Fracture Analysis of HFIR Beam Tube Caused by Radiation Embrittlement

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Abstract

With an attempt to estimate the neutron beam tube embrittlement condition for the Oak Ridge High Flux Isotope Reactor (HFIR), fracture mechanics calculations are carried out in this paper. The analysis provides some numerical result on how the tube has been structurally weakened. In this calculation, a lateral impact force is assumed. Numerical result is obtained on how much the critical crack size should be reduced if the beam tube has been subjected to an extended period of irradiation. It is also calculated that buckling strength of the tube is increased, not decreased, with irradiation.

Introduction

The 6061-T6 Al embrittlement data was reported earlier by K. Farrell and R.T. King. New 6061-T6 Al embrittlement data of 20 years irradiation in HFBR was obtained by technical staffs in Brookhaven National Laboratory. The (BNL) notch-impact tests are the first such tests for heavily irradiated 6061-T6 alloy. The test data reinforce the concern about the HFIR beam tubes that caution should be taken to avoid impacting the tubes because of the loss of ductility by irradiation. Fracture mechanics calculations are carried out in this paper to quantitatively evaluate the embrittlement condition. The analysis provides some numerical result on how the tube has been structurally weakened. In this calculation, a lateral impact force is assumed. Numerical result is obtained on how much the critical crack size should be reduced if the beam tube has been subjected to an extended period of irradiation. It is also calculated that buckling strength of the tube is increased, not decreased, with irradiation.

6061-T6 Aluminum Embrittlement Data

The 6061-T6 aluminum embrittlement data reported earlier by K. Farrell and R. T. King indicates that the effect of neutron irradiation creates damage in 6061-T6 aluminum which tends to increase the yield stress and to reduce the ductility. These effects were plotted against a range of neutron fluences in that report. The ductility is strongly correlated to the fracture toughness of the material. A loss of ductility implies a decrease in toughness. A modified plot is shown in Fig. 1 that shows the effect of irradiation to the yield strength increase and the toughness decrease. This plot is the basic material property for the aluminum alloy to be used in this fracture mechanics analysis of beam tubes.
The chemical composition of the 6061 aluminum alloy has 1.0 weight percent of magnesium and 0.6 percent silicon with smaller quantities of copper and chromium. "T6" tempered condition represents 1 hour at 795K followed by water quench, than aged 18 hours at 433K and air-cooled. This tempered process creates fine precipitates of Mg-Si which induces high strength to the alloy while still retaining adequate ductility. The specimen of Farrell's experiment was heavily irradiated in Oak Ridge High Flux Isotope Reactor (HFIR). The effect of neutron irradiation creates damage structures consisting of dislocations, a precipitate of transmutation-produced silicon, and some voids, all of which contributes to the strengthening of the alloy and the associated loss of ductility. The heat treated specimens were irradiated in HFIR at about 328K for periods up to 3 1/2 years, during which they accumulated fast (E>0.1 MeV) neutron fluences up to $1.8 \times 10^{27}$ neutrons/m$^2$. The maximum silicon level generated from aluminum was estimated to be 7.15 weight percent. After irradiation, the specimens were tension tested to failure at a strain rate of $3 \times 10^{-4}$/s at temperature of 323K.

In Fig. 1, for the neutron fluences up to $1.8 \times 10^{27}$ n/m$^2$ the yield stress was increased from 40 ksi to 67 ksi. The loss of ductility as reported by Farrell et al. reached a saturated value for an extended period of neutron fluences. Therefore, the fracture toughness is also assumed to reach a saturated value in Fig. 1. For the unirradiated 6061-T6 Al, the fracture toughness of 25 ksis/in was obtained by D. Alexander$^4$ from the Metals and Ceramics Division, ORNL. The value is plotted in Fig. 1. The test specimens have been irradiated in HFIR target area for an extended period of time and are ready to be tested for the determination of the irradiated toughness of the alloy. The test data will be available shortly. At present, Alexander recommends an estimated value of 15 ksis/in at saturation. The toughness is believed to reach the saturated value at the fluences of $10^{28}$ n/m$^2$ and remains constant up to $2.0 \times 10^{28}$ n/cm$^2$. The estimated toughness curve is plotted in Fig. 1. The reduced toughness of 15 ksis/in is a rough estimate. by using The estimate can, at most, be based on the recent impact energy data$^{23}$. The impact energy of the HFBR irradiated control rods was measured by staffs from BNL. The impact energy was reduced from 18 ft-lb at unirradiated condition to 3 ft-lb after irradiated.

**Failure Assessment Diagram**

A fracture mechanics analysis procedure, the failure assessment diagram$^6$ (FAD), was developed by the Central Electricity Generation Board (CEGB) in U.K. and by the U.S. Nuclear Regulatory Commission (NRC) for predicting structure fracture. The method requires a set of material constants including fracture toughness, yield stress and elastic constants.

The method is based on the theoretical elastic-plastic crack model of Dugdale. This model can be expressed by a curve in a two dimensional plane with x-axis representing the applied force and y-axis the material toughness. Any point that is enclosed within the curve represents the condition of no fracture. Both CEGB R/6 procedure and the NRC procedure are based on this theory but adapted to realistic conditions. The CEGB R/6 failure assessment diagram will be used in the present analysis because of its simplicity.
The FAD curve is plotted in Fig. 2. The applied stress $S$ along the $x$-axis is non-dimensionalized by the stress $S_a$, and the stress intensity factor $K$ along the $y$-axis by the fracture toughness $K_c$. The variable $S_r$ is defined by

$$S_r = \frac{S}{S_a}$$

where

$$S_a = \sigma_y (1 - \frac{a}{t})$$

In the above equation, $\sigma_y$ is the yield stress, $a$ is the crack depth and $t$ is the thickness of the beam tube. The variable $K_r$ for the $R/6$ curve is also a non-dimensional quantity with the following form:

$$K_r = (1 - 0.14 S_r^2) [0.3 + 0.7 \exp (-0.65 S_r^3)]$$

where

$$K_r = \frac{K}{K_c}$$

The corresponding curve derived by using Dugdale’s model is also plotted in Fig. 2. The two curves are almost identical for small values of $S_r$. They deviate at large values of $S_r$ because of the work-hardening property of the material.

It was shown in Fig. 1 that both the yield stress $\sigma_y$ and the brittle toughness $K_c$ vary as functions of the neutron fluences for the aluminum alloy. The two material constants $\sigma_y$ and $K_c$ are only implicit variables that is used to nondimensionalize the applied stress $S$ and the stress intensity factor $K$ in the FAD curve. The FAD curve assumes a unique form irrespective to the magnitudes of $\sigma_y$ and $K_c$. The diagram can be used for either the unirradiated or the radiated structure. For the structure under irradiation, the point in the FAD decreases in $S_r$ and increases in $K_r$, reflecting the effect of radiation embrittlement of the structure.

**Path to Failure Curve**

The method to assess the fracture of the beam tube by applying FAD will be illustrated. The path to failure curve can be constructed. At fracture, it reaches the $R/6$ curve. It is assumed that the beam tube is subjected to lateral impact which may be represented by a concentrated force acting at the midpoint of the beam tube.
Given a series of crack depths prescribed on the surface of the tube and a lateral force acting on the tube, a curve can be generated in the failure assessment diagram. This curve is defined as the path to failure curve. The intersection of this curve to the R/6 curve gives the critical crack depth at which the structure fractures.

For the unirradiated beam tube, three curves are plotted in Fig. 2, corresponding to lateral forces of 1, 2 and 3 kips. Three critical crack depths of 0.85t, 0.59t, and 0.38t, are obtained as the curves intersect the FAD curve. For the same lateral forces, the path to failure curves for the irradiated tube are shown in Fig. 3. The critical crack depths for fracture are reduced to 0.83t, 0.43t, and 0.28t, respectively. The unirradiated curves are relocated in the FAD plane to the new position because the yield stress $\sigma_y$ is increased from 40 ksi to 60 ksi and the toughness is reduced from 25 ksi/\text{in} to 15 ksi/\text{in}. The derivation of the path to failure curve will be shown in the next section.

**Stress Intensity Factors**

To determine the path to failure curve requires the numerical values of $S$ and $K_I$ for a range of crack depths at a given lateral force. The definitions of these variables have been defined earlier in Eqs. 1 and 4. For the beam tube problem, $S$ is the tensile stress along the surface of the tube and $K_I$ is the stress intensity factor at the crack front of an assumed crack depth. Both $S$ and $K_I$ are linear functions of the lateral force applied at the beam tube.

Newman and Raju$^7$ made some calculation and determined the stress intensity factor $K_I$ for a given surface cracks on the rectangular plate. We shall use this solution to approximately represent the stress intensity factor for the beam tube problem.

The $K_I$ value has the expression,

$$K_I = S\sqrt{\frac{\pi a}{Q}} Q_o$$

where $a$ is the crack depth and $t$ is the tube thickness. $Q_o$ is a coefficient that is tabulated in the paper and

$$Q = 1 + 1.464 \left(\frac{a}{c}\right)^{1.65}$$

For the crack depth to length ratio $a/c = 0.2$, the numerical values of the coefficient for a range of crack depths $a/t$ is approximately represented by

$$Q_o = 0.144 \left(\frac{a}{t}\right)^2 + 1.015 \left(\frac{a}{t}\right) + 0.956$$
The parametric representation of the path to failure curve is

$$K_r = \frac{S\sqrt{\pi}t}{K_c} \left[ -\frac{1}{\sqrt{Q}} \right] \sqrt{\frac{a}{t} \frac{Q_o(a)}{a}} = a_1 \left[ -\frac{1}{\sqrt{Q}} \right] \sqrt{\frac{a}{t} Q_o(a/t)}$$

$$S_r = \frac{S}{\sigma_y} \frac{1}{1 - \frac{a}{t}} = a_2 \frac{1}{1 - \frac{a}{t}}$$

For values of $a/t$ from 0.1 to 0.8, the curves are plotted in Figs. 2 and 3. In both figures,

$$a_1 = \frac{S\sqrt{\pi}t}{K_c},$$

$$a_2 = \frac{S}{\sigma_y}$$

The coefficients $a_1$ and $a_2$ are directly proportional to the tensile stress $S$ on the surface of the tube. For the lateral force of 1000 lbs acting at the midpoint of the tube, the maximum stress on the tube surface is

$$S = 7.33 \text{ ksi}$$

The above solution is obtained by using the following dimensions of the tube. For the beam tube HB-3, the length of the tube, the inner radius of the tube, the thickness of the tube, the unirradiated toughness and the yield stress are, respectively,

$$l = 144 \text{ in}$$

$$r = 2 \text{ in}$$

$$t = 0.374 - 0.02 = 0.354 \text{ in}$$

$$K_c = 25 \text{ ksi} \sqrt{\text{in}} \text{ unirradiated at room temperature}$$

$$\sigma_y = 40 \text{ ksi} \text{ unirradiated at } 373^\circ\text{K}$$

where an effective thickness $t$ is defined by subtracting a corrosion layer estimated of at most 0.02 inches.

By using these constants and 1000 lbs lateral force, we obtain
The corresponding path-to-failure curve is tabulated by the following numerical values:

<table>
<thead>
<tr>
<th>a/t</th>
<th>Sr</th>
<th>Kt</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.1</td>
<td>0.20</td>
<td>0.0989</td>
</tr>
<tr>
<td>0.2</td>
<td>0.23</td>
<td>0.1538</td>
</tr>
<tr>
<td>0.3</td>
<td>0.26</td>
<td>0.2059</td>
</tr>
<tr>
<td>0.4</td>
<td>0.30</td>
<td>0.2586</td>
</tr>
<tr>
<td>0.5</td>
<td>0.36</td>
<td>0.3130</td>
</tr>
<tr>
<td>0.6</td>
<td>0.45</td>
<td>0.3700</td>
</tr>
<tr>
<td>0.7</td>
<td>0.60</td>
<td>0.4286</td>
</tr>
<tr>
<td>0.8</td>
<td>0.90</td>
<td>0.4921</td>
</tr>
</tbody>
</table>

The other two curves may be obtained by using the stress S to be $2 \times 7.33$ and $3 \times 7.33$, respectively. For the irradiated beam tube, the curves are recalculated by using a yield stress of 60 ksi and a toughness of 15 ksi/in and, therefore,

$$a_1 = \frac{S}{K_t} = \frac{7.33/0.384\pi}{25} = 0.31$$

$$a_2 = \frac{S}{\sigma_y} = \frac{7.33}{40} = 0.18$$

The three irradiated curves are plotted in Fig. 3.

The fracture lateral force versus crack depth for irradiated and unirradiated tubes are plotted in Fig. 4. It shows quantitatively how the fracture lateral force could be reduced as a result of radiation. Lateral force is not generated under normal operating condition. The lateral force may be generated under seismic excitation.

The equivalent lateral force under seismic event is estimated here. The total weight of the tube of 144 inches long is 68.3 pounds. If a peak ground acceleration is applied, then a total lateral force is 10.25 pounds. This force can be located at far left end of Fig. 4. Obviously, it poses little threat to the integrity of the tube.
Buckling Calculations for the Beam Tube

For most of the earlier analyses, the beam tube were assumed to be a straight tube with no end cap. The beam tube design analyses were mostly based on its resistance to buckling due to external pressure that was the regular operating pressure. An examination of the stress distribution of the beam tube structure with the effect of the end cap will be made here by using the finite element method. The finite element calculations are made to obtain the deformation shape and the stress distribution of the beam tube with the effect of the cap. The purpose of the calculation is to verify how the end cap of the tube will disturb the stress distribution of the tube and whether we may neglect the effect of the end cap. The resulting calculation shows that the maximum stress is located at the main portion of the tube and the maximum compressive stress is approximately 7 times that of the applied external pressure.

The straight pipe geometry is analyzed by using the elementary methods of elastic buckling and elastic-plastic buckling. The purpose of the calculation is intended to illustrate that buckling is not a critical issue for the life extension analysis of the beam tube. The irradiation of the beam tube does not decrease, but increase, the strength of the tube if buckling is used as a failure criterion.

The elastic-plastic buckling stress is

\[
\sigma_{cr} = \frac{\sigma_y}{1 + \frac{\sigma_y (1-\nu^2)}{E} \frac{4r_o^2}{h^2}} = 23.8 \text{ ksi}
\]

and that for the embrittled beam tube is

\[
\sigma_{cr} = \frac{60}{1 + \frac{60(1-\nu^2)}{E} \frac{4r_o^2}{h^2}} = 35 \text{ ksi}
\]

After irradiation the buckling strength is increased from 23.8 ksi to 35 ksi. Under neutron irradiation, the yield stress can increase from 40 ksi to 60 ksi after a few years of service and the loss of ductility will reduce the effect of creep strain. In general, the effect of neutron irradiation increases the buckling strength of the tube.

Conclusions

By applying the method of failure assessment diagram, a range of critical crack sizes for the unirradiated beam tube subjected to lateral forces are obtained. The calculation shows how the beam tube may fail through lateral impact. The possible
impact may result from earthquake or possible accident. For a period of neutron irradiation, the critical crack sizes are also obtained. The sizes of the cracks are substantially reduced, reflecting the amount of radiation embrittlement of the beam tubes. As an alternative failure mechanism, simple beam tube buckling loads are calculated. The result shows that for the tubes under irradiation the buckling strength of the tube actually is increased. The radiation increases the strength of the beam tube against failure by buckling.

References


4. Alexander, D, Technical Communication, April 10, 1992


Figure Captions:

1. 6061-T6 aluminum alloy tensile and fracture properties vs. neutron fluences

2. Failure assessment diagram and path to failure curves for unirradiated HFIR beam tube

3. Failure assessment diagram and path to failure curves for irradiated HFIR beam tube

4. Fracture of embrittled beam tube caused by lateral force
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Failure Assessment Diagram, Irradiated

\[ K_{lc} = 15 \text{ ksi/in}, \sigma_y = 60 \text{ ksi} \]

Lateral Force = 1, 2, and 3 kip

Dugdale

CEGB R/H/R6

path to failure
\[ a/t = 0.1 \text{ to } 0.8 \]
Failure Assessment
Diagram, Unirradiated
Klc = 25 ksi/in, σy = 40 ksi
Lateral Force = 1, 2 and 3 kip

Dugdale

CEGB R/H/R6

path to failure
a/t = 0.1 to 0.8

Kr

0 0.2 0.4 0.6 0.8 1 1.2

Sr

a1 = 0.93, a2 = 0.54
a1 = 0.62, a2 = 0.36
a1 = 0.31, a2 = 0.18

Klc = 25 ksi/in, σy = 40 ksi
Lateral Force = 1, 2 and 3 kip
Crack Depth (fraction of thickness)

Lateral Force (1000 lb)

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- Iradiated
- Uniradiated

1000 Kg