MATERIAL IRRADIATION DAMAGE STUDIES FOR HIGH POWER ACCELERATORS*

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Abstract

The feasibility of multi-MW accelerators, currently under consideration and study, is directly linked to the production target and its survivability under severe shock and high irradiation exposure. The limitations of solid materials to function as high performance targets and in particular the effects of irradiation on key material properties are assessed through an extensive experimental study and findings to-date are presented and discussed.

INTRODUCTION

High-performance targets intercepting multi-MW proton beams are key toward the generation of intense muon or neutrino beams. To achieve this goal one must push the envelope of the current knowledge of material science, material endurance, and survivability to both short and long proton beam exposure. The demand imposed on the targets of high power accelerators and the limitations of most materials in playing such pivotal roles have led to an extensive search and experimentation with new alloys and composites. These new high-performance materials, developed to support technologies unrelated to accelerators and their targets but which at first glance appear to possess the right combination of mechanical and physical properties, are explored through a multi-phased experimental study at Brookhaven National Laboratory (BNL). The overall 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 and assess the survivability potential of solid materials. During short exposure the effects of the thermo-mechanical shock on the solid target of choice is addressed and the limits of pulse intensity is established. A BNL experiment [1] based on high intensity proton pulses from AGS at 24 GeV on various solid targets was conducted and the ability to predict the target response was tested. Results of this initial phase of the overall study have already been presented [2] and will not be discussed further here except to state that the study (a) identified the superiority of composites such as carbon-carbon over graphite to absorb shock and (b) established that advancements in computational science and simulation can predict the response of solid targets under beam-induced shock.

The primary focus of this paper is the irradiation damage or long exposure aspect of the effort. Specifically, the irradiation damage on attractive candidates, based on their physical and mechanical properties in the un-irradiated state, has been sought through a series of irradiation exposures to high proton fluences using the BNL Linac beam at the Isotope Production Facility which provides 200 and 117 MeV protons on targets.

Presented in this paper are results of the post-irradiation analysis seeking to assess the changes taking place in mechanical and physical properties of the candidate materials. Results shown are those exhibiting interesting response to irradiation as well as post-irradiation treatment such as annealing and damage reversal. The post-irradiation analysis on the exposed target specimens is conducted at the BNL hot labs.

EXPERIMENTAL EFFORT

The BNL target irradiation study consists of various phases that either focused on specific target candidates or on an array of candidates with the purpose of screening-out materials that appear to be susceptible to damage even from limited irradiation exposure. The overall material matrix includes different graphite grades, carbon composites and "super" alloys in addition to traditional materials (such as beryllium, copper, tungsten and tantalum) that have been included in the analysis for additional scrutiny, and possible identification of favorable behavior under the conditions required by muon and neutrino targets.

The study focused initially on super Invar in an effort to exploit the low coefficient of thermal expansion (CTE) that this material exhibits at temperatures below 200º C. A low material CTE is highly desirable for a high-performance target in that it helps reduce the stress shock generated by high intensity pulses. As will be discussed in the next section, the initial assessment was that even modest levels of irradiation alter the material behavior resulting in the exclusion of super Invar from further consideration. During the second irradiation phase attention was focused on carbon-carbon composite (two- and three-dimensional fiber arrangement). In addition the material matrix was expanded to include AlBeMet (a beryllium-aluminum composite or alloy), beryllium, titanium alloy (Ti-6Al-4V), Vascomax and annealed Gum metal. Irradiation damage approaching 0.28 displacements per-atom (dpa) was achieved from this proton exposure. Following the post-irradiation analysis of the expanded material matrix and based on the interesting behavior exhibited by some of the irradiated materials, a new irradiation cycle was put in motion in order to (a) re-confirm the post-irradiation response under higher dose and (b) expand the matrix further to include new materials

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in support of other target concepts (such as muon targets consisting of a special bonding between graphite and titanium alloy), copper and Glidcop as well as high-Z targets made of tantalum and tungsten. The irradiation of the latest matrix has recently been completed and no post-irradiation analysis has been performed as yet. The estimated damage achieved during the latest cycle is about 1 dpa for the high-Z targets.

The post-irradiation analysis of the selected target materials consists of measurements of changes in thermal expansion as well as stress-strain relations. As pointed out earlier, CTE is key in maintaining low levels of shock stress while the stress-strain is indicative of the loss of ductility and subsequently loss of fatigue strength. Preparations are under way to identify the changes in thermal diffusivity and conductivity that control the diffusion of heat deposited by the proton pulse on the target. A special laser-flash method is being implemented to test heavily irradiated targets.

POST-IRRADIATION RESULTS

Initial evaluation of the irradiated super Invar revealed that even modest levels of irradiation (~0.20 dpa) resulted in dramatic increase of its CTE, as shown in Fig. 1. While no further consideration was given to this material at the time, it became apparent that materials such as carbon composites with similarly low CTEs benefit from thermal annealing and pretty much reverse the induced damage. That finding prompted the re-examination of super Invar and the identification of the threshold temperature (>600º C) that is needed for complete annealing. This annealing is shown in Fig. 2.

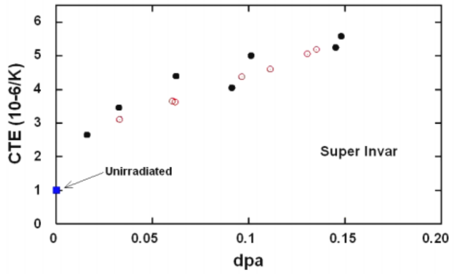

Figure 1: Irradiation effects on super Invar CTE.

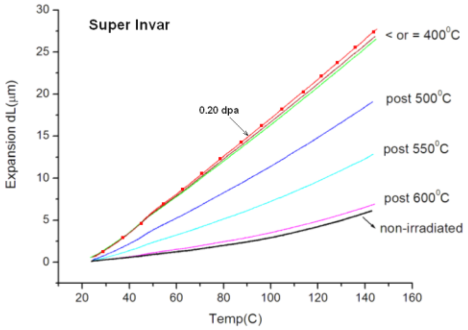

Figure 2: Damage reversal or CTE restoration in irradiated super Invar through thermal annealing.

The analysis also revealed that carbon composites (3D and 2D fiber arrangement shown in Figs. 3 and 4 respectively) could reverse damage by thermal annealing.

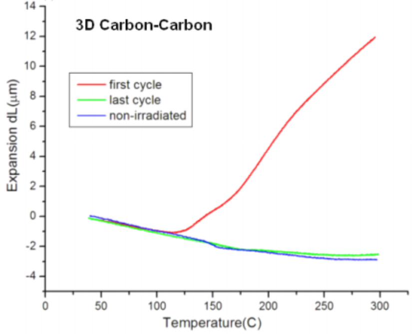

Figure 3: Thermal annealing of irradiated 3D carbon.

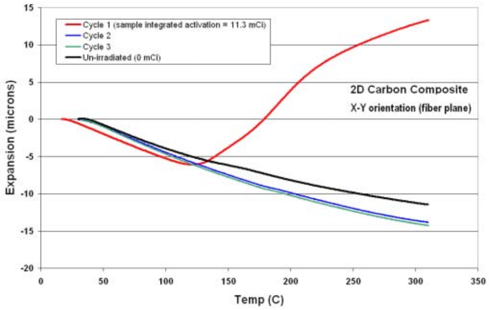

Figure 4: Thermal annealing of irradiated 2D carbon.

While Figs. 3 and 4 depict the response of the composite on the fiber planes (expected to be similar), Fig. 5 and shows remarkable recovery in the direction normal to the fiber planes for different levels of irradiation damage. However, the analysis showed that the 2D composite suffers structural damage at higher doses. Both the 3D and 2D versions of the composite have been exposed to protons during the last phase and will be re-examined.

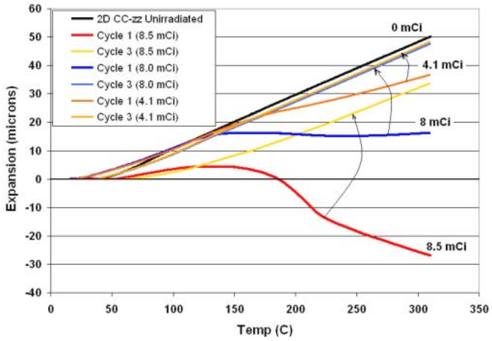

Figure 5: Annealing in 2D carbon exposed to low dose.

The super alloy Gum metal [4] held a lot of promise in that it has a wide range of very low CTE (up to 450º C), high strength, high ductility and low elastic modulus. Its superb properties are depicted in Fig. 6. Irradiation of the annealed version of the material, however, revealed that modest levels of irradiation damage remove its ductility Fig. 7a). The 90% cold-worked Gum metal has been irradiated during the last beam exposure. As shown in Fig.

7b, however, the low CTE exhibited by the material to ~ 400° C is removed with a single thermal cycle. The Vascomax stress-strain relations, shown in Fig. 8, reveal that the material holds onto the ductility it possesses while acquiring strength with irradiation. The titanium alloy on the other hand, Fig. 9, strengthens with irradiation but sheds some of its ductility. Of interest is the finding that AlBeMet actually sees its CTE reduced with increased proton fluence as shown in Fig. 10. A special target for the muon facility at J-PARC consisting of a special silver blazing bonding between graphite and titanium has been irradiated during the latest irradiation phase. The goal is to examine the resilience to irradiation of the distinct interface that exists between the two materials clearly depicted in Fig. 11.

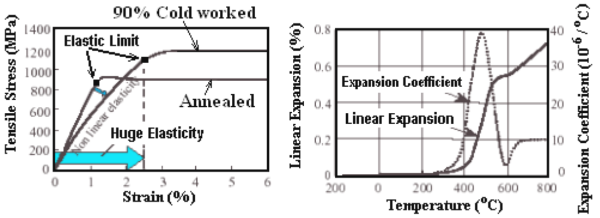

Figure 6: Un-irradiated Gum material properties [4].

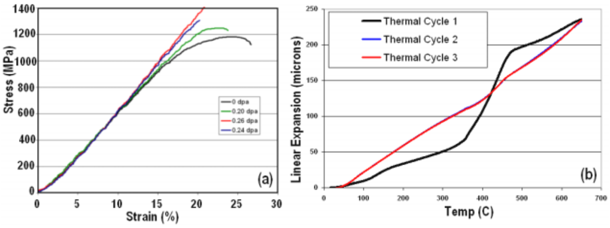

Figure 7: Irradiation-induced ductility loss and thermal cycle effects on Gum metal.

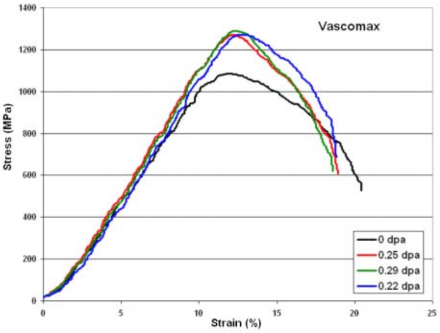

Figure 8: Stress-strain relation in irradiated Vascomax.

SUMMARY

The BNL irradiation R&D has explored the potential of a whole host of alloys and composites in playing the role of high performance accelerator targets and continues to expand the scope of the study by assessing irradiation damage in new materials and super-alloys. The study has shown, thus far, that certain materials and composites, while initially affected by irradiation damage, can be restored through annealing. It was also found that some materials maintain ductility after irradiation such as Vascomax while others turn brittle even with modest irradiation exposure. The upcoming post-irradiation analysis of the recently irradiated matrix of materials will shed more light into the effects of irradiation on materials considered for high performance accelerator targets.

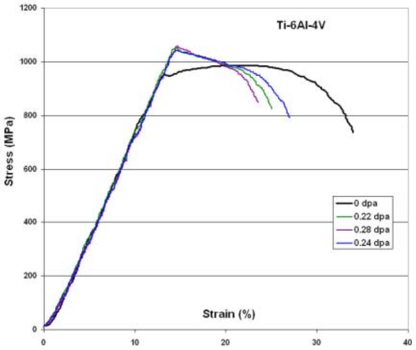

Figure 9: Stress-strain relation in irradiated Ti-6Al-4V.

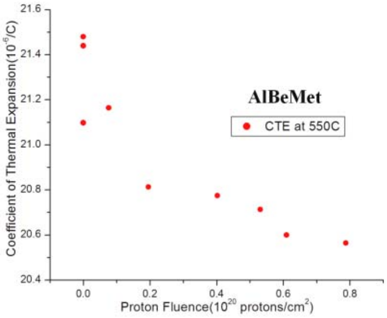

Figure 10: Effect of proton fluence on AlBeMet CTE.

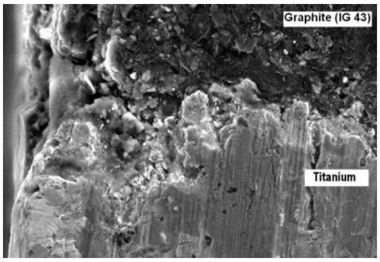

Figure 11: Special graphite and titanium bond.

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