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Radiation Effects In Material Microstructure

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ABSTRACT

Next generation nuclear power systems, high-power particle accelerators and space technology will inevitably rely on higher performance materials that will be able to function in the extreme environments of high irradiation, high temperatures, corrosion and stress. The ability of any material to maintain its functionality under exposure to harsh conditions is directly linked to the material structure at the nano- and micro-scales. Understanding of the underlying processes is key to the success of such undertakings. This paper presents experimental results of the effects of radiation exposure on several unique alloys, composites and crystals through induced changes in the physio-mechanical macroscopic properties.

KEY WORDS: Irradiation damage, annealing, microstructure

INTRODUCTION

Material performance under the combined influence of intense radiation fluxes, elevated temperatures, corrosive environment and applied stress represents the limiting factor for several next generation systems that include and are not limited to nuclear reactors, fusion technology, multi-MW class particle accelerators and to a lesser extent space-related applications. Exposure of materials to any combination of these harsh conditions will result in at times dramatic changes in their macroscopic physical properties, which in turn ensure their functionality. Macroscopic physical properties are the expression of processes taking place either at the atomic level of the material lattice as well as at the nano- and micro-scale.

The dominant role of radiation-induced changes in properties of materials has long been recognized but despite the wealth of experimental as well as reactor-based experience data gaps in the understanding of the mechanisms responsible still remains. It is generally accepted, however, that the buildup of displacement damage (lattice disorder due to elastic collisions of bombarding particles and solid material atoms) with radiation exposure causes gradual but permanent changes in component performance and limits device lifetime in a radiation environment. While the database and experience on material irradiation damage is quite extensive as a result of nuclear reactor operation, it almost exclusively applies to the effects of neutron bombardment on materials. The correlation, however, between damage induced by neutrons to damage caused by energetic protons is still elusive. In addition, regardless of the irradiating species, the next generation systems mentioned above would require at least one order of magnitude higher irradiating intensity and as a result materials capable of operating at these levels and under faster rates of exposure are needed. Extrapolation from the known response of materials to the desired levels would be very risky. Materials that have been extensively used in these systems thus far may not be able to survive the high fluences, which are typically accompanied by high temperatures and corrosive conditions. Engineered materials, however, such as super-alloys and composites have been developed and some exhibit extraordinary properties that can be utilized in these next generation systems. These new materials, however, lack the track record of irradiation-induced changes to their properties. The same holds true for nano-structured materials that can achieve superb macroscopic properties as a result of an ordered lattice. Of interest is the establishment of relationships between exposure to irradiating particles and the lattice disorder or lack off in the nano-structured materials. In space applications the need for multi-functional materials, which can operate within a strict envelope while maintaining diverse properties, is central. Radiation damage, while at much lower levels than those anticipated in reactor or particle accelerator systems, is expected to affect these properties in asynchronous ways and therefore only experimental studies that simulate the environment can provide the confirmation of multi-functional material performance.

Therefore, the fundamental understanding at the nanoscale level of processes controlling macroscopic material properties under extreme conditions, processes such kinetics of microstructure, defect generation, defect mobility and trapping, will provide the means of tailoring the nano- or micro-structure of a material in ways that will make it more tolerant of these harsh conditions. Nano-structured materials, designed through an iterative process that implements vital information extracted from experiments looking specifically into the role that high radiation doses, for example, have on disordering the structure and instigating changes in the micro- and macroscopic material properties, have the potential of meeting the challenge.

Recent experimental studies on irradiated super-alloys and composites revealed the role of temperature in the self-healing capabilities of some materials. The mobilization of radiation-induced defects and their eventual arrest is a process that takes place at the nanoscale level. The mobility of defects and their arrest at pre-engineered nano-structured defects presents a promising path towards the realization of materials with the ability to self heal induced damage to its microstructure.

The focus in the experimental study results of which are presented in the following sections is primarily the effect of irradiation on materials and in particular the changes that occur in their macroscopic physical and mechanical properties. Using high-energy protons and neutrons at the Brookhaven National Laboratory accelerator complex and in particular at the medical isotope production facility, an extensive array of super-alloys and composites have been studied. Post-irradiation analysis results on the effects of irradiation exposure, including the role of annealing in damage reversal that is exhibited by some of the studied materials, are presented in this paper.

IRRADIATION EFFECTS ON MATERIALS

Irradiation-induced effects on materials are the result of interactions between atoms of solid materials with energetic, bombarding particles. The interaction manifests itself in the form of (a) electronic excitations that are responsible for the energy deposited in the solid material, (b) elastic collisions through which recoil energy is transferred from the incident particle to atoms in the lattice resulting in the displacement of atoms and the formation of vacancies and interstitials, and (c) inelastic collisions between the bombarding particle and the nuclei of the solid resulting in the production of gases such as helium and hydrogen which tend to occupy grain boundaries and have detrimental effects on the solids. The combination of the latter two processes constitute what is termed as irradiation damage in the material microstructure that in turn is observed as changes in the macroscopic properties such as diffusivity, thermal expansion, ductility loss and hardening (attributed to increase of dislocation density which in turn impedes dislocation movement), and density reduction.

While radiation damage expresses itself in the form of defects at the nanoscale level, ultimately it is the macroscopic properties of the material that determine its ability to play a role in the next generation nuclear power systems, fusion energy systems and MW-class particle accelerators. The ability of any material to resist irradiation-induced changes in macroscopic properties such as thermal conductivity, thermal expansion, ductility and mechanical strength is directly linked to processes that take place at the nanoscale level. These include defect generation, defect mobility, clustering and trapping as well as generation and retention of gaseous elements like helium. Establishment of the link between the changes in the nanostructure and these macroscopic properties will enable the design and/or the altering of a nanostructure in ways that will make it able to hold onto key properties under irradiation.

Even though the interaction between ionizing radiation and nanometer-scale features of materials is far from being fully understood, various experiments suggest that nano-sized particles embedded into bulk material matrices act as damage stabilizers by trapping radiation-induced defects. The maturity in the field of engineered nano-materials will permit the synthesis of nanostructures containing defects in their ordered form that may potentially play the role of defect sinks. During interaction of materials with radiating particles, the ensuing collisions and cascades are fundamentally tied to the type of impinging particle. Despite the wealth of data on proton and neutron exposure of materials, for example, the basic questions as to why the resulting damage differs are still very much in debate. The research study that is reported in this paper attempts to address these questions and by focusing on how different irradiation species (i.e. protons and neutrons) affect the ordered structure of solid materials (metallic and non-metallic) by observing the transformation in the micro- and macroscopic properties (i.e. thermal conductivity and mechanical behavior).

IRRADIATION DAMAGE STUDY

In an effort to assess the effects of irradiation on materials by different species and primarily damage from energetic protons an extensive experimental effort had been initiated. Of primary interest in this effort is the establishment of the relationship between the radiation exposure normalized to displacement-per-atom (dpa) units and the changes that are induced in certain physio-mechanical properties of materials that are being considered for special roles in a variety of initiatives. For particle accelerator targets (pion production, spallation sources etc.), which are expected to intercept high-energy, high-intensity proton pulses and be subjected to intense thermo-mechanical shock, properties such as thermal expansion, enthalpy, thermal diffusivity, elasticity modulus, strength and ductility are of primary interest. Therefore, materials that exhibit favorable macroscopic properties (or combination of) are prime candidates. With advancements in material engineering, super-alloys and composites are now being customized and, with special treatments or combination of alloying elements that affect their nanostructure or microstructure, macroscopic physical and mechanical properties that occasionally defy the general trend of materials are being achieved. These include extremely low, even negative, thermal expansion coefficient (CTE), extreme ductility combined with super-strength, non-linear elastic response and low elasticity modulus. The micro-structural changes due to interactions between bombarding particles and atoms in these solids that result in, typically, detrimental changes in the macroscopic properties exhibited in the unirradiated state of these alloys, however, are not yet known. Several studies, (Simos, et al, 2006a and 2006b, Lohmann et al, 1986, Ullmaier and Carsughi, 1995) interested in material behavior under proton irradiation for use in particle accelerators have explored the changes in key macroscopic physio-mechanical that occur in materials of interest.

Protons and spallation neutrons from the BNL linac have been used in this experimental effort to study the irradiation-induced changes in an extensive array of materials, super-alloys and composites. Specifically, 200 MeV or 112 MeV protons, depending on the mode of operation of the BNL isotope facility, are used to irradiate specially designed specimens of these materials arranged to either get exposed to direct protons or neutron fluxes generated by isotope-producing targets upstream of these materials. With a Linac current of ~90 μA integrated fluxes of 10^{21} protons/cm^2 have been achieved which translate to approximately 1 dpa for the higher-Z materials in the matrix (such as tungsten or tantalum). The post-irradiation analysis and study of the radiation-induced changes in the microstructure that manifest themselves as changes of physical and mechanical macroscopic properties in the wide range covered by the selected matrix of materials (from low Z to high Z) takes place in a special experimental area that allows both handling and experimentation under remote operations. In particular, the post-irradiation analysis consists of radiation dose characterization procedures such as spectroscopy and autoradiography, micro-structural examination and measurements of physical and mechanical properties using nanometer level sensitivity instruments for thermal expansion changes and tensile tests of specially designed specimens. Investigations of helium and hydrogen generation and its connection with micro-structural changes will be conducted in upcoming phases of the experimental study.

Radiation Damage in Super Alloys

Prompted by the needs of the particle accelerator community where special materials are sought to play the role of secondary particle production targets (i.e. pions, muons, and kaons) or neutron liberation through spallation, attention was focused on a group of super-alloys that exhibit very favorable combination of physical and mechanical properties. Given that the functionality of these materials as high energy proton-intercepting targets depends on two dominant factors, namely their ability to absorb the induced shock brought on by the intense proton pulse and their resistance to microstructural damage resulting from accumulated radiation dose, materials that exhibit low thermal expansion, ductility and high strength are of special interest. The primary unknown, however, is the effect irradiation has on these key properties of engineered super-alloys. As a result, the experimental effort turned its attention to alloys such as the Super-Invar, Inconel-718, the beta-type titanium alloy fundamentally expressed as Ti_3 (Ta+Nb+V)+(Zr, Hf)+O and widely known as "gum" metal, the Ti-6Al-4V alloy and AlBeMet (an alloy of beryllium and aluminum).

The super-Invar alloy in its unirradiated state exhibits a remarkably low thermal expansion behavior between room temperature and about 150 °C at which point there is a dramatic increase in the rate of expansion. This temperature range characterized by extremely low CTE could be utilized for proton-induced shock absorption for as long as irradiation does not alter the material microstructure and remove such macroscopic behavior. During the first irradiation phase of this research, Super-Invar and Inconel-718 samples were irradiated with 200 MeV protons to modest dose levels. As seen in Fig. 1, a five-fold increase in the expansion property of Invar is observed while minimal changes are induced in the CTE of Inconel-718 as seen in Fig. 2.

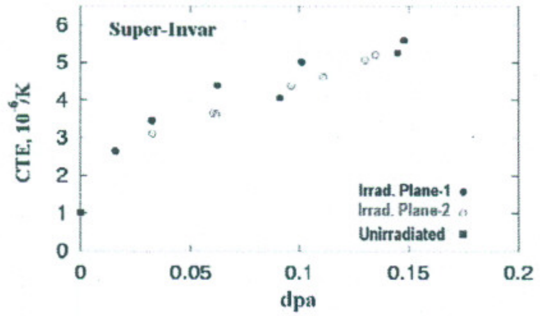


Fig 1: Effects of modest proton irradiation exposure on the thermal expansion coefficient of Super-Invar

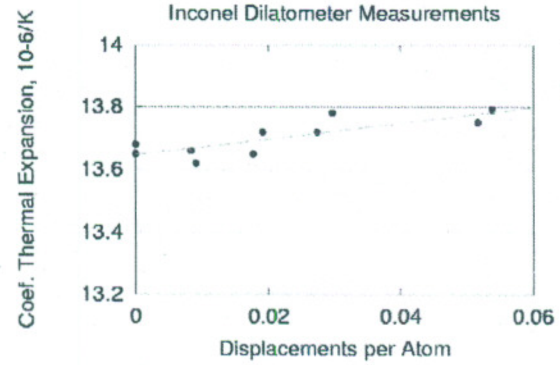
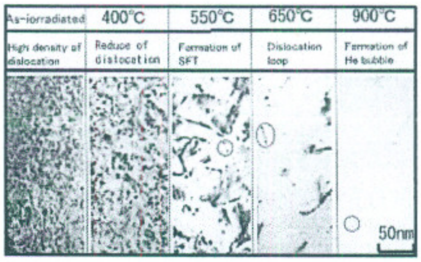


Fig 2: Effects of modest proton irradiation exposure on the thermal expansion coefficient of Inconel-718

Experimental studies on certain carbon composites (discussed in this paper) and other metals revealed the role of temperature in the self-healing or damage reversal attributed to the mobilization of radiation-induced defects and their eventual arrest. As shown in Fig. 3 (Ishiyama, 1996) radiation induced defects mobilize and are eventually removed from the microstructure. The damage recovery shown relates to SS-304 exposed to neutrons at a fluence of 1.4 x 10^{22} n/cm^2. To assess whether super-Invar has the ability to recover from irradiation damage through annealing, it was subjected to thermal cycling that would also allow the identification of temperature thresholds. Indeed, as seen in Fig. 4, this super-alloy exhibits damage reversal abilities that start above 400 °C and lead to complete reversal above the 600 °C threshold temperatures. Studies focusing on neutron irradiation exposure of nuclear materials have revealed that irradiation following recovery through annealing leads to higher defect densities in the "healed" microstructure and thus acceleration of damage. To assess the behavior of Invar under similar conditions annealed samples were re-exposed to proton fluences. As seen in Fig. 5, Invar exhibits the remarkable ability to recover completely following re-irradiation. Future studies will focus on the relationship between lattice re-arrangement and restoration that take place during irradiation and thermal annealing.



Y. Ishiyam et. al., J. Nucl. Mtrl. 239 (1996) 90-94

Fig. 3: Recovery of radiation-induced micro structural damage in stainless steel as observed by TEM (after Y. Ishiyama, 1996)

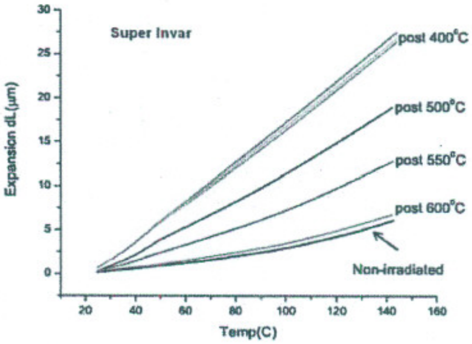


Fig 4: Relationship between amplitude of thermal cycling and annealing of irradiation damage in Super-Invar

Fig. 6 depicts the changes in the mechanical macroscopic properties of super-Invar induced by proton irradiation and temperature. No changes in the elastic modulus (a physical property that depends on inter-atomic bonds or electronic states) are attributed to irradiation. This is indeed quite an interesting point since thermal expansion is also a physical property linked to the same interatomic bonds. Proton fluence results, as in other metallic materials, in reduction of ductility and increase in strength. Ductility loss due to proton fluence, however, appears to be very limited. Heat treatment on the other hand at temperatures of ~500 °C (a process that is expected to induce modifications at the microstructural level) has a profound effect on its stress-strain relationship seen as strength reduction and "softening" expressed with increase in plastic deformation.

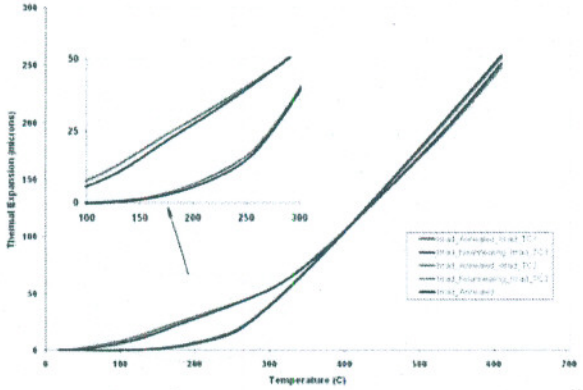


Fig 5: Damage healing in Super-Invar following successive irradiation exposures

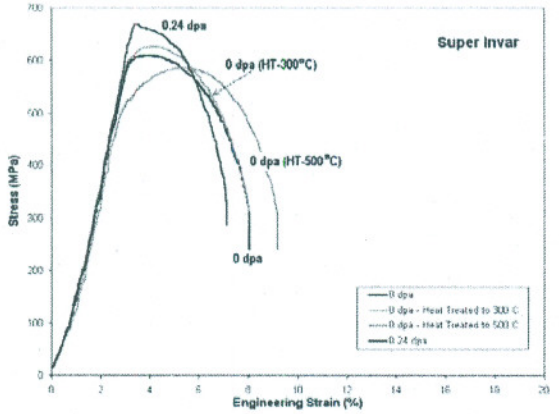


Fig 6: Proton irradiation and thermal treatment effects on the macroscopic stress-strain relationship of Super-Invar and in particular effects on elasticity modulus, yield strength and ductility.

Proton irradiation of the titanium alloy Ti-6Al-4V and post-irradiation analysis, seen in Fig. 7, revealed that the effects on the coefficient of thermal expansion are minimal. This super-alloy exhibits much larger CTE than Invar that is not attributed to dislocation-free plastic deformation. Similarly, proton bombardment does not affect the interatomic bonds and thus inducing no change in the elastic modulus. As in the case of super-invar, increase in strength accompanied by strong resistance to ductility loss is also observed.

In this study attention was also focused on the super-alloy "gum metal" family that exhibit ultra-low elastic modulus, exceptional strength, super plasticity and Invar-like behavior (extremely low thermal expansion) over a wider temperature range. At first look, the combination of these physical and mechanical properties makes this family of materials ideal for particle accelerator applications. Fig. 8 depicts some of the properties of "gum" metal both in its annealed state and the 90% cold-worked state (after Saito, 2003). These "super" properties are the result of dislocation-free plastic deformation mechanisms, which in the case of cold-worked alloys, form nanometer to micrometer scale elastic strain fields. While large elastic deformations in certain alloys are attributed to phase transformations, the super-elastic behavior of the "gum metal" family is not accompanied by any phase transformations. Further, while the Invar-like properties (extremely low CTE over a temperature range) have been linked to magnetic moment, these materials are paramagnetic. The process of cold-working on both the mechanical and physical properties appears to enhance these properties in a dramatic fashion. Because of the special relationship that appears to exist between the macroscopic properties of these materials with (a) interatomic bonds and (b) nano-scale and micro-scale fields they represent ideal candidates for studying the effects of irradiation which, as discussed in an earlier section, affects the electronic states as well as lattice re-arrangement and gas generation from transmutation following inelastic collisions. Irradiation exposure and post-irradiation analysis revealed a set of interesting results. Specifically, as shown in Fig. 9a, modest irradiation doses (~ 0.25 dpa) resulted in complete removal of its super-plasticity thus leading to a super brittle state. The invar-like behavior (low CTE over a wide temperature range) shown in Fig. 9b is influenced by temperature in a dramatic fashion. The thermal expansion of the 90% cold-worked gum undergoes a dramatic increase above ~600 K. The abnormality exhibited over a relatively narrow temperature range appears similar to the one observed in shape memory alloys (Saito, 2003). Fig. 9b indicates that a single heating pass with the temperature traversing the shown abnormality results in the removal of the invar-like behavior. Fig. 10 sheds light in the way proton radiation affects the invar-like property. It is observed that radiation leaves the CTE abnormality intact while a single thermal cycle of peak temperature exceeding the threshold of 600 °C reclaims the invar behavior exactly the same way as in the unirradiated case.

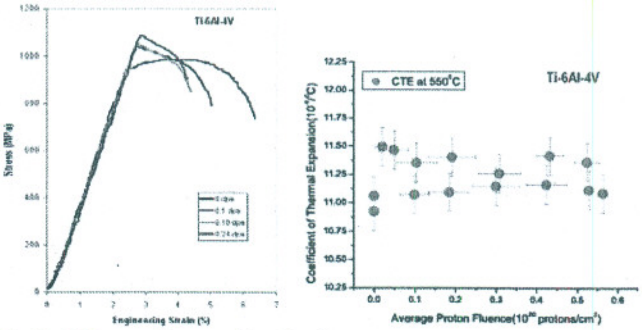


Fig 7: Effects of proton irradiation exposure on the stress-strain relationship and CTE of Ti-6Al-4V.

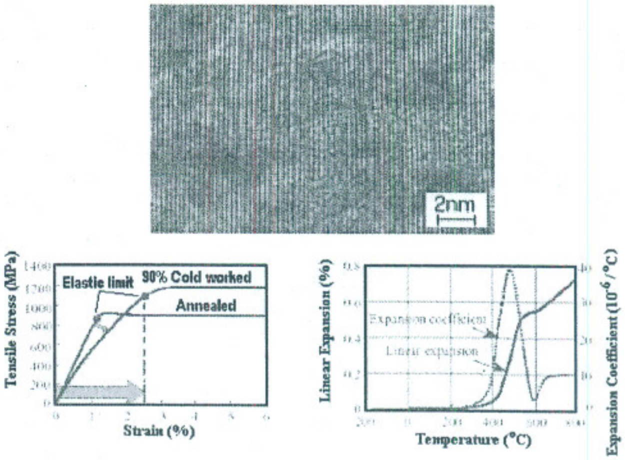


Fig 8: Crystal lattice in 90% cold-worked gum metal and mechanical and physical properties of its un-irradiated state (Saito et al, 2003)

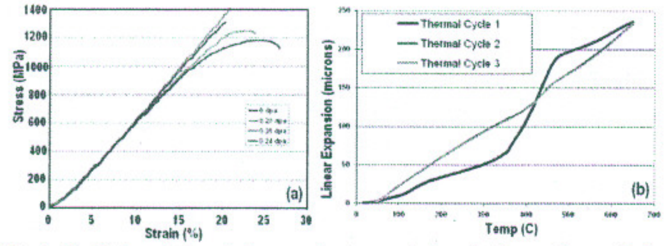


Fig 9: Radiation-induced changes in stress-strain relations of annealed gum metal (a), and temperature effects on the thermal expansion of 90% cold-worked gum metal (b)

Studies of dislocation microstructure under TEM observation for irradiated AlMg-alloy (Lohmann et al, 1986) observed that doses of as low as 0.2 dpa are sufficient to dissolve the cold-worked microstructure. In the case of the gum metal that appears to be partially true since irradiation only affects the super-plasticity of the material and not the invar-like CTE. Further studies focusing at the microstructural changes of this super-alloy are planned.

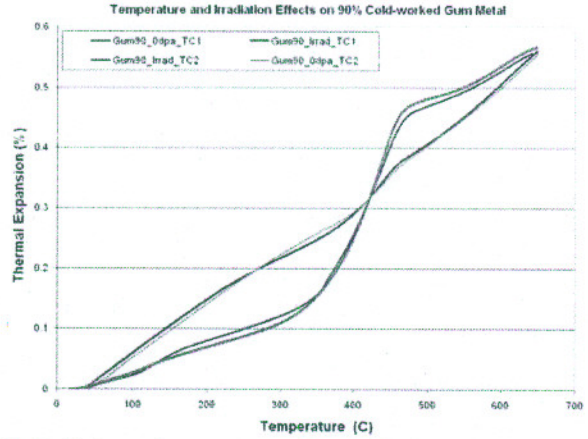


Fig 10: Radiation and temperature effects on the invar-like behavior of 90% cold-worked gum metal

In an effort to establish a relation between the macroscopic behavior of the mid-Z super alloys and high-Z materials, irradiation damage studies were performed on high-Z materials such as tantalum and tungsten.

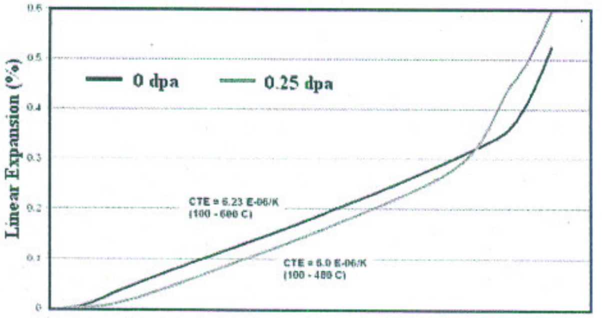


Fig 11: Radiation effects on the CTE of pure tantalum

Fig. 11 depicts the thermal expansion of tantalum from room temperature to 650 °C. Tantalum exhibits an "invar-like" behavior in the sense that there is a distinct increase in its thermal expansion after crossing a temperature threshold. The abnormality is exhibited by both the irradiated and the un-irradiated state of the material. Irradiation appears to have a positive effect at low temperatures (< 100 °C) but also resulting in the lowering of the transition temperature. Also observed during the tantalum studies is the volatile nature of its interaction with certain elements in the testing atmosphere. Specifically, carbon combined with oxygen at temperatures in excess of 500°C result in the formation of carbide phases at the surface of tantalum. As it has been observed and discussed by Fairbrother (1967), heating of tantalum in the presence of carbon causes small amounts of carbon to diffuse as individual atoms into the metal lattice to form a solid solution. The body-centered cubic lattice of the metal is expanded to accommodate the carbon atoms allowing the formation of the carbide and leading to the stripping of carbide layers. What is significant in this research is that the solubility of carbon and the carbide formation occurs at temperatures as low as 500 °C. The accelerated "sublimation" of tantalum at lower threshold temperatures may have been influenced by the reaction of tantalum with a volatile silicon compound leading to the formation of metal silicides. The behavior was equally observed in unirradiated and radiated samples. Further tests on unirradiated tantalum revealed that the threshold temperature causing the initiation of sublimation appears to coincide with the temperature related to the abnormality in the CTE. The formation of tantalum carbides and silicides and the effects on the metal lattice via the formation of new phases and occupation of interstitial positions will be further explored.

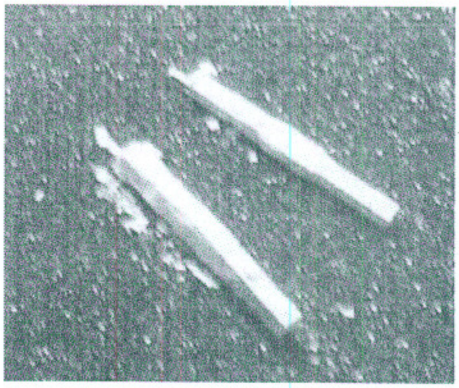


Fig 12: Tantalum "sublimation" following interaction with carbon

Radiation Effects on Composites

Low-Z materials are attractive because of the particular energy spectrum of secondary particles they liberate following interaction with energetic protons. In addition, their use in the nuclear field has been extensive. Such material class includes various graphite grades, carbon composites as well as other low-Z alloys such as AlBeMet. As in the case of super-alloys of particular interest are low-Z materials that exhibit low thermal expansion, are strong and can resist irradiation damage. Carbon-carbon fibers reinforced composites, with fibers along parallel planes (2-D arrangement) or with fiber planes along the normal direction as well (3-D arrangement), have been engineered and "appear" with all accounts to be superior to graphite. In particular, carbon composites exhibit a very low, even negative thermal expansion coefficient below 800 °C and, because of the fiber arrangement, have higher strength. These properties make it a favorable material for high intensity proton pulse absorption that is associated with thermo-mechanical shock. Fig. 13 depicts dynamic strain response of graphite and 3-D carbon composite targets intercepting 24 GeV, high-intensity proton pulses. Evident is the superiority of carbon composite to absorb shock.

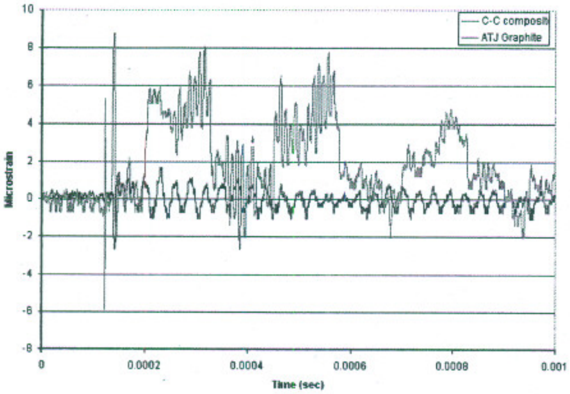


Fig 13: Dynamic strains in carbon composite and graphite induced by a high-intensity, 24 GeV protons

Following the shock absorption confirmation, extensive radiation damage studies were conducted to assess the resilience of these composites to long exposure. Figures 14 and 15 demonstrate the ability of these composites to reverse the damage through annealing. In particular, shown in Fig. 14 is the behavior of the two types of fiber arrangement and along the fiber reinforcing direction. Along the fiber planes the response of the 2-D and 3-D carbon composite types is remarkably similar. Fig. 15 depicts the damage reversal along the direction with no fiber reinforcement in the 2-D carbon composite as a function of the accumulated dose shown in mCi. The results indicate a strong relation between the dose and the changes in the microstructure of the material expressed as changes in the thermal expansion behavior. Of interest is the similarity in the material damage and subsequent annealing of two different samples exposed to similar irradiation doses.

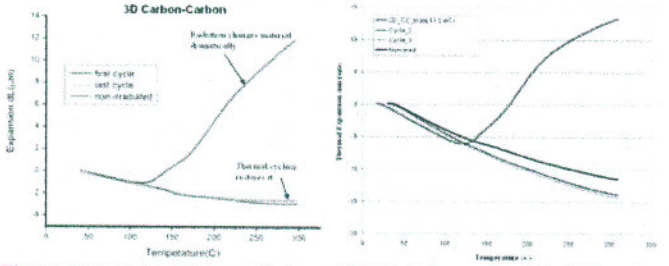


Fig 14: Proton irradiation effects on CTE and “annealing” in 2-D and 3-D carbon fiber reinforced composites (along fiber orientation)

The experimental effort on these composites as well as various graphite grades also revealed the vulnerability of these composites to high doses. In particular, proton fluences in excess of 10^{21} protons/cm^2 lead to serious structural degradation of the composite structure. Whether such response is an inherent property of these composites needs to be further researched. However, most recent post-irradiation analysis of graphite exposed to similarly high levels of proton fluence (~ 0.2 dpa) exhibited degradation tendencies. Nuclear reactor experience data indicate that graphite has much higher radiation damage resilience to neutron exposure that reaches several dpa. Two possible mechanisms are considered responsible for the dramatically different behavior observed. One is the difference between bombarding neutrons and protons that potentially have a very different interaction with the inter-atomic bonds and the material microstructure. The second possible explanation is the irradiation rate that is much higher in this case of irradiating protons than the rate associated with neutron exposure of the same materials. Follow-up studies that focus on the micro-structural changes due to helium or hydrogen formation from nuclear interactions are planned in an effort to explain this peculiar behavior.

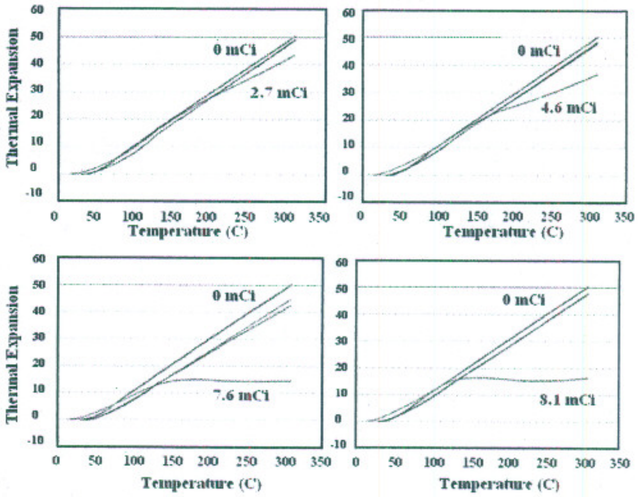


Fig 15: Proton irradiation induced changes in the CTE of 2-D carbon reinforced composite followed by thermal annealing. Traces shown in blue depict the thermal expansion characteristics in subsequent thermal cycles.

The observed structural degradation of carbon composites and of graphite following high rate proton irradiation has led to radiation damage assessment of special bonds between dissimilar materials. Shown in Fig. 16 under SEM examination are interfaces between graphite and Ti-6Al-4V alloy (a) and Cu with Ti-6Al-4V. This special material arrangement represents the muon production target at the J-PARC facility in Japan.

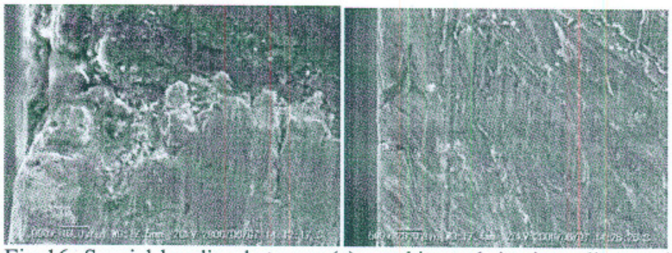


Fig 16: Special bonding between (a) graphite and titanium alloy, and (b) Cu and titanium alloy

The interfaces shown are prior to irradiation exposure. Of primary interest is the confirmation of survival of the bonding between graphite and titanium alloy following exposure to high proton fluences and the ability to transfer heat across the interfaces following irradiation. Specially designed samples have been fabricated and have been exposed to 200 MeV protons. Fluences of the order of 10^{21} protons/cm^2 have been achieved. While no signs of structural degradation are apparent in the post-irradiation examination, comprehensive assessment of the radiation-induced changes will be performed.

The expanded value of this particular study on the bonds between dissimilar materials is that similar issues regarding radiation effects would apply to nano-structured films. Studies are under way to assess the effects of neutron exposure of nano-films on Ti-6Al-4V and stainless steel substrates.

Radiation Effects in Fused Silica

Several studies have focused in the past on the effects of irradiation on fused silica and in particular on the degradation of its optical properties. Of particular interest has been the identification of the mechanism of defect formation and of the energy threshold for ionization processes which is responsible for lattice defect formation. The appearance of these defects, which follow the displacement of lattice atoms, result in the trapping of charges that lead to the formation of optical absorption bands which in turn impede the transmission of photons.

To assess the rate of photo-transmission degradation with increased dose that could be of the order of several Grad, an irradiation experiment was been undertaken that allowed the exposure of fused silica fibers to direct, 200 MeV protons and, in a separate configuration, to a wide energy range of neutrons.

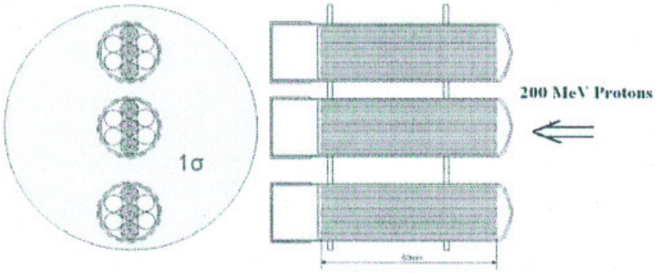


Fig 17: Experimental arrangement of fused silica exposure to 200 MeV protons at the BNL Isotope Facility

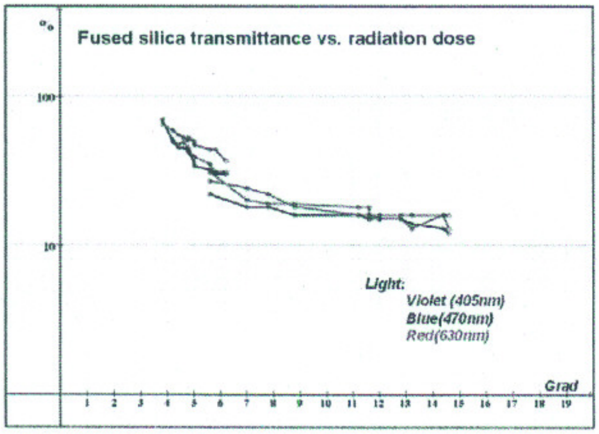


Fig 18: Transmittance degradation as a function of dose

Shown in Fig. 17 is the special arrangement of fused silica fibers of various diameters intercepting the 200 MeV proton beam. Also shown is the approximate footprint of the 1-σ of the Gaussian beam profile. Transport codes were used to estimate the exposure time that would lead to a desired dose level. With a slightly different arrangement that allowed the positioning of the fused silica fibers downstream of a series of isotope-producing targets, exposure to spallation neutron flux of different energies was achieved. Following exposure to protons and neutrons, the effect of dose on the transmittance was established as seen in Fig. 18.

In order to obtain a visual assessment of the damage induced, the fused silica fibers underwent microscopic examination. Shown in Fig. 19 is the un-irradiated surface of the fiber. Figure 20 depicts the damage induced by the bombarding particles appearing in the form of particle tracks and localized liquefaction due to thermal energy deposition. Fiber material disintegration due to surface grazing by an energetic particle is depicted in Fig. 21 in a dramatic fashion. It is important to note the similarities of the observed damage in the fused silica fibers (Fig. 20a) and the fission fragment tracks observed in nonmetallic lattices (Chadderton, 1964). While the nature of the mechanisms that result in the formation of tracks observable in solid materials is complex, it is generally accepted that it represents, more or less, a continuous filament of atomic disorder and associated with the disorder is a strain field which in turn provides the diffraction contrast in crystalline materials such as the fused silica.

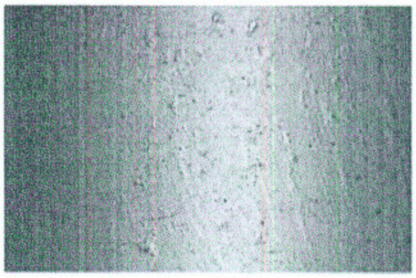


Fig 19: Unirradiated surface of fused silica seen under the microscope

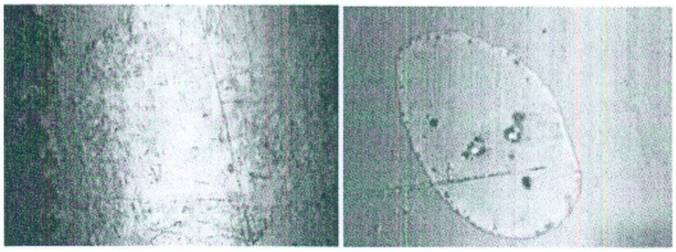


Fig 20: Particle tracks on fused silica surface following irradiation

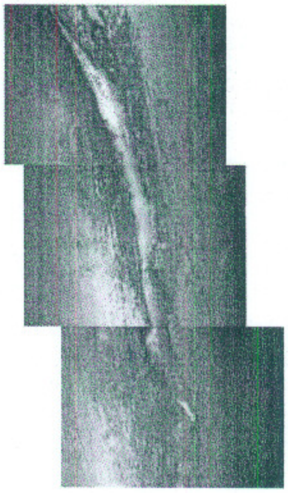


Fig 21: Particle track on the surface of fused silica fiber associated with material phase transformation

CONCLUSIONS

In an effort to assess the effect of irradiation on material properties that are particular interest to a number of next generation systems such as nuclear and fusion energy systems, MW-class particle accelerators and space technology a comprehensive experimental study has been undertaken. In particular, the study focused on radiation-induced changes in a number of super-alloys that possess optimal combination of physio-mechanical properties, composites and crystals. While the post-irradiation analysis is far from complete and in addition exposure to neutron flux of some of these new super-alloys is currently under way, preliminary conclusions from the analysis to-date can be drawn. Specifically,

- Alloys such as super-Invar, while experience dramatic changes in the physical properties that characterize them (i.e. CTE) exhibit the remarkable ability to reverse the damage through annealing
- Super-alloys from the family of gum metals tend to loose their super-elasticity even under very modest irradiation levels. Further, temperature increases above very characteristic thresholds have been observed to affect physical properties by removing the cold working.
- Carbon fiber-reinforced composites while exhibit dramatic damage annealing characteristics, have shown to suffer structurally from intense exposure and in particular from high-rate irradiation
- Protons and neutrons interacting with the crystalline structure of fused silica have a dramatic effect on its photon transmittance in the excess of a few Grad exposures.

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