SUPER-INVAR AS A TARGET FOR A PULSED HIGH-INTENSITY PROTON BEAM

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Abstract

We describe measurements performed on samples consisting of the alloy Super-Invar, which is a candidate material for a robust solid target used in conjunction with an intense pulsed proton beam. A low coefficient of thermal expansion is the characteristic property which makes Super-Invar an attractive target candidate. We have irradiated our samples at the Brookhaven Linac Isotope Producer facility. Tests for variations of the thermal expansion coefficient as a function of inflicted radiation damage are described. The high radiation dose is severely detrimental to its low coefficient of thermal expansion.

INTRODUCTION

Increasing the power of proton accelerator facilities will generate new physics opportunities. This is especially true in the fields of high-energy physics where intense secondary beams of pions, muons and neutrinos are of great interest. Material sciences can greatly benefit from the production of intense pulsed neutrons. A key issue to realize these possibilities is the development of new target systems which can function with proton beams at power levels of 1 MW or more. The target must withstand very elevated values of both peak and average power. We discuss in this paper a study of two candidate materials for a high-peak power target.

We have previously reported studies[1] in which rods of carbon were exposed to intense proton pulses and the amplitude of the generated pressure waves recorded. The results showed a very clear reduction in the pressure wave amplitude for carbon-carbon, as compared to ATJ carbon. We attribute the difference to the extremely low value of the coefficient of thermal expansion (CTE) of the carbon-carbon rod.

We are led to consider other materials which also have a low coefficient of thermal expansion (CTE). Invar is a metal alloy which predominantly consists of 62% Fe, 32% Ni and 5% Co. The form of Invar which we have tested is Super-Invar, which is heat treated so as to have a particularly low CTE. The CTE for Super-Invar at room temperature is typically at $0.6 \times 10^{-6}/^\circ$K, but its variation after radiation damage from an intense proton beam is unknown.

EXPERIMENTAL LAYOUT

The irradiated Super-Invar samples consisted of 28 3/16$''$ rods each 1.688$''$ long. Half of the samples were necked down to a diameter of 0.08$''$ in the center region The necked-down samples were used for post-irradiation mechanical tensile testing. In addition, 8 Inconel rods were used as fillers in the target stack. Fig. 1 depicts the configuration of the samples within the target holder. In addition, 16 1mm diameter nickel wires were placed between sample cylinders, half each at the target entrance and exit. These were used as horizontal and vertical profile monitors for the proton beam.

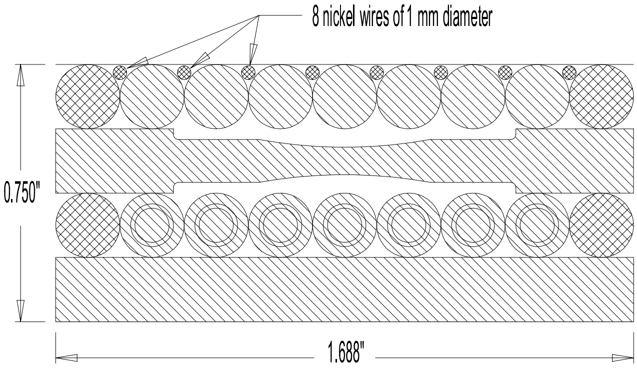

Figure 1: Target sample layout. Cross-hatched samples are Inconel. The proton beam enters from the top.

The irradiation was done at the Brookhaven Linac Isotope Producer (BLIP) facility with a 200 MeV proton beam from the linac which also serves as an injector for the AGS booster. The integrated beam current over a two week period was 24 mA-hrs which corresponds to a total of 5.4×10^{20} protons on target. The proton fluence at the target center was 1.3×10^{20} protons/cm^2. The beam energy after attenuation in the water surrounding the target was 190 MeV at our sample entrance.

The samples, with holder, were immersed in a water tank for target cooling purposes. In addition, water was directed to flow through each sample holder. The unobstructed water flow rate is 11 GPM. We estimate that the actual water flow rate through the sample was reduced to the order of 2 GPM. Given this flow rate and the peak proton current of 108 μA experienced during the exposure, we calculate that the peak temperature within the interior of a sample

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rod was on the order of 200° C.

After exposure, the target sample was removed and placed in a lead shielded enclosure for seven months to allow for the radio-activity to decline to more manageable levels for the subsequent measurements. Nonetheless, our measurements of the CTE and tensile properties had to be performed within the confines of a hot cell equipped with remote handling capabilities.

Upon removal of the samples from the target holder, the individual cylinders were washed in an acid bath to remove corrosion from the rods. Samples were then sorted by position in the the target, making use of identifying marks on each cylinder and nickel wire.

MEASUREMENTS

Activation Measurements

The samples were placed individually into an ATOMLAB 100 dose calibrator in order to measure the integrated activation levels. The first (entrance) plane (Fig. 1) consisted of straight cylindrical rods and wire positioned in a horizontal orientation, while the the fourth (exit) plane had a similar arrangement but with a vertical orientation. The activation levels of the front plane could then be used to extract information as to the vertical profile of the incident proton beam, while the exit plane could be used for obtaining the horizontal profile of the proton beam (Fig. 2). The nickel wire and Invar rods have different volumes as well as composition, hence overall normalization for each data set differ. However, the beam rms widths extracted from each set of material agree well.

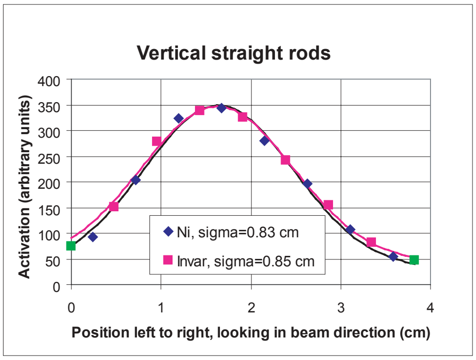

Figure 2: Measured specimen activity as a function of target position. The lines are Gaussian fits.

This measured beam profile, along with the total proton flux and incident energy, served as input into the code MCNPX[2] which calculated the atomic displacements within each sample. Results of the activation measurements of each sample correlate well with the calculated values for the atomic displacements averaged over each rod.

Thermal Expansion Measurements

Measurement of the coefficient of thermal expansion utilized an L75 dilatometer purchased from LINSEIS, Gmbh. This device was specifically fabricated to allow ease of remote operation since the measurements were confined to a hot cell where remote manipulation of the equipment as well as the mechanical insertion of the samples was required. Measurement of non-irradiated samples demonstrated that the stock material had the expected CTE of 0.6×10^{-6} /°K at room temperature while the base line for the temperature range of 50°C to 150°C was an average CTE of 1.0×10^{-6} /°K (see Fig. 3). This figure also demonstrates that irradiation dramatically alters the thermal expansion properties of Super-Invar. The results for all fourteen straight irradiated specimens are shown in Fig. 4.

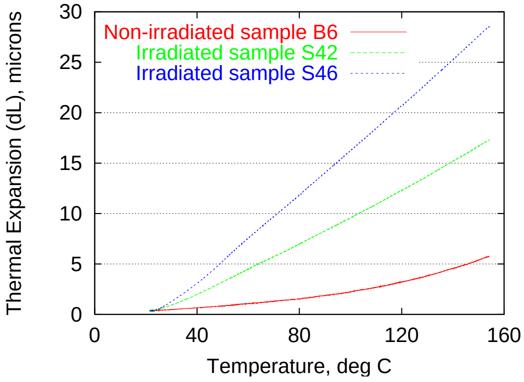

Figure 3: Measured thermal expansions for three different Super-Invar specimens.

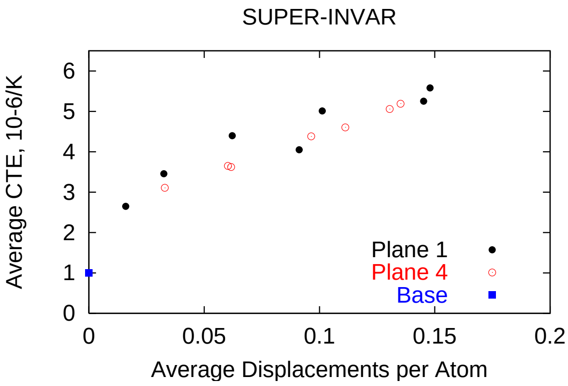

Figure 4: Measured average coefficients of thermal expansion as a function of calculated average atomic displacements per atom.

It should be noted that the average CTE values reported here correspond to a temperature interval from 50°C to 150°C and are also averaged over the length of each sample. Auxiliary measurements of un-irradiated samples heat treated to temperatures up to 400°C indicate that most of the observed effect is due to radiation damage, but some contribution from heating during irradiation and from possible effects of thermo-mechanical shock caused by the pulsed beam can not be excluded.

We also measured the average CTE of the eight Inconel rods as well as two non-irradiated Inconel specimens. Since the Inconel rods were used as spacers at the edges of the target, their levels of activation and atomic displacement are typically less than for the Super-Invar samples. Nonetheless, we do observe a small change in the CTE for Inconel (see Fig. 5).

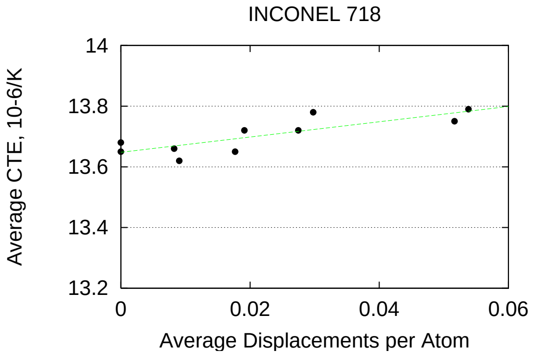

Figure 5: Measured average coefficients of thermal expansion of the Inconel samples as a function of calculated average atomic displacements per atom.

Tensile Measurements

The effect of different levels of irradiation on the mechanical properties of Super-Invar was assessed by performing a tensile test on specimens that have been specially designed for that purpose. In particular, the two middle planes of the target were formed by specimens which had been necked-down to a diameter of 80 mils. The maximum irradiation levels reached during the exposure to the beam has been calculated to be 0.25 dpa.

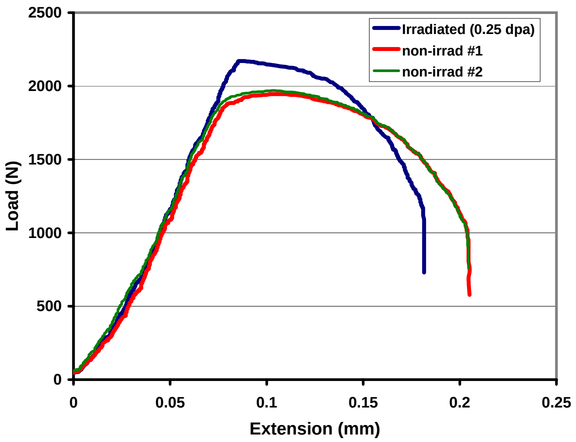

Figure 6: Load-displacement curves for irradiated and non-irradiated invar specimens.

The load-displacement curves of virgin as well as irradiated specimens from the same block of material were obtained. Particular care was taken to maintain the same parameters of tensile test in order to avoid scattering of the data. As a result very similar load-displacement curves were achieved for the non-irradiated specimens. This provided a reference for the mechanical properties (such as the yield strength, the ultimate strength and the modulus of elasticity) that are evaluated as a function of the irradiation.

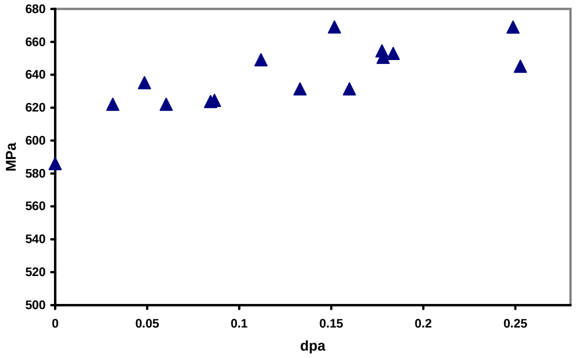

Figure 7: Yield vs atomic displacement for irradiated and non-irradiated invar specimens.

While no effect was observed for the modulus of elasticity, irradiation effects are apparent. Specifically, the material becomes stronger but brittle. A 15% increase in tensile strength was observed. The irradiated material, however, lost its post-yield strength (no ultimate strength) and fractured at smaller displacement (strain) levels.

SUMMARY

Our results indicate that selecting a target material based on it's attractive coefficient of thermal expansion should be preceded by a consideration of the effects that radiation damage can impart on this property. Super-Invar can be considered a serious target candidate for an intense proton beam only if one can anneal the atomic displacements followed by the appropriate heat treatment to restore its favorable expansion coefficient. On the other hand, the more modest influence of radiation damage on the Inconel samples suggests that targetry material selection based on yield strength rather than low thermal expansion coefficient may lead to a more favorable result.

REFERENCES

[1] H.G. Kirk, *TARGET STUDIES WITH BNL E951 AT THE AGS*, Proceedings of the 2001 Particle Accelerator Conference, Chicago, Il., March 2001, p.1535.

[2] MCNPX Users Manual-Version 2.1.5, L.S. Waters, ed., Los Alamos National Laboratory, Los Alamos, NM. TPO-E83-G-UG-X-00001. (1999)