Effect of Thermal Aging on Mechanical Properties of Cast Stainless Steels*

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ABSTRACT: A procedure and correlations are presented for predicting mechanical properties of cast stainless steels in service at temperatures <450°C from known material information. The “saturation” fracture properties of a cast stainless steel, i.e., the minimum values that would be achieved for the material after long-term service, are estimated from the chemical composition of the steel. Fracture properties as a function of time and temperature of service are estimated from the kinetics of embrittlement, which are also determined from chemical composition. The correlations successfully predict fracture toughness, Charpy-impact, and tensile properties of cast stainless steels from the Shippingport-, Ringhals-, and Gundremmingen-reactor components.

INTRODUCTION

Investigations at Argonne National Laboratory (ANL) have shown that thermal embrittlement of cast stainless steels (SSs) (ASTM Specification A-351 grades CF-3, CF-3A, CF-8, CF-8A, and CF-8M) can occur during service at temperatures up to 450°C. Thermal aging of cast SSs at these temperatures increases hardness and tensile strength and decreases ductility, impact strength, and fracture toughness of the material, and shifts the Charpy transition curve to higher temperatures. In general, the low-C CF-3 steels are the most resistant to thermal embrittlement, and the Mo-bearing, high-C CF-8M steels are the least resistant. The extent of thermal embrittlement increases with increased ferrite content.

Aging of cast SSs at temperatures <500°C leads to precipitation of additional phases in the ferrite, e.g., formation of a Cr-rich α' phase by spinodal decomposition; nucleation and growth of the α' phase; precipitation of a Ni- and Si-rich G phase, M23C6, and γ2 (austenite); and additional precipitation and/or growth of existing carbides at the ferrite/austenite phase boundaries. Thermal embrittlement is caused primarily by formation of the Cr-rich α' phase and, to some extent, by precipitation and growth of carbides at the phase boundaries. Predominantly brittle failure occurs when either the ferrite phase is continuous (e.g., in cast material with a large ferrite content) or the ferrite/austenite phase boundary provides an easy path for crack propagation (e.g., in high-C grades of cast steel with large phase-boundary carbides). Consequently, the amount, size, and distribution of the ferrite phase in the duplex structure, and the presence of phase-boundary carbides are important parameters in controlling the degree of thermal embrittlement.

Based on material information readily available in certified material test records (CMTRs), a procedure has been developed at ANL for assessing thermal embrittlement of cast SSs. This paper presents the correlations for predicting Charpy-impact, tensile, and fracture toughness properties of cast SS components. Mechanical-property data for service-aged material from the Gundremmingen (KRB) reactor in Germany, Ringhals reactor in Sweden, and the Shippingport reactor in the United States are used to validate the correlations.

ASSESSMENT OF THERMAL EMBRITTLEMENT

A procedure and correlations have been developed for estimating fracture toughness, tensile, and Charpy-impact prop-
Mechanical properties of a specific cast SS are estimated from the extent and kinetics of thermal embrittlement. The extent of thermal embrittlement is characterized by the room-temperature (RT) Charpy-impact energy. A correlation for the extent of thermal embrittlement at “saturation,” i.e., the minimum impact energy that would be achieved for a material after long-term aging, is given in terms of the chemical composition of the material. The extent of thermal embrittlement as a function of time and temperature of reactor service is estimated from the extent of embrittlement at saturation and from the correlations that describe the kinetics of embrittlement, which are also given in terms of chemical composition. The fracture toughness J-R curve for the material is then obtained from the correlation between the fracture toughness parameters and the RT Charpy-impact energy that is used to characterize the extent of thermal embrittlement. Tensile yield and flow stresses, and engineering stress-vs.-strain curve are estimated from the flow stress of the unaged material and the kinetics of embrittlement. Fracture toughness $J_{IC}$ and tearing modulus can then be determined from the estimated J–R curve and tensile flow stress.

A flow diagram for estimating mechanical properties of cast SSs is shown in Fig. 1. A detailed description of the procedure and the correlations for predicting Charpy–impact, fracture toughness, and tensile properties of cast SS have been presented elsewhere. The estimation scheme is divided into three sections on the basis of available information. In Section A, “predicted lower-bound” J–R curve for cast SSs with unknown chemical composition is also defined for a given grade of steel, range of ferrite content, and temperature.

Sections B and C of the flow diagram present procedures for estimating mechanical properties when a CMTR is available.
mated CVsat and the kinetics of embrittlement. The decrease in RT Charpy-impact energy CV with time is expressed in terms of the aging parameter P by

$$\log_{10} C_V = \log_{10} C_{Vsat} + \beta \left[ 1 - \tanh \left( \frac{P - \theta}{\alpha} \right) \right]$$

(11)

and

$$P = \log_{10}(t) - \frac{1000Q}{19.143 \left( \frac{1}{T_s + 273} - \frac{1}{673} \right)}.$$  

(12)

where t is service time in h, Ts is service temperature in °C, Q is the activation energy for thermal embrittlement in kJ/mole, and the constants \(\alpha\) and \(\beta\) are determined from the initial impact energy \(C_{Vint}\) and the \(C_{Vsat}\) as follows:

$$\alpha = -0.585 + 0.795\log_{10}C_{Vsat}$$

(13)

and

$$\beta = (\log_{10}C_{Vint} - \log_{10}C_{Vsat})/2.$$ 

(14)

The value of \(\theta\) varies with service temperature; it is 3.3 at temperatures <280°C, 2.9 at 280–330°C, and 2.5 at 330–360°C. Activation energy \(Q\) for thermal embrittlement is expressed in terms of chemical composition and the constant \(\theta\), by the equation

$$Q = 10 \left( 74.52 - 7.20 \theta - 3.46 \text{ Si} - 1.78 \text{ Cr} - 4.35 I_1 \text{ Mn} + (148 - 125 I_2) N - 61 I_2 \text{ C} \right).$$

(15)

where \(I_1\) and \(I_2\) for CF-3 or CF-8 steels are, respectively, 0 and 1, and, for CF-8M steels, assume the values of 1 and 0, respectively. Equation 15 is applicable to compositions within ASTM A-351, with an upper limit of 1.2 wt.% for Mn content. Actual Mn content is used when materials contain up to 1.2 wt.% Mn; for steels that contain >1.2 wt.% Mn, 1.2 wt.% is assumed. Furthermore, Q is assumed to be 65 kJ/mole if the predicted value is lower, and 250 kJ/mole if the predicted value is higher.

The fracture toughness J–R curve of a specific cast SS as a function of time and temperature of aging is determined from the estimated RT impact energy, \(C_V\). The J–R curve for static- and centrifugally cast steels is given by

$$J_d = a(C_V)^b(\Delta a)^n,$$ 

(16)

where

$$n = c + d(\log_{10} C_V)$$

(17)

and the values of constants a, b, c, and d are given in Table 1. The J–R curve of the unaged material or the material at saturation is obtained by using \(C_{Vint}\) or \(C_{Vsat}\), respectively, in Eqs. 16 and 17.

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Table 1. Values of constants in Eqs. 16 and 17 for estimating power-law \( J-R \) curves for cast stainless steels

<table>
<thead>
<tr>
<th>Grade</th>
<th>Room Temperature</th>
<th>290°C</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>( a^a )</td>
<td>( b )</td>
</tr>
<tr>
<td>CF-3</td>
<td>49 (57)</td>
<td>0.52</td>
</tr>
<tr>
<td>CF-8</td>
<td>49 (57)</td>
<td>0.52</td>
</tr>
<tr>
<td>CF-8M</td>
<td>16 (20)</td>
<td>0.67</td>
</tr>
</tbody>
</table>

\( ^a \) Values of constant \( a \) are different for static- and centrifugally cast steels. Values in parentheses are for centrifugally cast steels.

Table 2. Chemical composition of cast stainless steels from the Shippingport, KRB, and Ringhals reactor components

<table>
<thead>
<tr>
<th>Material</th>
<th>Composition, wt.%</th>
<th>Ferrite, %</th>
</tr>
</thead>
<tbody>
<tr>
<td>CA4a</td>
<td>0.056</td>
<td>0.041</td>
</tr>
<tr>
<td>MA1a</td>
<td>0.052</td>
<td>0.049</td>
</tr>
<tr>
<td>PVa</td>
<td>0.108</td>
<td>0.027</td>
</tr>
<tr>
<td>KRBb</td>
<td>0.062</td>
<td>0.038</td>
</tr>
<tr>
<td>Hot Legc</td>
<td>0.037</td>
<td>0.044</td>
</tr>
<tr>
<td>Crossover Legc</td>
<td>0.039</td>
<td>0.057</td>
</tr>
</tbody>
</table>

\( ^a \) Hot-leg main valve MA1, and cold-leg check valve CA4 and pump volute PV from the Shippingport reactor in service for \( \approx \)13 y at 264°C for cold leg and at 281°C for hot leg.

Recirculating pump cover plate from the KRB reactor in service for \( \approx \)8 y at 284°C.

Hot-leg and crossover-leg elbows from the Ringhals 2 reactor in service for \( \approx \)13 y at 325°C for hot leg and at 291°C for crossover leg, and at hot standby for \( \approx \)2 y at 303°C for hot leg and 274°C for crossover leg.

The increase in yield or flow stress of aged cast SSs is estimated from a correlation between the ratio of tensile yield or flow stress of aged, and unaged material and the aging parameter \( P \). The procedure and correlations have been described elsewhere. The engineering stress-vs.-strain behavior of aged cast SS can also be obtained from the estimated flow stress. The engineering stress-vs.-strain curve is expressed by the Ramberg-Osgood equation

\[
\varepsilon = \varepsilon_0 + \alpha_1 \left( \frac{\sigma}{\sigma_0} \right)^{\eta_1},
\]

where \( \sigma \) and \( \varepsilon \) are engineering stress and strain, respectively; \( \sigma_0 \) is an arbitrary reference stress, often assumed to be equal to flow or yield stress; the reference strain \( \varepsilon_0 = \sigma_0/E \); \( \alpha_1 \) and \( \eta_1 \) are Ramberg-Osgood parameters; and \( E \) is elastic modulus. For all grades of cast SS, the parameter \( \eta_1 \) does not change with thermal aging. The parameter \( \alpha_1 \) decreases with aging and shows good correlation with the flow stress \( \sigma_f \) of the material. For engineering stress-vs.-strain curves up to 5% strain, the Ramberg-Osgood parameters at room temperature, for CF-8 steels, are given by

\[
\alpha_1 = 153.3 - 0.373\sigma_f \quad (\eta_1 = 7.1);
\]

and for CF-8M steel, by

\[
\alpha_1 = 145.9 - 0.314\sigma_f \quad (\eta_1 = 6.6).
\]

ESTIMATION OF MECHANICAL PROPERTIES

Charpy-impact, tensile, and fracture toughness properties of several cast SS materials from the Shippingport, KRB, and Ringhals reactors have been characterized. The chemical composition of the cast SSs is given in Table 2. Baseline mechanical properties of the unaged material were determined from tests on either recovery-annealed material, i.e., material that had been annealed for 1 h at 550°C and then water quenched, or on material from a cooler region of the component. The Shippingport and KRB materials exhibited modest degradation of mechanical properties, as would be expected at the relatively low operating temperatures. The hot-leg elbow from the Ringhals reactor indicated significant degradation of impact strength and fracture toughness after \( \approx \)15 y of service at 325°C, whereas the crossover-leg elbow in service at 291°C, showed only moderate degradation.

The procedure and correlations presented in the previous section have been used to estimate Charpy-impact, tensile, and fracture toughness properties of service-aged materials from the Shippingport, KRB, and Ringhals reactor components. Some materials were aged further in the laboratory.

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at 320, 350, and 400°C to validate the estimates of $C_{V\text{sat}}$ and kinetics of thermal embrittlement. The estimated and measured impact energies for some of the materials are plotted in Fig. 2 as a function of aging time at various temperatures. The estimates were obtained from assumed as well as experimental values of $\Theta$. The estimated impact energies show very good agreement with the experimental data. The predicted values of $C_{V\text{sat}}$ also are in excellent agreement with the measured values.

The fracture toughness $J$-$R$ curves for the various materials after reactor service were estimated from Eqs. 16 and 17. The correlations described in Eqs. 1-17 account for the degradation of mechanical properties of typical heats of cast SS. They do not consider the initial fracture properties of the unaged material. Some heats of cast SS may exhibit a low initial fracture toughness, and the estimated $J$-$R$ curve may be higher than the initial curve. When the estimated $J$-$R$ curve is higher than the initial fracture toughness $J$-$R$ curve, the latter is used as the $J$-$R$ curve of the material.

Examples of estimated and experimental fracture toughness $J$-$R$ curves at room temperature and at 290°C for cast SS components in the unaged or recovery-annealed condition, after service, and at saturation (i.e., aged 10,000 h at 400°C), are shown in Fig. 3. The estimated $J$-$R$ curves either show good agreement, or are lower (30-50%) than the experimental results. The somewhat conservative estimates are expected for some compositions of cast SS; the criteria used in developing the estimation scheme ensure that the estimated mechanical properties are adequately conservative for cast SS as defined by ASTM A-351. They do not consider the effects of metallurgical differences that may arise from differences in production heat treatment or casting processes and, therefore, may be overly conservative for some steels.

The changes in tensile flow stress and engineering stress–vs.–strain behavior of the various cast SSs were estimated from the tensile properties of the unaged material and the kinetics of thermal embrittlement. The estimated values show good agreement with the experimental data. Estimated and measured engineering stress–vs.–strain curves at 290°C for material from the KRB pump cover plate and Shippingport pump volute are shown in Fig. 4.

**CONCLUSIONS**

A procedure and correlations are presented for predicting Charpy–impact energy, fracture toughness $J$–$R$ curves, and tensile properties of aged cast SSs (ASTM A 351) from known material information. Mechanical properties of a specific cast SS are estimated from the extent and kinetics of

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Figure 3. Estimated and measured fracture toughness J–R curves at room temperature and 290°C for materials from the Shippingport and KRB reactors.

Figure 4. Estimated and measured tensile stress–vs.–strain curves at 290°C for service-aged material from the Shippingport and KRB reactor components.
thermal embrittlement. Embrittlement of cast SSs is characterized in terms of RT Charpy-impact energy. The correlations successfully predicted the mechanical properties of service-aged cast SSs from the Shippingport, Ringhals 2, and KRB reactor components.

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