POST-IRRADIATION PROPERTIES OF CANDIDATE MATERIALS FOR HIGH-POWER TARGETS

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Abstract

The desire of the high-energy-physics community for more intense secondary particle beams motivates the development of multi-megawatt, pulsed proton sources. The targets needed to produce these secondary particle beams must be sufficiently robust to withstand the intense pressure waves arising from the high peak-energy deposition which an intense pulsed beam will deliver. In addition, the materials used for the targets must continue to perform in a severe radiation environment. The effect of the beam-induced pressure waves can be mitigated by use of target materials with high-yield strength and/or low coefficient of thermal expansion (CTE) [1, 2, 3]. We report here first results of an expanded study of the effects of irradiation on several additional candidate materials with high strength (AlBeMet, beryllium, Ti-V6-Al4) or low CTE (a carbon-carbon composite, a new Toyota "gum" metal alloy [4], Super-Invar).

INTRODUCTION

With ever-increasing demand for higher proton beam power in support of new physics opportunities at future facilities such as neutron spallation sources, neutrino super-beams, neutrino factories, muon colliders, the number of target materials that can survive the correspondingly more intense proton bombardment is dramatically reduced. The targets must withstand the pulse-by-pulse stresses of beam-induced pressure waves, and well as the long term effects of radiation damage. This papers reports on a continuing evaluation of the effects of irradiation on solid target materials that exhibit high strength or low coefficient of thermal expansion [1, 2, 3], properties that mitigate beam-induced pressure waves. Our studies build on extensive prior work of the nuclear-physics community, such as the Accelerator Production of Tritium (APT) Material Handbook [5], by studying high-performance engineered materials some of which have become available only recently. A cautionary result from our previous work is that the initially low coefficient of thermal expansion of Super-Invar was observed to rise quickly with radiation dose [2]. Thus, while we have also demonstrated that a carbon-carbon (CC)-composite with a 3-D weave, designed for very low coefficient of thermal expansion, indeed exhibits much lower beam-induced stress than, say, graphite [3], as shown in Fig. 1, the question of whether this superior response remains after irradiation required additional study. We report here preliminary results from a recent irradiation of seven materials described in the next section, by 100-200 MeV protons to roughly 0.25 DPA (displacements per atom). We will eventually examine the effect of irradiation on the CTE, ductility, yield strength, heat capacity, and the fracture toughness of these materials.

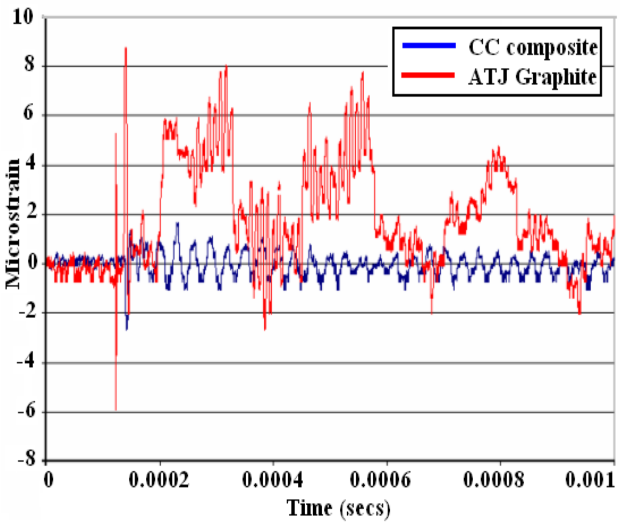

Figure 1: Comparison of the internal stresses in graphite and in a 3-D carbon-carbon composite induced by 24-GeV protons [3].

THE IRRADIATED MATERIALS

Carbon-carbon composite.
Graphite (IG43).
Titanium Ti-6Al-4V alloy. This combines good tensile strength and relatively low CTE.
Toyota "Gum" Metal [4]. This alloy (developed for disc brakes) exhibits ultra-low elastic modulus, high strength and near-zero linear expansion coefficient for the temperature range −200 C to +250 C.
Vascomax, a high-strength iron alloy.
Beryllium.

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AlBeMet, a low-Z alloy of Be and Al.

EXPERIMENTAL SETUP

The irradiation was performed at the Brookhaven Linac Isotope Producer (BLIP) facility with a 200 MeV proton beam from the linac that also serves as an injector for the AGS booster. The beam energy at the material samples varied from 190 MeV down to 110 MeV. The samples were arrayed in three holders (boxes), as sketched in Fig. 2, that permitted cooling water to flow through each sample holder at a rate of 2 gpm. Two types of samples of each material were irradiated: "dog bones" for tensile tests, and rods for thermal tests. One layer of such samples is shown in Fig. 3. At the conclusion of the irradiation of the test samples, a short irradiation under similar beam and water flow conditions was made of Aluminum and Stainless steel plates coated with heat-sensitive paint. From the heat-induced discoloration of the paint, we can deduce the heat transfer and water flow parameters required to establish the temperature profiles that our test samples experienced while being irradiated.

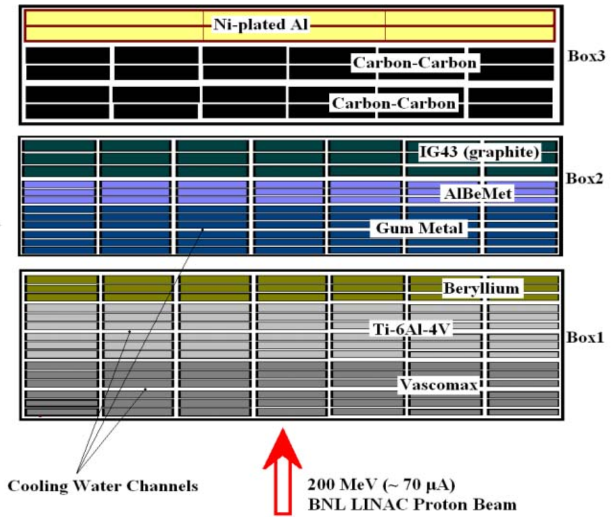

Figure 2: Specimen layout in the three holders.

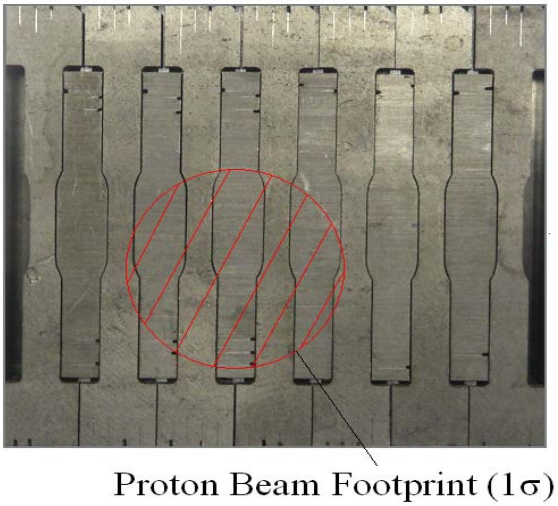

Figure 3: Arrangement of one layer of thermal and tensile test specimens during proton irradiation.

The irradiation extended over two weeks with holder Boxes 2 and 3 receiving a total of 5.3×10^{20} protons, while Box 1, which was inserted later, received 3.7×10^{20} protons. We subsequently measured the spot size of the proton beam with auto-radiography techniques and determined the beam dimensions to be $\sigma_x = 8.1$ mm and $\sigma_y = 8.4$ mm. This corresponds to a peak proton fluence of 1.3×10^{20} protons/cm^2 for Boxes 2 and 3 and 0.91×10^{20} protons/cm^2 for Box 1.

FIRST RESULTS

Figure 4 shows the expansion of carbon-carbon composite samples as a function of temperature. The red and green curves are the first and last heating cycles of an irradiated sample and the blue curve is the last heating cycle of a non-irradiated sample. Measurements taken during the first heating cycle after irradiation show much larger expansions of the samples at temperatures above 125 C than non-irradiated samples. However, a second measurement of irradiated samples, after they had reached a maximum temperature of 300 C in the first measurement cycle, show expansions very similar to those of non-irradiated samples. We infer that the irradiation caused an increase in the coefficient of thermal expansion of the carbon-carbon composites, but this effect largely disappears after annealing during a thermal cycle up to 300 C. Having become aware of the possible benefit of thermal cycles in reducing the coefficient of thermal expansion that had been increased by radiation damage, we remeasured the Super-Invar from our previous irradiation study [2]. Now we were able to perform thermal cycles up to 600 C (compared to maximum of 300 C in the previous study). When the temperature during a thermal cycle exceeds 500 C we found that the low coefficient of thermal expansion of irradiated Super-Invar begins to approach its non-irradiated behavior (Fig. 5). Our preliminary measurements indicate that the coefficient of thermal expansion of Toyota "gum" metal [4] is affected by thermal cycling to high temperatures whether or not it has been irradiated. Details of this complicated behavior will be presented elsewhere. Figure 6 shows a different effect of irradiation on the "gum" metal, namely a loss of ductility as a function of radiation dose.

CONCLUSIONS

The first results from our recent irradiation of high-performance materials already show several important qualitative features. We confirm that materials engineered to have a low coefficient of thermal expansion tend to lose

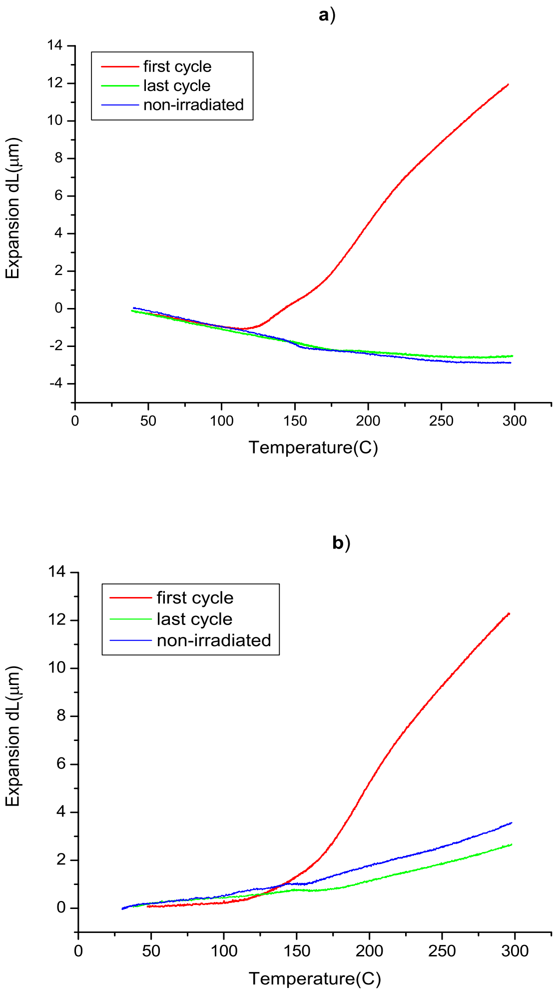

Figure 4: Expansion *vs.* temperature of CC composites: a) expansion along one of the fiber axes; b) expansion at 45° to the fiber axes.

this desirable feature with radiation doses only a fraction of a DPA. However, we find that the original behavior of the coefficient of thermal expansion can be largely restored by appropriate thermal cycling. We confirm that the modulus of elasticity (slope of the stress-strain curve) is little affected by radiation damage, and we confirm that the ductility of materials near yield stress can be significantly reduced (embrittlement), which effect is very pronounced in the Toyota “ gum” metal.

ACKNOWLEDGMENTS

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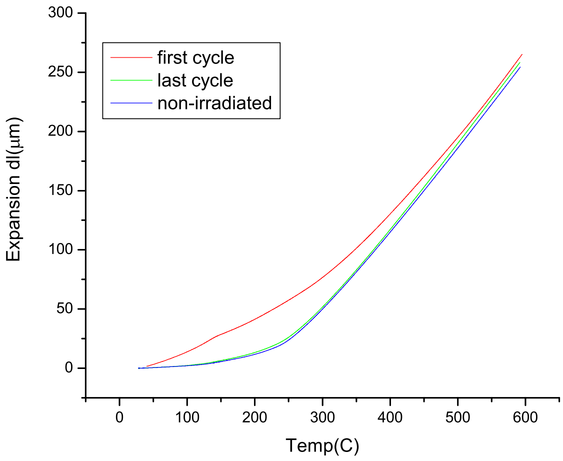

Figure 5: Expansion *vs.* temperature of Super-Invar at higher temperature cycles. The coefficient of thermal expansion is restored to its non-irradiated value after annealing at temperatures above 500 C.

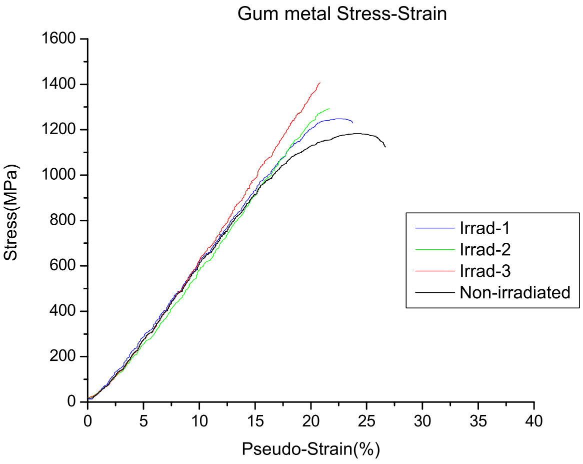

Figure 6: Effects of irradiation on the stress-strain relationship of the “gum” metal [4]. The radiation dose was greatest in sample 3, and least in sample 1, of the irradiated sample. The straightness of the curve for sample 3 indicates an almost complete loss of ductility compared to the non-irradiated sample.

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