Material characterization in a 10^{15} neutron $cm^{-2}s^{-1}$ flux using light source X-rays

M.A.M. Bourke, D.J. Rej, R.D. Fulton, J.L. Sarrao

1Abstract

This paper advocates the measurement of material properties using high energy X-ray photons in an extreme neutron flux environment. We believe that this would, to use the current vernacular, be a technology disrupter for materials design for high field environments. For the last 50 years most, though not all, irradiated material characterization has been destructive, ex situ, post irradiation examination (PIE). However the extreme fluences of high energy X-ray photons produced by third and recent fourth generation light sources offer, for the first time, the possibility to probe materials in radiation environments such as those produced by spallation neutron sources. Relevance to the fusion community would derive from unique insights on material properties that intrinsically differ in the irradiation environment. Creep, radiation induced conductivity and corrosion are just three examples. The capability could offer hitherto unimaginable validation avenues for models. The in situ and non destructive nature of the measurements would rapidly augment data pertaining to kinetics and path dependent evolution of material properties.

2 Performance gaps

The science and facilities necessary to enable materials qualification in high fluence neutron environments have long been recognized as thrusts necessary for the implementation of fusion energy (and fission energy). This has lead to proposals and definition of facilities such as IFMIF or the Materials Test Station (MTS) at Los Alamos [1,2]. However the need for "*new science-based methods incorporating improved cross-cutting fundamental knowledge of basic radiation damage mechanisms in materials*" has also been recognized as a priority (Fusion Energy Sciences advisory committee report, 2007). Implicit in this statement is an increased reliance on modeling and simulation for certification[3]. Thus there is a renewed interest in obtaining validation data over the widest possible range of times, length scales and conditions. For example one could imagine asking what data is needed to validate simulations of point defect migration to interfaces and grain boundaries under realistic irradiation conditions[4]? Prediction of a radiation damage effects is a canonical problem requiring the comprehension of phenomena that span pico seconds to years and nanometers to meters. As such there are disconcerting gaps in our current ability to measure data at times shorter than PIE enables to connect the insights derived first principles calculations to predictions of macroscopic engineering properties. This is a weakness. To draw a somewhat tongue in cheek analogy, trying to use PIE measurements as an end point validation of atomistic models is a bit like trying to understand the origin of life without access to the fossil record.

3 Material properties and light source examination

As stated above, one rationale for *in situ* measurements are the suite of material properties that intrinsically differ in a radiation environment when compared to ex situ measurement. A second rationale is the greatly augmented quantity of data that rapid *in situ* measurements would provide. This would improve our understanding of path dependence and nucleation that in temporal and spatial regimes typically precluded to efficient examination by PIE interrupted tests. Many early stage cracking, swelling and nucleation phenomena occur at low doses and times are amenable to rapid non destructive examination using X-ray scattering probes. This is particularly true if temperature and pressure are added as control parameters.

The current performance of high energy beam lines at facilities such as the advanced photon source or European synchrotron radiation facility show the range of tools and insights that are possible. Many of the techniques necessary to draw insights on swelling, phase stability, structural integrity, corrosion or thermal properties already exist. Small angle scattering, diffraction, tomography , xanes or exafs are all mature techniques. To highlight just one example, work by Pyzalla et al (already four years old) demonstrated simultaneous tomography and diffraction analysis of creep damage in brass[5]. The measurements demonstrated the development of in situ void growth and microstructure development with a temporal resolution of about one minute. These are techniques that would have relevance to real time in situ studies of radiation damage effects.

High energy beam lines routinely produce 100KeV X-rays. Photon fluences implicit in 4th generation sources, such as free electron lasers, enable scattering measurements in multi millimeter thickness samples, even for high Z materials, in timescales far shorter than a second. It is notable that small angle scattering and diffraction measurements, made at high energies, typically involve data collection in the forward scattering direction. This facilitates integration of such techniques with spallation irradiation source concepts by enabling the probe to lie orthogonally to the spallation beams.

The discussion above addressed measurements of irradiation processes with subsecond timescales and spatial resolutions comparable to typical microstructures. These are within the capability of current facilities and as such the justification stands by itself. There is however a further intriguing possibility that has no current analogue. This is the capability that might be enabled by the intense (10^{10} or more photons per pulse) ultra short (0.05 psec) pulses of X-rays produced by free electron lasers. Specifically, if one could imagine phasing the X-ray pulses with the instrinsically pulsed nature of a spallation source it *might* be possible to experimentally explore temporal regions that have hitherto uniquely been as the sole domain of atomistic modelers.

4 Proposed Initiative

This paper advocates the use of a 3rd or 4th generation light source to study material properties in a high neutron fluence environment. Conceptually one might consider rabbits used to insert and remove samples from an examination position in a spallation dosing facility while longer term irradiations continue unaffected in adjacent positions. The expense would be considerable but the value would be relevant to both the fusion and fission communities. Implementation on a spallation irradiation source is plausible. By providing sample conditions offering a range of temperature, pressure, strain rate regimes insights on the phenomenology of radiation effects, from void formation to defect concentrations would be unparalleled and would support first principles as well as engineering simulations of materials under extreme conditions.

In the US at this time there are at least two plausible neutron irradiation facilities where such an approach could be explored, MTS and SNS. We believe that implementation would likely take 5 to 10 years on the materials test station, which is being advocated as a testbed for fusion materials qualification[6].

It's probably a truism that there will never be enough PIE capability and it is not suggested that this approach will replace it. Moreover there are significant technological hurdles to enabling this approach. One of the more obvious ones will be the survival and operation of the detector electronics in the face of the radiation coming from the target. Many of the challenges one could envisage however are entirely consistent with the fusion energy program in general. As such developing the in situ characterization would prove exceptionally complementary to other efforts.

In the short term, actively stimulating the engagement of light and neutron sources to handle highly radioactive samples would provide immediate insights while nurturing the wider community to engage in discussion of the opportunities of in situ measurement.

5 References

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