Measurement of mechanical properties of a PHWR operated pressure tube using an in-house developed ‘In situ Property Measurement System (IProMS)’

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Abstract
In the field of alternate methods for estimation of properties of materials, cyclic ball indentation is an emerging technique. Reactor Engineering Division has developed an ‘In situ Property Measurement System (IProMS)’, suitable for Zr-2.5Nb pressure tubes of 220 MWe PHWRs. It can be deployed for cyclic indentation trials inside a pressure tube at any axial location. Trials have been carried out at Post Irradiation Examination Division using IProMS in a reactor operated pressure tube, removed from Kakrapar Atomic Power Station-2 after 12.76 Full Power Years of operation. This report describes ball indentation technique and the results obtained from the trials carried out.

Introduction
Cyclic ball indentation is an emerging technique used for estimation of mechanical properties of materials. In this technique, a selected location on the surface of the test material is subjected to 8 to 10 loading and unloading indentation cycles using a tungsten carbide ball indenter. An analysis of the indentation load applied and the corresponding indentation depth produced using a methodology developed by Hagagg et. al. [1] gives an estimate of the mechanical properties of the test material. A material specific constant, independent of its condition is used to evaluate the properties. The systems available worldwide for doing ball indentation trials are mostly of fixed location based or are capable of doing the experiment on the outside surface of pipes. It may be noted that mechanical properties of many of the reactor components change during reactor operation due to nuclear radiation. Many times it may not be possible to remove the component from the reactor and, even in cases where the component can be removed, it is necessary to bring it to radiological laboratories in heavily shielded flasks to prepare the specimens for measurement by conventional technique. The whole process, including the removal of the component is highly cumbersome and consumes large amount of radiation dose. In such cases, availability of a system which can be used under in-situ conditions to measure the properties would be highly appreciated. With this objective, an innovative system called, ‘In situ Property Measurement System (IProMS)’ that can be located inside a tubular component to do the cyclic indentation trial has been developed by Reactor Engineering Division (RED) [2-6]. The system is specifically meant for pressure tubes of 220 MWe Pressurised Heavy Water Reactors (PHWRs). Periodic assessment of mechanical properties of pressure tube is a requirement for assessing its fitness for service [7]. Previously, the system has been qualified by conducting large number of trials inside Zr 2.5 wt% Nb pressure tubes having different known
mechanical properties. In the present work, indentation trials have been carried out at different axial locations inside a pressure tube Q10, removed from KAPS-2 (Kakrapar Atomic Power Station, Unit-2) after 12.76 Full Power Years (FPYs) of operation. The trials have been carried out at Post Irradiation Examination Division (PIED) of Bhabha Atomic Research Centre (BARC), where the tube has been shifted from reactor site for PIE studies. Description of IProMS, details of the trials carried out and the results obtained are highlighted in this report.

**Description of IProMS**

IProMS, shown in Fig. 1(a) basically consists of a tool head, a control and recording station and a pressurization module. Indentation is done using a tungsten carbide ball of diameter 1.5 mm, mounted at the tip of a piston. Indentation load is applied hydraulically from a remote location and the depth of indentation is measured using a LVDT, mounted on the piston. IProMS being installed inside a pressure tube spool piece is shown in Fig. 1(b).

**Technique of measurement**

The technique of measurement used in IProMS is based on an analysis of the data generated from multiple indentation cycles with intermittent partial unloading at the same location on the surface of the material being tested using a tungsten carbide ball. Each cycle consists of indentation, partial unload and reload sequences. The indentation load and corresponding depth of indentation are recorded in a computer system during the test. Material properties like yield strength, ultimate tensile strength (UTS) and strain hardening exponent etc. are estimated from a post-processing of the data recorded.

**Estimation of mechanical properties**

The methodology used for estimation of mechanical properties from ball indentation test is described by Haggag [1]. From the data recorded during the test, values of peak load, total depth of indentation and plastic part of the depth of indentation corresponding to each unload cycle are used to estimate the mechanical properties. Schematic representation of ball indentation technique is shown in Fig. 2, the cyclic loading and unloading
Methodology of estimation of properties

i) Estimation of yield strength

In order to estimate the yield strength, the Meyer’s equation (1) is fit to the data points corresponding to each unload cycle. A is called the proportionality constant and m is called Meyer’s coefficient. P is the load applied at the beginning of unload; D is diameter of ball; \( d_i \) is total indentation diameter at the beginning of unload \([1]\).

\[
\frac{P}{d_i^2} = A\left[\frac{d_i}{D}\right]^{m-2}
\] (1)

Values of A and m are derived from the fit of \( \frac{P}{d_i^2} \) vs. \( \frac{d_i}{D} \).

Yield strength is given by equation (2), in which \( \beta_m \) is a constant specific to the material class \([1]\).

\[
\sigma_y = \beta_m A
\] (2)

ii) Estimation of ultimate tensile strength, UTS

In order to estimate the UTS, corresponding to each unload cycle, the values of true stress and true strain are estimated using equations (3) and (4).

\[
\sigma_t = \frac{4P}{\pi d_p^2 \delta}
\] (3)

\[
\varepsilon_p = 0.2 \frac{d_p}{D}
\] (4)

where,

\( \sigma_t \) is true stress, \( \varepsilon_p \) is true plastic strain, \( d_p \) is diameter of indentation after unloading, given in equation (5) and \( \delta \) is a material deformation parameter, estimated based on equation (7) \([1]\).

\[
d_p = \left( 0.5CD\frac{h_p^2 + (d_p/2)^2}{h_p^2 + (d_p/2)^2} \right)^{1/3} \] (5)

\[
C = 5.47P[1/E_1 + 1/E_2] \] (6)

where,

\( h_p \) is the depth of indentation after unloading, \( E_1 \) is Young’s modulus of indenter material and \( E_2 \) is Young’s modulus of test material.

\[
\begin{align*}
\delta &= \begin{cases} 
1.12 & \phi \leq 1 \\
1.12 + \phi \ln \phi & 1 < \phi \leq 27 \\
\phi > 27 & \phi \leq 27
\end{cases}
\] (7)
\( \phi = \varepsilon_p E / 0.43 \sigma_t \)  
(8)

\( \delta_{\text{max}} = 2.87 \alpha_m \)  
(9)

\[ \tau = (\delta_{\text{max}} - 1.12) / \ln(27) \]  
(10)

where,

\( \alpha_m \) is a strain rate sensitivity parameter, and is taken as 1.0 [1].

Power equation (11) is fit to the values of true stress and true strain.

\[ \sigma_t = k \varepsilon_p^n \]  
(11)

The values of strength coefficient \( k \) and strain hardening exponent \( n \), obtained by fitting equation (11) to the estimated values of \( \sigma_t \) and \( \varepsilon_p \), are used to estimate the value of UTS using equation (12).

\[ \text{UTS} = k(n/e)P, e = 2.71 \]  
(12)

\[ \text{HB} = \frac{2P_{\text{max}}}{\pi D (D - (D^2 - d_{pf}^2)^{1/2})} \]  
(13)

where,

\( P_{\text{max}} \) is the maximum load applied during the last unload cycle and \( d_{pf} \) is the diameter of indentation after final unloading.

**Trials inside irradiated pressure tube**

As the radioactivity level of the pressure tube is high, to reduce the exposure to personnel, trials were carried out by locating the pressure tube inside a shielded flask and restraining its movement. Against the standard procedure of polishing of the surface before ball indentation tests, the trials were done at different axial locations in as received surface condition of the pressure tube. An extension pipe having the axial test locations marked, carrying the cables of LVDT and hydraulic hose was attached to the tool head and it was guided through the pressure tube. The measurement operation in progress is shown in Fig. 4(a) and 4(b).

**Results of analysis**

Variation of load vs. indentation depth data acquired from inlet end, outlet end and middle portion of the irradiated pressure tube is shown in Fig. 5. Properties estimated from indentation tests carried out at different axial locations of the pressure tube are tabulated in Table 1. In Table 1, the value of yield strength is derived from equation (2), \( k \) and \( n \) are derived from equation (11), UTS is derived from equation (12) and hardness is derived from equation (13). The variation of properties estimated along...
the length of the pressure tube along with the mean estimate is given in Fig. 6 and Fig. 7. The IProMS estimated true stress vs. true plastic strain data acquired from irradiated and a typical unirradiated pressure tube is shown in Fig. 8.

**Discussion**

**Table 1: IProMS Estimated properties of irradiated pressure tube Q10 of KAPS-2**

<table>
<thead>
<tr>
<th>Test No.</th>
<th>Distance from pressure tube inlet end (mm)</th>
<th>Yield strength (MPa)</th>
<th>UTS (MPa)</th>
<th>Hardness (BHN)</th>
<th>Strain hardening exponent (n)</th>
<th>Strength coefficient, k (MPa)</th>
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<tr>
<td>1</td>
<td>130</td>
<td>655</td>
<td>888</td>
<td>277</td>
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<td>834</td>
<td>269</td>
<td>0.099</td>
<td>1158</td>
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<td>3</td>
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<td>559</td>
<td>757</td>
<td>251</td>
<td>0.12</td>
<td>1101</td>
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<tr>
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<td>602</td>
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<td>0.089</td>
<td>1029</td>
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<tr>
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<td>831</td>
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<tr>
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<tr>
<td>7</td>
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<td>259</td>
<td>0.105</td>
<td>1155</td>
</tr>
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</table>

Material constants: $\alpha_m = 1$, $\beta_m = 0.2652$ [5]; Young’s modulus of Zr-2.5Nb = 95 GPa [8];
An innovative system based on cyclic ball indentation technique has been used to estimate the mechanical properties of an irradiated pressure tube Q10, removed from KAPS-2 after 12.76 FPYs of operation. It can be observed from Fig. 5 that the slope of load-indentation depth data acquired from the middle portion of the pressure tube is more compared to that acquired from its ends. Figures 6 and 7 show the variations of YS, UTS and hardness along the length of the irradiated pressure tube showing highest values at its middle portion. Based on the data given in Table 1, the average yield strength of the pressure tube is 620 MPa and the UTS is 840 MPa, with standard deviations of 31 MPa and 49 MPa respectively. It is to be noted that the test surface of the pressure tube was not specially prepared before the tests, which is the procedure normally followed. Figure 8 shows the comparison between the true stress-true plastic strain data of the tests carried out on irradiated pressure tube Q10 and a typical unirradiated pressure tube using IProMS. It can be observed from Fig. 8 that there is a 20 to 30% increase in strength of the pressure tube after irradiation. The mean values of strain hardening exponent (n) of irradiated and unirradiated pressure tube based on the data shown in Fig. 8 are 0.164 and 0.168 respectively and the mean values of strength coefficient (k) for the same are 1395 MPa and 1098 MPa respectively. It is to be noted that IProMS tests have been carried out on irradiated pressure tube Q10 all along its length of about 5 m, whereas for the tests on unirradiated tube, a spool piece of about 200 mm length has been used. Hence, the scatter in true stress-true plastic strain data is observed to be more for the tests carried out on irradiated pressure tube than that of the unirradiated tube.

**Conclusion**

An innovative system called ‘In situ Property Measurement System (IProMS)’ developed in-house by Reactor Engineering Division has been used for measurement of mechanical properties of an irradiated pressure tube removed from KAPS-2 after 12.76 FPYs of operation. Properties have been estimated at different axial locations of the pressure tube, by keeping the tube inside a shielded flask at Post Irradiation Examination Division, BARC. The results show 20 to 30% increase in mechanical properties of the pressure tube after 12.76 FPYs of irradiation, as compared to that of a typical unirradiated pressure tube. As this was the first attempt towards such an activity of measurement of mechanical properties of irradiated pressure tube using remotely operable IProMS, the properties estimated need to be validated with that derived from conventional tensile tests to be done on samples prepared from different axial locations of the tube. More tests need to be done on pressure tubes irradiated for different time periods for further optimization of the test procedure.
Acknowledgement

The authors are grateful to Shri K.K. Vaze, Former Director, Reactor Design & Development Group and Shri S. Anantharaman, Head, PIED for their support and encouragement in the execution of the job. Authors are also grateful to all the technicians of RED and PIED who are associated with the experimental programme.

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