Studies of Aged Cast Stainless Steel from the Shippingport Reactor

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STUDIES OF AGED CAST STAINLESS STEEL FROM THE SHIPPINGPORT REACTOR*

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The mechanical properties of cast stainless steels from the Shippingport reactor have been characterized. Baseline properties for unaged materials were obtained from tests on either recovery-annealed material or material from a cooler region of the component. The materials exhibited modest decrease in impact energy and fracture toughness and a small increase in tensile strength. The fracture toughness J–R curve, $J_{IC}$ value, tensile flow stress, and Charpy-impact energy of the materials showed very good agreement with estimations based on accelerated laboratory aging studies. The kinetics of thermal embrittlement and degree of embrittlement at saturation, i.e., the minimum impact energy that would be achieved after long-term aging, were established from materials that were aged further in the laboratory at temperatures between 320 and 400°C. The results showed very good agreement with estimates: the activation energies ranged from 125 to 250 kJ/mole and the minimum room-temperature impact energy was >75 J/cm². The estimated impact energy and fracture toughness J–R curve for materials from the Ringhals reactor hot and crossover-leg elbows are also presented.

1 Introduction

Cast duplex stainless steels used in LWR systems for primary pressure-boundary components such as valve bodies, pump casings, and primary coolant piping are susceptible to thermal embrittlement after extended service at reactor operating temperatures, i.e., 280–320°C (536–608°F). Aging of cast stainless steels at these temperatures leads to increased hardness and tensile strength and decreased ductility, impact strength, and fracture toughness. Most studies of thermal embrittlement of cast stainless steels involve simulation of end-of-life reactor conditions by accelerated aging at higher temperatures, viz., 400°C (752°F), because the time period for operation of power plants (~40 y) is far longer than can generally be considered in laboratory studies. Thus, estimates of mechanical–property degradation suffered by cast stainless steel components during service are based on an Arrhenius extrapolation of high-temperature data to reactor operating conditions.

Several laboratory studies have investigated thermal embrittlement of cast stainless steels under LWR operating conditions [1–12]. A procedure and correlations have been developed for estimating fracture toughness, tensile, and Charpy-impact properties of cast stainless steel components during thermal aging [13,14]. Because the embrittlement mechanisms and kinetics are complex, microstructural studies and mechanical testing of actual component materials that have completed long in-reactor service are necessary, to ensure that the mechanisms observed in accelerated aging experiments are the same as those occurring in reactors. Cast stainless steels from the decommissioned Shippingport reactor offer a unique opportunity to validate and benchmark the laboratory studies.

The objectives of this paper are to characterize the mechanical-property degradation of cast stainless steel components from the Shippingport reactor and compare the results with estimates from accelerated laboratory aging studies. Cast stainless steel materials were obtained from four cold-leg check valves, two hot-leg main shutoff valves, and two pump volutes of the Shippingport reactor. One of the volutes is a "spare" that had seen service only during the first core loading, whereas the other was in service for the entire life of the plant. The actual time-at-temperature for the materials was \( =13 \text{ y at } 281^\circ \text{C (538°F)} \) for the hot-leg components and \( =264^\circ \text{C (507°F)} \) for the cold-leg components. The components were in a hot stand-by condition of \( =204^\circ \text{C (400°F)} \) for an additional \( =2 \text{ y} \).

Service-aged material was also obtained from the recirculating-pump cover assembly of the KRB reactor, which was in service in Gundremmingen, Germany, for \( =8 \text{ y at } 284^\circ \text{C (543°F)} \). The mechanical-property degradation of cast stainless steel (CF-8M) elbows from the Ringhals reactor hot leg and crossover leg was also assessed and compared with experimental data [15].

2 Material Characterization

The various cast materials were characterized to determine their chemical composition, hardness, grain structure, and ferrite content and distribution. Samples were obtained from different locations of the casting and from different regions across the thickness of the wall. The chemical composition, hardness, and amount and distribution of ferrite for the cast materials are given in Table 1. All materials are CF-8 grade cast stainless steel with measured ferrite contents in the range of 2–16% for the Shippingport components and 34% for the KRB pump cover plate. Hardness increases with an increased ferrite content. Some differences in hardness and ferrite content were observed for material from different locations in the casting. Such differences appear to be related to compositional variations.

All valve materials have a radially oriented columnar grain structure. Typical examples of the grain structure for the check valves and main shutoff valves are shown in Figs. 1 and 2, respectively. The inner surface of all the valves contained repair welds; an example is shown in Fig. 2. The pump volutes have a mixed grain structure of columnar and equiaxed grains (Fig. 3). The ferrite morphology of the check valves and main shutoff valves is shown in Figs. 4 and 5, respectively. The materials contain a lacy ferrite with a mean ferrite spacing in the range of 150–300 μm. The check valve materials show a significant amount of carbides at the ferrite/austenite phase boundaries. Also, most of the phase boundaries have migrated. The original phase boundaries are decorated with carbides, which most likely formed during production heat treatment of the casting.

Microstructural examination indicates that the mechanism of low-temperature embrittlement of the cast materials is the same as that of the laboratory-aged materials [16,17]. All materials showed spinodal decomposition of the ferrite to form a chromium-rich \( \alpha' \) phase. In addition, the check-valve materials contained a nickel- and silicon-rich G phase in the ferrite and \( \text{M}_{23} \text{C}_{6} \) carbides at the austenite/ferrite phase boundary. An unexpected microstructural feature, i.e., \( \sigma \) phase precipitates on slip bands and stacking faults, was also observed in the austenite of the check-valve material. Precipitation of \( \sigma \) phase generally occurs at temperatures \( >550^\circ \text{C (>1022°F)} \). The presence of \( \sigma \) phase and
phase-boundary migration indicate significant differences between the production heat treatment of the check valves and that of the other materials.

3 Mechanical Properties

Specimens for Charpy-impact, tensile, and fracture toughness J-R-curve tests were obtained from different locations across the thickness of the various components. All specimens were in the LC orientation.* Impact tests were conducted on standard Charpy V-notch specimens machined according to ASTM Specification E 23. A Dynatup Model 8000A drop-weight impact machine with an instrumented tup and data readout system was used for the tests. Tensile tests were performed on cylindrical specimens 5 mm in diameter, with a gauge length of 20 mm. The tests were conducted at an initial strain rate of \(4 \times 10^{-4} \text{ s}^{-1}\). The J-R-curve tests were conducted according to ASTM Specifications E 813-85 and E 1152-87. Compact-tension specimens, 25.4-mm thick (i.e., 1T size), were used for the tests.

The baseline mechanical properties for the as-cast materials must be known to establish the thermal-aging effects during reactor service. Microstructural and annealing studies [2,16-19] on laboratory- and reactor-aged materials indicate that mechanical properties of unaged material can be determined from recovery-annealed material, i.e., embrittled material that has been annealed for 1 h at 550°C and then water-quenched. To obtain baseline properties, Charpy-impact tests were also conducted on material from a cooler region of the main shutoff valve. Charpy transition curves for MA9 material and recovery-annealed MA9 and MA1 material are shown in Fig. 6. These materials are from the Loop A main shutoff valve, although MA9 is from a cooler region of the valve. The results indicate that MA9 material suffered little or no thermal-aging embrittlement, i.e., annealing had no effect on the transition curves. The results for annealed MA1 material also show good agreement on the transition curves. The results for annealed MA1 also show good agreement with the transition curve for MA9. The upper-shelf energy (USE) for both materials is not constant but decreases as temperature increases. The average impact energies at room temperature and at 290°C, respectively, are 356 and 253 J/cm² for MA9, and 320 and 254 J/cm² for annealed MA1. The Charpy data were fitted with a hyperbolic tangent function of the form

\[
C_v = K_o + B[1 + \tanh \left(\frac{T - C}{D}\right)],
\]

where \(K_o\) is the lower-shelf energy, \(T\) is the test temperature in °C, \(B\) is half the distance between upper- and lower-shelf energy, \(C\) is the mid-shelf Charpy transition temperature (CTT) in °C, and \(D\) is the half-width of the transition region. The best-fit curves for MA9, with or without annealing, and for annealed MA1 indicate that the latter is marginally weaker; the CTT of MA1 is ~10°C higher and the average USE ~30 J/cm² lower. Such differences in impact energy are most likely due to minor variations in composition and structure of the materials from different locations of the casting. The Charpy data for MA9 and annealed MA1 may be represented by a single best-fit transition curve, as shown in Fig. 6.

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* The first digit represents the direction normal to the plane of the crack and the second digit indicates the direction of crack propagation: L = longitudinal and C = circumferential.
Charpy Impact Energy

Charpy transition curves for the various cast materials from the Shippingport reactor are shown in Figs. 7-9. The Charpy data were fitted with the hyperbolic-tangent expression given in Eq. 1; the values of the constants for the various materials are given in Table 2. The results indicate that the room-temperature impact energy of the materials is relatively high and the mid-shelf $C_{IT}$, i.e., constant $C$ in Eq. 1, is very low. The check valve materials CA4 and CB7 are weaker than MA1 and PV, e.g., the mid-shelf $C_{IT}$ is $=100^\circ$C higher for CA4 and CB7. The higher $C_{IT}$s are due to the presence of phase-boundary carbides in the check-valve materials. The carbides weaken the phase boundaries and thus provide an easy path for fracture.

The decrease in impact strength from $=13$ y of service at reactor temperatures is minimal for the materials. The room-temperature impact energy of PV, MA1, and CA4 materials is decreased by $=90$, 70, and 40 J/cm$^2$, respectively. The large difference in USE for the unaged and service-aged materials from Row 1 of MA1 (Fig. 7), is not due to thermal aging. The inner 15-mm region of the MA1 valve body contains a high density of inclusions/flaws and is inherently weak. The inner surface of all the valves contained repair welds. No significant difference was observed in the chemical composition or ferrite content of the material across the thickness of the valve body.

Tensile Properties

Tensile tests were conducted at room temperature and at 290°C on CA4, PV, MA1, and MA9 materials. Tensile properties were also estimated from the instrumented Charpy-impact test data. For a Charpy specimen, yield stress is given by

$$\sigma_y = 1.50 P_y B / W b^2, \quad (2)$$

and ultimate stress by

$$\sigma_u = 2.28 P_m B / W b^2, \quad (3)$$

where $P_y$ and $P_m$ are the yield and maximum loads obtained from the load-time traces of the Charpy test, $W$ is the specimen width, $B$ is the specimen thickness, and $b$ is the uncracked ligament [20]. The estimated values of yield and ultimate stress, the values obtained from tensile tests, and estimated tensile stresses for recovery-annealed materials are shown in Figs. 10 and 11.

The estimated tensile properties are in good agreement with the measured values. The tensile strength of CA4, PV, and MA1 materials is comparable. The results show that thermal aging during reactor service had no effect on yield stress and that the increase in ultimate stress is minimal for all materials. Two specimens of MA1 (Fig. 11) show low ultimate strength (and also poor ductility). These specimens were obtained from the inner-15-mm region of the valve body. The poor tensile properties are caused by inclusions in the material. As discussed above, the room-temperature impact energy of Row 1 specimens is also low, e.g., $=177 \pm 33$ J/cm$^2$, compared to $=299 \pm 33$ J/cm$^2$ for specimens from other regions of the valve body.
4 Estimation of Mechanical Properties

Charpy-Impact Energy

A procedure and correlations have been presented\(^*\) for predicting Charpy-impact energy, tensile flow stress, and fracture toughness J–R curves of aged cast stainless steels from the chemical composition of the steel. Embrittlement of cast stainless steels is characterized in terms of room-temperature Charpy-impact energy. The extent or degree of embrittlement at “saturation,” i.e., the minimum impact energy that would be achieved for the material after long-term aging, is described in terms of a material parameter Φ, which, for CF-3 and CF-8 steels, is expressed as

\[
\Phi = δ_C(Cr+Si)(C+0.4N)
\] (4a)

and for CF-8M steels as

\[
\Phi = δ_C(Ni+Si+Mn)^2(C+0.4N)/5.
\] (4b)

where the ferrite content δC is in % and chemical composition of the steel is in wt.%. The ferrite content is calculated from Hull’s equivalent factors \(^[21]\); the values for the various cast materials are given in Table 1. The saturation room-temperature impact energy \(C_{V_{sat}}\) (J/cm\(^2\)) for CF-3 and CF-8 steels is given by

\[
\log_{10}C_{V_{sat}} = 1.15 + 1.36\exp(-0.035Φ),
\] (5a)

and for CF-8M steels with >10% Ni by

\[
\log_{10}C_{V_{sat}} = 1.10 + 2.64\exp(-0.064Φ).
\] (5b)

The room-temperature saturation impact energy is also estimated from the chemical composition of the steel. For CF-3 and CF-8 steels, \(C_{V_{sat}}\) (J/cm\(^2\)) is given by

\[
\log_{10}C_{V_{sat}} = 5.64 - 0.006δ_C - 0.185Cr + 0.273Mo - 0.204Si + 0.044Ni - 2.12(C + 0.4N),
\] (6a)

and for CF-8M steels by

\[
\log_{10}C_{V_{sat}} = 7.28 - 0.011δ_C - 0.185Cr - 0.369Mo - 0.451Si - 0.007Ni - 4.71(C + 0.4N).
\] (6b)

The saturation impact energy for a specific cast stainless steel is determined by both the methods given in Eqs. 4–6; and the lower value is then used for estimating mechanical properties.

Room-temperature impact energy as a function of time and temperature of aging is estimated from the room-temperature saturation impact energy \(C_{V_{sat}}\) and kinetics of embrittlement. The decrease in room-temperature impact energy \(C_V\) (J/cm\(^2\)) with time is expressed as

\[ \log_{10} C_V = \log_{10} C_{Vsat} + \beta [1 - \tanh \left( \frac{P - \theta}{\alpha} \right)]. \] (7)

where \( \beta \) is half the maximum change in \( \log C_V \), \( \theta \) is the log of the time at 400°C to achieve \( \beta \) reduction in impact energy at 400°C, and \( \alpha \) is a shape factor. The aging parameter \( P \) is the log of the aging time for a specific degree of embrittlement and is defined by

\[ P = \log_{10} t - \frac{1000Q}{19.143(T_s+273)} - \frac{1}{673}. \] (8)

where \( Q \) is the activation energy (kJ/mole) for thermal embrittlement and \( t \) and \( T_s \) are the time (h) and temperature (°C) of aging, respectively. The activation energy \( Q \) (kJ/mole) is also determined from the chemical composition of the steel. For CF-3 and CF-8 steels

\[ Q = 10 \left[ 74.52 - 7.20\theta - 3.46Si - 1.78Cr + 148N - 61C \right] \] (9a)

and for CF-8M steels

\[ Q = 10 \left[ 74.52 - 7.20\theta - 3.46Si - 1.78Cr - 4.35Mn + 23N \right], \] (9b)

where the constant \( \theta \) is defined in Eq. (7). The constants \( \beta \) and \( \alpha \) in Eq. (7) can be determined from the initial room-temperature impact energy of the material \( C_{Vint} \) and the saturation room-temperature impact energy \( C_{Vsat} \). Thus,

\[ \beta = (\log_{10} C_{Vint} - \log_{10} C_{Vsat})/2, \] (10)

and

\[ \alpha = -0.585 + 0.795 \log_{10} C_{Vsat}. \] (11)

For a specific cast stainless steel, the values of room-temperature impact energy as a function of time and temperature of reactor service and the minimum impact energy that would be achieved for the material after long-term aging (i.e., saturation value) can be estimated from Eqs. 4–11. The information required for the estimations includes the chemical composition, initial impact energy of the unaged material, and the constant \( \theta \). However, parametric studies indicate that the aging response at 280–330°C, is relatively insensitive to the value of \( \theta \). Varying \( \theta \) between 2.1 and 3.6 results in almost identical aging behavior at 300°C and differences in aging behavior at 280–330°C are minimal. A value of 2.9 is assumed for the constant \( \theta \) in Eqs. 7 and 9 when estimating impact energy of cast stainless steel components in service at 280–330°C.

Room-temperature impact energy of the various service-aged materials was estimated from Eqs. 4–11. The initial impact energy of the unaged materials was determined from the data for recovery-annealed material or material from a cooler region of the casting. Some materials were aged further in the laboratory at 320, 350, and 400°C (608, 662, and 752°F) to obtain an accurate value of \( \theta \) and to validate the estimates of the saturation impact energy \( C_{Vsat} \) and activation energy for embrittlement of the materials.

The change in estimated Charpy-impact energy with aging time at temperatures between reactor service temperature for the Shippingport and KRB materials and 400°C is shown in Figs. 12–14. The high-temperature aging data for CA4 and MA1 materials represent service-aged material that was aged further in the laboratory at 350 and 400°C.
Aging times were adjusted to include the effect of aging at reactor temperature. The high-temperature aging data for the KRB pump cover plate were obtained on recovery-annealed material.

The impact energies estimated with experimental $\theta$ show good agreement with the measured impact energies at all temperatures; those estimated with $\theta = 2.9$ show good agreement at temperatures $\leq 320^\circ$C. As mentioned above, estimations based on $\theta = 2.9$ are valid only for service temperatures between 280 and 330$^\circ$C. For higher temperatures, the estimated values would be nonconservative for materials that have a $\theta$ value $< 2.9$, e.g., KRB pump cover plate and VR material (Fig. 14). A $\theta$ value of 2.5 would give a conservative estimate of impact energy for all materials at 330–360$^\circ$C service temperature.

The impact energy for main valve MA1 was estimated from the compositions of MA1 and MA9 materials; the differences in the compositions of the two materials are minor. Figure 12 shows that, although the aging behavior at 400$^\circ$C and the kinetics of embrittlement for MA1 and MA9 are significantly different, the estimates based on MA1 and MA9 agree well with the observed values for $\approx 13$ y of service at 281$^\circ$C. The aging behavior estimated from MA9 is slightly slower than that estimated from MA1.

The predicted minimum saturation room-temperature impact energies also are in very good agreement with the experimental data. The measured impact energies for VR, MA9, and KRB materials aged at 400$^\circ$C achieve saturation at the predicted values.

**Fracture Toughness**

Thermal aging decreases the fracture toughness of cast stainless steels at both room temperature and reactor temperature. The fracture toughness J-R curve for a specific cast stainless steel can be estimated from its room-temperature impact energy $C_v$ (J/cm$^2$). The J-R curve is expressed by the power-law relation $J_d = C_\Delta a^n$, where $J_d$ is deformation $J$ (kJ/m$^2$) per ASTM Specifications E 813-85 and E 1152-87, $\Delta a$ is crack extension (mm), and $C$ and $n$ are constants. At room temperature, the J–R curve for static-cast CF-8 steels is given by

$$J_d = 49[C_v]^{0.52}[\Delta a]^n,$$

and for static-cast CF-8M steels by

$$J_d = 16[C_v]^{0.67}[\Delta a]^n.$$  

At 290–320$^\circ$C, the J–R curve for static cast CF-8 steels is given by

$$J_d = 102[C_v]^{0.28}[\Delta a]^n,$$

and for static-cast CF-8M steels by

$$J_d = 49[C_v]^{0.41}[\Delta a]^n.$$  

At room temperature, the exponent $n$ for static- or centrifugally cast CF-8 steels is given by

$$n = 0.22 + 0.139 \log_{10} C_v.$$
and for static–cast CF-8M steels by

\[ n = 0.25 + 0.077\log_{10}C_v. \]  

(14b)

At 290–320°C, the exponent \( n \) for static– or centrifugally cast steels is given by

\[ n = 0.22 + 0.074\log_{10}C_v. \]  

(15a)

and for static–cast CF-8M steels by

\[ n = 0.23 + 0.057\log_{10}C_v. \]  

(15b)

The estimated and experimental fracture toughness \( J-R \) curves at room temperature and at 290°C for the CA4, MA1, and PV materials and KRB pump cover plate are shown in Figs. 15 and 16. All materials exhibit relatively high fracture toughness. The estimated \( J-R \) curves for CA4 and MA1 show good agreement with the experimental results and those for PV and KRB materials are 30–50% lower. The lower values for the PV and KRB materials are due to a conservative estimate of the kinetics of embrittlement, i.e., the correlations predict a faster decrease in impact energy than that observed during service, i.e., the estimated room–temperature impact energy is ≈40% lower than the average experimental value.

Tensile Properties

Thermal aging of cast stainless steels increases their tensile strength, particularly their ultimate stress. The tensile strength of the unaged materials from the Shippingport and KRB reactors were determined from tensile tests or estimated from instrumented Charpy–impact tests on recovery–annealed materials. The materials show little or no increase in tensile stress. The increase in flow stress of aged cast stainless steels is estimated from a correlation between the ratio of tensile flow stress of aged and unaged material and a normalized aging parameter. Flow stress is characterized as the mean of the 0.2% yield and ultimate stresses, and the aging parameter \( P \) (defined in Eq. 8) is normalized with respect to a \( \theta \) value of 2.9. The flow stress ratio \( R = (\sigma_{\text{aged}}/\sigma_{\text{unaged}}) \) is given by

\[ R = a + b(P - \theta + 2.9). \]  

(16)

Equation 16 is valid for ferrite contents >7% and \( R \) values between 1 and a constant \( c \). Values of the constants \( a, b, \) and \( c \) for different grades of steel and test temperatures are given in Table 3. The tensile flow stresses for the Shippingport and KRB materials were estimated from Eq. 16 with a value of 2.9 for \( \theta \). The results, given in Table 4, show good agreement with the measured values.

Fracture toughness \( J_{IC} \) values for service–aged materials can be determined from the estimated \( J-R \) curve and flow stress, and are also given in Table 4. The estimated \( J_{IC} \) shows very good agreement with the measured value for CA4 and is conservative for MA1 and PV.

5 Ringhals Reactor Elbows

Investigation of the hot– and crossover-leg elbows from the Ringhals reactor indicated significant degradation of impact strength and fracture toughness of the hot–leg elbow after 15 y of service at 325°C, whereas the crossover–leg elbow, in service at 291°C, showed only
moderate degradation [15]. The mechanical properties of the Ringhals elbows were estimated from Eqs. 4–16 with the correlations for CF-8M steel containing >10% Ni. Information on the chemical composition and impact energy of the unaged materials was used in the estimations; \( \theta \) was assumed to be 2.9.

The experimental data and estimated decrease in impact energy for hot- and crossover-leg elbows during service at 325 and 291°C, respectively, are shown in Fig. 17. The estimated value of 67 J/cm\(^2\) for the hot-leg elbow is marginally higher than the measured average values of 45 J/cm\(^2\) (equivalent Charpy V-notch impact energy converted from U-notch value) and 50 J/cm\(^2\) (from Charpy V-notch specimens). The estimated 112 J/cm\(^2\) impact energy for the crossover-leg agrees well with 107 J/cm\(^2\) measured from U-notch specimens and is significantly lower than the 177 J/cm\(^2\) obtained from V-notch specimens. The difference between the V- and U-notch impact energy for the crossover-leg elbow is most likely due to a significant variation in the ferrite content of the material. The saturation impact energies for hot- and crossover-leg elbows are estimated to be 56 and 67 J/cm\(^2\), respectively.

Fracture toughness J-R curves can be estimated from the impact energy. Room temperature J-R curve for hot- and crossover-leg elbows after \( \approx 15 \) y of service are shown in Fig. 18. Only the experimental \( J_{IC} \) values (not the complete J-R curve) have been reported for these materials [15]. The estimated tensile flow stress and \( J_{IC} \) at room temperature and at 290°C for the Ringhals elbows are given in Table 4. The estimated flow stresses are in good agreement with the measured values. The \( J_{IC} \) for the hot-leg elbow also is comparable to the measured value whereas that for the crossover-leg elbow is 50–70% lower. As mentioned above, the ferrite content of the crossover-leg elbow varies significantly. Furthermore, the correlations do not consider the effect of microstructural differences, and may be conservative for some materials.

6 Conclusions

Charpy-impact, tensile, and fracture toughness properties of several cast stainless steel materials from the Shippingport, KRB, and Ringhals reactors have been characterized. Baseline mechanical properties for as-cast 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 materials exhibited modest degradation of mechanical properties. The room-temperature impact energy was relatively high, >120 J/cm\(^2\) (>70 ft-lb). Check-valve materials were weaker than main valve materials because of the presence of phase-boundary carbides. The CTT for the check valves was \( \approx 100°C \) higher than that for the main shutoff valves or pump volute. The results show good agreement with estimations based on accelerated laboratory aging studies. The procedure and correlations developed at ANL for estimating thermal aging degradation of cast stainless steels, predict accurate or slightly conservative values for Charpy-impact energy, tensile flow stress, fracture toughness J-R curve, and \( J_{IC} \) of the Shippingport and KRB materials. The correlations successfully predict the mechanical properties of the Ringhals reactor hot- and crossover-leg elbows after service of \( \approx 15 \) y.
Acknowledgments

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References


Table 1. Chemical composition, ferrite morphology, and hardness of cast stainless steel components from the Shippingport, KRB, and Ringhals reactors.

<table>
<thead>
<tr>
<th>Mater. ID</th>
<th>C</th>
<th>N</th>
<th>Si</th>
<th>Mn</th>
<th>P</th>
<th>S</th>
<th>Ni</th>
<th>Cr</th>
<th>Mo</th>
<th>Cu</th>
<th>Ferrite Calc. (%)</th>
<th>Ferrite Meas. Spacing (%)</th>
<th>Hardness [Rg]</th>
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<td>Cold Leg Check Valve</td>
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<tr>
<td>CA4</td>
<td>0.056</td>
<td>0.041</td>
<td>1.45</td>
<td>1.10</td>
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<td>10.9</td>
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<td>MA9</td>
<td>0.052</td>
<td>0.051</td>
<td>0.24</td>
<td>0.72</td>
<td>0.041</td>
<td>0.011</td>
<td>10.54</td>
<td>20.78</td>
<td>0.24</td>
<td>0.13</td>
<td>5.1</td>
<td>10.0</td>
<td>245 77.6</td>
</tr>
<tr>
<td>MB2</td>
<td>0.042</td>
<td>0.073</td>
<td>0.51</td>
<td>0.72</td>
<td>0.043</td>
<td>0.017</td>
<td>10.77</td>
<td>19.74</td>
<td>0.19</td>
<td>0.12</td>
<td>2.6</td>
<td>1.9</td>
<td>74.2</td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>VR</td>
<td>0.046</td>
<td>0.049</td>
<td>1.14</td>
<td>0.50</td>
<td>0.027</td>
<td>0.017</td>
<td>9.56</td>
<td>20.79</td>
<td>0.04</td>
<td>0.07</td>
<td>9.8</td>
<td>16.2</td>
<td>181 82.9</td>
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<td>PV</td>
<td>0.108</td>
<td>0.027</td>
<td>0.89</td>
<td>1.11</td>
<td>0.032</td>
<td>0.008</td>
<td>9.30</td>
<td>19.83</td>
<td>0.38</td>
<td>0.25</td>
<td>4.1</td>
<td>13.0</td>
<td></td>
</tr>
<tr>
<td>KRB Pump Cover Plate</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<td></td>
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</tr>
<tr>
<td>KRB</td>
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<td>0.038</td>
<td>1.17</td>
<td>0.31</td>
<td></td>
<td></td>
<td>8.03</td>
<td>21.99</td>
<td>0.17</td>
<td></td>
<td>27.7</td>
<td>34.0</td>
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<tr>
<td>Ringhals Reactor Elbows</td>
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<td></td>
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<td></td>
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<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
</tr>
<tr>
<td>H</td>
<td>0.037</td>
<td>0.044</td>
<td>1.03</td>
<td>0.77</td>
<td>0.022</td>
<td>0.008</td>
<td>10.60</td>
<td>20.00</td>
<td>2.09</td>
<td>0.17</td>
<td>13.0</td>
<td>20.1</td>
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<tr>
<td>C</td>
<td>0.039</td>
<td>0.037</td>
<td>1.11</td>
<td>0.82</td>
<td>0.020</td>
<td>0.012</td>
<td>10.50</td>
<td>19.60</td>
<td>2.08</td>
<td>0.08</td>
<td>12.3</td>
<td>19.8</td>
<td></td>
</tr>
</tbody>
</table>

a For the valves, the second digit indicates the loop where the valve was located and the number designates the segment of the component from which the material was removed (segments 1, 2, and 7 are from the top of the valve, segment 4 is from the bottom, and segment 9 is from a cooler region).

b In service for ~13 y at 264°C for cold leg and at 281°C for hot leg.

c Spare pump volute VR in service only during initial core loading and PV in service for ~13 y at 264°C.

d In service for ~8 y at 284°C.

e In service for ~8 y at 325°C for hot leg and at 291°C for crossover leg, and a hot stand-by for 2.3 y at 303°C for hot leg and at 274°C for crossover leg.
Table 2. Values of constants in Eq. 1 for Charpy transition curve of CF-8 cast stainless steels from the Shippingport reactor and KRB pump cover plate

<table>
<thead>
<tr>
<th>Material ID</th>
<th>Service Condition</th>
<th>Constant ID</th>
<th>Constants</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>$K_0$ (J/cm²)</td>
<td>B (J/cm²)</td>
</tr>
<tr>
<td>Cold-Leg Check Valves</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CA4</td>
<td>Annealed</td>
<td>25</td>
<td>98.6</td>
</tr>
<tr>
<td>CA4</td>
<td>264</td>
<td>25</td>
<td>79.2</td>
</tr>
<tr>
<td>CB7</td>
<td>264</td>
<td>76</td>
<td>108.8</td>
</tr>
<tr>
<td>Hot-Leg Main Shutoff Valve</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MA9&lt;sup&gt;a&lt;/sup&gt;</td>
<td>Annealed</td>
<td>96</td>
<td>112.0</td>
</tr>
<tr>
<td>MA9</td>
<td>&lt;200</td>
<td>83</td>
<td>110.1</td>
</tr>
<tr>
<td>MA1/23&lt;sup&gt;ab&lt;/sup&gt;</td>
<td>Annealed</td>
<td>96</td>
<td>112.0</td>
</tr>
<tr>
<td>MA1/1&lt;sup&gt;c&lt;/sup&gt;</td>
<td>281</td>
<td>73</td>
<td>87.6</td>
</tr>
<tr>
<td>Pump Volutes</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>PV</td>
<td>Annealed</td>
<td>150</td>
<td>116.2</td>
</tr>
<tr>
<td>PV</td>
<td>264</td>
<td>75</td>
<td>109.4</td>
</tr>
<tr>
<td>VR</td>
<td>Unaged</td>
<td>61</td>
<td>88.1</td>
</tr>
<tr>
<td>Pump Cover Plate&lt;sup&gt;d&lt;/sup&gt;</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KRB</td>
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<td>8</td>
<td>161.9</td>
</tr>
<tr>
<td>KRB</td>
<td>284</td>
<td>8</td>
<td>119.7</td>
</tr>
</tbody>
</table>

<sup>a</sup> Determined from combined data for MA9 and annealed MA9 and MA1.

<sup>b</sup> Material from Rows 2 & 3, which corresponds to 15- to 45-mm region of the wall.

<sup>c</sup> Material from Row 1, which corresponds to inner 15-mm region of the wall.

<sup>d</sup> Obtained from the KRB reactor in Gundremmingen, Germany.
Table 3. Values of the constants in Eq. 16 for estimating tensile flow stress of aged cast stainless steels

<table>
<thead>
<tr>
<th>Grade</th>
<th>Room Temp.</th>
<th>290–320°C</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>a</td>
<td>b</td>
</tr>
<tr>
<td>CF-3</td>
<td>0.94</td>
<td>0.047</td>
</tr>
<tr>
<td>CF-8</td>
<td>0.90</td>
<td>0.074</td>
</tr>
<tr>
<td>CF-8M</td>
<td>0.80</td>
<td>0.101</td>
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</tbody>
</table>

Table 4. Measured and estimated tensile flow stress and $J_{IC}$ values for service-aged cast stainless steels

<table>
<thead>
<tr>
<th>Material ID</th>
<th>Temp. (°C)</th>
<th>Flow Stress [MPa]</th>
<th>$J_{IC}$ [kJ/m$^2$]</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Observed</td>
<td>Estimated</td>
<td>Observed</td>
</tr>
<tr>
<td>Shippingport Component</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CA4</td>
<td>25</td>
<td>377 (377)</td>
<td>397</td>
</tr>
<tr>
<td></td>
<td>290</td>
<td>251 (246)</td>
<td>259</td>
</tr>
<tr>
<td>PV</td>
<td>25</td>
<td>370 (362)</td>
<td>395</td>
</tr>
<tr>
<td></td>
<td>290</td>
<td>266 (268)</td>
<td>295</td>
</tr>
<tr>
<td>MA1</td>
<td>25</td>
<td>345 (345)</td>
<td>354</td>
</tr>
<tr>
<td></td>
<td>290</td>
<td>237 (233)</td>
<td>238</td>
</tr>
<tr>
<td>KRB Pump Cover Plate</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>KRB</td>
<td>25</td>
<td>428 (428)</td>
<td>475</td>
</tr>
<tr>
<td></td>
<td>290</td>
<td>329 (294)</td>
<td>342</td>
</tr>
<tr>
<td>Ringhals Elbows</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Hot</td>
<td>25</td>
<td>424 (399)</td>
<td>469</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>315 (292)</td>
<td>362</td>
</tr>
<tr>
<td>Cross-over</td>
<td>25</td>
<td>392 (368)</td>
<td>409</td>
</tr>
<tr>
<td></td>
<td>350</td>
<td>277 (290)</td>
<td>333</td>
</tr>
</tbody>
</table>

* The values within parentheses represent unaged material.
Figure 1. Microstructure along axial section of Loop A check valve.

Figure 2. Microstructure along axial section of Loop B main shutoff valve. A repair weld is also seen on the outer diameter of the valve.
Figure 3.  Microstructure along axial section of spare volute

Figure 4.  Ferrite morphology of cast materials from Loops A, B, and C cold-leg check valves
Figure 5. Fretting morphology of cast materials from loops A, B, and C.
Effect of annealing on Charpy transition curve for cast material from the hot-leg main shutoff valve. Material MA9 is from a cooler region of the valve. $\delta_c$ and $\delta_m$ are calculated and measured ferrite contents, respectively.

Charpy transition curves for hot-leg main shutoff valve after 13 y service at 281°C. Row 1 represents inner 15-mm region and rows 2 and 3 represent 15- to 50-mm region of the valve body. Results from recovery-annealed MA1 are shown as the baseline Charpy transition curve.
Figure 8. Charpy transition curves for cold-leg check valves from Loops A and B after 13 y of service at 264°C. Baseline transition curve for CA₄ is represented by results for recovery-annealed material.

Figure 9. Charpy transition curves for service-aged (13 y of service at 264°C) and spare pump volutes. Baseline transition curve for PV is represented by results for recovery-annealed material.
Figure 10. Yield and ultimate stress values (estimated from Charpy–impact data and obtained from tensile tests) for cold-leg check valve and pump volute, and estimated tensile stresses of recovery–annealed materials.

Figure 11. Yield and ultimate stress values (estimated from Charpy–impact data and obtained from tensile tests) for hot-leg main valve, and estimated tensile stresses for recovery–annealed materials. Material MA9 is from a cooler region of the valve.
Figure 12. Variation of estimated room-temperature Charpy–impact energy with service time for Loop A hot-leg main valve materials MA1 and MA9. Material MA9 is from a cooler region of the valve. $\delta_c$ is calculated ferrite content.

Figure 13. Variations of estimated room-temperature Charpy–impact energy with service time for Loop A cold-leg check valve CA4 and pump volute PV. $\delta_c$ is calculated ferrite content.
Figure 14. Variations of estimated room-temperature Charpy-impact energy with service time for the KRB pump cover plate and Shippingport spare pump volute VR. $\delta_c$ is calculated ferrite content.

Figure 15. Estimated and measured fracture toughness J-R curve at room temperature and 290$^\circ$C for the Shippingport cold-leg check valve and hot-leg main valve.
Figure 16. Estimated and measured fracture toughness J-R curve at room temperature and 290°C for the Shippingport cold-leg pump volute and the KRB pump cover plate.
Figure 17. Estimated and experimentally observed room-temperature Charpy-impact energy for the Ringhals hot- and crossover-leg elbow.

Figure 18. Estimated fracture toughness J-R curve at room temperature for the Ringhals hot- and crossover-leg elbows after ~13 y of service.