Meeting on Structural Materials for Heavy Liquid Metal Cooled Fast Reactors
IAEA Headquarters

Overview of materials research for LFR in China

—— R & D of SIMP steel for LFR

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Oct. 15-17, 2019, VIC, Vienna, AUSTRIA

Outline

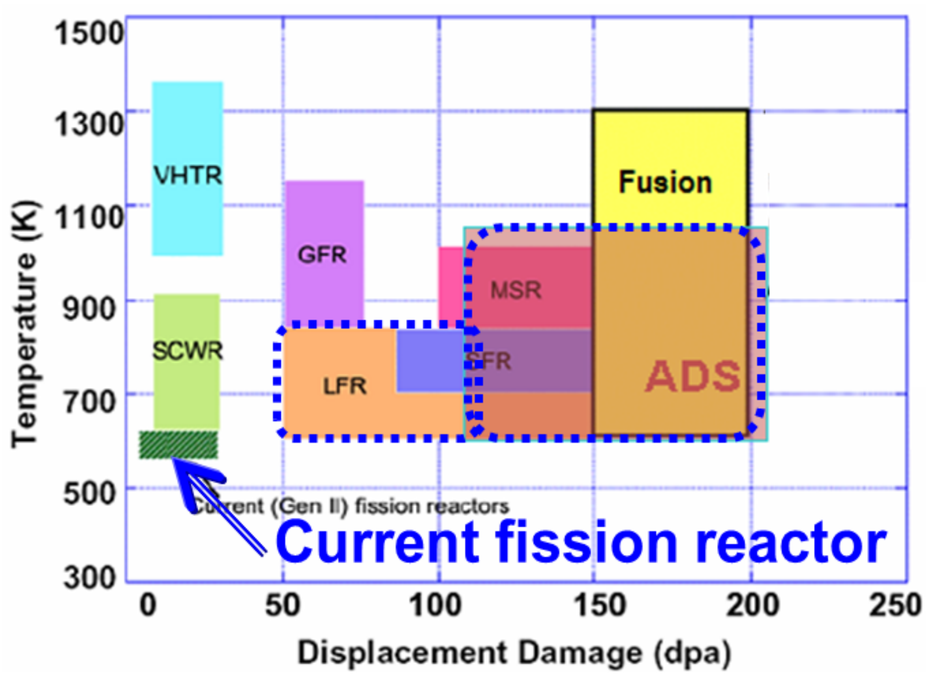
1. Motivation

2. R & D of SIMP steel

3. Summary & Future works

Motivation

LFR — One of advanced nuclear energy systems



LFR — advantages:

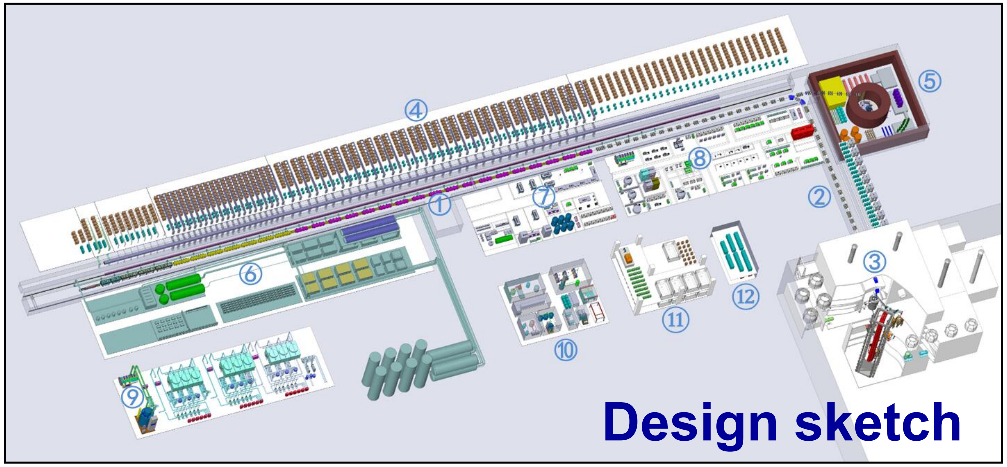
- **Sustainability**
- **safety**
- **Economy**

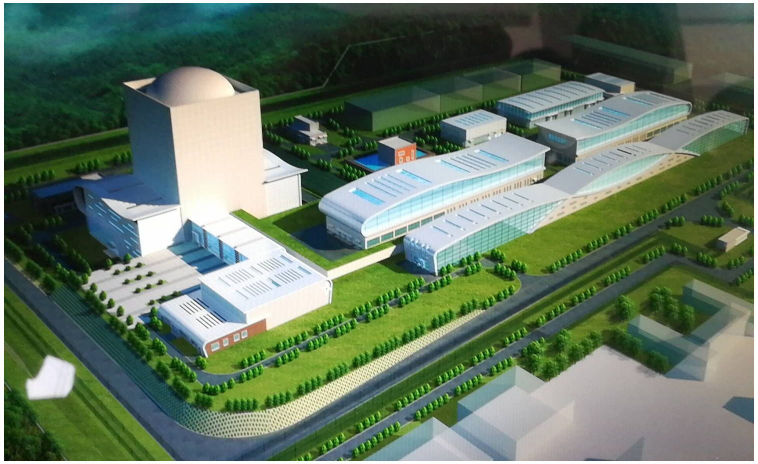
Plans ——
SVBR-100 and BREST in Russia
ELSY, ALFRED, MYRRHA in Europe
SSTAR in USA
……

China —— Small module lead cooled reactors,
CiADS (China inititave Accelerator Driven System), …

Motivation

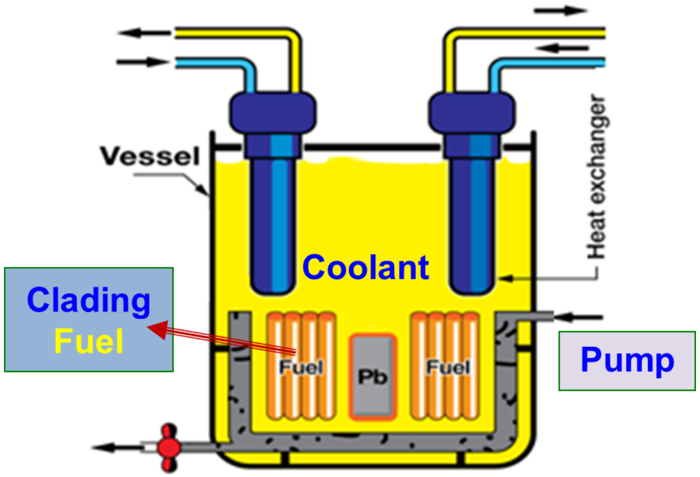
CiADS (China initiative Accelerator Driven System)

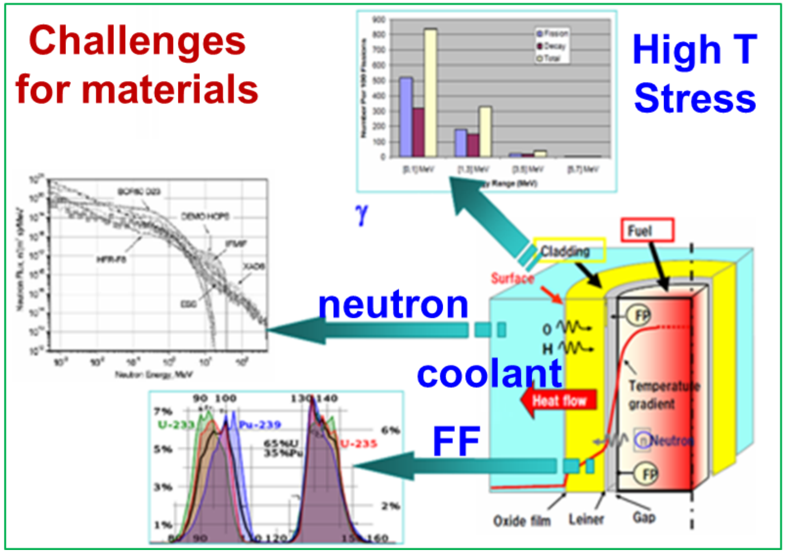




Motivation

Materials serve in extreme conditions

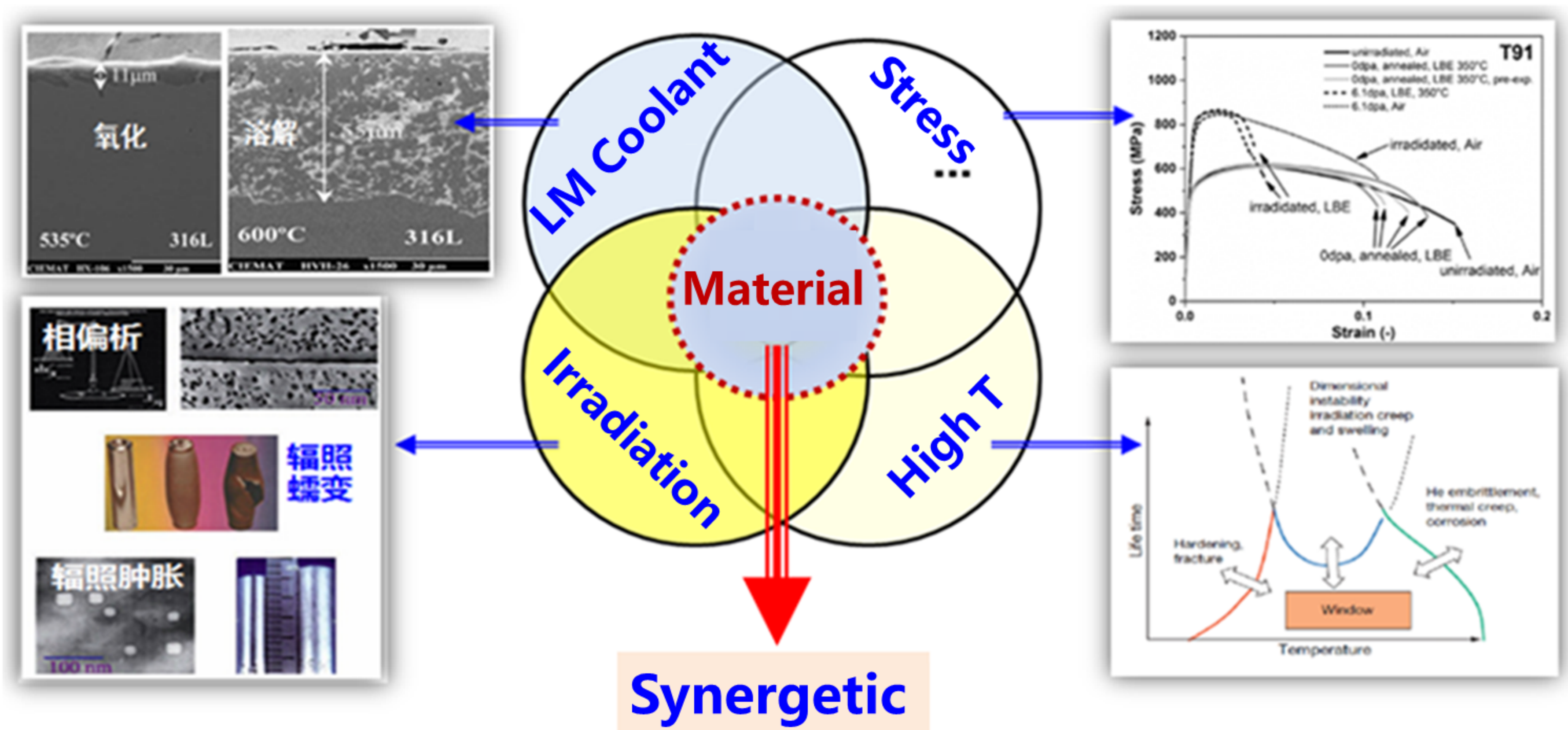




	Thermal neutron fission reactor	Fast reactor	Fusion reactor	ADS
Temperature (° C)	300 - 900	350 - 600	300 - 600	300-800
Damage rate (dpa/year)	Up to 2	20	20 - 30	100
Yield of He (appm/dpa)	Up to 10*	~ 0.2	10 - 15	~100

Motivation

Material — Bottleneck for R&D of LFR



Motivation

Candidate materials for R&D of LFR

Design parameter	MYRRHA	EFIT	ELFR(ELSY)	ALFRED	BREST-OD-300	SVBR-100	SSTAR	DLFR	JAEA's reference ADS
Developer	SCK •CEN	EURATOM	EURATOM	EURATOM	NIKIET (Russia)	AKME (Russia)	DOE National laboratories	Westinghouse	JAEA
Power ,MWt/MWe）	110/	400/	1500/600	300/	700/300	280/100	45/20	500/210	800/
Primary system type	Pool	Pool	Pool	Pool	Pool	Pool	Pool	Pool	Pool
Fuel	$(U\text{-}Pu)O_2$ MOX	U-free Pu+MA	$(U\text{-}Pu)O_2$ MOX	MOX	(U +Pu+MA)N	UO2, mixed oxide, UPuN	TRU Nitride-N15 enriched	UO_2	(Pu+MA)N+ZrN
Coolant	LBE	Pb	Pb	Pb	Pb	LBE	Pb	Pb	LBE
Inlet/outlet (^{0}C)	270/400	400/480	400/480	400/480	420/540	340/490	420/567	390/510	300/410
Cladding	15-15Ti/T91	T91	T91, Fe-Al coated	15-15Ti	FM	EP823	Si-enhanced FM steel	D9 coated with Al_2O_3	First :T91 or F82H Second: 316 or JPCA
Wrapper	T91	T91	T91	15-15Ti/T91 Aluminized				D9	First :T91 or F82H Second: 316 or JPCA
Steam generators	T91	T91	T91	T91/316L	EP302-M			316L/347, possibly coated	
Primary Pump	MAXTHAL,316L	MAXTHAL $(Ti_3SiC_2)_3$	MAXTHAL ,316L	Al, Ta coated T91, 316L, MAXTHAL			Nat. circulation	Ti_3SiC_2 coated AISI 400 series	
Reactor Vessel	316L	316L,Al coated	316L	316L				316(L)	First :T91 or F82H Second: 316 or JPCA

Motivation

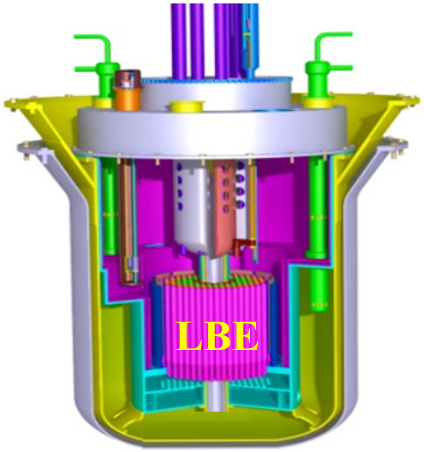
◆ R&D of new structural material (for future ADS)

Properties: Significant tolerance to high-T, dpa, LBE

Analysis
Design
Fabrication
Processing
Evaluation

→

Structural material for LFR — Pb/LBE Coolant



Status

- The existing reactor materials cannot be directly used as LFR and ADS structure materials.
- Material / LBE compatibility data is limited.
- Synergetic effect of irradiation/LBE/high-T is lack of study.

Outline

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R & D of SIMP steel

Collaboration ——

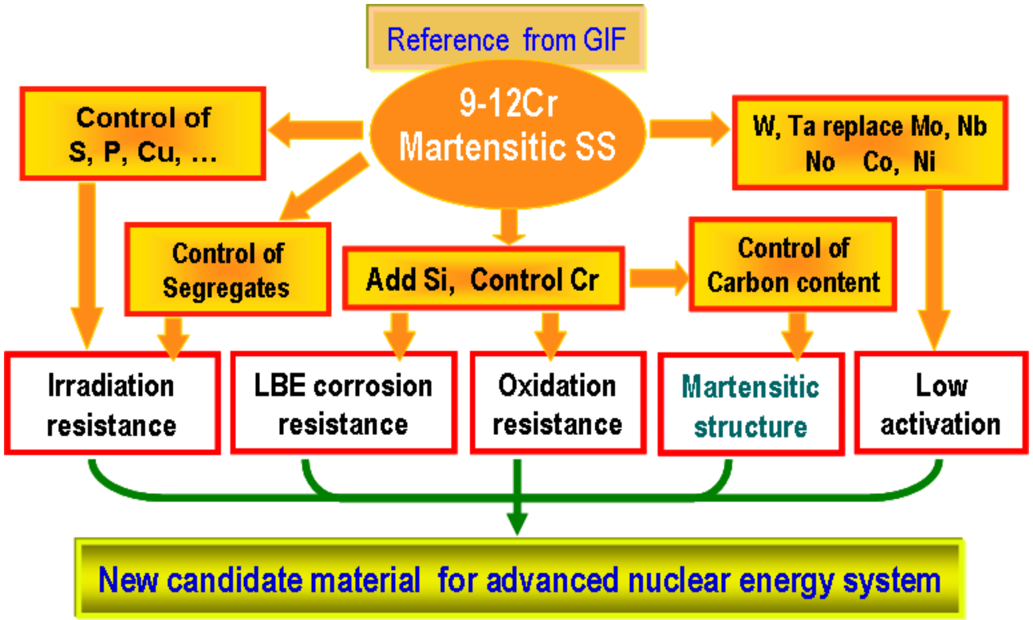
Institute of Modern Physics (IMP), Chinese Academy of Sciences (CAS)
IMR Institute of Metal Research(IMR), CAS

SIMP steel —— FeCr base martensitic alloy

Steel designed by **IMP**-CAS and **IM**R-CAS

Supported by Strategic science and technology leading project
of Chinese Academy of Sciences

Chemical composition design



SIMP steel

Chemical compositions:

C(0.15-0.35)- Si(1.0-1.5)- Cr(10-11)- 1.5W- 0.2V- (0.10-0.15) Ta

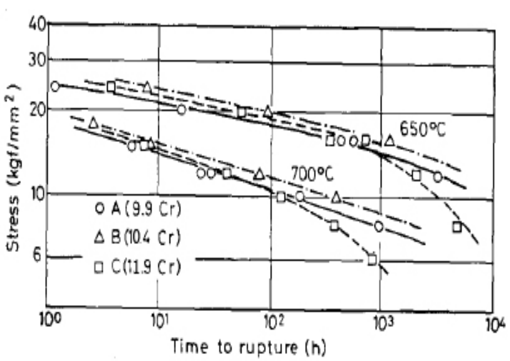
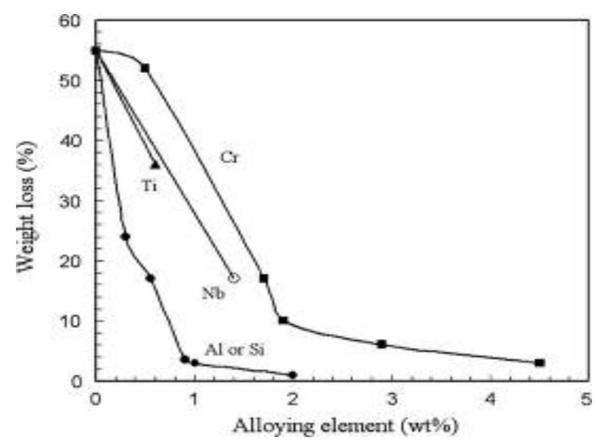
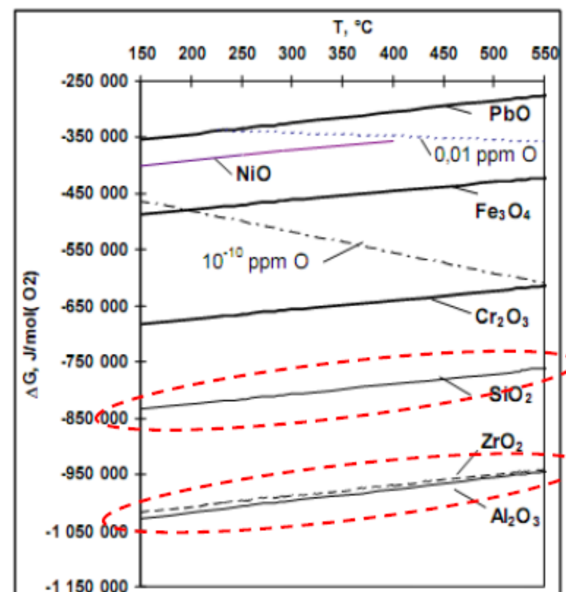


Fig. 1. Creep rupture curves at 650 and 700°C.

9-12Cr martensitic steels: good creep property

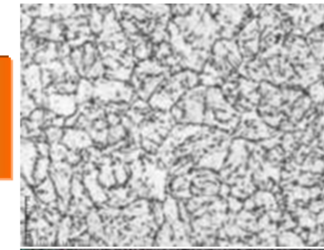




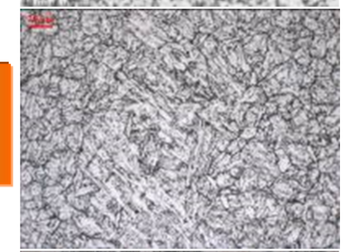
1%-2% Si containing ferritic/martensitic steels exhibit lower oxidation rate

Microstructure design

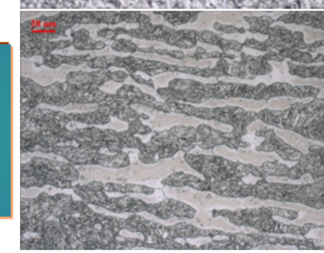
Microstructure thermal stability → T/P91, T/P92 → Tempered martensite



Radiation resistance → Euro97, F82H, 9Cr2WVTa, CLAM, JLF-1 → Tempered martensite



Liquid metal corrosion resistance → EP823 → Mainly Tempered martensite



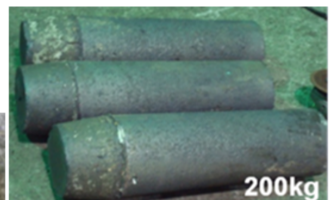
Tempered martensite:

Excellent thermal stability and good irradiation and corrosion resistance

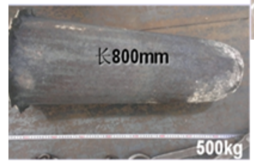
Smelting & casting

Industrial grade !

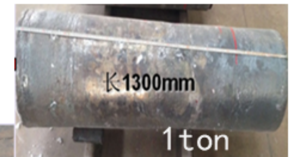
2011



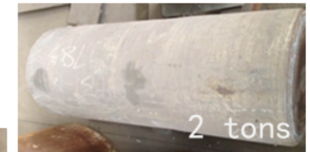
2012



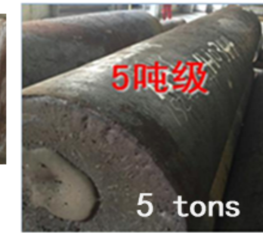
2013



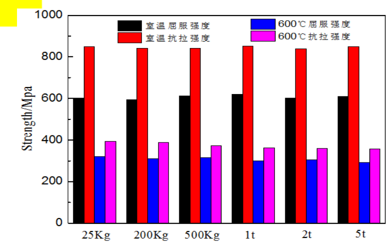
2014



2015

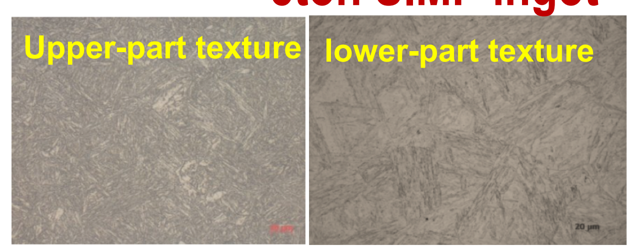


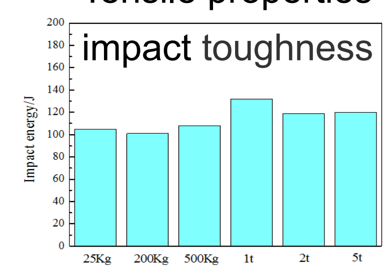
2016



Tensile properties

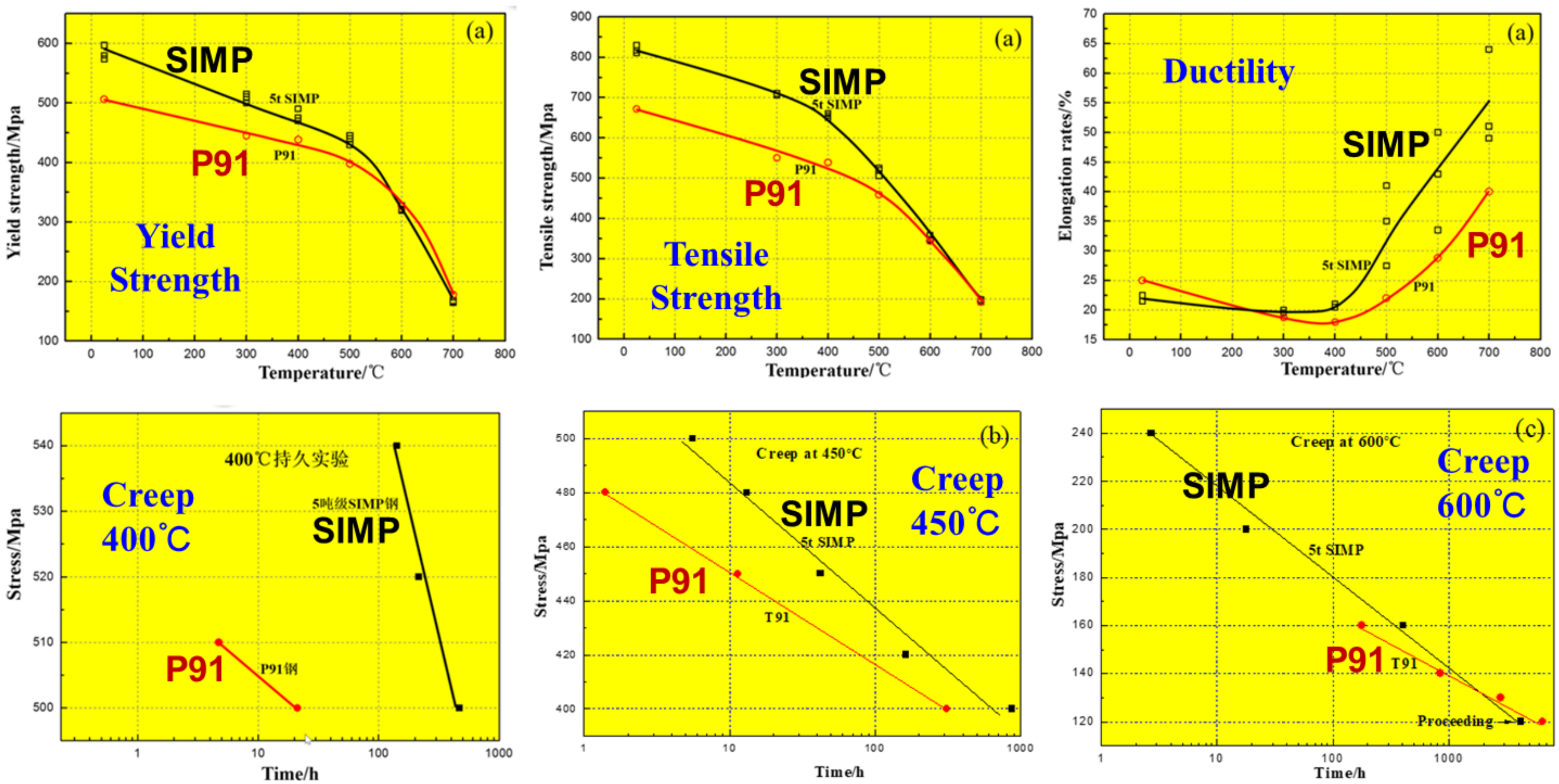
5ton SIMP ingot





Control: purity, homogeneity, mechanical property

Mechanical properties



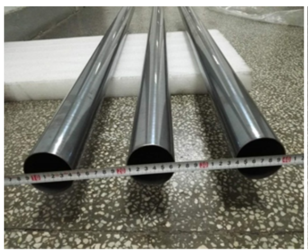
The mechanical of SIMP steel is superior to T/P91 in a temperature range from RT to 550 ^{o}C

Processing

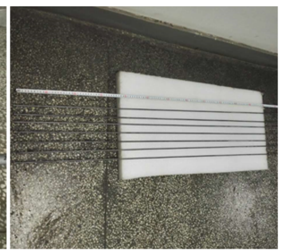
➢ Tubes/pipes

Φ60mm×10mm

Φ60mm×5mm

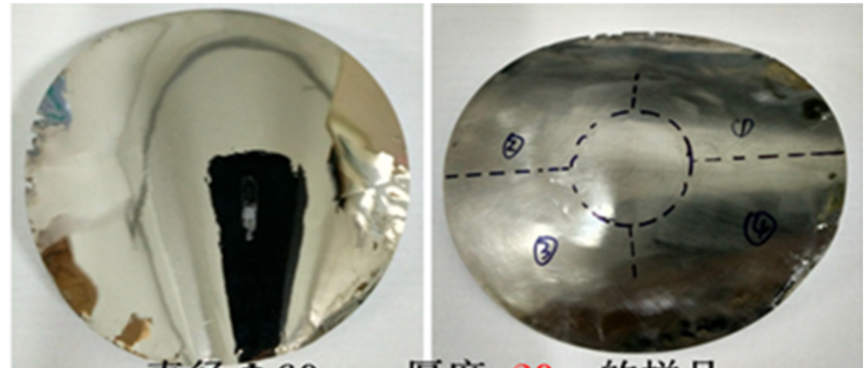


Φ60mm×1mm



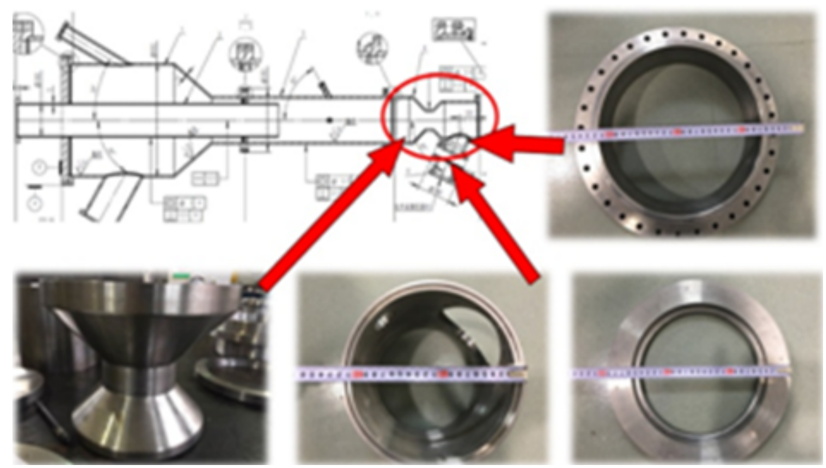
Φ5mm×1mm

➢ Thin foil

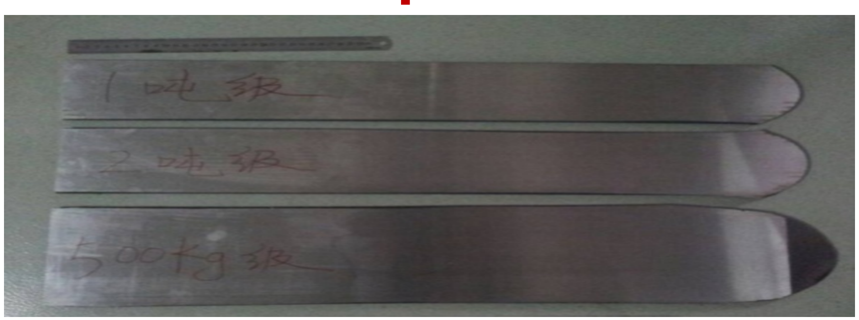


直径Φ60mm，厚度~20um的样品

➢ Component

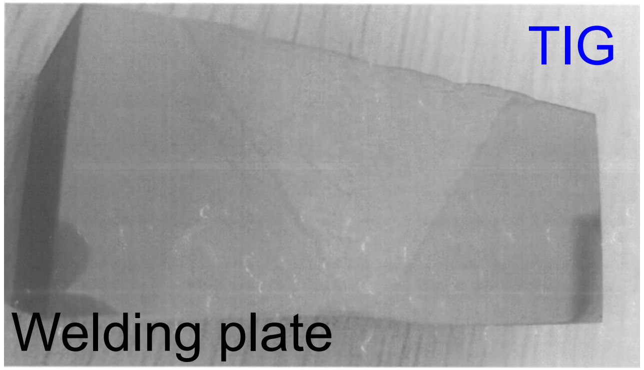


➢ Panel / plate



Welding property

◆ **Welding property assessment (ASME code)**



Mean impact energy at weld: 117J

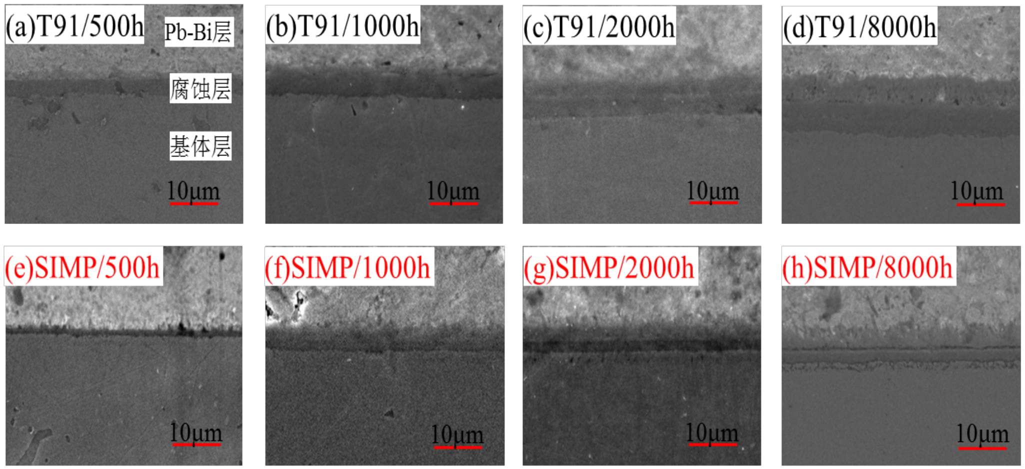
Mean impact energy at HAZ: 81J

SIMP steel shows good weldability and satisfactory post-weld ductility

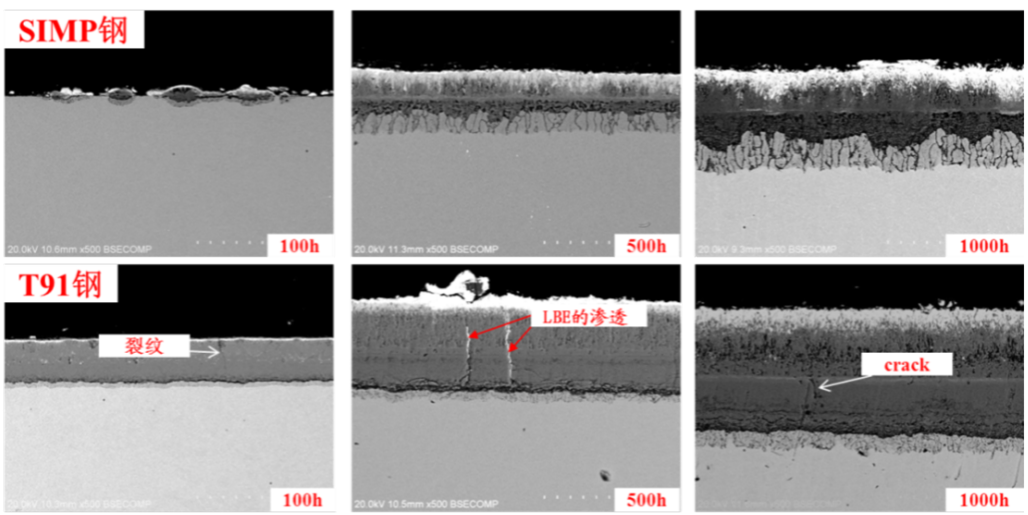
Liquid LBE corrosion resistance

450°C/600 °C, static, saturation oxygen

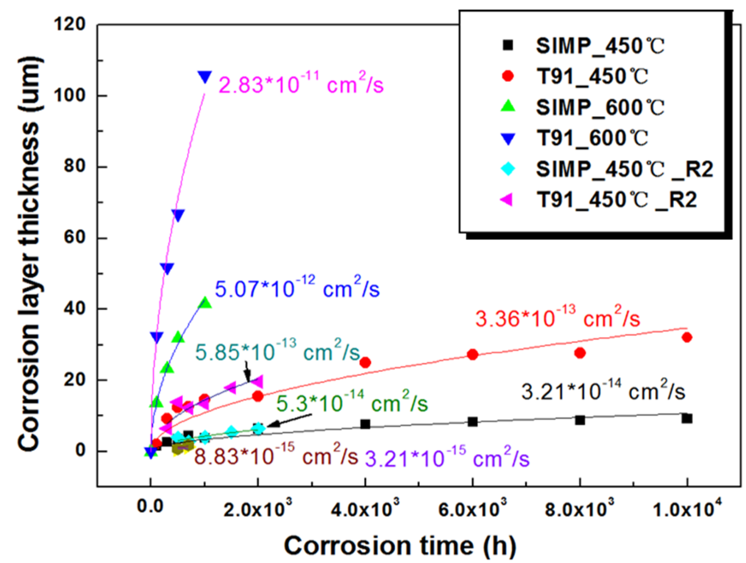
450°C



600°C



$$h^2 = K_p t$$

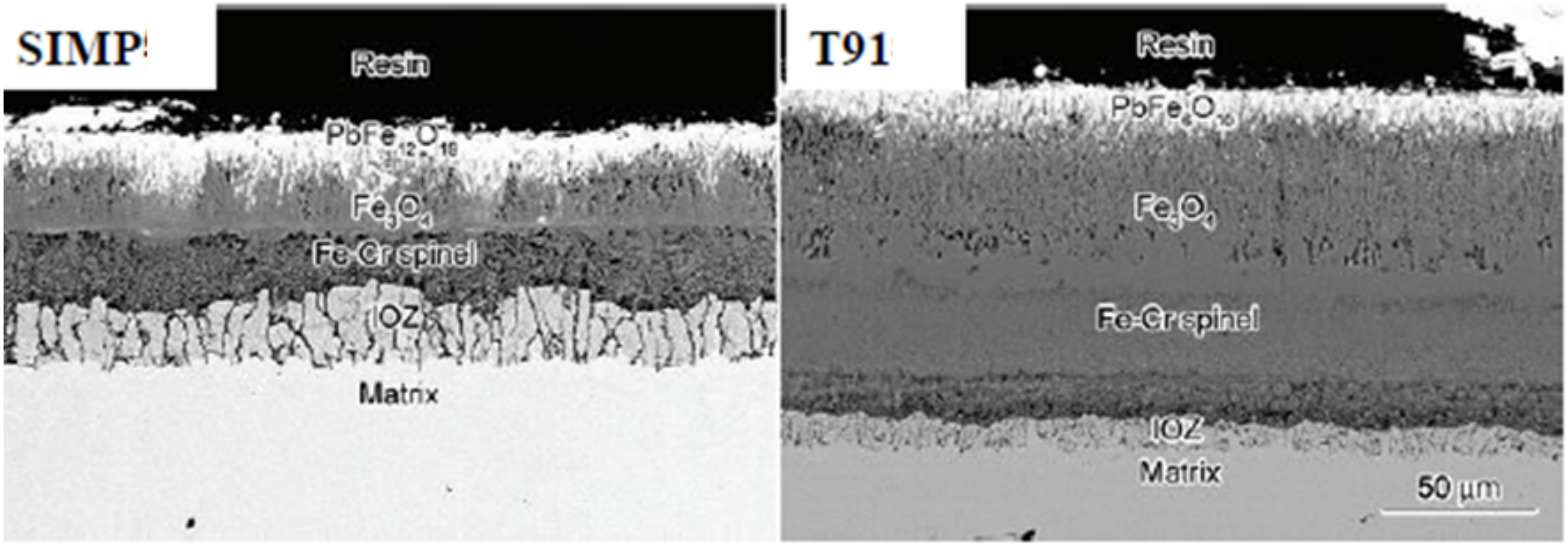


Liquid LBE corrosion resistance :

SIMP is better than T91

Liquid LBE corrosion resistance

600 °C, static, saturation oxygen

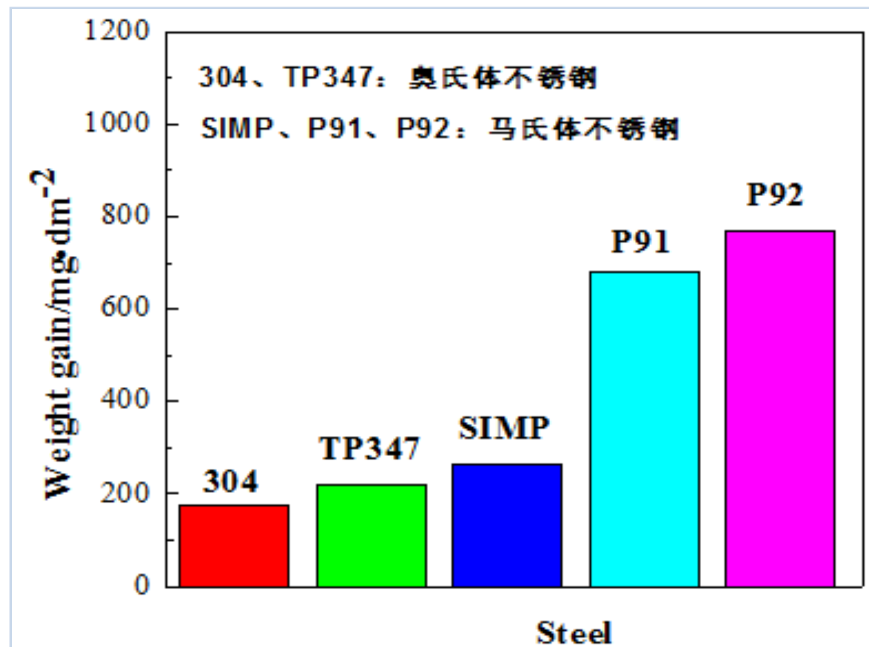


Liquid LBE corrosion resistance :
SIMP is better than T91

Oxidation resistance in supercritical water

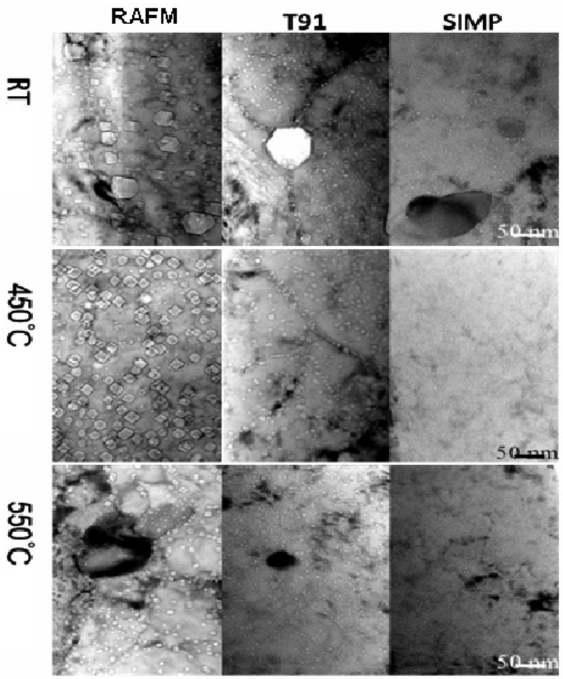
Steel	C	Si	Cr	Mn	W	Ta	V	Nb	Ni	Mo	S/ppm	P/ppm
SIMP	0.22	1.22	10.24	0.52	1.45	0.12	0.18	0.01	—	—	43	40
T/P91	0.1	0.26	8.5	0.46	—	—	0.20	0.04	0.17	0.92	20	30
T/P92	0.1	0.38	8.63	0.42	1.59	—	0.164	0.053	0.15	0.37	10	14
TP347	0.08	0.6	18	1.6	—	—	—	0.8	10	—	<30	<40
304	0.09	<0.03	18	<1.0	—	—	—	0.05	9.7	—	<10	<40

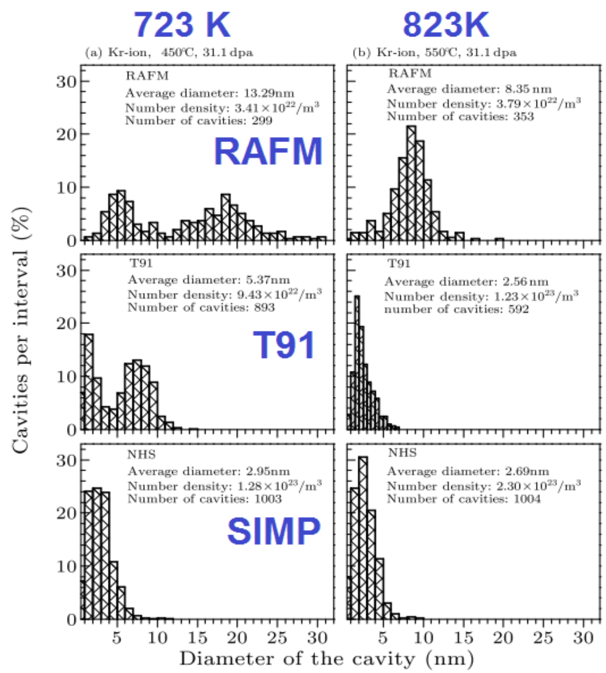
Corrosion Test in SC Water (600℃, 25MPa, 1000h)



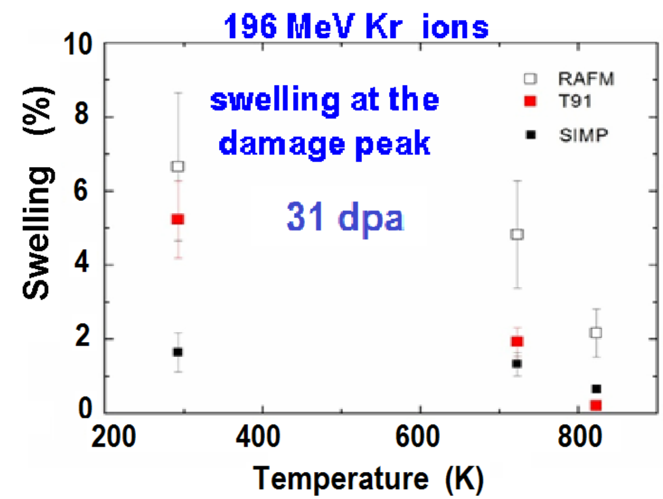
Ion irradiation resistance

Irradiation swelling





Samples are irradiated at the same condition



Ion irradiation swelling resistance:

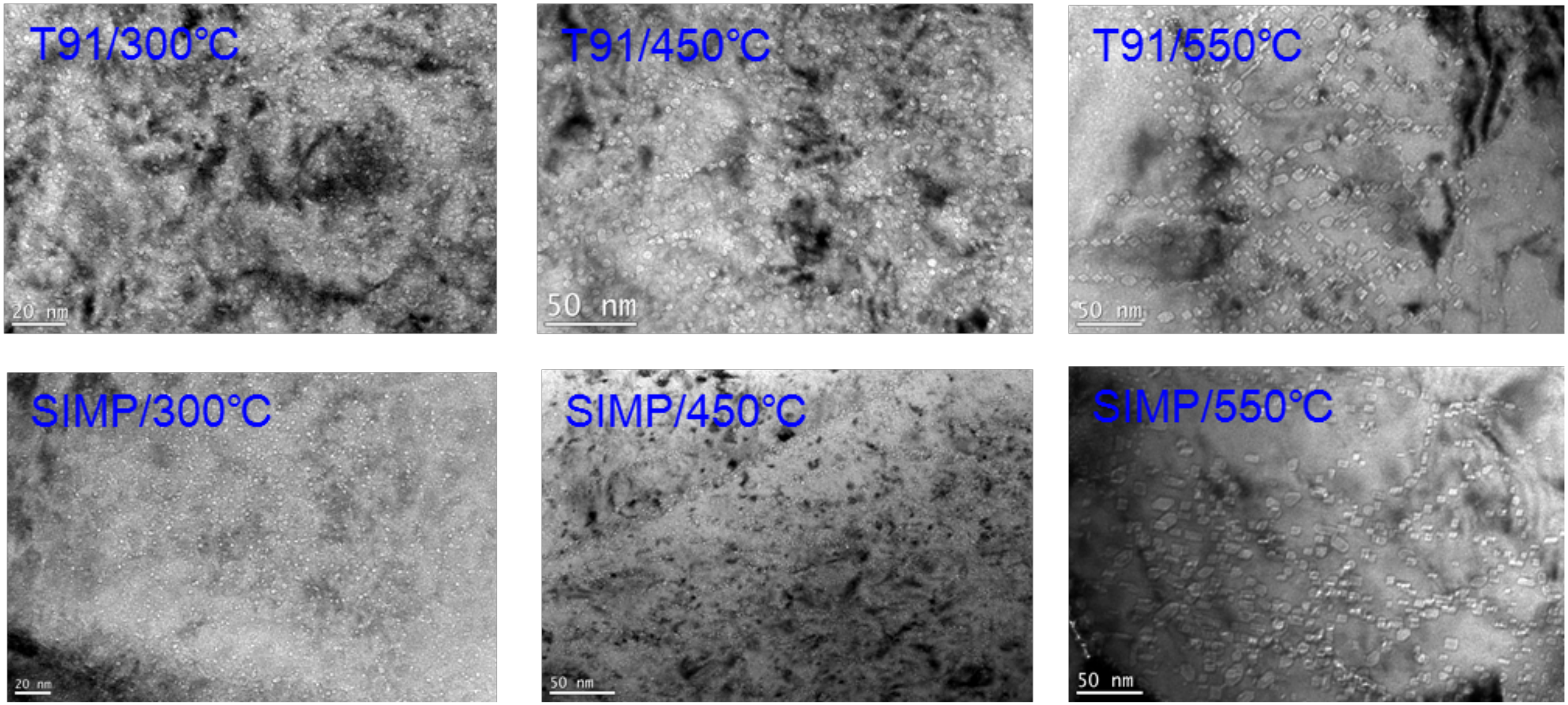
SIMP > T91 > RAFM*

SIMP steels irradiated at SINQ-PSI, (n/p, ~20dpa, 2012-2014)
Post Irradiation Examination (PIE) is under way.

Ion irradiation resistance

He-effect

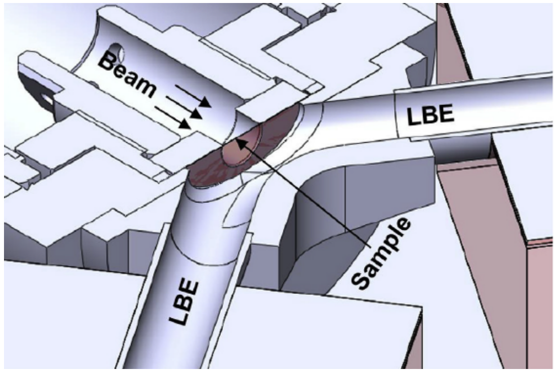
Samples are at the same condition

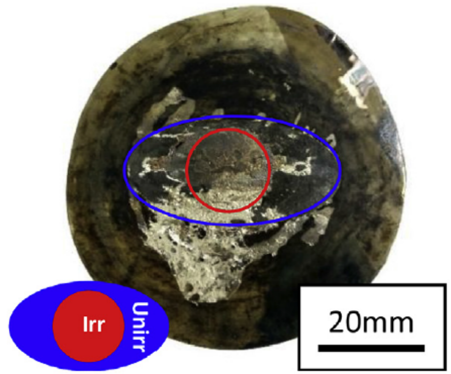


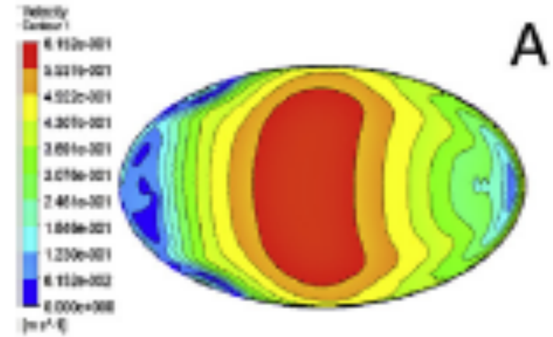
Mean size of helium bubbles, 5×10^{16} ions/cm^2, 200 keV He ions

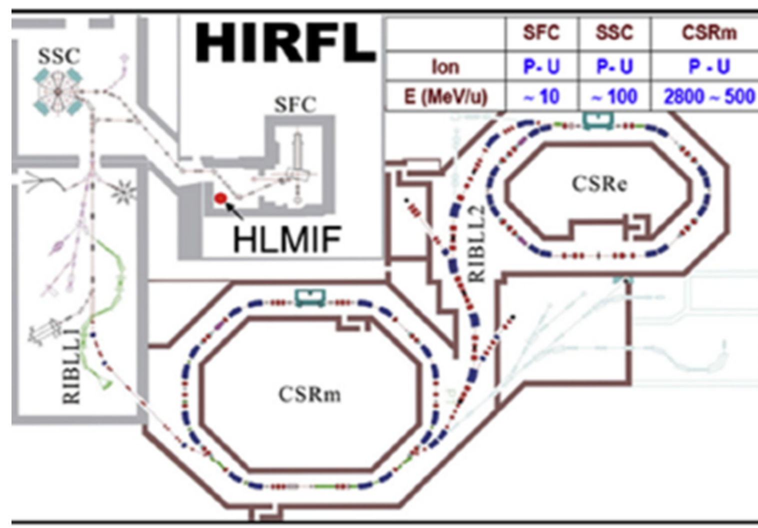
He-bubble size: SIMP < T91

Irradiation/LM corrosion resistance









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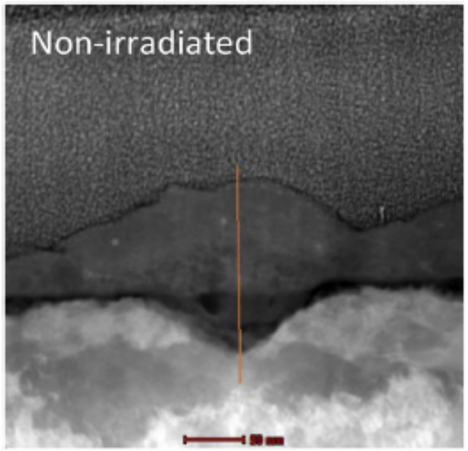
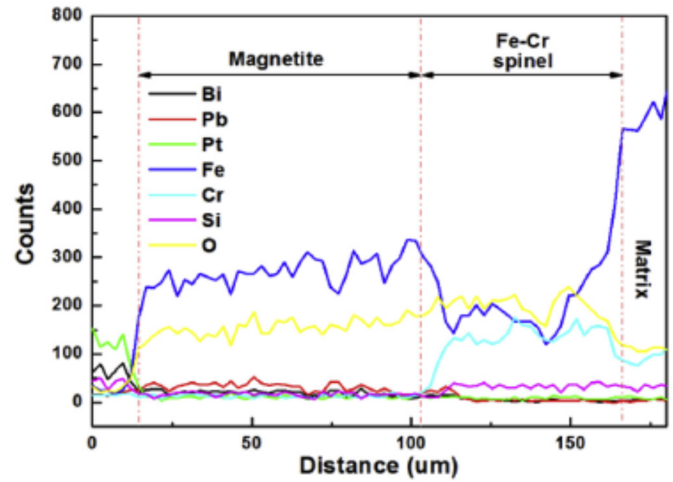
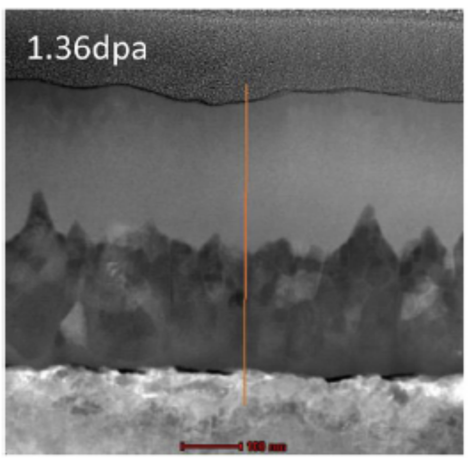
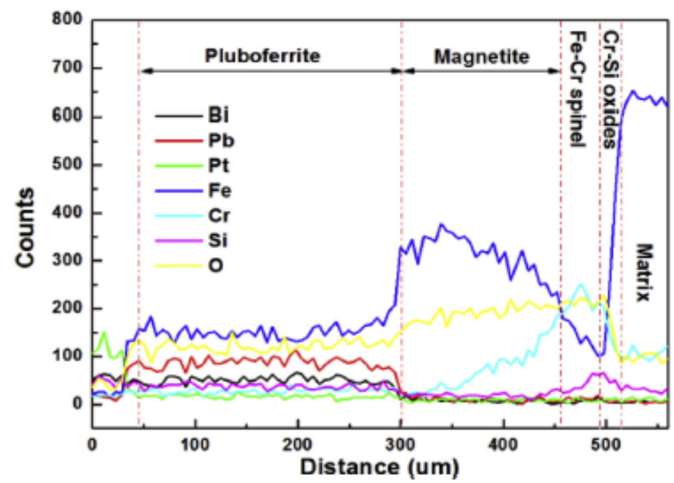
Irradiation/LM corrosion resistance









247MeV Ar, 350°C, LBE-SO, 0.6 m/s, J Nucl Mater 523 (2019) 260

Outline

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3. Summary & Future works

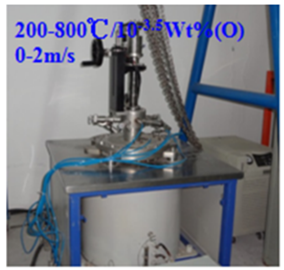
Brief summary

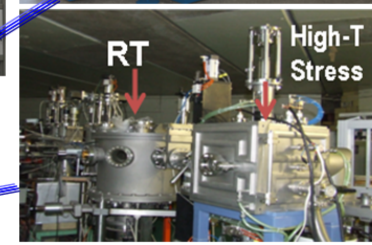
1. SIMP steel, a novel FeCr base martensitic alloy, was developed;
2. An industrial scale of 5 tons SIMP steel ingots have been produced.
3. A series of tests shown that SIMP steel exhibits good performance under processing, high temperature, liquid metal and ion irradiation.
4. The synergistic effect of irradiation and liquid LBE is a key issue for the future development of SIMP steel .

Future works

- **Database**

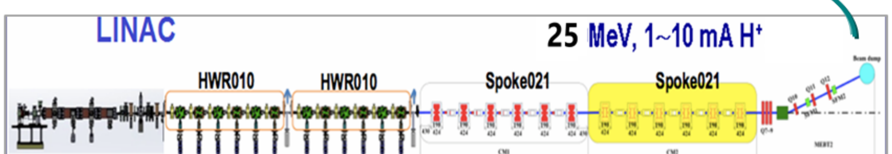
Evaluations at “true” environment
— Synergetic effects
(Coolant, DPA, High-T, Dopant, Stress, …)

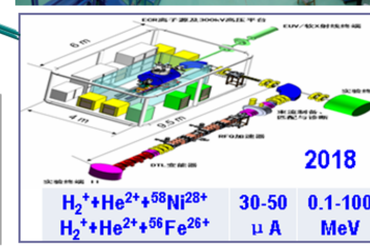




- Coolant + High-T + Stress +……
- DPA + Coolant + High-T
- DPA + Stress + High-T
- H (or He) + DPA (self ions) + High-T
- H + He + DPA (self ions) + High-T
- H + He + DPA + Stress + High-T
- H + DPA + Stress + High-T

Neutron irradiation





- **Criteria/standard + License + …**

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IAEA Headquarters

Thank You !

Oct. 15-17, 2019, VIC, Vienna, AUSTRIA