The Fracture Toughness Evaluation of Mini-CT specimen Test Results of the Irradiated Midland RPV Beltline Material

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The Fracture Toughness Evaluation of Mini-CT specimen Test Results of the Irradiated Midland RPV Beltline Material

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EXECUTIVE SUMMARY

Small specimens are playing the key role in evaluating properties of irradiated materials. The use of small specimens provides several advantages. Typically, only a small volume of material can be irradiated in a reactor at desirable conditions in terms of temperature, neutron flux, and neutron dose. A small volume of irradiated material may also allow for easier handling of specimens. Smaller specimens reduce the amount of radioactive material, minimizing personnel exposures and waste disposal. However, use of small specimens imposes a variety of challenges as well. These challenges are associated with proper accounting for size effects and transferability of small specimen data to the real structures of interest.

Any fracture toughness specimen that can be made out of the broken halves of standard Charpy specimens may have exceptional utility for evaluation of reactor pressure vessels (RPVs) since it would allow one to determine and monitor directly actual fracture toughness instead of requiring indirect predictions using correlations established with impact data. The Charpy V-notch specimen is the most commonly used specimen geometry in surveillance programs.

Mini-CT specimens are becoming a highly popular geometry for use in reactor pressure vessel (RPV) community for direct measurement of fracture toughness in the transition region using the Master Curve methodology. In the present study, Mini-CT specimens were machined from previously tested Charpy specimens of the Midland low upper-shelf Linde 80 weld in both, unirradiated and irradiated conditions. The irradiated specimens have been characterized as part of a joint ORNL-EPRI-CRIEPI collaborative program. The Linde 80 weld was selected because it has been extensively characterized in the irradiated condition by conventional specimens, and because of the need to validate application of Mini-CT specimens for low upper-shelf materials - a more likely case for some irradiated materials of older generation RPVs. It is shown that the fracture toughness reference temperatures, $T_o$, derived from these Mini-CT specimens are in good agreement with $T_o$ values previously recorded for this material in the unirradiated and irradiated conditions. However, this study indicates that in real practice it is highly advisable to use a much larger number of specimens than the minimum number prescribed in ASTM E1921.
1. INTRODUCTION

Any fracture toughness specimen that can be made out of the broken halves of standard Charpy specimens may have exceptional utility for evaluation of reactor pressure vessels since it would allow one to determine and monitor directly the actual fracture toughness instead of requiring indirect predictions using correlations established with impact data. The Charpy V-notch specimen is the most commonly used specimen geometry in surveillance programs. The advantage of the Mini-CT specimen technique is that it has the same cross-section (10x10 mm) as a standard Charpy specimen such that it can be made from the simple slice of a broken half of a Charpy specimen. On the other side, the thickness of this Mini-CT (slightly below 5 mm) is just large enough to fit in a very narrow validity limit window allowed by ASTM E1921. Up to now, most of the work on validation of this type of specimen has been performed on base metals and only recently has limited work been performed on weld metals in the unirradiated condition (1-9). In this study, Mini-CT specimens were used to perform fracture toughness characterization of a low upper-shelf Linde 80 weld, designated WF-70. This weld was utilized in the Midland Reactor Unit 1 beltline weld and has been previously well characterized at the Oak Ridge National Laboratory (ORNL) with various conventional fracture toughness specimens (10-14). The unirradiated broken Charpy specimens were machined into Mini-CT specimens at ORNL and preliminary results have been previously reported (9). The irradiated broken Charpy specimens that were tested on lower part of transition curve and some broken halves of precracked Charpy specimens were retrieved from storage and machined into Mini-CT specimens as part of a joint ORNL-EPRI-CRIEPI collaborative project. The Mini-CTs were machined and distributed for testing to different laboratories. The details of this joint program can be found in (15). This report describes results of fracture toughness characterization of these specimens at ORNL and is prepared in satisfaction of Milestone M3LW-18OR0402012—“Complete report on the fracture toughness evaluation of mini-compact tension specimen test results of the irradiated Midland reactor pressure vessel beltline material”

2. MATERIAL DESCRIPTION

In the 1990’s, the Heavy Section Steel Irradiation Program at ORNL performed a very wide-ranging characterization program of the beltline and nozzle course welds from Midland Nuclear Power Plant Unit 1 in the unirradiated and irradiated conditions. The Midland Unit 1 had been canceled prior to operation and large pieces of various parts of the beltline and nozzle course welds from the RPV were removed and used for that study. The current study deals with the unirradiated and irradiated beltline weld of this reactor which was a double-V submerged-arc (WF-70) weld made with Heat No. 72105 weld wire and lot 8669 Linde-80 flux.

The goal of that original program was to perform a very comprehensive characterization of chemical composition, Charpy impact toughness, drop weight nil-ductility, tensile, and fracture toughness properties of the beltline and nozzle course welds before and after irradiation in test reactors. For example, a total of 230 Charpy specimens were tested for impact toughness characterization of the beltline weld in the unirradiated condition. Fourteen 0.5T, thirty-five 1T, fourteen 2T, and two 4T compact tension and nineteen precracked Charpy specimens were used to perform transition region fracture toughness characterization of the beltline weld in the unirradiated condition, while twenty-four 1T, sscheventeen 0.5T and twenty-five precracked Charpy specimens were tested in the irradiated condition. Based on the results of such a large number of conventional fracture toughness specimens, the reference fracture toughness temperatures, $T_o$, were determined to be -54°C and 24°C for the unirradiated and irradiated beltline weld, respectively. The irradiation experiment was performed at the University of Michigan Ford reactor at 288°C to 1.0x10^19 n/cm² (E>1MeV). The detailed results of this program can be found in references (10-14). It is important to point out that the main goal of that original program was to investigate the variability of chemical composition and RTNDT in a low upper-shelf weld from an actual reactor vessel. The Master Curve methodology was still in the development stage at that time and was
considered as an alternative method for fracture toughness characterization of RPV materials. Indeed, the first version of ASTM E1921 was issued only a few months before the final report on characterization of the Midland weld (12) was completed. That first version of the standard was quite different from the current E1921 standard and the methods used to analyze Mini-CT data in the present study.

There are three major differences in the way these “old” data from conventional specimens were analyzed in comparison with the current features of E1921 used for treating Mini-CT data. First, the $K_{Jc}$ data were considered plain stress rather than plain strain as now considered in E1921. Typically, conversion from plain stress to plain strain increases the $K_{Jc}$ value by approximately 5% which in turn should result in a decrease of $T_o$ value by few degrees. Second, the multi-temperature concept of $T_o$ determination simply did not exist at that time. Thus, the authors of Ref. (12) grouped specimens of the same size that were tested at the same temperature in several sets and calculated $T_o$ as a single temperature value for these various sets. The grand total values, -54°C for unirradiated condition and 27°C for irradiated condition, then reported were simply average values of these several single test temperature sets. Careful review of the data treatment in Ref. (12) revealed that a good number of specimens were left out from contribution to $T_o$ determination. Most notably, none of the precracked CVN data and 4T C(T) were used in the $T_o$ determinations in Ref. (12). Finally, the limitation on the use of data only within plus/minus 50°C range from $T_o$ was introduced much later in E1921 development and the Ref. (12) analysis did not follow this limitation. Recognizing these dissimilarities prompted the author to re-analyze the old data following the modern procedure that was used in analysis of the current Mini-CT data. As a result of this re-analysis, the updated values of $T_o$ for the Midland beltlene weld are -60°C and 29°C for the unirradiated and irradiated conditions respectively. Moreover, $T_o$ values were determined for each type of specimens separately and reported in Table 1.

**Table 1. Re-analyzed $T_o$ values for Midland Beltline weld in the unirradiated and irradiated conditions.**

<table>
<thead>
<tr>
<th>Specimen Type</th>
<th>Number of Specimens, N/r</th>
<th>$T_o$, °C</th>
<th>$\sigma$, °C</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Unirradiated</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>84/59</td>
<td>-60</td>
<td>4.6</td>
</tr>
<tr>
<td>2T C(T)</td>
<td>14/10</td>
<td>-61</td>
<td>6.0</td>
</tr>
<tr>
<td>1T C(T)</td>
<td>35/26</td>
<td>-56</td>
<td>5.3</td>
</tr>
<tr>
<td>0.5T C(T)</td>
<td>14/8</td>
<td>-65</td>
<td>7.5</td>
</tr>
<tr>
<td>PCVN</td>
<td>19/13</td>
<td>-61</td>
<td>6.4</td>
</tr>
<tr>
<td><strong>Irradiated</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>All</td>
<td>47/39</td>
<td>29</td>
<td>4.9</td>
</tr>
<tr>
<td>1T C(T)</td>
<td>14/11</td>
<td>28</td>
<td>6.7</td>
</tr>
<tr>
<td>0.5T C(T)</td>
<td>17/16</td>
<td>26</td>
<td>6.0</td>
</tr>
<tr>
<td>PCVN</td>
<td>16/14</td>
<td>33</td>
<td>6.3</td>
</tr>
</tbody>
</table>

In Table 1, “N” is the total number of specimens used to determine $T_o$ value and “r” is the number of uncensored $K_{Jc}$ values in a dataset. Last column is the standard deviation, $\sigma$, on the estimate on $T_o$ which incorporates sample size and experimental uncertainties. The Mini-CT data will be compared to these re-analyzed values.

The availability of such an ample data bank of irradiated properties by means of conventional fracture toughness specimens was one of the reasons for selecting this beltline material to perform validation of Mini-CT specimens for fracture toughness characterization of a lower upper-shelf weld material for the joint ORNL-EPRI-CRIEPI program.
3. TEST RESULTS

A slightly modified version of the Mini-CT specimen is being used at ORNL (9). The main modification is related to use of grooves to allow an “outboard” clip gage with sharp razor blades to be placed such that load-line displacement can be directly measured for J-integral calculation rather than front face gage placement; this modification avoids subsequent recalculation to load-line displacement. Moreover, from previous experience in the fracture mechanics laboratory at ORNL, it was determined that razor blades improved reliability and sensitivity as compared to integrated front-face cut-off notches like the one suggested in the CRIEPI-run round robin specimen design (4-7). Another advantage of this set-up is simplicity of handling such a small specimen and clip gage in the hot cell or other remote conditions. All specimens were fatigue precracked to the target $a/W$ value of 0.5.

The testing was performed under carefully controlled conditions in accordance with ASTM E1921 such that the values can be compared to the fracture toughness performance of previously tested large specimens. The analysis of unirradiated Mini-CT data (9) yielded the $T_o$ value of -53°C which is in very good agreement with the $T_o$ value of -60°C derived from a substantial number of larger fracture toughness specimens as discussed in the previous chapter. The irradiated Mini-CT specimens were precracked and tested on the same equipment, following the same procedure as the unirradiated specimens. A total of 15 Mini-CT specimens have been tested in the irradiated condition. All tests were performed at -10°C. Out of 15 specimens, only one specimen did not cleave. This test was stopped after the specimen developed substantial stable crack growth and the final $J$ value was well in excess of $K_{Jc (limit)}$. All other specimens cleaved and all measured $K_{Jc}$ values were within the validity limit of E1921 as per equation 1:

$$K_{Jc (limit)} = \sqrt{\frac{E(W-a_0)\sigma_{ys}}{30(1-v^2)}}$$

(1)

In equation 1, $W$ is the width of the specimen, $a_0$ is the initial crack length, and $v$ is Poisson’s ratio. Also, $E$ is the Young’s modulus determined using the following equation from ASTM E1921-17:

$$E = 204 - \frac{T}{16}, \text{ GPa}$$

(2)

where $\sigma_{ys}$ is the yield strength determined using the following equation from ASTM E1921-17:

$$\sigma_{ys} = \sigma_{ysRT} + \frac{100000}{(491+1.8T)} - 189$$

(3)

where $T$ is the test temperature, °C, and $\sigma_{ysRT}$ is the yield strength at room temperature in the irradiated condition as reported in (12). Test results are summarized in Table 2.

<table>
<thead>
<tr>
<th>Specimen ID</th>
<th>$K_{Jc}$</th>
<th>$K_{Jc (limit)}$</th>
<th>$a_0$</th>
<th>$\Delta a^*$</th>
<th>Note</th>
</tr>
</thead>
<tbody>
<tr>
<td>9AI4-B2</td>
<td>124.15</td>
<td>155.56</td>
<td>3.44</td>
<td>0.33</td>
<td>$a_0&lt;$0.45W</td>
</tr>
<tr>
<td>15AE4-B1</td>
<td>61.58</td>
<td>138.74</td>
<td>4.41</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>9AI5-A1</td>
<td>68.26</td>
<td>144.42</td>
<td>4.17</td>
<td>none</td>
<td>Fails 8.9.1</td>
</tr>
<tr>
<td>15AK3-B1</td>
<td>124.56</td>
<td>142.82</td>
<td>4.18</td>
<td>0.24</td>
<td>$K_{Jc}=a_0$</td>
</tr>
<tr>
<td>15DE2-B1</td>
<td>119.81</td>
<td>144.91</td>
<td>4.14</td>
<td>0.20</td>
<td></td>
</tr>
<tr>
<td>15AK3-A2</td>
<td>59.86</td>
<td>149.67</td>
<td>3.83</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>9AI4-B1</td>
<td>90.30</td>
<td>149.23</td>
<td>3.89</td>
<td>none</td>
<td></td>
</tr>
<tr>
<td>9AI5-A2</td>
<td>119.95</td>
<td>156.55</td>
<td>3.41</td>
<td>none</td>
<td>$a_0&lt;$0.45W</td>
</tr>
</tbody>
</table>
Post-test examination of the fracture surfaces revealed that two specimens, 9AI4-B2 and 9AI5-A2, were precracked to a crack length $a_0 < 0.45W$, which falls below the limit prescribed in section 7.1 of ASTM E1921. Thus, the data from those two specimens cannot be used in the calculation of $T_o$ as per section 10.5 of ASTM E1921-17. For specimen 9AI5-A1, one crack measurement on a side of the specimen differed from the average crack length measurement by more than 0.5 mm, thus violating the qualification of data requirement 8.9.1 in ASTM E1921-17 and was eliminated from $T_o$ calculation.

A few specimens cleaved after some amount of stable crack growth and column “$\Delta a$” in Table 2 lists the longest crack extension among nine measurements for a given specimen. Out of these few, three specimens, 15AK3-B1, 15AE3-B1, and 15DE2-B2, exhibited stable crack growth extension prior to cleavage in excess of $0.05(W-a_0)$, which violates the $K_{Jc,\Delta a}$ limit as per section 8.9.2 in ASTM E1921-17. Figure 1 illustrates the way $\Delta a$ was measured and reported for specimen 15DE2-B2.

Figure 1. Example of measuring initial, $a_0$, and the largest crack extension, $\Delta a$, for specimen 15DE2-B2.
It is noted that E1921 prescribes in section 8.8.1 to measure stable crack growth in the same fashion as for the initial \( a_0 \). Yet, that value of stable crack growth is not used anywhere in the standard procedure. Instead, the value of stable crack growth comes to play only in section 8.9.2 which deals with qualification of the data and only the longest crack extension among the nine measurements is required to be considered. For specimen 15DE2-B2, the longest \( \Delta a \) of the nine measurements is 0.27 mm and it exceeds the 0.05(\( W - a_0 \)) limit set by section 8.9.2. It is worth to point out that overall crack extension for this specimen as defined in section 8.8.1 of E1921 is only 0.12 mm. One more specimen, 15DE2-B1, barely met the \( K_{\Delta c, a} \) requirement.

Out of all 15 specimens, only one specimen exhibited pop-in just past the linear part of the load-displacement trace. The pop-in value of \( K_{\Delta c} \) is reported value in Table 1.

Figure 2 illustrates 1-T adjusted fracture toughness data of Midland beltline weld WF-70 from the present study in the irradiated condition and data in the unirradiated condition from (9) as derived using Mini-CT specimens. These results (red color) are superimposed on the large fracture toughness database for the Midland WF-70 weld previously produced at ORNL using a large number of conventional specimens in both the unirradiated and irradiated conditions (12).
4. CENSORING AND $T_0$ DETERMINATION

To summarize the test results in the previous sections, out of 15 specimens tested, three specimens produced invalid data, four specimens violated some requirements and needed to be censored for $T_0$ determination, and eight specimens cleaved with valid, uncensored $K_{lc}$ values – thus satisfying the requirement for size of the data set as per 10.3 in ASTM E1921-17. The next step was to perform censoring.

For specimen 15AK3-B2, the test was terminated prior to the cleavage with a final $K_J$ value well above $K_{ec,lim}$ for this specimen. The ASTM E1921-17 prescribes to use this specimen in $T_0$ determination by censoring it a value of $K_{ec,lim}$ as in Table 2.

Another censoring is prescribed for three specimens that violated the $K_{Jc,lim}$ limit. Section 10.2.1 prescribes use of the highest uncensored $K_{Jc}$ value in this data set as a censored value for this violation. In this data set that value is 114.79 MPa√m, see Table 1. Now all uncensored and censored data need to be converted to 1T equivalence and a $T_0$ value can be determined. Following these steps yields a $T_0$ value of 12°C.

However, section 10.2.1 gives permission for use a $K_{Ic}$ value, if available, as censoring value for specimens that violated $K_{Jc,lim}$ limit as well: “The $K_{Ic}$ value defined in E1820 can also be used for $K_{Jc,lim}$ if $J_{lc}$ is known for the test material”. In the present study, all tests were performed following the E1921 procedure and $J_{lc}$ was not determined. However previous ORNL data (12) reported a $J_{lc}$ value for the irradiated condition at 150°C. It was derived by testing 1T C(T) specimens and $K_{Jc} = 163$ MPa√m. This value exceeds the $K_{ec,lim}$ value and as per section 8.9.2 and 10.2.1 of ASTM E1921-17 standard, the $K_{ec,lim}$ value shall be used for censoring purposes (the lower of the two limits). By following this option, $T_0$ is determined to be 2°C. The difference between $T_0$ values derived using two ASTM E1921 censoring limits is somewhat high, 10°C. Still E1921 does not contain clear language which censoring to use.

5. DISCUSSION

As it has been pointed out in the preliminary study with the unirradiated weld specimen (9), a low upper-shelf material may present additional challenges when using these small Mini-CT specimens. The present study with irradiated material confirmed this observation. Indeed, out of the available 15 specimens, three specimens did not satisfy qualification requirements of E1921. Out of the remaining 12 specimens, four specimens violated various $K_{lc}$ capacity limits. All of these four violations are related to stable crack growth in some manner. It is also pointed out that one more specimen almost exceeded the limiting amount of stable crack growth prior to cleavage. As a reminder, this was not a blind test case. The key reason for selecting this material was that a large data base already existed. Yet, the 15-specimen dataset barely met requirements to produce an ASTM E1921 valid $T_0$ value.

Overall, the $T_0$ values derived from a relatively small number of Mini-CT specimens in this study and (9) are in remarkable agreement with the updated $T_0$ values from previously reported fracture toughness data generated using a much larger number of bigger, conventional fracture toughness specimens. Visual comparison of the present Mini-CT and previous conventional specimens data in Figure 3 show very good overall agreement between Mini-CT and conventional specimens data. In this Figure, the previous ORNL data are plotted after converting from plane stress to plane strain $K_J$ values according current procedure in ASTM E1921. The master curve and 5% and 95% tolerance bounds are based on the current study Mini-CT data. It is shown that the master curves derived from the Mini-CT specimens envelope very well scatter of large number of various conventional specimens in wide temperature range.
The irradiated data require more detailed consideration. The previously reported $T_o$ value from conventional large specimens is 27°C (12). The revised $T_o$ value from the same data following the current Master curve methodology is almost the same, 26°C. As it was mentioned above, the $T_o$ from the present study of irradiated Mini-CT specimens is either 12°C or 2°C depending on the censoring procedure. While section 10.2.1 does not prescribe the preferred scheme of censoring in the case of violating a $K_{IC,da}$ limit (the highest uncensored $K_{IC}$ or $K_{IC}$), it is believed by the author that the language of the standard is aimed to select the lowest available value for censoring purpose when several limits are violated. Once again, based on the testing of the irradiated Mini-CT specimens in this study and the unirradiated Mini-CT in (9), it appears that the optimal temperature window for testing of these small specimens is 25 to 30°C below the expected $T_o$ value.

6. SUMMARY

The ability of a small number of Mini-CT specimens to determine the fracture toughness reference temperature, $T_o$, of a low upper-shelf material has been examined on the unirradiated and irradiated Linde 80 WF-70 weld from the Midland RPV Unit 1. These Mini-CT specimens were machined from broken halves of previously tested Charpy specimens as part of the Midland beltline weld characterization. The $T_o$ values derived from a relatively small number of Mini-CT specimens in this study are in very good agreement with the $T_o$ values previously reported for a much larger number of conventional fracture toughness specimens. At the same time, this study indicates that in real practice it is highly advisable to use a much larger number of specimens than the minimum amount prescribed in ASTM E1921. The
selection of censoring criteria in the case of violating $K_{JCda}$ limit in ASTM E1921 needs better clarification in the standard.

7. REFERENCES


