Irradiation Experiment to Determine Effect of Long Term Low Dose Irradiation on FBTR Grid Plate Material

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International Conference on Fast Reactors and Related Fuel Cycles: Safe Technologies and Sustainable Scenarios, 4 – 7 March, 2013, Paris, France
Introduction

Fast Breeder Test Reactor (FBTR) at Kalpakkam, India, has been operating for more than 27 years.

- The near core permanent structures have undergone low dose irradiation that induces changes in mechanical properties.

- Grid plate of FBTR is one of the permanent core structures supporting the core subassemblies and is subjected to low fluence neutron irradiation conditions over its life time. Life of the grid plate is one of the main factors that decides the operating life of FBTR.

This paper describes the details of an irradiation experiment on the grid plate material, and the results obtained from post-irradiation mechanical tests.
Materials

- Type 316 stainless steel (SS) has been used in the fabrication of grid plate of FBTR.
- To assess the mechanical properties of the material, an accelerated irradiation test was performed in FBTR to characterize the mechanical property changes of 316 SS subjected to low dose irradiation.
- Chemical composition of the type 316 SS grid plate material of FBTR, as analysed by spark emission spectrometry:

<table>
<thead>
<tr>
<th>Element</th>
<th>Cr</th>
<th>Ni</th>
<th>Mn</th>
<th>Mo</th>
<th>C</th>
<th>Si</th>
<th>Cu</th>
<th>Co</th>
<th>Pb</th>
<th>Al</th>
<th>Sn</th>
<th>Ti</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>15.2</td>
<td>12.3</td>
<td>1.80</td>
<td>2.06</td>
<td>0.06</td>
<td>0.76</td>
<td>0.12</td>
<td>0.22</td>
<td>&lt; .01</td>
<td>.03</td>
<td>&lt; .01</td>
<td>&lt;0.08</td>
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</table>
Irradiation Experiment

- Flat sub-size tensile specimens and disc specimens (8.0 mm diameter and 1.0 mm thick) were machined from the available stock of FBTR grid plate material.

- A vented type irradiation capsule of 20 mm outer diameter and 18 mm inner diameter was fabricated with five compartments (C1 to C5).

- Each compartment was loaded with 6 tensile and 6 disc specimens.

- The irradiation capsule was locked in a special steel subassembly and loaded in FBTR for irradiation.
Irradiation Parameters

- During irradiation, reactor sodium entered and surrounded the specimens through the holes made in the wall of irradiation capsule
- The irradiation temperature of the specimens was 350 to 370°C
- The neutron doses attained in the specimens in the five partitions from top to bottom were 1.1, 2.0, 2.6, 2.1, and 1.2 dpa, respectively
- After completion of irradiation, post irradiation examination of the specimens was carried out in hot cells.
Extraction of Irradiated Specimens

- The carrier subassembly was received in the RML hot cells and cleaned in ethyl alcohol for removing the residual sodium.
- The capsule was unlocked from the carrier assembly and safely retrieved.
- Capsule was cut with precision at various locations using an Nd-YAG Laser system to retrieve the specimens from each compartment.
- The specimens from each compartment were identified and stored in labeled containers after ultrasonic cleaning.
Remote Tensile Testing

- Uni-axial tensile tests were carried out on irradiated grid plate tensile specimens retrieved from each partition.
- Remote tensile tests were performed as per the ASTM E-8 and ASTM E-21 standards using a 2 Ton capacity tensile test machine having a resistance heating furnace installed in the hot cells.
- Tensile tests were performed at a nominal strain rate of $4 \times 10^{-4}$/s at temperatures of ambient ($28^\circ$C), $350^\circ$C and $400^\circ$C ($\pm 2^\circ$C).
Analysis of Tensile Data

- Load-crosshead displacement data recorded during the tensile tests was converted into stress-strain data using the original dimensions of the specimen measured prior to its loading in the capsule.

- Stress-strain plots of the tested specimens were analyzed to estimate the 0.2% offset yield strength (YS) and ultimate tensile strength (UTS).

- Ductility values were defined by the parameters Strain to Necking (STN) and Strain to Failure (STF).

- STN was evaluated as the plastic strain from 0.2% yield offset to maximum load prior to onset of necking.

- STF was evaluated as strain from 0.2% yield offset to failure load.
Irradiated SS316 undergoes an increase in YS and UTS with respect to the unirradiated values for all the dpa conditions. Increase in YS is considerably higher than the increase in UTS (compared to unirradiated values) for the irradiated specimens. Narrowing of the difference between YS and UTS with increase in dpa reduces the ability of the steel to work harden leading to the onset of plastic instability at lower strains. This resulted in the reduction in STN to about 22-32% for the specimens irradiated to 1.2 - 2.6 dpa from a value of about 45% for the un-irradiated condition for tests conducted at 350°C.
Tensile Test Data

The trends of radiation hardening and loss of ductility in tensile tests carried out at 400°C and 28°C were similar to that of 350°C tests.
Comparison with trends reported in literature

- **Variation of tensile ductility with dpa of SS 316 steel irradiated at 425 to 475°C and tested at 350°C [Tavassoli, A. A., STP 1046]**

<table>
<thead>
<tr>
<th>Material</th>
<th>dpa</th>
<th>T&lt;sub&gt;irrad&lt;/sub&gt;</th>
<th>T&lt;sub&gt;test&lt;/sub&gt;</th>
<th>Ductility</th>
</tr>
</thead>
<tbody>
<tr>
<td>Test in Rapsodie</td>
<td>316 SS</td>
<td>1.3</td>
<td>425-475°C</td>
<td>350°C</td>
</tr>
<tr>
<td>Tavossoli et al.</td>
<td>316 L</td>
<td>4-5</td>
<td>400°C</td>
<td>350-400°C</td>
</tr>
<tr>
<td>Research Reactor ORR</td>
<td>J316</td>
<td>5</td>
<td>330-400°C</td>
<td>330-400°C</td>
</tr>
<tr>
<td>FBTR grid plate (present work)</td>
<td>316 SS</td>
<td>2.57</td>
<td>350°C</td>
<td>350°C &amp; 400°C</td>
</tr>
</tbody>
</table>

Our results are in the same ranges as reported in literature for similar irradiation and test conditions.
Estimation of residual life from ductility criterion

- Based on the results of several studies, a design limit for fast accumulated neutron dose was set to maintain 10% fracture elongation.

- This criterion, adopted using ASME code definition of ductile material as that which has more than 10% fracture elongation, was found to give the most conservative estimate of irradiation damage of FBR structural materials.
Extrapolation from present study

Extrapolation of reduction in uniform elongation to 10% corresponds to a dose of 4.37 dpa. This corresponds to 6.5 EFPY of reactor operation.
Estimation of residual life from ductility criterion

- The residual ductility limit for the FBTR grid plate has been considered to be based on % STN instead of % STF, conservatively.
- A STN of above 20% at test temperatures of 28°C, 350°C and 400°C of SS 316 indicated retention of adequate ductility in SS 316 grid plate of FBTR for an accumulated fast neutron dose of 2.6 dpa.
- By extrapolating the experimental data of % STN and dpa at 400°C, it can be inferred that the limit of 10% STN will be reached at 4.4 dpa.
- Irradiation of further samples is planned to validate this extrapolation.
Conclusions

- An accelerated irradiation test was performed in FBTR to characterize the mechanical property changes of the type 316 SS grid plate material subjected to low dose irradiation.
- SS 316 irradiated to neutron doses of 1.1 - 2.6 dpa showed an increase in YS and UTS from the unirradiated values.
- The increase in YS was more pronounced than increase in UTS and this resulted in a reduction of uniform elongation or strain to necking.
- These results are consistent with the results of irradiated SS316 reported in the literature.
- The 2.6 dpa specimen exhibiting a uniform elongation of above 20% at test temperatures of 28°C, 350°C and 400°C indicated retention of adequate residual ductility in SS 316 irradiated to this displacement damage.
- Based on an extrapolation of the experimental data, the limiting value of 10% on uniform elongation is estimated to be reached after 6.5 EFPY, at a dose of 4.4 dpa.
- Further irradiation experiments are planned to validate this extrapolation.
Thank You