Mechanical Properties and Microstructural Studies on Core Structural Material of FBTR

■ EXECUTIVE SUMMARY

The irradiation experience worldwide has proved that the main factor affecting high fuel burn-up in fast reactors is related to the irradiation damage of the structural materials. Stainless Steel SS316 (20% cold worked) is the structural material for the fuel cladding and hexagonal wrapper of the Fast Breeder Test Reactor (FBTR) at IGCAR. To understand the irradiation performance of the SS316 in FBTR at various levels of displacement damage (dpa- displacement per atom), mechanical testing and TEM (Transmission Electron Microscopy) studies have been carried out on the core structural material of FBTR. The trends in the evolution of mechanical properties and microstructure of irradiated wrapper with dpa and void swelling have been established.

■ OUTLINE

The core materials of fast reactors are subjected to a high neutron flux (10^{15} n/cm^{2}s^{-1}) coupled with high temperatures (400-650°C). Under such irradiation conditions and high temperatures, austenitic stainless steels undergo significant microstructural alterations which induce dimensional changes and affect mechanical properties. The irradiation induced microstructural changes are a strong function of irradiation temperature and the displacement per atom (dpa)

Tensile Testing of Cladding

To qualify the irradiated SS 316 cladding, elevated temperature tensile testing is employed for strength and residual ductility evaluation. The remote tensile tests are executed as per the ASTM E-8 and ASTM E-21 standards using a 2 ton capacity UTM fitted with a resistance heating furnace in the hot cells. Special collet type gripping fixtures have been designed and developed in-house for holding the cladding at elevated temperatures during the test. The results of the tensile tests indicated that uniform elongation has reduced from 6.8 % for unirradiated tube to 3 % for irradiated tube of 56 dpa at test and irradiation temperature of 430°C as seen in Fig 1. The presence of sufficient strength and residual ductility in the irradiated cladding enabled extending its life to the present damage level of 83 dpa without any failure.

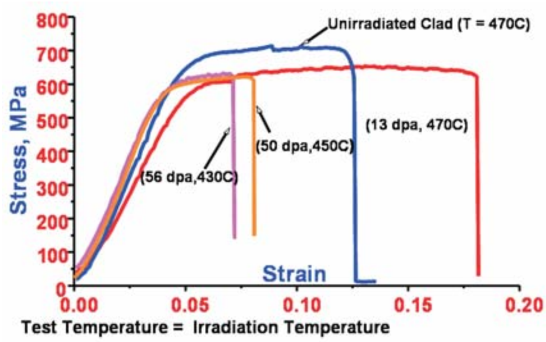

Fig. 1 : Stress strain curves of Irradiated SS316

Shear punch testing and TEM examination of Irradiated Wrapper

Small specimen test techniques are used for evaluating the changes in the mechanical properties of the irradiated wrapper. The Shear punch (ShP) testing is a small specimen testing technique, in which a cylindrical punch with a flat end is forced to punch a hole in a clamped small disk specimen of 1 mm thick and 8 mm diameter. The load-displacement curve obtained during the ShP test is similar to the load-displacement plot of a conventional tensile test and can be analyzed to extract the uniaxial tensile properties like yield strength (YS), Ultimate Tensile Strength (UTS) and % elongation. The shear punch tests have been standardized and a tensile-shear correlation established using various microstructures generated from unirradiated SS316.

Small specimens of 8 mm diameter are extracted from different axial locations of the hexagonal wrapper which has undergone different displacement damage (dpa) for microstructural studies and estimation of mechanical properties by shear punch technique. Using the shear punch test results on irradiated specimens and the correlation equations, the tensile properties of the irradiated specimens have been estimated.

Disc specimens of 3mm diameter obtained after shear punch testing are used for preparing TEM specimens for structure property correlation studies. TEM specimens are prepared using special fixtures developed for handling irradiated specimens. Irradiated specimens which had undergone displacement damage from 2 dpa to 56 dpa have been examined using 200 keV Analytical TEM. Volumetric swelling estimates as a function of dpa have also been performed on these irradiated specimens.

A considerable increase in the strength and decrease in the ductility of the wrapper with increasing displacement per atom (dpa) have been observed from the small specimen mechanical tests. The transmission electron microscopic studies revealed the presence of voids and precipitates in the matrix (Fig. 2). Precipitates were identified to be of $M_{23}C_6$ type and precipitation of second phases corroborates the hardening observed on the wrapper.

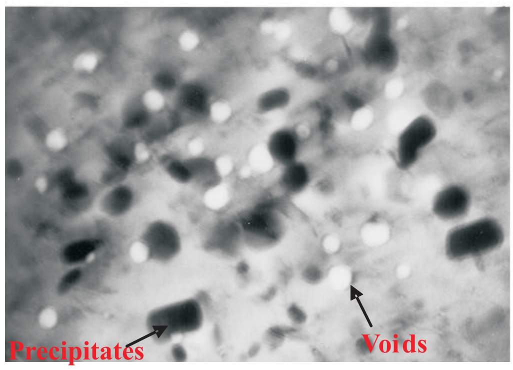

Fig. 2 : TEM image of the Irradiated SS316 at a displacement damage of 40 dpa

■ ADDITIONAL INFORMATION

Fast breeder reactor (FBR) core consists of hexagonal wrapper tubes that contain thin walled fuel pins, which forms the first barrier against possible dispersion of fissile material and fission products. Because of the use of fast neutrons which have lower fission cross sections, the neutron flux levels in FBRs are about two orders of magnitude higher ($\sim10^{15}$ n/cm^2s^{-1}) than that in thermal reactors to achieve comparable power density. The core materials are, therefore, subjected to a very demanding environment of high fast neutron flux coupled with high temperatures. One major consequence of this high flux of fast neutrons is the occurrence of very high level of atomic displacements in the core structural materials. This damage is characterized in terms of the average number of times that an individual atom is displaced from its lattice site (dpa - displacements per atom) and for some core components, such exposure can be greater than 100 dpa. Under such irradiation conditions and high temperatures (400-650°C), austenitic stainless steels undergo significant microstructural alterations which induce dimensional changes and affect mechanical properties.

■ GENERAL EXPLANATION

Irradiation induced changes in properties is dependent on temperature of irradiation, prior microstructural condition and neutron fluence (dpa). One area of major concern is the loss of ductility in these structural materials. Mechanical tests provide valuable data on the residual strength and ductility and are correlated with the swelling and microstructural studies. Fig 3 shows the view of the tensile test system installed inside the hot cells for remote mechanical testing of the irradiated cladding.

Among the different radiation damage mechanisms, void swelling is the predominant factor which limits the residence time of the fuel subassembly and the achievable burnup. The immersion density measurements are used to estimate the swelling while TEM studies provided more insights into the void evolution and other microstructural related phenomena.

Limit on minimum residual ductility for the safe operation of the cladding and wrapper is not available in the literature. But international experience shows drastic ductility reduction above 12 % void swelling indicating a strong link between the void swelling and the degradation of mechanical properties.

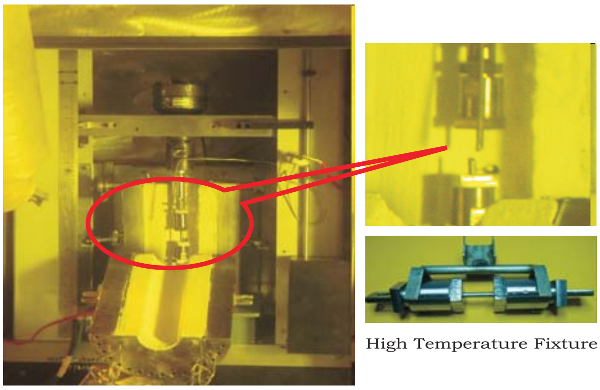

Fig. 3 : View of the remote tensile test machine inside the hot cells and fixtures

■ BRIEF DESCRIPTION OF THEORETICAL BACKGROUND

In core structural materials, significant microstructural alterations occur due to high level of atomic displacements induced by neutron irradiation. Defect structures like dislocation loops, vacancy clusters, vacancy loops, voids, helium bubbles etc form as a function of temperature of operation and neutron fluence (quantified by displacement per atom-dpa). Major phenomena affecting structural materials are void swelling, irradiation creep, phase stability and changes in mechanical properties. Voids form in austenitic stainless steels in the temperature range 400-550°C under neutron irradiation resulting from the agglomeration of vacancies. The formation and growth of voids are sensitive to all metallurgical variables like chemical composition and thermo-mechanical history and irradiation parameters like fluence, dose rate and irradiation temperature. Irradiation creep is caused due to the combined effects of external non-hydrostatic stresses and presence of both interstitial atoms and vacancies at very large super saturation levels.

■ ACHIEVEMENT

The estimation of strength and residual ductility in the irradiated cladding enabled extending the use of the SS 316 cladding in FBTR to the present level of 83 dpa without any cladding failure. The structure property correlation studies on the irradiated SS 316 provided useful insights into the irradiation performance of irradiated SS 316.

■ PUBLICATIONS ARISING OUT OF THIS STUDY AND RELATED WORK

1. N.G.Muralidharan, V.Karthik, V.Venugopal, Jojo Joseph, Shaji Kurien, V.Anandaraj, A.Vijayaraghavan and K.V.Kasiviswanathan, *J. Nucl. Mater.* (In Press)
2. N.G.Muralidharan, C.N.Venkiteswaran, V.Anandraj, V.Karthik, V.Venugopal, P.Parameswaran, Saroja Saibaba, M.Vijayalakshmi, K.V.Kasiviswanathan and Baldev Raj, International Symposium on Advances in stainless steel, (ISAS), April 9-11, 2007, Chennai.
3. N.G.Muralidharan, V.Karthik, A.Vijayaraghavan, Shaji Kurien, V.Venugopal, Jojo Joseph, K.V.Kasiviswanathan and Baldev Raj, Proceedings of "Modern Developments and Practices in Mechanical testing (MDPMT-2007), BARC, Mumbai.

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