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FRACTURE TOUGHNESS EVALUATION OF A LOW UPPER-SHELF WELD METAL FROM THE MIDLAND REACTOR USING THE MASTER CURVE*

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ABSTRACT

The primary objective of the Heavy-Section Steel Irradiation (HSSI) Program Tenth Irradiation Series was to develop a fracture mechanics evaluation of weld metal WF-70, which was taken from the beltline and nozzle course girth weld joints of the Midland Reactor vessel. This material became available when Consumers Power Company of Midland, Michigan, decided to abort plans to operate their nuclear power plant. WF-70 is classified as a low upper-shelf steel primarily due to the Linde 80 flux that was used in the submerged-arc welding process. The master curve concept is introduced to model the transition range fracture toughness when the toughness is quantified in terms of $K_{Jc}$ values. $K_{Jc}$ is an elastic-plastic stress intensity factor calculated by conversion from $J_{eq}$; i.e., J-integral at onset of cleavage instability.

INTRODUCTION

Because the design life for many currently operating nuclear reactors is beginning to run out, there is a need to improve on the precision and accuracy of transition temperature definition for irradiated reactor vessel steels. Important decisions are soon going to have to be made about the integrity of nuclear reactor pressure vessels. Presently the technology relies on correlations between fracture mechanics type data and data obtained from test methods developed decades ago. Such correlations often lack accuracy. Highly conservative margins of safety must be applied by necessity because of the uncertainty associated with these correlations.

The master curve concept that is to be presented here is a relatively new data analysis methodology that has the advantage of using only fracture mechanics data to establish the fracture mechanics-based ductile-to-brittle transition range for materials [1]. The methodology has been under development for the past 15 years and is now sufficiently mature to apply to certain special cases of reactor vessel evaluations. This paper will compare the use of the current American Society of Mechanical Engineers (ASME) Boiler and Pressure Vessel Code practice [2] and the master curve methodology as applied to weld metal taken from a nuclear reactor vessel.
A decision by Consumers Power Company, Midland, Michigan, to abandon plans to operate a newly constructed nuclear power plant provided an opportunity to acquire, for research evaluations, data on a material of generally high interest to the nuclear industry [3]. In particular, the weld metal used around the vessel beltline and nozzle course girth was WF-70, a low upper-shelf steel that has been used in several currently operating nuclear reactors. WF-70 is a Babcock and Wilcox code for the specific weld wire (Ht 72105) and flux (Linde 80, Lot 8669). Although this combination of weld wire and flux has produced a weld that is ideal for nondestructive flaw inspection, it is also known to create a weld of low Charpy V-notch (CVN) upper-shelf toughness [4].

The master curve methodology has implicit components that make it possible to directly apply fracture mechanics-based data on a plant-specific basis [5]. Elastic-plastic computational techniques make it possible to accurately quantify fracture toughness when using small test specimens. Adjustments can be made to transform data from small specimens into their equivalent value for large specimens. Control is exercised on small specimen data in the form of limitations set on allowable constraint loss and allowable test temperatures [1]. Finally, the reason for extreme scatter of data that is a characteristic of testing within the transition range is explained. It has been demonstrated that the data scatter can be modeled using statistical methods. The following three-parameter Weibull statistical model is used:

\[ P_f = 1 - \exp \left( -\frac{\left(\frac{K_c - K_{min}}{K_o - K_{min}}\right)^b}{b} \right) \]  

\( P_f \) represents the probability that an arbitrarily selected specimen taken from a large population of specimens of a given material will fail at or before reaching crack drive level, \( K_c \). \( K_c \) is an elastic-plastic stress intensity factor obtained by conversion of J-integral at the point of cleavage crack instability. The fitting parameters that represent the data population are the Weibull slope, \( b \), the lowest possible fracture toughness value of the data population, \( K_{min} \), and the scale parameter, \( K_o \). Wallin [6] has performed a sensitivity study that had shown that when \( K_{min} \) is used as a deterministic parameter in the model; namely, fixed at 20 MPa√m, most data distributions will tend to display a Weibull slope either at or near to \( b = 4 \). Hence, two deterministic parameters of the model were created and the result is that only scale parameter, \( K_o \) needs to be established from experimental data. Six specimens are usually sufficient.

The following equation expresses the trend of median fracture toughness for 1T data distributions as a function of test temperature:

\[ K_{jc} = 30 + 70 \exp \left[ 0.019(T - T_o) \right], \text{ MPa}√m \]  

(2)
where $T$ is the test temperature and $T_o$ is the reference temperature set at the toughness level of 100 MPa$\sqrt{m}$. The curve of Eq. (2) is a universal curve, covering all ferritic structural steels. Hence, the establishment of $T_o$ completely defines the fracture toughness throughout the transition range.

In this paper, a 2% tolerance bound based on the known Weibull slope of 4 will be used. The following equation applies:

$$K_{Jc(0.02)} = 24.3 + 30 \exp \left[0.019(T - T_o)\right], \text{ MPa}\sqrt{m}$$  (3)

Equation (3) has at times been observed to closely align with the ASME lower-bound $K_{k}$ curve provided that $R_{T_{NDT}}$ is only established from the drop-weight NDT temperature. However, there is a basic universal curve shape disagreement here that prohibits close agreement on both the lower shelf and upper-shelf fracture toughness. Equation (3) is the most conservative of the two. An example is shown in Fig. 1.

MATERIALS AND FRACTURE MECHANICS SPECIMENS

Even though the WF-70 weld metal in the beltline and nozzle course regions of the Midland reactor vessel were supposed to be the same material, they were considered to be different materials in this project because of a difference in copper content (Table 1). A significant part of the overall objective here was to study irradiation damage effects and copper is known to be the most important element for irradiation damage effects. On the other hand, copper is not known to influence the unirradiated fracture toughness properties. Other material properties are given in Tables 2 and 3.

All fracture mechanics specimens were the compact [C(T)] type, ranging in size from 1/2T to 4T for the beltline weld and 1/2T to 1T for the nozzle course weld. The specimens exposed in irradiation capsules were all 1/2T or 1T size.

ASME $K_{k}$ CURVE POSITIONING

$R_{T_{NDT}}$ was determined 19 times for the beltline weld, giving 19 individual determinations of the lower-bound $K_{k}$ curve by the ASME procedure for low upper-shelf steels. The two extreme $R_{T_{NDT}}$ values that resulted are $-20$ and $+37^\circ$C; almost a $60^\circ$C spread [7]. Such a spread is not unusual, as had been discovered in other similar CVN surveys. Figure 2 shows two lower-bound $K_{k}$ curves using the extreme $R_{T_{NDT}}$ values and the corresponding fracture mechanics data developed with compact specimens of the beltline weld. Certainly the ASME method of setting the lower bound of fracture mechanics toughness is conservative here, but the unnecessarily large potential penalty from the lack of accuracy is obvious.
Fig. 1. Raw $K_{ic}$ data for weld 73W with 2% tolerance bound on the master curve and the ASME $K_{ic}$ curve.

Fig. 2. Fracture toughness data and range of $K_{ic}$ lower bound.
Table 1. Summary of major radiation elements in Midland vessel welds

<table>
<thead>
<tr>
<th>Weld</th>
<th>Copper</th>
<th>Nickel</th>
<th>Phosphorus</th>
<th>Manganese</th>
<th>Silicon</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beltline</td>
<td>0.256 ± 0.034</td>
<td>0.574 ± 0.023</td>
<td>0.017 ± 0.0019</td>
<td>1.607 ± 0.049</td>
<td>0.622 ± 0.033</td>
</tr>
<tr>
<td>Nozzle</td>
<td>0.37 ± 0.028</td>
<td>0.572 ± 0.017</td>
<td>0.015 ± 0.002</td>
<td>1.590 ± 0.037</td>
<td>0.550 ± 0.048</td>
</tr>
</tbody>
</table>

Table 2. Tensile properties

<table>
<thead>
<tr>
<th>Test temperature (°C)</th>
<th>Yield strength (MPa)</th>
<th>Tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Beltline</td>
<td>Nozzle course</td>
</tr>
<tr>
<td>Room temperature</td>
<td>512</td>
<td>545</td>
</tr>
<tr>
<td>288</td>
<td>469</td>
<td>484</td>
</tr>
<tr>
<td>150</td>
<td>478</td>
<td>485</td>
</tr>
<tr>
<td>−50</td>
<td>569</td>
<td>580</td>
</tr>
<tr>
<td>−100</td>
<td>625</td>
<td>650</td>
</tr>
</tbody>
</table>

Table 3. Drop-weight NDT temperatures

<table>
<thead>
<tr>
<th>Girth location (°)</th>
<th>Beltline (°C)</th>
<th>Nozzle course (°C)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1/4t</td>
<td>3/4t</td>
</tr>
<tr>
<td>0</td>
<td>−60</td>
<td>−50</td>
</tr>
<tr>
<td>90</td>
<td>−60</td>
<td>−50</td>
</tr>
<tr>
<td>180</td>
<td>−60</td>
<td>−45</td>
</tr>
<tr>
<td>270</td>
<td>−45</td>
<td>−55</td>
</tr>
</tbody>
</table>
MASTER CURVE POSITIONING

For the previously mentioned reason, the master curve data analysis method has been applied to the beltline and nozzle course welds independently and the results appear in Figs. 3 and 4. Although the original specimens sizes are referenced by symbols, all the $K_c$ data shown appear after conversion to 1T C(T) equivalence. The master curve is a best-fit median $K_c$ path for 1T specimens as converted to 1T C(T) size equivalence. The 2% tolerance bound underpins the data scatter at about the appropriate location. Note that there is a difference between the beltline and nozzle course fracture toughness, $T_o$, of about 20°C. At 100 MPa/m, the $T_o$ temperatures are -54 and -32°C for the beltline and nozzle course welds, respectively. This difference in fracture toughness could not be detected by the drop-weight NDT test nor by the CVN curve evaluations.

METHODS OF EVALUATING IRRADIATION DAMAGE

Specimens of both weld metals were irradiated to nominally $1.0 \times 10^{19} \text{n/cm}^2 (>1 \text{MeV})$ at 288°C (550°F). Two capsules contained compact, tensile, and CVN specimens. The postirradiation properties are shown in Table 4. The Code of Federal Regulations, Title 10, Part 50 [8], references ASTM E 185 [9] as the method to determine transition temperature shift. It is to be determined from CVN transition curve shift keyed at the 41-J (30-ft-lb) energy level, $\Delta T_{41}$. The average initial $RT_{NDT}$ on the beltline weld was -9°C and adding $\Delta T_{41}$ of 103°C sets the 100-MPa/m ASME lower-bound toughness level at 122°C. Master curve analysis of irradiated specimens of the beltline weld puts $T_o$ at 27°C and Eq. (3) puts the 2% tolerance bound for 100 MPa/m at 76°C, a calculated 46°C penalty from the use of current ASME practices. The same type of determination on the nozzle course weld gave 117°C by ASME practice and 111°C by the master curve 2% tolerance bound. Again, it should be pointed out that the ASME initial $RT_{NDT}$ temperatures have about a 60°C scatter band that could push the ASME result up to 30°C above or 30°C below these reported postirradiation temperatures.

<table>
<thead>
<tr>
<th>Material</th>
<th>Condition</th>
<th>Average CVN $T_{41J}$ (°C)</th>
<th>Average $T_o$ (°C)</th>
<th>Room temperature yield strength (MPa)</th>
<th>Room temperature ultimate tensile strength (MPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Beltline</td>
<td>Unirradiated</td>
<td>-9</td>
<td>-54</td>
<td>512</td>
<td>613</td>
</tr>
<tr>
<td></td>
<td>Irradiated (1 x $10^{19}$ n/cm$^2$ at 288°C)</td>
<td>94</td>
<td>27.4</td>
<td>646</td>
<td>747</td>
</tr>
<tr>
<td>Nozzle course</td>
<td>Unirradiated</td>
<td>-1</td>
<td>-32</td>
<td>545</td>
<td>654</td>
</tr>
<tr>
<td></td>
<td>Irradiated (1 x $10^{19}$ n/cm$^2$ at 288°C)</td>
<td>89</td>
<td>62</td>
<td>701</td>
<td>791</td>
</tr>
</tbody>
</table>

Table 4. Before-and-after irradiation properties
Fig. 3. Master curve fit to Midland beltline WF-70 weld metal data. All data converted to 1T equivalence.

Fig. 4. Master curve fit to Midland nozzle course WF-70 weld metal data. All data converted to 1T equivalence.
CONCLUSIONS

The master curve methodology is a new approach to determine fracture toughness in the transition range. The method uses only fracture mechanics data. Where the appropriate material is available, methods of toughness characterization used in the ASME Code can be improved. Specimens of sizes compatible with surveillance capsule space can be used to develop usable fracture mechanics type data, and direct plant-specific fracture mechanics analyses can be developed after each exposure cycle, eliminating the need for inferring transition temperature shift from alternative test methods.

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