A Literature Review of Radiation Damage Studies of Nickel, Nickel-Aluminum and Nickel-Silicon Alloys

D.B. Bullen

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FUSION TECHNOLOGY INSTITUTE

UNIVERSITY OF WISCONSIN

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A LITERATURE REVIEW OF RADIATION DAMAGE STUDIES OF NICKEL, NICKEL-ALUMINUM AND NICKEL-SILICON ALLOYS

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I. Introduction

Early experiments attempting to determine the effect of radiation on metals centered on pure materials in hopes of gaining an understanding of basic processes without dealing with complex microstructures or phase changes. Therefore, there exists in the literature a great number of studies on pure metals such as copper, nickel, aluminum, iron, vanadium, etc. The methods of irradiation include fast and thermal neutron, heavy and light ion, and electrons. This paper consists of four sections with associated tables devoted to the irradiation of pure nickel with ions, electrons and neutrons, and irradiations of Ni-Al and Ni-Si binary alloys with all types of radiation.

II. Heavy Ion Irradiations of Pure Nickel

Numerous heavy ion irradiations of nickel[1-24,40] have been completed during the past decade. A majority have used nickel ions[1-4,7,8,10-13,16-18,21-24] as the source of damage, while others have used protons,[5,9] helium,[14] selenium,[6,11] carbon,[15,19,20] and copper.[21,22] The effect of interstitial gas atoms on cavity nucleation has been studied using simultaneous helium irradiation,[4,10] helium pre-injection,[4,7,9-11,14-16,18,40] and hydrogen introduced during specimen preparation.[21-23] A summary of the experiments reviewed for this report is given in Table I. Current interest in nickel centers around the effect of non-steady state irradiation conditions. Brimhall et al.[1] recently completed a study of the effect of pulsed and steady state irradiation on cavity formation in pure nickel with no interstitial gas content. As noted by the data presented in Table I, the samples subjected to a pulsed irradiation environment which forms a pre-damage microstructure, had a lower density of larger voids and produced swelling which was an order of magnitude larger than comparable steady state irradiations.

TABLE I. HEAVY ION IRRADIATIONS OF HIGH PURITY NICKEL

Material	Gas (appm) Content	Ion	dpa rate $\times 10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv $\times 10^{20}$ (m^{-3})	$\bar{d}$ (nm)	Swelling $\Delta V/V\%$	Comment	Ref.
High Purity Ni	0	5 MeV Ni	5	2 dpa Steady State	775	4.3-4.8	43-44	1.8-2.1		1
High Purity Ni	0	5 MeV Ni	5	2 dpa Steady State	775	3.8	43	1.6		1
High Purity Ni	0	5 MeV Ni	5	10 dpa Steady State	775	1.4-5.5	45-64	1.9-4.8		1
High Purity Ni	0	5 MeV Ni	5	10 dpa Steady State	775	2.7-5.9	36-60	1.5-3.0		1
High Purity Ni	0	5 MeV Ni	5	2 dpa Steady 10 dpa Pulsed	775	1.7-3.2	46-63	1.7-2.2		1
High Purity Ni	0	5 MeV Ni	5	10 dpa Pulsed	775	2.3-8	45-56	2.1-3.8		1
High Purity Ni	0	5 MeV Ni	5	10 dpa Steady State	900	0.089-0.091	138-200	1.3-4.2		1
High Purity Ni	0	5 MeV Ni	5	2 dpa Steady 10 dpa Pulsed	900	0.05-0.17	178-210	2.4-5.3		1
High Purity Ni	0	5 MeV Ni	5	10 dpa Steady State	975	0.05-0.26	170-260	5.1-11		1
High Purity Ni	0	5 MeV Ni	5	2 dpa Steady 10 dpa Pulsed	975	0.03	270	3.3		1
0.99995 Ni	0	2.8 MeV Ni	70	13	598	0	0	0		2

TABLE I. (continued)

Material	Gas (appm) Content	Ion	dpa rate $\times10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv x 10^{20} (m^{-3})	$\bar{d}$ (nm)	Swelling $\Delta V/V\%$	Comment	Ref.
0.99995 Ni	0	2.8 MeV Ni	70	13	648	0	0	0		2
0.99995 Ni	0	2.8 MeV Ni	70	13	698	0	0	0		2
0.99995 Ni	0	2.8 MeV Ni	70	13	748	0	0	0		2
0.99995 Ni	0	2.8 MeV Ni	70	13	798	76	10	0.48		2
0.99995 Ni	0	2.8 MeV Ni	70	13	848	69	13	0.90		2
0.99995 Ni	0	2.8 MeV Ni	70	13	898	18	22.5	1.20		2
0.99995 Ni	0	2.8 MeV Ni	70	13	948	0.3	72.5	0.62		2
0.99995 Ni	0	2.8 MeV Ni	70	13	998	0.14	80	0.40		2
0.99995 Ni	0	2.8 MeV Ni	70	4	848	110	7.5	0.28		3
0.99995 Ni	0	2.8 MeV Ni	70	13	848	69	13.0	0.90		3
0.99995 Ni	0	2.8 MeV Ni	70	40	848	55	15.0	1.23		3
0.99995 Ni	0	2.8 MeV Ni	70	130	848	6.6	38.0	2.16		3
0.9999 Ni	100 (He) Preinjected	5 MeV Ni	5	1.0	898	50-90	8.5-12.5	0.3-0.5		4
0.9999 Ni	16 Simul-taneous	5 MeV Ni	5	0.35	898	3-10	12-24	0.12-0.28		4
0.9999 Ni	100 (He) Preinjected	5 MeV Ni	5	1.0	798	50-90	6.0	0.05-0.1		4

TABLE I. (continued)

Material	Gas (appm) Content	Ion	dpa rate $\times 10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv x 10^{20} (m^{-3})	$\bar{d}$ (nm)	Swelling $\Delta V/V\%$	Comment	Ref.
0.9999 Ni	16 (He) Simultaneous	5 MeV Ni	5	0.35	798	20	8.0-15.0	0.05-0.4		4
0.9999 Ni	6 (He) Preinjected	5 MeV Ni	5	1.2	848	60	10.0	0.5		4
0.9999 Ni	10 (He) Simultaneous	5 MeV Ni	5	1.1	848	2	21.0	0.1		4
0.9999 Ni	67 (He) Simultaneous	5 MeV Ni	5	2.0	848	8	19.0	0.3		4
0.9994 Ni	0	4 MeV H	0.006	1	723	6	25.0	---	Faulted Interstitial Loop	5
0.999 Ni	0	6-11 MeV Se	30	0.47	798	3	9.0	0.0012		6
0.999 Ni	0	6-11 MeV Se	30	2.0	798	17	8.0	0.1		6
0.999 Ni	0	6-11 MeV Se	30	2.3	798	27	12.0	0.24		6
0.999 Ni	0	6-11 MeV Se	30	12	798	36	21.0	1.7		6
0.999 Ni	0	6-11 MeV Se	30	47	798	40	27.0	4.1		6
0.999 Ni	0	6-11 MeV Se	30	95	798	76	22.0	4.2		6

TABLE I. (continued)

Material	Gas (appm) Content	Ion	dpa rate $x10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv x 10^{20} (m^{-3})	$\bar{d}$ (nm)	Swelling $\Delta V/V\%$	Comment	Ref.
0.999 Ni	0	6-11 MeV Se	30	400	798	140	18.0	4.4	Void Lattice	6
0.9999 Ni	15	5 MeV Ni	20	140	898	19	46.5	12		7
0.99995 Ni	0	5 MeV Ni	10	10	458	0	0	0	Dense Loops	8
0.99995 Ni	0	5 MeV Ni	10	10	553	0	0	0	Aligned Loops	8
0.99995 Ni	0	5 MeV Ni	10	10	643	0	0	0	Aligned Loops	8
0.99995 Ni	0	5 MeV Ni	10	10	708	0	0	0	Aligned Loops	8
0.99997 Ni	0.3 (He)	1.4 MeV H	0.2	1	573	5	4.0	0.001		9
0.99997 Ni	0.3 (He)	1.4 MeV H	0.2	1	673	85	8.0	0.28		9
0.99997 Ni	0.3 (He)	1.4 MeV H	0.2	1	773	90	11.0	0.10		9
0.99997 Ni	7 (He)	1.4 MeV H	0.2	1	673	50	6.5	0.10		9
0.99997 Ni	28 (He)	1.4 MeV H	0.2	1	673	150	5.5	0.12		9
0.99995 Ni	0	4 MeV Ni	3	0.6	773	1.6	19.8	0.065		10
0.99995 Ni	0	4 MeV Ni	3	0.6	773	1.9	13.4	0.024		10
0.99995 Ni	0	4 MeV Ni	3	1	773	0.2	14.9	0.0032		10

TABLE I. (continued)

Material	Gas (appm) Content	Ion	dpa rate $\times 10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv $\times 10^{20}$ (m^{-3})	$\bar{d}$ (nm)	Swelling $\Delta V/V\%$	Comment	Ref.
0.99995 Ni	20 (He) Simultaneous	4 MeV Ni	3	1	773	27.0	13.7	0.36		10
0.99995 Ni	20 (He) Preinjected	4 MeV Ni	3	1	773	5.0	7.4	0.011		10
0.99995 Ni	0	4 MeV Ni	3	0.6	823	3.4	18.1	0.10		10
0.99995 Ni	0	4 MeV Ni	3	0.6	823	0.3	25.9	0.033		10
0.99995 Ni	0	4 MeV Ni	3	1	823	---	---	---	High Loop Concentration	10
0.99995 Ni	0	4 MeV Ni	3	1	823	2.7	30.2	0.33		10
0.99995 Ni	0	4 MeV Ni	3	1	823	---	---	---	High Loop Concentration	10
0.99995 Ni	20 (He) Simultaneous	4 MeV Ni	3	1	823	5.5	22.0	0.30		10
0.99995 Ni	20 (He) Simultaneous	4 MeV Ni	3	1	823	2.8	26.2	0.26		10
0.99995 Ni	20 (He) Preinjected	4 MeV Ni	3	1	823	9.9	20.4	0.44		10
0.99995 Ni	0	4 MeV Ni	3	0.6	873	0.4	46.3	0.22		10
0.99995 Ni	0	4 MeV Ni	3	0.6	873	0.8	40.7	0.30		10
0.99995 Ni	0	4 MeV Ni	3	0.6	873	0.2	57.6	0.24		10

TABLE I. (continued)

Material	Gas (appm) Content	Ion	dpa rate $x10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv x 10^{20} (m^{-3})	$\bar{d}$ (nm)	Swelling ΔV/V%	Comment	Ref.
0.99995 Ni	0	4 MeV Ni	3	1	873	2.3	33.8	0.46		10
0.99995 Ni	0	4 MeV Ni	3	1	873	3.8	33.2	0.66		10
0.99995 Ni	0	4 MeV Ni	3	0.9	873	7.1	22.4	0.42		10
0.99995 Ni	0	4 MeV Ni	3	0.9	873	---	---	---	Low Loop Concentration	10
0.99995 Ni	0	4 MeV Ni	3	0.9	873	---	---	---	Low Loop Concentration	10
0.99995 Ni	20 (He) Simultaneous	4 MeV Ni	3	1	873	2.1	42.1	0.75		10
0.99995 Ni	20 (He) Preinjected	4 MeV Ni	3	1	873	21	15.6	0.42		10
0.99995 Ni	0	4 MeV Ni	3	0.6	923	0.16	60.5	0.18		10
0.99995 Ni	0	4 MeV Ni	3	0.6	923	0.17	47.2	0.094		10
0.99995 Ni	0	4 MeV Ni	3	1	923	0.51	56.7	0.48		10
0.99995 Ni	0	4 MeV Ni	3	1	923	0.10	78.1	0.25		10
0.99995 Ni	20 (He) Simultaneous	4 MeV Ni	3	1	923	0.64	48.3	0.37		10
0.99995 Ni	20 (He) Simultaneous	4 MeV Ni	3	1	923	---	---	---	Low Loop Concentration	10

TABLE I. (continued)

Material	Gas (appm) Content	Ion	dpa rate $x10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv x 10^{20} (m^{-3})	$\bar{d}$ (nm)	Swelling ΔV/V%	Comment	Ref.
0.99995 Ni	20 (He) Preinjected	4 MeV Ni	3	1	923	12	17	0.33		10
0.99995 Ni	0	4 MeV Ni	3	0.6	973	0.0089	69	0.02		10
0.99995 Ni	0	4 MeV Ni	3	0.6	973	0.011	67	0.018		10
0.99995 Ni	20 (He) Simultaneous	4 MeV Ni	3	1	973	---	---	---	Low Loop Concentration	10
0.99995 Ni	20 (He) Simultaneous	4 MeV Ni	3	1	973	0.093	82	0.28		10
0.99995 Ni	20 (He) Preinjected	4 MeV Ni	3	1	973	1.5	39	0.47		10
0.99995 Ni	3 (He) Preinjected	5 MeV Ni	20	1	798	11	9.0	0.07		11
0.99995 Ni	3 (He)	5 MeV Ni	20	4.4	798	20	15.0	0.19		11
0.99995 Ni	3 (He)	5 MeV Ni	20	6.5	798	29	14.5	0.46		11
0.99995 Ni	3 (He)	5 MeV Ni	20	10	798	32	15.5	0.61		11
0.99995 Ni	3 (He)	5 MeV Ni	20	25	798	35	21.0	1.7		11
0.99995 Ni	3 (He)	5 MeV Ni	20	58	798	33	25.0	2.7		11

TABLE I. (continued)

Material	Gas (appm) Content	Ion	dpa rate $\times 10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv x 10^{20} (m^{-3})	$\bar{d}$ (nm)	Swelling ΔV/V%	Comment	Ref.
0.99995 Ni	3 (He)	6 MeV Ni	20	67	798	27	30.5	4.0		11
0.99995 Ni	3 (He)	5 MeV Ni	20	360	798	42	25.0	3.4		11
0.99995 Ni	3 (He)	5 MeV Ni	20	480	798	40	26.0	3.7		11
0.99995 Ni	0	6 MeV Ni	20	0.43	798	3.8	13.5	0.048		11
0.99995 Ni	0	6 MeV Ni	20	1.3	798	9.9	14.0	0.14		11
0.99995 Ni	0	6 MeV Ni	20	6	798	34	14.0	0.49		11
0.99995 Ni	0	6 MeV Ni	20	44	798	41	26.5	3.95		11
0.99995 Ni	0	11 MeV Se	20	0.47	798	3	9.0	0.012		11
0.99995 Ni	0	11 MeV Se	20	2	798	17	7.0	0.05		11
0.99995 Ni	0	11 MeV Se	20	2.3	798	27	12.0	0.24		11
0.9995 Ni	0	8 MeV Se	20	12	798	36	21.0	1.7		11
0.99995 Ni	0	8.8 MeV Se	20	47	798	40	27.0	4.1		11
0.99995 Ni	0	8.8 MeV Se	20	95	798	76	22.0	4.2		11
0.99995 Ni	0	6 MeV Se	20	400	798	140	18.0	4.4		11
0.99995 Ni	0	2.8 MeV Ni	0.7	13	573	0	0	0		12

TABLE I. (continued)

Material	Gas (appm) Content	Ion	dpa rate $\times 10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv x 10^{20} (m^{-3})	$\bar{d}$ (nm)	Swelling $\Delta V/V\%$	Comment	Ref.
0.99995 Ni	0	2.8 MeV Ni	0.7	13	623	0	0	0		12
0.99995 Ni	0	2.8 MeV Ni	0.7	13	673	0	0	0		12
0.99995 Ni	0	2.8 MeV Ni	0.7	13	698	61	8.0	0.20		12
0.99995 Ni	0	2.8 MeV Ni	0.7	13	723	16	20.0	0.73		12
0.99995 Ni	0	2.8 MeV Ni	0.7	13	773	7.7	29.0	1.1		12
0.99995 Ni	0	2.8 MeV Ni	0.7	13	823	8.3	36.5	2.4		12
0.99995 Ni	0	2.8 MeV Ni	0.7	13	823	9.3	30.0	1.6		12
0.99995 Ni	0	2.8 MeV Ni	0.7	13	873	0.66	58.5	0.73		12
0.99995 Ni	0	2.8 MeV Ni	0.7	13	873	1.3	51.5	0.98		12
0.99995 Ni	0	2.8 MeV Ni	70	13	898	0.07	32.0	0.015		12
0.99995 Ni	0	2.8 MeV Ni	70	13	648	0	0	0		12
0.99995 Ni	0	2.8 MeV Ni	70	13	698	0	0	0		12
0.99995 Ni	0	2.8 MeV Ni	70	13	748	0	0	0		12
0.99995 Ni	0	2.8 MeV Ni	70	13	798	76	10.0	0.48		12
0.99995 Ni	0	2.8 MeV Ni	70	13	848	69	13.0	0.90		12
0.99995 Ni	0	2.8 MeV Ni	70	13	898	18	22.5	1.2		12
0.99995 Ni	0	2.8 MeV Ni	70	13	948	0.3	72.5	0.62		12

TABLE I. (continued)

Material	Gas (appm) Content	Ion	dpa rate $\times 10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv $\times 10^{20}$ (m^{-3})	$\bar{d}$ (nm)	Swelling ΔV/V%	Comment	Ref.
0.99995 Ni	0	2.8 MeV Ni	70	13	998	0.14	80.00	0.40		12
0.99995 Ni	0	2.8 MeV Ni	40	0.8	898	10	12.5	0.13		13
0.99995 Ni	0	2.8 MeV Ni	40	2.5	898	7.0	23.0	0.5		13
0.99995 Ni	0	2.8 MeV Ni	40	8.1	898	18	22.5	1.2		13
0.99995 Ni	0	2.8 MeV Ni	40	25	898	2.7	55.0	2.6		13
0.99995 Ni	0	2.8 MeV Ni	40	8.1	823	8.3	36.5	2.4		13
0.99995 Ni	600 (He)	500 keV He	---	0.04	773	320	2.5	0.04	He bubbles	14
0.99995 Ni	3000 (He)	500 keV He	---	0.22	773	760	2.8	0.10	He bubbles	14
0.99995 Ni	15000 (He)	500 keV He	---	1.10	773	1750	3.0	0.22	He bubbles	14
0.99995 Ni	30000 (He)	500 keV He	---	2.20	773	2990	4.1	1.50	He bubbles	14
High	10 (He)	20 MeV C	---	1	525	18	---	0.2		15
High	10 (He)	20 MeV C	---	10	525	30	---	2.0		15
0.9999 Ni	10 (He)	46.5 MeV Ni	0.33	18	723	120	10	1.2		16
0.9999 Ni	10 (He)	46.5 MeV Ni	0.33	18	773	90	11	2.0		16
0.9999 Ni	10 (He)	46.5 MeV Ni	0.33	18	823	20	11	0.6		16

TABLE I. (continued)

Material	Gas (appm) Content	Ion	dpa rate $\times 10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv x 10^{20} (m^{-3})	$\bar{d}$ (nm)	Swelling ΔV/V%	Comment	Ref.
0.9999 Ni	10 (He)	46.5 MeV Ni	0.33	18	873	15	25	3.1		16
0.9999 Ni	10 (He)	46.5 MeV Ni	0.33	18	923	10	35	3.0		16
0.9999 Ni	10 (He)	46.5 MeV Ni	6.7	18	723	0	---	0		16
0.9999 Ni	10 (He)	46.5 MeV Ni	6.7	18	773	60	11	0.6		16
0.9999 Ni	10 (He)	46.5 MeV Ni	6.7	18	823	75	12	2.0		16
0.9999 Ni	10 (He)	46.5 MeV Ni	6.7	18	873	70	12	2.5		16
0.9999 Ni	10 (He)	46.5 MeV Ni	6.7	18	923	50	12	2.1		16
0.9999 Ni	10 (He)	46.5 MeV Ni	6.7	18	973	10	20	1.9		16
0.9999 Ni	0	2.8 MeV Ni	70	13	898	5	37.0	1.3		17
0.99995 Ni	1 (He)	5 MeV Ni	6	0.06	848	0.07	4.1	0.0025		18
0.99995 Ni	2 (He)	5 MeV Ni	6	0.16	848	0.02	9.3	0.008		18
0.99995 Ni	8 (He)	5 MeV Ni	6	0.27	848	0.17	8.2	0.054		18
0.99995 Ni	32 (He)	5 MeV Ni	6	2.2	848	0.08	18.9	0.32		18
0.99997 Ni	0	2.8 MeV Ni	2.5	2	798	8.0	18.0	0.50		19
0.99997 Ni	0	2.8 MeV Ni	2.5	5	798	13	26	1.5		19
0.99997 Ni	0	2.8 MeV Ni	2.5	10	798	10	30	2.0		19
0.99997 Ni	0	2.8 MeV Ni	2.5	30	798	15	32	3.5		19

TABLE I. (continued)

Material	Gas (appm) Content	Ion	dpa rate $\times 10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv $\times 10^{20}$ (m^{-3})	$\bar{d}$ (nm)	Swelling ΔV/V%	Comment	Ref.
0.99997 Ni	0	2.8 MeV Ni	2.5	47	798	10	41	4.6		19
0.99997 Ni	0	2.8 MeV Ni	2.5	60	798	4	60	6.0		19
0.99997 Ni	0	1 MeV C	2.5	8	748	21	28	2.9		19
0.99997 Ni	0	1 MeV C	2.5	8	798	6	52	4.0		19
0.99997 Ni	0	1 MeV C	2.5	8	848	3.2	66	3.4	Double Peak Swelling vs. Temperature	19
0.99997 Ni	0	1 MeV C	2.5	8	898	2.0	73	3.1		19
0.99997 Ni	0	1 MeV C	2.5	8	973	1.0	90	3.9		19
0.99997 Ni	0	1 MeV C	2.5	1	798	12	14	0.3		19
0.99997 Ni	0	1 MeV C	2.5	5	798	15	32.5	2.5		19
0.99997 Ni	0	1 MeV C	2.5	10	798	12	45	5.3		19
0.99997 Ni	0	1 MeV C	2.5	20	798	7	71	12		19
0.99995 Ni	0	8.1 MeV Al	0.40	9.5	798	45	10	0.5	All Values at Damage Peak	20
0.99995 Ni	0	8.1 MeV Al	0.4	2	798	15	33	3.2	All Values at Damage Peak	20
0.99995 Ni	0	5 MeV C	0.5	12	798	35	21	2.5	All Values at Damage Peak	20

TABLE I. (continued)

Material	Gas (appm) Content	Ion	dpa rate $x10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv x 10^{20} (m^{-3})	$\bar{d}$ (nm)	Swelling ΔV/V%	Comment	Ref.
0.99995 Ni	0	5 MeV C	0.5	6.5	798	45	12	0.5	All Values at Damage Peak	20
0.99995 Ni	0	14 MeV Ni	1.6	15	798	20	30	2.0	All Values at Damage Peak	20
0.99995 Ni	H Not Outgassed	19 MeV Cu	1.5	10	798	40	---	---	All Values at Damage Peak	21
0.99995 Ni	H Not Outgassed	19 MeV Cu	1.5	5	798	32	---	---	All Values at Damage Peak	21
0.99995 Ni	H Not Outgassed	19 MeV Cu	1.5	3	798	20	---	---	All Values at Damage Peak	21
0.99995 Ni	H Not Outgassed	14 MeV Cu	1.5	15	798	15	25	2.5	All Values at Damage Peak	21
0.99995 Ni	H Not Outgassed	14 MeV Ni	1.5	15	798	20	30	3.0	All Values at Damage Peak	21
0.99995 Ni	H Not Outgassed	19 MeV Cu	1.5	5	798	32	---	---	All Values at Damage Peak	22
0.99995 Ni	0 Thoroughly Outgassed	18 MeV Ni	1.5	4.3	798	0.3	140	4.5	All Values at Damage Peak	22
0.99995 Ni	H Not Outgassed	14 MeV Ni	1.5	2	798	45	12	0.5	All Values at Damage Peak	23
0.99995 Ni	H Not Outgassed	14 MeV Ni	1.5	5	798	28	15	0.5	All Values at Damage Peak	23

TABLE I. (continued)

Material	Gas (appm) Content	Ion	dpa rate $\times10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv $\times 10^{20}$ (m^{-3})	$\bar{d}$ (nm)	Swelling $\Delta V/V\%$	Comment	Ref.
0.99995 Ni	H Not Outgassed	14 MeV Ni	1.5	10	798	35	18	1.0	All Values at Damage Peak	23
0.99995 Ni	H Not Outgassed	14 MeV Ni	1.5	20	798	40	20	2.0	All Values at Damage Peak	23
0.99995 Ni	H Not Outgassed	14 MeV Ni	1.5	40	798	52	22	3.5	All Values at Damage Peak	23
0.99995 Ni	H Not Outgassed	14 MeV Ni	1.5	75	798	30	24	3.0	All Values at Damage Peak	23
0.99995 Ni	H Not Outgassed	14 MeV Ni	1.5	140	798	25	22	2.0	All Values at Damage Peak	23
0.99995 Ni	0	2.8 MeV Ni	40	8.1	948	23	30.8	4.1	High Disloca- tion Density	24
0.99995 Ni	0	2.8 MeV Ni	40	8.1	898	42	23.7	3.3	High Disloca- tion Density	24
0.99995 Ni	0	2.8 MeV Ni	40	8.1	798	19	61.0	2.7	High Disloca- tion Density	24
0.9992 Ni	15 (He)	4 MeV Ni	6	25	867	28	24	---	7 wt ppm Carbon No Effect	40
0.9992 Ni	15 (He)	4 MeV Ni	6	25	867	28	24	---	106 wt ppm Carbon No Effect	40

TABLE I. (continued)

Material	Gas (appm) Content	Ion	dpa rate $\times 10^{-3}$ (sec^{-1})	dpa	Temp. (°K)	Nv $\times 10^{20}$ (m^{-3})	$\bar{d}$ (nm)	Swelling $\Delta V/V\%$	Comment	Ref.
0.9992 Ni	15 (He)	4 MeV Ni	6	25	867	28	24	---	686 wt ppm Carbon No Effect	40

Sprague et al.[2,3,13] completed a temperature scan of void formation in nickel irradiated with 2.8 MeV Ni ions. Sprague noted a swelling peak at 898°K which is about half the melting temperature (0.52 T_m). Subsequent work by Sprague to high doses (25 dpa) continued to show this peak in the swelling behavior versus temperature.

Brimhall et al.[4,8,18] have also reported results from other nickel irradiations. Early work completed by Brimhall indicated dense loop formation with loops becoming aligned at higher irradiation temperatures and doses of 10 dpa. More recent work investigated the effect of interstitial helium atoms on cavity formation. The comparison between pre-injected and simultaneous injection of helium atoms during heavy ion irradiation with 5 MeV nickel ions indicates a greater swelling for pre-injected specimens over simultaneously injected specimens for similar doses. This is due to nucleation of cavity embryos with the pre-injection which allows growth to begin immediately upon heavy ion irradiation.

Kulcinski et al.[6,11] studied radiation damage produced in nickel with Se ion irradiations to very high doses (400-480 dpa) at a high dose rate (3×10^{-2} dpa/sec) and a temperature of 798°K. Extremely high swelling (~ 4%) was observed in these irradiated samples. A void lattice structure was noted in samples irradiated at 798°K with 6 MeV Se ions and with 6 MeV Ni ions to doses greater than 100 dpa.

The work of Whitley et al.[20-23] introduces a unique aspect to the study of radiation damage in metals. The cross section technique for TEM sample preparation greatly enhances the information which may be obtained from one sample. The irradiated specimen is studied in a plane normal to the incident beam direction allowing the dose and dose rate dependencies of the microstructure formation to be evaluated. Whitley studied the effect of irradiating ion (C, Cu, Ni) and found little correlation between ion species and damage microstructure. The effect of interstitial hydrogen atoms is also addressed by Whitley. In samples in which hydrogen had been introduced during preparation, Whitley found copious void growth, while in samples which were thoroughly outgassed the void formation was notably less.

III. HVEM Studies in Pure Nickel

The stability of voids growing in a pure nickel sample during electron irradiation appears to depend upon the proximity of a local perturbation in the microstructure such as a dislocation. Studies by Norris(64-67) indicate that voids grew only near dislocations in nickel. Norris noted that should a dislocation climb away from a growing void, the void would stop growing and eventually begin shrinking. This is an indication that in an otherwise perfect crystal, with an equal supersaturation of vacancies and interstitials, a void will preferentially attract interstitials. Norris also stated that should a crystal contain both defect types, voids and dislocations, the dislocation will have the stronger bias for interstitials. Urban(68,69) found that vacancy loops grow in the presence of straight edge dislocations which is another confirmation of the stronger bias of dislocations for interstitials. Harbottle(70) found that voids could only grow in the presence of a dislocation density of 10^9 cm^{-2}. The conclusion drawn from these experiments is that a dislocation has a stronger attraction for interstitials than a void and acts as the biased sink which facilitates void growth.

HVEM studies in general are not of great value when attempting to simulate displacement cascade events since only a very few point defects are produced. However, for the case of phase stability, the ability to observe the effects of irradiation in real time while transformations take place is of particular interest. This is indicated in the HVEM studies completed on nickel alloys as outlined in Section V of this paper.

IV. Neutron Irradiations of Pure Nickel

Many of the early neutron irradiations of nickel were completed by Brimhall et al.(25-30) shortly after the first observation of voids in stainless steel. Brimhall(27) was the first to observe voids in nickel. Following this observation, numerous other neutron irradiation investigations of nickel were performed.(31-40) The results of these experiments are summarized in Table II. However, caution should be exercised in the comparison of these irradiations since the accepted means of reporting the amount of irradiation each sample encounters is the neutron fluence and not the number of displacements per atom. This may lead to a discrepancy in results if the energy spectrum of the neutron fluences to which identical specimens are exposed is not the same. Since the displacement cross section is highly energy dependent, a variation in energy spectrum may lead to completely different results for the same fluence.

It must also be noted that knowledge of the neutron energy spectrum is essential in determining the transmutation rates for a material. The transmutation of $^{58}Ni(n,\gamma)^{59}Ni$ followed by a (n,α) reaction can introduce helium into a nickel specimen which is subjected to a thermal neutron flux since the transmutation reaction has a high thermal cross section. This interstitial helium may act to stabilize void embryos or even form helium bubbles, greatly affecting the swelling behavior.

As noted in Table II, voids have been noted to form in neutron irradiated nickel over a wide temperature range (533°K to 1123°K) when irradiated to a

TABLE II. NEUTRON IRRADIATED NICKEL

Material	Fluence (cm^{-2}) E > 0.1 MeV	Temp. (°K)	Nv x 10^{20} (m^{-3})	d (nm)	ΔV/V %	Comments	Ref.
0.99997 Ni	4×10^{19}	323	0	0	0	Formed Stacking Fault Tetrahedra on Annealing	25
0.99997 Ni	1.2×10^{20}	533	200	6	0.21		25
0.99997 Ni	5.7×10^{19}	653	40	8.3	0.11		25
0.99997 Ni	5.7×10^{19}	773	8	16.5	0.16		25
0.99997 Ni	6.2×10^{19}	848	2.5	24.5	0.16		25
0.99997 Ni	5×10^{19}	653	40	8.3	0.11		26
0.99997 Ni	1.2×10^{20}	533	400	5.5	0.30		26
0.99997 Ni	5×10^{19}	653	40	10	0.20		27
0.99997 Ni	4×10^{19}	698	20	10	0.10		27
0.99997 Ni	5.2×10^{19}	913	0.8	27	0.07		28
0.99997 Ni	5.2×10^{19}	1023	0.001	40	0.001		28
0.9999 Ni	5.5×10^{18}	558	0.7	5	0.00043		29
0.9999 Ni	1.3×10^{19}	558	1.5	7	0.0025		29
0.9999 Ni	2.4×10^{19}	558	3.6	10.5	0.2		29
0.9999 Ni	2.5×10^{19}	623	1.2	21	0.06	Note Nickel Purity Variation	30

TABLE II. (continued)

Material	Fluence (cm^{-2}) E > 0.1 MeV	Temp. (°K)	Nv x 10^{20} (m^{-3})	d (nm)	ΔV/V %	Comments	Ref.
0.99998 Ni	2.5×10^{19}	673	0.5	28	0.05		30
0.99998 Ni	2.5×10^{19}	723	0.4	34	0.07		30
0.99997 Ni	2.5×10^{19}	623	16	9.7	0.06	Note Nickel Purity Variation	30
0.99997 Ni	2.5×10^{19}	673	9	12	0.07		30
0.99997 Ni	2.5×10^{19}	723	5	13.2	0.06		30
0.9999 Ni	2.5×10^{19}	623	3.6	15.5	0.06	Note Nickel Purity Variation	30
0.9999 Ni	2.5×10^{19}	673	1.2	19.2	0.04		30
0.9999 Ni	2.5×10^{19}	723	0.9	25.4	0.06		30
0.99998 Ni	1.4×10^{20}	658	2.9	12.6	0.05	Cubic Voids	31
0.99998 Ni	1.4×10^{20}	683	3.2	13.3	0.07	Cubic Voids	31
0.99998 Ni	1.4×10^{20}	713	2	15.1	0.06		31
0.99998 Ni	1.4×10^{20}	743	3.2	16	0.08	Octahedral Voids	31
0.99998 Ni	1.4×10^{20}	798	2.4	---	---	Elongated Voids	31
0.99998 Ni	1.4×10^{20}	643	1.2	6	---	Cubic Voids	31
0.99998 Ni	1.4×10^{20}	643	2.9	10.3	---	Cubic Voids	31
0.99998 Ni	1.4×10^{20}	743	1	30	---	Cubic Voids	31

TABLE II. (continued)

Material	Fluence (cm^{-2}) E > 0.1 MeV	Temp. (°K)	Nv x 10^{20} (m^{-3})	d (nm)	ΔV/V %	Comments	Ref.
0.9995 Ni	2.3 x 10^{20}	573	40	9	0.18	Swelling Increase With Cold Work	32
0.9995 Ni	2.3 x 10^{20}	673	8.5	16	0.20	Swelling Increase With Cold Work	32
0.9995 Ni	2.3 x 10^{20}	773	5.8	20	0.23	Swelling Increase With Cold Work	32
0.9995 Ni	2.3 x 10^{20}	873	5	27	0.07	Swelling Increase With Cold Work	32
0.99995 Ni	5.4 x 10^{20}	573	11	9.3	0.044		33
0.99995 Ni	5.4 x 10^{20}	623	12	18.6	0.42		33
0.99995 Ni	6.3 x 10^{20}	673	3.4	29.3	0.44		33
0.99995 Ni	6.2 x 10^{20}	723	7.8	20.3	0.34		33
0.99995 Ni	6.2 x 10^{20}	773	2	26.5	0.197		33
0.99995 Ni	6.95 x 10^{21}	823	0.78	23.7	0.056		33
0.99995 Ni	6.9 x 10^{20}	1023	0.044	32.2	0.007		33
0.99995 Ni	1.04 x 10^{21}	1123	0.022	42.5	0.0086		33
0.9999 Ni	4 x 10^{18}	773	0.20	14.6	0.006	4 wt ppm Carbon	34
0.9999 Ni	4 x 10^{18}	773	0.15	14.8	0.005	16 wt ppm Carbon	34
0.9999 Ni	4 x 10^{18}	773	0.1	15.7	0.004	27 wt ppm Carbon	34

TABLE II. (continued)

Material	Fluence (cm^{-2}) E > 0.1 MeV	Temp. (°K)	Nv x 10^{20} (m^{-3})	d (nm)	ΔV/V %	Comments	Ref.
0.9999 Ni	4×10^{18}	773	0.01	20.0	0.001	84 wt ppm Carbon	34
0.9999 Ni	4×10^{18}	773	No Voids	---	---	600 wt ppm Carbon	34
0.9999 Ni	5.3×10^{19}	773	2.5	19.8	0.19	4 wt ppm Carbon	34
0.9999 Ni	5.3×10^{19}	773	1.8	20.5	0.15	16 wt ppm Carbon	34
0.9999 Ni	5.3×10^{19}	773	1.3	21.4	0.13	27 wt ppm Carbon	34
0.9999 Ni	5.3×10^{19}	773	0.6	24.7	0.09	84 wt ppm Carbon	34
0.9999 Ni	5.3×10^{19}	773	No Voids	---	---	600 wt ppm Carbon	34
0.99995 Ni	2×10^{17}	673	0	---	0		35
0.99995 Ni	5×10^{17}	673	0.1	---	0.0001	Cubic Voids	35
0.99995 Ni	1×10^{18}	673	0.2	---	0.001	Cubic Voids	35
0.99995 Ni	5×10^{18}	673	1.1	---	0.004		35
0.99995 Ni	1×10^{19}	673	2	---	0.02	Octahedral Voids	35
0.99995 Ni	1×10^{20}	673	20	---	0.3	Octahedral Voids	35
0.9998 Ni	1.4×10^{20}	658	---	11.0	---		36
0.9998 Ni	1×10^{21}	698	---	---	0.25	20% CW No Effect	37
0.9998 Ni	3.5×10^{21}	698	---	---	0.85	20% CW No Effect	37
0.996 Ni	1×10^{21}	698	---	---	0	20% CW No Effect	37

TABLE II. (continued)

Material	Fluence (cm^{-2}) E > 0.1 MeV	Temp. (°K)	Nv x 10^{20} (m^{-3})	d (nm)	ΔV/V %	Comments	Ref.
0.996 Ni	3.5×10^{21}	698	---	---	0.1	20% CW No Effect	37
0.99995 Ni	1.8×10^{20}	728	3.4	37.5	1.4		38
0.99995 Ni	3.8×10^{20}	838	---	---	2.0		39
0.99995 Ni	3.7×10^{20}	873	---	---	2.0		39
Pure Ni	5.5×10^{21}	733	---	---	1.58		43
Pure Ni	1.1×10^{22}	733	---	---	2.05		43
Pure Ni	4.3×10^{22}	733	---	---	2.73		43
Pure Ni	4.3×10^{22}	773	---	---	2.50		43
Pure Ni	4.3×10^{22}	873	---	---	0.64		43

fluence of about 10^{18} n/cm^2 or greater. The shapes of the voids varied from cubic[31] at relatively low temperatures to elongated or octahedral voids[31] at high temperatures. The addition of impurity carbon by Sorensen[34] appears to have the effect of decreasing the amount of swelling by an order of magnitude. This is most likely due to the trapping of point defects or disruption of the displacement cascade which enhances recombination.

Differing results were reported by Adda[32] and Holmes[37] pertaining to the effect of cold work or pre-irradiation dislocation structure on swelling. Adda reported an increase in swelling with cold work, while Holmes noted no effect. Since these were early studies with relatively low swelling rates it is easy to understand how results may be misinterpreted. Current models indicate that cold working provides an incubation period during which there is little swelling. When the incubation dose is reached swelling begins and increases linearly.

V. Irradiations of Ni-Al and Ni-Si Alloys

The stability of the Ni_3X (X = Al, Si, Ti) precipitate in an irradiation environment is of great importance since this precipitate can influence mechanical properties, such as hardness, of stainless steels. The segregation of solute atoms toward or away from the material surface is of particular interest since the behavior of different solute atoms (Al and Si) shows different radiation induced characteristics. The silicon solute atoms tend to segregate toward the surface of an irradiated specimen, while the aluminum solute atoms segregate away from the surface of the irradiated sample.

Earlier studies of the Ni-Al system irradiated with heavy ions were designed primarily to characterize the microstructure formation and behavior. Kirchner et al.[41] completed a temperature and dose scan of a Ni-14 Al alloy irradiated to 20 dpa and 998°K. A peak precipitate size was noted as a function of temperature at 898°K for 20 dpa while low dose specimens (4 dpa) exhibited the largest precipitates overall (see Table III). Potter et al.[56,57,59-61] have completed a number of studies on the Ni-Al system noting the effect of dose and temperature on the evolution of precipitate microstructure. The formation of precipitate free zones accompanied by the dissolution and re-nucleation of γ' precipitates as a function of dose has been well documented by Potter.[59-61] The precipitate free zones (PFZ's) were associated with the nucleation and growth of dislocation loops and grew linearly at a rate similar to loop growth. Potter also extensively studied the mechanisms of radiation enhanced coarsening.[56,57]

The effect of dose rate on the re-nucleation of Ni_3Al precipitates was recently addressed by Sprague et al.[63] This study noted that at high dose rates (4.4×10^{-2} dpa/sec) the average precipitate size decreased with increasing dose and a bimodal distribution of precipitate sizes formed. This indicates re-nucleation of precipitates in the precipitate free zones formed by dislocation loop growth at high dose rates. For the low dose rate case only continued coarsening of the precipitates was noted. Therefore, dose rate is an important consideration when designing an irradiation study of phase stability.

The effect of the γ' precipitate on swelling behavior in irradiated Ni-Al and Ni-Si alloys was recently investigated by Roarty et al.[24] A comparison between pure nickel, Ni-Al and Ni-Si irradiated with heavy ions over the temperature range 798°K to 998°K indicated marked suppression of swelling in the alloys as compared to the pure nickel. The Ni-Al samples were found to swell to a small degree, while the Ni-Si samples suppressed swelling complete-

TABLE III. Ni-Al AND Ni-Si IRRADIATIONS

Material	Radiation Type	Dose or Fluence	Dose Rate (10^{-3} dpa/s)	Temp. (°K)	Analysis Method	Nv (m^{-3}) x 10^{-20}	d (nm)	ΔV/V %	Comments	Ref.
Ni-1 Al	2.8 MeV Ni	8.1 dpa	40	948	TEM	0.04	39.2	0.04		24
Ni-1 Al	2.8 MeV Ni	8.1 dpa	40	898	TEM	0.53	30.4	---		24
Ni-1 Al	2.8 MeV Ni	8.1 dpa	40	798	TEM	0.35	16.0	---		24
Ni-1 Al	Fast Neutron	7.6 dpa 2.2×10^{22} n/cm^2	---	728	TEM	4.2	48.8	---		24
Ni-1 Si	2.8 MeV Ni	8.1 dpa	40	948	TEM	---	---	0	Complete Swelling Suppression	24
Ni-1 Si	2.8 MeV Ni	8.1 dpa	40	898	TEM	---	---	---		24
Ni-1 Si	2.8 MeV Ni	8.1 dpa	40	798	TEM	---	---	---		24
Ni-1 Si	Fast Neutron	7.6 dpa 2.2×10^{22} n/cm^2	---	728	TEM	3.8	21	---		24
Ni-14 Al	2.8 MeV Ni	20 dpa	44	798	TEM	---	---	---	d_{precip} = 13.0 nm	41
Ni-14 Al	2.8 MeV Ni	20 dpa	44	848	TEM	---	---	---	d_{precip} = 13.7 nm	41
Ni-14 Al	2.8 MeV Ni	20 dpa	44	898	TEM	---	---	---	d_{precip} = 21.3 nm	41
Ni-14 Al	2.8 MeV Ni	20 dpa	44	948	TEM	---	---	---	d_{precip} = 18.0 nm	41
Ni-14 Al	2.8 MeV Ni	20 dpa	44	998	TEM	---	---	---	d_{precip} = 8.5 nm	41
Ni-14 Al	2.8 MeV Ni	20 dpa	44	998	TEM	---	---	---	d_{precip} = 7.2 nm	41

TABLE III. (continued)

Material	Radiation Type	Dose or Fluence	Dose Rate (10^{-3} dpa/s)	Temp. (°K)	Analysis Method	Nv (m^{-3}) x 10^{-20}	d (nm)	ΔV/V %	Comments	Ref.
Ni-14 Al	2.8 MeV Ni	4 dpa	44	898	TEM	---	---	---	d_{precip} = 23.2 nm	41
Ni-14 Al	2.8 MeV Ni	20 dpa	44	898	TEM	---	---	---	d_{precip} = 21.3 nm	41
Ni-14 Al	2.8 MeV Ni	56 dpa	44	898	TEM	---	---	---	d_{precip} = 13.7 nm	41
Ni-14 Al	2.8 MeV Ni	125 dpa	44	898	TEM	---	---	---	d_{precip} = 13.3 nm	41
Ni-2 Si	500 keV Ni	1 dpa	2.08	773	TEM	---	---	---	Precipitates Identified With Diff. Pattern Superlattice Spots	42
Ni-4 Si	500 keV Ni	10 dpa	2.08	773	TEM	---	---	---	Precip. Nucleated on Faulted Loops	42
Ni-6 Si	500 keV Ni	10 dpa	2.08	773	TEM	---	---	---	Precip. Nucleated on Faulted Loops	42
Ni-8 Si	500 keV Ni	10 dpa	2.08	773	TEM	---	---	---	Precip. Nucleated on Faulted Loops	42
Ni-0.1 Si	Fast Neutron	1.1×10^{22}	---	733	TEM	---	---	0.85		43
Ni-0.1 Si	Fast Neutron	4.3×10^{22}	---	733	TEM	---	---	1.31		43
Ni-0.1 Si	Fast Neutron	4.3×10^{22}	---	773	TEM	---	---	0.40		43
Ni-0.1 Si	Fast Neutron	4.3×10^{22}	---	873	TEM	---	---	0.31		43
Ni-1 Si	Fast Neutron	1.1×10^{22}	---	733	TEM	---	---	0.08		43
Ni-1 Si	Fast Neutron	4.3×10^{22}	---	733	TEM	---	---	0.32		43

TABLE III. (continued)

Material	Radiation Type	Dose or Fluence	Dose Rate (10^{-3} dpa/s)	Temp. (°K)	Analysis Method	Nv (m^{-3}) x 10^{-20}	d (nm)	ΔV/V %	Comments	Ref.
Ni-1 Si	Fast Neutron	4.3 x 10^{22}	---	773	TEM	---	---	0.02		43
Ni-1 Si	Fast Neutron	4.3 x 10^{22}	---	873	TEM	---	---	0.02		43
Ni-8 Si	Fast Neutron	1.1 x 10^{22}	---	733	TEM	---	---	0		43
Ni-8 Si	Fast Neutron	4.3 x 10^{22}	---	733	TEM	---	---	0.01		43
Ni-8 Si	Fast Neutron	4.3 x 10^{22}	---	733	TEM	---	---	-0.07	Note Negative Swelling	43
Ni-8 Si	Fast Neutron	4.3 x 10^{22}	---	873	TEM	---	---	-0.02	Note Negative Swelling	43
Ni-1 Si	3.5 MeV Ni	8.5 dpa	2.5	833	AES	---	---	---	Surface Segregation 4 at.% Si	44
Ni-1 Si	3.5 MeV Ni	10 dpa	2.5	893	AES	---	---	---	No Surface Segregation (SS)	44
Ni-2 Si	3.5 MeV Ni	11.4 dpa	2.5	873	AES	---	---	---	Irradiated = SS Irradiated & Annealed = No SS	44
Ni-4 Si	3.5 MeV Ni	5.9 dpa	2.5	873	TEM	---	---	---	Surface Precips.	44
Ni-12.7 Si	3.5 MeV	12.3 dpa	2.5	943	TEM	---	---	---	Ni_3Si Surface Film	44
Ni-6 Si	1 MeV e^-	0.5 dpa	0.58	789	TEM	---	---	---	Copious Precip.	45
Ni-8 Si	500 keV Ni	10 dpa	2.08	823	TEM	---	---	---	Copious Precip.	45
Ni-6 Si	1 MeV e^-	0.5 dpa	0.58	468	TEM	---	---	---	No Precipitation	45

TABLE III. (continued)

Material	Radiation Type	Dose or Fluence	Dose Rate (10^{-3} dpa/s)	Temp. (°K)	Analysis Method	Nv (m^{-3}) x 10^{-20}	d (nm)	ΔV/V %	Comments	Ref.
Ni-6 Si	500 keV Ni	10 dpa	2.0	673	TEM	---	---	---	Few Precipitates	45
Ni-1 Si	3 MeV Ni	6.5 dpa	2.5	795	AES	---	---	---	28 at.% Si on Surface	46
Ni-1 Si	3 MeV Ni	2.8 dpa	2.5	798	AES	---	---	---	25 at.% Si on Surface	46
Ni-1 Si	3 MeV Ni	0.5 dpa	2.5	794	AES	---	---	---	15 at.% Si on Surface	46
Ni-1 Si	3 MeV Ni	0.16 dpa	2.5	810	AES	---	---	---	13 at.% Si on Surface	46
Ni-1 Si	3 MeV Ni	0.05 dpa	2.5	808	AES	---	---	---	10 at.% Si on Surface	46
Ni-0.33 Si	100 keV He	1.2 dpa	0.332	773	SIMS	---	---	---	Noted Diffusion of Pre-injected Cr	47
Ni-0.33 Si	100 keV He	1.2 dpa	0.332	873	SIMS	---	---	---	Noted Difusion of Pre-injected Cr	47
Ni-12.7 Si	3.5 MeV Ni	5 dpa	2.7	723	TEM	---	---	---	Slow Surface Si Film Growth	48
Ni-12.7 Si	3.5 MeV Ni	1 dpa	2.7	873	TEM	---	---	---	Rapid Surface Si Film Growth	48
Ni-12.7 Si	3.5 MeV Ni	12.3 dpa	2.7	973	TEM	---	---	---	Slow Surface Si Film Growth	48

TABLE III. (continued)

Material	Radiation Type	Dose or Fluence	Dose Rate (10^{-3} dpa/s)	Temp. (°K)	Analysis Method	Nv (m^{-3}) x 10^{-20}	d (nm)	ΔV/V %	Comments	Ref.
Ni-4 Si	2 MeV e^-	1.2×10^{-3} dpa	5.5×10^{-6}	405	TEM & CURIE	---	---	---	No Precipitation	49
Ni-4 Si	2 MeV e^-	1.2×10^{-3} dpa	5.5×10^{-6}	523	TEM & CURIE	---	---	---	TEM & Curie Temp. Indicate Precip.	49
Ni-4 Si	2 MeV e^-	6.2×10^{-3} dpa	5.5×10^{-6}	623	TEM & CURIE	---	---	---	TEM & Curie Temp. Indicate Precip.	49
Ni-4 Si	2 MeV e^-	4.8×10^{-4} dpa	5.5×10^{-6}	623	TEM & CURIE	---	---	---	TEM Indicates Precip.; Curie Temp. Failed	49
Ni-4 Si	2 MeV e^-	7.9×10^{-4} dpa	5.5×10^{-6}	723	TEM & CURIE	---	---	---	TEM = No Precip. Curie Temp = Precip.	49
Ni-4 Si	2 MeV e^-	1.2×10^{-3} dpa	5.5×10^{-6}	723	TEM & CURIE	---	---	---	TEM & Curie Temp. Indicate Precip.	49
Ni-4 Si	2 MeV e^-	9.7×10^{-4} dpa	5.5×10^{-6}	823	TEM & CURIE	---	---	---	No Precipitation	49
Ni-4 Si	2 MeV e^-	1.3×10^{-3} dpa	5.5×10^{-6}	823	TEM & CURIE	---	---	---	No Precipitation	49
Ni-4 Si	2 MeV e^-	5.4×10^{-4} dpa	5.5×10^{-6}	923	TEM & CURIE	---	---	---	No Precipitation	49
Ni-12.7 Si	3.5 MeV Ni	0.012 dpa	1.0	523	TEM	---	---	---	Studying Disordering of Surface Ni_3Si	50

TABLE III. (continued)

Material	Radiation Type	Dose or Fluence	Dose Rate (10^{-3} dpa/s)	Temp. (°K)	Analysis Method	Nv (m^{-3}) x 10^{-20}	d (nm)	ΔV/V %	Comments	Ref.
Ni-12.7 Si	3.5 MeV Ni	0.06 dpa	1.0	523	TEM	---	---	---	Studying Disordering of Surface Ni_3Si	50
Ni-12.7 Si	3.5 MeV Ni	1.2 dpa	1.0	523	TEM	---	---	---	Studying Disordering of Surface Ni_3Si	50
Ni-10 Si	5 keV Ar	---	---	848	RBS	---	---	---	Surface Depleted in Silicon	51
Ni-10 Si	5 keV Ar	---	---	738	RBS	---	---	---	No Discernable Surface Concentration Change	51
Ni-6 Si	400 keV H	0.21 dpa	0.04	823	TEM	---	---	---	No Precipitation	52
Ni-6 Si	400 keV H	0.21 dpa	0.04	873	TEM	---	---	---	No Precipitation	52
Ni-6 Si	400 keV H	0.21 dpa	0.04	923	TEM	---	---	---	No Precipitation	52
Ni-6 Si	400 keV H	0.42 dpa	0.04	823	TEM	---	---	---	No Precipitation	52
Ni-6 Si	400 keV H	0.42 dpa	0.04	873	TEM	---	---	---	γ' Formed 1.2 μm Depth	52
Ni-6 Si	400 keV H	0.42 dpa	0.04	923	TEM	---	---	---	No Precipitation	52
Ni-6 Si	400 keV H	0.84 dpa	0.04	823	TEM	---	---	---	No Precipitation	52
Ni-8 Si	400 keV H	0.21 dpa	0.04	823	TEM	---	---	---	No Precipitation	52

TABLE III. (continued)

Material	Radiation Type	Dose or Fluence	Dose Rate (10^{-3} dpa/s)	Temp. (°K)	Analysis Method	Nv (m^{-3}) x 10^{-20}	d (nm)	ΔV/V %	Comments	Ref.
Ni-8 Si	400 keV H	0.21 dpa	0.04	873	TEM	---	---	---	γ' Formed 1.2 μm Depth	52
Ni-8 Si	400 keV H	0.21 dpa	0.04	923	TEM	---	---	---	No Precipitation	52
Ni-8 Si	400 keV H	0.42 dpa	0.04	823	TEM	---	---	---	γ' Formed 1.3 μm Depth	52
Ni-8 Si	400 keV H	0.42 dpa	0.04	873	TEM	---	---	---	γ' Formed 1.3 μm Depth	52
Ni-8 Si	400 keV H	0.42 dpa	0.04	923	TEM	---	---	---	γ' Formed 1.3 μm Depth	52
Ni-8 Si	400 keV H	0.84 dpa	0.04	823	TEM	---	---	---	γ' Formed 1.3 μm Depth	52
Ni-12.7 Si	1.5 MeV He	1.56 dpa	3.1	793	RBS	---	---	---	γ' Thickness = 27.5 nm	53
Ni-12.7 Si	2.0 MeV Li	1.32 dpa	4	793	RBS	---	---	---	γ' Thickness = 25-30 nm	53
Ni-12.7 Si	2.75 MeV Kr	3.6 dpa	5	793	RBS	---	---	---	γ' Thickness = 10 nm	53
Ni-1 Si	3.5 MeV Ni	2.0 dpa	2.5	790	TEM AES	0.05	11.5	0.00013	Si Surface Segre-gation	54
Ni-1 Si	3.5 MeV Ni	2.0 dpa	2.5	848	TEM AES	0.22	10.9	0.005	Si Surface Segre-gation	54

TABLE III. (continued)

Material	Radiation Type	Dose or Fluence	Dose Rate (10^{-3} dpa/s)	Temp. (°K)	Analysis Method	Nv (m^{-3}) x 10^{-20}	d (nm)	ΔV/V %	Comments	Ref.
Ni-1 Si	3.5 MeV Ni	1.9 dpa	2.5	893	TEM AES	0.07	10.3	0.0004	Si Surface Segregation	54
Ni-1 Si	3.5 MeV Ni	1.6 dpa	2.5	954	TEM AES	0	0	0	Si Surface Segregation	54
Ni-1 Al	3.5 MeV Ni	1.7 dpa	2.5	778	TEM AES	8.8	15.8	0.21	Al Surface Depletion	54
Ni-1 Al	3.5 MeV Ni	1.5 dpa	2.5	848	TEM AES	5.6	24.7	0.50	Al Surface Depletion	54
Ni-1 Al	3.5 MeV Ni	1.9 dpa	2.5	893	TEM AES	0.6	43.7	0.28	Al Surface Depletion	54
Ni-1 Al	3.5 MeV Ni	1.6 dpa	2.5	940	TEM AES	2.7	37.2	0.81	Al Surface Depletion	54
Ni-1 Al	3.5 MeV Ni	10.3 dpa	2.5	873	AES	---	---	---		55
Ni-1 Al	3.5 MeV Ni	10.7 dpa	2.5	893	AES	---	---	---		55
Ni-1 Si	3.5 MeV Ni	5.0 dpa	2.5	658	AES	---	---	---	Si Surface Segregation	55
Ni-1 Si	3.5 MeV Ni	3.6 dpa	2.5	753	AES	---	---	---	Si Surface Segregation	55
Ni-1 Si	3.5 MeV Ni	4.0 dpa	2.5	803	AES	---	---	---	Si Surface Segregation	55
Ni-1 Si	3.5 MeV Ni	8.5 dpa	2.5	833	AES	---	---	---	Si Surface Segregation	55

TABLE III. (continued)

Material	Radiation Type	Dose or Fluence	Dose Rate (10^{-3} dpa/s)	Temp. (°K)	Analysis Method	Nv (m^{-3}) x 10^{-20}	d (nm)	ΔV/V %	Comments	Ref.
Ni-1 Si	3.5 MeV Ni	3.9 dpa	2.5	873	AES	---	---	---	Si Surface Segregation	55
Ni-1 Si	3.5 MeV Ni	4.4 dpa	2.5	933	AES	---	---	---	Si Surface Segregation	55
Ni-14 Al	3.2 MeV Ni	5.6 dpa	2.7	823	TEM	---	---	---	Cuboidal γ'	56
Ni-14 Al	3.2 MeV Ni	19.4 dpa	2.7	823	TEM	---	---	---	Fragmented γ'	56
Ni-14 Al	3.2 MeV Ni	1.7 dpa	2.7	823	TEM	---	---	---		56
Ni-14 Al	3.2 MeV Ni	5 dpa	2.7	723	TEM	---	---	---		56
Ni-14 Al	3.2 MeV Ni	5 dpa	2.7	923	TEM	---	---	---	Loop γ' Denuded	56
Ni-14 Al	3.2 MeV Ni	1.7 dpa	2.7	823	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 5 nm	57
Ni-14 Al	3.2 MeV Ni	5.6 dpa	2.7	823	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 7 nm	57
Ni-14 Al	3.2 MeV Ni	24.1 dpa	2.7	823	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 10 nm	57
Ni-14 Al	3.2 MeV Ni	34.1 dpa	2.7	823	TEM	---	---	---	Internal γ' dissolution	57
Ni-19.6 Al	3.2 MeV Ni	4 dpa	2.7	723	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 40 nm	57
Ni-14 Al	2.8 MeV Ni	0.81 dpa	44	998	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 41.5 nm	58
Ni-14 Al	2.8 MeV Ni	0.81 dpa	0.44	998	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 41.1 nm	58
Ni-14 Al	2.8 MeV Ni	2.5 dpa	44	998	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 43.6 nm	58

TABLE III. (continued)

Material	Radiation Type	Dose or Fluence	Dose Rate (10^{-3} dpa/s)	Temp. (°K)	Analysis Method	Nv (m^{-3}) x 10^{-20}	d (nm)	$\Delta V/\bar{V}$ %	Comments	Ref.
Ni-14 Al	2.8 MeV Ni	2.5 dpa	0.44	998	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 42.0 nm	58
Ni-14 Al	2.8 MeV Ni	8.1 dpa	44	998	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 5.0 nm	58
Ni-14 Al	2.8 MeV Ni	8.1 dpa	0.44	998	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 40.5 nm	58
Ni-12.8 Al	3.2 MeV Ni	0.5 dpa	2.7	923	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 7.3 nm	59
Ni-12.8 Al	3.2 MeV Ni	3 dpa	2.7	923	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 16.8 nm Precip. Free Zones Form	59
Ni-12.8 Al	3.2 MeV Ni	6 dpa	2.7	923	TEM	---	---	---	PFZ's Grow	59
Ni-12.8 Al	3.2 MeV Ni	15 dpa	2.7	923	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 28.2 nm	59
Ni-12.8 Al	3.2 MeV Ni	30 dpa	2.7	923	TEM	---	---	---	Re-nucleation of γ' in PFZ's	59
Ni-12.8 Al	1 MeV Ni	4.8 dpa	3.4	873	TEM	---	---	---	PFZ on Surface High Internal γ' Vol. Fraction	60
Ni-12.8 Al	3.5 MeV Ni	1.7 dpa	2.7	823	TEM	---	---	---	Few Small Voids Nonuniform Precip.	61
Ni-12.8 Al	3.5 MeV Ni	8 dpa	2.7	823	TEM	---	---	---	PFZ's Forming	61
Ni-12.8 Al	3.5 MeV Ni	19.4 dpa	2.7	823	TEM	---	---	---	γ' Re-nucleation in PFZ's	61
Ni-12.8 Al	3.5 MeV Ni	3 dpa	2.7	918	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 10 nm	61

TABLE III. (continued)

Material	Radiation Type	Dose or Fluence	Dose Rate (10^{-3} dpa/s)	Temp. (°K)	Analysis Method	Nv (m^{-3}) x 10^{-20}	d (nm)	ΔV/V %	Comments	Ref.
Ni-12.8 Al	3.5 MeV Ni	6 dpa	2.7	918	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 15 nm	61
Ni-12.8 Al	3.5 MeV Ni	9 dpa	2.7	918	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 18 nm	61
Ni-12.8 Al	3.5 MeV Ni	12 dpa	2.7	918	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 20 nm	61
Ni-12.6 Al Single Xtal	1 MeV e^-	0.5-1 dpa	5	150-300	HVEM	---	---	---	Low Temp - Low Dose Disordering of Ni_3Al	62
Ni-12.6 Al Single Xtal	1 MeV e^-	1-8 dpa	5	350-440	HVEM	---	---	---	Intermediate Degree of Order	62
Ni-12.6 Al Single Xtal	1 MeV e^-	15.5-26 dpa	5	575-775	HVEM	---	---	---	Voids Form d_v = 15-25 nm	62
Ni-12.8 Al	2.8 MeV Ni	0.81 dpa	44	1048	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 18.4 nm Bimodal Distribution	63
Ni-12.8 Al	2.8 MeV Ni	2.5 dpa	44	1048	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 13.6 nm Bimodal Distribution	63
Ni-12.8 Al	2.8 MeV Ni	8.1 dpa	44	1048	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 4.2 nm Re-nucleated Precips.	63
Ni-12.8 Al	2.8 MeV Ni	0.81 dpa	0.44	1048	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 37.2 nm	63
Ni-12.8 Al	2.8 MeV Ni	2.5 dpa	0.44	1048	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 37.7 nm	63
Ni-12.8 Al	2.8 MeV Ni	8.1 dpa	0.44	1048	TEM	---	---	---	$\bar{d}_{\gamma'}$ = 42.3 nm	63

ly. Comparison to similar samples irradiated with fast neutrons showed different swelling characteristics which can be attributed to different controlling mechanisms for void nucleation in ion and neutron irradiation.

Carpenter and Schulson[62] completed an HVEM study of the behavior of the ordered Ni_3Al to study the response of this phase to radiation. The results indicated that at intermediate doses and at intermediate temperatures some degree of re-ordering takes place in an irradiation environment. At low temperatures and doses the ordered Ni_3Al structure is merely disordered, while at higher temperatures thermal disordering and radiation enhanced diffusion decrease the order parameter.

The Ni-Si alloy system has been extensively studied since the observation by Silvestre et al.[43] of radiation induced precipitation and radiation induced solute segregation to the surface. A number of studies have been completed by Potter, Okamoto, Wiedersich and others at Argonne[42,44,46,48,50,54] noting surface segregation of silicon using transmission electron microscopy and Auger electron spectroscopy. Variation in temperature and irradiation conditions allowed observations which assisted in the development of models to describe this surface segregation.

A number of techniques have been used to study the segregation of silicon to the surface of irradiated Ni-Si alloys. These include Auger electron spectroscopy,[44,46,54,55] Rutherford backscatter spectroscopy,[51,53] Curie temperature determination[49] and secondary ion mass spectrometry (SIMS).[47] These studies, which are summarized in Table III, investigate surface segregation, radiation induced precipitation and precipitate size distribution as a function of irradiation dose and temperature.

Potter and Hernandez[50] recently noted heterogeneous Ni_3Si precipitation at internal and external surfaces and determined the growth rate of Ni_3Al thin films on stacking faults within the material. The growth rates were determined via infrared (i.r.) emittance measurements as a function of dose rate and irradiation temperature. The film growth rate was small below 673°K and above 973°K with a peak at 823°K. This growth rate was directly proportional to dose rate between 10^{-4} to 10^{-2} dpa/sec. A solute-defect coupling, as outlined in the Johnson-Lam model[71,72], is suggested as the mechanism for film formation and growth. The temperature dependence is similar to that for void growth in pure nickel and relates well to the temperature dependence of defect fluxes arriving at sinks in most solute segregation models.[71-74]

The effect of solute misfit and temperature on solute segregation in Ni-Al and Ni-Si is addressed by Rehn et al.[55] Rehn noted that undersized solutes such as Si segregate to the surface via interstitial diffusion mechanisms. Oversized solute atoms which preferentially exchange with vacancies will be depleted at the surface. This surface depletion was noted by Rehn for aluminum in nickel. These effects are in agreement with the Johnson-Lam model.[71,72]

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