Refabrication of Fuel Rods – Qualification of the End Plug Welds

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Abstract

Refabrication of irradiated fuel rods is applied at SCK•CEN, both to make short fuel rodlets for tests in research reactors and to reconstitute full-size rods for their reinsertion in the original fuel assembly as an elegant back end solution for industrial fuel rods after their use in fuel research programmes. In both cases the end cap welds have to be qualified thoroughly, to prove their proper performance either under irradiation and/or during long-term storage.

The paper describes the qualification process that is applied at the hot laboratory LHMA at SCK•CEN to qualify the welding methodology and the actual welds made according this methodology. The results obtained on a typical refabrication case are included.

Keywords: Fuel rod refabrication, weld qualification.

Introduction

At present days nuclear fuel research often relies on fuel rods being extracted from fuel assemblies at nuclear power plants. These industrial full-size rods are ~4 m long. To accommodate this fuel in a research reactor, that has a core height of ~1 m, short fuel rodlets have to be extracted and refabricated (and instrumented) for irradiation in the research reactor. At the end of the research programme, one has to dispose of the fuel remnants. The most elegant back end solution applied at SCK•CEN entails the reconstitution of original full size rods from the fuel remnants that can be reinserted in the original fuel assembly. In this way the fuel can join the standard back end practice applied at the power plant. The key for acceptance by the safety authorities of both the refabrication and reconstitution practice is the proven quality of the end cap welds.

The present paper describes the end cap welding qualification methodology applied at the SCK•CEN for a specific case, i.e. the refabrication of fuel rodlets for a burn up credit programme.[1] The burn up credit programme aims to validate neutronic codes criticality calculations for spent fuel. The experimental part comprises the insertion of both a fresh and irradiated fuel assembly in SCK•CEN's VENUS zero power reactor in order to determine experimentally the reactivity change of irradiated fuel relative to fresh fuel. The irradiated fuel assembly is made up of 25 fuel rodlets of 1,139 m length with a 1 m fuel stack stemming from industrial full size PWR power plant fuel rods. The end caps are designed with a threaded outer end such that the fuel rodlets, after their use at the VENUS criticality facility at SCK•CEN, can be screwed together to reconstitute original full-size rods for reinsertion in the original fuel assembly at the PWR power plant.

Fuel rodlet refabrication

The 25 fuel rodlets are fabricated from segments extracted from the middle flat power profile part of 13 full-size PWR fuel rods – Fig. 1.

The manufacturing of appropriate rodlets according to the burn up credit programme encompasses the following mechanical machining steps:

An appropriate ~1022 mm long fuel rod section is cut – the exact cutting positions are based on the total γ-activity scans (Fig. 1);

The rodlets with a length of 1022 mm are first flattened with a chisel at both ends to a length of 1020 mm;

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Fig. 1 Total $\gamma$-activity scan of a PWR fuel rod with the position of the 2 extracted segments indicated.

The rodlet ends are defuelled over a distance of 9.5 mm by drilling with a hollow diamond drill. The outer cladding surface is cleaned over a distance of 50 mm by abrasive paper. The inner cladding is cleaned with a grinding pin, that has a flat diamond coated end surface, allowing to grind a flattened fuel surface – resulting in a 10 mm deep clean inner bore (free of fuel and zirconium oxide) and a flat fuel stack extremity. The inner diameter is measured with a micrometer and the end plugs are machined to the right dimensions, i.e. to fit tightly in the cladding. The rodlet ends and the end plugs are cleaned with ethanol, dried and the end plugs are pressed into the rodlet ends. The whole rodlet is cleaned with paper and ethanol prior to the end cap welding.

The end plugs are designed with a welding chamber – providing an easy control of the weld penetration depth – and a central ventilation hole and two spiral outer venting grooves extending over the inner cladding part – providing an escape route for the enclosed gases such as to prevent the blowing up of the circular welds during welding. The inner ventilation hole further allows gas tight seal welding of the rodlet after being filled with helium to the design gas pressure (2 bar He).

The Gas Tungsten Arc Welding (GTAW) technique is applied for the end cap welding. This technique – also referred to as Tungsten Inert Gas (TIG) welding – is commonly used when high quality, precision welding is required. In TIG welding, an arc is formed between a non-consumable tungsten electrode and the metal being welded. An inert gas (He) atmosphere is installed to shield the electrode and the molten weld pool form environmental contaminants which could have an adverse effect on the weld quality. The orbital welding unit developed at SCK•CEN (Fig. 2), consists essentially of a gas tight welding chamber where the electrode is rotating around the fuel rodlet. At one side of this chamber the rodlet is inserted and airtight clamped. At the opposite side, an exchangeable end plug adaptor is mounted to adjust the axial position of a loaded rodlet with respect to fixed TIG electrode position for the circular end cap welding. To perform the horizontal pressurized seal weld, the plug adaptor piece is replaced by an electrode holder. The welding chamber is connected by three gas lines to a vacuum pump, an inert gas bottle (He) and an oxygen analyser. This allows the welding chamber to be evacuated and flushed or pressurized with inert gas while monitoring the oxygen content of the atmosphere. It is generally known that $N_2$ has an adverse effect on the quality of zircaloy welds. In the case of Zry2 and Zry4, it is recommended to limit the nitrogen content of the weld pool environment to $\leq 32$ ppm, $N_2$ to assure good quality welds. Hence the (measurable) oxygen content has to be limited to $\leq 8$ ppm, $O_2$ – as air, composed of about $80\text{vol}\%$ $N_2$ and $20\text{vol}\%$ $O_2$, is the main gaseous environment contaminant. A vacuum and pressure gauge control the evacuation and gas filling of the welding chamber. In this way an appropriate clean atmosphere can be installed in the welding chamber by repeated evacuation / inert gas flushing cycles. The circular welds are performed under a dynamic inert gas flow and the seal welds under a static inert gas pressure. The maximal (absolute) pressure the welding chamber is designed for amounts to 10 bar.
End cap welding qualification

The end cap welding qualification encompasses screening tests to fix the optimal welding parameters and specifications, pre-qualification tests to prove the robustness of the welding process and qualification tests accompanying the actual rodlet end cap weldings to assure their quality. All these qualification tests are being performed with actual end plugs and fully representative cladding. Hydriding/oxidation of the reference cladding is performed in a closed furnace at 550°C flushed with an Ar/2%H₂ mixture to hydride the cladding and flushed with an Ar/5%O₂ mixture to produce a representative oxide layer on the cladding.

Screening tests

Welding trials lead to the optimal welding parameters (torch shape, torch positioning, current settings, torch travel speed, etc.) and welding procedure (flushing regime, welding atmosphere monitoring, etc.). Several quality controls guide the optimization process (e.g. Figs. 3, 4 and 5):
Visual control of the weld general aspect (e.g. absence of pits), inclusive the coloration (e.g. at the weld borders where "white" deposits are indicative for an inadequate welding atmosphere);
Measurement of the weld location and width;
Destructive examination by optical metallography to reveal the weld penetration depth, the presence/absence of cracks/pores/inclusions, and the weld constriction;
Corrosion tests in steam (T=400°C, p=10MPa) for 3 days according the ASTM standard G2-88 [2] – in PWR-type water, containing 2 ppm Li and 400 ppm H₃BO₃.

Fig. 3 Visual (a) and optical microscopic (b and c) control of a circular welding screening test – performed with inferior current settings as shown by the reduced weld penetration depth of the otherwise sound weld.
The corrosion tested sample shows a lustrous, black oxide layer, with different reflectivity in the weld area compared to the tube. The discoloration induced by the deposit is still visible after the three day corrosion test, but the oxide layer does not differ from the oxide layer found on the tube. There are no indications of the formation of white or nodular corrosion or any other sign of bad corrosion behaviour as a result of the welding of the specimen.

The optical microscopic pictures show the excellent quality of the weld: it penetrates appropriately as proved by the partly filling up of the welding chamber and no any defect is visible.

Pre-qualification

Once the optimal parameters have been fixed, the robustness of the welding procedure is qualified by pre-qualification welding including the optimal parameters and a lower/higher heat input (i.e. peak current level) parameters envelope corresponding to the resolution of the welding generator (± 1 A). In addition the circular pre-qualification weldings are performed on both hydried/oxidized cladding and fresh cladding to cope with variations in the cladding condition as they might be present in the actual fuel rods. The weld inspections are identical to those performed at the screening tests and revealed the following results (e.g. Figs. 6 – 8):

Visual inspection shows the same sound aspect for all welds, with a quite similar coloration pattern near the weld borders as induced by the deposition of welding induced material evaporation/condensation.

The centre of the weld is about 0.2 mm more close to the clad/plug interface for the fresh cladding, as due to the better electrical characteristics of the fresh cladding – this slight shift of the arc has however no effect on the weld quality as an appropriate joining of the cladding and end plug is still obtained;

Destructive optical microscopic examinations reveal an appropriate penetration depth - as demonstrated by the rounding of the initial rectangular welding chamber as well as by the appearance of the weld pool and heat affected zone after etching with etchant 9 ml HNO₃ + 9 ml H₂O₂ + 1 ml HF – (note the dark coloration of the cladding in Figs. 6c and 8c as due to the hydrides);

The absence of any cracks, pores and inclusions with dimensions > 0.2 mm;

The cladding thickness is almost completely preserved – only limited restriction of the cladding is present in the welding zone;

Autoclave testing in steam resulted again in a lustrous black oxide layer being formed over the entire sample indicating good corrosion behaviour.
As a conclusion it can be stated that all welds show a good quality. The variation of the heat input, both in + and -, with a level corresponding to the instrument resolution does not affect the weld quality. Furthermore the quality is not affected by the hydriding/oxidation aspect of the cladding neither. Thus the optimal welding parameters and procedure specifications are found to deliver reproducible high quality welds.

For the seal welding, that is less demanding as performed always on the same fresh end plug material, the same high reproducible quality was obtained as well.

**Qualification**

Foregoing screening tests and pre-qualification tests were all done with a welding unit situated outside the hot cell that is completely identical to the one implemented inside the hot cell. Hence, the qualification of the actual fuel rodlet end cap weldings is assured by accompanying qualification weldings performed with the reference cladding on this hot cell installed welding unit according the following scheme:

Prior to the actual irradiated fuel rodlet refabrication campaign: circular welding tests on hydried/oxidized cladding at optimum, optimum- and optimum+ parameter settings plus one seal weld;

At the renewal of the electrode (rotating circular weld torch or seal weld electrode – the electrodes are subject to erosion and have to be replaced at the latest after 20 weldings): 1 welding test at the optimal parameter settings (2 intermediate circular weld qualification tests and 2 intermediate seal weld qualification tests were finally performed at intermediate stages during the refabrication campaign of the 25 fuel rodlets);

After the irradiated fuel rodlet refabrication campaign: circular welding tests on hydried/oxidized cladding at optimum, optimum- and optimum+ parameter settings plus one seal weld.
All these accompanying qualification tests are analyzed visually, geometrically, by optical microscopy and for their corrosion resistance. All these analyses on all the qualification tests confirmed the high quality as obtained in the pre-qualification tests. The controls on the actual fuel rodlets end cap welds encompasses:

Visual inspection of both end caps, taking photographs at 0°, 120° and 240° to cover the whole circumference;
Dimensional control of the weld location;
Weld diameter control – by means of a 9.7 diameter bore calibre – in order to allow easy introduction of the refabricated rodlets into an assembly;

Helium leak testing for rodlet tightness.

It should be noted that the welding generator records the current/voltage course versus time for each welding cycle and that these curves serve as well to monitor the normal proceeding of the welding process.

![Fig. 9](image9.jpg) Sound visual aspect of the circular and seal weld from the bottom (a) and top (b) end plug of a refabricated fuel rodlet, i.e. a well located, defect free and discoloration free weld.

At the helium leak tightness testing, one of the refabricated irradiated fuel rodlets was found to be leaking. Visual examinations revealed a small longitudinal crack in the cladding adjacent to the weld being the cause, probably induced at the insertion of the tightly fitting end cap. The welds themselves were found to be in order. To repair this rodlet, the original end plug has been cut off and replaced by a new one. Optical microscopic examination of the cut end plug confirmed the good quality of the welding itself:

![Fig. 10](image10.jpg) The optical microscopic examination of an irradiated fuel rodlet end cap confirms the excellent quality of the circular welding, i.e. complete crack/pore/inclusion free joining of the cladding to the end plug without any clad restriction.

**Conclusion**

A profound qualification methodology has been developed for the end plug weldings for the refabrication of irradiated fuel rods. Its application in a typical fuel research programme, resulting in the faultless refabrication of 25 fuel rodlets out of industrial full size PWR rods, proved the excellent reproducibility of the applied method (quality assurance in a very durable manner).
References
