Hardening effect of helium bubbles in ferritic/martensitic steels

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Outline

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Introduction

Helium-induced hardening of RAFMs

The Reduced Activation Ferritic/Martensitic (RAFM) steels are presently considered as the primary candidate blanket structural materials for fusion reactors. They have also great potential to be applied to target structures of high power spallation neutron sources.

High displacement damage and helium (He) concentration will be produced in structural materials by intense flux of high energy neutrons. The understanding of helium-induced hardening and embrittlement effects in MF steels is one of key issues in the current fusion and spallation materials programs.

Fusion reactors

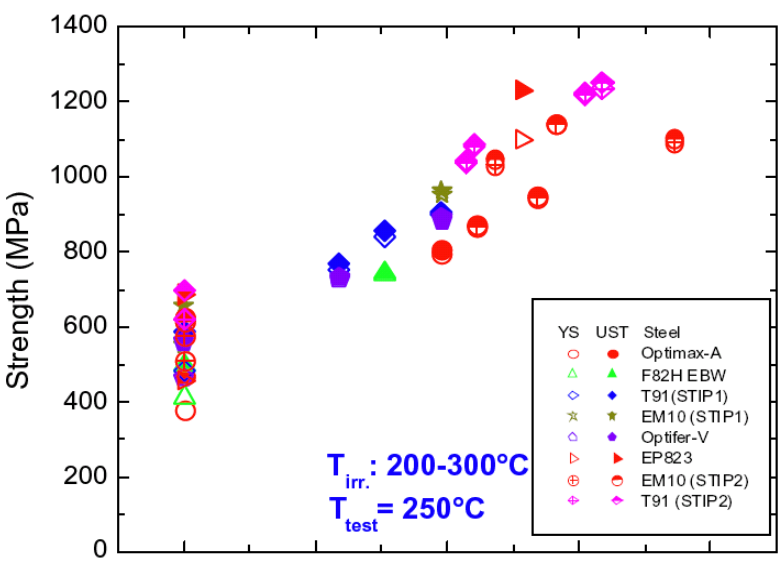
Flux (n/cm^2·s)	**>10^{15}**
Dose	**20-30 (dpa/yr)**
He production	**10-15 (appm/dpa)**

Spallation targets

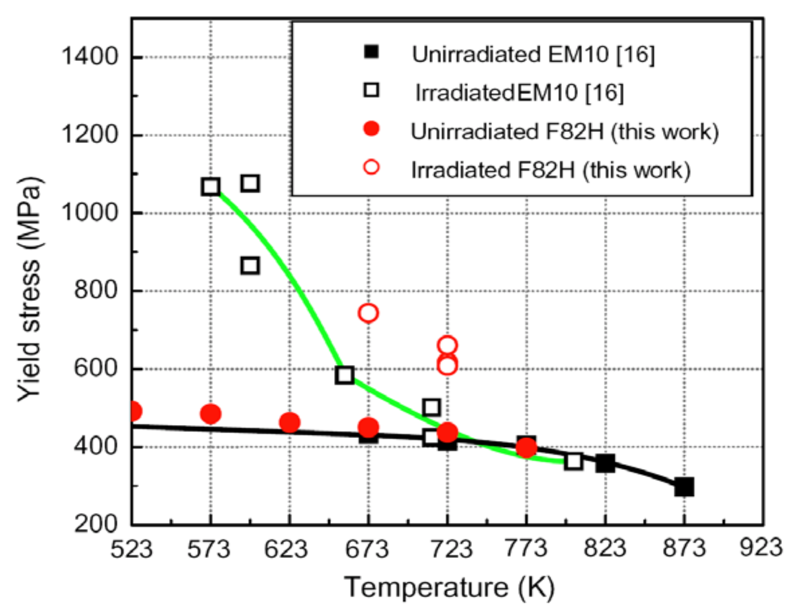
Flux (n/cm^2·s)	**>10^{14}**
Dose	**10-20 (dpa/yr)**
He production	**< 100 (appm/dpa)**

Helium effects on hardening

In recent studies, various RAFM steels were irradiated to 20 dpa / 1800 appm He at Swiss spallation neutron source (SINQ). A series of studies have been conducted on the mechanical properties and microstructure of F82H and Optimax-A steels in SINQ target irradiation program (STIP). The results demonstrate that He can introduce significant hardening effects, even at temperatures above 400° C where neutron irradiations don't show any evident changes in strength of RAFM steels .



~70 appm/dpa He， <400°C



~70 appm/dpa He， >400°C

Micro-hardness and microstructure

To investigate the effects of helium on hardening after irradiation, annealing experiments have been done to recover the irradiation-induced changes in mechanical properties and microstructure.

Fast and inexpensive hardness testing have been used for rapid overall mechanical property evaluations instead of elaborate tensile testing because of its non-destructively testing and saving in material.

Hardness and strength have a good correlations.

In the present work, micro-hardness and microstructure before and after annealing of RAFM steels, F82H and Optimax-A, after irradiation (4.6~11.3 dpa, 300~1200 appm, <400℃) have been investigated.

Experimental

Materials

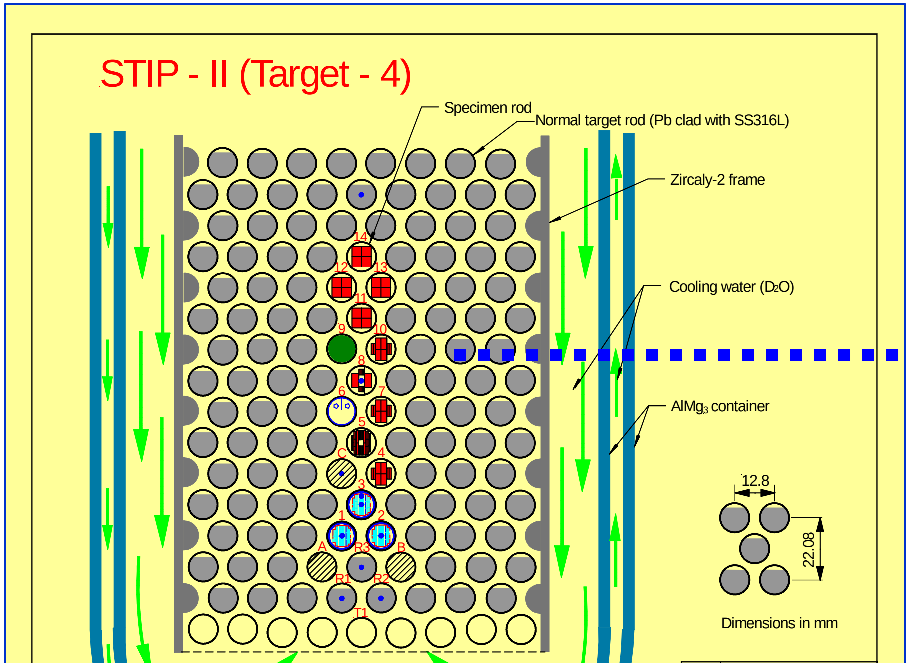
➢ Compositions

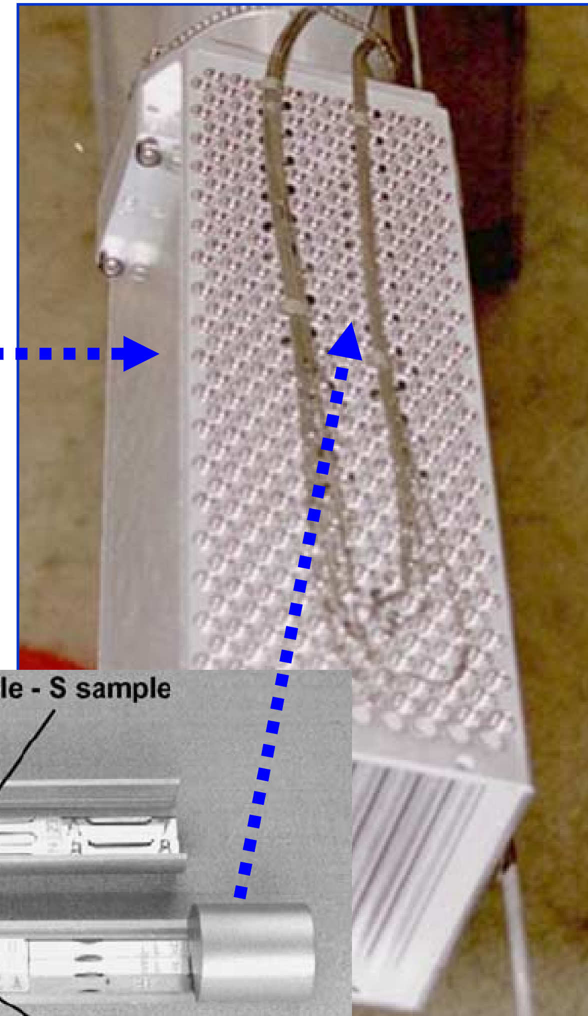
RAFMs	Cr	W	V	Mn	C	Si	Mo	Nb	P
Optimax-A	9.3	0.97	0.24	0.6	0.098	0.02	0.09	<0.01	0.01
F82H	7.87	1.98	0.19	0.1	0.09	0.07	0.003	0.002	0.003

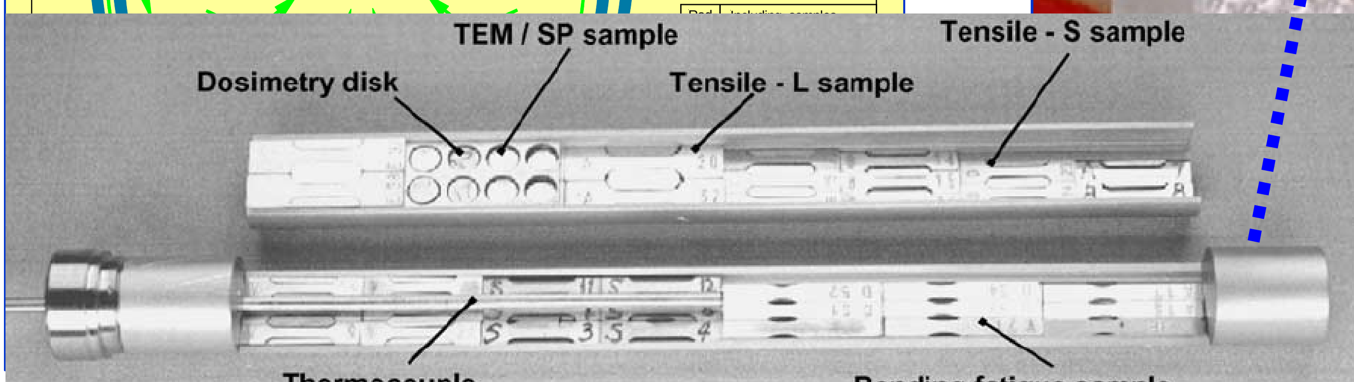
➢ Heat treatments

RAFMs	Normalizing	Tempering
Optimax-A	1050 ℃	750 ℃ /120min
F82H	1040 ℃ /30min	750 ℃ /60min

SINQ Target Irradiation Program - STIP







Specimen package

Irradiation conditions

➢ STIP-I

Miniature type tensile specimens were irradiated in SINQ spallation targets

RAFMs	Irr. Temp. (℃)	Dose (dpa)	He (appm)
F82H	184	5.3	340
	159	4.64	300
	175	5.3	340
	151	4.64	300
	260	8.96	720
	307	10.49	910
	256	8.96	720
	302	10.49	910
	369	11.32	1173
	369	11.32	1173
	345	11.32	1173
	345	11.32	1173

RAFMs	Irr. Temp. (℃)	Dose (dpa)	He (appm)
Optima x-A	161	6.27	430
	116	4.64	280
	161	6.27	430
	116	4.64	280
	277	10.49	910
	235	8.96	720
	235	8.96	720
	277	10.49	910

➢ Helium Implanting

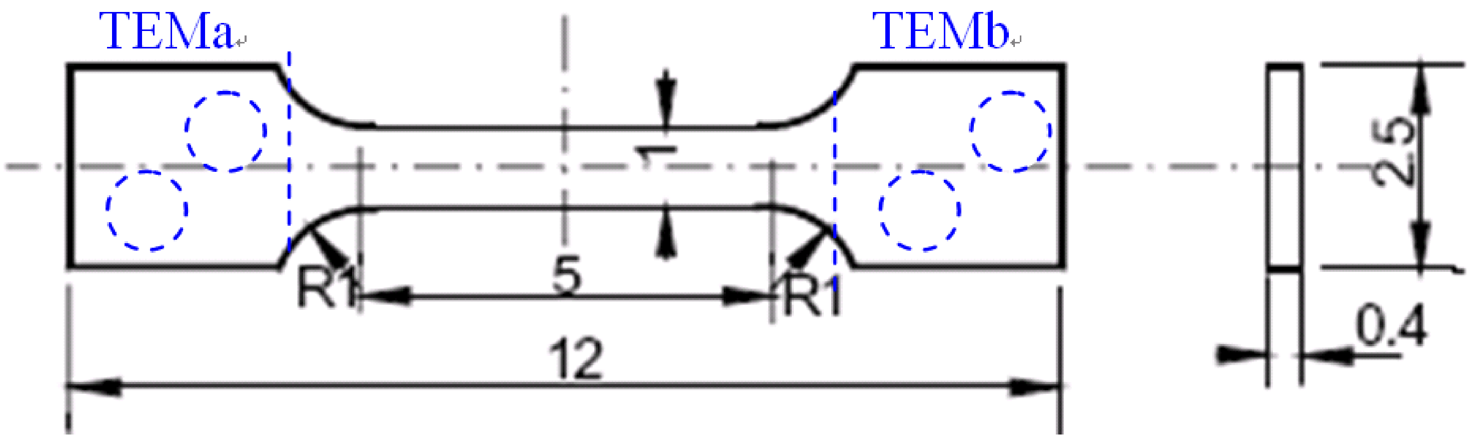
560 appm / 0.09 dpa,

1350 appm / 0.22 dpa; 25~70℃.

Sample preparation

➢ **Procedure**

Cutting	(from grip sections of tensile specimen)
Punching	(1 mm disc)
Annealing	(500℃/600℃/700℃, 2 hours)
Embeding	(in 3 mm SS316 ring)
Polish	
Electron polish	(for TEM observation)



Test methods

➢ Micro-hardness Test

Vickers micro-hardness measurements (HV 0.05) on the grip sections of tensile specimen. (Mean value of 10 identations)

➢ TEM Observation

The TEM investigation on the microstructure was performed with a JEOL 2010 type microscope. The most often used image conditions were two beam bright field (TBBF) and weak beam dark field (WBDF) at (g, 5g), g = 110.

Micrographs of WBDF at (g, 5g), g = 110 were used to quantifying the size and number density of defect clusters and dislocation loops for all the samples and micrographs of two beam

TBBF (g = 110) were used for quantifying the size and number density of helium bubbles for most samples.

The thickness of observed area of a thin foil was deduced from the number of fringes in micrographs of WBDF at (g, 5g), g = 110.

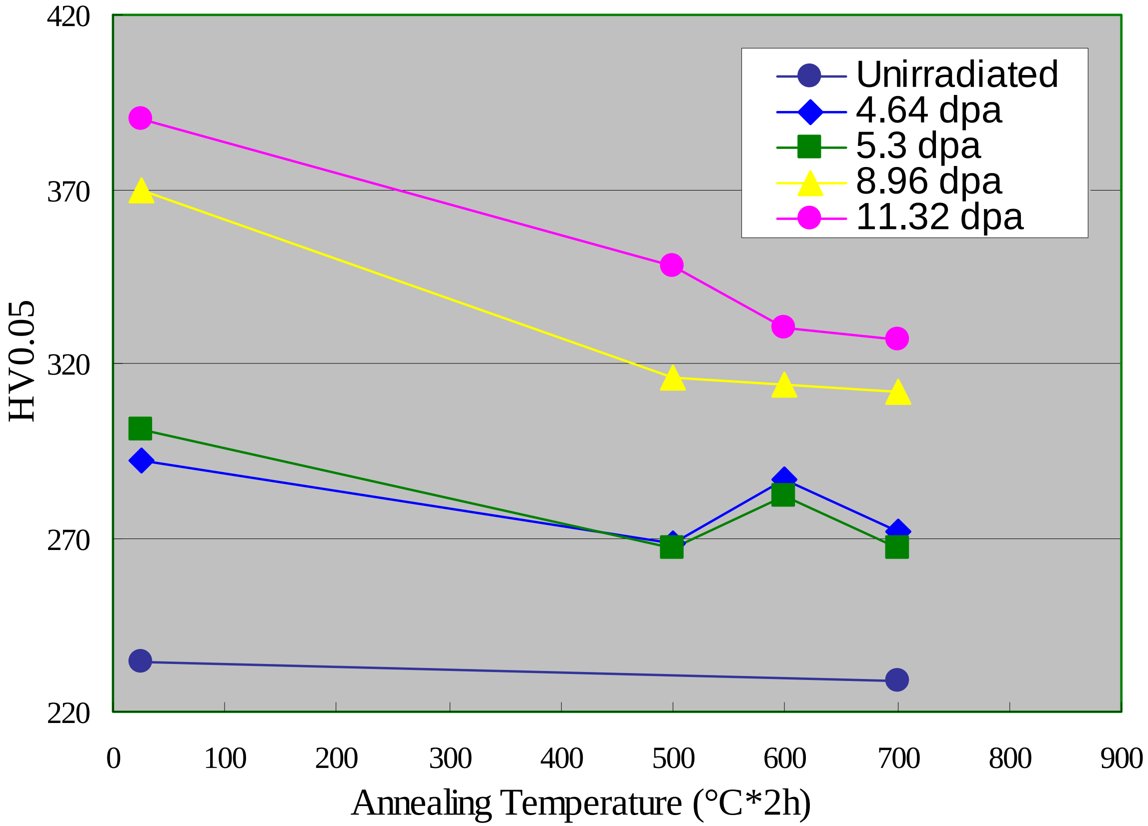
Results

(Micro-hardness and Microstructure)

- Different temperature annealing
- 600° C/2h annealing on F82H
- 600° C/2h annealing on Optimax-A
- Annealing on F82H after He implanted

Different temperature annealing

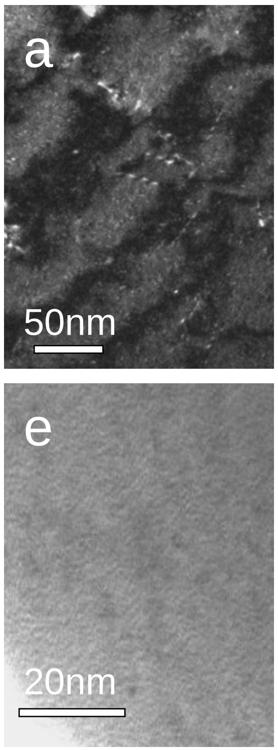
Micro-hardness

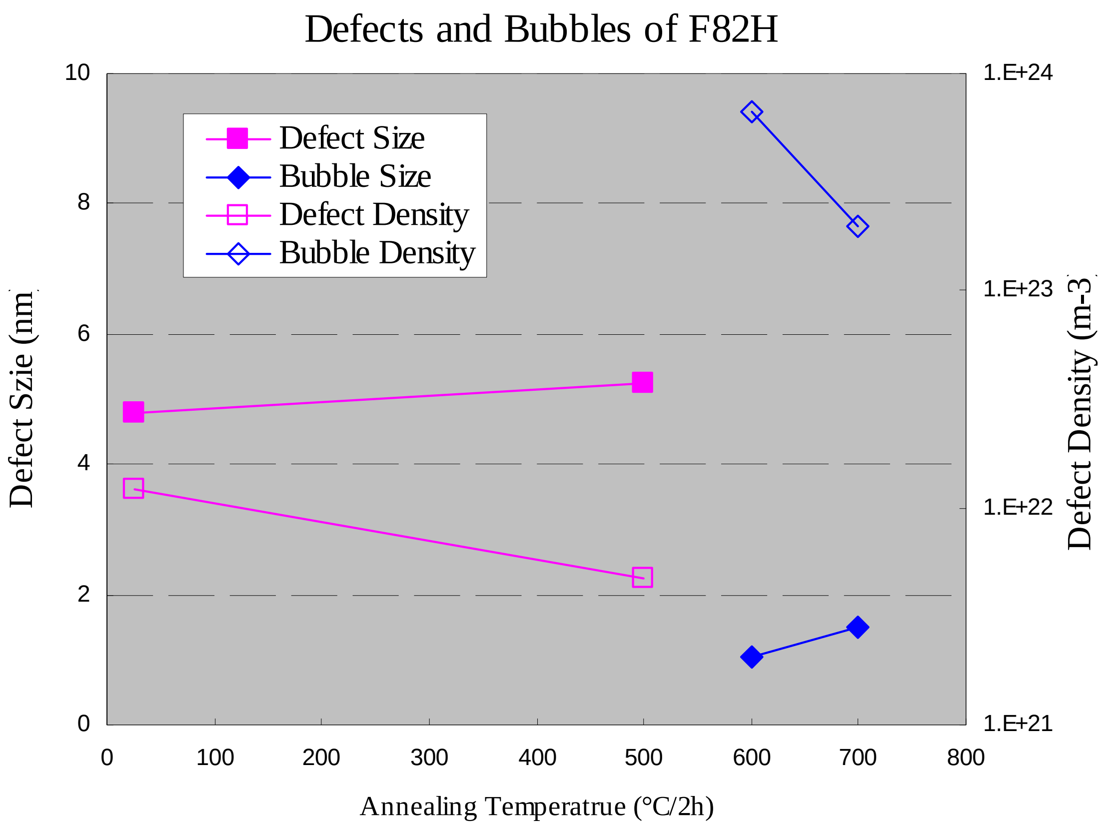


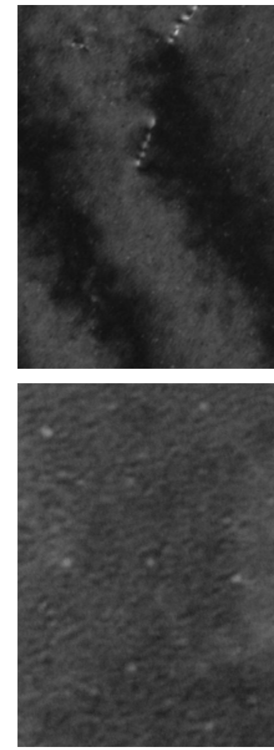
Micro-hardness of F82H after different temperature annealing

Different temperature annealing

Microstructure（5.3 dpa/340 appm He/175℃）







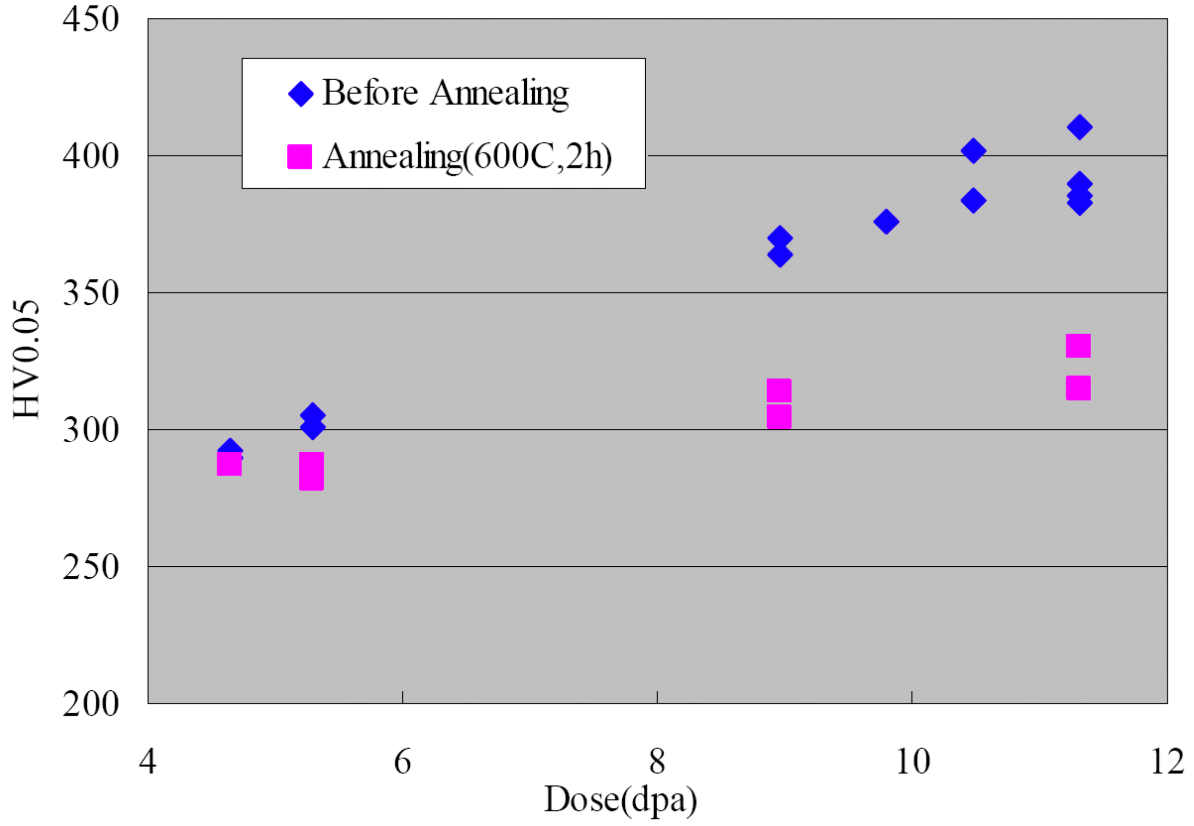
Before Annea

700°C/2h

Defects are mostly recovered after annealing at 600 ℃ for 2 hours.

Micro-hardness and Mircrostructure (F82H)

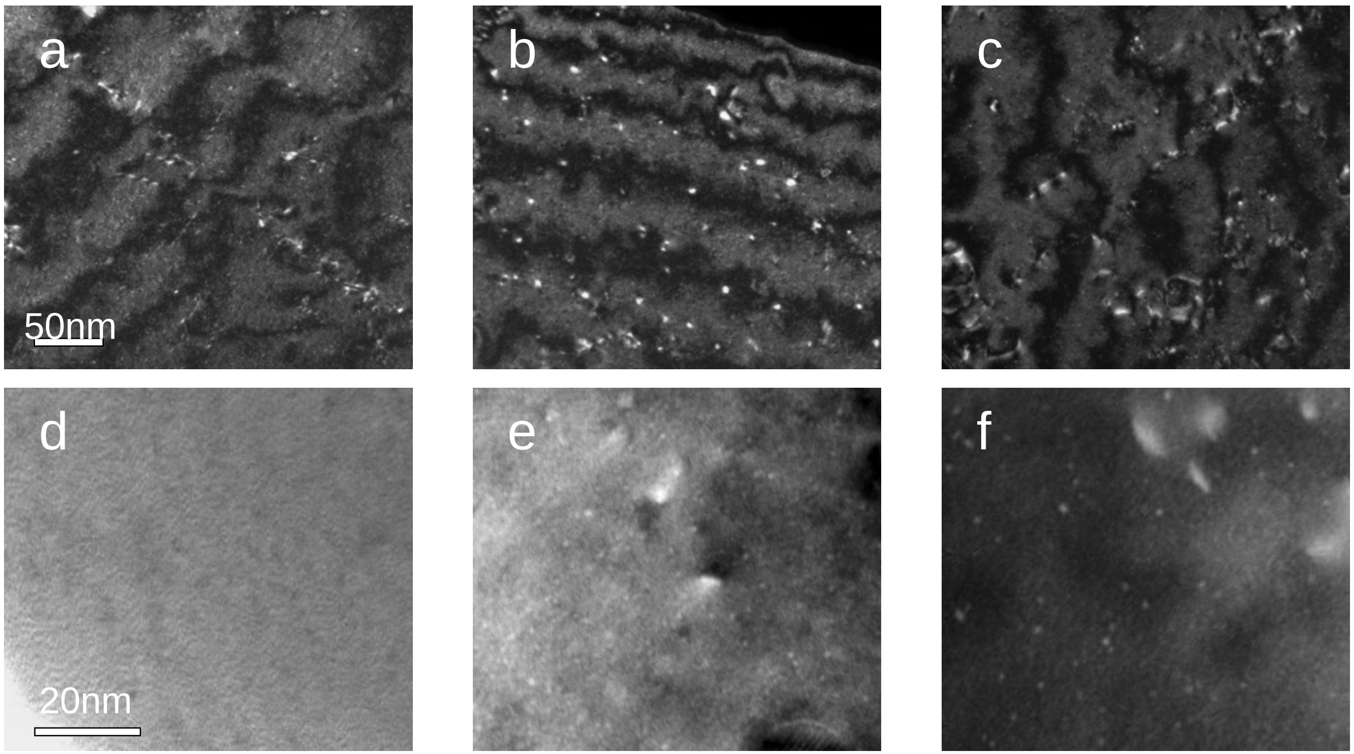
Micro-hardness of F82H after STIP irradiation



Micro-hardness of F82H before and after 600℃/2h annealing

Micro-hardness and Mircrostructure (F82H)

Microstructure of F82H before annealing



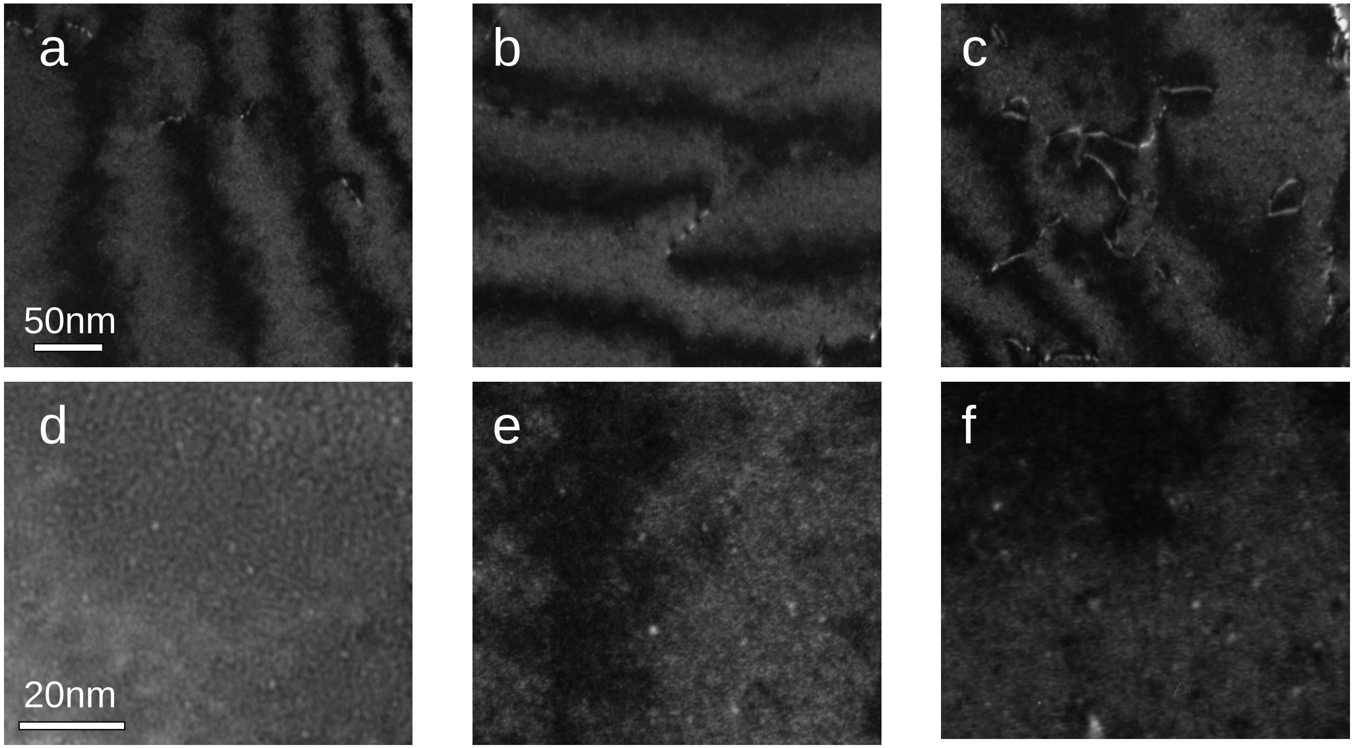
Defects

Bubbles

5.3dpa/340appm He   8.96dpa/720appm He   11.32dpa/1173appm He

Micro-hardness and Mircrostructure (F82H)

Microstructure of F82H after 600°C/2h annealing



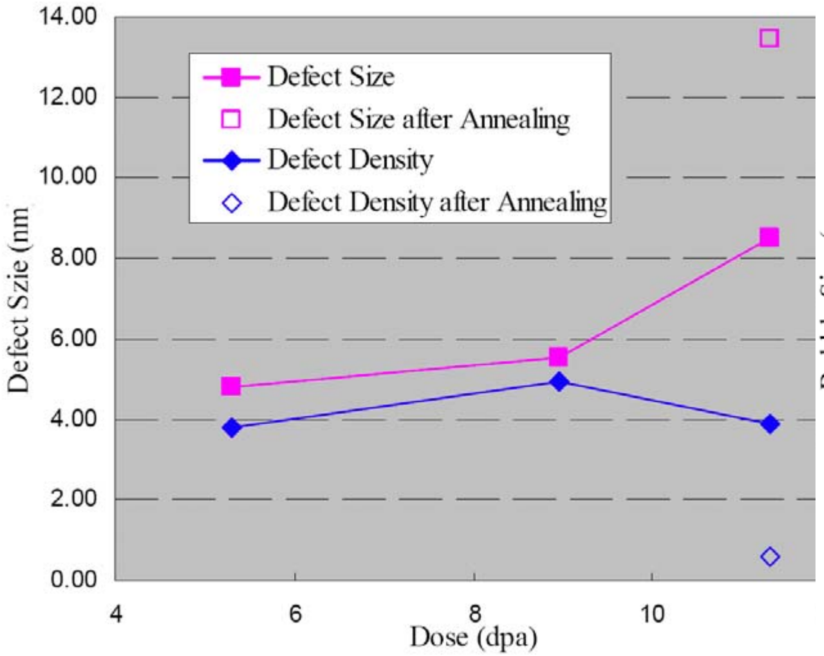
Defects

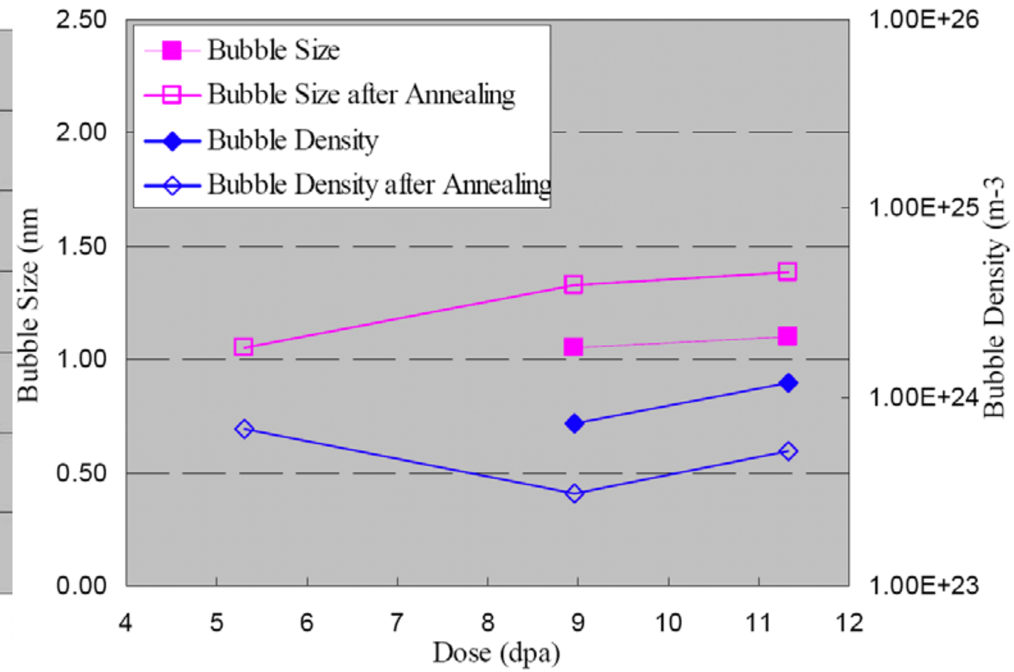
Bubbles

5.3dpa/340appm He   8.96dpa/720appm He   11.32dpa/1173appm He

Micro-hardness and Mircrostructure (F82H)

Quantitative analysis of defects and bubbles in F82H after STIP irradiation

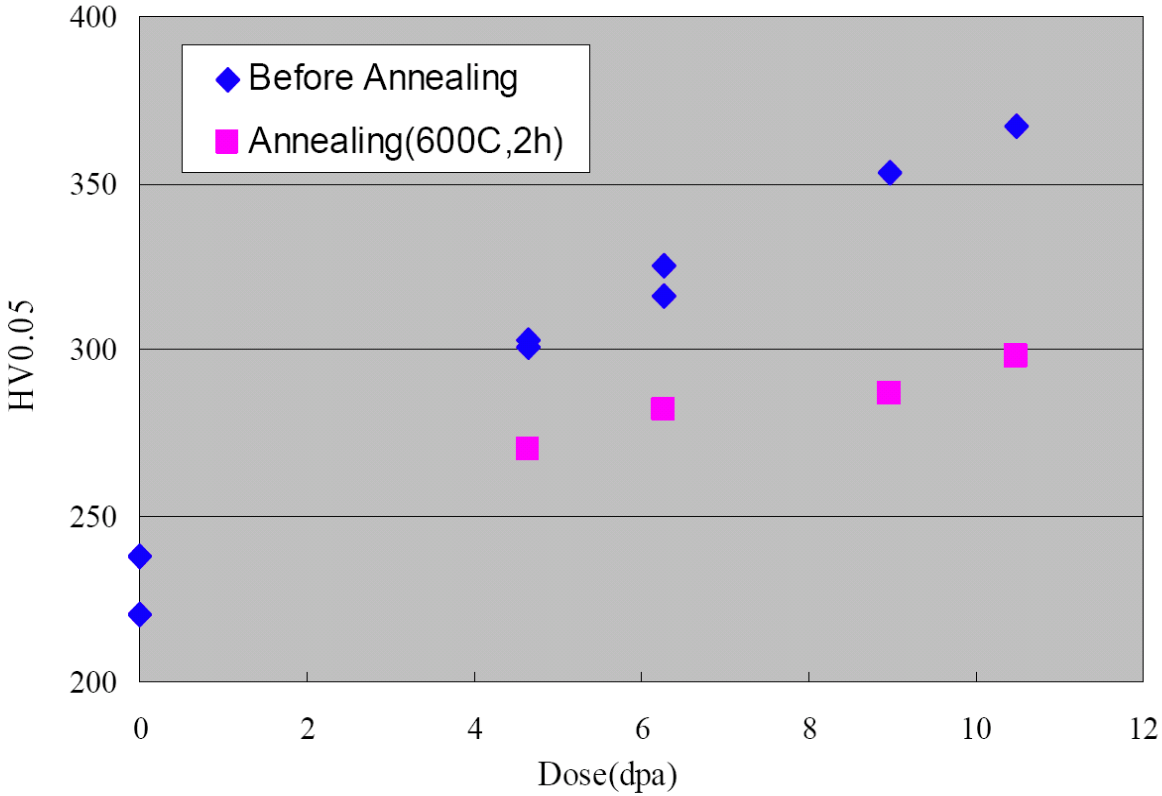




Size and density of defects (left) and bubbles (right) of F82H

Micro-hardness and Mircrostructure (Optimax-A)

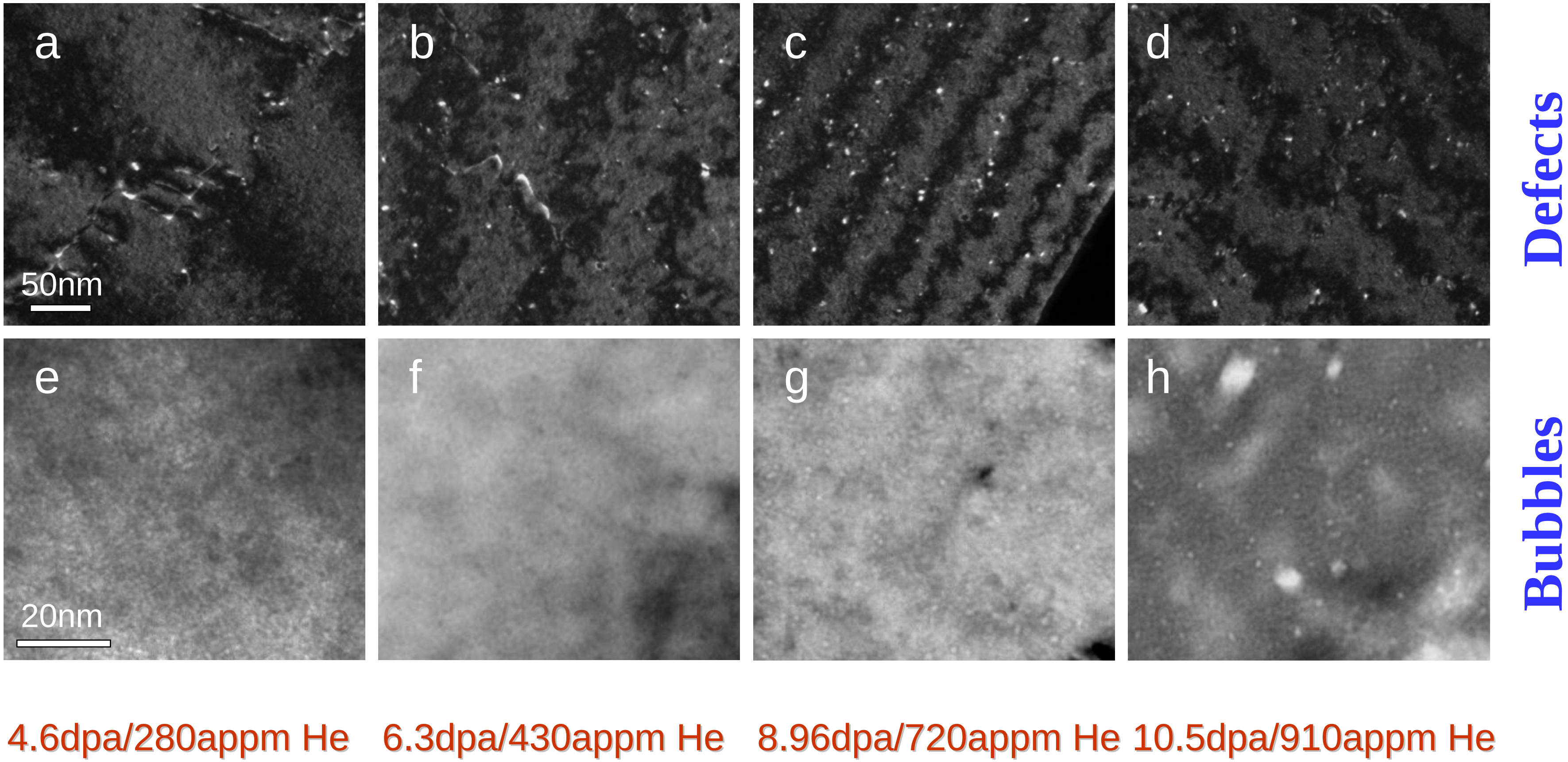
Micro-hardness of Optimax-A after STIP irradiation



Micro-hardness of Optimax-A before and after 600℃/2h annealing

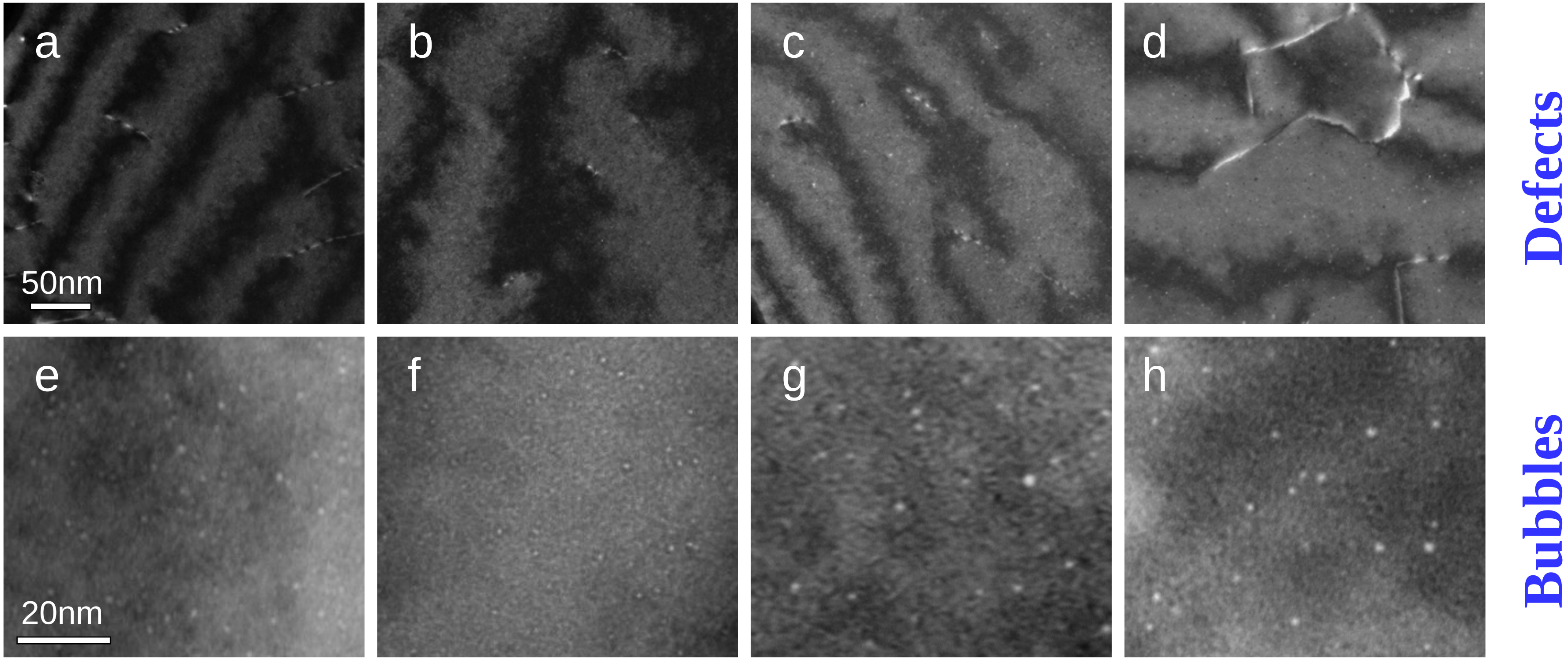
Micro-hardness and Mircrostructure (Optimax-A)

Microstructure of Optimax-A before annealing



Micro-hardness and Mircrostructure (Optimax-A)

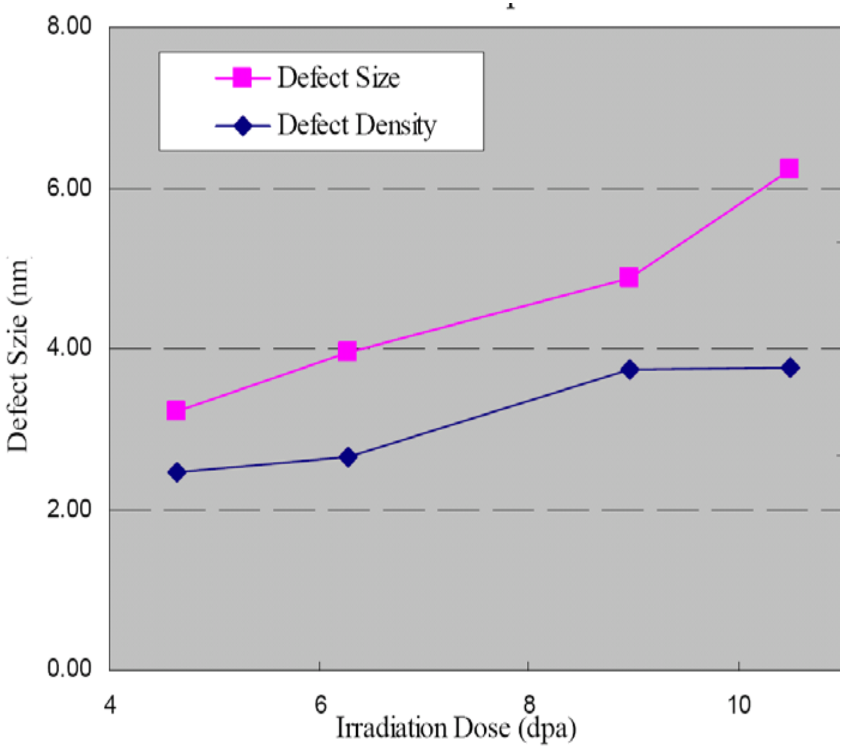
Microstructure of Optimax-A after 600°C/2h annealing

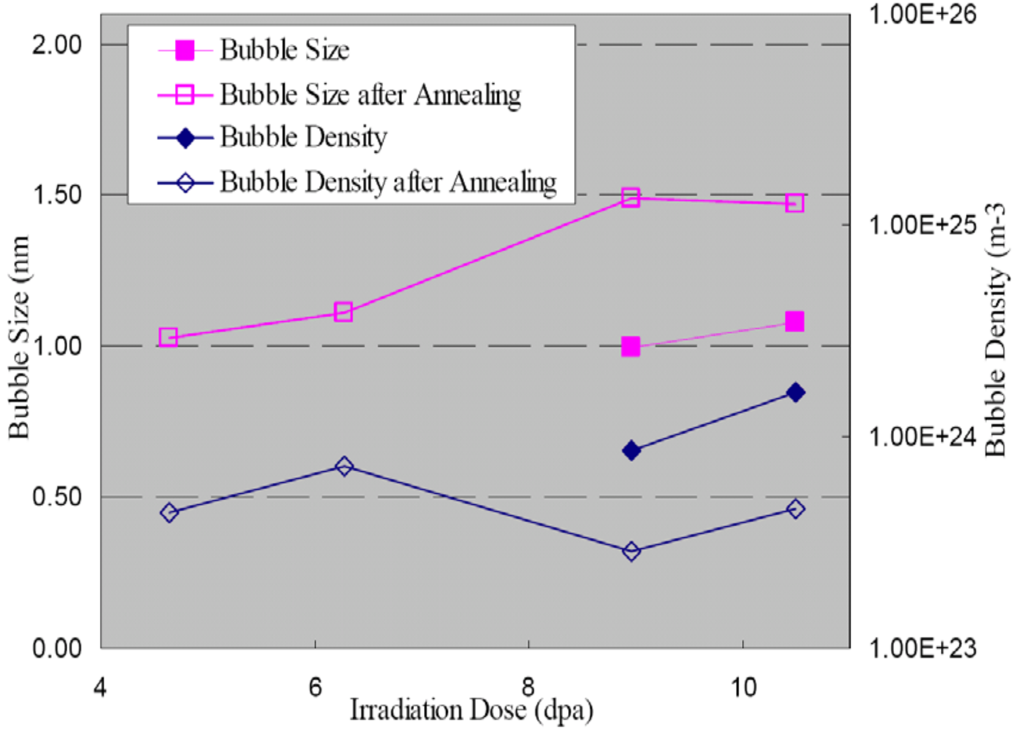


4.6dpa/280appm He 6.3dpa/430appm He 8.96dpa/720appm He 10.5dpa/910appm He

Micro-hardness and Mircrostructure (Optimax-A)

Quantitative analysis of defects and bubbles in Optimax-A after STIP irradiation

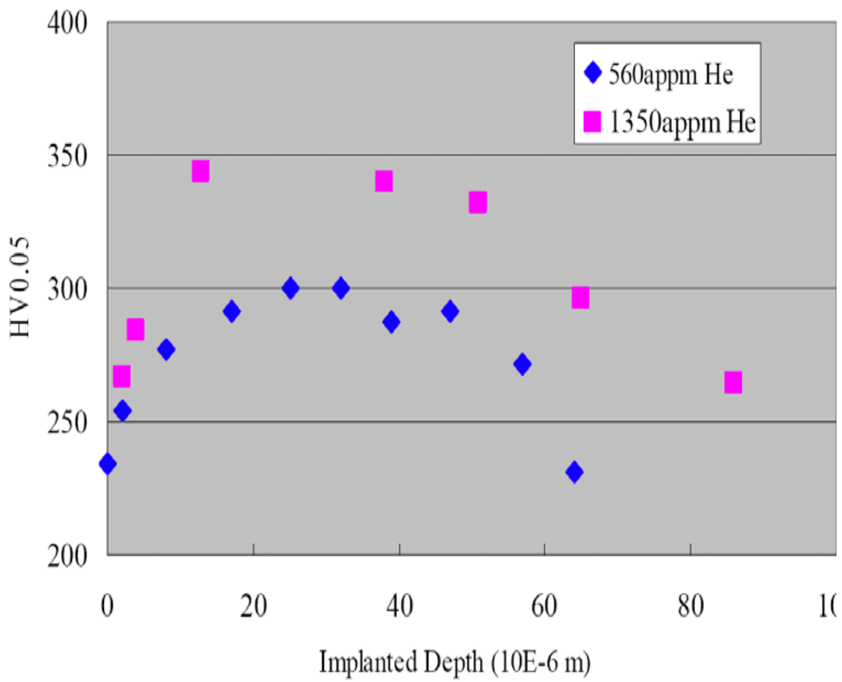




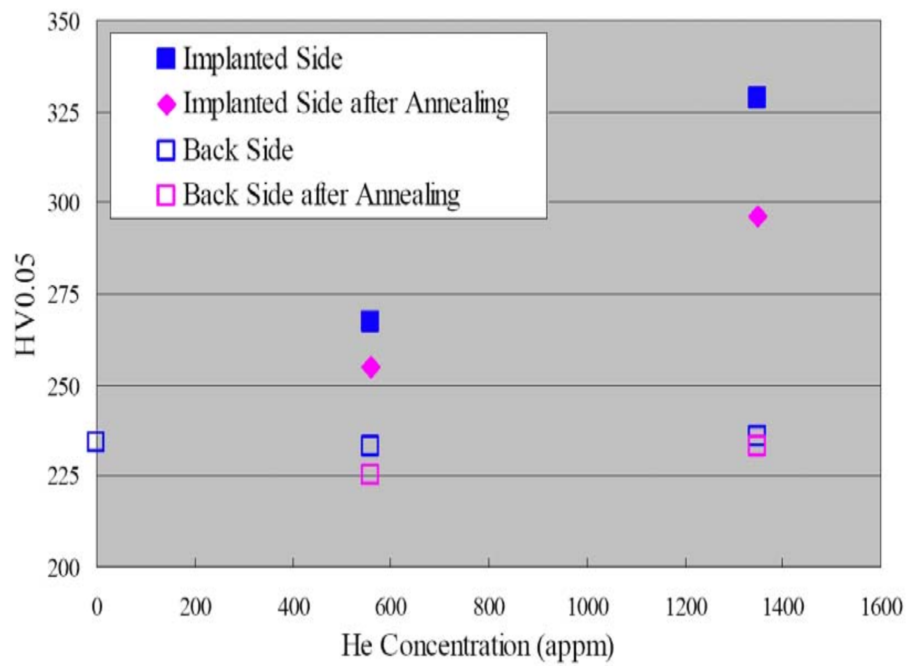
Size and density of defects (left) and bubbles (right) of Optimax-A

Micro-hardness and Mircrostructure (F82H)

Micro-hardness of F82H after Helium implanted



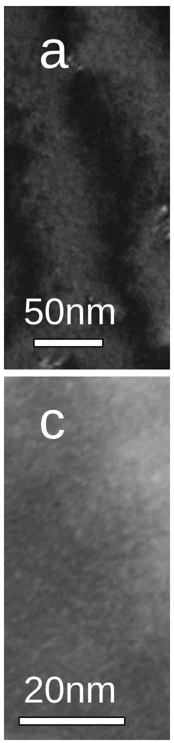
Micro-hardnessof F82H after Helium implanted with implanted depth

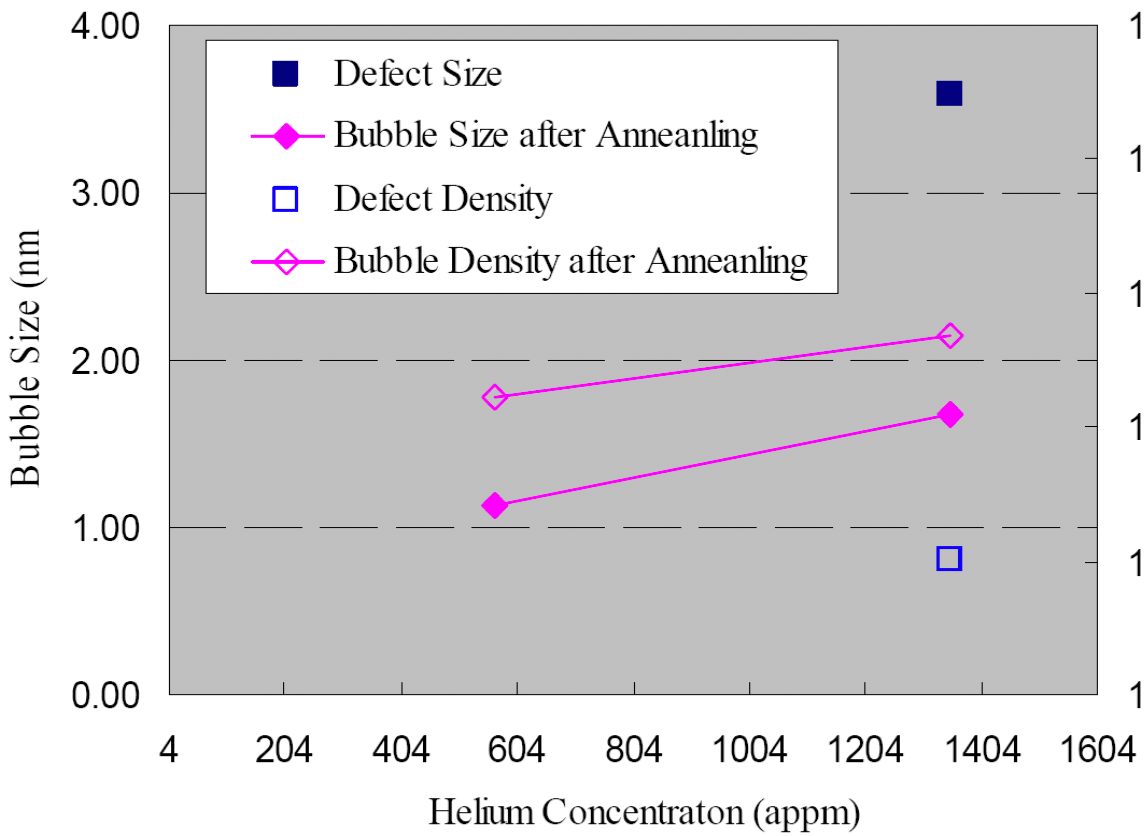


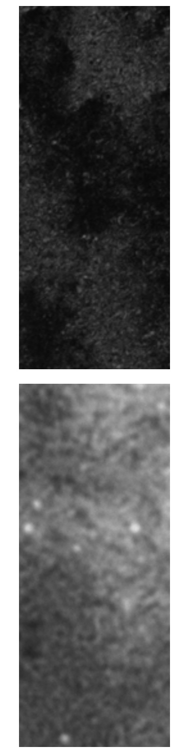
Micro-hardnessof F82H after Helium implanted with He concentration

Micro-hardness and Mircrostructure (F82H)

Microstructure of F82H after Helium implanted







Defects

Bubbles

560appn

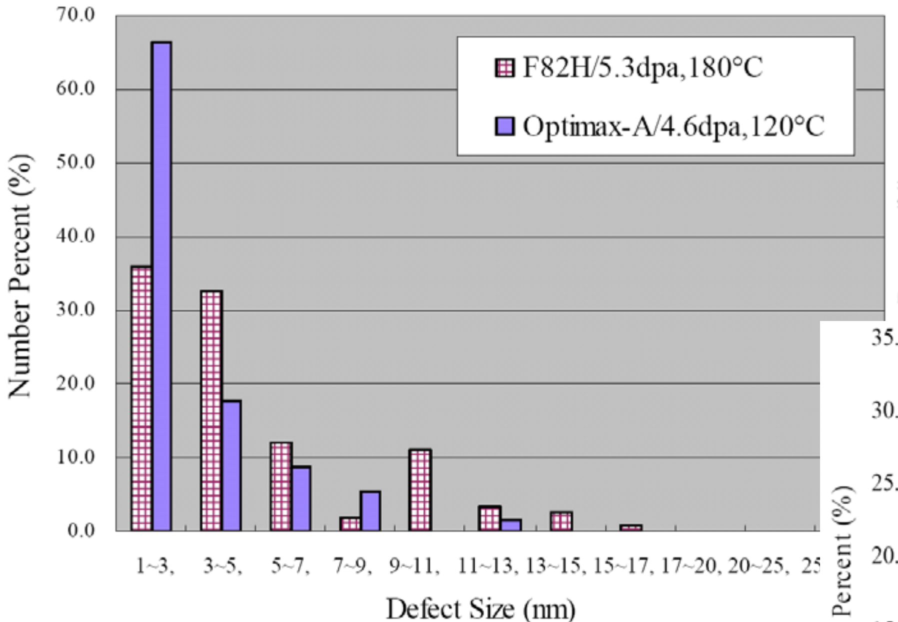
le at R.T.

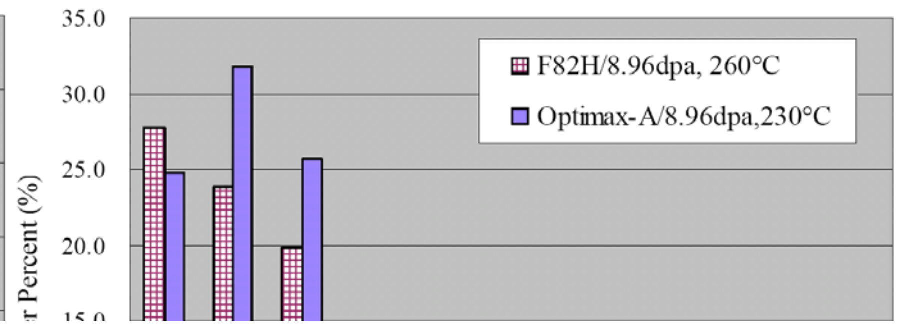
600°C/2h annealing 600°C/2h annealing

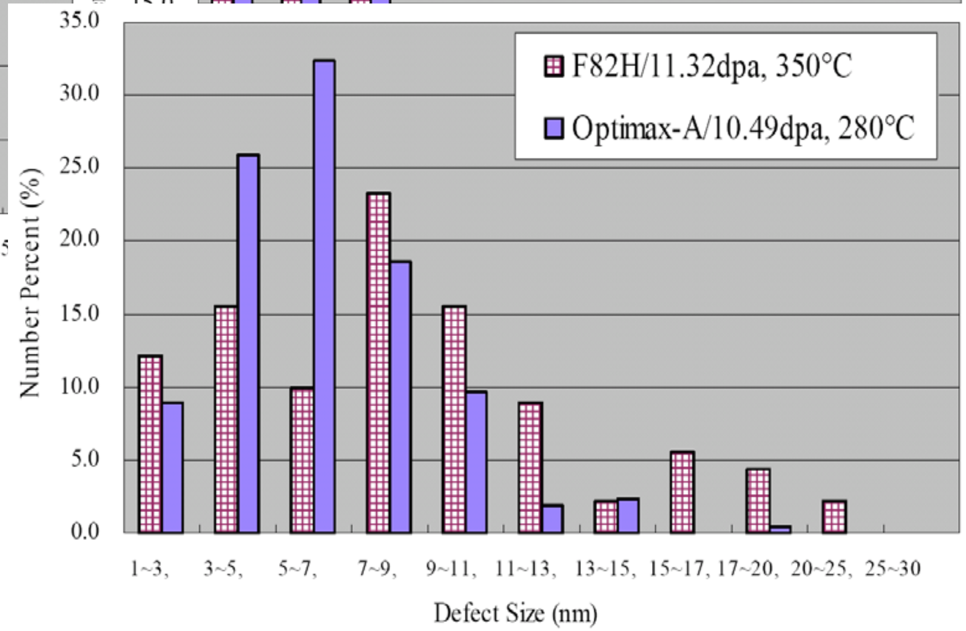
Discussion

Discussion

Defects with irradiation temperature





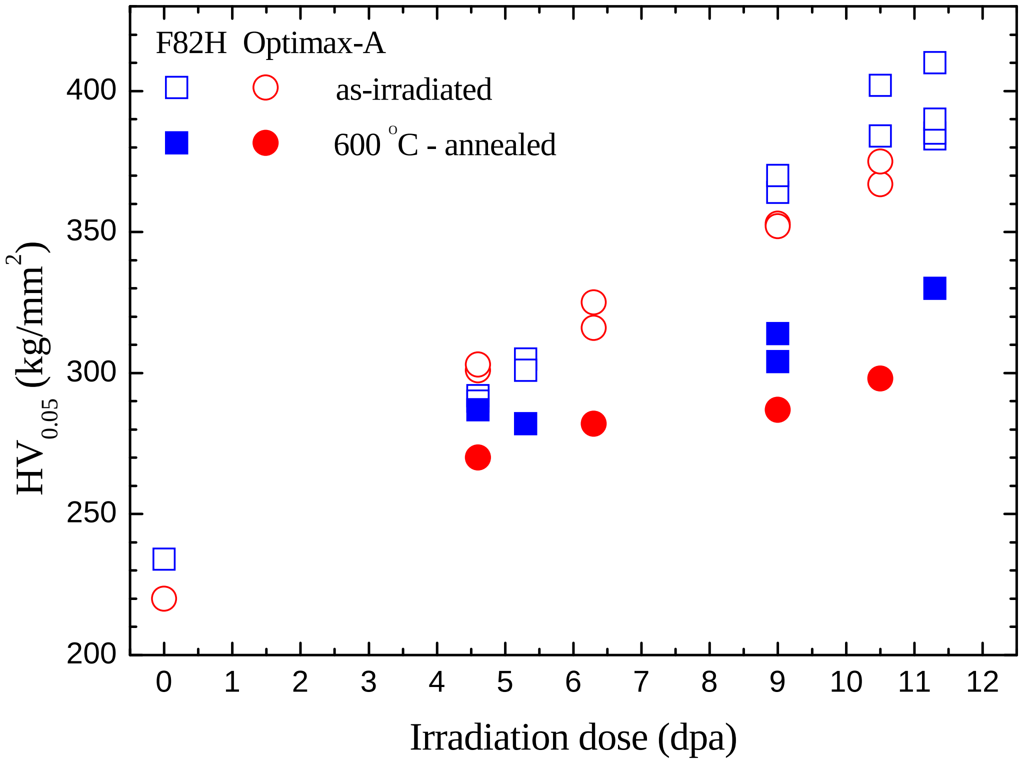


Defects after STIP irradiation

Mean size of F82H is lager than that of Optimax-A. Probable reason is the irradiation temperature of F82H was higher than that of Optimax-A.

Discussion

Defects with irradiation dose



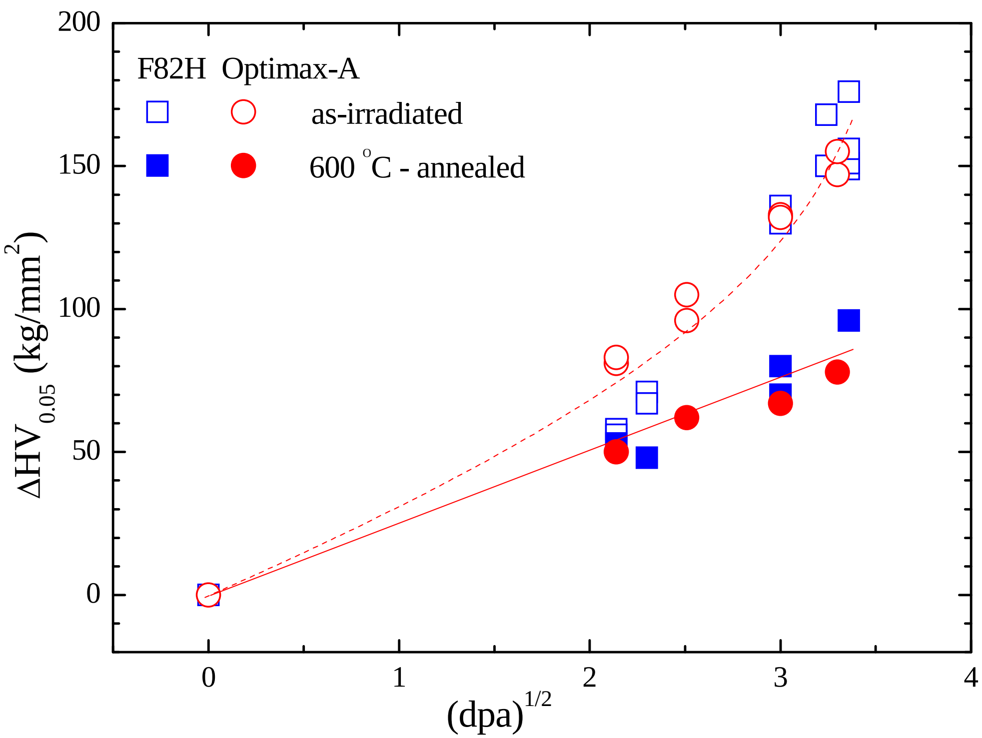
Micro-hardness of F82H and Optimax-A after STIP irradiation

Microhardness increased with irradiation dose before and after annealing.

Good linearly relationship before annealing.

Discussion

Helium effects on hardening



Micro-hardness of F82H and Optimax-A after STIP irradiation

$$\Delta\sigma = 2.7\ \Delta Hv$$

$$\Delta\sigma = 3.06\ \Delta\tau_s$$

$$\Delta\tau_s = \alpha G b (Nd)^{1/2}$$

$$\alpha = \sim 0.1$$

G: Shear modulus, 80 Gpa

b: Burgers vectors, 2.49 Å

Barrier strength (α) of helium bubbles with sizes 1~1.5 nm is about 0.1.

Conclusions

Conclusions

The present results of FM steels irradiated in STIP show that:

1) There is a good linear correlation between micro-hardness and irradiation dose (4.6~11.3 dpa) before annealing.
2) Hardening in the as-irradiated specimens can be attributed to the combined contribution of defect clusters and bubbles. 600° C/2h annealing can mostly anneal out the irradiation induced defects.
3) Although the small helium bubbles are week obstacles, significant hardening can still be produced because of their very high density, 10^{23} ~10^{24} m^{-3}. Preliminary evaluations indicate that the barrier strength of helium bubbles with sizes 1 ~1.5 nm is about 0.1.

Thank you for attention!