Mechanical property evaluation of irradiated stainless steels using sub size and miniature specimens

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Austenitic stainless steel is the major core structural material of sodium cooled fast reactors in India. The various stainless steels chosen for use in the upcoming Prototype Fast Breeder Reactor (PFBR) are (i) alloy D9 (in 20% CW) as material of replaceable core components like fuel cladding and wrapper and (ii) SS316 LN/ SS304 LN as material of permanent structures like main vessel, safety vessel, grid plate etc. The performance of the stainless steels has been studied through irradiation experiments in Fast Breeder Test Reactor (FBTR) and their mechanical properties and microstructure evaluated in hot cell experiments.

The mechanical properties have been evaluated using (a) sub size tensile and impact specimens with dimensions proportionally reduced from standard ASTM specimen and (b) miniature disc specimens of diameter 8.0 mm and 0.5 -1.0 mm thickness. As compared to standard size specimens, sub size and miniature disc specimens (i) permit efficient use of costly reactor space for test irradiations (ii) experience lesser flux and temperature gradients across its volume and (iii) permit easy handling due to reduced activated dose. The test procedures of various mechanical tests on irradiated specimens and the trends in mechanical properties of the stainless steels as function of displacement damage will be presented in this paper.

Experimental - Sampling and test methods

The test samples for mechanical testing were sourced from (i) irradiated clad & wrapper tube components of alloy D9 with displacement damages in the range of 40-60 dpa and (ii) pre-fabricated specimens of SS316 LN and SS304 LN irradiated to displacement damages of about 2-5 dpa in experimental capsules.

For tensile test of alloy D9 claddings, tubular clad section of 60 mm length extracted from various axial locations of the fuel pin were used after removing the fuel by chemical dissolution. Mandrels inserted from the ends of the tube enabled gripping and the free distance inside the clad tube between the mandrels (set as $5.65\sqrt{Area}$) was taken as the initial gauge length. Sub size flat tensile specimens (total length: 40 mm, gage length: 12.0 mm, gage width: 3.0 mm) were machined from alloy D9 wrapper faces using a 4-axis CNC machine for tensile testing. A customised wedge action gripping system was employed for holding the tubular and flat tensile samples in hot cell UTM fitted with an electric resistance furnace. In addition to the tensile tests, shear punch (ShP) tests were carried out on disc specimens (8.0 mm diameter and 1.0 mm thick) extracted from alloy D9 wrapper. The test fixture, experimental procedures and analysis methodology adopted are detailed elsewhere. (Karthik et al., 2013). The room temperature tensile properties of alloy D9 wrapper were estimated from ShP test data using tensile-shear punch correlations.

For mechanical property evaluation of SS316LN/SS304LN, pre-fabricated Charpy V notch (5 mm x 5mm x 55 mm) specimens of the two steels were irradiated in FBTR in addition to sub size tensile and disc specimens. A 450J capacity pendulum type instrumented impact testing machine calibrated as per ASTM E23 protocols was used for the impact tests. A mobile shielded setup consisting of a steel shielding wall fitted with Master Slave Manipulators (MSMs), viewing glass window and camera, and the test machine with customised specimen aligning tools was erected and used for remote impact testing.

Recent Developments

The use of Digital Image Correlation (DIC) for strain measurement during tensile testing in hot cells is being attempted. The challenges in implementing DIC for hot cell experiments and initial results of remote strain measurements in subsize tensile specimen of 12 mm gage length using DIC will be presented. Further miniaturization of tensile specimen has been carried out with a gage length of 3.0 mm and gage width of 1.5 mm carved out from a disc sample of 10 mm diameter and 0.5 mm thick. (Sham & Natesan, 2017) The ultra subsize (USS) tensile specimen (Figure 39) has been optimised using finite element analysis w.r.t the fillet radius and geometrical tolerances for gage width and thickness. The methodologies developed for implementing the USS specimen for testing irradiated components in hot cells will be presented.

Results

The combined data sets of tensile and shear punch tests of alloy D9 cladding/wrapper shows that for low irradiation temperatures around 673 K-723 K (lower portion of fuel column), there is significant increase in YS and UTS with a decrease in uniform elongation. The hardening effect decreases in both cladding and wrapper with recovery of uniform elongation at axial locations corresponding to upper portions of fuel column where the irradiation temperature increased beyond 723 K.

The trend curves of strength and uniform elongation of SS 316LN and SS 304LN with dpa reveal that SS 304 L(N) exhibited a higher rate of hardening with dpa and correspondingly a lower ductility compared to SS316 L(N) at all dpa (Figure.40). The Charpy-V notch energy (Cv) of SS316 LN showed no significant changes as displacement damage increased to 5.6 dpa, while that of SS 304 LN decreased by ~8% at 4.7 dpa and by ~20% at 5.6 dpa. Both tensile and Charpy test results indicate superior performance of SS 316LN compared to SS304 LN.

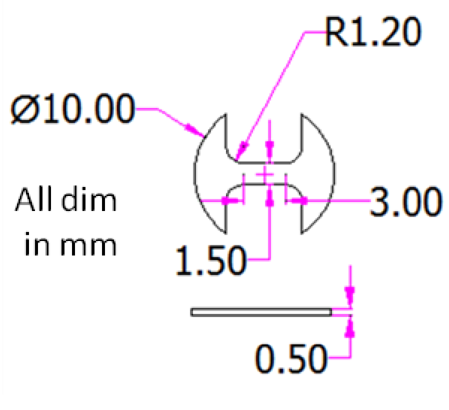

Figure 39: Ultra sub size tensile specimen

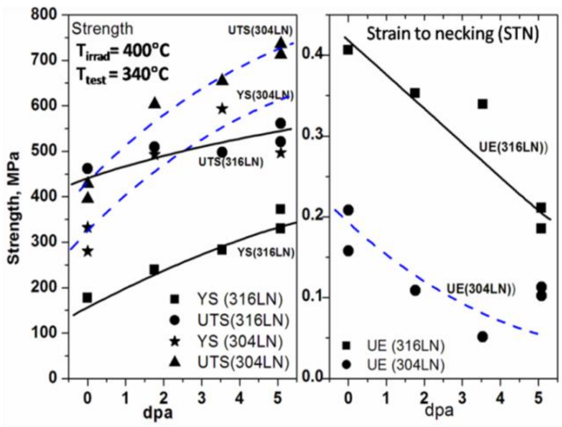

Figure 40: Strength and ductility of SS316/304 LN with dpa.

References

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