Effect of Post Irradiation Transient Heating on Ring Tensile Properties of Zircaloy-4 Fuel Cladding

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1. Introduction

Fuel cladding is the key component of reactor core for the purpose of retaining the fuel & fission products inside the fuel pin. Hence, the integrity of clad is of great importance for the safe and reliable operation of the reactor. Neutron irradiation in the reactor causes significant degradation of the mechanical properties of the claddings. In order to study the mechanical property of the claddings, the ring tension test (RTT) method can be used which provides a measure of transverse ductility. This technique has been found to be most suitable for irradiated cladding because it needs rings of around 3 mm width which can be tested without carving a gage section in them, reduces the man-rem consumption during testing and de-fuelling the fuel pin slices can be done easily to get a clad ring [1]. The objective of present experiment is to study the effect of neutron irradiation on degradation of mechanical properties and see the influence of post irradiation transient heating on the behaviour of the fuel cladding. This paper describes the studies carried out and results obtained on the estimation of ring tensile properties of the fuel claddings in different conditions such as unirradiated, as-irradiated and post irradiation heat treated.

2. Material

In 540 MWe Indian Pressurised Heavy Water Reactor (PHWR) each fuel bundle contains 37 fuel pins. Fuel pins are fabricated by encapsulating uranium di-oxide (UO₂) fuel pellets in hollow Zircaloy-4 cladding tube followed by sealing the ends with end caps by resistance welding. Each fuel pin has its diameter and wall thickness of 13.1 mm and 0.4 mm, respectively. The clad rings used in the present study were extracted from the outer fuel pin of a fuel bundle removed from Tarapur Atomic Power Station-3 PHWR. The fuel bundle had accumulated a burnup of ≈3500 MWd/tU during residence of 150 days in the reactor. Ring tension tests were also carried out on unirradiated Zircaloy-4 clad.

3. Experimental

Axial discs of 3 mm width were cut from the fuel pin using slow speed diamond cut-off machine in hot-cell. Discs were subjected to defueling in a specially designed and fabricated device. Empty clad rings were deburred by grinding on 400 grit papers in a grinding machine to get rings of uniform width. The ring width was measured using digital vernier callipers and cleaned in ultrasonic cleaner. Further, few rings were subjected to transient heating for 2 minutes at different temperatures viz. 400, 500, 600 and 700°C. Rings were heated in a horizontal retort furnace, soaked for 2 minutes at these temperatures and air cooled to room temperature (25°C).

Rings were also prepared from unirradiated clad for the base line data generation and comparison with that of irradiated rings. Unirradiated, as-irradiated and post irradiation heat treated ring samples were tested at 25°C. Few of the unirradiated and as-irradiated samples were also tested at 300°C after soaking them for half an hour in the furnace. All the tests were performed using specially designed and fabricated grips in a screw driven universal testing machine (UTM) at a crosshead speed of 0.5 mm/min.
The grips had two split semi-circular mandrels with a curvature that fitted into the inner diameter of the rings. The split mandrels open up and strain the specimens during testing.

4. Results and Discussion

The stress-strain curves obtained from unirradiated and as-irradiated ring samples tested at 25°C & 300°C are given in Fig. 1(a). The ring tensile properties obtained from as-irradiated cladding at 25°C indicated a decrease in ductility and an increase in yield strength (YS) of about 60% and 30%, respectively, as compared to that of unirradiated cladding. At 300°C, there was a distinct variation in the ductility ranging from 23-37% in comparison to 10-12% at 25°C and the YS decreased significantly. The decrease in ductility and increase in strength in irradiated clads is due to the irradiation damage. It causes microstructural changes in the material by displacing the atoms from their lattice position and creating defects in the matrix that gives rise to irradiation hardening. The ductility variation at 300°C is mainly because of the partial annihilation of point defects that takes place with increased mobility of interstitials and vacancies at higher temperature.

Figure 1(b) shows the stress-strain curves obtained from post irradiation heat treated samples tested at 25°C. The effect of transient heating is relatively less for the rings heated at 400 and 500°C. It could be seen that the strength has dropped slightly with restoration of strain hardening capability of material and the ductility has increased to some extent at these temperatures. The ductility was strongly enhanced for the rings heated at 600 and 700°C and the strength dropped drastically with restoration of strain hardening capability of the material to nearly unirradiated condition of the cladding. Ribis J. et. al. and Karb E.H. et. al. have also reported that irradiation defects are not stable at higher temperatures and if irradiated Zircaloy is heated to high temperature (>580°C) the defects are annihilated and the material recovers its original properties [2,3].

Figure 1. The stress-strain curves obtained for (a) unirradiated and as-irradiated rings and (b) post irradiation heat treated rings
5. Conclusion

All the ring samples, prepared from the tubes of various conditions (unirradiated, as-irradiated and post irradiation heat treated) and tested at RT, fractured in ductile mode along with cup and cone, cup and cup and 45° shear lip type fracture. Deformation took place in the right and the left hand sides of the rings i.e. at locations ±90° of the loading direction where the space between two split mandrels increases with straining. However, the amount of gross plastic deformation varied with the conditions of the clad. The rings heated at 400 and 500°C showed an improved ductility in comparison to as-irradiated condition while at 600 and 700°C the ductility was significantly enhanced. The strength was dropped drastically at higher temperatures (≥ 600°C) with restoration of strain hardening capability. In these conditions, the defects created by irradiation get annihilated partially at temperatures ≥ 400°C and fully above 600°C.

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Reference

