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Discussion session summary: radiation effects

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The most significant physical differences between radiation effects in a high energy proton plus spallation neutron spectrum and those in a fission neutron spectrum are higher primary knock-on energies, larger displacement cascades, and significantly increased generation of hydrogen and helium. To investigate how these differences affect mechanical properties, austenitic stainless steels, Alloy 718 and ferritic–martensitic steels have been tested after irradiation in a high energy proton beam and compared to results after irradiation in a fission neutron flux (where data is available).

The effects observed in austenitic stainless steels after irradiation in a high energy proton beam are as follows. Maloy et al. observed a drop in strain-to-necking (STN) to less than 1% at 3–4 dpa for test temperatures from 50–160 °C after irradiation at 30–120 °C. When the test temperature was decreased to 25 °C, ~10% STN was observed for specimens irradiated to as high as 10 dpa. 304 stainless steel failed with a significant fraction of intergranular fracture in tensile tests after a dose of ~ 7 dpa for $T_{irr} < 230$ °C (Chen et al.). A greater decrease in toughness is observed at 1 dpa for 304 stainless steel irradiated in a proton beam than for the same heat of 304 stainless steel irradiated in a fission neutron flux (Maloy, Snead).

The trends in uniform elongation and yield stress for Alloy 718 in the precipitation hardened condition with high energy proton dose are similar to those for fission neutron irradiation at doses up to 1 dpa (Farrell). After proton irradiation to a dose of 20 dpa, zero uniform elongation is observed and failure is 100% intergranular for a test temperature of 25 °C and $T_{irr} = 300$–500 °C (Chen). This is not observed after fission neutron irradiation at 220 °C but there is no data to compare to at this higher irradiation temperature (300–500 °C).

A ferritic–martensitic steel (Mod 9Cr–1Mo, T91) in the normalized and tempered condition shows similar changes with proton dose in yield stress and uniform elongation as are observed for irradiation fission neutron flux at doses to 10 dpa for $T_{irr} = 50$–160 °C, $T_{test} = 50$–160 °C (Farrell, Maloy). Recent results on T91 irradiated in STIP I also show similar trends in uniform elongation and yield stress for doses up to 7–8 dpa, $T_{irr} < 300$ °C, $T_{test} = 250$ and 25 °C. The uniform elongation measured after the highest irradiation dose (~10 dpa) is increased over that measured at lower dose and at this point this is not fully understood (Henry). TEM analyses of ferritic–martensitic steels irradiated in STIP I show bubbles in the microstructure for irradiation temperatures above 175 °C (Jia). T91 irradiated in the as-quenched (normalized) condition had zero uniform elongation and intergranular failure after irradiation from 0.5 to 10 dpa in the STIP I irradiation. This drop in ductility is not observed after irradiation of the same material in a fission neutron flux.

BCC refractory metals generally show a quick drop in ductility at doses above 0.5 dpa. Farrell et al observed this in Ta–10W. This was a commercial grade alloy produced without any effort to remove interstitials. On the other hand, 99.999% pure tantalum irradiated in ISIS showed greater than 5% uniform elongation for irradiations up to 10 dpa (Chen et al.). There is no known fission reactor comparison for this high purity material.

The observations above lead to several interesting questions. For austenitic stainless steels, what is the effect of irradiation produced hydrogen on the mechanical properties at low temperatures? Is this what causes the ductility drop observed in LANSCE irradiated austenitic stainless steels at 3–4 dpa? In the LANSCE irradiated data, values of uniform elongation vary from less than 1% to above 20% after irradiation in the dose range 3–4 dpa. What causes this scatter? It was suggested that such large scatter might be caused by slight changes in work hardening rate over this dose range. As the work hardening rate changes from slightly positive to slightly negative, the uniform elongation drops from ~20% to less than 1% causing a large variation in the data. There are slight variations caused by thickness of the specimens (0.25 and 0.75 mm) but these are not as significant

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as those caused by changes in work hardening rate. It was pointed out that because of the large scatter in uniform elongation, a better measure of true ductility might by reduction in area for these high does specimens.

For the ferritic–martensitic steels, how do the high amounts of helium affect swelling at temperatures above 300 °C? How does interstitial content affect irradiation damage? Why is it that low levels of interstitials can affect irradiation damage? This is surprising because during irradiation in a proton beam, impurity concentration builds up quickly from spallation?

To try to answer these questions, the following future tests were suggested. For austenitic alloys irradiated in LANSCE, the same heats of 316L and 304L stainless steel will be irradiated to 1, 3, 5 and 9 dpa in a fission reactor. Tests after irradiation will be performed at 25, 50 and 164 °C. To understand the effect of hydrogen on mechanical properties, it is suggested that the hydrogen be removed from irradiated specimens and that they be tested at 50–160 °C. Specimens irradiated at the Paul Scherrer Institute in the STIP irradiation should have much less hydrogen because of their higher irradiation temperature, but unfortunately that also strongly affects the irradiation microstructure.

For ferritic–martensitic steels, swelling will be measured in the specimens irradiated at higher temperatures in STIP I. Although bubbles were observed in the TEM analysis, the low volume percent suggests that the swelling is low also. To understand why the uniform elongation improves with irradiation to 2–3 dpa when tested at 400–500 °C, the microstructure will be investigated with TEM. It was suggested that coarsening of the microstructure with irradiation causes initial improvements in properties.

For refractory alloys, ORNL has now irradiated Ta–10W and three grades of Ta (ISIS material and two other grades with higher impurity levels) in HFIR to 0.5 dpa. These will be tested to investigate the effect of initial interstitial impurity concentration on radiation damage in tantalum.

It was suggested that, since the ductility of materials is related to deformation mode and the deformation mode above about 0.1 dpa is by dislocation channeling in these irradiated metals, this is an important research topic. To elucidate what is happening during deformation of irradiated samples, study of the effects of strain rate on dislocation channeling is suggested. In addition, modeling may help the understanding of this mode of deformation. Other factors that may affect channeling are large He bubbles, larger tensile specimens or multiaxial stresses (e.g., as in fracture toughness tests). This may explain why specimens exhibiting almost zero uniform elongation still retain appreciable fracture toughness.