LAPPEENRANTA UNIVERSITY OF TECHNOLOGY
LUT School of Energy Systems
LUT Mechanical Engineering

Jussi Tuominen

DISSIMILAR METAL JOINT WELDING PROPERTIES AND COST ANALYSIS

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Examiners: Professor Timo Björk
M. Sc. Miika Kallonen

TIIVISTELMÄ

Lappeenrannan teknillinen yliopisto
LUT School of Energy Systems
LUT Kone

Jussi Tuominen

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Tarkastajat: Professori Timo Björk
DI Miika Kallonen

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Tässä työssä tutkitaan suurlujuusteräksen ja teräsvalujen hyödynnettävyyttä maanalaisen kaivoskuormaajan eturunkorakenteessa. Tutkimus keskittyy entuudestaan tuntemattoman materiaaliparin hitsauksen ominaisuuksien ja raja-arvojen selvittämiseen. Lisäksi arvioidaan uusien materiaalien ja uuden eturunkokonseptin vaikutusta materiaali- ja hitsauskustannuksiin.

Valitun materiaaliparin, SSAB Domex 500 ML ja G24Mn6+QJ2, hitsaukselle suoritetaan standardin SFS-EN ISO 15614-1 mukaiset hitsin aineenkoetuskokeet. Näihin kuuluu radiografinen tutkimus, makrohietutkimus, poikittainen vetokoe, poikittainen taivutuskoe, kovuuskoe ja iskukoe. Lisäksi suoritetaan jäähtymisajan mittauksia ja mikrohietutkimuksia. Aineenkoetuskokeita varten suoritetaan koehitsit sekä laboratorio-olosuhteissa että konepajaolosuhteissa. Kokeiden tuloksena saatavaa tietoa voidaan hyödyntää hitsausprosessin verifioimisessa ja tulevaisuuden projektien lujuuslaskennan lähtötietona.

Koetuloksien perusteella valittu materiaalipari osoittautui kelvolliseksi hitsata. Rajaehdot käytettävälle lämmöntuonnille ja esilämmitykselle tulee G24Mn6+QJ2:n myötä ja materiaaliparin hitsaus on haastavampaa kuin pelkän SSAB Domex 500 ML:n hitsaus. Materiaalipari on hyödynnettävissä kuormaajan eturunkorakenteessa, mutta kun hitsauksen haasteiden lisäksi selvisi, että uusi runko tulee olemaan hitsaus- ja materiaalikustannukset huomioon ottaen useamman tuhatta euroa kalliimpi, ei uutta konseptia ole syytä käyttöönottaa harkitsemattomasti.

Jatkotutkimuksen aiheiksi jäi eturungon painon optimointi ja hitsausprosessin lisäselvitykset. Hitsausprosessin lisäselvityksissä tutkittavina aiheina voisi olla kovuuden madaltaminen, iskusitkeyden ja vetolujuuden parantaminen, puoli-v hitsin ja pienahitsin selvittäminen sekä hitsin käyttäytyminen väsyttävän kuormituksen alaisena.

ABSTRACT

Lappeenranta University of Technology
LUT School of Energy Systems
LUT Mechanical Engineering

Jussi Tuominen

Dissimilar metal joint welding properties and cost analysis

Master's thesis

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69 pages, 39 figures, 12 tables and 14 appendices

Examiners: Professor Timo Björk
M. Sc. Miika Kallonen

Keywords: welding, SSAB Domex 500 ML, G24Mn6+QJ2, heat input, preheat

This thesis investigates of high-strength steel and steel casts in underground loader front frame structure. It focuses on the welding properties and limits of a previously unknown material pairing. In addition, the impact on material and welding costs for a new front frame concept is estimated.

Material testing for welds in accordance with the SFS-EN ISO 15614-1 standard is performed for the material pair SSAB Domex 500 ML and G24Mn6+QJ2. Testing includes radiographic examination, macroscopic examination and transverse tensile, hardness, and impact tests. Also, some cooling time measurements and microscopic examinations are performed. Welding of test pieces for material testing is performed in laboratory and workshop environments. Test results are used to verify the welds and as baseline information for strength analysis in future projects.

Test results showed that it is possible to weld the chosen material pair. Boundary values for the preheat and heat input used are generated by G24Mn6+QJ2. Welding of the material pair is more challenging than welding only SSAB Domex 500 ML. The material pair is usable for loader front frames, but, because material and welding costs increase by several thousands of euro, the new concept should not be implemented without further evaluation.

Future projects would consist of front frame weight optimisation and further development of the welding process. Further development of the welding process could include improving impact energy, hardness and tensile properties, discovering single bevel butt welds and fillet welds and determining weld behaviour under fatigue stresses.

ACKNOWLEDGEMENTS

It has been such a long, sometimes frustrating but mostly rewarding road, to the point where I can honestly say, it's completed. For someone Master's studies takes 4,5 years and for someone else 6, but, for me, if counting my first try at Tampere in 2002, it took 17. Even Over the last two years with the thesis, it never seemed that it would come to an end, but now it's there.

First of all, I want to thank my examiners, Timo at LUT and Miika at Sandvik, for their solid support during the thesis. My thanks also go to all the welding, manufacturing and laboratory professionals and specialists who took part in this thesis on behalf of LUT and Sandvik. You know who you are.

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Last but not least, I want to thank my family for their support, patience and encouragement. My old Ma and Pa in the early years and my wife, Elina, and kids, Arttu and Lilli, in the later years. I know you felt "Don't I have any better things to do," and you know I felt the same.

Jussi Tuominen

Mynämäki, June 21, 2019

TABLE OF CONTENTS

SYMBOLS AND ABBREVIATIONS

a	Fillet weld throat thickness (mm)
c_m	Material cost (€)
c_w	Welding cost (€)
CE	Carbon equivalent (%)
CET	Carbon equivalent (%)
CEV	Carbon equivalent, same as CE (%)
d	Thickness of plate (mm)
Δc	Cost change (€)
E	Energy consumption (kWh/kg)
e	Duty cycle
F_2	Shape factor for two-dimensional heat flow
g	Gas multiplier
H_E	Energy price (€/kWh)
H_m	Material cost per kilo (€/kg)
H_L	Filler material price (€/kg)
H_S	Shielding gas price (€/m3)
H_T	Labour cost per hour (€/h)
H_w	Welding cost per hour (€/h)
HD	Diffusible hydrogen content (ml/100 g)
$HV5$	Vickers hardness
I	Welding current (A)
k	Thermal efficiency
K_E	Energy costs (€/m)
K_L	Filler material costs (€/m)
K_S	Shielding gas costs (€/m)
K_T	Labour costs (€/m)
M	Amount of filler material (kg/m)
m	Mass (kg)
N	Deposition efficiency
Q	Heat input (kJ/mm)
ρ	Density (kg/m^3)

s	Butt weld depth (mm)
t	Welding time (h)
T	Deposition rate (kg/h)
T_0	Initial plate temperature (°C)
$t_{8/5}$	Cooling time from 800 °C to 500 °C (s)
T_p	Preheat temperature (°C)
T_{pCET}	Carbon equivalent dependent preheat temperature (°C)
T_{pd}	Plate thickness dependent preheat temperature (°C)
T_{pHD}	Hydrogen content dependent preheat temperature (°C)
T_{pQ}	Heat input dependent preheat temperature (°C)
U	Arc voltage (V)
V	Shielding gas volume flow (l/min)
v	Travel speed (mm/s)

BM	Base material
HAZ	Heat-affected zone
LHD	Load, haul and dump
MAG	Metal active gas welding
WPS	Welding procedure test

1 INTRODUCTION

Requirements and competition in the modern auto and utility vehicle industry are growing constantly. Companies are eager to find technical solutions to gain competitive advantage. The high-level objective of this thesis is to develop a new approach to a specific problem in specific equipment to give it a cutting edge. This thesis is conducted for Sandvik Mining and Rock Technology, which is part of Sandvik Group. The equipment under investigation is a wheel loader for underground mining. The problem addressed involves the loader's front frame steel structure and is presented in upcoming sections.

1.1 Company and loader application

Sandvik Group is a Swedish international company with over 40,000 employees. It is listed on the Stockholm stock exchange. The group covers three business areas: Sandvik Machining Solutions, Sandvik Mining and Rock Technology and Sandvik Materials Technology. Sandvik Mining and Rock Technology produces, develops and offers services for equipment used in mining and the construction industry. The Sandvik Mining and Rock Technology site in Turku develops and produces load-haul-dump (LHD) machines and dump trucks for underground mining. LHD machines are wheel loaders, known in the mining industry as LHDs or loaders. (Sandvik 2019a)

Usually a loader is used in the mining industry to dig rock material from muck piles, haul it short distances and dump it to another application for further hauling. This other application can be, for example, a dump truck, belt conveyor or shaft.

Figure 1. Underground loader (Sandvik 2019a)

One key factor and indicator in estimating superiority over competitors in loader application is productivity. In the mining segment, productivity is often measured in produced tons per hour. In loader application, productivity consists of spend time and carried load, in other words, the length of duty cycle and payload of the loader. The duty cycle is the time spent on the muck pile, hauling time, dump time and travel time back to muck pile. Time spent per duty cycle is then a combination of machine efficiency and mine layout. Instead of improving the time spent in the duty cycle, this thesis focuses on offering tools to improve the other variable: payload.

A limiting factor for LHD payload is tyre approval. Tyre approval sets limits for the load supplied to tyres. LHD front frame and payload capacity is designed with these limits in mind. The only option to increase payload is to get tyre approvals with higher limits or decrease machine weight. Tyre approval is out of the company's hands, so the only way to increase payload is to reduce front frame structure weight.

The purpose of using high-strength steel is to make front frame structure lighter by reducing material and increasing structural stress. The problem is then exposure of the welds to higher stresses. Steel casts are used to reduce the number of welds and, even more, to increase freedom of design shapes to avoid placing welds in unfavourable areas with respect to stresses.

1.2 Research problem

The objective of this thesis is to find answers to two separate problems. First, the properties of high-strength steel material and cast steel material are provided by the material supplier, but the properties of welds are unknown. Second, the use of high-strength steel and steel castings probably increases material costs while fewer welds decreases welding costs. The overall effect these changes is unknown. The lack of knowledge about relevant characteristics requires investigations to find answers to the following questions:

1. Is it possible to join the selected material pair by welding?
2. Does the weld fulfil requirements stated in standards?
3. What kind of mechanical weld properties can be achieved for selected materials with the defined welding procedure?
4. Does workshop welding quality correspond to laboratory quality?
5. Does the cost structure of steel construction increase?
6. What is the magnitude of the decrease in welding costs and increase in material costs?

1.3 Goals

This thesis is one step in a longer process presented in figure 2. The overall goal is to provide baseline information and preliminary targets for steps 2 and 3 in figure 2. Baseline information in this case refers to fixed material selection and the welding process that can be qualified with the welding procedure test in accordance with the SFS-EN ISO 15614-1 standard. Preliminary targets in this case refer to the need for manufacturing cost-cutting. These goals and targets are assumed to be achieved by finding answers to the questions under "Research problems" and detailed questions under "Research". Additionally, a 3D concept for a new front frame will be designed. That will serve as a basis for cost analysis and the starting point for future projects.

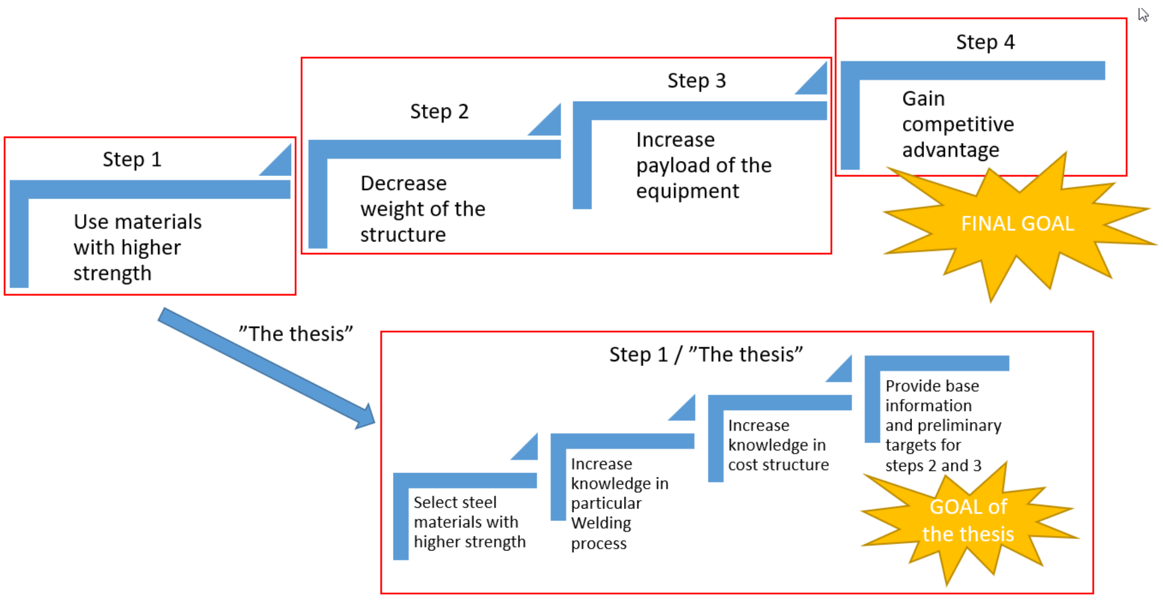


Figure 2. Steps in product improvement process and goal of the thesis

2 RESEARCH

As mentioned under "Research problem", two problems are stated, thus two frameworks formulated. One addresses welding metallurgy and the other welding and material costs. Matters that do not fall under either of these frameworks are excluded from the thesis, for example any kind of weight and strength optimization or fatigue stress analysis. More exclusions explained in next sections.

2.1 Welding metallurgical framework

The welding metallurgical framework aims to find answers to questions 1–4 in section 1.2. The assumption is that answers to the research questions in figure 3 below provide responses to the questions in section 1.2. In the literature, weldability is divided into several categories. Here, only metallurgical weldability is important. Of course, the concept 3D-model is created in accordance with good engineering practice, which means that structural weldability is considered to some degree.

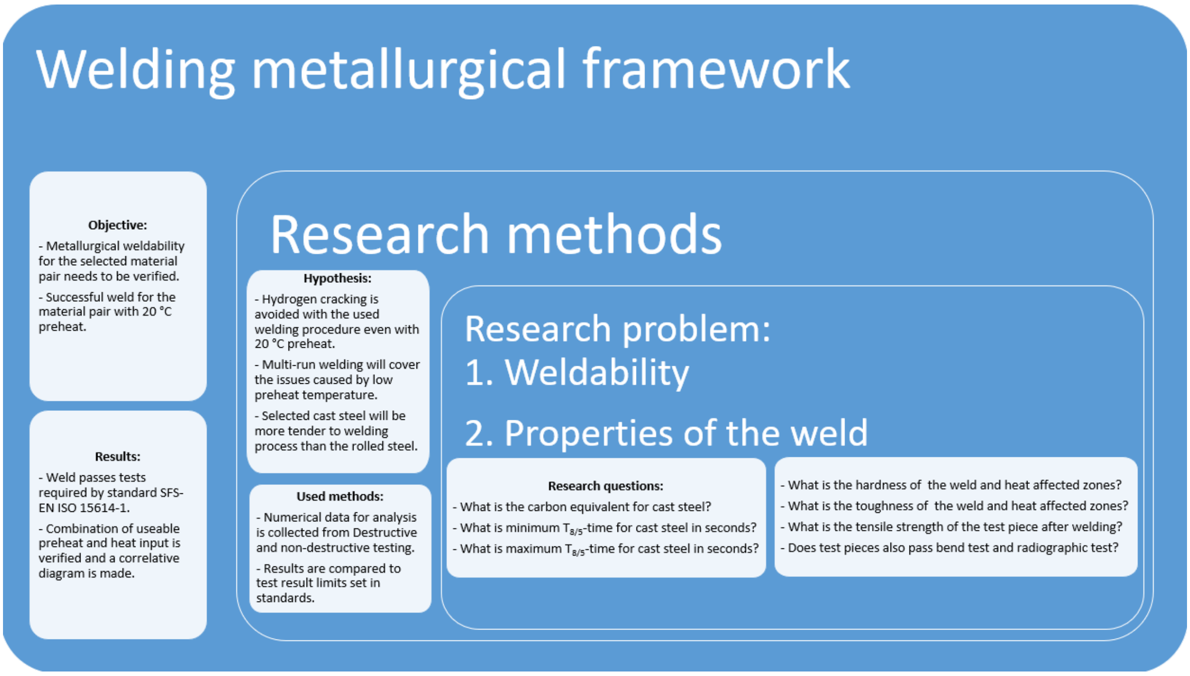


Figure 3. Welding metallurgical framework

The advantage of these questions compared with earlier, higher-level questions is that they provide the opportunity to get numeric data from proven test methods. The test data is comparable with any data collected from similar tests before or in the future. The selected tests are listed below and are chosen to be performed for test pieces with further selected criteria:

- Radiographic examination: SFS-EN 1435
- Macroscopic and microscopic examination of welds: SFS-EN ISO 17639
- Hardness test on arc welded joints: SFS-EN ISO 9015-1 and SFS-EN ISO 6507-1
- Impact test: SFS-EN ISO 9016 and SFS-EN ISO 148-1
- Transverse tensile test: SFS-EN ISO 4136
- Bend test: SFS-EN ISO 5173

In addition, $t_{8/5}$-cooling time is measured for some test pieces.

The welding process used in welding tests is defined and restricted by the Welding Procedure Specification (WPS) in appendix 1. The only variables in tests are heat input, preheat and interpass temperature.

These tests address all research questions except "What is the carbon equivalent for cast steel?" Because the project is non-recurring and does not allow iterations based on the test results, this question is fundamental. Carbon equivalent is calculated for preselected cast steel materials, and final selection is based on these calculations.

2.2 Welding and material cost framework

Manufacturing costs, which in this case means welding and material costs, play a minor role in this study compared to welding investigations. The results of this framework are rough estimations and work as a guide to future development. The welding and material cost framework responds to questions 5 and 6 in section 1.2. The framework is presented in figure 4.

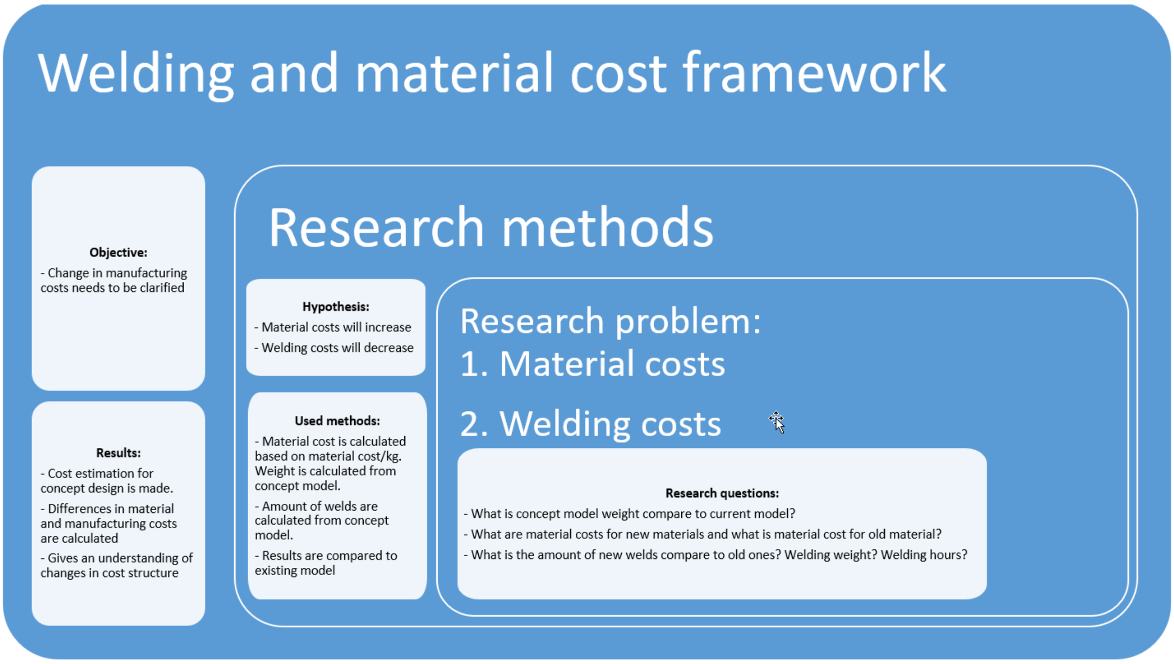


Figure 4. Welding and material cost framework

Data to find answers to the research questions is collected from a concept 3D model. All rolled steel materials are defined as high-strength steel, and all steel castings are defined as high-strength cast steel. Materials are presented below in under "Literature review". Change in number of welds is defined as the comparison of the concept 3D model and current 3D model. As the welding and material cost framework requires little research and plays a minor role in the thesis, it is addressed separately under "Cost analysis" and not discussed under "Experiments", "Results" or "Analysis". Those sections cover the welding metallurgical framework.

3 LITERATURE BACKROUND OF THE EXPERIMENTS

To conduct this research and obtain reliable results, the literature on the topic must be reviewed. This section is a collection of findings from the literature. It provides protocol descriptions and indirectly describes why protocols are being performed. The focus here is on metal active gas (MAG) welding process used for high-strength steel and steel cast materials and welding tests required by the welding procedure test. These are the theoretical topics in this thesis. The theory behind the cost analysis is kept to minimum and is included under "Cost analysis".

3.1 Welding

Welding is the most commonly used method in manufacturing for joining metallic materials (Lukkari 1998, p. 13). According to the SFS 3052 standard, welding is a manufacturing method by which parts are joined using heat and/or pressure in a way that the parts form a continuous connection (SFS 3052 1995, p. 2). Welding is divided into two fusion methods: welding and pressure welding (Lukkari 1998, p. 15). These methods are further divided into hundreds of welding procedures, which are not presented here. This thesis focuses on MAG welding with metal cored electrode, process number 135 (SFS-EN ISO 4063 2011, p. 12).

MAG welding is a gas shielded metal arc welding process by which an electric arc is generated between the welding wire and workpiece. The arc is surrounded by active shield gas (Lukkari 1998, p. 159). The principle of the MAG welding process appears in figure 5. The process consists of multiple variables, for example, wire properties, heat input, preheat, shield gas properties and post-weld heat treatment. These variables determine the outcome of the weld. These and many other welding procedure variables are shown in appendix 1, "Welding Procedure Specification (WPS)".

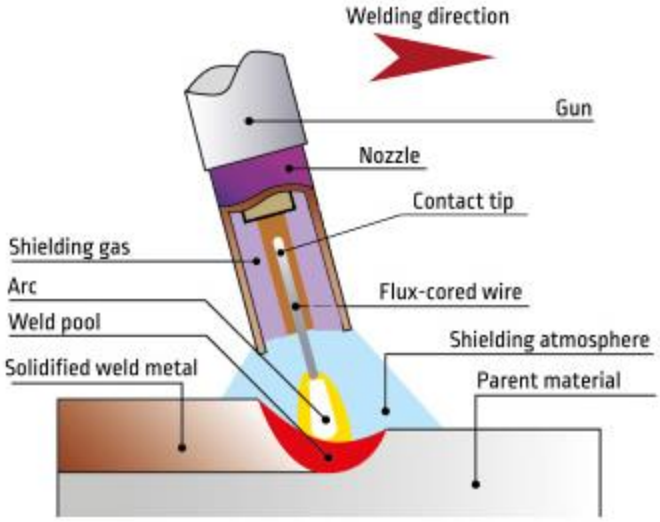


Figure 5. MAG welding process (Lincoln Electric, 2019a)

The WPS in appendix 1 is based on a real MAG-135 welding process for the material SSAB Domex 500ML and is modified to support the welding tests performed in this thesis. Changes are marked in red and green. Red indicates unknown variables that change in welding experiments performed for this thesis. Green indicates features that differ from the original WPS but are invariable during the experiments. Others are left unchanged. The usability of the selected wire and welding gas is confirmed in the literature. The consumable manufacturer Lincoln Electric suggests using SupraMig Ultra for S460 steel, which is similar to SSAB Domex 500ML (Lincoln Electric, 2019b). Yield strength for the consumable is 500 MPa (Lincoln Electric, 2019b). According to shield gas manufacturer AGA, used shield gas works well as a multipurpose shield gas (Kuusisto, 2014).

3.1.1 Carbon equivalent

Carbon is an alloying component that has an effect on the mechanical material properties of ferritic steels. Many other alloying components have a similar effect (Kyröläinen & Kauppi 2016, p. 75). The carbon equivalent is a mathematical equation that describes the proportion of carbon that corresponds to the overall combination and proportion of other alloying materials. The carbon equivalent value is an indicator for material hardening and is in a way indicating the need for preheat in welding. Several different kinds of equations to describe the same phenomenon are consisted in different places at different times. This thesis uses only those that appear in SFS-EN1011-2:

(1) $$CE = C + \frac{Mn}{6} + \frac{Cr+Mo+V}{5} + \frac{Ni+Cu}{15} \ (\%),$$ (SFS-EN 1011-2 2001, p. 25)

(2) $$CET = C + \frac{Mn+Mo}{10} + \frac{Cr+Cu}{20} + \frac{Ni}{40} \ (\%),$$ (SFS-EN 1011-2 2001, p. 59)

where *C*, *Mn*, *Cr*, *Mo*, *V*, *Ni*, *Cu* are the content of the element. CE is sometimes replaced by CEV, which is based on the same equation.

When selecting a new material for a welded structure, the CE carbon equivalent can be used as a tool to estimate whether preheat in welding is needed or not. Boundary values for CE presented below:

CE $<$0,40 (%): No preheat needed (Kyröläinen & Kauppi 2016, p. 75).
CE = 0,40–0,50 (%): Usually no preheat needed for small thicknesses, low-hydrogen consumables needed (Kyröläinen & Kauppi 2016, p. 75).
CE $>$0,50 (%): Preheat and low-hydrogen consumables needed, possibly post-weld heat treatment (Kyröläinen & Kauppi 2016, p. 75).

3.1.2 Preheat, heat input and $t_{8/5}$ cooling time

In the MAG welding process, heat energy is applied to the weld in two ways: preheat and heat input. Preheat is heat energy applied to components before the welding process. It is expressed as a material temperature, usually in °C. In multirun welding, preheating for following runs is called interpass temperature. If the preheat value is set, the interpass temperature is usually set to the same value, with a boundary for the maximum temperature.

Heat input is the heat applied during the welding process and is the energy that melts the material. Heat input is expressed as heat energy per distance, usually in kJ/mm or kJ/cm. Heat input is calculated using the following equation, which can be found in SFS-EN 1011-1:

(3) $$Q = k \times \frac{U \times I}{v} \times 10^{-3} \ (kJ/mm),$$ (SFS-EN 1011-1 2009, p. 19)

When welding a steel material, the combination of preheat and heat input must be set within specific limits. Factors that determine these limits include risk of hydrogen cracking, increase in hardness and degrees of toughness. Standards also define the maximum preheat temperature for some materials, which should be used then also as a limiting factor. An example of this kind of heat energy window appears in figure 6. The figure is generated with the commercial calculation tool WeldCalc 2.2 provided by SSAB AB.

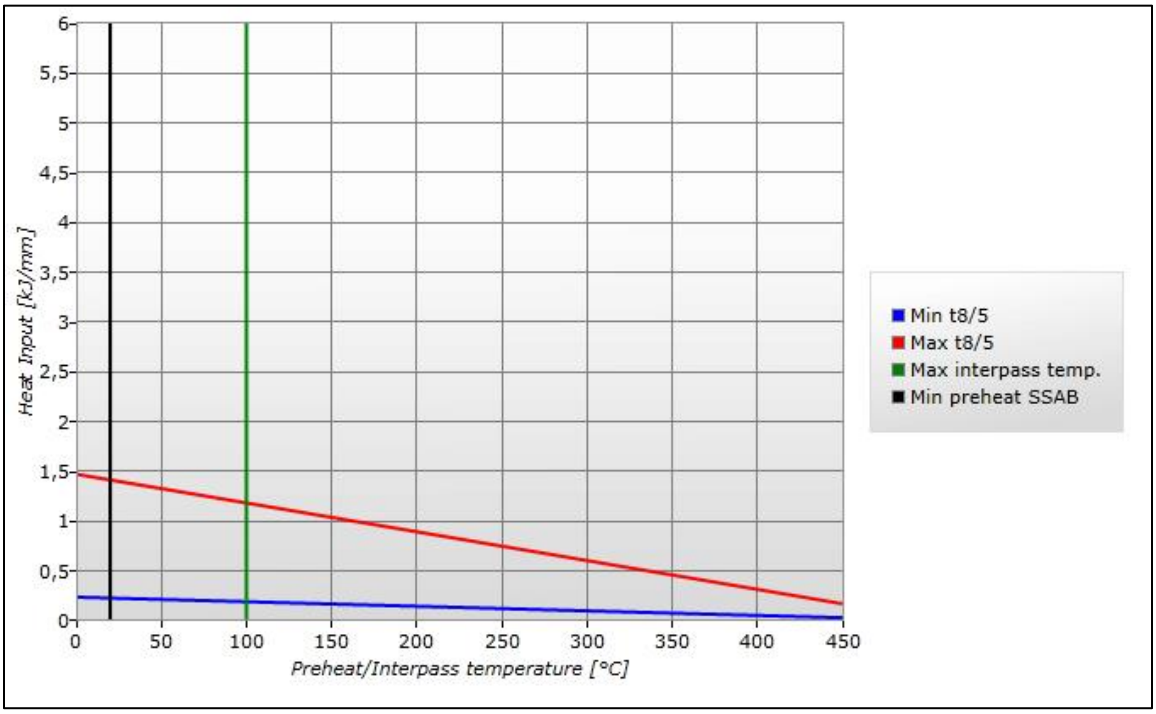


Figure 6. Heat energy window for one steel material, generated using WeldCalc 2.2

The combination of preheat and heat input should remain within the window bordered by the black, blue, green and red lines. These lines follow specific equations and can be generated using a spreadsheet program. These equations are presented below.

(4) $t_{8/5}=(4300-4{,}3T_0)\times 10^5\times\frac{Q^2}{d^2}\times\left[\left(\frac{1}{500-T_0}\right)^2-\left(\frac{1}{800-T_0}\right)^2\right]\times F_2\ (s)$, (SFS-EN 1011-2 2001, p. 79)

Based on this equation, $t_{8/5}$ is depended on preheat, heat input, material thickness and weld form. If $t_{8/5}$ is set to its minimum value, this equation determines the blue line. If $t_{8/5}$ is set to its maximum value, this equation determines the red line. The $t_{8/5}$ limits are provided by the material manufacturer. Heat input *(Q)* and preheat *(T_0)* are variables here. All other factors are constants.

The black line in figure 6 can be replaced with the following equation, which represents the risk of hydrogen cracking:

(5) $T_p = T_{pCET} + T_{pd} + T_{pHD} + T_{pQ}$ (°C), (SFS-EN 1011-2 2001, p. 65) (5)

(6) $T_{pCET} = 750 \times CET - 150$ (°C), (SFS-EN 1011-2 2001, p. 59) (6)

(7) $T_{pd} = 160 \times \tanh\left(\frac{d}{35}\right) - 110$ (°C), (SFS-EN 1011-2 2001, p. 61)

(8) $T_{pHD} = 62 \times HD^{0,35} - 100$ (°C), (SFS-EN 1011-2 2001, p. 63)

(9) $T_{pQ} = (53 \times CET - 32) \times Q - 53 \times CET + 32$ (°C), (SFS-EN 1011-2 2001, p. 63)

Based on these equations, T_p is depended on carbon equivalent, material thickness, heat input and the welding consumable used. When all these equations are combined, heat input *(Q)* and preheat (in this case T_p) are variables and all other factors are constants.

The green line illustrates the maximum preheat temperature mentioned earlier and is sometimes defined in standards or provided by the material manufacturer.

A diagram, similar to the one in figure 6, was constructed to support the case in this thesis. It is presented in figure 7, and more information about the constants and how they are used is presented in section experiments.

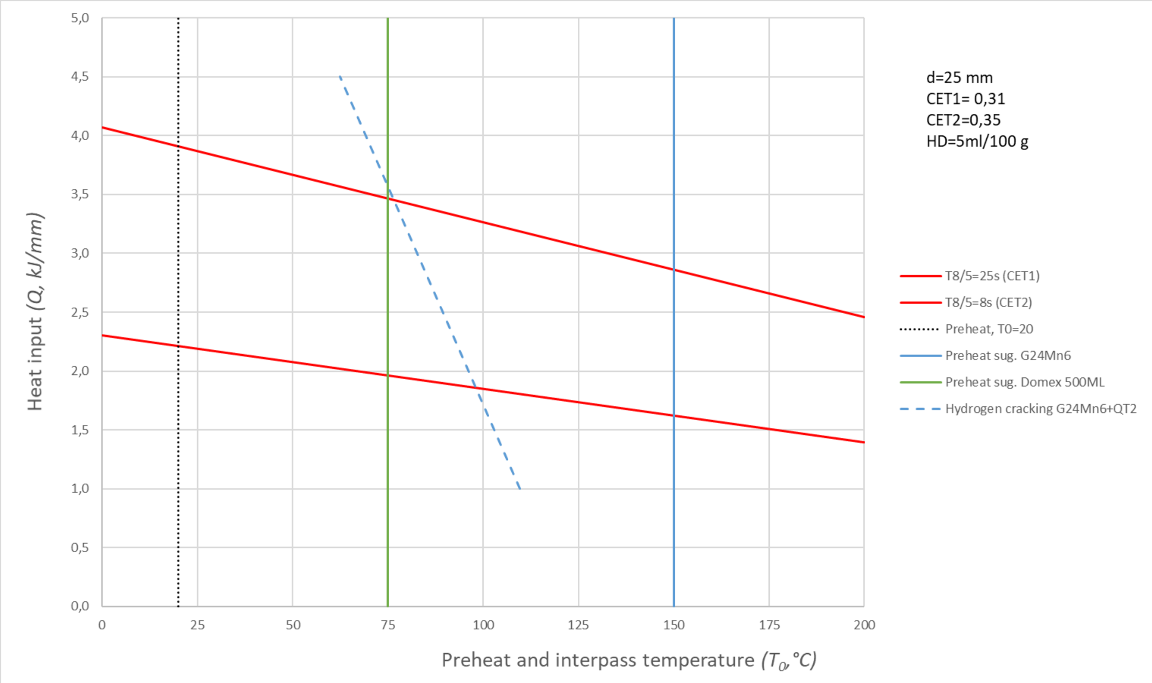


Figure 7. Heat energy window

3.2 Materials

Material selection only focuses on suitable cast steel material. Two driving definitions for material selection were set. Yield strength must be similar to used rolled steel, and weldability must be at least satisfactory. Keeping in mind that, within the welding metallurgical framework, one hypothesis is the assumption of successful welds without preheat, satisfactory in this case means this hypothesis is fulfilled.

SSAB Domex 500ML is used as a rolled steel material. Lincoln SupraMig Ultra is used as welding consumable because it is in routine use in the company and is the consumable used with SSAB Domex 500ML in the related WPS. The material properties for these are presented in appendix 2, and the next section provides a brief introduction to SSAB Domex 500ML. Further investigation related to this, consumables and shield gas are excluded.

3.2.1 Domex 500ML

Domex 500ML is thermomechanically rolled steel manufactured by SSAB. It does not have equivalence in steel material standards like SFS-EN 10025-4 "Hot rolled products of structural steels". Even so, Domex 500ML is fine-grained steel and well weldable (SSAB 2018, p. 1). Important material properties for this thesis are presented in table 1.

Table 1 Domex 500ML material properties (SSAB 2018, p. 1)

Carbon equivalent	Carbon equivalent	Yield strength	Tensile strength	Impact energy	$t_{8/5}$
CEV_{max}=0,43	CET_{max}=0,31	R_{eH}=480 Mpa	R_m=570-720 Mpa	40 J (-60 °C)	5-25 s

3.2.2 Cast steels

Cast steel is material from which steel casts are made. The composition of cast steel closely resembles that of formed steel, except for higher alloying of silicon and manganese. Manganese and silicon are used to tie free oxygen in the casting process. Cast steels can be grouped in many ways based on their properties. The most common groupings are listed below:

- Based on carbon content
- Based on alloying
- Based on phosphorus and sulphur alloying
- Based on purpose of use (Metalliteollisuuden keskusliitto 2001, p. 156–159)

Common cast steels are defined in standard SFS-EN 10293 "Steel castings for general engineering uses". The designation of cast steels follows this standard. Chemical composition and mechanical properties are specified for each designated steel cast material. The standard also includes guidance data for welding. This is the most valuable part of the standard related to this thesis. Furthermore, the standard includes numerous references to the EN 1559-1:1997 and EN 1559-2:2000 standards and is used in conjunction with them. The EN 1559-1:1997 and EN 1559-2:2000 standards serve as guides regarding the technical conditions of delivery for casts in general and for steel casts in particular. These standards do not offer much information that can be used here, except for the permissible deviations in specified cast analysis. These values are indicated in SFS EN 1559-2 and can provide explanations of the differences revealed in welding experiments (SFS-EN 10293 2005).

Preselection for cast steel material follows a suggestion by the steel cast manufacturer in accordance with the specification defined earlier. Three materials were suggested, and the final selection was made based on the lowest carbon equivalent value that presumably defines the best weldability. Preselected materials with calculated carbon equivalents are listed below in table 2. Chemical compositions appear in appendix 2.

Table 2 Cast steel carbon equivalents

Material		CEV (%)	CET (%)
G24Mn6+QT2	min	0,450	0,350
	max	0,550	0,430
G28Mn6	min	0,450	0,370
	max	0,620	0,500
G10MnMoV6-3	min	0,630	0,325
	max	0,880	0,430

Based on calculated carbon equivalents, G24Mn6+QT2 is selected to pair with Domex 500ML in this investigation. G24Mn6+QT2 and Domex 500ML fall under the same material group in technical report CEN ISO/TR 15608 "Welding. Guidelines for a metallic materials grouping system". The group for these materials is 2.2 "Thermomechanically treated fine-grain steels and cast steels with a specified minimum yield strength R_{eH} >460 N/mm^2" (CEN ISO/TR 15608 2017, p. 6). The benefit is that some limits for results in welding tests are based on the grouping in CEN ISO/TR 15608. Therefore, test result limits for both heat-affected zones (HAZs) in welding are the same. The material properties of G24Mn6+QT2 are presented in table 3.

Table 3 G24Mn6+QT2 material properties (SFS-EN 10293 2005, p. 14)

Carbon equivalent	Carbon equivalent	Yield strength	Tensile strength	Impact energy	$t_{8/5}$
CEV=0,45-0,55	CET=0,35-0,43	$R_{0,2}$=500 Mpa	R_m=650-800 Mpa	27 J (-30 °C)	?

Cooling time $t_{8/5}$ for G24Mn6+QT2 was unknown and unavailable even from the steel casting supplier. This raised a key issue in the welding research. An estimate of the $t_{8/5}$ minimum value was made based on chemical composition. The maximum value was initially set to the Domex 500ML $t_{8/5}$ maximum value of 25 s. To estimate $t_{8/5}$ cooling time, Ovako Oy offers a commercial tool called "Heat treatment guide", which calculates cooling time based on chemical composition. The minimum value for $t_{8/5}$ was set to 8 s. The diagram on which it is based appears in appendix 3.

3.3 Material testing

The purpose of material testing is to demonstrate material properties, for example, yield strength, impact toughness and hardness. Welding is a complicated manufacturing process controlled by quality standards (Kyröläinen & Kauppi 2016, p.139). Quality standards, for example, ISO 3834 series, rely on approved material tests specified in related standards. SFS EN-ISO 3834-1 specifies the criteria for quality requirements for fusion welding (SFS-EN ISO 3834-1 2006, p. 10). When a manufacturer chooses to follow comprehensive quality requirements, defined in SFS EN-ISO 3834-2, it must fulfil the requirements for welding documentation in SFS EN-ISO 3834-5 (SFS-EN ISO 3834-2 2006, p. 6). SFS-EN ISO 3834-5 points out that arc welding procedures must be qualified by several standards, for example, SFS-EN ISO 15614-1 "Specification and qualification of welding procedures for metallic materials. Welding procedure test. Part 1: Arc and gas welding of steels and arc welding of nickel and nickel alloys" (SFS EN-ISO 3834-5 2006, p. 11). Finally, the SFS-EN ISO 15614-1 standard sets out the required testing, specifies the test piece, and sets the acceptance levels and range of qualification (SFS-EN ISO 15614-1 2012, p. 8). It is notable that a separate standard, SFS-EN ISO 11970, for production welding of steel castings also exists. It is unclear whether it should be used separately or with SFS-EN ISO 15614-1. Because SFS-EN ISO 15614-1 is stricter and more precise than SFS-EN ISO 11970, SFS-EN ISO 15614-1 is followed.

Material testing for welds takes place in accordance with SFS-EN ISO 15614-1. The selected tests and related standards appear in figure 8. A brief introduction to them is provided in following sections.

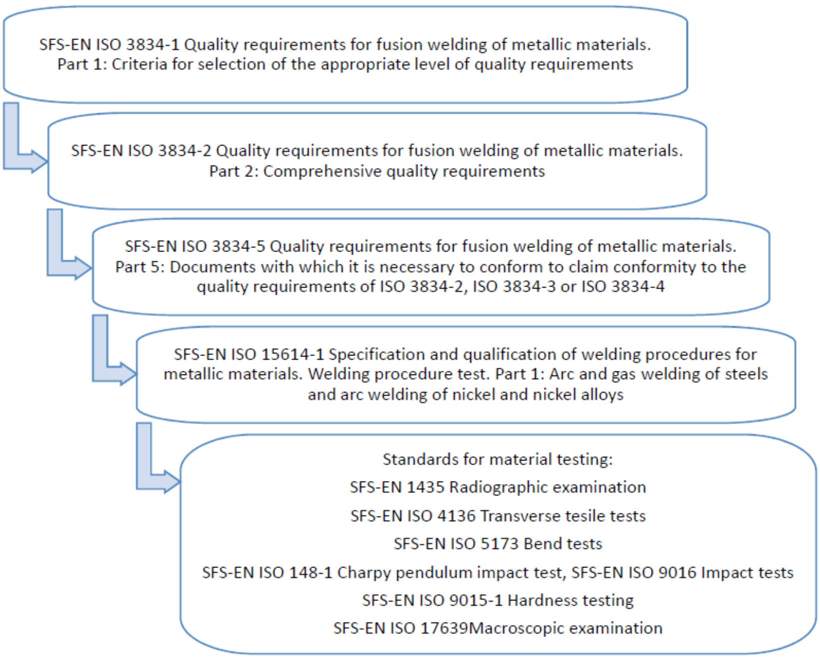
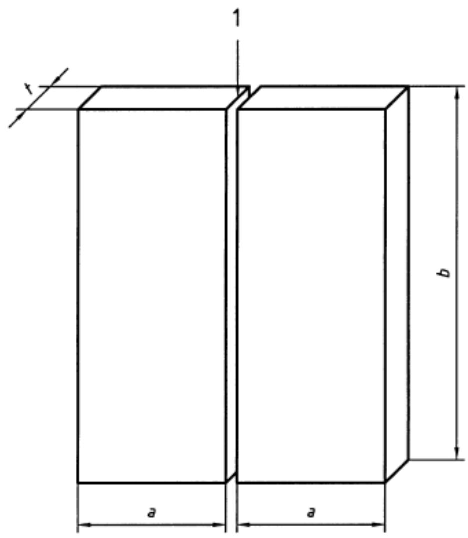


Figure 8. Hierarchy of standards

The welding test piece is designed in accordance with SFS-EN ISO 15614-1. The principal drawing is in figure 9 and detailed drawing with material information in appendix 4.



Key

1 Joint preparation and fit-up as detailed in the preliminary Welding Procedure Specification (pWPS)

a Minimum value 150 mm

b Minimum value 350 mm

t Material thickness

Figure 9. Test piece for a butt joint (SFS-EN ISO 15614-1 2012, p. 15)

3.3.1 Hardness test

Material hardness isn't actually a pure material character. Instead it is a feature that depends on multiple elements, such as impact toughness and yield strength (Kyröläinen & Kauppi 2016, p. 148). Material hardness can be measured with several standardized methods, such as the Brinell and Vickers hardness test. SFS-EN ISO 9015-1 defines the approved methods and measuring locations on welds. Theoretical measuring locations are presented in figure 10.

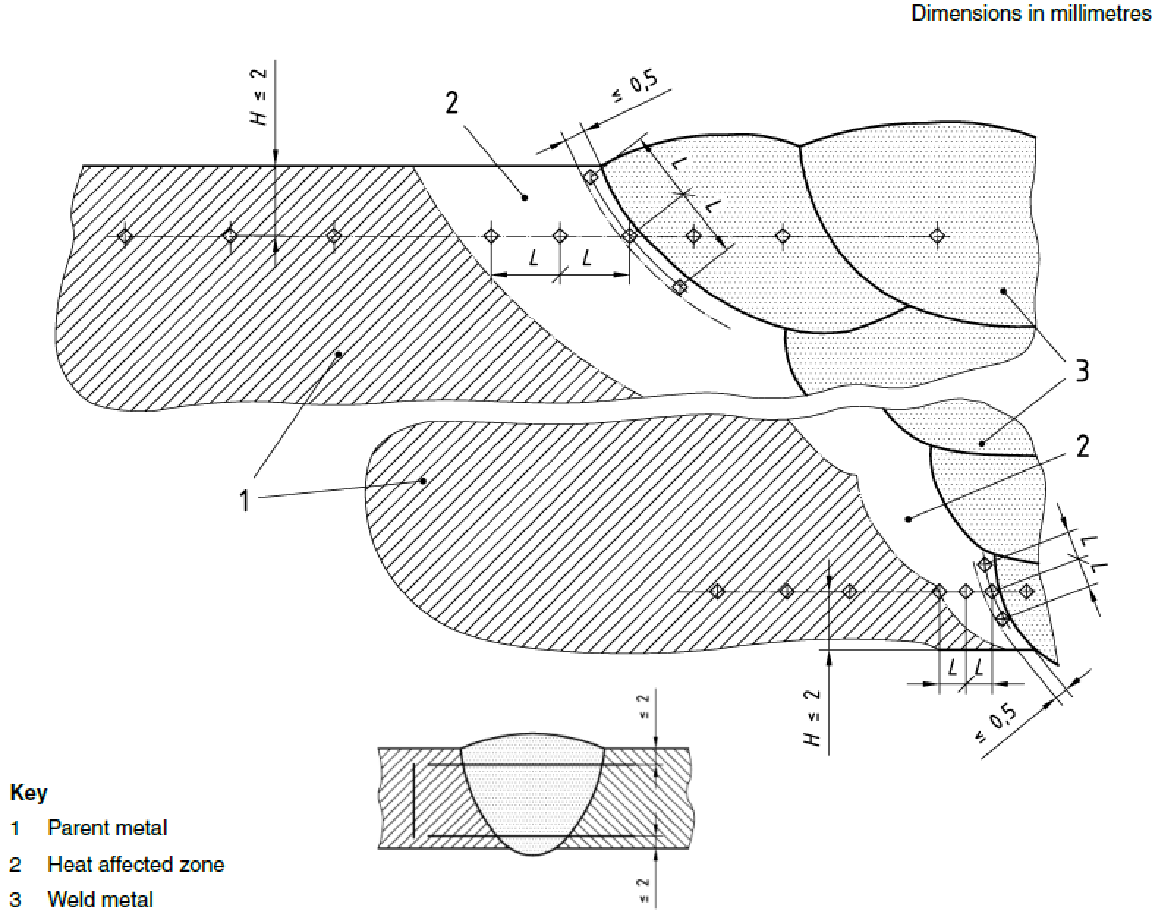


Figure 10. Hardness measurement point locations (SFS-EN ISO 9015-1 2011 p. 15 and 29)

Hardness testing in this thesis was performed using Vickers hardness HV5, which follows the standard SFS-EN ISO 6507-1 "Metallic materials – Vickers hardness test. Part1: Test method". As material thickness is greater than 5 mm, hardness measurement must be performed below the upper surface and above the lower surface. The acceptance level in the hardness test for selected materials is HV5=380 (SFS-EN ISO 15614-1 2012, p. 33) because the materials belong to group 2 in CEN ISO/TR 15608.

3.3.2 Impact test

The impact test measures the amount of energy needed to break down the test piece. The test piece can break down in three ways: ductile fracture, brittle fracture or a combination of the two. Steel material fractures are usually a combination. It can start to break down as a ductile fracture and end as a brittle fracture. The higher the impact energy is the more ductile the material is. Further, the fracture type depends on the crystalline structure, meaning that the impact test is somehow representing the crystalline structure of the material.

SFS-EN ISO 15614-1 specifies the impact test for welds to be performed in accordance with SFS-EN ISO 9016, which describes test specimen location and notch orientation for the impact test for welded butt joints (SFS-EN ISO 9016 2012, p. 9). It states that the test method used must follow SFS-EN ISO 148-1 "Metallic materials. Charpy pendulum impact test". Test specimen location and orientation used in this thesis appear in figure 11.

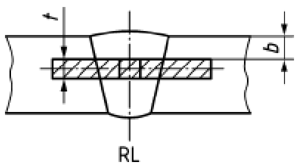
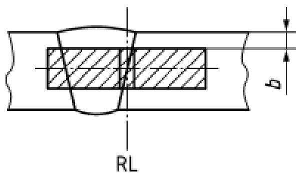
Denomination	**Centre of the weld**	**Denomination**	**Fusion/joint line**
	Representation		Representation
VWT 0/*b*		VHT 0/*b*	

Figure 11. Test specimen location and orientation in the impact test (SFS-EN ISO 9016 2012, p. 9)

The acceptance level in here is set for the impact energy stated for the material G24Mn6+QT2. It is 27 J at −30 °C.

3.3.3 Transverse tensile test

One method of determining how much material can withstand forces that cause tension on a structure is to perform a tensile test on test pieces. To determine tensile strength for a welded joint, the welding procedure specification standard requires a transverse tensile test in accordance with SFS-EN ISO 4136.

The SFS-EN ISO 4136 standard specifies the dimensions of the test piece and the test procedure. The standard specifies the test procedure for metallic materials of all forms. Here, the object of interest is a rod with a rectangular cross-section. The test specimen dimensions follow SFS-EN ISO 4136. General dimensioning is represented in figure 12 (SFS-EN ISO 4136 2012, p. 9).

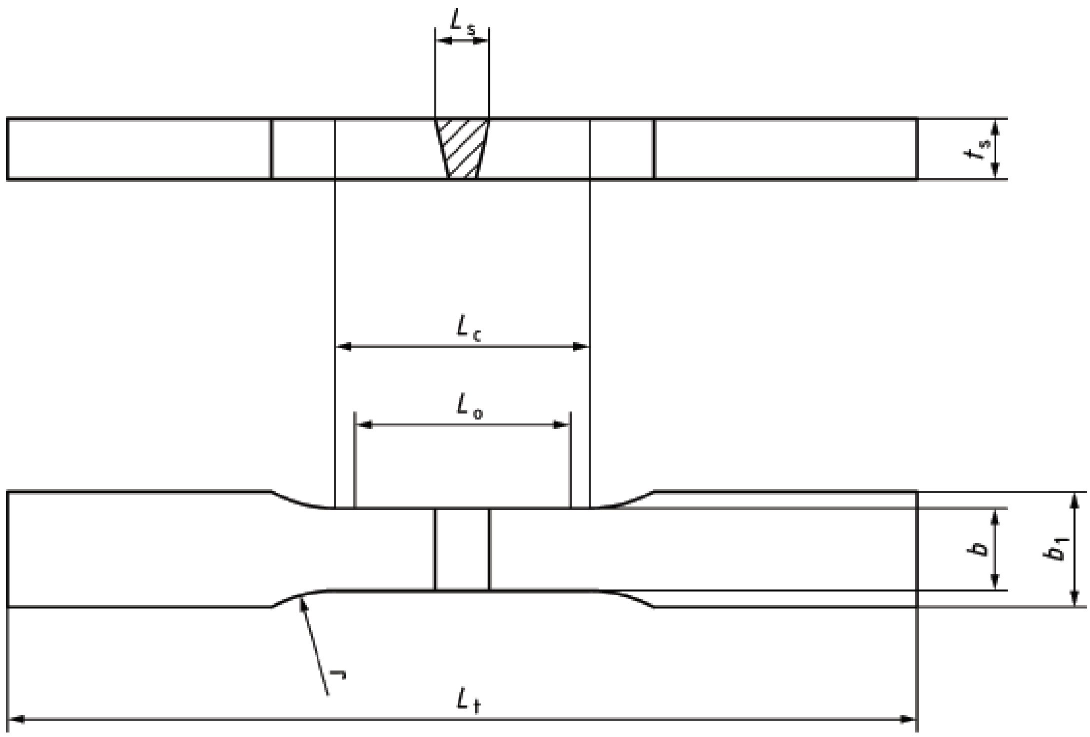


Figure 12. Test specimen dimensions (SFS-EN ISO 4136 2012. p. 15)

The tensile test procedure is performed in accordance with the ISO 6892-1 standard. After a rupture of the specimen, the fracture location is noted and reported in the test report. The fracture surface is also examined, and the existence of welding imperfections is reported. Test reports are presented in appendix 9 (SFS-EN ISO 4136 2012, p. 19).

Here, the acceptance level is 570 MPa. It is based on the tensile strength of the base material, which in this case is SSAB Domex 500ML as it has lower tensile strength than G24Mn6+QT2.

3.3.4 Bend test

In a structure exposed to fatigue stresses, one of the most important material properties is ductility. In addition to the impact test, material ductility can be examined using the material bend test. Bend tests executed for welds also reveal welding imperfections. To fulfil the requirements in the welding procedure specification standard, a bend test in accordance with the SFS-EN ISO 5173+A1 standard is required.

SFS-EN ISO 5173+A1 specifies the dimensions of the test piece and the test procedure. The standard specifies the test procedure for metallic materials of all forms. Here, the object of interest is the transverse side bend test for a butt weld. The dimensions of test specimen are in accordance with the standard and represented in figure 13 (SFS-EN ISO 5173+A1 2011, p. 9).

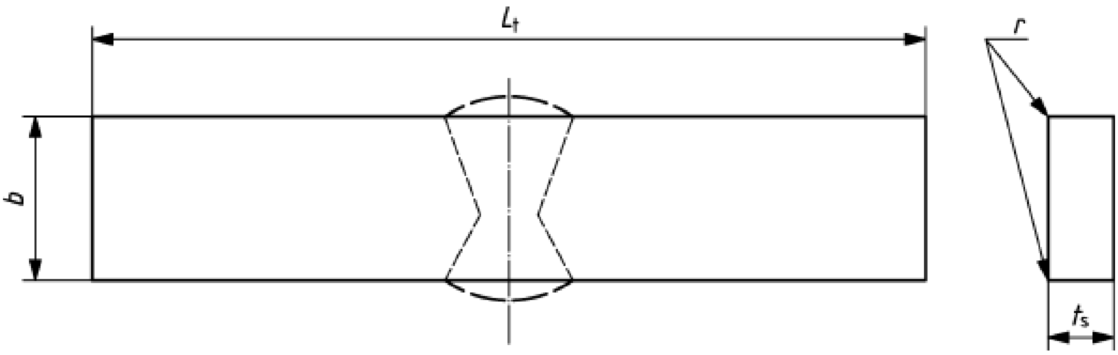
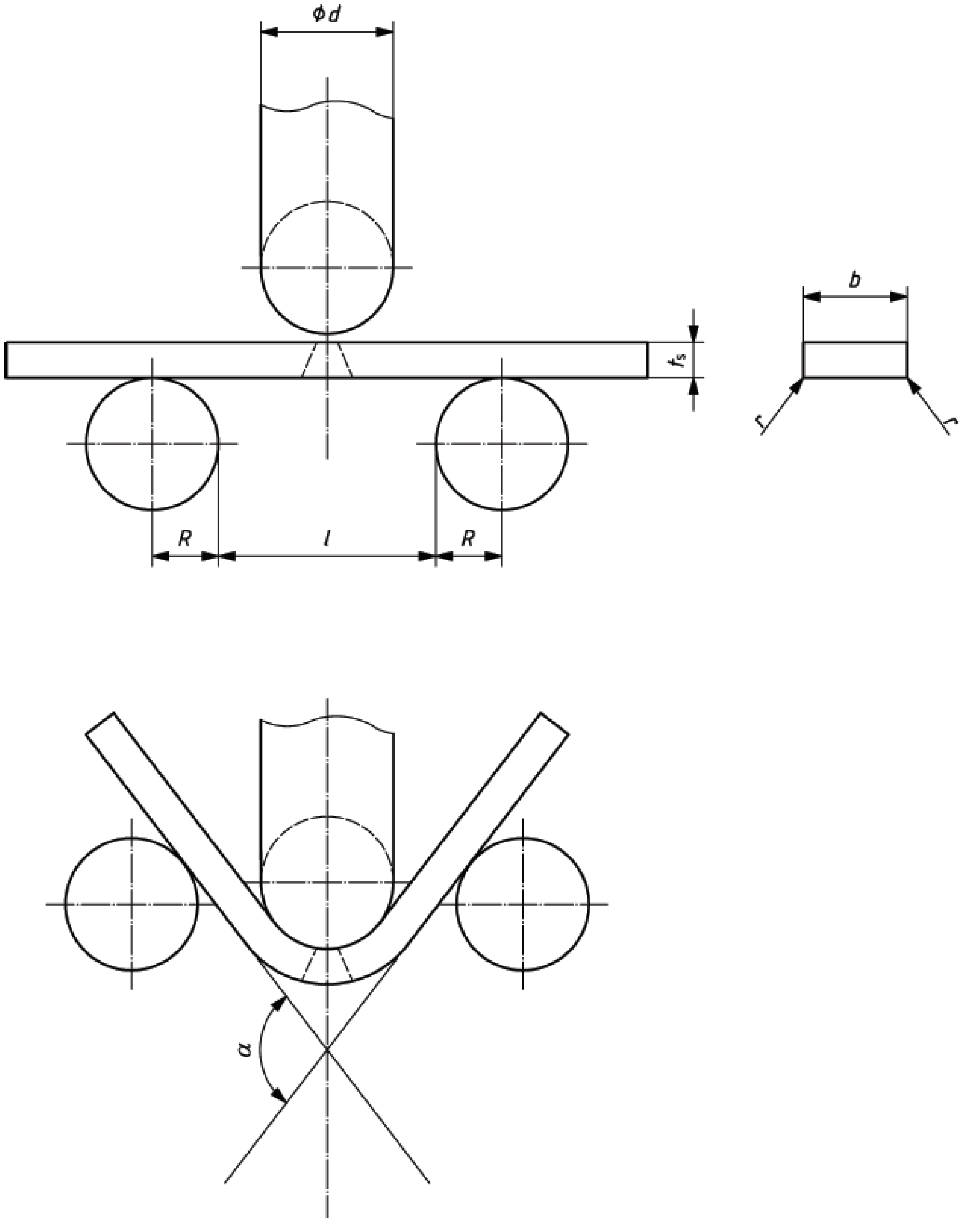


Figure 13. Transverse side bend test specimen (SFS-EN ISO 5173+A1 2011, p.13)

The standard defines the methods of performing the bend. One method is to use a former and the other is to use a roller. For steel materials, as the case is here, testing is done using a former. The transverse bend test is executed at a position where the centreline of the weld is underneath the middle former parallel to the former centreline. The test configuration is represented in figure 14.



$d + 2t_s + 3 \leq l \leq d + 3t_s$

Figure 14. Transverse bend test configuration (SFS-EN ISO 5173+A1 2011, p. 27)

The test is completed when the former is detached from the test specimen. After the test is executed, the test specimen sides and external surface are examined. Also, the elongation of the test specimen is cleared out and test results are reported. The test report is presented in appendix 7 (SFS-EN ISO 5173+A1 2011, p. 37).

The acceptance level is presented in the SFS-EN ISO 15614-1 standard. The test is accepted if the test specimen does not reveal any flaws larger than 3 mm in any direction (SFS-EN ISO 15614-1 2012, p. 31).

3.3.5 Macroscopic and microscopic examination of welds

The purpose of macroscopic and microscopic examination is to estimate the structure of the weld, including its granular structure, welding imperfections and bead structure. Microscopic examination also reveals phase structure, texture and granular sizes (Kyröläinen & Kauppi 2016, p. 15 and 161).

Macroscopic examination is performed in accordance with SFS-EN ISO 17639 "Macroscopic and microscopic examination of welds". SFS-EN ISO 15614-1 does not require microscopic examination, but it might be essential for test result analysis.

The test specimen is oriented in transverse direction of the welding test piece, meaning perpendicular to the welding direction. The test piece must include a complete cut of the weld, HAZ and base material. An example of a macroscopic and microscopic image is shown in figure 15.

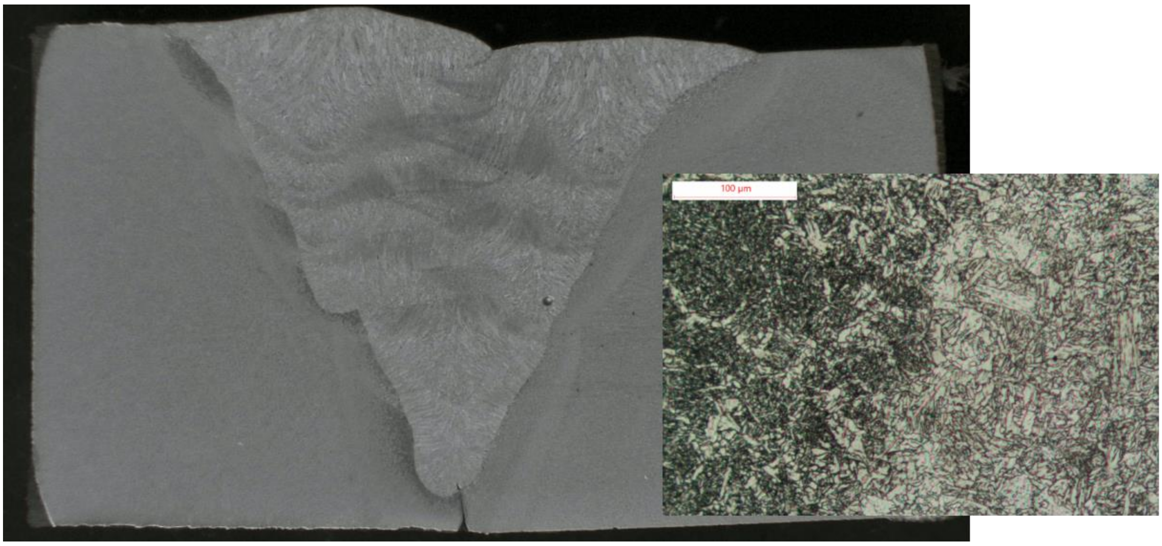


Figure 15. Macroscopic and microscopic images

Examination is accepted if welding imperfections are within limits of quality level B in SFS-EN ISO 5817 "Welding. Fusion-welded joints in steel, nickel, titanium and their alloys (beam welding excluded). Quality levels for imperfections", except imperfections specified in SFS-EN ISO 15614-1.

3.3.6 Radiographic examination

Radiographic examination provides information about welding imperfections along the entire weld, not only for one random weld cross-section. According to SFS-EN ISO 15614-1, non-destructive testing like radiographic examination is performed for the entire weld before cutting the test specimen (SFS-EN ISO 15614-1 2012, p. 29). Radiographic examination is performed in accordance with the SFS-EN 1435 "Non-destructive examination of welds. Radiographic examination of welded joints" standard. The principle for arranging the radiographic test for butt welds is presented in figure 16. The acceptance level for radiographic examination is the same as for macroscopic examination.

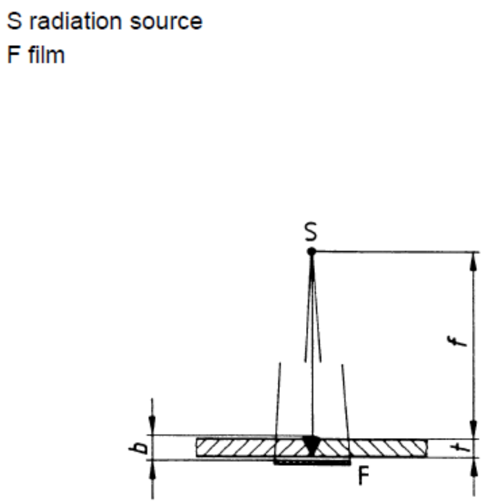


Figure 16. Radiographic examination

4 EXPERIMENTS

To find answers to the research questions, experiments were conducted. Because the subject of the questions in two frameworks differ, two kinds of experiments were conducted. Welding experiments addresses questions concerning the welding metallurgical framework and are presented in this section. The other is cost analysis addressing questions regarding welding and the material cost framework. It is presented under "Cost analysis".

To cover the entire field of study in the framework, six welding test pieces were welded. Four welded laboratory conditions and two in workshop conditions. Laboratory welds were performed in the welding laboratory at Lappeenranta University of Technology, and workshop welds were performed in the workshop at the Sandvik Mining and Construction Oy Turku site.

4.1 Predefinition of variables and constants

Before conducting welding tests, the process was predefined using the heat energy window presented earlier. To support this case, a specific heat energy window was constructed with following constants:

- $t_{8/5min}=8\ s$, value estimated from the figure in appendix 3.
- $t_{8/5max}=25\ s$, maximum for SSAB Domex 500ML (SSAB 2018, p. 1).
- $d=25\ mm$, predetermined material thickness of test pieces.
- $F_2=0,9$, shape factor for butt welds (SFS-EN1011-2 2001, p. 81).
- $CET=0,35$, calculated for G24Mn6 from equation 2
- $HD= 5\ ml/100g$, diffusible hydrogen content for solid wires (SFS-EN1011-2 2001, p. 29).

After setting these, only preheat and heat input remain as variables. The heat energy window constructed in appendix 5, includes target values for test pieces. The target values are predefined by the examiner before and during the tests. The purposes of the targets are described in next section.

4.2 Welding of test pieces in the laboratory environment

Welding tests started with laboratory welding at Lappeenranta. Robot welding was used. The test setup appears in figure 17.

Equipment:

- Kemppi A7, MAG welding inverter
- Micro-Epsilon Thermometer 2MH-CF4 pyrometer
- Mastercool 52224 thermometer

Variables:

- Welding current (welding parameter)
- Arc voltage (welding parameter)
- Preheat temperature
- Interpass temperature
- $t_{8/5}$ cooling time

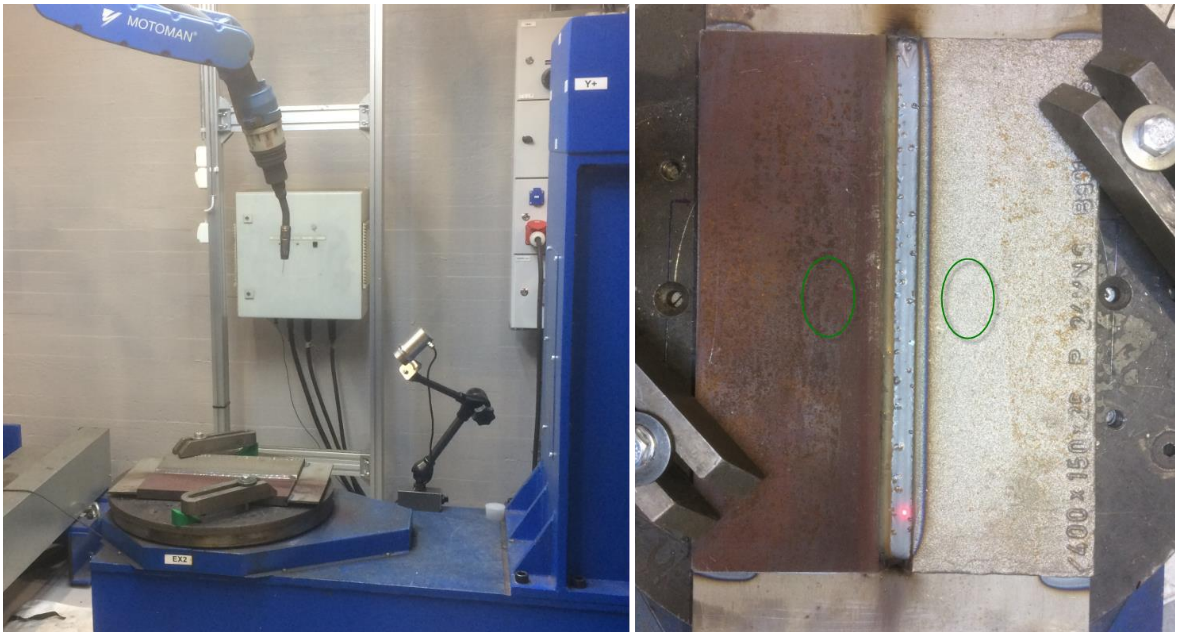


Figure 17. Welding setup and welded test piece

Welding parameters were read from the inverter display. They fluctuated significantly at the beginning and end of welding, so the parameters were recorded halfway through the process. Preheat and interpass temperatures were measured with a surface thermometer at the areas shown with green ellipses in figure 17. Cooling time was calculated from temperatures measured with the pyrometer. Pyrometer-measured temperatures were recorded during entire process. The measurement point was adjusted before every run to point to the upcoming run. An example of a measurement point appears in figure 17 as a red dot. Although welding velocity is needed to calculate heat input, it was not measured separately because it was set as a constant parameter for the welding robot.

The target preheat and heat input for the four welds were set up by the examiner. The welding parameters were set up by the welder to match the target heat input. The targets, test piece numbering and naming are presented in table 4. The heat energy window appears in appendix 5.

Table 4 Laboratory welding test pieces

Test piece number	Test piece name	Heat input, Q (kJ/mm)	Heat input on first bead, Q (kJ/mm)	Preheat, T_0 (°C)
1.	S20020	2	2	20
2.	S15020	1,5	1,5	20
3.	S15075	1,5	1,5	75
4.	S20075	2	1,5	75

Welding piece 1:
The purpose was to discover whether an acceptable weld could be achieved when preheat is 20 °C and heat input is 2 kJ/mm. During the welding process, it was noticed that waiting for the test piece temperature to drop to 20 °C before starting the next run takes excessive time. Thus, the interpass temperature was raised to 50 °C.
Limiting factor examined: Excessive hardness because of excessively short $t_{8/5}$ cooling time.

Welding piece 2:

The purpose was to discover whether the acceptance level for hardness could be reached when the preheat temperature is 20 °C, heat input is 1,5 kJ/mm and interpass temperature is allowed to increase as much as possible during the process. Welding the next run was started right after the previous run.

Limiting factor examined: Excessive hardness because of excessively short $t_{8/5}$ cooling time.

Welding piece 3:

The purpose was to discover whether an acceptable weld could be achieved when the preheat temperature is 75 °C and heat input is 1,5 kJ/mm. The interpass temperature was set to the same value as the preheat temperature.

Limiting factor examined: Excessive hardness because of excessively short $t_{8/5}$ cooling time.

Welding piece 4:

The purpose was to discover whether the failure level could be reached when the preheat temperature is 75 °C, heat input is 2,0 kJ/mm and interpass temperature is allowed to increase as much as possible during the process. Welding the next run was started right after the previous run. Differing from welding piece 1, the first run was welded with 1, 5 kJ/mm heat input because the first run in piece 1 burned through.

Limiting factor examined: Excessively low impact energy because of excessively long $t_{8/5}$ cooling time.

4.3 Welding of the test pieces in workshop environment

After the laboratory welds were executed, tested and pre-analysed, a similar test in the workshop in Turku was conducted. Hand welding was performed with a setup similar to that in the laboratory. A welded test piece is shown in figure 18.

Figure 18. Welded test piece

Equipment:

- Kemppi A7 MAG welding inverter
- Mastercool 52224 thermometer
- Apple iPhone 5s stopwatch

Variables:

- Welding current (welding parameter)
- Arc voltage (welding parameter)
- Welding time
- Waiting time between runs
- Preheat temperature
- Interpass temperature

The welding parameters were measured in the same way as for laboratory tests. This time, the welding time had to be measured to be able to calculate the welding velocity. Time measurements were taken with a stopwatch. The waiting time between runs was measured similarly. Preheat and interpass temperatures were measured in the same way as for laboratory tests. In contrast with the laboratory welds, the measurement points were painted black, which can be seen in figure 18. The reason for this is that it was believed that the preheat and interpass measurements during laboratory welds were incorrect. More about this is presented in the analysis.

The target preheat and heat input for the two welds were set up by the examiner. The welding parameters were set up by the welder to match the target heat input. The targets, test piece numbering and naming are presented in table 5. The heat energy window is shown in appendix 5.

Table 5 Workshop welding test pieces

Test piece number	Test piece name	Heat input, Q (kJ/mm)	Heat input on first bead, Q (kJ/mm)	Preheat, T_0 (°C)	Interpass temperature, T_0 (°C)
5.	TKU1	2	1,5	20	variable
6.	TKU2	max	1,5	20	limited to 200 °C

Welding piece 5:

The purpose was to discover whether an acceptable weld could be achieved when the preheat temperature is 20 °C, heat input is 2,0 kJ/mm and time between the runs was set to 180 s. This creates a situation in which bead length would measure about 800 mm and beads are welded back to back. The interpass temperature is allowed to increase as much as possible.
Limiting factor: Either excessive hardness because of excessively short $t_{8/5}$ cooling time or low impact energy because of excessively long $t_{8/5}$ cooling time.

Welding piece 6:

The purpose was to discover whether an acceptable weld could be achieved when preheat temperature is 20 °C, heat input is set to its maximum value, welding still feels comfortable and it is believed that the weld remains successful based on experience. The maximum heat input was determined by the welder. The maximum interpass temperature was limited to 200°C.
Limiting factor: Either excessive hardness because of excessively short $t_{8/5}$ cooling time or excessively low impact energy because of excessively long $t_{8/5}$ cooling time.

The welding test record for all six test welds appear in appendix 6.

4.4 Material testing of weld test pieces

Before material testing began, the phenomenon of hydrogen cracking had to be assessed. Waiting time greater than 24 hours would reveal the appearance or absence of the phenomenon. With test pieces 1 and 3, cooling time was about 24 hours. With other test pieces, it was counted in days or weeks. Not all tests were performed for all test pieces. The tests executed are listed in table 6.

Table 6 Tests executed

Test piece number	Test piece name	Radiographic examination	Macroscopic examination	Microscopic examination	Hardness test	Bend test	Impact test	Transverse tensile strength test
1.	S20020	x	x	x	x			
2.	S15020	x	x	x	x	x	x	x
3.	S15075	x	x	x	x			
4.	S20075	x	x		x	x	x	x
5.	TKU1		x		x		x	x
6.	TKU2		x		x		x	x

Radiographic examination was performed first, as it must be performed for entire test welds. Radiographic examination in accordance with SFS-EN 1435 was performed for test pieces 1 to 4 at LUT University with the Andrex CMA20 X-ray machine. Radiographic film was developed using the Structurix NDT M film processor.

After radiographic examination, test specimens for destructive material testing were cut from the test pieces. Test specimen locations in the test pieces are defined in the standard (SFS-EN ISO 15614-1 2012, p. 29) and are presented in figure 19.

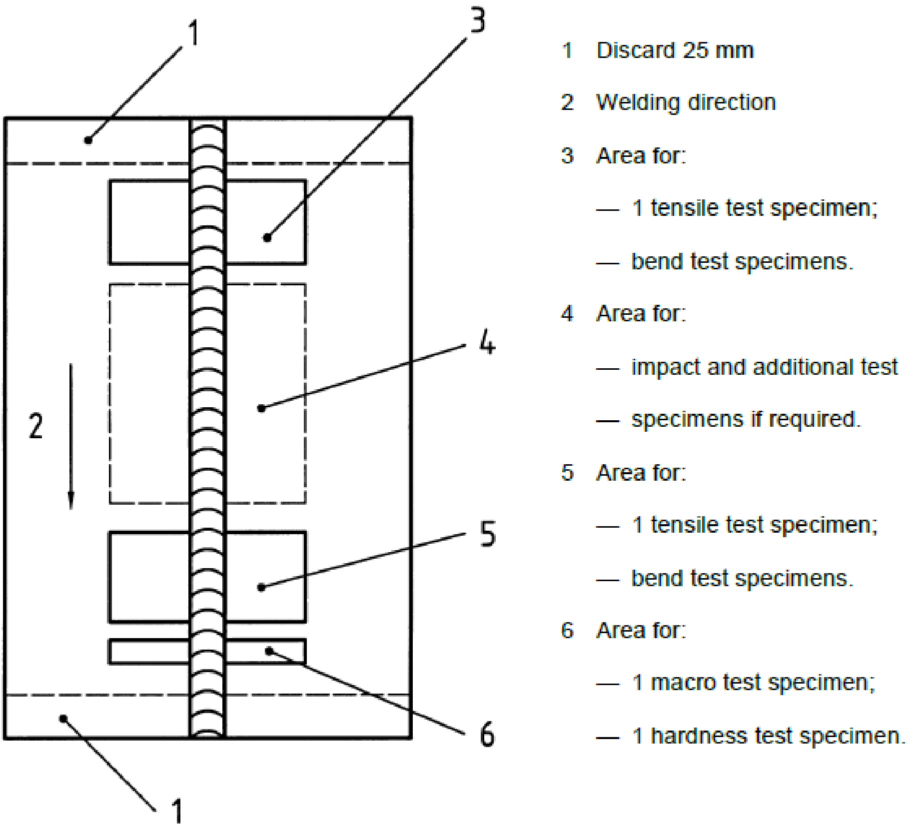


Figure 19. Test specimen locations (SFS-EN ISO 15614-1 2012, p. 23)

Macroscopic and hardness examinations were performed for all six test pieces. One specimen per test piece was manufactured, and both tests were performed for all specimens. Also, images from the microscopic examination were taken from test pieces 1-3. Specimens were made in accordance with the EN 1321 standard at LUT University. Macroscopic examinations were performed in accordance with the SFS-EN ISO 17639 standard using the Meiji Techno IM7000 microscope. Hardness examinations were performed in accordance with the SFS-EN ISO 6507-1 standard as HV5 measurements. Measurements were taken near the upper and lower surfaces. Examination rows covered both base materials, HAZs and weld. The distance between measurement points in the base materials and weld was 1 mm and on HAZs 0,5 mm. Example in figure 20. Hardness measurements were performed using the Struers DuraScan-70 hardness tester.

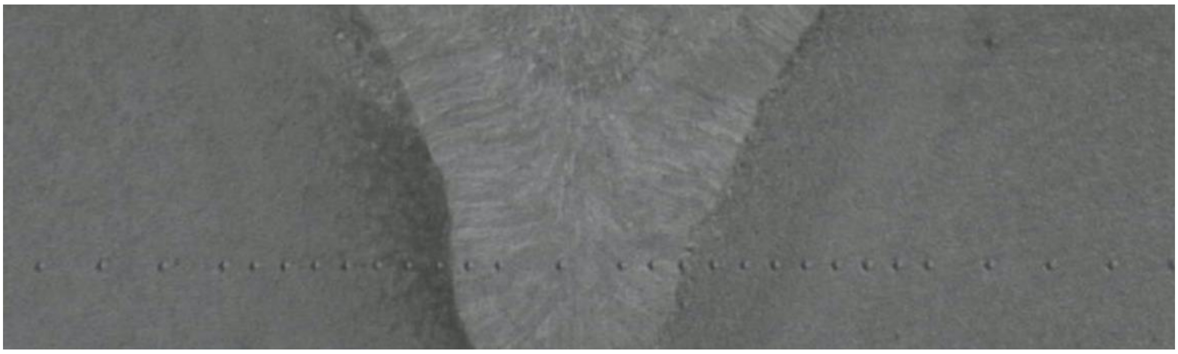


Figure 20. Hardness measurement row in test specimen of piece S15020

Bend tests were performed in accordance with the SFS-EN ISO 5173 standard as a transverse side bend test (SBB). Tests were performed for test pieces 2 and 4. The required four specimens for both test pieces were tested. The distance between bend rollers and roller diameters, as well as other test specifications, can be found in the bend test report in appendix 7. Tests were performed with the bend test machine VEB WPM20 at LUT University.

Figure 21. VEB WMP20 bend test machine

Impact tests were performed in accordance with the SFS-EN ISO 9016 and SFS-EN ISO 148-1 standards at −30 °C as Charpy-V tests. Tests were performed for test pieces 2 and 4 to 6. Three test specimens from welds and both HAZs were made and tested (VWT and VHT). All related specifications and results appear in the impact test reports in appendix 8. Tests were performed using the impact test machine VEB WPM at LUT University.

Figure 22. VEB WPM impact test machine

Transverse tensile strength tests were performed in accordance with the SFS-EN ISO 4136 standard, except for the test specimen dimensions. The test machine was not sized for test pieces as thick as those used in the welding experiments and could not produce enough force to break the test specimens required. Instead of making test specimens covering the entire material thickness, two test specimens for each test pieces were made, one from the upper part of the test piece and another from the lower part of the test piece. The principle is shown in figure 23. Tests were performed for test pieces 2 and 4 to 6 at LUT University with the same VEB WPM20 machine used for the bend test but with different tooling. All related specifications and results appear in the transverse tensile strength test reports in appendix 9.

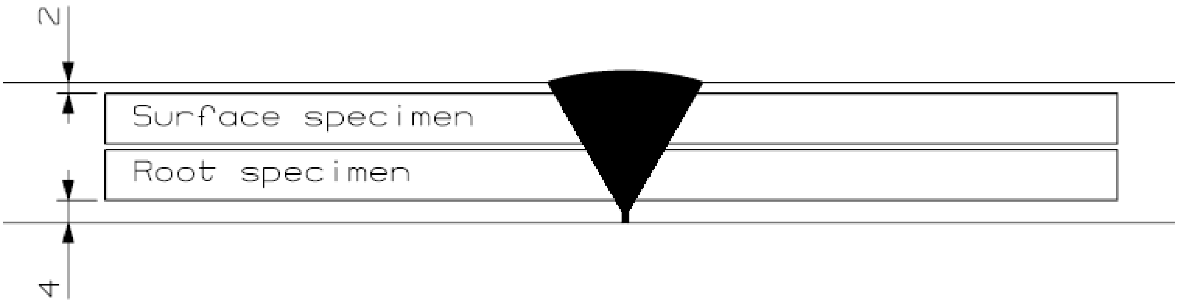


Figure 23. Transverse tensile strength test specimen locations

5 RESULTS

Results from the experimental part are presented here. Some of the welding test results were remarkably similar to each other and are therefore not presented. In those cases, only an example is presented with a comment indicated whether the test was passed or failed.

Radiographic examination was performed for test pieces 1 to4. Test piece 4 failed the test but others passed. Pass and fail radiographic images are presented in figure 24.

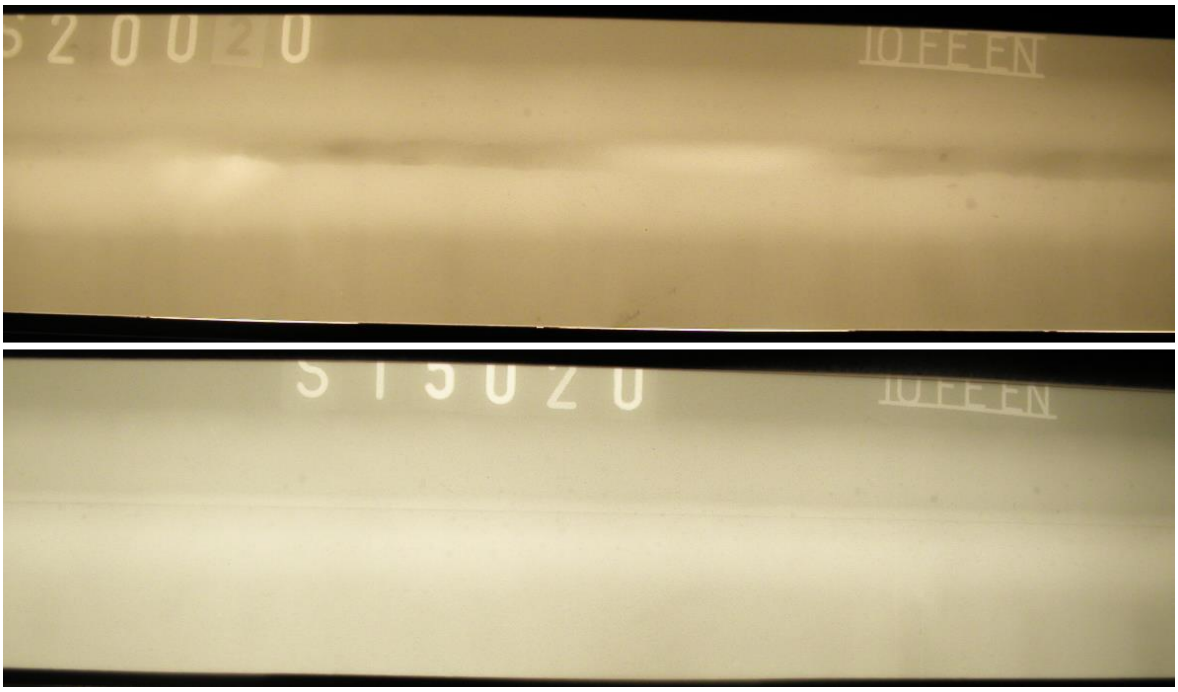


Figure 24. Fail (S20020) and pass (S15020) radiographic test

Macroscopic examination was passed for all test pieces. Pieces 1and 3 failed the hardness test because of excessive hardness. Figure 25 shows a microscopic image of a hardened area in test piece 2. More hardened area and microscopic samples throughout the cross-section of test piece 3 is presented in appendix 10.

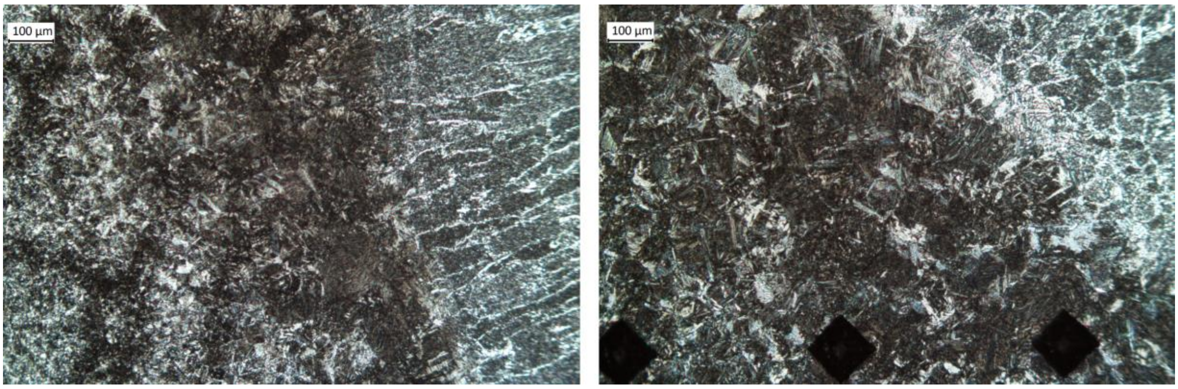


Figure 25. Microscopic examination: S15020 fusion line, near root and top

Macroscopic and hardness test specimens are presented in figure 26. Common to all is the dark area near the fusion line. For 1 to5, this can be seen on the left side of the weld and for 6 on right side of the weld.

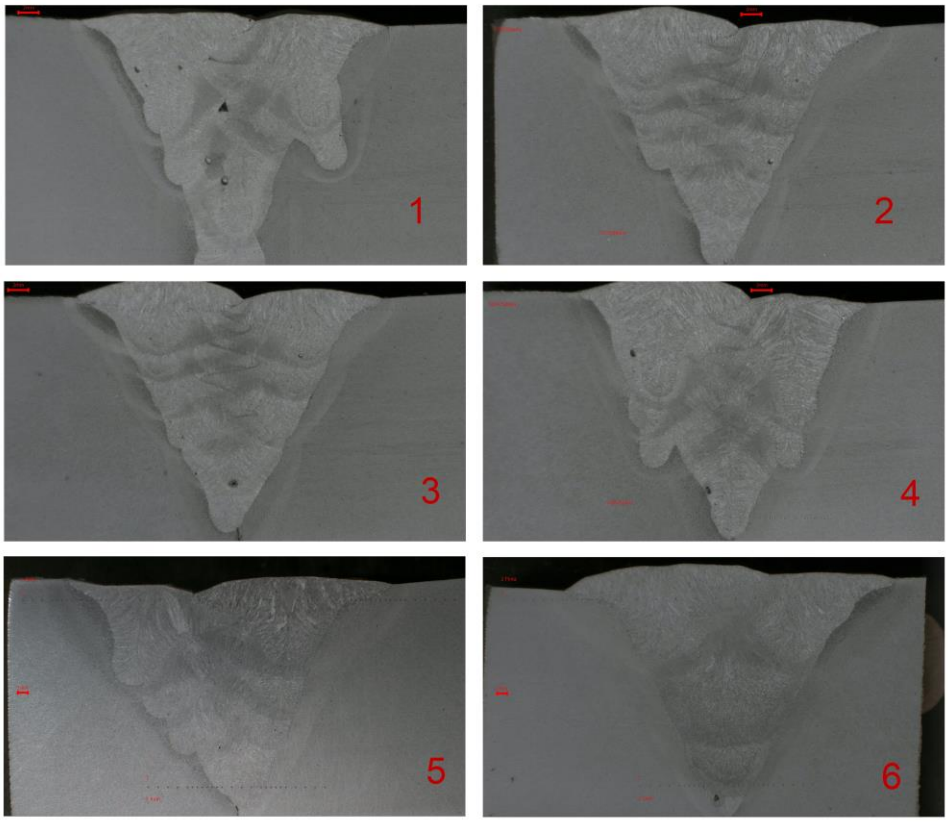


Figure 26. Macroscopic and hardness test specimens

Hardness test results are presented in table 7. In the table, red stands for "fail" and green for "pass".

Table 7 Hardness test results

Test piece number	Test piece name	Test location	Maximum hardness, HV5	Acceptance level, HV5	Hardness test result	Hardness test overall result
1.	S20020	Root	295	380	Pass	Fail
1.	S20020	Top	439	380	Fail	Fail
2.	S15020	Root	342	380	Pass	Pass
2.	S15020	Top	380	380	Pass	Pass
3.	S15075	Root	314	380	Pass	Fail
3.	S15075	Top	404	380	Fail	Fail
4.	S20075	Root	279	380	Pass	Pass
4.	S20075	Top	338	380	Pass	Pass
5.	TKU1	Root	277	380	Pass	Pass
5.	TKU1	Top	319	380	Pass	Pass
6.	TKU2	Root	221	380	Pass	Pass
6.	TKU2	Top	353	380	Pass	Pass

Figure 27 presents the complete hardness test results for test piece 2. The highest value (HV5=380) is found near the cast steel fusion line on upper hardness row in the dark area. The highest value in lower row is HV5=342 and is also located in the dark area. Variation of hardness values through cross-section was similar for all test pieces.

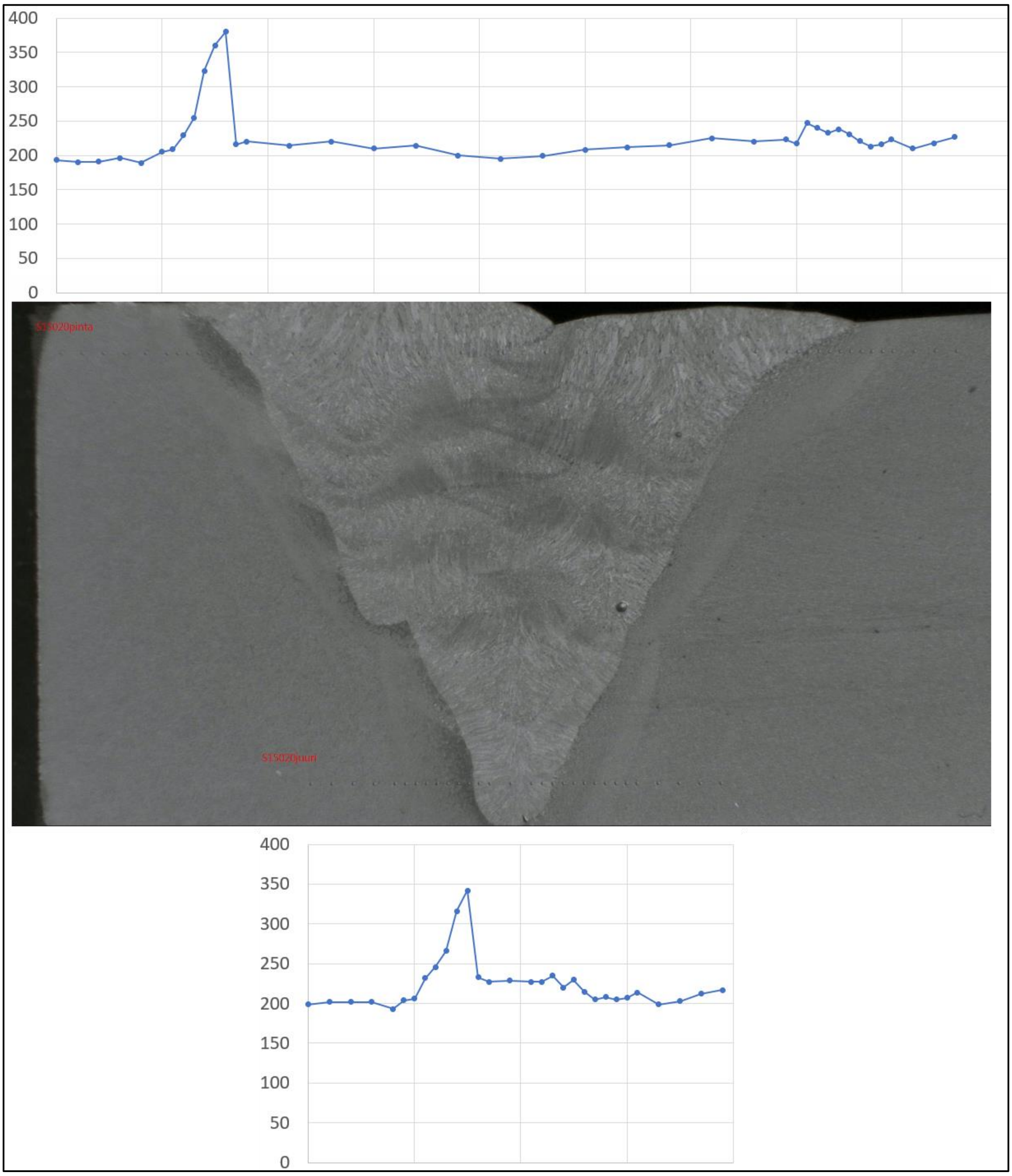


Figure 27. Hardness throughout complete weld cross-section in S15020

Figure28 presents two impact test specimens from test piece 2. On the left is specimen 75.6 from the SSAB Domex 500ML fusion line, and on the right is specimen 75.9 from the G24Mn6 fusion line.

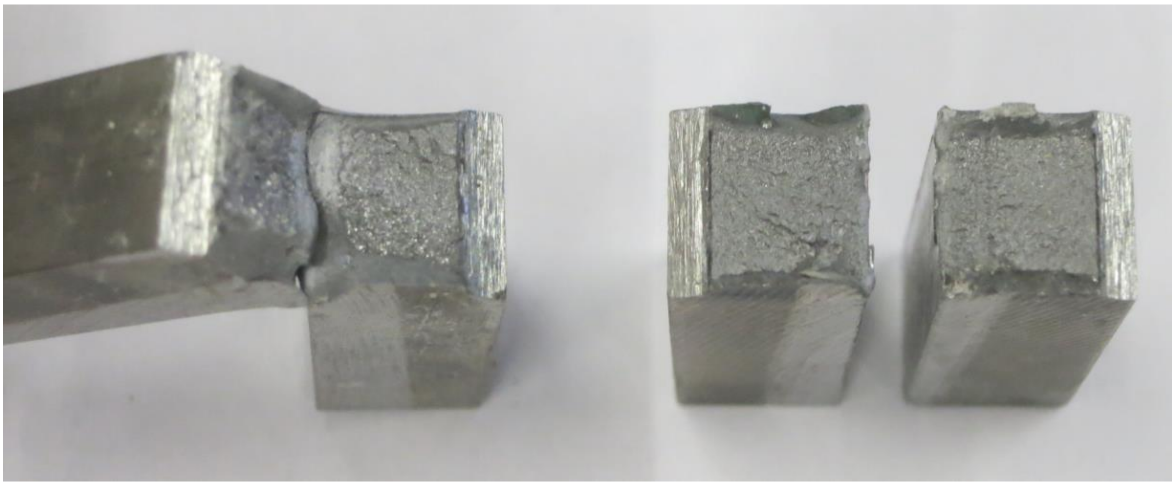


Figure 28. Test piece 2 S15020: impact test specimens 75.6 and 75.9

All the impact test results are presented in table 8. In the table, red stands for "fail" and green for "pass".

Table 8 Impact tests results

Test piece number	Test piece name	Test location	Value 1, J	Value 2, J	Value 3, J	Average, J	Acceptance level, J	Impact test result	Impact test overall result	Range of variation, R	Mean deviation, s
2.	S15020	Weld	45	45	30	40	27 J (-30 °C)	Pass	Pass	15	7,1
2.	S15020	HAZ domex 500ML	140	125	175	147		Pass		50	21,0
2.	S15020	HAZ G24Mn6+QT2	30	38	27	32		Pass		8	4,7
4.	S20075	Weld	33	31	30	31		Pass	Fail	3	1,3
4.	S20075	HAZ domex 500ML	52	45	58	52		Pass		13	5,3
4.	S20075	HAZ G24Mn6+QT2	25	26	24	25		Fail		2	0,8
5.	TKU1	Weld	120	117	112	116		Pass	Pass	8	3,3
5.	TKU1	HAZ domex 500ML	198	206	217	207		Pass		19	7,8
5.	TKU1	HAZ G24Mn6+QT2	32	66	50	49		Pass		34	13,9
6.	TKU2	Weld	82	57	74	71		Pass	Pass	25	10,4
6.	TKU2	HAZ domex 500ML	215	235	223	224		Pass		20	8,2
6.	TKU2	HAZ G24Mn6+QT2	50	57	43	50		Pass		14	5,7

Table 9 presents preheat, heat input and $t_{8/5}$ cooling time. Heat input is calculated from the measured welding parameters. $t_{8/5}$ is calculated from the temperature measurements, measured with the pyrometer.

Table 9 *$t_{8/5}$ cooling times of test pieces 1 to 4.*

1. S20020

run	Q (kJ/mm)	T_0 (°C)	$t_{8/5m}$(s)
1	2,33	20	15,7
2	2,15	50	12,7
3	2,19	50	14,2
4	2,22	50	11,2
5	2,16	50	
6	2,19	50	10,8

2. S15020

run	Q (kJ/mm)	T_0 (°C)	$t_{8/5m}$(s)
1	1,57	20	9,4
2	1,49	65	9,0
3	1,51	75	9,7
4	1,54	110	10,3
5	1,48	120	10,6
6	1,51	135	12,0
7	1,49	135	11,8
8	1,52	160	13,4
9	1,50	160	13,3

3. S15075

run	Q (kJ/mm)	T_0 (°C)	$t_{8/5m}$(s)
1	1,54	20	12,9
2	1,50	75	11,2
3	1,51	75	10,3
4	1,52	75	9,5
5	1,48	75	9,2
6	1,49	75	8,7
7	1,50	75	
8	1,50	75	8,4
9	1,50	75	9,3

4. S20075

run	Q (kJ/mm)	T_0 (°C)	$t_{8/5m}$(s)
1	1,55	60	12,2
2	2,00	75	16,9
3	1,97	120	16,4
4	2,03	160	20,6
5	1,95	165	22,6
6	1,99	200	25,4
7	1,96	183	27,2

Figures 29-32 shows a broken transverse tensile test specimen. On every image, the specimen on top is the upper surface specimen and the specimen at the bottom is the lower surface specimen. Red lines show the locations of the welds.

Figure 29. Test piece 2 S15020: transverse tensile test specimens

Figure 30. Test piece 4 S20075: transverse tensile test specimens

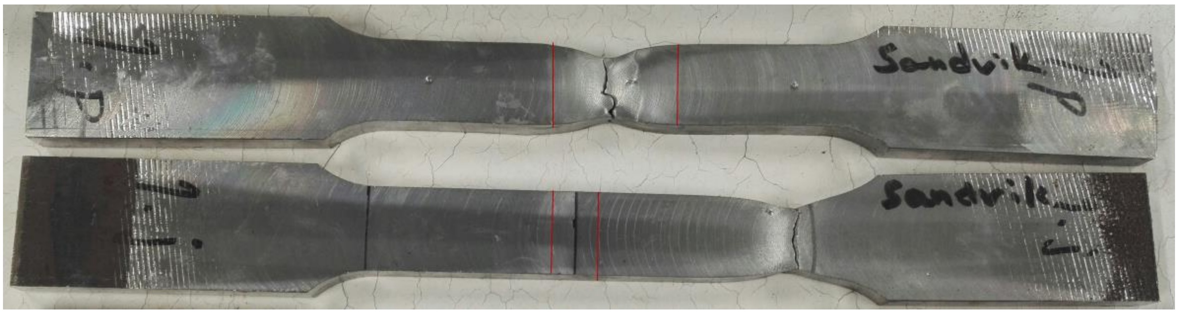


Figure 31. Test piece 5 TKU1: transverse tensile test specimens

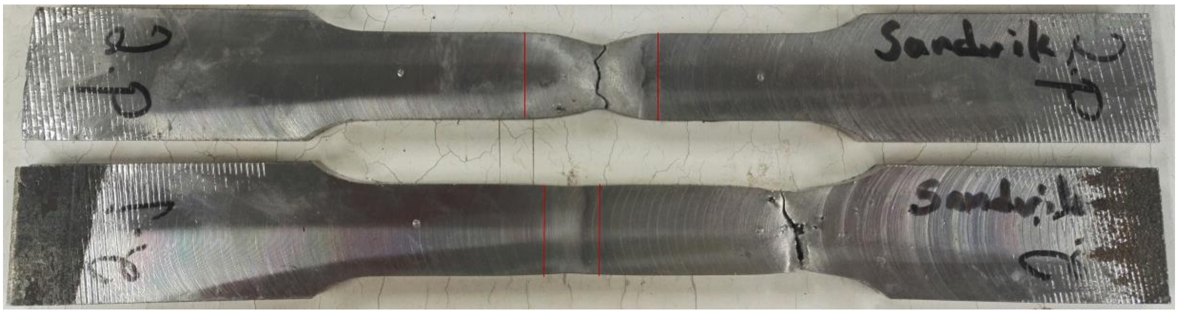


Figure 32. Test piece 6 TKU2: transverse tensile test specimens

Table 10 presents the transverse tensile strength test results for all test pieces. In the table, red stands for "fail" and green for "pass".

Table 10 Transverse tensile strength test results

Test piece number	Test piece name	Test location	Failure location	Tensile strength, MPa	Acceptance level, MPa	Tensile strength test result	Tensile strength test overall result
2.	S15020	Root	BM G24Mn6	602,1	570	Pass	Pass
2.	S15020	Top	BM G24Mn6	601		Pass	
4.	S20075	Root	BM G24Mn6	596,3		Pass	Pass
4.	S20075	Top	BM G24Mn6	613,8		Pass	
5.	TKU1	Root	BM G24Mn6	603,7		Pass	Pass
5.	TKU1	Top	Weld	619,2		Pass	
6.	TKU2	Root	BM G24Mn6	605,7		Pass	Pass
6.	TKU2	Top	Weld	614,6		Pass	

Figure 33 shows one bent bend test specimen. All the specimens looked relatively the same after bending.

Figure 33. Test piece 2 S15020: bend test specimen

A summary of all welding test results is presented in table 11. Red stands for "fail", green for "pass" and orange for "not tested".

Table 11 Overall test results

Test piece number	Test piece name	Radiographic examination result	Macroscopic examination result	Hardness test result	Bend test result	Impact test result	Transverse tensile strength test resu	Overall test result
1.	S20020	Fail	Pass	Fail				Fail
2.	S15020	Pass	Pass	Pass	Pass	Pass	Pas	Pass
3.	S15075	Pass	Pass	Fail				Fail
4.	S20075	Pass	Pass	Pass	Pass	Fail	Pas	Fail
5.	TKU1		Pass	Pass		Pass	Pas	Fail
6.	TKU2		Pass	Pass		Pass	Pas	Fail

6 ANALYSIS

S20020 failed radiographic examination because of incomplete fusion with a range of complete weld, which is shown in figure 24 (SFS-EN ISO 5817 2014, p. 19). The reason for incomplete fusion might have been the alignment of bead 3, which made the situation for the fourth run impossible. This is shown in figure 34.

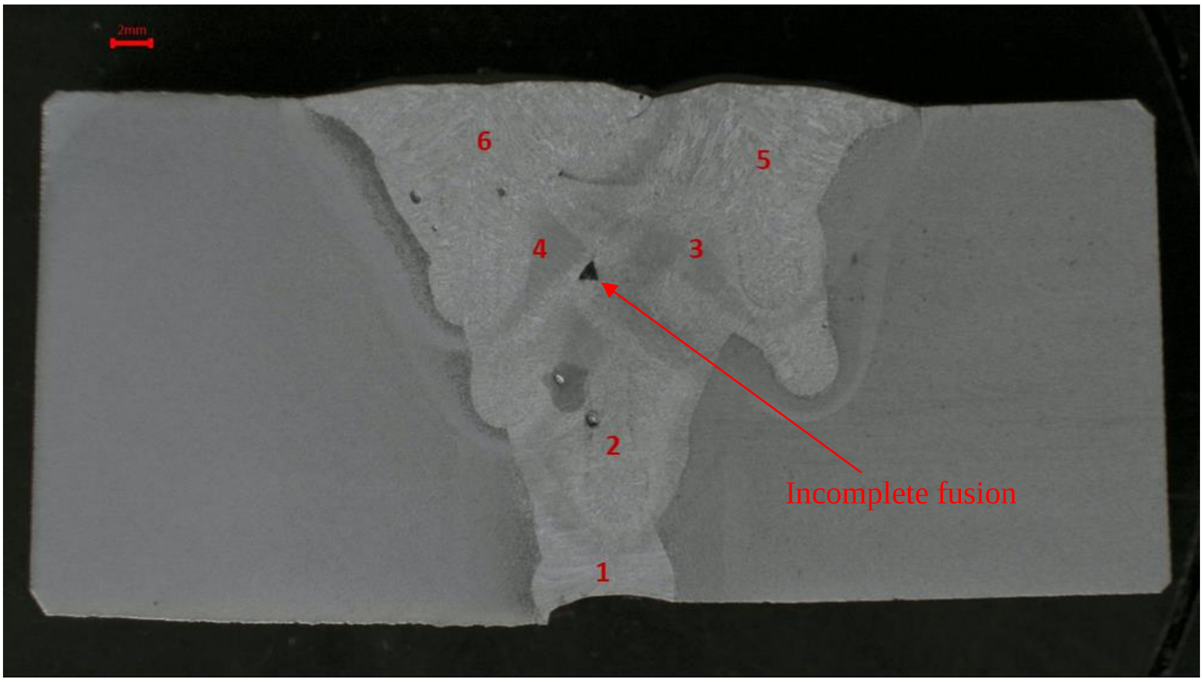


Figure 34. Incomplete fusion in S20020

Otherwise, radiographic examinations were passed with some imperfections that are no cause for failure. For example, in the radiographic examination for S15020 in figure 24, incomplete root penetration can be seen as a straight black line, but because the weld is defined as a partial penetration weld, it is not a cause for failure. Also, some wormholes and porosity seen as single black dots in the radiographic image were discovered. Lukkari 1998 (p. 41–43) was used to assist in interpreting the radiographic image of the test pieces.

All macroscopic examinations were passed with some findings listed below:

- Incomplete root penetration in welds 2–6

- Some porosity in all welds, without significant difference, whether near the G24Mn6 HAZ or Domex 500ML HAZ
- Incompletely filled grooves on welds 2, 3 and 5. No cause for failure. Within the limit h ≤ 0,5 mm (SFS-EN ISO 5817 2014, p. 25).
- Linear misalignment between plates in welds 1, 3, 5 and 6. No cause for failure. Within the limit h ≤ 2,5 mm (SFS-EN ISO 5817 2014, p. 43).
- Multiple imperfections in any cross-section, in all welds. No cause for failure. Within the limit $\sum h \leq 5$ mm (SFS-EN ISO 5817 2014, p. 45)

More interesting than the findings for the macroscopic specimens was the darkening near the G24Mn6 fusion line on the base material side. One example of the area can be seen in appendix 10, and another in figure 35.

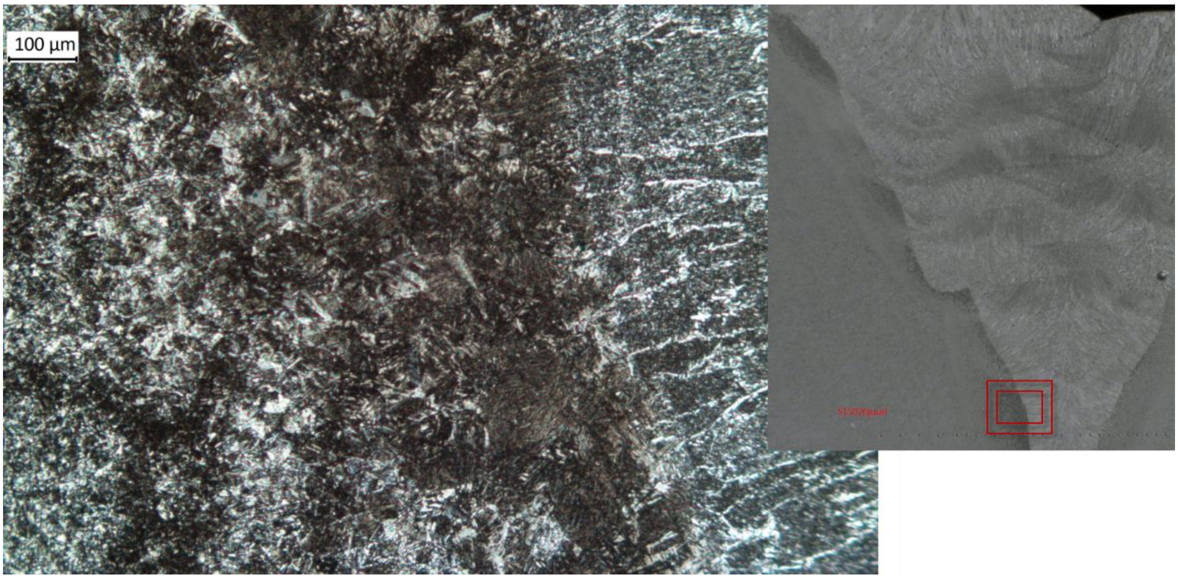


Figure 35. Dark and hardened zone in S15020

Random microscopic samples of these dark zones were collected, and all seemed to look the same. Other commonality for these dark zones in all tests was high hardness (*HV5 300–450*). Pictorial and numerical comparison with the literature supports an estimate of these areas including martensite. Findings in the literature are presented in figures 36 and 37.

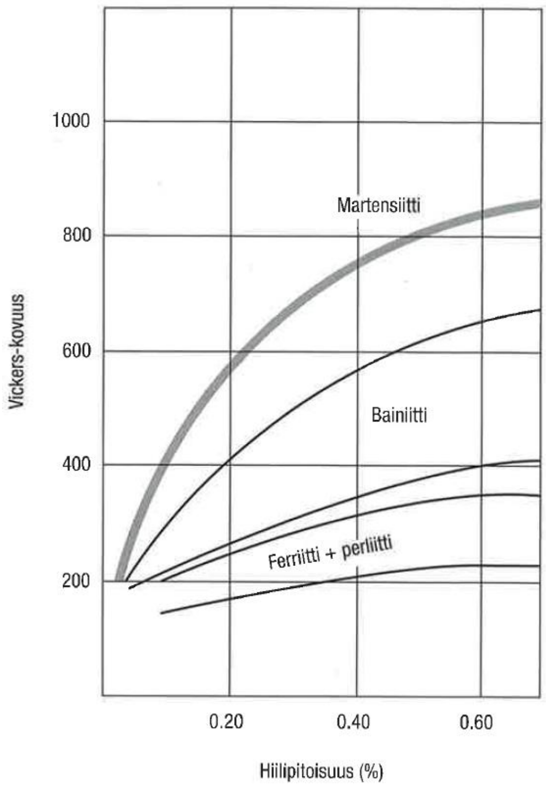


Figure 36. Relationship between carbon content, hardness and phase structure (Kyröläinen & Kauppi 2016, p. 17)

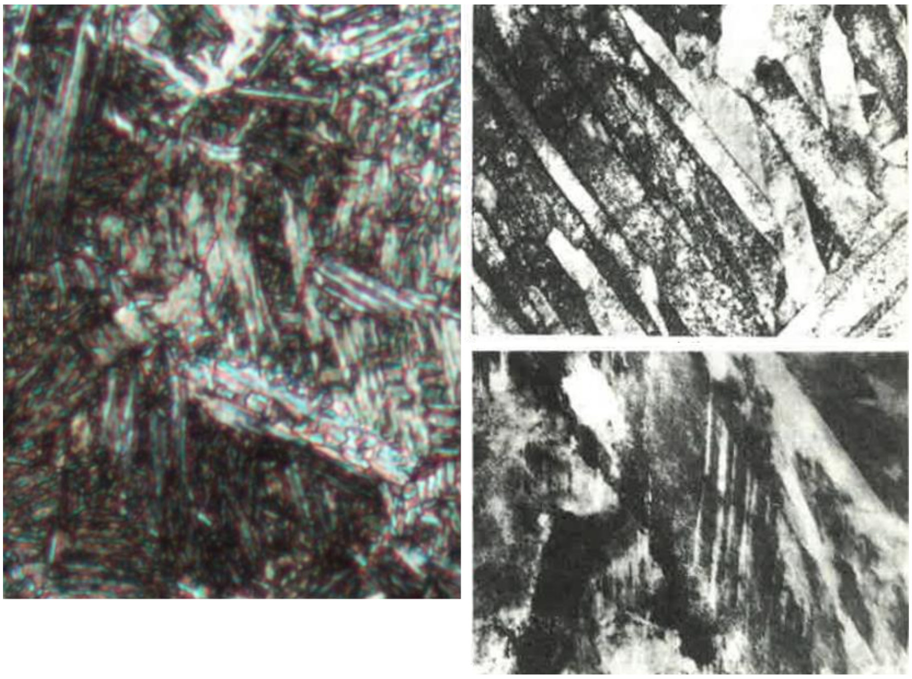


Figure 37. Martensite in S15020 and in the literature (Lindroos Sulonen & Veistinen 1986, p. 286)

Figure 37 presents, on the left, a phase structure near the fusion line of G24Mn6 in S15020. On the right are images of lath martensite and plate martensite for comparison (Lindroos Sulonen & Veistinen 1986, p. 286).

Hardness test results support the conclusion of martensite's existence. All test specimens have the dark area, and, in all welds, that area was hard, in some cases extremely hard. Test specimens 1 and 3 failed because of hardness exceeding the limits. That was caused by excessively low heat energy, which led to excessively short cooling time, causing carbon diffusion from austenite to ferrite and cementite to fail and leading to excessively high carbon supersaturated ferrite (martensite) content and excessively high hardness (Lindroos Sulonen & Veistinen 1986, p. 285). It is noteworthy that hardness was not a problem on the SSAB Domex 500ML fusion line for any test specimen.

In addition to the hardness tests, impact tests revealed a problem for G24Mn6+QJ2. Domex 500ML passed the tests, which is understandable, as the test was run at −30 °C and SSAB Domex 500ML is certified for 40 J at −60 °C (SSAB 2018, p. 1). Test piece 4 failed the impact test because the impact test for G24Mn6+QJ2 HAZ failed. This was caused by excessively long cooling time making the structure fragile with low resistance to impact. A fragile rupture of G24Mn6+QJ2 HAZ and a ductile rupture of SSAB Domex 500ML can be seen in figure 28. The fragile rupture area was measured in accordance with the SFS-EN ISO 148-1 standard. Compared with the standard, the ductility for G24Mn6+QJ2 HAZ specimen is about 20 % and the ductility of the SSAB Domex 500ML HAZ specimen is about 47 % (SFS-EN ISO 148-1 2016, p. 53).

The most confusing result in the test was the combination of $t_{8/5}$ cooling time, preheat, heat input, hardness and impact energy. All four test pieces for which $t_{8/5}$ was measured showed unusual contradictions between the theoretical values and results. This contradiction is presented following by examining the lasts runs of pieces 1 to 4:

- Piece 1, 6th run: $Q=2{,}19$ *kJ/mm*, $T_0=50$ *°C*, $t_{8/5}=10{,}8$ *s*, $HV5_{max}=439$. No match! According to theory, if $t_{8/5}>8$, then $HV5<380$.
- Piece 2, 9th run: $Q=1{,}50$ *kJ/mm*, $T_0=160$ *°C*, $t_{8/5}=13{,}3$ *s*, $HV5_{max}=380$, impact energy=32 J. No match! According to theory, if $t_{8/5}=8$, then $HV5=380$.

- Piece 3, 9th run: $Q=1{,}50\ kJ/mm$, $T_0=75$ °C, $t_{8/5}=9{,}3\ s$, $HV5_{max}=404$. No match! According to theory, if $t_{8/5}>8$, then $HV5<380$.
- Piece 4, 7th run: Q=1,96 kJ/mm, T_0=183 °C, $t_{8/5}$=27,2 s, $HV5_{max}$=338, impact energy=25 J. No match! According to theory, with measured Q and T_0, $t_{8/5}$ and impact energy should be well within the limits.

These suggest that the $t_{8/5}$ measurements or 8 s limit value was flawed. The first factor checked was the precise chemical composition of the material. It turned out that the composition slightly differed from that estimated. In addition, the test pieces were made in two batches with different compositions, without specifying the exact batch for each test piece. It was decided to continue with the worst case and choose new *CE* and *CET* values based on the batch with higher values, which was batch 2 in appendix 2. The corrected $t_{8/5}$ cooling time was estimated from the figure in appendix 13. The new corrected values for the heat energy window are $CE=0{,}506$, $CET=0{,}386$ and $t_{8/5min}=13\ s$. New heat energy windows are shown in appendix 11. The corrections of these values justify the results in tests 1 and 3 better but do not provide complete explanations of tests 2 and 4.

The explanation of the inaccuracy between theoretical values and the tests of pieces 2 and 4 might be found in the measurements in test 5. Before the workshop welds, there was suspicion that the preheat and interpass temperature measurements in the laboratory were unreliable. It is understood in the company that more accurate surface temperature measurements can be achieved if the measured surface is painted black. Tests 4 and 5 in the record in appendix 6 show that the welding processes were similar. Still, the difference in interpass temperature was almost 100 °C before last run, even though there was about 2 minutes waiting time between runs in test 5. That can explain the conflict between theoretical values and the results in tests 2 and 4. Assuming that all other test results were correct, the real interpass temperature can be calculated from the $t_{8/5}$ equation by solving it with respect to T_0. Otherwise, it can be estimated in heat energy window with measured hardness, impact energy and $t_{8/5}$. Here, the correction is based on the estimate in the heat energy window. This estimate appears in appendix 12. After these, cooling times and hardness correspond to each other well, except for test 1, which seems to show slightly excessive hardness. It also seems that the test pieces were made from batch 2. Cooling times and hardness appear in appendix 14.

All specimens passed the transverse tensile test. It is notable that nearly all the specimens broke down in the G24Mn6+QJ2 base material far from the weld. Because of this, elongation in those cases could not be measured. All those specimens had lower yield strengths than the nominal yield strength for either base material. The reason was not determined, but it is possible that the tests were faulty. Was the lining of test specimen should? Could the welding process have been improved? Two specimens broke down at the middle of the weld and had higher yield strength than the nominal yield strength for either base material.

The bend tests were successful. All the bend test specimens were approved with no flaws. The only exception was the open root, which, in this case, is acceptable. The welds withstood transformations well.

7 COST ANALYSIS

Generally, the cost of a welded steel structure consists of the cost of the steel material and the cost of welding. The breakdown of the steel material cost is not covered here, as it does not change. What is significant here is the difference between the price of used rolled steel material and that of steel casts. One of the main purposes of using steel casts was to reduce welding, so more attention is paid to welding costs.

The reason for using steel materials with higher strength is to reduce machine weight, but this cannot be implemented at any cost. In the literature, there are cases in which basic S355 is changed to steel materials with higher strength, lowering the total cost of ownership. For example, the article "Ultralujien terästen ominaisuudet lopputuotteeseen osaavan suunnittelun ja valmistuksen avulla" presents a case illustrating the effect of changing S355 to higher strength steel materials. It is estimated that the savings are achieved from using the machine, which is lighter and thus more effective. That could justify cost increase. Of course, this requires weight reduction, which is excluded here (Mikkonen Björk Skriko & Tuominen 2017, p. 26).

7.1 Welding costs

Welding costs can be broken down into welding material costs, manufacturing costs and equipment costs. In addition, welding material costs consist of filler material and shielding gas costs. Manufacturing costs include labour costs and energy costs (Lukkari 1998, p. 58).

Welding costs can be calculated using following equations (Lukkari 1998, p. 58):

Filler material costs, K_L:

$$K_L = M \times \frac{H_L}{N}, \ (€/m) \quad (10)$$

Shielding gas costs, K_S:

$$K_S = \frac{M}{T} \times V \times H_s \times g, \ (€/m) \quad (11)$$

Labour costs, K_T:

$$K_T = \frac{M}{T} \times \frac{1}{e} \times H_T, \ (€/m) \quad (12)$$

Energy costs, K_E:

$$(13) \qquad K_E = M \times E \times H_E, \ (€/m)$$

The interest here is not how welding costs are broken down, more how does the costs change. Thus, these equations are used only partly. Calculations are based on the company's experience with welding costs per hour. The only factor that must be clarified is how many welds and what types of welds are included in and excluded from the new design compared with the old design. Instead of calculating cost per welded meter, the equations use welded mass, calculating how many hours are spent in the welding process. When cost per hour is known, total cost can be estimated. The following equations are used:

Amount of filler material, *M*, is calculated in two separate ways, depending on the shape of the weld and whether it is a fillet weld or a 38° single bevel weld.

Fillet weld:

$$(14) \qquad M = \frac{a^2 \times \rho}{N}, \ (kg/m)$$

38° single bevel weld:

$$(15) \qquad M = \frac{s^2 \times \tan(38) \times \rho}{2 \times N}, \ (kg/m)$$

Mass of weld, *m*:

$$(16) \qquad m = M \times l, \ (kg)$$

Welding time, *t*:

$$(17) \qquad t = \frac{m}{T \times e}, \ (h)$$

Welding cost, c_w:

$$(18) \qquad c_w = H_w \times t, \ (€)$$

In the calculations, the following constants are used: $\rho = 7850\ kg/m3$ (Valtanen 2012, p. 310), $T = 5\ kg/h$ (Lukkari 1998, p. 165) (Lahtinen 2018), $e = 0{,}3$ (Lukkari 1998, p. 58) (Lahtinen 2018) and $H_w = 60$ *€/h* (Marjasto 2019).

Welding lengths were calculated from 3D models. An example appears in figure 24. New welds were calculated from the concept 3D model, and reduced old welds were calculated from the current 3D model.

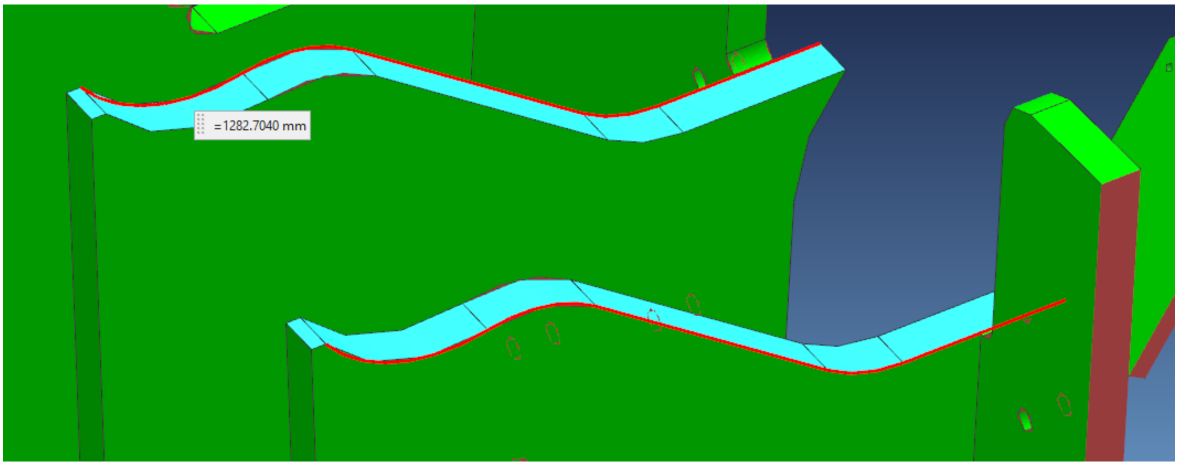


Figure 38. Two new welds

The shapes and sizes of the new welds are estimated based on the mechanical design experience of the researcher. The shapes and sizes of old welds are based on the current welding drawing. All welds are calculated separately using the equations presented, and the results are sums of all individual calculations.

7.2 Material costs

The estimate of changed material costs is based only on the mass of required materials and material cost per ton. The following equations is used:

Material cost, c_m:

$$(19) \qquad c_m = \sum (m \times H_m), \quad (€)$$

Masses (m) in the old and new concept design are calculated from 3D models. Material costs per ton (H_m) are based on mean values calculated from the company's real purchasing prices.

Finally, the total cost structure is calculated as a sum of changed material costs and changed welding costs. The following equation is used:

Cost change, Δc:

$$(20) \quad \Delta c=(c_{mnew}-c_{mold})+(c_{wnew}-c_{wold}),\ (€)$$

A positive result from this equation indicates increased cost, while a negative result indicates decreased cost.

7.3 Results and analysis summary

The difference in manufacturing cost was calculated using the equations in the previous section. The results are owned by the company, and only a summary and an analysis based on actual results are presented here. Figure 39 shows silhouettes of old and new frames for guidance reading the results.

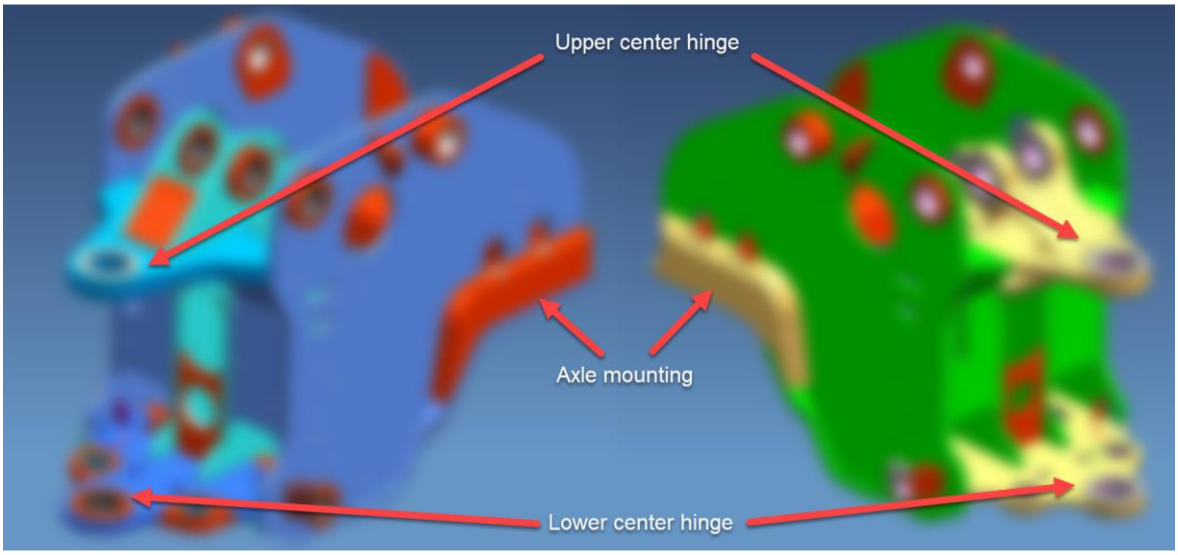


Figure 39. Old and new front frame

The total mass of the construction remained about the same as the old one, with some percentage increase. The increased weight resulted mostly from the design of the new upper centre hinge. The axle mounting and lower centre hinge design did not have a significant effect on weight.

Although the number of welds decreased by tens of meters, the increase in material costs was much larger than the decrease in welding costs. The overall increase in manufacturing cost with the new concept is 15–50 %. Table 12 presents an indicative summary of how each new part of the structure affects mass and cost.

Table 12 Effect of the new design

	Change in mass	**Chance in overall cost**	**Manufacturability**
upper center hinge	Increase	Increase by 5-15 %	challenging
lower center hinge	Decrease	Increase by 2-8 %	easy
axle mouting	No affect	Increase by 5-15 %	easy
rolled steel (Domex 500ML)	Decrease	Increase by 4-12 %	no affect
overall	Increase	increase by 16-50 %	

The largest increase in cost results from the change in the upper centre hinge, with possibly over 15 % increase in overall cost. The total increase of about 15–50 % in euro could be covered by decreased weight, which was outlined in the research. Another solution is to use high-strength steel only in specific areas and continue using old structural steel on rest of the frame.

8 CONCLUSIONS

Although most of the welding tests failed for several reasons, the results are reasonable. Pieces 1 and 3 failed because of excessively high hardness, and piece 4 failed because of excessively low impact energy. All these were just at the limits, which were supposed to be exposed. Pieces 5 and 6 failed because only some of the required tests were performed, although both pieces completed all the tests performed.

The main purpose of this thesis was to increase knowledge in welding material pairing of high-strength steel and cast steel and determine the limits for usable preheat and heat input. The limits for cooling time, welding parameters and preheat were determined. The answers to all the research questions concerning the metallurgical framework were found, and a weld, accepted in accordance with the SFS-EN ISO 15614-1 standard, was made. The hypothesis was proved correct. Hydrogen cracking was absent, and the multirun weld covered low preheat. Major differences between laboratory and workshop welds were not found. There was more value in the finding that parameter settings commonly used by the company's welder could be used in welding the material pair. Missing information for the draft prequalified Welding Procedure Specification (pWPS) was found, and the final pWPS is provided for the company but is not presented here.

The conclusion derived from the welding test results was that cast steel is more tender in the welding process than rolled steel. It more readily failed the impact, hardness and transverse tensile tests. For this material pair, if welding is successful for G24Mn6+QJ2, it is successful for SSAB Domex 500ML. Welding them can take place, but the boundary conditions for the preheat-heat input combination were narrower than expected. Although a successful weld was possible with 20 °C preheat, preheat is potentially required when welding larger structures. This is because larger masses conduct more heat energy, which might prevent interpass temperatures from reaching sufficiently high levels.

Increased cost was viewed as a risk from the outset, and that is how it turned out. When combining this with the challenges in the welding process, it would be wise to start using high-strength steel and steel castings step by step. An effective way forward would be to implement the lower centre hinge first. The concept design for this involves a simple cast piece. The cost increase is not that high, and this part of the frame is not exposed to a high loads as upper centre hinge. The advantages compared with risks support implementing this first. Future projects should include weight reduction, cost reduction and further development of the welding process. Weight and cost reduction should be considered together. Although the original cost might be unreachable, the value added to the machine, for example, higher payload, would justify the cost increase. Welding process development would include investigation of single bevel welds and fillet welds and study of how to meet the challenges concerning hardness, impact energy and tensile strength. Bearing in mind the application, fatigue stress investigations would also provide useful information.

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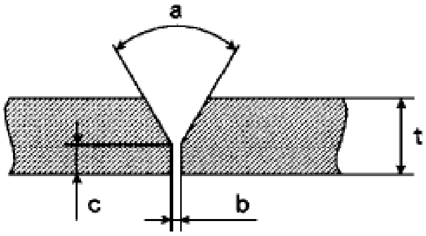
APPENDIX 1. DRAFT PWPS FOR DOMEX 500 ML AND G24MN6+QT2

Hitsausiohje Domex 500 ML - G24Mn6+QT2

WELDING PROCEDURE SPECIFICATION (WPS)

According to EN ISO 15609-1		*Hyväksymistapa / Approval by*	SFS-EN ISO 15614-1+A1+A2:2012
paikka Location: Turku	Menetelmäkoe-pöytäkirjan nro.		Rev 1
Paikka Location	**Turku Loaders**	Railon valmistus Preparation	**Flame cutting / grinding or machining**
Valmistaja Manufacture	**Sandvik Mining and Construc.**	Perusaine Parent Material	**Domex 500 ML - G24Mn6+QT2**
Hitsaajan nimi Welder's name		Ainepaksuus Material thickess	**12,5-50 (25 mm in test)**
Hitsausprosessi Welding process	**MAG-135**	Ulkohalkaisija Outside diameter	**-**
Liitosmuoto Joint type	**BW**	Hitsausasento Welding Position	**PA**

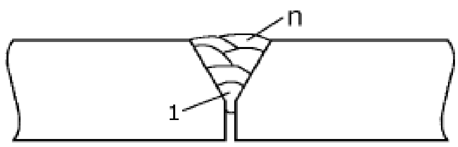
Liitoksen kuva
Joint Desing



a = 40°- 60°, b = 0-2mm, c ≥ 3mm

OSATUNKEUMA PÄITTÄISHITSI
PARTIAL PENETRATION BUTT WELD

Hitsausjarjestys
Weld. Sequences



Welding Details

Palko Run	Hitsausprosessi Process	Lisäaineen mitat Filler Metall (mm)	Hitsausvirta Current (A)	Kaarijännite Voltage (V)	Virtalaji Polarity +/-	Syöttönopeus Wire feed Speed m/min	Kuljetusnopeus Travel Speed (cm/min)	Lämmöntuonti Q Heat input (kJ/cm)
1-n	**135**	**1,2**	**250 - 360**	**33 - 36**	**DC+**	**10 - 13**	**30 - 38**	**10,4 - 20,7**
Kun hitsataan alhaalta ylöspäin (PF), when you weld in PF position:								

Tämä hitsausohje on osatunkeumapäittäishitseille. This WPS is for partial penetration butt welds.

Lisäaine voidaan vaihtaa toiseen, kunhan lisäaineen luokittelumerkintä ja kemiallinen koostumus pysyy samana.
Fillermetal can be changed to another one, if classification and composition remains the same.

Filler Metal		Juuren avaus Back Gouging		Ei avausta / No gouging
Kauppanimi Trade name	**esim. / e.g. Lincoln SupraMig Ultra tai / or Elga Elgamatic 103**	Juurituki Backing		Ei / No
Luokittelu Classification	**AWS A/SFS 5.18: ER70S-6**	Esilämmitys Preheat temp.		20 °C / 75 °C
Käsittely Handling		Palkojen väl. Interpass Temp.		50 °C - 250 °C
Suojakaasu Gas	**EN ISO 14175-Z-ArC+NO-18/0,03 (Mison 18**	Hits. jälkeinen lämpökäsittely Post-Weld Heat Treatment	Aika Time	-
Virtausnopeus Gas Flow Rate	**15-20 l/min**		lämpötila Temperature	-
Elektrodin tyyppi Electrode Type	**-**		Menetelmä Method	-

Other information

Sivuttaisliike Weaving	**max 5 mm**	Sykehitsaus Pulse welding	-
Vapaalankapit. Stand off distan.	**15-20 mm**	Polttimen kulma Torch angle	

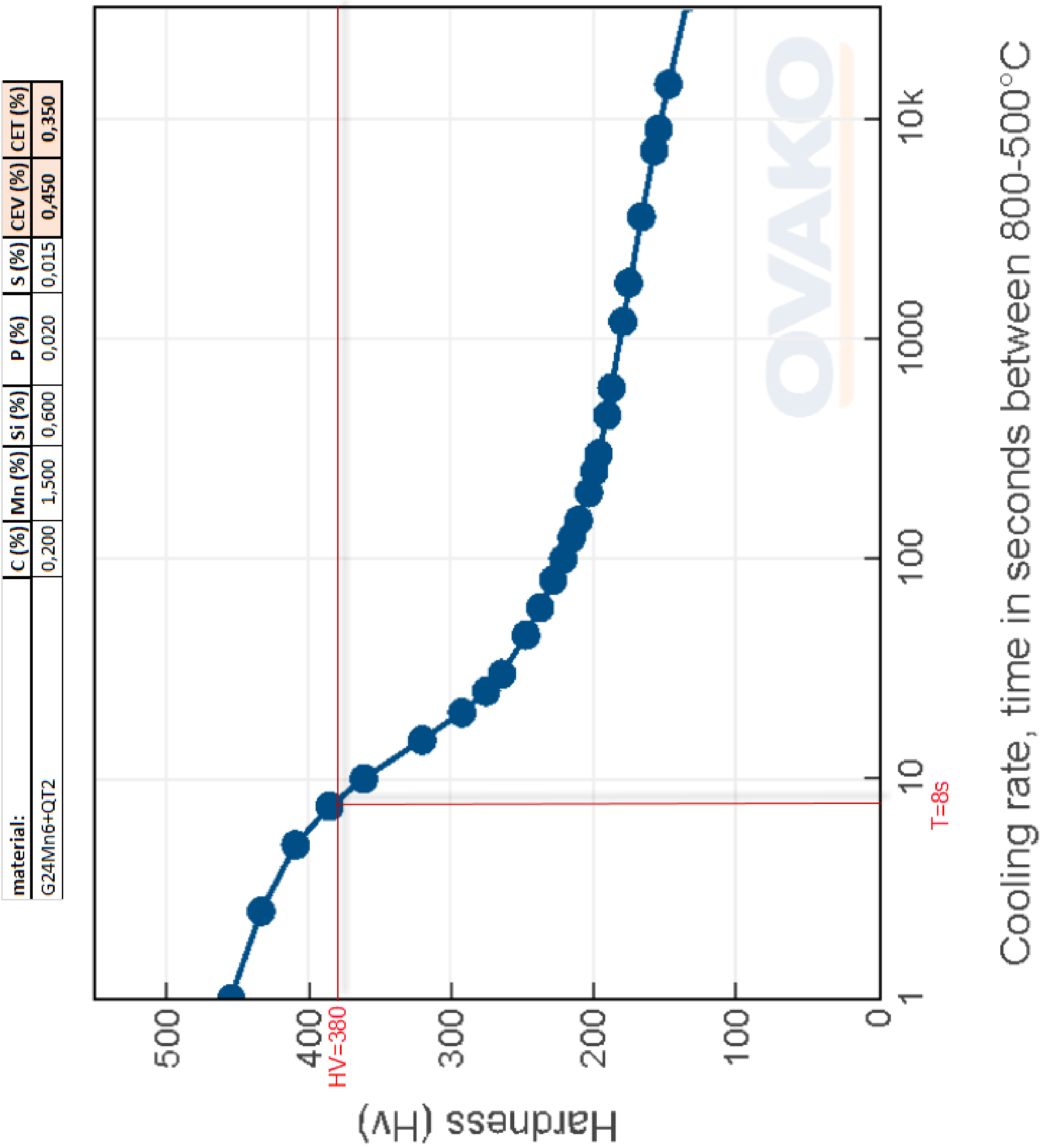
Manufacturer	Examiner or test body
Name, date and signature	Name, date and signature

APPENDIX 2. CHEMICAL COMPOSITIONS OF MATERIALS

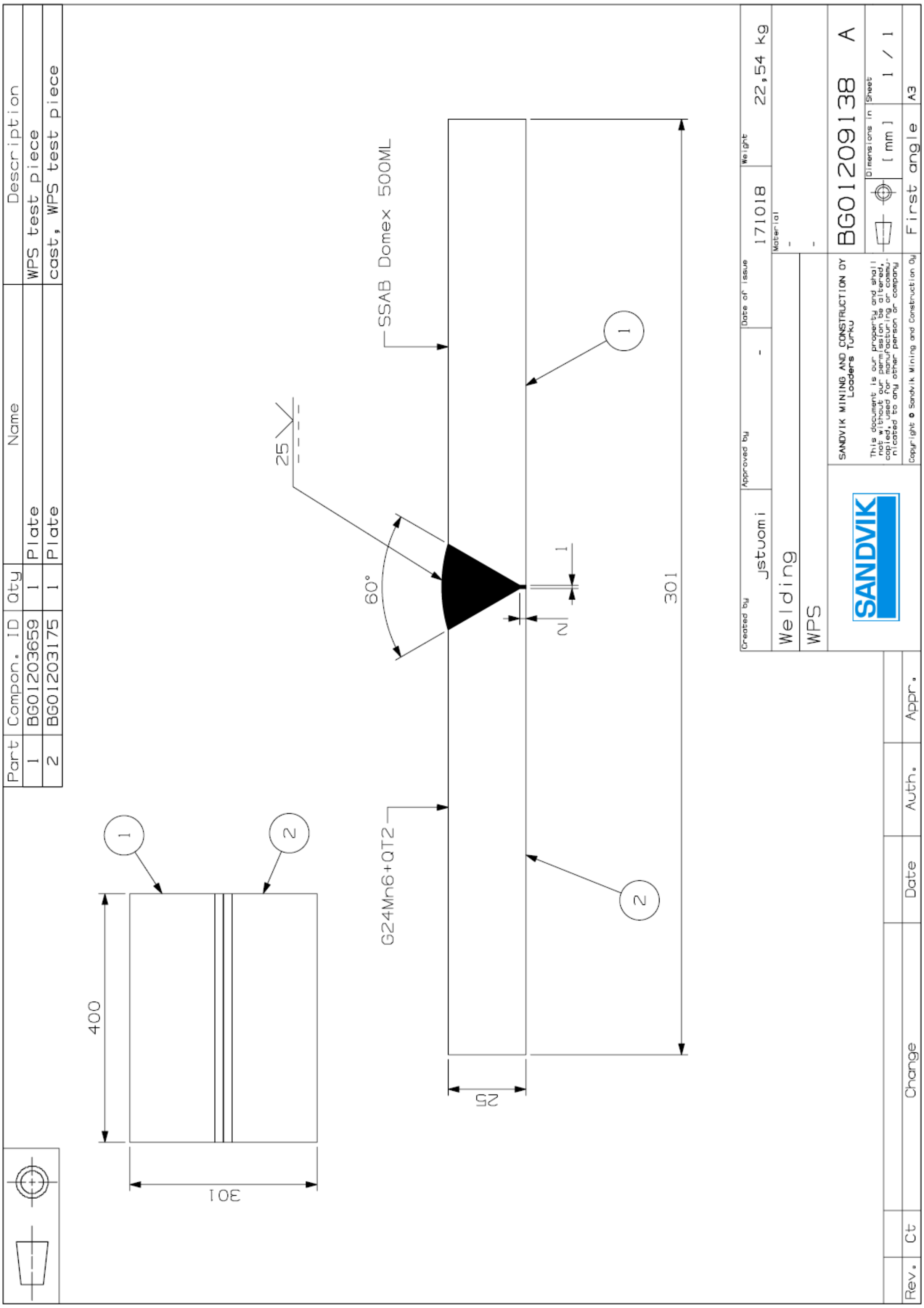
materials:		**C (%)**	**Mn (%)**	**Cr (%)**	**Mo (%)**	**V (%)**	**Cu (%)**	**Ni (%)**	**Si (%)**	**P (%)**	**S (%)**	**Al (%)**	**Nb (%)**	**N**	**Ti**	**CEV (%)**	**CET (%)**
SSAB Domex 500ML (Optim 500ml)	**min**															**0,000**	**0,000**
	max	0,180	1,700			0,120		1,000	0,500	0,020	0,015	0,020	0,050	0,015	0,050	**0,554**	**0,375**
G24Mn6+QT2	**min**	0,200	1,500						0,600	0,020	0,015					**0,450**	**0,350**
	batch 1	0,214	1,510	0,064	0,008	0,012	0,039	0,047	0,370	0,016	0,006	0,053	0,017	0,000	0,001	**0,488**	**0,372**
	batch 2	0,222	1,578	0,065	0,004	0,012	0,037	0,041	0,414	0,016	0,005	0,032	0,010	0,008	0,000	**0,506**	**0,386**
	max	0,250	1,800						0,600	0,020	0,015					**0,550**	**0,430**
G28Mn6	**min**	0,250	1,200						0,600	0,040	0,030					**0,450**	**0,370**
	max	0,320	1,800						0,600	0,040	0,030					**0,620**	**0,500**
G10MnMoV6-3	**min**	0,120	1,200	1,300	0,200	0,050			0,600	0,030	0,020					**0,630**	**0,325**
	max	0,120	1,800	1,800	0,400	0,100			0,600	0,030	0,020					**0,880**	**0,430**

Welding consumables:		**C (%)**	**Mn (%)**	**Cr (%)**	**Mo (%)**	**V (%)**	**Cu (%)**	**Ni (%)**	**Si (%)**	**P (%)**	**S (%)**	**Al (%)**	**Nb (%)**	**N**	**Ti**	**CEV (%)**	**CET (%)**
Supra MIG Ultra	**min**	0,080	1,700						0,850							**0,363**	**0,250**
	max	0,080	1,700						0,850							**0,363**	**0,250**

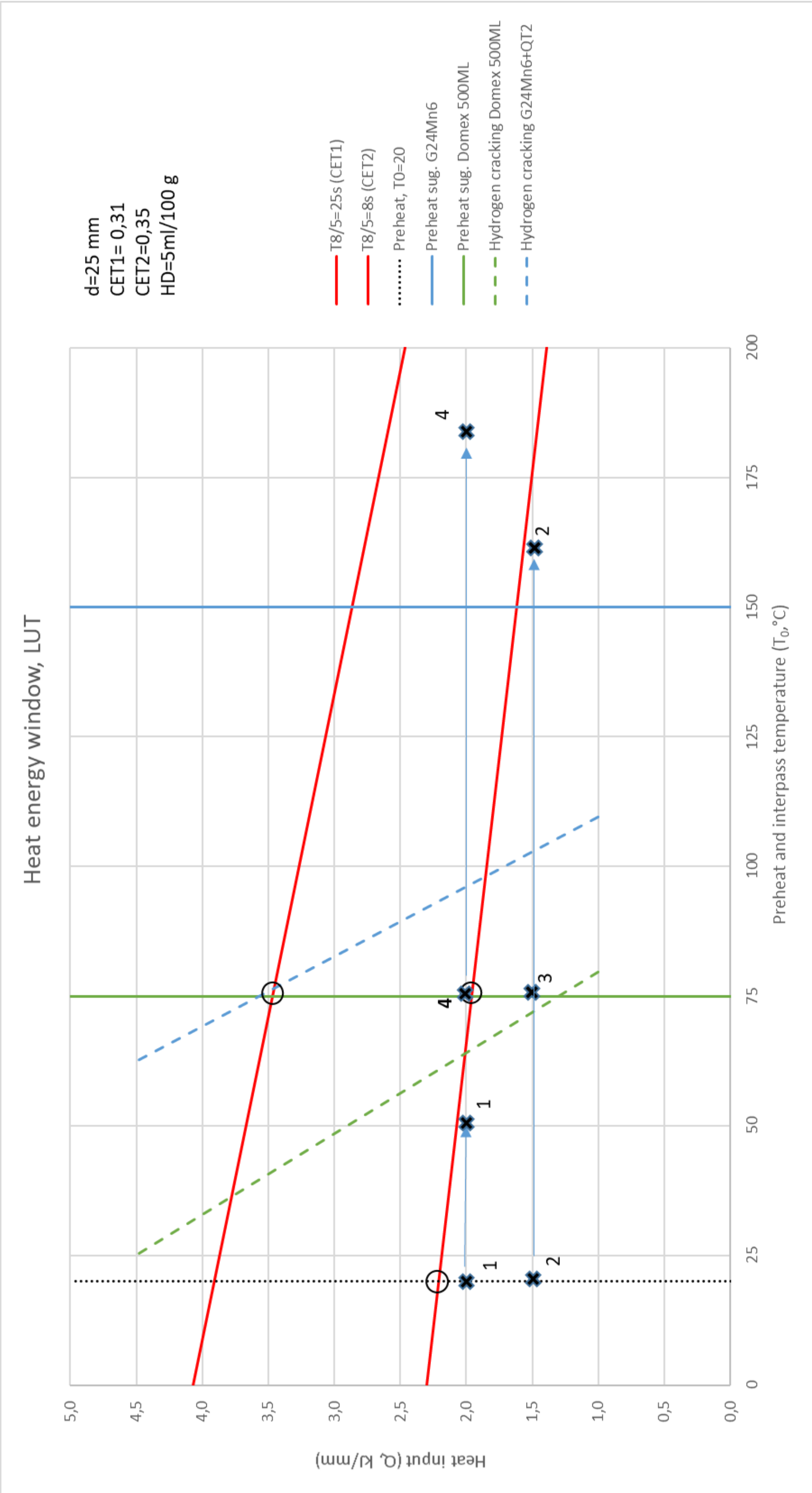
APPENDIX 3. COOLING RATE OF G24MN6+QT2

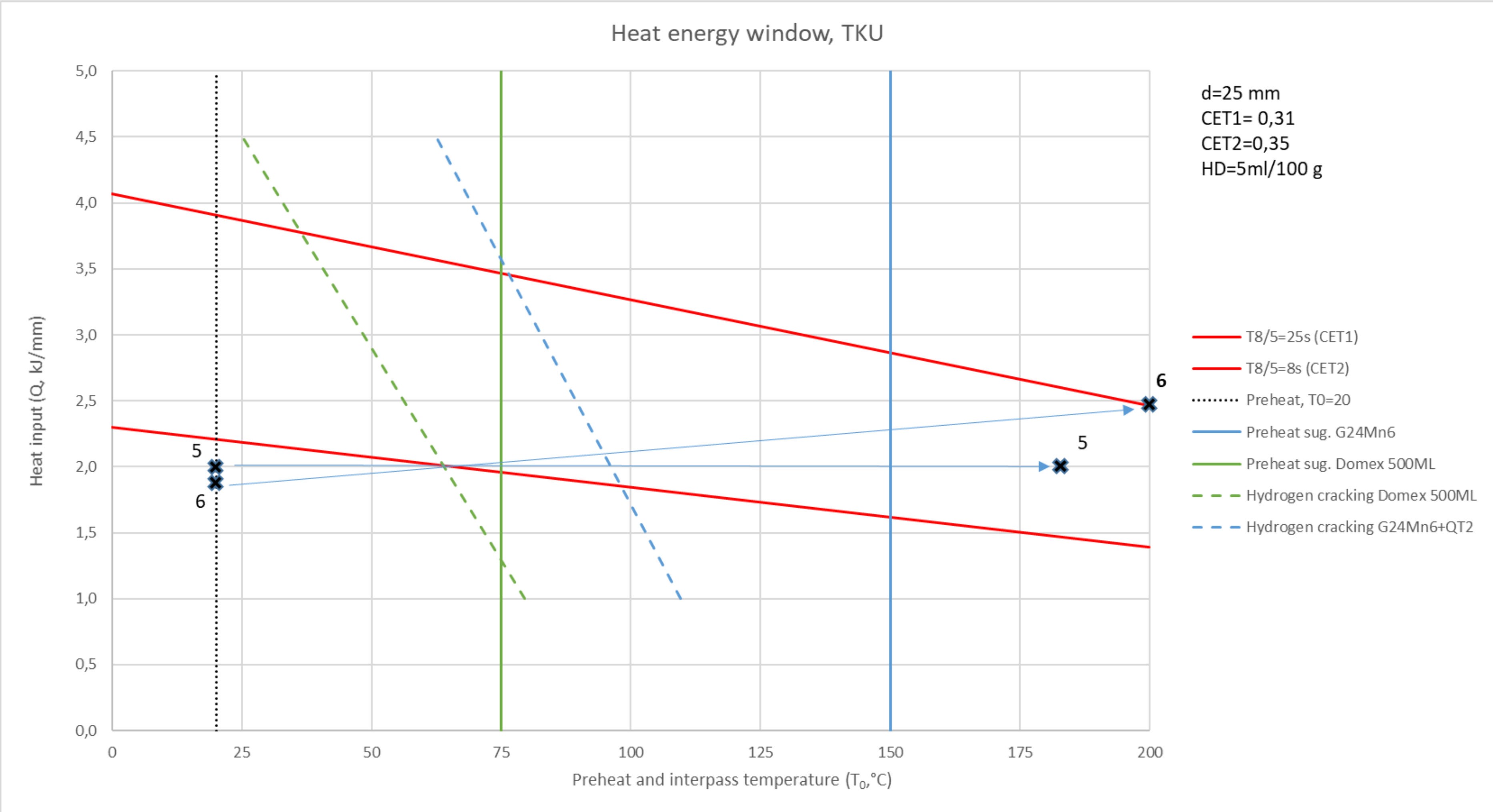


APPENDIX 4. WPS TEST PIECE



APPENDIX 5. HEAT ENERGY WINDOW FOR WELDS AT LUT AND TKU



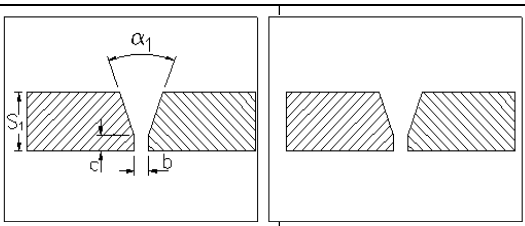


Heat energy window, TKU
d=25 mm
CET1= 0,31
CET2=0,35
HD=5ml/100 g
T8/5=25s (CET1)
T8/5=8s (CET2)
Preheat, T0=20
Preheat sug. G24Mn6
Preheat sug. Domex 500ML
Hydrogen cracking Domex 500ML
Hydrogen cracking G24Mn6+QT2
Heat input (Q, kJ/mm)
Preheat and interpass temperature (T0,°C)
5,0
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
0
25
50
75
100
125
150
175
200
5
6
5
6

APPENDIX 6. RECORD OF TEST WELDS

Asiakas	Sandvik Mining and Construction		Railonvalmistus	Polttoleikkaus ja hiominen/koneistus		
Perusaineet	Domex 500 ML	G24Mn6+QT2	Liitosmuoto	BW		
Levynpaksuus	25	mm	Hitsausasento	PA		
Lisäaine		Lincoln SupraMig Ultra	Suojakaasu	Mison 18	Juurituki	Ei
Huom!						

s_1 = 25 mm
c = 3 mm
b = 0...2 mm
α_1 = 60°



Palko	Prosessi	Lisäaine	I [A]	U [V]	w [m/min]	v [mm/s]	Suutinet. [mm]	Q [kJ/mm]	T_0 [°C]
S15075	135	1,2	290	29,3	9,5	4,7	18	1,54	1. 60°
S15075	135	1,2	280	29,6	9,5	4,7	18	1,50	2. 75°
S15075	135	1,2	279	29,9	9,5	4,7	18	1,51	3. 75°
S15075	135	1,2	285	29,4	9,5	4,7	18	1,52	4. 75°
S15075	135	1,2	278	29,5	9,5	4,7	18	1,48	5. 75°
S15075	135	1,2	280	29,5	9,5	4,7	18	1,49	6. 75°
S15075	135	1,2	282	29,5	9,5	4,7	18	1,50	7. 75°
S15075	135	1,2	279	29,8	9,5	4,7	18	1,50	8. 75°
S15075	135	1,2	277	29,9	9,5	4,7	18	1,50	9. 75°
S20020	135	1,2	363	31,0	12,5	4,1	18	2,33	1. 20°
S20020	135	1,2	335	31,0	12,5	4,1	18	2,15	2. 50°
S20020	135	1,2	340	31,0	12,5	4,1	18	2,19	3. 50°
S20020	135	1,2	345	31,0	12,5	4,1	18	2,22	4. 50°
S20020	135	1,2	335	31,1	12,5	4,1	18	2,16	5. 50°
S20020	135	1,2	340	31,1	12,5	4,1	18	2,19	6. 50°
S15020	135	1,2	295	29,4	9,5	4,7	18	1,57	1. 20°
S15020	135	1,2	278	29,7	9,5	4,7	18	1,49	2. 65°
S15020	135	1,2	280	29,8	9,5	4,7	18	1,51	3. 75°
S15020	135	1,2	286	29,7	9,5	4,7	18	1,54	4. 110°
S15020	135	1,2	277	29,6	9,5	4,7	18	1,48	5. 120°
S15020	135	1,2	282	29,7	9,5	4,7	18	1,51	6. 135°
S15020	135	1,2	279	29,5	9,5	4,7	18	1,49	7. 135°
S15020	135	1,2	279	30,1	9,5	4,7	18	1,52	8. 160°
S15020	135	1,2	278	29,9	9,5	4,7	18	1,50	9. 160°
S20075	135	1,2	292	29,4	9,5	4,7	18	1,55	1. 60°
S20075	135	1,2	342	31,0	12,5	4,5	18	2,00	2. 75°
S20075	135	1,2	335	31,1	12,5	4,5	18	1,97	3. 120°
S20075	135	1,2	346	31,1	12,5	4,5	18	2,03	4. 160°
S20075	135	1,2	333	31,0	12,5	4,5	18	1,95	5. 165°
S20075	135	1,2	338	31,1	12,5	4,5	18	1,99	6. 200°
S20075	135	1,2	334	31,1	12,5	4,5	18	1,96	7. 183°
TKU1	135	1,2	270	32,0	9,5	6,1	18	1,21	1. 16°
TKU1	135	1,2	310	35,3	11,5	4,7	18	1,98	2. 70°
TKU1	135	1,2	315	35,3	11,5	5,6	18	1,70	3. 140°
TKU1	135	1,2	305	35,3	11,5	5,9	18	1,56	4. 182°
TKU1	135	1,2	310	35,3	11,5	6,3	18	1,49	5. 210°
TKU1	135	1,2	305	35,3	11,5	5,7	18	1,60	6. 227°
TKU1	135	1,2	320	35,3	11,5	4,8	18	1,99	7. 247°
TKU1	135	1,2	320	35,3	11,5	4,5	18	2,14	8. 272°
TKU2	135	1,2	260	32,0	9,5	4,7	18	1,52	1. 17°
TKU2	135	1,2	310	36,0	12,0	4,7	18	2,04	2. 100°
TKU2	135	1,2	395	41,0	20,2	4,4	18	3,10	3. 170°
TKU2	135	1,2	390	40,5	20,2	4,1	18	3,29	4. 200°
TKU2	135	1,2	320	36,0	12,0	4,4	18	2,23	5. 200°
TKU2	135	1,2	325	36,0	12,0	4,5	18	2,19	6. 200°

APPENDIX 7. BEND TEST REPORT

TAIVUTUSKOE

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LUT Kone

Pöytäkirjan numero ____________

pWPS	-
Sovellustandardi	***SFS-EN 5173***
Asiakas / viite	***Sanvik / Jussi Tuominen***
Perusaine	***Domex 500ML / G24Mn6***
Aineenpaksuus	***25 mm***
Hitsityyppi	***BW***
Hitsausprosessi	***135***
Hitsausaine	***Lincoln SupraMig Ultra Ø1.2***
Koelämpötila	***20 C***
Huomautuksia	***Taivutussauvoihin jäi "juuri auki".***

Taivutintelan halkaisija ***d = 4xt***
Tukitelojen väli ***l > (d+2xt)***
t = levynpaksuus

FBB *Päittäishitsin pintaivutuskoe*
RBB *Päittäishitsin juuritaivutuskoe*
SBB *Päittäishitsin sivutaivutuskoe*

Koesauva Nro / sijainti	Koemene-telmä	Mitat mm	Taivutintelan halkaisija/ mm	Tukitelojen väli / mm	Taivutus-kulma / °	Alkumitta-pituus / mm	Venymä %	Huom!
S15020/1	***SBB***	***15 x 25***	***60***	***100***	***160***	-	-	-
S15020/2	"	***15 x 25***	"	"	"	-	-	-
S15020/3	"	***15 x 25***	"	"	"	-	-	-
S15020/4	"	***15 x 25***	"	"	"	-	-	-
S20075/1	***SBB***	***15 x 25***	***60***	***100***	***160***	-	-	-
S20075/2	"	***15 x 25***	"	"	"	-	-	-
S20075/3	"	***15 x 25***	"	"	"	-	-	-
S20075/4	"	***15 x 25***	"	"	"	-	-	-

Taivutuskokeen koetulosten mukaisesti koetulos " ***hyväksytty***

Testauksen suorittaja	***Esa Hiltunen***
Päivämäärä ***24.1.2019***	Allekirjoitus
Kokeen valvoja	
Päivämäärä	Allekirjoitus

APPENDIX 8. IMPACT TEST REPORTS

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LAPPEENRANNAN TEKNILLINEN YLIOPISTO
LUT Kone

Pöytäkirjan numero ____________

ISKUKOE

pWPS	-	Nimikemerkintä:
Sovellustandardi	***SFS-EN ISO 9016, EN ISO 148-1***	*Muoto: 1 2 3 a/b*
Asiakas / viite	***Sanvik / Jussi Tuominen***	*1: sauvan tyyppi (V tai U)*
Perusaine	***Domex 500ML / G24Mn6***	*2: loven paikka (W tai H)*
Aineenpaksuus	***25 mm***	*3: lovetun pinnan suunta (S tai T)*
Hitsityyppi	***BW***	*a: loven etäisyys vertailuviivasta*
Hitsausprosessi	***135***	*b: koekappaleen ja sauvan pinnan*
Hitsausaine	***Lincoln SupraMig Ultra ø1.2***	*välinen etäisyys*
Huomautuksia	***Iskusauvat kokeesta S15020. Sauvat pinnan puolelta, 2 mm levypinnan alapuolelta. Sauvat 1, 2 ja 3 ovat hitsistä, sauvat 4, 5 ja 6 Domexin puolelta ja sauvat 7, 8 ja 9 valuteräksen puolelta.***	

Koesauva Nro	Nimike	Sauvan mitat / mm	Koelämpö-tila / °C	Vasaran energia/ J	Iskusitkeys J	Murtuman sijainti	Murtuman tyyppi	Virheen tyyppi ja koko
20.1	VWT0/2	10x10x55	-30	300	45	Weld	-	-
20.2	"	"	"	"	45	"	-	-
20.3	"	"	"	"	30	"	-	-
Keskiarvo	"	"	"	"	**40**	"	-	-
20.4	VHT2/2	"	"	"	140	HAZ Domex	-	-
20.5	"	"	"	"	125	"	-	-
20.6	"	"	"	"	175	"	-	-
Keskiarvo	"	"	"	"	**147**	"	-	-
20.7	VHT2/2	"	"	"	30	HAZ G	-	-
20.8	"	"	"	"	38	"	-	-
20.9	"	"	"	"	27	"	-	-
Keskiarvo	"	"	"	"	**32**	"	-	-
	"	"	"	"		-	-	-
	"	"	"	"		-	-	-
	"	"	"	"		-	-	-
Keskiarvo	"	"	"	"		-	-	-

Iskukokeen koetulosten mukaisesti koetulos " ______________________________ ".

Testauksen suorittaja

Päivämäärä	Allekirjoitus
1.2.2019	Esa Hiltunen

Kokeen valvoja

Päivämäärä	Allekirjoitus

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LAPPEENRANNAN TEKNILLINEN YLIOPISTO
LUT Kone

Pöytäkirjan numero ____________

ISKUKOE

pWPS	-	Nimikemerkintä:
Sovellustandardi	***SFS-EN ISO 9016, EN ISO 148-1***	*Muoto: 1 2 3 a/b*
Asiakas / viite	***Sanvik / Jussi Tuominen***	*1: sauvan tyyppi (V tai U)*
Perusaine	***Domex 500ML / G24Mn6***	*2: loven paikka (W tai H)*
Aineenpaksuus	***25 mm***	*3: lovetun pinnan suunta (S tai T)*
Hitsityyppi	***BW***	*a: loven etäisyys vertailuviivasta*
Hitsausprosessi	***135***	*b: koekappaleen ja sauvan pinnan*
Hitsausaine	***Lincoln SupraMig Ultra ø1.2***	*välinen etäisyys*
Huomautuksia	***Iskusauvat kokeesta S20075. Sauvat pinnan puolelta, 2 mm levypinnan alapuolelta. Sauvat 1, 2 ja 3 ovat hitsistä, sauvat 4, 5 ja 6 Domexin puolelta ja sauvat 7, 8 ja 9 valuteräksen puolelta.***	

Koesauva Nro	Nimike	Sauvan mitat / mm	Koelämpötila / °C	Vasaran energia/ J	Iskusitkeys J	Murtuman sijainti	Murtuman tyyppi	Virheen tyyppi ja koko
75.1	VWT0/2	10x10x55	-30	300	33	Weld	-	-
75.2	"	"	"	"	31	"	-	-
75.3	"	"	"	"	30	"	-	-
Keskiarvo	"	"	"	"	**31**	"	-	-
75.4	VHT2/2	"	"	"	52	HAZ Domex	-	-
75.5	"	"	"	"	45	"	-	-
75.6	"	"	"	"	58	"	-	-
Keskiarvo	"	"	"	"	**52**	"	-	-
75.7	VHT2/2	"	"	"	25	HAZ G	-	-
75.8	"	"	"	"	26	"	-	-
75.9	"	"	"	"	24	"	-	-
Keskiarvo	"	"	"	"	**25**	"	-	-
	"	"	"	"		-	-	-
	"	"	"	"		-	-	-
	"	"	"	"		-	-	-
Keskiarvo	"	"	"	"		-	-	-

Iskukokeen koetulosten mukaisesti koetulos " ______________________________".

Testauksen suorittaja	
Päivämäärä 1.2.2019	Allekirjoitus Esa Hiltunen
Kokeen valvoja	
Päivämäärä	Allekirjoitus

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LAPPEENRANNAN TEKNILLINEN YLIOPISTO
LUT Kone

Pöytäkirjan numero ____________

ISKUKOE

pWPS	-	Nimikemerkintä:
Sovellustandardi	***SFS-EN ISO 9016, EN ISO 148-1***	*Muoto: 1 2 3 a/b*
Asiakas / viite	***Sanvik / Jussi Tuominen***	*1: sauvan tyyppi (V tai U)*
Perusaine	***Domex 500ML / G24Mn6***	*2: loven paikka (W tai H)*
Aineenpaksuus	***25 mm***	*3: lovetun pinnan suunta (S tai T)*
Hitsityyppi	***BW***	*a: loven etäisyys vertailuviivasta*
Hitsausprosessi	***135***	*b: koekappaleen ja sauvan pinnan välinen etäisyys*
Hitsausaine	***Lincoln SupraMig Ultra Ø1.2***	
Huomautuksia	***Iskusauvat kokeesta 1. Sauvat pinnan puolelta, 2 mm levypinnan alapuolelta. Sauvat 1, 2 ja 3 ovat hitsistä, sauvat 4, 5 ja 6 Domexin puolelta ja sauvat 7, 8 ja 9 valuteräksen puolelta.***	

Koesauva Nro	Nimike	Sauvan mitat / mm	Koelämpötila / °C	Vasaran energia/ J	Iskusitkeys J	Murtuman sijainti	Murtuman tyyppi	Virheen tyyppi ja koko
1.1	VWT0/2	10x10x55	-30	300	120	Weld	-	-
1.2	"	"	"	"	117	"	-	-
1.3	"	"	"	"	112	"	-	-
Keskiarvo	"	"	"	"	**116**	"	-	-
1.4	VHT2/2	"	"	"	198	HAZ Domex	-	-
1.5	"	"	"	"	206	"	-	-
1.6	"	"	"	"	217	"	-	-
Keskiarvo	"	"	"	"	**207**	"	-	-
1.7	VHT2/2	"	"	"	32	HAZ G	-	-
1.8	"	"	"	"	66	"	-	-
1.9	"	"	"	"	50	"	-	-
Keskiarvo	"	"	"	"	**49**	"	-	-
	"	"	"	"		-	-	-
	"	"	"	"		-	-	-
	"	"	"	"		-	-	-
Keskiarvo	"	"	"	"		-	-	-

Iskukokeen koetulosten mukaisesti koetulos " ______________________________ ".

Testauksen suorittaja

Päivämäärä	Allekirjoitus
18.6.2019	Esa Hiltunen

Kokeen valvoja

Päivämäärä	Allekirjoitus

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LAPPEENRANNAN TEKNILLINEN YLIOPISTO
LUT Kone

Pöytäkirjan numero ____________

ISKUKOE

pWPS	-	Nimikemerkintä:
Sovellustandardi	***SFS-EN ISO 9016, EN ISO 148-1***	*Muoto: 1 2 3 a/b*
Asiakas / viite	***Sanvik / Jussi Tuominen***	*1: sauvan tyyppi (V tai U)*
Perusaine	***Domex 500ML / G24Mn6***	*2: loven paikka (W tai H)*
Aineenpaksuus	***25 mm***	*3: lovetun pinnan suunta (S tai T)*
Hitsityyppi	***BW***	*a: loven etäisyys vertailuviivasta*
Hitsausprosessi	***135***	*b: koekappaleen ja sauvan pinnan*
Hitsausaine	***Lincoln SupraMig Ultra Ø1.2***	*välinen etäisyys*
Huomautuksia	***Iskusauvat kokeesta 2. Sauvat pinnan puolelta, 2 mm levypinnan alapuolelta. Sauvat 1, 2 ja 3 ovat hitsistä, sauvat 4, 5 ja 6 Domexin puolelta ja sauvat 7, 8 ja 9 valuteräksen puolelta.***	

Koesauva Nro	Nimike	Sauvan mitat / mm	Koelämpötila / °C	Vasaran energia/ J	Iskusitkeys J	Murtuman sijainti	Murtuman tyyppi	Virheen tyyppi ja koko
2.1	VWT0/2	10x10x55	-30	300	82	Weld	-	-
2.2	"	"	"	"	57	"	-	-
2.3	"	"	"	"	74	"	-	-
Keskiarvo	"	"	"	"	**71**	"	-	-
2.4	VHT2/2	"	"	"	215	HAZ Domex	-	-
2.5	"	"	"	"	235	"	-	-
2.6	"	"	"	"	223	"	-	-
Keskiarvo	"	"	"	"	**224**	"	-	-
2.7	VHT2/2	"	"	"	50	HAZ G	-	-
2.8	"	"	"	"	57	"	-	-
2.9	"	"	"	"	43	"	-	-
Keskiarvo	"	"	"	"	**50**	"	-	-
	"	"	"	"		-	-	-
	"	"	"	"		-	-	-
	"	"	"	"		-	-	-
Keskiarvo	"	"	"	"		-	-	-

Iskukokeen koetulosten mukaisesti koetulos " ______________________________".

Testauksen suorittaja	
Päivämäärä 18.6.2019	Allekirjoitus Esa Hiltunen
Kokeen valvoja	
Päivämäärä	Allekirjoitus

APPENDIX 9. TRANSVERSE TENSILE STRENGTH TEST REPORTS

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HITSAUSLIITOKSEN POIKITTAINEN VETOKOE

Pöytäkirjan numero ______

pWPS	-
Sovellustandardi	***SFS-EN 895***
Asiakas / viite	***Sanvik / Jussi Tuominen***
Perusaine	***Domex 500ML / G24Mn6***
Aineenpaksuus	***25 mm***
Hitsityyppi	***BW***
Hitsausprosessi	***135***
Hitsausaine	***Lincoln SupraMig Ultra ø1.2***
Koelämpötila	***20 °C***
Huomautuksia	***Vetosauvat irroitettu siten, että pintasauvat ovat n. 2 mm pinnasta ja juurisauvat n. 4 mm levyn alapinnalta (auki olevan juuren paksuus koneistettu pois).***

Re = Fe / So

Rm = Fm / So

Lo = 5,65 * sqrt (So)

A =(Lu-Lo) / Lo

Z = (So-Su) / So

Koesauva Nro/sijainti	Mitat/halkaisija mm	Poikkipinta So / mm2	Myötövoima Fe / kN	Myötöraja Re / N/mm2	Murtovoima Fm / kN	Murtolujuus Rm / N/mm2	Alkumittapituus Lo / mm	Loppumittapit. Lu / mm	Murtovenymä A / %	Poikkip./murto Su / mm2	Murtokurouma Z / %	Murtuman sijainti	Huom!
S15020p	*24,8x9,9*	*245,52*	*106*	*431,7*	*147,6*	*601,0*	*88,7*	*103,8*	*17,0*	-	-	*PA*	*Pintasauva*
S15020j	*24,8*9,9*	*245,52*	*106*	*431,7*	*147,8*	*602,1*	*88,9*	*)	*)	-	-	*PA*	*Juurisauva*
S20075p	*24,7*9,9*	*244,53*	*111*	*453,9*	*150,1*	*613,8*	*89,8*	*104,8*	*16,7*	-	-	*PA*	*Pintasauva*
S20075j	*24,7*10*	*247*	*108*	*437,2*	*147,3*	*596,3*	*89,7*	*)	*)	-	-	*PA*	*Juurisauva*

*) Sauvan murtuma alkumittapituuden ulkopuolella ja murtovenymää ei voinut määrittää

Kaikki sauvat murtuivat materiaalin G24Mn6 puolelta perusaineesta

Vetokokeen koetulosten mukaisesti koetulos " ______________________ ".

Testauksen suorittaja	***Esa Hiltunen***	Kokeen valvoja	
Päivämäärä ***24.1.2019***	Allekirjoitus	Päivämäärä	Allekirjoitus

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HITSAUSLIITOKSEN POIKITTAINEN VETOKOE

Pöytäkirjan numero ________

pWPS	-
Sovellustandardi	***SFS-EN 895***
Asiakas / viite	***Sanvik / Jussi Tuominen***
Perusaine	***Domex 500ML / G24Mn6***
Aineenpaksuus	***25 mm***
Hitsityyppi	***BW***
Hitsausprosessi	***135***
Hitsausaine	***Lincoln SupraMig Ultra ø1.2***
Koelämpötila	***20*** °C
Huomautuksia	***Vetosauvat irroitettu siten, että pintasauvat ovat n. 2 mm pinnasta ja juurisauvat n. 4 mm levyn alapinnalta (auki olevan juuren paksuus koneistettu pois). Sandvikin hitsaamat hitsit.***

Re = Fe / So

Rm = Fm / So

Lo = 5,65 * sqrt (So)

A =(Lu-Lo) / Lo

Z = (So-Su) / So

Koesauva Nro/sijainti	Mitat/halkaisija mm	Poikkipinta So / mm2	Myötövoima Fe / kN	Myötöraja Re / N/mm2	Murtovoima Fm / kN	Murtolujuus Rm / N/mm2	Alkumittapituus Lo / mm	Loppumittapit. Lu / mm	Murtovenymä A / %	Poikkip./murto Su / mm2	Murtokurouma Z / %	Murtuman sijainti	Huom!
1P	*24,9x9,65*	*240,3*	*117*	*486,9*	*148,8*	*619,2*	*89,5*	*104,8*	*17,1*	-	-	*Hitsi*	*Pintasauva*
1J	*24,2x9,8*	*237,2*	*103*	*434,2*	*143,2*	*603,7*	*89*	-	**)*	-	-	*PA*	*Juurisauva*
2P	*25,3x9,5*	*242,1*	*118*	*487,4*	*148,8*	*614,6*	*88,4*	*101,8*	*15,2*	-	-	*Hitsi*	*Pintasauva*
2J	*25,2x9,5*	*247,0*	*111*	*449,4*	*149,6*	*605,7*	*87,5*	-	**)*	-	-	*PA*	*Juurisauva*

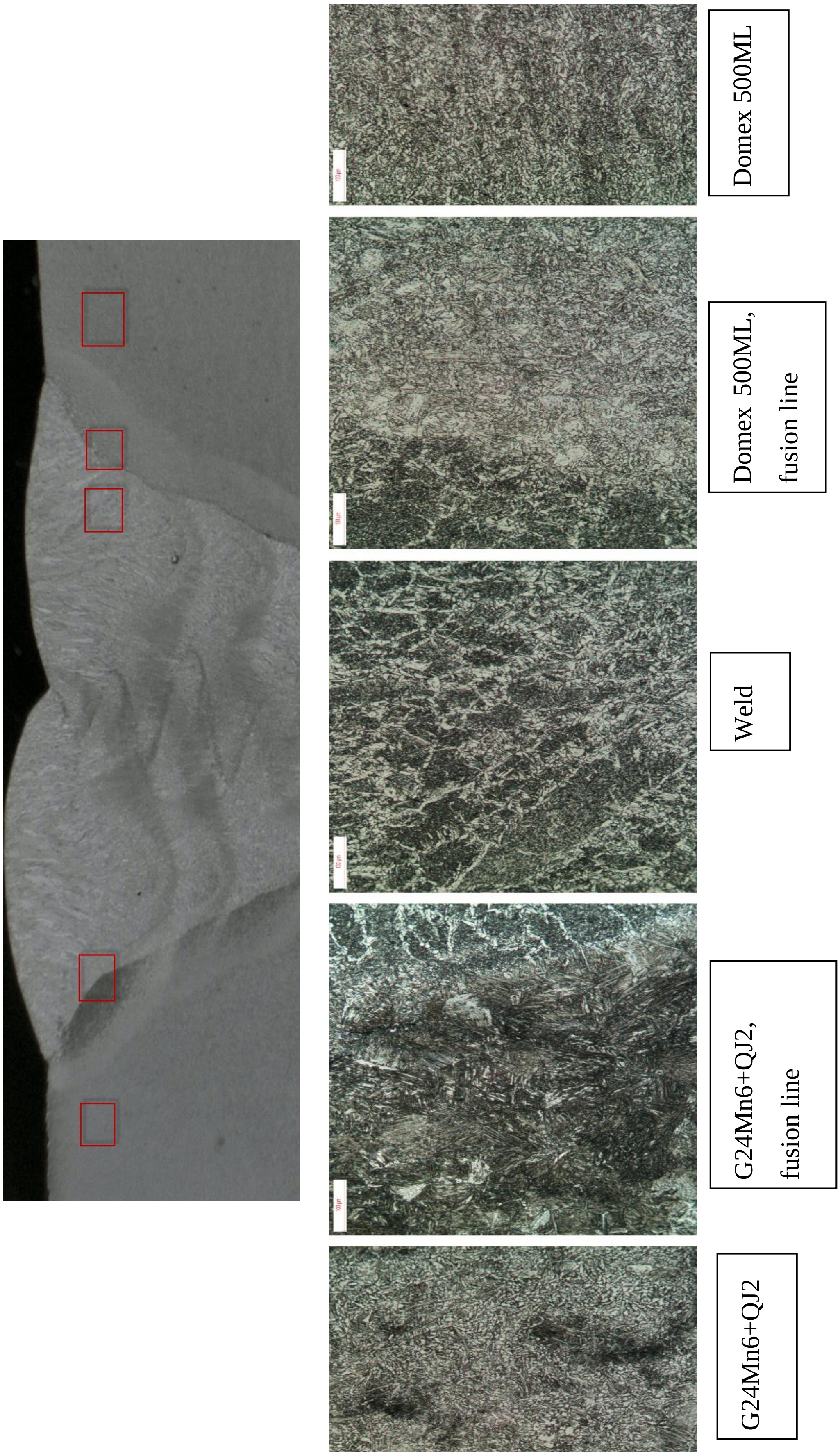
*) Sauvan murtuma alkumittapituuden ulkopuolella ja murtovenymää ei voinut määrittää

Kaikki sauvat murtuivat materiaalin G24Mn6 puolelta perusaineesta

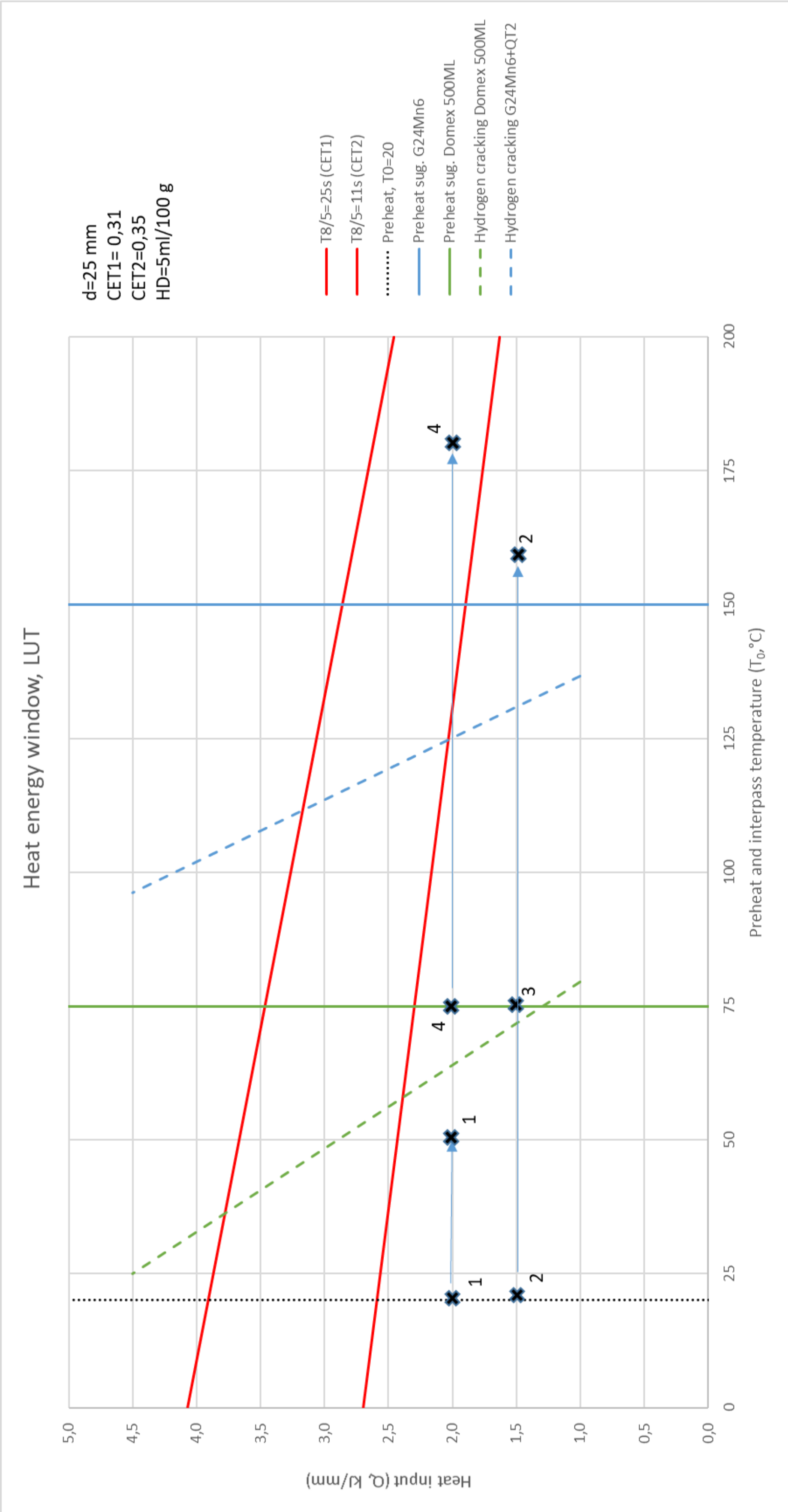
Vetokokeen koetulosten mukaisesti koetulos " ________________ ".

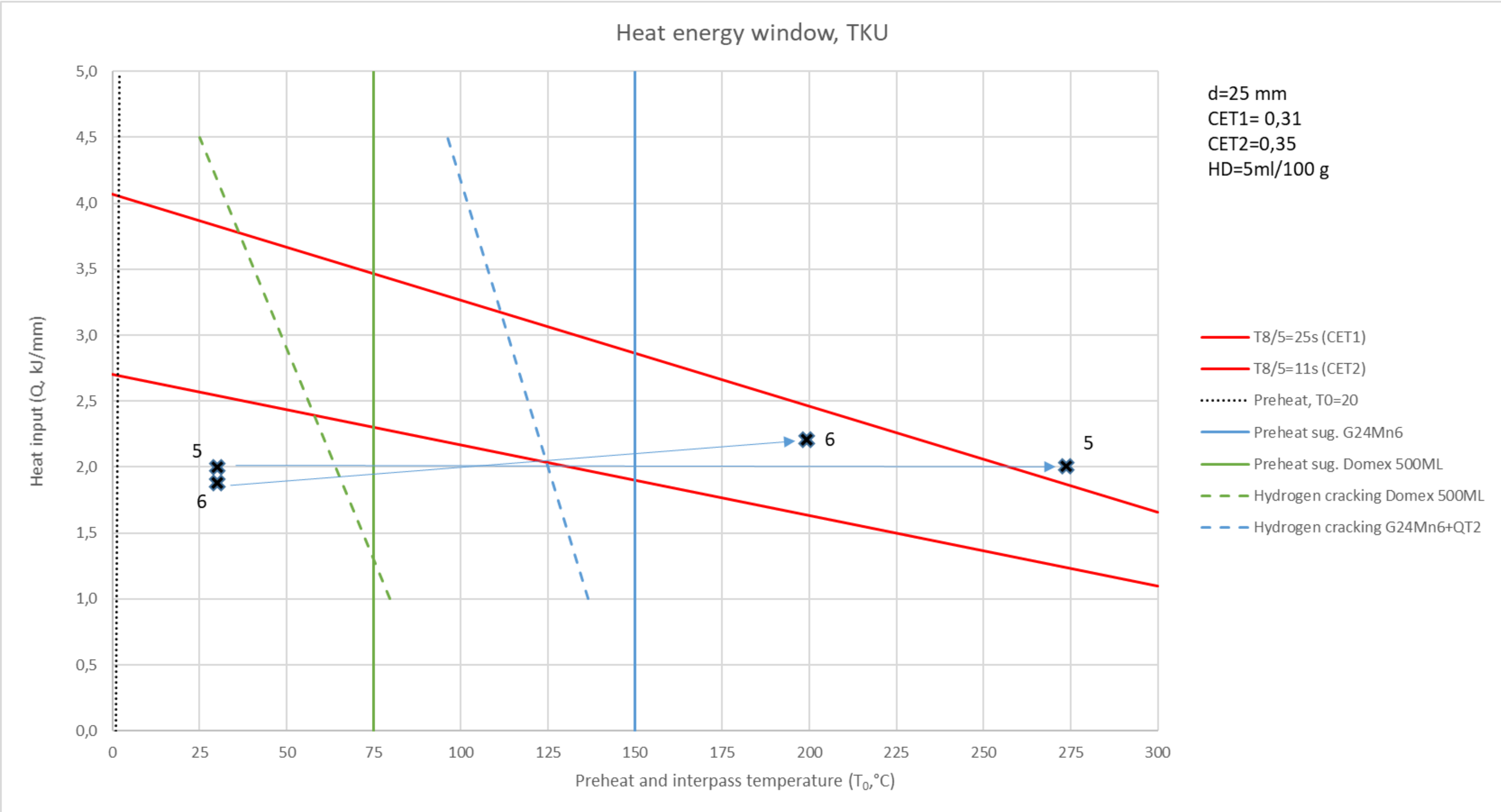
Testauksen suorittaja	***Esa Hiltunen***	Kokeen valvoja	
Päivämäärä ***31.5.2019***	Allekirjoitus	Päivämäärä	Allekirjoitus

APPENDIX 10. MICROSCOPIC CROSS-SECTION OF S15075

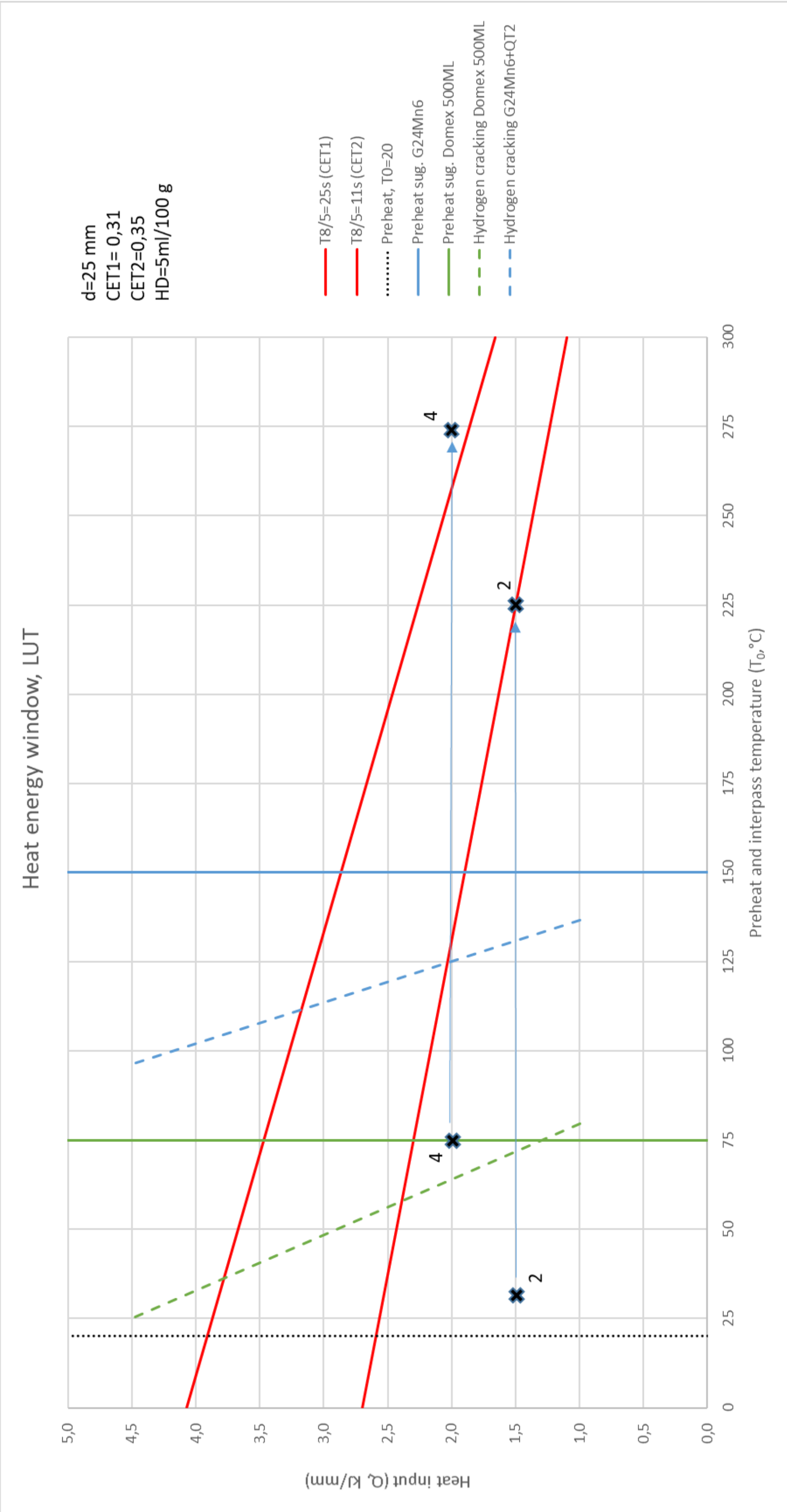


APPENDIX 11. HEAT ENERGY WINDOWS WITH CORRECTED VALUES



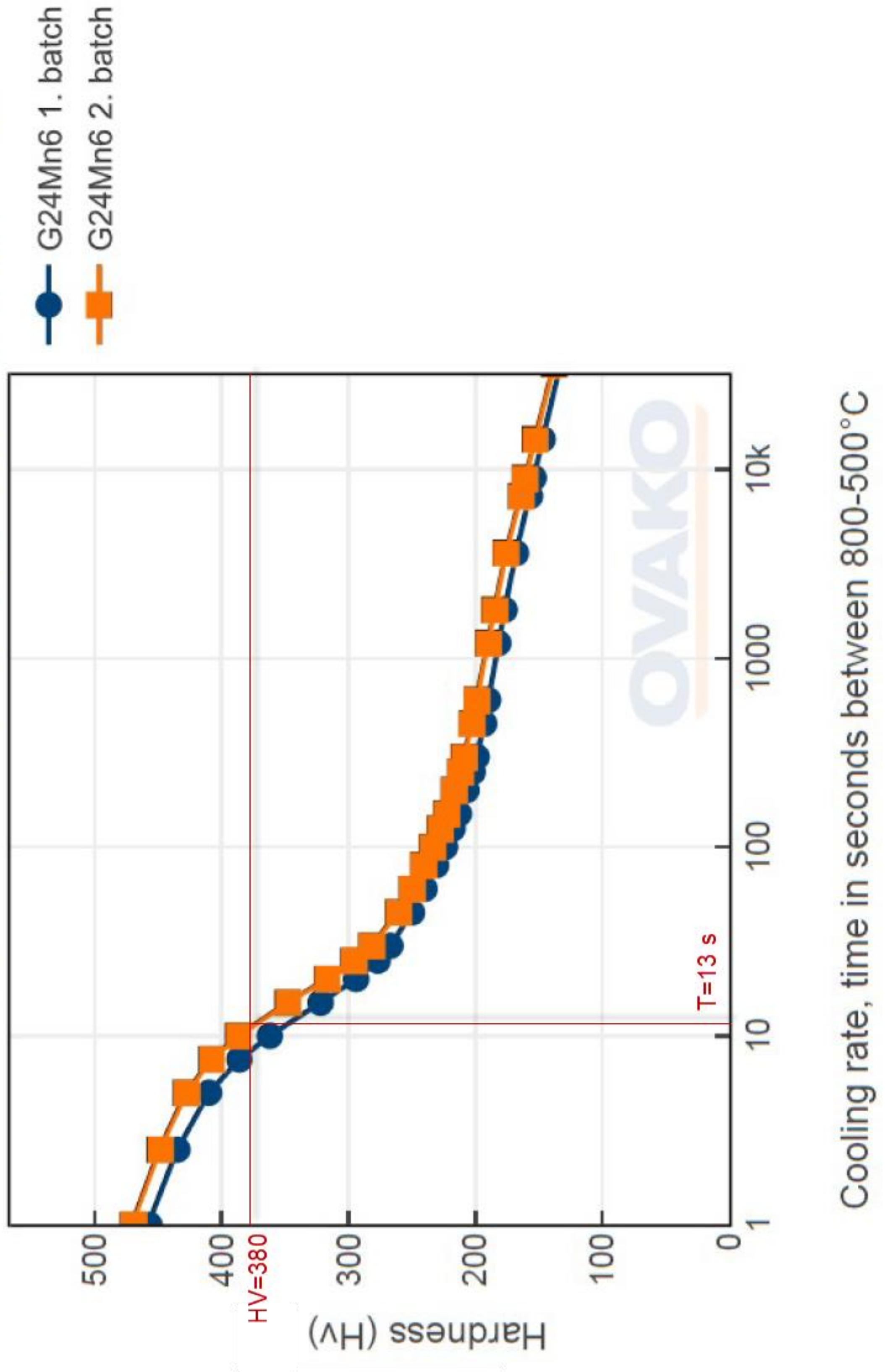

Heat energy window, TKU
d=25 mm
CET1= 0,31
CET2=0,35
HD=5ml/100 g
T8/5=25s (CET1)
T8/5=11s (CET2)
Preheat, T0=20
Preheat sug. G24Mn6
Preheat sug. Domex 500ML
Hydrogen cracking Domex 500ML
Hydrogen cracking G24Mn6+QT2
Heat input (Q, kJ/mm)
Preheat and interpass temperature (T0,°C)
5
6
6
5
5,0
4,5
4,0
3,5
3,0
2,5
2,0
1,5
1,0
0,5
0,0
0
25
50
75
100
125
150
175
200
225
250
275
300

APPENDIX 12. INTERPASS TEMPERATURE CORRECTION FOR TESTS 2 AND 4



APPENDIX 13. COOLING RATE OF G24MN6+QT2, BATCHES 1 AND 2

material:		C (%)	Mn (%)	Cr (%)	Mo (%)	V (%)	Cu (%)	Ni (%)	Si (%)	P (%)	S (%)	Al (%)	Nb (%)	N	Ti	CEV (%)	CET (%)
G24Mn6+QT2	batch 1	0,214	1,510	0,064	0,008	0,012	0,039	0,047	0,370	0,016	0,006	0,053	0,017	0,000	0,001	**0,488**	**0,372**
	batch 2	0,222	1,578	0,065	0,004	0,012	0,037	0,041	0,414	0,016	0,005	0,032	0,010	0,008	0,000	**0,506**	**0,386**



APPENDIX 14. MEASURED COOLING TIME AND HARDNESS OF TEST PIECES

material:		C (%)	Mn (%)	Cr (%)	Mo (%)	V (%)	Cu (%)	Ni (%)	Si (%)	P (%)	S (%)	Al (%)	Nb (%)	N	Ti	CEV (%)	CET (%)
G24Mn6+QT2	batch 1	0,214	1,510	0,064	0,008	0,012	0,039	0,047	0,370	0,016	0,006	0,053	0,017	0,000	0,001	**0,488**	**0,372**
	batch 2	0,222	1,578	0,065	0,004	0,012	0,037	0,041	0,414	0,016	0,005	0,032	0,010	0,008	0,000	**0,506**	**0,386**