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Irradiation damage studies of high power accelerator materials

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A B S T R A C T

High-performance production targets and other critical accelerator components intercepting intense, energetic proton beams are essential as the accelerator community envisions the next generation, multi-MW accelerators. Materials that have served the nuclear sector well may not be suitable to play such a role which demands that the material comprising the beam-intercepting element must, in addition to the long exposure which leads to accumulated irradiation damage, also endure short exposure that manifests itself as thermo-mechanical shock. The ability of materials to resist irradiation-induced degradation of its properties that control shock and fatigue is of primary interest. The need for such materials that extend beyond resistance to the neutron-driven irradiation damage of reactor components has led to an extensive search and experimentation with new alloys and composites. These new high-performance materials, which appear to possess the right combination of mechanical and physical properties, are explored through a multi-phased experimental study at Brookhaven National Laboratory (BNL). This study, which brings together the interest in accelerator targets of different facilities around the world, seeks to simulate conditions of both short and long exposure to proton beams to assess the survivability potential of these new alloys and composite materials. While thermo-mechanical shock effects have been studied in the early stages of this comprehensive effort, it is irradiation damage that is currently the focus of the study and results to-date are presented in this paper along with the status and objectives of on-going studies. Of special interest are results depicting damage reversal through post-irradiation annealing in some of the materials. High fluences of 200 and/or 117 MeV protons provided by the BNL Linac beam that serves the Isotope Production Facility were used to assess irradiation damage in these new composites and alloys.

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1. Introduction

With the ever-increasing accelerator power required to support high-energy physics initiatives, the pool of materials forming production targets or other critical components capable to withstand the pulse intensities associated with these multi-MW-class machines is reduced. MW-class accelerator targets must endure fluences that may approach those of high dose reactor-based materials and must be able to continuously absorb and diffuse the severe thermo-mechanical shock resulting from the intense proton pulses. Tightly focused, high-energy proton pulses must be intercepted by the envisioned accelerator targets within several nanoseconds leading to instantaneous fluxes of the order of 10^{24} protons/cm^2/s. Densities of energy deposited under these conditions on the target as well as other beam-intercepting elements like collimators are estimated to be extremely high and far beyond what common materials, even those with extensive reactor-based track record, can tolerate. Further, the thermo-mechanical fatigue issue, direct result of the pulsed nature of these MW-class accelerators, adds additional performance requirements on these materials because of the need to extend the operational life of these components. Fatigue limits, even under the best of circumstances in which materials can resist irradiation-induced degradation of their properties, can be reached in short time given that accelerator pulse frequencies can reach 60 Hz.

The need to identify materials that go beyond the neutron-driven irradiation damage of reactor components and are able to tolerate severe beam-induced shock has led to an extensive search and experimentation with new alloys and composites. These new high-performance materials, which, in the absence of irradiation exposure, appear to possess the right combination of mechanical and physical properties, are explored through a multi-phased

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Table 1
Material chemical composition

Element	C	Al	Si	S	Ti	Cr	Mn	Fe	Co	Ni	Cu	Nb	Mo	V	Zr	Ta	O
Super-invar	.05	.07	.09	.01		.03	.4	62	5.4	31.8	.08						
Inconel-718		0.5			1.0	19		19		52.5		5	3				
Vascomax-350	.02	0.1	.05	.005	1.4		.05	63	12	18.5			4.8				
Ti–6Al–4V	.08	5.5–6.76			Balance			.25						3.5–4.5			.2
Gum metal					68.5							9		3	6	12	1.5

experimental study at Brookhaven National Laboratory (BNL). During the first phase of the study target and beam-window materials were exposed to 24 GeV, high-intensity proton pulses provided at the BNL Alternating Gradient Synchrotron (AGS). The objectives of this study [4] were to assess how carbon composites and other super-alloys respond to the beam-induced shock and whether prediction of their response is possible based on simulation models. The latter is an essential element towards achieving the ultimate goal of multi-MW beam intensities. Verification of the ability to predict shock response at intensity levels the current accelerators can provide will form the foundation for extrapolating the understanding to the MW-class accelerators that are being conceptualized. While it is desirable to induce beam shock conditions on materials that have experienced cumulative degradation of their properties as a result of prolonged exposure, a condition that exactly simulates what the real target materials will experience in MW-class accelerators, facilities capable of delivering both aspects of 'damage' simultaneously are currently unavailable. Therefore, this study, as well as other relevant studies being pursued, while relying on addressing the two components separately, attempt to inch ever closer to the desired state that can only be delivered by the multi-MW accelerator that is in its conceptual state. In this paper, the results of the BNL shock studies will be mentioned briefly since they have been reported in prior reports [1–4]. Instead the focus will be on the aspects of the experimental study that address the effects of irradiation on the material properties of new alloys and composites that are pertinent to their performance as targets and other beam-intercepting accelerator elements.

While a wealth of relevant materials damage data, even on materials that may be considered to play roles other than targets in high-power accelerators, is available to the accelerator community from reactor studies and experience data [5] this information is almost entirely linked to neutron exposure damage effects on these materials. The correlation between prolonged neutron and proton exposure effects is still too incomplete to allow for direct use of the reactor-based data to proton accelerators. In addition, irradiation damage data from either neutrons or protons for the recently developed 'smart' alloys and composites, which hold most of the promise, are either scarce or non-existent.

The irradiation damage effort that is the focus of this paper has been conducted in a series of phases. During the first phase of the study Inconel-718 and super-invar where irradiated using the 200 MeV protons of the Brookhaven Linac Isotope Producer (BLIP). The primary objective was to primarily assess how the extremely low thermal expansion coefficient (CTE) of super-invar survives prolonged exposure to protons. CTE is one of the physical properties that play a pivotal role in determining the state of thermal stress in the material following interception of proton pulses. A low CTE is desirable, since the generated stress is proportional to it and the question is whether irradiation induces significant changes in its unirradiated value. The study of Inconel-718, although of secondary interest, was to confirm that the material is stable regarding its reported [6] stable CTE under irradiation conditions. The damage levels achieved during this first phase were approximately 0.25 displacements-per-atom (dpa) for super-invar and approximately 0.05 dpa for inconel-718. Results of irradiation-induced changes on the two materials are presented in this paper.

In the second phase of study, the search for new alloys, composites and 'smart' materials continued and a new and expanded matrix was established. It included materials in the low-Z and mid-Z regimes in an effort to satisfy accelerator initiative needs that are linked to the atomic number of the target material. Specifically, the low-Z regime was comprised by the three-dimensional (3D) weaved carbon–carbon composite, graphite grade IG-43, alloy (or even termed composite) AlBeMet (62% beryllium and 38% aluminum), and pure beryllium. The mid-Z regime included the titanium alloy Ti–6Al–4V, an annealed version of the super-alloy 'gum' metal, and Vascomax-350. Table 1 lists the chemical composition of the alloys studied. In addition, nickel-plated aluminum samples were introduced in the irradiation matrix to study the combined effects of irradiation and corrosive environment on this special plating. A dedicated study on the effects of proton irradiation on the two-dimensional (2D) carbon–carbon composite structure was also conducted. Assessment of the structural integrity of this particular composite and its ability to maintain low CTE were the primary objectives.

Most recently, a new phase of the study has been launched in an effort to address some of the issues that resulted from the previous phases and to achieve higher exposure. Some of the already tested materials were re-introduced into the matrix along with all new materials such as the 'cold-worked' gum metal, copper, glidcop and the high-Z materials tungsten and tantalum. Noteworthy is the re-introduction of post-irradiation annealed super-invar into the matrix to assess the response to re-exposure of materials that have undergone annealing. While the irradiation portion of the last phase has been completed after approximately doubling the damage of phase two, the post-irradiation analysis is still pending. Results and discussion on the new findings will be reported in a follow-up report.

2. Experimental effort

2.1. Irradiation facility and proton beam

Shown in Fig. 1 is a schematic of the irradiation facility where materials are exposed to protons. The 117 or 200 MeV proton beam at the end of the Linac is directed toward the isotope production facility where a special target station submerged in ~30 ft of water and with water flowing through the assemblies has been designed and installed. The operation normally shares the beam with the accelerator complex (Booster-AGS-RHIC) in a mode that allows six out of the seven pulses of protons to be directed toward the isotope or irradiation targets. As shown in Fig. 1, the typical beam current is 80 μA with some fluctuation around this nominal value. During the various irradiation phases beam current as high as 95 μA were seen. The proton beam is purposely de-focused in order to expose as much as possible of the volume of the special targets used for harvesting isotopes. Special nickel foils integrated into the irradiation assemblies help establish the beam spot size, shape and location during irradiation. Beam spot sizes with full width at half maximum (FWHM) ≈ 15 mm are typical.

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