Material Property Determination of Aged Cast Austenitic Stainless Steel Components for LBB Application

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ABSTRACT: The Leak-before-break (LBB) concept is widely used for integrity evaluation of nuclear piping systems and associated components. In order to perform LBB analyses for cast austenitic stainless steels, a change in material properties should be considered because of thermal embrittlement at operating temperatures. In this paper, a computer program was developed for material property determination of aged cast austenitic stainless steels which consists of two major sections: the main section for the database and the other section for the material property prediction. Several basic assessments and LBB analyses were also performed to verify the usefulness and the applicability of this program.

1. INTRODUCTION

Cast austenitic stainless steels (CASS), composed of austenite and ferrite phases, are used for primary pressure boundary components such as primary coolant pipe, pump casings, pressurizer spray head and so on in PWRs. However, the CASS which contains about 15% of ferrite phases has been known to experience a thermal embrittlement when exposed to reactor operating temperatures, 280–320 °C, over a long period. Thermal embrittlement of CASS causes an increase in hardness, yield strength and tensile strength while it decreases the ductility, impact energy and fracture toughness of the materials. In general, the thermal embrittlement of CASS is due to precipitation of a Cr-rich \( \alpha' \) phase by spinodal decomposition, generation of a Ni- and Si-rich G phase and a carbide precipitation at ferrite/austenite phase boundaries. The precipitation of Cr-rich \( \alpha' \) phase in ferrite by spinodal decomposition has been reported to be the primary strengthening mechanism of thermal embrittlement[1, 2], so it should be considered. The purpose of this paper is to introduce a computer program named KOTEP, which is used to estimate the change in material properties caused by thermal embrittlement and provide results of case studies including LBB analyses.

2. ESTIMATION OF THERMAL EMBRITTLEMENT

An estimation method for CASS has been developed at ANL[2] which consists of four parts; Ferrite content estimation, Charpy impact energy estimation, J-R curve estimation and Tensile property estimation. A brief description of these four parts for SA351 CF8M is summarized in the following sub-sections.
2.1 FERRITE CONTENT ESTIMATION
When the chemical compositions of CASS are known, ferrite content(δc) can be calculated from either Eq. (1) or the Schaefer diagram[3]. Conservatively, the higher value is selected as the final ferrite content.

\[ Cr_{eq} = Cr + 1.21Mo + 0.48Si - 4.99 \]

\[ Ni_{eq} = Ni + 0.11Mn - 0.0086Mn^2 + 18.4N + 24.5C + 2.77 \]

\[ \delta_c = 100.3(Cr_{eq} / Ni_{eq})^2 - 179.72(Cr_{eq} / Ni_{eq})^2 + 74.22 \]  
(1)

2.2 CHARPY IMPACT ENERGY ESTIMATION
When the chemical compositions of CASS are known, room temperature Charpy impact energy can be calculated from Eq. (2) − (5).

\[ \phi = \delta_c (Ni + Si + Mn)^2 (C + 0.4N) / 5 \]  
(2)

\[ \log_{10} Cvsat = 1.1 + 2.12 \exp(-0.041\phi) \]

\[ \log_{10} Cvsat = 1.1 + 2.64 \exp(-0.064\phi) \]  
(3)

\[ \log_{10} Cvsat = 7.28 - 0.011\delta_c - 0.185Cr - 0.369Mo - 0.451Si - 0.007Ni - 4.71(C + 0.4N) \]

\[ \log_{10} Cv = \log_{10} Cvsat + \beta(1 - \tanh((P - \theta) / \alpha)) \]  
(4)

2.3 J-R CURVE ESTIMATION
The J-R curve can be estimated by inserting the calculated Cvsat or Cv into Eq. (6), (7). The values of constants a, b, c and d in these equations are determined according to material types and test temperatures.

\[ J_d = a(Cvsat)^4 (\Delta a)^n \]  
(6)

\[ n = c + d(\log_{10} Cvsat) \]  
(7)

2.4 TENSILE PROPERTY ESTIMATION
2.4.1 Flow Stress
Flow stress can be estimated from Eq. (8), (9) using the ratio(Rf) of the tensile flow stress of aged and unaged CASS and a normalized aging parameter(P). The values of a and b correlated to P are also determined according to material types and test temperatures[4].

\[ \sigma_{faged} = \sigma_{faged} \times R_f \]  
(8)

\[ R_f = a + bP \]  
(9)

2.4.2 Ramberg-Osgood Parameters
The σ - ε curve can be estimated by the Ramberg-Osgood relationship, which is represented in Eq. (10). In this equation, \( a_1 \) values are varied with the estimated flow stresses and \( n_1 \) values are varied with the operating temperatures[4].
\[
\frac{E_e - \sigma}{\sigma_f} = \alpha \left( \frac{\sigma}{\sigma_f} \right)^n
\] (10)

3. DEVELOPMENT OF THERMAL EMBRITTLEMENT PREDICTION PROGRAM

In order to predict the thermal embrittlement, a computer program named KOTEP (KOPEC Thermal Embrittlement Prediction) was developed using the Visual Basic Ver. 5.0. This program consists of two major sections; one section is the database and the other section is the program to predict the material properties, which are adopted the method to predict thermal embrittlement effects. Fig. 1 shows the initial window of the KOTEP.

3.1 DATABASE SECTION

The database section contains several material properties such as chemical compositions (Cr, Mo, Si, Ni, Mn, C, N), experimental and predicted charpy impact energies, experimental and predicted ferrite contents, tensile strength and yield strength. Users can add a new data or edit and delete the previous data saved in the database window of the KOTEP.

![Fig. 1 Initial Window](image)

![Fig. 2 Input Property Window](image)

3.2 PREDICTION SECTION

Fig. 2 shows a sample of the input window. To predict material properties of CASS, changed by thermal embrittlement, users select a specific material type (CF3, CF8, CF8M) and input chemical composition, charpy impact energy, yield strength and tensile strength of selected material, and then through the above mentioned equations, ferrite content can be predicted. Fig. 3 shows a sample of the "Fracture behavior prediction" window. Users can obtain the saturation charpy impact energy and minimum J-R curve for a specific CASS and also obtain the charpy impact energy and J-R curve according to operating temperature and time using this window. The calculated results can be plotted (Fig. 4) and saved in data file form. Fig. 5 shows a sample of the "Tensile behavior prediction" window. When users know the specific yield strength and tensile strength of unaged material and operating temperature and time, the flow stress of aged material and the Ramberg-Osgood parameters with strain range can be calculated. These calculated results and \(\sigma - e\) curve for a specific stainless steel can be plotted (Fig. 6) and saved in data file form.
4. CASE STUDIES AND DISCUSSION

To ensure the validity of the KOTEP program, the basic assessments to predict $\sigma - \varepsilon$ curves and J-R curves and the prototypical LBB analyses using the experimental and predicted material properties were carried out for SA351 CF8M materials.

4.1 BASIC ASSESSMENTS

Experimental and estimated $\sigma - \varepsilon$ curves at operating temperature are shown in Fig. 7. The estimated curves are similar to the experimental ones, and the estimated $\sigma - \varepsilon$ curves increase as the strain range increases. Fig. 8 shows the estimated room temperature $\sigma - \varepsilon$ curves of older domestic nuclear power plant piping materials[5], and these curves were compared to upper bound and lower bound $\sigma - \varepsilon$ curves of foreign materials[4, 6] since the full $\sigma - \varepsilon$ curves and tensile strength of domestic materials do not exist. The results indicate that the estimated $\sigma - \varepsilon$ curves of domestic materials show similar behavior to foreign data.
but the changing behavior of $\sigma - \varepsilon$ curves with strain range appear to be slightly different. The J-R curves at operating temperature are shown in Fig. 9, where the estimated curves are lower than the experimental curves[2] due to conservatism used in the estimated equations. Hereafter, if more experimental data are obtained, additional related work will be needed. Fig. 10 shows the estimated J-R curve of domestic nuclear power plant piping materials[5], and these curves were compared to upper bound and lower bound estimation J-R curves of foreign materials since the experimental curves of older domestic materials do not exist. The results indicate that the estimated J-R curves of domestic materials show a similar behavior to the previous foreign data.

Fig. 7 Basic Assessments Results for $\sigma - \varepsilon$ Curves (1)  
Fig. 8 Basic Assessments Results for $\sigma - \varepsilon$ Curves (2)

Fig. 9 Basic Assessments Result for J-R Curves (1)  
Fig. 10 Basic Assessments Results for J-R Curves (2)

4.2 LBB ANALYSES

4.2.1 Evaluation Conditions

Basic evaluation conditions used in LBB analyses can be found from a previous study[7]. For example, location 1 shown in Fig. 11 was selected as the most critical region, and piping geometries and both normal and faulted loading conditions of the region are summarized in Table 1.
Fig. 11 Schematic Diagram of RCS

Table 1: Geometry and Loading Condition in Location I[7]

<table>
<thead>
<tr>
<th>Outside Diameter (in.)</th>
<th>Minimum Thickness (in.)</th>
<th>Normal Condition</th>
<th>Faulted Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Axial Load (kips)</td>
<td>Bending Moment (in-kips)</td>
</tr>
<tr>
<td>34.40</td>
<td>2.595</td>
<td>1498</td>
<td>27344</td>
</tr>
</tbody>
</table>

4.2.2 Material Properties

Material properties of SA351 CF8M used in pipe of the evaluation region were determined from experimental[4, 6] and estimated data. Fig. 12 and Fig. 13 show the $\sigma - \varepsilon$ curves and J-R curves of aged CF8M specimens respectively. The median $\sigma - \varepsilon$ curve in Fig. 12 was selected for critical leakage size determination, and the lower bound $\sigma - \varepsilon$ curve and J-R curve were used for the piping integrity evaluation. The selected $\sigma - \varepsilon$ curve was fitted from yield strength to tensile strength in order to determine the Ramberg-Osgood Parameters. The chemical compositions and the material properties of CF8M used in LBB analyses are summarized in Table 2 and Table 3.

Fig. 12 $\sigma - \varepsilon$ Curves used in LBB Analyses

Fig. 13 J-R Curves used in LBB Analyses
Table 2. Chemical Composition [wt%]

<table>
<thead>
<tr>
<th>Ident.</th>
<th>Cr</th>
<th>Mo</th>
<th>Si</th>
<th>Ni</th>
<th>Mn</th>
<th>C</th>
<th>N</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>742-41/744-36</td>
<td>19.11</td>
<td>2.51</td>
<td>0.73</td>
<td>9.03</td>
<td>0.54</td>
<td>0.064</td>
<td>0.048</td>
<td>-</td>
</tr>
<tr>
<td>75</td>
<td>20.86</td>
<td>2.58</td>
<td>0.67</td>
<td>9.12</td>
<td>0.53</td>
<td>0.065</td>
<td>0.052</td>
<td>-</td>
</tr>
</tbody>
</table>

Table 3. Material Properties used in LBB Analysis

<table>
<thead>
<tr>
<th>Ident.</th>
<th>σ Y (Mpa)</th>
<th>σ U (MPa)</th>
<th>E (GPa)</th>
<th>ν</th>
<th>α</th>
<th>n</th>
<th>σ - ε Curve</th>
<th>Jfc (kN/m)</th>
<th>C1</th>
<th>C2</th>
<th>J-R Curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>Medium</td>
<td>190.3</td>
<td>483.3</td>
<td>176.08</td>
<td>0.3</td>
<td>3.39</td>
<td>3.79</td>
<td>742-41</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Lower</td>
<td>165.2</td>
<td>424.1</td>
<td>176.08</td>
<td>0.3</td>
<td>11.87</td>
<td>2.81</td>
<td>744-36</td>
<td>139.2</td>
<td>188.27</td>
<td>0.316</td>
<td>75Sat.</td>
</tr>
</tbody>
</table>

4.2.3 Leakage Size Crack
Using PICEP computer code[8] (a useful tool for the leakage size crack calculation), the leakage size crack was determined to be 10 gpm leak which is equivalent to 10 times the plant leak detection capability. Considering uncertainties such as fracture type and crack type during normal load, the most conservative analysis produced a crack length value of 4.5 inch, which was selected for the piping integrity evaluation.

4.2.4 Integrity Evaluation
After determining the crack length from PICEP code, two cases of integrity evaluation were performed using FLET computer code[9]: The first case for crack length(a) combined with [√2 faulted loading] condition and the second case for [2×crack length] combined with faulted loading condition. As a result, safety margins of 1.29 for the first case and 1.15 for the second case were obtained, so LBB concept seemed to be applicable if further realistic work is supported.

4.3 DISCUSSION
Two case studies were carried out to verify a usefulness and an applicability of the KOTEP program. In the case of basic assessments, the predicted σ - e curves showed a similar trend to corresponding experimental curves, while predicted J-R curves represented somewhat underpredicted trend. And in the case of LBB analyses, the prototypical analyses results satisfied the corresponding allowable criteria, so it seemed that the KOTEP program can be utilized appropriately in prediction the material property of aged CASS. However, further study is also required because the results of basic assessments were mainly produced from foreign experimental data due to the lack of domestic experimental data. In conjunction with these, regulatory position has not been established yet in Korea and more realistic work including both plant specific tests and extensive analyses is needed for practical application of LBB concept.
5. CONCLUSIONS

1) KOTEP program which consists of the database section and the prediction section was
developed to assess the thermal embrittlement of CASS.

2) To verify the KOTEP, two types of case studies were performed. One is basic assessments
to predict $\sigma - \varepsilon$ curves and J-R curves, and the other is LBB analyses.

3) In the case of basic assessments, predicted results show similar behavior to the
experimental ones. However, due to lack of domestic data, more experimental data are
necessary to improve KOTEP program and extend its applicability.

4) In the case of LBB analyses, it is shown that the prototypical analyses results satisfied the
requirement. So, LBB concept for domestic operating plant seemed to be applicable if
further realistic work is supported.

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