Notch Toughness of Austenitic Stainless Steel Weldments with Nuclear Irradiation

Types 304 and 316 weldments show significant reductions in dynamic tear and Charpy-V notch ductility with elevated temperature irradiation to intermediate neutron fluence in the EBR-II reactor

BY J. R. HAWTHORNE AND H. E. WATSON

ABSTRACT. The pre- and postirradiation notch toughness of austenitic stainless steel plate and weld deposits was explored to aid materials selection and application for liquid metal fast breeder (LMFBR) reactors. The study encompassed six plates (AISI Types 304, 316, 304L, 316L), two submerged arc weld deposits (Types 308 and 316), and one shielded metal-arc weld deposit (Type 308). Dynamic tear (DT) and Charpy-V (Cv) test methods were employed to determine notch toughness trends. Specimen irradiations were conducted in the EBR-II reactor in sodium at temperatures from 700 F to 840 F (371 C) to 449 C. Neutron fluences ranged from 1 to 12 x 10^21 n/cm^2 >0.1 MeV.

Significant radiation reductions in notch toughness were observed for both weld deposit and plate materials. Postirradiation toughness of weld deposits in general appeared to be inferior to that of base metals.

Introduction

Designs for liquid metal fast breeder reactor (LMFBR) systems project extensive use of austenitic stainless steel weldments. The choice of stainless steel for primary circuit structural components reflects a demand for both high temperature strength and high resistance to liquid metal (sodium) corrosion. Welding is expected to play a vital role in component fabrication because of component sizes and complexity. For most, if not all, nuclear system components, fracture resistance retention during service is a primary requirement. This study explores the pre- and postirradiation notch toughness of austenitic stainless steel plate and weld deposits representing different filler compositions and welding processes. Primary emphasis centers on AISI Types 304 and 316 plate compositions and on AISI Types 308 and 316 filler metals as leading candidates for LMFBR structures.

Irradiation tends to increase the yield strength and reduce the dynamic tear (DT) and Charpy-V (Cv) notch toughness of structural alloys. Both effects are in the direction of decreased fracture toughness. If sufficiently severe, the effects can result in a frangible metal state. Variable sensitivity to elevated temperature irradiation has also been observed frequently with structural alloys. Accordingly, a determination of postirradiation fracture resistance characteristics for various stainless steel plate and weld compositions was deemed important to LMFBR material selection and application. In simulation of LMFBR service, specimen irradiations for this study...
were conducted in the Experimental Breeder Reactor-II (EBR-II).

**Materials**

Six plates and three experimental weld deposits were evaluated by the study and are identified by type, composition, and heat treatment condition in Tables 1 and 2. Welding parameters and procedures are given in Table 3. The submerged arc weldments conformed to specifications established by the Division of Reactor Development and Technology, U.S. Atomic Energy Commission (AEC-RDT) and were fabricated by the Oak Ridge National Laboratory. The shielded metal-arc weldment was made with lime-coated electrodes by the Combustion Engineering Corporation (CE). Conformance to AEC-RDT specifications was not tested in this case since comparable weldments previously satisfied the requirements.

Tensile, standard C and %-in. DT test specimens were taken with their long dimension parallel to the primary rolling direction for base metal plates and perpendicular to the welding direction for weld deposits. The tensile specimens contained a 0.182 in. diam by 1 in. long gage section. The C and DT specimens had the notch oriented perpendicular to the plate or weldment surface. After machining, the DT specimen notch was sharpened using the pressed knife edge technique described in Reference 5.

### Material Irradiations

Three irradiation experiments were conducted in the EBR-11 reactor core (flow 7 fuel lattice positions). Details of individual experiments are outlined in Table 4. All specimens were irradiated in direct contact with the reactor sodium coolant flow. Coolant temperature at the inlet to the assembly was about 700 F (371 C). Coolant outlet temperature was estimated to be either 760 F (404 C) or 840 F (449 C), depending upon the experiment and the nominal reactor power level. For optimum use of irradiation assembly space only the central test section (2.2 in.) of the DT

### Table 2—Heat Treatment Condition

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield strength, ksi</th>
<th>Heat treatment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>75 F (24 C)</td>
<td>800 F (427 C)</td>
</tr>
<tr>
<td><strong>Type 308</strong> S/A weld</td>
<td>66.0 (b)</td>
<td>49.4 (b)</td>
</tr>
<tr>
<td><strong>Type 304</strong> base metal</td>
<td>37.0</td>
<td>24.0 (b)</td>
</tr>
<tr>
<td><strong>Type 316</strong> S/A weld</td>
<td>50.9 (b)</td>
<td>47.4 (b)</td>
</tr>
<tr>
<td><strong>Type 316</strong> base metal</td>
<td>44.1</td>
<td>28.6 (b)</td>
</tr>
<tr>
<td><strong>Type 308</strong> SMA weld</td>
<td>62.8</td>
<td>(c)</td>
</tr>
<tr>
<td><strong>Type 304</strong> plate</td>
<td>21.1</td>
<td>20.8</td>
</tr>
<tr>
<td><strong>Type 304L</strong> plate</td>
<td>21.5</td>
<td>19.6</td>
</tr>
<tr>
<td><strong>Type 316</strong> plate</td>
<td>20.3</td>
<td>21.9</td>
</tr>
<tr>
<td><strong>Type 316L</strong> plate</td>
<td>21.5</td>
<td>19.7</td>
</tr>
</tbody>
</table>

(a) Uniaxial tension test except as noted
(b) Compression test
(c) Not available

### Table 3—Welding Materials and Parameters for Experimental Test Weldments

<table>
<thead>
<tr>
<th>Material/parameter</th>
<th>Type 308 S/A weldment</th>
<th>Type 316 S/A weldment</th>
<th>Type 308 SMA weldment</th>
</tr>
</thead>
<tbody>
<tr>
<td>Base metal</td>
<td>Type 304H plate (1 in.)</td>
<td>Type 316 plate (1 in.)</td>
<td>Type 304 plate (2 in.)</td>
</tr>
<tr>
<td>Filler metal</td>
<td>Type 308 (5/32 in. diam.)</td>
<td>Type 316 (1/8 in. diam.)</td>
<td>Type 308 (1/4 in. diam.)</td>
</tr>
<tr>
<td>Flux</td>
<td>Arcos S-4 (Lot 9D7F)</td>
<td>Arcos S-16 (Lot 1C9L)</td>
<td>CE special electrode</td>
</tr>
<tr>
<td>Backing</td>
<td>Type 304L (1/4 X 2 X L)</td>
<td>Type 316 (1/4 X 1 X L)</td>
<td>Lime coating</td>
</tr>
<tr>
<td>Joint</td>
<td>Single vee (80 deg incl. angle)</td>
<td>Single vee (90 deg incl. angle)</td>
<td>Equal double U, (5/8 in. rad., 7 1/2 deg bevel)</td>
</tr>
<tr>
<td>Restraint</td>
<td>Full (mechanical)</td>
<td>Full (mechanical)</td>
<td>Full (mechanical)</td>
</tr>
<tr>
<td>Current</td>
<td>600 A, ac</td>
<td>420 A, dc</td>
<td>250 A, dc</td>
</tr>
<tr>
<td>Voltage</td>
<td>33-35 V</td>
<td>30-32 V</td>
<td>24 V dcrp</td>
</tr>
<tr>
<td>Travel</td>
<td>18 ipm</td>
<td>12 ipm</td>
<td>8 ipm</td>
</tr>
<tr>
<td>Stickout</td>
<td>1 1/2 in.</td>
<td>1 1/4 in.</td>
<td>&lt;300 (149 C)</td>
</tr>
<tr>
<td>Interpass temperature</td>
<td>&lt;350 F (177 C)</td>
<td>&lt;350 F (177 C)</td>
<td>Acetone, wire brush</td>
</tr>
<tr>
<td>Interpass cleaning</td>
<td>Grinding, acetone, wire brush</td>
<td>Grinding, acetone, wire brush</td>
<td>Acetone, wire brush</td>
</tr>
<tr>
<td>Postweld HT</td>
<td>900 F (482 C) 1 hr, FC</td>
<td>900 F (482 C) 1 hr, FC</td>
<td>None</td>
</tr>
</tbody>
</table>
this section by the gas tungsten-arc method, using automatic equipment specially adapted for remote hot cell operation. It is pointed out also that, after irradiation, the specimen V-notch was machined (broached) after irradiation.

Neutron fluence values \((n/cm^2 >0.1\text{ MeV})\) for Experiments Nos. 1 and 2 were developed using the Guide for Irradiation Experiments in EBR-II (Revision 4), Appendix C — Core Environment issued by the Argonne National Laboratory. Fluence values for Experiment No. 3 were calculated by the Fast Reactor Materials Dosimetry Center with aid of measurements from iron wire neutron detectors \([^{56}\text{Fe}(n,p)^{56}\text{Mn}}\) reaction in the assembly.

It is specially noted that the in-reactor time for specimen assemblies exceeded reactor operating time significantly. Nominal specimen temperatures during reactor outages were 700 F (371 C). To ascertain the effects of long term thermal conditioning, selected unirradiated specimens were aged at 700, 800, and 900 F (371, 427, and 449 C) for 1000 hr prior to test.

### Results and Discussion

Figures 1-5 summarize notch ductility determinations for pre- and postirradiation conditions. For the shielded metal-arc weld data, were developed only for the preirradiation and aged conditions (Table 5). Postirradiation tensile property determinations for Experiment No. 3 are given in Table 6.

Looking first at preirradiation performance, all plates evaluated demonstrated high initial \(C_v\) toughness at elevated temperatures. In addition, notch toughness appeared relatively independent of temperature for the range 75 F (24 C) to 1100 F (593 C). This general performance was confirmed by DT assessments of the 1 in. Types 304 and 316 plates. Average DT energy values for the plates were, respectively, 1300 ft-lb and 1700 ft-lb for temperatures to 900 F (482 C). In contrast to base metal performance, the three weld deposits exhibited a much lower preirradiation toughness. Average DT energy values for the Types 308 and 316 submerged arc welds and for the Type 308 shielded metal-arc weld were 690, 630, and 975 ft-lb, respectively.

Comparison of the preirradiation properties of the two Type 308 weld deposits (Table 5) denotes a superior product by the shielded metal-arc process. The higher preirradiation toughness of this weld, in particular, would promote a higher postirradiation toughness. It is noted, however, that the delta ferrite contents of the respective welds were not the same (15% for submerged arc versus 7% for shielded metal-arc). An influence of this factor on relative irradiation response is suspected. The Type 316 submerged arc weld deposit contained 7% delta ferrite comparable to the shielded metal arc weld.

Long term (1000 hr) thermal aging at 700 F (371 C) and at 900 F (482 C) produced some lowering (-20 ft-lb) in \(C_v\) energy absorption for both submerged arc weld deposits and for base metal plates (Figs. 1 and 3). A similar reduction was evident for the shielded metal-arc weld deposit when aged at 900 F (482 C) but not at 700 F (371 C). For the high toughness levels described, the decrease in plate toughness due to aging would be insignificant to in-service performance. However, for the weld deposits, a decrease with aging would appear quite important. Microstructure changes from either of the aging

### Table 4 — Summary of Irradiation Experiments

<table>
<thead>
<tr>
<th>Experiment number</th>
<th>Materials</th>
<th>Specimen types</th>
<th>EBR-II lattice position</th>
<th>Irradiation temperature, F C</th>
<th>Fluence range, (n/cm^2 &gt;0.1\text{ MeV})</th>
<th>Irradiation time, hr</th>
<th>In-reactor period, days</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (X095)</td>
<td>S/A weldment: Type 304 plate, Type 308 weld</td>
<td>DT, (C_v)</td>
<td>7A5</td>
<td>700-840 371-449</td>
<td>7—12.5</td>
<td>120.8 (7553 Mwd)</td>
<td>331 (a)</td>
</tr>
<tr>
<td>2 (X139)</td>
<td>S/A weldment: Type 316 plate, Type 316 weld</td>
<td>(C_v)</td>
<td>7A5</td>
<td>700-840 371-449</td>
<td>9.5</td>
<td>98.8 (6177 Mwd)</td>
<td>247</td>
</tr>
<tr>
<td>3 (X026)</td>
<td>Plate: Types 304, 316, 304L, 316L</td>
<td>(C_v), T</td>
<td>7D5</td>
<td>700-760 341-404</td>
<td>1.6—8.0</td>
<td>108.0 (4091 Mwd)</td>
<td>242</td>
</tr>
</tbody>
</table>

(a) Specimen temperatures \(\geq 700\text{ F (371 C)}\) except for 107 days at 300 F (149 C).

### Table 5 — Properties Comparison of Experimental Type 308 Weld Deposits

<table>
<thead>
<tr>
<th></th>
<th>2 in. SMA deposit</th>
<th>1 in. S/A deposit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Yield strength (ksi)</td>
<td>62.8</td>
<td>66.0 (a)</td>
</tr>
<tr>
<td>Tensile strength (ksi)</td>
<td>94.5</td>
<td>107.4 (a)</td>
</tr>
<tr>
<td>DT energy (ft-lb) 700 F (371 C)</td>
<td>1030</td>
<td>740</td>
</tr>
<tr>
<td>800 F (427 C)</td>
<td>—</td>
<td>640</td>
</tr>
<tr>
<td>900 F (482 C)</td>
<td>920</td>
<td>700</td>
</tr>
<tr>
<td>Average</td>
<td>975</td>
<td>690</td>
</tr>
<tr>
<td>(C_v) energy (ft-lb)</td>
<td>108</td>
<td>65</td>
</tr>
<tr>
<td>700 F (371 C)</td>
<td>—</td>
<td>61</td>
</tr>
<tr>
<td>800 F (427 C)</td>
<td>114</td>
<td>54</td>
</tr>
<tr>
<td>900 F (482 C)</td>
<td>111</td>
<td>—</td>
</tr>
<tr>
<td>1100 F (593 C)</td>
<td>—</td>
<td>—</td>
</tr>
<tr>
<td>Average (700-900 F)</td>
<td>111</td>
<td>60</td>
</tr>
<tr>
<td>(C_v) energy (ft-lb) Aged (b)</td>
<td>114 (c)</td>
<td>55 (d)</td>
</tr>
<tr>
<td>700 F (371 C)</td>
<td>—</td>
<td>44 (d)</td>
</tr>
<tr>
<td>800 F (427 C)</td>
<td>92 (c)</td>
<td>46 (e)</td>
</tr>
<tr>
<td>900 F (482 C)</td>
<td>—</td>
<td>15</td>
</tr>
</tbody>
</table>

(a) Compression data
(b) Aged and tested at same temperature
(c) 2400 hr age, duplicate tests
(d) 1000 hr age
(e) Average 3 procedures
treatments were not detected by optical microscopy.

With irradiation, marked decreases in DT and Cv energy absorption values as well as increases in strength were observed for both weld deposit and plate materials. The experimental results denote progressive property changes with increasing fluence above 1 to $2 \times 10^{14}$ n/cm² $>0.1$ MeV. For the exposure temperature range investigated, property changes did not appear greatly influenced by the particular exposure temperature employed. Only a small decrease in irradiation effect with increasing irradiation temperature was anticipated, however.

Comparisons among the Types 316 and 304 plates indicate better postirradiation toughness by the Type 316 composition. This trend pattern is repeated in comparisons between the Type 316L versus Type 304L plates (Fig. 5) and between the Type 316 and the Type 308 submerged arc weld deposits. In summary, the results describe a general relation between postirradiation properties and alloy composition.

From Figs. 1-3, it is clear that intermediate electron exposures at 700 to 840 F (371 to 449 C) can lower weld deposit notch toughness to a marked extent. If the postirradiation yield strength of the Type 308 submerged arc weld deposit is 120 ksi or higher, for example, the postirradiation DT energy level would suggest caution.

### Table 6 — Tensile Properties of Stainless Steel Plates Irradiated in Experiment No. 3

<table>
<thead>
<tr>
<th>Plate</th>
<th>Test temperature, F</th>
<th>Fluence (n/cm²) $&gt;0.1$ MeV</th>
<th>Irradiation temperature, F</th>
<th>Y.S., ksi</th>
<th>T.S., ksi</th>
<th>True stress at max. load, ksi</th>
<th>Natural strain at max. load, in./in.</th>
</tr>
</thead>
<tbody>
<tr>
<td>304 SS (% in.)</td>
<td>700</td>
<td>371</td>
<td>1.1</td>
<td>700</td>
<td>371</td>
<td>23.6</td>
<td>66.6</td>
</tr>
<tr>
<td>304 SS (% in.)</td>
<td>800</td>
<td>427</td>
<td>2.9</td>
<td>700</td>
<td>371</td>
<td>24.6</td>
<td>69.2</td>
</tr>
<tr>
<td>304 SS (% in.)</td>
<td>900</td>
<td>482</td>
<td>4.2</td>
<td>700</td>
<td>371</td>
<td>39.9</td>
<td>73.7</td>
</tr>
<tr>
<td>316 SS (% in.)</td>
<td>700</td>
<td>371</td>
<td>2.9</td>
<td>700</td>
<td>371</td>
<td>20.8</td>
<td>66.3</td>
</tr>
<tr>
<td>316 SS (% in.)</td>
<td>800</td>
<td>427</td>
<td>4.2</td>
<td>700</td>
<td>371</td>
<td>38.6</td>
<td>72.3</td>
</tr>
<tr>
<td>316 SS (% in.)</td>
<td>900</td>
<td>482</td>
<td>7.3</td>
<td>719</td>
<td>376</td>
<td>66.2</td>
<td>82.2</td>
</tr>
<tr>
<td>304L SS (% in.)</td>
<td>700</td>
<td>371</td>
<td>1.1</td>
<td>700</td>
<td>371</td>
<td>25.8</td>
<td>73.4</td>
</tr>
<tr>
<td>304L SS (% in.)</td>
<td>800</td>
<td>427</td>
<td>6.2</td>
<td>704</td>
<td>373</td>
<td>44.3</td>
<td>78.9</td>
</tr>
<tr>
<td>304L SS (% in.)</td>
<td>900</td>
<td>482</td>
<td>6.2</td>
<td>704</td>
<td>373</td>
<td>43.8</td>
<td>73.5</td>
</tr>
<tr>
<td>316L SS (% in.)</td>
<td>700</td>
<td>371</td>
<td>1.1</td>
<td>700</td>
<td>371</td>
<td>22.7</td>
<td>72.3</td>
</tr>
<tr>
<td>316L SS (% in.)</td>
<td>800</td>
<td>427</td>
<td>6.2</td>
<td>704</td>
<td>373</td>
<td>43.8</td>
<td>73.5</td>
</tr>
<tr>
<td>316L SS (% in.)</td>
<td>900</td>
<td>482</td>
<td>6.2</td>
<td>704</td>
<td>373</td>
<td>43.8</td>
<td>73.5</td>
</tr>
</tbody>
</table>

(a) Calculated spectrum determination
(b) Calculated exposure temperature
with regard to low fracture resistance for 2 in. or thicker components. Plate toughness retention, on the other hand, appears adequate for fluences to \( \sim 1 \times 10^{22} \text{n/cm}^2 > 0.1 \text{MeV} \), especially if the lower postirradiation yield strength of plates relative to that of weld deposits is considered (Table 6). It should be noted, however, that directional properties behavior was not assessed. In another investigation involving the Type 316L plate and <300 F (149 C) irradiation conditions, a 3 to 1 difference in postirradiation toughness was observed between longitudinal and transverse test directions. Accordingly, further investigation of this aspect is warranted.

A final observation is the inflection in postirradiation toughness for plate and weld deposits between 900 F and 1100 F (482 C and 593 C). The DT results of Fig. 2 infer that the inflection may, in fact, take place above 1040 F (560 C). The change may be due to an annealing of radiation effects during specimen conditioning (heating and conditioning time was \( \frac{1}{2} \text{hr, average}, \text{and } 1 \text{hr. maximum} \)) or to a fracture mode transition. A clarification was precluded by the limited number of specimens available. Carbide precipitation, in contrast, would have an opposite effect on toughness. The experimental findings describe a need for more detailed study of weld metal performance with irradiation. In particular, the influence on performance of delta ferrite content and morphology should be qualified. Also, the relative importance of welding parameters versus weld process to postirradiation toughness requires assessment. Nonetheless, on the basis of the above results, it would appear that weld metal properties will primarily govern the fracture resistance characteristics of welded LMFBR stainless steel components.

Conclusions

Primary observations and conclusions as related to 700 to 840 F (371 to 449 C) irradiation are as follows:

1. Significant reductions in the DT and \( C_v \) energy absorption of stainless steel weld deposits are possible with irradiation to intermediate neutron exposures (7 to \( \times 10^{21} \text{n/cm}^2 > 0.1 \text{MeV} \)). One submerged arc Type 308 weld deposit exhibited less than 20 ft-lb \( C_v \) and \( \sim 250 \text{ ft-lb DT after irradiation} \).

2. Shielded metal-arc weld deposits, because of superior preirradiation properties, appear to offer higher postirradiation notch toughness than submerged arc weld deposits.

3. Delta ferrite content may be a

![Fig. 1](https://example.com/fig1.png)

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![Fig. 2](https://example.com/fig2.png)

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![Fig. 3](https://example.com/fig3.png)
critical factor governing the performance of weld deposits both with and without neutron exposure.

4. Large reductions in the DT and CV energy absorption of stainless steel base metals are also possible with irradiation to intermediate neutron exposures. Postirradiation values, however, remain generally high because of preirradiation levels.

5. The composition Type 316 generally offers higher postirradiation performance of weld deposits both with and without neutron exposure. Stainless steel weld deposits and plates is relative independent of test temperature between 700 and 840 °F (371 and 449 °C).

6. Notch ductility as well as strength property changes with irradiation are progressive with increasing fluence over 1 to 2 × 10¹¹ n/cm² >0.1 MeV and are relatively independent of exposure temperature between 700 and 840 °F (371 and 449 °C).

7. The notch ductility of stainless steel weld deposits and plates is relatively independent of test temperature for the range 75 to 900 °F (24 to 482 °C). For the irradiated condition, DT and CV values tend to be higher at 1100 °F (593 °C) than at 900 °F (482 °C).

8. Thermal aging at 700 and 900 °F (371 and 482 °C) for 1000 hr can produce a small reduction in DT and CV notch ductility for both weld deposits and base metals. Microstructural changes with aging were not observed.

9. Further investigation should focus on the influence of delta ferrite content on postirradiation properties and on the relative contribution of welding parameters and conditions to postirradiation performance.

Acknowledgments

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Fig. 4—Comparison of the Charpy-V notch ductility of the 3/4-in. thick Types 304 and 316 plates after EBR-II irradiation (Experiment No. 3)

Fig. 5—Comparison of the Charpy-V notch ductility of the Types 304L and Type 316L plates after EBR-II irradiation (Experiment No. 3)

References


