PERFORMANCE EVALUATION OF Wf/W PFM DEVELOPED AT SWIP FOR APPLICATION IN NUCLEAR FUSION REACTORS

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Southwestern Institute of Physics

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01 Introduction and background

1. Introduction and background

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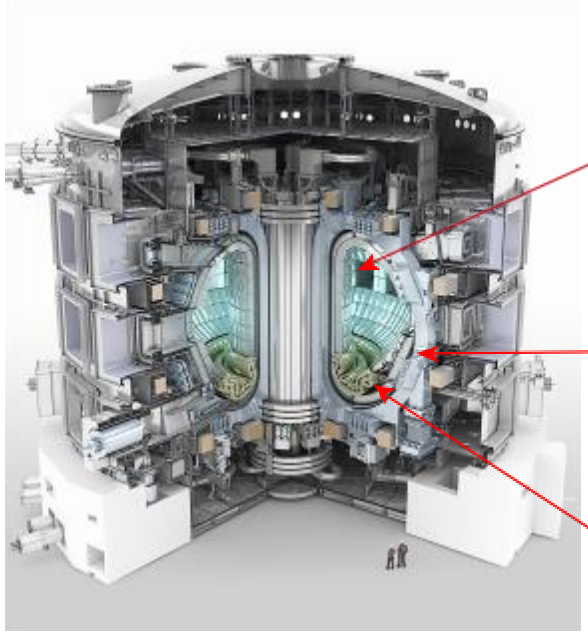
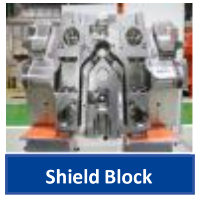
1.1 Materials development platform at SWIP

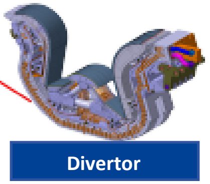
ITER In-Vessel Components



60 High-Heat-Flux First Wall Panels



220 units of Shield Block (SB)



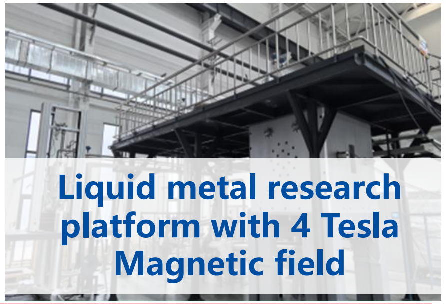
Integrated assembly of 58 cassettes

Material and component testing platform

The CNAS approved mechanical testing senario

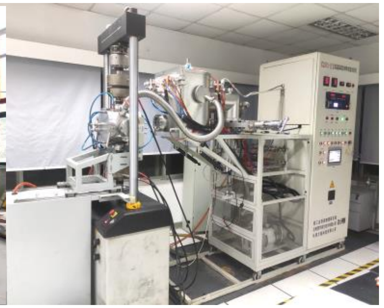
EMS-200, The IO approved HHF test technology

The 1st ISO standard in the nuclear fusion



Liquid metal research platform with 4 Tesla Magnetic field

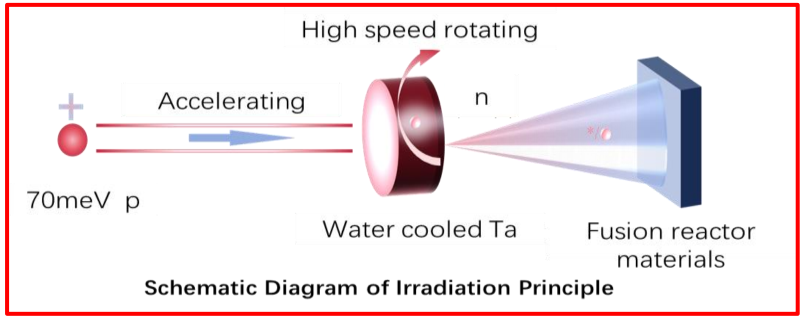
Hydrogen Sinte. Furn. (2200°C)



Fatigue machine (1600°C)

Tensile Machine (2300°C)

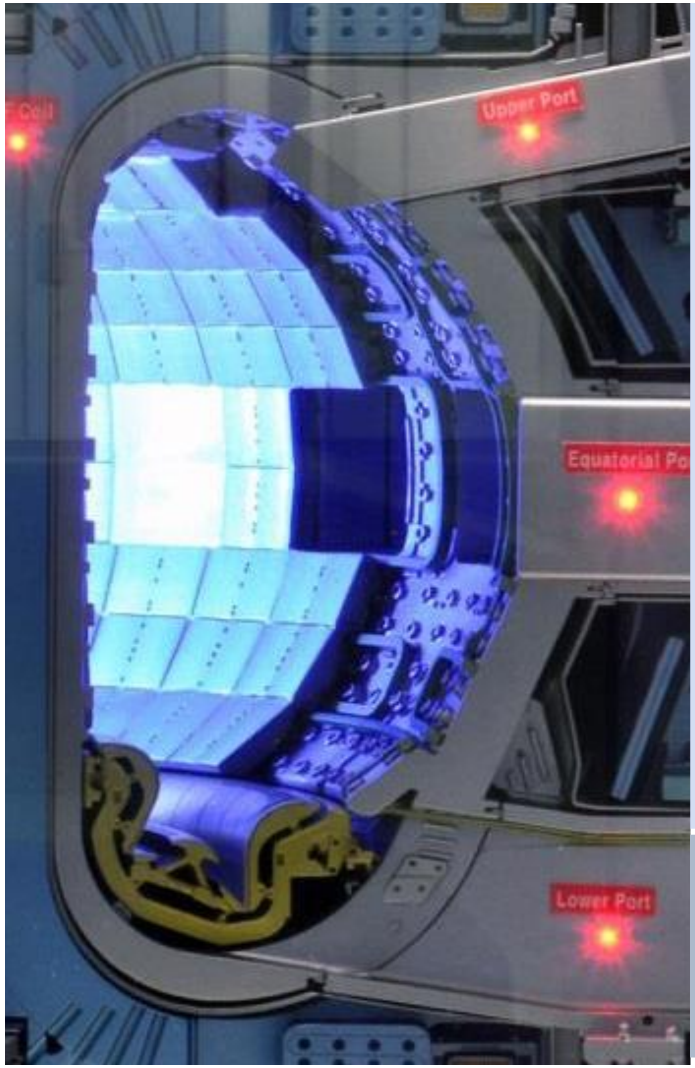
Recrystallization test furn. (2000°C)



Schematic Diagram of Irradiation Principle

1. Introduction and background

1.2 Introduction materials research at SWIP



Blanket:

Plasma facing Material:

- Tungsten plate
- CVD Tungsten

Structure Material:

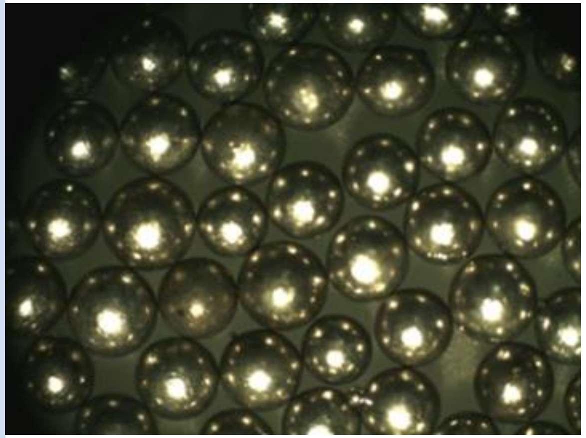
- CLF-1(TMT-CLF)
- ODS steel
- vanadium alloy/liquid metal

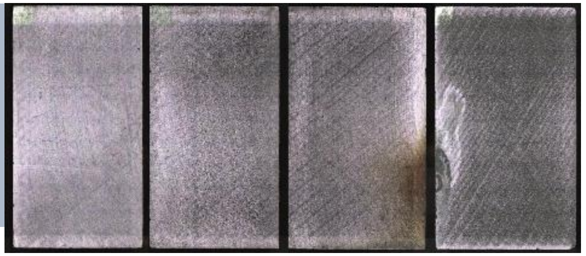
Functional Material

- Tritium Breeding: Li_4SiO_4、 Li_2TiO_3-Li_4SiO_4
- Neutron multiplier: $Be_{12}Ti$
- Barrier coatings: Al_2O_3、 HEA coatings

Divertor:

- Advanced Tungsten,
- ODS Cu/Cu alloy





1. Introduction and background

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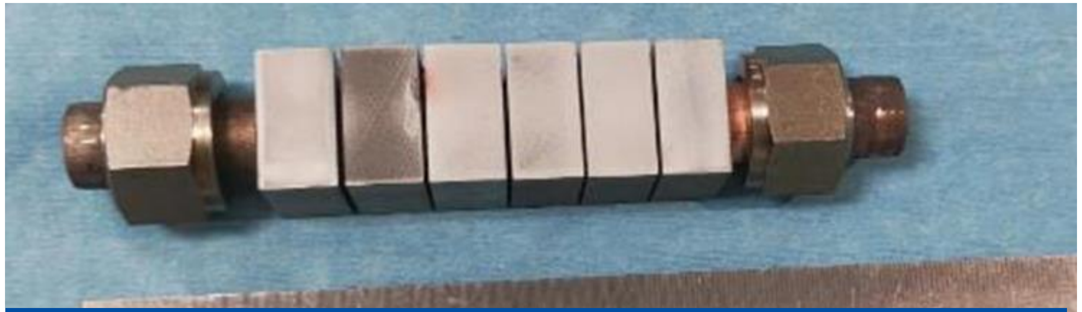
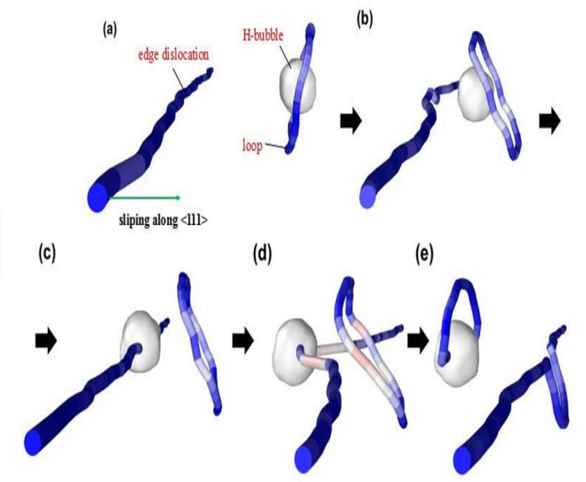
1.2 Introduction materials research at SWIP

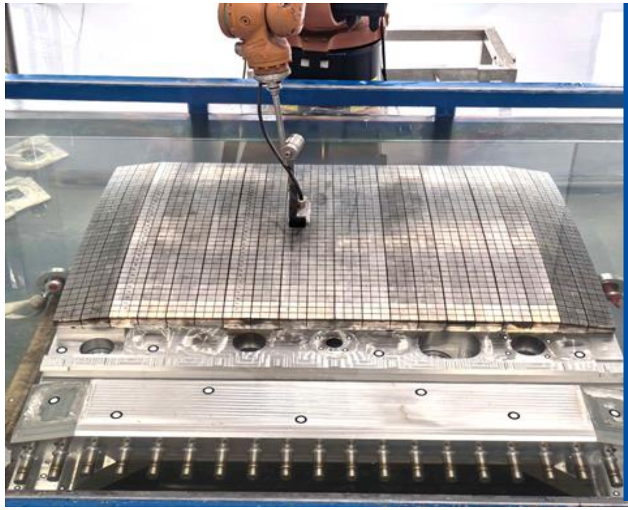
Posters 5, 8:30-12:20 17 Oct, B-55, G.Yang, Progress on the engineering qualification of CN-RAFM steel



Posters 5, 8:30-12:2017 Oct, B-67, F. Feng, HHF performance of monoblock target prepared with advanced W-K plate



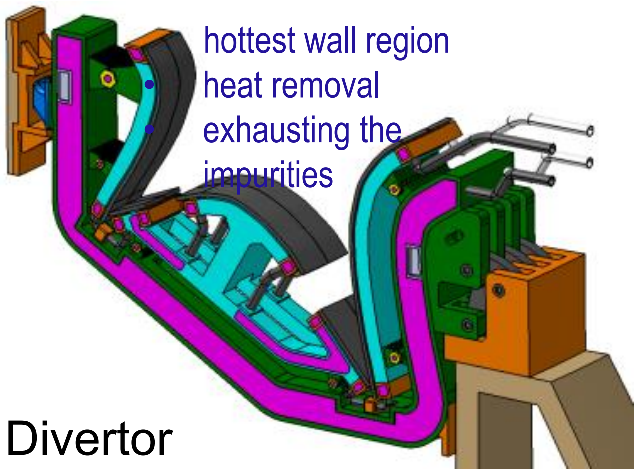
Posters 5, 8:30-12:20 17 Oct, B-68, Y.X. Wei, The interaction between the edge dislocation and the dislocation loop bubble complex under shear stress in BCC iron



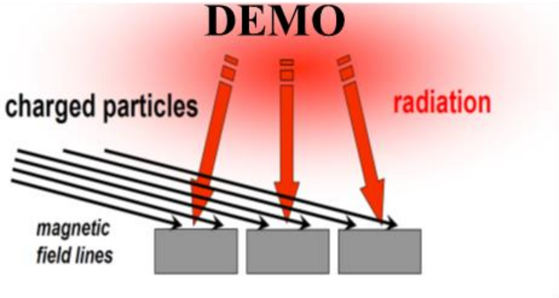
Posters 7, 8:30-10:40 18 Oct, B-36, Jiming Chen, R&D on W First Wall for ITER and Future Fusion Reactors

1. Introduction and background

1.3 Advance Tungsten PFMs research at SWIP



Divertor



HHF： ~20MW/m^2
life： > 2fpy
erosion: ~2mm/fpy
n:~2MW/m^2(3-4dpa/fpy)

P. Norajitra et al

High DBTT, Embri. due to Recry. &Neutr.

Strategy for advanced Tungsten

Multi-Component Alloys
- W-3.6Re-0.26HfC: precipitation hardened
- Self Passivating Alloys: e.g. W-Cr-(Ti/Y)
- High entropy alloys: e.g. W-Ta-Mo-Nb-V-(Hf)-(Ti)

Binary Solid Solution Alloys
- **W-Re**: typically with 3-5%, 10%,25-26 % Re, e.g. thermo-couples
- W-Ta, W-V, W-Mo, W-Ti , W-Nb

Doped Tungsten
- **Potassium** (< 100 ppm): e.g. bulb wires
- **Oxides** (< 2 %): CeO_2 , La_2O_3, (ThO_2 ,ZrO_2 ,Y_2O_3) , e.g. TIG weld electrodes
- Carbides (< 2 %) : TiC , ZrC , (TaC , NbC , HfC)

Tungsten Composites
- **Heavy Metal Alloys**: W particles (90 – 98%) in Ni-Fe or Ni-Cu-(Fe) matrix, e.g. X-ray shields
- Laminates: W foils with interlayers of Cu, Cu-Ag , Ag , V , Ta , Ti
- Fiber Composites: coated or pure W fibers embedded in W matrix

Ingot via rotary swaging

Plate of Yi2O3 doped Tungsten

1. Introduction and background

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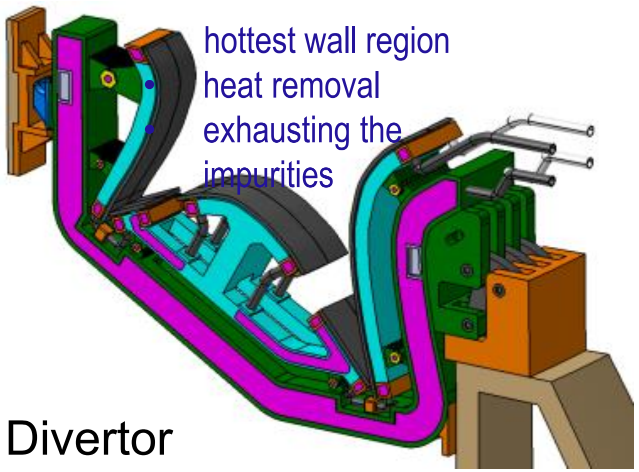
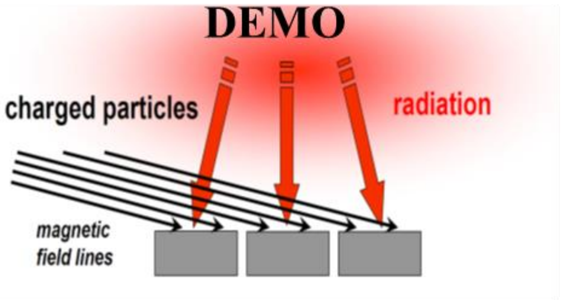
1.3 Advance Tungsten PFMs research at SWIP



Divertor



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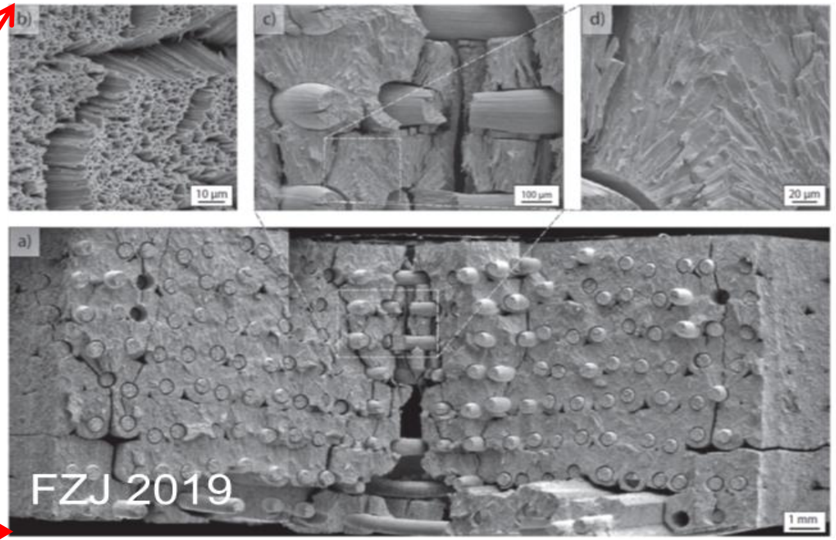
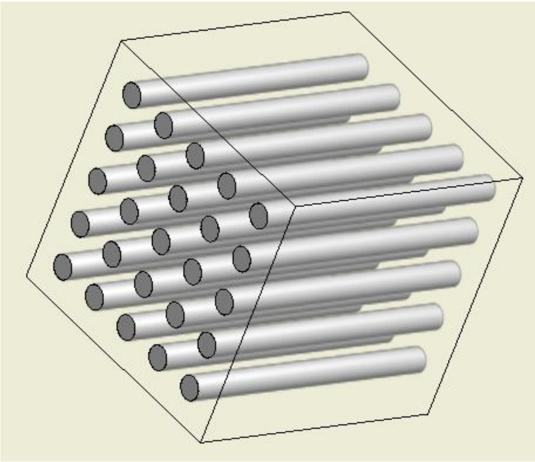
- Fiber Composites: coated or pure W fibers embedded in W matrix

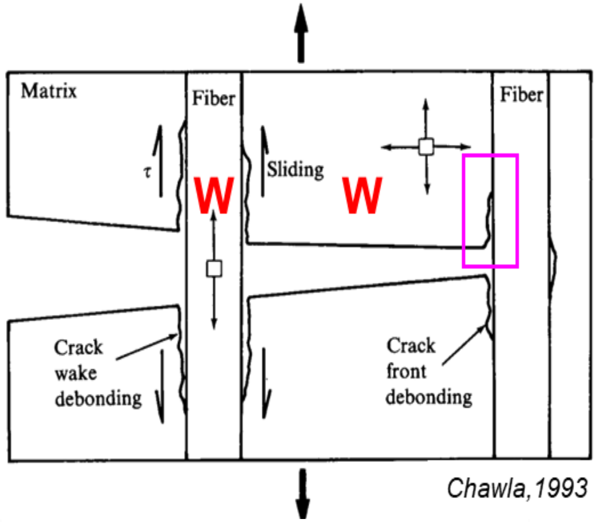
SWIP launched research on Wf/W in 2021.

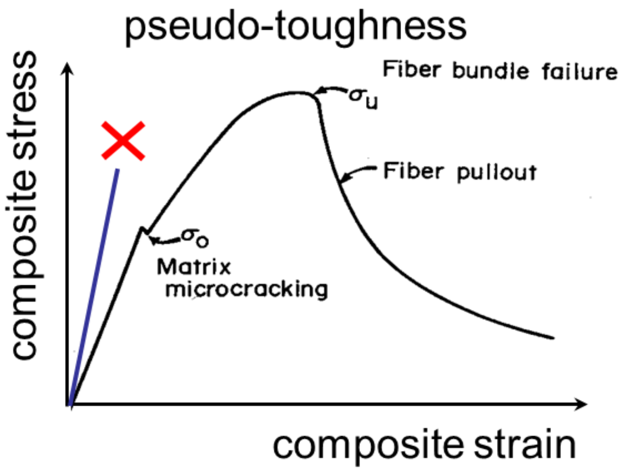


1. Introduction and background

1.4 Tungsten fiber reinforced tungsten matrix composite(Wf/W)



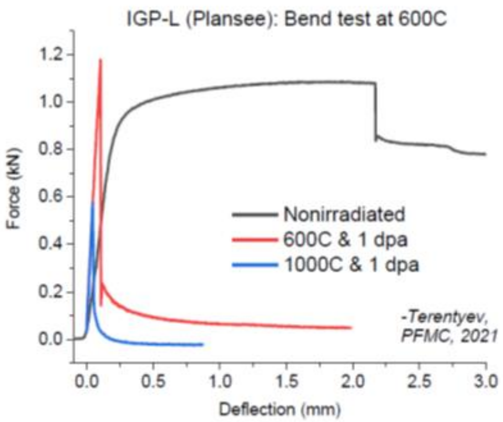


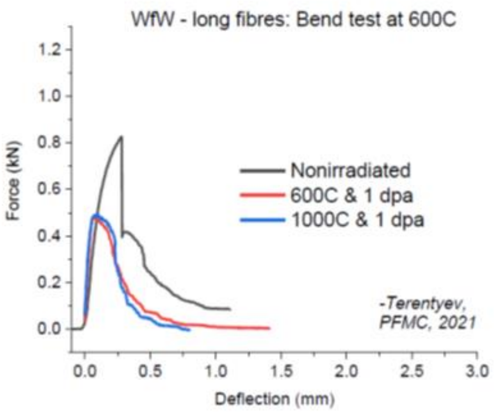


Benefit by the energy dissipation：

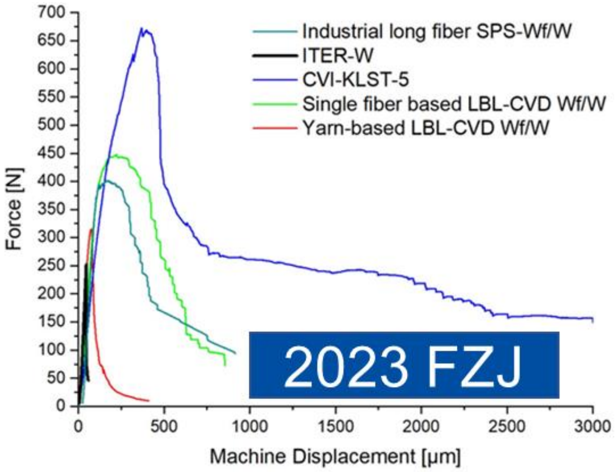
- **interface debonding**
- **fiber sliding**

W_f/W_m composite shows excellent ductility, which is called—
Pseudo Toughness.





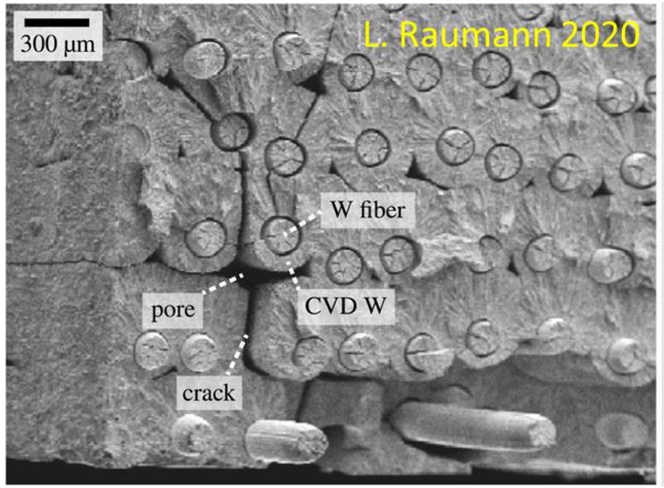
T. Hoeschen 2020



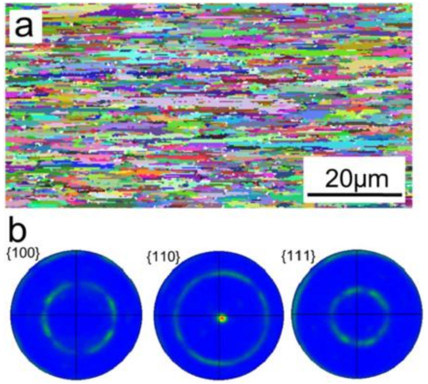
W_f/W material is one of the most promising plasma facing materials for the future fusion reactor.

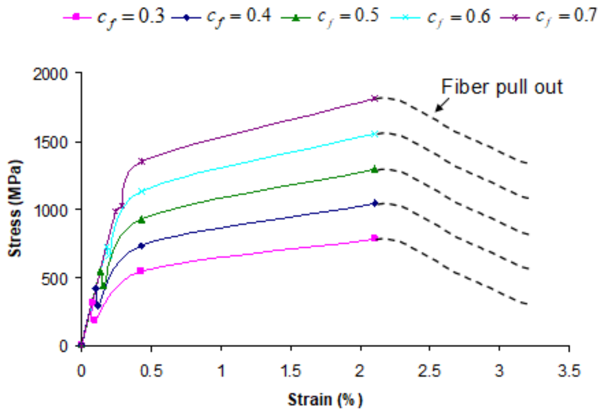
1. Introduction and background

1.5 Key points of Wf/W fabrication



Fiber volume ratio





Density

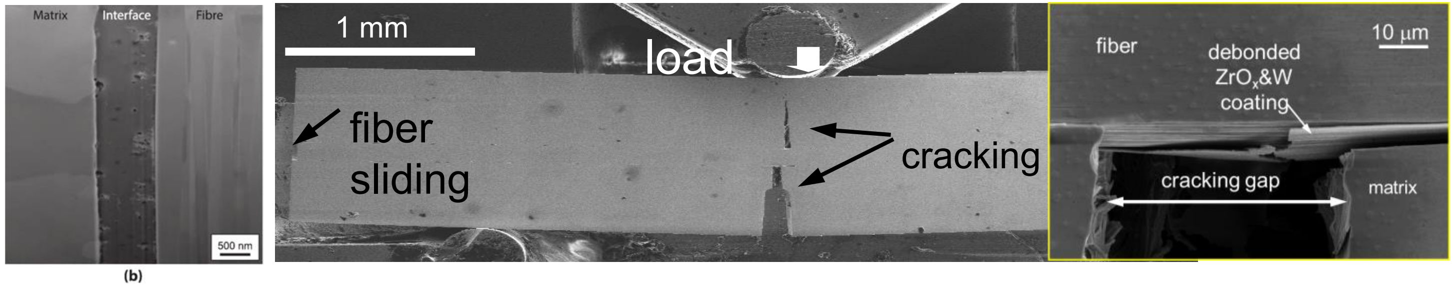
Therm. Conduct.: $\lambda = \alpha \cdot C_p \cdot \rho$, W/m·k

α —therm. Expa. Coeffi., m²/s

c_p —spec. heat capa., J/kg·K

ρ —density, kg/m³

Functional interface



Fiber volume, Functional interface, Density, 3D !

02

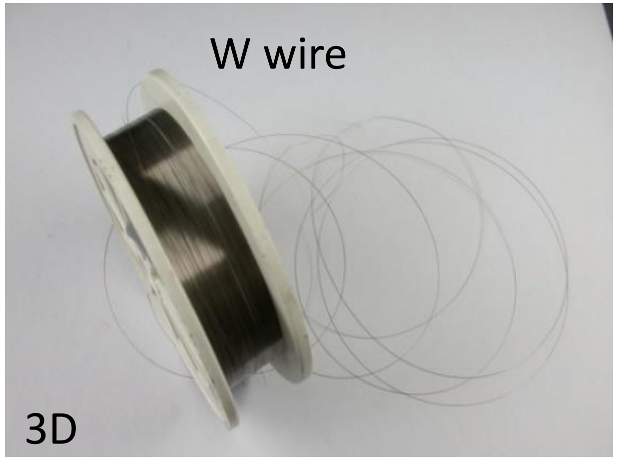
Manufacturing of Wf/W at SWIP

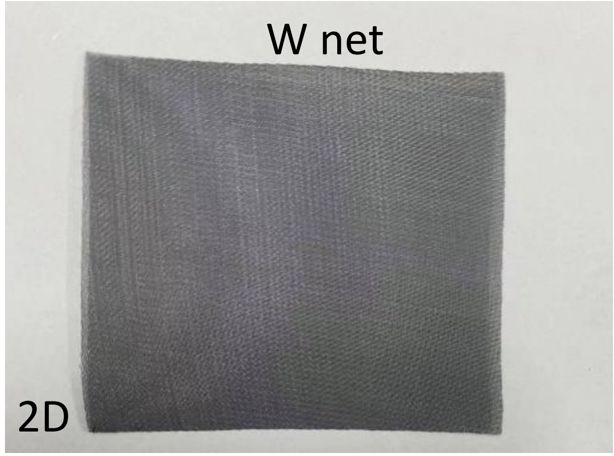
2. Manufacturing of Wf/W

2.1 Fiber with functional interface

Fiber

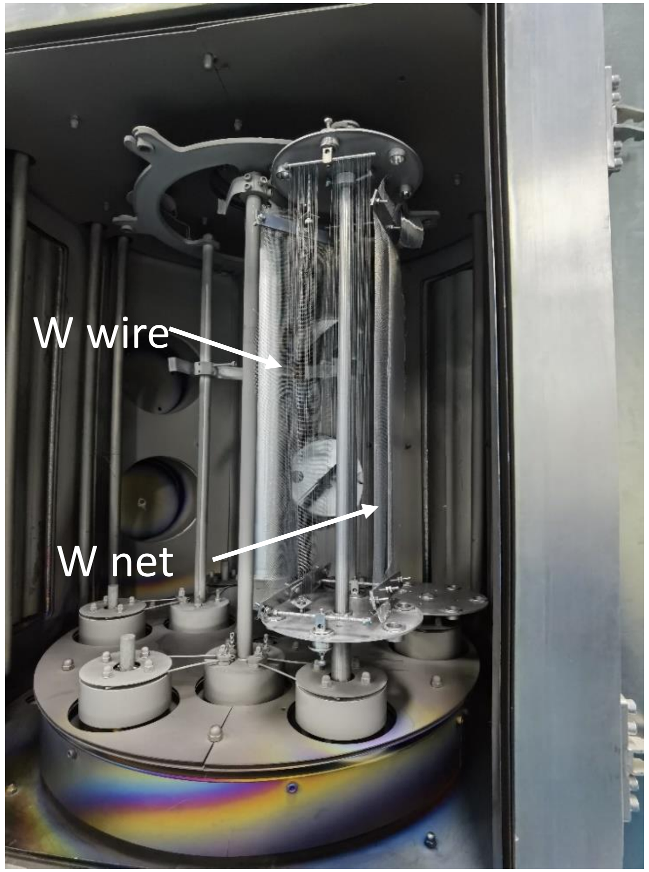
commercial W wire and W net





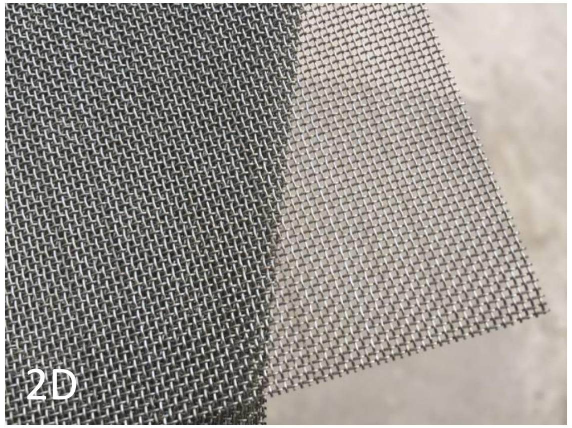
Interface

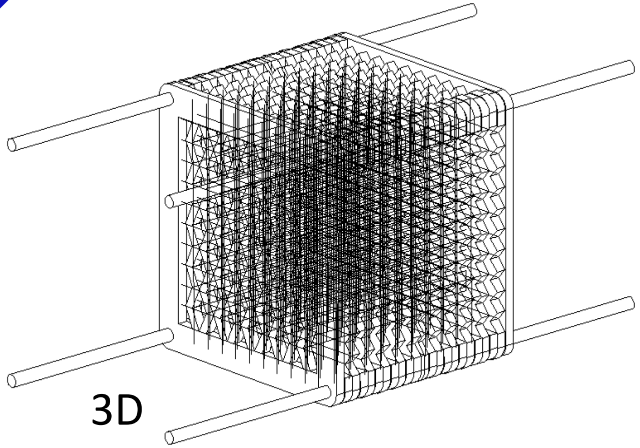
magnetron sputtering deposition



Reinforcement

fiber with interface

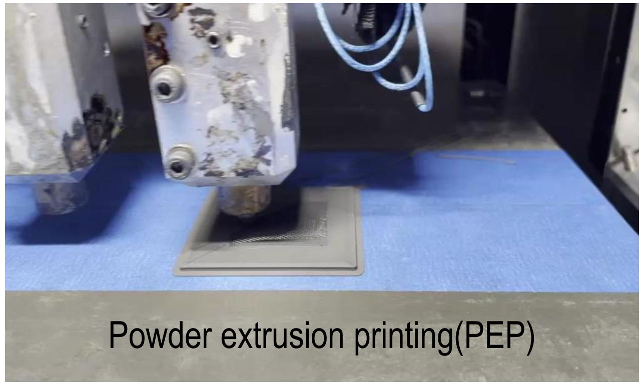




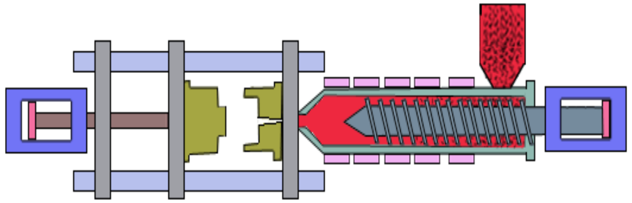
2. Manufacturing of Wf/W

2.2 Composite fabrication-green part

Green part fabrication



Powder extrusion printing(PEP)

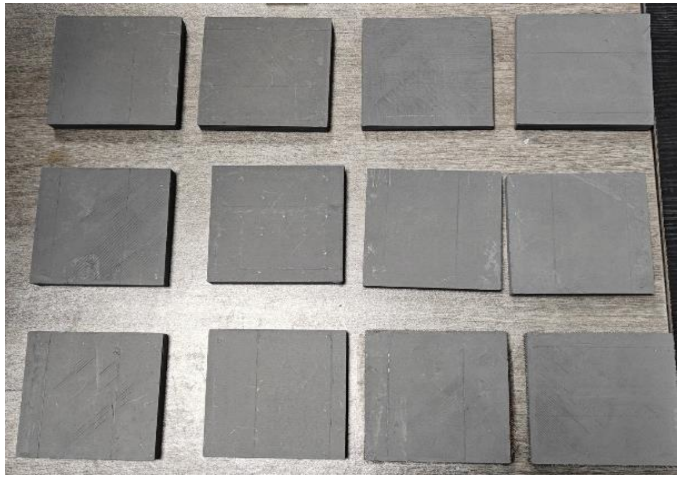


合模

Injection molding

Green part before debinding

Green part after debinding

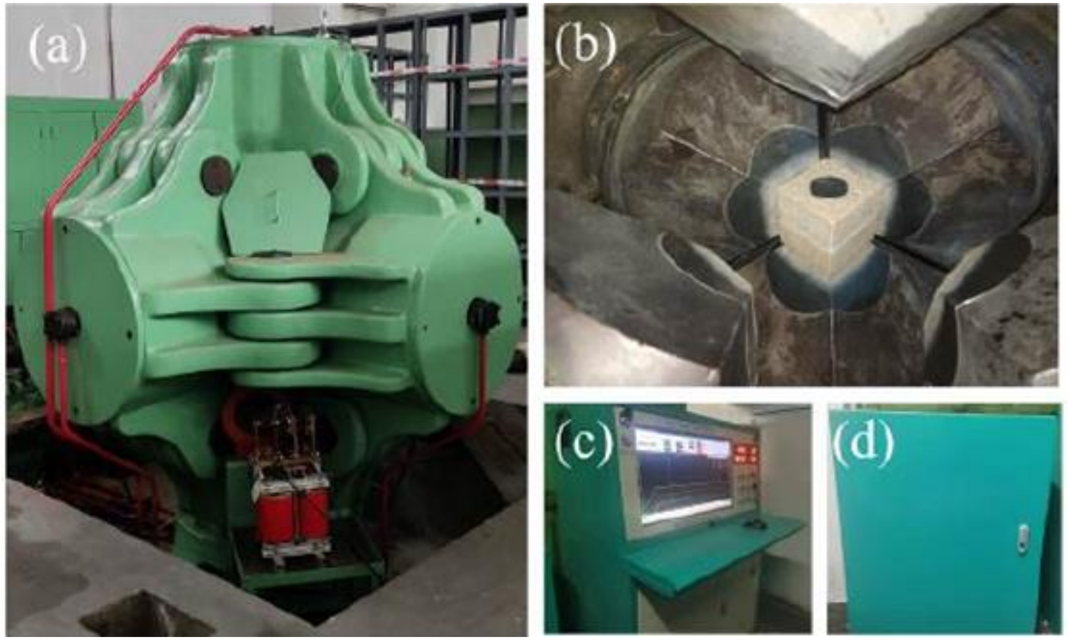


2. Manufacturing of Wf/W

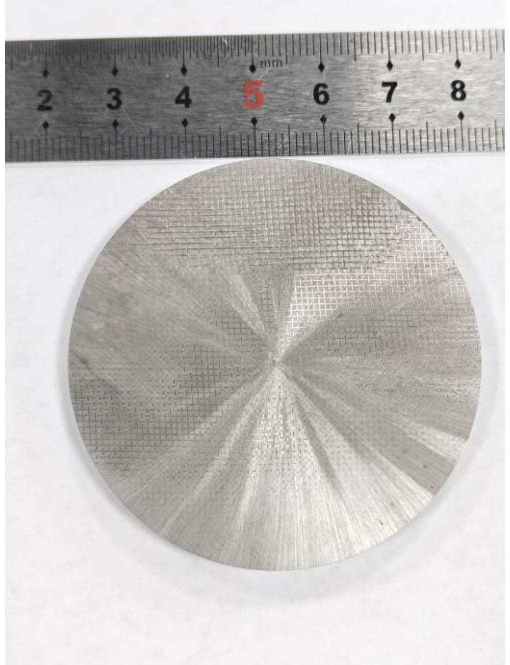
2.3 Composite fabrication-final densification

Green part

High pressure high temperature sintering device



Finished sample



86.6×86.8×10.2mm^3
Relative density:50%

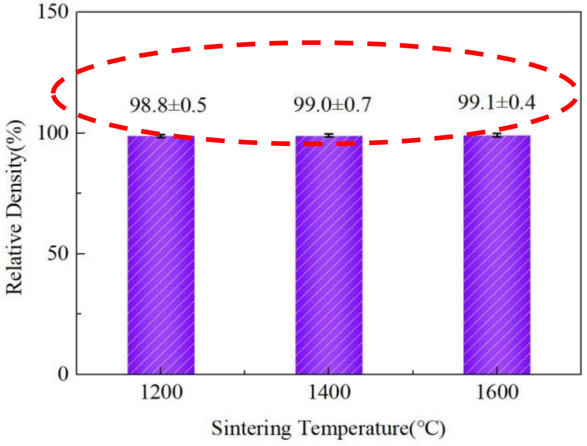
Isotropic pressure: 3~5GPa
Sintering temperature: 1400~1600℃
Sintering duration: 30min

Relative density:98~99%

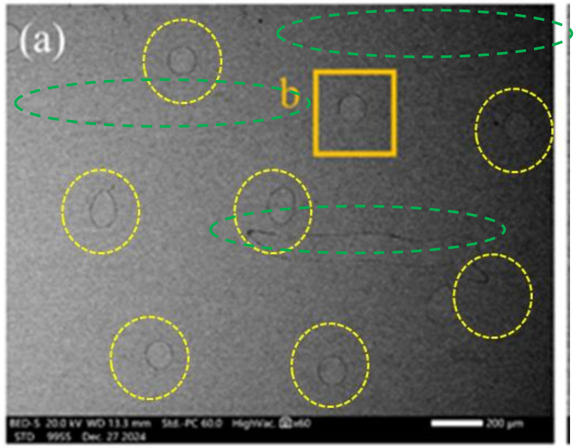
2. Manufacturing of Wf/W

2.4 Properties of Wf/W

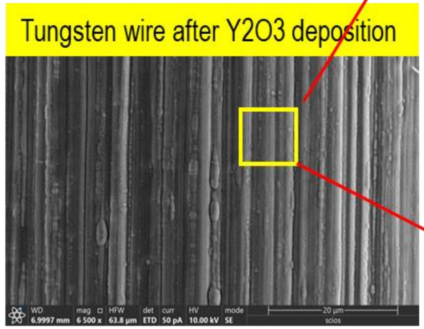
Relative density

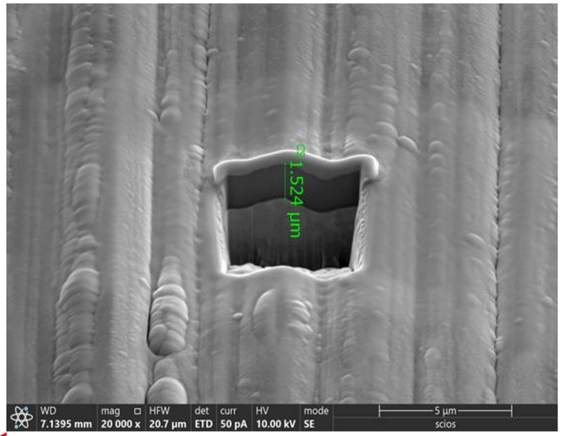


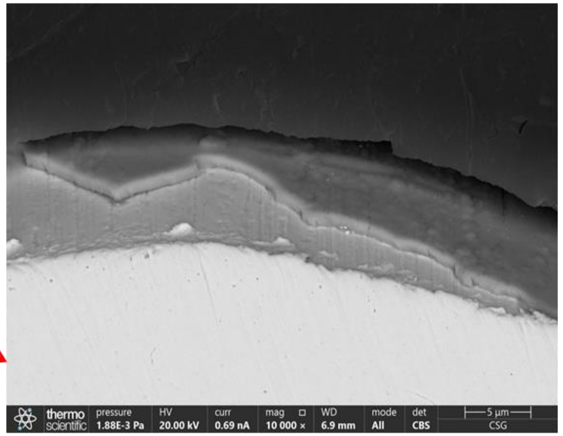
Fiber volume:3~10%

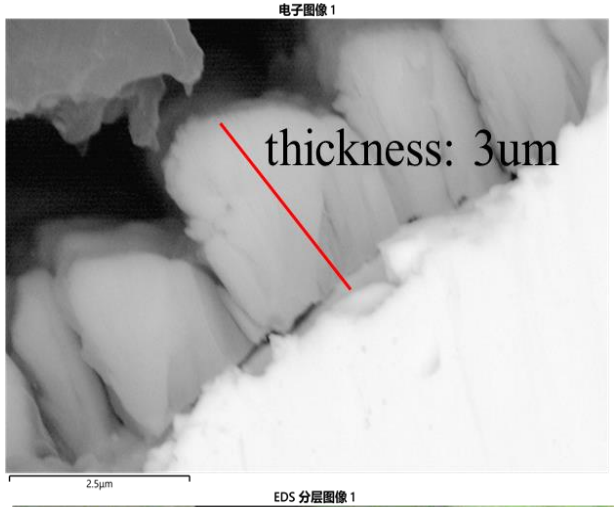


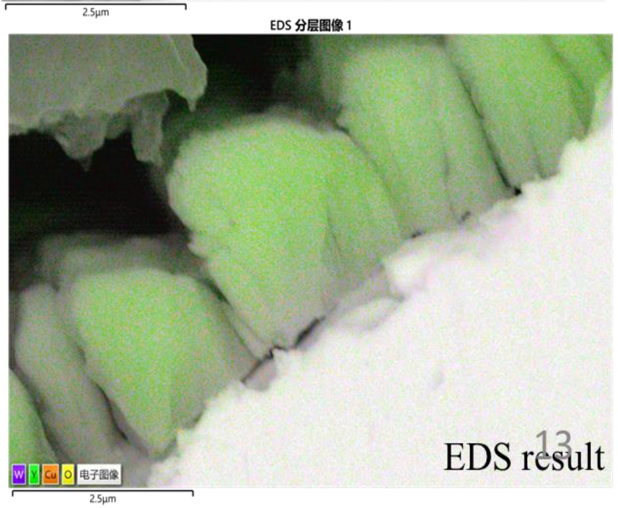
Functional interface







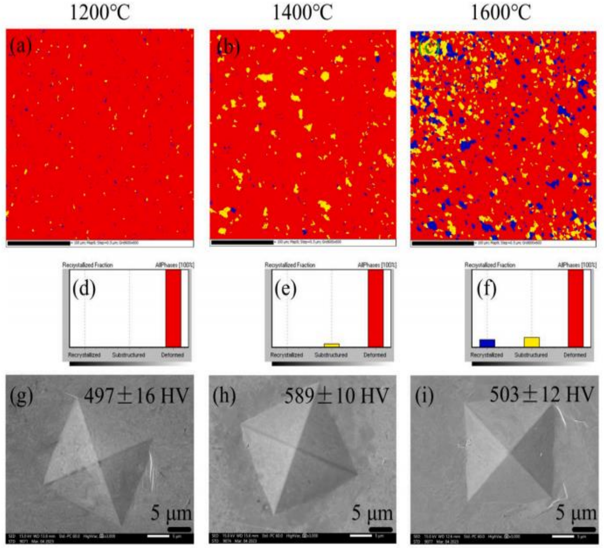




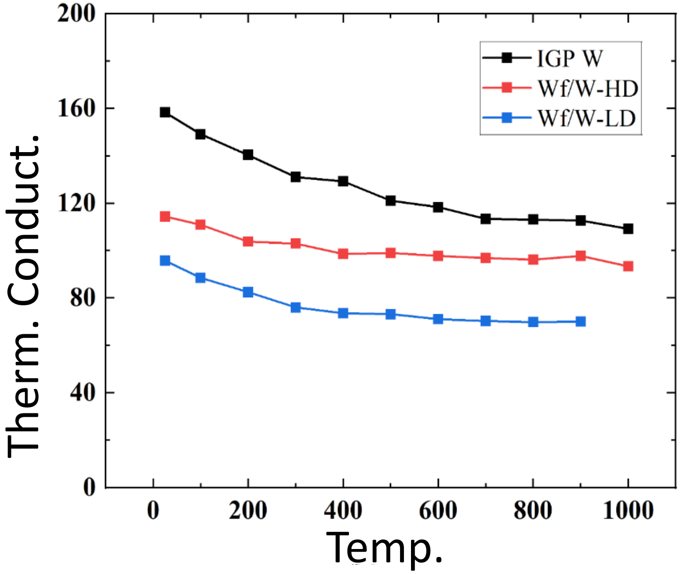
2. Manufacturing of Wf/W

2.4 Properties of Wf/W

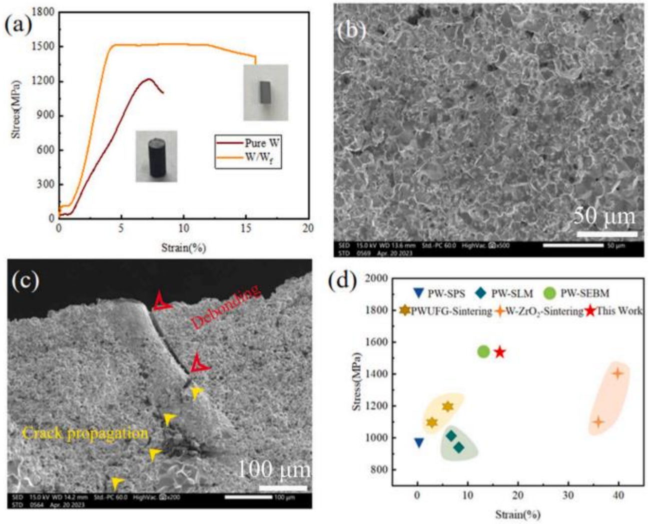
Vickers hardness



Thermal conductivity

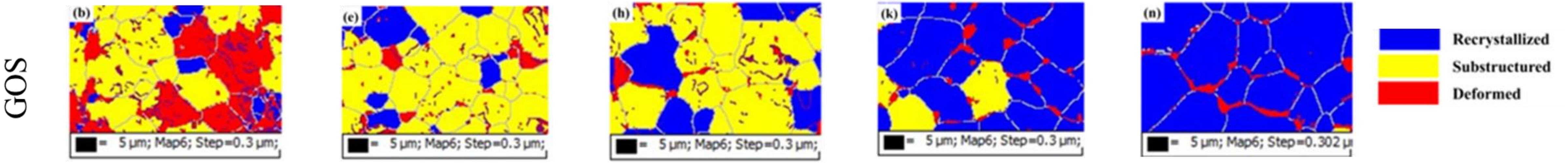


Compression test



Heat treatment test: RCT of Wf/W is around 1600℃.

1200℃,1h 1300℃,1h 1400℃,1h 1500℃,1h 1600℃,1h

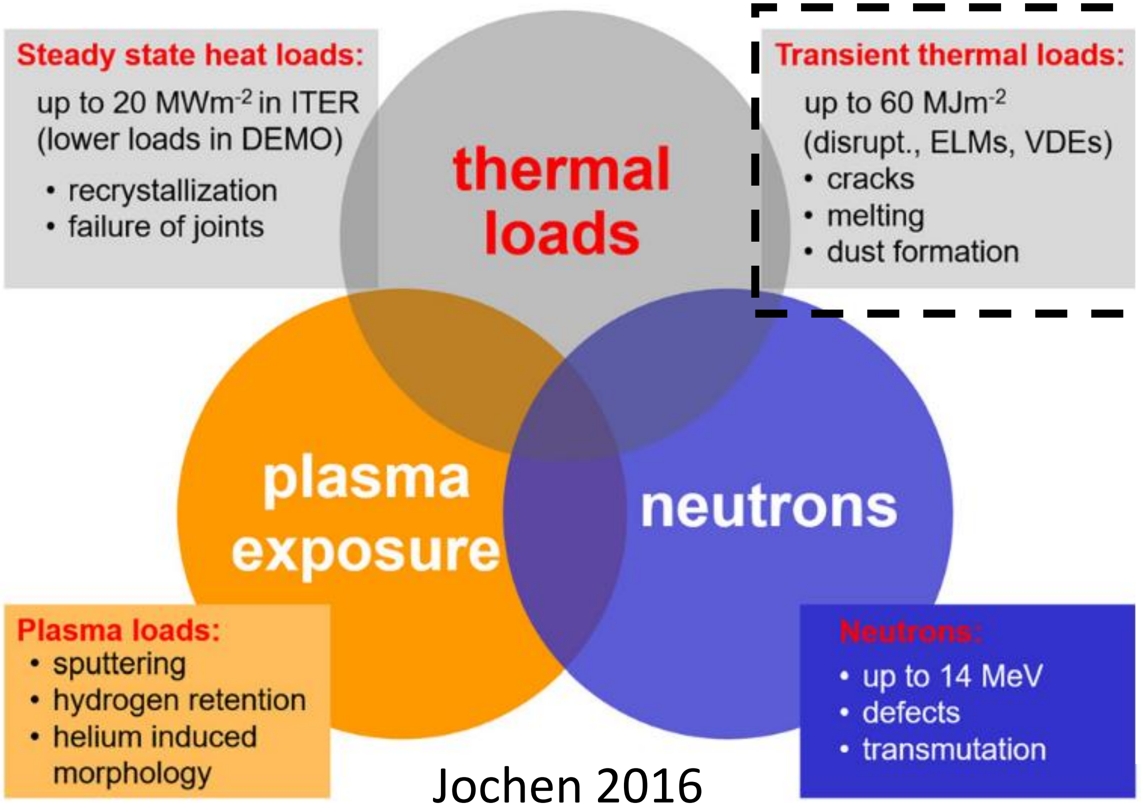


03

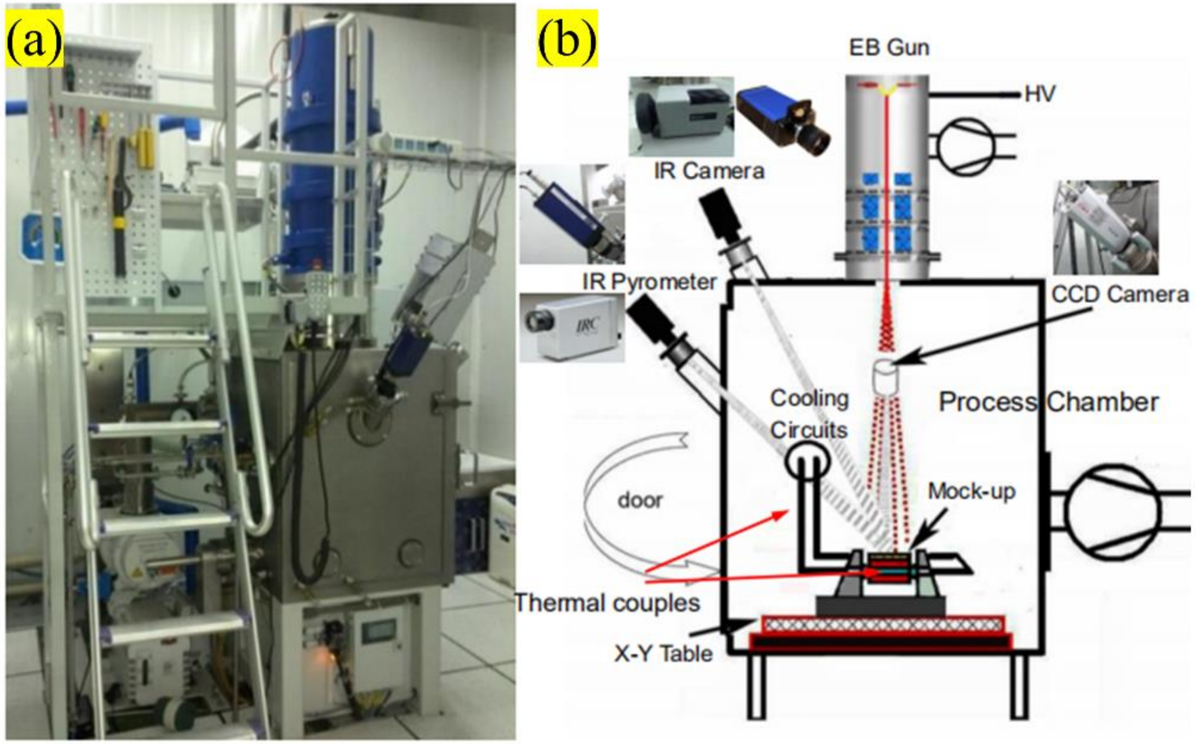
Performance of Wf/W

3. Properties of Wf/W

3.1 Performance Wf/W under transient thermal loads



Jochen 2016

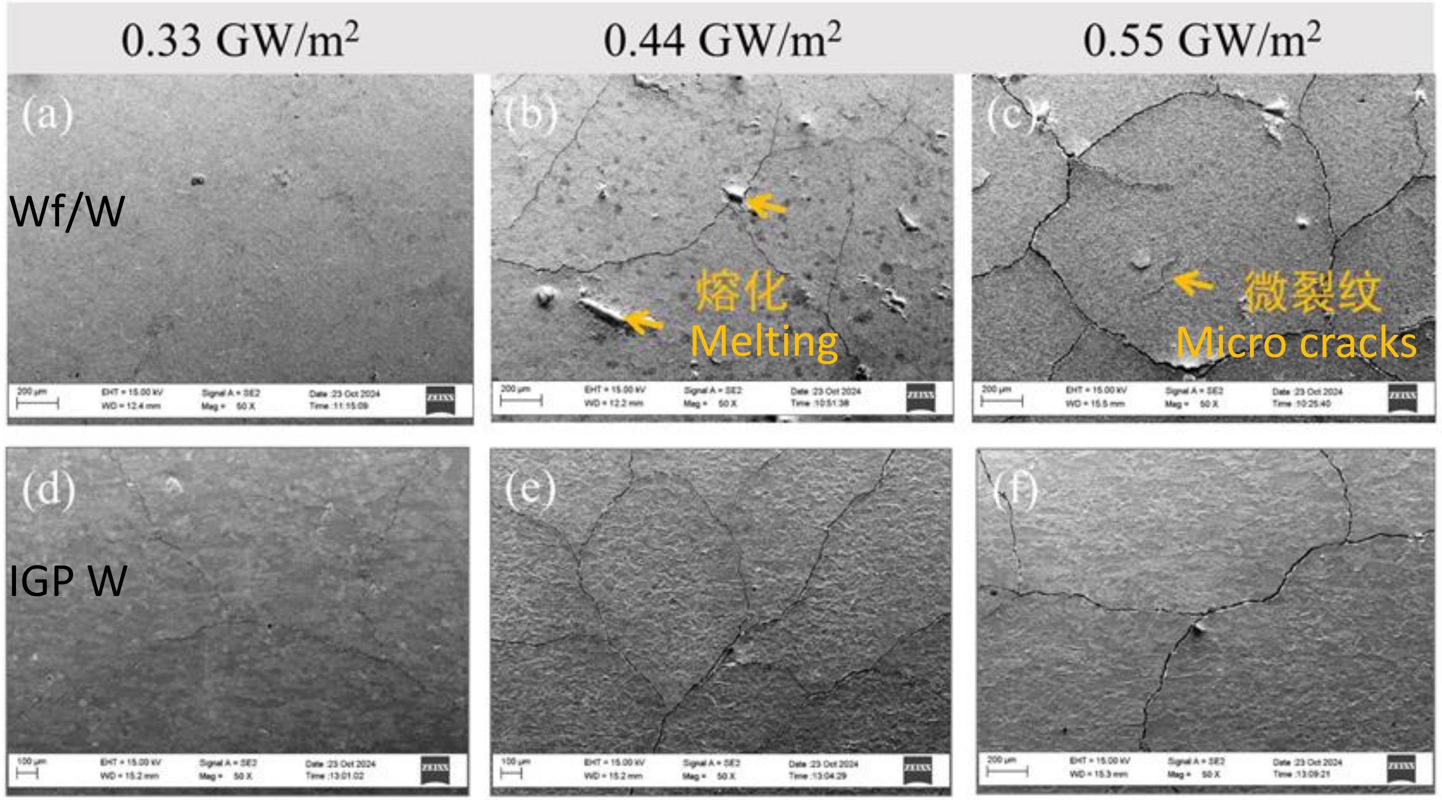


EMS-60 at SWIP, HHF via electron beam

3. Properties of Wf/W

3.1 Performance Wf/W under transient thermal loads

Morphology of top surface the samples after 100 cycles



Cracking threshold comparison

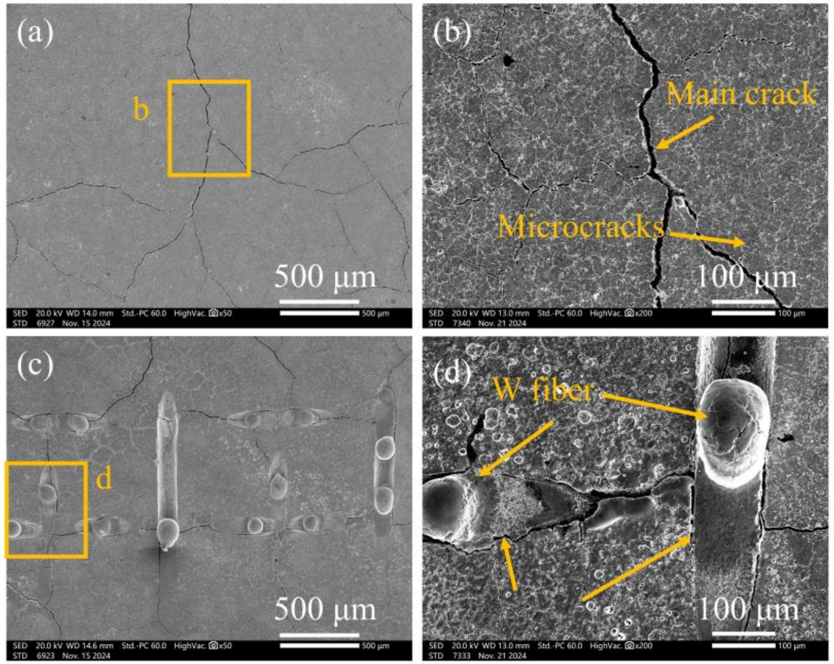
Tungsten grades	Pulse duration (s)	Cracking threshold (GW/m^2)
IGP W	1	0.22-0.33
W-K via SPS	5	0.37-0.50
W via SPS	5	< 0.37
W Forged	1	0.19-0.38
W-Y2O3 Forged	1	0.22-0.33
W-ZrC via SPS	1	0.22-0.33
W-ZrC Rolled	1	0.22-0.33
W-TaC Rolled	1	0.33-0.44
Wf/W(this work)	1	0.33-0.44

- Cracking threshold is higher than IGP W and comparable to most advanced W！

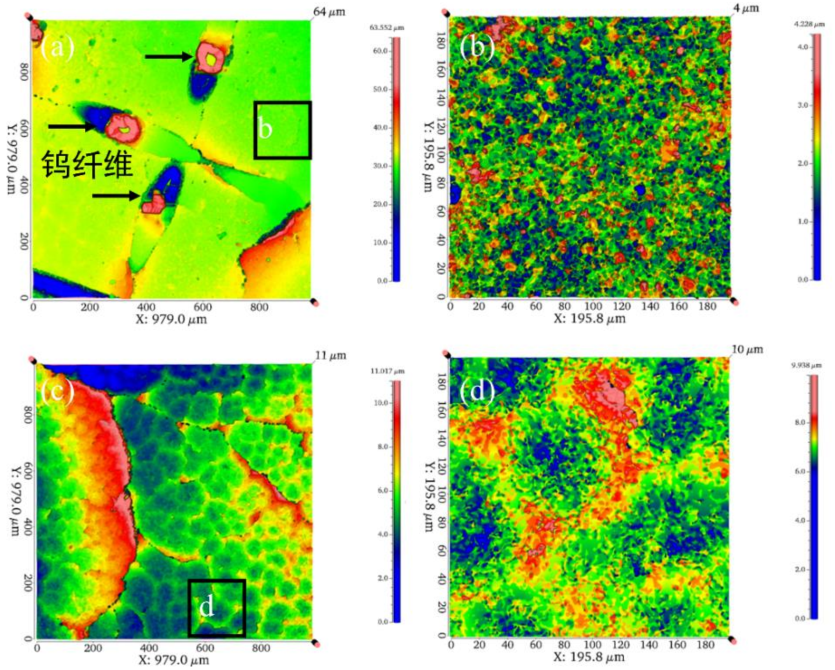
3. Properties of Wf/W

3.1 Performance Wf/W under transient thermal loads

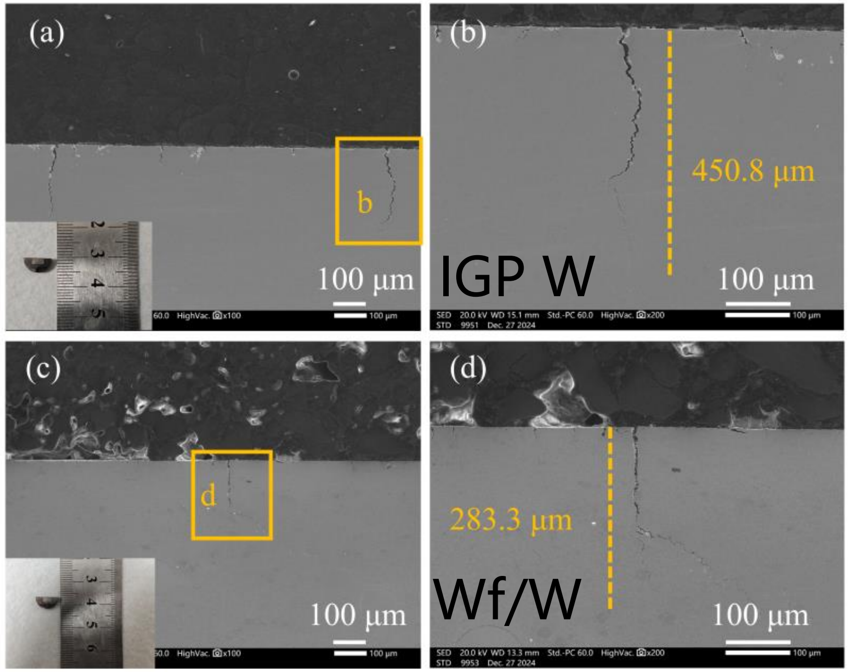
Morphology of top surface the samples after 1000 cycles @ 0.55 GW/m^2



Top surface



Roughness

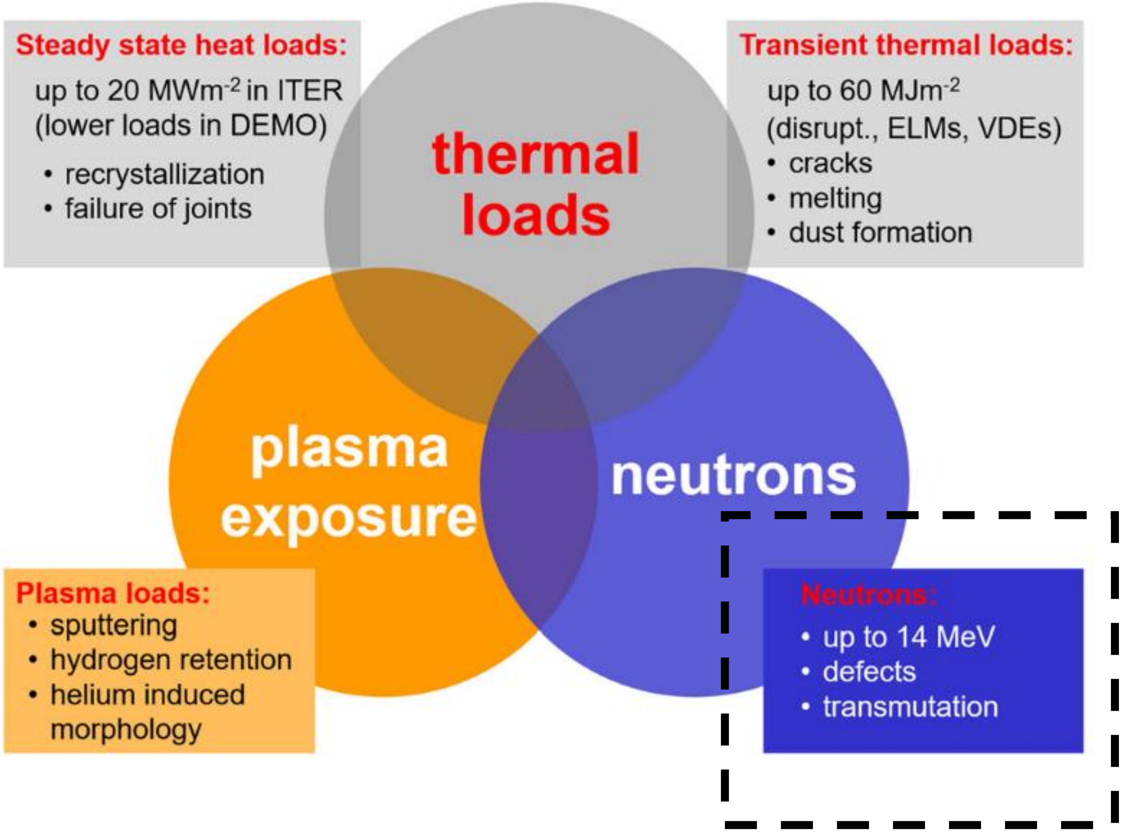


Cross section image

- Crack depth is reduced by 40% due to the pseudo toughness!

3. Properties of Wf/W

3.2 Performance Wf/W under displacement damage

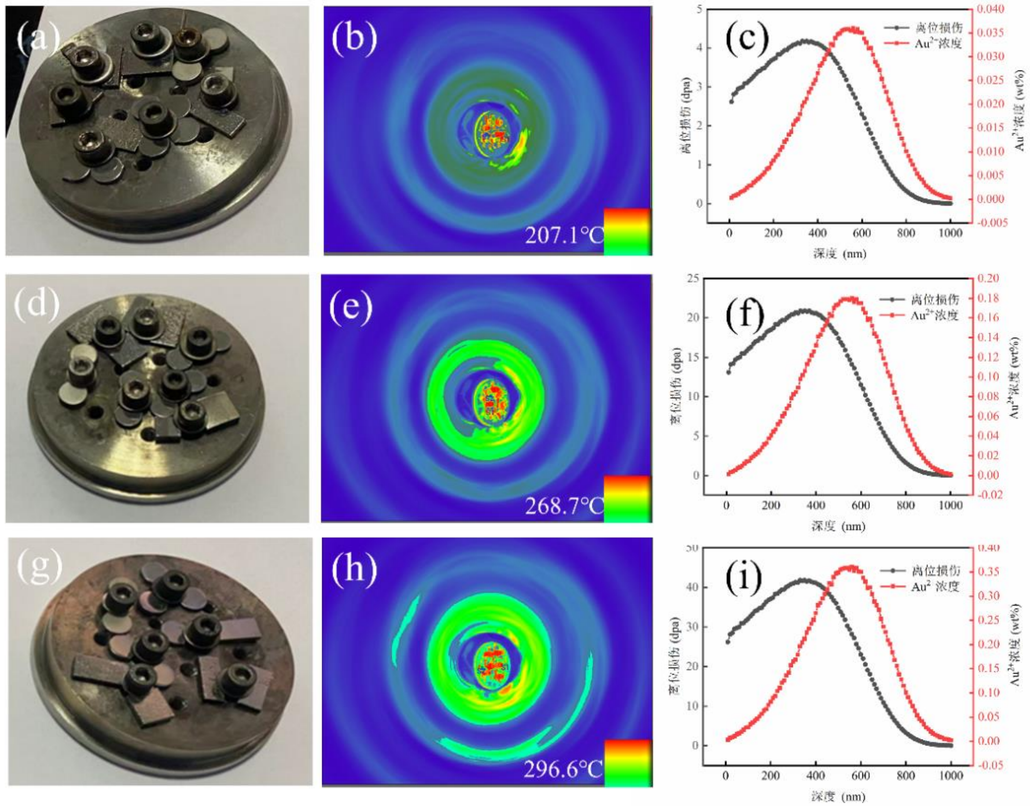


HVE-3MV Tandetron Accelerator at SCU

3. Properties of Wf/W

3.2 Performance Wf/W under displacement damage

7.5 MeV Au^{2+}， total accumulated fluences were $1*10^{15}$ ion/cm²、5×10^{15} ion/cm² and $1*10^{16}$ ion/cm²

Fluences		Peak damage
$1*10^{15}$ ion/cm²		4.5 dpa
5×10^{15} ion/cm²		22.5 dpa
$1*10^{16}$ ion/cm²		45 dpa

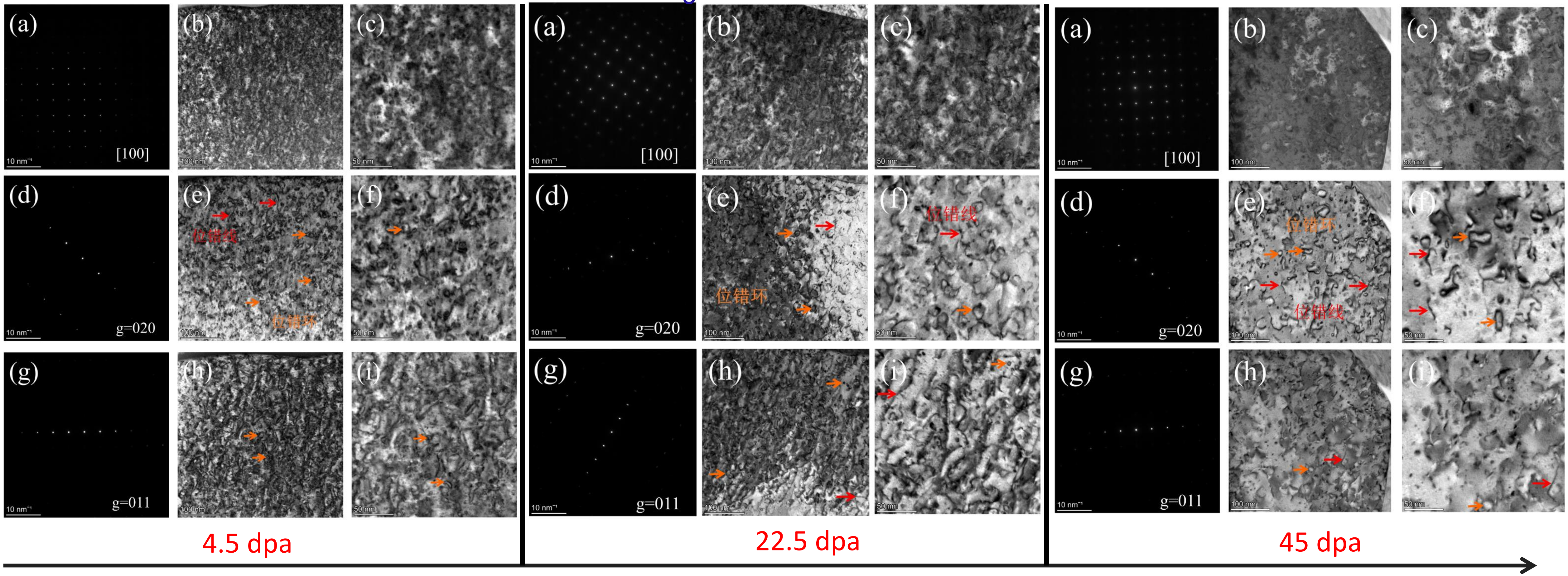
Via SRIM calculation, the damaged zone extends to around 800 nm and the peak damage is located at around 400 nm.

3. Properties of Wf/W

3.2 Performance Wf/W under displacement damage

7.5 MeV Au^{2+}， total accumulated fluences were $1*10^{15}$ ion/cm²、 5×10^{15} ion/cm² and $1*10^{16}$ ion/cm²

Damage evolution in matrix



- The damage accumulate more due to the increase of dpa dose.

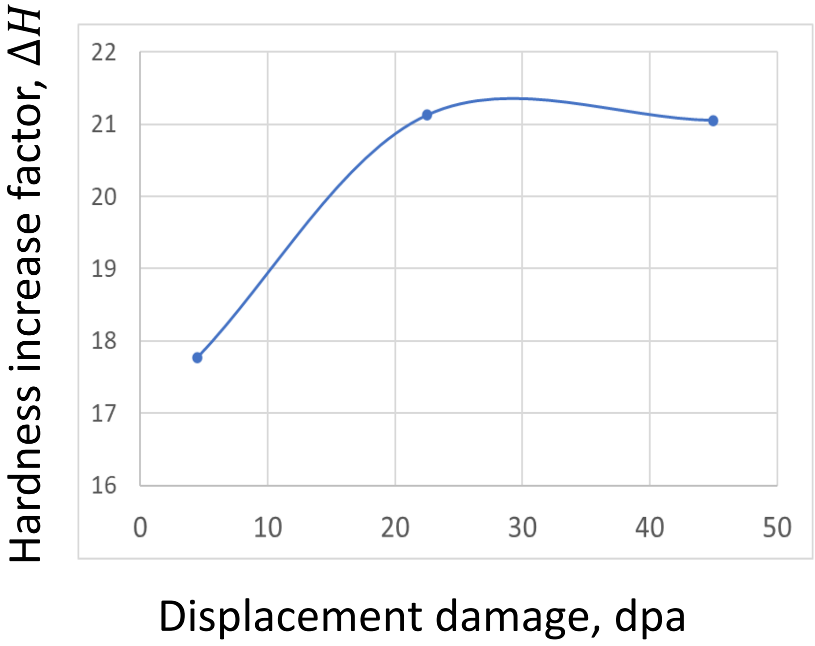
3. Properties of Wf/W

3.2 Performance Wf/W under displacement damage

Dislocation summary

Disp. Dama(dpa)	Average size of the dislocation loop d (nm)	Density of dislocation loop N ($/cm^3$)
4.5	4.03	4.41×10^{16}
22.5	8.95	2.36×10^{16}
45	10.63	1.98×10^{16}

$$\Delta H \propto N^{1/2} \cdot \mathrm{d}^{1/2}$$

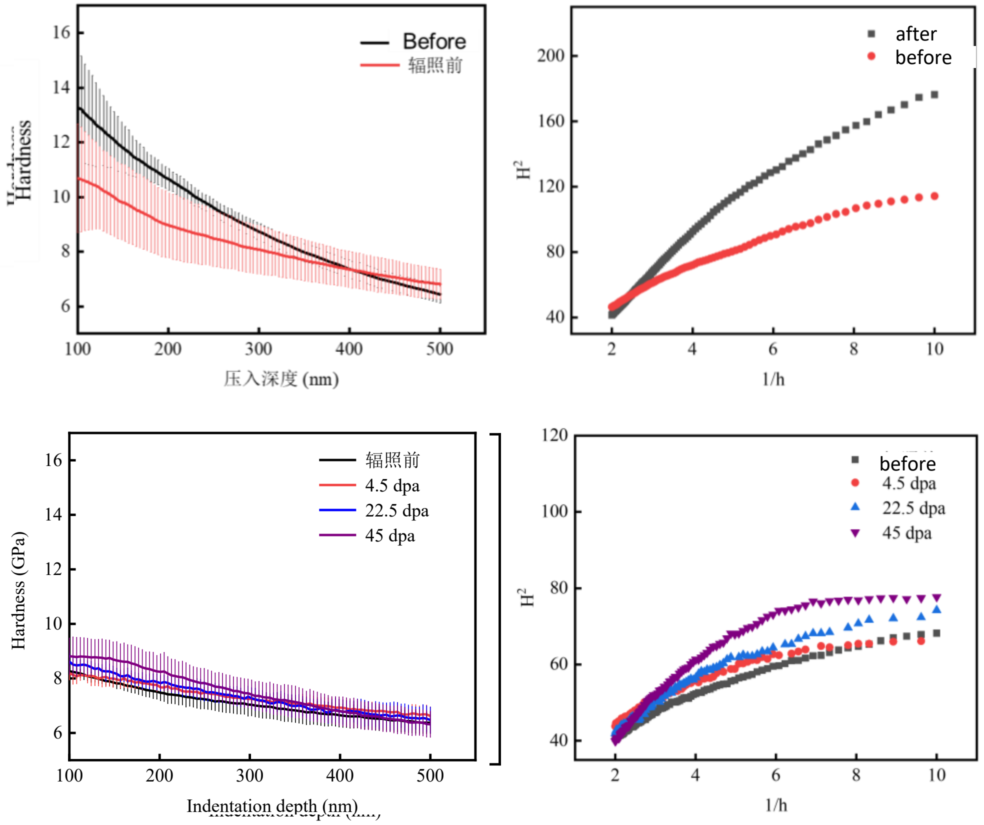


- The damage accumulate more due to the increase of dpa, with a saturation phenomenon after high dose of damage.

3. Properties of Wf/W

3.2 Performance Wf/W under displacement damage

Irradiation hardening via Nano-indentation



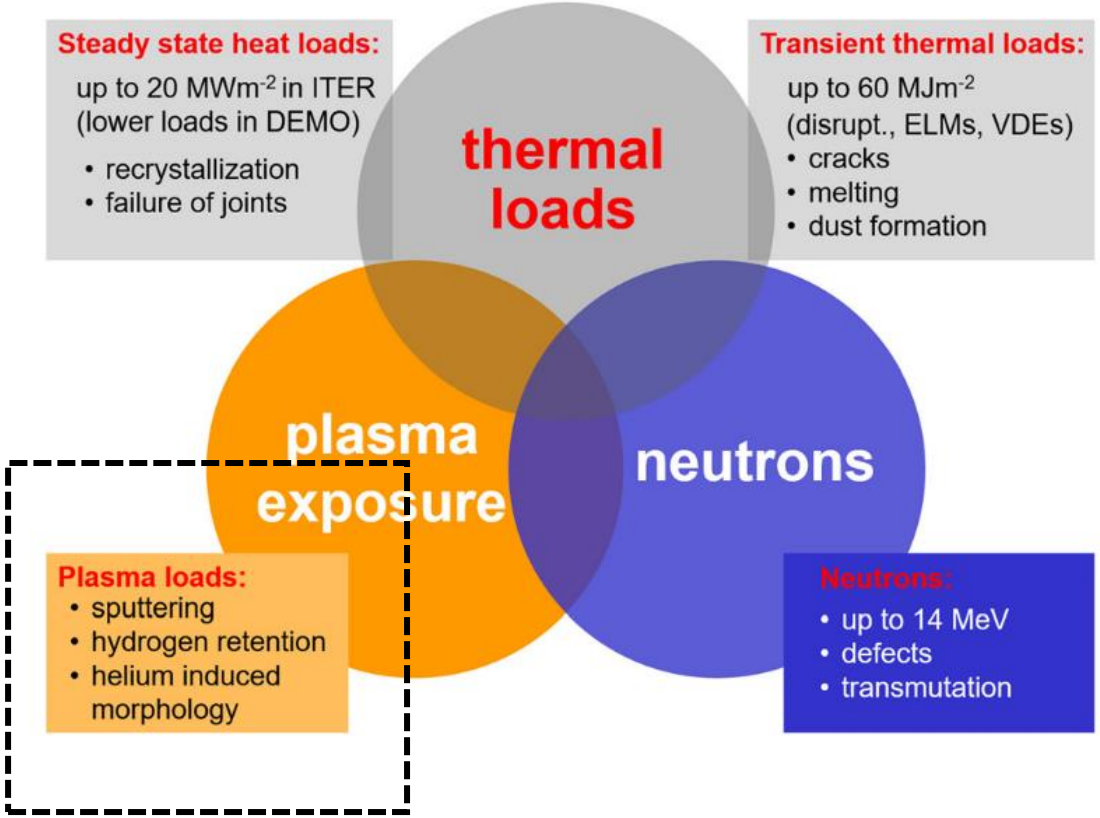
Hardness value before and after displacement damage

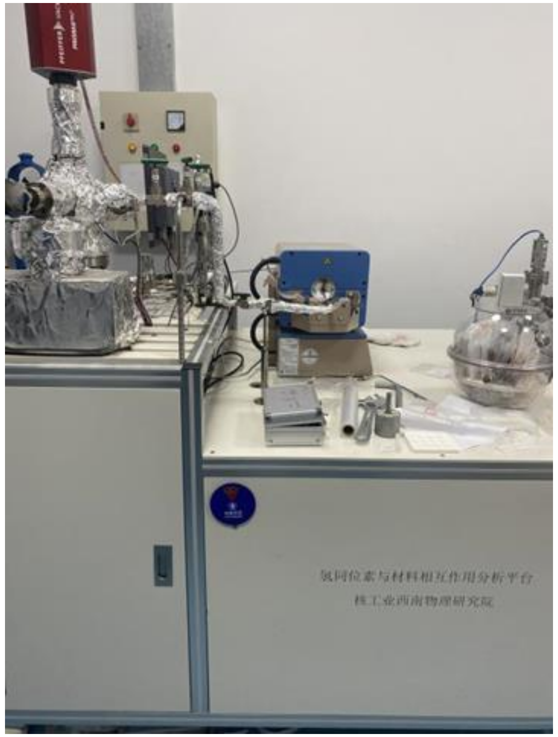
Sample	Damage (dpa)	Temp. (°C)	Hard. before (GPa)	Hard. after (GPa)	ΔH (GPa)
W fiber	45	RT	8.07	8.39	0.32
W matix	45	RT	6.95	8.25	1.3
W matix	22.5	RT	6.95	7.97	1.02
W matix	4.5	RT	6.95	7.44	0.49
W-K	0.45	127	-	-	0.7
Pure W	7	500	-	-	1.1
W-ZrO	100	RT	-	-	4.52
W-K	11.5	650	-	-	1

- Tungsten fiber has better irradiation resistance than matrix suggests promising radiation tolerance in Wf/W.

3. Properties of Wf/W

3.3 Plasma exposure





Analysis platform for the hydrogen isotopes

3. Properties of Wf/W

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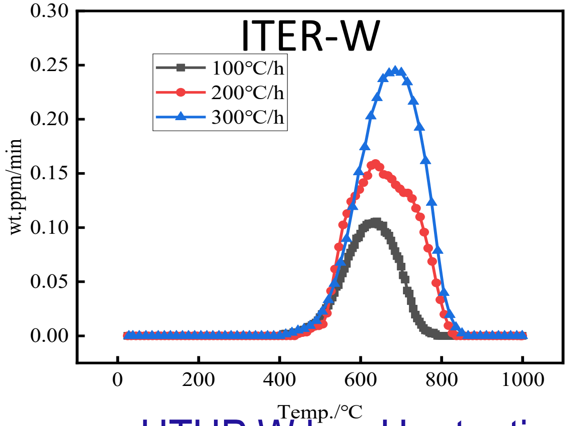
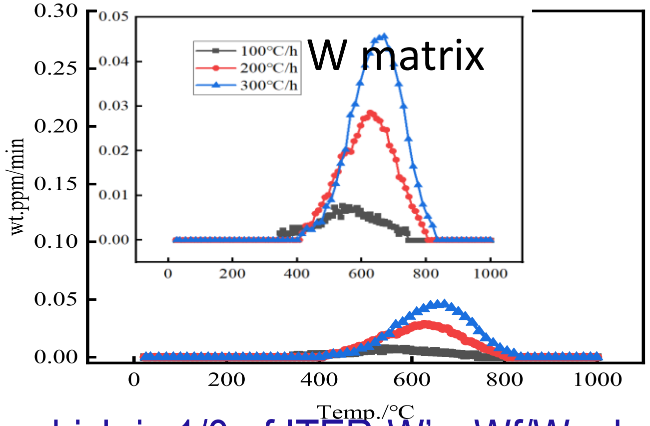
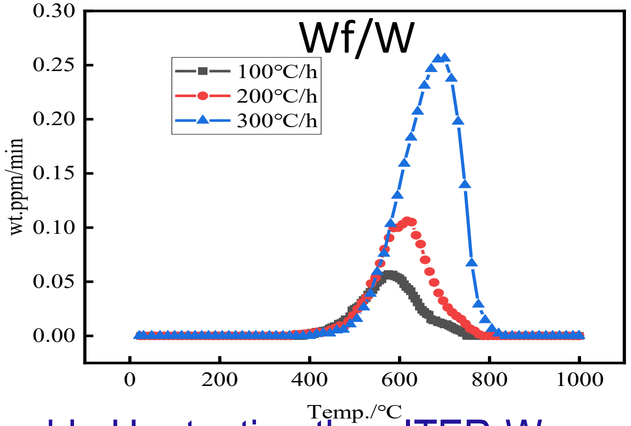
3.3 Plasma exposure-Hydrogen retention



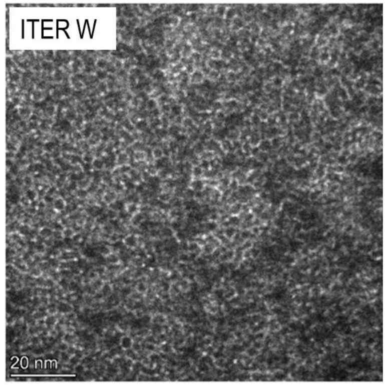


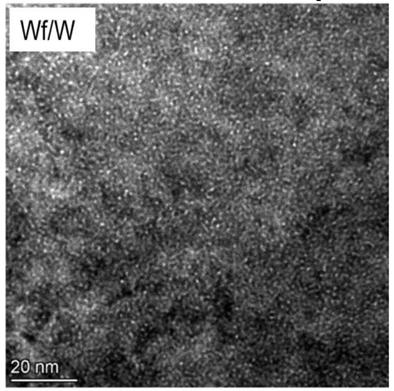


- HTHP W has H retention of 1 ppm， which is 1/8 of ITER-W's. Wf/Wm has comparable H retention than ITER-W.

3.4 Plasma exposure- Helium ion irradiation

50keV He^{2+}， total accumulated fluences $2*10^{17}$ ion/cm²





Sample	Fluences (ion/cm²)	He bubble size (nm)	He bubble density (/cm³)
Wf/W	$2*10^{17}$	1.45	$1.72*10^{13}$
ITER W	$2*10^{17}$	1.21	$1.45*10^{13}$

- The helium bubble size and density of Wf/W samples are around 85% of ITER-grade tungsten.

4. Summary

- Injection moulding combined with high-pressure high-temperature sintering demonstrates potential for fabricating high-density three-dimensional Wf/W.

- The composite exhibits enhanced transient HHF resistance, attributed to its pseudo-ductile behavior enabled by interfacial debonding and sliding mechanisms.

- The superior irradiation resistance of tungsten fibers compared to the tungsten matrix suggests promising radiation tolerance in Wf/W under fusion-relevant conditions.

- Wf/W displays favorable hydrogen retention properties and outperforms ITER W in He^{2+} irradiation resistance, positioning it as a candidate material for plasma-facing components in future fusion reactors.

Thanks for listening!

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