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TITLE: DEFECT STRUCTURES IN COPPER AND GOLD IRRADIATED WITH
FAST NEUTRONS, 14 MEV NEUTRONS AND 600-800 MEV PROTONS

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**Defect Structures in Copper and Gold
Irradiated with Fast Neutrons,
14 MeV Neutrons and 600-800 MeV Protons**

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ABSTRACT

Copper and Gold have been irradiated with fast neutrons (mixed spectrum thermal reactor), 14 MeV neutrons (RTNS-II) and 600-800 MeV protons (PIREX II & LAMPF) at 300-373 K over a dose range of 10^{21} - 10^{24} particles.m⁻². Defect cluster concentrations and sizes have been obtained by transmission electron microscopy. The variation in cascade damage structures resulting from a change in average recoil energy from 10^4 to 10^6 eV is shown.

1. Introduction

An understanding of the dependence of microstructural evolution on recoil energy is a key factor in the correlation of neutron and other energetic particle irradiations. Cascade effects and the subdivision of primary recoil energy into sub-cascades has now been well documented for 14 MeV neutron irradiations through the RTNS-II experiments [1]. It has been shown that defect clusters result from "cascade collapse" following high energy collision events; analysis of defect cluster densities, sizes and distributions produced at irradiation temperatures below that of substantial thermally activated vacancy mobility yields valuable information on collision damage processes and the consequent damage

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In this report, we show observations of collapsed cascade damage structures in high purity copper and gold which have been irradiated with fast neutrons, 14 MeV neutrons and 600-800 MeV protons at 313-363K to doses between 10^{21} and 10^{24} particles/m². Fast and 14 MeV neutrons produce recoils of the order of 10^4 and 10^5 eV average energy respectively. The 600-800 MeV protons do not directly transfer kinetic energy to the struck nucleus. Instead the interaction is between the energetic proton and individual protons or neutrons in the nucleus which is followed by an intranuclear cascade; of interest here is the subsequent production of average 10^6 eV recoils homogeneously distributed throughout the irradiated material [2].

2. Experimental Procedure

High purity, fully annealed, 0.1 - 0.4 mm thick specimens of copper and gold were irradiated in the DR-3 (Risø) and Omega West Reactor (Los Alamos) reactors (mixed spectrum), the Rotating Target Neutron Source (RTNS-II) facility at Lawrence Livermore, and at Los Alamos Meson Physics Facility (LAMPF) and PIREX-II (Paul Scherrer Institute). Details of irradiation conditions are given in Table 1. TEM observation was carried out at Risø using a JEOL 2000 FX microscope operated at 200 kV. Dark field, weak beam images used in the present analysis were obtained using with a beam direction of $B=011$ and diffraction vectors g_{111} or g_{200} . The dark field, weak beam technique was used with 6g excited; the observations were made in foil regions of thickness between 20 and 50 nm.

3. Results

Analysis of micrographs of the type shown in Fig. 1. were carried out to determine the total visible cluster densities (> 0.5 nm diameter). The corresponding densities of stacking fault tetrahedra were determined from the ratios of the number of observed stacking fault tetrahedra to the number of loops plus the number of un-identified clusters; the quoted SFT densities thus represent a lower limit. The results are summarized in Tables 2 & 3. Ideally, we would like to be able to express the total number of defects produced per recoil. However, since recoil production cross-sections are as yet poorly determined, particularly at high incident particle energies, we have simply determined the concentrations of all visible defects, C_T , and the concentrations of stacking fault tetrahedra, C_{SFT} , per incident particle, N_p . Comparing these results with those in the literature we note that the concentrations of defect clusters produced by fission neutrons and 14 MeV neutrons observed in this study are broadly comparable over the range of

fluence studied. However, defect cluster production by 600-800 MeV protons (per incident particle) is consistently lower in both copper and gold. The rate of increase in cluster density appears to be directly proportional to fluence for the different recoil energies covered. Clear indication of saturation in defect cluster density at around 10^{24} defect clusters/m³ is observed for proton irradiations in both copper and gold.

The size distributions of defect clusters are shown in Fig. 2. The sizes of collapsed cascade defects depend on the number of defects produced in the cascade collision, their densities in the cascade region and on the recombination processes during cascade quenching. Detailed analysis is required to quantify all factors to be considered in correlation between different incident particles and different target materials. Nevertheless, gold may be identified as producing high energy density cascades and sub-cascades; sub-cascades are dense and closely spaced. Copper shows widely spaced, less dense, sub-cascades. The size distributions for copper show only small differences on changing average recoil energy from around 10^4 eV to 10^6 eV. 600 MeV proton irradiation of gold, however, clearly results in a significantly larger average defect cluster size. Work is currently in progress to improve damage energy calculations for medium energy protons in which the possible effect of fission events in high Z materials will be taken into account [3]. Further, details of the partitioning of very high recoil energy into sub-cascades for the 10^6 eV recoils obtained in 600-800 MeV proton irradiations is under investigation.

4. Conclusions.

The dependence of "collapsed cascade" defect cluster densities and defect cluster sizes on recoil energy variations in the range 10^4 to 10^6 eV has been investigated in copper and gold. Initial results suggest that the mechanism of recoil energy division into sub-cascade production is not changed significantly over the recoil energy range considered. Further study of the very high energy recoils resulting from 600-800 MeV proton irradiation is currently underway in order to study the details of sub-cascade production and subsequent defect interactions. Transmutation impurity and gas production rates are greatly enhanced during medium energy proton irradiation in comparison with neutron irradiations [4]. Impurity interactions with cascade defects must therefore also be considered in further work.

References

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TABLE 1: Irradiation Conditions

Particle	Material	Flux particles · m ⁻² · s ⁻¹	Fluence particles · m ⁻²	Temp. K
Fission neutrons DR-3 OWR	Cu, Au Cu	3.5 x 10 ¹⁷	5 x 10 ²² 6 x 10 ²¹ — 1 x 10 ²³	323 363
14 MeV neutrons	Cu	-	6 x 10 ²⁰ — 1 x 10 ²²	363
600 MeV protons	Cu, Au	1.3 x 10 ¹⁸ — 4 x 10 ¹⁸	3 x 10 ²¹ — 7 x 10 ²²	323-363
800 MeV protons	Cu	2.5 x 10 ¹⁷	7 x 10 ²³ — 2 x 10 ²⁴	313-323

TABLE 2: Defect Densities in Copper

Particle	T_{IRR} K	Fluence ($10^{22}/m^2$)	Cluster Density (m^{-3})		C_{SFT}/N_p (m^{-1})	C_T/N_p (m^{-1})
			SFT	Total		
Fission Neutrons ($E > 1$ MeV)	363	0.6	2×10^{22}	8×10^{22}	3.33	13.33
	363	1.7	1.25×10^{23}	5×10^{23}	7.35	29.41
	323	4.7	2×10^{23}	6.7×10^{23}	4.25	14.25
14 MeV Neutrons	363	0.06	0.72×10^{22}	2.9×10^{22}	12.0	48.33
	363	1.16	0.62×10^{23}	2.5×10^{23}	5.3	21.55
600 MeV Protons	323-363	0.3	0.34×10^{22}	1.7×10^{22}	1.13	5.66
		0.6	0.88×10^{22}	4.4×10^{22}	1.46	7.33
		1.8	1.70×10^{22}	8.5×10^{22}	0.94	4.72
		7	1×10^{23}	5×10^{23}	1.43	7.14
800 MeV Protons	313-323	71	2.2×10^{23}	8.8×10^{23}	0.31	1.24
		178	0.27×10^{24}	1.1×10^{24}	0.15	0.62

TABLE 3: Defect Densities in Gold

Particle	T_{IRR} K	Fluence ($10^{22}/m^2$)	Cluster Density (m^{-3})		C_{SFT}/N_p (m^{-1})	C_T/N_p (m^{-1})
			SFT	Total		
Fission Neutrons ($E > 1$ MeV)	323	4.7	2.4×10^{22}	8.2×10^{22}	0.51	1.74
600 MeV Protons	323-333	0.2	0.8×10^{22}	1.6×10^{22}	4	8
		4	0.62×10^{23}	1.25×10^{23}	1.55	3.1
		50	2.7×10^{23}	5.4×10^{23}	0.54	1.08