Overview of Fusion Reactor Materials Study at SWIP

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Outline

1. Motivations
2. Plasma facing materials/components.
   W alloys
   W joining with heat sink or structural materials
3. Structural materials.
   Ferrite/martensite steels
   Vanadium alloys
4. Functional materials.
   Tritium breeder
   Neutron multiplier
5. Summary

Motivations

PFMs → C, Be, W, Li liquid → W → Temp. windows → W alloys

CVD-W, ODS-W, CDS-W

W-K

Structural materials → RAFM / V alloy / $SiC_{f/}SiC_f$ → Near or middle-term goals → RAFM / V alloys

CLF-1, ODS-CLF-1

V-4Cr-4Ti, ODS-V

Functional materials → N-multiplier / T-multiplier → Helium Cooling Solid Blanket

Be pebbles

Li_4SiO_4 pebbles

Potential application for HL-2M, ITER-TBM

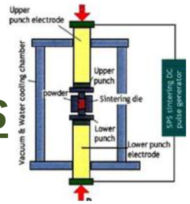
CFETR or DEMO-China

Plasma facing materials

W alloys

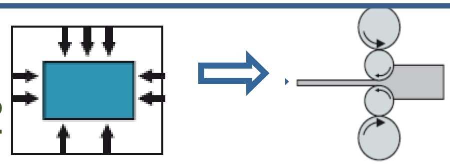
Milling

SPS



Milling

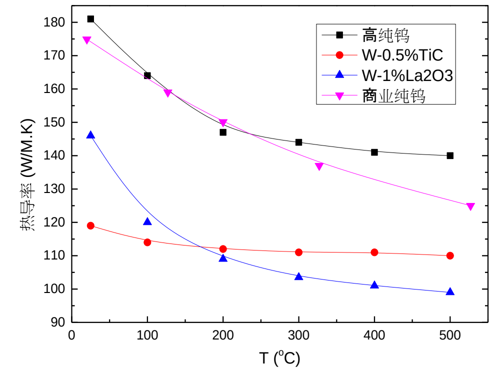
HIP



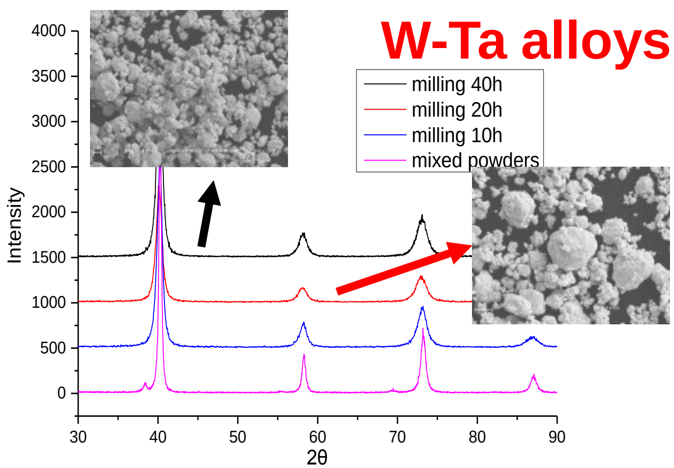
Hot deformation

Thermal conductivity

(PM-W vs W-TiC, W-La_2O_3)

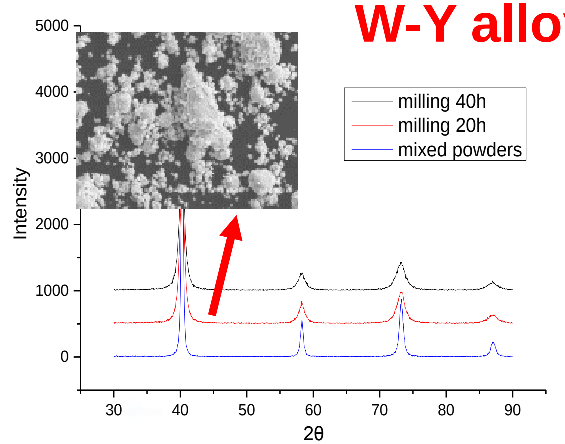


W-Ta alloys



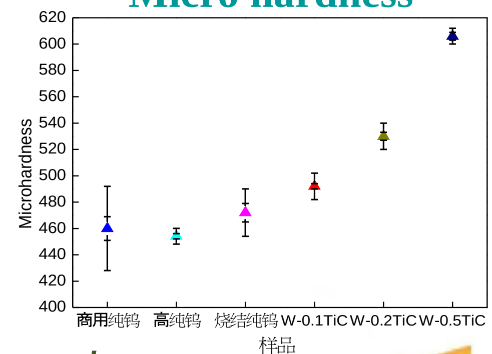
XRD of milled W-5Ta powders

W-Y alloys



XRD of milled W-1Y powders

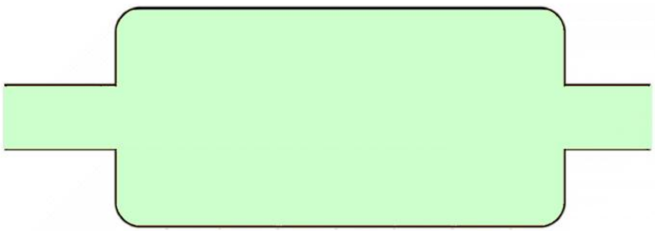
Micro hardness



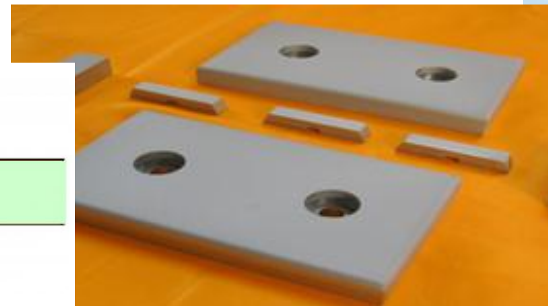
Plasma facing materials

Fast CVD-W coating (up to 0.5 mm/h)

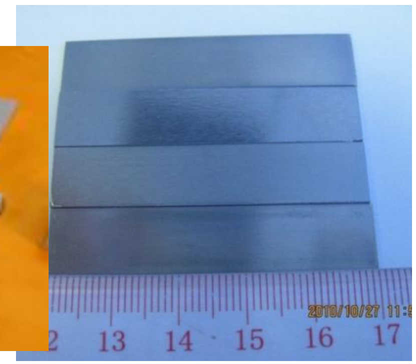
CVD-W coating process



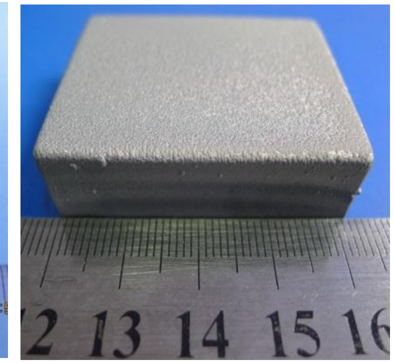
W/Cu



W/RAFM Steel

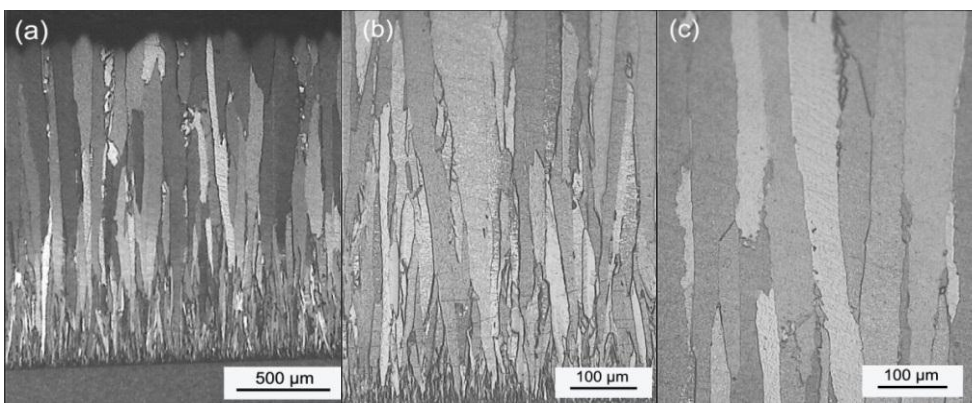


W/graphite



Deposition rate	0.3-0.5 mm/h
Thickness	1-3mm
Purity	99.9999%
Thermal conductivity	>180 W.m/K
density	>99%
Hardness (HV)	430
bonding strength	W/Cu >50Mpa

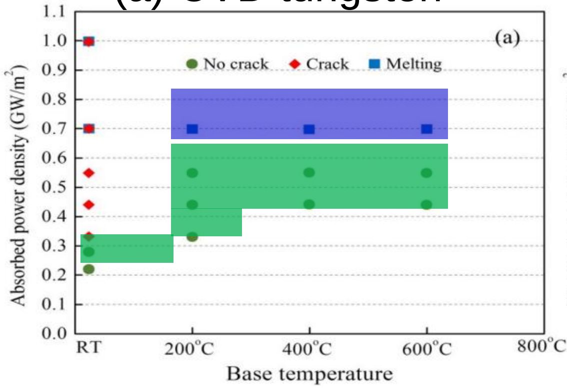
Microstructure characterization



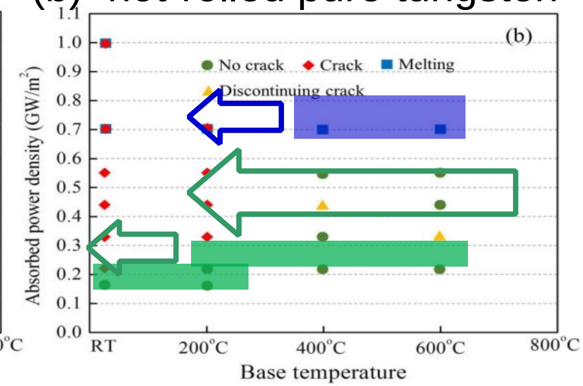
Transient event simulations of W materials

disruption-like thermal loads (single shot)

(a) CVD tungsten

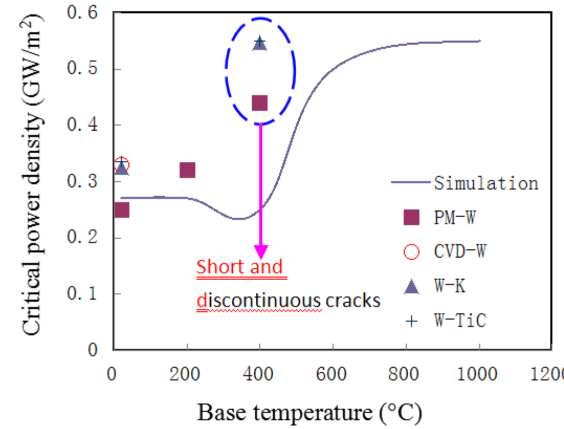


(b) hot-rolled pure tungsten



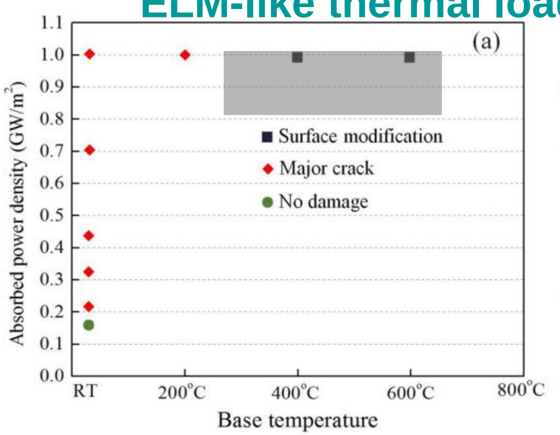
Numerical simulations

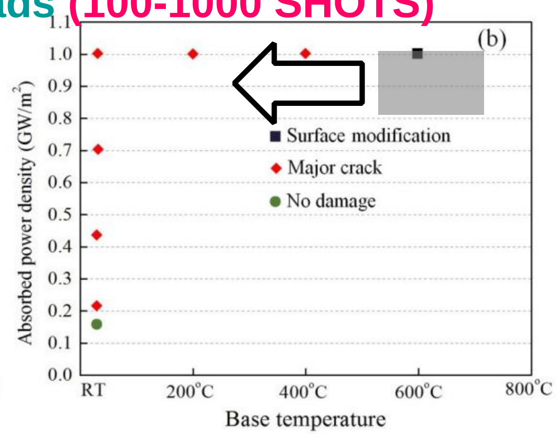
--Cracking thresholds--



CVD-W seems more sensitivity to the cracking suppression at elevated temperature

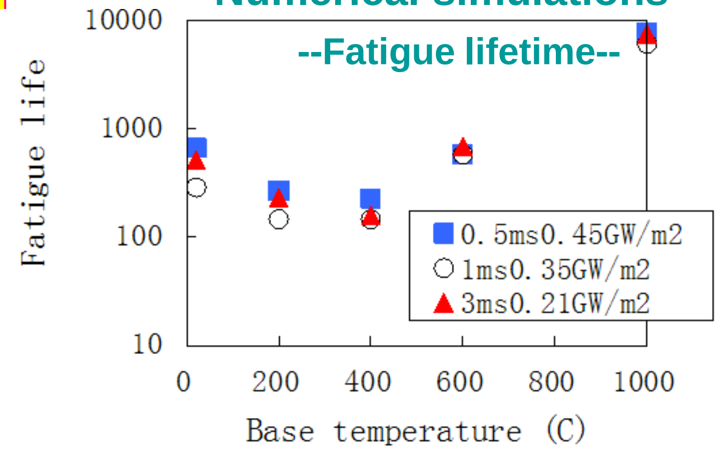
ELM-like thermal loads (100-1000 SHOTS)





Numerical simulations

--Fatigue lifetime--



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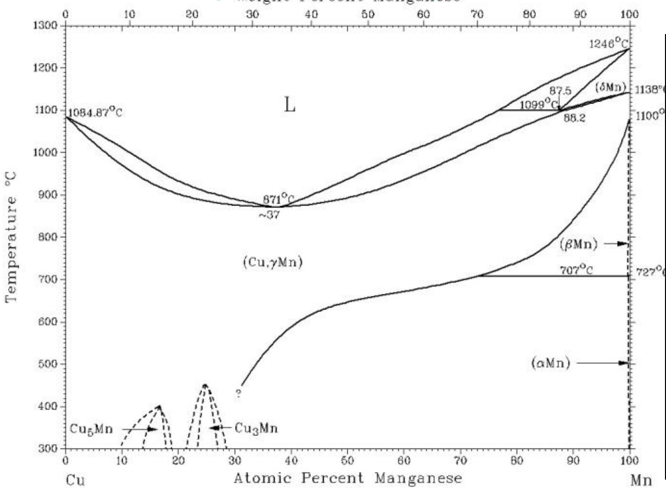
Plasma facing components

--W/CuCrZr mockups--

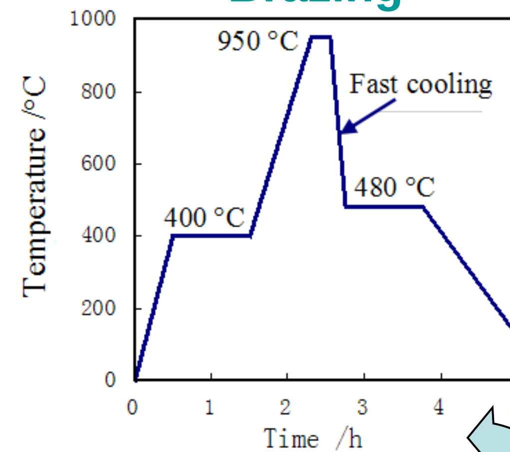
Cu-Mn filler



Chemical composition

Element（wt.%） No.	Mn	Ni	Ti	Cu
1	25	-	-	75
2	25	1-	-	74
3	25	-	1	74
4	25	-	3	72

Brazing



Inductive melting + Forging + Cold rolling

Forging machining

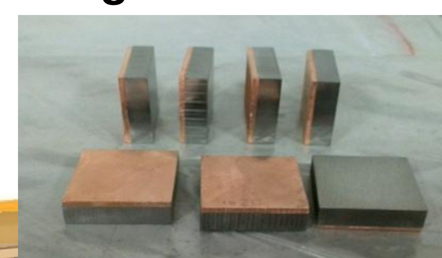
Cold rolling

Processes

No.	melting	reprocess	O content
1	Inductive melting	Re-melting 1times	75 ppm
2	Inductive melting	Add C powder	126 ppm
3	Inductive melting	Re-melting 2 times	40 ppm
4	Resistance heating	Add deoxidizer	-

Already developed technique:

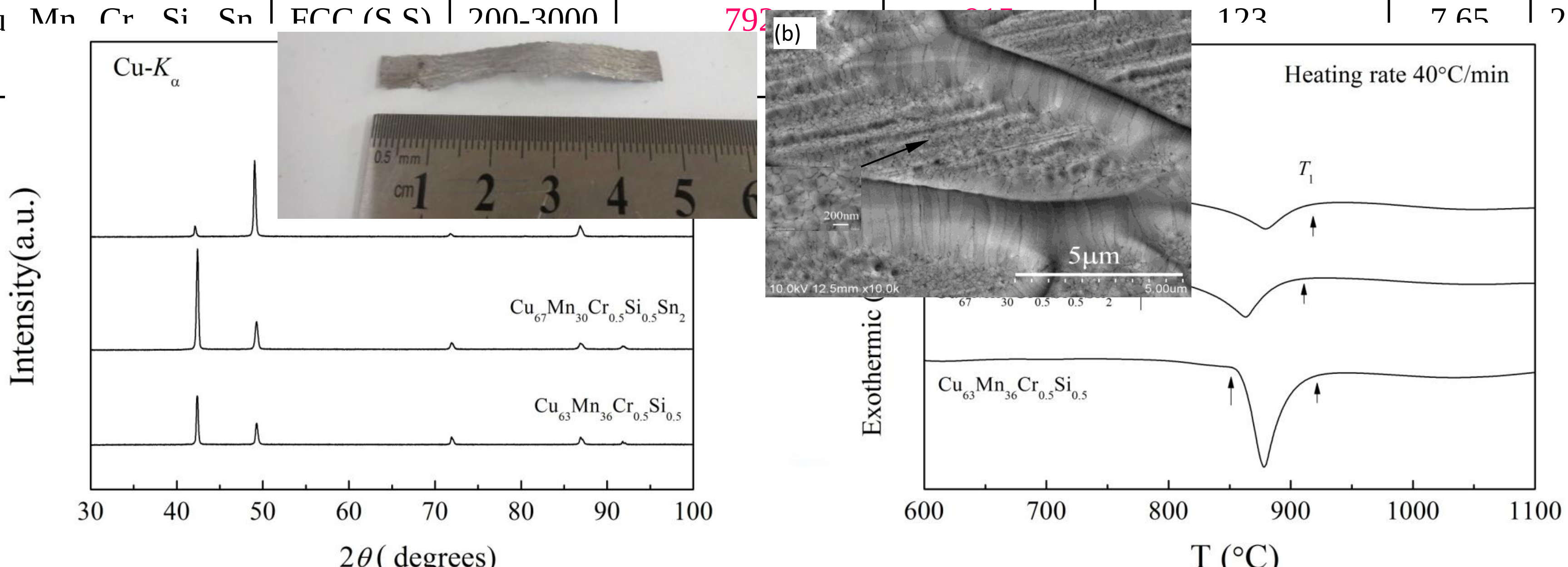
- Traditional furnace + fast cooling + aging
- Fast brazing using Electron-Beam
- Cupper coating + HIPing with fast cooling



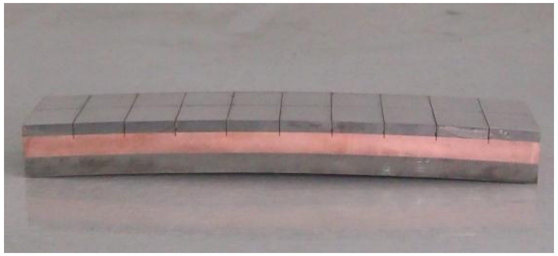
Cu-Mn non-crystalline filler

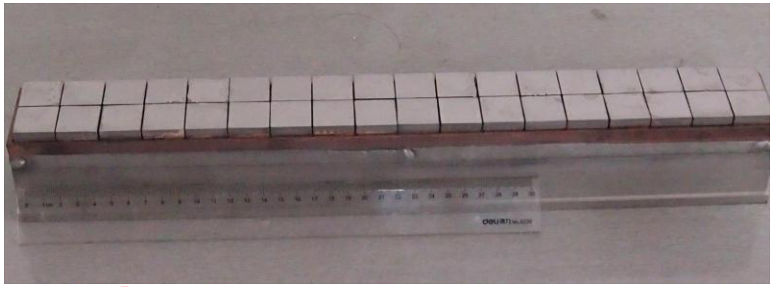
--Design based on molecular cluster theory--

Compositions at.%, Ce-addition	Structure	Grain size (nm)	Onset melting temperature T_m (°C)	Liquidus temperature T_l (°C)	Melting temperature span $\Delta T = T_l - T_m$ (°C)	Mass density (g/cm³)	Hardness (H_v)
$Cu_{63}Mn_{36}Cr_{0.5}Si_{0.5}$	FCC (S.S)	200-3000	857	905	48	7.54	185±10
$Cu_{67}Mn_{30}Cr_{0.5}Si_{0.5}Sn_2$	FCC (S.S)	200-3000	774	889	115	7.72	150±10
Cu Mn Cr Si Sn	FCC (S.S)	200-3000	792	[illegible]	123	7.65	225±10



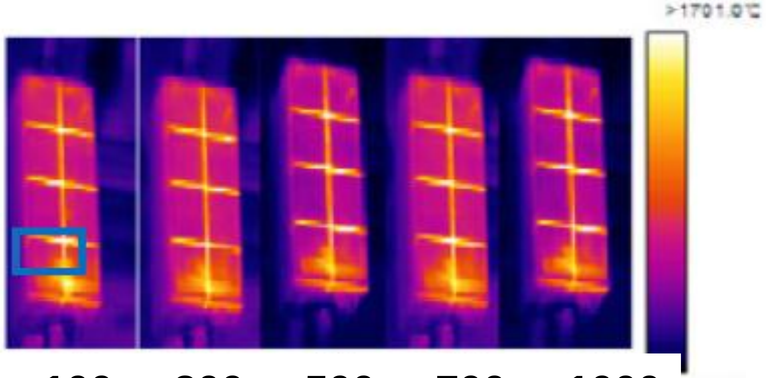
HHF tests--Plasma facing components





Castellated mockup (30×60×30 mm) with 5 mm thickness of W tile

Thermal fatigue tests:
(increase water cooling to 10m/s)
1) Screening test:1-9 MW/m2
2) 1000 cycles at 8 MW/m2
Surface temperature variation < 10%
No visible damage



EMS 60

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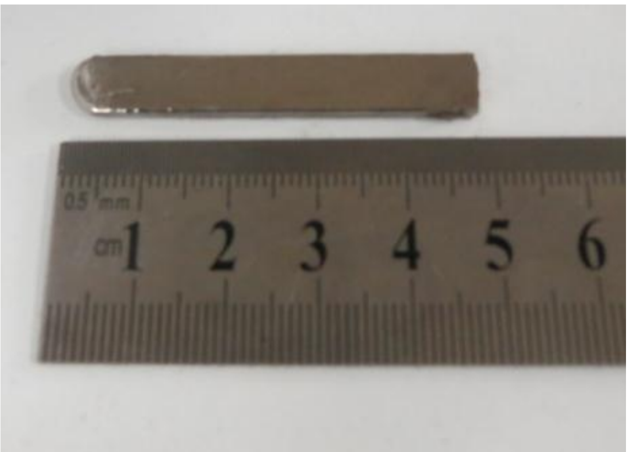
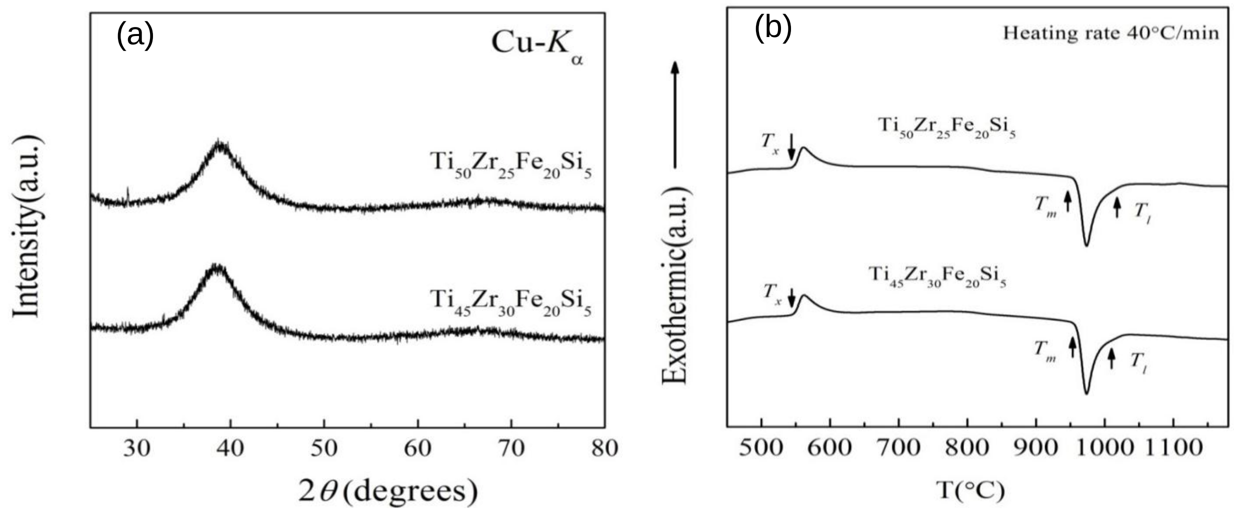
100 300 500 700 1000

(a)surface temperature variation vs. cycles

Filler for He cooling divertor targets

Ti-base and Fe-base amorphous brazing alloys





Compositions	Structure	T_x (°C)	T_m (°C)	T_l (°C)	ΔT	Mass density (g/cm^3)	Hardness (H_v)
$Ti_{45}Zr_{30}Fe_{20}Si_5$	amorphous	550	**955**	**993**	38	5.85	645±20
$Ti_{50}Zr_{25}Fe_{20}Si_5$	amorphous	541	**952**	**1030**	78	5.74	650±20

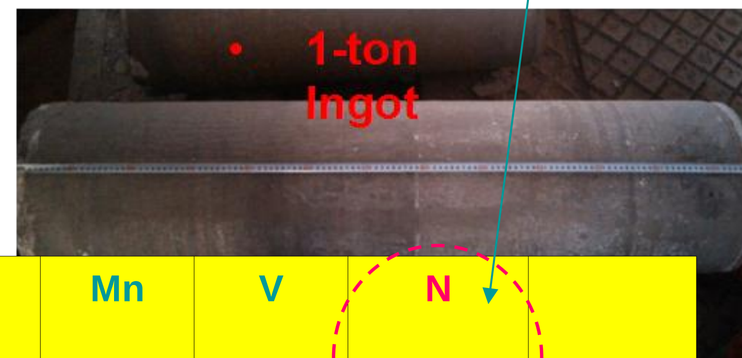
Samples	T_X(℃)	T_m(℃)	T_l(℃)	ΔT
$Fe_{60}Mn_{15}B_{16.67}Si_{6.33}Sn_2$	556	1072	1113	41
$Fe_{50}Mn_{25}B_{16.67}Si_{6.33}Sn_2$	558	1046	1095	49

Structural materials-RAFM steel

Composition and fabrication technique optimization--up to 1 ton ingots

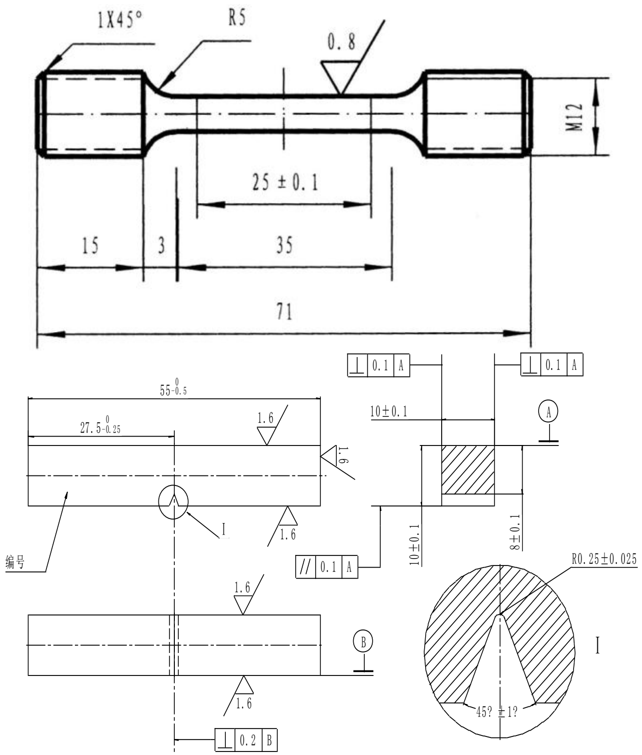
- Cooperated with domestic institutes and factories

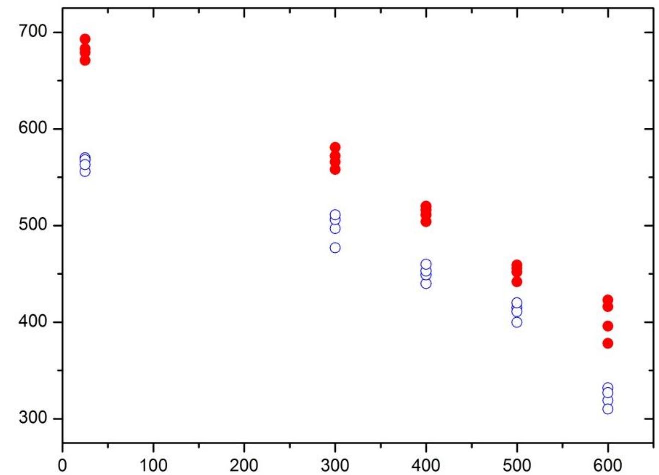
N as the controllable element, at the upper limit



Alloy element	Cr	C	W	Ta	Mn	V	N	
Content control	8.5±0.3	0.11±0.015	1.5±0.2	0.10±0.03	0.5±0.2	0.3±0.1	0.02-0.035	
Impurity	S	P	Ti	B	Nb	O	Ni	Mo
Content control	<0.005	<0.005	<0.01	<0.005	<0.01	<0.005	<0.01	<0.01
Impurity	Cu	Al	Si	Co	As	Sn	Sb	Zr
Content control	<0.01	<0.03	<0.05	<0.01	As+Sn+Sb+Zr<0.05			

Properties database of CLF-1 steel (1)

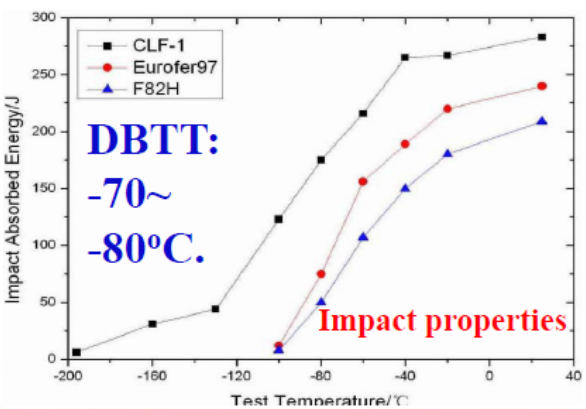




Tensile properties

Thermo-mechanical properties

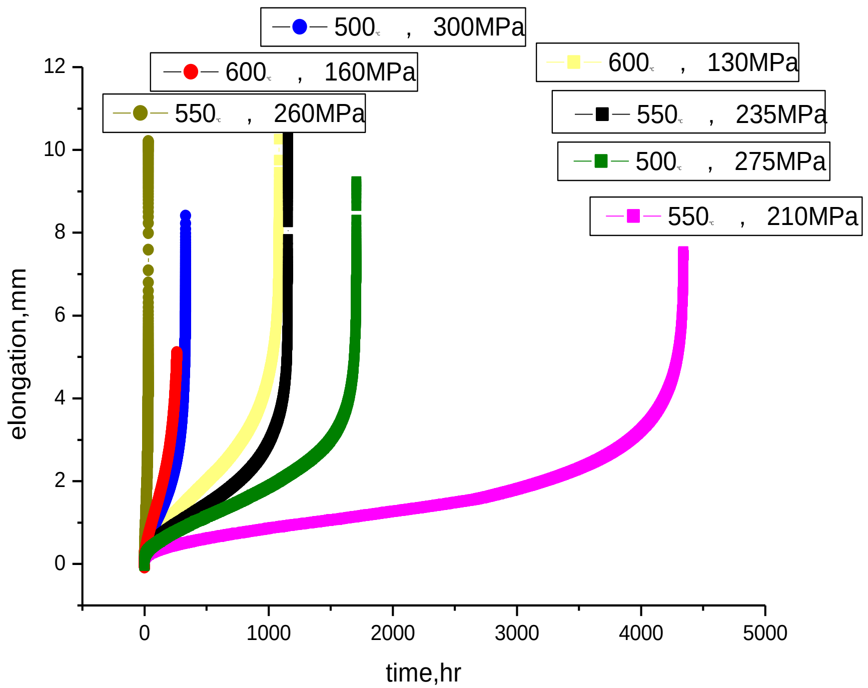
Test T. (℃)	*Thermal Diffusivity ($10^{-6}m^2/s$)*	*Specific heat (J/kg·℃)*	*Thermal Conductivity (W/m·℃)*	*Linear Expansion Coefficient (10^{-6}/℃)*
100	*7.97*	*523*	*33.1*	*10.9*
200	*7.37*	*553*	*32.0*	*11.4*
300	*6.77*	*583*	*30.8*	*12.1*
400	*6.17*	*617*	*29.8*	*12.6*
500	*5.55*	*661*	*29.0*	*12.8*
600	*4.86*	*735*	*28.0*	*13.0*
700	*4.03*	*847*	*26.8*	*13.2*



Properties database of CLF-1 steel (2)

Thermal creep properties

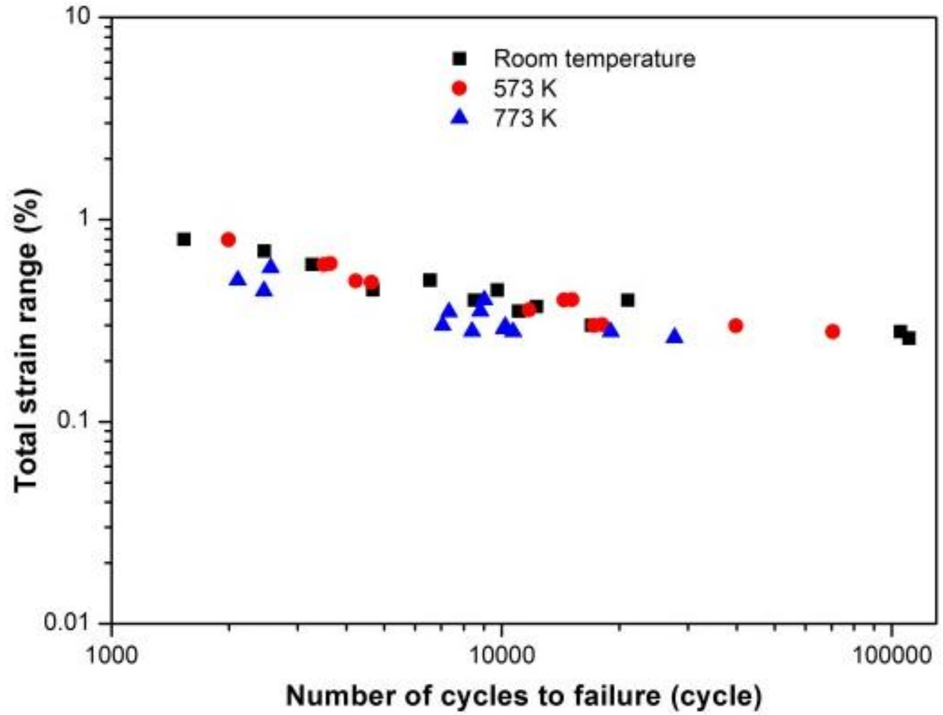
- **Temperature: 500℃, 550℃, 600℃ ;**
- **Stress level : 250- 300MPa (500℃), 180-260MPa (550℃), 100-160MPa (600℃)**



The CLF-1 steel shows adequate creep rupture level with low minimum creep rate long rupture time. Some of the tests have been carried out for more than 11000 h and are still in progress.

Thermal fatigue properties

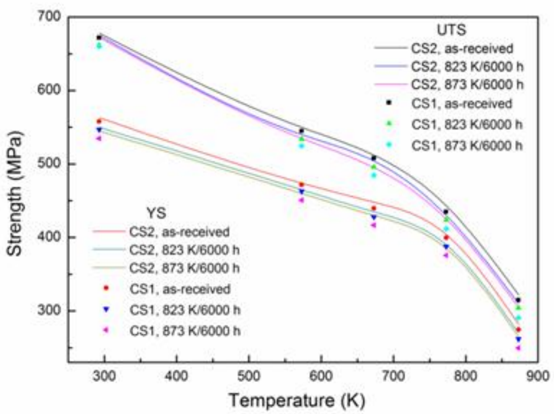
- **Temperature: room temperature, 300℃, 500℃ ;**
- **total strain of 0.2%~1%。**
- **Stress rate of 0.1 %/s**

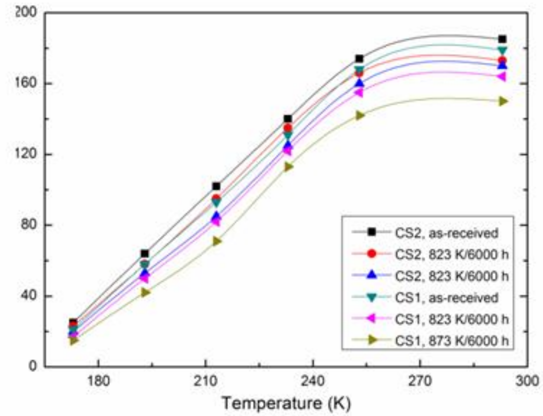


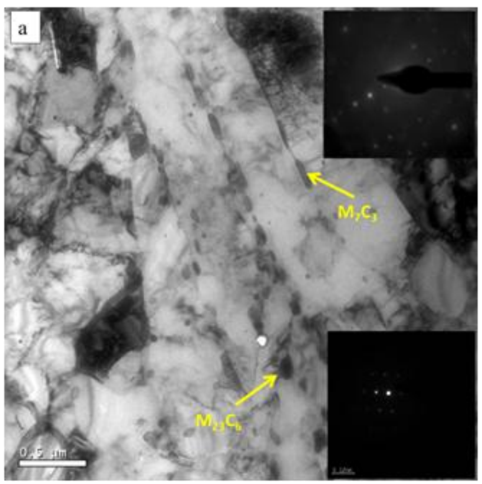
Cyclic softening was observed at all test temperatures under strain controlled fatigue test. The effect of test temperature on fatigue property of CLF-1 steel is very small.

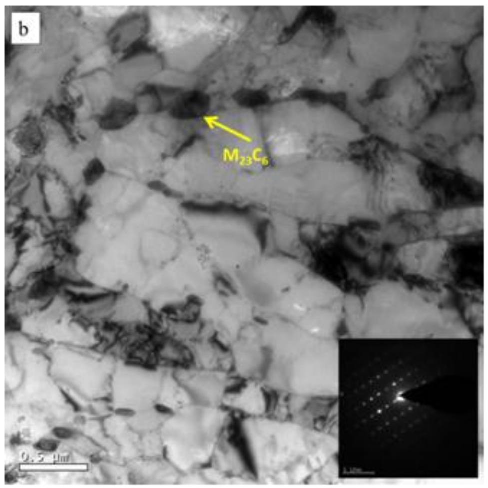
Thermal stability of CLF-1 steel

•**CLF-1 steel; Thermal aged: 550℃ and 600℃ for 6,000hr**





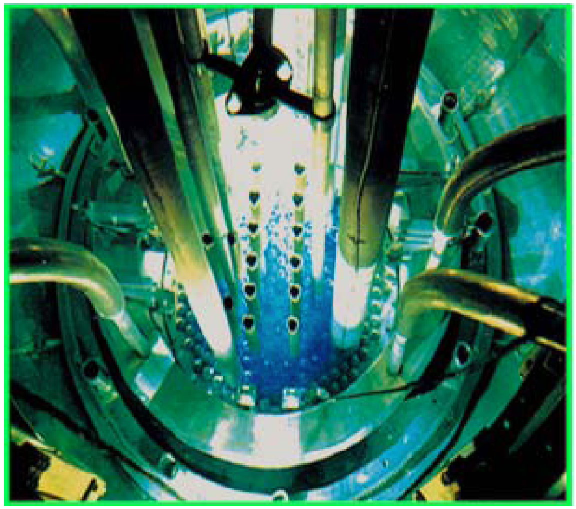




- No obvious degradation in tensile properties, only a DBTT shift.
- thermal ageing did not affect the grain size but strongly affected the precipitation behaviors
- $M_{23}C_6$ type carbides coarsened and agglomerated
- No obvious increase of the MX-type precipitates was observed.
- Higher nitrogen content cause finer MX-type precipitates and the coarsening and agglomeration of $M_{23}C_6$ carbides is much lower.

Neutron irradiation data

--1 dpa data will be available by the end of this year--



High Flux Engineering Test Reactor

Neutron irradiation of CLF-1, CLAM steels

Power: 125MW
Maximum Flux: 6.2×10^{14}n/cm^2.s

Post-irradiation examination

1) Mechanical properties

-Tensile properties

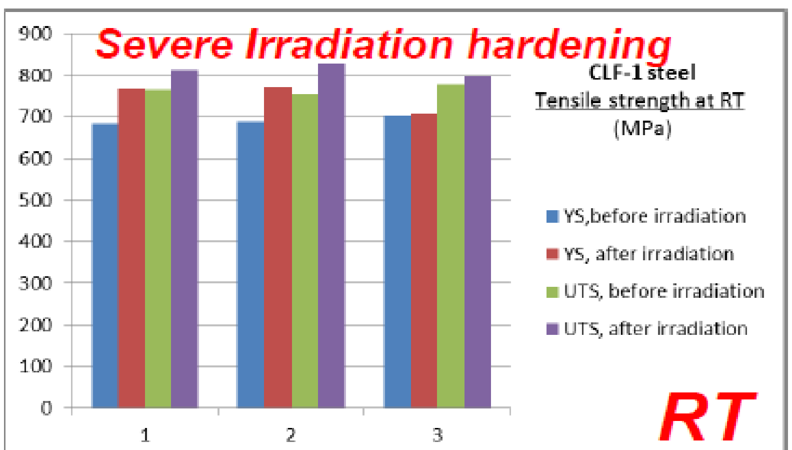
-Charpy impact properties

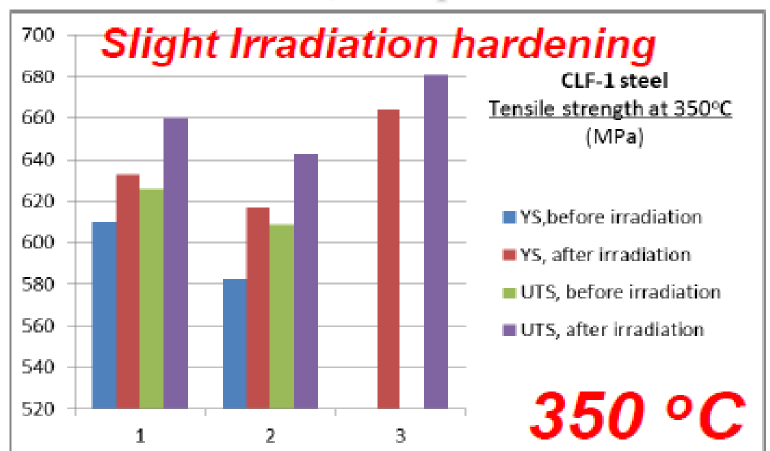
2) Microstructure analysis

More detail:

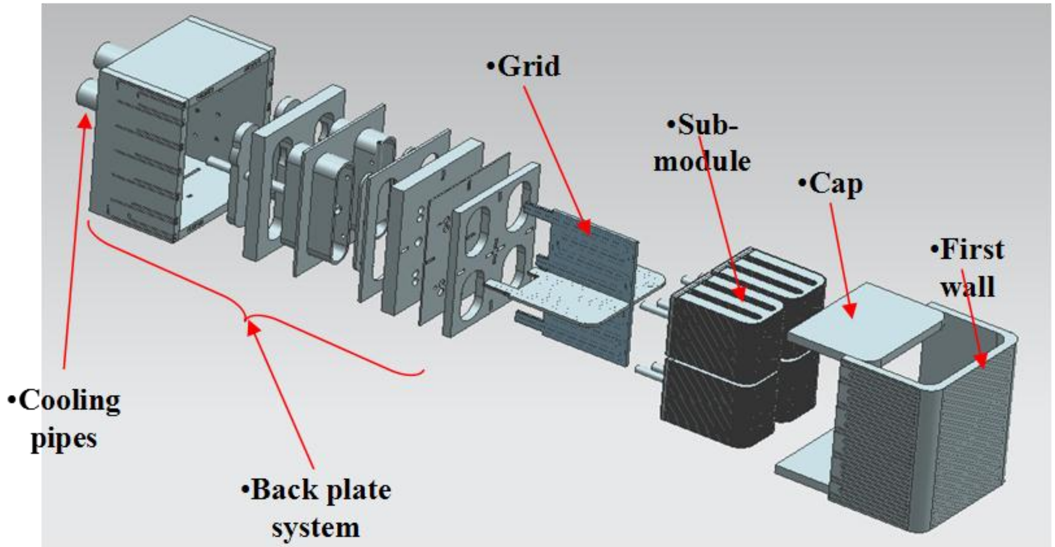
<u>P.H. Wang, Poster MPT/P8-7</u>

CLF-1 steel, 0.5dpa achieved

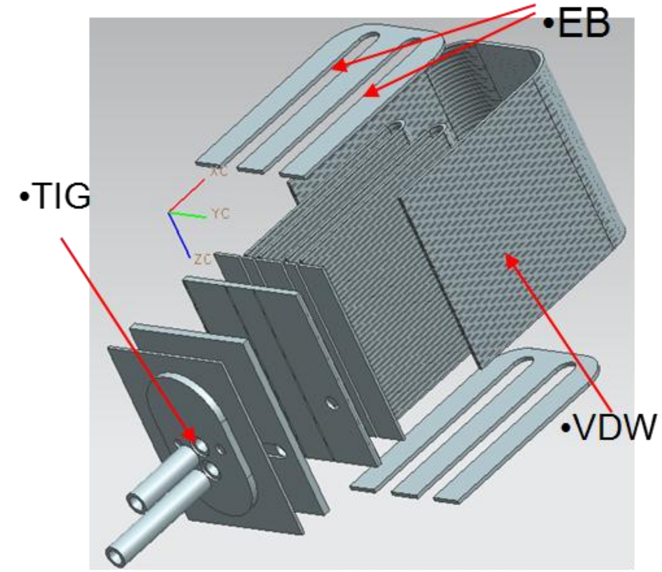




Material preparation for TBM fabrications



•Explosive view of CN HCCB TBM



•Sub-module

•According to the structure design of CN HCCB TBM, different joining technologies will be used for the fabrication of the mock-ups, such as:

•Vacuum diffusion welding (VDW): First wall; Sub-module.

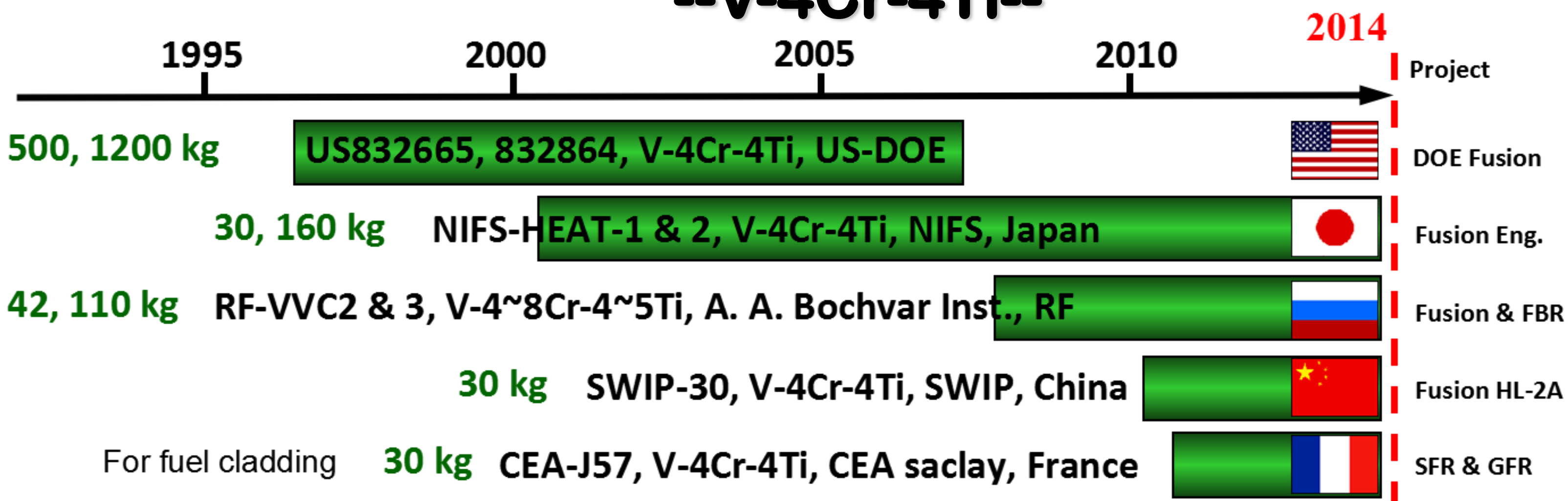
•electron beam welding(EB): Sub-module; The welding between the grids and the plates and pipes of the back system.

•Tungsten Inert Gas (TIG): The welding between the grids and the plates and pipes of the back system. Grid and the first wall.

More detail: K.M. Feng, FIP/3-5Ra

Structural materials-V alloys

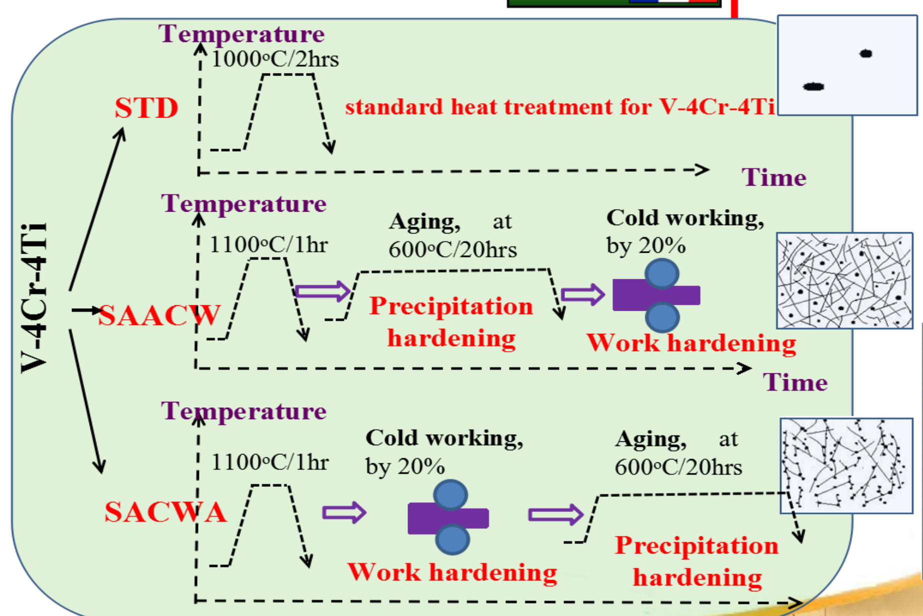
--V-4Cr-4Ti--



30 kg

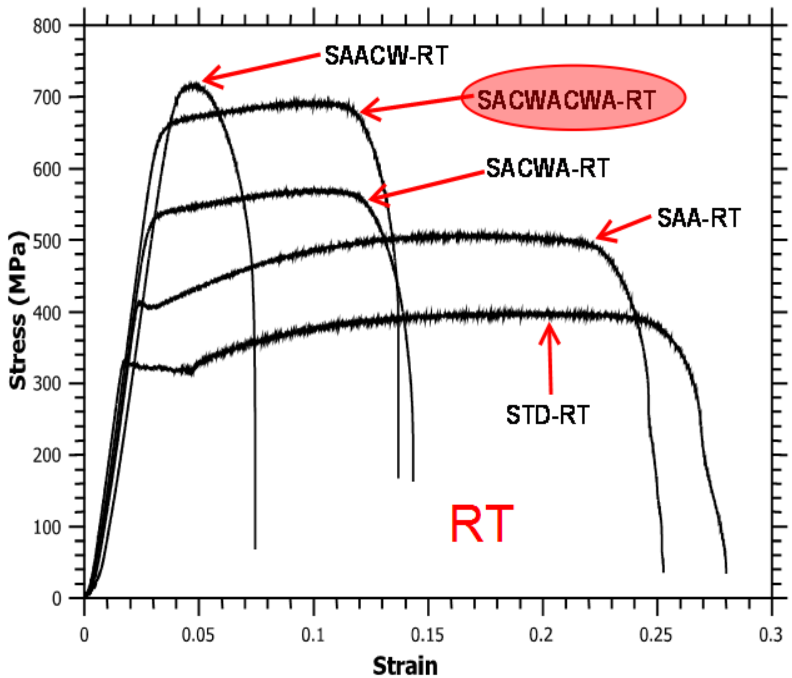
Melting

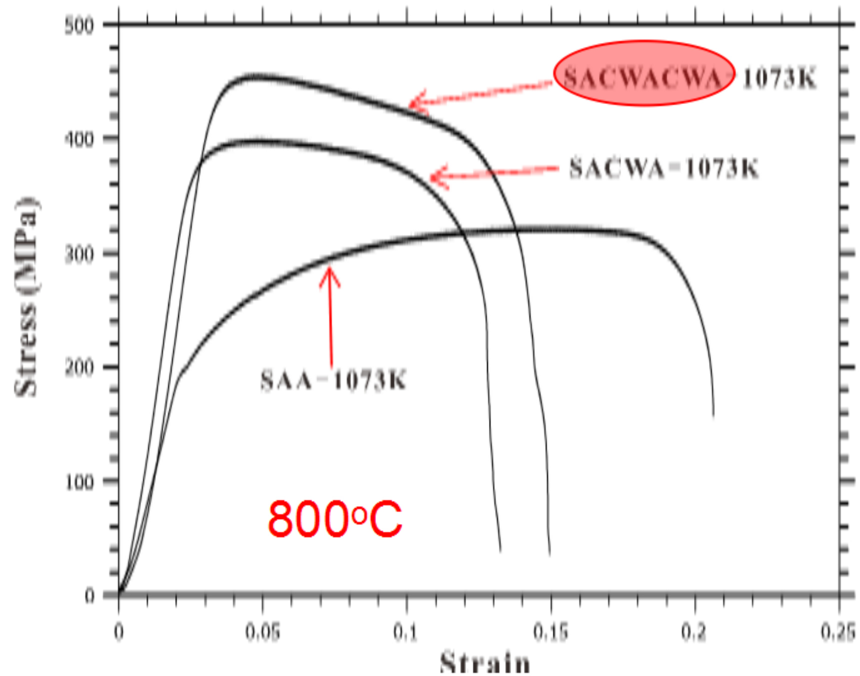
V-4Cr-4TI development



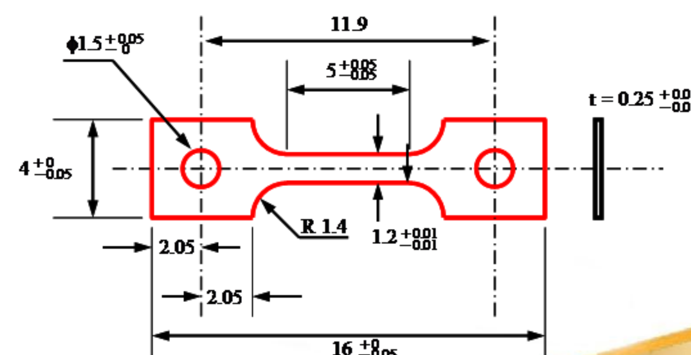
Structural materials-V alloys

--Heat treatments of V-4Cr-4Ti--





Repeated cold working followed by aging (SA+CW+A+CW+A) is effective to strengthen the V-4Cr-4Ti alloy at both room temperature and high temperatures, while the ductility loss is comparatively small.



Key point: to stabilize the line defects

Work cooperated with NIFS

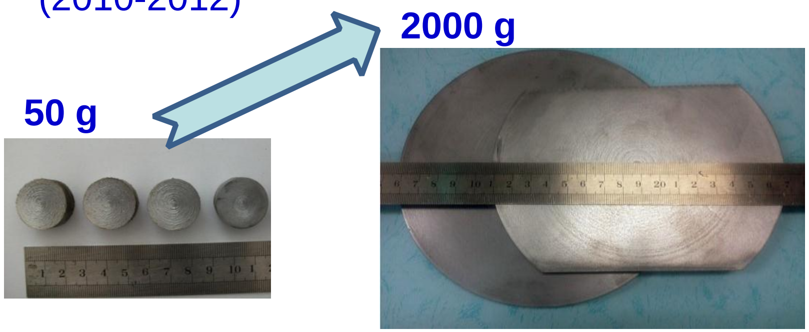
Structural materials-V alloys
--Dispersion strengthened--

Co-combined particles dispersion strengthened V alloy

Mechanical alloyed V-alloys are expected to work at higher temperatures. Research of such V-alloys is a main work in recent years in the word.

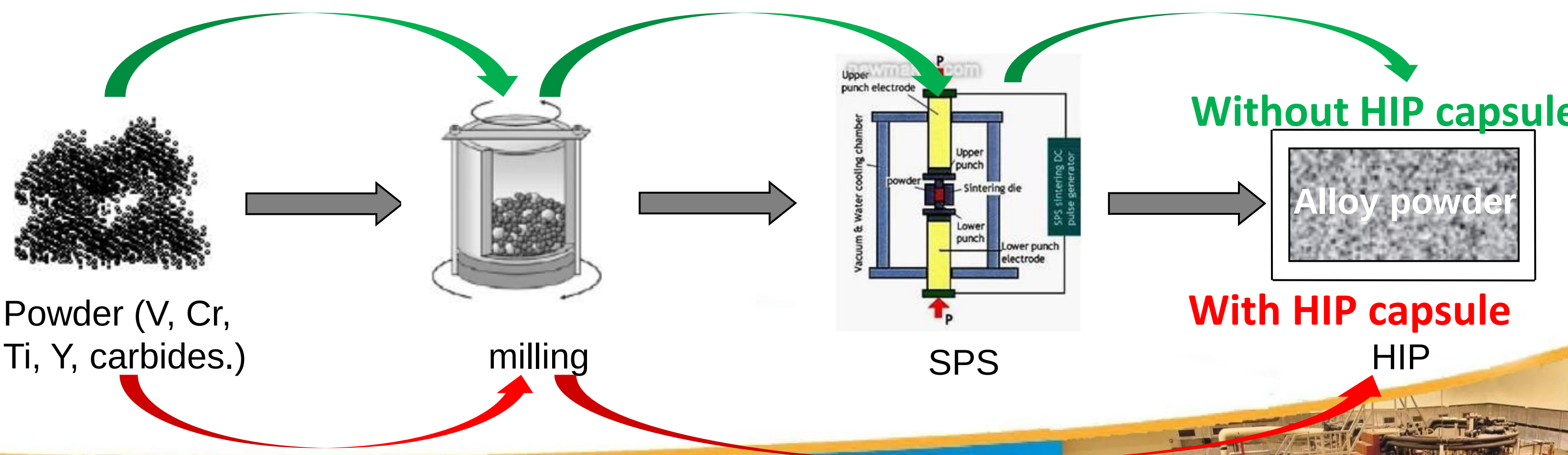
Scale-up
(2010-2012)

Mechanical alloying



V-4Cr-4Ti-1.8Y-0.4Ti_3SiC_2

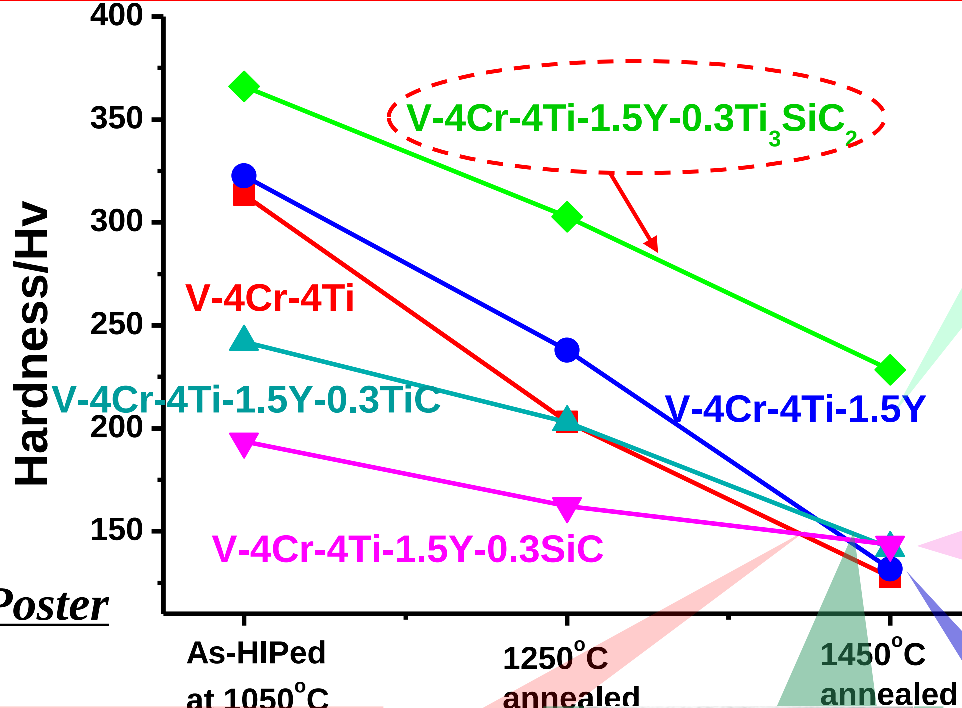
V-4Cr-4Ti-1.5Y-0.3Ti_3SiC_2
V-4Cr-4Ti-1.5Y-0.3SiC
V-4Cr-4Ti-1.5Y-0.3TiC
V-4Cr-4Ti-1.5Y
V-4Cr-4Ti

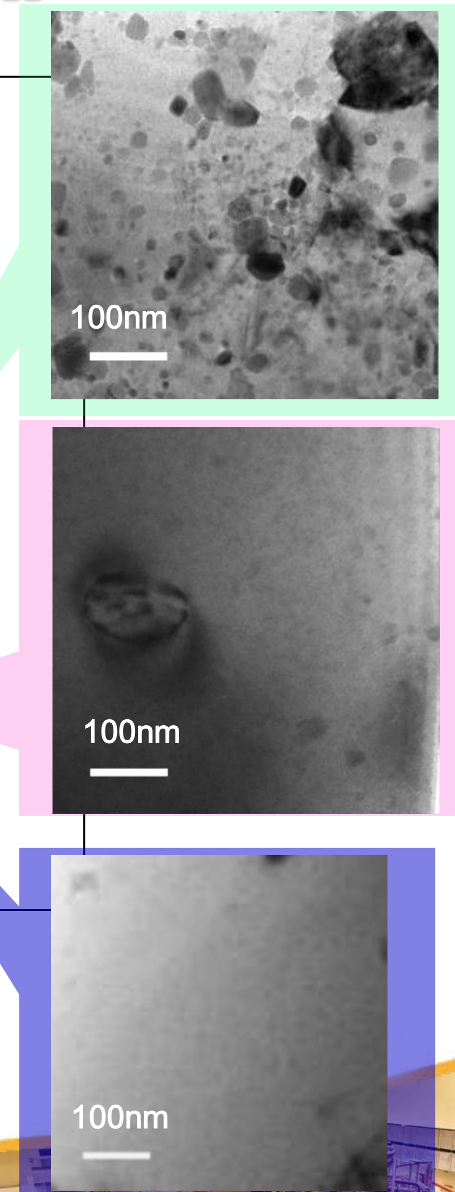


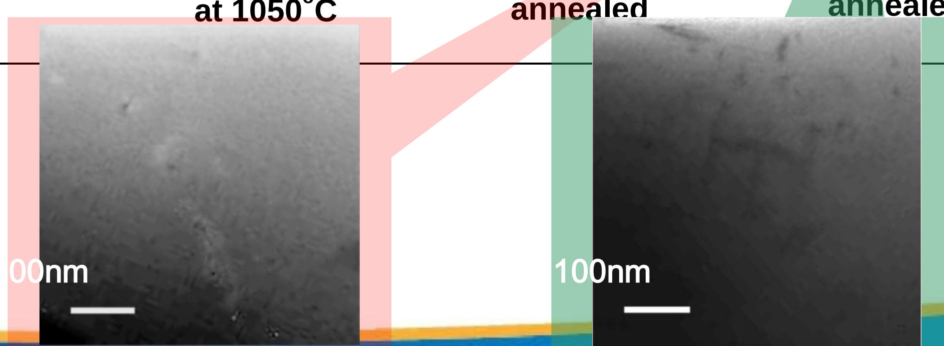
Structural materials-V alloys

--Dispersion strengthened--

Alloy with Ti_3SiC_2 addition is always the hardest
Ti_3SiC_2 has a large amount at high temperatures







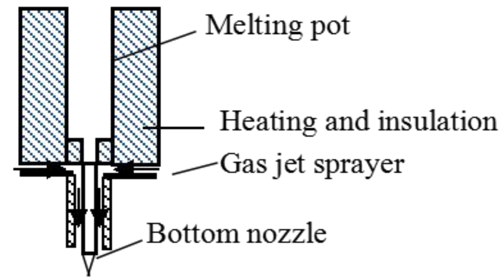
More detail:

P.F. Zheng, Poster MPT/P7-32

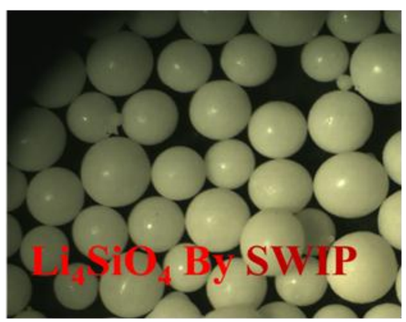
Functional materials-Tritium multiplier

Tritium Breeder Material--Li_4SiO_4 pebbles

- Tritium breeding material of the CN HCCB breeder blanket concept is a ceramic breeder in the form of pebble beds
- Reference option: Lithium Orthosilicate (Li4SiO4; OSi); 1.0 mm pebbles produced by melt-spraying process ;SWIP&KUST
- Back-up option: Lithium Metatitanate (Li2TiO3; MTi); 1.0 mm pebbles; SWIP
- For TBM → Li-6 enrichment of 80 at%



Schematic drawing of melt-spray for OSi

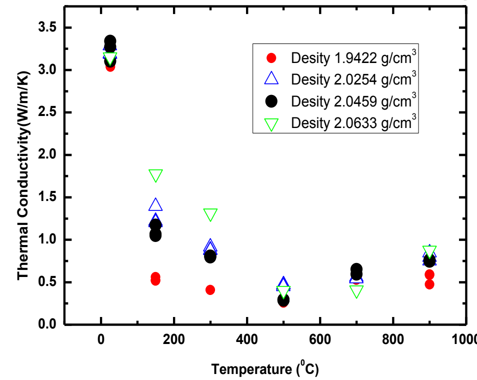



Fabrication facility

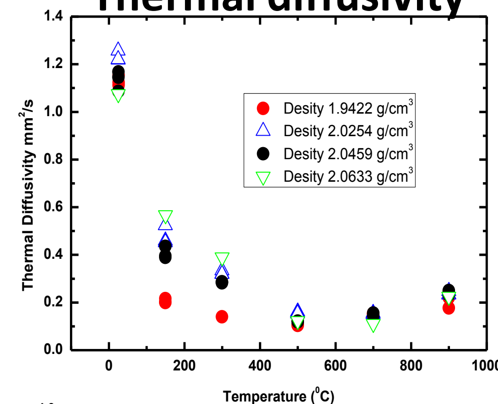
Thermal properties of Li4SiO4 pellets and pebble beds

Li_4SiO_4 pellets

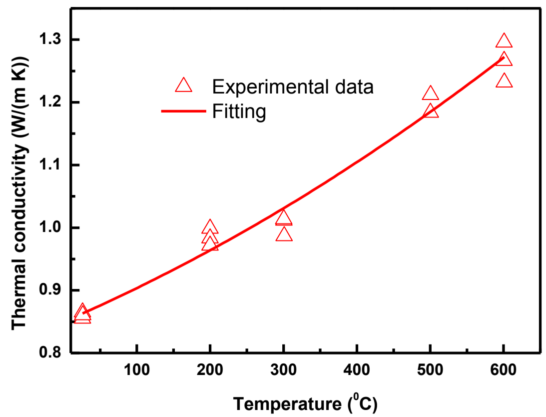
Thermal conductivity

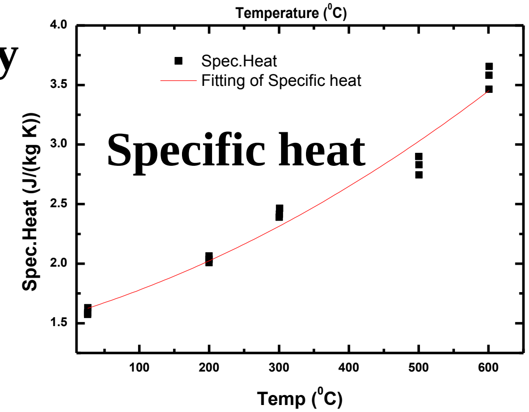


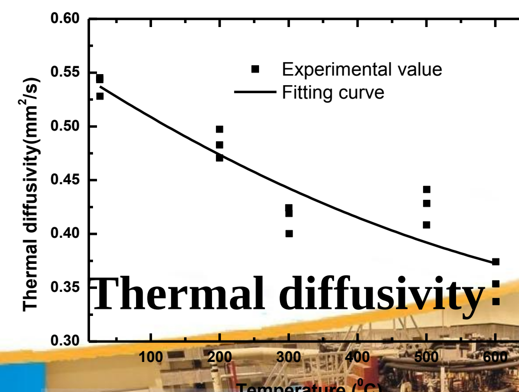
Thermal diffusivity



Effective thermal conductivity





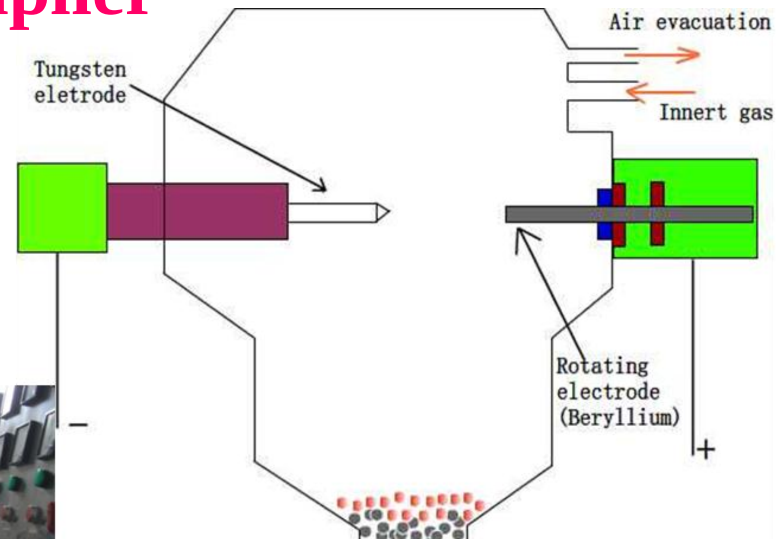


Sample	Li_4SiO_4 pebbles	Ave. diameter	~1.0 (mm)
Process	Melt spraying Method	Packing factor	60.5%

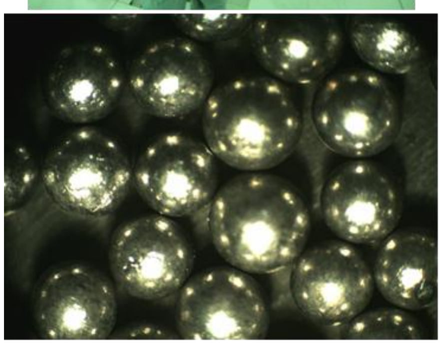
Functional materials

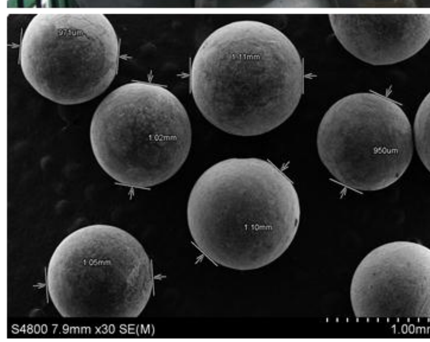
-Neutron multiplier--

Beryllium electrode



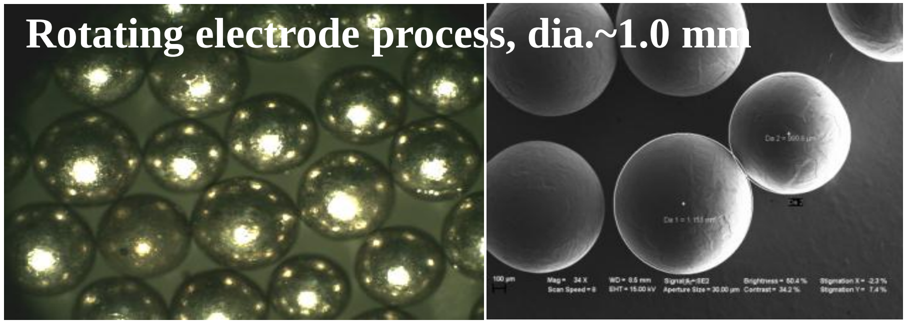
Schematic Section of the REP for Be pebbles

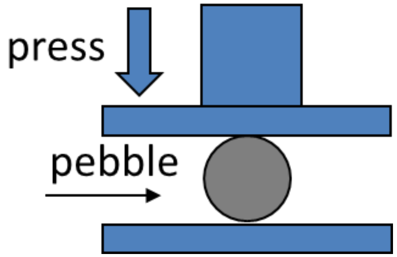


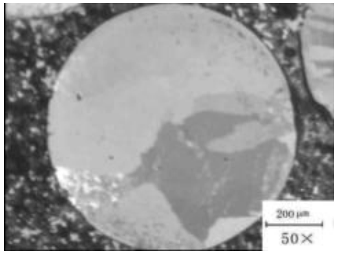


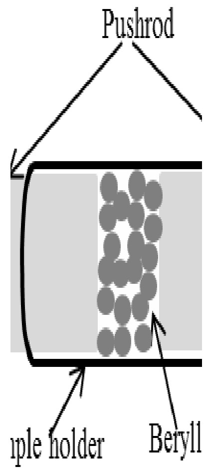
Thermal properties of Be pebbles

Rotating electrode process, dia.~1.0 mm

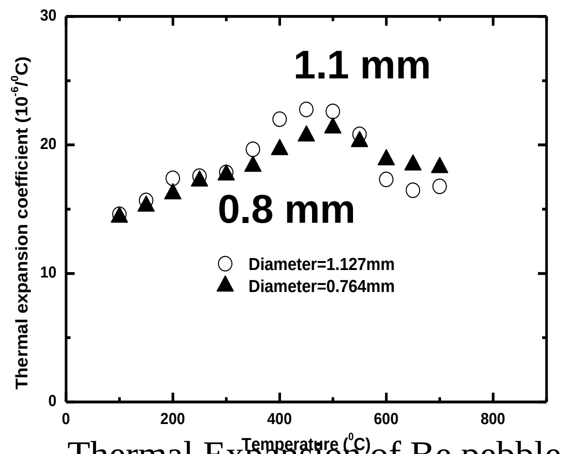




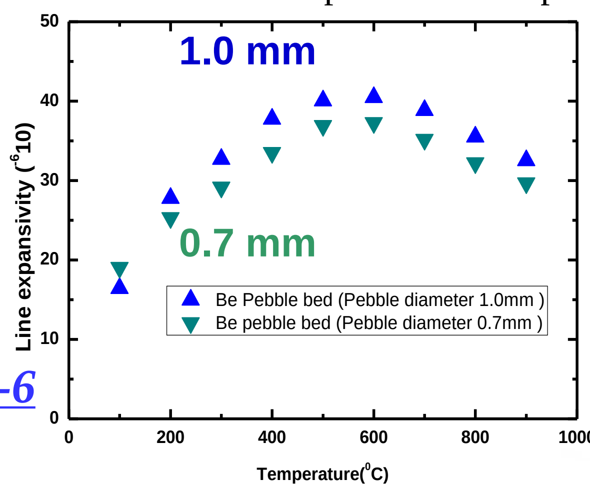


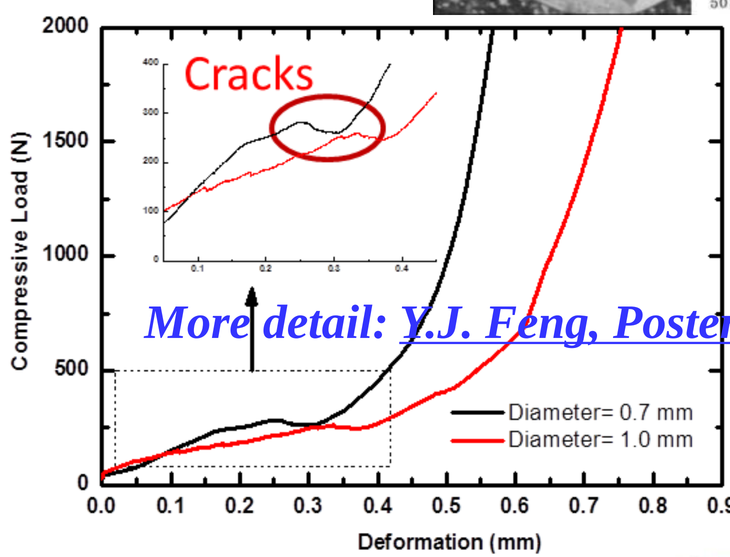


Thermal Expansion of single pebble



Thermal Expansion of Be pebble bed





More detail: Y.J. Feng, Poster MPT/P8-6

Fracture properties of the Be pebbles are not affected by pebble size remarkably

Summary

1, Fusion materials study at SWIP is focusing on the applications of HL-2A(M), ITER-TBM and CFETR or DEMO-China.

2, For PFMs/PFCs, several kinds of tungsten based materials are developed, such as oxides and carbides dispersion strengthened W alloy, and a fast CVD-W coating. They shows higher cracking thresholds at transient heat loading. CVD-W indicates a better crack suppression effect at elevated temperature.

3, One kind of RAMF steel CLF-1 is developed for the use of CN-ITER-HCCB TBM. The property data base is being established, including creep tests by more than 11000 h and neutron irradiation data at 0.3-1 dap (by the end of this year). Meanwhile Its qualification is under way according to ITER requirements.

4, An engineering scale V-4Cr-4Ti alloy (30kg) was prepared. Further strengthening by combined Y, Ti and SiC particles was carried out and V-4Cr-4Ti-1.5Y-0.3Ti_3SiC_2 shows better strengthened effects.

5, Beryllium and Li_4SiO_4 pebbles as neutron and trillium multipliers have been developed and characterized.

Thanks for your attentions !