A METHOD FOR SIMULATING FUSION REACTOR RADIATION
DAMAGE USING TRIPLE ION BEAMS*M. B. Lewis
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An ion beam technique has been developed to simulate the microstructural damage expected in materials in future fusion reactors. The simulation technique utilizes two beam lines simultaneously, one with Ni ions to create a high atomic displacement density, and the other with a mixture of molecular deuterium D_2 and atomic He^+ . The profiles of the implanted deuterium and helium have been measured by the method of nuclear microanalysis.

Introduction

In future fusion reactors the high flux of fast neutrons is expected to generate significant quantities of helium and hydrogen in the volume of structural materials. The gaseous products from the (n,p) and (n, α) nuclear reactions accumulate in materials while all interactions of neutrons with nuclei produce atomic displacements. These processes cause permanent radiation damage to the materials (e.g., swelling and embrittlement) and in this way limit the lifetime of the reactor.

Simulation of neutron damage using particle accelerators is now used extensively to study damage patterns at high displacement levels, and to understand interaction between the gases and the displacement events.²⁻⁴ But these experiments usually involve only one gas at a time. This paper describes a new technique that incorporates displacement events and both gases simultaneously. The microstructural damage is reported elsewhere.⁵⁻⁶

Experimental

This method involves the use of two Van de Graaff (VDG) accelerators which operate simultaneously to produce ion beams on a single target. A 5-MV VDG equipped with a heavy ion source produces a 4-MeV nickel beam of current (Ni^{++}) approximately 2.0-3.0 μA uniformly spread over an area of 1.0 cm^2 . Such a beam produces a region in a stainless steel target in which a high atomic displacement density exists at approximately 0.5-0.8 μm below the surface. These Ni ions have a range somewhat deeper than the damage region and being already a constituent in the target are assumed inert once they have come to rest.

The second accelerator is an 0.4-MV VDG which produces beams of hydrogen and helium up to about 1.0 μA spread uniformly over the target of 1.0 cm^2 . While the Ni beam strikes the target normal to its surface, the second beam impinges at an angle of 15 deg from the target normal. The energies and intensities of the beams can be independently adjusted so that the second beam can implant light ions of arbitrary density and depth in a region below the surface which overlaps the region of high displacement density caused by the nickel ions.

The problem remains that there are two light species, hydrogen and helium, which one wishes to implant simultaneously with the second accelerator.

However, we propose that this difficulty can be overcome by recalling that (1) a diatomic deuterium (D_2^+) beam, having the same mass and charge as atomic helium He^+ , can be produced and accelerated in a single VDG system, (2) the diatomic deuterium of energy E dissociates upon impact with the target surface yielding two isolated deuterium ions each with half the beam energy $1/2 E$, (3) the range of these low energy deuterium ions should be near that of the helium ions. Table 1 shows some calculated and measured ranges, X_0 , and rms width, σ , relevant to this work.

Table 1. A Comparison of Mean Range and Standard Deviation Characteristics of Various Ions as Discussed in the Text

E (MeV)	Ion	$X_0 (\mu m)$	$\sigma (\mu m)$	Reference
0.150	D^+	0.78	0.14	A & Z ^a
0.300	D_2^+	0.75 $\pm$.03	0.20 $\pm$.01 ^b	Measured*
0.300	He^+	0.72	0.102	EDEP ^b
		0.72	0.134	BRICE ^c
		0.72	0.080	A & Z ^a
0.300	He^+	0.65	0.087	EDEP ^b
		0.65	0.068	A & Z (extrapolated) ^d
		0.65	0.114	BRICE (extrapolated) ^d
		0.65 $\pm$.03	0.10 $\pm$.02	Measured*

*Range values have been corrected for the 15 deg from normal implantation angle.

^aRef. 7, ^bRef. 9, ^cRef. 8, ^dBased on the ratio He/He of Ref. 9.

In order to verify the dissociation mechanism and to measure the resulting densities of deuterium and helium, we have employed the method of nuclear microanalysis. This was carried out before and after bombardments.

Before bombardment of the target the VDG source bottle was filled with a specific mixture of deuterium and helium gas. A beam of mass = 4 and E = 0.4 MeV was then steered into a scattering chamber and allowed to impinge upon a simple target of pure metal. A surface barrier detector was set up at a backangle to measure the backscattered ion spectrum. This spectrum showed the expected overlay of two backangle spectra, one for 0.4-MeV He^+ ions and one for 0.2-MeV D^+ ions. The absolute magnitudes of these spectra were compared with a theoretical spectra generated by the convolution integral method. Details of the calculations will be given elsewhere.¹⁰ An example of such a calculation is given in Fig. 1. For our purpose we adjusted the gas mixture by trial and error until we obtained the desired ratio.

Actual double and triple beam bombardments were carried out on 3 mm diameter polycrystalline nickel and stainless steel disks which were fine polished with alumina and subsequently electropolished. Beam currents were measured by a vibrating profilometer normalized to a Faraday cup. In some bombardments the

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Fig. 1. Computer simulation of a typical backscattering spectrum from a beam of helium and diatomic deuterium incident upon a nickel target.

targets were heated to about 600–700°C. The implantation densities were purposefully kept low in order to keep the gas density below 1 at. %, thus more realistically simulating the levels expected in a reactor. To date five beam bombardment configurations have been investigated, and these are summarized in Table 2.

After bombardment the depth profiles of the helium and deuterium were measured by the method of nuclear reactions using deuterons from the 0.4-MeV VDG in a conventional scattering chamber arrangement. The resulting deuterium density distribution is shown in Fig. 2. The lower half of the figure shows the proton spectra from the $D(d,p)$ reaction in high purity 316 stainless steel. The bombardment was done with $E_d = 0.45$ MeV and beam and detector angles $\alpha_1 = 45$ deg and $\alpha_2 = 70$ deg relative to the target surface normal. The top half of Fig. 2 shows the depth profile of the deuterium density implied by the proton spectra. In this case it is assumed that the profile follows a Gaussian distribution and the convolution integral method¹⁰ is used to deduce the mean depth X_0 and standard deviation σ of the density curve (Bragg peak). The corresponding fit to the data points is shown in the lower half of the figure.

Fig. 2. Energy spectrum from the $D(d,p)$ reaction in which deuterium has been implanted in a stainless steel sample as discussed in the text. The depth profile deduced from the data is shown at the top of the figure.

Table 2. Summary of 5 Bombardment Configurations and Results

Target (Temp°C)	Ni ⁺⁺ Beam	D ₂ ⁺ Beam (0.3-MeV)	He ⁺ Beam (0.3-MeV)	Profile (D or ³ He)	
				$X_0(\mu\text{m})$	$\sigma(\mu\text{m})$
Nickel (25)	No	No	³ He	0.65 ± 0.03	0.10 ± 0.02
Nickel (≈ 700)	No	No	³ He	0.65 ± 0.03	0.15 ± 0.02
Nickel (≈ 700)	Simultaneous	No	³ He-Simultaneous	0.65 ± 0.03	0.17 ± 0.01
316 SS (25)	Pre-Bombardment	Simultaneous	⁴ He-Simultaneous	0.75 ± 0.03	0.20 ± 0.01
PE16, 316 SS (≈ 640)	Simultaneous	Simultaneous	⁴ He-Simultaneous	<5% of gas retained	

In a similar way the helium profile was determined in a separate experiment. Targets of pure polycrystalline nickel ^3He were implanted with ^3He at an energy of 0.3 MeV. Subsequently, the targets were bombarded with 0.40 or 0.47-MeV deuterium. In this case the $^3\text{He}(d,\alpha)$ reaction was measured with $\alpha_1 = 0$ deg and $\alpha_2 = 20$ deg. An example of one of the spectra is shown in Fig. 3. The deduced profile parameters are given in Table 1 and 2 along with those for deuterium.

Fig. 3. Energy spectrum from the $^3\text{He}(d,\alpha)$ reaction along with the simulated spectrum and deduced profile parameters.

Conclusions

A summary of the measured values of X_0 and σ are shown in Table 1 along with some theoretical predictions. We find that the mean projected depth of the ions is in good agreement with theory. The range for the deuterium ions ($0.75 \mu\text{m}$) is as expected for $E_D = 1/2 E_{D_2}$ and is near that for ^4He ($0.72 \mu\text{m}$) as anticipated. The measured standard deviation of the helium distribution lies between two theoretical values, but the deuterium distribution is broader than expected. The absolute values of the total amount of gas measured in the samples in Figs. 2 and 3 were 10–20% lower than that expected on the basis of beam current measurements during bombardments. Since uncertainties in the known reaction cross sections and beam current measurements are at least 10% each, the profile measurements appear satisfactory.

Similar experiments were carried out at high temperature regions more relevant to reactor environments. The results are summarized in Table 2. The helium distributions were somewhat broadened at the higher temperature with $\sigma = 0.15\text{--}0.17 \mu\text{m}$. Since the targets were held at the high temperature for about 2 hours, appreciable helium bubble formation and migration were expected.¹¹

Diffusion of hydrogen and deuterium is known to be very high in pure nickel,¹² but trapping at the site of dislocations and ion damage is expected to retard the

hydrogen migration.¹³ We measured no significant diffusion of deuterium in any of our stainless steel samples predamaged at room temperature. However, at $T \approx 640^\circ\text{C}$ at least 95% of the implanted deuterium totally escaped the region of the mean implantation depth ($\approx 0.7 \mu\text{m}$) in all stainless steel samples. We hope to characterize further the hydrogen and helium migration in future experiments at intermediate temperatures.

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