International Journal of Engineering Research & Technology (IJERT)
ISSN: 2278-0181
Vol. 3 Issue 7, July - 2014

# Development and Validation of In-Situ Boat Sampling Technique for Mechanical Property Evaluation and Life Management of TAPS Core Shroud

Kundan Kumar1*, K. Madhusoodanan[1], R. N. Singh[2], J. K. Chakravartty[2], B. K. Dutta[3] and R. K. Sinha[4]
[1]Reactor Engineering Division, [2]Mechanical Metallurgy Division, [3]Reactor Safety Division,
Bhabha Atomic Research Centre, Trombay, Mumbai-400085
[4]Atomic Energy Commission, DAE, Anushakti Bhavan, Mumbai-400001

*Abstract:*-**The core shrouds of twin reactors at Tarapur Atomic Power Station (TAPS) belong to the early class of Boiling Water Reactors and are in operation since 1969. With the background information of many cases of core shroud cracking in foreign countries, a technique has been developed for in-situ scooping out of material and evaluation of mechanical properties of TAPS core shrouds. This paper gives a brief history of core shroud cracking experience world over and related findings; development of scooping technique; preparation of miniature specimens from scooped material, evaluation of mechanical properties using miniature test specimens and validation.**

***Keywords-Life management, boat sampling technique, core shroud, miniature specimen***

## I. INTRODUCTION

In boiling water reactor (BWR), core shroud is an assembly of cylinders fabricated from rolled and welded stainless steel plate material, which has a series of circumferential or horizontal welds named as H1, H2, H3 etc. It supports the top guide which provides lateral support to the fuel assemblies and maintains core geometry during operational transients and postulated accidents to permit control rod insertion. It partitions feed water in the reactor vessel down-comer annulus region from cooling water flowing through the reactor core. While in operation, the core shroud experiences radiation field, high temperature and various static & dynamic loads resulting in degradation of material's mechanical and fracture properties, leading to reduction in safe operating margin. Many of the welds and the adjoining heat affected zone (HAZ) region of core shroud are known to be susceptible of various forms of Stress Corrosion Cracking (SCC) due to simultaneous presence of aqueous environment, high temperature and tensile stress.

Many cases of core shroud cracking have been reported from countries like Germany, Sweden, USA, Japan, etc [1].The first documented incident of cracking in a core shroud was reported in August, 1990 at the KernkraftwerkMühleberg BWR (GE-type BWR/4).This reactor had completed approximately 190 months of power operation before the cracks were discovered. Latercracks were reported from H3 (circumferential weld joins the top guide support ring to the middle shroud shell)weld region and a crack was located in the Heat Affected Zone (HAZ)of Brunswick Steam Electric Plant Unit 1, USA in July, 1993.Boat samples,taken from the H3 weld, suggested crack growth by Intergranular Stress Corrosion Cracking (IGSCC). The visual examination also revealed circumferential cracking along significant portions of welds H1 and H2 and minor cracking associated with the HAZs of circumferential welds H4, H5, H6a, and H6b.Cracking in the core shrouds of Dresden Unit 3 and Quad Cities Unit 1 were found in 1994 refueling outages. The most extensive cracking at each plant was associated with the H5 weld, which joins the mid-shroud shell to the shroud's core plate support ring. The examinations included both enhanced visual examination and ultrasonic testing (UT) methods. Using conservative assumptions, it was determined that the cracks could extend nearly 360° around the circumference of the welds [2].Core shroud of Oyster Creek Nuclear Generation Station was inspected during the 1994 refueling outage using UT inspections of accessible areas on shroud welds H1, H2, H4, H5, and H6a, and enhanced visual examinations of welds H3, H6b, and H9. The results of the shroud examinations indicated significant cracking at the H4 weld. H4 weld joins the upper mid-shroud shell to the lower mid-shroud shell, and is in the vicinity of the reactor beltline region. Some minor cracking at the H2 and H3 welds were also reported[2].The inspection of core shroud of Vermont Yankee Nuclear Power Plant, indicated a significant degree of cracking, approximately 340°—345° in circumference, existed in the weld H5, which joins the lower mid-shroud shell to the core support ring. Cracking of a lesser degree was also indicated at shroud welds H1, H2, H3, H4, and H6[2]. Cracks were found across the weld line of the core shroud in Fukushima Daiichi units 2, 3 and 4 in 1994 [3-5]. Nearly 360° circumferential discrete cracks, which were several mm away from the fusion line, were found in ring along the weld between the shroud shell and the ring. Several radial cracks were found in the HAZ of H4 weld, some of which propagated into the weld metal [3, 4].

The important factors for initiation and growth of IGSCC of SS304 type of steels have been reported as chromium depletion at grain boundaries (known as sensitization),presence of oxidizing environments and influence of local stresses [5, 6]. SS316L was developed in 1977, which has excellent resistance to sensitization and this was assumed to be the only solution for SCC in those days [7].Many core shrouds, earlier made of SS304 were replaced with SS316L material, viz. Fukushima daiichi Unit 3 (1998), Fukushima daiichi Unit 2 (1999), Tsuruga Unit 1 (2000), Fukushima daiichi Unit 5 (2000), Shimane Unit 1 (2001) and Fukushima daiichi Unit 1 (2001) [8, 9].

The cracking of pressure vessel nozzle made of 316L, in 1985,and later cracking in SS316L core shrouds changed the perception of low-carbon SS being the solution for SCC and study in this area started in 1992 [7]. The study revealed that the SCC of low carbon SS was attributed to the depletion of Chromium and enrichment of Nickel and Silicon at grain boundaries as a result of radiation induced segregation (RIS), increase in surface hardness of the material and its sensitivity to SCC [10]; combined effects of high residual stressesassociated with the shroud construction, the presence of a more aggressive, oxidising environment in the core and to micro structural changes in the material [11]; cold work and surface deformation, surface treatment causing surface roughness and hardening [5, 7, 10, 11]; and, residual stresses generated during manufacturing and machining [5,12] of core shroud.

The irradiation assisted stress corrosion cracking (IASCC) is another form of SCC which is more prone to occur after a threshold value of neutron fluence is seen by the core shroud. For austenitic stainless steels in normal water chemistry of BWR environment the threshold value is suggested as 5x1024 n/m2, for high energy neutron (E>1MeV), however experiments have shown this value may be even lower as 2x1024 n/m2[13] for commercial purity SS. It is caused due to exposure to neutron irradiation for extended periods, which changes the microstructure, due to radiation hardening effect; and microchemistry due to RIS of the SS; and degrades their fracture properties [13-16].

Later it was also concluded that all grades of SS and environmental conditions are susceptible to SCC in high temperature water, whether de-aerated or aerated, high or low H2, theoretically pure water or contaminated, lower or higher temperature [17]. However, the kinetics of SCC growth varies enormously with stress intensity, yield strength, degree of sensitization, water chemistry, irradiation, temperature etc. The role of yield strength is especially important because it changes with surface cold work, bulk cold work, weld shrinkage strain, and irradiation hardening. It was also argued that the role of metallurgical strengthening mechanism may have a similar effect [17]. Further it is stated that as core shrouds are subjected to relatively low fluence, and most cases of core shroud cracking have been attributed to classical IGSCC of thermally sensitized stainless steels and because of the applied stresses on the shroud are also very low, the nature of the cracking experienced by the core shroud is strongly influenced by the residual stresses associated with the core shroud welds [18].

Although safety analysis done by concerned agencies for the potential significance associated with the core shroud cracking does not pose a high degree of risk in short term however it is a safety concern in long term because of the uncertainties associated with the behavior of core shrouds with 360° cracks under accident conditions and because it could eliminate a layer of defense in depth [18]. Therefore regular and reliable monitoring for degradation of core shroud material and its weld regions is a requirement which should be followed religiously.

The twin reactors at TAPS belong to the early class (1969) of BWRs. They are dual cycle reactor with primary and secondary loop with installed capacity of 210MWe each unit, however later both units were re-rated to 160 MWe and are operating only on primary loop. TAPS core shrouds have been constructed from various heats of SS304 cylinders (Table-1 provides the chemical composition of various heats of material used), by way of a number of horizontal welds, Fig. 1. The core shroud have served for 26 EFPYs and it is expected that the material would have undergone irradiation hardening during its service and may have worked out surfaces near welds formed during its construction about 45 years ago resulting in hardened surface and due to ignorance about the role of these parameters in SCC may be susceptible to cracking by SCC. It is pertinent to mention that there is no surveillance programme for TAPS core shroud to monitor its health. Hence, a need was felt to develop a technique of scooping out small coupons, machining miniature samples from the coupon for mechanical property evaluation and microstructural characterization, and assess the health of the core shroud material, as has been done in various reactors abroad [7,10,19]. To achieve this objective the scooping technique, known as boat. sampling technique, has been developed for scooping out boat shaped samples from the core shroud. The system has been qualified in a number of shop floor trials, and in full scale mockup trials at TAPS site, and is under safety clearance stage for its reactor deployment. The technique consists of a sampling module, a handling manipulator and process system. This paper describes the sampling module, its use for obtaining boat

TABLE I. CHEMICAL COMPOSITION OF VARIOUS HEATS OF TAPS CORE SHROUD MATERIAL

| Sl No. | C | Mn | P | S | Si | Cr | Ni | Mo |
|---|---|---|---|---|---|---|---|---|
| Heat 1 | 0.055 | 1.640 | 0.025 | 0.018 | 0.5 | 18.58 | 9.57 | 0.24 |
| Heat 2 | 0.058 | 1.21 | 0.019 | 0.013 | 0.54 | 18.9 | 9.38 | |
| Heat 3 | 0.048 | 0.85 | 0.027 | 0.024 | 0.54 | 18.59 | 9.30 | 0.24 |
| Heat 4 | 0.044 | 1.2 | 0.016 | 0.012 | 0.8 | 18.20 | 9.06 | |
| Heat 5 | 0.052 | 1.15 | 0.014 | 0.004 | 0.72 | 18.70 | 9.04 | |
| Heat 6 | 0.068 | 1.24 | 0.018 | 0.015 | 0.46 | 18.89 | 9.07 | |

samples, schemes for preparation of miniature samples, evaluation of mechanical properties using miniature samples and its comparison with those obtained by conventional tests for its validation. Metallographic test for presence of sensitization and for any other applications can also be carried out using boat sample, however, these are not part of this paper.

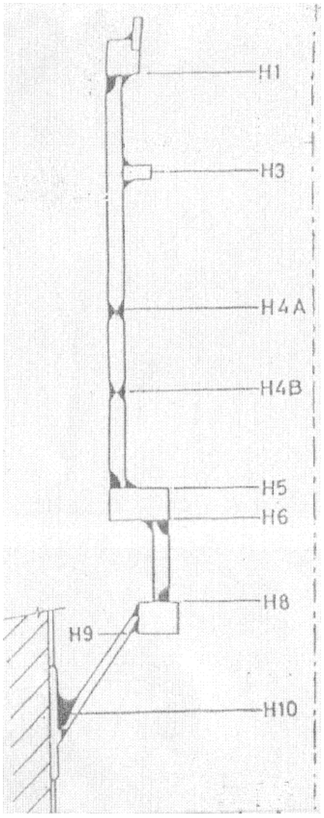


Fig. 1 Horizontal welds of TAPS Core Shroud

## II. BOAT SAMPLING TECHNIQUE

The Boat Sampling Technique (BST) is a remotely operated non-destructive technique for obtaining boat-shaped coupon from the core shroud. The technique, utilizes a scooping device, known as ‘Sampling Module’, shown in Fig. 2a and2b, which operates under water filled condition of reactor and grinds out a boat-shaped sample from the core shroud. The sampling operation is an internal grinding operation and the sample is obtained by spinning the cutter, Fig. 2c, about its axis of symmetry, Fig. 2d, while slowly advancingit about a perpendicular axis to feed the cutter into the parent material. The abrasive coated cutter generates a 1mm wide kerfthrough the material and scooping by its leading edge, which is coated by abrasive particles. Depending upon the operating asymmetries, the actual kerf width may vary. The depth of the depression left in the base material is known as scooped region and is equivalent to the sample thickness plus the kerf width. The contour of the scooped region merges smoothly with the surface profile of the core shroud and there is no loss of integrity or reduction in service life of the core shroud.

The scooped material, known as ‘boat sample’, is used to carry out required mechanical &metallurgical tests. Since the core shroud is filled with water to minimize the radiation dose to personnel, various motors or drives, used in the sampling module are provided with water-sealed muffles. The overall process of scooping is remotely controlled and operable with the help of a number of sensors and control elements.

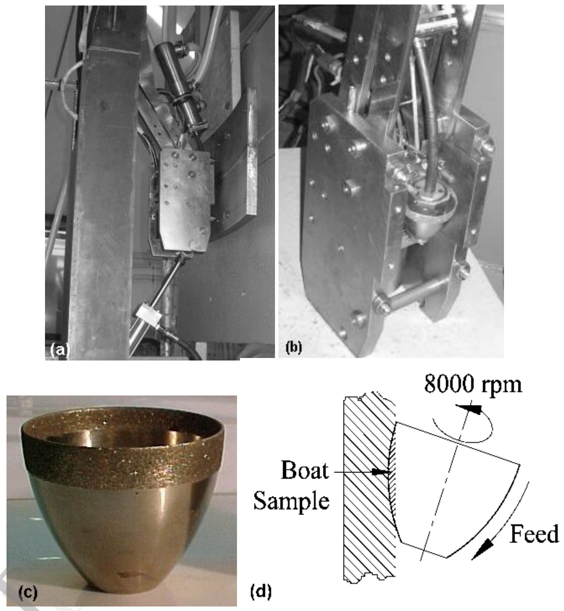
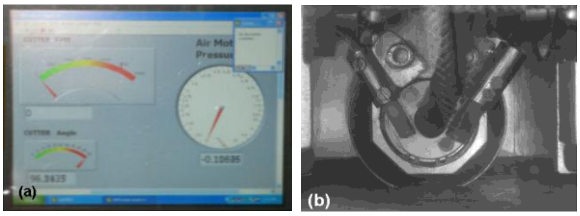


Fig. 2 a) Sampling module positioned for scooping operation, (b) Sampling Module, (c) Cutter, (d) A metal sample is obtained by spinning the cutter about its axis of symmetry, while slowly advancing it about a perpendicular axis to feed the cutter into the parent material.

### A. *Sampling Module*

The sampling module consist of a sampling cutter, Fig. 2c, driving motor, feeding motor, control for the motors, feedback sensors for speed and position monitoring, sample enclosure and thickness control device etc. The driving motor rotates the cutter at 8000 rpm, which is monitored with the help of a hall-sensor based tachometer. The feed motor advances or retracts the cutter in a controlled manner, which senses position by the potentiometer based sensor degrees and displayed in the Human Machine Interface console of the control panel, Fig. 3.The sampling module has been provided with an enclosure for protection against escaping of boat sample, due to centrifugal force, just after its detachment from the shroud wall. The thickness of the boat sample can be controlled by the thickness of the control device in the module.



.3 :Displays in the Human Machine Interface console of the control panel shows (a) RPM and cutter position (b) camera view while sampling operation.

### B. *Sampling Cutter*

The sampling cutter is cup-shaped and is coated with cubic boron nitride abrasive for grinding operation.Cubic Boron Nitride (CBN) is the second hardest known material, only diamond being harder than CBN and is synthesised from hexagonal boron nitride under conditions similar to those used to produce synthetic diamond from graphite. Its properties of high thermal stability and resistance to chemical attack make it suitable for machining of ferrous materials, in areas where diamond abrasives are not normally employed.CBN is known for thermal resistance up to a temperature of 1000°C, like diamond up to 650°C. CBN is free from carbon and does not have any reaction with steel. This property of CBN makes it the ideal for grinding of hardened steel.The nature of bonding of the coating on the cutter is very important. The electroplated bond has been selected on the basis of requirement of geometry of cutter. The coating of CBN is single layer and CBN was deposited uniformly over the steel body of the cutter by the process of electroplating. The higher speed is preferable for high speed grinding process. The size of chips sheared by abrasive grain in electroplated CBN grinding wheel decreases as the cutting speed is increased. This improves grinding efficiency and makes the wheel grind cooler. A large proportion of available power is utilized into shearing chips and less is wasted as heat. High speed grinding machines have short cycle time but highest material removal rate to maximise productivity. They are usually equipped with automated parts loading/unloading.

The grit size is selected along with the bond to suit the component to be ground and surface finish requirement. The performance of grinding by the electroplated cutters is measured in terms of Specific Volume ground value, which is ratio of Volume of parent material removed in mm3 to the Area available in cutter for grinding in mm2.

### C. *Boat Samples*

A boat sample removed from a flat surface,shown in Fig. 4a, is elliptical in shape and has approximate dimension as 40mm long, 25mm wide and 3mm thick at centre. The contour of scooped region, shown in Fig. 4b, is smooth merging with the parent material and has approximate dimensions as 45mm long, 30mm wide and 4.5mm depth at centre.

At the end of the sampling operation, the boat sample falls in the cutter shell by gravitation mode or in the housing of the sampling module, which is collected remotely. Fine mesh powder is generated due to grinding action during sampling which is lost in the pool water.

### D. *Qualification of Sampling Technique*

The qualification of sampling technique includes the individual qualification of sampling module components, viz. cutter, flexible shaft, feed motor, drive motor and motor muffles; sample; scooped region; integrated system and operational procedure based on the safety and operation requirements. The sampling cutter is subjected to circularity test, run out test; the flexible shaft is subjected to life test for 8 hours of operation at 8000 rpm; the motors are subjected to torque margin measurement and the muffles of motors are subjected to leak test. Various mock up trials, shown in Fig. 5and given inTable-2, are conducted for study of the following:

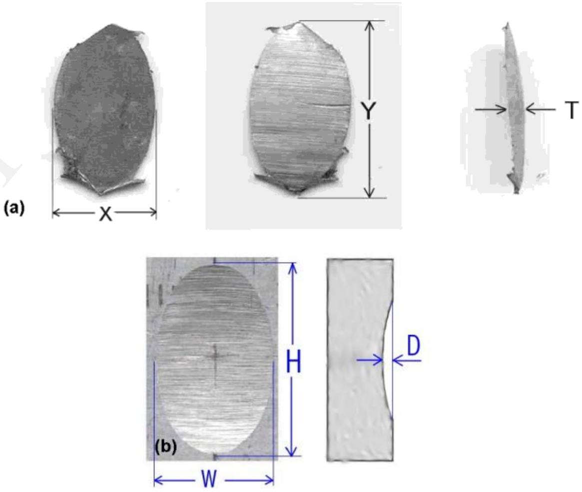


Fig. 4 : Geometry of (a) Boat Sample & (b) Scooped Region

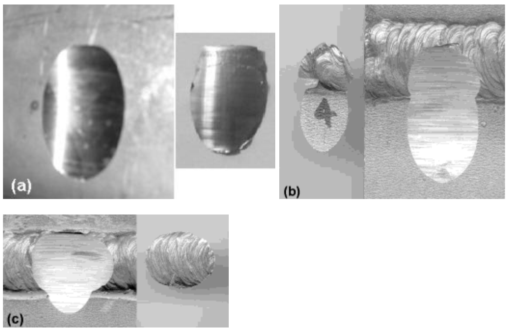


Fig. 5 Boat Samples obtained during qualification trials of sampling operation (a) Sample from Stainless Steel Plate, (b) Sample from HAZ of Welded SS Plate and (c) Sample from Welded SS Plate

a) Dimensional Study of Sample and Scooped Region

b) Surface Finish of Sample and Scooped Region

c) Life Test of Cutter and flexible shaft

d) Optimisation of Sampling Duration

e) Ultrasonic Examination

f) Visual Examination of Scooped Region

g) Fluorescent Dye-Penetrant Test of Scooped Region to find out any crack due to sampling operation

h) Micro-Hardness test of the region to study any hardness change due to sampling operation

i) The dimension and volume of the sample are ensured to be sufficient to carryout mechanical and metallurgical tests.

TABLE II SCOOPING TRIALS ON DIFFERENT MATERIAL CONDITIONS

| **Parent Material** | **Dimensions (in mm)** | |
|---|---|---|
| | Boat Sample (X*Y*T) | Scooped Region (H*W*D) |
| SS-304 | 20x34x1.8 | 39.5x27.6x3.5 |
| | 24x37x2.1 | 42.2x28.8x3.7 |
| Weld SS304 | 25.4x31.5x4.4 | 36x36x6.9 |
| HAZ of SS304 | 17x38x2.7 | 48x25x3.5 |

A full scale mock up facility, Fig. 6a, was created for the 12 m deep under-water operation.The sampling module is attached to the handling manipulator, Fig. 6b, for operation in the core shroud. The mock-up trialswere successfully conducted to reaffirm its capability for actual core shroud sampling operation. The sampling operation was monitored through camera apart from the features available in the sampling module.

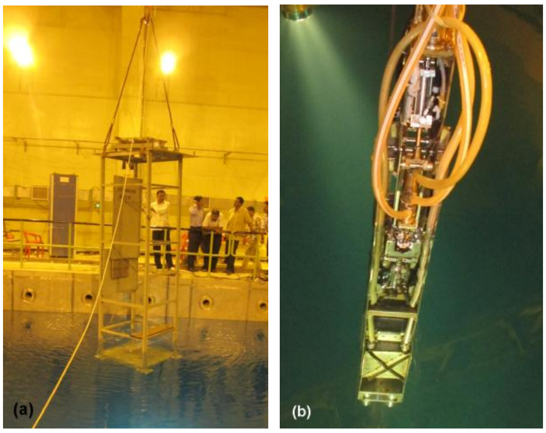


Fig 6 A full scale mock up trials were conducted at TAPS in (a) a water pool under 12metre head using simulated upper & lower grids structures and core shroud, and (b) Integrated assembly of Sampling Module and handling Manipulator

## III. POST EXAMINATION OF BOAT SAMPLE AND VALIDATION

TABLE 3 CHEMICAL COMPOSITION OF MATERIAL USED FOR EXPERIMENT

| **Material** | **C** | **Cr** | **Ni** | **Mo** | **V** | **S** | **P** | **Co** | **Fe** | **N** |
|---|---|---|---|---|---|---|---|---|---|---|
| 304LN | 0.02 | 18.34 | 8.32 | 0.37 | 0.07 | 0.0196 | 0.03 | 0.13 | 70.71 | 0.075 |

Post process of boat sample involves preparation of a various types of miniature test specimens and evaluation of mechanical properties using them. We made dummy boat samples from SS304, Table-3, and they were subjected to Electro discharge machining (EDM) for extraction of various types of miniature test specimens, shown in Fig. 7a & 7b, viz. Miniature tensile specimen of gauge length 3mm, small punch test specimen of diameter 3mm, miniature hour-glass shaped fatigue test specimen of 3mm diameter, and miniature charpy impact test specimen. The specimens, in both methods of preparation, were finally polished using SiC paper in wet condition upto 4000 grit size to obtain scratch free surfaces. The remaining portion of the boat sample can be subjected to other tests like chemical analysis, sensitization test, micro hardness evaluation etc. of the material.

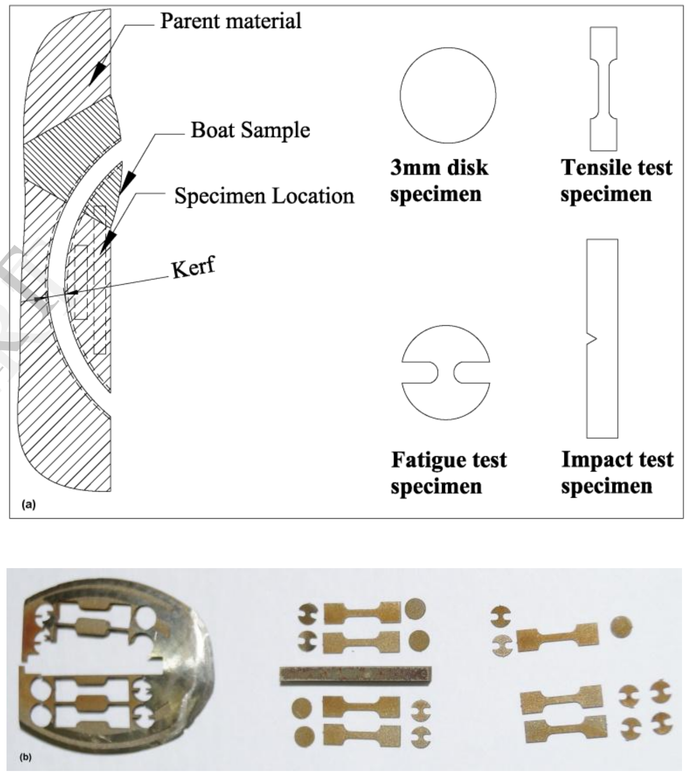


Fig 7 Scheme for extraction of miniature test specimen (7a) Pictorial representation of boat sample from HAZ region & kerf width and 3mm disk specimen, miniature size tensile specimens, 3mm hour glass shaped fatigue specimen and miniature charpy impact test specimen. (7b) preparation of miniature test specimens by EDM

To ensure the usefulness of miniature test techniques it is important to have comparable results of miniature tests and conventional tests with respect to the mechanical properties, viz. UTS, YS and elongation. Validation of mechanical properties obtained from miniature tensile specimen has been done by comparing them with the results of sub-size tensile specimens, Fig. 8, from same block of material SS304.

## IV. RESULTS AND DISCUSSION

Tensile tests were conducted at room temperature at a strain rate of 10-3 per sec on miniature size test specimens, prepared from boat samples of SS304 materials. The tests were conducted on screw driven machine. The strain values were measured using single camera video extensometer. The sub-size specimens from the same block were also tested under similar conditions. The results are summarized in Table-4 and Fig 9. For miniature specimen the UTS and YS are in the range of 725-751 MPa and 423-471 MPa in comparison to respective sub-size values as 727-741MPa and 438-455MPa. The minimum UTS values for both the cases are very close to each other while the minimum YS values are within 3.5% range. The percentage uniform elongation and total elongation values for miniature specimen are 46.2-59.6 and 58.6-74.3 in comparison to respective sub-size values as 46.6-62.7 and 64.5-75. The minimum uniform percentage elongation for both the cases are very close to each other, however the minimum total percentage elongations are within 10% range. Due to high ductility of SS304 material, during testing, there is overall stretching in the parallel section of the specimen and there is continuous strain hardening till the failure and there is not much deformation after necking. Therefore uniform elongation values are very close to total elongation values. Overall it can be concluded that the results obtained by miniature test specimens are comparable with those obtained by conventional sub-size test specimens within a very close error band. With the precise control of surface finish of test specimen, dimensional deviations, alignment of test fixtures, better strain measurement, the error band can be further minimized. It can be emphasized that the method has the potential for successful implementation for mechanical properties evaluation of TAPS core shroud or any other pressure vessel which needs an urgent attention of its life management issues.

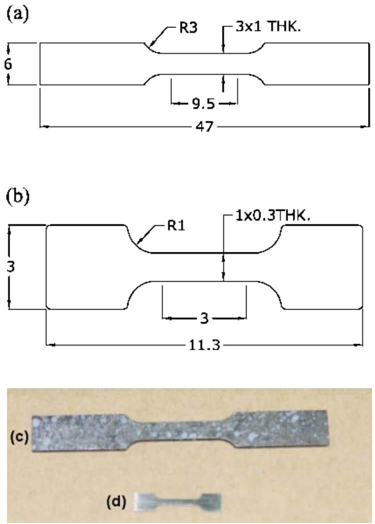


Fig. 8 Dimensional details of (a) Sub-size flat specimen and (b) Miniature Tensile Test Specimens and respective photographs in (c) and (d)

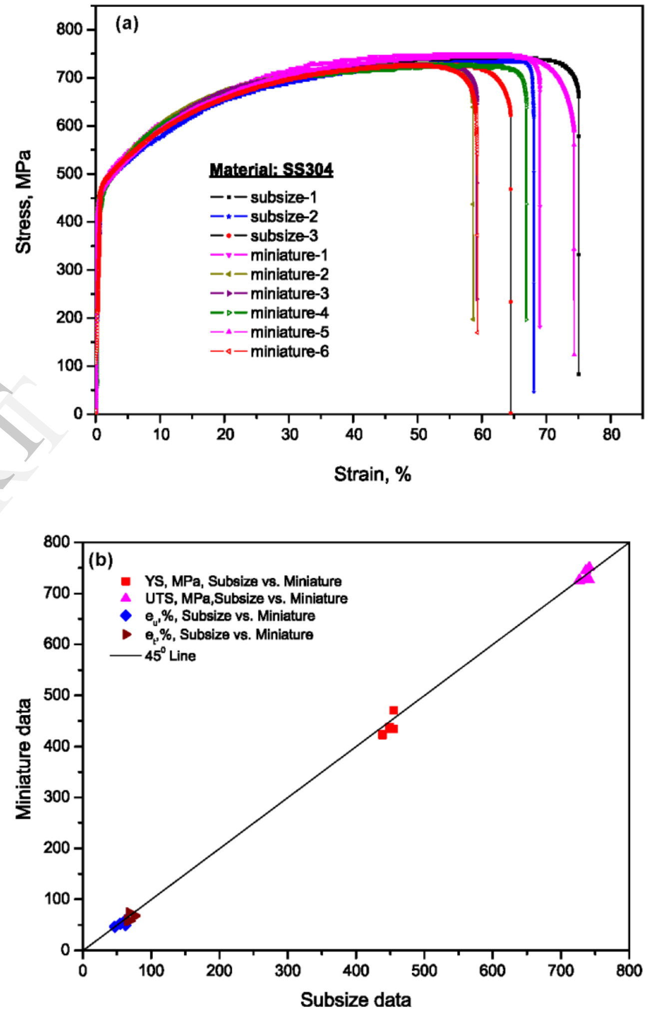


Fig. 9 (a) The engineering stress – strain plot obtained using sub-size

TABLE-4 TEST RESULTS

| | Sub-size specimen | | | Miniature Specimen | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| Specimen No. | 1 | 2 | 3 | 1 | 2 | 3 | 4 | 5 | 6 |
| YS, MPa | 438.3 | 449.1 | 454.6 | 423.3 | 438.5 | 435.0 | 424.6 | 435.0 | 471.0 |
| UTS, MPa | 741.4 | 736.3 | 727.2 | 750.9 | 728.1 | 727.3 | 726.6 | 745.1 | 724.9 |
| Uniform Elongation, % | 54.5 | 62.7 | 46.6 | 52.6 | 49.5 | 46.5 | 52.0 | 59.6 | 46.2 |
| Total Elongation, % | 75.0 | 68.1 | 64.5 | 69.0 | 58.6 | 59.2 | 66.9 | 74.3 | 59.3 |

and miniature specimens for SS304; (b) Scatter in yield strength (YS) and ultimate tensile strength (UTS), uniform and total elongation data of miniature specimens in comparison to sub-size specimens for SS304

## V. CONCLUSION

There has been some sort of uncertainty as well as curiosity regarding the material condition of core shroud of TAPS, which are made of SS304 material and are in operation since 1969, despite the fact that no cracking etc.has been reported during various in-service inspections that have been carried out regularly. This is more important with reported information of cracking of a number of core shrouds world over made of various grades of austenitic stainless steels. In absence of any surveillance programme in placeand to know the present mechanical properties of the core shroud, a sampling technique has been developed for scooping out boat sample from the TAPS core shroud and the system has been successfully tested and qualified in shop floor trials and full scale mock-up trials at TAPS and is under safety clearance for its deployment for sampling operation of core shrouds of unit 1 &2. The mock boat samples were used to obtain miniature test specimens for uni-axial tensile test, small punch test, miniature fatigue test and miniature charpy impact tests. The tensile properties obtained using miniature specimens were found to be in agreement with the results of conventional test specimen and have the potential for acceptability for life assessment tool for TAPS core shroud or for any pressure vessel material in future.

## ACKNOWLEDGEMENTS

The authors are thankful to their colleagues in Reactor Engineering Division, BARC for their support in development and qualification of the system, Division of Remote Handling and Robotics, BARC for making the handling manipulator for the system and TAPS site personnel for their support in qualification of the system and providing logistics for making the system ready for reactor operation.

## REFERENCES

[1] Stress Corrosion Cracking in Light Water Reactors: Good Practices and Lessons Learned, IAEA Nuclear Energy Series, Sept 2011,No. NP-T-3.13

[2] Status Report: Intergranular Stress Corrosion Cracking of BWR Core Shrouds and Other Internal Components, NUREG-1544, March 1996, USNRC

[3] S. Ooki et al, ‘Study on SCC growth behavior of BWR core shroud’ Proceedings of the 12th International Conference on, Environmental Degradation of Materials in Nuclear Power System – Water Reactors –Edited by T.R. Allen, P.J. King, and L. Nelson TMS (The Minerals, Metals & Materials Society), 2005

[4] H. Yamashita, ‘SCC growth behavior of BWR core shroud materials’ International Journal of Pressure Vessels and Piping 85 (2008) 582–592

[5] Wade Karlsen, ‘Localized deformation as a key precursor to initiation of intergranular stress corrosion cracking of austenitic stainless steels employed in nuclear power plants’ Journal of Nuclear Materials 406 (2010) 138–151

[6] Masayuki Kamaya et al, ‘Influence of local stress on initiation behaviour of stress corrosion cracking for sensitized 304 stainless steel’ Corrosion Science 49 (2007) 3303–3324

[7] Y Okamura et al., ‘Latest SCC Issues of Core Shroud and Recirculation Piping in Japanese BWRs’, Transactions of the 17th International Conference on Structural Mechanics in Reactor Technology (SMiRT 17), Prague, Czech Republic, August 17-22, 2003

[8] Replacement of Reactor Internals and Full System Decontamination at a Japanese BWR, ISOE INFORMATION SHEET, ISOE Asian Technical Center - NUPEC Information Sheet No. 9, October, 1999,

[9] Jun Matsumoto, ‘Core shroud replacement of Fukushima-Daiichi Unit-3’, Tokyo Electric Power Company, April 1999

[10] Report of examination of the Sample from Core Shroud (1F4-H4) at Fukushima Dai-ichi Nuclear Power Station Unit-4, JAERI-Tech 2004-004

[11] R.M. Horn et al, ‘Experience and assessment of stress corrosion cracking in L-grade stainless steel BWR internals’ , Nuclear Engineering and Design 174 (1997) 313–325

[12] Swati Ghosh et al, ‘Role of residual stresses induced by industrial fabrication on stress corrosion cracking susceptibility of austenitic stainless steel’, Materials and Design 32 (2011) 3823–3831

[13] O.K. Chopra and A.S. Rao, ‘A review of irradiation effects on LWR core internal materials – IASCC susceptibility and crack growth rates of austenitic stainless steels, Journal of Nuclear Materials 409 (2011) 235–256

[14] K. Chatani et al, ‘Irradiation assisted stress corrosion cracking susceptibility of core component materials, Proceedings of the 12th International Conference on, Environmental Degradation of Materials in Nuclear Power System – Water Reactors –Edited by T.R. Allen, P.J. King, and L. Nelson TMS (The Minerals, Metals & Materials Society), 2005

[15] H M Chung et al, ‘Irradiation-assisted stress corrosion cracking of austenitic stainless: steels: recent progress and new approaches’, Journal of Nuclear Materials 239 (1996) 61-79

[16] T. Onchi et al, ‘Mechanism of irradiation assisted stress corrosion crack initiation in thermally sensitized 304 stainless steel’ Journal of Nuclear Materials 340 (2005) 219–236

[17] Peter L. Andresen, ‘IGSCC of non-sensitized stainless steels in high temperature water’ Journal of Nuclear Materials 383 (2008) 97–111

[18] J. Zhang et al., ‘Modeling of weld residual stresses in core shroud structures’, Nuclear Engineering and Design 195 (2000) 171–187

[19] Mato Cvitanovic et al., ‘Boat Sampling and inservice inspections of the reactor pressure vessel weld No. 4 at Kozoduy NPP, Unit 1’ Nuclear Engineering and Design 191 (1999) 293-312