The effect of displacement damage and helium bubble on Eurofer97 steel tensile property

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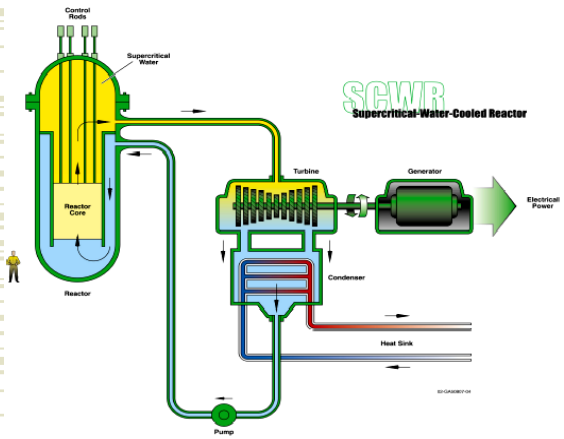
Outline

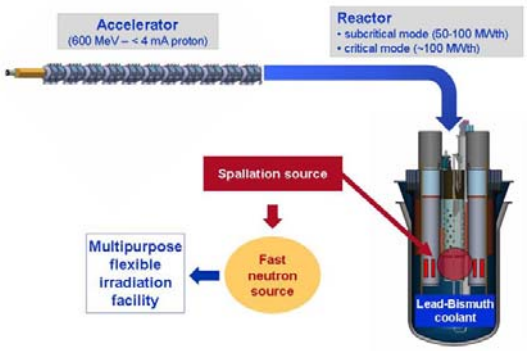
- Introduction
- Material and experiment methods
- Results
- Discussion
- Conclusion

Introduction

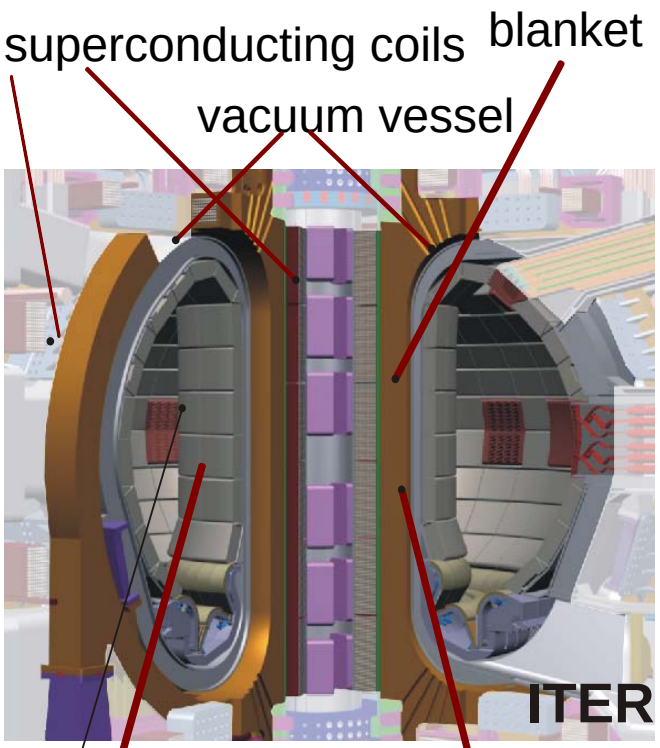
RAFM steels are candidate materials for structural application in advanced nuclear energy systems



Gen IV



ADS



Cladding tubes in advanced nuclear fission reactors (Gen IV, such as Liquid Metal Fast Breeder Reactors and Super Critical Pressurized Water Reactors) ;

Blanket and divertor in fusion reactor.

Introduction

ADVANCED NUCLEAR SYSTEMS

	GFR	SFR	LFR & ADS	VHTR Thermal neutrons	SCWR Thermal neutrons	Fusion	
Coolant	He, 70 bar 480-850°C	Na, few bar 390-600°C	Lead alloys	He, 70 bar 600-1000°C	SC H_2O, 250bar, 280-500°C	He, 80bar 300-480°C	Pb 17Li, 1bar 480-700°C
Fuel	(UPu)C / O2 in plates of pins in hexagonal subassemblies	(UPu)O2 in pins in hexagonal subassemblies	Various concepts	Coated particles (SiC or ZrC) in a graphite matrix	UO_2 enriched	Dual coolant blanket	
Core structures	SiC-SiCf composite or ODS (backup)	Cladding: ODS Wrapper: 9Cr Mart.Steel	Cladding: 9Cr Mart.Steel, ODS Wrapper: 9Cr Mart.Steel	Graphite Composites C/C, SiC/SiC for control rods	Cladd. Aust Steel (Ni alloys?)	9Cr Mart.Steel, ODS SiCf-SiC	
Temperature	500-1200°C	390-750°C	350-480°C	600-1600°C	280-750°C	Up to 650°C	
Dose	60-90dpa	up to 200dpa	100dpa	7-25dpa	Several 10 dpa	100dpa + He	
Other structures Out of core	vessel & core struct: 9-12Cr Steels 350-500°C <<1dpa	prim/sec/steam circ.: 9-12Cr Steels 390-600°C	ADS target: 9Cr Mart.Steel 350-550°C 100dpa+He+H	N.A.	N.A.	N.A.	

Material&Experiment Methods

25 mm thick plate

Element	Cr	Ni	Mo	Mn	Ti	V	Nb	W
Eurofer97	8.93	0.022	0.0015	0.47	0.009	0.20	0.002	1.07
Element	Ta	Cu	C	Si	P	S	B	N
Eurofer97	0.14	0.003	0.12	0.06	＜0.005	0.004	＜0.001	0.018

The heat number was E83697.

The steel was normalized at 980 ^{o}C for 27 min followed by air cooling,

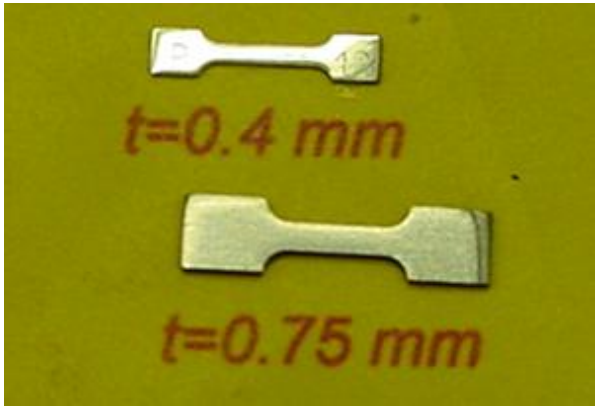
Tempered at 760 ^{o}C for 1.5 h and followed by air cooling.

Mean grain size: 16 ± 2 μm

Size effect on tensile properties

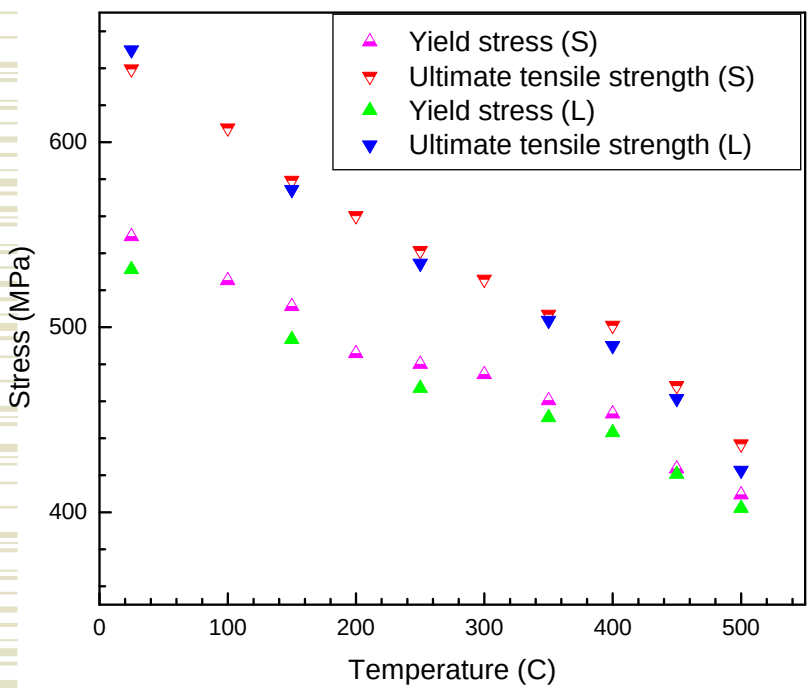
- Two kinds of specimen were selected for tensile test

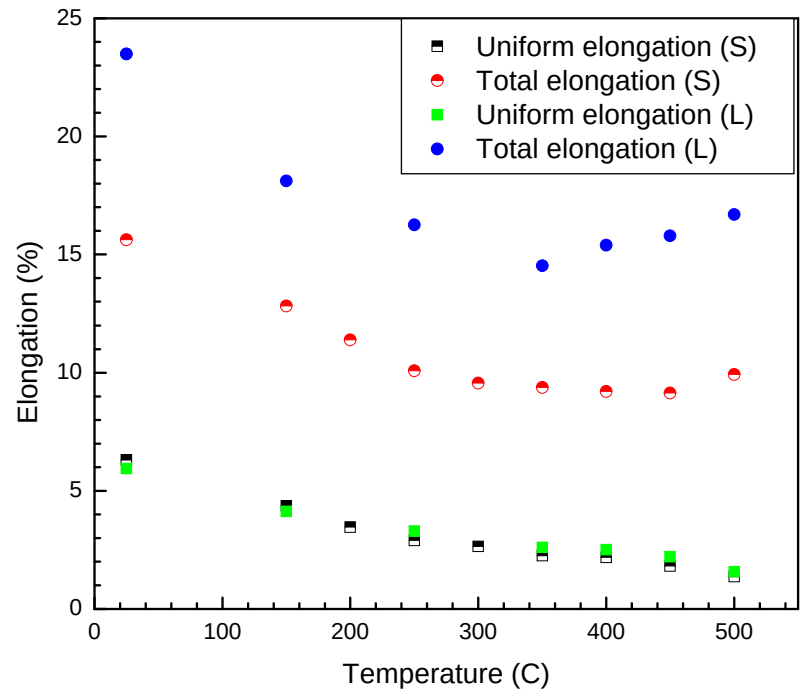
The small sample with 0.4 mm thickness
The large sample with 0.75mm thickness
Both of them have a 5mm gauge length



Material&Experiment Methods

Tensile results comparison between small sample and Large sample

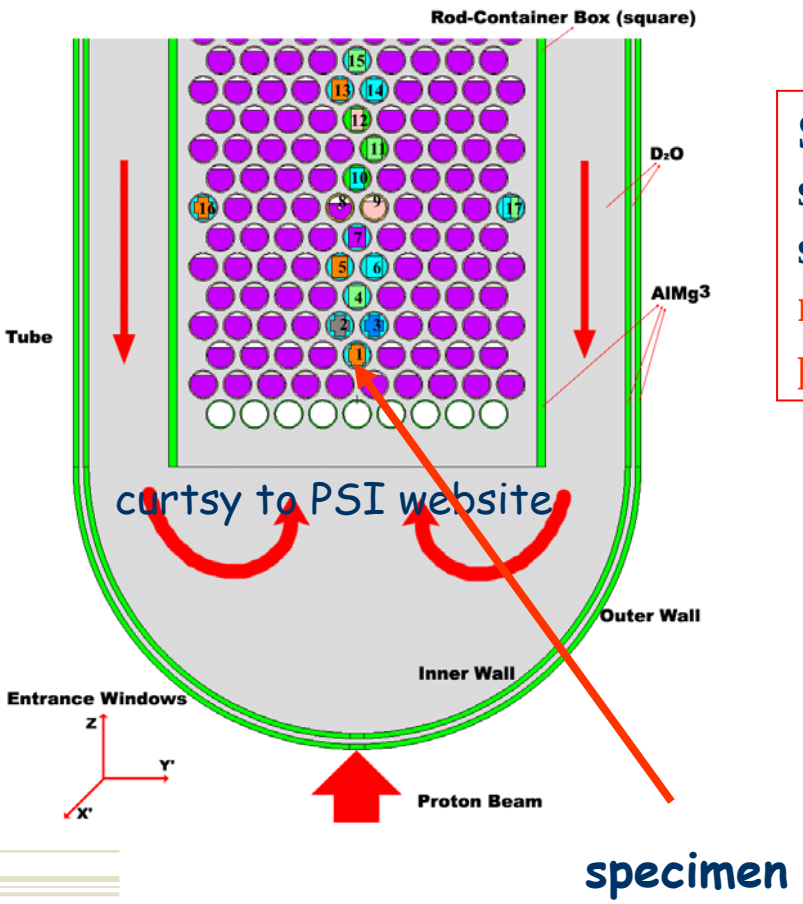


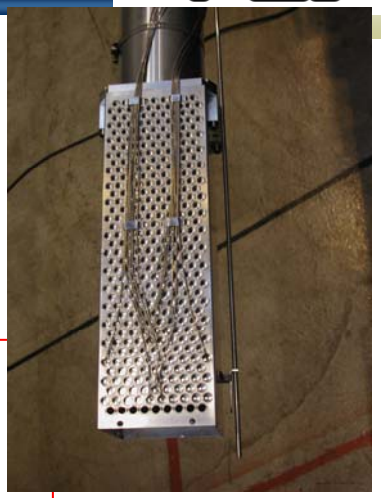


Eurofer 97

Material&Experiment Methods

Irradiations at SINQ (STIPs)





STIP program is aiming at studying radiation damage in structural materials under a mixed spectrum of high-energy protons plus spallation neutrons.

Irradiation parameters:

- beam energy: ~ 570MeV
- irradiation temperature: 100 – 550 °C
- irradiation dose: max. 20 dpa
- He concentration: max. 1750 appm

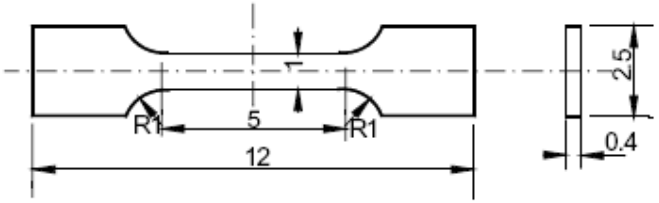
Material&Experiment Methods

Tensile test of STIP III specimens

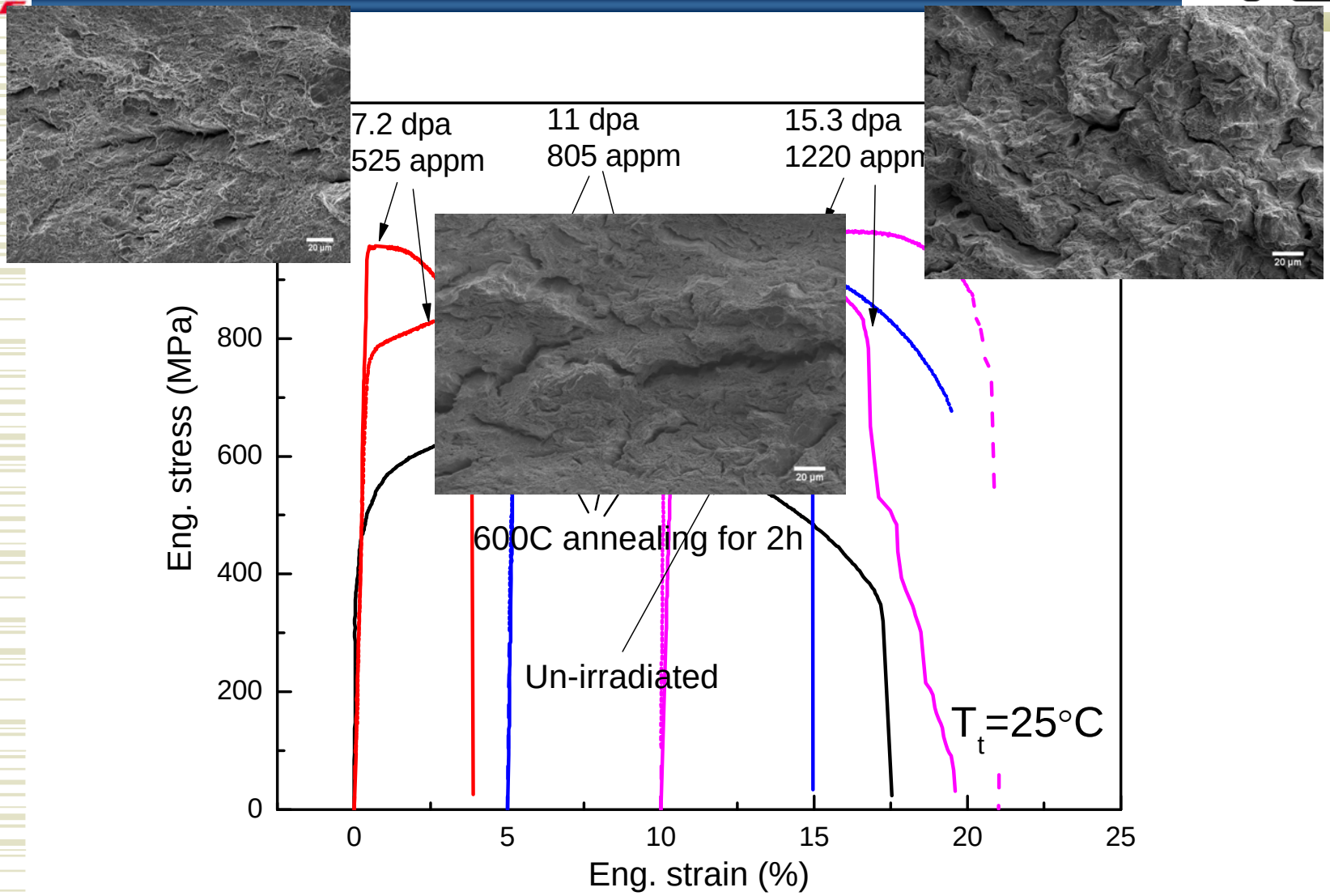
- Materials: Eurofer 97 steel

  Tensile rate: 0.3mm/m
- Irradiation dose: 7-20 dpa

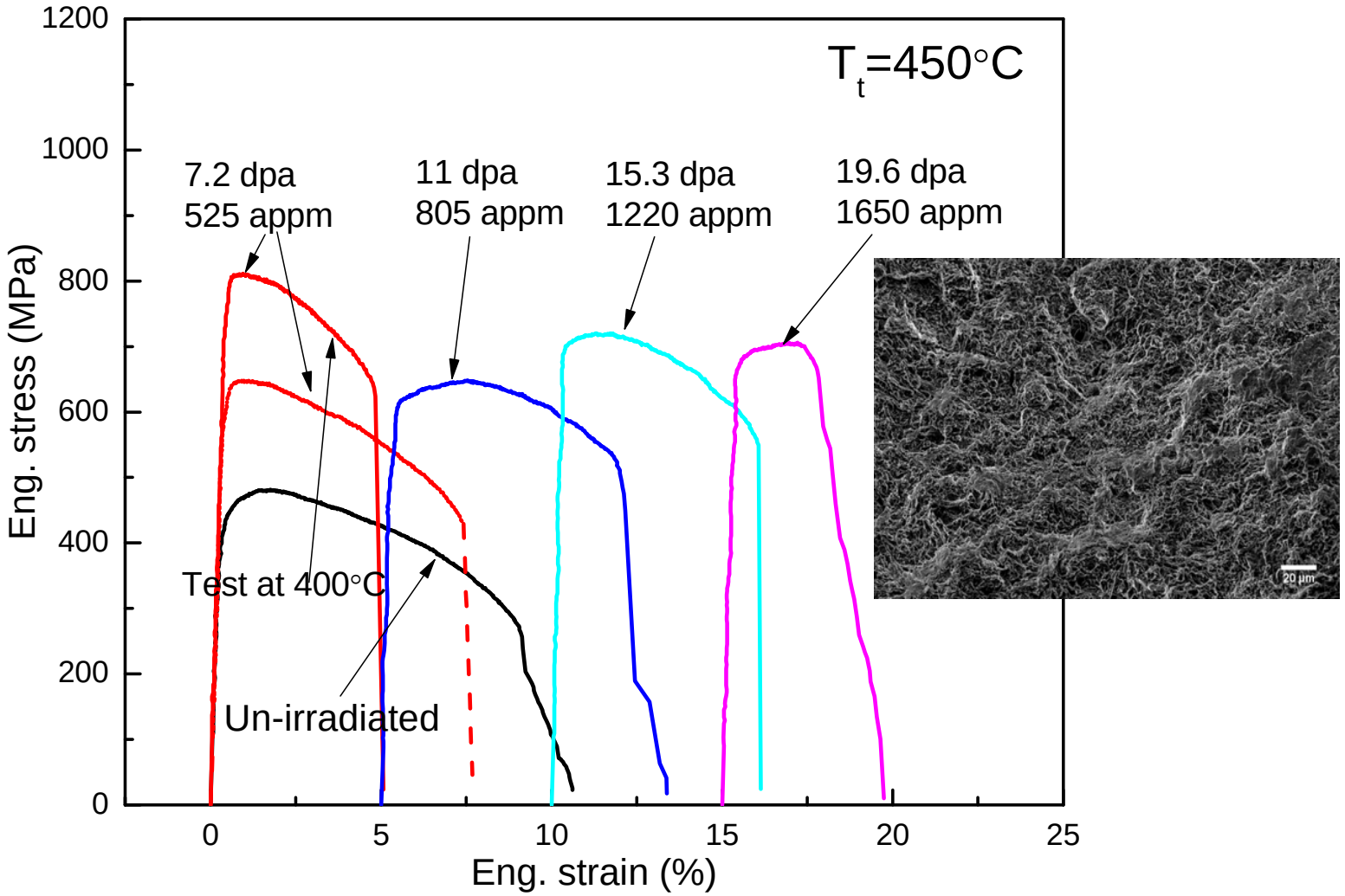
  Test temperature: 25-450^{0}C
- He concentration: 520-1700 appm
- Irradiation temperature:200-510^{0}C
- Specimen dimension:



Results —Tensile test (RT)



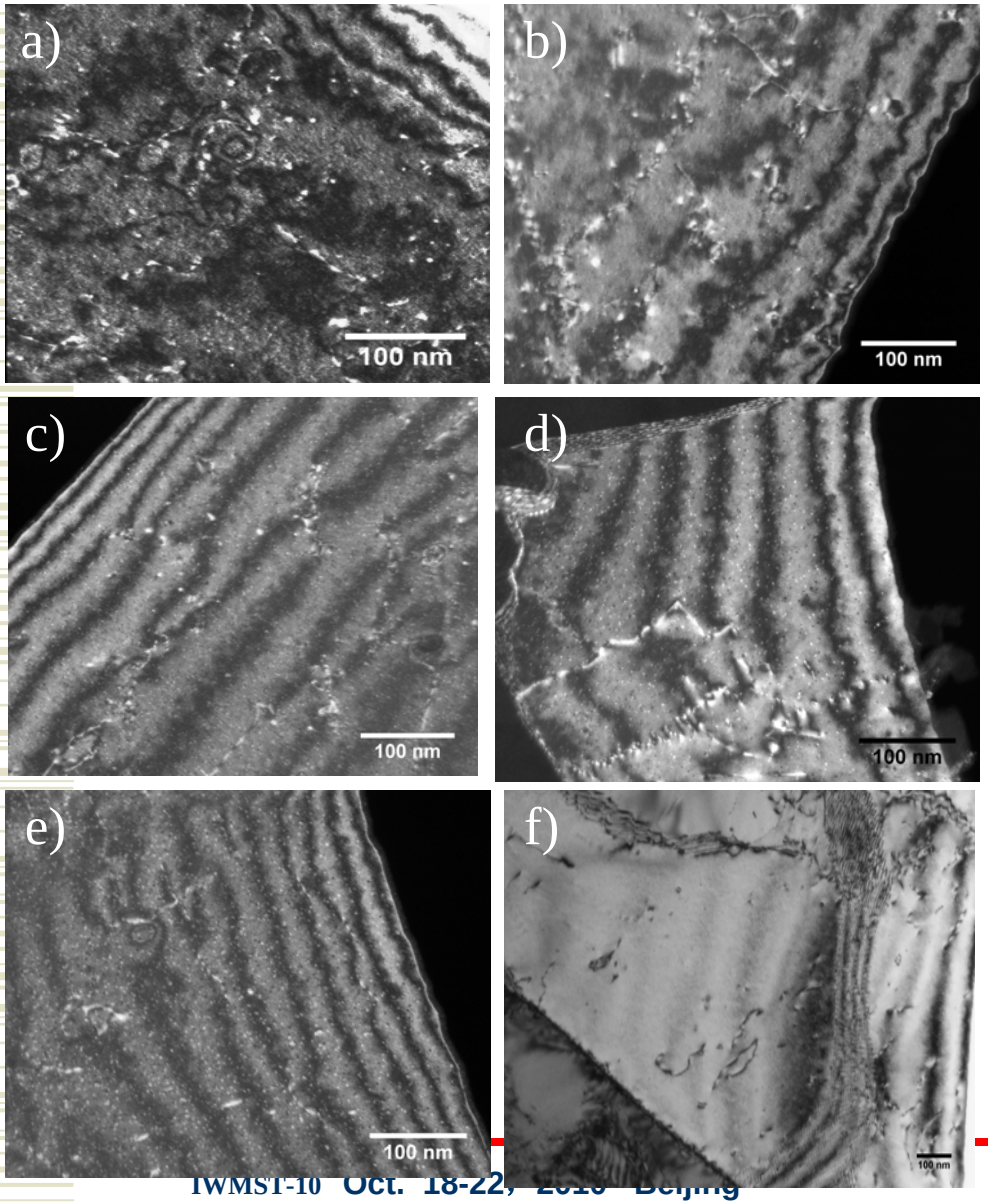
Results —Tensile test (HT)

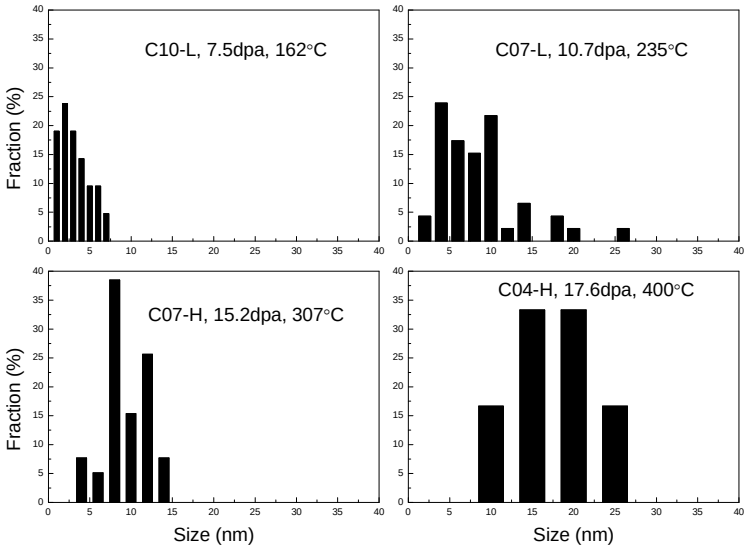


Tensile Test Results

Sample No.	$T_{irrad.}$ (ºC)	Dose (Dpa)	He (appm)	$T_{Ann.}$ (ºC)	T_{test} (ºC)	YS (MPa)	US (MPa)	UE (%)	TE (%)
C10	240	7.2	525	----	25	954	956	1.16	3.82
C22	250	7.2	525	600	25	776	868	7.27	14.33
C07	415	11	805	----	25	830.2	961.6	4.45	9.95
C09	415	11	805	600	25	825.4	937.8	7.79	14.53
C05	695	15.3	1220	----	25	816.6	887.2	4.91	6.77
C04	615	15.3	1220	600	25	904.7	981.7	6.15	10.28
C12	240	7.2	525	----	400	804.9	809.4	0.91	4.83
C11	265	7.2	525	----	450	636.9	646.8	0.99	7.42
C19	445	11	805	----	450	619.8	646.8	2.52	7
C18	660	15.3	1220	----	450	706.2	718.8	1.73	6.07
C15	805	19.6	1650	----	450	681.4	705.5	1.96	2.78

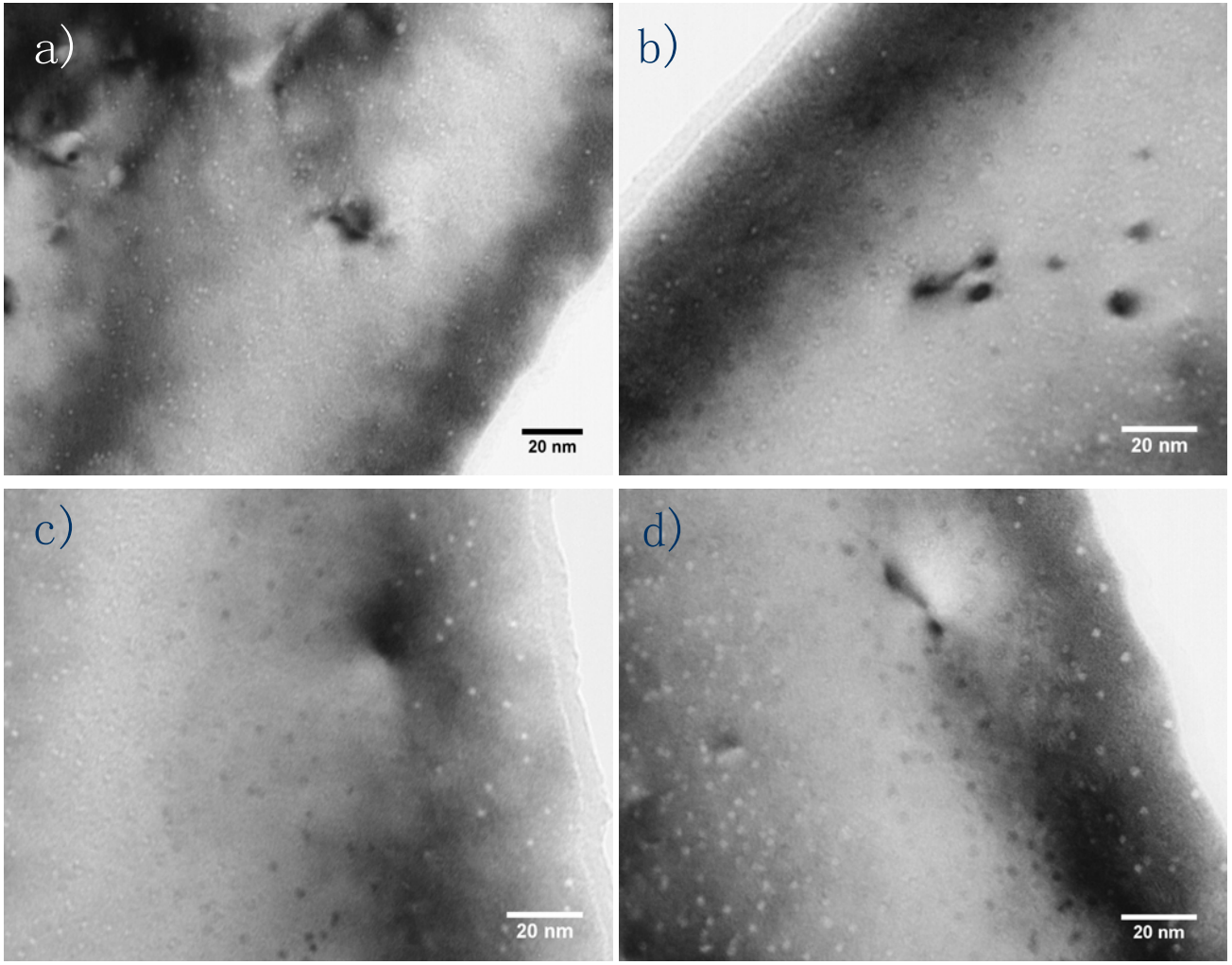
Microstructure Results —Defect Clusters





a) 7.5dpa/162° C, b） 10.7dpa/235° C, c)15.2 dpa/307° C, d) 17.6dpa/400° C, e） 20.4dpa/511 ° C, f) BF 20.4 dpa /511° C， ×40000

Microstructure Results —Helium Bubble

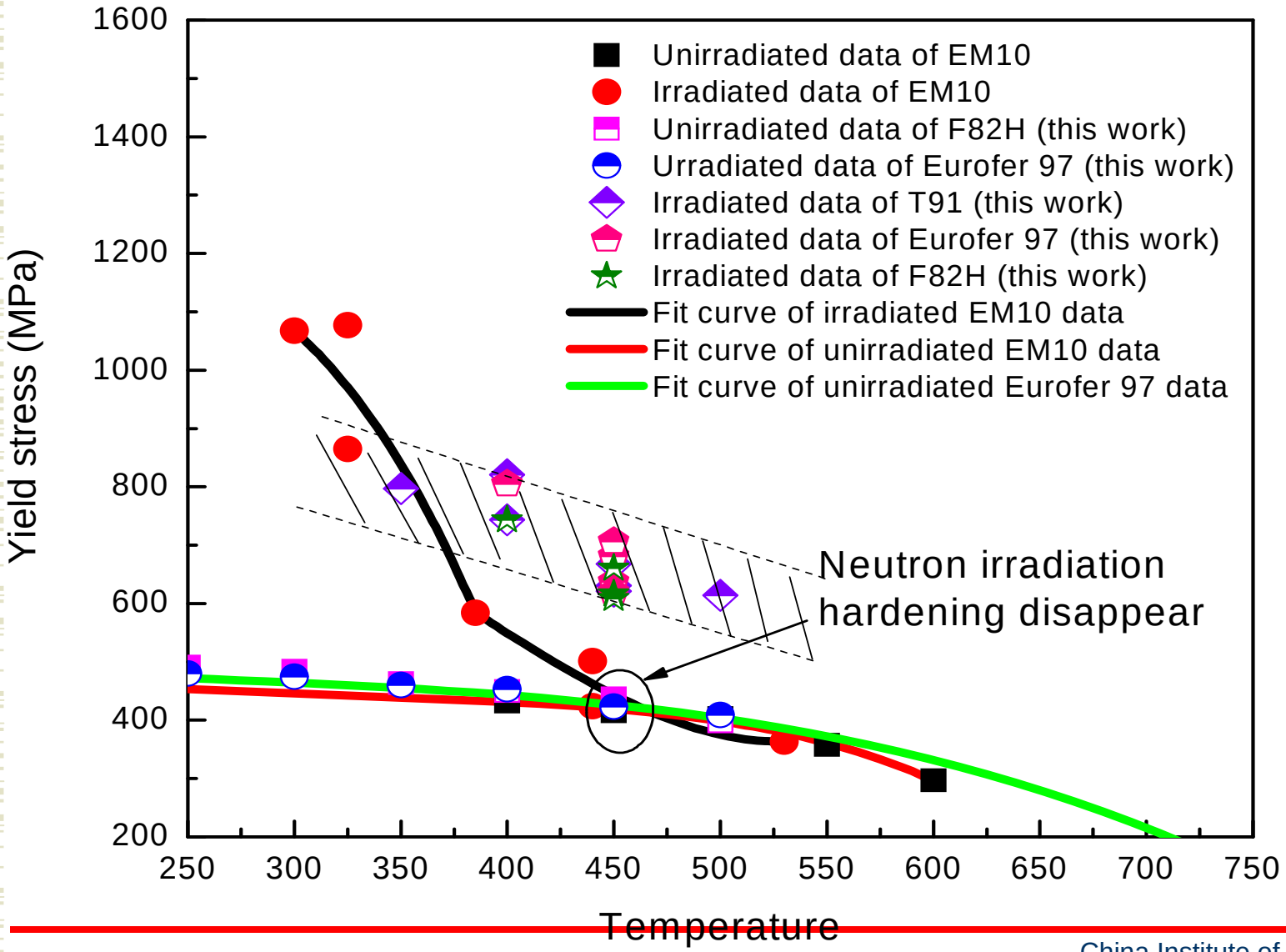


Eurofer 97 TEM Photos for helium bubble, a) 9.6dpa, b) 12.6dpa, c)17.3dpa, d)20.4dpa

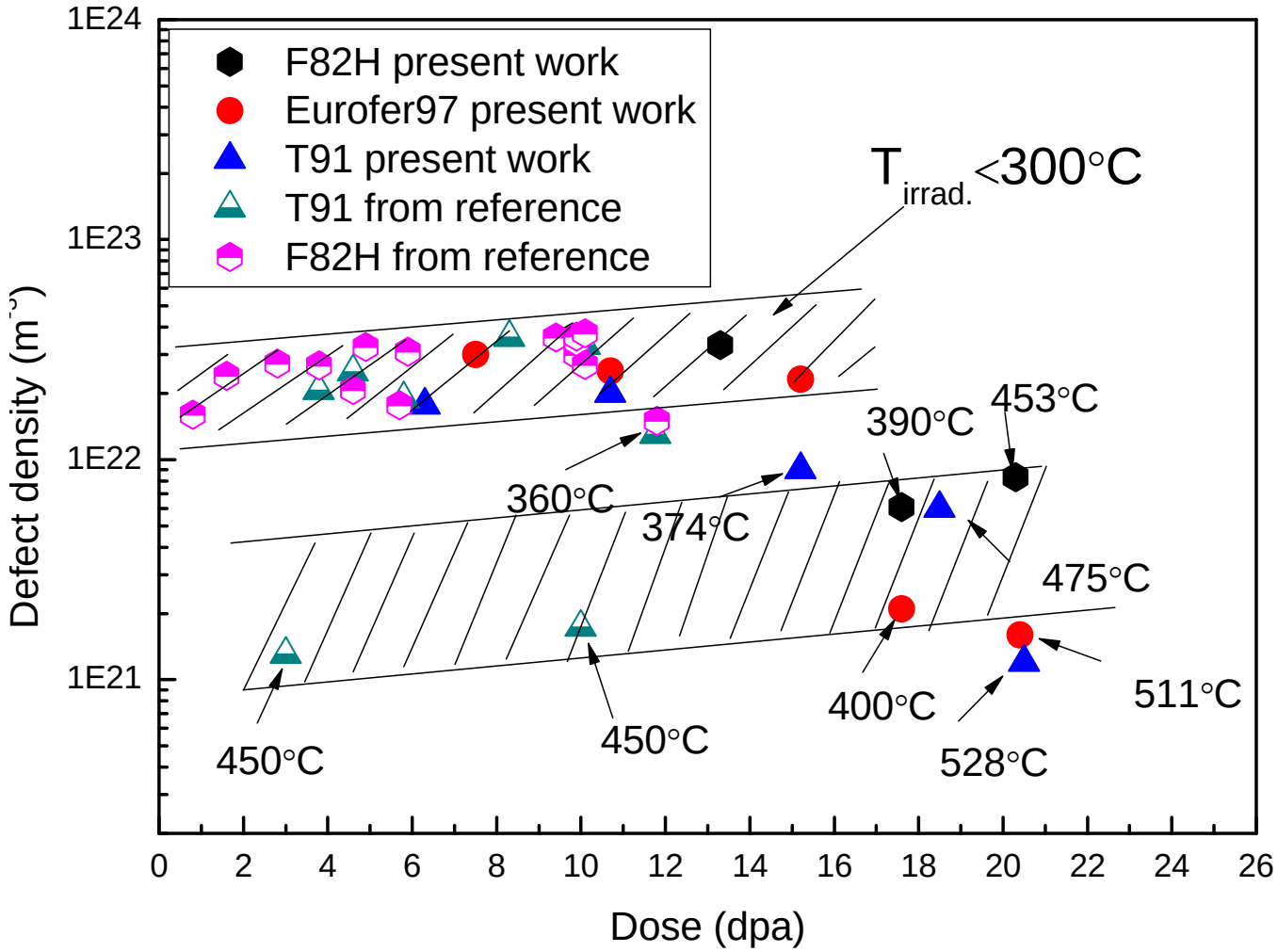
Microstructure Results

Materials	Sample No.	Tirrad (°C)	Dose (dpa)	He (appm)	Bubble size (nm)	Bubble density ($10^{23}/m^3$)	Cluster size (nm)	Cluster density ($10^{22}/m^3$)
F82H	D01L	153	6.3	410	—	—	—	—
	D04L	213	9.8	705	1.27	6.23	7.27	3.59
	D04H	294	13.3	1020	1.28	8.45	13.58	1.31
	D09H	390	17.6	1445	1.78	6.43	14.4	0.61
	D12H	453	20.3	1725	2.3	5.14	12.29	0.83
Eurofer97	C10L	162	7.5	505	—	—	7.5	3
	C07L	235	10.7	785	1.17	2.86	7.19	2.53
	C07H	307	15.2	1195	1.58	6.12	8.04	2.32
	C04H	400	17.6	1445	1.85	5.0	15	0.21
	C15H	511	20.4	1740	2.49	4.6	17.3	0.16

Discussion—Irradiation Hardening

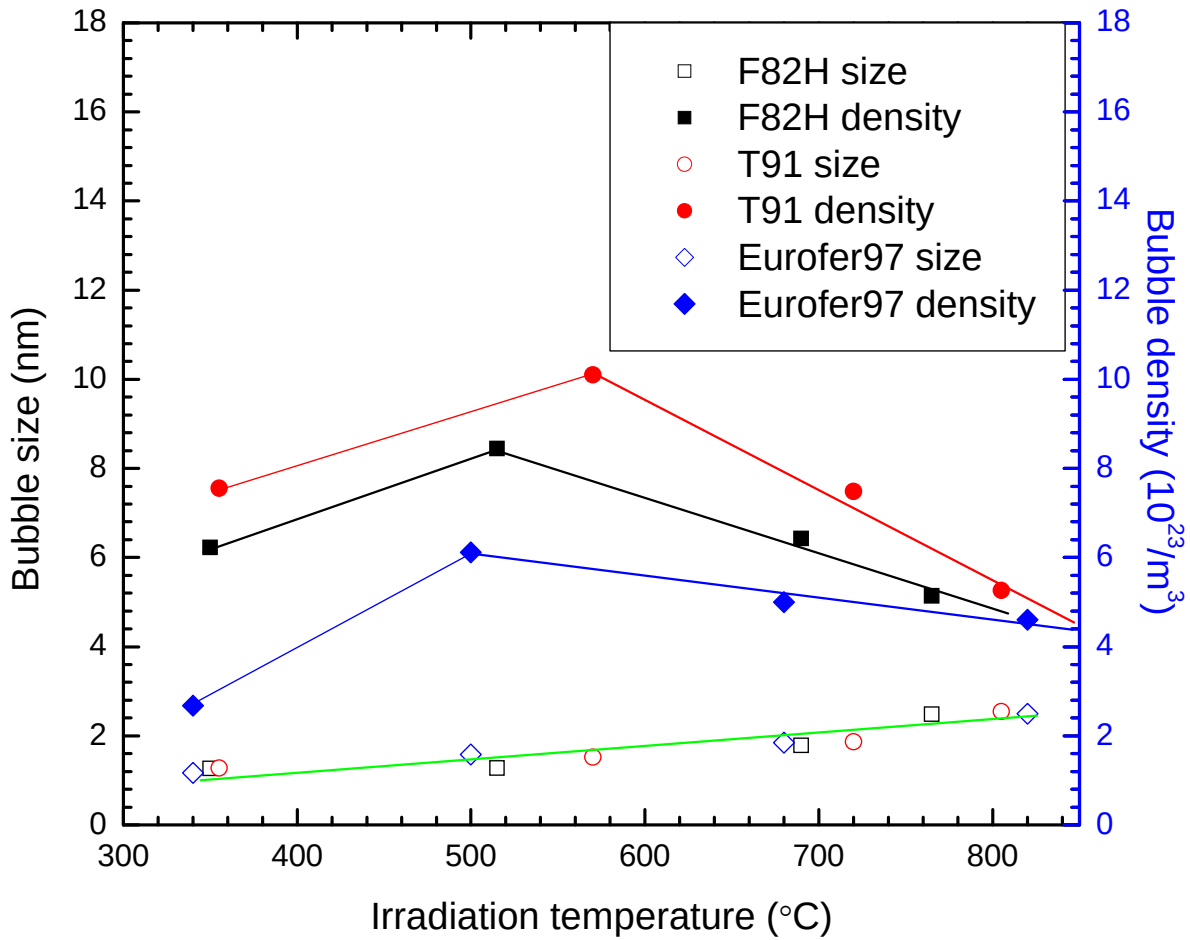


Discussion—Defect clusters



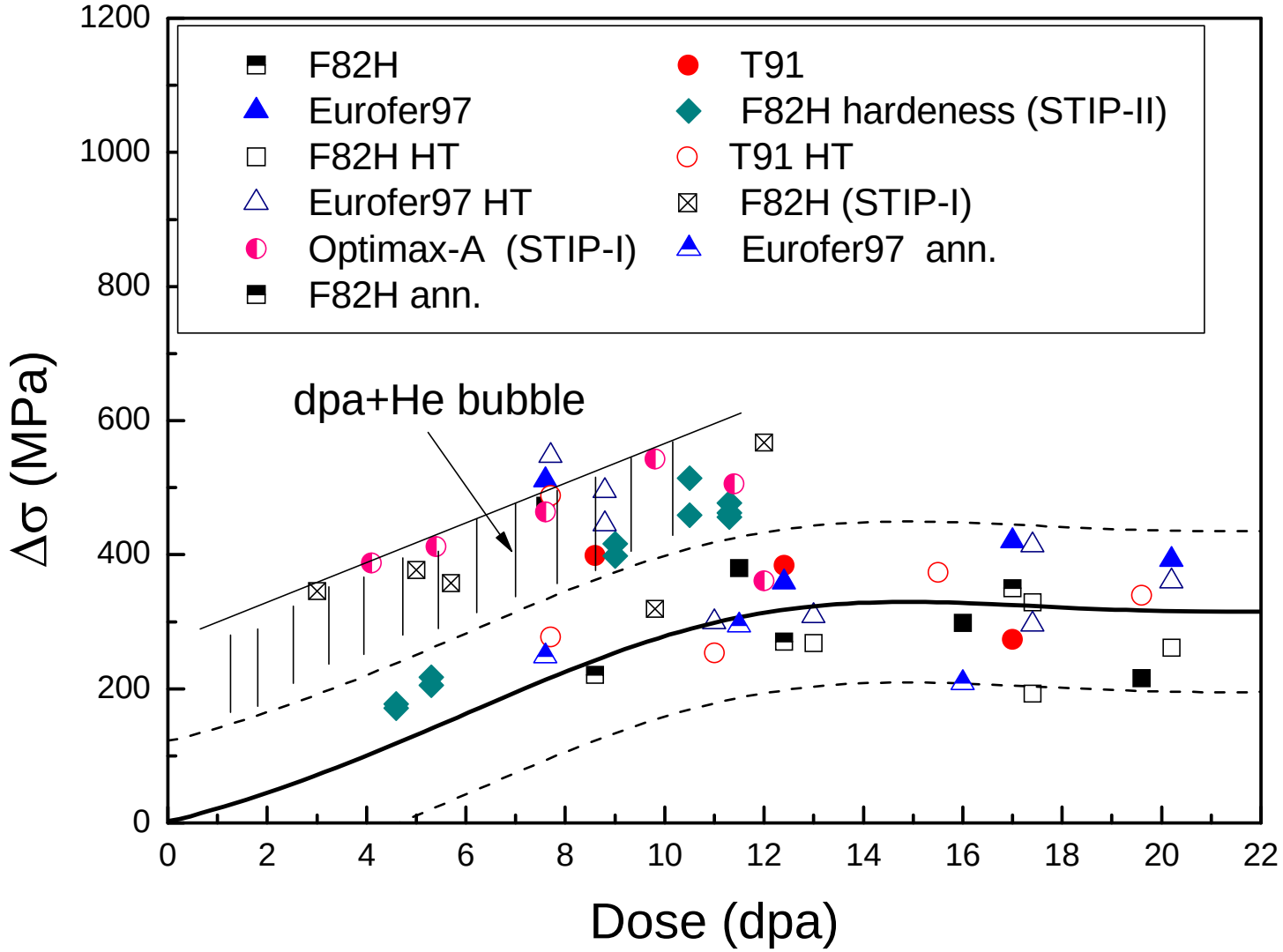
Reference: X. Jia, Y. Dai / Journal of Nuclear Materials 318 (2003) 207－214

Discussion—Helium bubble



Helium bubble calculation in ferritic martensitic steels

Discussion—Irradiation effect



Conclusion

Eurofer 97 steel was irradiated in STIP-III to doses between 6.5 and 20.4 dpa at temperatures ranging from ~120 to ~510°C. Tensile tests were conducted at 25, 400 and 450°C. TEM observations were performed on 1 mm discs punched from the grip sections of the tensile specimens tested at 25°C. The main conclusions drawn from the results are as the following:

(i) Radiation-induced defect clusters and small dislocation loops were observed in specimens irradiated to lower doses at lower temperatures. In specimens irradiated at higher temperatures > ~400°C, much less clusters or loops were observed. He-bubbles were seen in specimens irradiated to ⩾ 9.5 dpa / 680 appm He at ⩾ 260°C. But the size of the bubbles did not increase so much with increasing irradiation dose as observed in the previous work, which should be attributed to the high-density bubbles nucleated at low temperatures during the first irradiation period.

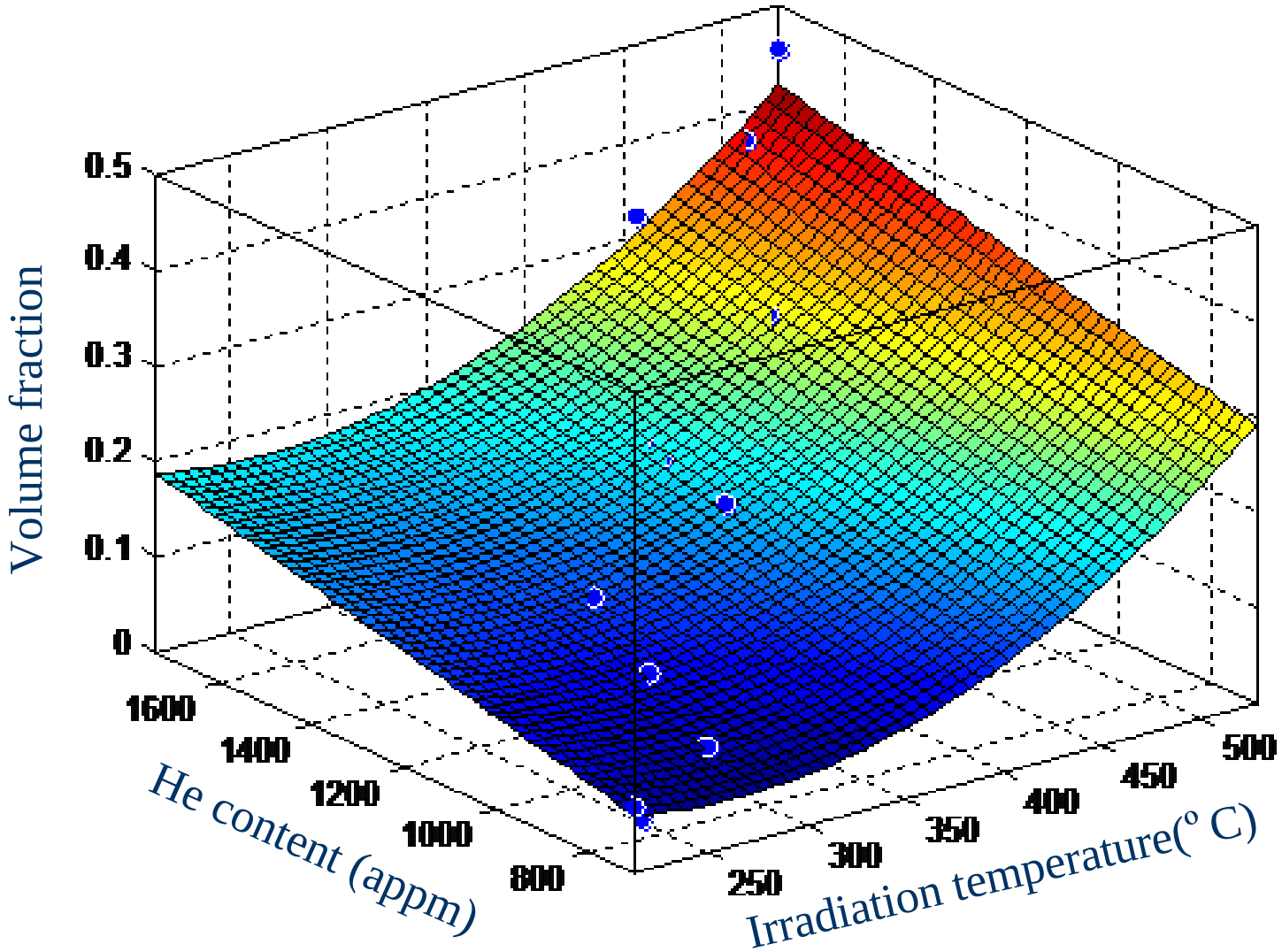
Conclusion

(ii) Not only the specimens irradiated at lower temperatures < ~350°C, but also those irradiated at higher temperatures above > 400°C show significant hardening effect. The hardening observed in these specimens should be attributed to the hardening effect of He bubbles.

(iii) The three FM steels show great similarity in tensile properties under similar irradiation and testing conditions, except for the brittle fracture observed from two F82H specimens of 17.4 and 20.2 dpa tested at 25°C, which was not detected for the T91 and Eurofer 97 steels.

Thanks for Your attention!

Helium Bubble Volume Fraction



Introduction

中国原子能科学研究院

PAUL SCHERRER INSTITUT

Generation I

Prototype Reactor

Generation II

Commerical Power Reactor

Generation III

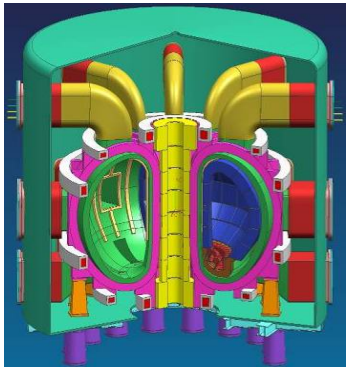
Advanced Power Reactor

Generation IV

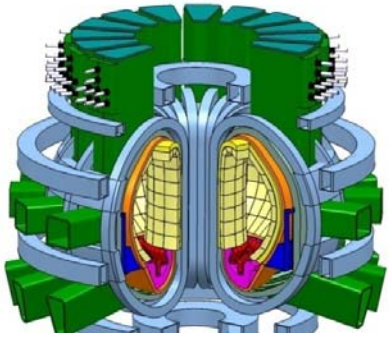
SCWR,VHTR,MSR
SFR,LFR,GFR

1985

Fission reactor



Fusion reactor



DEMO & Prototype