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EXPERIMENTAL STUDIES USING LIGHT IONS TO SIMULATE FUSION NEUTRON DAMAGE EFFECTS ON MECHANICAL PROPERTIES*

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ABSTRACT

This paper presents some first results from ongoing experimental work to compare effects of light ion and fusion neutron damage on tensile yield strengths of Ni and Nb. Comparisons of these results with calculated damage energy values are discussed, and the significance of such measurements evaluated.

The present paucity of data on the influence that fusion neutron induced damage has on the mechanical properties of materials is an immediate concern to the U.S. fusion reactor program. Relatively little time remains to accumulate the bulk material data needed to design and build an operational power reactor system by the year 2000, the target date for operation of a Demonstration Power Reactor (DPR). To meet this schedule requires that materials selection for such systems be made by 1985 in order that newly developed materials be available, commercially, in time for reactor construction. Such decisions must be based, to a large extent, on our understanding of damage effects of fusion neutrons at fluxes and tolerable fluences anticipated for fusion reactors; present designs indicate about 10^{14} $cm^{-2}s^{-1}$ and 10^{21} cm^{-2}, respectively. But neutrons are not available presently at fluxes needed for accelerated damage studies, although construction has begun on sources which will produce useable fluxes of the order of 10^{13}-10^{14} $cm^{-2}s^{-1}$. Early fusion neutron bulk radiation damage design data will, therefore, rely heavily on damage studies by particles other than fusion neutrons; for example, fission neutron damage experiments or charged particle irradiation damage experiments.

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DISCLAIMER

In the case of nickel bearing alloys, mixed spectrum fission reactors can be used to produce the displaced atom (dpa)/helium ratios induced in these materials by fusion environments. Helium production by the thermal spectra is through the following two stage transmutation reaction:

$$^{58}Ni + n \ldots {}^{59}Ni$$

$$^{59}Ni + n \ldots {}^{56}Fe + {}^{4}He.$$

But this technique is not applicable to other materials, nor does it include the high energy neutron component which is contained in the fusion environment.

Until high flux, fusion neutron sources become available, the relationship between damage by fusion neutrons and mechanical properties will have to be studied, to a large extent, using charged particles as the irradiating species. For example, irradiation by protons of the appropriate energy may produce a defect structure which resembles the damage from 14 MeV neutrons. Indeed, Logan, Anderson and Mukherjee[1] have calculated, from elastic-scattering and inelastic reaction cross-section data, that 16 MeV protons and 14 MeV neutrons produce similar displacement damages in niobium when recoil energies are greater than 10 kev. However, it should be noted that these displacement energies diverge considerably at lower recoil energies. Similar results are obtained from damage calculations by Omar, Robinson and Thompson for Fe, Ni, Cu, Zr and Nb.[2] Comparisons of 14 MeV neutron and 16 MeV proton radiation damage have also been made by comparing microstructures of irradiated copper samples.[3] These results indicate close similarities between defect cluster densities and sizes for 10^{13} and 5×10^{11} $cm^{-2}s^{-1}$ proton and neutron fluxes, respectively.

To be useful, for simulating bulk irradiation by fast neutrons, the ion beams must be capable of producing bulk damage rates equal to and in excess of damage rates expected from neutron fields in magnetic fusion energy devices. Existing accelerators can produce 10^{14} $cm^{-2}s^{-1}$ fluxes of charged particles with displacement cross-sections greater than the fusion neutron displacement cross-sections. Ratios of 16 MeV proton to 14 MeV neutron displacement cross-sections are about 3 and 1.6 for Ni and Nb, respectively. It is likely, therefore, that the beam intensity will not be the factor limiting meaningful accelerated damage studies by light charged particle irradiation. The capability of removing the thermal energy, induced in the test samples by charged particle bombardment, is more likely to limit the damage production rate.

Bulk behavior should be simulated by the unirradiated and irradiated small test samples required for ion irradiation. Unfortunately, these relatively small sample thicknesses, imposed by ion penetration depths, can have a significant influence on the mechanical properties being investigated. This dependence of mechanical properties on sample size can be attributed to three factors: 1) the influence of surfaces and surface contamination on dislocation motion via image forces and surface energy, 2) influence of effective grain size to sample size ratios on flow properties, and 3) stresses introduced on tensile test samples by sample grip clamping procedures. These factors are of major importance in the design and control of the ion simulation experiment.

Contamination of the test sample can result from contaminants in the test chamber, from the sample cooling procedures or from contaminants in the ion beam. These contaminants can alter the surface energy or the sample chemistry. Grain boundary diffusion and precipitation of contaminants are likely, and the resulting effects could dominate mechanical behavior even more than surface contamination. However, for surface related effects on mechanical behavior, image forces on near-surface dislocations are likely to be most significant.[4]

There have been numerous observations of the strong influence of environments on mechanical properties. For example, the fatigue life of copper was measured by Wadsworth to increase from 5×10^5 cycles at 760 torr to 10^7 cycles at 10^{-5} torr.[5] Shahanian and Achter found creep rates of nickel to be highest in a nitrogen atmosphere and lowest in vacuum while creep rates in air and a helium -27% oxygen mixture were intermediate.[6] Johnson, Barrett and Nix measured minimum creep rates of a Ni - 6% W alloy at 10^{-5} torr and one atmosphere of commercial purity argon.[7] They found environmental effects to occur for samples containing eight grains across the thinnest direction of the gauge section.

In order that charged particle irradiations not introduce bulk chemical contamination the sample must be transparent to the irradiating species. For high z ions having several MeV energy, sample dimensions of a few microns in the beam direction for low Z ions. Figure 1 shows the displacement cross-section profile for 10 and 16 MeV protons on Ni and Nb. It is apparent that, in order to minimize damage gradients along the beam direction, this sample dimension must be considerably smaller than the ion range in the sample material. It is apparent, from the above discussion, that difficulties involving experimental investigations of light ion damage effects on mechanical properties are related primarily to sample size and contamination.

Irradiation creep has typically been the principal parameter measured in studies of mechanical behavior of materials irradiated with light ions. However, dpa rates from neutrons produced by existing fusion neutron sources are not likely to be sufficient for similar creep studies of neutron effects; other mechanical parameters have to be measured.

Table I lists measured yield strength changes for several fluences of 16 MeV protons and 14 MeV neutrons. The previously discussed results from damage energy calculations and defect clusters measurements are included, with calculated displacement cross-sections, for comparison. Inconsistencies with total damage energies may be explained by differences in the damage energy spectra. The protons produced more low energy recoils and possibly more simple point defects as predicted by the Kinchin and Pease model;[10] divacancy and small vacancy cluster formation can then follow. Kimura and Maddin have shown that for gold and copper, at least, these vacancy combinations will not increase the yield strength.[11]

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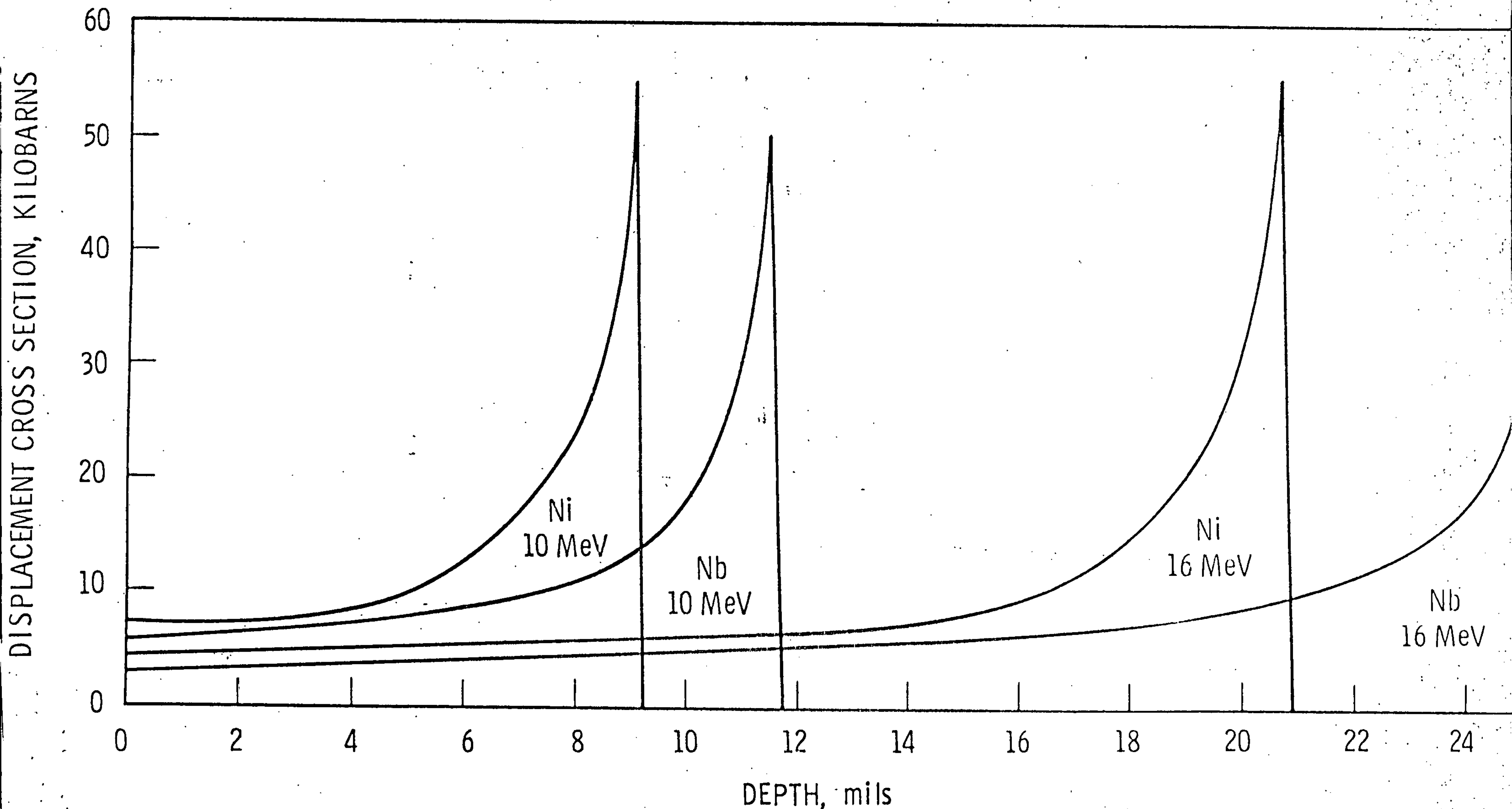
DISPLACEMENT CROSS SECTION, KILOBARNS
60
50
40
30
20
10
0
0
2
4
6
8
10
12
14
16
18
20
22
24
DEPTH, mils
Ni
10 MeV
Nb
10 MeV
Ni
16 MeV
Nb
16 MeV

Captions

Figure 1. Displacement cross-section depth profiles for 10 and 16 MeV protons incident on Ni and Nb.

TABLE I

COMPARISON OF 16 MeV PROTON/14 MeV NEUTRON DAMAGE PARAMETERS

Target Material	Damage Parameter	16 MeV Proton	14 MeV Neutron	Reference
Nickel	Total Damage Energy (barn-kev)	592	254	Omar, Robinson Thompson[2]
	Displacement, Cross-Section, (kilobarn)	4.6 Coulomb Scattering Only	1.5	Doran[8] Doran, Graves[9]
	ΔYS @ Fluence	4MPa @ $5x10^{15}$ cm^{-2} 10MPa @ $6x10^{16}$ cm^{-2} 18MPa @ $1.1x10^{17}$ cm^{-2}	28MPa @ $8x10^{16}$ cm^{-2} 100MPa @ $2x10^{17}$ cm^{-2}	Present Work
Copper	Defect Clusters 25-50 A° 50-75 A° 100-125 A°	$2.1x10^{15}$ cm^{-3} $4.5x10^{14}$ cm^{-3} $5.2x10^{13}$ cm^{-3} $\phi=10^{13}/cm^2$-s	$1.7x10^{15}$ $5.8x10^{14}$ cm^{-3} $8.0x10^{13}$ cm^{-3} $\phi=5x10^{11}/cm^2$-s	Mitchell, Logan Echer[3]
	Total Damage Energy (barn-kev)	589	267	Omar et. al.
Niobium	Total Damage Energy (barn-kev)	793 (636 @ T > .035 kev)	266	Omar et. al.
		600	258	Logan, Anderson Mukherjee[1]
	Displacement Cross-Section (kilobarn)	4.0 Coulomb Scattering Only	2.5	Doran et. al.
	ΔYS†† @ Fluence	1MPa @ $5x10^{15}$ cm^{-2} 4MPa @ $6x10^{16}$ cm^{-2} 10MPa @ $1.1x10^{17}$ cm^{-2}	28MPa @ $8x10^{16}$ cm^{-2} 37MPa @ $2x10^{17}$ cm^{-2}	Present Work

† 0.02% yield stress

†† lower yield point