Fracture, Damage and Structural Health Monitoring

On the determination of the reference temperature \( T_0 \) of the Master-Curve method using subsized compact tension specimens

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Abstract

Structural integrity of reactor pressure vessel (RPV) is of primary importance to ensure the long-term safety of light water reactors. The pressure vessel made of ferritic steel presents a ductile to brittle transition and experiences neutron embrittlement that needs to be quantified. The so-called Master-Curve (MC) method, standardized in the ASTM-E1921, is commonly used to determine a reference temperature \( T_0 \), which indexes the median toughness-temperature curve in the transition at 100 MPa m\(^{1/2}\) for one-inch-thick specimens, referred as 1T-specimen. Since brittle fracture toughness is strongly specimen size and geometry dependent, provisions are given in the ASTM-E1921 standard to take into account this effect. The standard also imposes restrictions on the testing temperature range where the fracture tests have to be performed. In this study, we carried out a series of fracture tests with subsized compact tension small specimens (0.18T) to determine \( T_0 \). In a first step, we calculated \( T_0 \) by following all recommendations of the standard strictly to get a valid \( T_0 \) value. Then, we took in consideration fracture toughness data obtained out of the recommended testing temperature range and showed that a reliable determination of \( T_0 \) can be done under these circumstances. Statistics show that this approach is quite reliable if more than 10 data are considered.

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1. Introduction

Reactor pressure vessel structure integrity has been one of the most concerned issues in nuclear reactor safety and characterization of fracture toughness of irradiated materials is an essential input for the structural integrity assessment.

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Surveillance programs were initially organized to monitor fracture toughness typically with the Charpy impact technique, which is an indirect measurement method (Terán et al. 2016). The Master Curve (MC) approach for assessing the fracture toughness, which was first proposed and developed by Wallin (Wallin 1993; Wallin 1999), has been gaining acceptance throughout the world since it is a direct toughness evaluation approach rather than a semi-empirical one based on Charpy measurements (Rosinski and Server 2000; Joyce and Tregoning 2001; Odette et al. 2003). The MC procedure was standardized by the American Society for Testing and Materials in 1997 and has undergone several revisions up to the current version: ASTM E1921-22a (2022). One of the greatest challenges in assessing irradiation embrittlement is related to the fact that only relatively small specimens are used in surveillance specimen matrix. However, it is well known that brittle fracture in the ductile to brittle transition is strongly specimen size dependent. Thus, it is imperative to develop either models to account for this effect or to evaluate the reliability of small specimen in comparison with large ones. A great deal of studies have been carried out in the last decades to address the issue of specimen size effect on fracture. For example, Kasada et al. evaluated the fracture toughness of blanket structural materials with the Master-Curve method using 1/2-CT specimens (Kasada et al. 2006). Chaouadi et al. discussed the reliability of miniaturized CT specimens (thickness 4.2 mm) in comparison to large specimens (Chaouadi et al. 2016). Miura et al. also measured fracture toughness of two RPV steels with 4 mm-thick specimens (Miura and Soneda 2012). Mueller et al. reported fracture toughness data for the tempered martensitic steel Eurofer97 with two different sizes of specimens and pointed out that Master-Curve shape adjustments may have to be considered when analyzing the lower part of the transition region (Mueller et al. 2009).

Currently, the European H2020 FRACTESUS project aims at validating subsized compact tension specimens to determine the reference temperature $T_0$ of the Master-Curve. Indeed, there is a strong interest to use such subsized specimens in reactor pressure vessel surveillance programs. FRACTESUS consortium proposes an innovative approach using subsized compact tension specimen that could be machined from a previously tested broken Charpy specimen. Typically eight to ten specimens could be extracted from a Charpy specimen (Cicero et al. 2020).

In this study, undertaken in the frame of FRACTESUS, we estimated the reference temperature $T_0$ of the Japanese Reference Quality (JRQ) ferritic steel based on the Master-Curve approach with sub-sized compact tension specimens. In addition, we looked at the possibility to incorporate low temperature toughness data into the Master-Curve analysis, which under the current version of the ASTM-E1921 standard would be rejected.

2. Experiments

2.1. Material and specimen preparation

The material investigated is the low-alloy reactor pressure vessel ferritic steel JRQ (Japanese Reference Quality) (2005). It is a A533B steel produced within the IAEA coordinated research project on the optimization of reactor pressure vessels and surveillance programs. The steel was produced by Kawasaki Steel Corporation. The chemical composition is given in Table 1. After rolling, the plates were heat treated by normalizing at 900 °C, quenching from 880 °C and tempering at 665 °C for 12 hours, then stress relieving at 620 °C for 40 hours.

<table>
<thead>
<tr>
<th>Compostion</th>
<th>C</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Cu</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
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<tr>
<td>min</td>
<td>0.16</td>
<td>0.24</td>
<td>1.35</td>
<td>0.017</td>
<td>0.003</td>
<td>0.13</td>
<td>0.85</td>
<td>0.12</td>
<td>0.49</td>
<td>0.002</td>
<td>0.012</td>
</tr>
<tr>
<td>max</td>
<td>0.20</td>
<td>0.26</td>
<td>1.43</td>
<td>0.019</td>
<td>0.004</td>
<td>0.14</td>
<td>0.82</td>
<td>0.12</td>
<td>0.51</td>
<td>0.003</td>
<td>0.014</td>
</tr>
</tbody>
</table>

Sub-sized compact tension (CT) specimens were designed for fracture tests having a thickness $B$ of 4.5 mm, which was referred as to 0.18T according to the specifications of the ASTM-E1921 standard (2022). Note that 1T specimen is used to refer to fracture specimen having a thickness of 25.4 mm. The width $W$ of the 0.18T CT specimens was equal to 2B. The specimens were sampled from the inner half of the original block 5JRQ56. Fig. 1 shows the geometry of the CT specimen and the comparison between the standard (1T) with the sub-sized (0.18T) CT specimens, highlighting the drastic reduction of specimen volume. Specimens were fatigue pre-cracked until the crack length $a$ was controlled within the range $0.45 < a/W < 0.55$ according to the requirement of the ASTM-E1921 standard.
2.2. Fracture tests

Elastic plastic fracture mechanics (EPFM) tests were performed with an electro-mechanical testing machine Schenck-RMC100 equipped with a temperature chamber (Fig. 2). The specimens were fatigue pre-cracked at low K values at room temperature. The cracks grew until their length length \( a \) was within the specified range \( 0.45 < a/W < 0.55 \). The fracture specimens were then quasi-statically loading with a machine piston velocity of 0.5 mm/min. The applied load and displacement were recorded up to failure. The displacement was measured with a crack mouth opening clip extensometer attached to the clevises. The specimens were cooled by a controlled flow of liquid nitrogen in the temperature chamber, where the temperature was monitored with a thermocouple attached to the specimen. In total 22 specimens were tested and all the tests were performed in the range [-120, -50 °C].

2.3. Estimation of the fracture toughness \( K_{JC} \) and determination of reference temperature \( T_0 \)

For all ferritic steels, the median toughness-temperature curve of 1T-size fracture specimens is described by the universal Master-Curve equation the reference temperature \( T_0 \), which indexes the curve on temperature at 100 MPam\(^{1/2}\).

\[
K_{JC,med}^{1T} = 30 + 70 \exp(0.019(T - T_0))
\]
To determine $T_0$, the measured toughness of the 0.18T specimen has to be calculated first. Brittle toughness being intrinsically specimen size dependent, the toughness of 0.18T specimen must then be adjusted to an equivalent 1T value (see below). Fracture toughness $K_{f_c}$ was estimated based on the elastic-plastic theory following the recommendations of ASTM-E1921 (2022). $K_{f_c}$ was obtained from the value $J$-integral at the onset of cleavage fracture $J_c$, calculated from the load-displacement curves:

$$K_{f_c} = \sqrt[2]{\frac{J_c}{1- \nu^2}}$$

(2)

where $E$ is Young’s modulus and $\nu$ is Poisson’s ratio, and $J_c$ consists of the elastic component of the $J$-integral, $J_e$, and the plastic component, $J_p$:

$$J_c = J_e + J_p$$

(3)

Constraint loss is addressed in the ASTM-E1921 standard by defining a specimen maximum measuring capacity with Eq. (4):

$$K_{f_c, \text{limit}} = \sqrt[4]{\frac{Bb_0 \sigma_{yy}}{M (1- \nu^2)}}$$

(4)

where $b_0$ is the initial ligament length and $\sigma_{yy}$ the yield stress. According the ASTM-E1921 standard, $M = 30$ and this value should be sufficient to ensure that a high level of constraint is maintained along the crack front length. In addition, the standard provides a toughness size adjustment if specimen sizes different from 1T are used. This correction accounts for the statistical size effect associated with the crack front length and reads:

$$K_{1T-\text{adjusted}} = K_{\text{min}} + (K_{2} - K_{\text{min}}) \left(\frac{B_s}{B_{1T}}\right)^{1/4}$$

(5)

with $K_{\text{min}} = 20 \text{ MPa m}^{1/2}$

The standard also assumes that the cumulative failure probability of a dataset at a given temperature follows Eq. (6) if $K_{f_c} < K_{f_c, \text{limit}}$.

$$P(K_{f_c} < K) = 1 - \exp \left( - \left( \frac{K - K_{\text{min}}}{K_0 - K_{\text{min}}} \right)^4 \right)$$

(6)

The temperature dependence in Eq. (6) appears in $K_0$, $K_{\text{min}}$ is taken as constant and equal to 20 MPam$^{1/2}$. For values greater than the limit, $K_{f_c} > K_{f_c, \text{limit}}$, it is assumed that loss of constraint affects the measured $K_{f_c}$ by increasing it to an apparent toughness, which in turn is reflected in a deviation of the data from Eq. (6). However, a value above the limit still carries useful information: the toughness of the specimen was at least equal or greater than the limit because before reaching the limit it did not lose constraint and did not break.

The standard combines the equations above to determine $T_0$ by means of the maximum likelihood method. This derives to Eq. (7), which is solved for $T_0$ by iteration.

$$\sum_{i=1}^{N} \delta_i \frac{\exp(0.019(T_i - T_0))}{11 + 77 \exp(0.019(T_i - T_0))} + \sum_{i=1}^{N} (K_{f_c(i)} - 20)^4 \exp(0.019(T_i - T_0)) = 0$$

(7)

- $N =$ is the number of tested specimens.
- $K_{f_c(i)} = K_{f_c(i)}$ if $K_{f_c(i)} < K_{f_c, \text{limit}}$, or $K_{f_c(i)} = K_{f_c, \text{limit}}$ if $K_{f_c(i)} > K_{f_c, \text{limit}}$.
- $\delta_i = 1.0$ if $K_{f_c} < K_{f_c, \text{limit}}$, and $\delta_i = \text{if} K_{f_c} \geq K_{f_c, \text{limit}}$. 


3. Results & Discussions

As example, several load-displacement curves at various temperatures are shown in Fig. 3. These curves were processed to determine the corresponding $K_{Jc}$ values from which the reference temperature $T_0$ was calculated with Eq. (7). $T_0$ was found equal to $-50.4 ^\circ C \pm 8.7 ^\circ C$. The $8.7 ^\circ C$ uncertainty is defined according to a standard two-tail normal distribution with two basic variables: the test temperature and the number of specimens used for the $T_0$ determination.

\[ \sigma = Z_{0.95\%} \sqrt{\frac{\beta^2}{r}} \]  (8)

We selected $Z_{0.95\%}$, the Z-score for the 90.5% confidence level ($Z_{0.95\%}$=1.67), $\beta$ is the sample size uncertainty factor and $r$ the total number of uncensored data ($r=13$). The considered data set has 13 uncensored data ($r = 13$) and $\beta$ is 18.8 (calculated according to the section 10.9.1 of the ASTM-E1921 standard). The $T_0$ at $-50.4 ^\circ C \pm 8.7 ^\circ C$ is in good agreement with previously determined $T_0$ from another set of toughness data of the same material but obtained with larger specimens, namely 0.5T C(T) which was equal to $-42.7 \pm 7 ^\circ C$ (Bryn et al. 2022). The 1T-adjusted fracture data are shown in Fig. 4. The data that are below $K_{Jc\_limit}$ are plotted in black (open and full circles). Only three data points, the red ones, were above $K_{Jc\_limit}$ and were replaced by the value of $K_{Jc\_limit}$. The 1% and 99% failure bounds were calculated according to Eq. (9) where 0.xx represents the cumulative probability level.

\[ K_{Jc,0.xx} = 20 + \left[ \ln \left( \frac{1}{1 - 0.xx} \right) \right] \left[ 11.77 \exp \left( 0.019 \left( T - T_0 \right) \right) \right] \]  (9)

Fig. 3. Load-displacement curves of fracture tests at (a) -120~ -105°C, (b) -105~ -90 °C, (c) -90~ -80 °C, and (d) -80~ -50 °C.

Fig. 4. Adjusted fracture toughness to 1T versus temperature and the master curve.

In Fig. 4, the yellow areas represents the temperature domain where the data must be considered to determine $T_0$. Indeed, only fracture data that lie within the range $T_0 \pm 50 ^\circ C$ can be used in Eq. (7). Data exclusion and $T_0$ recalculation processes can take place for several times before the valid temperature range stabilizes. Consequently, a number of data points may fall out the range $T_0 \pm 50 ^\circ C$. As mentioned in the Introduction section, there are situations where number of available specimens is limited. This is typically the case with irradiated material. Thus, it would be an interesting option not to discard data points obtained at temperature lower than $T_0 - 50 ^\circ C$. However, one has to demonstrate first that those data points can be included reliably into the determination of $T_0$. Looking at
Fig. 4 and in particular at the low temperature data below $T_0 - 50 \, ^\circ \text{C}$ suggests that these data (open circles) are consistent with the Master-Curve. It is of course possible to consider only these data and perform a $T_0$ determination using the same procedure as for the valid data. This was actually done and $T_0$ evaluated with the six specimens out of the temperature windows and it was found that $T_0 = -48.7 \, ^\circ \text{C}$, which is fully consistent with the reference temperature at -50.4°C. While such a determination does not comply with the requirement of the standard, it suggest that that extending the temperature windows of the valid data should be possible. In other words, we want to assess the opportunity to determine $T_0$ with 10 data points taking into consideration some points obtained below $T_0 - 50 \, ^\circ \text{C}$.

To better assess this possibility, random combinations of 10 data points among the 22 available data were considered to determine $T_0$. A small subroutine program was written to select randomly 10 data points from the 22 of our experimental data set and to calculate $T_0$. In addition, the number of points within and outside of the temperature windows, namely $T_0 \pm 50\, ^\circ \text{C}$ were determined. Again, the choice of 10 data points was motivated by the fact that 10 miniaturized CT specimens can be extracted from one full Charpy specimen. In Fig. 5, the calculated $T_0$ from randomly drawn sets of 10 data is plotted against the number of data that lie in the valid temperature range. 1000 different sets of 10 data were considered in Fig. 5. The $T_0$ median value is indicated in red as well as the reference temperature $T_0 = -50.4 \, ^\circ \text{C}$ with the uncertainty range of $\pm 8.7\, ^\circ \text{C}$. It is observed that most calculated $T_0$ fall within the expected scatter band but some were above yielding a conservative value of $T_0$. It has to be noted that the number of calculated $T_0$ greater than $-41.7 \, ^\circ \text{C}$ ($=-50.4 + 8.7 \, ^\circ \text{C}$) is relatively small as it represents only 3.5% of all data points.

![Fig. 5. $T_0$ calculations based on randomly drawn set of 10 data points versus number of data out the valid T-range ($T_0 \pm 50\, ^\circ \text{C}$).](image)

It is worth reminding here that in the best case, it is theoretically possible to determine $T_0$ with only six valid data provided that the data are in the range $-14 \, ^\circ \text{C} < (T-T_0) < 50 \, ^\circ \text{C}$. However, when dealing with 0.18T C(T) specimen, we have to focus the testing in the lower temperature range, typically in the $-50 \, ^\circ \text{C} < (T-T_0) < -36 \, ^\circ \text{C}$, where at least 8 valid tests are necessary for a valid $T_0$ determination. The reason for testing in the lower temperature part is to avoid having data above the $K_{\text{limit}}$ that is quickly reached when testing at and above $T_0$ (see Fig. 4). Considering again that only 10 specimens can be cut out of a Charpy specimen and that it is likely that some of them will not meet other requirements of the ASTM-1921 standard (like the straightness or initial length the pre-crack for instance), only one Charpy specimens might not be enough to get 8 valid data points. Thus, considering a number of fracture data below $T_{\text{fr}}50 \, ^\circ \text{C}$ to be included in $T_0$ determination remains an interesting option. As mentioned above, including these low temperature points may result in slightly conservative $T_0$ estimates. This was quantified by randomly selecting datasets containing 8 to 21 data and calculating the corresponding $T_0$. In Fig. 6 and Table 2, we report the percentage of $T_0$
values that fall in three different temperature ranges, namely $|\Delta T_0| < 8.7 \, ^\circ C$, $8.7 \, ^\circ C < |\Delta T_0| < 15 \, ^\circ C$, and $|\Delta T_0| > 15 \, ^\circ C$. Clearly, most of the data fall within the uncertainty range such that $|\Delta T_0| < 8.7 \, ^\circ C$, and the percentage of data in $|\Delta T_0| < 8.7 \, ^\circ C$ increases with the number of data considered in a dataset. Only less than 1% of $T_0$ are such $|\Delta T_0| > 15 \, ^\circ C$ if more than 9 data are used. Therefore, including low temperature data in the analysis seems appropriate for all cases where limited amounts of materials or specimens exist.

![Image](image.png)

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**Table 2.** Statistics of variations of $T_0$ with various number of data considered in each data set.

<table>
<thead>
<tr>
<th>Number of data considered</th>
<th>8</th>
<th>9</th>
<th>10</th>
<th>11</th>
<th>12</th>
<th>13</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\Delta T_0</td>
<td>&lt; 8.7$</td>
<td>86.6%</td>
<td>88.9%</td>
<td>91.0%</td>
<td>93.0%</td>
</tr>
<tr>
<td>$8.7 &lt;</td>
<td>\Delta T_0</td>
<td>&lt; 15$</td>
<td>11.8%</td>
<td>10.2%</td>
<td>8.4%</td>
<td>6.7%</td>
</tr>
<tr>
<td>$</td>
<td>\Delta T_0</td>
<td>&gt; 15$</td>
<td>1.6%</td>
<td>0.8%</td>
<td>0.6%</td>
<td>0.3%</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Number of data considered</th>
<th>16</th>
<th>17</th>
<th>18</th>
<th>19</th>
<th>20</th>
<th>21</th>
</tr>
</thead>
<tbody>
<tr>
<td>$</td>
<td>\Delta T_0</td>
<td>&lt; 8.7$</td>
<td>99.2%</td>
<td>99.6%</td>
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<td>100%</td>
</tr>
<tr>
<td>$8.7 &lt;</td>
<td>\Delta T_0</td>
<td>&lt; 15$</td>
<td>0.8%</td>
<td>0.4%</td>
<td>0.1%</td>
<td>0</td>
</tr>
<tr>
<td>$</td>
<td>\Delta T_0</td>
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<td>0</td>
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</tbody>
</table>

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**Fig. 6.** Percentage of deviation from the reference $T_0$ at -50.4 °C with the number of data considered in each data set.

### 4. Conclusions

In the frame of the European project FRACTESUS, fracture toughness in the ductile to brittle transition of the JRQ ferritic steel at various temperatures was measured with sub-sized 0.18T CT specimens. The fracture behavior was found consistent with the Master-Curve approach. The reference temperature $T_0$ determined with the 0.18T CT specimens (-50.4°C ± 8.7°C) is in good agreement with $T_0$ previously obtained with larger 0.5T CT specimens on the same material (-42.7 ± 7°C). On the one hand, these results show that a reliable $T_0$ assessment, fully in line with the requirement of the ASTM-E1921 standard, can be realized with sub-sized 0.18T CT specimens. On the other hand, we demonstrated the possibility to relax a bit the restrictions of the standard by considering fracture data obtained at lower testing temperatures than those recommended. Indeed, including data obtained at $T_0$ - 50 °C, namely 20 °C lower than recommended, does not seem to affect $T_0$ from a statistically point of view.
Acknowledgements

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