MACHINING AND INSPECTION OF FINE REFERENCE NOTCHES ON ULTRASONIC CALIBRATION BLOCK FOR THE INSPECTION OF COOLANT CHANNELS USING BARCIS

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ABSTRACT

Indian Pressurized Heavy Water Reactor (PHWR) is a type of nuclear reactor that consists of multiple horizontal pressure tubes rather than a single large pressure containment. Periodic in-service inspection of these pressure tubes is carried out by an Inspection System popularly known as BARCIS (BARC Channel Inspection System). During shutdown all the channels are inspected from ID side by inserting the inspection head from one end with the help of remotely operated drive mechanisms. Besides sag measurement of pressure tube, BARCIS is capable of performing ultrasonic testing (UT) and eddy current testing (ET) for detecting flaws oriented in longitudinal as well as circumferential direction using inspection head containing probes for UT and ET. The acceptance or rejection of flaws in the test specimen is determined by comparing their signal or indications to that from an artificial flaw in the reference block, preferably made from the cut piece of the actual product. However, in case of 540 MWe PHWR, to meet the regulatory requirement it was desirable to have full size reference tube without any cutout so that calibration could be carried out during mock up, simulating the pressure and flow of the coolant maintained at the time of actual inspection when reactor is in shut down condition. It was a challenging task to inspect as well as machine, 0.150 mm wide and 0.086 mm deep notches with close tolerances, especially on ID of 6.332 m long Zirconium – Nb 2.5% pressure tube having 103.4 mm ID and 4.3 mm wall thickness. Since no established process was available to machine the specified notches, number of trials was made using (1) EDM and micro EDM, (2) live tool such as slot milling cutter along with radial attachment on CNC lathe machines and (3) micro scribing tool on a hollow spindle lathe with manual linear and rotational motion. Considering the size of the job and feasibility to machine notches on both inner and outer surface without any cut out, micro scribing was found to be the best suitable process. In this process, a special micro scribing tool with stringent dimensional control was developed for machining longitudinal as well as circumferential notches. Machining and inspection processes were qualified on small sample pieces before carrying out final machining on full size pressure tube. Simultaneously an inspection technique using replica was developed, certified and validated. This paper describes merits and demerits of various machining processes for making notches on a long tube. It also outlines the inspection method developed for the inspection of notches having restricted access.

Keywords: Ultrasonic Testing, Pressure Tube, Indian PHWR, Notch Machining, Micro Scribing, Replica

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INTRODUCTION

Periodic In service Inspection (PISI) is an essential tool for monitoring the health and structural integrity of any pressure containment. Ultrasonic and EddyCurrent Tests play important roles during the PISI of coolant channels used as primary pressure boundaries in Indian Pressurised Heavy Water Reactors (PHWR).

Presently in-service inspection (ISI) of coolant channels of each 235 MWe PHWR is being done by a semi-automated remotised channel inspection system known as BARCIS (Bhabha Atomic Research Centre Channel Inspection System). Design of a new system for the ISI of 540 MWe PHWR coolant channels is under progress.

In each 235 MWe PHWR 306 number of coolant channels also known as pressure tubes (PT) are positioned horizontally between two tube sheets, within a cylindrical vessel, the Calandria. Each PT contains 12 fuel bundles and heavy water coolant flowing inside PT removes the heat generated by nuclear fission. Pressure tube is made of Zircaloy 2 having nominal outside diameter 90.33 mm, wall thickness 3.92 mm
and length 5435.6 mm. External and concentric with the PT is 1 mm thick calandria tube, that separates the hot pressure tube from the cool moderator (heavy water) filled in the surrounding space between reactor tank and calandria tubes. Garter springs are positioned inside the annular space to maintain the gap between PT and calandria tube in order to avoid any heat transfer from primary heat transport system to moderator system.

The BARCIS inspection head contains various Ultrasonic and Eddy Current Transducers enabling it to perform wall thickness measurement and flaw detection besides other activities. Ultrasonic Testing (UT) and Eddy Current Testing (ET) are indirect non-destructive testing methods in which information about the presence of any discontinuity is not obtained directly on the component. Instead, interpretation of signal received due to interaction with the discontinuity is carried out to know its detail.

Since UT is a comparative method, in order to ascertain the shape, size and type of discontinuity, the signal must be compared with that of known flaws in a representative part. In the absence of natural flaw of similar type, it is a standard practice to machine artificial flaws of acceptable size in acoustically similar material. The three most common types of artificial discontinuities are flat bottom holes (FBH), side drilled holes (SDH) and notches. FBH are representative of embedded flaws like inclusions, lamination etc. whereas linear flaws inside the materials are represented by SDH. Notches, representing the most severe type of surface breaking flaws such as cracks, are difficult to machine even on a flat surface having proper access. The difficulty level increases if it has to be machined on the inner surface of a curved specimen with constant depth throughout its length. Generally, to facilitate the insertion of a cutting tool, a sectorial opening is provided on the opposite side of the notch. However, it becomes extremely difficult to machine precision notch deep inside a tube or pipe without any cutout for tool insertion. In case of 540 MWe PHWR, to meet the regulatory requirement it was desirable to have reference tube of circular cross section without any cutout, so that calibration could be carried out during mock up, simulating the pressure and flow of the coolant at the time of actual inspection. Further, depth of the flaw has been reduced to 2% from 3% of the wall thickness, to take care of poor reflectivity of actual flaw.

Indian 540 MWe PHWR consists of 392 coolant channels having 103.4 mm inside diameter and 4.3 mm wall thickness and made of Zirconium 2.5% Niobium. It was required to make different type of notches on 6.332 m long tube in circumferential and axial directions on inner and outer surface. It was a challenging task to machine 0.150 mm wide and 0.086 mm deep, with a tolerance of 5 micron, square notches on the inner surface of 103.4 mm diameter tube at 300 mm from one end. Not only machining but inspection was also difficult for such type of notches due to limited access for inserting any measuring instrument.

Considering the geometry and size of the notch and length of the job three machining processes Electro-Discharge Machining (EDM), Milling on CNC lathe machine and micro scribing on a lathe machine were considered for machining the notch. After several trials, made by these processes, micro scribing was considered as the most suitable process, based on the accuracy and repeatability of the notch dimensions obtained by this process. Measurement of notch dimensions was done by replica method and same was validated by other direct measurement technique.

**REVIEW OF THE MACHINING PROCESSES**

The simplest method of making any notch on a flat surface is to use circular milling cutter on a milling machine, provided variation of notch depth along its length is acceptable. In this process depth is maximum at the centre of the notch and minimum at both the ends. In case of convex surface i.e. notch machining on the outer surface of a pipe in circumferential direction the depth decreases rapidly as we move towards the end from the centre of the notch. Further, using milling cutter, it is difficult to machine notch on the inner surface of a pipe, even with a cutout due to limited accessibility. Axis of the tool cannot be made parallel to the job surface. To overcome these problems, normally Electro Discharge Machining (EDM) is preferred. In the EDM process electrode of required shape and size with proper tolerance is machined and used as formed tool. Both job and electrode are submerged in a liquid such as Kerosene having high dielectric constant offering large resistance to the flow of electrical current. During passage of current, continuous arc between job and electrode is responsible for removing the material from the job as per the shape of the electrode. During machining, depth of the profile is controlled by the feed given to the electrode. Biggest advantage of EDM is that the contour of notch similar to the curvature of the job can be machined.

In EDM process size of the job is controlled by the size of the Kerosene tank. Hence any job larger than the tank can not be machined without any special attachment. Another associated problem is difficulty in maintaining the exact profile of the notch at microscopic level due to continuous erosion of the form tool through which arc is generated. Further, if the thickness of the form tool is very less, as in the present case it was 0.150 mm, erosion of the tool is very fast. Moreover, machining such a thin electrode (0.150 mm) is very difficult. In Micro EDM, electrode machining in the required shape is carried-out by the machine itself and with same holding setup the machined electrode is used as a form tool. With CNC facility, machining of profile is as per the drawing data fed to the machine. Because machining of form tool and EDM process are done in the same set up, a very high level of accuracy is obtained as regard to geometrical features such as perpendicularity, parallelism etc. Like EDM, only small size of specimen can be machined in Micro EDM facility.

**REVIEW OF THE INSPECTION TECHNIQUES**

Because of the limited access, direct measurement of the notch dimensions particularly on inner surface of a pipe or tube is very difficult. Following methods were explored for measurement and qualification:
(i) Conventional measuring instrument: Measurement of notch cross section dimensions i.e. depth and width using conventional measuring instrument such as vernier caliper could not be done because size of the notch is very small and the instrument could not be inserted to take the measurement.

(ii) Co-ordinate Measuring Machine (CMM): This machine is used for various high precision measurements in metrology. The minimum probe size available on CMM machine is $\Phi 0.3$ mm, which could not go in the notch of size 0.150 mm width. Therefore the method was not found suitable for measurement.

(iii) Direct measurement on microscope: Microscope is used for direct measurement of notch dimensions on a cut out of a small size specimen. It has different magnifications for different purpose. In this measuring machine, the magnified image of the component is obtained which is seen through eyepiece (FIGURE 1). The measurement is taken using a dedicated PC and software. This measurement, being a direct method, was used for machining process qualification.

(iv) Replica Method: In this method an impression of the notch is taken and the impression is measured at high magnification on a microscope or a profile projector (FIGURE 1). Care is taken that the impression material should fill up to the bottom of the notch so that correct impression could be obtained. Since it was possible to prepare replica of notches located up to 300 mm distance from one end on the ID side, replica technique was considered suitable for measurement. The technique was qualified by comparing its result with that of direct measurement on a small test piece.

DEVELOPMENT OF THE MANUFACTURING TECHNIQUE

Since length of the job was the major limitations for established machining as well as inspection process, several trials were made on small sample pieces with proper cut out in order to check the quality of machined notches and validate the process. In each process at least one notch was machined up to the edge so that measurement of the depth, width corner radius etc. can be done directly using microscope by magnifying the cross section of the notch.

Micro EDM

The first trial was made on a 200 mm long sample piece using micro EDM. The notch at the edge on OD was inspected using high magnification optical instrument. Since uneven circular bottom, instead of flat bottom was obtained, EDM micro machining was not considered suitable for machining the notches.

Milling with Live Radial Tool

The second trial was made using live radial tool on CNC lathe machine having a milling component attached to it. Some of the pockets on the turret have motors which are able to rotate milling/drilling device independently. Unlike ordinary lathe in which tool is stationary, in this technique tools can also be rotated, hence the name live tool. Enlarged view of the slot milling cutter used for making notch is shown in FIGURE 2. Material is removed by the cutting edges, two in number for the present cutter. In this trial, sample piece was held in chuck and slot milling cutter was mounted on a turret. Length of the circumferential notch was controlled by the indexing motion of the chuck where as turret movement was used for maintaining the length of the axial notches keeping the work piece stationary. In this machine job length up to 1 meter can be accommodated however the major limitation was the size of the cutter. Slot mill cutter less than 300 micron diameter was not available; hence 300 micron was the minimum width which can be obtained by this process. Further, in spite of good bottom profile this technique was not considered suitable due to following two reasons (a) inability to machine ID notch and (b) inability to accommodate 6.3 m long job.
Micro Scribing Technique

Considering the softness of the material (Hardness BHN 205-215) scribing technique was considered feasible, as this technique can be used on a hollow spindle lathe machine which can accommodate large job. In this method a micro scribing tool was employed for notch machining. Since standard scribing tool is not available, a micro scribing tool of the required dimensions was developed using tool and cutter grinder. The micro scribing tool was made using a HSS single point cutting tool (FIGURE 2). Since notch width is same as the width of cutting edge, it was very critical to maintain the width of the small edge and therefore high skill was required to perform the tool grinding operation. Before using, each tool was checked for its all dimensions and geometrical features.

Notch machining is carried out on hollow spindle lathe machine. For longitudinal notch, tool is given reciprocating motion manually, against the stationary job, held in the chuck. Marking was done on the tool holding bar for the length of the notch. For making radial notch, tool was kept fixed and job was given rotational movement manually. Marking corresponding to the length of the notch was done on the head stock and a pointer was fixed to the chuck for setting the length of the notch. Control of depth in case of ID notch was very difficult due to boring bar deflection. Numbers of trials were made to establish a relation between feed depth and actual depth obtained by measurement. Actual machining was carried out in two stages. After first stage depth was measured and then depending upon the requirement, final cut was given. This ensured that depth was within the specified tolerance.

Cross sectional images of notch made by micro EDM, live radial tool and scribing tool on a coolant tube cut piece are shown in Fig. 3.

RESULTS AND DISCUSSIONS

Using the scribing technique in total eight notches, four at each end, were machined on the pressure tube of 540MWe. Out of four notches two were on OD and two were on ID. One pair of OD or ID notches consists of one each axial and circumferential notch. All these notches were measured by replica method using 50x magnification on the Profile Projector. The dimensions actually obtained are indicated in the Table 1. It can be seen from the Table 1 that the obtained

<table>
<thead>
<tr>
<th>Type and Location of Notch</th>
<th>Notch Dimensions (mm)</th>
<th>Remarks</th>
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<tbody>
<tr>
<td></td>
<td>Specified</td>
<td>Obtained</td>
</tr>
<tr>
<td>Axial Notch at 200 mm on Inner Surface</td>
<td>L=25.0 ±0.50</td>
<td>L= 25.0</td>
</tr>
<tr>
<td></td>
<td>W=0.15 ±0.05</td>
<td>W= 0.13</td>
</tr>
<tr>
<td></td>
<td>D= 0.086 ± 0.005</td>
<td>D=0.084</td>
</tr>
<tr>
<td>Circumferential Notch at 300 mm on Inner Surface</td>
<td>L=25.0 ±0.50</td>
<td>L= 25.0</td>
</tr>
<tr>
<td></td>
<td>W=0.15 ±0.05</td>
<td>W= 0.13</td>
</tr>
<tr>
<td></td>
<td>D= 0.086 ± 0.005</td>
<td>D=0.100</td>
</tr>
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</table>

Table 1: Result of Micro Scribing Technique

Fig. 2 : Enlarged view of the slot milling cutter (left) and micro scribing tool (right)

Fig. 3 : Notch by micro EDM (left), slot milling cutter (center) and micro scribing technique (right)
dimensions of notches are well within the tolerance specified. The geometrical requirements of notches i.e. flat bottom and square sides were also achieved. Therefore, the procedure developed for notch machining and measurement are capable of producing the specified quality notches required for carrying out the Non Destructive Examination (NDE) of pressure tube of 540MWe PHWR.

CONCLUSION

Machining of the notches of size 0.086mm depth and 0.150mm width, on 6.3 m long pressure tube for 540 MWe PHWR is very difficult. The manufacturing process is further complicated by the geometry requirement of the notch. The difficulty in manufacturing is because of (a) the requirement of machining notches on ID as well as OD, on large size of the pressure tube without any cut out, (b) non availability of established procedure and (c) non availability of the single point or multi point standard cutting tool of the required size. Considering the difficulties in notch machining, various machining methods such as micro EDM, milling with live tool and micro scribing were explored. The critical requirement of dimensions and geometry of the notches could be achieved by using micro scribing technique. Measurement of the notch dimensions was done by preparing its replica.

REFERENCES