Evaluation of accuracy about prediction method of cryogenic tensile strength for austenitic stainless steels in ITER Toroidal Field Coil Structure procurement activity

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Background

- Toroidal Field Coil Structure (TFCS) was required high tensile strength at liquid helium temperature (4K) to withstand huge magnetic force.
- JAEA has responsibility to procure 19 sets TFCS. Large amount of stainless steels required for TFCS: 3,800 tons.

- To establish efficient quality control method to avoid expensive and time consuming tests at 4K.
- Material for actual TFCS will be qualified to show correlation with mechanical properties of 4K (Prediction method).
- JAEA has also developed prediction curves to estimate 4K strengths not only qualification.

<table>
<thead>
<tr>
<th>Class</th>
<th>YS @4K</th>
<th>Material</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>&gt;1000MPa</td>
<td>FMJJ1</td>
</tr>
<tr>
<td>C2</td>
<td>&gt;900MPa</td>
<td>FM316LNH (C+N≥0.18%)</td>
</tr>
<tr>
<td>C3</td>
<td>&gt;700MPa</td>
<td>FM316LNM (C+N≥0.13%)</td>
</tr>
<tr>
<td>C3A</td>
<td>&gt;700MPa, &gt;280MPa @RT</td>
<td>FM316LNH (C+N≥0.18%)</td>
</tr>
<tr>
<td>C4</td>
<td>&gt;500MPa</td>
<td>FM316LNL (C+N≥0.08%)</td>
</tr>
</tbody>
</table>
Prediction method

**JSME code**

1. Strengths of material is determined by only (C+N) contents.
2. Temperature dependence of strength is expressed by a quadratic curve.
3. Correction factor (ratio of measured strength and predicted one) does not depend on temperate.

\[
y = 3415.1x + 401.21 \quad R^2 = 0.9606 \\
y = 1729.7x + 482.35 \quad R^2 = 0.9092 \\
y = 367.76x + 245.44 \quad R^2 = 0.4451
\]

\[
ST_{296P} = (A_1(C+N)+A_2) \times 296^2 + (A_3(C+N)+A_4) \times 296 + (A_5(C+N)+A_6)
\]

\[
\alpha = \frac{\text{Measured strength at RT}}{ST_{296P}}
\]

\[
ST_P = \alpha \left[ (A_1(C+N)+A_2)T^2 + (A_3(C+N)+A_4)T + (A_5(C+N)+A_6) \right]
\]
1. **To estimate strength at 4K of actual materials.**
   - Accuracy of applying this prediction method to three-dimensional complex shaped forgings and round bar forgings have not been confirmed.
   - Tensile test at 4K these materials (B3 Wing, B4 Side Plate and A1 Side Plates) were conducted.

2. **To estimate the accuracy of prediction method when it is applied to actual shaped materials.**

This estimation was conducted by following step;
① Prediction of 4K strength using prediction method are conducted.
② 4K tests at same sampling positions are conducted.
③ Comparisons prediction and tested 4K results are conducted.
④ These estimations for round bar forgings and complex shape forgings were also conducted in order to compare these results.
Materials for test

Round bar forgings

- Argon Oxygen Decarburization (AOD) process
- Solution treatment at 1050 degree C
- Oil hydraulic press or high speed radial forging machine
- Forging Ratio is around 7 - 10 (depend on diameter)

Complex shape forgings

- Vacuum Oxygen Decarburization (VOD) process
- Solution treatment at 1010-1150 degree C
- Formed at similar configuration of final dimension by 8000ton press or/and 13000ton press.
- Forging Ratio is around 13.
Screw-driven Tensile test machine

JAEA has own cryogenic material test facilities for mechanical test of structural materials, which is mechanical screw-driven machine for 4K tensile test.

<Turret disk : 16 specimens>

<Following Standard>
The Japanese Industrial Standards
JIS Z 2277 for 4K test.
JIS Z 2241 for RT test.
## Results of evaluation (Round bar )

<table>
<thead>
<tr>
<th>Material name</th>
<th>Measured at 4K</th>
<th>C+N contents [mass%]</th>
<th>Measured at RT</th>
<th>Predicted 4K value</th>
<th>Accuracy of Prediction from Measured</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>YS [MPa]</td>
<td>UTS [MPa]</td>
<td>YS [MPa]</td>
<td>UTS [MPa]</td>
<td>Accuracy (4K YS) [%]</td>
</tr>
<tr>
<td>410-1T-1</td>
<td>1000</td>
<td>1642</td>
<td>0.225</td>
<td>298</td>
<td>657</td>
</tr>
<tr>
<td>410-1T-2</td>
<td>959</td>
<td>1652</td>
<td>0.225</td>
<td>323</td>
<td>659</td>
</tr>
<tr>
<td>410-1T-3</td>
<td>943</td>
<td>1661</td>
<td>0.225</td>
<td>323</td>
<td>659</td>
</tr>
<tr>
<td>410-1L-1</td>
<td>1056</td>
<td>1665</td>
<td>0.225</td>
<td>323</td>
<td>659</td>
</tr>
<tr>
<td>410-1L-2</td>
<td>1049</td>
<td>1681</td>
<td>0.208</td>
<td>306</td>
<td>664</td>
</tr>
<tr>
<td>285-2L-1</td>
<td>948</td>
<td>1692</td>
<td>0.208</td>
<td>306</td>
<td>664</td>
</tr>
<tr>
<td>285-2L-2</td>
<td>966</td>
<td>1685</td>
<td>0.208</td>
<td>306</td>
<td>664</td>
</tr>
<tr>
<td>190-1T</td>
<td>1088</td>
<td>1694</td>
<td>0.213</td>
<td>321</td>
<td>664</td>
</tr>
<tr>
<td>190-2T</td>
<td>963</td>
<td>1685</td>
<td>0.226</td>
<td>309</td>
<td>665</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>997</strong></td>
<td><strong>1673</strong></td>
<td><strong>0.219</strong></td>
<td><strong>311</strong></td>
<td><strong>662</strong></td>
</tr>
</tbody>
</table>

- All minimum YS at RT and 4K satisfied ITER requirement (>900MPa)
- The accuracy for round bar forgings was estimated about 10.2% (4K YS), 2.5% (4K UTS)
### Results of evaluation (Complex shape)

<table>
<thead>
<tr>
<th>Material name</th>
<th>Measured at 4K</th>
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<th>Measured at RT</th>
<th>Predicted 4K value</th>
<th>Accuracy of Prediction from Measured</th>
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<tr>
<td></td>
<td>YS [MPa]</td>
<td>UTS [MPa]</td>
<td>YS [MPa]</td>
<td>UTS [MPa]</td>
<td>(4K YS) [%]</td>
</tr>
<tr>
<td>B3 Wing-1T</td>
<td>1078</td>
<td>1616</td>
<td>0.223</td>
<td>294</td>
<td>644</td>
</tr>
<tr>
<td>B3 Wing-2T</td>
<td>1081</td>
<td>1627</td>
<td>0.228</td>
<td>303</td>
<td>653</td>
</tr>
<tr>
<td>B4 side plate-1T</td>
<td>1082</td>
<td>1626</td>
<td>0.222</td>
<td>308</td>
<td>661</td>
</tr>
<tr>
<td>B4 side plate-2T</td>
<td>1097</td>
<td>1647</td>
<td>0.229</td>
<td>327</td>
<td>676</td>
</tr>
<tr>
<td>A1 side plate-1T</td>
<td>1063</td>
<td>1642</td>
<td>0.213</td>
<td>294</td>
<td>648</td>
</tr>
<tr>
<td>A1 side plate-2T</td>
<td>1039</td>
<td>1631</td>
<td>0.231</td>
<td>304</td>
<td>657</td>
</tr>
<tr>
<td><strong>Average</strong></td>
<td><strong>1073</strong></td>
<td><strong>1632</strong></td>
<td><strong>0.224</strong></td>
<td><strong>305</strong></td>
<td><strong>656</strong></td>
</tr>
</tbody>
</table>

### Accuracy of Prediction from Measured

- Accuracy (4K YS): $-2.7\%$ to $1.8\%$
- Accuracy (4K UTS): $-1.8\%$ to $-0.8\%$

- All minimum YS at RT and 4K satisfied ITER requirement (>900MPa)
- The accuracy for complex shape forgings was estimated about 1.8% (4K YS), -0.8% (4K UTS).
Discussion

- The chemical component and tensile RT YS of complex shape and round bar were almost same. → There should be no difference at predicted value between complex shape and round bar.

- However, measured 4K YS value of complex shape is 76MPa higher than round bar’s one. → It is assumed that less accuracy caused of manufacturing process. Manufacturing round bar forging tend to less Forging Ratio than other forgings to make round form.

To more improve accuracy, a coefficient calculated for each manufacturing conditions (form, process).
Accuracy of prediction method developed by JAEA, which predicts strengths at 4K from strengths at RT and C+N content of products, has been estimated. The following conclusions are obtained in this study.

(1) The accuracy for round bar forgings was estimated about 10.2% (4K YS), 2.5% (4K UTS), and the accuracy for complex shape forgings was estimated 1.8 % (4K YS), -0.8% (4K UTS).

(2) Measured C+N and RT YS of complex shape and round bar were not so different. Accuracy of 4K YS for round bar is less than complex shape’s one, it is assumed that less accuracy caused of manufacturing process.

(3) Prediction method can presume the tendency of tensile strength. A coefficient calculated for each manufacturing conditions (form, process), it can also be predicted with sufficient accuracy by taking in the coefficient to prediction relation.
Thank you for your attention