LUT UNIVERSITY
LUT School of Energy Systems
LUT Mechanical Engineering

Joona Toikka

REPAIR WELDING OF HIGH ALLOYED AUSTENITIC CAST STAINLESS STEEL

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Examiners: Professor Timo Björk
D. Sc. (Tech.) Miikka Karhu

TIIVISTELMÄ

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Tarkastajat: Professori Timo Björk
Tekniikan tohtori Miikka Karhu

Hakusanat: kuumahalkeilu, austeniittinen ruostumaton teräs, TIG hitsaus, korjaushitsaus, valukappaleet

Tämän tutkimuksen tarkoituksena oli tuottaa toimiva korjaushitsausohjeistus korkeaseosteiselle austeniittiselle ruostumattomalle teräkselle. Materiaalia aiotaan käyttää valetuissa pumpun osissa, prosesseissa joissa pumpataan kuumia ja vahvoja typpi- sekä rikkihappoja. Työ toteutettiin austeniittisen ruostumattoman teräksen kuumahalkeilua käsittelevää kirjallisuutta tutkimalla. Kirjallisuushavaintoja kuumahalkeilusta ja sen välttämisestä, austeniittista ruostumatonta terästä hitsattaessa, testattiin laboratoriossa. Testikappaleisiin suoritettujen hitsauskokeiden tuloksia analysoitiin hitsauskokeiden välillä kokeissa käytettyjen hitsausparametrien tarkentamiseksi.

Hitsauskokeissa keskityttiin lämmöntuonnin minimoimiseen. Pulssihitsauksen avulla laskennallinen lämmöntuonti saatiin aiempia testejä matalammalle tasolle. Matala lämmöntuonti ei kuitenkaan varmistanut hyväksyttäviä hitsejä. Kuumahalkeilua oli nähtävissä osassa testihitsejä, vaikka osa vastaavilla parametreillä valmistetuista hitseistä säilyi ehjänä laskennallisten lämmöntuontien vastatessa toisiaan. Perusmateriaalin sekoittumisaste vaikutti kuumahalkeilun ilmentymiseen hitsissä. Parhaissa testihitseissä tämä suhdeluku oli alle 0.50. Kokeet osoittivat, että vastaava perusmateriaalin sekoittumissuhde hitsiin tulee saavuttaa, jottei hitsissä ilmenisi kuumahalkeilua.

Testipumpun pesään suoritettujen hitsauskokeiden tulokset olivat ristiriidassa laboratoriossa suoritettujen hitsauskokeiden kanssa. Havaitut virheet hitseissä yhdessä kirjallisuusosion tiedon kanssa vahvistavat käytetyn materiaalin kuumahalkeiluherkkyyden olevan erittäin suuri. Materiaalin kemiallista koostumusta on muutettava mikäli sen herkkyyttä kuumahalkeilulle halutaan vähentää. Koostumuksen muokkaamisen jälkeen työssä käytettyjä ja laboratoriotesteissä hyväksi todettuja hitsausparametrejä voidaan hyödyntää lämmöntuonnin laskemiseen korjaushitsauksissa. Materiaalin nykyinen koostumus tekee siitä kuumahalkeilualttiina vaikeasti hitsattavan.

ABSTRACT

LUT University
LUT School of Energy Systems
LUT Mechanical Engineering

Joona Toikka

Repair welding of high alloyed austenitic cast stainless steel

Master's thesis

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63 pages, 51 figures, 13 tables and 1 appendix

Examiners: Professor Timo Björk
D. Sc. (Tech.) Miikka Karhu

Keywords: hot cracking, austenitic stainless steel, TIG welding, repair welding, casted components

This thesis aimed to produce an adequate repair welding procedure for high alloyed austenitic stainless steel. Material intended to be used is for casted pump parts in applications where hot and concentrated nitric and sulfuric acids are present. Literature from the topic of hot cracking was studied. Findings made from previous tests and literature were tested in laboratory. Welding tests made to sample pieces casted from the studied material were analyzed to refine welding parameters used.

In welding tests heat input caused by welding was tried to be minimized. Due applied pulse welding heat input was achieved to be kept on lower levels compared to previous independent tests. Low heat input didn´t still guarantee adequate repair welds. Cracks emerged to some of the test welds whereas others remained intact with heat inputs close to one another. Base material mixing ratio affected to the cracking which in best test results appeared only in base material of heat affected zone (HAZ). On test welds it could be seen that base material mixing ratio of below 0.50 resulted welds where no cracks were present in weld metal.

The results of welding tests in which welding parameters from laboratory tests were used in welding of actual pump casing conflicted with the laboratory test results. These failures in welds together with earlier literature findings indicated that material in weldability point of view can be very prone to hot cracking. Changes to materials chemical composition needs to be made so that its susceptibility to hot cracking decreases. After these modifications, parameters which were found to be applicable in laboratory test can be tested again in welding of actual pump parts. With a current chemical composition of the material studied welding is possible but it most likely leads to hot cracking of a produced weld.

ACKNOWLEDGEMENTS

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Greatest acknowledgements I still want to point out for my family. Especially to my parents. Without their guidance and endless support through my whole life and different school grades to this point, upcoming graduation of mine and this thesis wouldn´t have happened. Thank you. You both have been perfect role models for me, siblings of mine and their children to look up to.

Joona Toikka
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LIST OF SYMBOLS AND ABBREVIATIONS

Cr_{eq}	Chrome equivalent
I	Arc current
I_b	Base arc current in pulse welding
I_m	Arithmetical average of arc current in pulse welding
I_p	Peak arc current in pulse welding
k	Thermal efficiency factor of welding process
Ni_{eq}	Nickel equivalent
Q	Heat input
U	Arc voltage
v	Travel speed of weld
T	Total duration of pulse cycle
t_b	Base current time in pulse welding
t_p	Pulse time in pulse welding
$t_{8/5}$	Cooling time from 800 to 500 °C
$t_{12/8}$	Cooling time from 1200 to 800 °C

Ar	Argon
C	Carbon
Cr	Chrome
Cu	Copper
He	Helium
Mo	Molybdenum
N	Nitrogen
Ni	Nickel
P	Phosphorus
S	Sulfur
Si	Silicon

AS1	Internal code for material studied
FCC	Face-centered cubic structure
FN	Ferrite number
GMAW	Gas metal arc welding
GTAW	Gas tungsten arc welding
HAZ	Heat affected zone
MMAW	Manual metal arc welding
NDT	Nondestructive testing
PAW	Plasma arc welding
pWPS	Preliminary Welding Procedure Specification
SAW	Submerged arc welding
SPFIN	Sulzer Pumps Finland Oy
TIG	Tungsten Inert Gas welding
WPS	Welding Procedure Specification

1 INTRODUCTION

This master´s thesis was done for Sulzer Pumps Finland Oy (SPFIN) located at Kotka, Finland. SPFIN produces pumps, agitators, mixers and compressors for wide range of industrial purposes and is a part of Sulzer Ltd under its Pumps Equipment division. Sulzer Ltd has 180 production and service locations around the world which employ around 16500 persons and had sales of 3.4 billion euros in 2019.

1.1 Background and motivations

SPFIN is aiming to use high alloyed austenitic stainless steel, containing high amount of silicon, in casted pump parts made for environments containing concentrated sulfuric and nitric acids. Internal code for this material still under research is AS1 at the moment. First castings ordered for material studying purposes out of AS1, which chemical composition follows closely Sandvik SX, were wet-end parts for a process pump. During visual inspection of the test castings defects were found. These faults were then opened, and repair welded. Penetrant fluid tests carried out after welding showed that failures still existed in three of five welds. Figure 1 shows faults in one of the welds. Failure on producing working repair weld showed that welding of AS1 needed to be studied more. Repair welding of casted parts entering to production is common procedure at SPFIN so guidelines for welding AS1 are needed. Repair welds made at factory need to be failure free so that those can be trusted to last the whole life cycle of a pump.

Figure 1. Weld in the first test piece. (Hurri, Sulzer Pumps Finland Oy)

1.2 Aim of the study

This thesis aims to clarify the process of repair welding of casted AS1 parts. Welding parameters, correct welding consumables and preparations needed in achieving adequate repair welds in AS1 are studied. Best combinations are used to form guidelines for repair welding AS1 at SPFIN´s factory in future.

1.3 Research problem and questions

Previous tests done with AS1 parts showed that porosity and other imperfections found in castings are difficult to repair by welding as the repair welds have also tendency to crack easily. Thesis focuses on sorting out the reasons behind the hot cracking when welding austenitic stainless steels, by examining material properties and effect of impurities to welding. High silicon content increases the corrosion resistance abilities against strong sulfuric acids when compared to more traditional austenitic stainless steels. This change is thought to affect negatively to the welding abilities of the material studied.

1.4 Methods

Reasons for cracking are studied by examining the written literature made from the subject. Laboratory tests are carried out along literature findings to search the best possible combinations of welding parameters, consumables and preparations needed in achieving acceptable repair welds in AS1 parts. Test welds are inspected visually, with penetrant fluid and by cutting the test specimen half from welds cross-section so that further microscopic and macroscopic examinations can be made. Finally repair welds for actual pump parts are made at SPFIN´s factory in Karhula by utilizing the findings made from laboratory tests.

1.5 Limitations

Corrosion resistance abilities of repair welds made during the tests aren´t studied in this thesis. If findings made in this thesis are used in repair welding of AS1 or similar material, corrosion resistance tests need to be made. Welds abilities to withstand corrosion in the acid surroundings corresponding to the liquids affecting to the pump parts in their normal use needs to be further investigated.

2 LITERATURE STUDY ON WELDING OF AUSTENITIC STAINLESS STEELS

Welding of austenitic stainless steels is possible with all the common arc welding processes, such as Gas Metal Arc Welding (GMAW), Gas Tungsten Arc Welding (GTAW), Manual Metal Arc Welding (MMAW), Plasma Arc Welding (PAW) and Submerged Arc Welding (SAW). Even though welding of austenitic steels is possible, it is also known to be difficult due to its face-centered cubic (FCC) atom structure. When comparing austenitic and ferritic stainless-steel grades, which have a body-centered cubic (BCC) atom structure, it can be seen that the bond between individual atoms is stronger in BCC structure. As the material expands due rising heat, FCC structure has more tendency to crack under similar conditions when compared to BCC structure. Because of this ability it can be stated that austenitic structure exhibits more frequently hot cracking in welded joints. To avoid hot cracking in austenitic stainless steels it is important to eliminate all other possible factors leading to it (Bernasovský, 2005, p.84). These factors will be explained later on in this thesis.

2.1 Material composition and properties of AS1

Difference in material composition of AS1 compared to more traditional austenitic stainless steel type 316 can be evaluated with Table 1 and Table 2. Chemical composition of AS1 along material certificate EN 10204 3.1, provided by the foundry used to manufacture the castings, can be seen in Table 1. Table 2 instead shows the chemical composition of volute case used as a reference. Case is casted from, material ASTM A743-98a CF8M, stainless steel type 316. Sulzer´s internal code for this material is 42.

Table 1. Chemical composition of casted AS1 test pieces. (Karhula Foundry test report)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu
0.012	5.02	1.76	0.007	0.006	17.27	18.14	0.46	1.91

Table 2. Chemical composition of casted stainless steel 316. (Dalian Green Precision Casting CO., Ltd., Certificate EN 10204 3.1)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu
0.05	0.60	0.72	0.029	0.008	18.30	9.40	2.24	0.00

Chemical compositions show that amounts of silicon (Si), nickel (Ni) and copper (Cu) are notably higher in AS1. It must also be noted that amounts of chromium (Cr) and molybdenum (Mo) have degreased over 1 % compared to stainless steel 316.

The content of chromium and molybdenum can be increased, making steel more resistant to corrosive conditions. It must be noticed that the content of nickel must also be increased to ensure the austenitic microstructure. (Kyrölainen, 2002, p.16) Amount of nickel needed in stabilizing the austenitic structure is around 8 %. Nickel also eases the formability, weldability and ductility of the stainless steels and because of that it is used commonly as an alloying material. It has been proven also that higher amount of copper in the steel composition increases the corrosion resistance against sulfuric acids (de Lima, 2019, p.2). The content of copper is increased at the cost of chromium and molybdenum in AS1 so that this ability is reached.

It has been demonstrated that a 3.5 % silicon composition improves the corrosion resistance of stainless steel in hot, concentrated nitric acid in the presence of oxidizing species (Laurent, 2017, p.1). High silicon composition ensures good corrosion resistance abilities also in high concentrated sulfuric acids. Sandvik SX´s corrosion resistance abilities against H_2SO_4 acid is presented in Figure 2. This isocorrosion diagram pictures the corrosion rate of 0.1 mm in a year as a line for Sandvik SX. In circumstances above the line corrosion rate is higher, and below the line lower, than 0.1 mm in a year. It is noticeable that the composition used has actually better abilities against corrosion at least in sub 160 °C liquid temperatures when the acid concentration is increased. This ability is compared with the abilities of other alloys in same conditions at Figure 3.

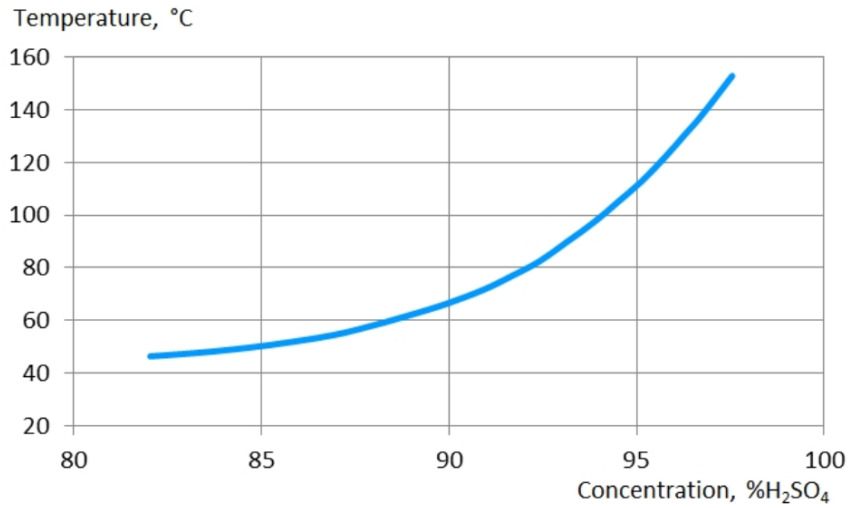


Figure 2. Corrosion diagram for Sandvik SX against H_2SO_4 in static conditions. (Sandvik SX datasheet)

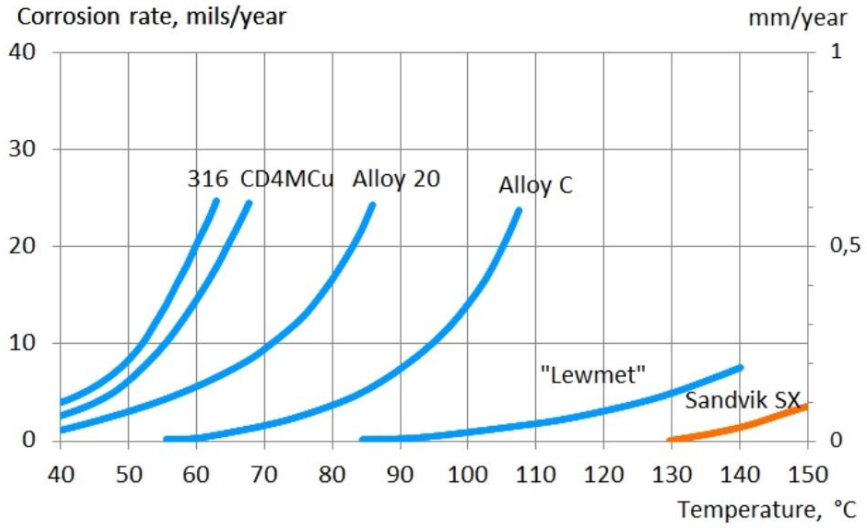


Figure 3. Approximated corrosion rates of different alloys in 98% H_2SO_4 at static conditions. (Sandvik SX datasheet)

The positive effect of high silicon content in steel compositions used at surroundings containing strong nitric acids (HNO_3) can be seen in Figure 4. Sandvik SX has excellent corrosion resistance abilities when process includes strong acids. Corrosion rates of steels that have 14 % of silicon alloy in their composition can be matched with Sandvik SX in such surroundings including strong acids. Sandvik SX has much lower 5 % silicon composition. Lower amount of silicon allows material to have other better abilities such as weldability for example. Sandvik SX should be welded with as low heat input as possible (max 1.0 kJ/mm). The interpass temperature shall be kept below 60 °C. Sandvik states that the welding

properties of SX are good. The welds produced with parameters mentioned are smooth and corrosion properties are comparable to the base material. (Sandvik, 2017, p.5)

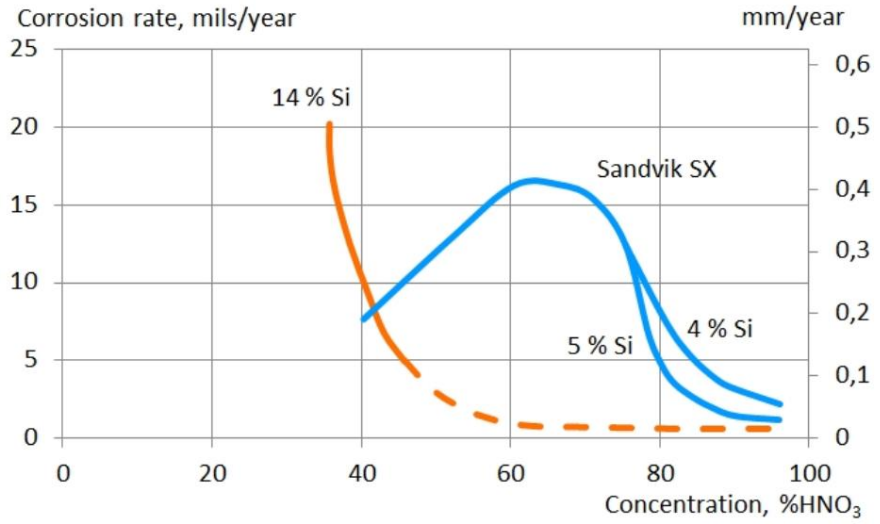


Figure 4. Effect of silicon content to corrosion resistance in HNO_3. (Sandvik SX datasheet)

2.2 Hot cracking

Hot cracking usually forms to the weld during solidification at weld metal or at parent metal in heat affected zone (HAZ) as liquation cracking. Liquation cracking is commonly noticed only when welds with austenitic steel base material are analyzed with destructive testing techniques. In thick pieces maximum crack length is usually just couple of millimeters which doesn´t usually appear as a leaking weld during a leak testing. Even still these cracks may cause problems such as corrosion, creep and reduced fatigue properties in welded joints. (Bernasovský, 2005, p.85) Solidification cracking is greatly affected by the solidification mode. It is known that ferritic solidification of weld leads to much lower sensitivity to hot cracking. Therefore, austenitic stainless steels are usually balanced in a way to provide ferritic solidification resulting a weld with ferrite content between 3-15 FN. Ferrite content can be affected by choosing the filler material in a way that weld forms out as ferritic. Also, the composition along with solidification model of stainless steel weld affects to the amount of ferrite in produced weld. (Kyrölainen, 2002, p.100)

Proper welding conditions decrease the possibilities of hot cracking in austenitic stainless steels. Impurities from surroundings should be kept minimal with optimum cleanliness and correct selection of welding consumables. Parameters and methods helping to prevent hot cracking failures when welding austenitic stainless steels are discussed in following chapters.

2.2.1 Impurities, weld metal chemistry and solidification mode

Hot cracking is strongly associated to impurities in molten material. From those impurities sulfur (S) and phosphorus (P) affect the most by moving in the molten material near to grain boundaries and interdendritic regions. Impurities form liquid films of low melting point phases which can cause susceptibility of cracking upon solidification when the temperature of base material and weld decreases. (SFS-EN 1011-3:2018, p.12) Because of these unwanted abilities sulfur and phosphorus must be minimized in casting phase to ease possible future processing of steel, for example welding of austenitic steels (Kyrölainen, 2002, p.20).

Carbon (C) and nitrogen (N) are vital elements on balancing and strengthening austenitic structure but both elements also affect negatively to it if amounts of them surpass maximum composition values set up for the material. These mentioned chemical elements are the main cause of failures occurring in welds, most usual of which is hot cracking when welding austenitic stainless steels. Porosity in weld may also occur if the vaporized gasses released from the molten material get caught to the weld pool during solidification.

Susceptibility to solidification cracking on point of austenitic stainless steels has been studied for example by Finnish researchers Kujanpää and Suutala with their team. They made a series of test welds with AISI/AWS 300 series steels, see Figure 5. Results of these test were discussed in studies published from the topic. Team concluded that solidification cracking is highly dependent on the solidification mode, which is affected essentially by the chemistry of the weld metal more specifically its chrome equivalent (Cr_{eq}) and nickel equivalent (Ni_{eq}). Duplex ferritic-austenitic solidification in welds with median values of 1.5 - 2.0 Cr_{eq}/Ni_{eq} ratio produce the minimum cracking susceptibility. As a comparison austenitic solidification welds, Cr_{eq}/Ni_{eq} ratio below 1.4, commonly are very susceptible for cracking. Material´s solidification cracking susceptibility can be estimated prior welding if exact

material composition is known. This tendency for cracking can be estimated with the mentioned value of Cr_{eq}/Ni_{eq} and with sum of impurities, phosphor and sulfur (P + S). (Kujanpää et al., 1980) Cr_{eq} and Ni_{eq} values can be calculated with Equation 1 and 2.

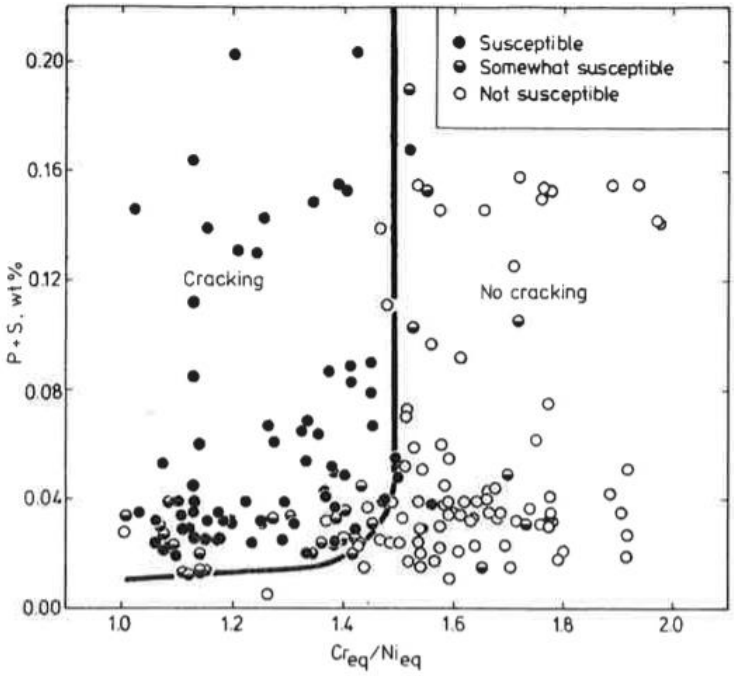


Figure 5. Results of hot cracking tests plotted on field of Cr_{eq}/Ni_{eq} – (P + S). (Kujanpää et al.)

$$Cr_{eq} = \%Cr + \%Mo + 1.5\%Si + 0.5\%Nb \quad (1)$$

$$Ni_{eq} = \%Ni + 30\%C + 0.5\%Mn \quad (2)$$

2.2.2 Geometry of weld

The shape of the weld cross-section, more precisely the width to depth ratio of it, must be considered when welding austenitic steels. Large width to depth ratio decreases the risk of hot cracking. With a proper choice of welding parameters this ratio can be affected and adjusted to be larger. It is stated that this ratio must be within values 1.5 - 2.0 to prevent hot cracking. (Kyrölainen, 2002, p.187) Welding standard SFS-EN 1011-3:2018 guides to use even lower width to depth ratio of 1.0-1.5 for the weld pool. It can be assumed that a correct

ratio will be found between these values presented. In repair welding, correct shape of weld is ensured by grinding the surrounding of the crack so that width to depth ratio of the grinded area is within the values mentioned. Weld which depth is larger than its width eases the cracking by guiding and concentrating the impurities to the middle of the weld, see Figure 6.

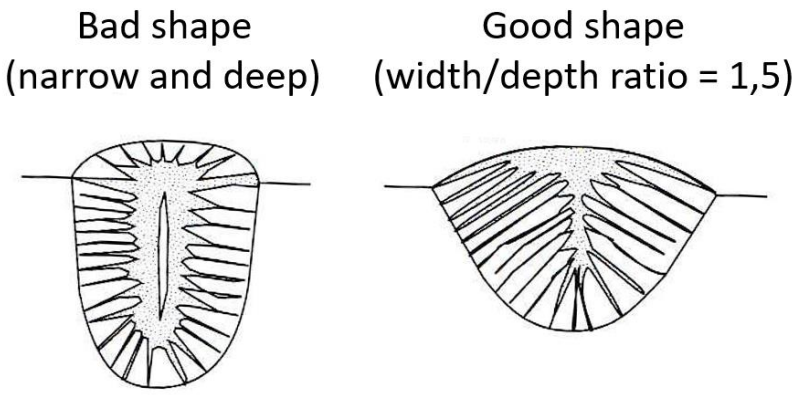


Figure 6. Illustration of weld cross sections in terms of preventing hot cracking. (Kyröläinen)

Other important factors that should be noticed, when welding austenitic stainless steels and aiming for the best possible outcome, are the visual shape of the weld and the weld procedure itself. Convex shape of the weld has been proven to act better against hot cracking compared to concave shaped weld when the base material is austenitic steel. The weld bead should be made with direct transportation and any unnecessary weaving should also be avoided. (Kyrölainen, 2002, p.187) This way the actual melt pool will stay as small as possible and best coverage for shield gas is achieved. Good width to depth ratio as mentioned in Figure 6 still needs to be fulfilled. Welding procedure itself also needs to be planned properly so that minimum amount or no multipass welding is needed. This ensures minimal amount of impurities to end up into the weld. All unnecessary inconsistencies in welds should also be avoided for the same reasons. If weld bead needs to be continued attention must be paid for thorough grinding. Any cracking in previous weld pass needs to be grinded off for best possible outcome.

2.2.3 Solidification of weld

The main problems encountered in solidification of welds when welding stainless steels with Tungsten Inert Gas (TIG) process are a loss of nitrogen and manganese from the weld pool,

the formation of nitrogen bubbles which do not fully escape from the molten pool and get caught in the mushy zone forming pores and precipitation to the weld and HAZ. The effect of losing the vaporized nitrogen from the weld pool can be tackled by changing the composition of shielding gas and filler material used. For example, by mixing few percent of nitrogen to argon shielding gas as a counteract to the loss of nitrogen via bubbles formation. Filler metal with higher nitrogen solubility will also have similar affect. The pressure of the shield gas slows the evaporation of manganese from the pool. Good coverage for the shield gas is achieved when the weld bead is kept narrow. (Berns, 2013, p.124-125) Manganese can also be added to the weld along filler material. This increase in content of manganese helps in preventing of hot cracking by increasing content of soluble nitrogen in material. (Senk, D. p.5)

Lowering travel speed of welding also helps as the weld pool won´t form out as tear drop. Tear drop shaped pool eases the movement of impurities towards the centerline of weld simultaneously easing the crack formation as molten material solidifies vertically against the fusion line of molten and solid material. If welding speed is high and molten material forms out as a tear drop, possibility for situation in which solidified grains from both sides of weld grow to the middle of the weld and merge exists. In that situation impurities at weld centerline may form out as a hot crack, see Figure 7. (Kyrölainen, 2002, p.62) This effect is similar to concentration of impurities caused by narrow and deep weld.

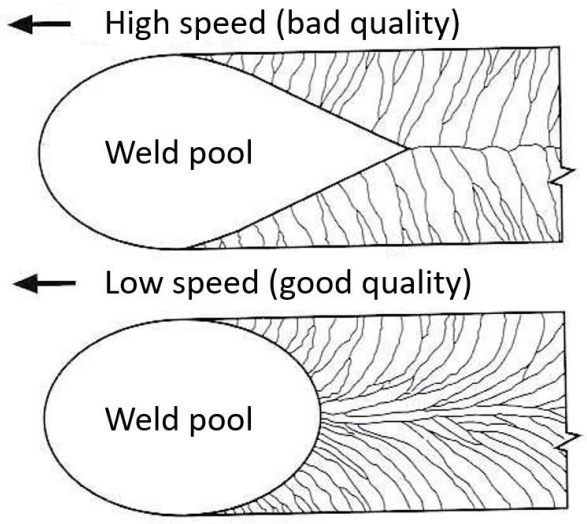


Figure 7. The effect of welding speed on concentration of impurities to the centerline of weld. (Kyröläinen)

2.3 Corrosion resistance

Corrosion resistance of austenitic stainless steels is mainly formed with chromium and molybdenum. It is vital that these elements are evenly distributed throughout parent and weld metal. Partial sensitization by carbides and nitrides, or precipitation of intermetallic phases should be avoided due the depletion of the mentioned main elements in these areas. Weld area should also be kept as free as possible from any impurities originated from the surroundings of welder's workstation. Contamination of weld may cause carbon and nitrogen deposits which lead to lower corrosion resistance in weld areas. (SFS-EN 1011-3:2018, p.13)

These changes in the weld leading to lower corrosion resistance can be tackled by keeping the heat input and interpass temperatures low in multipass welding, see 2.4.2. Welding consumables used should also be chosen in a way that they either match or are over-alloyed when compared with the parent metal. Consumables should not include any excess carbon or nitrogen. Properly chosen consumables can be assumed to be even more critical with AS1 due the fact that the material composition has already smaller amounts of chromium and molybdenum in it to prevent carbides and nitrides from forming unwanted changes to material, described above.

2.4 Welding methods and parameters

Gas Tungsten Arc Welding (GTAW) also known as TIG welding is commonly used method in welding of stainless steels. Mainly as the weld pool and weld penetration are easy to handle while welding but it has also been discovered that the produced weld is usually very pure of impurities which means that the weld produced is also metallurgically solid. On the other hand, maximum material thickness to be welded with TIG is about 6 mm. Because of this limitation multipass welding is needed in some applications. Multipass welding can increase the possibility of failures occurring in welds. (Kyrölainen, 2002, p.351) SPFIN uses TIG welding when there is a need for repairing cracks or porosity found in casted parts that have already entered factory for manufacturing. TIG welding is also going to be the method used in experiments made in this thesis.

2.4.1 TIG welding

In TIG welding the arc is formed between a pointed tungsten electrode and the workpiece in an atmosphere or argon (Ar), helium (He) or mixture of both. In DC welding, normally applied when welding steels, electrode usually has negative polarity and the work piece has positive polarity. Positive effects of negative electrode polarity are strong arc concentration, deep weld penetration and small electrode consumption. Changing the polarities also change these effects vice versa. Electrode is not consumed during welding so additional metal needed in filling the joints must be added separately in a form of wire. (Lucas, 1990, p. 9) Working principle diagram in Figure 8 shows the essential machinery; electrode and electrode holder, AC or DC power source and shielding gas supply needed in TIG welding.

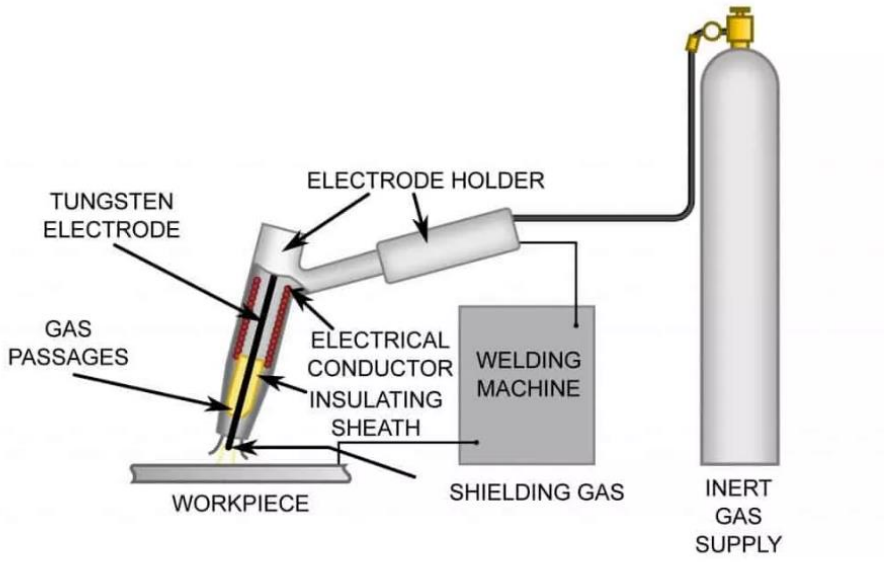


Figure 8. Working principle of TIG welding machinery. (www.weldingpros.net)

TIG welding can be carried out also by pulsating the electrical current used. In pulse TIG welding current used changes between two values, background current and peak current, see Figure 9. Weld pool and penetration of weld are created during the peak current. Background current allows the weld pool to cool down and solidify. Pulse TIG welding is used to ease the welder´s control of weld pool and heat input. (Kyrölainen, 2002, p.352) It can be stated that same weld penetration can be achieved with pulse TIG welding compared to constant current at the same time having significantly lower heat input.

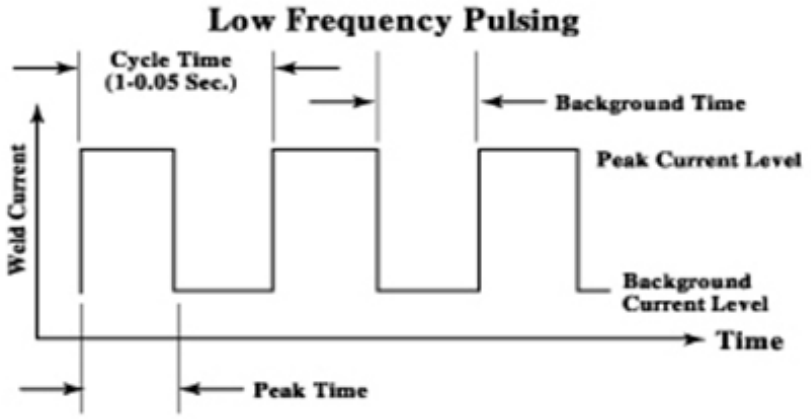


Figure 9. TIG pulse welding (https://www.adorwelding.com)

2.4.2 Heat input

Heat input should be low so that the risk of distortion, hot cracking and sensitization or intermetallic precipitation can be reduced. Preheating should also be avoided when welding austenitic stainless steels for the same reasons. (SFS-EN 1011-3:2018, p.11)

Fast and significant temperature changes ease the hot cracking of welds. Most significant changes in the microstructures of low-alloyed steels occur when the weld cools between the range of 800-500 °C, see Figure 10. Because of this cooling time for such materials is described with factor $t_{8/5}$ which indicates the time passing between temperatures previously mentioned. When studying austenitic stainless steels, the cooling time differs greatly between the phenomena's wanted to investigate so $t_{8/5}$ isn´t always the best indicator. (Kyrölainen, 2002, p.57) For austenitic stainless steels it is common to measure the cooling time between 1200-800 °C with factor $t_{12/8}$ as this temperature range covers the range in which hot cracking usually forms out in austenitic stainless steels. Naturally smaller the cooling time measured is the smaller are the effects of heat input in produced weld.

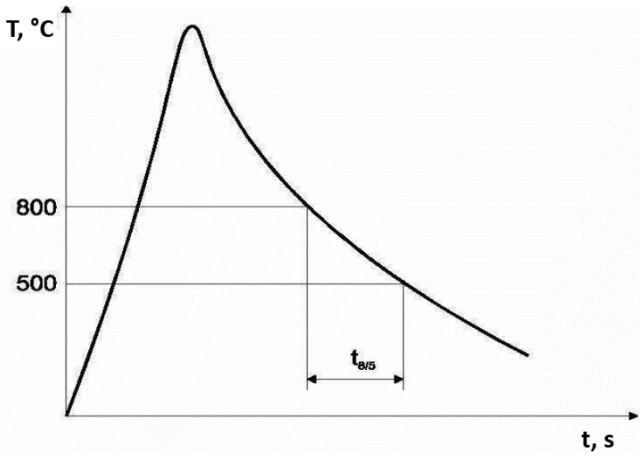


Figure 10. Thermal cycle of welding and the definition of cooling time $t_{8/5}$. (www.weldnet.com)

The temperature of base metal should be low when welding austenitic steels to avoid sensitization and hot cracking. Temperature can be kept as low as possible by using low welding energy and low interpass temperatures when multipass welding is applied. Suitable maximum interpass temperatures for austenitic stainless steels are in range of 150-250 °C. Welding energy is determined by the thickness of the sheet as well as the material itself. Maximum welding energy for austenitic stainless steels is 1.5-3.0 kJ/mm. (Kyrölainen, 2002, p.163) Again welding standard SFS-EN 1011-3:2018 guides to use even lower heat inputs. According to SFS-EN 1011-3:2018 interpass temperatures need to be kept below 150 °C.

2.5 Differences between welding plates and casted pieces

It is commonly known that welding of casted parts has more challenges than welding plates. Especially casted materials in which hardness is a pursued feature, cracking is the main problem faced. When welding casted materials, it is extremely vital to identify the alloy and use welding consumables that suit the purpose. Pre-heating is more commonly used when welding casted martensitic and ferritic steels. When the temperature of the welding material rises it simultaneously expands creating stresses to the HAZ. These stresses can be minimized by pre-heating bigger area around the area to be welded. As mentioned previously preheating of austenitic steels though should be avoided because of possible failures caused to the structure of base material by the higher heat input.

Steady rise and decrease of temperature in casted material to be welded is extremely important when trying to avoid cracking of welds. Pre-heating needs to be made properly

for large area around the weld. This ensures stresses caused by the heat input to stay as small as possible. Heat input during the welding should also be kept as low as possible to balance the expanding of material and stresses in weld areas caused by it. After welding, the temperature of the item should be monitored to allow it to cool down as slow as possible. To control the cooling, insulation can be added. Also, periodically added heat affects similarly.

Possibilities of cracking when welding casted materials can also be decreased with compressive stress. This means that deformable weld is moderately hit with a hammer to achieve opposite stresses for tensile stresses caused by the welding. This method should only be used when working with ductile weld metals. (Reliance Foundry Co. Ltd., 2020)

3 EXPERIMENTAL PART

The aim of this thesis was to find adequate welding parameters, suitable consumables and weld dimensions to manufacture durable repair welds into castings manufactured out of AS1 material. Literature findings from previous chapters were taken into consideration when parameter combinations were tested. Tests were made with casted test pieces provided by SPFIN. These pieces were prepared and welded in LUT Laboratory of Welding Technology. After welding, pieces were visually checked for failures. Further analyzes were made with microscopic and macroscopic examinations. These methods help to identify if used parameter combinations lead to repair welds where no porosity or cracks are present. Findings from suitable parameter combinations made with test pieces were then used in repair welding of actual pump casing. Nondestructive testing (NDT), in this case visual checking and penetrant fluid tests were carried out. After that the casing was pressure tested along SPFIN´s normal water pressure test procedure at Karhula factory.

3.1 Identification of occurring failure from initial test samples

Experienced failure is confirmed by manufacturing test pieces from original material samples at SPFIN using parameters set for repair welds previously by Hurri. Sandvik SX filler was used to manufacture welds to openings with width to depth ratio of 6 mm / 2mm. Arc current was set to 140 A and impurities were cleaned of from the test specimen with acetone. Penetrant fluid tests as well as microscopic and macroscopic examinations were carried out at LUT Laboratory of Welding Technology to confirm the failure occurring in produced welds. Figure 11 and Figure 12 show macroscopic images of the cracks found in the test specimens. These figures show that hot cracking failures are occurring in both the weld metal and parent metal.

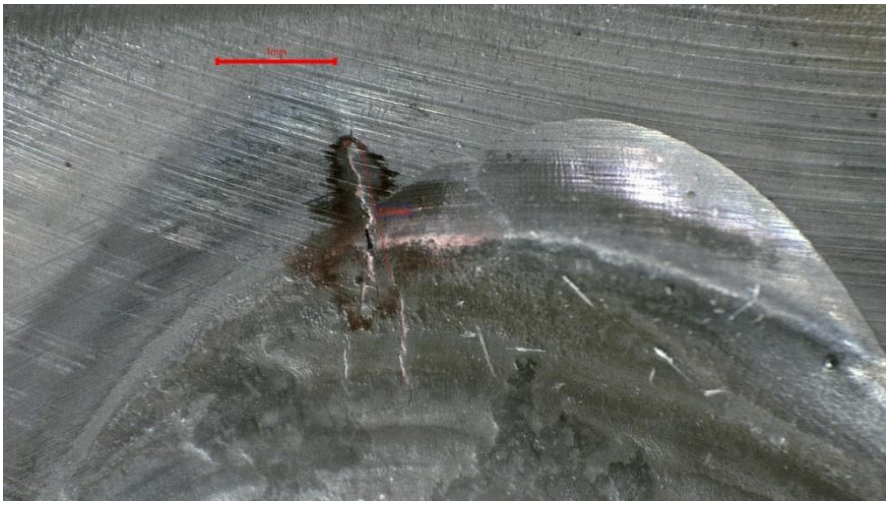


Figure 11. Crack found from the first test specimen welded with original parameters.

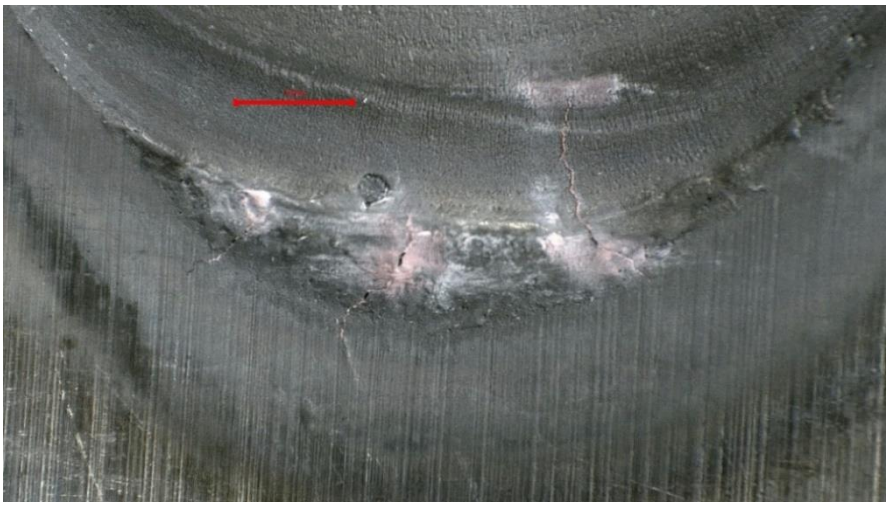


Figure 12. Cracks found at the second test specimen welded with original parameters.

Microsection samples were made by cutting and machining the samples from the test specimens in order to achieve better view of failures in welds. First the top plane of test piece was machined planar to see the formed cracks more clearly, Figure 13 and Figure 14. In both figures the cracks are formed to the starting point of the weld.

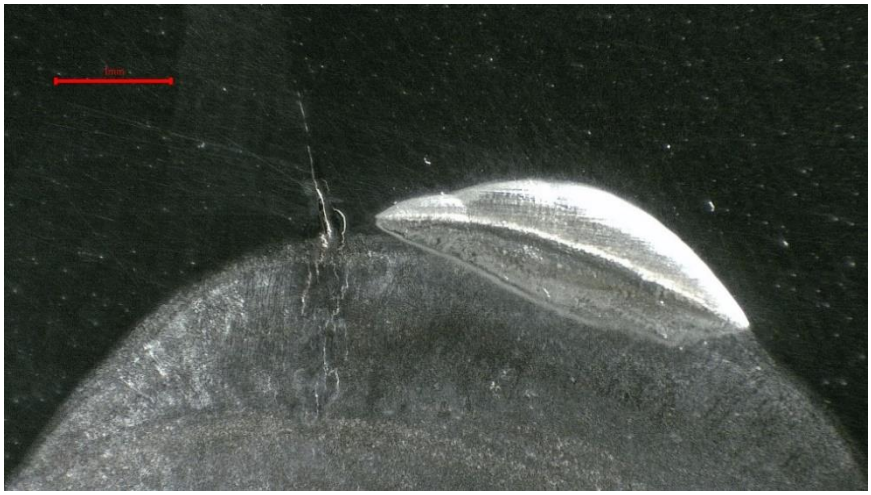


Figure 13. Appearance of crack in first test specimen after machining.

Figure 14. Appearance of crack in second test specimen after machining.

More similar cracks at weld starting and ending points can be seen on second test specimen on Figure 15 to Figure 18. As all the cracks have formed to the base material, it can be stated that the used filler metal seems to be suitable for these welds and it can be used for further studies.

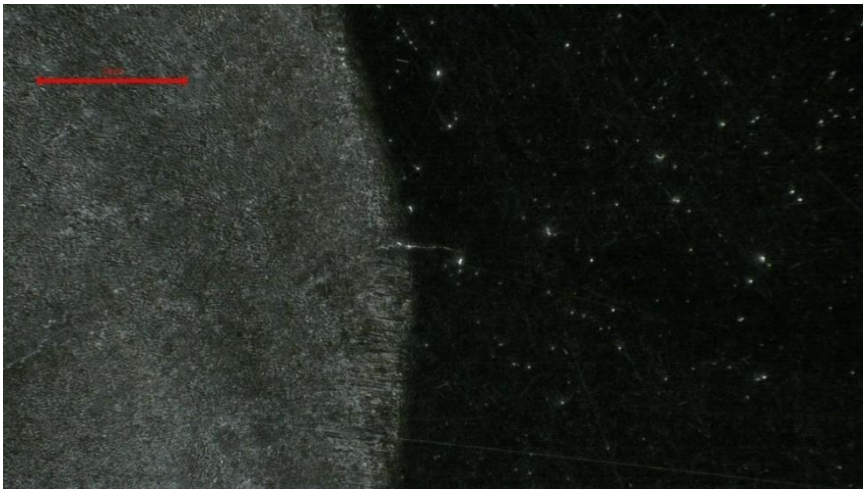


Figure 15. Crack in the weld´s beginning on second test specimen.

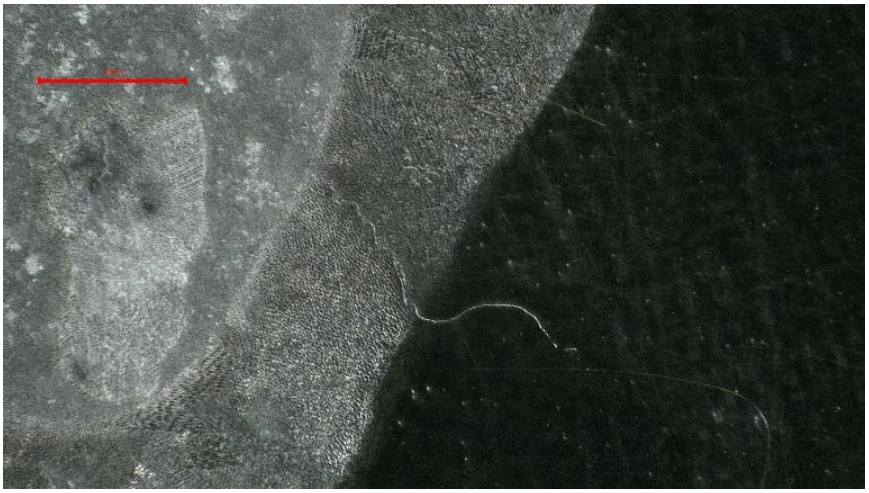


Figure 16. Crack in the weld´s end at the right side of second test specimen.

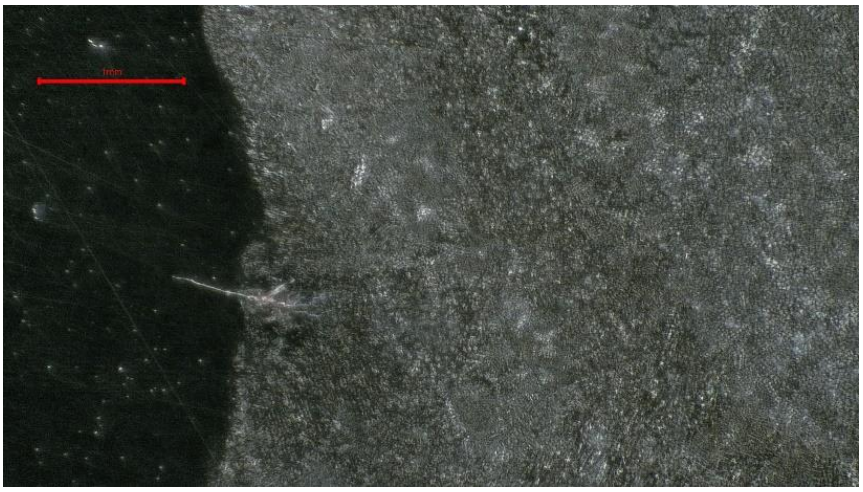


Figure 17. Crack in the weld´s end at the left side of second test specimen.

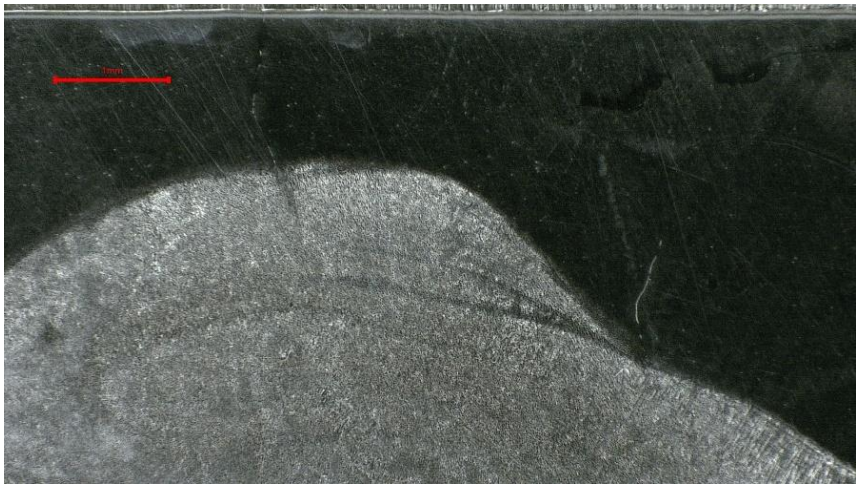


Figure 18. Cracks in the weld´s ending on second test specimen.

3.2 AS1´s susceptibility for hot cracking

AS1 as a material is very prone to hot cracking when welded. Figure 5 shows that when Cr_{eq}/Ni_{eq} value for the material is below 1.5 and amount of impurities, a sum of phosphor and sulfur, is higher than 0.01 %, material has a high tendency for hot cracking. In AS1 the value of impurities in composition is exceeded almost ten times, the value being 0.08 %. Chemical composition measurement made by foundry manufacturing the casting give also higher value than 0.01 % value being 0.017 %, see Table 4. The calculated Cr_{eq}/Ni_{eq} value of 1.15 to AS1 predict that the material will suffer from hot cracking when welded.

3.2.1 Chemical composition of weld test pieces

Material compositions of sample pieces were measured at laboratory to confirm that the compositions really matches the material analysis provided by foundry that provided the castings, see Table 1. Results of this measurement can be seen in Table 3.

Table 3. Chemical composition of test pieces. (LUT Laboratory of Welding Technology)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu
0.020	3.475	1.739	0.011	0.069	18.27	19.39	0.476	2.322

Most notable differences between chemical composition values in these analyses can be seen on silicon, sulfur, chrome and nickel. Another material analysis was ordered from the

foundry. This analysis was made from one of the sample pieces intended to be used for welding tests at laboratory. Result of the analysis can be seen on *Table 4*.

Table 4. Chemical composition of test piece measured at foundry. (Karhula Foundry)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu
0.029	4.80	1.67	0.011	0.006	17.52	19.86	0.48	2.05

By comparing these results to ones of Table 1 and Table 3 it can be seen that differences between analysis become more even. Chemical composition of castings can differ between points measured as measurements aren´t taken from exactly same piece of material.

Composition of the test specimen differs from the nominal material values shown in Table 5 most notably on point of increased amount of manganese and sulfur. Sulfur has been proven to increase the possibility of hot cracking in austenitic steels when preferred composition values are exceeded. See 2.2.1 and 2.2.3. For indicative estimation purposes hot cracking susceptibility of studied material AS1 can be assessed with using the aforementioned diagram Figure 5, Equations 1 and 2 and the existing chemical composition data. Table 3 shows the chemical composition of weld test pieces. Calculated Cr_{eq}/Ni_{eq} value for AS1 is 1.15 and sum of phosphor and sulfur form out 0.08 % of the composition. These values predict that material itself is very prone to hot cracking when welded. As Figure 5 shows maximum amount of impurities, a sum of phosphor and sulfur, is 0.01 % in materials which solidify as austenitic structure.

Table 5. Nominal chemical composition of Sandvik SX. (Sandvik SX datasheet)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu
≤0.025	5.00	0.50	≤0.045	≤0.030	17.50	19.50	0.40	2.00

3.3 Precautionary instructions set by company for repair welding

In first repair welding tests made at SPFIN during studies of 2018 it was guided to leave a day between machining and welding of parts to be welded so that excess machining fluids could evaporate from the surfaces. Rotating file was used in manufacturing the openings for welding. Rest of the machining fluids were removed from the parts with cleaner and by

heating the pieces to 110 °C. Welding wasn´t started until the temperature of material was below 60 °C, interpass temperature allowed. Precise cleaning of the pieces was recognize to be important factor on manufacturing working repair welds already during the first tests.

3.4 Welding experiments

Experimental welds made at LUT Laboratory of Welding followed literature finding describing clearly the maximum values for heat input and weld dimensions to be used when welding austenitic stainless steels. Sandvik states in its Sandvik SX Tube and pipe, Seamless datasheet that matching filler material is always recommended when welding SX. Datasheet guides to keep welding energy below 1.0 kJ/mm and interpass temperature below 60 °C. These values stated by Sandvik were also used in welds made at SPFIN. As the examination of welded test samples show, cracking still existed in these welds made with parameters suggested by Sandvik. To eliminate the cracking, it was focused to lower the level of applied heat input further in follow-up welding experiments.

3.4.1 Welding consumables

Sandvik SX TIG-rod was exclusively used as a filler material in all welding experiments. As pictures taken with macroscope, Figure 13 to Figure 18, show cracking forms to weld and base material. Cracks are only partly on weld material near fusion line. It is assumed that mostly molten base material is present in this area of weld where cracking exists. This indicated that the filler works as intended when parameters used, and heat input caused to the base material are in the limits set by Sandvik. Tests with other filler materials, for example ferritic fillers, were ruled out from these studies as possibilities for comparing corrosion resistance abilities wasn´t possible. Sandvik SX filler which was used has silicon, chrome and copper contents that match with the base materials composition. This should provide solid bond corrosion wise. Table 6 shows that the composition of filler differs from the composition of the base material used in the tests, shown in Table 3 by 6.6 % lower amount of nickel . Biggest difference can be seen between the amounts sulfur which acts as impurity in weld and increase the possibilities of failure.

Hot cracking susceptibility for filler material used was assessed similarly as for base material also with diagram shown in Figure 5, Equations 1 and 2 and the existing chemical composition data. Table 6 shows the chemical composition of Sandvik SX filler material

used. Calculated Cr_{eq}/Ni_{eq} value for filler is 1.8 and sum of phosphor and sulfur form out 0.015 % of the composition. According to evaluation made from the diagram, filler material isn´t as susceptible for cracking as the base material is. Due this, small ratio of mixed base material in welds needs to be aimed to achieve. In this case weld metal susceptibility to hot cracking is assumed to be lesser when filler metal portion comprises the largest part of the weld. In that way Cr_{eq}/Ni_{eq} value can be increased in by controlling the dilution ratio and simultaneously decreasing the risk of weld metal hot cracking.

Table 6. Chemical composition of Sandvik SX filler material. (Outotec AB, Certificate EN 10204 3.1)

C	Si	Mn	P	S	Cr	Ni	Mo	Cu
0.007	5.02	1.70	0.014	0.001	18.4	13.3	-	2.00

3.4.2 Parameters used in the welding experiments

Actual test welds were made with small modifications in each test by changing just one parameter between welds, see Table 7. These modifications include tests with different groove geometries and heat inputs affected by the used welding current. Best combinations of parameters in those tests, after visual checking, were used in multipass tests with an interpass temperature of 60 °C along Sandvik´s guidelines, Table 8. Welding tests were made to material sample pieces provided by SPFIN which were machined at LUT Laboratory of Welding Technology for wanted groove geometries. Welding was made manually to these test pieces by laboratory staff, Figure 19.

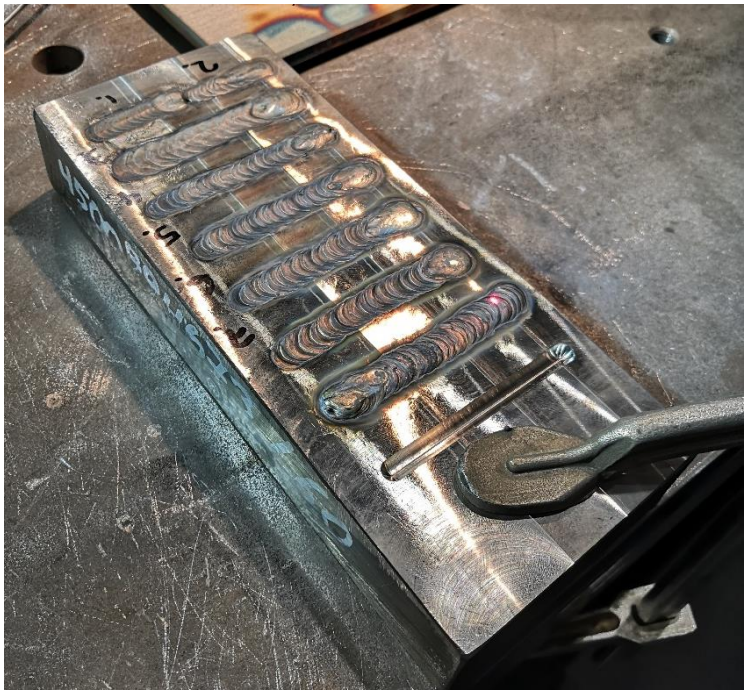


Figure 19. Test welds being welded to the test piece.

Heat input *Q* was calculated along Equation 3. In which *k* describes the thermal efficiency value of TIG welding (0.6), *U* is the arc voltage, *I* is the arc current and *v* the travel speed of weld.

$$Q = \frac{k*U*I}{v} \tag{3}$$

For tests in which pulsed welding was applied, arithmetical average for arc current I_m was calculated with Equation 4 and Equation 5. This value represents the electrical effect experienced during pulse welding, corresponding to the steady currents in tests were pulse welding wasn´t applied. I_p is the peak value for arc current and t_p the duration of peak arc current. Similarly, I_b is the value of base arc current and t_b the duration of it. *T* describes the total duration of pulse cycle. (Cornu, 1988, p.62)

$$I_m = \frac{I_p*t_p+I_b*t_b}{T} \tag{4}$$

$$T = t_p + t_b \tag{5}$$

Table 7. Parameters used in single pass welding tests.

Test No.	Groove geometry (width/depth)	Arc current (A)	Arc voltage (V)	Travel speed (mm/s)	Max arc current (A) *	Base arc current (A) *	Pulse frequency (Hz) *	Heat input (kJ/mm)
1	4 mm / 2 mm	140	11.0	2.50	-	-	-	0.37
2	4 mm / 2 mm	120	9.50	1.50	-	-	-	0.46
3	4 mm / 2 mm	200	12.0	2.50	-	-	-	0.58
4	4 mm / 2 mm	120	10.5	1.50	-	-	-	0.50
5	6 mm / 2 mm	120	12.0	1.16	-	-	-	0.76
6	6 mm / 2 mm	140	12.0	1.30	-	-	-	0.77
7	6 mm / 2 mm	120	9.50	1.16	218	54	179	0.67
8	6 mm / 2 mm	108	10.5	1.00	189	54	179	0.76
10	4 mm / 2 mm	108	9.50	1.42	-	-	-	0.43
12	6 mm / 2 mm	108	10.5	1.14	174	63	1	0.65
13	6 mm / 2 mm	95	10.4	1.05	153	56	1	0.63
14	4 mm / 2 mm	95	9.20	1.62	153	56	1	0.41

*Parameter used in pulse welding.

Table 8. Parameters used in multipass welding tests.

Test No.	Groove geometry (width/depth)	Arc current (A)	Arc voltage (V)	Travel speed (mm/s)	Max arc current (A) *	Base arc current (A) *	Pulse frequency (Hz)	Heat input (kJ/mm) **
9	6 mm / 3 mm	108	10	1.00	189	54	179	0.58
11	6 mm / 3 mm	120	11	1.16	-	-	-	0.62

*Parameter used in pulse welding.

**Heat input of the first manufactured weld.

3.4.3 Pulse welding

Pulse welding tests were made by using best parameter combinations from previous tests with constant current after visual inspections. Arc current of 120 A, working in constant current tests, was used as a base value for pulse welding tests. Other welding parameters used were suggested by the welding machine and later refined after visual inspections were made for the manufactured welds. In order to lower the heat input of welding further, pulse frequency was set to 1 Hz for the later tests, also arc current used was lowered to 108 A and after that to 95 A. In the subsequent tests where 1 Hz pulsing was used, filler material was added to the pulse sequence also to help to decrease the heat input and base material mixing.

3.5 Temperature examinations during tests

Temperature change in weld area was monitored in all the tests made at LUT Laboratory of Welding Technology. Changes were measured with pyrometer which can be seen in top left corner of Figure 21. Data collected from temperature changes in tests was used to determine cooling time $t_{12/8}$ for material AS1 studied. Cooling time $t_{12/8}$ was approximately 6 seconds when data from all test welds was put together and analyzed, see Figure 20.

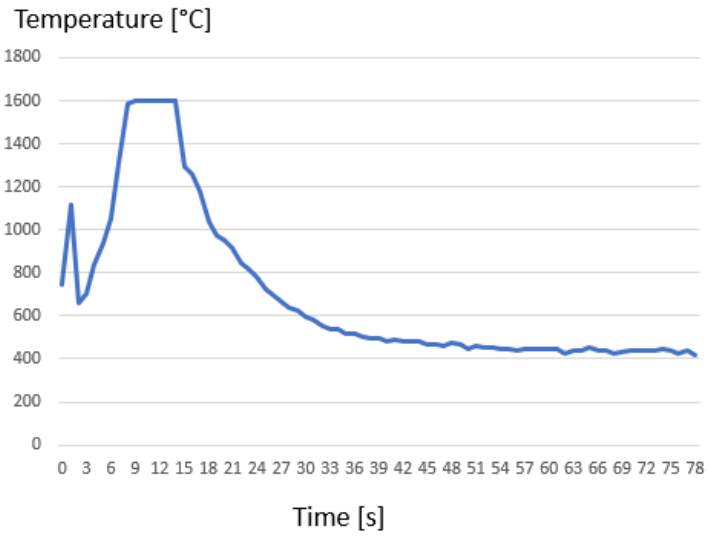


Figure 20. Thermal cycle for welding of AS1.

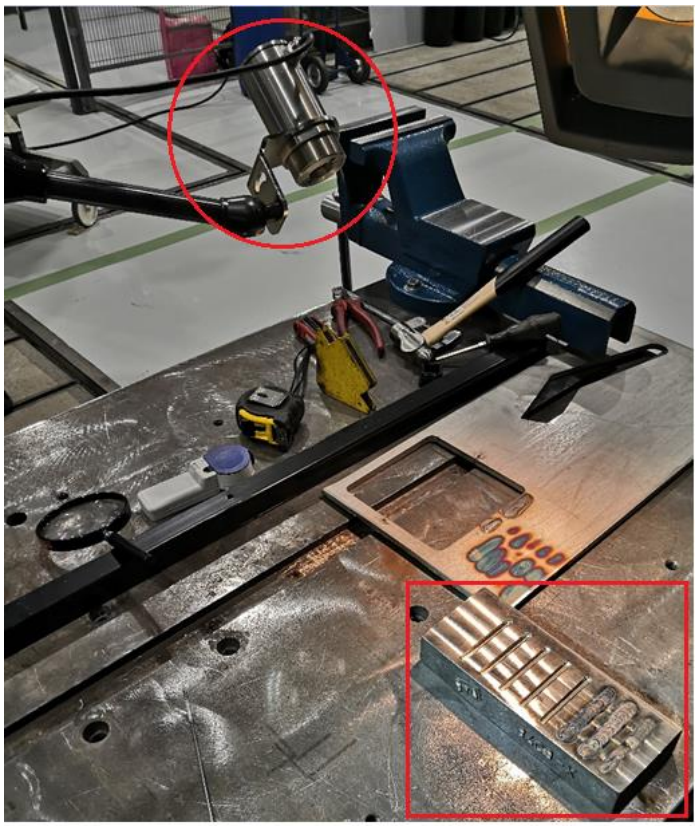


Figure 21. Test setup at LUT Laboratory of Welding Technology. Pyrometer highlighted at the top left corner of picture. Test specimen with machined grooves and already produced test welds can be seen at the bottom right corner.

3.5.1 Interpass temperatures

Pyrometer was used also in verifying the interpass temperature of 60 °C in multipass welding experiments. After the first tests with singlepass welds were made, best welding parameter combinations were tested in multipass welding. Interpass temperature of 60 °C was used in all of the experiments as it was already clear that higher temperatures would cause more cracking to appear. Aim of these tests was to produce welds from which could be stated that multipass welding wouldn´t cause any extra cracking to appear when comparing with singlepass welds manufactured with same parameters.

3.6 Analyzes made for welded test pieces at LUT

Penetrant fluid tests weren´t made for the test pieces as it was found with the sample pieces that the cracks in weld area properly appeared only after machining and macroscopic examinations. Welded test pieces were cut half from the middle of the weld to show the cross section needed for microscopic and macroscopic examinations. With these examinations the effect of parameters set in comparison to the cracks formed were sorted.

3.6.1 Macroscopic examinations

Macrographic pictures were taken from all the test welds. Sample pieces were cut in half to show the weld cross-sections. More cuts were made with a band saw in order to make separate sample pieces from each weld cross-section. These weld cross-sections were then grinded with machine shown in Figure 22. Multiple grinds were made with grinding papers that had different roughness values. After grinding, polishing was made with aluminum oxide. Acid containing 4 % nitric acid was applied after that to the polished surface so that weld base material and weld could be more clearly seen in macroscopic and microscopic examinations.

Figure 22. Grinding machine used in preparation of microscopic and macroscopic pieces.

Macrographic pictures were then taken with a microscope shown in Figure 23. Illustrative line of 1 mm was applied to all the macrographic pictures so that the scale of failures would be more easily compared between the samples.

Figure 23. Microscope used for macrographic pictures.

3.6.2 Mixing ratio of base material in weld

Base material´s mixing ratio i.e. dilution ratio was calculated from all test welds made at LUT Laboratory of Welding. Mixing ratio was calculated by determining the cross-section areas of weld geometry and groove geometry. By calculating how much base material is mixed to weld material. Dilution ratio can be calculated by reducing cross-sectional area of weld groove from cross-sectional area of weld metal. This cross-sectional area of melted base material is divided by weld materials cross-section. If the weld forms out as a convex, dome left above upper plane of base material needs to be added for groove cross-sectional area. Examinations were done by using ToupView3.7 software to draw the areas to existing pictures from welds, see Figure 24. Calculations with the values picked from the pictures were then made by using Microsoft Excel 365. For example, in Figure 24 area of weld metal is 10.94 mm^2 and area of groove geometry is 6.24 mm^2. This means that area of melted base metal is 10.94 mm^2 – 6.24 mm^2 = 4.70 mm^2 and dilution ratio is (4.70 mm^2 / 10.94 mm^2) * 100 ≈ 43 %.

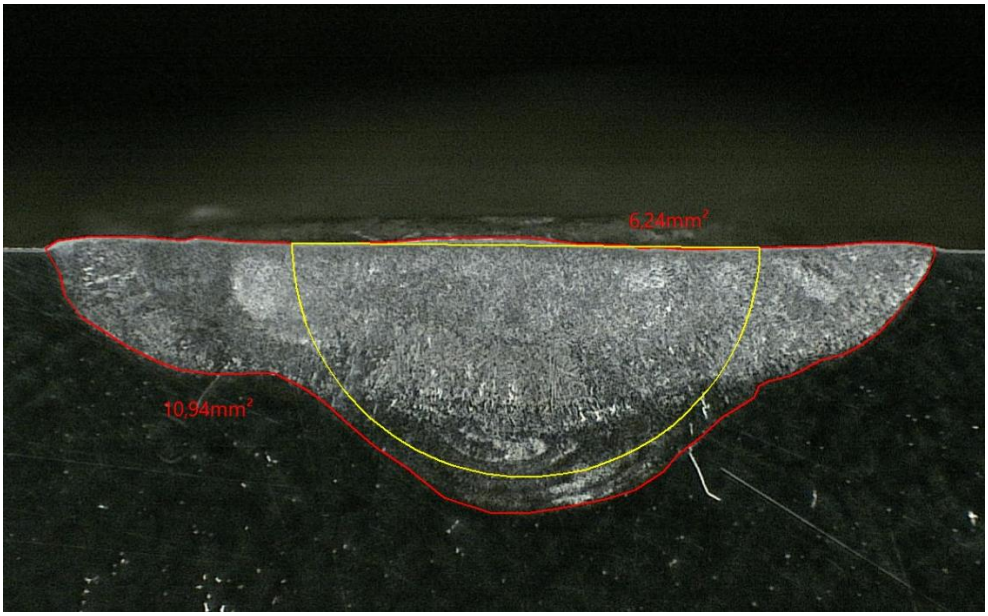


Figure 24. Areas needed to measure when determining base material´s mixing ratio. Area highlighted with red shows the cross-sectional area of weld metal and area highlighted with yellow describes the weld groove geometry. Area left between these two areas describes the cross-sectional area of molten base material.

Small ratio of mixed base material in welds was aimed. Welds abilities against hot cracking are better when the amount of base material mixed into the weld metal is as small as possible, see chapter 3.2.1 This can be affected by feeding high amount of filler material to the melt pool and of course with using proper welding parameters. Low heat input melts the base material less and simultaneously decreases the base material mixing ratio to the weld. Table 9 shows the base material mixing ratios for each test weld and also the cross-section areas needed for calculations.

Table 9. Base material mixing ratios for test welds.

Test No.	Filler material cross-section area (mm^2)	Weld metal cross-section area (mm^2)	Base material cross-section area (mm^2)	Base material mixing ratio
1	6.26	17.55	11.29	0.64
2	8.33	16.27	7.94	0.49
3	6.26	23.10	16.84	0.73
4	8,93	18.27	9.34	0.51
5	10.29	18.48	8.19	0.44
6	10.29	24.72	14.43	0.58
7	10.29	15.86	5.57	0.35
8	16.57	23.55	6.98	0.30
9	16.02	22.31	6.29	0.28
10	6.26	10.94	4.68	0.43
11	14.10	24.50	10.40	0.42
12	10.29	15.41	5.12	0.33
13	10.29	13.07	2.78	0.21
14	6.90	9.95	3.05	0.31

3.6.3 Microscopic examinations

Some of the welded test specimen were examined also with microscope to determine possible microstructural features behind the cracking. Microstructures in different parts of material samples were photographed for analyzing purposes. Figure 25 shows microstructure of AS1 base material. Porosity in base material, created in casting phase, can

be clearly seen. Figure 26 shows the weld material. Weld solidification path can be seen from it

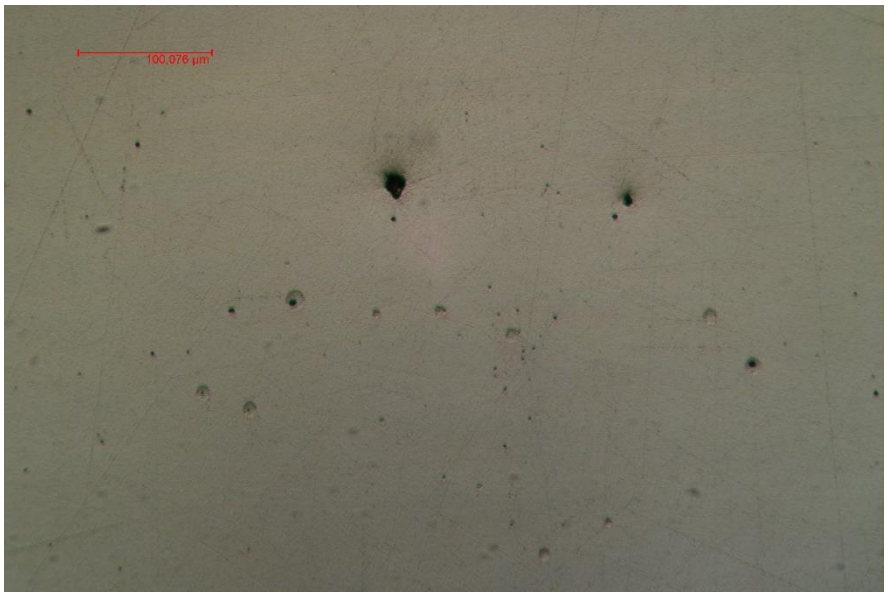


Figure 25. Micrographic image from AS1 base material.

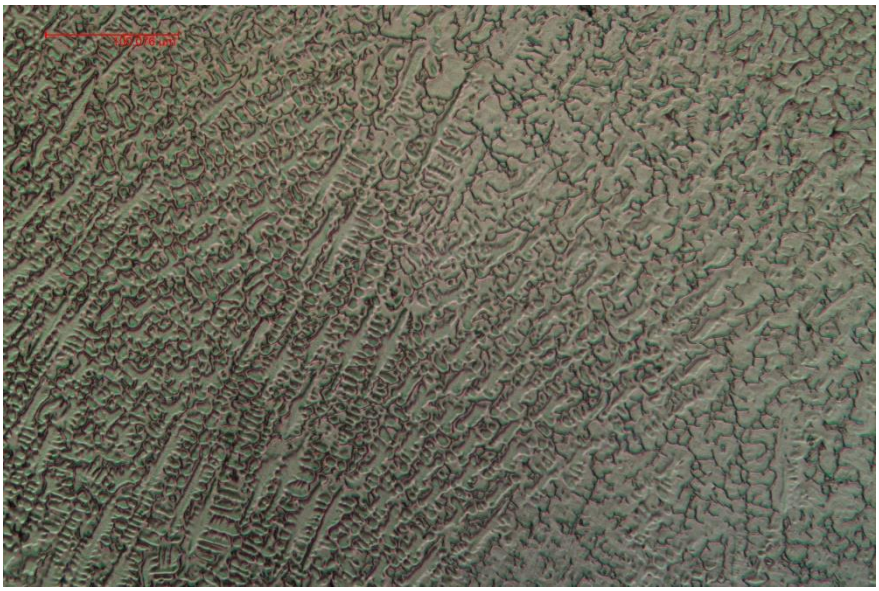


Figure 26. Micrographic image from weld produced to AS1.

Transition zone of base material and HAZ is smooth in welds examined. Though pores near the transition zone may effect negatively to cracking when located to the both sides of transition zone, compare Figure 27 and Figure 28.

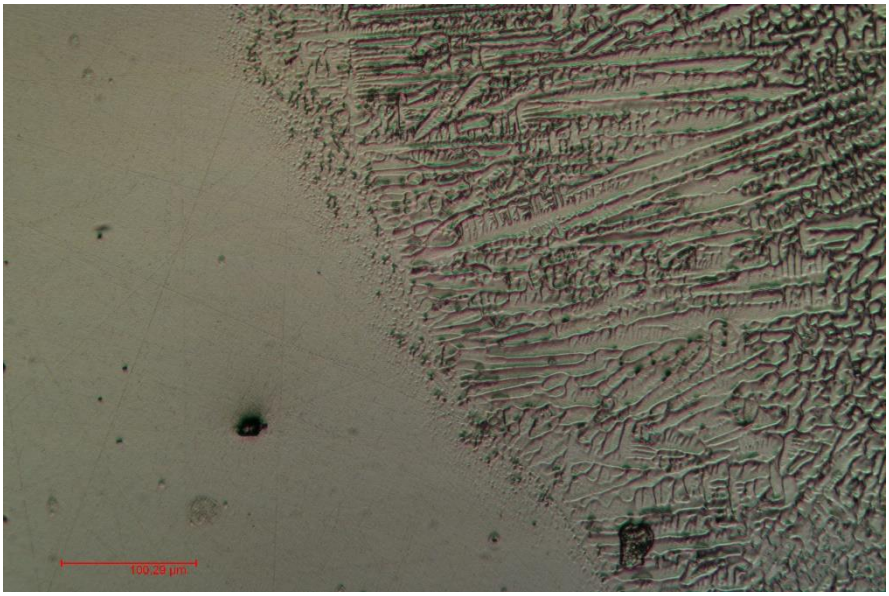


Figure 27. Micrographic image from transition zone between base material and HAZ in AS1.

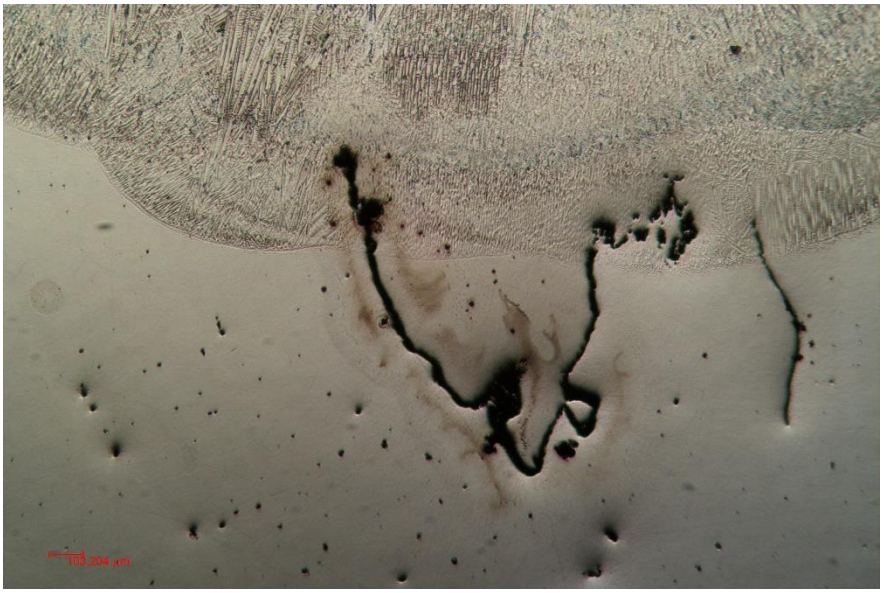


Figure 28. Crack formed between pore throughout HAZ and base material.

More cracks were analyzed with microscope to study the material and crack formation in it. Etching was again applied to the cross-section surface of the welded test samples in this point to get better view of grain boundaries of base material in vicinity of fusion zone. As AS1 is designed specifically to work in surroundings containing sulfuric and nitric acids this wasn´t that easy task to complete and acid treatment needed to be added multiple times.

Finally grain boundaries were managed to get visible with applied etching. Figure 29 and Figure 30 show that cracks are formed in grain boundaries and are continuously propagated into both the base material and across the fusion line in weld metal as well. Heat cycle caused by welding has created thin molten material films to the grain boundaries of base material leading to cracking.

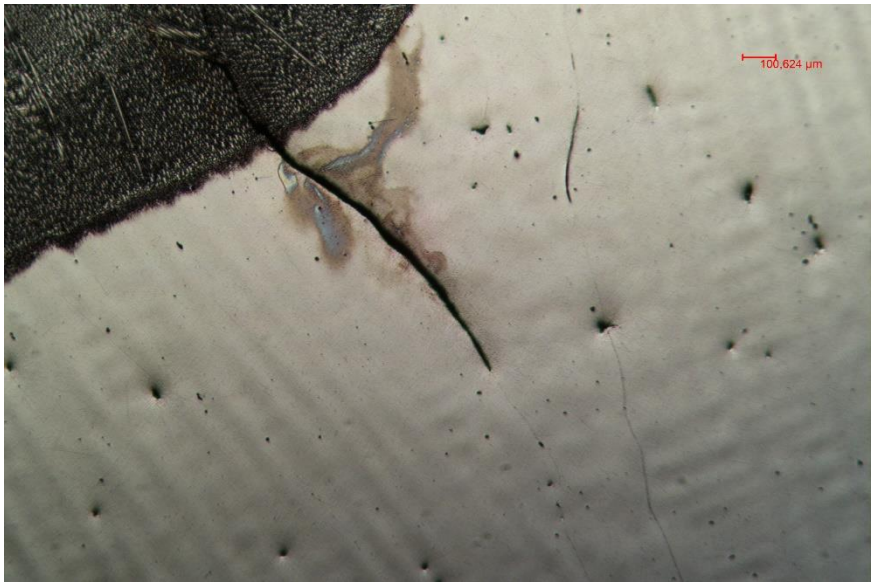


Figure 29. Microscopic image from crack in test weld 6.

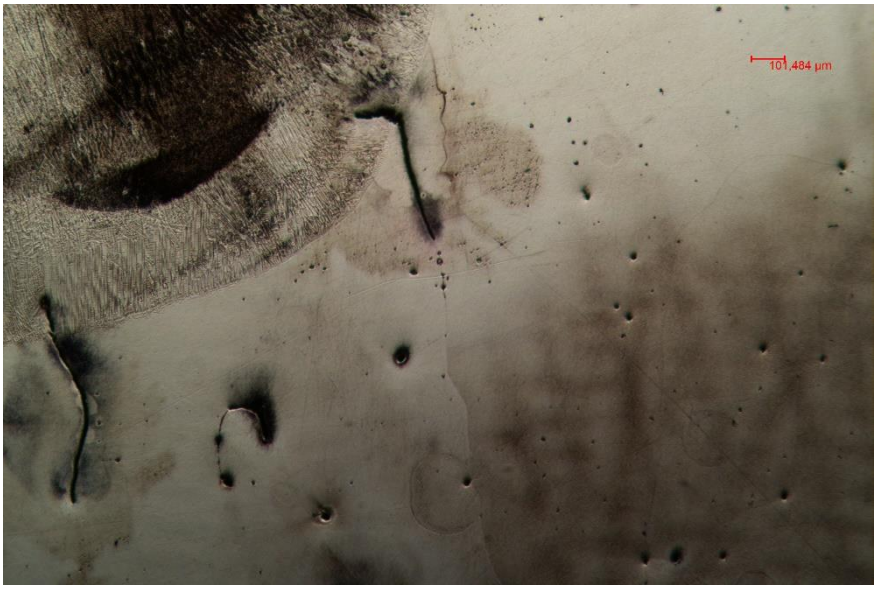


Figure 30. Microscopic image from crack in test weld 9.

3.7 Results of test welds made at laboratory

In this chapter results of carried out tests are presented and discussed. Test welds made at LUT Laboratory of Welding Technology are divided under subtitles of major cracks and minor cracks by the weld cross-section macrographic images. These images are further analyzed by comparing the welding parameters used in each test to the base material mixing ratios measured. Best parameter combinations were used in creating preliminary Welding Procedure Specification that was used as a guideline to weld the actual pump casing which was further subjected to be pressure tested at SPFIN´s factory in Karhula. Results of welding the actual pump casing are shown and discussed also

3.7.1 Major cracking

Obvious failures in weld material can be seen at the cross-section images taken from test welds. Welds in which such defects appear were eliminated from the later examinations of parameters to be used in welding of actual pump parts. Following micrographic images presented from Figure 31 to Figure 35 show these welds.

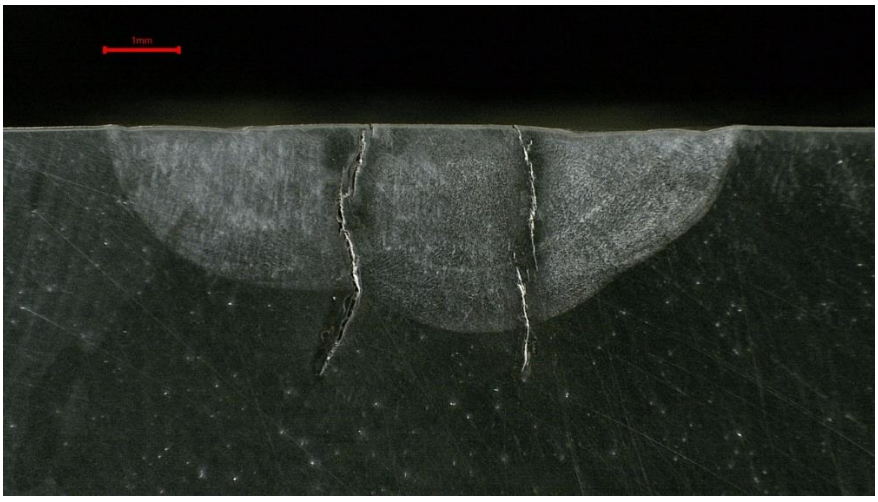


Figure 31. Test weld 1

Figure 32. Test weld 2

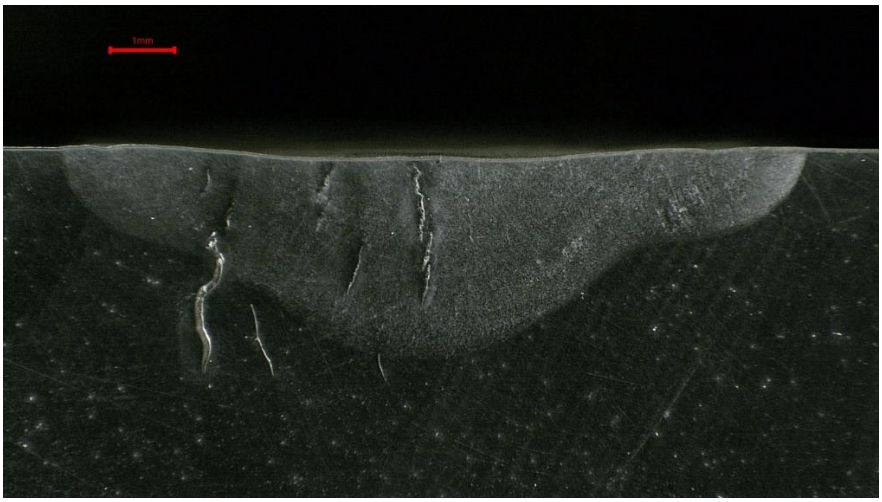


Figure 33. Test weld 3

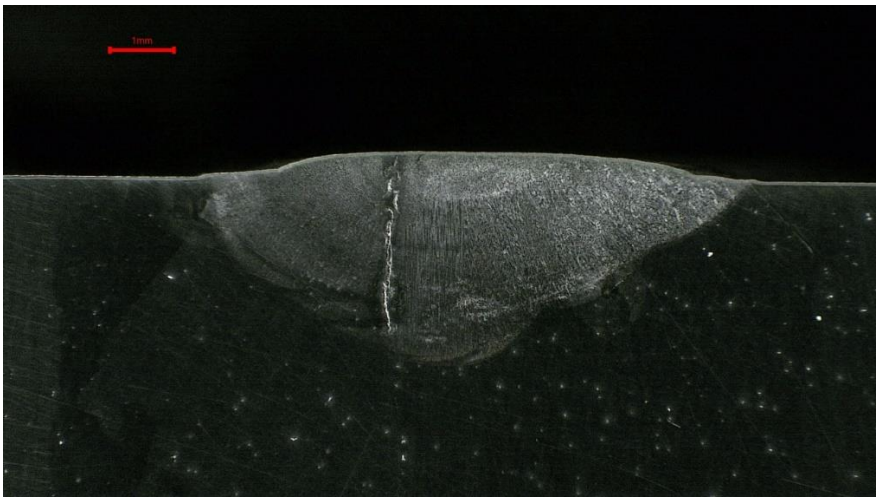


Figure 34. Test weld 4

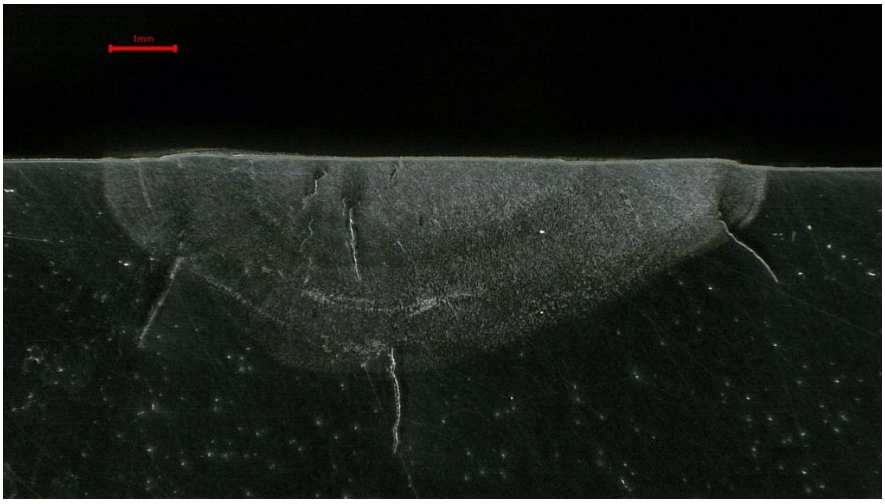


Figure 35. Test weld 6

Main parameters used and base materials mixing ratios are listed to the Table 10 presented below. High base material mixing ratio of over 0.50 is common to all the test welds in which failures were found. Variation of 0.37 – 0.77 kJ/mm between test welds was experienced. Though some welds had low calculated heat inputs significant cracking was found in those welds. High base material mixing ratio seems to be the common factor behind the cracking of welds.

Table 10. Welding parameters applied to welds in which major cracks appeared.

Test No.	Arc current (A)	Arc voltage (V)	Travel speed (mm/s)	Heat input (kJ/mm)	Base material mixing ratio
1	140	11	2.5	0.37	0.64
2	120	9.5	1.5	0.46	0.49
3	200	12	2.5	0.58	0.73
4	120	10.5	1.5	0.5	0.51
6	140	12	1.3	0.77	0.58

3.7.2 Minor cracking

Cross-section images where only small cracks in base material were found and weld metal itself was intact were considered as potential candidates when applicable welding parameters are further assessed. At this point it was clear that due material properties of AS1, liquation cracking in base material will be highly probable even with low heat input and small base material mixing ratio. The above mentioned weld cross-sections are presented from Figure 36 to Figure 44 below.

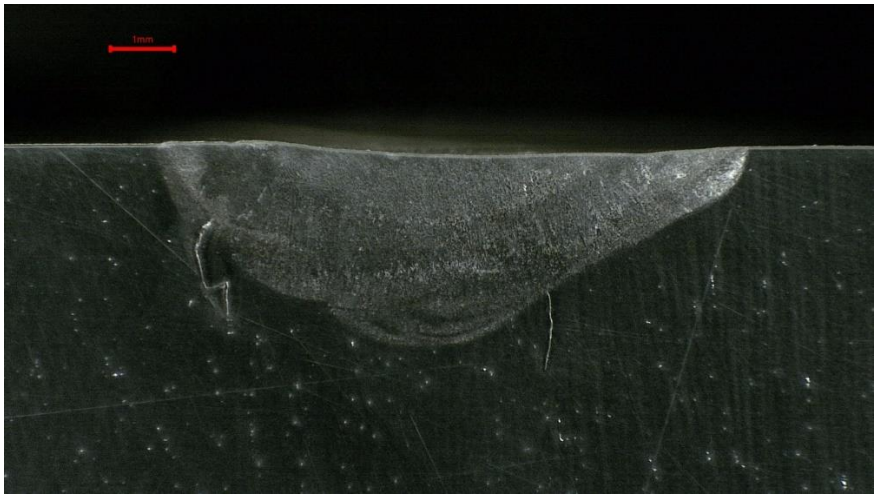


Figure 36. Test weld 5

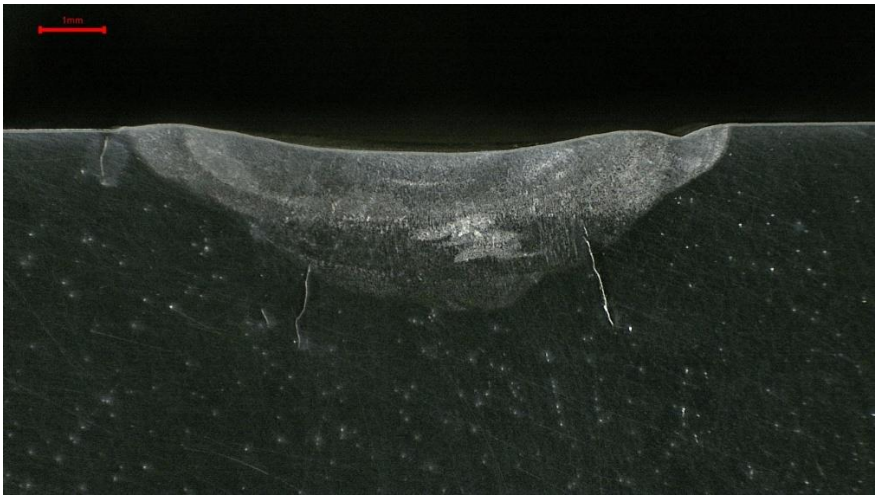


Figure 37. Test weld 7

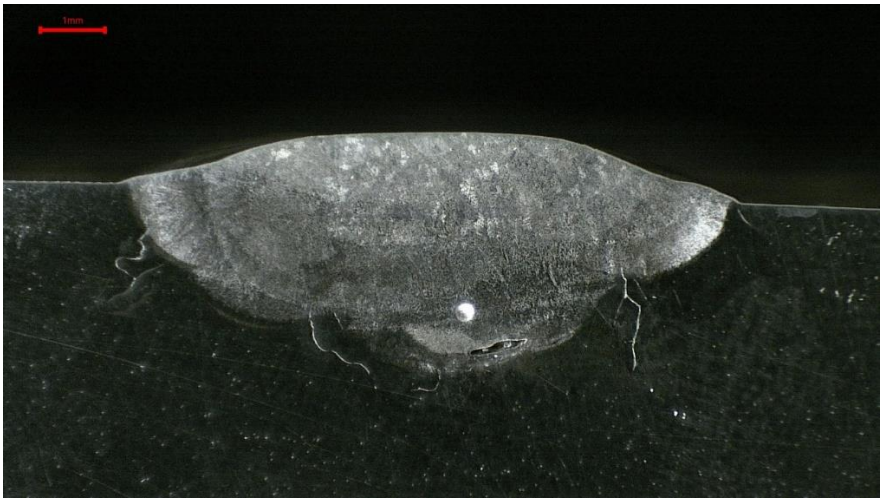


Figure 38. Test weld 8

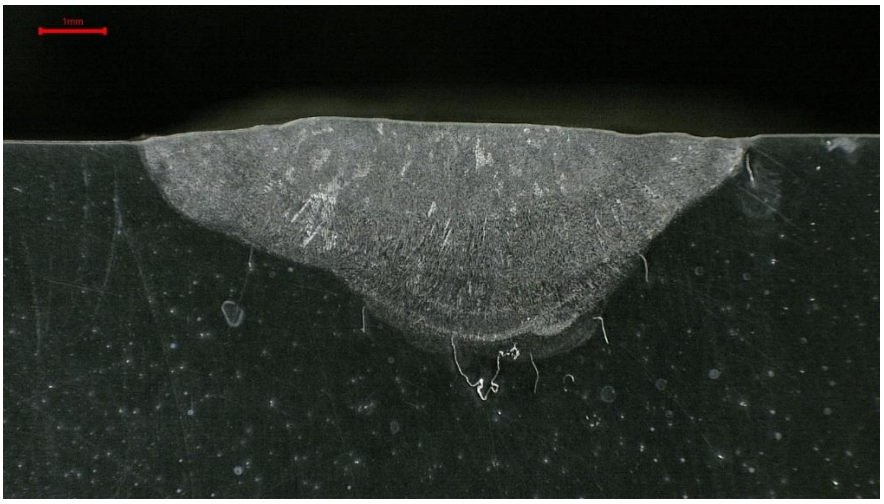


Figure 39. Test weld 9

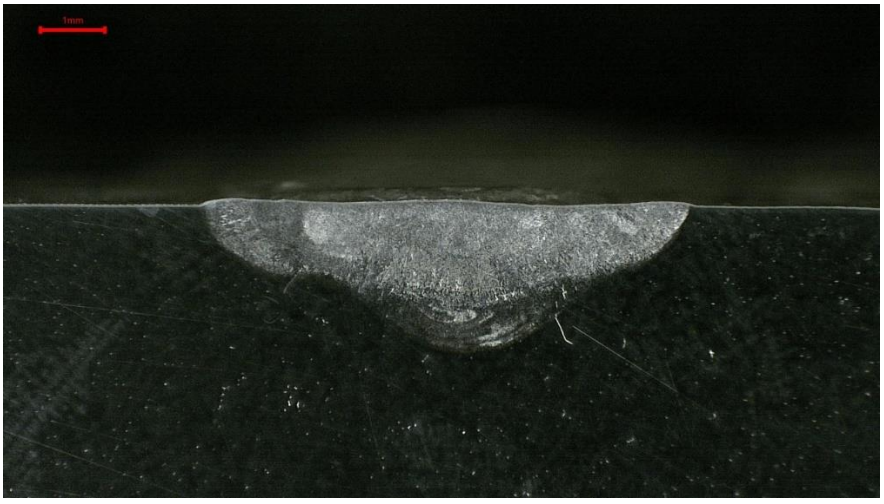


Figure 40. Test weld 10

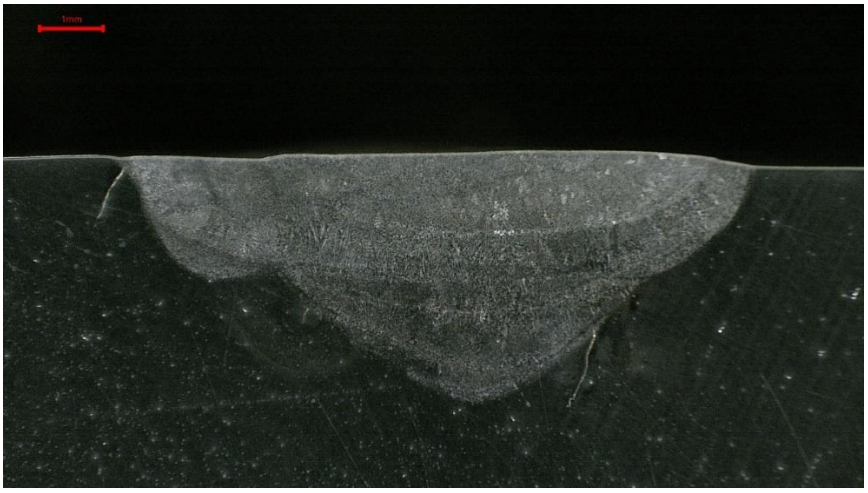


Figure 41. Test weld 11

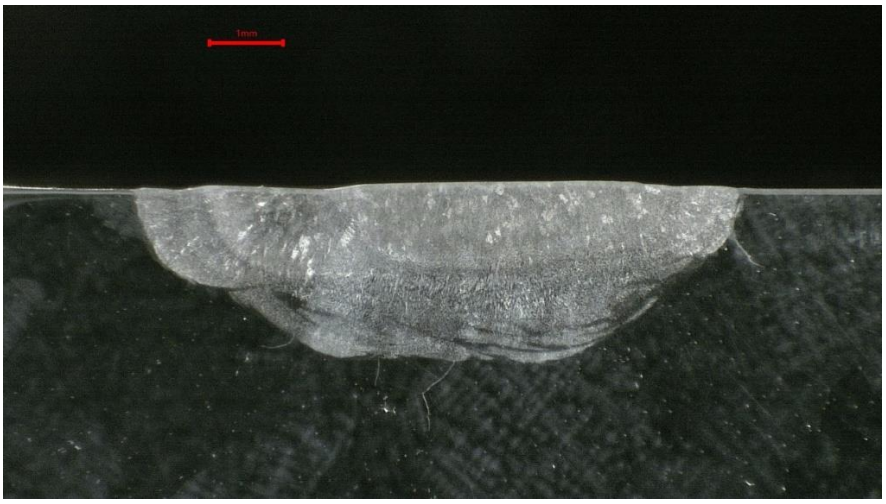


Figure 42. Test weld 12

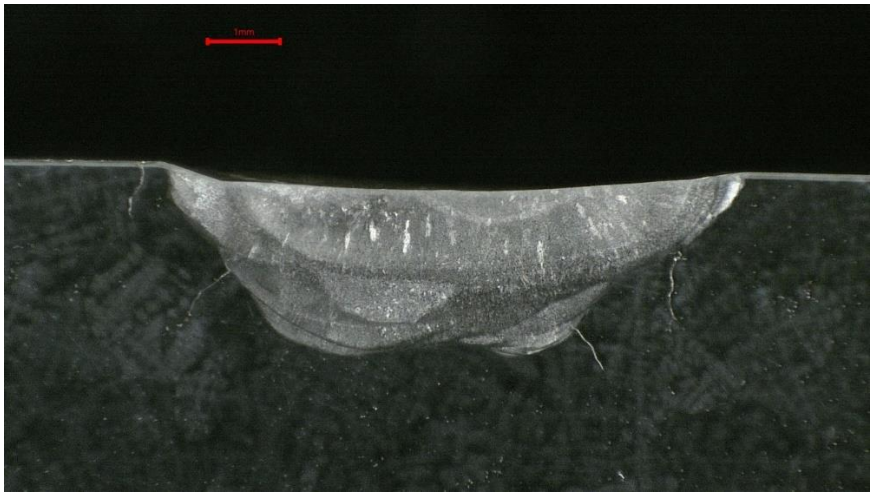


Figure 43. Test weld 13

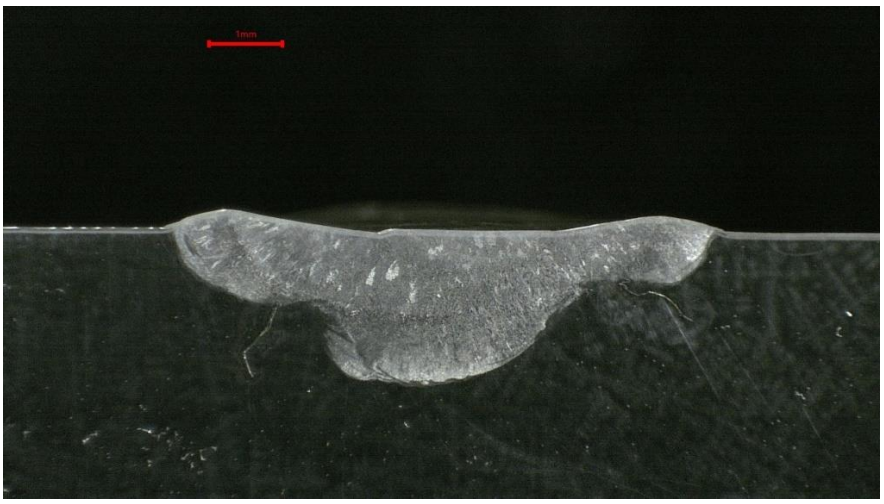


Figure 44. Test weld 14

Welding parameters and base material mixing ratios of welds were only minor cracking was found in base material are shown in Table 11. Base material´s mixing ratio i.e. dilution was below 0.50 in all these welds. Whereas calculated heat inputs differed between each test weld. Heat inputs were between values of 0.41 – 0.76 kJ/mm which are quite similar to those calculated for the cracked welds also. By comparing the results of welding tests made at LUT it can be clearly seen that in used filler metal and base material combination, a small base material mixing ratio in weld metal has the most significant effect to succeeding in repair welding of AS1. See comparison between different base material mixing ratios in Table 12. Figure 5 indicates that if Cr_{eq}/Ni_{eq} ratio is below 1.5 material has high tendency

for hot cracking. Pulse welding tests shown at Table 11 in which 108 A and 95 A mean arc currents were used, show the lowest mixing ratios of base material in weld metal.

Table 11. Welding parameters applied to welds in which only minor cracks appeared.

Test No.	Arc current (A)	Arc voltage (V)	Travel speed (mm/s)	Heat input (kJ/mm)	Base material mixing ratio
5	120	12	1.16	0.76	0.44
7	120	9.5	1.16	0.67	0.35
8	108	10.5	1	0.76	0.30
9	108	10	1	0.58	0.26
10	108	9.5	1.42	0.43	0.43
11	120	11	1.16	0.62	0.42
12	108	10.5	1.14	0.65	0.33
13	95	10.4	1.05	0.63	0.21
14	95	9.2	1.62	0.41	0.31

Table 12. Weld materials Cr_{eq}/Ni_{eq} ratio with different base material mixing ratios.

Cr_{eq}/Ni_{eq} ratio of base material	Cr_{eq}/Ni_{eq} ratio of filler material	Base material mixing ratio	Cr_{eq}/Ni_{eq} ratio of weld material
1.15	1.8	0.33	1.59
		0.44	1.51
		0.64	1.38
		0.73	1.33

3.8 Results of welding tests of actual pump parts

After tests welds made at LUT Laboratory of Welding Technology, results were examined, welding parameters resulting best welds were used in test welding actual pump parts casted from AS1 at SPFIN. Pump parts were tested against leaks along SPFIN´s factory standard water pressure test.

Pumps casing and backplate were assembled together with bearing housing adapter and pressure testing flanges so that pressure retaining wet end parts could be tested against leakages. Pressure of 24 bars was used. Test is passed if no leaks appear and test pressure remains the same for 10 consecutive minutes. To spot the possible leaks more effectively developer used in penetrant fluid tests was applied for casted parts to be tested, see Figure 45. Leaking spots were then marked, cleaned and welded. After that water pressure test was renewed to check if repairs made stopped the leaks. This procedure without the developer is made for all pumps manufactured at SPFIN.

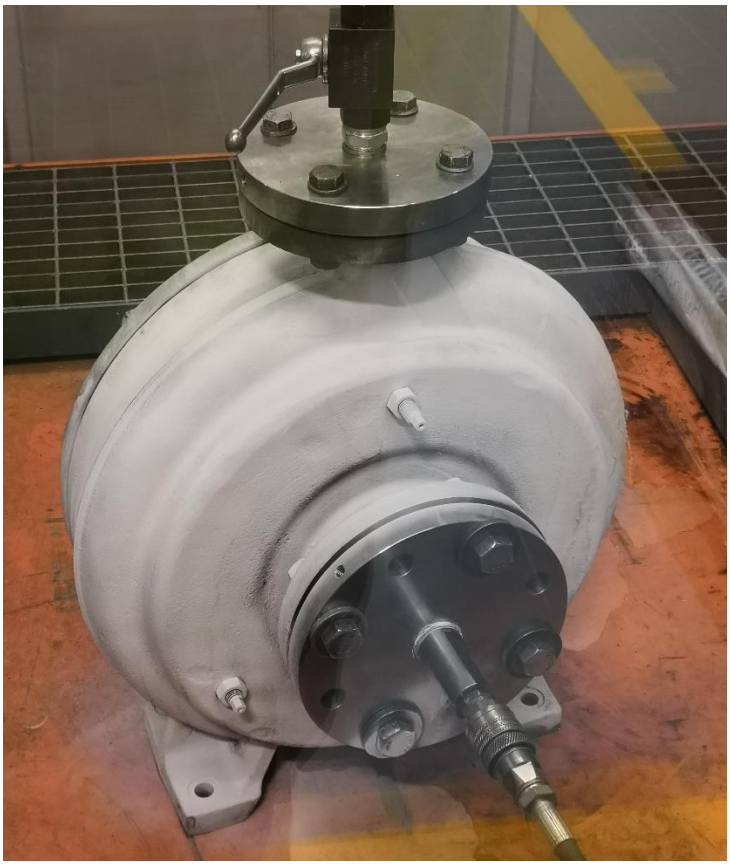


Figure 45. Pump assembled ready for water pressure test.

Figure 46 shows the two leaking spots found behind suction flange during pressure testing. As these actual leaks are in a spot that is hard to weld decision was made that test welds are made to the side of the casing to a spot were previous penetrant fluid test indicated porosity. This way welding parameters found suitable in laboratory tests could be tested to actual pump casing in a way that similar conditions for welding can be guaranteed for all welds. Parameters used in these tests are shown in Table 13.

Figure 46. Leaks found during the pressure testing.

Table 13. Welding parameters used in welding tests made at SPFIN.

Test No.	Weld geometry (width/depth)	Arc current (A)	Arc voltage (V)	Travel speed (mm/s)	Max arc current (A) *	Base arc current (A) *	Pulse frequency (Hz) *	Heat input (kJ/mm)
15	6 mm / 2 mm	108	11.5	0.89	143	63	1	0.79
16	6 mm / 2 mm	140	12.7	1.62	-	-	-	0.66
17	6 mm / 2 mm	95	10.4	1.05	153	56	1	0.63

*Parameter used in pulse welding.

After the results of laboratory tests were studied, welding of actual pump parts was tested at SPFIN. Preliminary Welding Procedure Specification (pWPS) was made according to the applicable parameters and findings gained from the previous laboratory welding tests. This pWPS followed closely parameters used in test weld 12. Only difference was that rotating file was used to manufacture openings with width to depth ratio 6 mm/2 mm whereas in laboratory tests these grooves were machined to the test pieces.

Figure 47 shows the result of first welding tests. As the penetrant fluid test shows, major cracking in welds occurred when pulsed welding with 108 A arc current was applied. Pulse frequency of 1 Hz was used as in laboratory tests where this parameter combination resulted small base material mixing ratio and low heat input. Despite these parameters worked in laboratory tests the outcome of welding actual casing showed exact opposite results as major cracking occurred. There can be multiple reasons for this. different welder handprint causing different base material mixing ratio might be one of those. Other welds shown in the same figure didn´t crack. These were made by following original welding guidelines set for the material during the first studies of SPFIN made by Hurri. Constant arc current of 140 A was used for these welds. As can be seen from Table 13 heat input applied to these welds was lower compared to the welds where 108 A pulsed current was used. Main difference was created with higher travel speed between welds. Heat input caused to the casing decreased as welding speed was doubled when compared with 108 A pulsed welding tests. Maximum interpass temperature of 60 °C was used between all the welds.

Figure 47. First test welds made to pump casing. Welds highlighted with circle were made by following parameters of pWPS. Other welds that can be seen in the picture were made along the original guidelines of Hurri.

As these results were unexpected after the data collected from laboratory tests, more welds were made to the other side of the casing. On that side no porosity was found, welds were again made to similar openings with 6 mm/2 mm width to depth ratio. Intention of these welds was to compare the parameters used in similar conditions once more. Welds were made by using constant current of 108 A and 140 A. Pulsed welding tests were carried out with 1 Hz pulse frequency and welding currents set to 108 A and 95 A. Results of penetrant fluid tests carried out for these welds can be seen from Figure 48 to Figure 51.

Figure 48. Test weld made with 108 A constant current.

Figure 49. Test weld made with 140 A constant current.

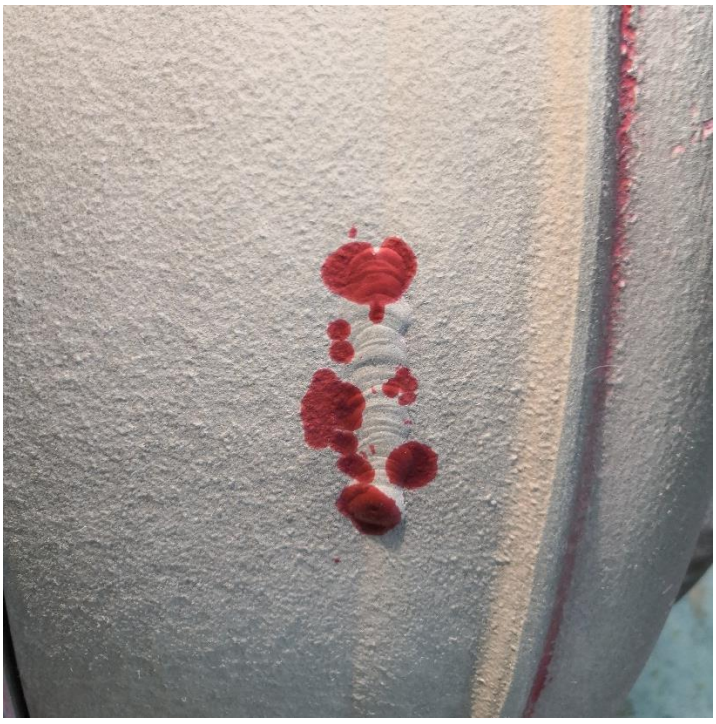


Figure 50. Test weld made with current of 95 A and pulse of 1 Hz.

Figure 51. Test weld made with current of 108 A and pulse of 1 Hz.

Indications of defects were found in all the welds. From tests made with constant current it can be seen that now more failures were found in weld made by using 140 A arc current compared to the weld made with arc current of 108 A. Figure 49 shows that penetrant fluid marked several defects in the weld metal as in Figure 48 markings are mainly at the fusion line of base and weld materials. In pulse welding tests several markings appeared in both tests so no real conclusions from the effects of parameters could be made. Failures in welds ending point is shown in all these welds.

4 ANALYSIS AND DISCUSSION

Even though welds where no cracks occurred in weld metal were succeeded to manufacture in laboratory circumstances, test welds made for actual pump casing, casted from AS1 conflicted with the results of these previous tests. There can be multiple reasons for these differing results. Material samples used in laboratory tests were from the same batch of casts as the casing used in factory weld tests so composition should not change remarkably between these two welding tests. Possible factors for the conflicts shown could be caused by the change of welder, impurities in the area to be welded or other casting failures and possible composition differences.

During laboratory tests, where significantly higher number of welds were made, welder got a lot more time to get used to the material and welding of it. Instead at factory different welder was given a pWPS to follow without any practice. In an ideal situation, similar material sample would be given also for the welder manufacturing the actual welds to practice the behavior of material when welded.

It must also be noted that first welds shown in Figure 47 were made to the part of casing where existing porosity was found. After opening the spots to be welded it couldn´t be guaranteed that all faults would be removed from the base material. As no tests were made so that faults would have been left to the bottom of the opening to be welded, connection between porosity and cracking can´t be determined. It is also notable that test welds made to different part of the casting where no failures existed seem to reflect the results of laboratory tests with welding parameters used.

After several material analyses slight doubt still existed that maybe the quality of castings could be better. As previous tests made independently by SPFIN showed, differences existed between different foundries when same material was casted. Methods, equipment and accuracy of chemical composition are all important factors of casting. Also, discussion with a welder of last tests raised a concern that maybe the quality of material isn´t as good as it should be.

5 CONCLUSIONS

Test welds made during this thesis indicate that AS1 base material has limited weldability. By lowering the base material mixing ratio in weld metal together with heat input caused, working repair welds where cracking existed only in base material can be manufactured to AS1 castings. This is shown by the laboratory tests as well as final factory weld tests made to side of the casing where no porosity was present.

To properly underline the effects of pulse welding against cracking of welds more tests should be made at factory so that the welder repairing the castings can have a routine to welding. Welders working with the material should be briefed to the specialties of AS1 as well as allow them to practice the welding of this material. Most importantly more tests should be made in which different parameter combinations could be tested onto real size material samples. These real size test pieces will distribute the heat input of welding more evenly through the material which may allow some adjustments to be made for the welding parameters. As the final tests made at SPFIN´s factory show that using pulse welding to lower the heat input may not be the answer to problems of cracking welds. Instead it seems that lowering the base material mixing ratio in welds could offer the best results in degreasing the hot cracking of welds made to AS1 castings. As the base material has a tendency for hot cracking, cracks forming to HAZ of base material can´t be affected with filler material choice.

Findings and pWPS made during this thesis aren´t resulting welds where no cracks exist and due to that these results can´t be used as a repair welding instruction for the material. More tests are needed to refine the parameters that should be used when repair welding AS1. Even though pWPS made from the findings of laboratory tests carried out during this thesis should act as a good base for further tests in which more attention should be paid to studying the chemical composition of the AS1 material itself.

Future tests should be made by using the best possible castings available to eliminate the possibility of problems caused by faulty casting. As mentioned on the literature review part of this thesis chemical composition of AS1 castings used during the experiments isn´t ideal as the Cr_{eq}/Ni_{eq} ratio is 1.15 and sum of phosphor and sulfur is 0.08 %. These values clearly

state along with Figure 5 that current composition version of AS1 is very prone to hot cracking when welded. When compared to the same values of the Sandvik SX filler material used in the tests, Cr_{eq}/Ni_{eq} ratio of is 1.8 and sum of phosphor and sulfur acting 0.015 % of the composition. It can be stated along with the diagram of Figure 5 that filler material isn´t as susceptible for hot cracking. By modifying the chemical composition of AS1 closer to the values of Sandvik SX filler material, cracking of welds could be tackled. Of course, as casted material is discussed some changes to the chemical composition are possibly needed so that casting as a manufacturing process can be utilized for the material. Diagram made from findings of Kujanpää, Suutala and their team needs to be compared when composition is modified. Susceptibility for hot cracking need to be ruled out from the composition of material itself. The filler material used followed the specs of Sandvik and is stated to provide weld where no cracking exists and other qualities necessary, for example corrosion resistance, are promised to remain the same as the ones of base material.

After modifying the chemical composition of the material, welding tests are needed to be renewed. For these tests pWPS can act as a base. As reasons of hot cracking in austenitic stainless steels remain the same, similar welding parameters tested during this thesis can be used also after modifying the materials chemical composition. Results of welding tests should also match the laboratory tests made during this thesis quite accurately. Corrosion resistance of manufactured welds weren´t studied in this thesis. Those tests also need to be made before releasing the material to production.

6 SUMMARY

The aim of this thesis was to find suitable welding parameters for repair welding SPFIN´s internally coded, high alloyed austenitic stainless steel, material AS1. Previous welding experiments with this material had already been made independently by SPFIN. Those tests didn´t lead to findings that would have ensured applicable repair welds. Instead it was found that hot cracking occurred often in weld material. This thesis focused on sorting the reasons behind cracking and aimed to refine the welding parameters used in repair welding of casted pieces.

Hot cracking of austenitic stainless steels was studied from the literature. From those findings' potential applicable values for welding parameters were sourced. Together with new findings and results of previous tests rough estimations for suitable welding parameters were made. These parameters were used as a base for laboratory tests at LUT Laboratory of Welding Technology. Different arc currents were used between the tests to figure out if cracking of weld material can be tackled by lowering the heat input caused to material when welded. Level of heat input was managed to lower by decreasing the arc current used and furthermore by applying pulse welding with the similar parameters. Cross-section macrographic images indicated that pulse welding would solve the problem of hot cracking in weld metal by lowering the heat input and base material mixing ratio. In HAZ and base material hot cracking still existed when cross-section macrographic images were studied

From the findings of laboratory tests, pWPS was created for repair welding AS1 casing at SPFIN´s factory. Welding tests made by using this pWPS as a guideline resulted cracked welds which conflicted with the laboratory tests. Also welds made with original parameters used in SPFIN´s independent tests seemed to remain intact. Similar higher arc current resulted cracks in laboratory tests made at LUT University. Conflicts between these two tests showed that topic needs to be even further studied to create repair welding procedure for AS1.

Lowering the heat input seemed to have no effects against cracking of welds that occurred in HAZ of welds. Considering the hot cracking susceptibility diagram made by Kujanpää

and Suutala Cr_{eq}/Ni_{eq} ratio and sum of phosphorus and sulfur derived from the chemical composition of AS1, the parent material is in a risk zone of hot cracking. In other words, this indicates that no matter what the welding circumstances are for AS1 its current chemical composition will be prone to hot cracking when welded. Chemical composition of material needs to be changed in a way that Cr_{eq}/Ni_{eq} ratio would be closer to the composition of Sandvik SX filler material for example. Higher Cr_{eq}/Ni_{eq} ratio would decrease material susceptibility for hot cracking. After that welding parameters tested during this thesis could be tested again for modified chemical composition of base material in which susceptibility for hot cracking would be lower on the starting point than compared to the current composition.

Even if hot cracking problems of AS1 welds weren´t managed to be solved during this thesis, reasons behind the cracking were noticed and listed. With the mentioned corrections to composition of base material further studies could be made from this subject. By lowering base materials susceptibility to hot cracking and applying the findings made in this thesis from lowered heat input and base material mixing ratio to weld material, applicable welding procedure specification to repair defects in AS1 castings most likely could be made.

LIST OF REFERENCES

Bernasovský, P. Contribution to HAZ Liquation Cracking of Austenitic Stainless Steels. Böllinghaus, T. & Herold, H. 2005. Hot Cracking Phenomena in Welds. Berlin, Heidelberg: Springer-Verlag Berlin Heidelberg. p. 84-103.

Berns, H., Gavriljuk, V. & Riedner, S. 2013. Manufacture. High Interstitial Stainless Austenitic Steels. Berlin, Heidelberg: Springer Berlin Heidelberg: Imprint: Springer. p. 111-126.

Cornu, J. & Weston, J. 1988. Advanced welding systems. 3, TIG and related processes. Bedford;: IFS.

de Lima, H. M. L. F., Tavares, S. S. M., Martins, M., & Araújo, W. S. 2019. The effect of copper addition on the corrosion resistance of cast duplex stainless steel. Journal of Materials Research and Technology, 8(2). p. 2107-2119.

Kujanpää, V., Suutala, N., Takalo, T., & Moisio, T. 1980. Solidification cracking. Metal Construction. 12. p. 282-825.

Kujanpää, V., Suutala, N., Takalo, T., & Moisio, T. 1979. Correlation between solidification cracking and microstructure in austenitic and austenitic-ferritic stainless steel welds. Welding Research International, 9(2). p. 55-75.

Kyröläinen, A. & Lukkari, J. 2002. Ruostumattomat teräkset ja niiden hitsaus. 2. p. Helsinki: Metalliteollisuuden keskusliitto.

Laurent, B., Gruet, N., Gwinner, B., Miserque, F., Rousseau, K. & Ogle, K. 2017. Dissolution and passivation of a silicon-rich austenitic stainless steel during active-passive cycles in sulfuric and nitric acid. Journal of the Electrochemical Society, 164(13), p. C892-C900. doi:10.1149/2.1531713jes

Lucas, W. 1990. TIG and Plasma Welding: Process Techniques, Recommended Practices and Applications. Abington Publishing.

Nickel institute. 2018. Stainless steel: The role of nickel [Online] Available at: https://www.nickelinstitute.org/about-nickel/stainless-steel (Accessed: 2.6.2020)

Olsen, Flemming Ove. 2009. Hybrid Laser-Arc Welding - 3.3.2 Arc Sources with Non-Consumable Electrodes. Woodhead Publishing. p. 64-68

Reliance Foundry Co. Ltd. 2020. How to Weld Cast Iron [Online] Available at: https://www.reliance-foundry.com/blog/how-to-weld-cast-iron#gref (Accessed: 29.6.2020)

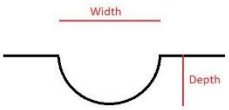
Sandvik AB. 2017. Sandvik SX Tube and pipe, Seamless -datasheet. Available as a PDF-file: https://www.materials.sandvik/en/materials-center/material-datasheets/tube-and-pipe-seamless/sandvik-sx/ (Accessed: 19.5.2020)

Senk, D., Christmann, K., Geimer, S., & Rzehak, D. 2016. Nitrogen Solubility in High-Manganese Steel Grades. steel research international. 87(1). p. 107-111.

SFS-EN 1011-3:2018. 2018. Welding. Recommendations for welding of metallic materials. Part 3: Arc welding of stainless steels. Helsinki, Suomen standardisoimisliitto SFS ry,

Preliminary Welding Procedure Specification

pWPS

Parent materials		AS1									
Material thickness		-					Joint type			Welding sequences	
Outside diameter		-					 Min width/depth ratio = 3				
Welding process		GTAW									
Welding position		1G									
Beveling method		Single U									
Groove cleaning		thoroughly with asetone									
Workpiece fixturing		-									
Tack welding		-									
Back gouging		-					Electrode Ø (TIG/Plasma)			-	
Backing		-					Sharpening angle (TIG/Plasma)			-	
	Designation of consumables and trade name						Torch angle			-	
	Filler material classification	-					Inclination angle			-	
		-					Distance contact tube to workpiece			-	
		-					Preheating and interpass temperature				
	Filler material trade name	Sandvik SX					Preheat temperature			-	
		-					Interpass temperature			max 60 °C	
	Flux	-					Preheating method			-	
	Shielding gas	Argon					Temperature measurement			-	
	Flow rate	-					Post-weld heat treatment				
	Plasma gas	-					Method			-	
	Flow rate	-					Heating rate			-	
	Backing gas	-					Temperature			-	
	Flow rate	-					Time			-	
	Type of current	Pulsed (1 Hz)					Cooling rate			-	
	Polarity	Electrode-negative					Post-weld treatment	-			
Remarks: Arc current 105-110 A, Peak current 170-180 A, Base current 60-70 A, Pulse frequency 1 Hz, Filler added to pulse							Date and name:				

Run	Process	Size of filler metal Ø (mm)	Current (A)	Voltage (V)	Travel speed (mm/s)	Wire feed rate (m/min)	Heat input (kJ/mm)	Run-out length (mm)	Weaving frequency (Hz)	Amplitude (mm)	Remarks
	GTAW	-	108	10,5	1,1	-	0,6	-	-	-	-

Customer	Approved