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Determination of T_0 with Miniature C(T) Specimens for a High-Ni Weld Metal used in a Boiling Water Reactor Pressure Vessel

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Abstract

In structural integrity analysis of the reactor pressure vessel (RPV), the fracture toughness needs to be determined. The welds can be the most critical parts of the RPV. The applicability of miniature compact tension (C(T)) specimens is of great interest in the nuclear power plant (NPP) field as it increases the amount of surveillance test material**.**

In this study, the reference temperature, T_0, of a non-irradiated high-Ni weld metal was determined by using miniature C(T) specimens manufactured from tested CVN specimen halves from a Boiling Water Reactor (BWR) surveillance programme. The Master Curve analysis yields a T_0 of -99 °C. The fracture toughness tests were carried out together with fractographic characterization and hardness measurements. Additionally, the crack initiation site location and the distance of the initiation site to the pre-fatigue crack tip were determined. The results verify the applicability of miniature C(T) specimens for fracture toughness determination of the non-irradiated high-Ni weld metal.

Keywords — RPV, reference temperature, weld metal, miniature C(T) specimen, crack initiation

1. Introduction

In structural integrity analysis of the reactor pressure vessel (RPV), the fracture toughness needs to be determined. The core region of a RPV is subjected to neutron irradiation from the fission reaction in the fuel. Irradiation causes degradation of mechanical properties and an increase of the reference temperature, T_0, of the RPV. The reference temperature is the temperature at which a critical fracture toughness or drop-weight energy is retained in the test samples, and is used to assure ductile behaviour of the material. The reference temperature T_0 is thus an important factor in the safety assessment.

Due to the large RPVs size, it is manufactured by welding from several individual parts. The structural integrity of the RPV require monitoring of both the base material and the weld metal. In many cases the weld is the more sensitive part of the structure. Monitoring is done by surveillance programmes, in which test specimens are located closer to the core than the RPV wall enabling proactive prediction of the RPV integrity. The data can be applied both to Boiling and Pressurized Water Reactors (BWRs and PWRs), where the dose accumulation is higher than in BWRs. Surveillance programmes of the Generation II NPPs were initially established based on a 40 years design life, while many plants are now considering extended life time of 60 years or even 80 or 100 years. Generation III NPPs, like the European Pressurized Water Reactor (EPR)

(e.g. Olkiluoto 3), has a design life time of 60 years. When extended life time is considered, further surveillance testing and with that an optimised use of the available material, e.g. using smaller specimens, reconstitution of tested specimens, application of new surveillance chains, etc.

The experimental investigations in surveillance programmes are traditionally done with impact tests which are performed with Charpy-V notch (CVN) specimens. These tested CVN specimens can be reuse for manufacturing of miniature size test specimens, see Figure 1. Since there is only a limited amount of valuable representative reference materials available this reuse is required.

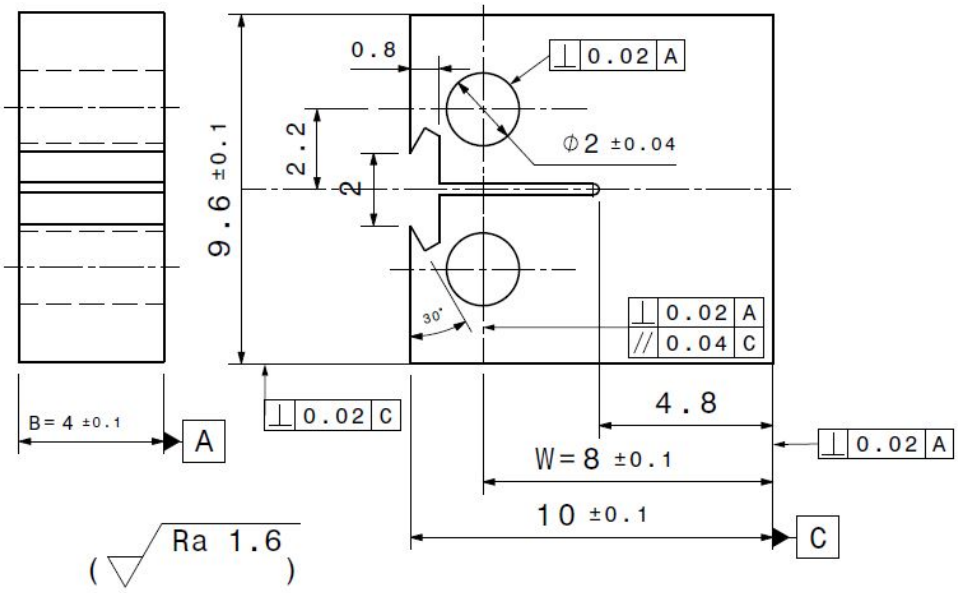

Figure 1. Miniature C(T) specimen.

RPV weld metals are acknowledged as a macroscopically homogeneous material [1] and thus, eligible to be characterized according to ASTM E1921 “Standard Test Method for Determination of Reference Temperature, T_0, for Ferritic Steels in the Transition Range” [2] which also enables the use of sub sized and miniature test specimens. Additionally, according to E1921, a minimum of six tests are required to determinate the reference temperature T_0 which is an advantage regarding the limited availability of surveillance material.

The aim of this study is to research the usability of miniature size C(T) specimens through determination of the reference temperature T_0 of high-Ni weld metal and study the reliability by comparing the test results to earlier studies.

2. Materials and methods

In this study a pressure vessel surveillance weld was investigated in reference condition. The chemical composition is presented in Table 1.

Table 1. Chemical composition (wt. %) of high -Ni weld metal in this study.

High-Ni WM	C	Si	Mn	P	Cr	Mo	Ni	Cu	S
	0.084	0.22	1.53	0.011	0.13	0.44	1.47	0.064	0.004

Miniature C(T) specimens were cut from tested surveillance CVN specimen halves and twelve specimens were tested in total. Macroetching of CVN halves revealed the microstructure in pursuance of pointing out the weld, Figure 2.

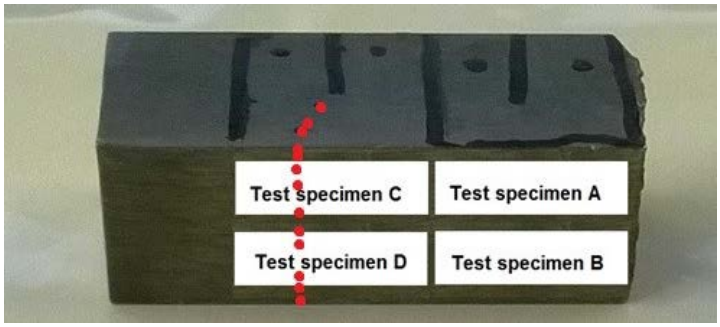

Figure 2. Miniature C(T) specimens were cut from tested CVN specimen halves as sketched above. Red dash line points out the fusion line of the weld.

Testing and specimen preparations were performed in accordance with ASTM E1921. Miniature C(T) specimens were pre-fatigued under load control prior to T_0-testing to an a0/W (see Figure 1) ratio of 0.5 with a material testing machine. A minimum depth of the pre-fatigue crack is 5% of the initial crack size. Side-grooving was not performed for the specimens in this study, since among others Wallin et al. [3], support the assumption that side-grooves have insignificant effect on the initiator location.

2.1 Testing

The testing was done with a servo-hydraulic testing machine with a loading capacity of 250 kN. The specimens were loaded by monotonic displacement control under loading rate of 0.1 mm/min which is in accordance with the ASTM E1921 where the loading rate in quasi static test is recommended to be between 0.1 and 2 MPa$\sqrt{m}$/s. The determination of the reference temperature T_0 requires a reduced temperature and thereby tests were performed inside an environmental chamber. The reduced temperature was achieved with liquid nitrogen. A crack-opening displacement (COD) gage with narrowed shafts was attached to the front face of the specimen (Figure 3). Throughout the test, the following data was recorded; displacement in axial direction, load, crack mouth opening displacement, temperature and time. The measuring frequency was 20 times per second.

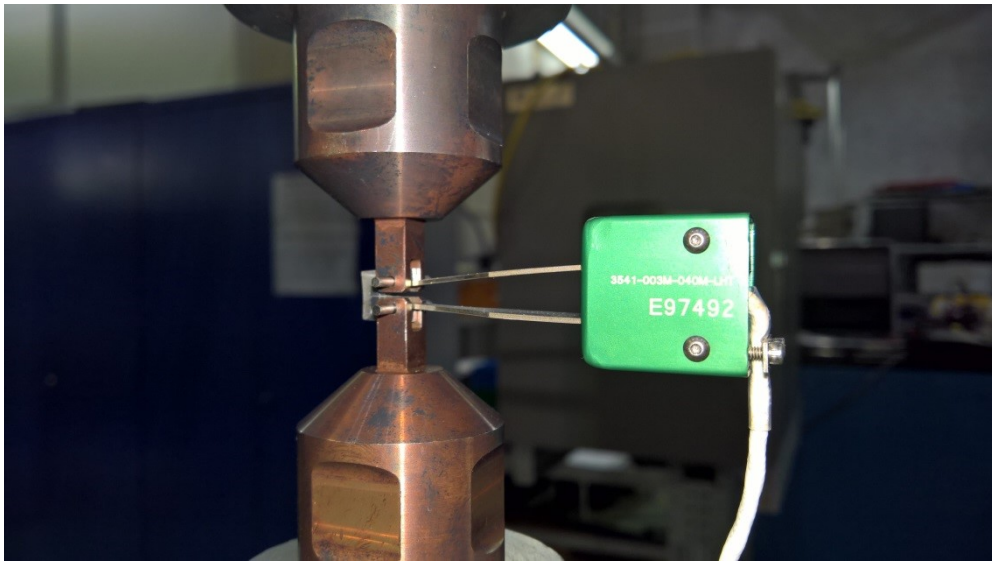

Figure 3. The miniature C(T) specimen attached to clevises with a COD gage on it.

Selection of suitable test temperature was based on results from prior testing of a similar material and tests were therefore carried out at -110 °C to -140 °C. A thermocouple was used to measure the test temperature.

Due to the fact that body-centred cubic (bcc) metals, as ferritic steel, have a strong yield strength - temperature correlation, the yield strength (σ_{YS}) was corrected to correspond the test temperature of each specimen with formulas given by the British Standard [4].

2.2 Post-test analysis

Two corrections were made to the test data; firstly during the test, there always appears slight rotation in the test specimen. Consequently, to diminish the influence of the rotation a crack growth needs to be corrected computationally with Equation 1 which includes Equation 2.

$$\frac{V_{LLc}}{V_{LL}} = \frac{1}{cos\,\theta - \frac{D}{R} sin\,\theta} \tag{1}$$

where V_{LLc} = rotation corrected load line displacement
R = radius of rotation = $\frac{W+a_0}{2}$
D = one half of the initial distance between the displacement measurement points
θ = angle of rotation.

The angle of rotation, required in Equation 1, is given by Equation 2.

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

Secondly; since the COD gage was attached to the specimen front face, the reading was multiplied with a factor to be equivalent to the load-line attach, Equation 3.

$$V_{LL} = V_C\left(\frac{a_0+r*b}{a_0+r*b+c}\right) \tag{3}$$

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.

2.3 Fractographic examination

All studied specimens were visually examined with a stereo microscope and a scanning electrode microscope (SEM), aiming to characterize the fracture surface and to locate the fracture initiation sites. Latter locations were defined qualitatively with SEM. SEM images of one tested specimen are presented in Figure 4. It shows a brittle cleavage fracture surface at different magnifications.

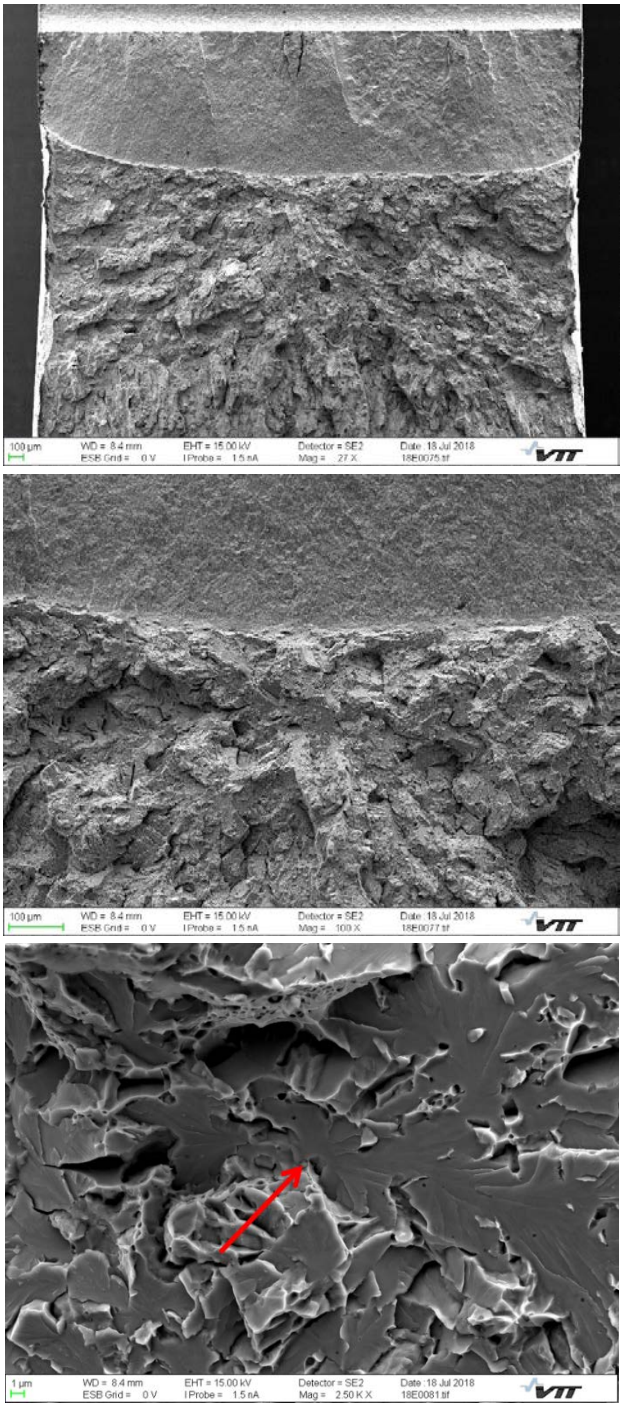

Figure 4. SEM images of studied high-Ni weld metal specimen where the initiation site is indicated by a red arrow.

Locating of the crack origin is important and the brittle fracture surface shows river patterns pointing back at the crack origin. It is possible for a crack to initiate by one mechanism but to propagate by another; these changes of mechanism may be identified by changes in texture of the fracture surface. The initiation site is interesting to examine since there are various possibilities of microstructural features for the actual initiation; it may be a secondary particle (carbide or inclusion), a grain boundary triple point, or some other detail in the microstructure. The interest is in the effort of combining crack origin and fracture toughness results to increase the understanding of factors affecting brittle fracture initiation. Additionally, the crack length was measured with a stereo microscope from the post-test fracture surface. Based on optical measurements, a

nine-point average procedure, presented in ASTM E1820 “Standard Test Method for Measurements of Fracture Toughness” [5], was used to determine the crack size. ASTM E1921 has a criterion for the straightness of the pre-fatigue crack front in order for K_{Jc} value to be valid. The standard requires that the maximum deviation of a single crack length from the average shall not deviate more than 5% or 0.5 mm from the average crack length; the larger value is selected.

2.4 Hardness measurement

The hardness of four specimens was measured with DuraScan-80 hardness tester using HV0.3 measurement head. The measurement pattern consisted of five longitudinal lines with 0.5 mm distance and had 20 measuring points in each line with a distance of 0.3 mm.

2.5 Master Curve adaptation

The Master Curve (MC) adaptation is based on a cleavage fracture model and it has two key features: a statistical model of the cleavage fracture and a temperature dependency of fracture toughness common to all ferritic steels. The MC theory presumes that the material consists randomly distributed defects or cleavage fracture initiators. The intention is to determine T_0 reference temperature defined as the median fracture toughness at 100 MPa√m.

The fracture toughness data obtained with a 4 mm thick miniature specimen, must be converted to correspond to the thickness of 25.4 mm (standard 1T specimen) before calculations of T_0. This ensures that all data is comparable regardless of the size of the test specimen. The determination of the reference temperature T_0 is done by an iteration process. The location of the median Master Curve $K_{Jc(med)}$ is based on T_0 according to Equation 4.

$$K_{Jc(med)} = 30 + 70exp[0.019(T - T_0)] \quad (4)$$

The Master Curves bounds, 95% upper and 5% lower, are calculated from Equation 5 where 0.xx represents the selected cumulative probability level (0 < 0.xx < 1); for the 5% lower tolerance bound 0.xx = 0.05.

$$K_{Jc(0.xx)} = 20 + \left[\ln\left(\frac{1}{1-0.xx}\right)\right]^{\frac{1}{4}}\{11 + 77\exp[0.019(T - T_0)]\} \quad (5)$$

3. Results and discussion

The test data used in determination of the transition temperature T_0 is presented in Table 2.

Table 2. Test data used in determination of the transition temperature T_0.

Specimen ID	Test Temperature. [°C]	Fracture toughness $K_{Jc\text{-}25mm}$ [MPa√m]	Yield strength σ_{YS} [MPa]
1	-110 °C	124	712
2	-110 °C	61	712
3	-120 °C	173	735
4	-120 °C	82	735
5	-130 °C	51	760
6	-130 °C	67	760
7	-130 °C	64	760
8	-140 °C	77	789
9	-140 °C	41	789
10	-140 °C	55	789
11	-140 °C	41	789
12	-140 °C	70	789

Two specimens exceed the measuring capacity of the specimen, and the values are censored. Even if the measuring capacity of the specimen is exceeded, $K_{Jc} > K_{Jc(limit)}$ and the value is invalid, the data contains still statistically useable information and can be adapted as censored data by replacing violated K_{Jc} value with $K_{Jc(limit)}$. Aforementioned fractographic examinations was used to determine the crack path, location of the crack origin and the initial crack length. The ASTM E1921 requires that the initial crack length a0 is 0.5W ± 0.05W; in this case 3.6 mm – 4.4mm. Table 3 indicates that this requirement was fulfilled.

Table 3. Table of initial crack lengths.

Specimen ID	Test Temperature [°C]	Initial crack length a_0 [mm]
1	-110 °C	4.11
2	-110 °C	4.00
3	-120 °C	4.16
4	-120 °C	4.06
5	-130 °C	4.15
6	-130 °C	4.38
7	-130 °C	4.36
8	-140 °C	4.25
9	-140 °C	4.24
10	-140 °C	4.07
11	-140 °C	4.04
12	-140 °C	4.28

Three specimens fail the crack front straightness criteria; however, with the two first-mentioned the exceeding was so minor that they were accepted but in the last-mentioned specimen, the pre-fatigue crack front was too skewed and failed to fulfil the validity requirements. The size corrected values, valid and censored, were used to calculate T_0 with the Master Curve analysis. The T_0 is -99 °C for the high-Ni weld metal in reference state. The standard deviation is 7 °C. Figure 5 shows the original data, before censoring, and the Master Curve, with the 5% and 95% confidence limits. Figure 5 shows also the allowable temperature range, T_0 ± 50 °C where the test data must fit to be applicable.

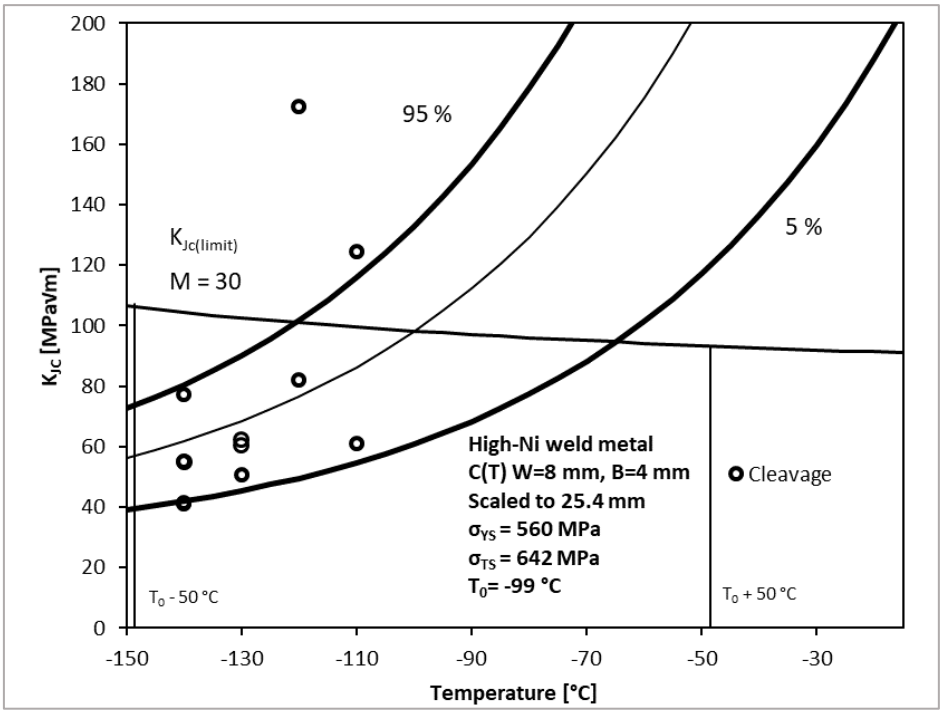

Figure 5. Master Curve analysis.

The hardness measurement results are presented in Table 4. The microstructure of the hardness measurement area was re-heated for 10 and 11, and as-welded for 4 and 6.

Table 4. Hardness measurements.

Specimen ID	Hardness HV0.3
10	208 ± 5
11	208± 5
4	210± 5
6	208± 5

Cleavage fracture tends to initiate near the maximum stress location when the stress ahead of the crack-tip exceeds the critical stress [6]. The location of the maximum stress relative to pre-fatigue crack can be estimated with equation 6 where J is the fracture toughness at the onset of cleavage fracture, σ_{YS} is yield strength and m is a constraint factor determined in ASTM E1820. The distance of the maximum stress from the pre-fatigue crack tip is approximately 2δ (2 times crack-tip-opening displacement).

$$2\delta = 2 * \left(\frac{J}{m * \sigma_{YS}}\right) \quad (6)$$

Figure 6 shows the locations for crack initiation sites (Table 5) and the calculated locations of maximum stress ahead of the pre-fatigue crack tip. If initiation was driven by maximum stress only, these points would merge.

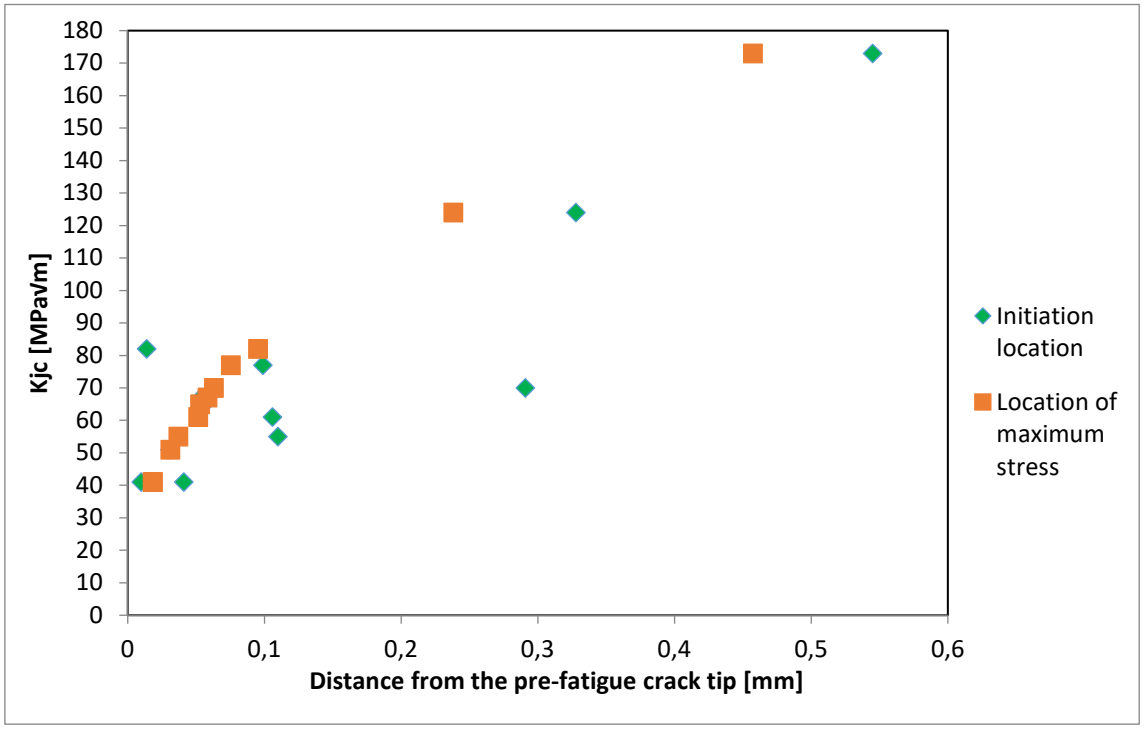

Figure 6. Locations of crack initiation sites and maximum stresses.

As can be seen from Figure 6 crack tends to initiate near the maximum stress site. In addition, there is a correlation between increasing fracture toughness and growing distance between initiation site and the pre-fatigue crack tip. However, the crack initiation site of one specimen located well beyond the maximum stress site. Such location is contrary to the general trend, and the reason for such a behaviour is under further investigations. The initiation locations respective to the pre-fatigue crack tip are presented in Table 5.

Table 5. Initiation distances from the pre-fatigue crack tip.

Specimen ID	Test Temperature [°C]	The initiation distance from the pre-fatigue crack tip [mm]	Fracture toughness $K_{Jc\text{-}25mm}$ [MPa√m]
1	-110°C	0.328	124
2	-110°C	0.106	61
3	-120°C	0.545	173
4	-120°C	0.139	82
5	-130°C	0.031	51
6	-130°C	0.054	67
7	-130°C	0.056	64
8	-140°C	0.099	77
9	-140°C	0.041	41
10	-140°C	0.110	55
11	-140°C	0.010	41
12	-140°C	0.291	70

A major question regarding miniature C(T) specimens is whether the usage of miniature sized C(T) specimens is applicable when determining fracture toughness of weld metals. Certainly, the miniature size itself is an advantage when the availability of test material is limited. Outcome of this research is in favour for the applicability. The K_{Jc} values were consistent and T_0 was determined successfully from 12 specimens despite sub sized specimen dimensions. In addition, prior experimental results [7] obtained with 5 mm and 10 mm specimens from a surveillance programme on similar type of weld metal, were in the same range.

Use of miniature size C(T) specimens is promising, but require still further research. Particularly comparison of fracture toughness results between standard 1T and miniature C(T) is important and more testing is needed. Additionally, finding an explanation for the unexpected location of crack initiation in one specimen is another thing for further investigations. Attempting to connect fracture toughness results with crack initiation locations and microstructure will undoubtedly promote an improved understanding of factors affecting brittle fracture initiation and fracture toughness characteristics.

4. Summary and conclusions

A reference temperature T_0 was determined with miniature size C(T) specimens manufactured from a non-irradiated weld metal surveillance programme specimens. The T_0 was determined to be -99 °C. The obtained results are consistent and in the same range as results from other similar materials. Determination of T_0 using miniature C(T) specimens was accomplished successfully, showing that the miniaturised specimen technique is a valid technique for determination of T_0.

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