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Analysis of Low Dose Irradiation Damages in Structural Ferritic/Martensitic Steels by Proton Irradiation and Nanoindentation

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1. Introduction

Harsh service conditions, high operating temperatures and increased irradiation damage due to high neutron fluence in fission power plants require enhanced safety [1]. The structural materials in fission reactors degrade due to exposure to thermo-mechanical stresses and irradiation damages due to neutron and particle flux. Therefore, the selection of structural materials for these applications must be appropriate [2]. The irradiation generates interstitials sites, vacancies, point defects, clusters of point defects, interstitial and vacancy loops, cavities, stacking faults, voids, and bubbles, etc., which severely affects the materials integrity [1]. The density of all these defects increases with increasing radiation doses [3]. These microscopic defects affect the integrity of materials by inducing hardening, embrittlement, precipitation, segregation, creep and swelling [4-7].

Ni-base superalloys, austenitic steels and ferritic-martensitic steels are eyed as candidates for structural materials of fission power plants. However, low conductivity of Ni-based alloys, and poor thermal conductivity, low weldability and high coefficient of thermal expansion of austenitic steels limit their utilization. As a result, ferritic-martensitic steels find applications in the in-core and out-of-core components which include ducts, piping, pressure vessel and cladding, etc [1,6,8-11] Moreover, due to ferromagnetism of F/M steel, it has been successfully employed in solenoid type fuel injector [12].

Although the irradiation induced degradation in ferritic martensitic steels is lower as compare to (i) reduced activation steels, (ii) austenitic steels and (iii) martensitic steels [9], F/M steels are still prone to irradiation induced hardening and void swelling [4]. The irradiation behavior may become more sophisticated due to transmutation and production of helium and hydrogen [13]. The ductile to brittle transition temperature of F/M steels is also expected to increase due to irradiation [14]. These irradiation induced degradations may deteriorate the integrity of F/M components [13].

The beneficial characteristics of F/M steels, for instance superior creep resistance, low thermal expansion, good oxidation and corrosion resistance and well developed scientific understanding etc. have persuaded researchers to exploit its irradiation behavior so that its nuclear applications may be guaranteed [1,8-10,15,16]. As a result of these investigations, it has found that the F/M steels experience no irradiation hardening above 400ºC, but below this temperature, up to 350ºC, weak hardening is observed. The irradiation hardening becomes more pronounced below 300ºC [17]. Moreover, the irradiation hardening has also found dependent upon radiation damage. The hardening was found increasing with increasing dose [17].

Due to pronounced irradiation hardening below 300ºC and increasing radiation damage with increasing dose (even at low dpa) [10,18], it is required to investigate the post irradiation mechanical properties of F/M steel, in order to confirm its usefulness in structural and magnetic components [12] which experience lifetime doses [9] as low as $1x10^{-5}$ dpa.

The following sections present the experiments conducted for investigating the effect of low irradiation doses on the ferritic martensitic steels.

2. Methods and Results

2.1 Simulation of irradiation

The irradiation of steel samples in reactors by neutron requires high cost [6] and a long time as it involves loading of samples in RPV, irradiation, cooling and unloading of samples. After that post-irradiated tests can be carried out, which involves challenging irradiated material handling tasks [15]. Thus, proton irradiation, which imparts same damages as neutron irradiation [19], by using accelerator is beneficially used to simulate neutron damage in steel samples. The proton irradiation offers short time and high damage rate. Moreover, the penetration depth and transmutation in proton irradiation is also very less [15,20].

2.2 Evaluation of irradiation damage

Due to the limited penetration depth of protons, the evaluation of irradiation-induced hardening of the material requires nano-scale measurement [20]. Hence, nanoindentation test is carried out to determine the effect of proton irradiation on mechanical properties of steels [15].

2.3 Experimental method

The irradiation damage (dpa), due to exposure of ferritic-martensitic steels, namely 410 and 410T, to 3 MeV proton flux of $5x10^{14}$ p/cm^2 were calculated. The penetration depth of 3 MeV proton in 410 and 410T steels were also calculated by using Stopping and Range of Ions in Matter (SRIM) code. Based upon SRIM calculations, the less ~35 µm thick sample of 410 and 410T steel were prepared. The samples were exposed to 3 MeV protons with the flux of $1x10^{14}$ p/cm^2 and $5x10^{14}$ p/cm^2 at KAERI Proton Accelerator. The as-received and irradiated samples were subjected to nano-indentation in order to examine the effects of irradiation on the hardness of the steel.

2.4 Results

Table 1 shows the radiation damage in dpa and the penetration depths by various 1 MeV ions in a ferritic-martensitic steel target when the fluence was $1x10^{14}$ ions/cm^2. It can be seen that the penetration power of protons is higher as compared to other ions of the same energy and fluence. Therefore, proton irradiation can be effectively used to simulate irradiation damage due to neutron flux in nuclear reactors.

Table 1. Penetration depths for various ions

Ion	Max. Damage (dpa)	Avg. Damage (dpa)	Penetration Depth (µm)
Proton	$1.1x10^{-4}$	$1.7x10^{-5}$	7.2
He	$2.2x10^{-3}$	$4.6x10^{-4}$	1.9
Fe	$1.3x10^{-1}$	$6.6x10^{-2}$	0.7

The penetration power of protons can be increased further by increasing energy. Table 2 shows the variation of penetration depth in a typical F/M steel with the energy of protons. The high energy protons penetrate deeper and impart reduced damage.

Table 2. Dependence of penetration depth on proton energies

Ion Energy	Max. Damage (dpa)	Avg. Damage (dpa)	Penetration Depth (µm)
300 keV	$2.0x10^{-4}$	$4.9x10^{-5}$	1.6
3 MeV	$4.0x10^{-5}$	$5.2x10^{-6}$	38
30 MeV	$3.3x10^{-6}$	$4.8x10^{-7}$	1820

The SRIM calculation revealed 35 µm deep penetration of 3 MeV protons with fluence $5x10^{14}$ p/cm^2, in 410 ferritic martensitic steels, see Fig. 1.

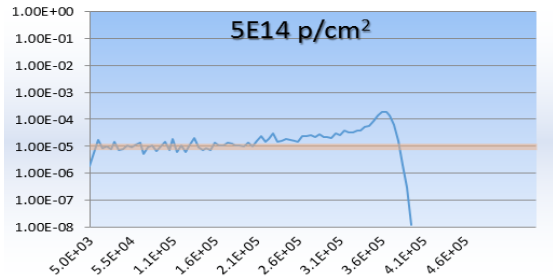

Fig. 1. Penetration depth of 3 MeV proton fluence of $5x10^{14}$ p/cm^2

The specimens of 410 and 410T ferritic-martensitic steels were exposed to 3 MeV proton fluence of $1x10^{14}$ and $5x10^{14}$ proton/cm^2 up to $1x10^{-5}$.

Because of very thin layer of irradiation affected material i.e. 35 µm, the nanoindentation test was carried out for the determination of irradiation hardening. Results of nanoindentation hardness measurement are shown in Fig. 2.

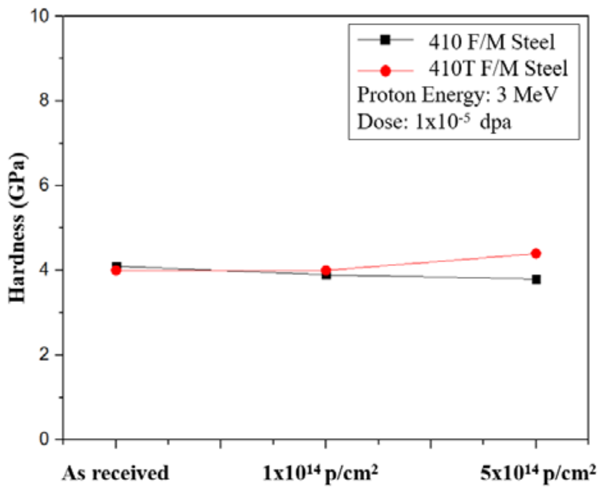

Fig. 2. Effect of proton irradiation on hardness of 410 and 410T F/M steels

Figure 2 shows that the damage up to $1x10^{-5}$ dpa has no effect on the hardness of these materials. Thus, the safety and integrity of structural F/M steels under a low dose irradiation can be ensured up to $1x10^{-5}$ dpa by utilizing AISI Type 410 and 410T steels.

3. Conclusions

By the simulation of low dose irradiation damage of ferritic-martensitic steels by using proton irradiation of AISI Type 410 and 410T F/M steels up to $5x10^{14}$

ions/cm^2 at room temperature it has found that the 3 MeV proton beam penetrates up to 35 µm in 410 and 410T F/M steels and impart a radiation damage up to 1x10^{-5} dpa. Due to low cumulative lattice damage associated with the low dose, the hardness variation in post irradiated samples was found insignificant. Thus, no effect on the hardness of AISI Type 410 and 401T F/M steels due to radiation damage up to 1x10^{-5} dpa is confirmed.

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