Emulation of reactor irradiation damage using ion beams

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general background

Fulfillment of the promise of advanced nuclear reactors with major improvements in safety, economics, waste generation and proliferation security, and life extension of existing light water nuclear reactors rest heavily on understanding how radiation degrades the materials that serve as the structural components in reactor cores [1,2].

specific background

In high-dose fission reactor concepts such as the sodium fast reactor, core internal components must survive up to 200 dpa[1] of damage at temperatures in excess of 400 °C, Figure 1. The traveling wave reactor pushes that limit to 600 dpa. At such high damage levels, the formation and growth of voids will affect the dimensional stability of components, the nucleation and growth (or dissolution) of precipitates will alter composition locally and can either embrittle or weaken the alloy, and both phenomena are affected by the evolving dislocation microstructure [3]. In some alloys these processes develop at low doses, but void swelling and radiation-induced precipitation may emerge only after high doses (100 dpa)

general background

[4,5]. While an understanding of the microstructural evolution of alloys under irradiation remains a major challenge to the integrity of reactor core components, a more pressing problem is the diminishing capability to study these processes.

knowledge gap

Radiation effects research is traditionally conducted by irradiating samples in test reactors, followed by comprehensive post-irradiation characterization. Predictive modeling of the radiation damage process helps to reduce the need for a full suite of experiments covering the entire parameter space. Several increasingly serious barriers are impeding the advancement of our understanding of radiation effects. The first is a paucity of worldwide test reactor capability, especially in the US, for addressing the unknowns in advanced reactor concepts. The US has only two test reactors capable of producing damage at a maximum rate of 8 dpa/year. Available reactors worldwide can only reach 20 dpa/year, making access to the required damage levels prohibitively time-consuming and expensive. Second, test reactors cannot create radiation damage significantly faster than that in commercial reactors, meaning that radiation damage research cannot “get ahead” of problems discovered during operation. Both of these factors conspire to create the third barrier: the extremely high cost of irradiation and post-irradiation characterization of highly radioactive samples.

why the reader should care

A promising solution to the problem is the use of ion irradiation as a surrogate for neutron irradiation. Ion irradiation can yield high damage rates with negligible (proton irradiation) or no (heavy ion irradiation) residual radioactivity and at very low cost. The use of ion beams for radiation damage study dates back to the 1960s and includes numerous significant contributions to our understanding of radiation effects (e.g. [6–9]). The advantages of ion irradiation are many: damage rates 10^4 times that of reactor irradiation can be attained, which means that 200 dpa can be reached in days instead of decades. Because there is little or no activation samples are easily handled, reducing the cost associated with post-irradiation characterization. Control of ion irradiation experiments (temperature, damage rate, damage level) is much better than irradiations in reactor and damage can even be observed in situ. However, the idea of using ion irradiation as a surrogate for neutron irradiation is relatively new and success requires both a high degree of experiment control and a systematic approach to accounting for the differences between reactor- and accelerator-based irradiations.

“here we show”

Capturing the full extent of the entire irradiated microstructure created in-reactor has not yet been attempted. This paper presents a “formula” for emulating reactor irradiation with well-controlled ion irradiation.