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Barsebäck as Research and Development Platform, Extraction and Analysis of Reactor Pressure Vessel Material

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Abstract

As part of the NKS-R program, VTT, Chalmers and KTH has performed a base-line study to prepare for a test program to analyze the as aged material properties of the retired reactor pressure vessel, RPV, from Barsebäck unit 2. The project started at July 1st, 2016. The initial activities focused on mapping of possibilities for future work between VTT, Chalmers and KTH, liason activities with Vattenfall to discuss extraction of the test material from the Barsebäck plant and collection of material for the base line testing.
The group has collaboratively prepared an extraction outline to give the basis for further discussions with the Swedish utilities regarding the materials extraction scheme and proposed amounts of materials and positions in the RPV. The work at Chalmers University focused on base-line high resolution atom probe tomography, APT, testing on un-irradiated material as well as sample materials irradiated in a test reactor. In addition to this some samples of thermally aged material was included to visualize the features that develops during both types of ageing. VTT has performed a base-line testing utilizing miniature fracture toughness testing samples of un-irradiated RPV material obtained from the original tests of the RPV of Barsebäck 2.
The actual retrieval of materials from Barsebäck, is foreseen to occur in 2018 and -19. The material harvesting is outside the scope of the research oriented program that was supported in 2016. The work has been supported from both SSM and SKC in Sweden and by the Finnish nuclear safety program, the SAFIR-program.
The main outcome so far apart from the actual data that has been produced and the proposed cutting scheme for materials retrieval, is the fact that the work enhances the collaboration in this technology driven area between two Swedish technical universities KTH and CTH and Aalto University in Finland, and the Finnish research institute VTT. In addition to this, it is functioning as a facilitator for contacts between the research driven academic world, safety and operability driven Finnish and Swedish nuclear operating companies and the Finnish and Swedish nuclear safety authorities.

Key words

Low alloy steel, irradiation effects, fracture toughness, ductile to brittle transition temperature, constraint effects, high resolution microscopy

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Final Report from the NKS-R BREDA2016 activity (Contract: NKS_R_2016_118)

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1. Introduction

As part of the NKS-R program in 2016, VTT, Chalmers and KTH has performed a baseline study to prepare the basis for a test program to analyze the as-aged material properties of the retired reactor pressure vessel, RPV, from Barsebäck unit 2. The project started on July 1st, 2016. The initial activities focused on mapping of possibilities for future work between VTT, Chalmers and KTH, liaison activities with Vattenfall to discuss extraction of the test material from the Barsebäck plant and collection of material for the baseline testing.

The activities at KTH has focused on overall program management and preparation of an extraction outline to give the basi sfor further discussions with the Swedish utility owners Vattenfall and Uniper regarding the materials extraction scheme and proposed amounts of materials and positions in the RPV. The work has been documented in a report that was sent to NKS as part of the second status report of the project. [Efsing] "Underlag för materialuttag ur Barsebäck 2". [Boåsen] The work is also presented in chapter 2 below.

The work at Chalmers University focused on baseline high resolution atom probe tomography, APT, testing on un-irradiated material as well as sample materials irradiated in a test reactor. In addition to this some samples of thermally aged material was included to visualize the features that develop during both types of ageing. In chapter 3, the work is presented at a high level. The work was also reported as part of the status report [Efsing] as attachment 2 of the letter report. [Lindgren and Thuvander]

VTT has performed a baseline testing utilizing miniature fracture toughness testing samples of un-irradiated RPV material obtained from the original tests of the RPV of Barsebäck 2. The testing has been reported in a VTT research report [Lindqvist and Seppänen] and is described briefly in chapter 4.

2. Test material sampling from Barsebäck 2

2.1 Introduction

Material sampling from the reactor pressure vessel (RPV) of Barsebäck 2 (B2) is proposed as a measure to estimate how the mechanical properties of the material have altered due to ageing during operation of the reactor. This includes changes in the fracture mechanical properties e.g. the ductile-to-brittle transition temperature, yield strength and plasticity, as well as the micro structure of the material. The method to understand the relative changes is by performing extensive mechanical testing of the actual pressure vessel and to compare the results in the as aged condition with both archived reference material and materials that has been part of the RPV surveillance program. The surveillance material has been tested as part of both the normal operation, for the period from 1977 until 2005, and a currently on-going research project that the Swedish nuclear operator Vattenfall is conducting.

2.2 Mechanical testing

2.2.1 Fracture Mechanical Testing

Fracture mechanical testing can be utilized to investigate the embrittlement of the RPV of B2 caused by neutron radiation. Parameters of particular interest are the transition temperature T_0 and the constraint sensitivity. Monitoring how these parameters vary with increasing neutron dose provides qualitative and quantitative measures of the development of the embrittlement. The same samples could be used for T_0 and full constraint, and then one set of samples would be needed for a lower constraint, adding to a requirement of approximately 20 samples in all. A summary of the proposed test sets for the study is given in table 1. A benefit of using B2 is

that there is original baseline material that can be used as a comparison to understand the relative effect of the ageing. Material obtained from B2 has already been tested as part of the current study and reported in [Lindqvist and Seppänen].

The initiation of cleavage fracture can also be investigated by means of fracture mechanical examination of the fracture surfaces. Analytical tools like for instance EBSD and TEM can be used to trace the initiation points to carbides or grain boundaries, and possibly detect dislocation channels in highly irradiated samples.

2.2.2 Tensile Testing and Hardness Testing

Tensile tests are useful to characterize the change in the mechanical properties due to radiation. In particular the plasticity of the material at the same temperature where the fracture mechanical tests are performed is important input and reference to modelling.

Tensile testing is planned to be performed at VTT in Finland, and the tensile test specimen design must therefore fit the equipment and the availability of test material. A sample size of approximately 5 mm diameter and 30 mm length is assumed for the testing.

Hardness testing is proposed to register a hardness profile radially through the RPV. The same sample could also be used for chemical analysis.

2.2.3 Impact Toughness

The original surveillance programs of the Nordic Nuclear Power Plants are generally based on impact toughness testing. For a proper comparison of the results in the proposed project some samples should be dedicated to determine the transition temperature T_{41J}. As an estimate one disc from one or two cylinders would be sufficient for the initial research effort, but more material should be saved for future needs. The disc from which Charpy V samples are taken should be cut from 1/4T to conform to standard ASTM E185-15 and be tested according to E23-16. The issues related to fracture mechanical testing can all be evaluated from two dedicated test series, i.e. one test series on three-point-bending samples and on series on mini-CT test samples. Impact toughness, hardness and tensile testing are separate series.

2.3 Thermal ageing of low alloy steel

Thermal ageing of lwo alloy steels at temperatures relevant for nuclear reactor operation is an issue that has been discussed over a long period of time. To date, the general view is that the effect of irradiation induced ageing by far exceed the effect of thermal ageing for light water reactor operating temperatures. However, combined effects of the two have been difficult to show or dismiss. Recent test results from a program ran by Ringhals AB involving KTH has shown that there can be a significant effect from pure thermal ageing at slightly higher temperatures, i.e. relevant for the pressurizer, PRZ, of the PWR reactor coolant pressure boundary. These tests exhibit relative changes of the ductile to brittle transition temperature, DBTT, at about half the level expected from irradiation ageing during that accumulated time of operation. Hence there is a case of thermally induced embrittlement since no neutron irradiation is present at the PRZ.

The manufacturing processes and guiding documents for all large components manufactured by the Swedish company Uddcomb Engineering are closely related, and as such the materials used for the welding process fulfill the same procurement documentation. There is a close relationship between the RPV at B2 and one of the components remaining in service at Ringhals, such that the same weld wire heat was used for the manufacturing of B2 as for the

PRZ of Ringhals 3. It is therefore of interest to use B2 welds as a reference in future investigations of the Ringhals 3 PRZ. The extraction of test material is executed at the same time as the material from the core region, but this material will not be part of the BREDA-project.

2.4 Microscopy and chemical analysis

Micro structural studies are of interest for understanding what has happened in the material during irradiation. Methods that can be applied are for example macro photography, metallography, SEM, EBSD, TEM and APT. The volumes needed for micro structure studies are small and often the same sample material can be used as for the mechanical testing. A summary of the respective methods that are foreseen to be used, the aim of the respective study and the beneficiary outcome are given in table 2.

RPV steel from Ringhals 4 from surveillance tests and material exposed for neutron irradiation in the Halden reactor have been analyzed by APT to investigate the relation between neutron flux and the formation of clusters in the micro structure. The Barsebäck 2 surveillance capsule G, with a neutron fluence of 5.87×10^{19} n/cm^2, would be relevant for comparison with the Ringhals samples. Although not from the same heat, the weld wire was from the same specifications.

Besides of microscopy, it is necessary to determine the chemical composition of the material that is taken from the RPV. In addition, it is of interest to use cladding material to determine the dose received at the RPV inner surface. The same sample material can be used for microscopy and chemical analysis.

2.5 Proposed scope

Welds suitable for sampling are listed in Table 3. It is beneficial to choose welds with the same heat for the weld filler material. W16 seems to be a better candidate than W10 if the maximum dose is sought after. The effect profile should be axially constant where samples are taken. There is more void (steam formation) in the upper part of the core which gives more velocity retention than in the parts of the core with more water, and therefore sampling should be planned in the upper part of the core region to achieve the highest possible fluence. To achieve sample specimens with varying dose a cylinder can be cut in discs which can be divided into parts according to appendix in [Boåsen] and finalized to requested specimen shapes. From a known fluence at the RPV inner surface it is possible to calculate a depth where the damping reduce fluence to equal the surveillance-tests and discs can be cut for relevant comparison of sample properties.

An estimate of the required amount of material to cover the need to produce test specimens is presented in table 4, where the need is presented per disc. Although this may cover the estimated need, given that 150 mm cylinders can be taken out, one more cylinder should be taken for redundancy.

The total material need is estimated to two cylinders with a diameter of 150 mm from weld W16 (irradiated) and two cylinders of the same size from a weld outside of the core region (un-irradiated). To cover the need for investigations on thermal ageing, another two cylinders are needed from “un-irradiated” weld.

Table 1. Mechanical testing methods.

Test procedure	**Test series**	**Issue**	**Expected understanding**
-Fracture mechanical, various initial crack length, fixed temperature -Tensile tests at selected temperatures	Constraint sensitivity	-Correlation of constraint sensitivity with dose of radiation?	Small changes at low dose assumed. However from capsule G larger change expected than in RPV material
-Fracture mechanical, can be evaluated from existing samples. -SEM to examine fracture surfaces.	Constraint-sensitivity and Mini-CT	-Does the initiation change for brittle cleavage at high neutron dose? -Grain boundary initiation favoured before carbide initiation at high neutron dose?	Better understanding of how fracture mechanisms are affected in irradiated ferritic steel.
- Fracture mechanical	Constraint-sensitivity and Mini-CT	-How does T_0 in the RPV material correlate to corresponding surveillance material?	Understanding regarding surveillance programs and their accuracy.
- Fracture mechanical -Hardness -Tensile tests etc.	Constraint-sensitivity and Mini-CT, Tensile tests and hardness	-How do the mechanical properties correlate throughout the RPV wall? -Does attenuation affect for instance T_0 and H_V radially, do they vary with dose?	Understanding of attenuation and mechanical properties through RPV.
- Fracture mechanical -Impact toughness	Constraint-sensitivity and Mini-CT, Charpy V testing.	-How do T_0 andT_{41J} correlate with radiation dose? -Is the difference constant or does it vary? -How does T_{41J} correlate in RPV vs. surveillance-tests?	Understanding of similarities and differences between the various measures for the transition temperature.
- Fracture mechanical	Constraint-sensitivity and Mini-CT	-How does the chromium content in the material affect T0? Comparison with literature.	Impact of the chemical composition on cleavage fracture properties.
-General mechanical properties		-How does ageing affect the material depending on the neutron spectrum? Compare results from Ringhals surveillance and B2 surveillance capsule G. different spectra – similar dose.	Understanding regarding the impact of the spectrum on changes in mechanical properties.

Table 2. Microscopy and chemical analysis methods.

Test procedure	**Test series**	**Aim**	**Expected understanding**
Spectroscopy	Hardness (radial strip)	- Chemical analysis	Chemical composition through the thickness of the weld
Spectroscopy	Dose determination	- Determination of dose in the RPV cladding	Improved understanding of the exact dose received by the sample material.
-Light Optical Microscopy	Metallography, constraint-sensitivity and Mini-CT	- Metallography -Fractography	Understanding grain structure in the different zones of the weld.
-SEM	Constraint-sensitivity and Mini-CT	- Identify initiation of cleavage fracture. - Search for evidence of cleavage fracture initiated at grain boundary by dislocation channel. - Identify impact of microstructure regarding point of initiation for cleavage fracture. - Fractography	Better understanding about changes in damage mechanisms in ferritic steel from irradiation.
-EBSD	Tensile test	- Study crack propagation and the relation to grain boundaries /grain structure	Better understanding about changes in damage mechanisms in ferritic steel from irradiation.
-TEM	TEM	-Study changes in the micro structure of the material caused by irradiation	Better understanding about what is created in the material by irradiation, and to explain better the impact on mechanical properties.
-APT	APT	-Find evidence of irradiation induced clusters of alloy elements -Investigation of irradiation induced clusters at BWR-spectrum to PWR-dose, regarding material from capsule G	Better understanding about what is created in the material by irradiation, and to explain better the impact on mechanical properties.

Table 3. Welds suitable for sampling in Barsebäck 2 RPV.

Weld	**Heat**	**Type**	**Max-fluence**
W10	7732	Circumferential	≈1.72e18
W11	7732, 7737	Axial, 155˚	≈1.2e18
W12	7737	Axial, 335˚	≈1.2e18
W13	4940	Circumferential	≈1.72e18
W14	7732	Axial, 20˚	≈1.0e18
W15	7732	Axial, 200˚	≈1.0e18
W16	7732	Circumferential	≈1.72e18
W20	7732	Axial, 20˚	≈0
W21	7732	Axial, 200˚	≈0
W28	7732	Circumferential	≈0

Table 4. Material requirement for mechanical tests.

Specimen	**Specimen size [mm]**	**Specimens per disc**	**Test series and aim**
SEN(B)	10x5x45	24	Constraint sensitivity and fracture mechanical study
Mini-CT	10x9.6x4	20	T0 and fracture mechanical studies on small size specimens
Charpy*	10x10x55	20	Impact toughness, comparison to surveillance and the fracture mechanical testing.
Tensile tests	Not specified	5	Materials characterization and constraint sensitivity
Continuous radial strip	25x5x154	1-2	Hardness testing (radially) and chemical analysis.

**Just one or two discs*

Table 5. Suggested number of cylinders.

Weld	**Test series**	**Number of cylinders**
W16	Irradiation ageing	2
W20	Irradiation ageing	2
W20	Thermal ageing	2

3. Reactor Pressure Vessel Steel Welds, Microstructure of Reference Material

The microstructural tests performed as part of the current program is reported in [Lindgren and Thuvander]. The study performed under the contract has focused on characterization of un-irradiated archive and surrogate material that has been made available by Ringhals AB and

Forsmarks Kraftgrupp AB as part of this and a further study at Chalmers in collaboration with the Swedish Centre for Nuclear Technology, SKC. The reference material has been analyzed successfully in both laser and voltage mode in the atom probe. There are some minor differences compared to the expected compositions of the materials, but these are likely the result of the analyzed volume being very small.

The distribution of the most interesting elements, i.e. Ni, Mn, Si and Cu, are very close to random, as expected. However, there seems to be a small tendency for Cu to cluster even in these un-irradiated materials. Cu is supersaturated in the matrix, so clusters could form during the cooling of the material. Another non-random feature that could be observed in the reference material is segregation of C and Mo to dislocations. Clusters of Mn were occasionally observed. These clusters are likely small MnS precipitates.

In summary, the deviations from a random solid solution observed is believed to have limited influence on the mechanical properties. The various clusters are very small, and the number densities are low. The segregation to dislocations can probably play some role for the strength of the material, making dislocation movement and plastic deformation harder. The knowledge gained will be useful when comparing the references material, i.e. the starting condition, with irradiated samples.

4. Fracture toughness measurements with miniature C(T) specimen in reference condition

In the third work package of the BREDA-program, the T_0 reference temperature which can be used as a measurement of the ageing effect due to irradiation was determined for two reactor pressure vessel welds in their reference conditions utilizing the Master Curve method.

The materials, reference material from the original acceptance test for the delivery of the reactor pressure vessel of B2, and a surrogate material mimicking the RPV welds of Ringhals 3. The T_0 reference temperature for the B2 material was determined to be -98°C, and for the surrogate weld material -68°C. These median T_0 values are generally low and brittle fracture at room temperature can be excluded for the materials in their reference conditions. The value has been analysed to estimate the homogeneity using the SINTAP-methodology. The results show that where-as the B2 material has good agreement with the method, i.e. show a homogenous behavior, the surrogate material exhibits a fairly large discrepancy, 16°C.

The results of this study are presented in appendix [Lindqvist and Seppänen].

5. Conclusions

The actual retrieval of materials from the Barsebäck RPV, is foreseen to proceed with preparatory work during 2017 which will allow for material to be available from 2018 and on-wards. The material harvesting is outside the scope of the research-oriented program that was supported by NKS in 2016. The work has in addition to the support from NKS, gained partial support from both SSM and SKC in Sweden and by the Finnish nuclear safety program, the SAFIR-program. Thus the project group will prepare a new proposal for continuation of the work to NKS for coming years which we hope will be considered positively.

The main outcome so far apart from the actual data that has been produced and the proposed cutting scheme for materials retrieval, is the fact that the work enhances the collaboration in this technology driven area between two Swedish technical universities KTH and CTH and

Aalto University in Finland, and the Finnish research institute VTT. In addition to this, it is functioning as a facilitator for contacts between the research driven academic world, safety and operability driven Finnish and Swedish nuclear operating companies and the Finnish and Swedish nuclear safety authorities.

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6. Appendicies

Boåsen M. et. al, Underlag för materialuttag ur Barsebäck 2, In Swedish

Efsing P., Status report – NKS project RPV-BREDA: NKS_R_2016_118, 2016-10-25

Lindgren K. and Thuvander M., Reactor Pressure Vessel Steel Welds Microstructure of Reference Material, 2016-10-31

Lindqvist S. and Seppänen T., BREDA: Fracture toughness measurements with miniature C(T) specimens in reference condition, VTT-R-00140-17

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Key words Low alloy steel, irradiation effects, fracture toughness, ductile to brittle transition temperature, constraint effects, high resolution microscopy

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Underlag för materialuttag ur Barsebäck 2

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1. Inledning

Som en fundamental del i de svenska och finska kraftbolagens åldringshantering av sina kärnkraftverk, följs utvecklingen av de mekaniska egenskaperna hos reaktortankstål med hjälp av fördefinierad och myndighetsstyrd provning genom stationsspecifika surveillance-program. I dessa program bestrålas material som är relevant för de respektive reaktortankarna med en, idealt, väl definierad acceleration (s.k. ledtal) för att möjliggöra en värdering av utvecklingen av egenskaperna under en rimlig tid framöver och ge underlag för verkens arbete med högsta tillåtna gränsvärden för tryck och temperatur under olika driftfall.

Frågeställningen kring inverkan av bestrålning på de mekaniska egenskaperna har varit aktuell från verkens startpunkt, då programmen initierades. Det var vid tidpunkten för konstruktionen av de svenska och finska ursprungliga reaktorprogrammen väl känt att t.ex. koppar kunde ge upphov till mätbara förändringar av såväl draghållfastheten som omslagstemperaturen hos de låglegerade stål som normalt används i reaktortryckkärlen som kraftbärande material.

Materialet till surveillance-programmen hämtades dels från de delar av grundmaterialet från de plåt- eller smidessvep som finns i den aktiva härdregionen (”belt-line” eller ”core region”) och skars bort i samband med tillverkningen samt dels från svetsprover som tillverkades och värmebehandlades i samband med reaktortanken. Det har ansetts att dessa prover fullt ut representerar tryckkärlen men detta har inte visats på ett tillfredställande sätt innan. Genom den förtida avvecklingen av Barsebäcks kärnkraftverk, där såväl ett fullständigt surveillance-program finns tillgängligt som tillfredställande tillverkningsdokumentation, har möjligheten öppnats för en utvärdering av dels den verkliga bestrålningspåverkan som reaktortryckkärlet upplever, dels en jämförelse med såväl surveillance-programmet som de prediktionsmodeller som använts för att utvärdera förändringen av relevanta materialegenskaper som funktion av drifttiden.

Genom ett välbalanserat materialuttag ur reaktortanken vid Barsebäck 2, kan flera aspekter ur ett långtidsdriftsperspektiv belysas och med stor sannolikhet värderas för att ge såväl de nordiska

kraftbolagen som myndigheterna ett underlag som är kritiskt för att värdera stationernas långtidsdriftsklarhet. Följande rapport belyser omfattningen av detta materialuttag med utgångspunkt från att uttag, provning och rapportering kan genomföras inom ramen för ett ägargemensamt projekt, nedan kallat BREDA-RPV.

Sammanfattningsvis föreslås materialuttag för att kunna bestämma hur materialets mekaniska egenskaper förändrats under drift av reaktorn, detta innefattar förändringar i materialets brottmekaniska egenskaper t.ex. omslagstemperaturen, i materialets sträckgräns och plastiska egenskaper, samt i materialets mikrostruktur.

2. Mekanisk provning

2.1. Brottmekanisk provning

Vid materialuttag ur Barsebäck 2 (B2) är brottmekanisk provning av intresse för att kunna genomföra en utredning av reaktortankens försprödning. Ett tekniskt jämförelsemått som ger en kvalitativ och kvantitativ beskrivning av försprödningen är den brottmekaniska omslagstemperaturen T_0, som finns beskriven i ASTM E1921. Den bestrålningsinducerade förändringen av klyvbrottsegenskaperna hos materialet kan fördelaktigt beskrivas som förändringen hos T_0. Utöver att undersöka förändringen hos T_0, ligger ett intresse i att undersöka hur ”constraint-känsligheten” hos materialet förändras med ökande stråldos.

För att kunna göra en kartläggning av större värde är det viktigt här att kunna genomföra den sortens provning både på material taget ur bestrålad svets från reaktortanken, men att även göra identisk provning på material från surveillance-kapslarna ur B2. Surveillanceprogrammen för de nordiska BWR-stationerna, som designats av ASEA Atom, är baserade på samma interna överväganden hos konstruktören och är likartade, med modifieringen att de första programmen, t.ex. i Barsebäck, innefattade fler provkapslar än de senare verken. Uttag av material från reaktortanken vid Barsebäck ger två goda fördelar forskningsmässigt sett, dels att få en jämförelse mellan surveillance och reaktortank, men även att kunna ge en jämförelse mot hur materialet i PWR-stationerna Ringhals 3 och 4, men till del även Fennovoima’s nu påbörjade VVER-stationen i Pyhäjoki, Finland, kommer att utvecklas i och med att det i surveillanceprogrammet ingår en accelererad provkapsel med en fluens på $5{,}87 \cdot 10^{19}$ n/cm^2, vilket ger en långdriftsvinkling på forskningen.

Provning av både T_0 och constraint-känsligheten går att kombinera i överlappande provserier, vilket är fördelaktigt för åtgången av material. För att prova T_0 krävs sex giltiga prov vid fullt constraint enligt ASTM E1921, beroende på svetsens heterogenitet kan det vara troligt att fler provstavar krävs. För att prova constraint-känsligheten krävs att provning sker vid två olika constraint-nivåer, detta fås genom att använda samma provstavsgeometri men med olika sprickdjup. Lämpligt är att man väljer ett sprickdjup vid fullt constraint (samma som T_0-provningen) och ett vid lägre constraint, där cirka tio provstavar troligen krävs vid varje constraint-nivå (fler kan krävas beroende på svetsens heterogenitet). Detta skulle då ge en god marginal vid T_0-provningen samt möjligheten att kunna fånga spridningen hos brottsegheten vid olika constraint.

Viktigt för provning av constraint-känsligheten är att den görs vid samma medianseghet för alla stråldoser, t.ex. K_{IC}=100 MPa√m, detta gör att provningen kommer att behöva ske vid olika temperaturer för de olika stråldoserna eftersom bestrålningen förändrar $T_{0.}$

En annan intressant frågeställning som kan utredas är huruvida initieringsmekanismen för klyvbrott eventuellt förändras med ökande stråldos. Flera forskare har påvisat uppkomsten av s.k. dislokationskanaler, ett fenomen där dislokationerna glider fram i band där de röjt undan de bestrålningsinducerade klustren som verkar som dislokationshinder. Detta skulle innebära att den primära plastiska deformationen skulle vara lokaliserad i dessa kanaler. Korngränser skulle i det här fallet agera hinder för kanalens utbredning och verka för att hindra dislokationernas passage, här kan man föreställa sig två fall – det ena där dislokationer emitteras på andra sidan korngränsen varpå en ny kanal uppstår på den nya sidan. Det andra fallet där inga dislokationer emitteras från andra sidan korngränsen, detta skulle innebära att en spänningskoncentration uppstår i gränsskiktet mellan kanal och korngräns, om denna spänning blir tillräckligt stor kommer korngränsen att öppna sig varpå en mikrospricka skapas. Givet detta händelseförlopp kan man tänka sig att initieringen av klyvbrott förändras från att primärt vara karbid-initierat till att bli korngräns-initierat. För att dislokationskanaler ska kunna uppstå krävs att material med hög stråldos utsätts för belastning, därför spås denna typ av deformation endast kunna hittas i materialet från surviellance-kapsel G som har en fluens på $5.87 \cdot 10^{19}$ n/cm^2. Givet att en brottmekanisk karaktärisering kan göras på detta material, kan brottytorna analyseras och klyvbrottsinitieringen förhoppningsvis identifieras. Eventuellt kanske man kan tänka sig att spår från dislokationskanaler kan upptäckas med EBSD eller TEM.

Givet att man kan skära ut rondeller med en diameter på 150 mm kommer detta att ge material till både en finsk och en svensk brottmekanisk provningsserie, förslag på uppdelning av rondell samt resulterande provstavsmängd ges i avsnitt 4.

2.2. Dragprov och hårdhet

För att utröna hur de mekaniska egenskaperna förändras med bestrålning är det viktigt att genomföra dragprov, där materialets plastiska egenskaper kan studeras. Av intresse är främst att genomföra dragprov vid temperaturen där de brottmekaniska proven genomförs, detta för att kunna använda resultaten som indata till och referens i materialmekanisk modellering. Dragprovstavarnas storlek bör bestämmas utefter möjligheterna hos utrustningen på VTT i Finland, detta för att genomföra provningen på ett sätt som konserverar material och resurser. En gissning är att en rundprovstav med diameter på 5 mm och längd på ca 30 mm är lämplig.

Utöver dragprov är det också intressant att mäta hårdheten hos materialet. Hårdhetsprovning bör ske på en obruten radiell provbit som skärs ur rondellen att se på variationen av hårdhet genom reaktortankväggen, på samma skiva torde kemibestämning kunna göras.

2.3. Slagseghetsprovning

De ursprungliga surveillance-programmen baserades på slagprovning av material. För att korrekt kunna jämföra resultat med de som uppnås under projektet bör en del av materialuttagen användas till att även bestämma omslagstemperatur via slagprovning, s.k. T_{41J}. Ett rimligt

antagande är att endast en skiva ur en eller två rondeller används till slagseghetsprovning för den forskningsansats som görs initialt, dock att materialuttag görs, ifall ett framtida behov av vidare slagseghetsprovning skulle komma till att finnas. Skivan som Charpy-provningen görs på bör skäras ut från 1/4T för att stämma överens med standarden ASTM E185-15 och provas enligt E23-16.

Tabell 1 Forskningsfrågeställningar kring mekaniska provmetoder

Provmetod	Provserie	Frågeställning	Förväntad förståelse
-Brottmekanisk, olika sprickdjup, samma temperatur -Dragprov vid valda temp.	Constraint-känslighet	-Förändras constraint-känsligheten på klyvbrottsegheten med ökande stråldos?	Troligen små förändringar vid lägre doser, dock spås kapsel G påvisa större förändring än material från reaktortanken.
-Brottmekanisk, kan utvärderas ur prov som redan finns i matrisen. -SEM för att undersöka brottytor.	Constraint-känslighet och Mini-CT	-Förändras initieringsmekanismen för klyvbrott vid högre stråldos? -Möjligt att korngränsinitiering av dislokationskanal premieras över karbider vid hög stråldos?	Bättre förståelse för hur skademekanismer påverkas i bestrålat ferritiskt stål.
-Brottmekanisk	Constraint-känslighet och Mini-CT	-Hur väl korrelerar T_0 i materialet från reaktortanken med motsvarande surveillance-material?	Förståelse kring surveillance-programmen och noggrannheten i dem.
-Brottmekanisk -Hårdhet -Dragprov etc.	Constraint-känslighet, Mini-CT, dragprov och hårdhet	-Hur korrelerar de mekaniska egenskaperna genom tjockleken på reaktortanken? -Hur ser attenueringen av t.ex. T_0 och H_V ut radiellt, följer den stråldosen?	Förståelse kring attenueringen av mekaniska egenskaper genom tanken.
-Brottmekanisk -Slagseghet	Constraint-känslighet, Mini-CT och Charpy-provning	-Hur korrelerar T_0 och T_{41J} med ökande stråldos? -Är skillnaden konstant eller varierande? -Hur korrelerar T_{41J} ur tanken relativt surveillanceprogrammet?	Förståelse kring likheter och skillnader mellan de olika måtten på omslagstemperatur.
-Brottmekanisk	Constraint-känslighet och Mini-CT	-Hur inverkar krommängden (Cr) i materialet på T0? Utförs som jämförelsestudie mot litteratur.	Inverkan av kemiska sammansättningen på klyvbrottsegenskaper
-Allmänt mekaniska egenskaper		-Hur förändrar åldringen materialet beroende av neutronspektrum? Jämföra resultat från Ringhals surveillance och B2 surveillance kapsel G. Olika spektrum – liknande dos.	Förståelse kring spektrumets inverkan på förändringar i mekaniska egenskaper.

De frågeställningar som anknyter till brottmekanisk provning kan alla utvärderas ur två provserier som avsätts för detta, nämligen en provserie som görs på trepunktsböjprovstavar och en som görs på mini-CT provstavar. Slagseghets-, hårdhets- och dragprovningen hör till egna provserier.

3. Mikroskopi och kemibestämning

Mikrostrukturella studier är av intresse för att bättre kunna förstå vad som skett i materialets mikrostruktur i och med bestrålningen, de intressanta provmetoderna går att kombinera med den övriga provningen. Till exempel, kan makrofotografering av svetsarnas strängar göras innan kapningen av skivor görs, metallografi kan göras på provämnen av intresse och metoder som SEM/EBSD, TEM och APT kräver en mycket liten materialmängd. Metallografi skall genomföras från makroskopisk till mikroskopisk nivå.

Reaktortankstål från Ringhals 4, bestrålat i den norska Haldenreaktorn och ur ordinarie surveillance-program har undersökts och jämförts med APT, undersökningen har bland annat centrerats kring neutron flux-beroendet hos bildandet av kluster i mikrostrukturen hos stålen. En unik möjlighet finns här att undersöka vilken effekt neutronspektrumet har på bildandet av klustren, i och med Barsebäck 2s surveillance-kapsel G som har uppnått en neutronfluens på $5{,}87 \cdot 10^{19}$ n/cm^2 – en dos som är relevant att jämföra med redan gjorda analyser. Här finns dock en mindre diskrepans i den kemiska sammansättningen mellan Ringhals 4 och Barsebäck 2, även om de båda tankarna är svetsade med samma svetstrådsspecifikation.

Utöver mikroskopi behöver kemibestämning göras av de rondeller som skärs ur tanken. För att kunna stärka undersökningen är det av intresse att tillvarata pläteringen på insidan av rondellen i syfte att genomföra dosbestämning av rondellen, t.ex. som beskrivet i Regulatory Guide 1.190. Planering av extra materialuttag utöver behovet för den mekaniska provningen anses inte vara nödvändigt för att täcka behovet för mikroskopi och kemibestämning.

Tabell 2 Forskningsfrågeställningar kring mikroskopimetoder

Provmetod	Provserie	Syfte	Förväntad förståelse
Spektroskopi	Hårdhet (radiell remsa)	-Kemibestämning	Kemiska sammansättningen genom tjockleken på svetsen
Spektroskopi	Dosbestämning	-Dosbestämning med pläteringen från insidan tanken	Ökad förståelse av den exakta dosen i uttaget material
-Ljusoptiskt mikroskop	Metallografi, constraint-känslighet och Mini-CT	-Metallografi -Fraktografi	Förståelse om materialets kornstruktur i svetsgodsets olika zoner
-SEM	Constraint-känslighet och Mini-CT	-Identifiera initiering av klyvbrott. -Leta bevis för klyvbrott initierat i korngräns av eventuell dislokationskanal -Identifiera mikrostrukturens inverkan kring initieringspunkten för klyvbrott -Fraktografi	Bättre förståelse för hur skademekanismer i ferritiskt stål förändras av bestrålning.
-EBSD	Dragprov	-Studera sprickutbredning och relationen till korngränser/kornstruktur	Bättre förståelse för hur skademekanismer i ferritiskt stål förändras av bestrålning.
-TEM	TEM	-Studera förändringar i materialets mikrostruktur från bestrålning	Bättre förståelse kring vad som skapas i materialet av bestrålning, samt att bättre kunna förklara påverkan på mekaniska egenskaper.
-APT	APT	-Leta bevis från bestrålningsinducerade kluster av legeringsämnen -Undersökning av bestrålningsinducerade kluster vid BWR-spektrum till PWR-dos, avser materialet ur kapsel G	Bättre förståelse kring vad som skapas i materialet av bestrålning, samt att bättre kunna förklara påverkan på mekaniska egenskaper.

4. Materialåtgång

Svetsar som bedöms lämpliga för uttag presenteras i Tabell 3, gynnsamt är förmodligen att välja svetsfogar som är av samma svetstrådscharge. Bedömningen är att W16 är en bättre kandidat för materialuttag än W10 om maximal dosbelastning eftersträvas. Effektprofilen skall vara axiellt plan där provuttagen planeras. Det är mer void (ångbildning) i övre delen av härden som gör att snabba neutroner inte bromsas upp i samma utsträckning som i de delar av härden där det är mer vatten och därför bör provuttag planeras i övre härdregionen för att erhålla så hög fluens som möjligt.

För att kunna få provstavar med olika nivåer av stråldos kan en rondell skäras upp i skivor som därefter kan delas in i provstavsämnen enligt figurerna i Appendix. Skivorna bör skäras till en tjocklek á ca 10 mm med en reserverad tjocklek på 15 mm per skiva (inklusive kapmån), var-ur provämnen därefter kan skäras. Enligt korrespondens med Martin Lundgren är max-fluens i skiktet cladding/tankvägg $1{,}72 \cdot 10^{18}$ n/cm^2 (E<1 MeV) och avtar till 2/3 på ett avstånd 40-50 mm in i svetsen och till 1/3 på 110-120 mm in i svetsen. Intressant är att skära skivor från djup där fluensen korrelerar med den som finns i surveillance-materialet, d.v.s. 0,575 och $0{,}102 \cdot 10^{18}$ n/cm^2. Skivor med de doserna bör kunna hittas på djup motsvarande 109-119 mm och 51-63 mm, respektive.

Tabell 3 Lämpliga skarvar att skära rondeller ur

Skarv	Charge	Typ	Max-fluens
W10	7732	Omkrets	≈1.72e18
W11	7732, 7737	Längs, 155˚	≈1.2e18
W12	7737	Längs, 335˚	≈1.2e18
W13	4940	Omkrets	≈1.72e18
W14	7732	Längs, 20˚	≈1.0e18
W15	7732	Längs, 200˚	≈1.0e18
W16	7732	Omkrets	≈1.72e18
W20	7732	Längs, 20˚	≈0
W21	7732	Längs, 200˚	≈0
W28	7732	Omkrets	≈0

Uppskattad materialmängd för att täcka provstavsbehovet för de experimentella ansatser som finns återgivna i det här dokumentet har uppskattats i Tabell 4, där provstavsbehovet återges per rondellskiva. Även om detta kan tänkas täcka det uppskattade behovet givet att rondeller med en diameter á 150 mm kan skäras ut ur tanken, bör ytterligare en rondell skäras ut för redundansens skull. Den totala materialåtgången uppskattas vara två rondeller med diameter á 150 mm ur svets W16 (bestrålad) samt två rondeller av samma storlek ur en lämplig svetsfog som ligger utanför härdzonen (”obestrålat”). För att kunna täcka upp materialbehovet gällande undersökningar kopplade till termisk åldring behövs ytterligare två rondeller ur ”obestrålad” svetsskarv.

Tabell 4 Materialåtgång för mekanisk provning

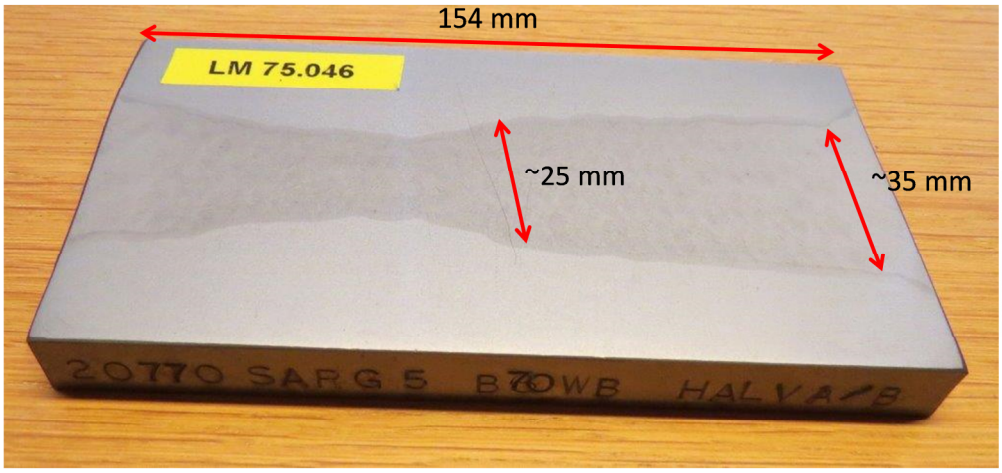
Provstav	Provstavsstorlek [mm]	Antal per skiva	Provserie och syfte
SEN(B)	10x5x45	24	Constraint-känslighet och brottmekanisk studie
Mini-CT	10x9,6x4	20	T_0 och brottmekaniska studier på små provstavar
Charpy*	10x10x55	20	Slagseghet, jämförelse mot surveillance och den brottmekaniska provningen
Dragprov	Ännu ospecificerat	5	Materialkaraktärisering samt betydande vid utredning av constraint-känslighet
Obruten radiell remsa	25x5x154	1-2	Hårdhetsprovning radiellt samt kemibestämmning

*Endast en-
två skivor

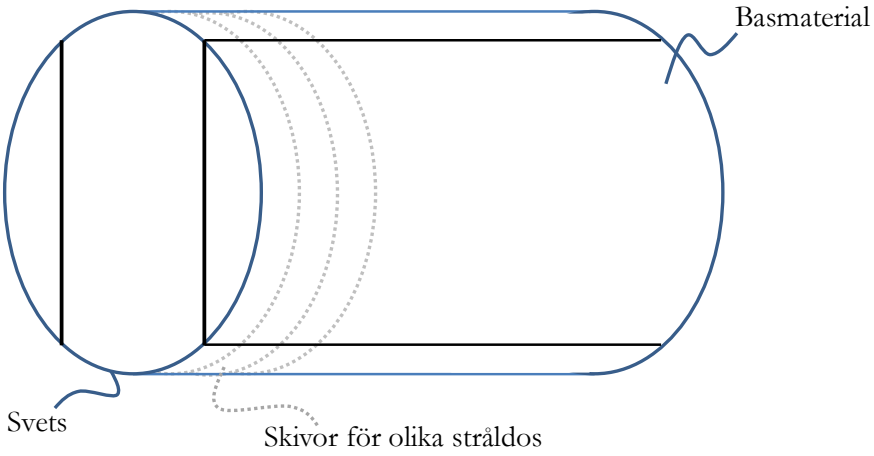
Förslag på hur en rondellskiva kan delas upp i provstavar ges i Appendix där svetsbredd ställs mot rondelldiameter och antalet möjliga provstavar uppskattas.

Appendix

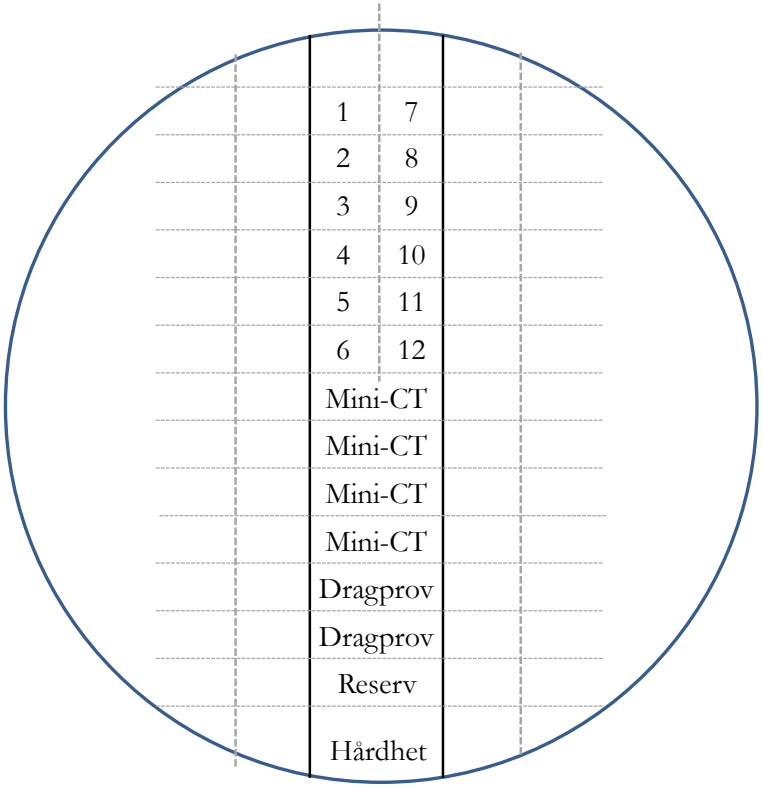
I en rondell som skärs ut från reaktortanken kommer svetsbredden att variera genom tjockleken, detta gör eventuellt att olika mängder provstavar kommer att kunna plockas ut. I efterkommande bilder har en uppskattning gjorts som presenterar visuellt antalet provstavar som kan tas ur varje skiva kontra rondelldiameter och svetsbredd.
Nedan ges ett exempel på hur svetsskarv W20 (B2s RPV) varierar genom tankens tjockleksriktning.



För att kunna göra bästa möjliga mekaniska provningsserie rekommenderas att rondelldiametern sätts till 150 mm, på så vis skulle en redundans i uttaget svetsgods finnas i varje rondell.
Material för att kunna genomföra mikrostrukturell karaktärisering anses kunna plockas ur de redan specificerade provstavsämnena efter att den mekaniska provningen skett. Makrokaraktärisering av svetsstrukturen kan göras innan skivorna kapas upp i provstavsämnen.



Scenario: Smal svets á 25 mm i rondell med diameter 150 mm



Varje rad tas som 10 mm

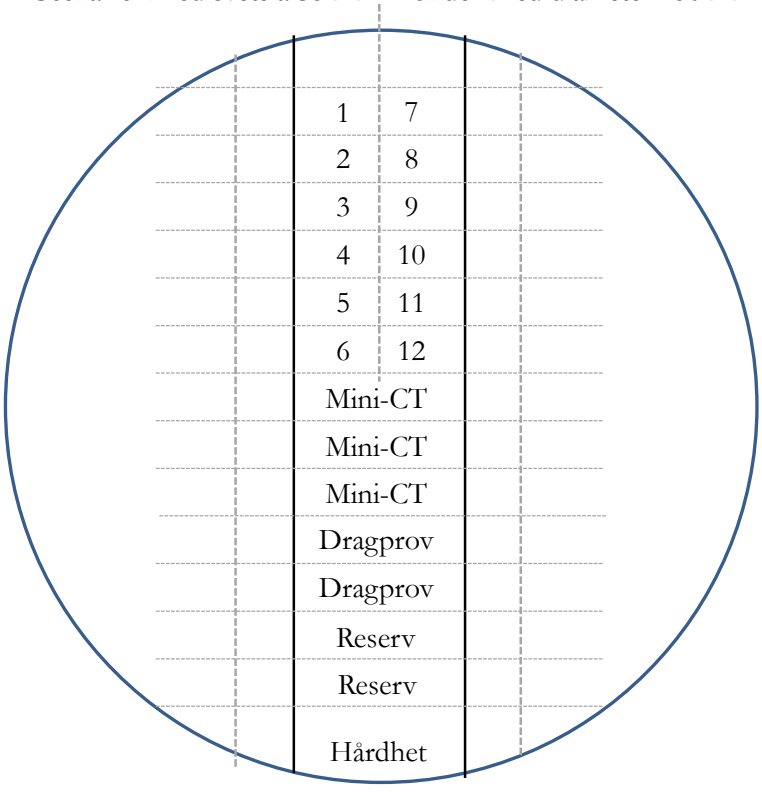
En skiva med diameter på 150 mm och en tjocklek på ca 10 mm skulle ge 24 SEN(B) provstavar med 5 mm tjocklek, markerat 1-12 i bilden. Dock skulle detta kräva påsvetsade ändar för att ge hela provsstavar.

Indelningarna markerade ”Mini-CT” skulle räcka var och en till fem provstavar, därför är här fyra rader reserverat för att totalt kunna ge 20 mini-CT provstavar

Två rader reserveras för dragprovsuttag, där specifikation utelämnas för tillfället om provstavsdimension

Längst ut i rondellen lämnas utrymme för att kunna ta en radiell remsa längs tankens tjockleksriktning (här benämnd ”Hårdhet”), d.v.s. innan rondellen skärs upp i skivor

Scenario: Bred svets á 35 mm i rondell med diameter 150 mm



Varje rad tas som 10 mm

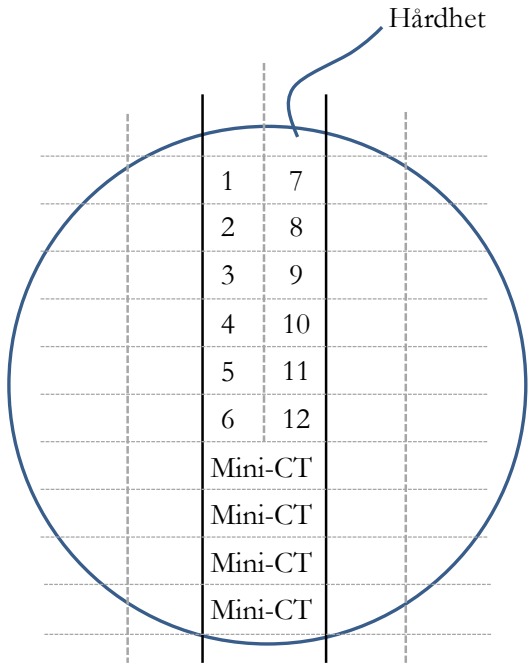
En skiva med diameter på 150 mm och en tjocklek på ca 10 mm skulle ge 24 SEN(B) provstavar med 5 mm tjocklek, markerat 1-12 i bilden. Dock skulle detta kräva påsvetsade ändar för att ge hela provsstavar.

Indelningarna markerade ”Mini-CT” skulle räcka var och en till åtta provstavar, därför är här tre rader reserverat för att totalt kunna ge 24 mini-CT provstavar

Två rader reserveras för dragprovsuttag, där specifikation utelämnas för tillfället om provstavsdimension

Längst ut i rondellen lämnas utrymme för att kunna ta en radiell remsa längs tankens tjockleksriktning (här benämnd ”Hårdhet”), d.v.s. innan rondellen skärs upp i skivor

Scenario: Smal svets á 25 mm i rondell med diameter 110 mm



En skiva med diameter på 110 mm och en tjocklek på ca 10 mm skulle ge 24 SEN(B) provstavar med 5 mm tjocklek, markerat 1-12 i bilden. Dock skulle detta kräva påsvetsade ändar för att ge hela provsstavar.

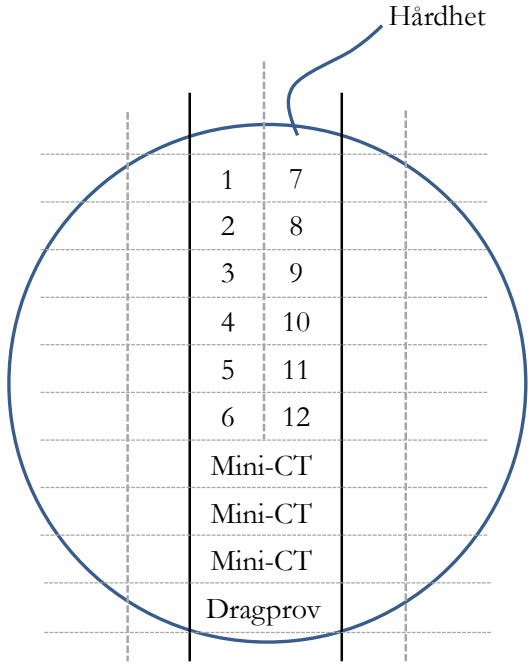
Indelningarna markerade ”Mini-CT” skulle räcka var och en till åtta provstavar, därför är här tre rader reserverat för att totalt kunna ge 24 mini-CT provstavar.

Inga rader kan i det här fallet reserveras för dragprovsstavs tillverkning, vilket ses som en stor nackdel.

Längst ut i rondellen lämnas utrymme för att kunna ta en radiell remsa längs tankens tjockleksriktning (här benämnd ”Hårdhet”), d.v.s. innan rondellen skärs upp i skivor

Varje rad tas som 10 mm

Scenario: Bred svets á 35 mm i rondell med diameter 110 mm



En skiva med diameter på 110 mm och en tjocklek på ca 10 mm skulle ge 24 SEN(B) provstavar med 5 mm tjocklek, markerat 1-12 i bilden. Dock skulle detta kräva påsvetsade ändar för att ge hela provsstavar.

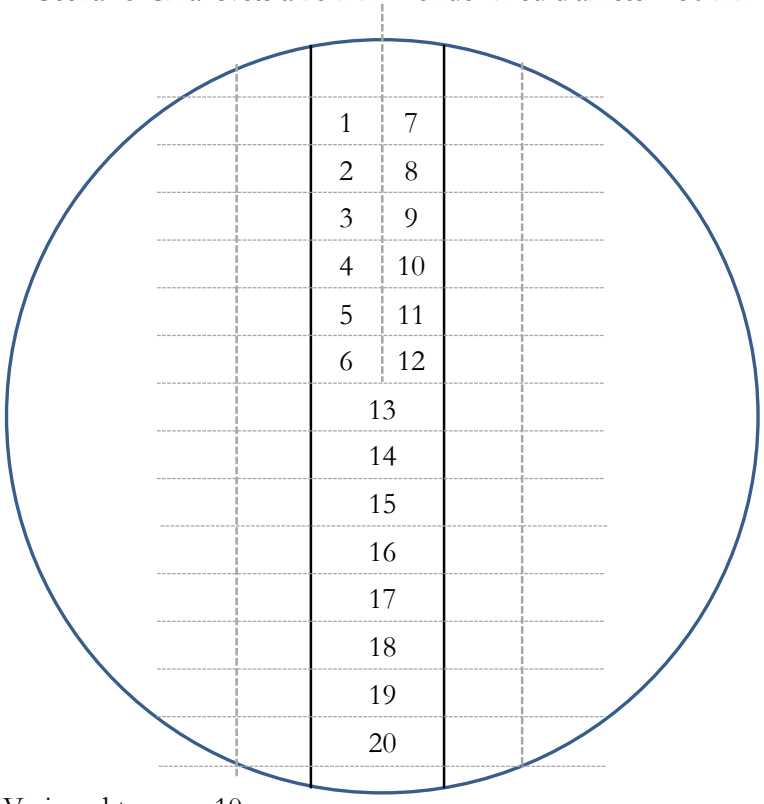
Indelningarna markerade ”Mini-CT” skulle räcka var och en till åtta provstavar, därför är här tre rader reserverat för att totalt kunna ge 24 mini-CT provstavar.

En rad reserveras för dragprovsuttag, där specifikation utelämnas för tillfället om provstavsdimension

Längst ut i rondellen lämnas utrymme för att kunna ta en radiell remsa längs tankens tjockleksriktning (här benämnd ”Hårdhet”), d.v.s. innan rondellen skärs upp i skivor

Varje rad tas som 10 mm

Scenario: Smal svets á 25 mm i rondell med diameter 150 mm



Varje rad tas som 10 mm

En skiva med diameter på 150 mm och en tjocklek på ca 10 mm skulle ge 20 Charpy-provstavar om de kapades enligt följande metod. De provstavar som skall slås av vid lägre energier kan högst troligen tas som halvor enligt markeringarna 1-12, eftersom den plastiska zonen inte kommer att växa sig stor i de här bitarna. Markeringarna 13-20 skulle lämpa sig för provning vid högre anslagsenergi eftersom den plastiska zonen i de provstavarna kommer utbreda sig mer än vid de lägre energierna.

Samma resonemang skulle vara rimligt vid 35 mm svets.

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Due to the time schedule and the changes of the activities during 2016, the project started 1st of July 2016. The initial activites has focused on mapping of possibilities for future work between VTT, Chalmers and KTH, liason activities with Vattenfall to discuss extraction of the test material from the Barsebäck plant and collection of material for the base line testing. The signing of the contract was finallized at KTH during the summer.

A start-up meeting regarding the fracture mechanical testing was held at VTTs offices in Esbo, Finland at the 13th of June involving the partners from VTT/Aalto University and KTH.

The un-irradiated base-line RPV material of the BREDA project arrived to VTT 7.9.2016. VTT received also background data of similar RPV material, e.g. chemistry, Charpy and fracture toughness data. The specimens are now under preparation and will be available for testing at the end of October/beginning of November. After the measurements, the results are to be analysed and a report will be written.

A report on proposed extraction of material from the reactor pressure vessel of Barsebäck 2 is currently being finallized, see attachement 1. The report outlines the needs not only for the BREDA-proposal as described here but also a number of parallell activities that are consistent with the current drive for long term operation, LTO, of some of the current nuclear reactors.

Base line high resolution atom probe tomography, APT, testing has been conducted on un-irradiated material as well as sample materials irradiated in a test reactor and thermally aged material to visuallize the features that develops during both types of ageing. A report is appended to this letter, see attachement 2.

Best regards,

Pål Efsing
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Reactor Pressure Vessel Steel Welds

Microstructure of Reference Material

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2016-10-31

Introduction

With the closing of the BWR reactors at Barsebäck power plant a unique possibility for research has emerged. The project *Barsebäck R&D Arena* (BReDA), coordinated by Energiforsk, will take advantage of the situation. One part of the project concerns ageing of the reactor pressure vessel (RPV). Within the activity called *Barsebäck RPV Trepan* (BREDA-RPV), supported by NKS, parts from the RPV welds will be extracted for mechanical evaluation and microstructure examination. This will presumably happen during 2017-2018. In the present report an investigation of reference materials, which have not been subjected to ageing, is presented. This will serve as a baseline for comparison when the RPV material from Barsebäck will become available for investigation.

Ageing of RPV welds leads to embrittlement, manifested by increased hardness, strength and ductile to brittle temperature and reduced toughness. The probably most important effect is caused by the formation of nanometer-sized clusters containing Ni, Mn, Si and Cu. The clusters are formed due to the neutron irradiation. As the features of prime interest are very small, atom probe tomography (APT) is a very well suited method for the characterization.

Experimental

The material

The material is low alloy bainitic steel welds. Material from two different sources, in the shape of non-tested Charpy samples, have been analyzed, both similar to the Barsebäck welds. The first material originates from the production of Ringhals R4 reactor. The composition of this material is presented in table 1, from an investigation of irradiated surveillace samples [Miller]. The second material comes from the production of a reactor in Forsmark. A light optical image and a scanning electron microscopy (SEM) image can be seen in figure 1. In the SEM micrograph some spherical carbides can be seen.

Table 1. Composition of the weld (at.%) [Miller].

Cu	Ni	Mn	Mo	Si	C	P	S	Cr	Al	Co	V
0.07	1.50	1.48	0.31	0.42	0.24	0.016	0.010	0.07	0.056	0.014	0.002

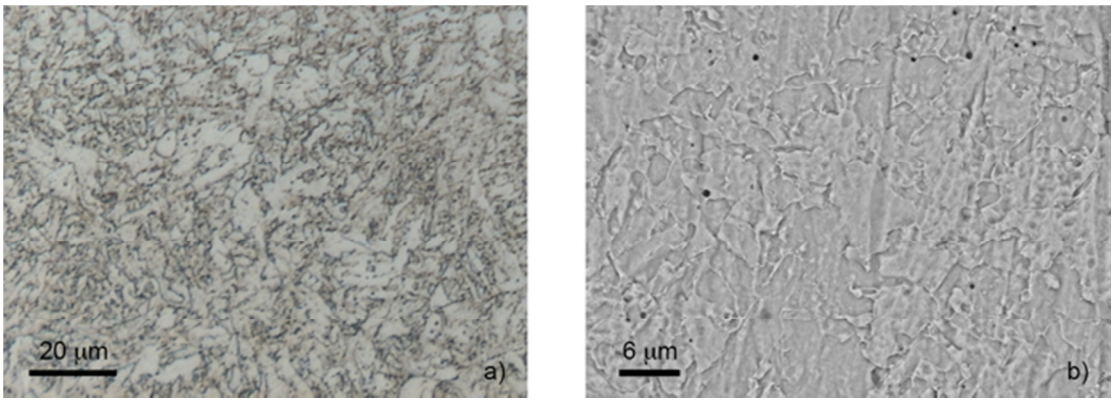


Figure 1. Light optical micrograph (left) and scanning electron micrograph (right). The polished sample was etched in Nital.

Instrumentation

For APT an Imago LEAP™ 3000X HR was used, with a repetition rate of 200 kHz and the evaporation rate 0.2%. In voltage mode the temperature of the specimen was 70 K and the pulse fraction was 20%. For laser mode the temperature was 50 K and the laser pulse energy 0.4 nJ. The data was evaluated using IVAS™ 3.6.6 software.

Sample preparation for APT

The sample for APT must be in the shape of a very sharp needle. This was achieved using electro-polishing. First, blanks of the size 15×0.3×0.3 mm^3 were prepared by low speed cutting. The electro-polishing was done in three steps. In the first step a neck is formed by electro-polishing in a thin layer of electrolyte (10 % perchloric acid in 20% glycerol and 70% methanol) floating on top of a heavy, inert liquid (Galden). The blank is moved up and down in the solution and a neck is formed at the middle of the blank. In the second step, a weak electrolyte (2% perchloric acid in 2-butoxy ethanol) is used, and the voltage is applied until the bottom part of the blank drops. With some care the dropped part of the blank can also be used as a sample. The third step is to use short pulses in the weak electrolyte to sharpen and clean the needles further. After this the tips of the needles have a radius <100 nm, suitable for APT analysis.

Results

The reference material has been analyzed successfully in both laser and voltage mode in the atom probe.

The composition from one APT analysis of the Ringhals sample is given in table 2. There are some minor differences compared to the expected composition (table 1), but these are likely the result of the analyzed volume being very small.

Table 2. Composition (at.%) of the material measured by voltage pulsed APT (Ringhals sample).

Cu	Ni	Mn	Mo	Si	C	P	Cr	Co	V	O
0.045	1.72	1.25	0.20	0.25	0.005	0.024	0.19	0.008	0.001	0.003

The distribution of the most interesting elements, i.e. Ni, Mn, Si and Cu, is very close to random, as expected. However, there seems to be a small tendency for Cu to cluster even in these un-irradiated materials, as can be seen in figure 2. Cu is supersaturated in the matrix, so clusters could form during the cooling of the material.

Figure 2. The distribution of Cu (Ringhals sample), laser pulsed APT. One or two very small clusters were observed.

Another non-random feature that could be observed in the reference material is segregation to dislocations. The elements C and Mo were enriched along linear features, which most probably are dislocations, see figures 3-6. The concentrations are rather low, with Mo barely exceeding 1 at.%, suggesting that this is mainly segregation to the dislocation. It is possible that some very small carbides are also present along the dislocations. At the dislocations some enrichments of Mn, Cr, V and P were also observed.

In some analyses small clusters (1 nm) of V were observed, see figures 3 and 6. The best guess is that these clusters are small VN precipitates. The identification is difficult because of the overlaps between Si^{2+} and N^{+}, and N_2^{+} and Fe^{2+}. Also the field evaporation of N partly occurs in bursts, making the detection difficult.

Clusters of Mn were occasionally observed, see figure 3. These clusters are likely small MnS precipitates. The reason why the identification is not straight forward is that the precipitates are very small, and that S overlaps with one Ni isotope and with O_2.

In one analysis, of the Forsmark material, a large (>50 nm) carbide was captured. The composition is presented in table 3. The carbide is basically Mo_2C. The quantification of C is problematic, so even if the carbide is large, the measured C concentration is 26 at.%, when it is expected to be 33 at.%. This behavior is normal.

In summary, the deviations from a random solid solution observed is believed to have limited influence on the mechanical properties. The varios clusters are very small, and the number densities are low. The segregation to dislocations can probably play some role for the strength of the material, making dislocation movement and plastic deformation harder. The knowledge gained will be useful when comparing the references material, i.e. the starting condition with irradiated samples.

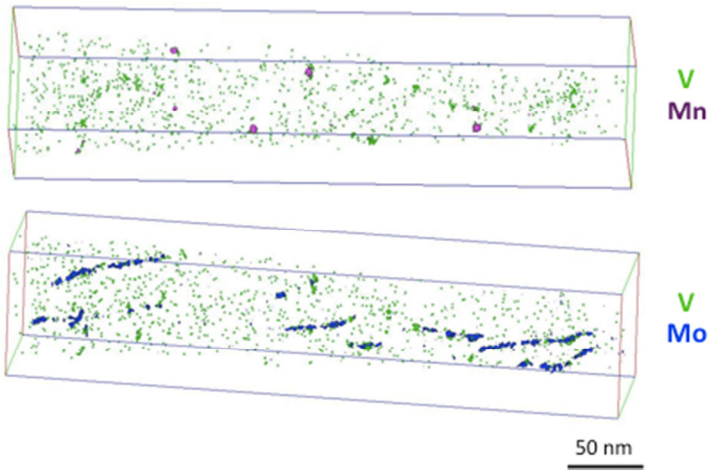


Figure 3. In this sample from Ringhals, clusters enriched in V, believed to be VN and clusters enriched in Mn, believed to be MnS were observed. A few dislocations enriched in Mo and C were also observed. Laser pulsed APT analysis. The isosurfaces represent 4.5 at.% Mn and 1.3 at.% Mo, respectively.

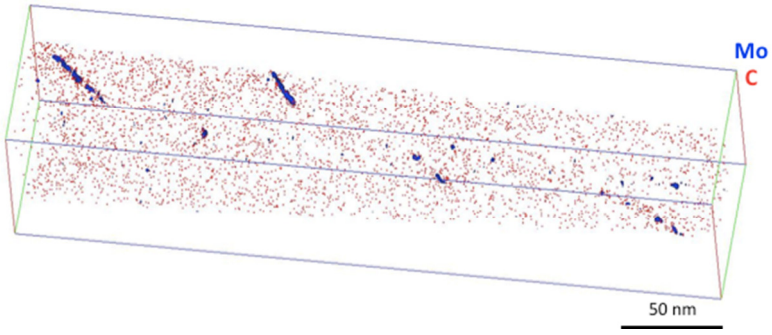


Figure 4. Another analysis (sample from x) containing two or three dislocations, enriched in Mo and C (Ringhals sample). Laser pulsed APT. The isosurfaces represent 1.0 at.% Mo.

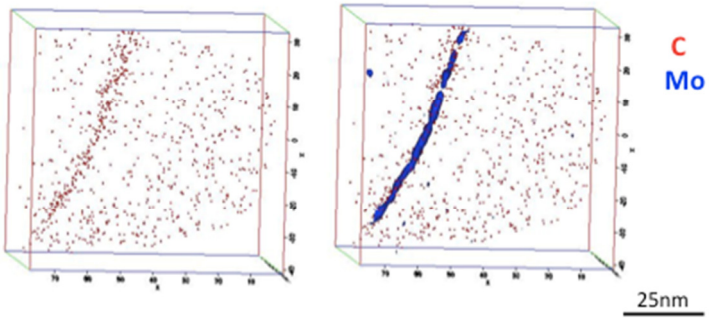


Figure 5. 5068. The analyzed volume contains one dislocation, which is enriched in Mo and C (Forsmark sample). Laser pulsed APT. The isosurfaces represent 1.2 at.% Mo.

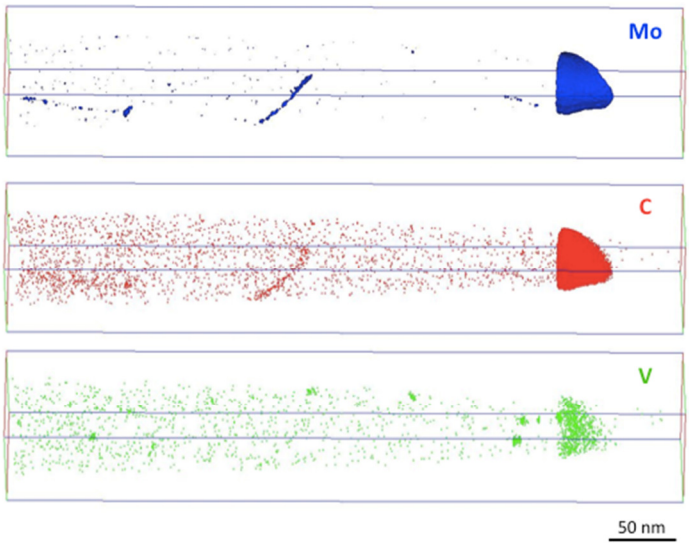


Figure 6. APT reconstruction of Forsmark sample showing a large carbide (in the right part of the image), segregation to dislocations (Mo and C) and small clusters containing V (probably VN) (Forsmark sample). Laser pulsed APT. The isosurfaces represent 1.0 at.% Mo.

Table 3. Approximate composition of the large carbide shown in figure 6 (at.%).

Ni	Mn	Mo	C	Cr	V	Fe
0.1	5	60	27	2	0.2	6

Some artefacts were encountered in the APT analyses. In laser mode, crystallographic poles could be seen for most elements, but the largest effect is in P and Si, see figure 7. Using voltage mode the poles are sometimes visible for P. In Si and Ni it can be seen as well, but much less pronounced than for the laser pulsed case. This visible pole structure is a problem since this means that a distribution without precipitates is still not random, and thus later statistical analysis needs to be done taking this into account. The reason for the larger effect in laser mode is that the evaporation is achieved by heating up the specimen for very short times (ns). Increased temperature gives higher surface diffusion. As there is still some pole structure visible in the voltage pulsed specimen there is some surface diffusion effects in this case as well. The temperature might be lowered, but the specimen temperature is a trade-off between surface diffusion and the risk of fracture. Risk of fracture is higher at lower temperatures since the material is more brittle.

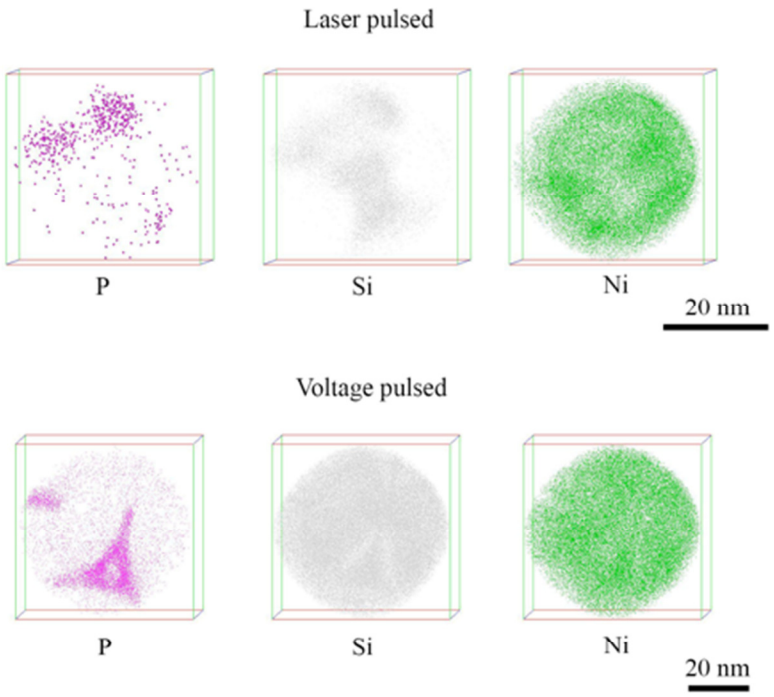


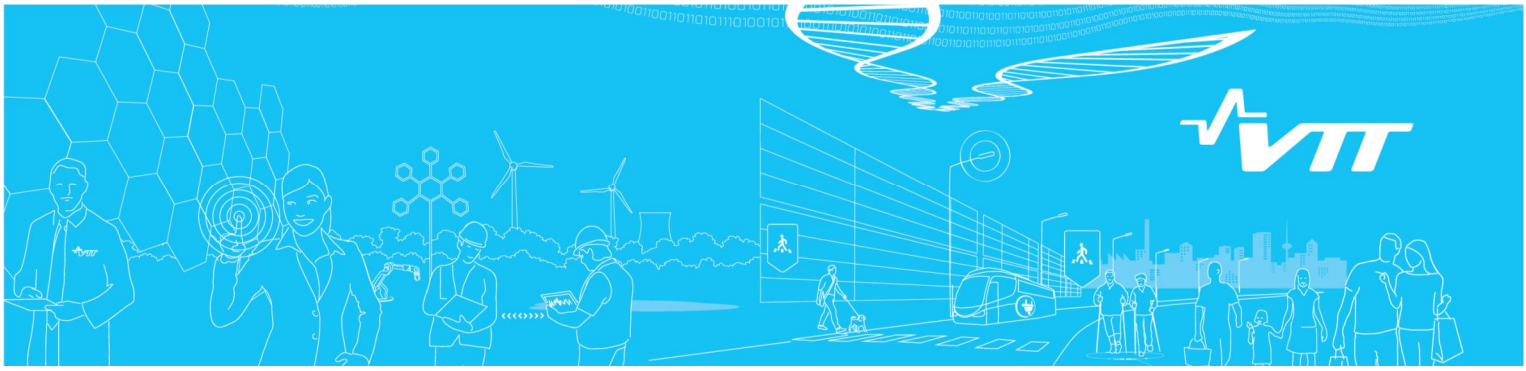
Figure 7. APT reconstructions of P, Si and Ni distribution in both laser and voltage mode. The viewing directions is along the analysis direction, which makes the crystallographic influence clear.

Conclusions

- The reference material does not contain any clusters of Ni, Mn or Si.
- Cu has a very weak clustering tendency.
- Enrichments to dislocations, primarily of Mo and C, were observed.
- Clustering of V was observed, likely due to very small VN precipitates.
- Clustering of Mn was observed, lekely due to very small MnS precipitates.
- One large carbide, likely Mo_2C, was analyzed.
- Laser pulsing gives larger datasets, but strongly affects the distribution measured of Si and P.

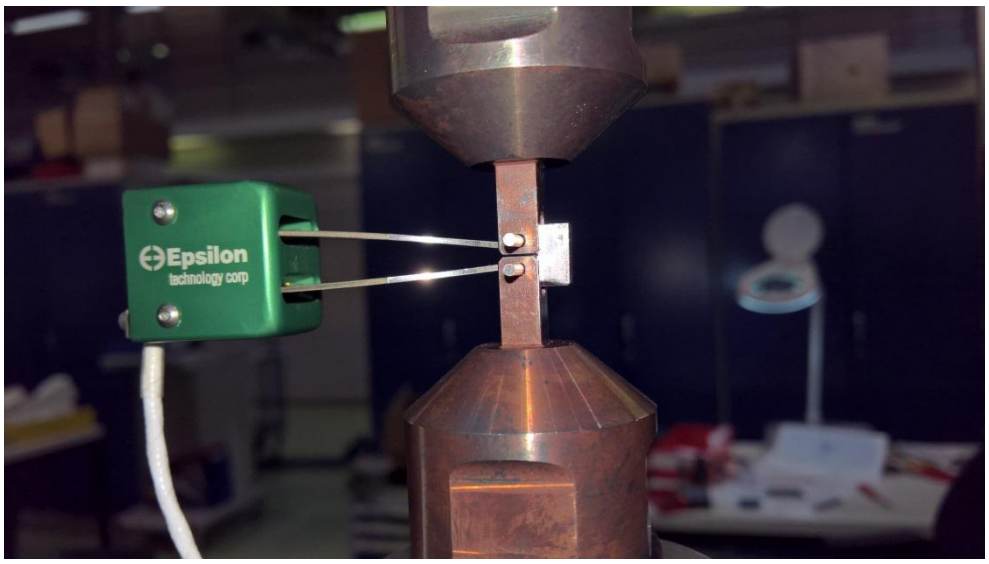
Reference

Miller, M.K., et al., *Atom probe tomography characterizations of high nickel, low copper surveillance RPV welds irradiated to high fluences.* Journal of Nuclear Materials, 2013. **437**(1-3): p. 107-115.



RESEARCH REPORT

VTT-R-00140-17



BREDA: Fracture toughness measurements with miniature C(T) specimens in reference condition

Authors: Sebastian Lindqvist, Tommi Seppänen

Confidentiality: Public

Report's title

BREDA: Fracture toughness measurements with miniature C(T) specimens in reference condition

Customer, contact person, address	**Order reference**
Project name	**Project number/Short name**
Long term operation aspects of structural integrity	LOST
Author(s)	**Pages**
Sebastian Lindqvist, Tommi Seppänen	50/
Keywords	**Report identification code**
Miniature C(T) specimens, Master Curve, T_0, weld metal, RPV	VTT-R-00140-17

Summary

The reference temperature T_0 was determined for two rector pressure vessel (RPV) welds in reference condition with the Master Curve method. The other material was the weld metal of Barsebäck RPV and the other was a surrogate weld metal of Ringhals-4 RPV. T_0 for the Barsebäck weld metal was -98 °C and for the surrogate weld metal -68 °C. These median T_0 values are low and brittle fracture at room temperature can be excluded for the materials in reference condition.

Confidentiality	Public

Espoo 13.1.2017

Written by	**Reviewed by**	**Accepted by**
Sebastian Lindqvist	Kim Wallin	Arja Saarenheimo
Research scientist	Research professor, Principal investigator	Research team leader

VTT's contact address

Distribution (customer and VTT)

SAFIR2018 and NKS

Preface

This report, deliverable D1.5.1, is part of project LOST (long term operational aspects of structural integrity). LOST is a project in SAFIR2018, The Finnish Research Programme on Nuclear Power Plant Safety 2015 - 2018. The report is also a part of BREDA-RPV, a NKS (Nordic Nuclear Safety Research) funded project including partners from Sweden, KTH (Royal Institute of Technology) and Chalmers. The test materials were delivered from Sweden, originating from Barsebäck and Ringhals nuclear power plants.

Espoo 13.1.2017

Contents

1. Introduction

Reactor pressure vessel (RPV) is a safety critical component in nuclear power plants. Thus, catastrophic failure of the RPV shall be avoided at all times. Catastrophic failure is possible when the RPV material is brittle at operation temperature. RPVs consist of ferritic steel that is ductile at high temperatures, but becomes brittle at low temperatures. To ensure that the ferritic steel is ductile at operation temperature, the Master Curve analysis method can be used to define the ductile-to-brittle reference temperature. If the ductile to brittle temperature is low enough, then the RPV can be operated without risk of catastrophic failure.

In this work, the Master Curve analysis method is used to define the ductile-to-brittle reference temperature, T_0, for two RPV welds. The T_0 reference temperature was measured for Barsebäck reactor pressure vessel weld and a surrogate weld of Ringhals-4 reactor pressure vessel (weld of Ringhals-4 RPV cover). The reference temperature is defined with miniature sized, 4 mm thick, C(T) specimens, validated in [1–5].

2. Materials and methods

2.1 Test material

Test material 1) was weld metal of Barsebäck reactor pressure vessel and test material 2) was surrogate weld metal of Ringhals-4 reactor pressure vessel (weld of Ringhals-4 RPV cover). Both materials were tested in the reference state, non-irradiated specimens. For the Barsebäck weld metal, the yield strength was 560 MPa and tensile strength was 642 MPa in room temperature. The same strength values were assumed for the surrogate weld metal. The nominal elastic modulus, E, was estimated from [6,7], 210 GPa.

The Barsebäck weld metal consisted of broken Charpy-V specimens, with thickness, width and length of 10 x 10 x 27.5 mm^3 (Figure 1 and 2). The Surrogate weld metal was delivered in three rectangular pieces, with thickness, width and length of 10 x 10 x 55 mm^3 (Figure 3).

Figure 1. Charpy specimen halves of Barsebäck weld metal. Length =27,5 mm, thickness 10 mm, width = 10 mm.

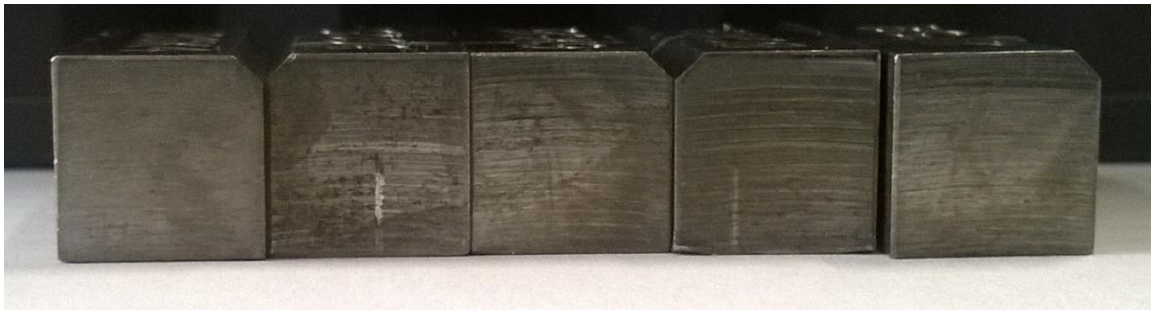


Figure 2. Each Charpy specimen half had a diagonal cut in one of the corners. The diagonal cut was left on the specimens.

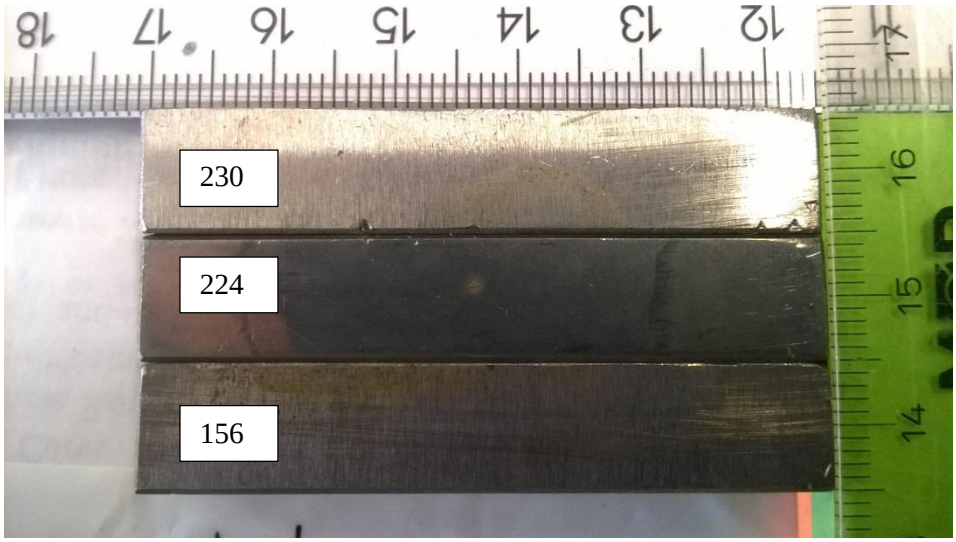


Figure 3. Surrogate weld metal. Length = 55 mm, thickness = 10 mm, width = 10 mm of one block.

2.2 Test specimens

2.2.1 Dimensions

Figure 4 shows the miniature C(T) specimen design following the guidelines given in ASTM E1921 [8]. Table 1 shows the nominal dimensions for the two materials. The main difference is that, for the Barsebäck weld metal, width, W, was 8 mm and for the surrogate weld metal the width was 7,5 mm. The location of the holes respective to the centre line, H*, were adjusted according to the width.

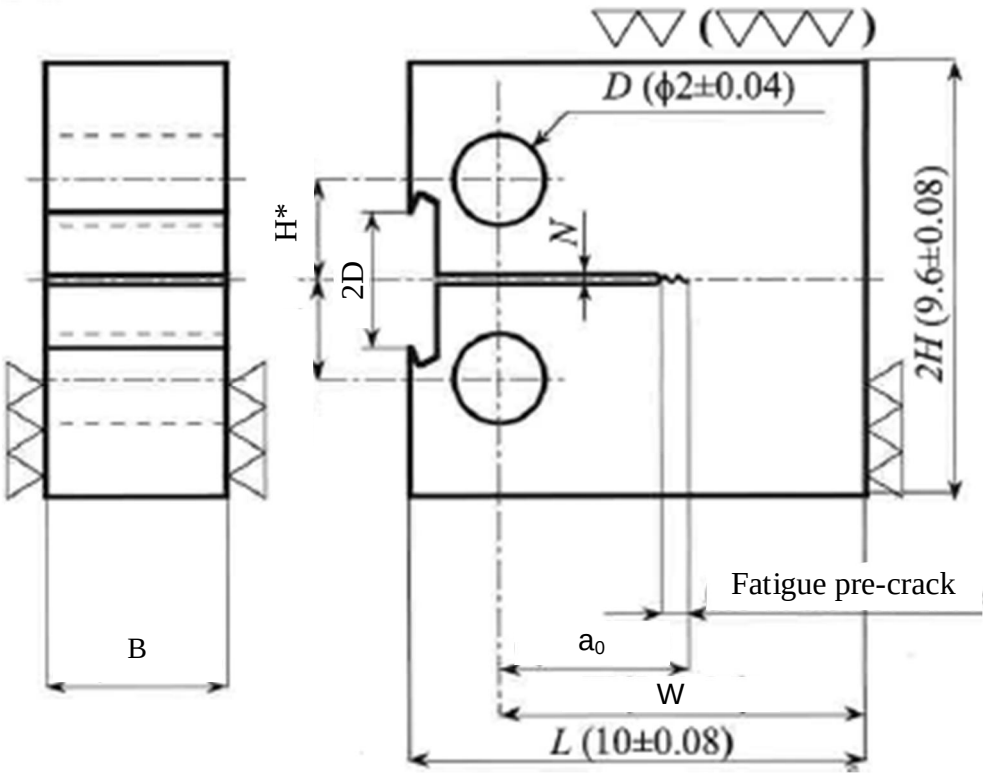


Figure 4. The C(T) specimen design.

Table 1. Nominal specimen dimensions.

		Barsebäck weld metal	Surrogate weld metal
thickness	B	4	4
width	W	8	7.5
initial crack size	a_0	4	3.75
distance from centre plane to the centre of the hole	H*	2.2	2.06
distance from the centre plane to the edge of the knife edge	D	1	1.5
notch thickness	N	0.3	0.3

2.2.2 Manufacturing of miniature C(T) specimens

From the broken Charpy V-notch halves, four miniature C(T) specimens were cut (Figure 5). The specimens were named after the identification on the Charpy specimens and a running number was used to identify the different C(T) specimens extracted from the same Charpy specimen (Figure 6).

From each surrogate weld metal block, 10 specimens were extracted (Figure 7). The specimens were also named with a running number.

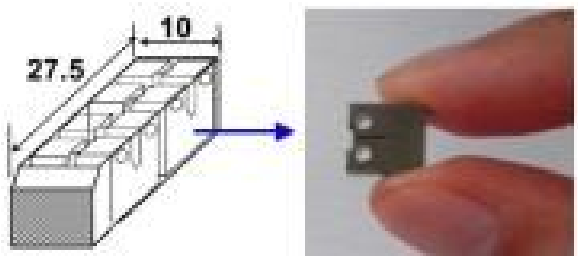


Figure 5. Four specimens were extracted from each Charpy specimen half.

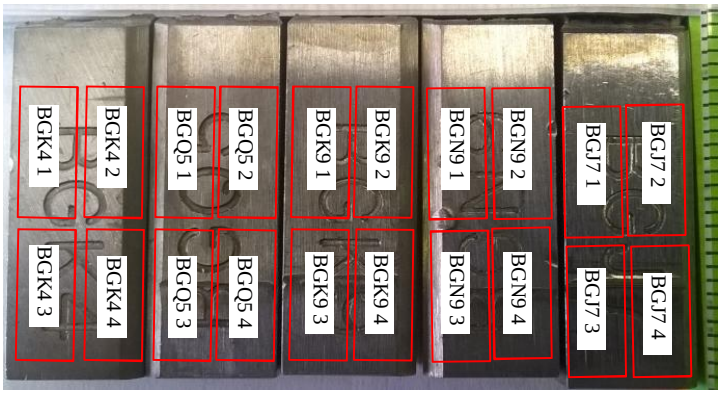


Figure 6. Barsebäck weld metal. Four specimens were extracted from each Charpy specimen half.

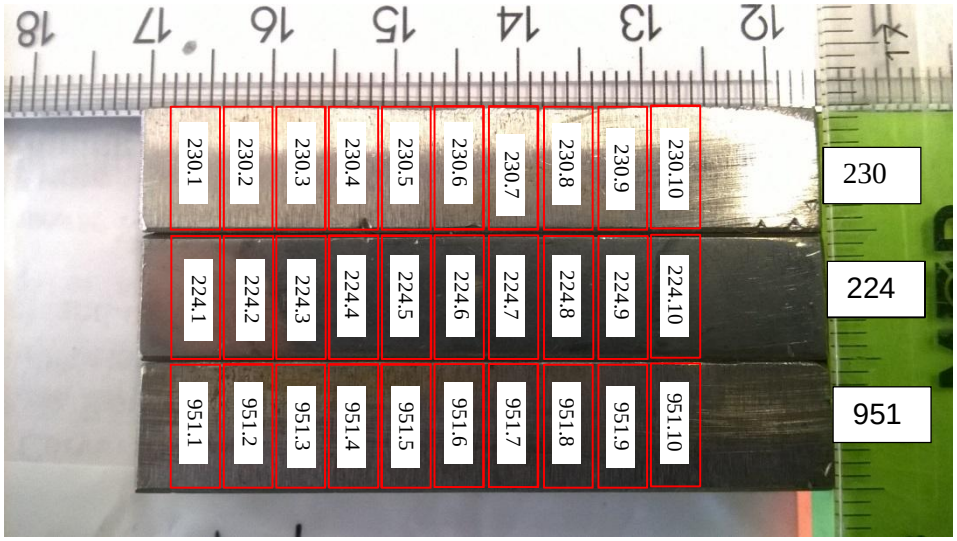


Figure 7. Surrogate weld metal. 10 specimens were cut from each block.

2.3 Test matrix

Table 2 shows the test matrix for the Barsebäck weld metal, together with the basic dimensions of the miniature C(T) specimens that were tested. Table 3 shows the test matrix for the surrogate weld metal, together with the basic dimensions of the miniature C(T) specimens that were tested.

Table 2. Barsebäck weld metal.

Specimen ID	Width	Thickness	Pin centre from crack plane	COD half-gage length	From front face to back side
	W [mm]	B [mm]	H* [mm]	D [mm]	[mm]
BGN9.1	8.07	3.98	2.20	1.09	10.01
BGN9.2	8.05	3.95	2.22	1.07	10.01
BGN9.3	7.98	3.98	2.22	1.09	10.01
BGN9.4	8.09	3.95	2.23	1.09	10.02
BGK9.1	8.06	3.96	2.23	1.09	10.01
BGK9.2	8.07	3.97	2.22	1.07	10.02
BGK9.3	8.08	3.96	2.21	1.08	10.01
BGK9.4	8.07	3.96	2.23	1.07	10.01
BGK4.1	8.11	3.96	2.19	1.09	10.01
BGQ5.1	8.06	3.96	2.22	1.08	10.01
BGQ5.2	8.09	3.95	2.19	1.09	10.02
BGJ7.1	8.05	3.96	2.20	1.07	10.01
BGJ7.2	8.07	3.99	2.19	1.07	10.01

Table 3. Surrogate weld metal.

Specimen ID	Width	Thickness	Pin centre from crack plane	COD half-gage length	From front face to back side
	W [mm]	B [mm]	H* [mm]	D [mm]	[mm]
224.1	7.54	3.97	2.04	1.58	9.98
224.2	7.58	3.98	2.13	1.58	10.00
224.3	7.50	3.99	2.07	1.59	10.00
224.4	7.51	3.96	2.06	1.58	9.98
224.5	7.57	3.96	2.07	1.60	10.00
224.6	7.57	4.03	2.09	1.67	9.95
224.7	7.57	3.98	2.06	1.59	10.00
224.8	7.51	3.99	2.07	1.58	9.99
224.9	7.45	3.99	2.09	1.58	10.00
224.10	7.58	3.99	2.07	1.58	10.00

156.3	7.58	3.95	2.05	1.58	10.05
156.9	7.57	3.98	2.06	1.58	10.03
156.8	7.56	3.98	2.05	1.57	10.02
156.5	7.52	3.93	2.06	1.57	10.03
156.2	7.56	3.91	2.07	1.58	10.02
230.2	7.50	3.92	2.07	1.57	10.00

3. Measurements and analyses

3.1 Fracture toughness tests

Fracture toughness testing was performed according to the standard procedures of ASTM E1921-13 "Standard Test Method for Determination of Reference Temperature, T_0, for Ferritic Steels in Transition Range" [8]. In the tests, reference temperature, T_0, characterising the dependence of fracture toughness on temperature, was determined.

Before testing, the specimens were fatigue pre-cracked to the initial crack length over specimen width ratio, a_0/W, of 0.5, using RUMUL resonant testing machine. In the end of fatigue pre-cracking, the maximum value of applied stress intensity factor, K_{max}, was kept below 16 MPa$\sqrt{m}$. The fracture toughness tests were performed using MTS universal servo hydraulic testing machine which was equipped with 10 kN load cell . Crack mouth opening displacement (CMOD) during the tests was measured using Epsilon 3541-003M-040M-LHT clip cage, with a measurement range of -1/+4 mm. During the tests, load, CMOD (Figure 8) and temperature were automatically recorded. The loading rate was 0.3-0.4 MPa$\sqrt{m}$/min.

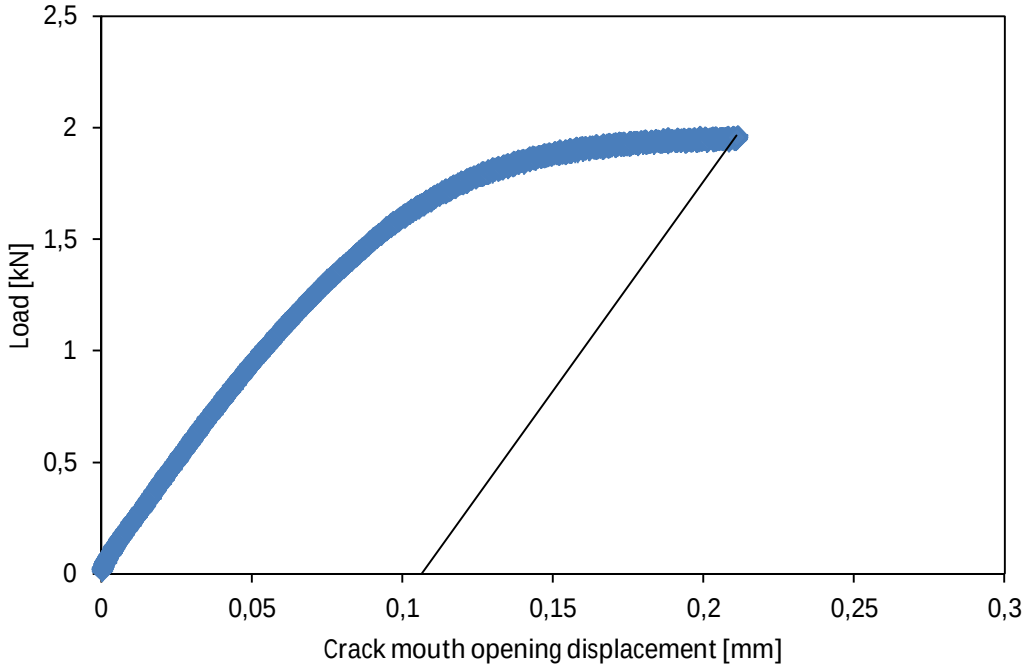


Figure 8. Load and CMOD raw data.

3.2 Initial crack size

After the measurement, the specimens were broken in liquid nitrogen into two halves to measure the crack lengths corresponding to the load instability moment and possible ductile crack growth. The crack size was determined from the fracture surfaces by using the 9 point measuring technique in ASTM E1921. The crack size was measured with a measuring microscope.

3.3 Calculation of K_{Jc} from the load-CMOD raw data

3.3.1 Correlation between CMOD and load line displacement

In the analysis, CMOD measured at a distance from the load line, $V_{C,}$ was first corrected to correspond to the displacement at the load line, Equation 1 [9]. This correction is required, because ASTM E1921 equations are based on the load line displacement.

$$V_{LL} = V_C\left(\frac{a_0+r\cdot b}{a_0+r\cdot b+c}\right) \quad (1)$$

where

V_{LL} = measured load line displacement,

V_C = front face displacement measured at a distance c from the load line,

a_0 = initial crack length,

b = un-cracked ligament length,

c = distance from load line to the point of front face displacement measurement,

r = the distance from the crack tip to the point of rotation divided by b, 0.33.

3.3.2 Rotation correction

After the first correction, the displacement at the load line and load were rotation corrected, Equation 2 and 3, respectively [10].

$$\frac{V_{LLc}}{V_{LL}} = \frac{1}{cos\theta-\frac{D}{R}sin\theta} \quad (2)$$

where

V_{LLc} = rotation corrected load line displacement,

R = radius of rotation = $\frac{W+a_0}{2}$,

θ = angle of rotation.

$$\frac{P_c}{P_m} = cos\theta - \frac{H^*}{R}sin\theta \quad (3)$$

where

P_c = rotation corrected load,

P_m = measured load.

The angle of rotation, required in Equation 2 and 3, is given by Equation 4.

$$\theta = arcsin\left[\frac{\frac{V_{LL}}{2}+D}{(D^2+R^2)^{0.5}}\right] - arctan\left(\frac{D}{R}\right) \quad (4)$$

3.3.3 Fracture toughness and size correction

The corrected load, P_c, and displacement, V_{LLc}, data was used to calculate the fracture toughness, J_c, according to the equations in ASTM E1921. J_c was transformed into K_{Jc} by Equation 5.

$$K_{Jc} = \sqrt{J_c \frac{E}{1-\nu^2}} \quad (5)$$

The results were size corrected to correspond to the stress intensity of 25.4 mm thick specimens, by Equation 6.

$$K_{Jc(25\,mm)} = 20\,MPa\sqrt{m} + (K_{Jc(B1)} - 20\,MPa\sqrt{m}) \times \left(\frac{B_1}{25.4\,mm}\right)^{0.25} \quad (6)$$

where

$K_{Jc(B1)}$ = stress intensity factor of test specimen with thickness B_1,

B_1 = thickness of the test specimen.

3.4 Quality and validity of the Master Curve data

The validity criteria in ASTM E1921 define the quality of the data for the Master Curve analysis. The validity criteria includes criteria for toughness (measuring capacity of the specimen), crack straightness, length difference adjustment between measured and calculated crack size, and the number of data points required for a valid Master Curve.

The validity criteria to be considered are:

1) Straightness of the crack front:

maximum deviation of a single crack length data point from the average (nine positions measured) shall not deviate more than 5% or 0.5 mm from the average crack length (the larger value is selected). Crack lengths exceeding this criterion are not included in the Master Curve evaluation.

2) Ductile crack growth:

the allowed crack growth in the specimen is 0.2 mm for 4 mm thick C(T) specimens.

If K_{Jc} in these cases exceed the measuring capacity then the data is used by treating it according to the principle in point 4. Otherwise, the data point is not included in the Master Curve analysis.

3) Mismatch between measured and calculated crack length:

to minimize the difference between the calculated and measured crack size, the nominal E value can be adjusted up to 10% of the nominal value, leading to an effective E, $E_{effective}$. The $E_{effective}$ is used in the fracture toughness calculations. Calculated crack size, a_p, is derived from Equation 7.

$$a_p = W \times (1.000196 - 4.06319u + 11.242u^2 - 106.043u^3 + 464.335u^4 - 650.677u^5) \quad (7)$$

where

$$u = \frac{1}{[BEC]^{1/2}+1}, \quad (8)$$

C = the compliance, inverse of the initial elastic slope, $\Delta V/\Delta P_m$.

4) Exceeding the measuring capacity of the specimen:

measuring capacity of specimen is defined as

$$K_{Jc(limit)} = \sqrt{\frac{Eb_0\sigma_{y(T)}}{30(1-\nu^2)}} \quad (9)$$

where

E = elastic modulus

b_0 = remaining ligament

$\sigma_{y(T)}$ = yield strength at test temperature. T

If the measured K_{JC}-values exceed this limit, the measured value is lowered to this limit and it is treated as ductile end of test value (non-cleavage fracture).

The yield strength at test temperature, $\sigma_{y(T)}$, was calculated from Equation 10 [11].

$$\sigma_{y(T)} = \sigma_{y(RT)} + \frac{10^5}{491+1.8T} - 189\ MPa \quad (10)$$

where

T = temperature in °C,

$\sigma_{y(RT)}$ = yield strength at room temperature.

4) Test temperature:

The data used for the Master Curve analysis shall not differ from T_0 with more than 50 °C. Data points outside this window are excluded from the analysis.

5) Number of data points in the Master Curve analysis:

In Master Curve analysis 8-10 specimens are required for a T_0 definition with miniature C(T) specimens [1]. If the derived T_0 is based on too few data points, then the T_0-value is considered uncertain.

3.5 Master Curve fitting

To the valid K_{Jc}-temperature data, T_0 was derived from the maximum likelihood estimation, Equation 11.

$$\sum_{i=1}^{n} \frac{\delta_i \times exp\{0.019\times[T_i - T_0]\}}{31-20\ MPa\sqrt{m}+77\times exp\{0.019\times[T_i-T_0]\}} - \sum_{i=1}^{n} \frac{\left(K_{Jc(i)}-20\ MPa\sqrt{m}\right)^4 \times exp\{0.019\times[T_i-T_0]\}}{(31-20\ MPa\sqrt{m}+77\times exp\{0.019\times[T_i-T_0]\})^5} = 0 \quad (11)$$

where

T_0 = reference temperature,

T_i = test temperature,

$K_{Jc(i)}$ = measured stress intensity,

δ_i = factor = 1, when the measured value refers to cleavage initiation, otherwise 0.

The standard deviation for T_0 is calculated with Equation 12.

$$\sigma = \sqrt{\frac{\beta^2}{r} + 4^2} \quad (12)$$

where

β = sample size uncertainty factor,

r = total number of valid specimens to establish the value of T_0.

The median Master Curve, $K_{Jc(med)}$, for a 25.4 mm thick specimen, is determined from Equation 13.

$$K_{Jc(med)} = 30 + 70exp[0.019(T - T_0)] \quad (13)$$

The 95 % upper and 5 % lower bound of the Master Curve are calculated from Equation 14.

$$K_{Jc(0.xx)} = 20 + \left[ln\left(\frac{1}{1-0.xx}\right)\right]^{1/4}\{11 + 77exp[0.019(T - T_0)]\} \quad (14)$$

3.6 SINTAP analysis

SINTAP-analysis reveals the inhomogeneity of the material [11]. In SINTAP analyses first a normal Master Curve analysis is performed. The data above the median Master Curve are censored and lowered to the median curve. After that, a new Master Curve analysis is done. These steps are continued until a constant value of T_0 is reached. If the difference between $T_{0,SINTAP}$ and T_0 is large, then the material is considered inhomogeneous.

4. Results

4.1 Barsebäck weld metal

Table 4 shows the measured initial crack length, a_0, and the effective elastic modulus, $E_{effective}$, used to match the calculated crack length with a_0.The nominal E was 210 GPa. For specimen BGK9.1, ductile crack growth was observed. For the other specimens, brittle fracture initiated at the tip of the fatigue pre-crack, therefore, a_0 defines the crack size of the specimens.

Table 4. Crack size and effective elastic modulus for Barsebäck weld metal specimens.

Specimen ID	**Temperature**	**Crack length**	**$E_{effective}$**
	T [°C]	**a_0 [mm]**	**[GPa]**
BGN9.1	-100	4.32	195
BGN9.2	-140	4.28	203
BGN9.3	-140	4.29	217
BGN9.4	-120	4.47	219
BGK9.1	-120	4.40	207
BGK9.2	-130	4.24	213
BGK9.C	-130	4.39	205
BGK9.4	-130	4.37	209
BGK4.1	-130	4.46	203
BGQ5.1	-140	4.51	200
BGQ5.2	-140	4.32	189
BGJ7.1	-140	4.34	218
BGJ7.2	-130	4.38	209

Table 5 shows the K_{Jc4mm}, $K_{Jc(limit)}$, and the censored and size corrected toughness values, $K_{Jc4mm(censored)}$ and K_{Jc25mm}, of the Barsebäck weld metal specimens. Only the data point of specimen BGK4.1 is invalid, the crack front is too skewed. Two specimens, BGN9.1 and BGK9.1, exceed the measuring capacity, and the values are censored in the Master Curve analysis. Ten specimens do not require any censoring. The size corrected values, valid and censored, are used to calculate T_0 in the Master Curve analysis.

Table 5. Fracture toughness data of Barsebäck weld metal.

Specimen ID	**Temperature**	**Fracture toughness**	**Fracture toughness limit values**	Censored **fracture toughness** values	Validity	**Thickness corrected fracture toughness for censored values**
	T [°C]	**K_{JC4mm} [MPa√m]**	**$K_{JC4mm(limit)}$ [MPa√m]**	$K_{Jc4mm(censored)}$ [MPa√m]		**K_{JC25mm} [MPa√m]**
BGN9.1	-100	302	136	136	TRUE	93
BGN9.2	-140	100	149	100	TRUE	70
BGN9.3	-140	104	152	104	TRUE	73
BGN9.4	-120	110	146	110	TRUE	76
BGK9.1	-120	170	143	143	TRUE	97
BGK9.2	-130	82	151	82	TRUE	59
BGK9.C	-130	94	145	94	TRUE	67
BGK9.4	-130	92	147	92	TRUE	65
BGK4.1	-130	63	143	63	FALSE	
BGQ5.1	-140	53	143	53	TRUE	41
BGQ5.2	-140	85	144	85	TRUE	61
BGJ7.1	-140	79	153	79	TRUE	57
BGJ7.2	-130	53	147	53	TRUE	40

The standard Master Curve analysis yields a T_0 of -98 °C for the Barsebäck weld metal in reference state. The standard deviation is 8 °C (Equation 12). Figure 9 shows the original data, before censoring, and the Master Curve, with the 5% and 95% confidence limits. The location of the Master Curve is determined based on T_0 according to Equation 13. The SINTAP analysis yields a T_0 of -95 °C, Figure 10. Since the difference in the two T_0 values is 3 °C, the material can be considered homogeneous.

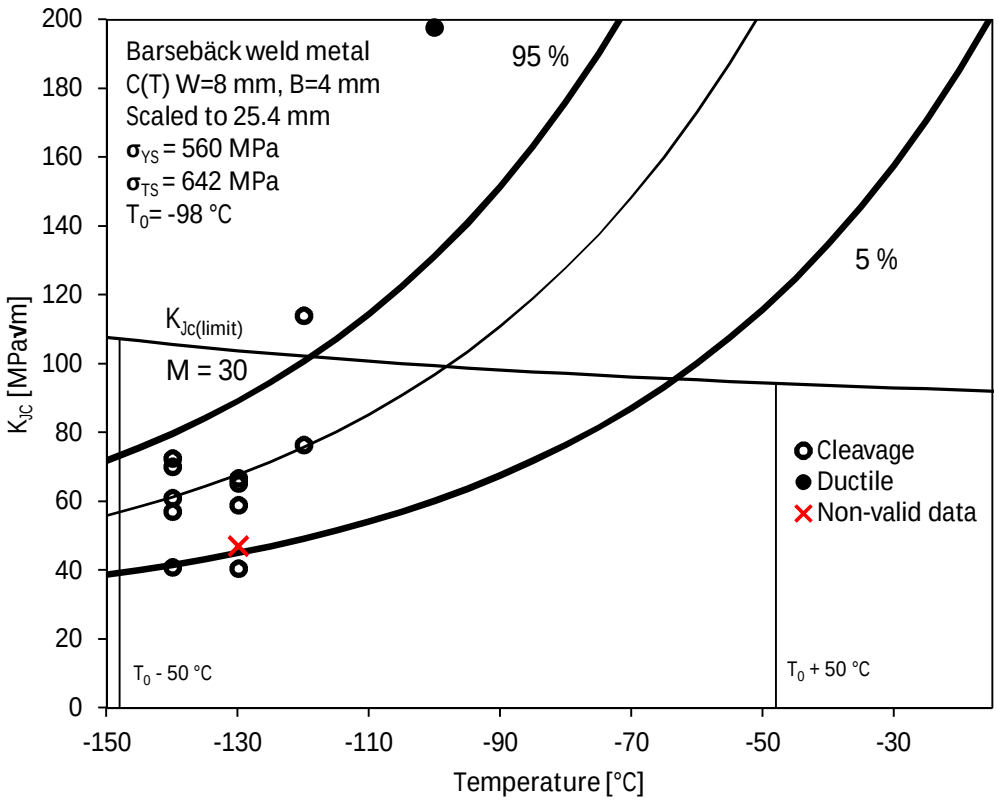


Figure 9. Master Curve analysis.

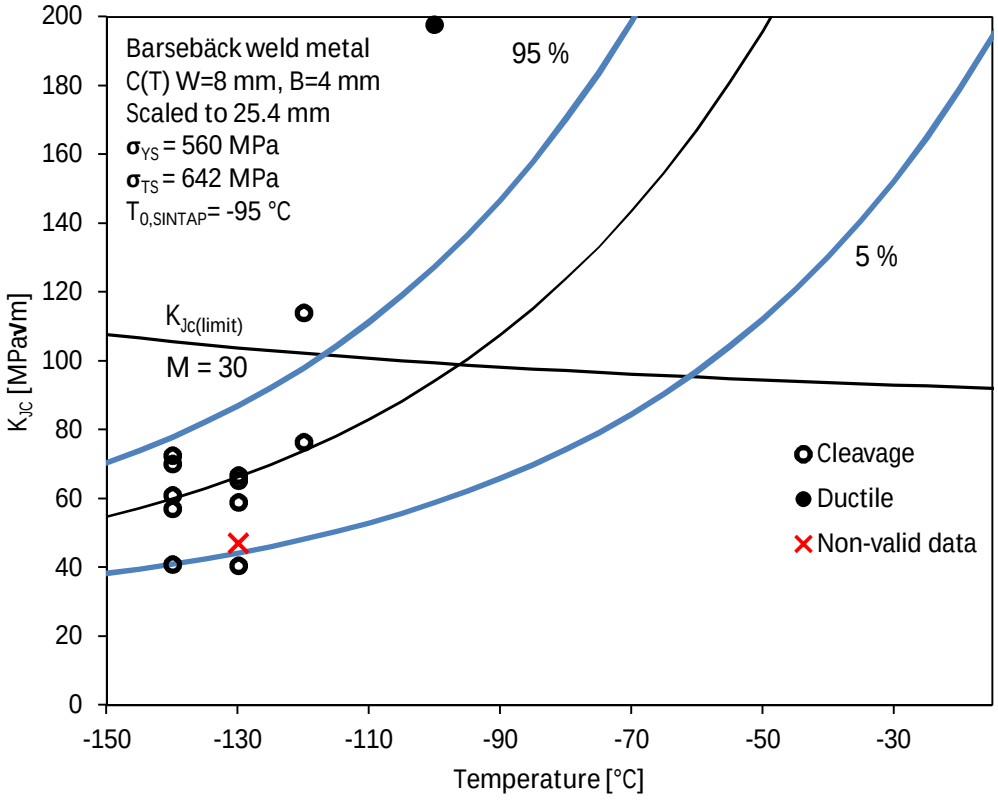


Figure 10.SINTAP analysis.

4.2 Surrogate weld metal

Table 6 shows the measured initial crack length, a_0, and the effective elastic modulus, $E_{effective}$. Brittle fracture initiated at the tip of the fatigue pre-crack, therefore, a_0 defines the crack size.

Table 6. Crack size and effective elastic modulus for the surrogate weld metal specimens.

Specimen ID	**Temperature**	**Crack length**	**$E_{effective}$**
	T [°C]	**a_0 [mm]**	**[GPa]**
224.1	-130	3.87	205
224.2	-130	4.19	199
224.3	-130	4.03	208
224.4	-120	4.09	189
224.5	-120	4.10	207
224.6	-80	4.06	228
224.7	-120	4.08	194
224.8	-110	3.91	194
224.9	-90	3.89	189
224.10	-100	4.05	206
156.3	-100	4.10	218
156.9	-100	3.97	206
156.5	-100	4.17	221
156.8	-100	4.06	215
156.2	-100	4.02	216
230.1	-100	3.82	206

Table 7 shows the K_{Jc4mm}, $K_{Jc(limit)}$, and the censored and size corrected toughness values, $K_{Jc4mm(censored)}$ and K_{Jc25mm}, of the surrogate weld metal. The data points of specimen 224.1-224.3 are invalid, the data points are located too far from T_0. Three specimens, 224.6, 224.9 and 156.2, exceed the measuring capacity, and the values are censored in the Master Curve analysis. Ten specimens do not require any censoring. The size corrected values, valid and censored, are used to calculate T_0 in the Master Curve analysis.

Table 7. Fracture toughness data of the surrogate weld metal.

Specimen ID	**Temperature**	**Fracture toughness**	**Limit values for measuring capacity**	Censored values	Validity	**Thickness corrected fracture toughness for valid values**
	T [°C]	**K_{JC4mm} [MPa√m]**	**$K_{JC4mm(limit)}$ [MPa√m]**	$K_{Jc4mm(censored)}$ [MPa√m]		**K_{JC25mm} [MPa√m]**

224.1	-130	74	145	74	FALSE	
224.2	-130	93	137	93	FALSE	
224.3	-130	49	142	49	FALSE	
224.4	-120	47	132	47	TRUE	36
224.5	-120	42	139	42	TRUE	33
224.6	-80	227	139	139	TRUE	95
224.7	-120	79	135	79	TRUE	57
224.8	-110	46	135	46	TRUE	36
224.9	-90	142	129	129	TRUE	88
224.10	-100	57	136	57	TRUE	43
156.3	-100	92	139	92	TRUE	65
156.9	-100	108	137	108	TRUE	75
156.5	-100	79	137	79	TRUE	57
156.8	-100	75	138	75	TRUE	54
156.2	-100	151	139	139	TRUE	94
230.1	-100	62	139	62	TRUE	46

The standard Master Curve analysis yields a T_0 of -68 °C for the surrogate weld metal in reference condition. This T_0 value is an average between -72 and -64 °C. If the data at -120 °C is included to the Master Curve analysis, then T_0 is -64 °C, which requires the data at -120 °C to be excluded from the analysis. If a new analysis is done, without the data at -120 °C, then the T_0 is -72 °C, and the data at -120 °C shall be included to the analysis. Therefore, the average of the two T_0 values is the reference temperature of the material.

The standard deviation for the surrogate weld metal is 8 °C (Equation 12). Figure 11 shows the original data, before censoring, and the Master Curve, with the 5% and 95% confidence limits. The SINTAP analysis yields a T_0 of -52 °C, Figure 12. Since the difference between T_0 and $T_{0,SINTAP}$ is 16 °C, the material can be considered heterogeneous.

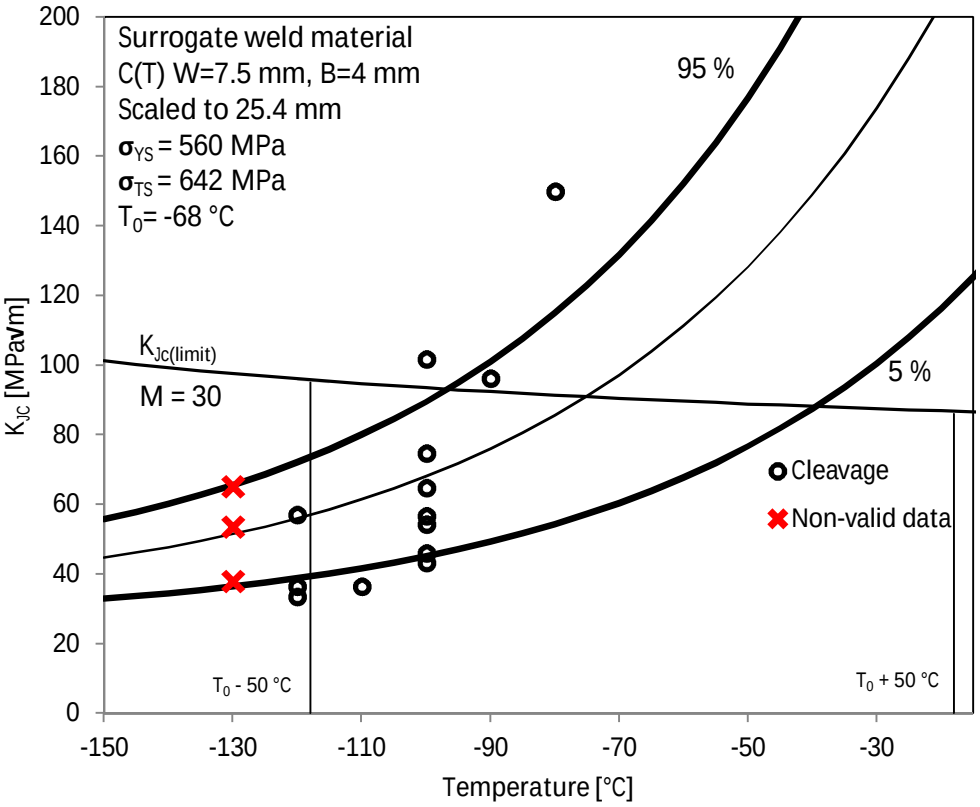


Figure 11. Master Curve analysis.

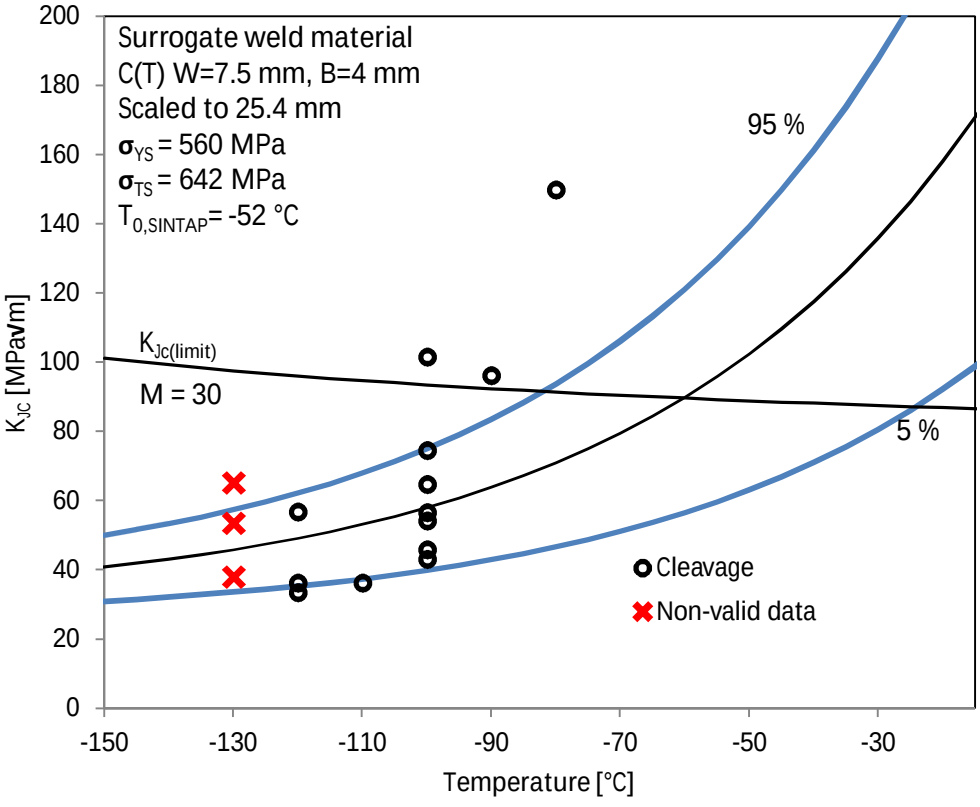


Figure 12. SINTAP analysis.

5. Discussion and conclusions

Table 8 summarises the results for the two materials, Barsebäck RPV weld metal and surrogate weld metal of Ringhals-4 RPV.

Table 8. The main results.

	T_0	±σ	$T_{0.SINTAP}$
	°C	°C	°C
Barsebäck weld metal	-98	8	-95
Surrogate weld metal	-68	8	-52

The Barsebäck weld metal can be considered homogeneous, the difference between T_0 and $T_{0,SINTAP}$ is 3 °C. The surrogate weld metal shows some heterogeneity, the difference between T_0 and $T_{0,SINTAP}$ is 16 °C. Both materials have low T_0 values. Thus, brittle fracture can be excluded at room temperature for these materials in reference condition.

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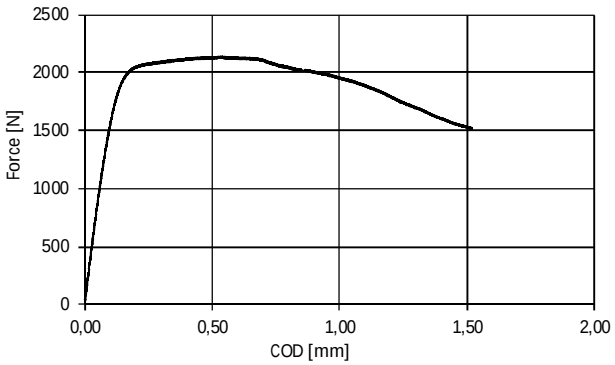
Appendix 1

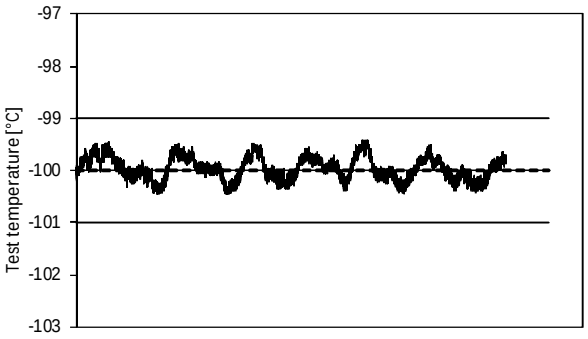
ASTM E1921-13 standard test to
determine reference temperature T0
Specimen BGN9.1



Material

Barsebäck weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

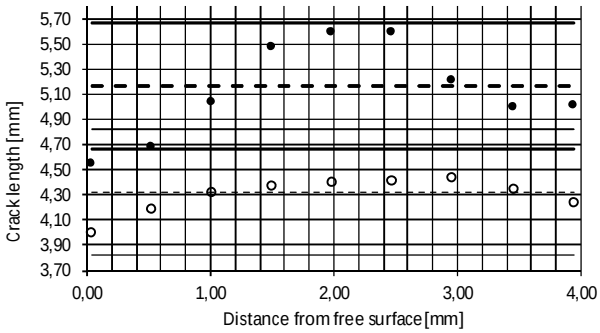


Specimen

Specimen name	BGN9.1
Specimen orientation	Same as Charpy-V
Specimen type	C(T)
Specimen thickness, B [mm]	3,98
Specimen net thickness, B_N [mm]	3,98
Specimen width, W [mm]	8,07
Precrack length, a_0 [mm]	4,32
Stable crack growth, Δa [mm]	0,84

Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	13,4
Test temperature, T [°C]	-100
Plastic area, A_p [Nm]	2,770
Fracture toughness K_{Jc} [MPa√m]	302,2



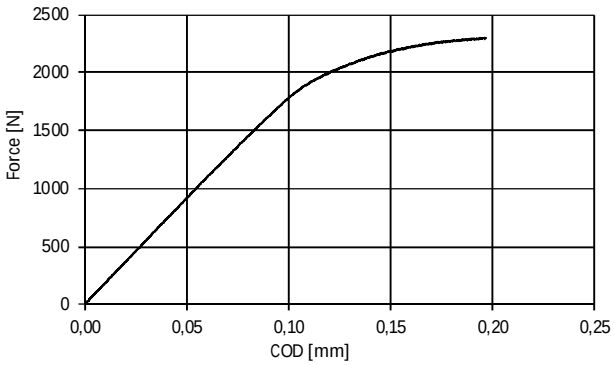
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	4,00	4,54	OK
a_2	0,53	4,18	4,68	OK
a_3	1,02	4,32	5,03	OK
a_4	1,50	4,38	5,47	OK
a_5	1,99	4,39	5,59	OK
a_6	2,48	4,41	5,59	OK
a_7	2,96	4,44	5,20	OK
a_8	3,45	4,34	5,00	OK
a_9	3,94	4,24	5,00	OK
average		a_0= 4,32	a_f= 5,17	
$(a_{i,max}-a_{i,min})/a$ [%]		10,2	20,5	

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: K_{JC} < $K_{JC(limit)}$	NOT OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	NOT OK
8.9.3	cleavage fracture	OK

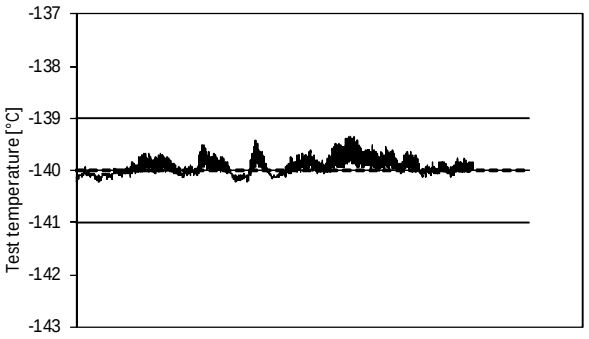
ASTM E1921-13 standard test to
determine reference temperature T0
Specimen BGN9.2



Material

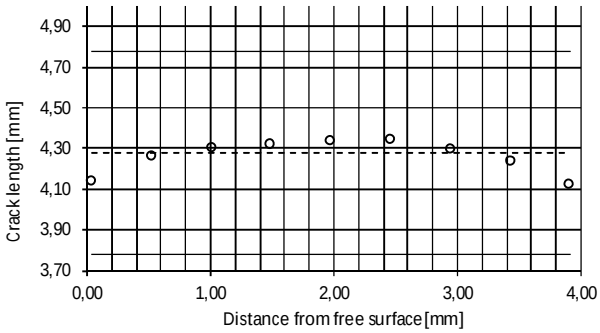
Barsebäck weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa



Specimen

Specimen name	BGN9.2
Specimen orientation	Same as Charpy-V
Specimen type	C(T)
Specimen thickness, B [mm]	3,95
Specimen net thickness, B_N [mm]	3,95
Specimen width, W [mm]	8,05
Precrack length, a_0 [mm]	4,28
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	13,4
Test temperature, T [°C]	-140
Plastic area, A_p [Nm]	0,154
Fracture toughness K_{Jc} [MPa√m]	99,9

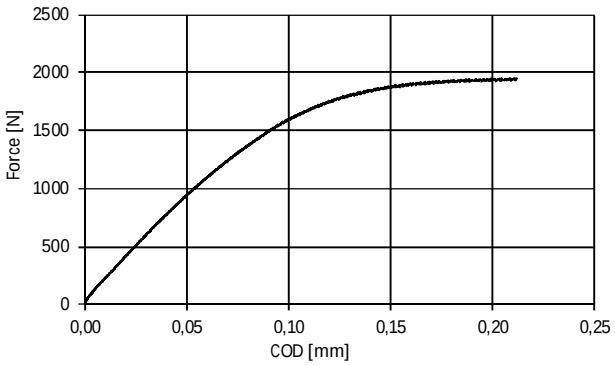
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	4,14		OK
a_2	0,52	4,27		OK
a_3	1,01	4,30		OK
a_4	1,49	4,32		OK
a_5	1,98	4,34		OK
a_6	2,46	4,34		OK
a_7	2,94	4,29		OK
a_8	3,43	4,24		OK
a_9	3,91	4,13		OK
average		a_0= 4,28	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		5,1		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

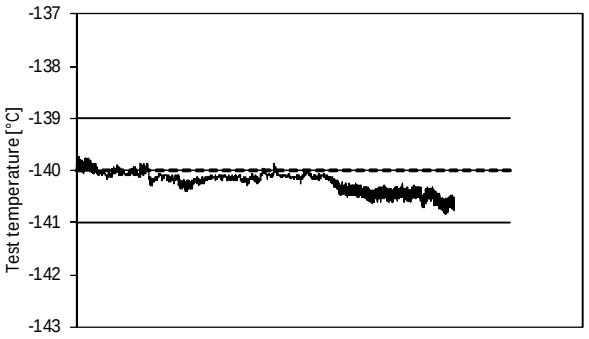
ASTM E1921-13 standard test to
determine reference temperature T0
Specimen BGN9.3



Material

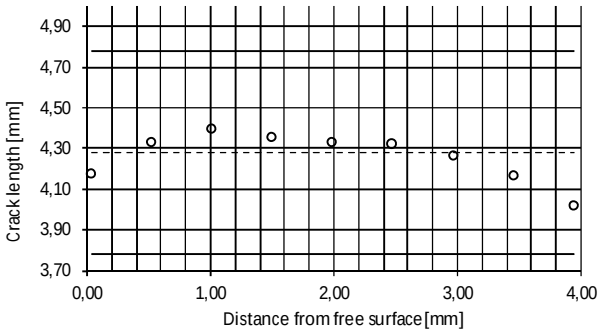
Barsebäck weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa



Specimen

Specimen name	BGN9.3
Specimen orientation	Same as Charpy-V
Specimen type	C(T)
Specimen thickness, B [mm]	3,98
Specimen net thickness, B_N [mm]	3,98
Specimen width, W [mm]	7,98
Precrack length, a_0 [mm]	4,28
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	13,6
Test temperature, T [°C]	-140
Plastic area, A_p [Nm]	0,198
Fracture toughness K_{Jc} [MPa√m]	103,6

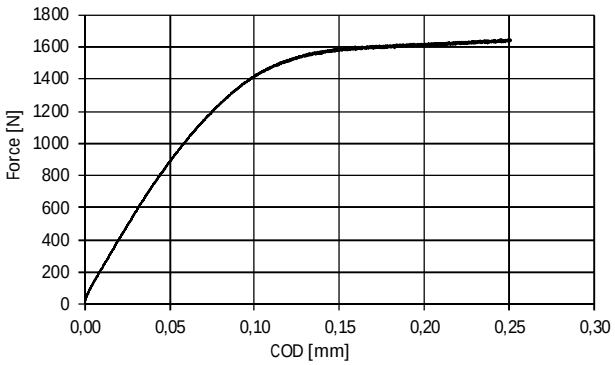
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	4,18		OK
a_2	0,53	4,33		OK
a_3	1,01	4,39		OK
a_4	1,50	4,36		OK
a_5	1,99	4,33		OK
a_6	2,48	4,32		OK
a_7	2,97	4,26		OK
a_8	3,45	4,16		OK
a_9	3,94	4,02		OK
average		a_0= 4,28	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		8,7		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen BGN9.4



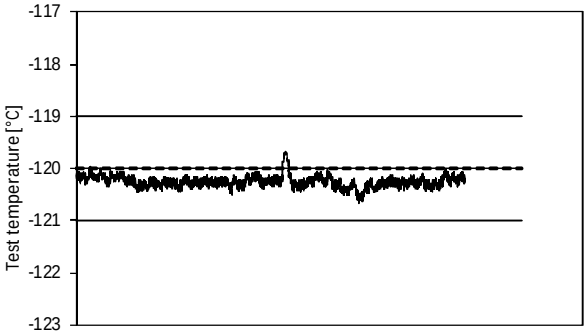
Material

Barsebäck weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

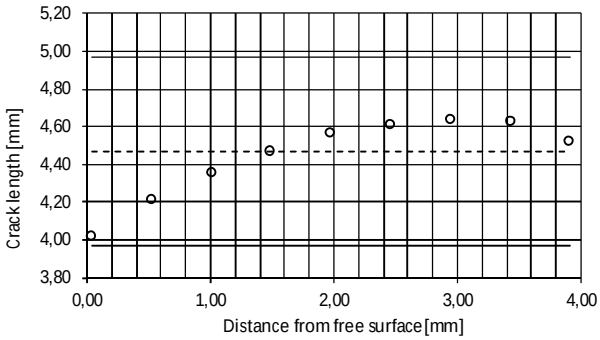
Specimen

Specimen name	BGN9.4
Specimen orientation	Same as Charpy-V
Specimen type	C(T)
Specimen thickness, B [mm]	3,95
Specimen net thickness, B_N [mm]	3,95
Specimen width, W [mm]	8,09
Precrack length, a_0 [mm]	4,47
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	14,3
Test temperature, T [°C]	-120
Plastic area, A_p [Nm]	0,247
Fracture toughness K_{Jc} [MPa√m]	109,9



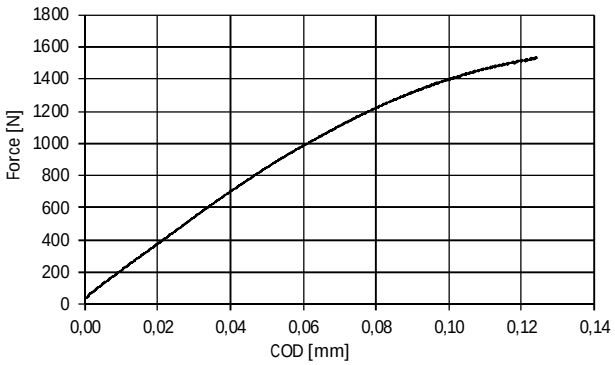
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	4,02		OK
a_2	0,52	4,21		OK
a_3	1,01	4,35		OK
a_4	1,49	4,47		OK
a_5	1,98	4,57		OK
a_6	2,46	4,61		OK
a_7	2,94	4,64		OK
a_8	3,43	4,63		OK
a_9	3,91	4,52		OK
average		a_0= 4,47	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		13,9		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen BGK4.1



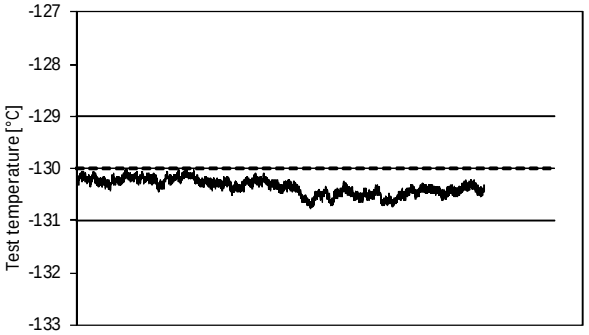
Material

Barsebäck weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

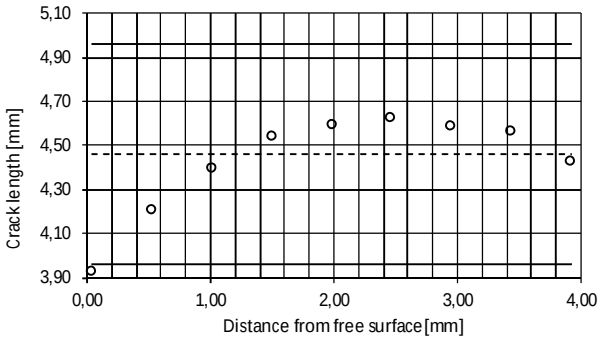
Specimen

Specimen name	BGK4.1
Specimen orientation	Same as Charpy-V
Specimen type	C(T)
Specimen thickness, B [mm]	3,96
Specimen net thickness, B_N [mm]	3,96
Specimen width, W [mm]	8,11
Precrack length, a_0 [mm]	4,46
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	14,2
Test temperature, T [°C]	-130
Plastic area, A_p [Nm]	0,046
Fracture toughness K_{Jc} [MPa√m]	63,0



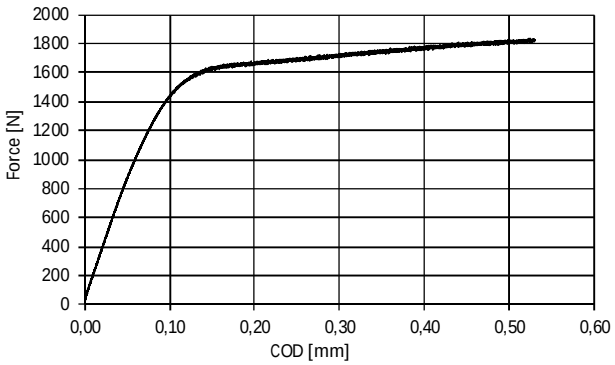
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,93		NOT OK
a_2	0,53	4,21		OK
a_3	1,01	4,40		OK
a_4	1,50	4,54		OK
a_5	1,98	4,60		OK
a_6	2,46	4,62		OK
a_7	2,95	4,58		OK
a_8	3,43	4,56		OK
a_9	3,92	4,43		OK
average		a_0= 4,46	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		15,6		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	NOT OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen BGK9.1



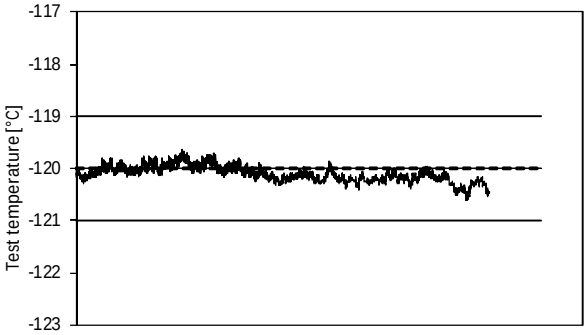
Material

Barsebäck weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

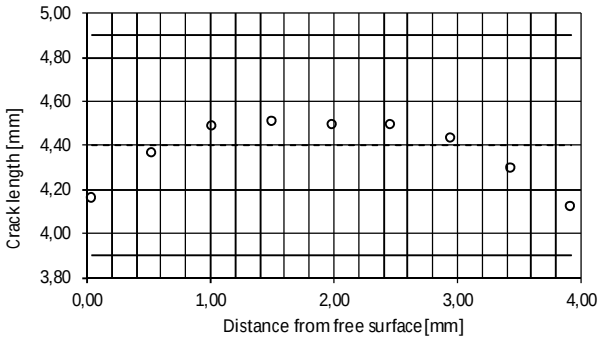
Specimen

Specimen name	BGK9.1
Specimen orientation	Same as Charpy-V
Specimen type	C(T)
Specimen thickness, B [mm]	3,96
Specimen net thickness, B_N [mm]	3,96
Specimen width, W [mm]	8,06
Precrack length, a_0 [mm]	4,40
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	14,0
Test temperature, T [°C]	-120
Plastic area, A_p [Nm]	0,724
Fracture toughness K_{Jc} [MPa√m]	169,6



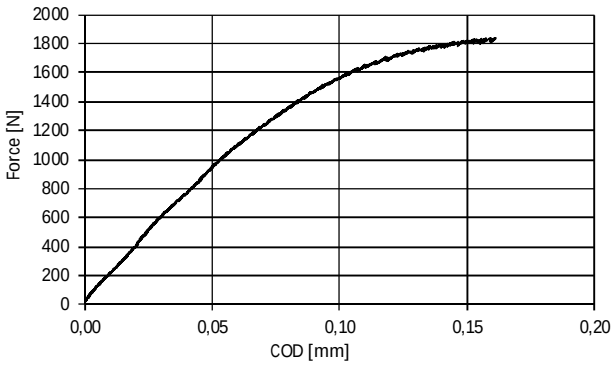
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	4,16		OK
a_2	0,53	4,36		OK
a_3	1,01	4,49		OK
a_4	1,50	4,51		OK
a_5	1,98	4,49		OK
a_6	2,46	4,49		OK
a_7	2,95	4,43		OK
a_8	3,43	4,29		OK
a_9	3,92	4,12		OK
average		a_0= 4,40	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		8,8		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	NOT OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

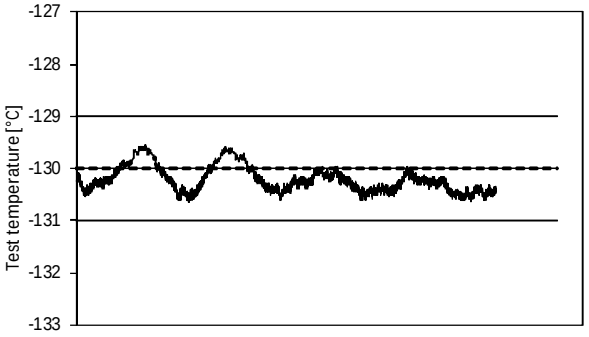
ASTM E1921-13 standard test to determine reference temperature T0
Specimen BGK9.2



Material

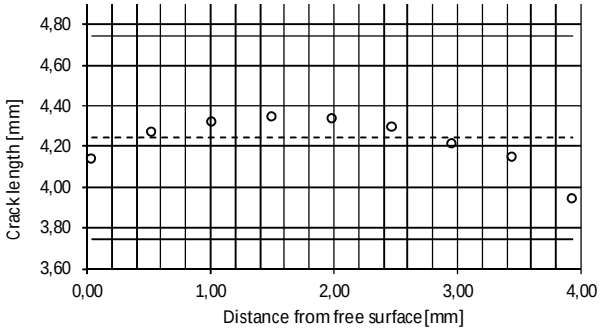
Barsebäck weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa



Specimen

Specimen name	BGK9.2
Specimen orientation	Same as Charpy-V
Specimen type	C(T)
Specimen thickness, B [mm]	3,97
Specimen net thickness, B_N [mm]	3,97
Specimen width, W [mm]	8,07
Precrack length, a_0 [mm]	4,24
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	13,1
Test temperature, T [°C]	-130
Plastic area, A_p [Nm]	0,111
Fracture toughness K_{Jc} [MPa√m]	82,1

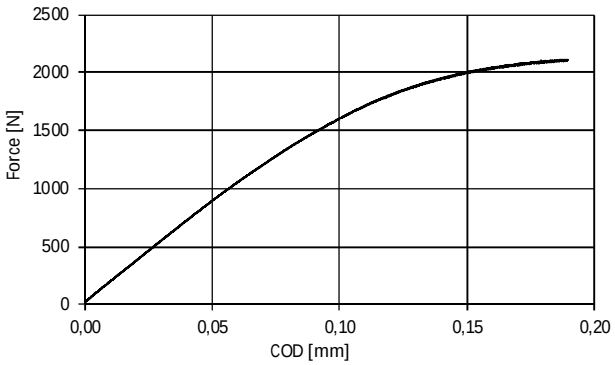
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	4,14		OK
a_2	0,53	4,27		OK
a_3	1,01	4,32		OK
a_4	1,50	4,35		OK
a_5	1,99	4,33		OK
a_6	2,47	4,29		OK
a_7	2,96	4,21		OK
a_8	3,44	4,15		OK
a_9	3,93	3,94		OK
average		a_0= 4,24	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		9,5		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

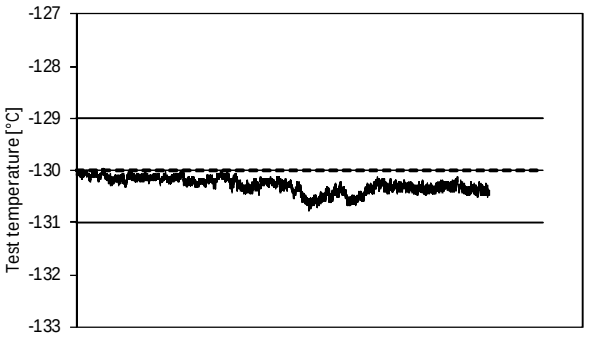
ASTM E1921-13 standard test to determine reference temperature T0
Specimen BGK9.3



Material

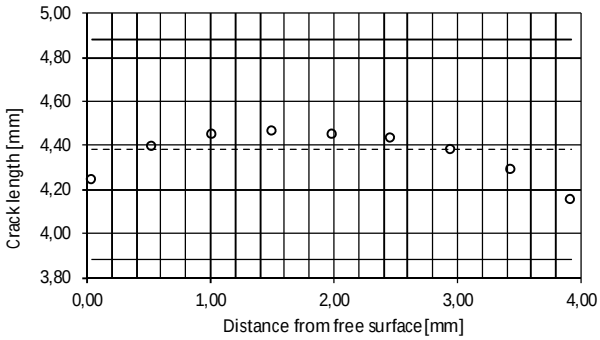
Barsebäck weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa



Specimen

Specimen name	BGK9.3
Specimen orientation	Same as Charpy-V
Specimen type	C(T)
Specimen thickness, B [mm]	3,96
Specimen net thickness, B_N [mm]	3,96
Specimen width, W [mm]	8,08
Precrack length, a_0 [mm]	4,38
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	13,8
Test temperature, T [°C]	-130
Plastic area, A_p [Nm]	0,134
Fracture toughness K_{Jc} [MPa√m]	94,4

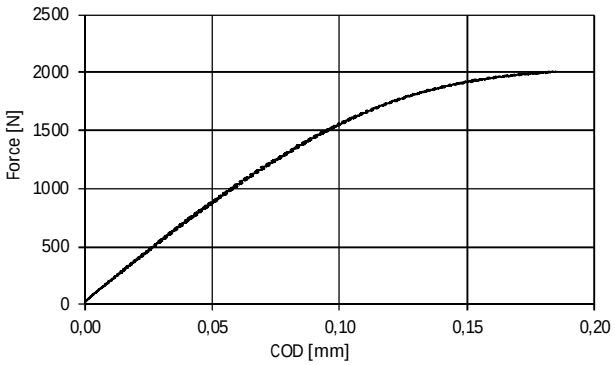
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	4,25		OK
a_2	0,53	4,39		OK
a_3	1,01	4,45		OK
a_4	1,50	4,47		OK
a_5	1,98	4,45		OK
a_6	2,46	4,43		OK
a_7	2,95	4,38		OK
a_8	3,43	4,29		OK
a_9	3,92	4,15		OK
average		a_0= 4,38	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		7,2		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen BGK9.4



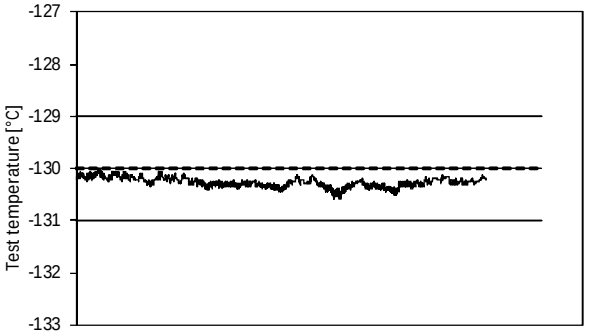
Material

Barsebäck weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

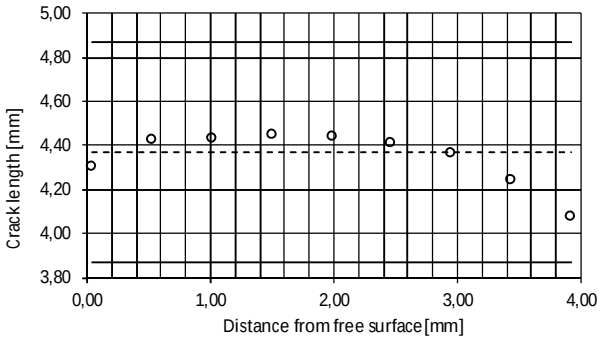
Specimen

Specimen name	BGK9.4
Specimen orientation	Same as Charpy-V
Specimen type	C(T)
Specimen thickness, B [mm]	3,96
Specimen net thickness, B_N [mm]	3,96
Specimen width, W [mm]	8,07
Precrack length, a_0 [mm]	4,37
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	13,8
Test temperature, T [°C]	-130
Plastic area, A_p [Nm]	0,130
Fracture toughness K_{Jc} [MPa√m]	92,0



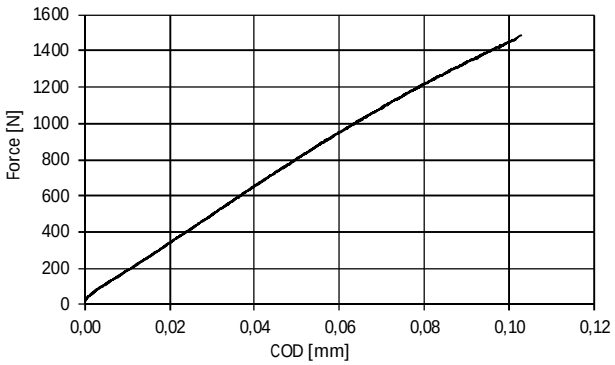
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	4,30		OK
a_2	0,53	4,42		OK
a_3	1,01	4,44		OK
a_4	1,50	4,45		OK
a_5	1,98	4,44		OK
a_6	2,46	4,41		OK
a_7	2,95	4,36		OK
a_8	3,43	4,24		OK
a_9	3,92	4,08		OK
average		a_0= 4,37	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		8,4		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen BGQ5.1



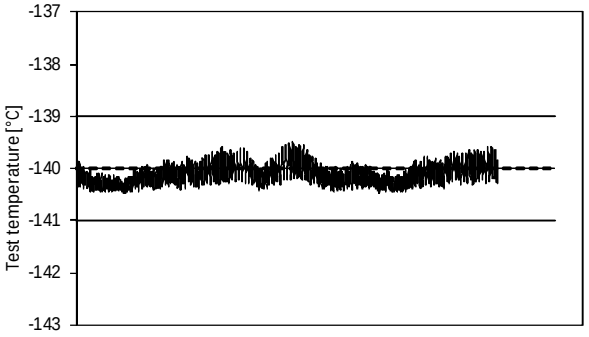
Material

Barsebäck weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

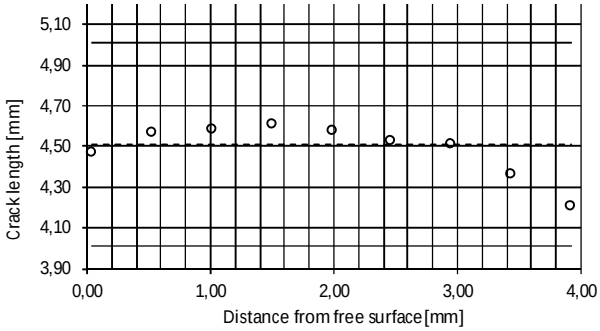
Specimen

Specimen name	BGQ5.1
Specimen orientation	Same as Charpy-V
Specimen type	C(T)
Specimen thickness, B [mm]	3,96
Specimen net thickness, B_N [mm]	3,96
Specimen width, W [mm]	8,06
Precrack length, a_0 [mm]	4,51
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	14,7
Test temperature, T [°C]	-140
Plastic area, A_p [Nm]	0,012
Fracture toughness K_{Jc} [MPa√m]	53,3



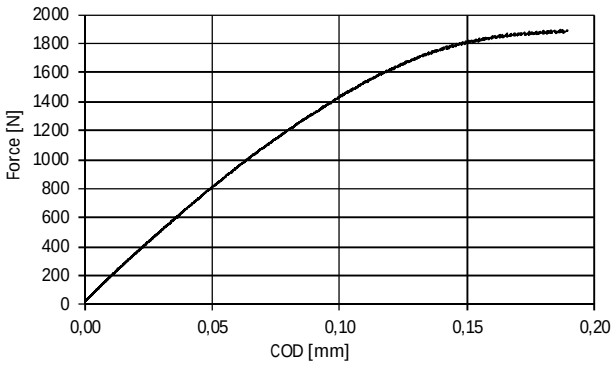
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	4,47		OK
a_2	0,53	4,57		OK
a_3	1,01	4,59		OK
a_4	1,50	4,61		OK
a_5	1,98	4,58		OK
a_6	2,46	4,53		OK
a_7	2,95	4,51		OK
a_8	3,43	4,37		OK
a_9	3,92	4,21		OK
average		a_0= 4,51	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		8,8		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to
determine reference temperature T0
Specimen BGQ5.2



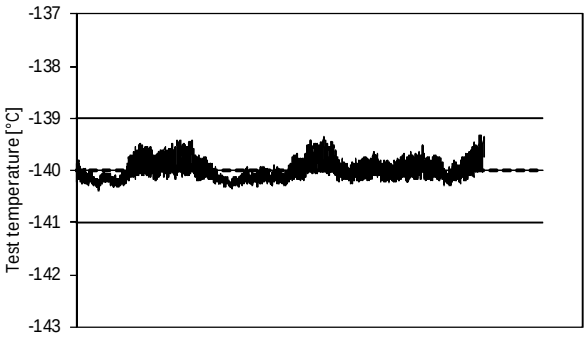
Material

Barsebäck weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

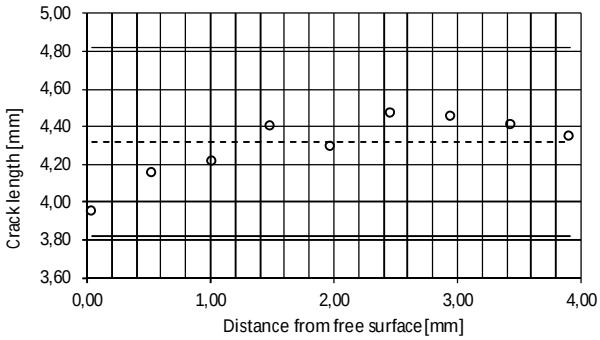
Specimen

Specimen name	BGQ5.2
Specimen orientation	Same as Charpy-V
Specimen type	C(T)
Specimen thickness, B [mm]	3,95
Specimen net thickness, B_N [mm]	3,95
Specimen width, W [mm]	8,09
Precrack length, a_0 [mm]	4,32
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	13,5
Test temperature, T [°C]	-140
Plastic area, A_p [Nm]	0,128
Fracture toughness K_{Jc} [MPa√m]	85,3



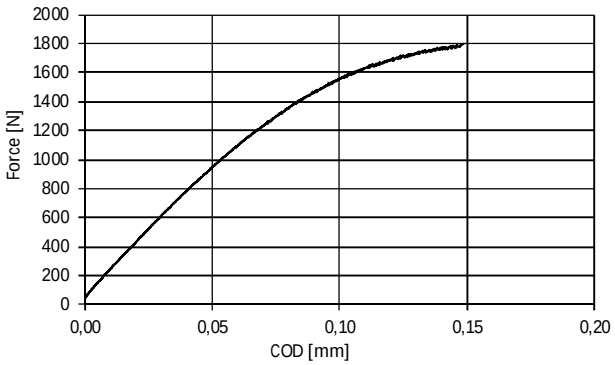
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,95		OK
a_2	0,52	4,15		OK
a_3	1,01	4,22		OK
a_4	1,49	4,40		OK
a_5	1,98	4,30		OK
a_6	2,46	4,47		OK
a_7	2,94	4,45		OK
a_8	3,43	4,41		OK
a_9	3,91	4,35		OK
average		a_0= 4,32	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		12,1		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 compliant test to determine reference temperature T0
Specimen BGJ7.1



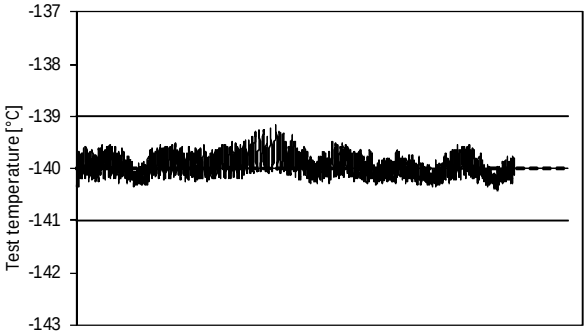
Material

Barsebäck weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

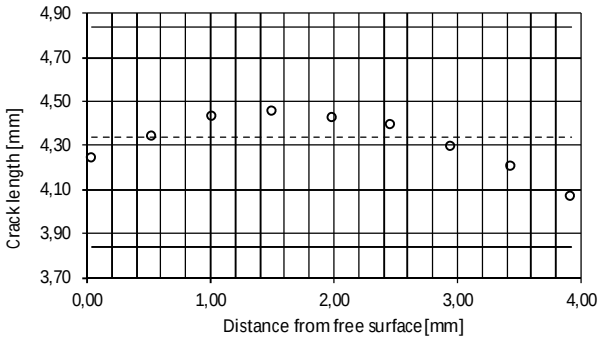
Specimen

Specimen name	BGJ7.1
Specimen orientation	Same as Charpy-V
Specimen type	C(T)
Specimen thickness, B [mm]	3,96
Specimen net thickness, B_N [mm]	3,96
Specimen width, W [mm]	8,05
Precrack length, a_0 [mm]	4,34
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	13,7
Test temperature, T [°C]	-140
Plastic area, A_p [Nm]	0,088
Fracture toughness K_{Jc} [MPa√m]	79,1



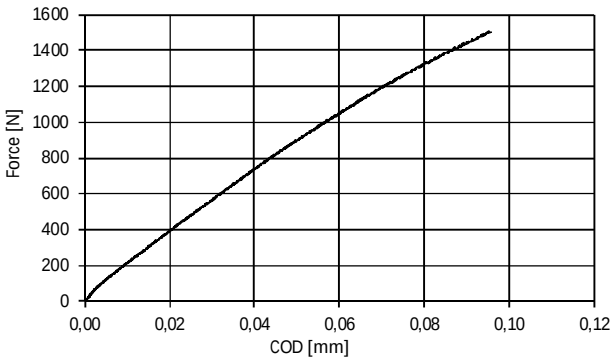
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	4,24		OK
a_2	0,53	4,34		OK
a_3	1,01	4,43		OK
a_4	1,50	4,46		OK
a_5	1,98	4,42		OK
a_6	2,46	4,40		OK
a_7	2,95	4,30		OK
a_8	3,43	4,20		OK
a_9	3,92	4,07		OK
average		a_0= 4,34	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		9,0		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen BGJ7.2



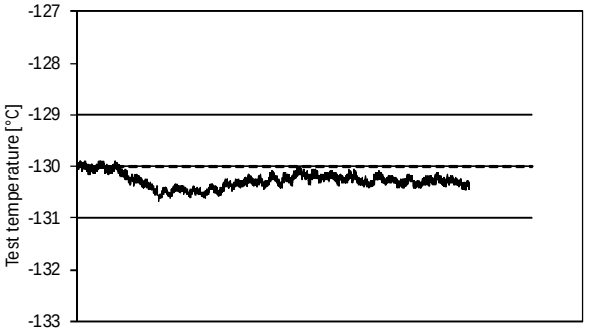
Material

Barsebäck weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

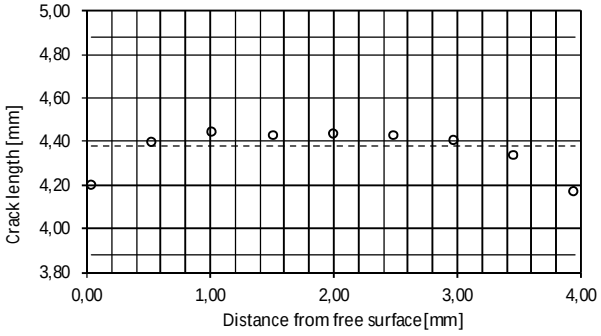
Specimen

Specimen name	BGJ7.2
Specimen orientation	Same as Charpy-V
Specimen type	C(T)
Specimen thickness, B [mm]	3,99
Specimen net thickness, B_N [mm]	3,99
Specimen width, W [mm]	8,07
Precrack length, a_0 [mm]	4,38
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	13,7
Test temperature, T [°C]	-130
Plastic area, A_p [Nm]	0,017
Fracture toughness K_{Jc} [MPa√m]	52,5



Crack length

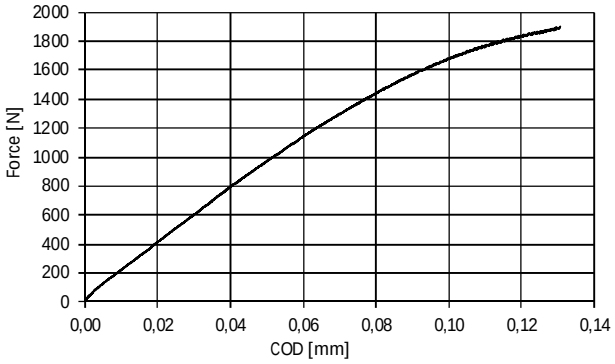
a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	4,20		OK
a_2	0,53	4,40		OK
a_3	1,02	4,44		OK
a_4	1,51	4,42		OK
a_5	2,00	4,44		OK
a_6	2,48	4,43		OK
a_7	2,97	4,40		OK
a_8	3,46	4,33		OK
a_9	3,95	4,17		OK
average		a_0= 4,38	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		6,2		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

Appendix 2

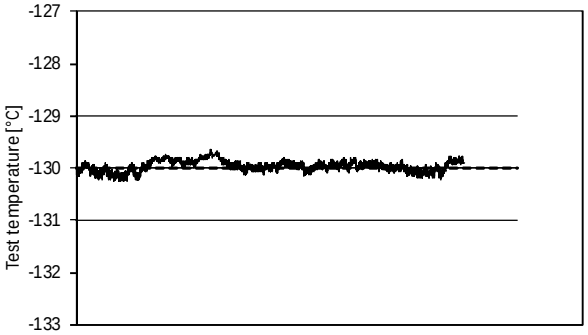
ASTM E1921-13 standard test to determine reference temperature T0
Specimen 224.1



Material

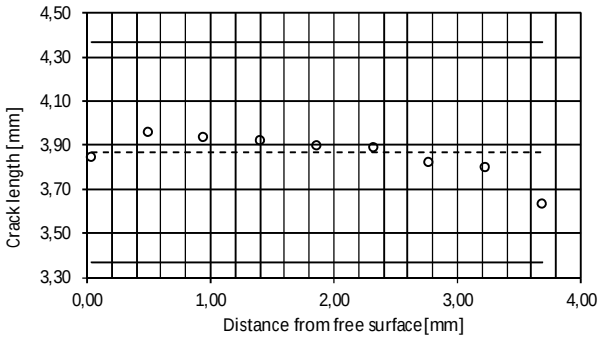
Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa



Specimen

Specimen name	224.1
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,72
Specimen net thickness, B_N [mm]	3,72
Specimen width, W [mm]	7,54
Precrack length, a_0 [mm]	3,87
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	13,7
Test temperature, T [°C]	-130
Plastic area, A_p [Nm]	0,056
Fracture toughness K_{Jc} [MPa√m]	74,2

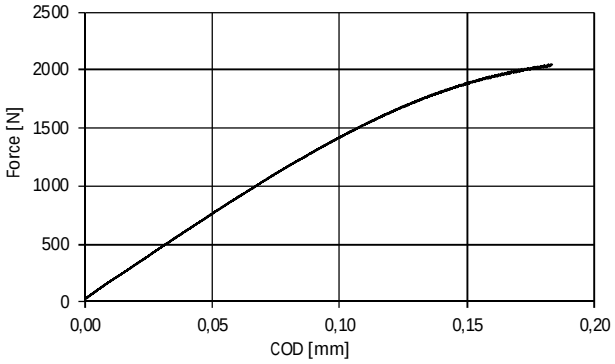
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,85		OK
a_2	0,49	3,95		OK
a_3	0,95	3,93		OK
a_4	1,41	3,92		OK
a_5	1,86	3,90		OK
a_6	2,32	3,89		OK
a_7	2,77	3,82		OK
a_8	3,23	3,80		OK
a_9	3,69	3,63		OK
average		a_0= 3,87	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		8,4		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen 224.2



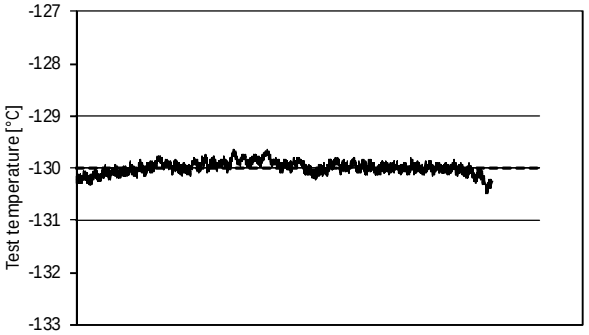
Material

Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

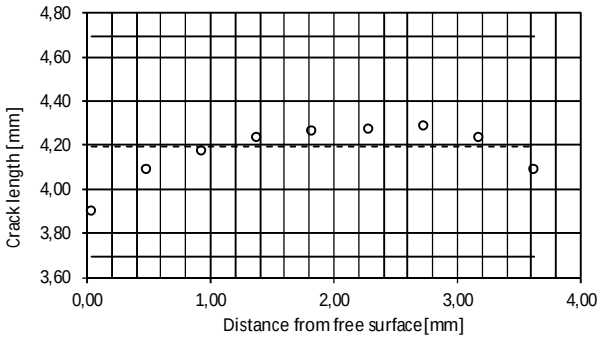
Specimen

Specimen name	224.2
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,66
Specimen net thickness, B_N [mm]	3,66
Specimen width, W [mm]	7,58
Precrack length, a_0 [mm]	4,19
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	15,9
Test temperature, T [°C]	-130
Plastic area, A_p [Nm]	0,085
Fracture toughness K_{Jc} [MPa√m]	93,3



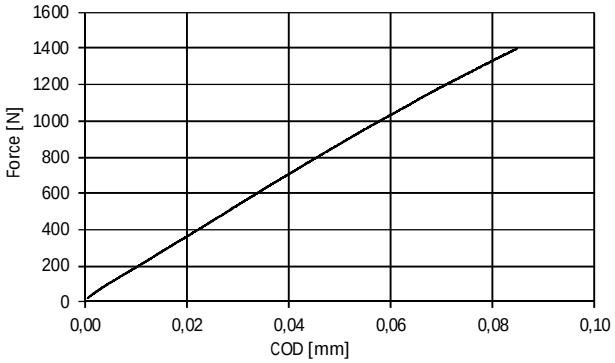
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,90		OK
a_2	0,49	4,09		OK
a_3	0,93	4,18		OK
a_4	1,38	4,24		OK
a_5	1,83	4,26		OK
a_6	2,28	4,27		OK
a_7	2,72	4,29		OK
a_8	3,17	4,23		OK
a_9	3,62	4,09		OK
average		a_0= 4,19	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		9,1		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

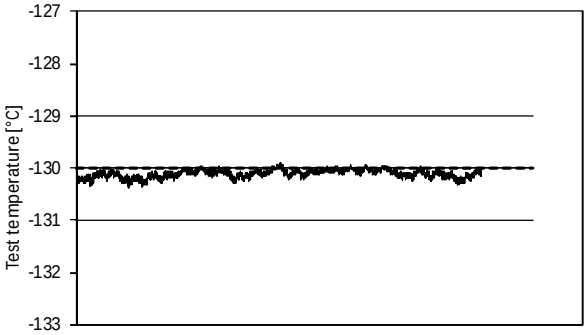
ASTM E1921-13 standard test to determine reference temperature T0
Specimen 224.3



Material

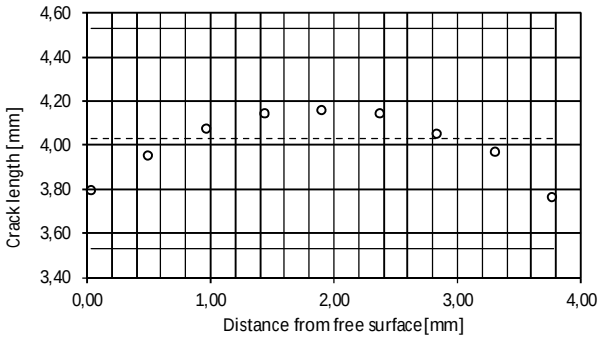
Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa



Specimen

Specimen name	224.3
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,81
Specimen net thickness, B_N [mm]	3,81
Specimen width, W [mm]	7,50
Precrack length, a_0 [mm]	4,03
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	14,5
Test temperature, T [°C]	-130
Plastic area, A_p [Nm]	0,007
Fracture toughness K_{Jc} [MPa√m]	48,8

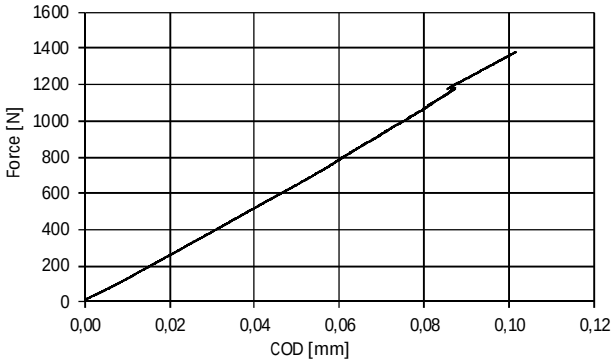
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,79		OK
a_2	0,50	3,95		OK
a_3	0,97	4,07		OK
a_4	1,44	4,14		OK
a_5	1,91	4,15		OK
a_6	2,37	4,14		OK
a_7	2,84	4,05		OK
a_8	3,31	3,97		OK
a_9	3,77	3,76		OK
average		a_0= 4,03	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		9,8		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen 224.4



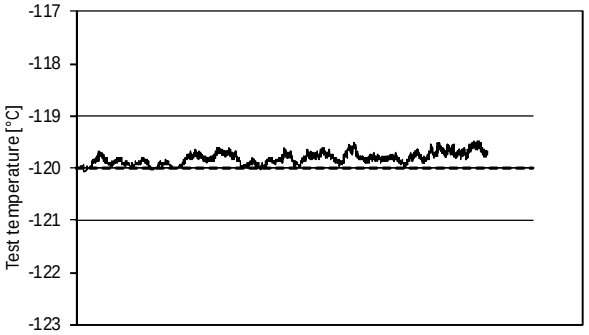
Material

Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

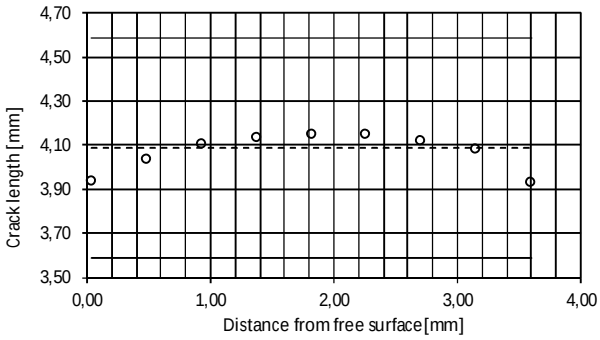
Specimen

Specimen name	224.4
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,63
Specimen net thickness, B_N [mm]	3,63
Specimen width, W [mm]	7,51
Precrack length, a_0 [mm]	4,09
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	15,5
Test temperature, T [°C]	-120
Plastic area, A_p [Nm]	-0,005
Fracture toughness K_{Jc} [MPa√m]	46,6



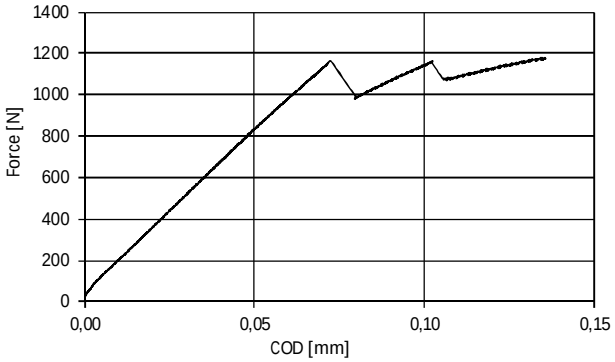
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,94		OK
a_2	0,48	4,03		OK
a_3	0,93	4,10		OK
a_4	1,37	4,13		OK
a_5	1,82	4,15		OK
a_6	2,26	4,15		OK
a_7	2,71	4,12		OK
a_8	3,15	4,08		OK
a_9	3,60	3,93		OK
average		a_0= 4,09	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		5,4		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen 224.5



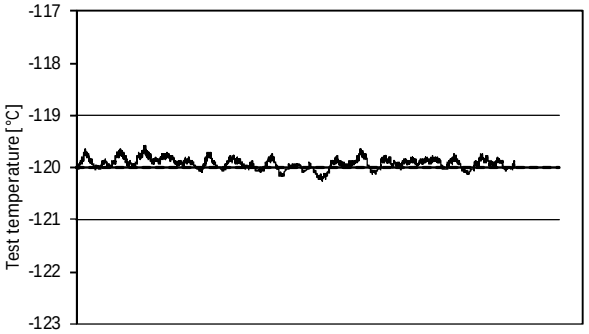
Material

Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

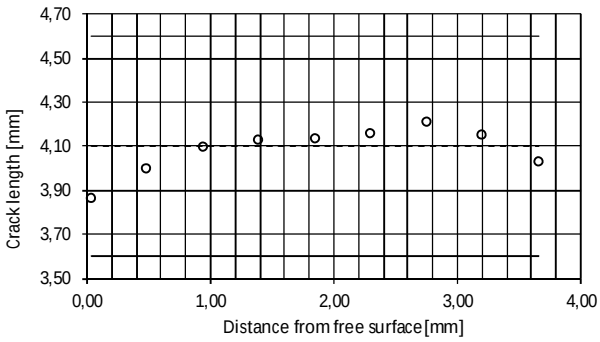
Specimen

Specimen name	224.5
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,69
Specimen net thickness, B_N [mm]	3,69
Specimen width, W [mm]	7,57
Precrack length, a_0 [mm]	4,10
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	yes,	0,78
Displacement measurement	front face	
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	15,1	
Test temperature, T [°C]	-120	
Plastic area, A_p [Nm]	0,004	
Fracture toughness K_{Jc} [MPa√m]	41,8	



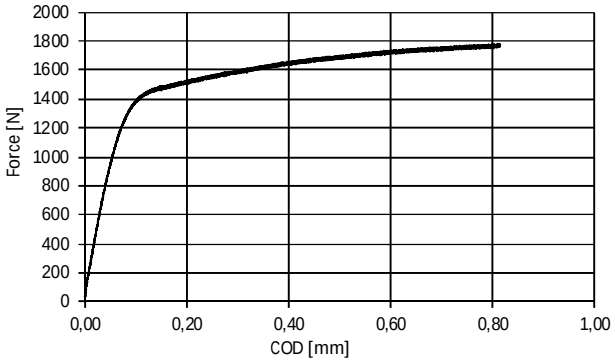
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,86		OK
a_2	0,49	3,99		OK
a_3	0,94	4,09		OK
a_4	1,39	4,13		OK
a_5	1,85	4,13		OK
a_6	2,30	4,16		OK
a_7	2,75	4,21		OK
a_8	3,20	4,15		OK
a_9	3,66	4,03		OK
average		a_0= 4,10	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		8,6		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

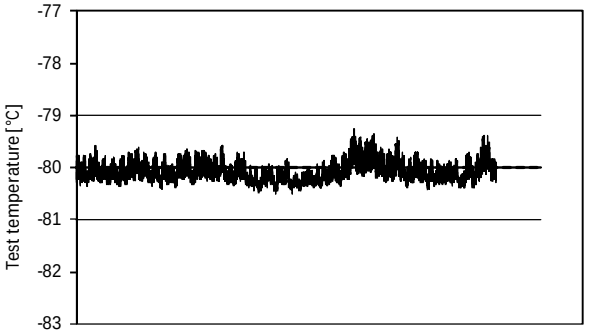
ASTM E1921-13 standard test to determine reference temperature T0
Specimen 224.6



Material

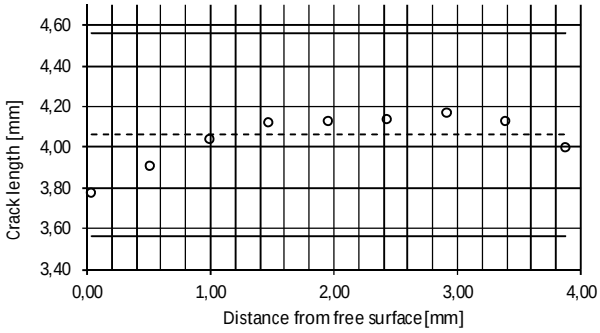
Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa



Specimen

Specimen name	224.6
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,91
Specimen net thickness, B_N [mm]	3,91
Specimen width, W [mm]	7,57
Precrack length, a_0 [mm]	4,06
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	14,0
Test temperature, T [°C]	-80
Plastic area, A_p [Nm]	1,185
Fracture toughness K_{Jc} [MPa√m]	227,4

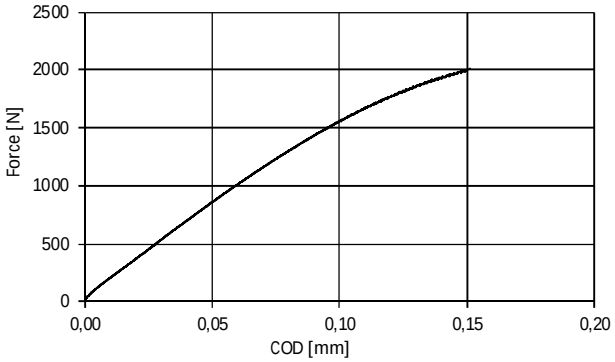
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,77		OK
a_2	0,52	3,91		OK
a_3	1,00	4,04		OK
a_4	1,48	4,12		OK
a_5	1,96	4,13		OK
a_6	2,43	4,14		OK
a_7	2,91	4,17		OK
a_8	3,39	4,13		OK
a_9	3,87	4,00		OK
average		a_0= 4,06	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		9,7		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	NOT OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen 224.7



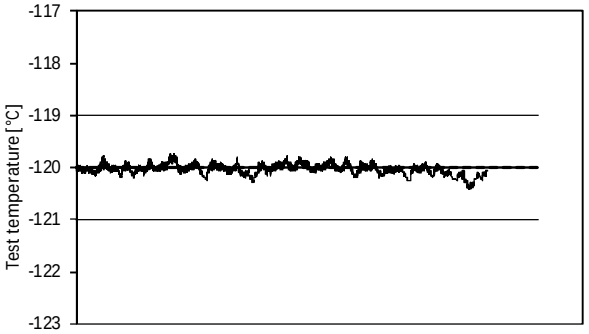
Material

Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

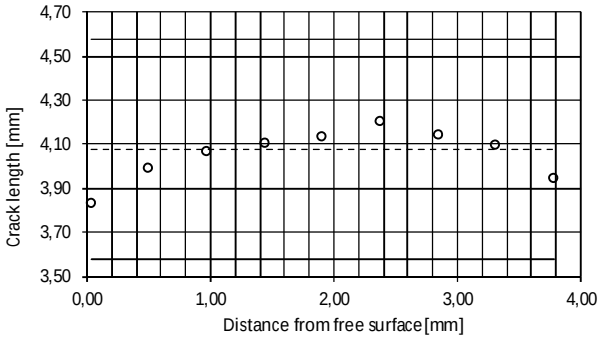
Specimen

Specimen name	224.7
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,82
Specimen net thickness, B_N [mm]	3,82
Specimen width, W [mm]	7,57
Precrack length, a_0 [mm]	4,08
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	14,5
Test temperature, T [°C]	-120
Plastic area, A_p [Nm]	0,053
Fracture toughness K_{Jc} [MPa√m]	79,3



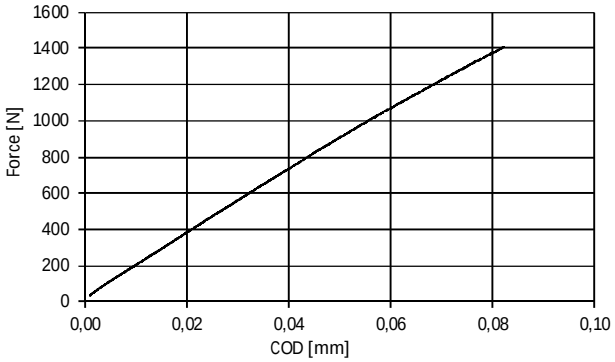
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,83		OK
a_2	0,51	3,99		OK
a_3	0,97	4,07		OK
a_4	1,44	4,11		OK
a_5	1,91	4,13		OK
a_6	2,38	4,20		OK
a_7	2,85	4,14		OK
a_8	3,31	4,10		OK
a_9	3,78	3,94		OK
average		a_0= 4,08	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		9,0		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen 224.8



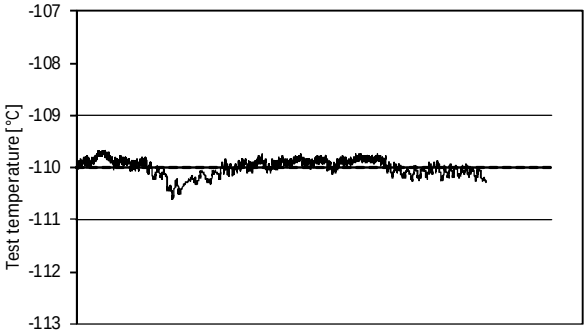
Material

Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

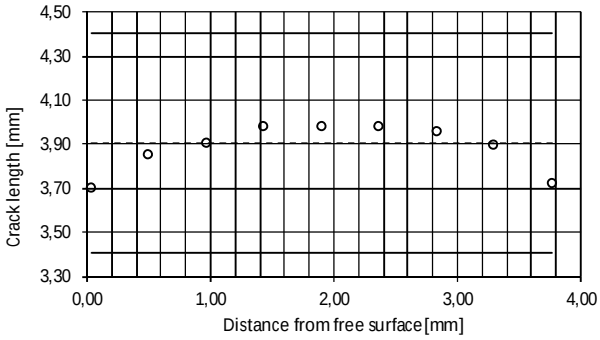
Specimen

Specimen name	224.8
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,80
Specimen net thickness, B_N [mm]	3,80
Specimen width, W [mm]	7,51
Precrack length, a_0 [mm]	3,91
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	13,8
Test temperature, T [°C]	-110
Plastic area, A_p [Nm]	0,006
Fracture toughness K_{Jc} [MPa√m]	46,3



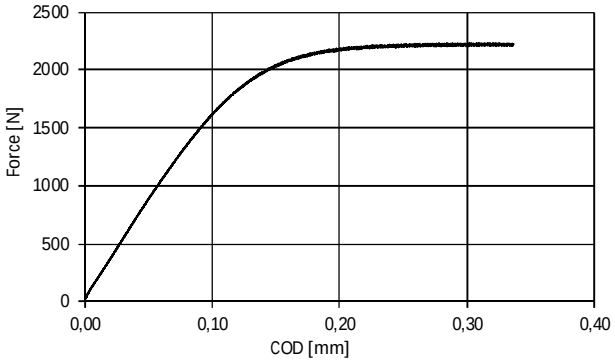
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,70		OK
a_2	0,50	3,85		OK
a_3	0,97	3,90		OK
a_4	1,43	3,98		OK
a_5	1,90	3,98		OK
a_6	2,37	3,98		OK
a_7	2,83	3,96		OK
a_8	3,30	3,89		OK
a_9	3,76	3,72		OK
average		a_0= 3,91	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		7,2		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

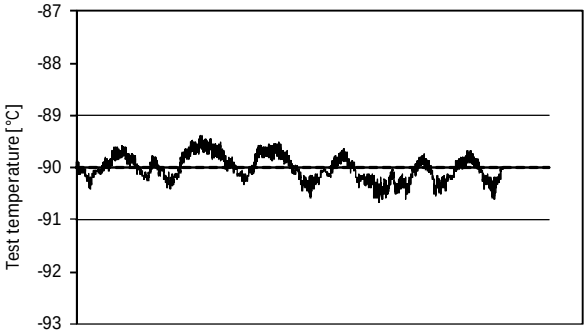
ASTM E1921-13 standard test to determine reference temperature T0
Specimen 224.9



Material

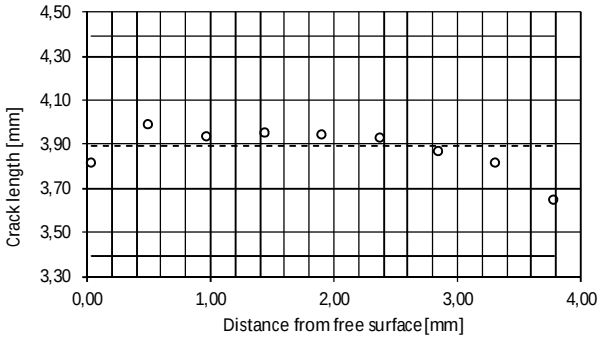
Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa



Specimen

Specimen name	224.9
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,82
Specimen net thickness, B_N [mm]	3,82
Specimen width, W [mm]	7,45
Precrack length, a_0 [mm]	3,89
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	13,8
Test temperature, T [°C]	-90
Plastic area, A_p [Nm]	0,446
Fracture toughness K_{Jc} [MPa√m]	142,3

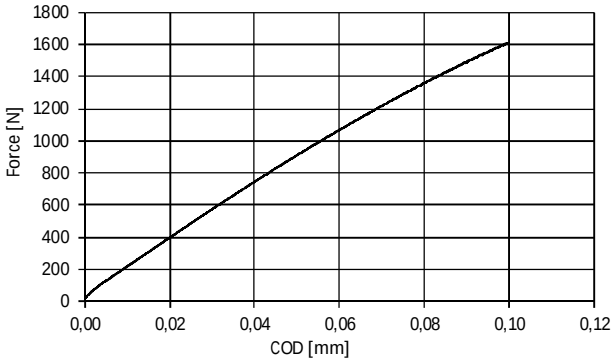
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,81		OK
a_2	0,51	3,99		OK
a_3	0,97	3,93		OK
a_4	1,44	3,95		OK
a_5	1,91	3,94		OK
a_6	2,38	3,92		OK
a_7	2,85	3,87		OK
a_8	3,31	3,81		OK
a_9	3,78	3,64		OK
average		a_0= 3,89	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		8,8		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	NOT OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen 224.10



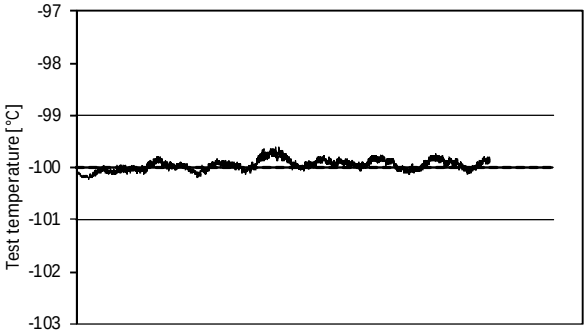
Material

Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

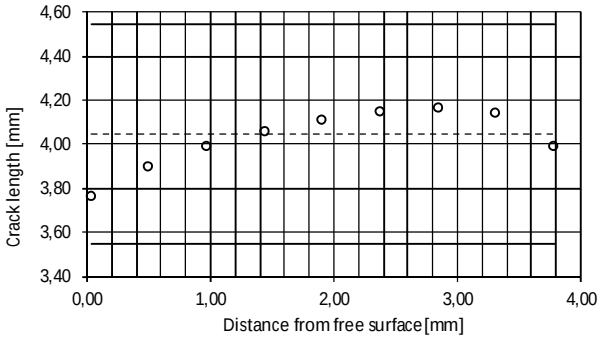
Specimen

Specimen name	224.10
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,82
Specimen net thickness, B_N [mm]	3,82
Specimen width, W [mm]	7,58
Precrack length, a_0 [mm]	4,05
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	14,2
Test temperature, T [°C]	-100
Plastic area, A_p [Nm]	0,015
Fracture toughness K_{Jc} [MPa√m]	57,3



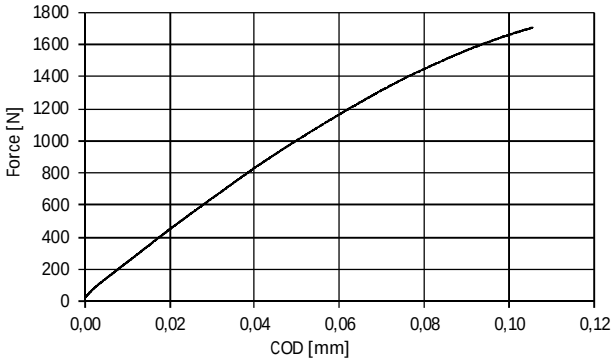
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,76		OK
a_2	0,51	3,89		OK
a_3	0,97	3,99		OK
a_4	1,44	4,06		OK
a_5	1,91	4,11		OK
a_6	2,38	4,15		OK
a_7	2,85	4,16		OK
a_8	3,32	4,14		OK
a_9	3,78	3,98		OK
average		a_0= 4,05	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		10,0		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

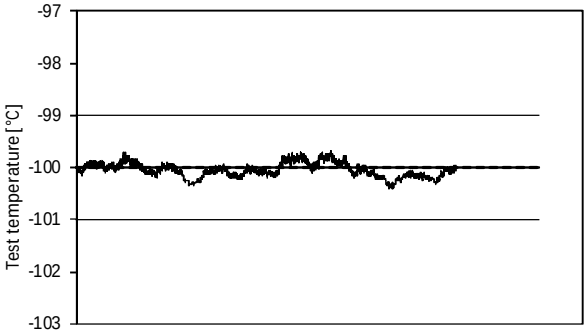
ASTM E1921-13 standard test to determine reference temperature T0
Specimen 230.1



Material

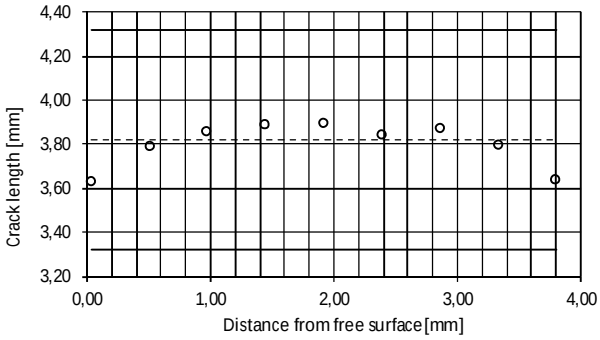
Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa



Specimen

Specimen name	230.1
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,84
Specimen net thickness, B_N [mm]	3,84
Specimen width, W [mm]	7,50
Precrack length, a_0 [mm]	3,82
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	13,2
Test temperature, T [°C]	-100
Plastic area, A_p [Nm]	0,033
Fracture toughness K_{Jc} [MPa√m]	61,7

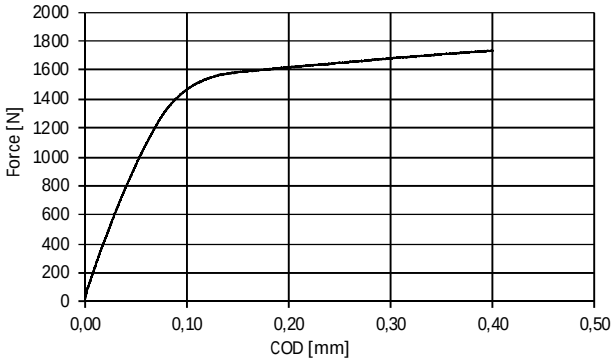
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,63		OK
a_2	0,51	3,79		OK
a_3	0,98	3,85		OK
a_4	1,45	3,89		OK
a_5	1,92	3,90		OK
a_6	2,39	3,84		OK
a_7	2,86	3,87		OK
a_8	3,33	3,79		OK
a_9	3,80	3,64		OK
average		a_0= 3,82	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		6,9		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

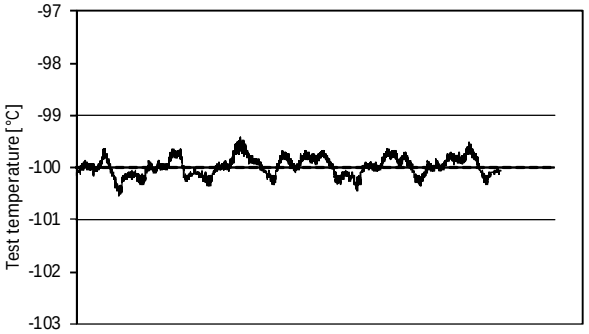
ASTM E1921-13 standard test to determine reference temperature T0
Specimen 156.2



Material

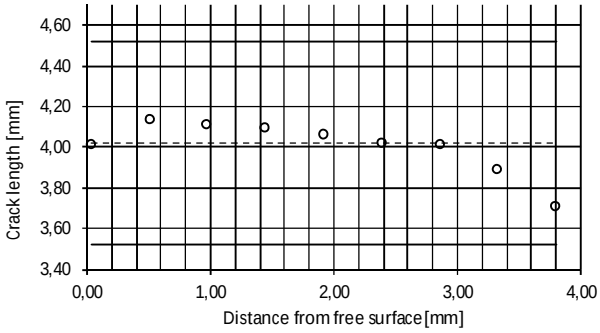
Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa



Specimen

Specimen name	156.2
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,84
Specimen net thickness, B_N [mm]	3,84
Specimen width, W [mm]	7,56
Precrack length, a_0 [mm]	4,02
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	14,1
Test temperature, T [°C]	-100
Plastic area, A_p [Nm]	0,503
Fracture toughness K_{Jc} [MPa√m]	151,0

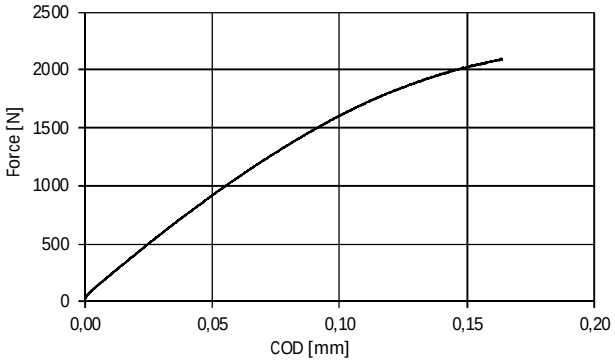
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	4,01		OK
a_2	0,51	4,13		OK
a_3	0,98	4,11		OK
a_4	1,45	4,09		OK
a_5	1,92	4,06		OK
a_6	2,39	4,02		OK
a_7	2,86	4,01		OK
a_8	3,33	3,89		OK
a_9	3,80	3,71		OK
average		a_0= 4,02	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		10,6		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	NOT OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

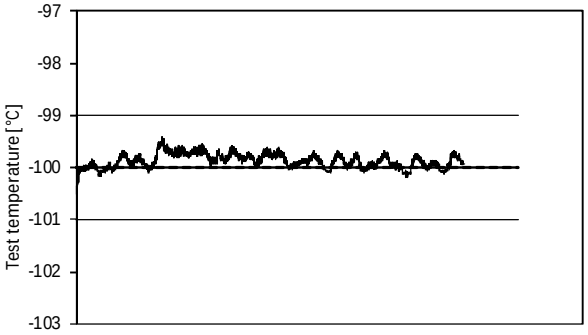
ASTM E1921-13 standard test to determine reference temperature T0
Specimen 156.3



Material

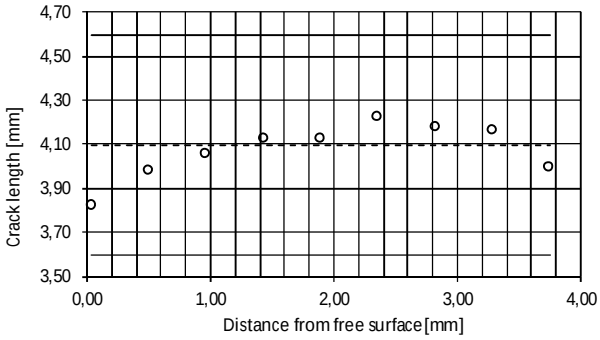
Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa



Specimen

Specimen name	156.3
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,79
Specimen net thickness, B_N [mm]	3,79
Specimen width, W [mm]	7,58
Precrack length, a_0 [mm]	4,10
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	14,7
Test temperature, T [°C]	-100
Plastic area, A_p [Nm]	0,089
Fracture toughness K_{Jc} [MPa√m]	92,1

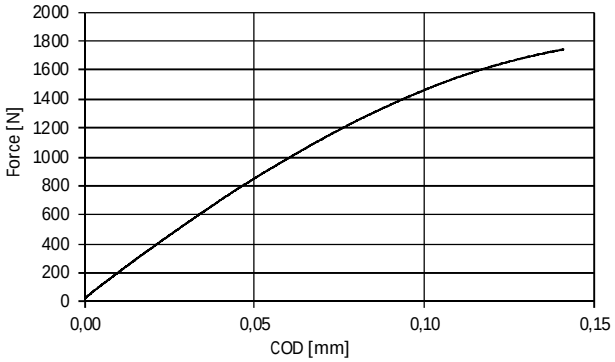
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,83		OK
a_2	0,50	3,98		OK
a_3	0,97	4,06		OK
a_4	1,43	4,13		OK
a_5	1,89	4,13		OK
a_6	2,36	4,22		OK
a_7	2,82	4,18		OK
a_8	3,28	4,16		OK
a_9	3,75	4,00		OK
average		a_0= 4,10	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		9,7		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen 156.5



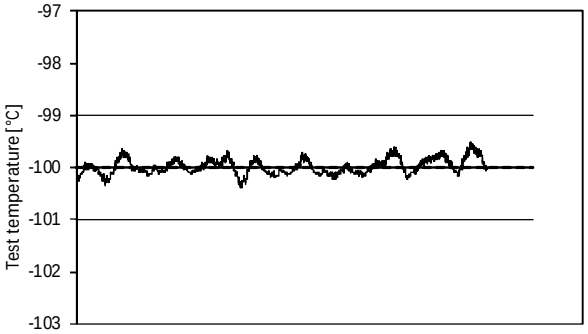
Material

Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

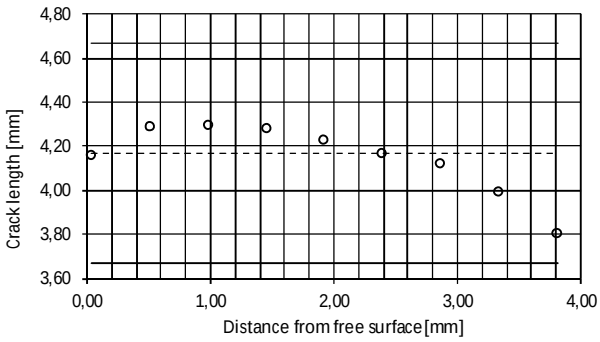
Specimen

Specimen name	156.5
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,85
Specimen net thickness, B_N [mm]	3,85
Specimen width, W [mm]	7,52
Precrack length, a_0 [mm]	4,17
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	15,2
Test temperature, T [°C]	-100
Plastic area, A_p [Nm]	0,060
Fracture toughness K_{Jc} [MPa√m]	78,6



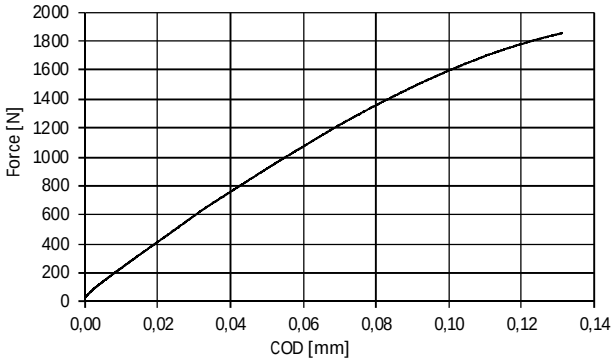
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	4,16		OK
a_2	0,51	4,29		OK
a_3	0,98	4,29		OK
a_4	1,45	4,28		OK
a_5	1,92	4,23		OK
a_6	2,40	4,17		OK
a_7	2,87	4,12		OK
a_8	3,34	3,99		OK
a_9	3,81	3,80		OK
average		a_0= 4,17	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		11,9		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen 156.8



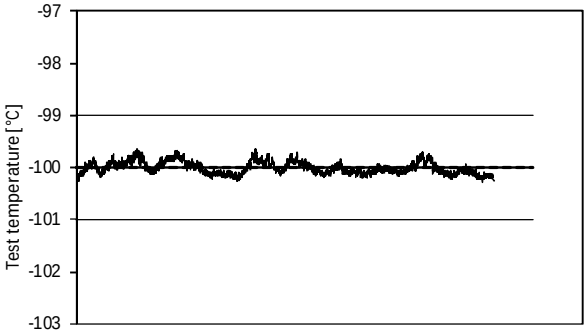
Material

Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

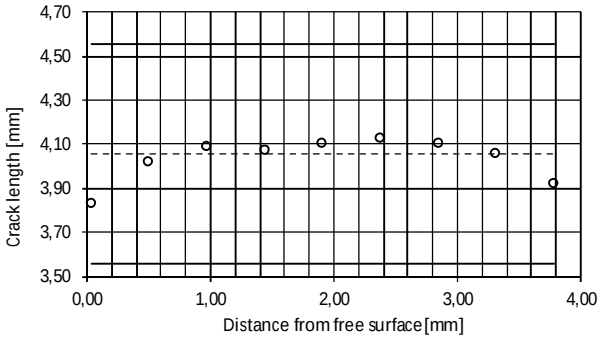
Specimen

Specimen name	156.8
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,82
Specimen net thickness, B_N [mm]	3,82
Specimen width, W [mm]	7,56
Precrack length, a_0 [mm]	4,06
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	14,4
Test temperature, T [°C]	-100
Plastic area, A_p [Nm]	0,049
Fracture toughness K_{Jc} [MPa√m]	75,0



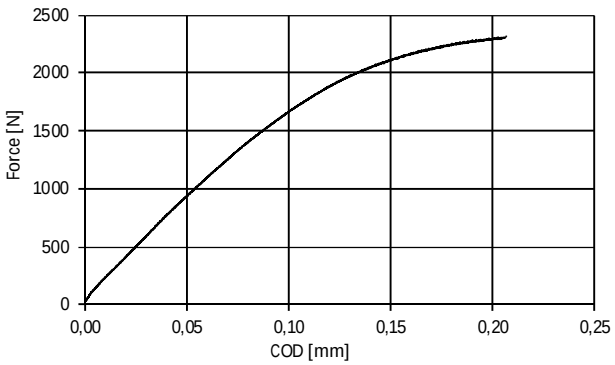
Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,83		OK
a_2	0,51	4,02		OK
a_3	0,97	4,09		OK
a_4	1,44	4,08		OK
a_5	1,91	4,10		OK
a_6	2,38	4,13		OK
a_7	2,85	4,11		OK
a_8	3,31	4,05		OK
a_9	3,78	3,92		OK
average		a_0= 4,06	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		7,3		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK

ASTM E1921-13 standard test to determine reference temperature T0
Specimen 156.9



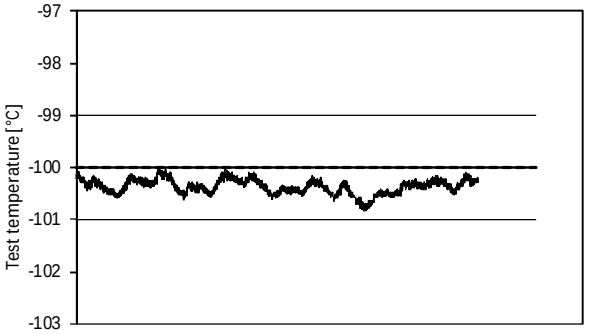
Material

Surrogate weld metal

$R_{p0,2\ (RT)}$	560	MPa
$R_{m\ (RT)}$	642	MPa

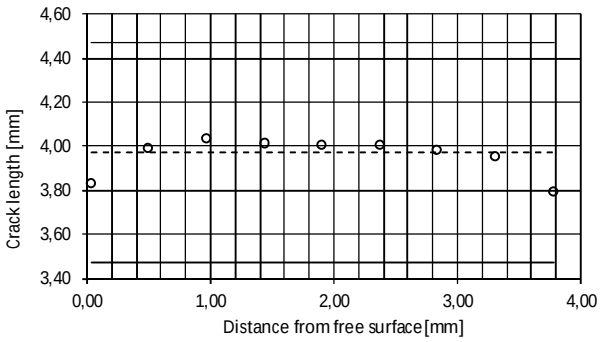
Specimen

Specimen name	156.9
Specimen orientation	
Specimen type	C(T)
Specimen thickness, B [mm]	3,82
Specimen net thickness, B_N [mm]	3,82
Specimen width, W [mm]	7,57
Precrack length, a_0 [mm]	3,97
Stable crack growth, Δa [mm]	



Test

Pop-in, C_i/C_0	no
Displacement measurement	front face
K_{max} for final 0,64 mm of fatigue precracking [MPa√m]	13,8
Test temperature, T [°C]	-100
Plastic area, A_p [Nm]	0,170
Fracture toughness K_{Jc} [MPa√m]	107,7



Crack length

a_i	Distance from free surface [mm]	Precrack length [mm]	Final crack length [mm]	Qualification according to 8.9.1
a_1	0,04	3,83		OK
a_2	0,51	3,99		OK
a_3	0,97	4,03		OK
a_4	1,44	4,01		OK
a_5	1,91	4,00		OK
a_6	2,38	4,00		OK
a_7	2,84	3,98		OK
a_8	3,31	3,95		OK
a_9	3,78	3,79		OK
average		a_0= 3,97	a_f=	
$(a_{i,max}-a_{i,min})/a$ [%]		6,0		

Qualification of data

8.9.1	a_i-a_0 < maximum (0,05*B, 0,5 mm)	OK
8.9.2	• measurement capacity: $K_{JC} < K_{JC(limit)}$	OK
	• crack growth validity: Δa_{stable} < minimum (0,05*(W-a_0), 1 mm) at the onset of cleavage fracture	OK
8.9.3	cleavage fracture	OK