Radiation Effects in Material Microstructure

Nicholas Simos
Brookhaven National Laboratory
Upton, New York, USA

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 remain. 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.