In-Situ Mechanical Property Measurement System for Zr 2.5 wt% Nb Pressure Tube

K. Madhusoodanan, S. Chatterjee, Sanjay Panwar and J.N. Kayal
Reactor Engineering Division

Abstract
Periodic assessment of mechanical properties of Zr 2.5 wt% Nb pressure tube is required for ensuring its fitness for continued operation in Pressurised Heavy Water Reactors. An In-situ Property Measurement System, designed and developed in house, is capable of doing the measurement of mechanical properties in a non-intrusive manner. The measurement process consists of ball indentation, partial unload and reload sequences at a location. The load and corresponding depth of indentation recorded during the test are analysed, using custom made software to generate information on mechanical properties. The system has been qualified using specimens with known mechanical properties and the safety related issues have been addressed by analytical and experimental work.

Introduction
Measurement of mechanical properties of the pressure tube, made of Zr 2.5 wt% Nb in Pressurised Heavy Water Reactors (PHWRs) is an integral part of the material surveillance programme, necessary to ensure safe operation of the reactor. As a reactor operated pressure tube is highly radioactive, removal of the pressure tube and preparation of specimens from it for testing, consumes high doses of radiation. Considering this aspect, an 'In-situ' Property Measurement System (IProMS), based on cyclic ball indentation has been developed, that can be used for in-situ measurement of the mechanical properties.

Technique of measurement
The technique of measurement used in IProMS is based on an analysis of the data, generated from multiple indentation cycles at the same location, on the surface of the testing material by a tungsten carbide ball. Each cycle consists of indentation, partial unload and reload sequences. The load and corresponding depth of indentation are recorded during the test. Material properties like yield strength, Ultimate Tensile Strength (UTS) strain hardening exponent etc. are estimated from a post-processing of the data recorded. Schematic representation of ball indentation technique is shown in Fig.1.

Fig. 1: Schematic representation of ball indentation technique.
Estimation of mechanical properties

The methodology used for estimation of mechanical properties from ball indentation test, is described in ref. [1, 2]. From the data recorded during the test, values of peak load, total depth of indentation and plastic depth of indentation, corresponding to each unload cycle are used, to estimate the mechanical properties.

System for measurement

IProMS mainly consists of a tool head, (Fig.2) that can be inserted in a pressure tube of 83 mm inside diameter, as shown in Fig.3. Indentation is carried out using a tungsten carbide ball of 1.5 mm diameter and the depth of indentation is measured, using a Linear Variable Differential Transformer. Design of the tool head is such that, there is minimum effect of global deformation on the measurement. System operation, control, data acquisition, analysis and display are achieved using a Control, Operation and Display (COD) Station.

Qualification trials

In order to qualify IProMS, tensile specimens were prepared from Zr 2.5 wt% Nb material, having different mechanical properties obtained through heat treatment, as given in Table 1. All the specimens were tensile tested at ambient temperature, as per the standard ASTM-E8M-1988, using a servo-hydraulic universal testing machine [3, 4]. Ball indentation test was carried out on three specimens each, from the four different categories.

Estimation of mechanical properties

Load deformation curve and variation of true strain vs. true stress for a typical case of H3-7, are shown in Fig. 4.

Table 1: Details of heat treatment carried out on different specimens

<table>
<thead>
<tr>
<th>Sl. No.</th>
<th>Specimen identification</th>
<th>Soaking temperature (°C)</th>
<th>Soaking time (Hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>H3-1</td>
<td>No heat treatment</td>
<td>-</td>
</tr>
<tr>
<td>2.</td>
<td>H3-6</td>
<td>700</td>
<td>2</td>
</tr>
<tr>
<td>3.</td>
<td>H3-7</td>
<td>550</td>
<td>6</td>
</tr>
<tr>
<td>4.</td>
<td>H3-8</td>
<td>800</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Comparison between the mechanical properties from conventional tests and IProMS tests are shown in Fig. 6 and Fig. 7. The difference between mechanical properties from conventional tests and IProMS tests is of the order of 5 to 10%.

**Estimation of residual stress**

When the residual stress introduced by indentation process along with operating stress exceeds a threshold value, hydrides present in the area can crack, leading to initiation of Delayed Hydride Cracking (DHC). Fig. 8 shows the residual stress contour in the tangential direction, obtained from an elastic plastic finite element analysis of the indentation process. It can be observed from Fig. 8, that the stress value exceeds the threshold on a considerably small area on the surface.

**Qualification of indentation area against initiation of DHC**

Pre-hydrided tensile specimens of Zr 2.5 wt% Nb material were subjected to ball indentation, and then tested for DHC as per standard procedure up to a tensile stress of 300 MPa. The indentation area observed under stereo microscope after the indentation test, shown in (Fig. 9), does not indicate initiation of any crack, thereby ruling out the possibility of initiation of DHC.
An 'In-situ Property Measurement System (IProMS)' has been developed, which can be used for in-situ measurement of mechanical properties of pressure tube. Comparison with experimental results from conventional tests indicates, that IProMS will be able to capture the change in mechanical properties of the pressure tube during irradiation. Analytical and experimental studies indicate, that there is no possibility for initiation of DHC from the indentation area.

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References