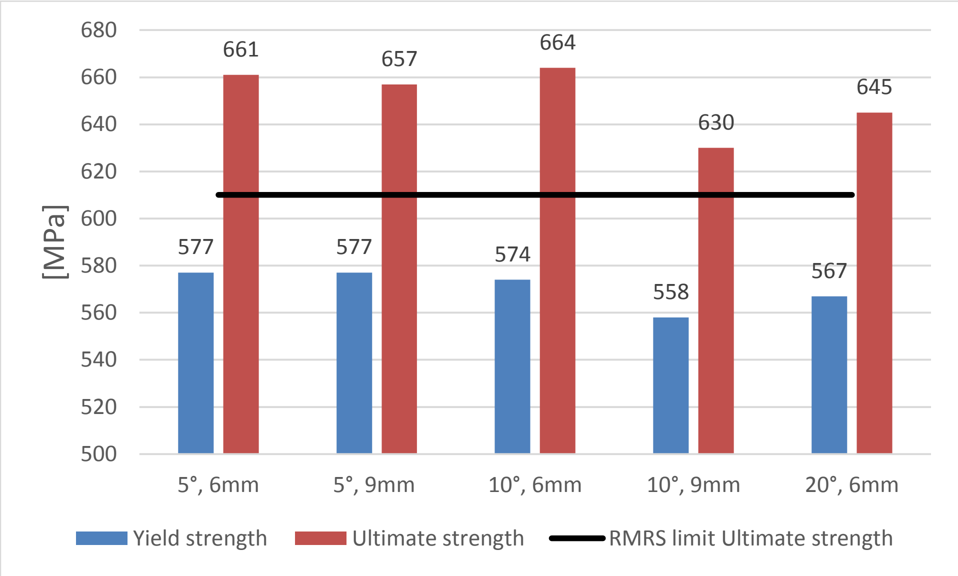


Figure 26. Tensile test results of E500 TM steel welded with M21 shielding gas

Two of the EH36 test specimens welded with CO_2 shielding gas had lower strength values compared to specimens welded with M21 shielding gas mixture. Interestingly the test specimen with 5° groove angle, 9 mm root gap and CO_2 was an exception and had similar strength values compared to the test pieces welded with M21 shielding gas mixture. One of the test specimens barely exceeds the RMRS limit of 490 MPa.

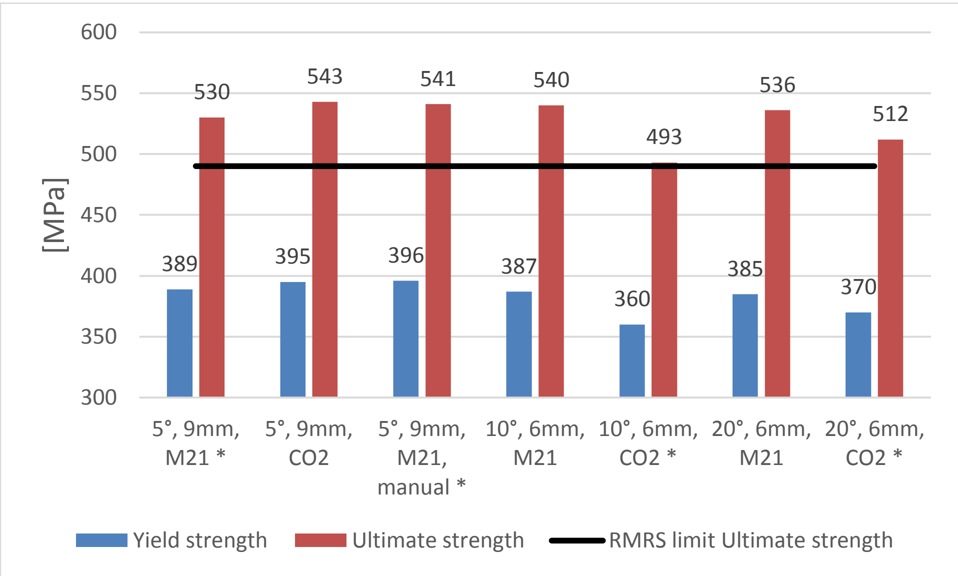


Figure 27. Tensile test results of EH36 steel

8.5 Hardness and macro testing

Row of identations were used to measure hardness values from base material, HAZ, fusion line and weld metal. All measured hardness values were below the limiting values of 380 HV10 and 420 HV10 for multipass welds according to EN 15614-1 and RMRS. Due to variation in weld shape and HAZ width between different test specimens, the amount of measuring points per test specimen also varies. Root hardness values of E500 TM are shown in figure 28 and surface hardness values of EH36 are shown in figure 29. The horizontal axis in the figures (location of the measuring point) is a guideline, complete test records are shown in Appendix 12. Majority of the peak hardness values are in root and surface HAZ. Middle of thickness values were lower, because of the heat treatment of subsequent weld beads.

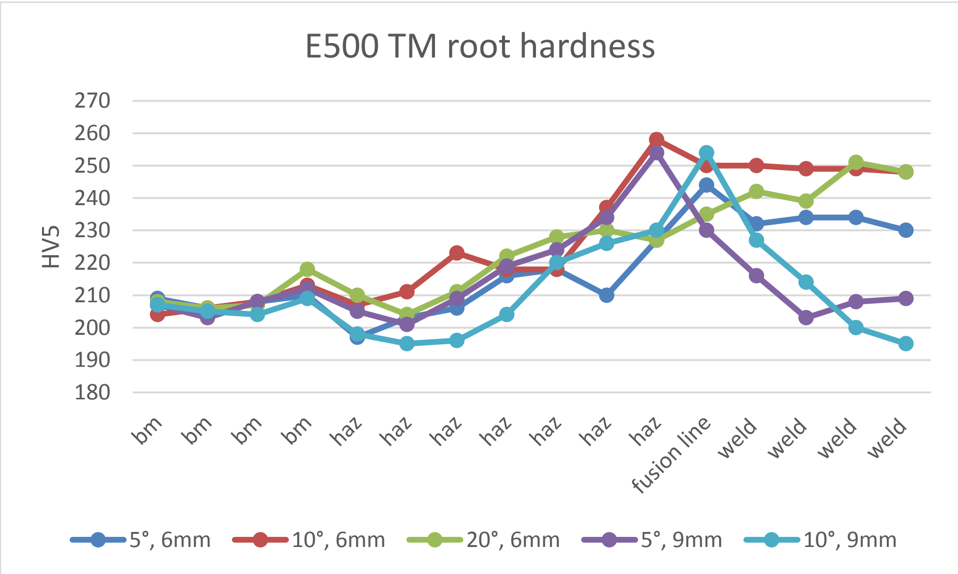


Figure 28. E500 TM hardness values measured from the root

Average E500 TM base material hardness was about 206 HV5 and average weld metal hardness was about 225 HV5. Corresponding values for EH36 were about 173 HV5 for base material and about 203 HV5 for weld metal. For both steels, the majority of the highest measured hardness values were in HAZ. Single highest hardness values were 259 HV5 for E500 TM steel and 247 HV5 for EH36 steel.

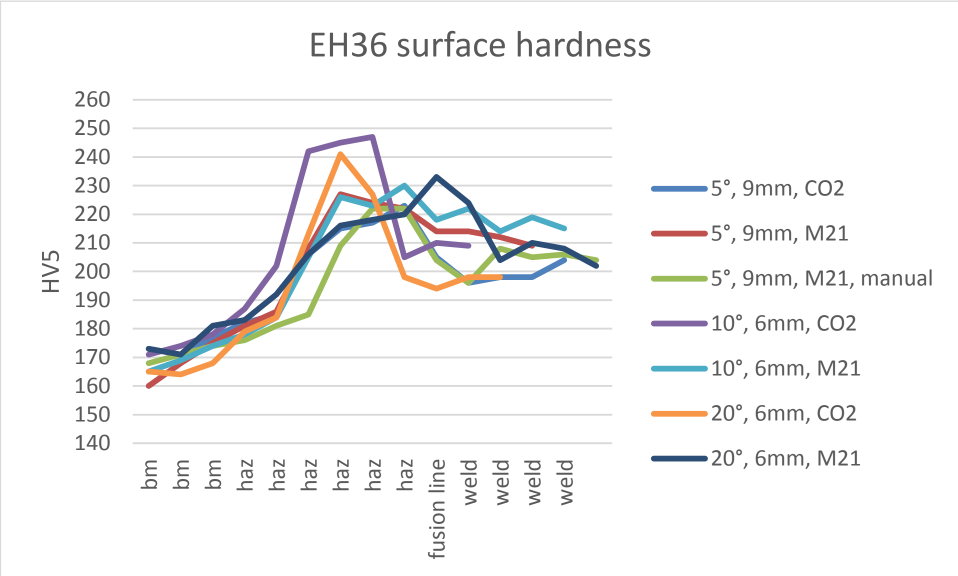


Figure 29. EH36 hardness values measured from the surface

Macro photos of the welds are shown in figure 30. Weld beads, fusion line, HAZ and coarse and fine-grained zones can be seen in the pictures. Narrow HAZ is clearly visible in E500 TM macro photos. The amount of weld beads needed is of course related to material thickness. Majority of the 10 mm thick EH36 test pieces were welded with two weld beads, only one specimen (A206C) has three weld beads. Most of the E500 TM test specimens have five weld beads. B206M has one more weld bead and its concave final run is clearly visible in the picture. The reason for the concave shape could be higher voltage or faster travel speed. A difference in cross-sectional area of test pieces welded with 6 mm and 9 mm root openings is also visible.

A spot with lack of fusion can be seen in the photo of the manual welded test piece A59MK. The reason for this is that the macro test specimen was cut from a point very close the end of the test piece, which would have normally been discarded. The rest of the A59MK weld had no imperfections and no imperfections are visible in other macro photos.

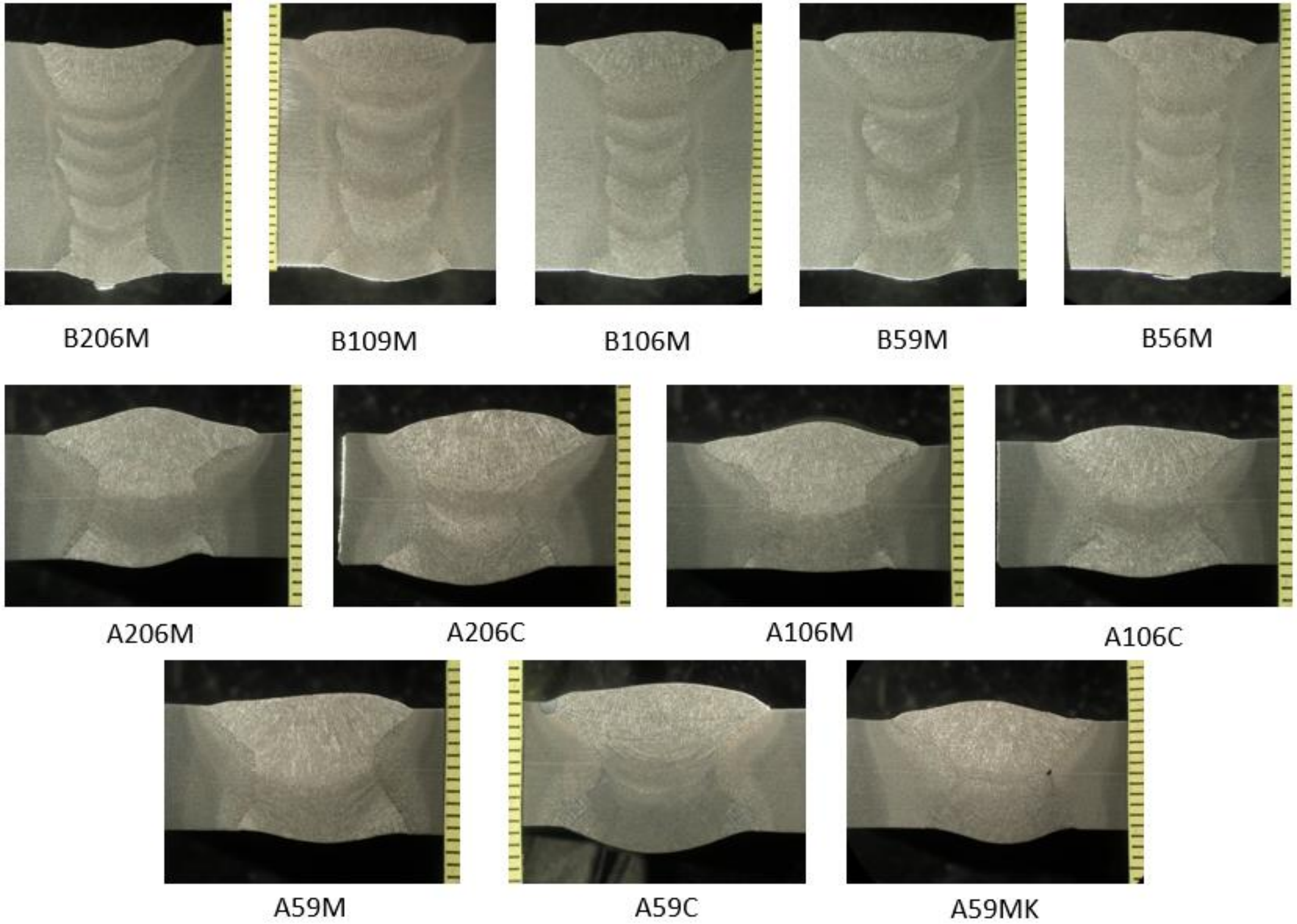


Figure 30. Macro photos of the test pieces with mm scale rule

8.6 pWPS

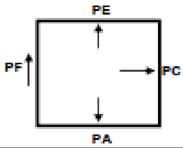
Preliminary welding procedure specification, shown in figure 31, was made based on the 5 degree groove angle test specimens (B56M and B59M) of E500 TM. Welding parameters chosen for the pWPS are combination of welding parameters used for both test specimens. The pWPS is intented for butt welding of plates on PF position with material thicknesses from 12,5 - 50 mm. The results of non-destructive and destructive testing of the test specimens proved that the pWPS is ready to be qualified. Qualification of the pWPS is intented to be carried out under supervision of RMRS. WisePenetration and WiseFusion processes are compulsory.

arctech
HELSINKI SHIPYARD

pWPS 1503
Rev. 1
8.1.2015

(pWPS)
PRELIMINARY WELDING PROCEDURE SPECIFICATION

Hitsausprosessi / Welding Process	**136 TÄYTELANKAHITSAUS - FCAW**
Menetelmäkoe / WPQR	
Vaatimukset / Requirements	SFS-EN 15614-1, RMRS
Hitsausasento	PF



Seostetuin perusaine / Most alloyed base material	**E500 TM**
Tuotelaji / Type of product	**LEVYT/ PLATES**
Liitosmuoto / Joint type	**PÄITTÄISLIITOS /BW**
Materiaalin paksuus / Material thickness	t = **12,5-50** mm
Putken halkaisija / Pipe diameter	∅ = **min 500** mm

Lisäaine / Consumable	AWS Luokitus / Classification	Indeksi / Index
FILARC PZ6115	E81T1-Ni2	A

A-mitta / Throat thickness		
Yksipalko / Single pass	-	mm
Monipalko / Multi pass	-	mm

Esilämmitys / kuivaus / Preheating / moisture removal	5	°C
Välipalkolämpötila / Interpass Temp.	max. 100	°C

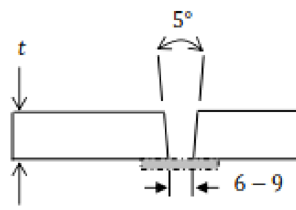
Polttimen kulma ja sivuttaisliike / Torch angle and weaving

Palko/Bead	T(työntö/push) V(veto/pull)	Kulma/Angle	Sivuttaisliike / Weaving
Asento PF / Position PF			
1-n	V	0-10°	0-9mm
Muut asennot / Other positions			
1-n	V	5-35°	0-10mm

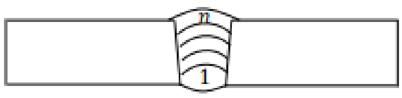
Suojakaasu / Shielding gas	**M21 (25%CO_2+75%Ar)**	**Kaasun virtaus**	18±2 l/min
Juurituki / Backing	Tarvittaessa keraaminen / Ceramic if needed	Juurijauhe / Root flux	-
Juurikaasu / Root Gas	-	Kaasun virtaus / Gas flow	- l/min

Railonvalmistus / Groove preparation	Juuren avaus / Back gouging	Muita tietoja / Volframielektrodi / Tyyppi / Koko / Other info / Tungsten elektrode / Type / Size
TERMINEN LEIKKAUS & HIONTA / THERMAL CUTING & GRINDING	Hiilikaaritalttaus ja hionta tarvittaessa / Carbon arc gouging and grinding if needed	-WisePenetration & WiseFusion

Liitoksen kuva/Joint design



Hitsausjärjestys/Welding Sequences



Palko Bead No.	Lisäaine-indeksi Filler Metal Index	Puikon/langan halk. Electrode/ Wire diam.	Virta Current A	Jännite Voltage V	Napaisuus Polarity AC/DC	Langan syöttönopeus / Wire feed speed m/min	Vapaalanka-kapituus Stick-out length mm	Kuljetus-nopeus Travel speed cm/min	Palon pituus/ pulkko Bead length/ Elektrode cm	Hitsaus energia Arc energy kJ/cm
ASENTO PF / POSITION PF										
1	A	1,2	185±5	26±1	DC+		15-20	12±2		19-31
2-n	A	1,2	205±15	27±1	DC+		15-20	17±5		12-29

Valmistaja / Manufacturer

Arctech, Helsinki Shipyard

Figure 31. pWPS for E500 TM steel

8.7 Conclusion and Discussion

Welding tests with narrowed groove angles of E500 TM steel were a success, although the planned welding with CO_2 shielding gas could not be done, because of the Dual Shield II 91-LT welding consumable. All the E500 TM test specimens with 20°, 10° and 5° groove angles produced quality results. Narrow groove welding tests with EH36 steel were more challenging. Though all the different groove angles of 20°, 10° and 5° were able to be welded, the absence of WisePenetration and WiseFusion is clearly seen with more inconsistent results. Overall the weld quality level B was achieved with test pieces.

By using narrower groove angles, it is possible to save in welding costs. The cross-sectional area of the joint preparation is about 40 - 55 % smaller depending on material thickness, groove gap and bevel angle, than with conventional 45° groove angle. Fewer welding runs are needed to complete the joint, which reduces the welding time and also less filler material is needed. WisePenetration and WiseFusion welding software solutions both are useful, especially when welding thicker plates and narrower grooves. WiseFusion kept the arc length optimal, helped to focus the arc and prevented the arc from wandering during the narrow groove welding. This combined simultaneously with constant input power of WisePenetration produced quality welds.

Mechanized narrow groove welding of 25 mm thick E500 TM steel on PF position with Wise processes was possible without any special equipment. Without the Wise processes, welding of such narrow grooves would be very hard. However 10 mm thick EH36 steel narrow groove test welding was performed without the Wise processes. It became clear that more adjustments had to be made to welding parameters during the welding. In the end good quality welds were achieved, even though the groove gap had to be made larger than first designed with the narrowest groove angle. It is possible to achieve good quality narrow groove welds on thinner plate thicknesses without Wise processes, but they certainly make the welding easier. The benefits of mechanization are clearly seen when comparing the impact test results of the test pieces. The manual welded test piece had clearly lower impact strength values than rest of the test pieces.

Bend testing revealed that weld and base material were properly fused and that the joints were ductile enough to endure the bending without cracking or other kind of failing.

Tensile test results were satisfactory and fulfilled the RMRS requirements. EH36 steel was welded with overmatching filler metal and all its specimens fractured from base material. E500 TM steel tensile test specimens failure locations had some variation and one even fractured from weld. Nonetheless the results were acceptable, because the tensile test results exceeded the specific minimum value for the parent metal.

Impact testing revealed, that mechanization will give consistent and good impact strength values with chosen heat inputs. The EH36 impact strength values were surprisingly good, considered that the PZ6113 filler metal is classified to -20 °C and the tests were performed at -40 °C. E500 TM impact strength values at -40 °C were above the limiting value of 50 J with some margin. Unlike PZ6113 the PZ6115 filler wire is alloyed with nickel, classified to -40 °C and outperforms the PZ6113. PZ6113 has also lower tensile strength values than PZ6115. PZ6113 is designed to be used with normal strength steels and PZ6115 with high strength steels. Hardness values were below the limiting values with great margin and hardening was not a problem with current steels and cooling times.

Some drawbacks were, that welding with CO_2 shielding gas and E500 TM steel could not be completed nor testing could be performed. Some minor problems occurred also with some of the EH36 tensile test specimens, which could not be tested. Interestingly the PZ6113 filler metal was still performing in temperatures colder than it is designed for. Also same amount of hardness values could have been measured from all the test specimens.

For future research the welding tests with CO_2 shielding gas and E500 steel should be completed with a different filler metal. This would enable a comparison of welds mechanical properties. Similar welding tests could also be done on different welding positions, because only vertical position was used in this thesis. The amount of distortions with narrower groove could be studied and compared to conventional groove designs. Improved mechanization devices with newly designed controllers and weaving motions could benefit the quality of welding. It would be interesting to find out, what is the limiting value for plate thickness on narrower groove designs, which can be welded with and without Wise processes.

9 SUMMARY

The aim of this thesis was to examine mechanized narrow gap welding on PF position with WisePenetration and WiseFusion processes. The goal was to achieve flawless welds, test them with destructive testing methods to find out their mechanical properties and make a preliminary welding procedure specification based on the welding tests. Three different groove angles (20°, 10º, 5º) were tested and two different thickness and strength steels were used.

Theory part of the thesis provides information about narrow gap welding, weldability of high strength steels, Kemppi Wise processes and quality assurance of welding. Conventional narrow gap welding is used for joining thick sections more economically. The welding procedure uses joint preparations with small angles that require less weld metal and less welding time to complete. With arc welding narrow gap welding has been used with SAW, GMAW, GTAW and FCAW. Usually narrow gap welding requires specialized equipment to access the root of the preparation. Not much research is found on using narrower groove with normal plate thicknesses, which do not necessarily require special welding equipment. Kemppi has recently developed WisePenetration and WiseFusion welding software solutions, which automatically readjust the welding parameters and make the welding with narrower groove designs easier. By using mechanization productivity and quality can be boosted even more.

Normal and higher strength structural steels such as EH36, are still the bulk material in shipbuilding. TMCP high strength steels are used in shipbuilding to meet the demands on reducing weight and increasing energy efficiency without impairing the weldability. Heat input must be taken into account when welding high strength steels because high heat input can lower the mechanical properties of the weld joint. Many factors affect the weldability of the steel. Weldability can be predicted with carbon equivalent equations, processing route of steel, chemical composition of steel, stress state, hydrogen content etc. To make certain that quality requirements are met welds are tested with non-destructive and destructive testing according to standards. Welding procedure test is the most common method.

The results of the narrow groove welding were encouraging. Non-destructive testing confirmed that welds were successful and free from imperfections. Destructive test results proved, that mechanical properties of the test specimens were at satisfactory level. A pWPS was made for 25 mm thick E500 TMCP steel based on the 5° groove angle test specimens. WisePenetration and WiseFusion processes provide excellent assist with narrow groove welding. Constant input power and optimal arc length together with mechanization provide a good solution for productive and high quality narrow groove welding. It is also possible to achieve good results without Wise processes on thinner material thicknesses, but the Wise processes certainly make narrow groove welding easier with current test setup without any special equipment.

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APPENDIX 1. Mechanical properties of rolled steel products with maximum thickness of 70 mm

Steel grade	Tensile test			Impact test		
	Yield stress, R_{eH} or $R_{p0,2}$, MPa min.	Tensile strength, R_m, MPa	Elongation A_5, %, min.	Test temperature, °C	Impact energy *KV*, J, min.	
					Longitudinal specimen	Transverse specimen
A420				0		
D420				-20		
E420	420	530 –	18	-40	42	28
F420		680		-60		
A460				0		
D460				-20		
E460	460		17	-40	46	31
F460		570 –		-60		
		720				
A500				0		
D500				-20		
E500	500		16	-40	50	33
F500				-60		
		610 –				
A550		770		0		
D550				-20		
E550	550		16	-40	55	37
F550				-60		
A620		670 –		0		

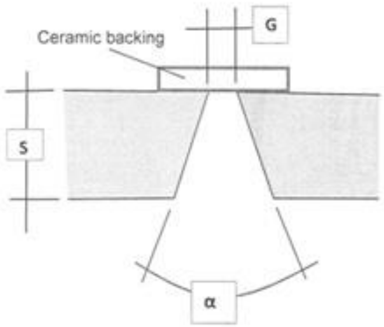
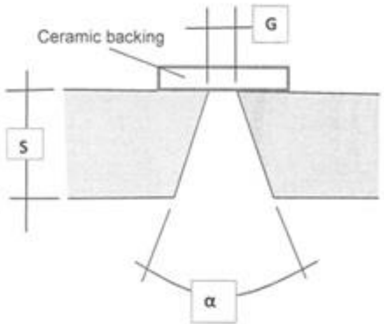
D620 E620 F620	620	830	15	-20 -40 -60	62	41
A690 D690 E690 F690	690	720 – 890	14	0 -20 -40 -60	69	46
		770 – 940				

APPENDIX 2. Minimum elongation values for standard specimens of full thickness with design length of 200 mm.

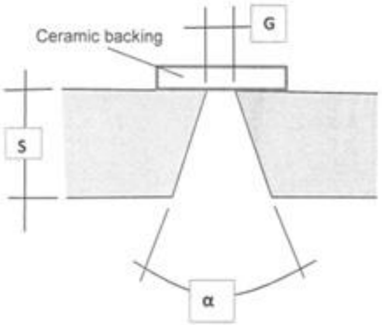
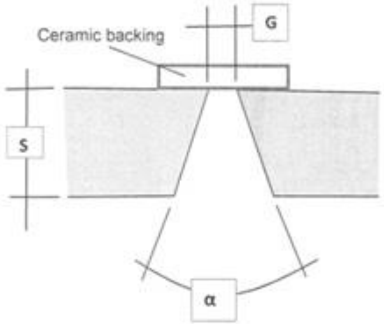
Strength level	Thickness mm						
	≤ 10	> 10 ≤ 15	> 15 ≤ 20	> 20 ≤ 25	> 25 ≤ 40	> 40 ≤ 50	> 50 ≤ 70
420	11	13	14	15	16	17	18
460	11	12	13	14	15	16	17
500	10	11	12	13	14	15	16
550	10	11	12	13	14	15	16
620	9	11	12	12	13	14	15
690	9	10	11	11	12	13	14

Grade of steel	Thickness t, mm							
	$t \leqslant 5$	$5 < t \leqslant 10$	$10 < t \leqslant 15$	$15 < t \leqslant 20$	$20 < t \leqslant 25$	$25 < t \leqslant 30$	$30 < t \leqslant 40$	$40 < t \leqslant 50$
A32 D32 E32 F32	14	16	17	18	19	20	21	22
A36 D36 E36 F36	13	15	16	17	18	19	20	21
A40 D40 E40 F40	12	14	15	16	17	18	19	20

APPENDIX 3. Preliminary experimental plan for M21 shielding gas.

Groove	S mm	G mm	α °	Base material	Welding position	Consumable + gas	WPS limits S/mm	Test No.	Impact °C	Welding week	Test week
	25	6-8	20	E500TMCP	PF	PZ6115 + M21	12,5-25	AHS 1401	-40	41	44
	25	6-8	10	E500TMCP	PF	PZ6115 + M21	12,5-25	AHS 1402	-40	41	44
	25	6-8	5	E500TMCP	PF	PZ6115 + M21	12,5-25	AHS 1403	-40	41	44
	10	6-8	20	EH36	PF	PZ6113 + M21	5-20	AHS 1404	-20	42	46
	10	6-8	10	EH36	PF	PZ6113 + M21	5-20	AHS 1405	-20	42	46
	10	6-8	5	EH36	PF	PZ6113 + M21	5-20	AHS 1406	-20	42	46
- Preliminary experimental plan					- Welding machine: Kemppi FastMig + wise penetration & fusion for E500TMCP						

APPENDIX 4. Preliminary experimental plan for CO2 shielding gas.

Groove	S mm	G mm	α °	Base material	Welding position	Consumable + gas	WPS limits S/mm	Test No.	Impact °C	Welding week	Test week
	25	6-8	20	E500TMCP	PF	DS II 91 LT + CO2	12,5-25	AHS 1407	-40	43	45
	25	6-8	10	E500TMCP	PF	DS II 91 LT + CO2	12,5-25	AHS 1408	-40	43	45
	25	6-8	5	E500TMCP	PF	DS II 91 LT + CO2	12,5-25	AHS 1409	-40	43	45
	10	6-8	20	EH36	PF	PZ6113 + CO2	5-20	AHS 1410	-20	42	47
	10	6-8	10	EH36	PF	PZ6113 + CO2	5-20	AHS 1411	-20	42	47
	10	6-8	5	EH36	PF	PZ6113 + CO2	5-20	AHS 1412	-20	42	47
- Preliminary experimental plan					- Welding machine: Kemppi FastMig + wise penetration & fusion for E500TMCP						

APPENDIX 5. Test certificate for E500 TM steel

RUUKKI

MILL SHEET AND TEST CERTIFICATE

RUSSIAN MARITIME REGISTER OF SHIPPING

1/3
96648A-005
05.08.2011

Tilaaja Purchaser
ARCTECH HELSINKI SHIPYARD OY
00150, HELSINKI, FINLAND
Tilaus nro Order No.
525583
Tilausvahvistus Order Confirmation
96648A

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
08.08.2011
11.03534.260
Valmistajan merkki
Mark of the Manufacturer

Todistus Certificate
PC
Laivaus Shipping

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
PART DELIVERY

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

Tuote Product
HEAVY PLATES
Laji Grade
PC E 500TMCP PC PART XIII CH.3:2011
Laatuselvitys Quality Specifications
EXTRA HIGH STRENGTH STEEL FOR SHIP STRUCTURES

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

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

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	MT
HOT ROLLED STEEL PLATES								
SURFACE CONDITION EN 10 163-2:2005 CLASS A3								
004	18.00 X 2300 X 8500		1	2815	35960 023	023		
SURFACE CONDITION EN 10 163-2:2005 CLASS A3								
010	21.00 X 2700 X 15500		1	7031	35960 021	021		
SURFACE CONDITION EN 10 163-2:2005 CLASS A3								
014	25.00 X 3000 X 15000		1	9000	35750 011	011		
		***	3	18846				

Raahe Steel Works

Testaus ja tarkastus Testing and Inspection

MINNA VALKAMA
Valtuutettu tarkastaja Authorized Inspector

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.

260-9
RUSSIAN MARITIME REGISTER OF SHIPPING

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 5.

ruukki

AINESTODISTUS TEST REPORT

RUSSIAN MARITIME REGISTER OF SHIPPING

2/3
96648A-005
05.08.2011

Tilaaja Purchaser
ARCTECH HELSINKI SHIPYARD OY

Tilaus nro Order No.
525583

Laji Grade
PC E 500TMCP

Laatuselvitys Quality Specifications
EXTRA HIGH STRENGTH STEEL FOR SHIP STRUCTURES

Vastaanottaja Consignee
JSC "VYBORG SHIPYARD"
LIC. NO 10206/200031

Asiakkaan merkki Shipping mark
CONTRACT NO.A-525549/A-52550 FOR NB-506/NB-507

Lisävaatimukset Additional requirements

Päivämäärä Date
08.08.2011

Valmistajan merkki
Mark of the Manufacturer
HMR

Jatkuvavalettua happiterästä
Oxygen steel, continuous casting

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
004	35960 023	TM	11					576	645			21												
010	35960 021	TM	51					608	642			21												
014	35750 011	TM	51		575				657			17												

K2: 11=TOP,TRANSV. 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
004	35960 023	112	-040	283	295	288	289											
010	35960 021	152	-040	284	273	311	289											
014	35750 011	152	-040	316	313	298	309											

K3: 112=CH-V/ISO-V(J),10X10,TOP,TRANSV,KV600 152=CH-V/ISO-V(J),10X10,BOTTOM,TRANSV,KV600

Raahe Steel Works

Testaus ja tarkastus Testing and Inspection

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.

260-9

MINNA VALKAMA
Valtuutettu tarkastaja Authorized Inspector

RTX97

APPENDIX 5.

RUUKKI

ANALYYSITODISTUS ANALYSIS CERTIFICATE
ANALYSE :SCHEINIGUNG COMPOSITIO CHIMIQU. :ERTIFICAT
СЕРТИФИКАТ АНАЛИЗА

3/3
96648A-005
05.08.2011

Päivämäärä Date Datum Date Дата
08.08.2011 HMR

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
35960		004	.19	.068	.26	1.50	.010	.001	.035	.034	.012	.015	.293	0.06	0.77	.019	.005	.0004	.002	.000
35960		010	.19	.068	.26	1.50	.010	.001	.035	.034	.012	.015	.293	0.06	0.77	.019	.005	.0004	.002	.000
35750		014	.18	.068	.26	1.50	.011	.001	.047	.036	.008	.015	.271	0.05	0.75	.008	.004	.0003	.002	.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.

RUSSIAN MARITIME REGISTER OF SHIPPING 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 Tlefax: 020 592 2736, +358 20 592 2736
Y-tunnus Business ID: 2389445-7

APPENDIX 6. Test sertificate for EH36 steel

INSPEKČNÍ CERTIFIKÁT 3.2 EN 10204:2004

INSPECTION CERTIFICATE, ABNAHMEPRÜFZEUGNIS, CERTIFICAT DE RÉCEPTION A02

EVRAZ VÍTKOVICE STEEL

A01,A05/ EVRAZ VÍTKOVICE STEEL, a.s.,
Ostrava-Hulváky Štramberská 2871/47, PSČ 709 00
ČESKÁ REPUBLIKA

A03/ Číslo dokumentu, No. Nr.	Z02/Datum,Date	Strana,Page,Seite
58150/2011	03.11.2011	1/ 6

A06/ Odběratel/příjemce, Customer/consignee, Besteller/Empfänger, Acheteur/destinataire

Arctech Helsinki Shipyard Oy
Helsinki
Laivakatu 1
00150
HELSINKI
FI

A08/ Číslo zakázky výrobce, Manufacturer´s works order No., Werksauftragsnr., Num. de la comande de l´usine productrice: 515413

A07/ Číslo objednávky odběratele, Purchaser´s order No., Kundenbestellnr., Numéro de la comande du klient: 525624

A10/ Aviso č., Advice Note No., Aviso Nr., Aviso No.: B14/Vagón č., Wagon No., Waggon Nr.: B13/Sk.hm. Act.mass, Ist-Masse, Masse eff.: 381 253 kg

Hot rolled steel plates.
PRA 1100907

EN ISO 9001 : TÜV NORD: 04100930144
EN ISO 14001: TÜV NORD: 04104030144

B01/ Výrobek, Product, Erzeugnis, Produit, B08/ Počet ks, No.of pieces, Stückzahl, B09-B11/Rozměry,Dimensions,Maße, B12/Teor.hm.,Th.mass,Th.Masse,Masse th.	B02/ Označení oceli, Steel designation, Stahlbezeichnung, Désignation de l´acier	B03/ Dodací podmínky, Terms of Delivery, Lieferbedingungen, Conditions de livraison
381 253 kg 106 plates	B04/Stav výrobku při dodání,Product delivery condition, Lieferzustand des Erzeugnisses, Etat de livraison: LREH36 N normalized B05/Referenční zprac., Reference treatment of samples, Referenz behandlung,Traitement de référence des échantillons: LREH36 N normalized	LR Rules Ch.2, Sec.2 EN 10029 B/N EN 10163-2. A/1

Zkouška tahem, Tensile test, Zugversuchkeit, Essai de traction — Zkouška rázem v ohybu (J), Impact test (J), Kerbschlagversuchkeit (J), Essai de résilience (J)

B14/ Tavba č. Heat No. Schmelze Nr. No de la coulée	C70	B08/ Počet ks No.of pieces Stückzahl No.de pièces / C00/Identifik. Identification Identifizierung Identification	C01	C02	C03 (°C)	C10	C11 Type	C13 Type	C11 (MPa)	C12 (MPa)	C13 (%)	C02	C03(°C)	C40, C41	C42	C42	C42	C43
24532	Y	288036	A	T	20	P	ReH	A200	397	563	25.0	L	-40	KV	148	146	148	147
		288037	A									L	-40	KV	152	152	148	151
		288038	A									L	-40	KV	122	148	154	141
		288039	A									L	-40	KV	86	104	132	107
		288040	A									L	-40	KV	154	144	136	145
		288041	A									L	-40	KV	158	150	152	153
		288042	A									L	-40	KV	106	110	152	123
		288043	A									L	-40	KV	140	150	152	147
		288044	A	T	20	P	ReH	A200	397	567	27.0	L	-40	KV	146	152	140	146
		288045	A									L	-40	KV	140	136	140	139
		288046	A									L	-40	KV	118	152	140	137
24533	Y	288047	A	T	20	P	ReH	A200	409	574	23.5	L	-40	KV	66	102	40	69
		288049	A									L	-40	KV2/7.5	100	30	92	74
		288050	A									L	-40	KV2/7.5	108	76	74	86
		288051	A									L	-40	KV2/7.5	78	32	76	62
		288052	A									L	-40	KV	130	84	84	99
		288053	A									L	-40	KV	72	82	116	90
		288054	A									L	-40	KV	108	38	38	61
		288055	A	T	20	P	ReH	A200	403	562	22.0	L	-40	KV	82	52	40	58
		288056	A									L	-40	KV	36	80	46	54
24534	Y	288057	A	T	20	P	ReH	A200	397	571	20.0	L	-40	KV	136	134	144	138
		288058	A	T	20	P	ReH	A200	403	569	20.0	L	-40	KV	76	104	56	79
		288059	A									L	-40	KV	98	128	58	95
		288060	A									L	-40	KV2/7.5	110	60	102	91

Z01/ Tímto prohlašujeme na svou výlučnou odpovědnost, že uvedené výrobky na něž se vztahuje toto prohlášení jsou ve shodě s předpisy, které jsou specifikovány kupní smlouvou a je na výrobky vydáno prohlášení o shodě podle zákona č. 22/1997 Sb., o technických požadavcích na výrobky a o změně a doplnění některých zákonů, ve znění pozdějších předpisů a nařízení vlády č. 190/2002 Sb.. Es wird hiermit auf ausschliessliche Verantwortlichkeit erklärt, dass die hier angeführten Erzeugnisse auf die sich diese Erklärung bezieht, entsprechen den im Kaufvertrag spezifizierten Vorschriften. Thereby we declare to our exclusive responsibility that the mentioned products to which this declaration is in accordance with regulations, which are specified by the contract. Nous déclarons à notre responsabilité exclusive que les produits mentionnés se référant à cette déclaration sont conformes aux prescriptions spécifiées par le contrat d´achat.

A04/ Značka výrobce:
Manufacturer´s mark:
Zeichen des Herstellers:
Marque du producteur:

Z02/ Ověření platnosti
Z03/ Razítko zástupce kontroly

EVRAZ VÍTKOVICE STEEL
Miloš PODGRABINSKI
independent authorized agent
unabhängiger berechtigter Vertreter
nezávislý oprávněný zástupce

Znalec / Inspector / Prüfer/ L´expert de l´usine

Lloyd's Register MATERIALS QUALITY SCHEME

This certificate is issued under the arrangements authorised by Lloyd's Register EMEA in accordance with the requirements of the Materials Quality Scheme and certificate number MQS 039.

C01/ Umístění vzorku, tělesa; A - hlava, Top, Kopf, tête; Z - pata, Bottom, Fuss, pied
C02/ Směr zkušebních vzorků: L - podélná, longitudinal, längs; T - příčná, transverse, quer, transversal; Z - vertikální, vertical, senkrecht
C03/ Zkušební teplota, Test temperature, Prüftemperatur, Température d'essai
C10/ Tvar zkušebního vzorku: P – prizmatický, prismatic, prismatisch, C- cylindrický, cylindric, zylindrisch
C11/ Význačná nebo smluvní mez kluzu, Yield or proof strength, Streck- oder Dehngrenze, Limite d'élasticité
C12/ Mez pevnosti v tahu, Tensile strength , Zugfestigkeit, Résistance à la traction
C13/ Tažnost, Elongation after fracture, Bruchdehnung, Allongement après rupture
C40/ Tvar zkušebního tělesa, C41/Šířka zkušebního tělesa, C42/Jednotlivé hodnoty, C43/ Střední hodnota
C70/ Způsob výroby oceli, Steelmaking process, Stahlherstellungverfahre, Mode d´élaboration de l´acier, BO=Y

200-F92

APPENDIX 6.

INSPEKČNÍ CERTIFIKÁT 3.2 EN 10204:2004

INSPECTION CERTIFICATE, ABNAHMEPRÜFZEUGNIS, CERTIFICAT DE RÉCEPTION A02

EVRAZ EVRAZ VÍTKOVICE STEEL

A01,A05/ EVRAZ VÍTKOVICE STEEL, a.s.,
Ostrava-Hulváky Štramberská 2871/47, PSČ 709 00
ČESKÁ REPUBLIKA

A03/ Číslo dokumentu, No./Nr.	Z02/Datum,Date	Strana,Page,Seite
58150/2011	03.11.2011	3/ 6

A08/ Číslo zakázky výrobce, Manufacturer´s works order No., Werksauftragsnr., Num. de la comande de l´usine productrice

EN ISO 9001 : TÜV NORD: 04100930144
EN ISO 14001: TÜV NORD: 04104030144

B04/ Tavba č. Heat No. Schmelze Nr. No de la coulée	C70	B08/ Počet ks No.of pieces Stückzahl No.de pièces	C00/Identifik. Identification Identifizierung Identification	C01	C02	C03 (°C)	C10	C11 Type	C13 Type	C11 (MPa)	C12 (MPa)	C13 (%)	C02	C03(°C)	C40, C41	C42			C43
24577	Y		288288	A									L	-40	KV	104	48	78	77
			288289	A									L	-40	KV	136	142	168	149
			288291	A									L	-40	KV	80	140	102	107
			288292	A									L	-40	KV	134	52	165	117
			288293	A									L	-40	KV	105	122	50	92
			288294	A									L	-40	KV	151	77	76	101
			288295	A	T	20	P	ReH	A200	408	577	23.0	L	-40	KV	110	125	110	115
24578	Y		288296	A	T	20	P	ReH	A200	415	573	22.0	L	-40	KV	76	141	101	106
			288297	A									L	-40	KV	92	68	103	88
			289276	A	T	20	P	ReH	A200	408	578	25.0	L	-40	KV	81	160	148	130
			289277	A									L	-40	KV	132	82	160	125

C71-C92/ Chemical composition [%]

heat	C	Mn	Si	P	S	Cu	Ni	Cr	Mo	V	Ti	Al	N	Nb
24532	0.172	1.440	0.380	0.019	0.005	0.050	0.020	0.060	0.004	0.028	0.003	0.036	0.007	0.003
24533	0.169	1.440	0.390	0.022	0.003	0.070	0.030	0.080	0.006	0.032	0.003	0.026	0.005	0.001
24534	0.163	1.460	0.390	0.027	0.003	0.070	0.030	0.080	0.005	0.031	0.003	0.027	0.005	0.001
24535	0.170	1.450	0.390	0.019	0.005	0.070	0.030	0.060	0.005	0.031	0.003	0.026	0.006	0.001
24576	0.168	1.410	0.390	0.017	0.003	0.080	0.030	0.080	0.007	0.026	0.002	0.030	0.006	0.002
24577	0.173	1.430	0.410	0.017	0.005	0.060	0.020	0.070	0.005	0.027	0.003	0.027	0.006	0.001
24578	0.175	1.420	0.400	0.020	0.006	0.080	0.030	0.080	0.005	0.028	0.003	0.026	0.006	0.001

B06/ Značení výrobku, Marking of the produkt Kennzeichnung des Erzeugnisses, Marquage du produit:
Vývalek, Plech, Tavba, Jakost, Zkouška / Rolled product No., Plate No., Heat No., Quality, Test No. / Walzstük, Blech, Schmelzen, Qualität, Probe

Z01/ Tímto prohlašujeme na svou výlučnou odpovědnost, že uvedené výrobky na něž se vztahuje toto prohlášení jsou ve shodě s předpisy, které jsou specifikovány kupní smlouvou a je na výrobky vydáno prohlášení o shodě podle zákona č. 22/1997 Sb., o technických požadavcích na výrobky a o změně a doplnění některých zákonů, ve znění pozdějších předpisů a nařízení vlády č. 190/2002 Sb.. Es wird hiermit auf ausschliessliche Verantwortlichkeit erklärt, dass die hier angeführten Erzeugnisse auf die sich diese Erklärung bezicht, entsprechen den im Kaufvertrag spezifizierten Vorschriften. Thereby we declare to our exclusive responsibility that the mentioned products to which this declaration is in accordance with regulations, which are specified by the contract. Nous déclarons à notre responsabilité exclusive que les produits mentionnés se référant à cette déclaration sont conformes aux prescriptions spécifiées par le contrat d´achat.

A04/ Značka výrobce:
Symbol of the manufacturer´s:
Herstellerzerchen:
Sigle de l´usine:

C01/ Umístění vzorku, tělesa: A - hlava, Top, Kopf, tete; Z - pata, Bottom, Fuss, pied
C02/ Směr zkušebních vzorků: L - podélná, longitudinal, längs; T - příčná, transverse, quer, transversal; Z - vertikální, vertical, senkrecht
C03/ Zkušební teplota, Test temperature, Prüftemperatur, Température d'essai
C10/ Tvar zkušebního vzorku: P - prismatický, prismatic, prismatisch, C- cylindrický, cylindric, zylindrisch
C11/ Výrazná nebo smluvní mez kluzu, Yield or proof strength, Streck oder Dehngrenze, Limite d'elasticité
C12/ Mez pevnosti v tahu, Tensile strength, Zugfestigkeit, Resistance à la traction
C13/ Tažnost, Elongation after fracture, Bruchdehnung, Allongement après rupture
C40/ Tvar zkušebního tělesa, C41/Šířka zkušebního tělesa, C42/Jednotlivé hodnoty, C43/ Střední hodnota
C70/ Způsob výroby oceli, Steelmaking process, Stahlherstellungverfahre, Mode d´élaboration de l´acier, BO=Y

Z02/ Ověření platnosti
Razítko útvaru kontroly
EVRAZ EVRAZ VÍTKOVICE STEEL

Miloš PODGRABINSKI
independent authorized agent
unabhängiger berechtiger Vertreter
nezávislý oprávněný zástupce

Znalec / Inspector / Prüfer / L´expert de l'usine

Lloyd's Register
MATERIALS QUALITY SCHEME

This certificate is issued under the arrangements authorised by Lloyd's Register EMEA in accordance with the requirements of the Materials Quality Scheme and certificate number MQS 039.

200-F93

APPENDIX 7. Dual Shield II 91 LT welding consumable test certificate

Mill Test Certificate

ESAB SeAH Corporation
56, JEONGDONG-RO 62BEON-GIL, SEONGSAN-GU
CHANGWON-SI, GYEONGNAM, KOREA 641-120
TEL:82-55-289-8111 FAX: 82-55-267-6344

Certificate No: 14-3054-0059
Issued Date : 2014.09.23

Brand Name : Dual Shield II 91 LT	Customer Name : ESAB GmbH
	P/O No. : sample
This Material conforms to Specification : AWS A5.29/A5.29M:2010, ASME SFA-5.29/5.29M:2013	Diameter Size : 1.2 MM
	Weight : 12.5 KG
	Lot Number : F232A4E407
Type : E91T1-Ni2C	Shielding Gas : 100% CO_2

	Chemical Compositions	Specification Requirements
C	0.05	MAX 0.12
Mn	1.06	MAX 1.50
Si	0.35	MAX 0.80
S	0.008	MAX 0.030
P	0.014	MAX 0.030
Cr	0.02	MAX 0.15
Ni	2.23	1.75 - 2.75
Mo		N/A
V		N/A
Al		N/A
Cu		N/A
Ti		N/A
Co		N/A
N		N/A
Cb+Ta		N/A
Fe		N/A
Zn		N/A
Be		N/A
Pb		N/A
Sn		N/A
W		N/A
Others		N/A

	Typical Mechanical Properties As welded	Specification Requirements As welded
Tensile Test		
Y.S.(0.2%) MPa	568	MIN 540
T.S. MPa	643	620 - 760
Elongation(2"),%	24	MIN 17
Reduction of Area,%	61	N/A
Impacts test, Joule (Charpy V-Notch)		
-40 ℃	89	MIN 27
Fillet Weld Test	Satisfactory	
Radiographic test	Satisfactory	

Remark:

The undersigned certifies that the products supplied will meet the applicable AWS or JIS(If applicable) Filler Metal specification when tested in accordanc with those specifications.
The chemistry and ferrite values (If applicable) are made from actual determinations with this lot of electrodes.

By : 김영도

Y.S.Kim, Manager, Q.M.Team

ESC-AT01-02E-F4 (Rev.2) (주) 세아 ESAB A4(210X297)

APPENDIX 7. PZ6115 welding consumable test certificate

ESAB

INSPECTION CERTIFICATE

in accordance with EN 10204 - 3.1

Date: 2014-10-10

Certificate number: **EC23620326 rev. 0**

Our order:
Our reference:
Customer number: 757883
Customer order date:

Your order:
Your reference:
Your fax number:
Your e-mail:

Invoice address
STX FINLAND OY TURKU
PL 666
20101 TURKU

Receiver of certificate

Delivery address
STX FINLAND OY
TURUN UUSI TELAKKA
TELAKKAKATU 1
20240 TURKU

DELIVERED PRODUCT

Brand: Filarc
Description: FILARC PZ6115 1.2mm 4x5kg
Item number: **2638125600**
Lot number: **PV1040095**
Quantity:

CLASSIFICATIONS

EN ISO 17632-A T 50 5 2Ni P M 2 H5

CHEMICAL ANALYSIS

All weld metal
Auxiliary:

C	0.05%
Si	0.37%
Mn	1.0%
P	0.017%
S	0.017%
Ni	2.50%

COMMENTS

Product supplied under a QA Programme fulfilling the EN ISO 9001 standard.
This certificate is produced electronically and is valid without signature.
Please refer any queries to:
ESAB Oy, Ruosilantie 18, P.B. 74 FIN-00391 Helsinki, Phone: +358 9-547 761

Validation
Josef Moravek Quality Manager

APPENDIX 7. PZ6113 welding consumable test certificate #1

INSPECTION CERTIFICATE

in accordance with EN 10204 - 3.1

Date: 2014-11-05

Certificate number: **EC23652162 rev. 0**

Our order:
Our reference:
Customer number: 757883
Customer order date:

Your order:
Your reference:
Your fax number:
Your e-mail:

Invoice address
STX FINLAND OY TURKU
PL 666
20101 TURKU

Receiver of certificate

Delivery address
STX FINLAND OY
TURUN UUSI TELAKKA
TELAKKAKATU 1
20240 TURKU

DELIVERED PRODUCT

Brand: Filarc
Description: FILARC PZ6113 1.2mm 4x5kg
Item number: **261912560G**
Lot number: **PV4270599**
Quantity:

CLASSIFICATIONS

SFA/AWS A5.36 E71T1-C1A0-CS2-H4
SFA/AWS A5.36 E71T1-M21A0-CS2-
EN ISO 17632-A H8 (for 1.2 and 1.4mm
EN ISO 17632-A T 42 2 P C 1 H5
T 46 2 P M 1 H10

CHEMICAL ANALYSIS

All weld metal
Auxiliary:

C	0.05%
Si	0.49%
Mn	1.2%
P	0.011%
S	0.020%
Cr	<0.1%
Ni	<0.1%
Mo	<0.1%
Nb	0.01%
Cu	0.02%
V	0.02%

COMMENTS

Product supplied under a QA Programme fulfilling the EN ISO 9001 standard.
This certificate is produced electronically and is valid without signature.
Please refer any queries to:
ESAB Oy, Ruosilantie 18, P.B. 74 FIN-00391 Helsinki, Phone: +358 9-547 761

Validation
Josef Moravek Quality Manager

APPENDIX 7. PZ6113 welding consumable test certificate #2

INSPECTION CERTIFICATE

in accordance with EN 10204 - 3.1

Date: 2014-11-05

Certificate number: **EC23652157 rev. 0**

Our order:
Our reference:
Customer number: 757883
Customer order date:

Your order:
Your reference:
Your fax number:
Your e-mail:

Invoice address
STX FINLAND OY TURKU
PL 666
20101 TURKU

Receiver of certificate

Delivery address
STX FINLAND OY
TURUN UUSI TELAKKA
TELAKKAKATU 1
20240 TURKU

DELIVERED PRODUCT

Brand: Filarc
Description: FILARC PZ6113 1.2mm 4x5kg
Item number: **261912560G**
Lot number: **PV4300657**
Quantity:

CLASSIFICATIONS

SFA/AWS A5.36	E71T1-C1A0-CS2-H4
SFA/AWS A5.36	E71T1-M21A0-CS2-
EN ISO 17632-A	H8 (for 1.2 and 1.4mm
EN ISO 17632-A	T 42 2 P C 1 H5
	T 46 2 P M 1 H10

CHEMICAL ANALYSIS

All weld metal
Auxiliary:

C	0.05%
Si	0.50%
Mn	1.2%
P	0.014%
S	0.021%
Cr	<0.1%
Ni	<0.1%
Mo	<0.1%
Nb	0.01%
Cu	0.01%
V	0.02%

COMMENTS

Product supplied under a QA Programme fulfilling the EN ISO 9001 standard.
This certificate is produced electronically and is valid without signature.
Please refer any queries to:
ESAB Oy, Ruosilantie 18, P.B. 74 FIN-00391 Helsinki, Phone: +358 9-547 761

Validation
Josef Moravek Quality Manager

APPENDIX 8. Welding parameter records

Test number AHS 1401									Date 7.10.2014								Page 1		
Bead no.	Electrode/ Wire diameter (mm)	Current (A)	Voltage (V)	Length of weld (cm)	Wire feed speed (m/min)	Arc time (min, sec)	Stick-out length (mm)	Travel speed (cm/min)	Heat input (kJ/cm)	Interpass temp (°C)	Torch angle		Polarity (AC/DC)	Oscillating speed (mm/s)	Oscillating width (mm)	Wise Penetration	Wise Fusion	Stop time (sec)	Groove gap (mm)
1	1,2	190	26,0	42	7,0	3min 9s	25	13,3	17,8	20	15	Push	DC+	12	3	x	x (35%)	0,1	6
2	1,2	215	26,4	40	8,5	1min 53s	20	21,2	12,9	30	0	-	DC+	18	3	x	-	0	
3	1,2	215	26,7	41	8,5	2min 8s	20	19,2	14,4	63	0	-	DC+	18	4	x	-	0	
4	1,2	215	26,5	42	8,5	2min 14s	20	18,4	14,9	84	0	-	DC+	18	5	x	-	0	
5	1,2	214	26,0	40	8,5	2min 18s	18	17,4	15,3	93	0	-	DC+	18	5	x	-	0	
6	1,2	207	26,7	40	8,0	3min 9s	18	12,7	20,9	77	0	-	DC+	20	8	x	-	0,2	

Test number AHS 1402									Date 8.10.2014								Page 2		
Bead no.	Electrode /Wire diameter (mm)	Current (A)	Voltage (V)	Length of weld (cm)	Wire feed speed (m/min)	Arc time (min, sec)	Stick-out length (mm)	Travel speed (cm/min)	Heat input (kJ/cm)	Interpass temp (°C)	Torch angle		Polarity (AC/DC)	Oscillating speed (mm/s)	Oscillating width (mm)	Wise Penetration	Wise Fusion	Stop time (sec)	Groove gap (mm)
1	1,2	191	23,3	41	7,9	2min 59s	25	13,7	15,6	19	15	Push	DC+	12	3	x	x (35%)	0,2	6
2	1,2	216	27,4	41	10,8	2min 29s	20	16,5	17,2	-	0	-	DC+	18	3	x	x (10%)	0	
3	1,2	212	26,2	42	9,6	2min 27s	20	17,1	15,6	24	0	-	DC+	18	3	x	x (10%)	0	
4	1,2	212	26,5	40	9,9	2min 7s	20	18,9	14,3	56	0	-	DC+	18	3	x	x (10%)	0	
5	1,2	209	25,5	40	7,9	3min 29s	20	11,5	22,2	60	0	-	DC+	20	6	x	x (10%)	0,2	

APPENDIX 8.

Test number AHS 1402-2									Date 8.10.2014								Page 3		
Bead no.	Electrode /Wire diameter (mm)	Current (A)	Voltage (V)	Length of weld (cm)	Wire feed speed (m/min)	Arc time (min, sec)	Stick-out length (mm)	Travel speed (cm/min)	Heat input (kJ/cm)	Interpass temp (°C)	Torch angle		Polarity (AC/DC)	Oscillating speed (mm/s)	Oscillating width (mm)	Wise Penetration	Wise Fusion	Stop time (sec)	Groove gap (mm)
1	1,2	185	23,2	42	7,8	3min 59s	25	10,5	19,6	19	15	Push	DC+	12	4	x	x (35%)	0,2	9
2	1,2	216	26,4	41	9,8	3min 13s	25	12,7	21,6	49	0	-	DC+	18	4	x	x (10%)	0,2	
3	1,2	216	26,2	41	9,5	3min 19s	20	12,4	21,9	69	0	-	DC+	18	4	x	x (10%)	0,2	
4	1,2	214	26,0	40	9,3	2min 55s	20	13,7	19,5	20	0	-	DC+	18	5	x	x (10%)	0,2	
5	1,2	196	24,4	40	7,5	3min 1s	16	13,3	22,2	50	0	-	DC+	20	7	x	x (15%)	0	

Test number AHS 1403									Date 8.10.2014								Page 4		
Bead no.	Electrode /Wire diameter (mm)	Current (A)	Voltage (V)	Length of weld (cm)	Wire feed speed (m/min)	Arc time (min, sec)	Stick-out length (mm)	Travel speed (cm/min)	Heat input (kJ/cm)	Interpass temp (°C)	Torch angle		Polarity (AC/DC)	Oscillating speed (mm/s)	Oscillating width (mm)	Wise Penetration	Wise Fusion	Stop time (sec)	Groove gap (mm)
1	1,2	190	24,1	42	8,8	3min 20s	25	12,6	17,4	19	15	Push	DC+	12	3	x	x (35%)	0,2	6
2	1,2	219	26,2	41	9,5	2min 26s	23	16,9	16,3	30	0	-	DC+	18	3	x	x (10%)	0	
3	1,2	213	26,0	41	9,3	2min 26s	20	16,9	15,7	59	0	-	DC+	18	2	x	x (10%)	0	
4	1,2	211	25,9	41	9,3	2min 24s	20	17,1	15,3	80	0	-	DC+	18	2	x	x (10%)	0	
5	1,2	196	24,9	40	8,0	2min 50s	20	14,1	16,6	95	0	-	DC+	20	5	x	x (15%)	0,2	

APPENDIX 8.

Test number AHS 1403-2									Date 8.10.2014								Page 5		
Bead no.	Electrode /Wire diameter (mm)	Current (A)	Voltage (V)	Length of weld (cm)	Wire feed speed (m/min)	Arc time (min, sec)	Stick-out length (mm)	Travel speed (cm/min)	Heat input (kJ/cm)	Interpass temp (°C)	Torch angle		Polarity (AC/DC)	Oscillating speed (mm/s)	Oscillating width (mm)	Wise Penetration	Wise Fusion	Stop time (sec)	Groove gap (mm)
1	1,2	186	24,4	42	9,5	3min 29s	25	12,1	18,0	17	15	Push	DC+	12	3	x	x (35%)	0,2	9
2	1,2	215	25,7	42	9,1	3min 27s	25	12,2	21,7	50	0	-	DC+	18	3	x	x (10%)	0,2	
3	1,2	212	26,2	41	9,6	3min 6s	20	13,2	20,2	79	0	-	DC+	18	3	x	x (10%)	0,2	
4	1,2	195	25,7	40	8,6	1min 47s	20	22,4	10,7	68	0	-	DC+	18	4	x	x (15%)	0,2	
5	1,2	196	24,9	40	7,8	2min 44	20	14,7	15,9	43	0	-	DC+	20	8	x	x (15%)	0,2	

Test number AHS 1404									16.10.2014								Page 6		
Bead no.	Electrode /Wire diameter (mm)	Current (A)	Voltage (V)	Length of weld (cm)	Wire feed speed (m/min)	Arc time (min, sec)	Stick-out length (mm)	Travel speed (cm/min)	Heat input (kJ/cm)	Interpass temp (°C)	Torch angle		Polarity (AC/DC)	Oscillating speed (mm/s)	Oscillating width (mm)	Wise Penetration	Wise Fusion	Stop time (sec)	Groove gap (mm)
1	1,2	165	22,4	41	6	4min 56s	20	8,3	21,4	24	10	Push	DC+	12	3	-	-	0,2	6
2	1,2	196	24,7	41	7	3min 26s	18	12,0	19,4	22	0	-	DC+	20	6	-	-	0	

Test number AHS 1405									16.10.2014								Page 7		
Bead no.	Electrode /Wire diameter (mm)	Current (A)	Voltage (V)	Length of weld (cm)	Wire feed speed (m/min)	Arc time (min, sec)	Stick-out length (mm)	Travel speed (cm/min)	Heat input (kJ/cm)	Interpass temp (°C)	Torch angle		Polarity (AC/DC)	Oscillating speed (mm/s)	Oscillating width (mm)	Wise Penetration	Wise Fusion	Stop time (sec)	Groove gap (mm)
1	1,2	163	22,3	42	6	4min 39s	20	9,0	19,4	13	10	Push	DC+	12	3	-	-	0,2	6
2	1,2	193	24,6	41	7	3min 18	16	12,4	18,4	72	0	-	DC+	20	6	-	-	0	

APPENDIX 8.

Test number AHS 1406									15.10.2014								Page 8		
Bead no.	Electrode /Wire diameter (mm)	Current (A)	Voltage (V)	Length of weld (cm)	Wire feed speed (m/min)	Arc time (min, sec)	Stick-out length (mm)	Travel speed (cm/min)	Heat input (kJ/cm)	Interpass temp (°C)	Torch angle		Polarity (AC/DC)	Oscillating speed (mm/s)	Oscillating width (mm)	Wise Penetration	Wise Fusion	Stop time (sec)	Groove gap (mm)
1	1,2	156	22,3	42	6	6min 27s	20	6,5	25,7	19	10	Push	DC+	12	5	-	-	0,2	9
2	1,2	199	25,6	41	8	3min 13s	18	12,8	19,1	30	0	-	DC+	20	8	-	-	0	

Test number AHS 1410									15.10.2014								Page 9		
Bead no.	Electrode /Wire diameter (mm)	Current (A)	Voltage (V)	Length of weld (cm)	Wire feed speed (m/min)	Arc time (min, sec)	Stick-out length (mm)	Travel speed (cm/min)	Heat input (kJ/cm)	Interpass temp (°C)	Torch angle		Polarity (AC/DC)	Oscillating speed (mm/s)	Oscillating width (mm)	Wise Penetration	Wise Fusion	Stop time (sec)	Groove gap (mm)
1	1,2	160	22,4	41	6	4min 52s	20	8,4	20,5	21	10	Push	DC+	12	3	-	-	0,2	6
2	1,2	191	24,9	41	7,5	1min 58s	20	20,9	10,9	82	0	-	DC+	18	5	-	-	0	
3	1,2	178	24,8	41	7	2min 54s	20	14,1	15,0	95	0	-	DC+	18	9	-	-	0	

Test number AHS 1411									15.10.2014								Page 10		
Bead no.	Electrode /Wire diameter (mm)	Current (A)	Voltage (V)	Length of weld (cm)	Wire feed speed (m/min)	Arc time (min, sec)	Stick-out length (mm)	Travel speed (cm/min)	Heat input (kJ/cm)	Interpass temp (°C)	Torch angle		Polarity (AC/DC)	Oscillating speed (mm/s)	Oscillating width (mm)	Wise Penetration	Wise Fusion	Stop time (sec)	Groove gap (mm)
1	1,2	161	22,5	41	6	4min 26s	20	9,3	18,7	21	10	Push	DC+	12	3	-	-	0,2	6
2	1,2	192	24,9	41	7,5	3min 3s	20	13,4	17,1	50	0	-	DC+	20	8	-	-	0	

APPENDIX 8.

Test number AHS 1412									15.10.2014								Page 11		
Bead no.	Electrode/ Wire diameter (mm)	Current (A)	Voltage (V)	Length of weld (cm)	Wire feed speed (m/min)	Arc time (min, sec)	Stick-out length (mm)	Travel speed (cm/min)	Heat input (kJ/cm)	Interpass temp (°C)	Torch angle		Polarity (AC/DC)	Oscillating speed (mm/s)	Oscillating width (mm)	Wise Penetration	Wise Fusion	Stop time (sec)	Groove gap (mm)
1	1,2	156	22,4	42	6	6min 42s	20	6,3	26,6	20	10	Push	DC+	12	5	-	-	0,2	9
2	1,2	190	24,2	41	7,5	2min 45s	19	14,9	14,8	90	0	-	DC+	18	7	-	-	0	
3	1,2	183	23,7	40	7,1	3min 17s	17	12,2	17,1	60	0	-	DC+	20	10	-	-	0	

Test number AHS 1413									15.10.2014								Page 12		
Bead no.	Electrode /Wire diameter (mm)	Current (A)	Voltage (V)	Length of weld (cm)	Wire feed speed (m/min)	Arc time (min, sec)	Stick-out length (mm)	Travel speed (cm/min)	Heat input (kJ/cm)	Interpass temp (°C)	Torch angle		Polarity (AC/DC)	Oscillating speed (mm/s)	Oscillating width (mm)	Wise Penetration	Wise Fusion	Stop time (sec)	Groove gap (mm)
1	1,2	156	22,3	41	6,0	6min 10s	10-30	6,7	24,9	19	10	Push	DC+	-	-	-	-	-	9
2	1,2	184	25,5	40	7,5	5min 3s	10-30	7,9	28,5	82	-	-	DC+	-	-	-	-	-	

APPENDIX 9. Bend testing records

pWPS	*AHS 14*
According to	*SFS-EN 5173*
Manufacturer	
Base material	*E500 TM*
Material thickness	*25 mm*
Joint type	*BW*
Welding process	*MAG Wise*
Consumable	*PZ6115*
Test temperature	*20 C*
Remark	

Diameter of former ***d = 4xt***
Distance between rollers ***l > (d+2xt)***

TFBB *Transverse face bend test specimen*
TRBB *Transverse root bend test specimen*
SBB *Transverse side bend test specimen*

Specimen No/position	Type of test	Dimensions mm	Former diameter/mm	Distance between rollers/mm	Bend angle/°	Original gauge length/mm	Elongation %	Remark!
B56M1	*SBB*	*12X20*	*45*	*70*	*180*	-	-	
B56M2	"	"	"	"	"	-	-	
B59M1	"	"	"	"	"	-	-	
B59M2	"	"	"	"	"	-	-	
B106M1	"	"	"	"	"	-	-	
B106M2	"	"	"	"	"	-	-	
B109M1	"	"	"	"	"	-	-	
B109M2	"	"	"	"	"	-	-	
B206M1	"	"	"	"	"	-	-	
B206M2	"	"	"	"	"	-	-	

APPENDIX 9.

pWPS	*AHS14*
According to	*SFS-EN 5173*
Manufacturer	
Base material	*EH36*
Material thickness	*10 mm*
Joint type	*BW*
Welding process	*MAG*
Consumable	*PZ6113*
Test temperature	*20 C*
Remark	

Diameter of former *d = 4xt*
Distance between rollers *l > (d+2xt)*

TFBB *Transverse face bend test specimen*
TRBB *Transverse root bend test specimen*
SBB *Transverse side bend test specimen*

Specimen No/position	Type of test	Dimensions mm	Former diameter/mm	Distance between rollers/mm	Bend angle/°	Original gauge length/mm	Elongation %	Remark!
A59C1	FBB	10X20	40	64	180	-	-	
A59C2	"	"	"	"	"	-	-	
A59C1	RBB	"	"	"	"	-	-	
A59C2	"	"	"	"	"	-	-	
A59M1	FBB	"	"	"	"	-	-	
A59M2	"	"	"	"	"	-	-	
A59M1	RBB	"	"	"	"	-	-	
A59M2	"	"	"	"	"	-	-	
A59MK1	FBB	"	"	"	"	-	-	
A59MK2	"	"	"	"	"	-	-	
A59MK1	RBB	"	"	"	"	-	-	
A59MK2	"	"	"	"	"	-	-	
A106C1	FBB	"	"	"	"	-	-	
A106C2	"	"	"	"	"	-	-	
A106C1	RBB	"	"	"	"	-	-	
A106C2	"	"	"	"	"	-	-	
A106M1	FBB	"	"	"	"	-	-	
A106M2	"	"	"	"	"	-	-	
A106M1	RBB	"	"	"	"	-	-	
A106M2	"	"	"	"	"	-	-	
A206C1	FBB	"	"	"	"	-	-	
A206C2	"	"	"	"	"	-	-	
A206C1	RBB	"	"	"	"	-	-	
A206C2	"	"	"	"	"	-	-	
A206M1	FBB	"	"	"	"	-	-	
A206M2	"	"	"	"	"	-	-	
A206M1	RBB	"	"	"	"	-	-	
A206M2	"	"	"	"	"	-	-	

APPENDIX 10. Impact test records.

pWPS	***AHS 14***	Identifier for test type:
According to	***SFS-EN ISO 9016, EN ISO 148-1***	*shape: 1 2 3 a/b*
Manufacturer		*1: type of notch (V or U)*
Base material	***E500 TM***	*2: notch location (W or H)*
Material thickness	***25 mm***	*3: orientation of notch plane (S or T)*
Joint type	***BW***	*a: notch distance from reference line*
Welding process	***MAG***	*b: distance between test specimen and*
Consumable	***PZ6115***	*sample surface*
Remark	***Test specimens B56M ja B59M.***	

Specimen No/position	Type of test	Dimensions mm	Test temperature / °C	Nominal energy of the testing machine / J	Absorbed energy / J	Fracture location	Fracture appearance	Type of flaw and dimensions
B56M1	*VWT0/2*	*10X10X55*	*-40*	*300*	*76*	*W*	-	-
B56M2	"	"	"	"	*81*	"	-	-
B56M3	"	"	"	"	*75*	"	-	-
Average	***VWT0/2***	"	"	"	***77***	***W***	-	-
B56M4	*VHT1/2*	"	"	"	*263*	*HAZ*	-	-
B56M5	"	"	"	"	*277*	"	-	-
B56M6	"	"	"	"	*266*	"	-	-
Average	***VHT1/2***	"	"	"	***269***	***HAZ***	-	-
B59M1	"	"	"	"	*66*	*W*	-	-
B59M2	"	"	"	"	*72*	"	-	-
B59M3	"	"	"	"	*66*	"	-	-
Average	***VWT0/2***	"	"	"	***68***	***W***	-	-
B59M4	"	"	"	"	*209*	*HAZ*	-	-
B59M5	"	"	"	"	*152*	"	-	-
B59M6	"	"	"	"	*164*	"	-	-
Average	***VHT1/2***	"	"	"	***175***	***HAZ***	-	-

pWPS	***AHS 14***	Identifier for test type:
According to	***SFS-EN ISO 9016, EN ISO 148-1***	*shape: 1 2 3 a/b*
Manufacturer		*1: type of notch (V or U)*
Base material	***E500 TM***	*2: notch location (W or H)*
Material thickness	***25 mm***	*3: orientation of notch plane (S or T)*
Joint type	***BW***	*a: notch distance from reference line*
Welding process	***MAG***	*b: distance between test specimen and*
Consumable		*sample surface*
Remark	***Test specimens B106M ja B109M.***	

Specimen No/position	Type of test	Dimensions mm	Test temperature / °C	Nominal energy of the testing machine / J	Absorbed energy / J	Fracture location	Fracture appearance	Type of flaw and dimensions
B106M1	*VWT0/2*	*10X10X55*	*-40*	*300*	*79*	*W*	-	-
B106M2	"	"	"	"	*78*	"	-	-
B106M3	"	"	"	"	*76*	"	-	-
Average	***VWT0/2***	"	"	"	***78***	***W***	-	-
B106M4	*VHT1/2*	"	"	"	*202*	*HAZ*	-	-
B106M5	"	"	"	"	*196*	"	-	-
B106M6	"	"	"	"	*232*	"	-	-
Average	***VHT1/2***	"	"	"	***210***	***HAZ***	-	-
B109M1	*VWT0/2*	"	"	"	*60*	*W*	-	-
B109M2	"	"	"	"	*67*	"	-	-
B109M3	"	"	"	"	*52*	"	-	-
Average	***VWT0/2***	"	"	"	***60***	***W***	-	-
B109M4	*VHT1/2*	"	"	"	*74*	*HAZ*	-	-
B109M5	"	"	"	"	*126*	"	-	-
B109M6	"	"	"	"	*112*	"	-	-
Average	***VHT1/2***	"	"	"	***104***	***HAZ***	-	-

APPENDIX 10.

pWPS	***AHS 14***	Identifier for test type:
According to	***SFS-EN ISO 9016, EN ISO 148-1***	*shape: 1 2 3 a/b*
Manufacturer		*1: type of notch (V or U)*
Base material	***E500 TM***	*2: notch location (W or H)*
Material thickness	***25 mm***	*3: orientation of notch plane (S or T)*
Joint type	***BW***	*a: notch distance from reference line*
Welding process	***MAG***	*b: distance between test specimen and*
Consumable		*sample surface*
Remark	***Test specimen B206M.***	

Specimen No/position	Type of test	Dimensions mm	Test temperature / °C	Nominal energy of the testing machine / J	Absorbed energy / J	Fracture location	Fracture appearance	Type of flaw and dimensions
B206M1	*VWT0/2*	*10X10X55*	*-40*	*300*	*76*	*W*	-	-
B206M2	"	"	"	"	*75*	"	-	-
B206M3	"	"	"	"	*85*	"	-	-
Average	***VWT0/2***	"	"	"	***79***	***W***	**-**	**-**
B206M4	*VHT1/2*	"	"	"	*295*	*HAZ*	-	-
B206M5	"	"	"	"	*132*	"	-	-
B206M6	"	"	"	"	*226*	"	-	-
Average	***VHT1/2***	"	"	"	***218***	***HAZ***	**-**	**-**

pWPS	***AHS 14***	Identifier for test type:
According to	***SFS-EN ISO 9016, EN ISO 148-1***	*shape: 1 2 3 a/b*
Manufacturer		*1: type of notch (V or U)*
Base material	***EH36***	*2: notch location (W or H)*
Material thickness	***10 mm***	*3: orientation of notch plane (S or T)*
Joint type	***BW***	*a: notch distance from reference line*
Welding process	***MAG***	*b: distance between test specimen and*
Consumable		*sample surface*
Remark	***Test Specimens A206M ja A59C.***	

Specimen No/position	Type of test	Dimensions mm	Test temperature	Nominal energy of the testing machine / J	Absorbed energy / J	Fracture location	Fracture appearance	Type of flaw and dimensions
A206M1	*VWT0/2*	*10X7.5X55*	*-40*	*150*	*48*	*W*	-	-
A206M2	"	"	"	"	*50*	"	-	-
A206M3	"	"	"	"	*44*	"	-	-
Average	***VWT0/2***	"	"	"	***47***	***W***	**-**	**-**
A206M4	*VHT1/2*	"	"	"	*129*	*HAZ*	-	-
A206M5	"	"	"	"	*73*	"	-	-
A206M6	"	"	"	"	*52*	"	-	-
Average	***VHT1/2***	"	"	"	***85***	***HAZ***	**-**	**-**
A59C1	*VWT0/2*	"	"	"	*43*	*W*	**-**	**-**
A59C2	"	"	"	"	*51*	"	**-**	**-**
A59C3	"	"	"	"	*48*	"	**-**	**-**
Average	***VWT0/2***	"	"	"	***47***	***W***	**-**	**-**
A59C4	*VHT1/2*	"	"	"	*161*	*HAZ*	**-**	**-**
A59C5	"	"	"	"	*53*	"	**-**	**-**
A59C6	"	"	"	"	*183*	"	**-**	**-**
Average	***VHT1/2***	"	"	"	***132***	***HAZ***	**-**	**-**

APPENDIX 10.

pWPS	***AHS 14***	Identifier for test type:
According to	***SFS-EN ISO 9016, EN ISO 148-1***	*shape: 1 2 3 a/b*
Manufacturer		*1: type of notch (V or U)*
Base material	***EH36***	*2: notch location (W or H)*
Material thickness	***10 mm***	*3: orientation of notch plane (S or T)*
Joint type	***BW***	*a: notch distance from reference line*
Welding process	***MAG***	*b: distance between test specimen and*
Consumable		*sample surface*
Remark	***Test specimens A106M ja A59MK.***	

Specimen No/position	Type of test	Dimensions mm	Test temperature	Nominal energy of the testing machine / J	Absorbed energy / J	Fracture location	Fracture appearance	Type of flaw and dimensions
A106M1	*VWT0/2*	*10X7.5X55*	*-40*	*150*	*46*	*W*	-	-
A106M2	"	"	"	"	*58*	"	-	-
A106M3	"	"	"	"	*47*	"	-	-
Average	***VWT0/2***	"	"	"	***50***	***W***	**-**	**-**
A106M4	*VHT1/2*	"	"	"	*60*	*HAZ*	-	-
A106M5	"	"	"	"	*81*	"	-	-
A106M6	"	"	"	"	*75*	"	-	-
Average	***VHT1/2***	"	"	"	***72***	***HAZ***	**-**	**-**
A59MK1	*VWT0/2*	"	"	"	*55*	*W*	-	-
A59MK2	"	"	"	"	*30*	"	-	-
A59MK3	"	"	"	"	*20*	"	-	-
Average	***VWT0/2***	"	"	"	***35***	***W***	**-**	**-**
A59MK4	*VHT1/2*	"	"	"	*47*	*HAZ*	-	-
A59MK5	"	"	"	"	*65*	"	-	-
A59MK6	"	"	"	"	*37*	"	-	-
Average	***VHT1/2***	"	"	"	***50***	***HAZ***	**-**	**-**

pWPS	***AHS 14***	Identifier for test type:
According to	***SFS-EN ISO 9016, EN ISO 148-1***	*shape: 1 2 3 a/b*
Manufacturer		*1: type of notch (V or U)*
Base material	***EH36***	*2: notch location (W or H)*
Material thickness	***10 mm***	*3: orientation of notch plane (S or T)*
Joint type	***BW***	*a: notch distance from reference line*
Welding process	***MAG***	*b: distance between test specimen and*
Consumable		*sample surface*
Remark	***Test specimens A59M ja A206C.***	

Specimen No/position	Type of test	Dimensions mm	Test temperature / °C	Nominal energy of the testing machine / J	Absorbed energy / J	Fracture location	Fracture appearance	Type of flaw and dimensions
A59M1	*VWT0/2*	*10X7.5X55*	*-40*	*150*	*50*	*W*	-	-
A59M2	"	"	"	"	*51*	"	-	-
A59M3	"	"	"	"	*48*	"	-	-
Average	***VWT0/2***	"	"	"	***50***	***W***	**-**	**-**
A59M4	*VHT1/2*	"	"	"	*46*	*HAZ*	-	-
A59M5	"	"	"	"	*54*	"	-	-
A59M6	"	"	"	"	*46*	"	-	-
Average	***VHT1/2***	"	"	"	***49***	***HAZ***	**-**	**-**
A206C1	*VWT0/2*	"	"	"	*55*	*W*	-	-
A206C2	"	"	"	"	*55*	"	-	-
A206C3	"	"	"	"	*57*	"	-	-
Average	***VWT0/2***	"	"	"	***56***	***W***	**-**	**-**
A206C4	*VHT1/2*	"	"	"	*74*	*HAZ*	-	-
A206C5	"	"	"	"	*83*	"	-	-
A206C6	"	"	"	"	*76*	"	-	-
Average	***VHT1/2***	"	"	"	***78***	***HAZ***	**-**	**-**

APPENDIX 10.

pWPS	***AHS 14***	Identifier for test type:
According to	***SFS-EN ISO 9016, EN ISO 148-1***	*shape: 1 2 3 a/b*
Manufacturer		*1: type of notch (V or U)*
Base material	***EH36***	*2: notch location (W or H)*
Material thickness	***10 mm***	*3: orientation of notch plane (S or T)*
Joint type	***BW***	*a: notch distance from reference line*
Welding process	***MAG***	*b: distance between test specimen and*
Consumable		*sample surface*
Remark	***Test specimen A106C.***	

Specimen No/position	Type of test	Dimensions mm	Test temperature	Nominal energy of the testing machine / J	Absorbed energy / J	Fracture location	Fracture appearance	Type of flaw and dimensions
A106C1	*VWT0/2*	*10X7.5X55*	*-40*	*150*	*48*	*W*	-	-
A106C2	"	"	"	"	*60*	"	-	-
A106C3	"	"	"	"	*50*	"	-	-
Average	***VWT0/2***	"	"	"	***53***	***W***	**-**	**-**
A106C4	*VHT1/2*	"	"	"	*67*	*HAZ*	-	-
A106C5	"	"	"	"	*56*	"	-	-
A106C6	"	"	"	"	*66*	"	-	-
Average	***VHT1/2***	"	"	"	***63***	***HAZ***	**-**	**-**

APPENDIX 11. Tensile test records

pWPS	***AHS 14***
According to	***SFS-EN 4136***
Manufacturer	
Base material	***EH36***
Material thickness	***10 mm***
Joint type	***BW***
Welding process	***MAG***
Consumable	***PZ6113***
Test temperature	***20*** °C
Remark	

$Re = Fe / So$

$Rm = Fm / So$

$Lo = 5{,}65 * \mathrm{sqrt}(So)$

$A = (Lu-Lo) / Lo$

$Z = (So-Su) / So$

Specimen No./position	Dimension/diameter mm	Cross-sectional area So / mm2	Yield load Fe / kN	Yield strength Re / N/mm2	Maximum load Fm / kN	Ultimate strength Rm / N/mm2	Original gage length Lo / mm	End gage length Lu / mm	Percentage elongation A / %	Su / mm2	Reduction of area Z / %	Location of fracture	Remark
A59C1	*11x25*	*275*	*109*	*396,4*	*148,9*	*541,5*	*94*	*115*	*22,3*	-	-	*bm*	
A59C2	*11x25*	*275*	*108*	*392,7*	*149,8*	*544,7*	*94*	*113*	*20,2*	-	-	*bm*	
Average				***394,5***		***543,1***			***21,3***	-	-		
A59M1	*11x25*	*275*	*107*	*389,1*	*145,8*	*530,2*	*94*	*112*	*19,1*	-	-	*bm*	
A59MK1	*11x25*	*275*	*109*	*396,4*	*148,7*	*540,7*	*96*	*126*	*31,3*	-	-	*bm*	
A106C1	*12x25*	*300*	*108*	*360,0*	*147,8*	*492,7*	*96*	*118*	*22,9*			*bm*	
A106M1	*11x25*	*275*	*106*	*385,5*	*147,9*	*537,8*	*93*	*113*	*21,5*			*bm*	
A106M2	*11x25*	*275*	*107*	*389,1*	*148,8*	*541,1*	*94*	*116*	*23,4*			*bm*	
Average				***387,3***		***539,5***			***22,5***				
A206C1	*11,5x24*	*276*	*102*	*369,6*	*141,4*	*512,3*	*94*	*115*	*22,3*			*bm*	
A206M1	*11x24*	*264*	*102*	*386,4*	*141,8*	*537,1*	*92*	*113*	*22,8*			*bm*	
A206M2	*11x24*	*264*	*101*	*382,6*	*141,2*	*534,8*	*92*	*111*	*20,7*			*bm*	
Average				***384,5***		***536,0***			***21,7***				

APPENDIX 11.

pWPS	***AHS 14***
According to	***SFS-EN 4136***
Manufacturer	
Base material	***E500 TM***
Material thickness	***25 mm***
Joint type	***BW***
Welding process	***MAG***
Consumable	***PZ6115***
Test temperature	***20*** °C
Remark	

Re = Fe / So

Rm = Fm / So

Lo = 5,65 * sqrt (So)

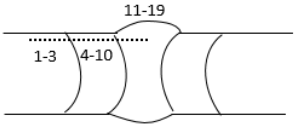
A =(Lu-Lo) / Lo

Z = (So-Su) / So

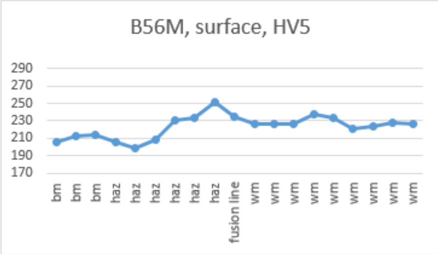
Specimen No./position	Dimension/diameter mm	Cross-sectional area So / mm2	Yield load Fe / kN	Yield strength Re / N/mm2	Maximum load Fm / kN	Ultimate strength Rm / N/mm2	Original gage length Lo / mm	End gage length Lu / mm	Percentage elongation A / %	Su / mm2	Reduction of area Z / %	Location of fracture	Remark
B56M1	*10x26*	*260*	*148*	*569,2*	*171,6*	*660,0*	*90*	*106*	*17,8*	-	-	*bm*	
B56M2	*10x25*	*250*	*146*	*584,0*	*165,4*	*661,6*	*90*	*109*	*21,1*	-	-	*bm*	
KA				***576,6***		***660,8***			***19,4***	-	-		
B59M1	*10x25*	*250*	*147*	*588,0*	*167,9*	*671,6*	*90*	*107*	*18,9*	-	-	***haz***	
B59M2	*10x26*	*260*	*147*	*565,4*	*167,1*	*642,7*	*92*	*110*	*19,6*	-	-	***haz***	
KA				***576,7***		***657,1***			***19,2***	-	-		
B106M1	*10x25*	*250*	*142*	*568*	*164,2*	*656,8*	*92*	*107*	*16,3*	-	-	*haz*	
B106M2	*10x25*	*250*	*145*	*580*	*167,7*	*670,8*	*90*	*108*	*20,0*	-	-	*haz*	
KA				***574***		***663,8***			***18,2***	-	-		
B109M1	*10x26*	*260*	*143*	*550*	*162,3*	*624,2*	*91*	*109*	*19,8*	-	-	***haz***	
B109M2	*10x26*	*260*	*147*	*565,4*	*165,5*	*636,5*	*91*	*109*	*19,8*	-	-	*weld*	
KA				***557,7***		***630,4***			***19,8***	-	-		
B206M1	*10x26*	*260*	*142*	*546,2*	*162,1*	*623,5*	*91*	*109*	*19,8*	-	-	*bm*	
B206M2	*10x25*	*250*	*147*	*588*	*166,7*	*666,8*	*91*	*109*	*19,8*	-	-	*haz*	
KA				***567,1***		***645,1***			***19,8***	-	-		

APPENDIX 12. Hardness test records

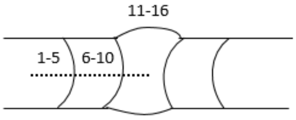
Measuring points



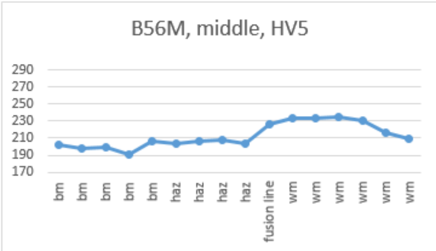
Point	Hardness	Point	Hardness
1	206	11	226
2	213	12	226
3	214	13	227
4	206	14	237
5	198	15	234
6	208	16	221
7	231	17	223
8	234	18	228
9	252	19	227
10	235		



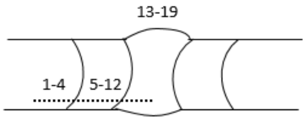
Measuring points



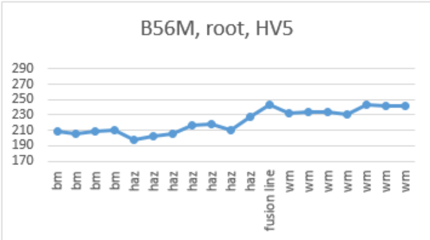
Point	Hardness	Point	Hardness
1	202	11	233
2	198	12	233
3	199	13	235
4	191	14	230
5	206	15	216
6	203	16	209
7	206		
8	208		
9	203		
10	226		



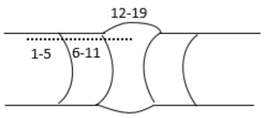
Measuring points



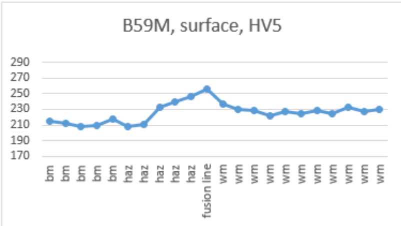
Point	Hardness	Point	Hardness
1	209	11	227
2	206	12	244
3	208	13	232
4	210	14	234
5	197	15	234
6	203	16	230
7	206	17	243
8	216	18	242
9	218	19	241
10	210		



Measuring points



Point	Hardness	Point	Hardness	Point	Hardness
1	215	11	256	21	227
2	212	12	237	22	230
3	208	13	230		
4	210	14	228		
5	217	15	222		
6	208	16	227		
7	211	17	225		
8	233	18	229		
9	240	19	224		
10	246	20	233		



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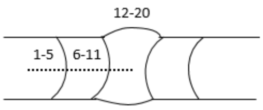
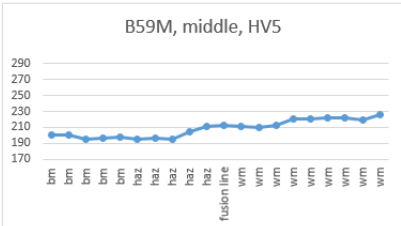


Point	Hardness	Point	Hardness	Point	Hardness
1	200	11	213		
2	200	12	211		
3	195	13	210		
4	196	14	213		
5	198	15	220		
6	195	16	220		
7	197	17	222		
8	195	18	222		
9	205	19	219		
10	211	20	226		



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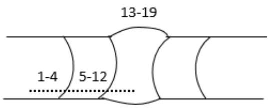
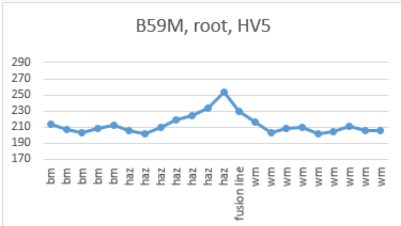
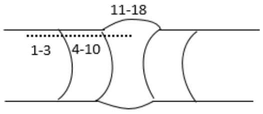


Point	Hardness	Point	Hardness	Point	Hardness
1	214	11	234	21	206
2	207	12	254	22	205
3	203	13	230		
4	208	14	216		
5	212	15	203		
6	205	16	208		
7	201	17	209		
8	209	18	201		
9	219	19	204		
10	224	20	211		

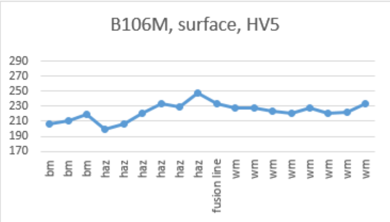


APPENDIX 12.

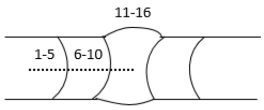
Measuring points



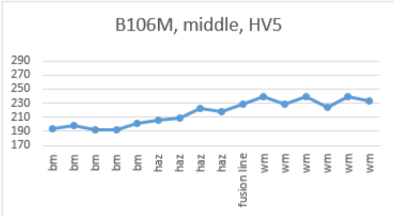
Point	Hardness	Point	Hardness	Point	Hardness
1	206	11	227		
2	211	12	227		
3	219	13	223		
4	200	14	221		
5	206	15	228		
6	220	16	220		
7	234	17	222		
8	229	18	233		
9	247				
10	234				



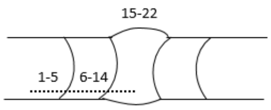
Measuring points



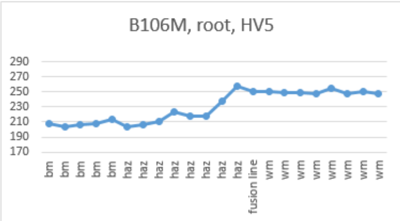
Point	Hardness	Point	Hardness	Point	Hardness
1	194	11	239		
2	198	12	229		
3	193	13	239		
4	192	14	224		
5	201	15	239		
6	206	16	233		
7	209				
8	222				
9	218				
10	228				



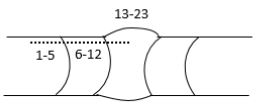
Measuring points



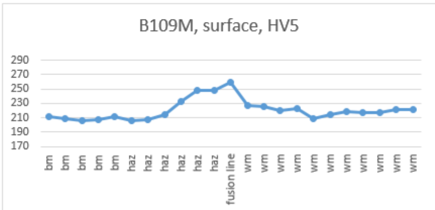
Point	Hardness	Point	Hardness	Point	Hardness
1	208	11	218	21	251
2	204	12	237	22	247
3	206	13	258		
4	208	14	250		
5	213	15	250		
6	203	16	249		
7	207	17	249		
8	211	18	248		
9	223	19	254		
10	218	20	248		



Measuring points



Point	Hardness	Point	Hardness	Point	Hardness
1	211	11	248	21	217
2	209	12	259	22	221
3	206	13	227	23	222
4	207	14	226		
5	211	15	220		
6	206	16	223		
7	207	17	209		
8	215	18	215		
9	233	19	219		
10	248	20	217		



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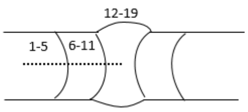
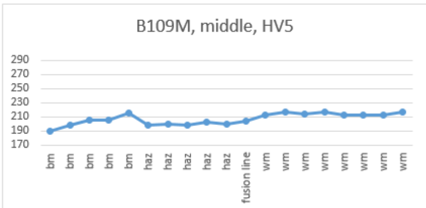
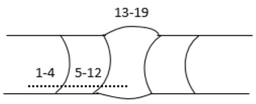


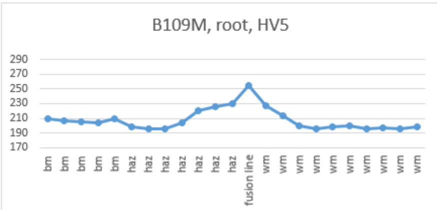
Point	Hardness	Point	Hardness	Point	Hardness
1	189	11	204		
2	198	12	212		
3	206	13	217		
4	205	14	214		
5	215	15	217		
6	198	16	213		
7	200	17	212		
8	198	18	213		
9	203	19	217		
10	200				



Measuring points

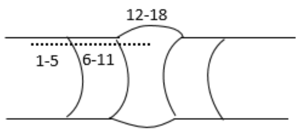


Point	Hardness	Point	Hardness	Point	Hardness
1	210	11	226	21	197
2	207	12	230	22	195
3	205	13	254	23	198
4	204	14	227		
5	209	15	214		
6	198	16	200		
7	195	17	195		
8	196	18	199		
9	204	19	200		
10	220	20	195		

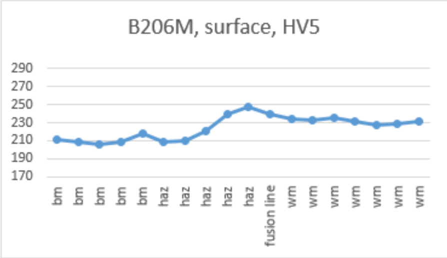


APPENDIX 12.

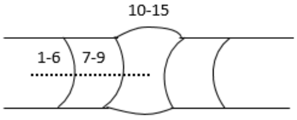
Measuring points



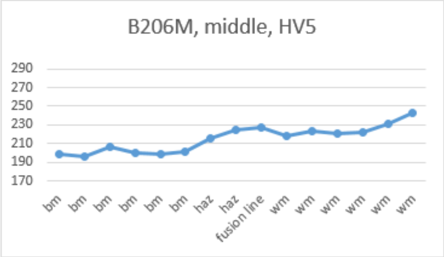
Point	Hardness	Point	Hardness
1	211	11	240
2	208	12	234
3	206	13	233
4	208	14	236
5	218	15	232
6	208	16	227
7	210	17	229
8	221	18	232
9	240		
10	247		



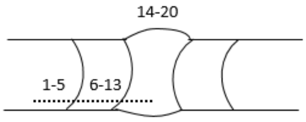
Measuring points



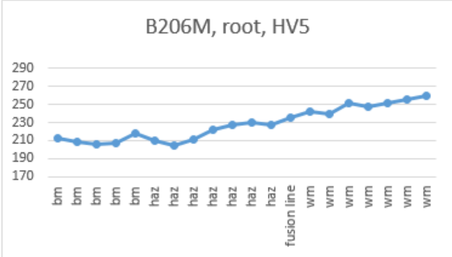
Point	Hardness	Point	Hardness
1	199	11	224
2	196	12	221
3	206	13	222
4	200	14	231
5	199	15	243
6	201		
7	215		
8	225		
9	227		
10	218		



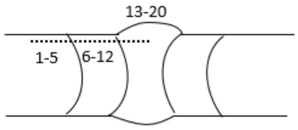
Measuring points



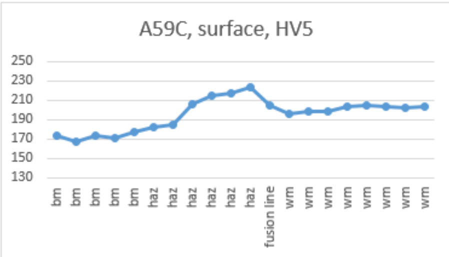
Point	Hardness	Point	Hardness
1	212	11	230
2	208	12	227
3	206	13	235
4	207	14	242
5	218	15	239
6	210	16	251
7	204	17	248
8	211	18	252
9	222	19	255
10	228	20	259



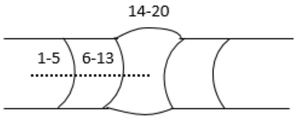
Measuring points



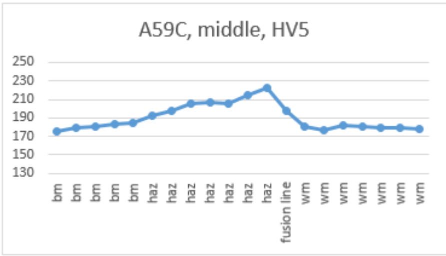
Point	Hardness	Point	Hardness
1	173	11	223
2	167	12	205
3	173	13	196
4	171	14	198
5	177	15	198
6	182	16	204
7	185	17	205
8	206	18	204
9	215	19	202
10	217	20	203



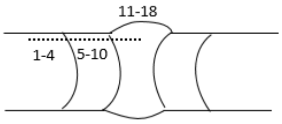
Measuring points

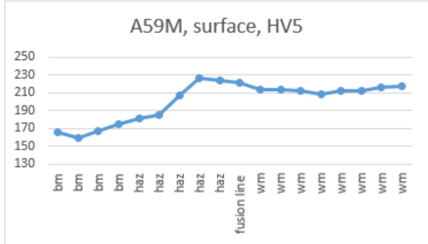


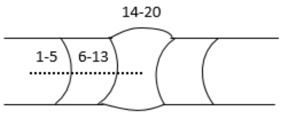
Point	Hardness	Point	Hardness
1	175	11	215
2	179	12	222
3	181	13	197
4	183	14	181
5	185	15	177
6	192	16	182
7	197	17	181
8	205	18	179
9	207	19	179
10	206	20	178

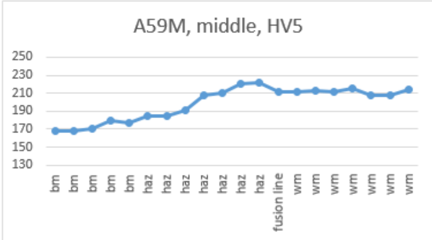


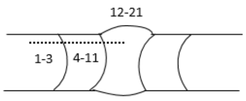
APPENDIX 12.

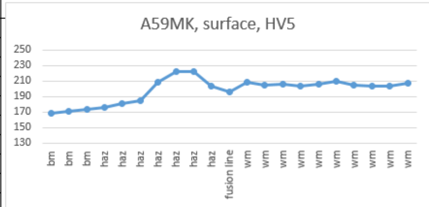
Measuring points	Point	Hardness	Point	Hardness
	1	166	11	214
	2	160	12	214
	3	168	13	212
	4	175	14	209
	5	181	15	213
	6	186	16	213
	7	208	17	216
	8	227	18	218
	9	224	19	
	10	222	20	

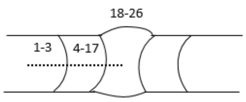


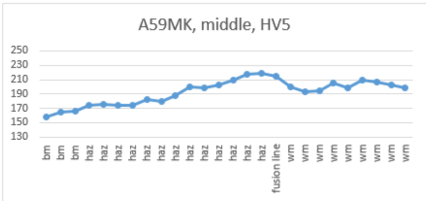
Measuring points	Point	Hardness	Point	Hardness
	1	168	11	220
	2	168	12	222
	3	170	13	211
	4	180	14	211
	5	177	15	213
	6	185	16	211
	7	185	17	215
	8	191	18	208
	9	208	19	208
	10	210	20	214

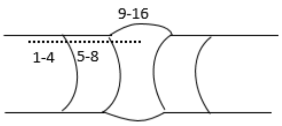


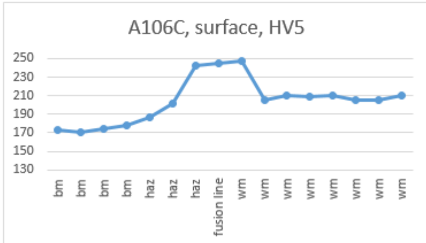
Measuring points	Point	Hardness	Point	Hardness	Point	Hardness
	1	168	11	196	21	207
	2	171	12	208		
	3	174	13	205		
	4	176	14	206		
	5	181	15	204		
	6	185	16	206		
	7	209	17	210		
	8	222	18	205		
	9	222	19	204		
	10	204	20	203		

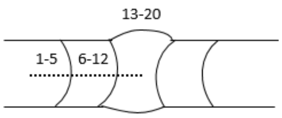


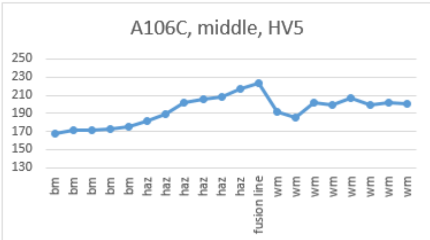
Measuring points	Point	Hardness	Point	Hardness	Point	Hardness
	1	158	11	200	21	205
	2	165	12	199	22	199
	3	166	13	203	23	209
	4	174	14	210	24	206
	5	176	15	218	25	203
	6	174	16	219	26	198
	7	174	17	215		
	8	182	18	200		
	9	180	19	193		
	10	188	20	195		



Measuring points	Point	Hardness	Point	Hardness
	1	173	11	210
	2	171	12	209
	3	174	13	210
	4	178	14	205
	5	187	15	205
	6	202	16	210
	7	242	17	
	8	245	18	
	9	247	19	
	10	205	20	

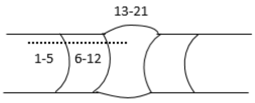


Measuring points	Point	Hardness	Point	Hardness
	1	168	11	217
	2	171	12	223
	3	171	13	192
	4	173	14	185
	5	175	15	202
	6	182	16	199
	7	189	17	207
	8	202	18	199
	9	205	19	202
	10	208	20	200

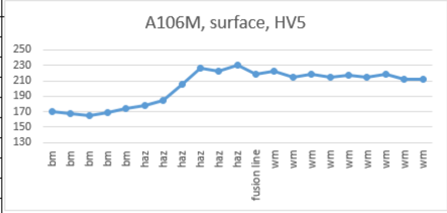


APPENDIX 12.

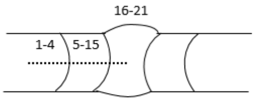
Measuring points



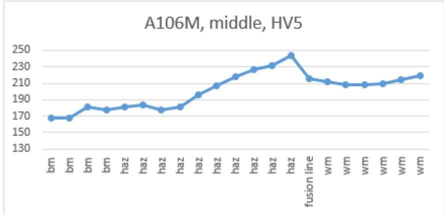
Point	Hardness	Point	Hardness	Point	Hardness
1	170	11	230	21	212
2	168	12	218		
3	165	13	222		
4	169	14	214		
5	174	15	219		
6	178	16	215		
7	184	17	217		
8	205	18	214		
9	226	19	219		
10	223	20	212		



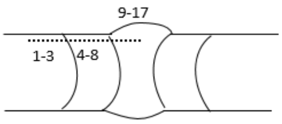
Measuring points



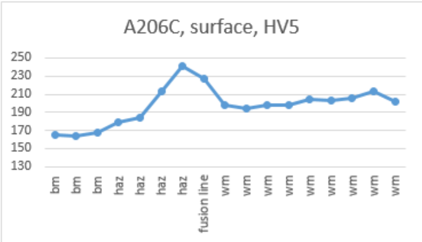
Point	Hardness	Point	Hardness	Point	Hardness
1	168	11	218	21	219
2	168	12	227		
3	181	13	231		
4	177	14	244		
5	181	15	216		
6	184	16	212		
7	177	17	208		
8	181	18	208		
9	196	19	209		
10	207	20	214		



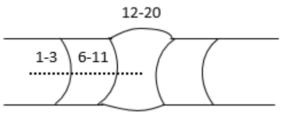
Measuring points



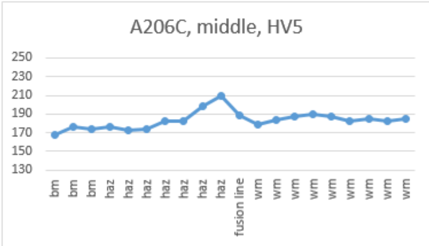
Point	Hardness	Point	Hardness
1	165	11	198
2	164	12	198
3	168	13	204
4	179	14	203
5	184	15	205
6	213	16	213
7	241	17	202
8	227	18	
9	198	19	
10	194	20	



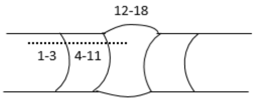
Measuring points



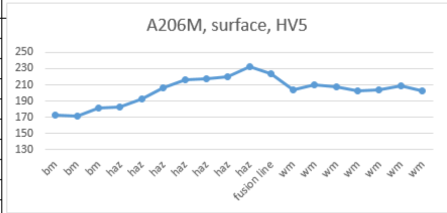
Point	Hardness	Point	Hardness
1	168	11	189
2	176	12	179
3	174	13	184
4	176	14	187
5	173	15	190
6	174	16	187
7	182	17	182
8	183	18	185
9	198	19	183
10	209	20	185



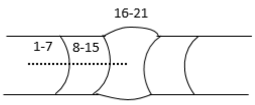
Measuring points



Point	Hardness	Point	Hardness	Point	Hardness
1	173	11	224		
2	171	12	204		
3	181	13	210		
4	183	14	208		
5	192	15	202		
6	206	16	204		
7	216	17	209		
8	218	18	202		
9	220				
10	233				



Measuring points



Point	Hardness	Point	Hardness	Point	Hardness
1	243	11	199	21	207
2	171	12	207		
3	173	13	208		
4	178	14	205		
5	180	15	210		
6	183	16	201		
7	183	17	204		
8	185	18	201		
9	195	19	211		
10	199	20	206