THE RADIATION DAMAGE IN ACCELERATOR TARGET ENVIRONMENTS (RADIATE) COLLABORATION R&D PROGRAM - STATUS AND FUTURE ACTIVITIES

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Abstract

The RaDIATE collaboration (Radiation Damage In Accelerator Target Environments), founded in 2012, has grown to over 50 participants and 11 institutions globally. The primary objective is to harness existing expertise in nuclear materials and accelerator targets to generate new and useful materials data for application within the accelerator and fission/fusion communities. Current activities include post-irradiation examination of materials taken from existing beamlines (such as the NuMI primary beam window from Fermilab) as well as new irradiations of candidate target materials at low energy and high energy beam facilities. In addition, the program includes thermal shock experiments utilizing high intensity proton beam pulses available at the HiRadMat facility at CERN. Status of current RaDIATE activities as well as future plans will be discussed, including highlights of preliminary results from various RaDIATE activities and the high level plan to explore the high-power accelerator target relevant thermal shock and radiation damage parameter space.

INTRODUCTION

In 2012, at a Proton Accelerators for Science and Innovation Workshop (PASI) held at Fermilab, workshop participants from a range of high power accelerator facilities (high energy physics, nuclear physics, spallation sources) identified radiation damage to materials as the most cross-cutting challenge facing high power target facilities [1]. The RaDIATE collaboration was formed to address this challenge by bringing together experts from the fields of nuclear materials (fission and fusion power) and accelerator target facilities. The collaboration has grown to 11 participating institutions globally with 3 more institutions set to join this year (listed in the acknowledgements section). Some of the more significant current and planned RaDIATE activities are described here.

Radiation damage effects in materials are dependent upon several irradiation parameters including irradiation temperature, dose rate, and gas production (from transmutation). These irradiation parameters are quite different between the nuclear power environment (relatively lower dose rate, lower gas production, continuous irradiation) and the accelerator target environment (relatively higher instantaneous dose rate, higher gas production, pulsed irradiation). In addition, there are significant differences between the nuclear and accelerator applications resulting in somewhat different material properties of interest. For instance, accelerator target and beam window are subjected to localized, cyclic thermal gradients (referred to as thermal shock), creating dynamic stress waves moving through the material. So, in the accelerator application, high-cycle fatigue and thermal diffusion are of prime concern. Therefore, research activities tailored specifically to the accelerator target and beam window application are required.

CURRENT RADIATE ACTIVITIES

To address these high power target research needs, a program of activities is in progress. RaDIATE activities are currently focused upon candidate materials useful for neutrino target facilities and as beam window materials for various facilities, namely graphite, beryllium, aluminum, and titanium alloys. In addition, several other candidate target materials, such as iridium, and more novel potential target or beam window materials, such as nanofiber electro-spun mats and flexible graphite are starting to be explored. Status and highlights of major current activities are given below.

Graphite Studies

High-Energy Proton Irradiation of Graphite In 2010, four grades of fine-grained, isotropic graphite were irradiated with 181 MeV protons at Brookhaven National Laboratory's Linac Isotope Producer facility (BLIP). The resulting post-irradiation examination (PIE) of these specimens supported the target material choice for the Long Baseline Neutrino Facility (LBNF) [2,3]. Figure 1 shows tensile specimens being recovered after irradiation. More recently, additional PIE of these specimens has continued as part of the RaDIATE R&D program.

- Specimens were exposed to 6.7 x 10^{20} protons/cm^2 or about 0.1 DPA (displacements per atom) at an irradiation temperature of 120-150 ˚C.
- Hexagonal Boron-nitride specimens structurally degraded in beam beyond recovery for testing.
- Tensile strength and elastic modulus increased 30-50% after irradiation (see Fig. 2).
- Coefficient of thermal expansion increased 5-20%.
- Annealing above the irradiation temperature partially recovers the previous properties (see Fig. 2).
- EDXRD examination at BNL's NSLS-1 facility indicated 3% lattice swelling and agreement with neutron irradiated graphite data [3].
- Future work includes a second irradiation experiment at elevated temperature (up to 1,000 ˚C) and recreation of the damaged microstructure using low-energy ion irradiation methods.

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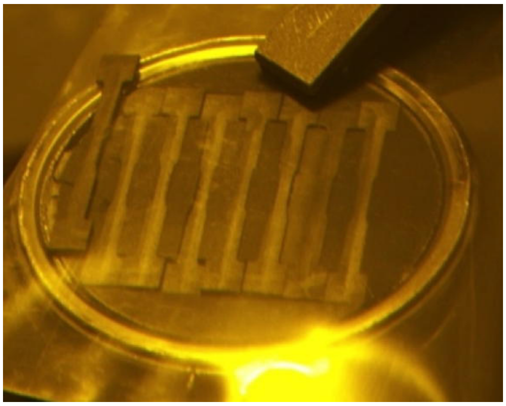

Figure 1: Graphite specimens being recovered after irradiation at BLIP (BNL).

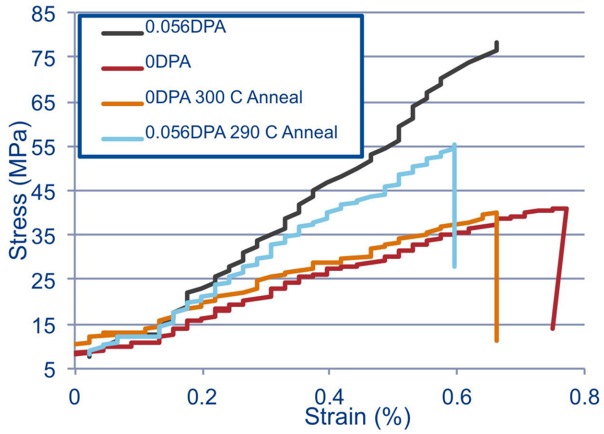

Figure 2: Tensile behavior of graphite specimens before and after irradiating at BLIP (BNL) to 0.056 DPA showing effect of annealing.

NuMI Target NT-02 Graphite Fin Study In 2015, graphite fins were recovered from the Fermilab NuMI target, NT-02, and sent to Pacific Northwest National Laboratory for PIE activities [4]. The fins were exposed to a total of 6.1 x 10^{20} protons (120 GeV) generating approximately 0.6 DPA (peak) over a service period of ~3.5 years. When removed from service, the target fins through-thickness cracks were observed in a location corresponding to beam passage.

- Dimensional swelling up to 4% was measured across the fin width corresponding to the beam spot.
- Elemental and fracture surface analysis indicated cracking occurred during operation.
- Transmission electron microscopy (TEM) did not reveal any noticeable signs of displacement damage, possibly due to the lower temperature of irradiation (50-200 ˚C).
- Future work includes micro-cantilever and hardness measurements to extract mechanical properties of graphite fin material at University of Oxford.

Beryllium Studies

NuMI Primary Beam Window Be Study In 2014, an irradiated disc of beryllium was recovered from the Fermilab NuMI primary beam window and sent to University of Oxford for PIE activities [5]. The window saw a total of 1.6 x 10^{21} protons (120 GeV) generating approximately 0.5 DPA (peak) and was irradiated at ~50 ˚C. When the disc was sheared from the window, cracks appeared in the central beam region.

- Crack morphology shifts at high doses from transgranular to grain boundary fracture indicating hardening of the crystal matrix within grains (see Fig. 3).
- Atom Probe Tomography (APT) indicates production of Li through transmutation matches MARS [6] calculation within 25% and remains homogeneous.
- Ongoing work includes micro-cantilever and hardness measurements to extract mechanical properties.

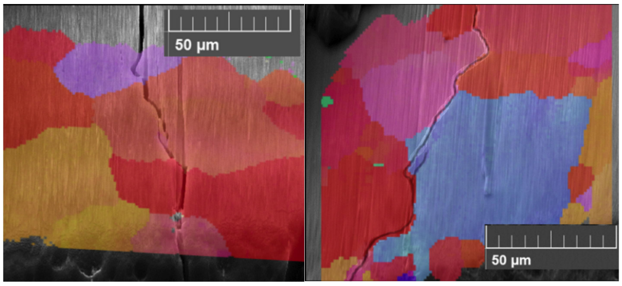

Figure 3: Electron Back-Scatter Diffraction (EBSD) images showing cracks in NuMI Be beam window irradiated to 0.29 DPA (left, transgranular fracture) and 0.44 DPA (right, intergranular fracture with crack image enhanced).

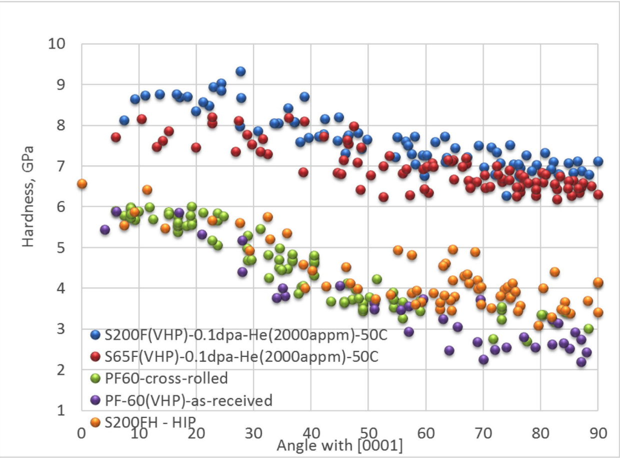

Figure 4: Hardening in He implanted beryllium (upper point set, 0.1 DPA and 2,000 appm He) compared to as-received beryllium (lower point set).

Helium Implantation of Be Study In order to mimic the radiation damage effects from high energy proton beam, low energy helium ion beam was implanted into beryllium specimens at the University of Surrey Ion Beam Centre. Irradiation was conducted with energies ranging from 0.2 to 1.2 MeV, at temperatures of 50 and 200 ˚C and up to 0.1 DPA and 2,000 atomic ppm He. Specimens were examined at University of Oxford [7].

- Nano-indentation revealed significant hardening at 0.1 DPA (see Fig. 4) was primarily due to implanted helium content rather than displacement damage.

- TEM analysis showed evidence of He implantation (nanometer scale black dots).
- Ongoing work includes micro-cantilever measurements to extract mechanical properties (see Fig. 5).

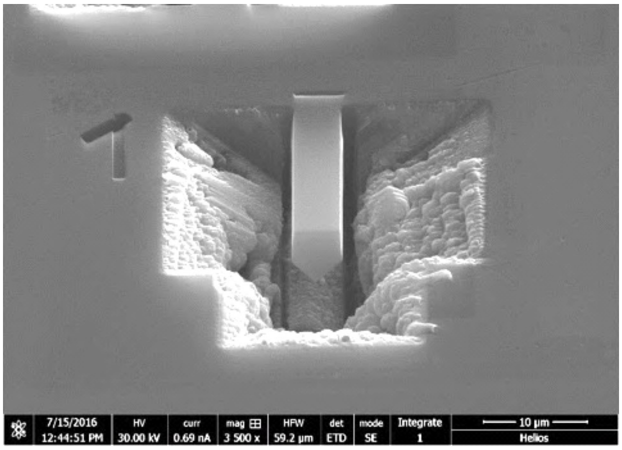

Figure 5: Micro-cantilever prepared in beryllium implanted with He to 2,000 appm.

In-beam Thermal Shock of Be Study To study the thermal shock effects on various grades of beryllium, specimens of varying thicknesses were exposed to pulses of high intensity beam at CERN's HiRadMat beamline [8]. Pulse intensities up to 2.8 x 10^{13} protons with pulse length of 5.4 µs) at beam spot sizes less than 0.3 mm (gaussian sigma radius) were explored pushing the specimens into plastic deformation at high temperatures [9].

- For the highest intensity pulse, profilometry measurements agree within 30% with results predicted by a high strain-rate strength model (see Fig. 6).
- Grade S200FH showed least plastic deformation.
- Multiple pulses in the same location showed diminishing ratcheting in plastic deformation.

FUTURE RADIATE ACTIVITIES

Multi-material BLIP Irradiation and PIE

A multi-national radiation damage experiment utilizing the BNL BLIP facility was begun in 2017 with almost all the RaDIATE participating institutions playing some significant role. Materials chosen are relevant to each participant's future program, and include beryllium, graphite, c-c composite, glassy carbon, titanium alloy (including 3D printed material), silicon, silicon carbide, aluminium alloy, TZM (molybdenum alloy), CuCrZr, and iridium. Specimen capsules (see Fig. 1) are currently being irradiated by 181 MeV protons, and will provide hundreds of individual, irradiated specimens for PIE work that is expected to extend well into 2018 [10].

HiRadMat In-beam Thermal Shock Testing

A follow-up thermal shock experiment utilizing the CERN HiRadMat beamline [8] is being planned for 2018. This experiment will place non-irradiated and irradiated specimens of beryllium, graphite, titanium alloy and glassy carbon into the intense 440 GeV proton beam. Specimens will be partially instrumented to record temperature and strain and PIE will include profilometry to measure out-of-plane plastic deformation. This will allow direct comparison of irradiated versus non-irradiated material, validation of simulation data and techniques, and prediction of how highly irradiated material reacts to the unique loading environment of intense proton beam.

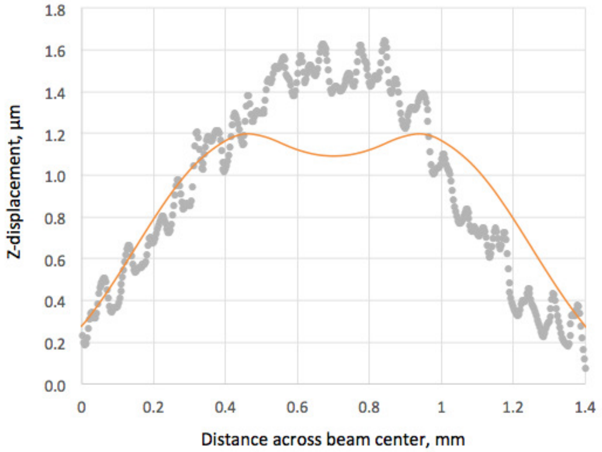

Figure 6: Comparison of simulation results (line) with raw profilometer measurement data (points) of permanent deformation in a Be disc exposed to HiRadMat beam.

CONCLUSION

The RaDIATE collaboration is strong and growing, with a several radiation damage and thermal shock studies underway. The primary objective is to harness existing expertise in nuclear materials and accelerator targets to generate new and useful materials data for application within the accelerator targetry community.

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