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Accelerated radiation damage test facility using a 5 MV tandem ion accelerator

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ABSTRACT

We have developed a new irradiation facility that allows to perform accelerated damage tests of nuclear reactor materials at temperatures up to 400 °C using the intense proton (<100 μA) and heavy ion (≈ 10 μA) beams produced by a 5 MV tandem ion accelerator. The dedicated beam line for radiation damage studies comprises: (1) beam diagnosis and focusing optical components, (2) a scanning and slit system that allows uniform irradiation of a sample area of 0.5–6 cm^2, and (3) a sample stage designed to be able to monitor in-situ the sample temperature, current deposited on the sample, and the gamma spectrum of potential radio-active nuclides produced during the sample irradiation. The beam line capabilities have been tested by irradiating a 20Cr–25Ni–Nb stabilised stainless steel with a 3 MeV proton beam to a dose level of 3 dpa. The irradiation temperature was 356 °C, with a maximum range in temperature values of ± 6 °C within the first 24 h of continuous irradiation. The sample stage is connected to ground through an electrometer to measure accurately the charge deposited on the sample. The charge can be integrated in hardware during irradiation, and this methodology removes uncertainties due to fluctuations in beam current. The measured gamma spectrum allowed the identification of the main radioactive nuclides produced during the proton bombardment from the lifetimes and gamma emissions. This dedicated radiation damage beam line is hosted by the Dalton Cumbrian Facility of the University of Manchester.

1. Introduction

Structural materials used for in-core fission reactor components face the challenge of maintaining their internal structure and integrity during their expected lifetime under extremely demanding conditions of elevated temperatures, intense radiation fields, high stress levels and aggressive coolants [1]. The potential life extension of the current nuclear reactor fleet or the realization of advanced fission and fusion reactors concepts [2–4] will require those materials to remain stable at even higher operating temperatures (<1000 °C) undergoing radiation damage levels above 50 displacements per atom (dpa) in the presence of alternative coolants (e.g. molten salts or liquid metals), and witnessing an increased production of hydrogen and helium (one to several hundreds of appm/dpa). This can potentially cause complex structural phenomena, such as irradiation creep, void swelling, phase instabilities or enhanced high-temperature helium embrittlement [5–7]. The occurrence of any of these radiation-induced structural phenomena and their effect on the material's properties should be predicted reliably, and consequently implemented into reactor design codes and assessment procedures for lifetime extensions [8,9].

In order to reach the sufficient level of reliability in our mechanistic understanding of radiation-induced structural processes in in-core reactor materials, we would need to accumulate relevant experimental data based on material tests under equivalent service conditions. Ideally we would aim to perform those tests using test reactors that would provide a similar neutron flux and energy spectrum. Unfortunately, access to those test reactors is limited, the feasible experiments would be lengthy and would yield highly active samples, whose post facto structural and mechanical characterization would require the use of specialised equipment in active labs. The possibility of using ion accelerators to simulate neutron damage emerged in the 1960s to study the potential changes in structure and properties of structural materials used in light water reactors [10]. The use of charged particles

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as a surrogate for neutron damage opens the door to perform accelerated studies of radiation damage in reactor-relevant materials with systematic variations of experimental conditions and reduced levels of sample activation [11,12]. This approach has recently been validated by comparing the radiation-induced defect structures in a ferritic/martensitic steel generated by heavy ions and neutrons [13], and also by assessing the irradiation assisted stress corrosion cracking behaviour in proton- and neutron-irradiated stainless steels [14]. Standard practices of using ion beams to emulate neutron damage have also been developed by the international community [15].

In this paper, we report the development of a new experimental facility to perform accelerated radiation damage experiments using the 5 MV tandem ion accelerator installed at the Dalton Cumbrian Facility (DCF) of The University of Manchester. DCF is accessible to potential users via the UK National Nuclear Users Facility network (www.nnuf.ac.uk). This facility allows systematic radiation damage studies of structural materials at controlled conditions of temperature, total dose and dose rate, using an intense beam of either light ions (H, He) or a range of heavy ions. We describe briefly the main accelerator and beam line components that yield a well-defined ion beam at the sample position, and afterwards we provide detailed information about the end station development, and how we measure the sample temperature, total charge deposited on the sample and potential activation levels using on-line gamma spectrometry. The capabilities of this irradiation facility have been tested by irradiating 20Cr–25Ni–Nb stabilised stainless steel, namely 20/25 stainless steel, used in UK Advanced Gas Reactor claddings [16] up to 3 dpa with a 3 MeV proton beam. The detailed characterization of the damage structure will be published in a future article.

2. Ion beam generation and conduction to the sample position

The ion beams used for radiation damage studies at DCF are produced using a 5 MV tandem Pelletron ion accelerator, in combination with the following negative ion sources: (1) a Source of Negative Ions by Caesium Sputtering (SNICS source) that produces heavy ion beams with a current of $\approx 10\,\mu A$ by bombarding the selected cathode material with Cs^+ ions [17,18]; (2) a TORoidal Volume Ion Source, i.e. TORVIS, where gas (H or He) is ionised by the plasma produced by a tungsten filament [19]. Due to the low electron affinity of helium, He^+ ions are first produced in the TORVIS source, and then passed through a Rubidium charge exchange cell to produce He^-/He^{2-} ions [20]. The TORVIS source is capable of delivering negative ion beam currents up to 100 μA (H) or 15 μA (He). The ion beam is extracted from the operative source, pre-accelerated, analysed by the injection magnet, and then accelerated by the terminal potential of the Pelletron. The negative ions pass through Ar stripper gas that converts them into positive ions. The energy of the ion beam exiting the Pelletron tank corresponds to:

$$E = (q+1) \times V_{term} + E_{inj} \quad (1)$$

where q is the charge state of the ions leaving the gas stripper, V_{term} is the applied terminal voltage and E_{inj} the injector energy, generally being of the order of a few tens of keV. The beam currents and energies achievable using this accelerator system are compared to those reported for other ion irradiations facilities in Table 1. For instance, proton beams of up to 10 MeV in energy are available using our accelerator system. These ions will have a penetration depth of $\approx 260\,\mu m$ in 20/25 stainless steel, which makes macro-scale testing of the irradiated materials feasible.

The positive ion beam generated is further directed into the beamline, at the end of which we are performing the radiation damage studies of nuclear materials. For this purpose we make use of a switching magnet with a length of $R_P = 0.48$ m. By using the expression:

$$R = \frac{R_P}{2 \times \sin\left(\frac{\phi}{2}\right)} \quad (2)$$

and the values of R_P and the deflecting angle (e.g. $\phi = 30^\circ$), we obtain a value of 0.93 m for the radius of curvature, R, of the trajectory of the ions to be injected into the 30° beam line. The applied field (B) in the switching magnet allows us to select the desired charge state of the ions that will be injected into the beamline, according to:

$$B = \frac{1440}{R}\sqrt{\frac{m \times E}{q^2}} \quad (3)$$

where m denotes the mass of the ions. The maximum field is 2×10^4 T; this constrains the energy, E, charge state, q, and mass of ions, m, available in the beam lines.

Fig. 1 displays the principal components of the beamline developed for radiation damage of materials for nuclear reactor applications. After being deflected by the switching magnet, the intensity of the beam can be measured by a Faraday cup. A rotating wire beam profile monitor (BPM) is then used to observe the beam profile. A quadrupole magnet is then used to re-focus the beam to a size of approximately 4–5 mm at the sample position.

3. Beam profile at the sample position

The beam profile at the end of the line is observed using a quartz scintillator slide before the sample position. Additionally, we achieved a uniform irradiation of a total sample area of 0.5–6 cm^2 by using a beam scanner in combination with a set of four independent slits, both installed between the quadrupole magnet and the sample position.

Table 1
Experimental capabilities of selected ion accelerator facilities used for radiation damage studies of nuclear materials [32–36]. p- protons, HI- heavy ions. Values in brackets are for accelerator to be installed by September 2015.

Facility	Primary beam	Dual Beam	Triple beam	Thermal control (°C)
Dalton Cumbrian Facility (DCF)	*p* 10 MeV 100 μA He 15 MeV 15 μA HI 10 μA	(*p* 3 MeV)		ambient – 400
Michigan Ion Beam Laboratory (MIBL)	*p* 3.2 MeV 70 μA			−180–600
JANNUS Saclay	HI 3 MV $<100\,\mu A$	HI 2 MV $<100\,\mu A$	p,d, ^{3}He, ^{4}He 2.5 MeV 40 μA	−195–850
Helmholtz Zentrum Dresden Rossendorf (HZDR)	p 6 MeV 0.5 μA	HI 450 keV 1 μA		ambient – 600
DUeT /HiMAS Kyoto University	HI e.g. Si 6.8 MeV 100 μA	He 1 MeV 100 μA	HI e.g. Ar 5 keV 40 μA	−270 – 1500
Paul-Scherrer-Institute (PSI)	p 72 MeV 50 μA			