13th international Conference on CANDU Fuel
Holiday –Inn Waterfront Hotel
Kinston, Ontario, Canada, 2016 August 15-18

Resistance Welding – Preferred technique for Appendage Welding in PHWR Fuel Manufacturing

***N. V. Satish Kumar, Tanumay Bhattacharya, S. K. Pathak, Dr. D. S. Setty, G. Kalyanakrishnan, Dr. N. Saibaba**
Nuclear Fuel Complex, Department of Atomic Energy, Hyderabad, India
*E-mail: nvsatish@nfc.gov.in, *Phone: +91-40-27184484

ABSTRACT-Nuclear Fuel Complex (NFC) at Hyderabad is the sole supplier of nuclear fuel bundles for all the PHWRs and BWRs currently operating in India and is the world's largest producer of PHWR fuel bundles. Empty tube resistance welding technique is used extensively for welding tiny Zircaloy-4 appendages and fuel tubes. On an average, about two lakh tubes per month are being appendage resistance welded successfully at NFC. A comprehensive study on the robustness of this welding process has been carried out in this paper and the findings demonstrate the process as a highly reliable technique with consistent product quality.

1.Introduction

Nuclear Fuel Complex (NFC) at Hyderabad is responsible for supplying nuclear fuel bundles for all the nuclear reactors operating in India and is currently world's largest producer of PHWR fuel bundles. Over last four decades, NFC has evolved into an excellent manufacturing facility of nuclear fuel bundles.The bearing pads and spacer pads of PHWR fuel bundles, which are collectively called as appendages, are tiny components made of Zircaloy-4 material, used for maintaining inter element spacing in nuclear fuel bundles and also acts as support in the coolant channel during reactor operations. The spacer and bearing pads are having typical thicknesses around 1.0 mm. The tiny components are brazed joined using beryllium (Be) as the brazing filler material according to standard CANDU-PHWR manufacturing operations worldwide [1,2]. This technique has been demonstrated to meet current CANDU fuel technical requirements adequately and consistently [3]. In addition to Beryllium (Be) being a toxic material, the induction brazing process requires heating large sections of the fuel tubes to around 1000°C, therefore forming a large heat affected zone (HAZ). As reported in literature, The HAZ is very much susceptible to stress corrosion cracking in the reactor operating conditions [3]. Other methods such as ultrasonic welding, laser welding are also attempted for joining appendages to fuel tubes. However, none of the techniques were adopted globally on industrial scale for PHWR fuel bundle fabrication.

Resistance welding technique was developed and standardized at NFC during 1980s for joining appendages to the Zircaloy-4 fuel tubes. The welding operations were carried out after loading fuel pellets inside the tubes, which used to act as support to prevent excessive deformation of the thin clad tube. The empty tube resistance welding technique was later on developed, which prevented the possibilities of pellet chipping and damage. The empty tube welding technique converted the joining operation into a non-radioactive eco-friendly process, as compared to earlier and helped as a major breakthrough in achieving higher production. On an average, currently about two lakh tubes per month are being appendage welded successfully at NFC. The indigenously developed resistance welding machines were customized over the years for semi-automatic operation and greatly reduced the operator dependency for achieving consistently good quality product. Continuous monitoring of welding process parameters is done by weld checker units installed on the machines. The welds are subjected to rigorous quality checking to ensure high quality. This is amply reflected in the performance of the fuel bundles inside the reactors over last three decades.

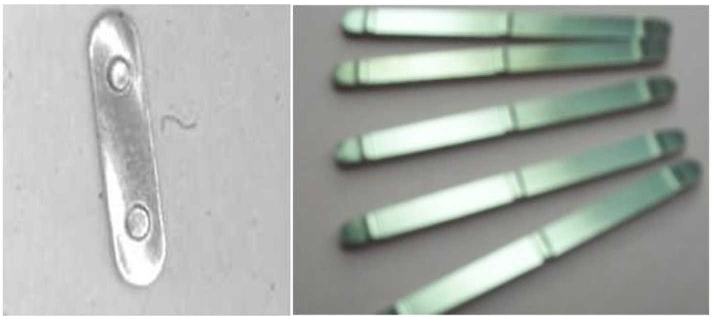


Figure 1: PHWR appendages, (a) Spacer pads; (b) Bearing pads

2. Principles of Empty Tube Welding

The set-up of empty tube resistance welding method is typically similar to single sided sheet-to-tube joining technique employed in automobile industry. Indigenously developed special purpose resistance welding machines are used to carry out the operations at NFC. The spacer pads were welded earlier on dedicated welding machines, but Integrated Spacer-cum-Bearing pad Welding machine (ISBU) were designed and developed over the years, which performs both the joining operations on a single unit. During routine production, the operators only need to stack sufficient stock of the tiny spacers, bearing pads and empty tubes onto the machine. The pads are kept in its position and orientation over tubes with the help of suitable shrouds. The welded tubes are collected from the attached storage baskets by the operators for further operations.

Figure 2: Indigenously developed ISBU unit under operation at NFC

An inflated mandrel supports the empty fuel tube from inside as compressed air at pressure about 5-6 Kg/cm^2 is applied while the welding operation is performed. The energy required of around 60-120 watt-seconds for welding is delivered using a capacitive discharge (CD) power source [4].The welding process is typically a solid-state joining technique where the peak temperature reaches maximum around 0.6-0.7 times the melting point of Zircaloy-4 (1850°C).

The projections provided on the spacer and bearing pads (figure 1) helps in increasing the current density and it collapses forming the weld joint. The CD power source can be used to deliver precise amount of energy within a very short span of time, in form of pulses (single or multiple), which helps in reducing the overall HAZ around the appendages. Typical pulse durations used are around 6.0 milli-secs (short), 8.0 milli-secs (medium) and 12.0 milli-secs (long). The welding parameters used for appendage welding are listed in table 1. Currently, dedicated resistance welding machines for both 19 and 37 element variety of PHWR bundle fuel tubes are used for mass production at NFC.

3. Stringent Quality Standards

After qualification of the individual welding machines, the weld quality is evaluated on a sample basis by performing non-destructive testing for shear strength of weld joints. Dedicated resistance weld shear strength testing units are employed for evaluating weld shear strengths. The criterions for shear strength for spacer and bearing pads are different based on the functional requirements inside the reactors during operation. Each weld on each appendage is tested separately to ensure meeting the reliable quality. The minimum weld strength values, standard deviation (σ) and mean strength (X) are mentioned in table 2 [4].

Table 1: Shear Strength Requirements for PHWR appendages

	Spacer pad	**Bearing pad**
Min. strength	60 Kgf.	80 Kgf.
Mean strength (x)	60 Kgf.	80 Kgf.
Standard deviation (σ)	≤ 2.8	≤ 2.8
X-2σ	≤ 60	≤ 80

4. Weld Characterization

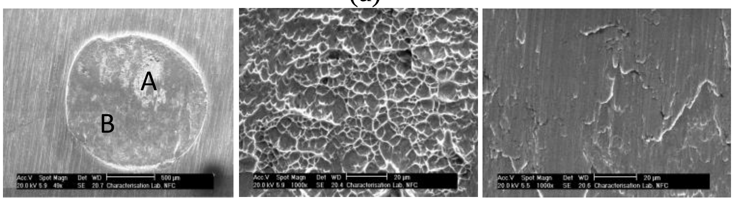
A detailed weld characterization study is performed for evaluating the robustness and consistency of the resistance welding process. The weld samples were cut in both longitudinal and transverse direction and the samples were polished and etched using a solution of 10% HF, 45% HNO_3 and 45% H_2O) and viewed under optical microscope with 50x magnification. The microstructure in both transverse (perpendicular to tube axis) and longitudinal (along tube axis) direction shows widemannstatten morphology or transformed β-structure, which forms due to high rate of cooling at the weld interface. The typical peak temperature in the weld area is predicted from the microstructures is around 800°-1000°C. The peak temperature range is supported by the non-existence of fully β-phase in and around the weld interface.

(a) (b) (c)

Figure 3: (a) Resistance welded spacer pad; (b) Resistance welded bearing pad; (c) Microstructure at weld interface of spacer and bearing pad viewed at 50x magnification

The weld interface expands as the projections collapses during welding thereby forms the weld joint. The weld interface (nugget) area is generally around 1.5 to 2 times the original diameter of the projections. The fractured surfaces after performing weld shear strength testing were viewed with magnification of 1000x.

(a)

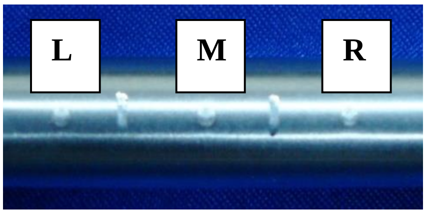


(b) (c) (d)

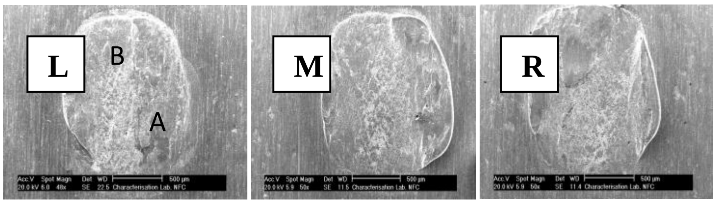
Figure 4: (a) Fractured surface of spacer pad weld; (b) Fractured projection at 50x magnification; (c) Location A in fig b at 1000x; (d) Location B in fig b at 1000x magnification

As it can be seen for both spacer and bearing pad, the fractured surfaces shows dimples, which indicates ductile failures at the interface during shear strength testing. Ductile failures are more preferred and absorb more energy during external loading conditions before failure.

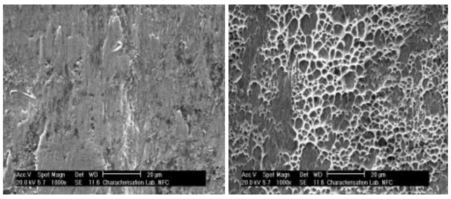
The extents of heat affected zones for spacer and bearing pad welding were measured in both longitudinal and transverse direction and it is found that a very fine microstructure exists around the weld area. The weld zones were almost indistinguishable compared to the base metal.



(a)

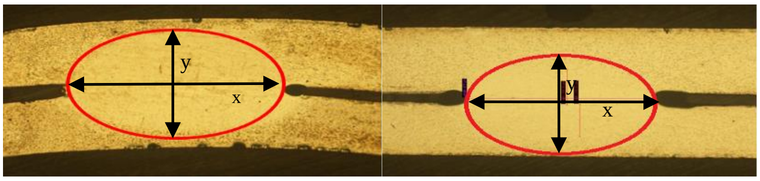


(b) (c) (d)

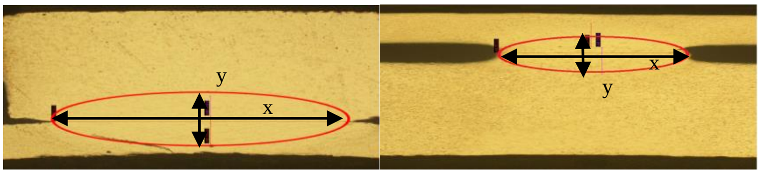


(e) (f)

Figure 5: (a) Fractured surface of bearing pad weld; (b),(c),(d) Fractured projection at 50x magnification (location L, M and R); (e) Location A in fig b at 1000x; (f) Location B in fig b at 1000x magnification



(a) (b)



(c) (d)

Figure 6: Extents of HAZ for spacer pad in (a) transverse section (y = 750µm, x =1075 µm); (b) longitudinal section (y = 590µm, x =970 µm); bearing pad in (c) transverse direction (y = 520µm, x =1510 µm); (d) longitudinal section (y = 610µm, x =965 µm)

Micro Vickers Hardness measurements were carried out for all three (3) projections of a bearing pad and two (2) projections of spacer pads with a given 10 sample welds each. The results are repeated for weld sections in both longitudinal and transverse direction. The weld interface area for bearing and spacer pad showed an average hardness value around 248 MPa, which is around 50 MPa higher than hardness value of base metal Zircaloy-4 (190 MPa). The higher hardness value indicates stronger mechanical properties at the interface compared to base metal. The base metal strength values were calculated theoretically using shear strength of Zircaloy-4 (380 MPa) and measured diameter (1.6 mm) of fractured interface. Upon comparison with measured weld shear strength, it was observed that the weld strengths are almost 1.1-1.3 times in shear loading as compared to the base metal.

As a special technique for evaluating tensile strength of appendage weld, peel tests were performed. The peel test for this type of tiny appendage weld is not a standard method practiced for quality evaluation in mass production at NFC. Both spacer and bearing pads were welded using energy input of around 80-120 watt-seconds. Fuel tubes were hold in-position using bench vice and the pads were manually pulled in the direction shown in figure 7(a). It was observed that, mostly button pull-out failure occurred at the weld interface, which indicated a stronger weld interface area compared to base metal. The peel tests showed that excellent weld joint strengths can be achieved beyond the standard quality acceptance requirements. The resistance weld joints can perform satisfactorily with no chances of appendage detachment in reactor operating conditions. The puncture in fuel tubes during strength test proves the weld joint to superior in mechanical properties compared to thin walled cladding.

(a) (b) (c)

Figure 7: (a) Direction of pull (F) in peel test; Button pull-out failure for (b) bearing pad and (c) spacer pad

5. Process Consistency & Robustness

Statistical measures are taken for qualifying the appendage resistance welding machines for mass production. The welding machines are qualified for different types of spacer pads (single type for 19-element PHWR bundle and two types for 37-element PHWR bundle) and single type of bearing pads. The purpose of qualification of welding machines is to identify and verify the operating range for various machine parameters that will result in welding of tubes of desired quality [4]. For machine qualification, all set-up welds are subjected to visual inspection. All spacer pads are subjected to orientation check, location and central distance measurement. The welds must be free from sparking, coloration, arc gauging, metal-flow etc. All tubes welded for machine qualification are tested with boroscope for any defects beneath the welds inside the tubes to ensure subsequent operation of fuel pellet loading. One tube is cut open and the depression on inside the sheath is measured, which should be less than 50 microns.

For regular process control during mass production, all random and process welds are subjected to visual inspection and shear strength testing. The production then further continues if the strength requirements as mentioned earlier in table 2 for spacer pads are met. If the acceptance criteria are not satisfied, the testing procedure is repeated again and to ensure that no faulty weld goes into bundle fabrication, all 60 fuel tubes are quarantined and checked for strength criteria. The process capability index (C_{pk}) values are calculated with respect to weld shear strength values for qualifying welding machines. The C_{pk} values indicate the ability of the process to produce output within specified limits. Since single sided specification weld strength is applied for evaluating weld quality, the value of C_{pk} must be more than 1.25.

6. Conclusions

A detailed characterization of resistance welding technique employed for appendage joining at NFC is carried out in this study. The weld microstructure, extent of heat affected zone and hardness distribution across the weld interface revealed excellent features of resistance weld joints and joints strength are always equal or more than parent Zircaloy-4 material. Peel test performed showed the excellent weld strength achieved beyond the standard quality acceptance requirements and button pull-out is most likely for weld joints. The quality procedures for achieving process consistency and robustness is also briefly described in the text. It can be concluded that resistance welding technique is an overall preferred and reliable methodology for joining appendages to fuel tubes.

7. References

[1] U. C. gupta, R. N. Jayaraj, Meena R, V. S. Sastry, C. Radhakrishna, S. M. Rao, K. K. Sinha, “Nuclear Fuel Fabrication-Developing Indigenous Capability”, Proceedings of the 5th international conference on CANDU fuel, 21-25 Sep, 1997, Toronto, ON (Canada).

[2] P. B. Desai, T. K. Ray, V. G. Date, D. S. C. Purushotham, “Advances in appendage joining techniques for PHWR fuel cladding”, Bhabha Atomic Research Centre, Trombay, Bombay, India.

[3] S. Livingstone, L. Xiao, E.C. Corcoran, G.A. Ferrier, K.N. Potter, “Development of laser welded appendages to Zircaloy-4 fuel tubing (sheath/cladding)”, Nuclear Engineering and Design, 284 (2015) 97-105.

[4] R. N. Jayaraj, B. Laxminarayana, P. S. A. Narayanan, U. C. Gupta, B. P. Varma, K. K. Sinha, “Improved techniques for appendage attachment to PHWR fuel elements”, Conference proceedings of the 4th International conference on CANDU fuel, 1-4 Oct, 1995, Pembroke, ON (Canada).