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 typically non-life-safety critical components and generally have localized volumes of intense cyclic irradiation (particle surrounded by cooler, non-irradiated material that challenge the limits of the material. Typical beam spot sizes range from a few millimeters to a few centimeters in radius. This gives rise 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. Whereas in a reactor application, structural materials often play a life-safety critical role, but are, during normal operation, exposed to a more uniform, continuous bulk irradiation. Reactor structural materials are only pushed to the limits by accident scenarios where they must retain damage tolerance. So, in the nuclear application, ductility and fracture toughness are of prime concern. Therefore, the differences between irradiation parameters and application-specific loading environments require research activities tailored specifically to the accelerator target and beam window application.

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CURRENT RADIATE ACTIVITIES

To address these high power target research needs, a program of activities was undertaken. Recent RaDIATE activities focused upon candidate materials primarily useful for neutrino target facilities and as beam window materials for various facilities, namely graphite and beryllium. Status and highlights of major current activities are given below. Although preliminary findings are listed below, full results will be published soon in relevant scientific journals.

Graphite Studies

High-Energy Irradiation of Graphite In 2010, four grades of fine-grained, isotropic graphite, one grade of hexagonal boron-nitride, and one grade of carbon-carbon composite (3-D fiber weave) 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]. 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% after irradiation.
- Annealing above the irradiation temperature partially recovers the previous properties (see Fig. 2).
- Annealing results indicate that irradiating at higher temperatures may be beneficial to limit radiation damage effects.

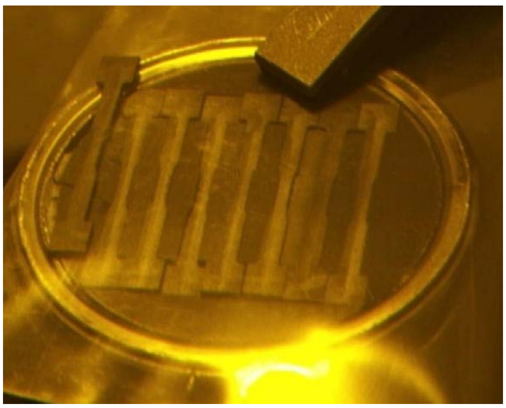

Figure 1: Graphite specimens being recovered after irradiation at BLIP (BNL).

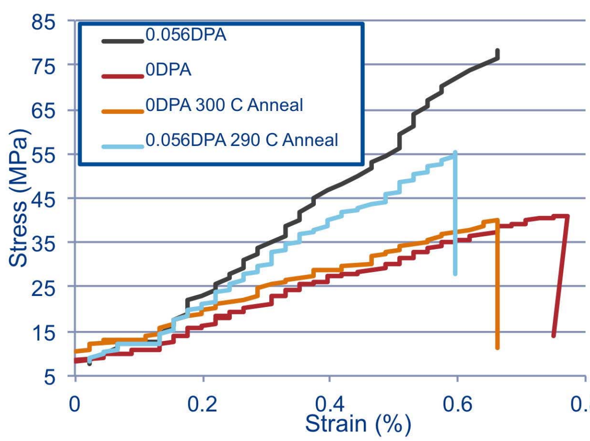

Figure 2: Tensile behavior of graphite specimens before and after irradiating at BLIP (BNL) to 0.056 DPA showing effect of annealing.

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 [3]. 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 in the fin width area corresponding to the beam center-line.
- 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).

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 [4]. 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 changes at higher doses from transgranular to grain boundary fracture indicating hardening of the crystal matrix within grains (see Fig. 3).
- Production of Li through transmutation matches MARS [5] calculation within 25% and remains homogeneously distributed.

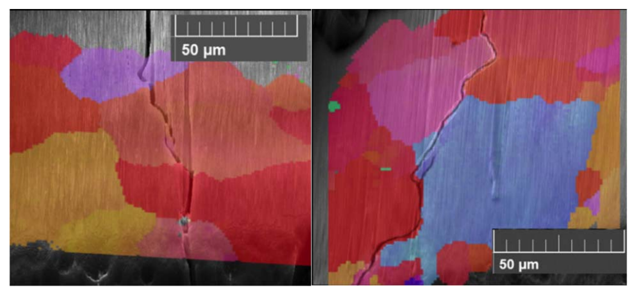

Figure 3: Electron Back-Scatter Diffraction (EBSD) images showing cracks in NuMI Be beam window irradiated to 0.29 DPA (left, transgranular fracture) and 0.44 DPA (right, grain boundary fracture with crack image enhanced).

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. Specimens were examined at the University of Oxford [4].

- Nano-indentation revealed significant hardening at 0.1 DPA (see Fig. 4).
- TEM analysis showed evidence of He implantation (nanometer scale black dots).

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 [6]. Pulse intensities up to 2.8 x 10^{13} protons at beam spot sizes less than 0.3 mm (Gaussian sigma radius) were explored pushing the specimens into plastic deformation at high temperatures [7].

- For the highest intensity pulse, profilometry measurements matched the deformation results predicted by generic strength models
- Grade S200FH showed least plastic deformation
- Multiple pulses showed diminishing ratcheting in plastic deformation

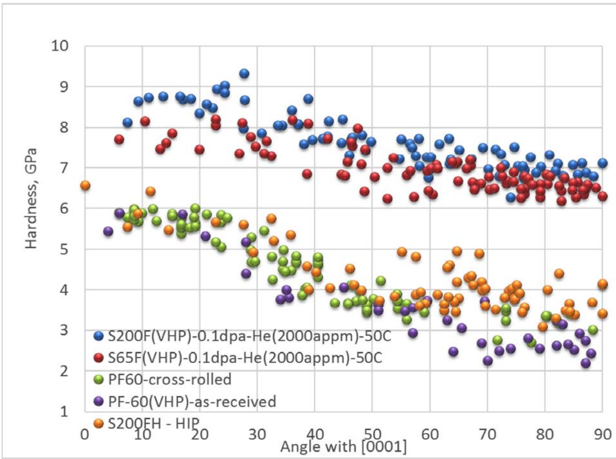

Figure 4: Nano-indentation hardness measurements showing hardening in He implanted beryllium (red and blue points, 0.1 DPA and 2,000 appm He) compared to as-received beryllium (green, orange and purple points).

FUTURE RADIATE ACTIVITIES

Future RaDIATE activities will continue the work described above, including conducting micro-mechanics (NuMI Be beam window and the NT-02 graphite fins) and expanding upon the He implantation studies. In addition, major new activities are already underway and described below.

Multi-Material BLIP Irradiation and PIE

A multi-national radiation damage experiment utilizing the BNL BLIP facility is being planned to start early in 2017 with almost all the RaDIATE participating institutions playing some significant role. Materials chosen are relevant to each participant's future program. Specimen capsules (see Fig. 1) are being prepared currently that will provide hundreds of individual, irradiated specimens for PIE work that is expected to extend well into 2018. Experiment details follow:

- 8-10 weeks of irradiation with 181 MeV proton beam (up to 165 µA) is planned.
- Materials 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.
- Expected peak DPA is 0.7 DPA in the titanium alloy
- In order to explore the benefits of annealing, irradiation temperatures will vary from 100 ˚C to 1,200 ˚C depending upon the specimen capsule environment (gas/vacuum), specimen material and specimen location within the array.
- Expected PIE includes tensile testing, thermal testing. micro-structural analysis, fatigue testing and micro-mechanics.

HiRadMat In-Beam Thermal Shock Testing

A follow-up thermal shock experiment utilizing the CERN HiRadMat beamline is being planned for 2018. This experiment will place non-irradiated and irradiated specimens of beryllium, graphite, and glassy carbon into the intense 400 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 pulses.

CONCLUSION

The RaDIATE collaboration is strong and growing, with a large number of studies into radiation damage and thermal shock 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. For the case of neutrino targetry, the LBNF reference design (1.2 MW primary beam power) requires exploration of thermal shock severity greater than 3 x 10^{14} protons/cm^2/pulse and radiation damage severity greater than 1 x 10^{22} protons/cm^2 fluence. RaDIATE activities are already generating useful data at these lower limits with plans to explore to even higher values in the near future.

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