Development of CFETR/DEMO Divertor Materials and Components at SWIP

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4th Technical Exchange Meeting: EU – China collaboration on CFETR and EU-DEMO Reactor Design

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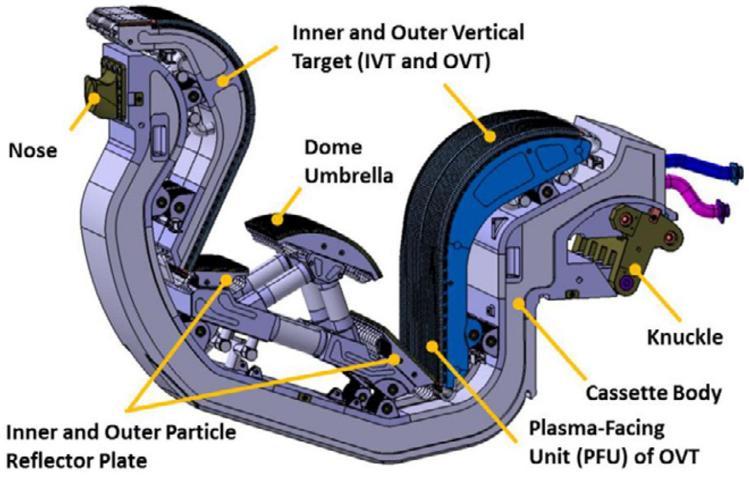
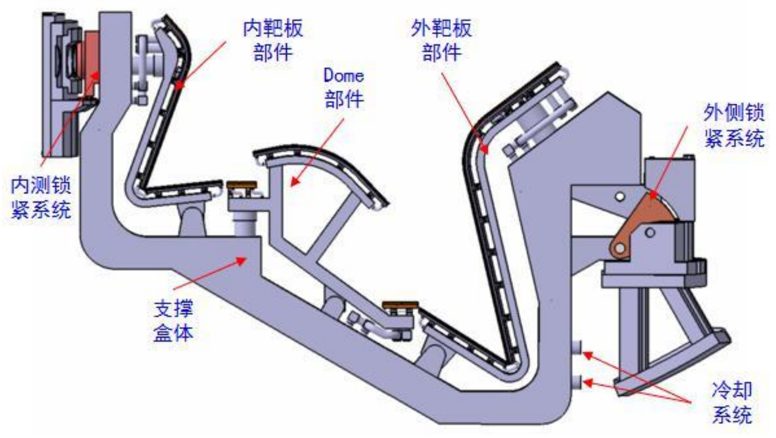
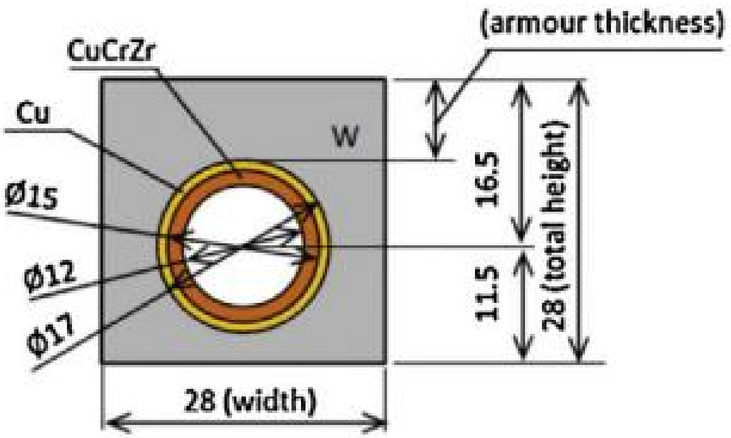


ITER water cooled divertor

ITER divertor components



CFETR water cooled diverter



W/Cu mockups

- Development of divertor high-heat flux materials:
  - Plasma facing materials ——W base materials
  - heat sink materials ——Cu base materials
- Development of divertor components
  - Joining technologies of high-heat flux materials
  - Manufacturing and testing technologies of components

2. Development of tungsten PFMs

Tungsten

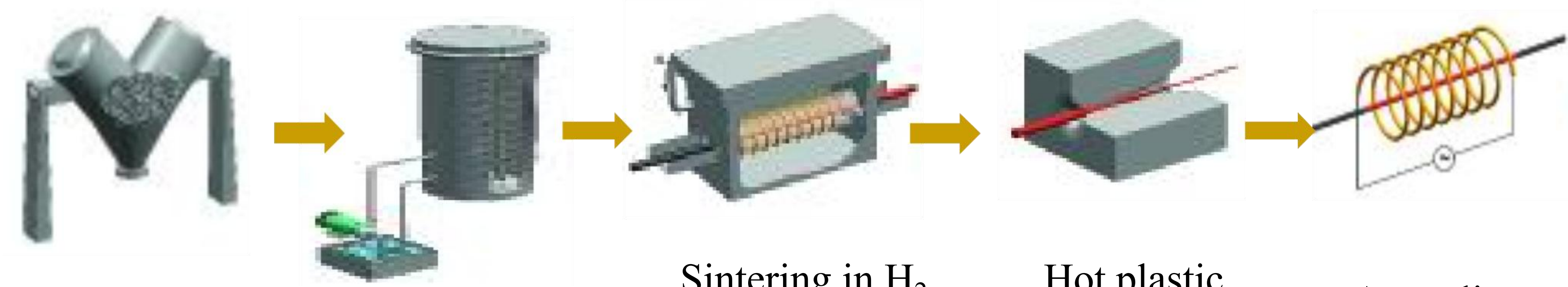
Advantages: high melting point, high thermal conductivity, low sputter yield, high temperature strength...
Disadvantages: low-temperature brittleness, recrystallization embrittlement, radiation-induced brittleness, inherent low fracture toughness....

Advanced tungsten alloys →

Alloying	Particle dispersion strengthening	K doping	Composite
W-Re/Ta/Hf	W-Y_2O_3/La_2O_3	W-K	Wf/W

Objective: Developing new advanced tungsten materials to improve the properties.

The fabrication route:

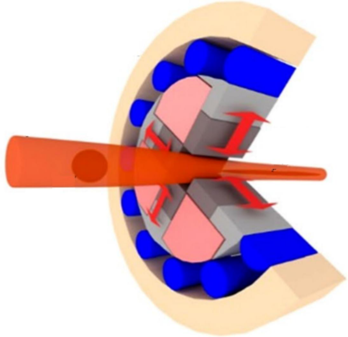


Composite powders → CIP → Sintering in H_2 atmosphere → Hot plastic deformation → Annealing

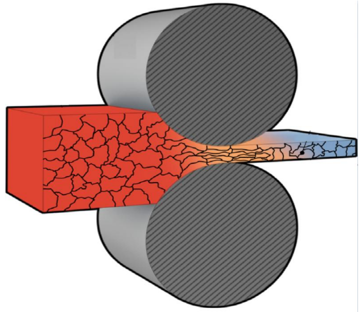
2. Development of tungsten PFMs

The prepared advanced tungsten alloys

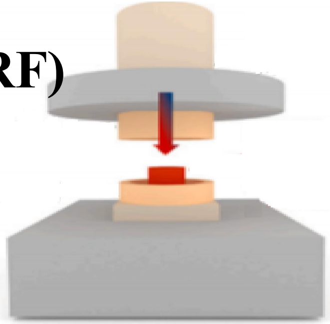
Hot-Swaging
W-Y_2O_3/W-K bars
10~20 kg/pc

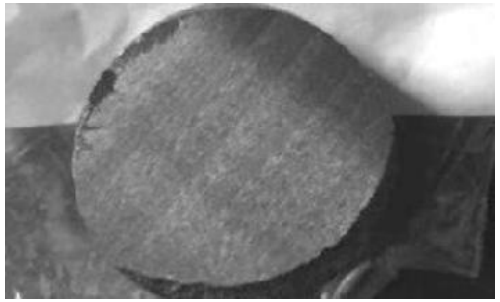


Hot-Rolling
W-Y_2O_3/W-K plates
~20-40 kg/pc



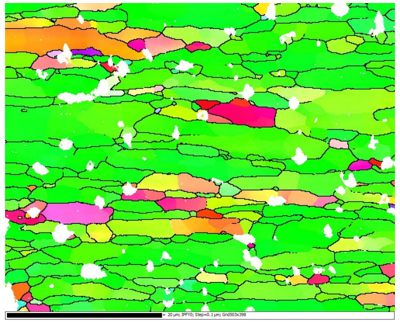
High-energy-rate forging (HERF)
W-Y_2O_3/W-K/W-Ta discs
~1 kg/pc

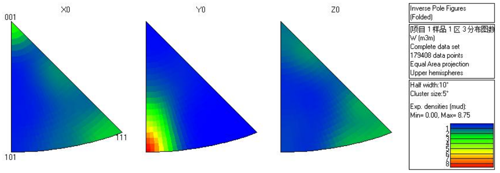




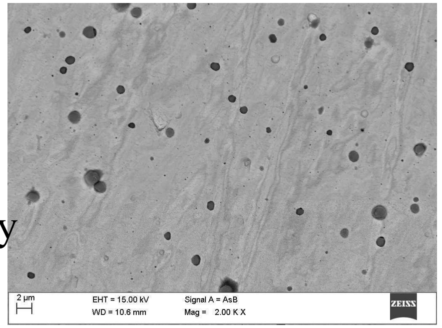
2. Development of tungsten PFMs

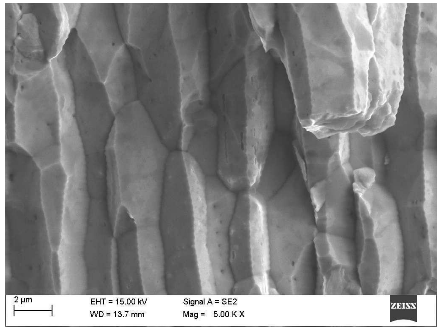
The mechanical properties of the swaged tungsten PFMs



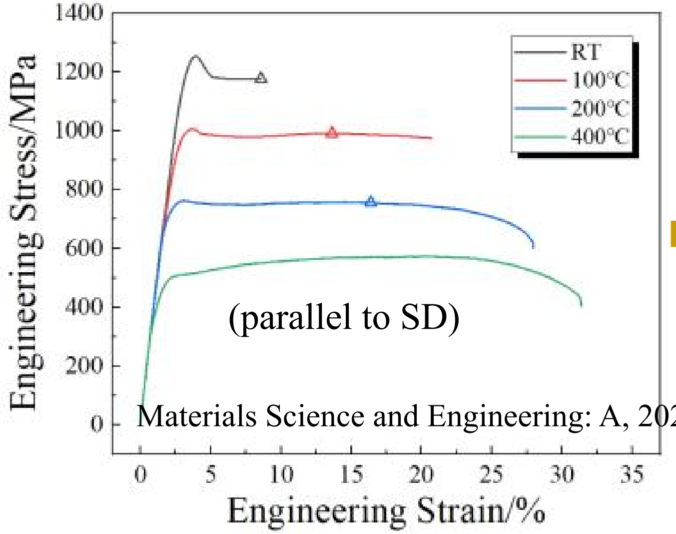


the swaged rod with a strongly preferred orientation [110]

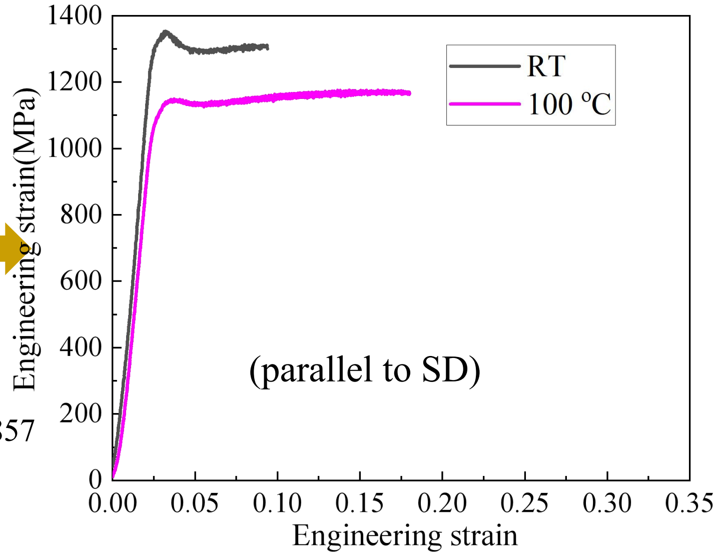




- The swaged W alloys exhibited severe anisotropy of microstructure

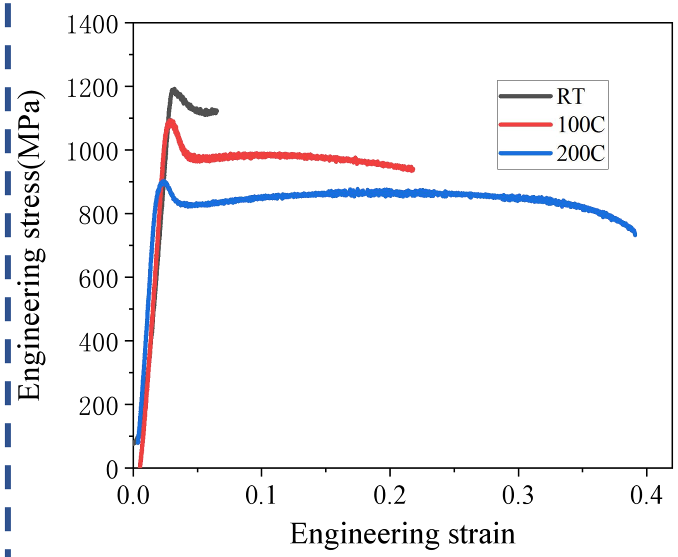


W- 0.26 wt.%Y_2O_3(φ 12mm)
Deformation degrees: 75%



W- 0.5 wt.%Y_2O_3(φ 16mm)

Swaged W-Y_2O_3 bar



W-K (60ppm)(φ 16mm)

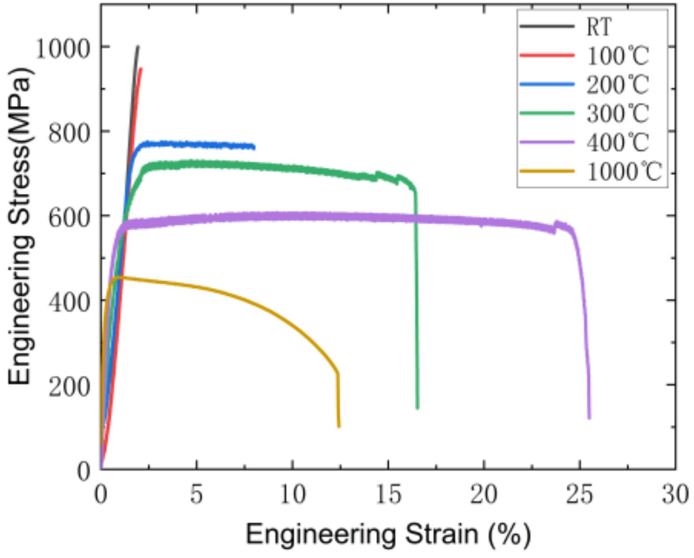
Swaged W-K bar

- The swaged W alloys show excellent low temperature ducitliy and strength.

2. Development of tungsten PFMs

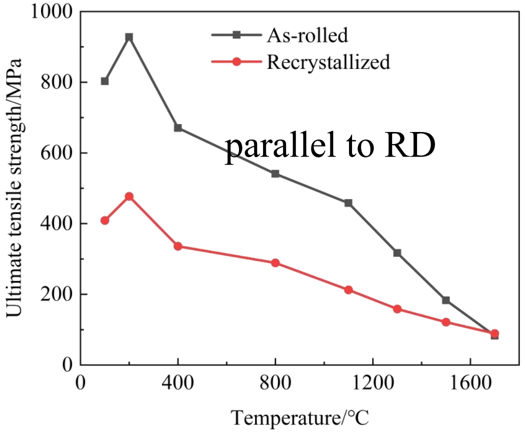
The mechanical properties of the rolled tungsten PFMs

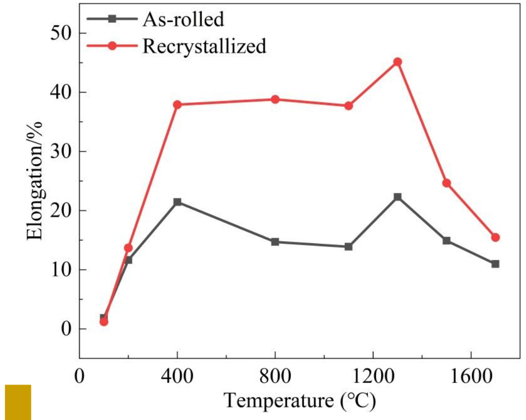
Rolled W-0.5 wt.%Y_2O_3
Thickness:10mm



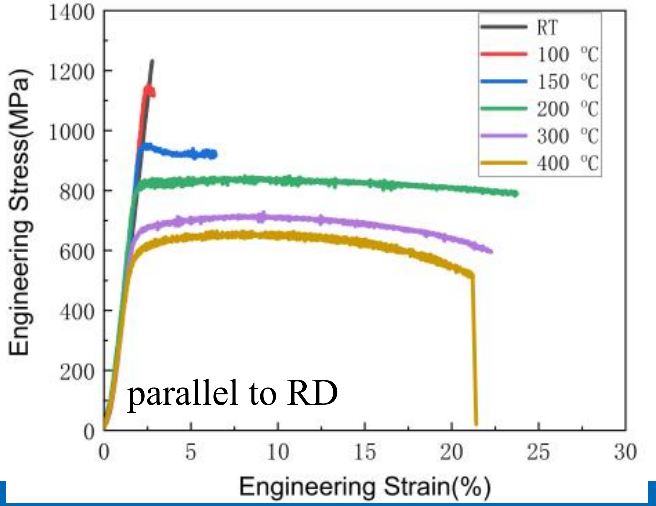
parallel to RD

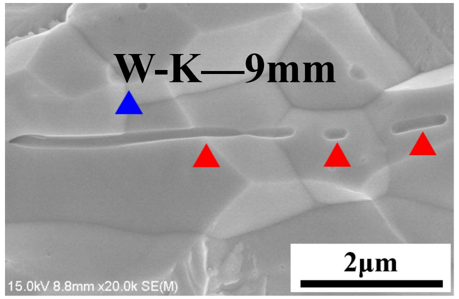
Rolled W-K(90ppm)—Thickness: 6mm
Deformation degrees~ 74 %

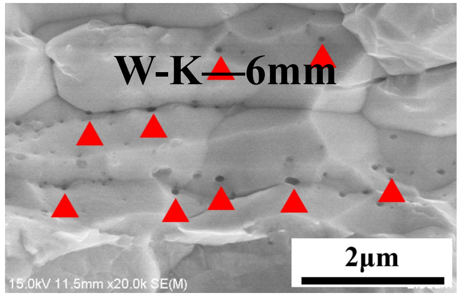




Rolled W-K(90ppm)—Thickness: 13.8mm



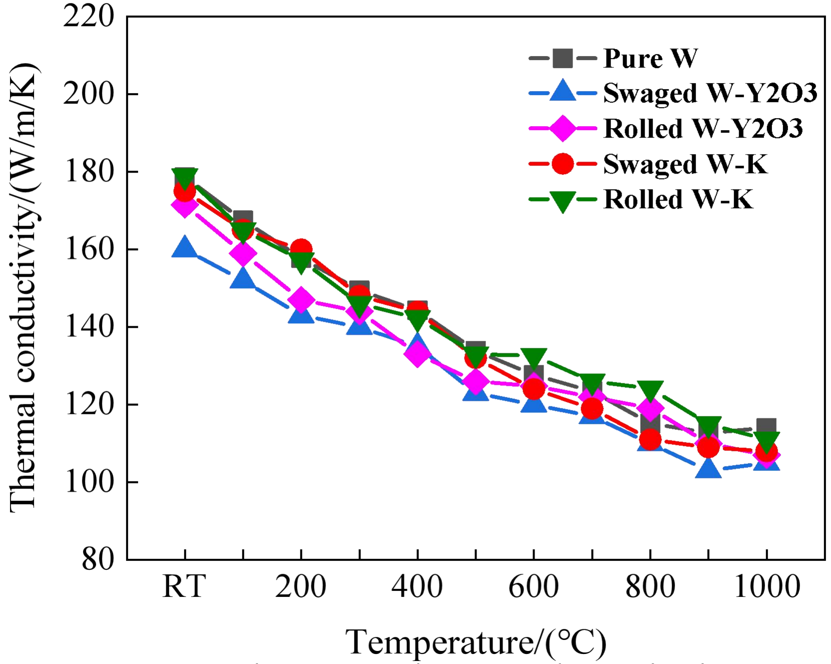




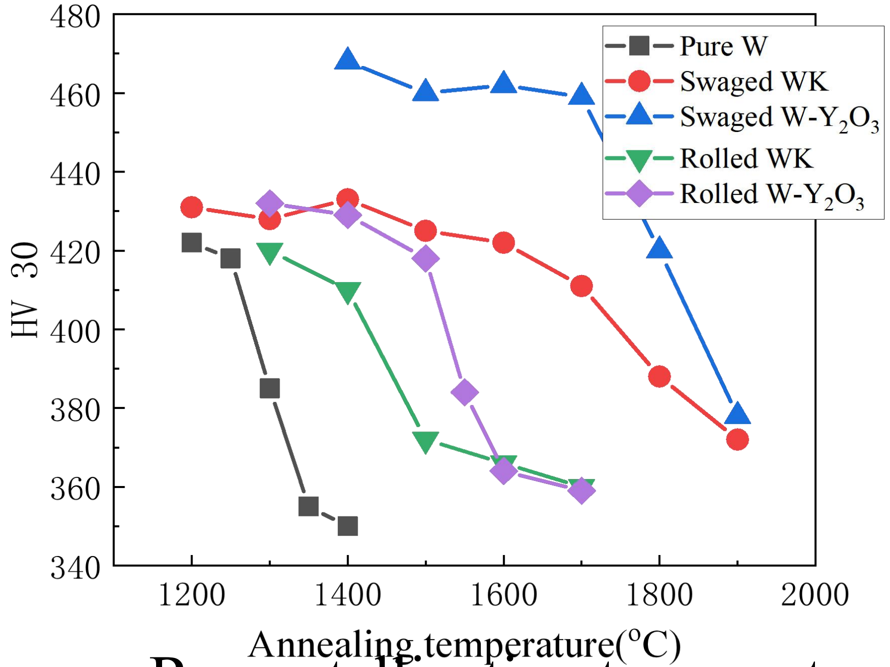
- The rolled tungsten materials exhibits a obvious tensile ductiliy at 150-200 °C

2. Development of tungsten PFMs

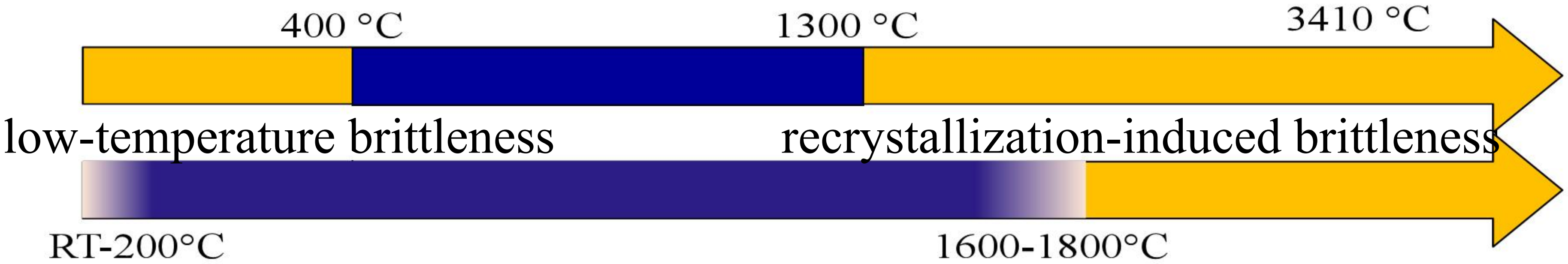
The large scale W alloys exhibt high thermal conductivity and recrystallization temperature
To obtain the datas of high temperature tensile, creep and mechanical fatigue properties
To research the behaviors of W materials under fusion high-heat flux, plasma and neutron irradiation conditions



Thermal conductivity

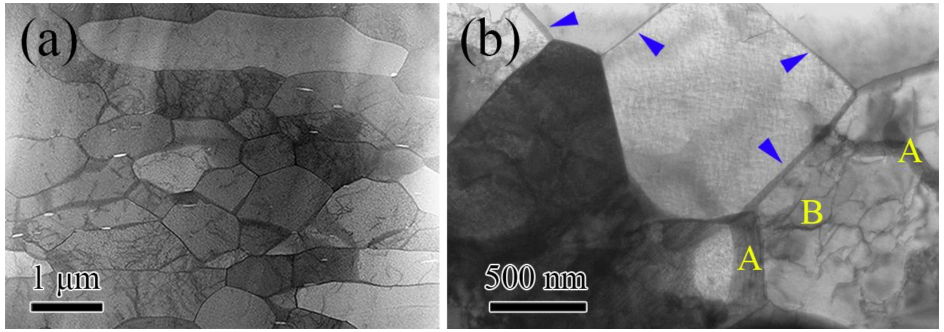


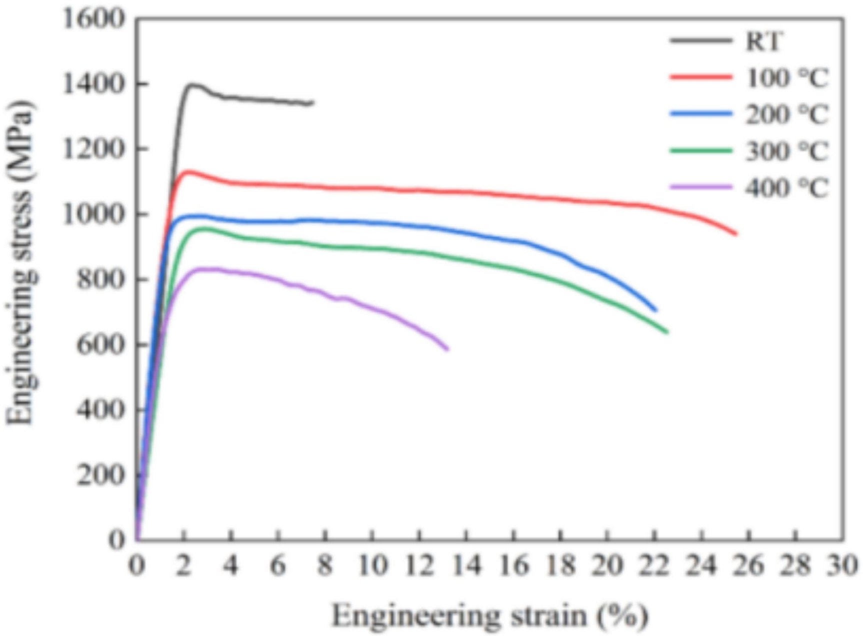
Recrystallization temperature



2. Development of tungsten PFMs

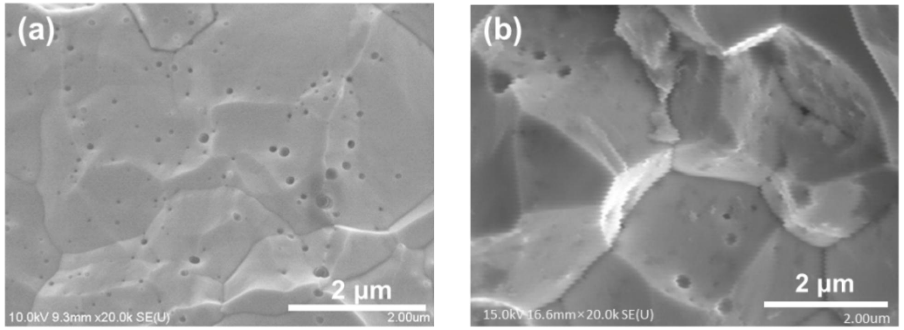
HERFed tungsten PFMs——W-Y_2O_3/W-K discs

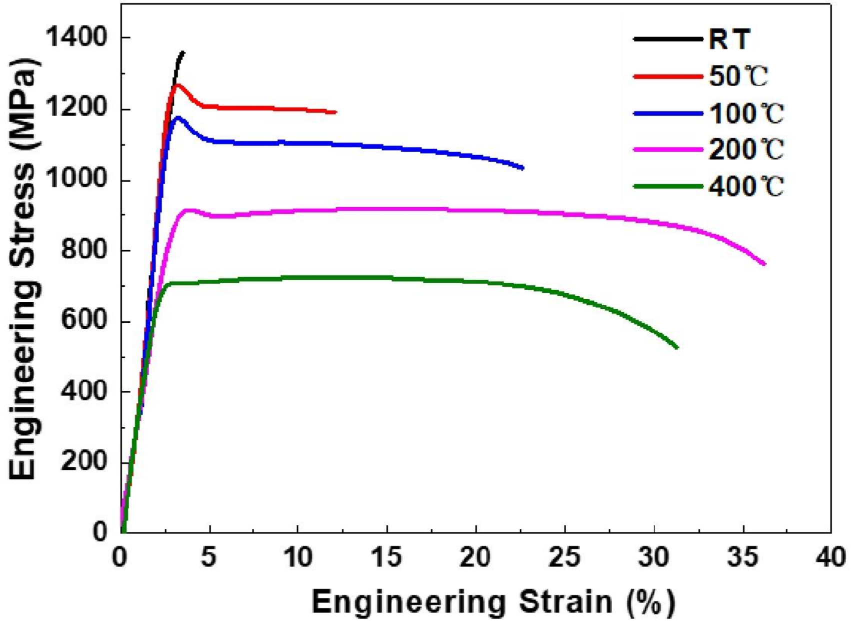




W- 0.26 wt.%Y_2O_3

International Journal of Refractory Metals and Hard Materials 114 (2023) 106261





W- K(83 ppm)

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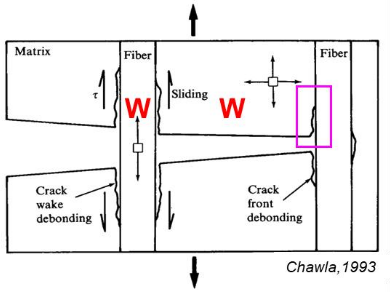
- Excellent tensile ductility and strength at low-temperature
- The low-temperature brittleness of the bulk W can be improved by controlling its microstructure

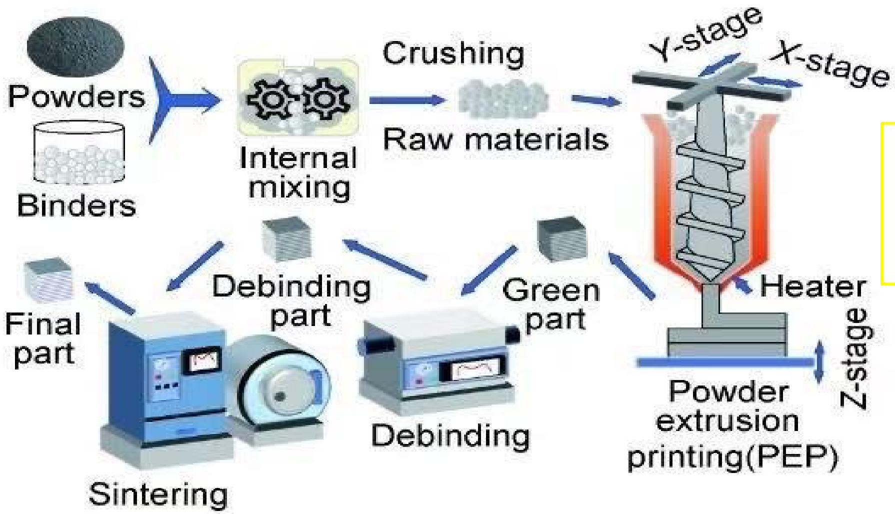
2. Development of tungsten PFMs

Tungsten fiber reinforced tungsten matrix(Wf/Wm)

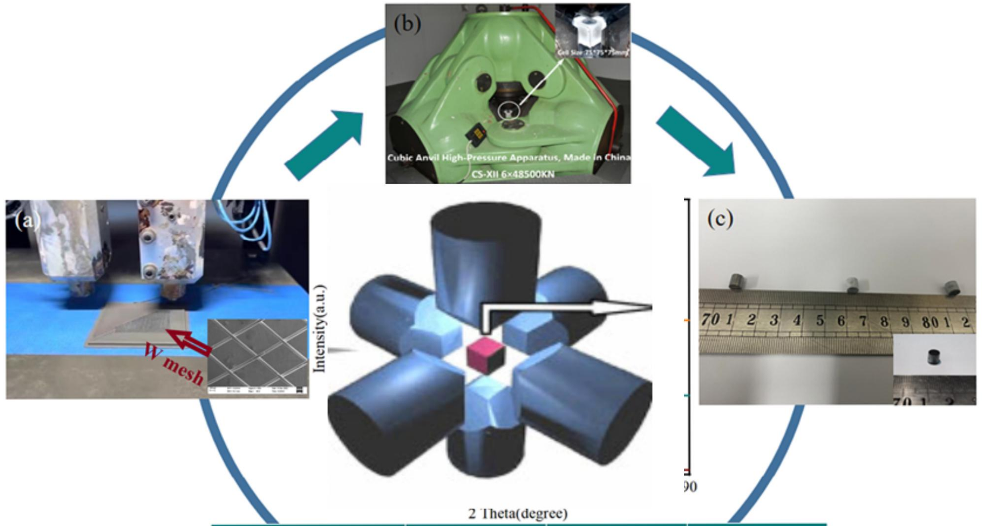


W_f/W_m material is one of the most promising plasma facing materials for the future fusion reactor.

Wf/Wm fabricated via advance power metallurgy techniques

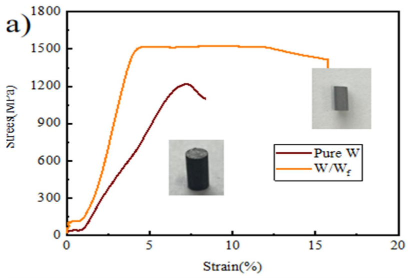


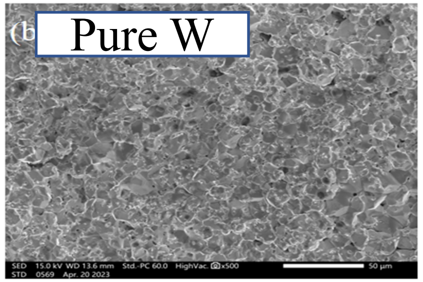
Powder extrusion printing(PEP) / Injection molding with reinforcement

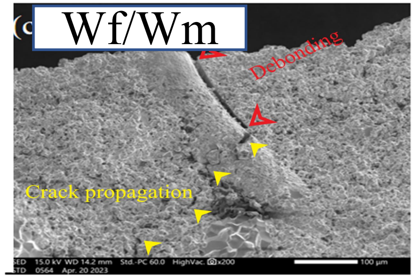


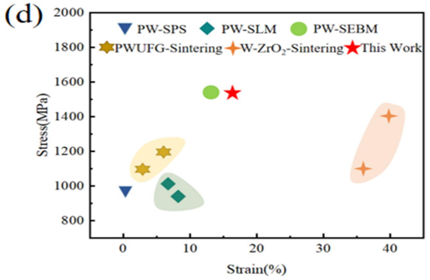
Sintering Temperature(℃)	1200	1400	1600
Relative Density(%)	99.1±0.3	99.5±0.4	99.6±0.4

Pure W vs. Wf/Wm









Wf/Wm: compress strength: 1530 MPa which plastic deformation 15.8%.

Compared other tungsten alloys, Wf/Wm composite showed excellence at both compression strength and plasticity at the same time.

3. Development of Cu heat sink

Cu alloys are considered as a divertor heat sink for ITER and CFETR/DEMO.

Precipitation hardened
- CuCrZr

Particle dispersion strengthening
- ODS-Cu—Cu-Al_2O_3/Cu-Y_2O_3
- Cu-W

Composite
- Wf/Cu

- CuCrZr has excellent thermal conductivity, good mechanical propertiesis and now wildly used as the heat sink for divertor in ITER and the present tokamak
- Improving the properties of CuCrZr: thermal stability, high temperature strength, impact properties, and radiation tolerance

→

ODS-Cu :High temperature strength, resistance to neutron irradiation, high resistance to softening temperature, etc.

→

Cu-Al_2O_3—Atomization → high temperature oxidation → sintering
Cu-Y_2O_3—Powder metallurgy

ODS-Cu:
Induction melting→
in-situ formation of oxides

3. Development of Cu heat sink

The fabrication route

Pure Cu | Amorphous Alloys

↓

Induction melting

↓

Casting

↓

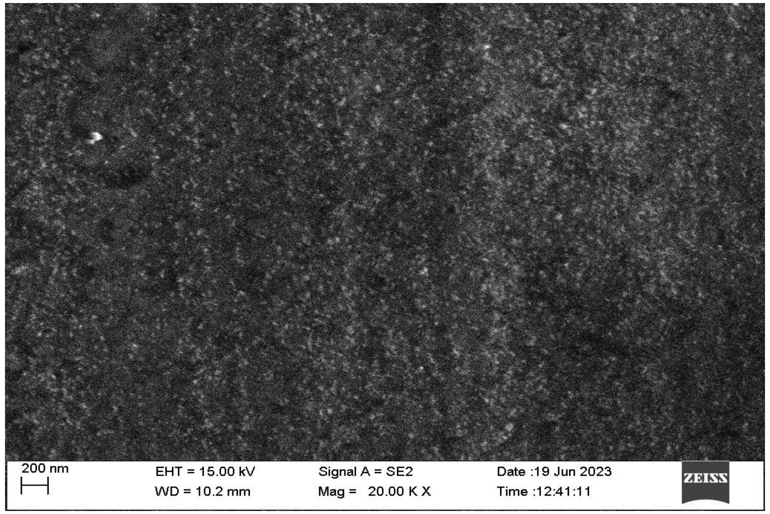
Plastic deformation

↓

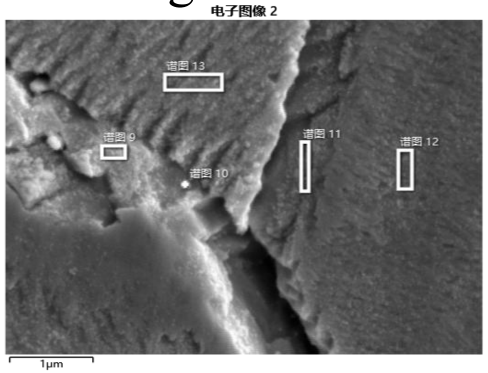
Microstructure | Mechanical property

Amorphous alloys containing oxygen (Cu-Zr-O, Cu-Y-O, Cu-Hf-O)

Casted ingots



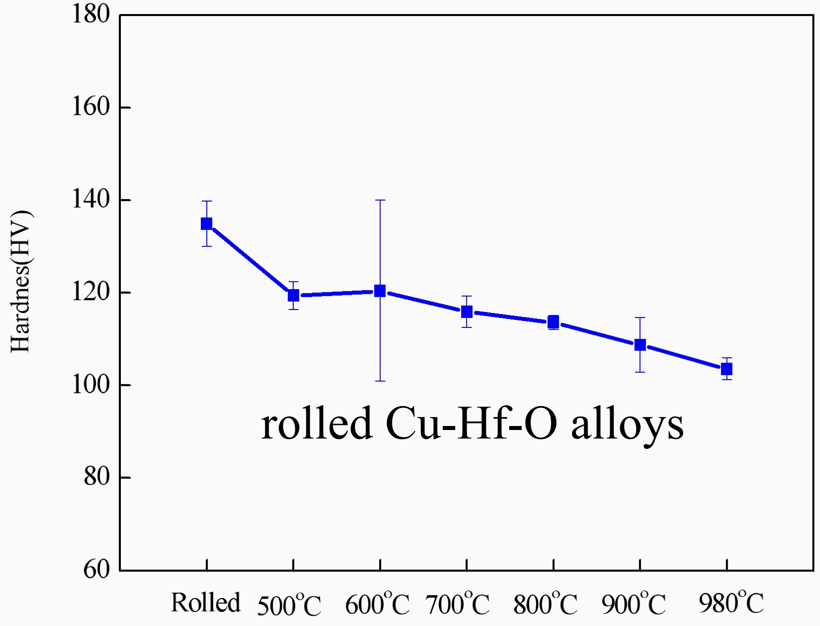
Microstructure of Cu-Hf-O ingot



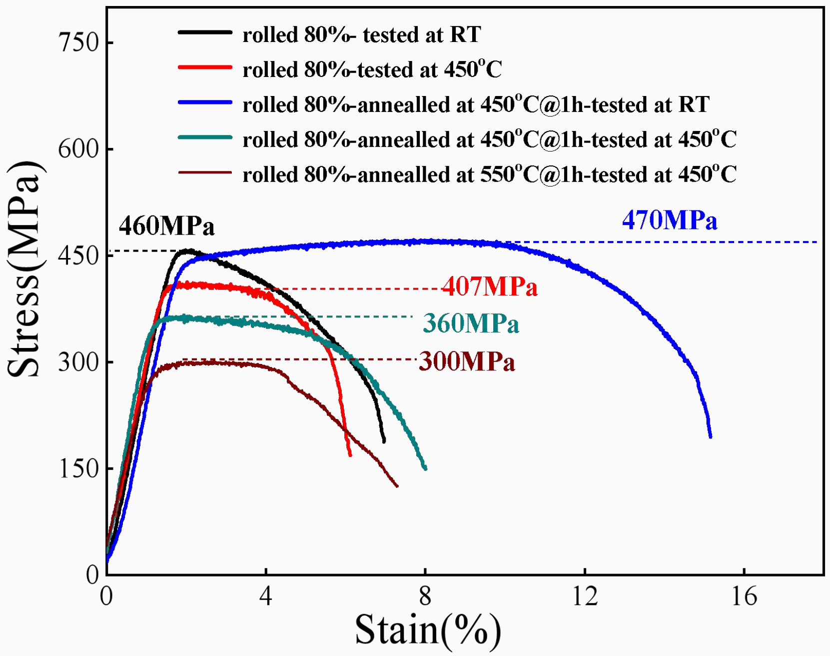
谱图标签	谱图 9	谱图 10	谱图 11	谱图 12	谱图 13
C	2.09	1.59		1.88	1.78
O	1.79	1.15	1.10		0.74
Cu	87.73	92.04	92.89	96.03	93.67
Hf	8.38	5.22	6.01	2.09	3.81
总量	100.00	100.00	100.00	100.00	100.00

3. Development of Cu heat sink

High-temperatuer microstructure stability and mechanical properties of the Cu-Hf-O alloys



Vickers hardness evolutions of the rolled Cu-Hf-O alloys after annealing for 1 h at different temperatures



Strain-stress Curves of the rolled and annealled Cu-Hf-O alloys

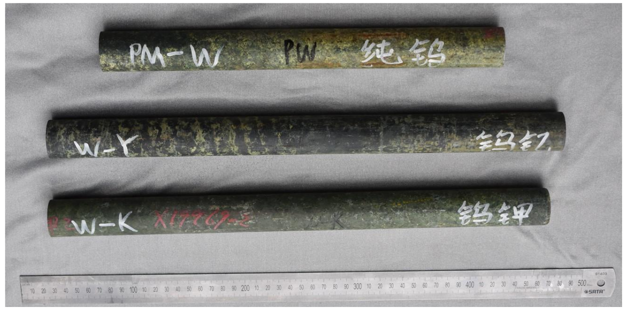
Next step: Formation mechanism of dispersed particles.
Optimiztaion of the preparation parameters
Preparation of large-scale ingots

4. W/Cu mock-ups and components

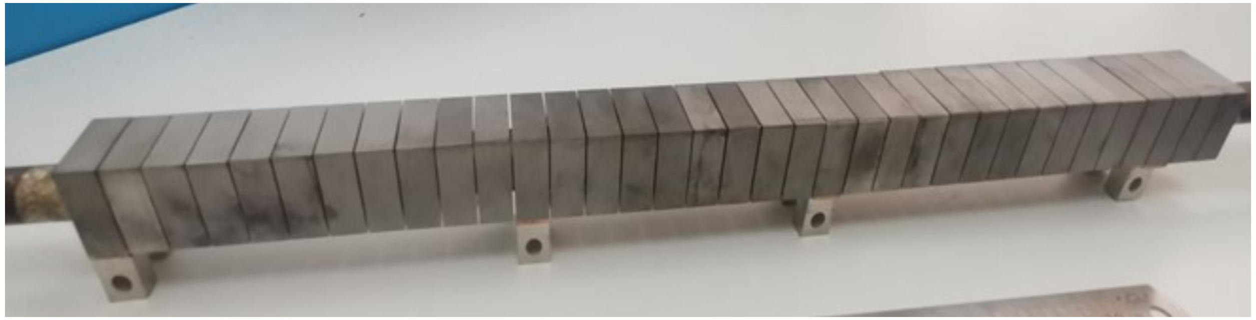
- **Development of joining technology**

  - Conventional Brazing
    - Vacuum Brazing
    - Induction Brazing
  - Diffusion bonding
    - Hot Isostatic Pressing
  - Joining with interlayers
    - Copper base interlayer
    - W/Cu interlayer
  - Joining of advanced materials

- **Preparation and HHFT of small scale mockups with advanced tungsten materials**



- **Manufacturing of large scale of components**

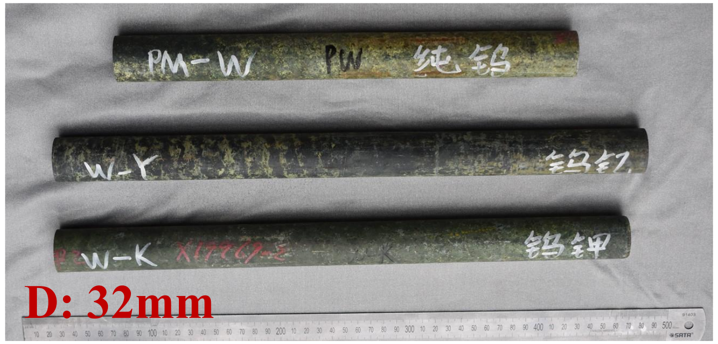


4. W/Cu mock-ups and components

- **Preparation and HHFT of small scale mockups with advanced tungsten materials**

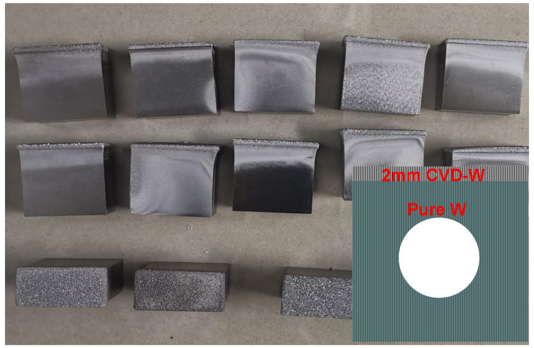
Mock-ups with the advanced W-based materials were prepared by copper casting and vacuum brazing.
HHFTs of the developed mock-ups were performed at electron beam facility EMS-60.
The brazed mock-ups experienced cyclic tests of 10-25 MW/m².

1 mockups with the swaged W (PW, W-K, W-Y2O3), rolled W-ZrC and CVD-W

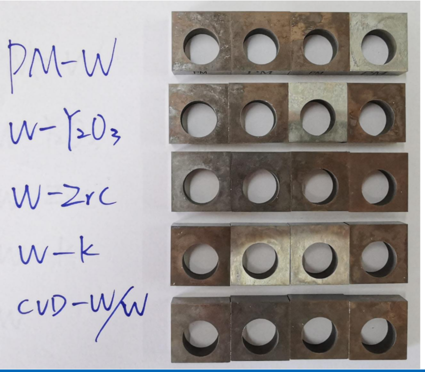


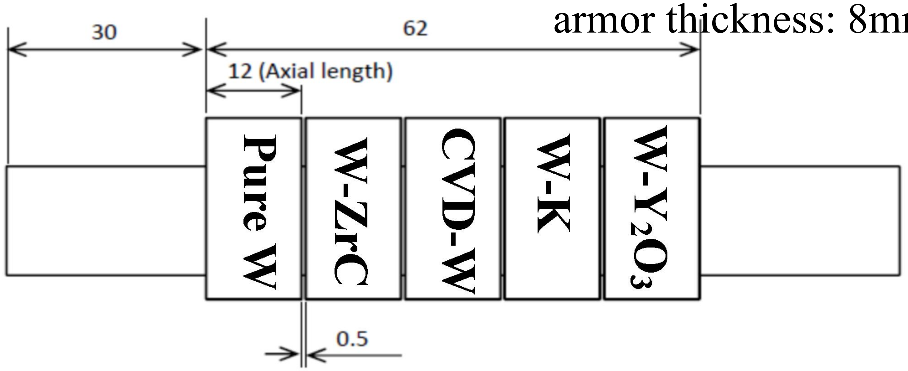
Swaged-Pure W, W-Y_2O_3, W-K rods

Rolled-W-ZrC Plate



CVD-W/W tiles





4. W/Cu mock-ups and components

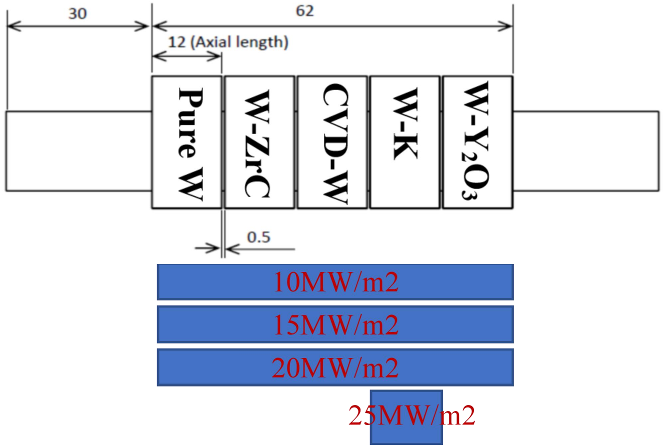
High heat flux performance

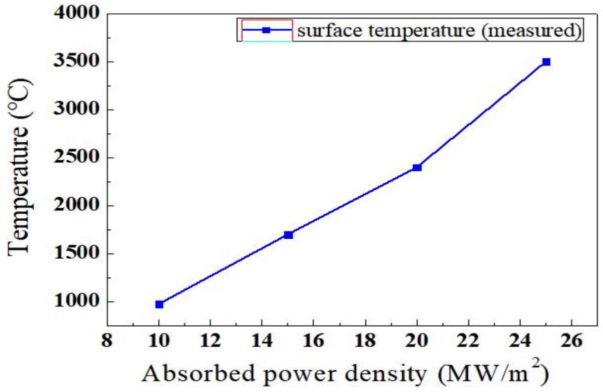
EMS-60

Cooling water： 25±5 °C; 1.5m³/h; thermal screening: 10-25MW/m²@ 10s on/ 15s off

Cycle thermal load: 15 MW/m² @ 300 cycles, 20 MW/m² @ 300 cycles

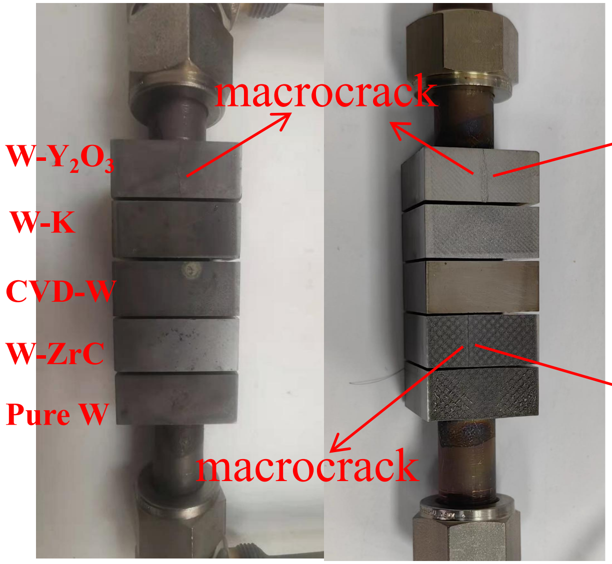
The swaged W-K materials: 25 MW/m² @ 100 cycles

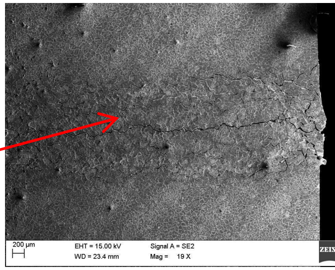


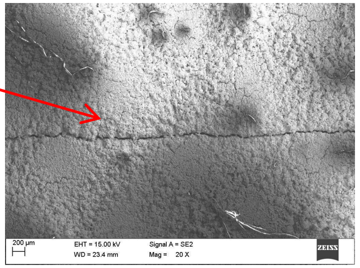


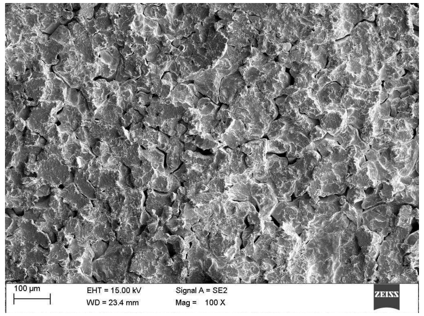
Peak surface temperatures during the HHFT

Mockup-1 Mockup-2

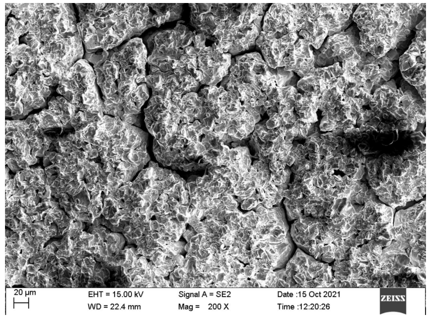








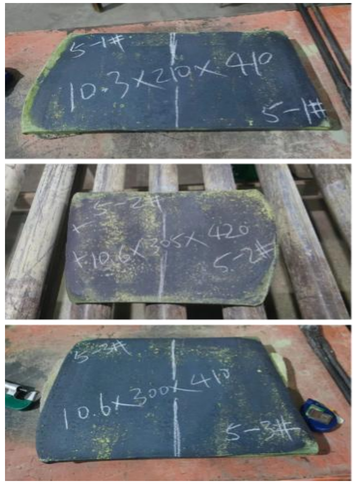
Swaged W-K@ 20 MW/m²

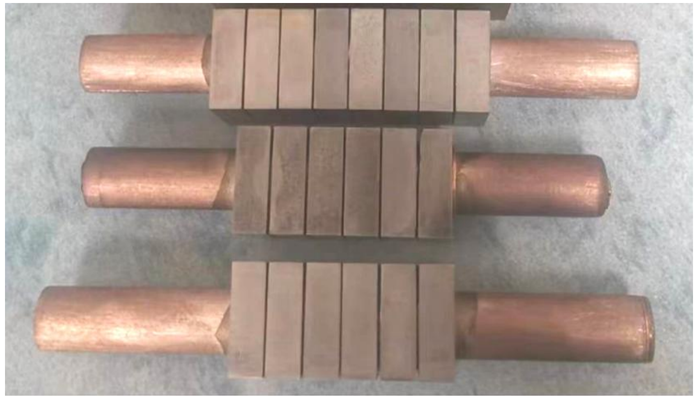


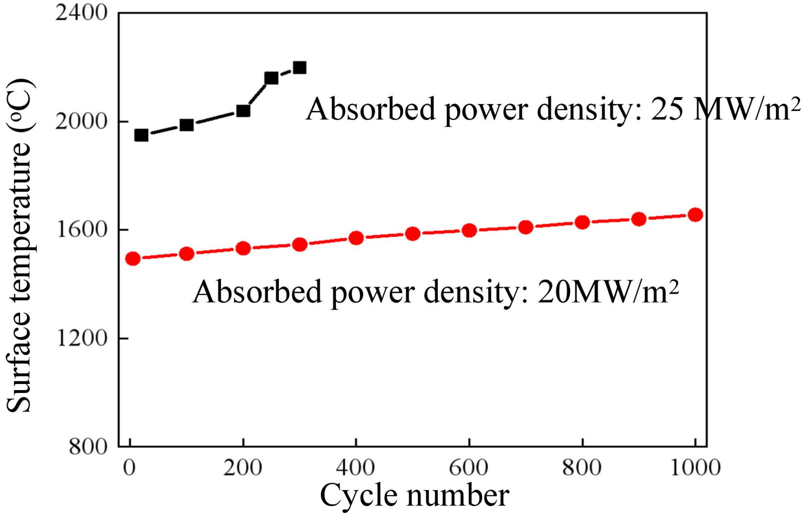
Swaged W-K@ 25 MW/m²

4. W/Cu mock-ups and components

2 mockups with the rolled W-Y_2O_3 and W-La_2O_3 (T: 10mm)







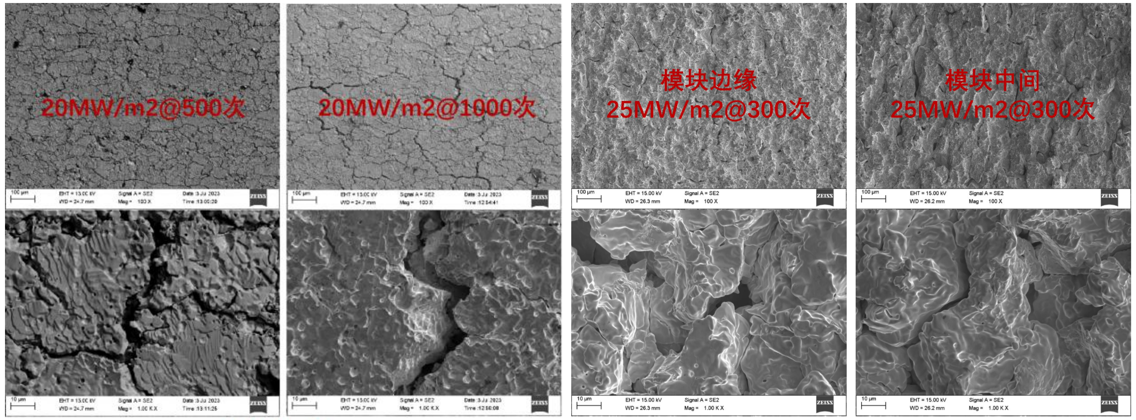
High heat flux performance

Rolled W-Y_2O_3: 24*26*8 mm， armor thickness: 5mm

Cooling water: 25±5 °C； 1.5m³/h；

Thermal fatigue： 10-25MW/m² ， 15s on/ 15s off

20MW/m² @500-1000cycles; 25MW/m² @300cycles

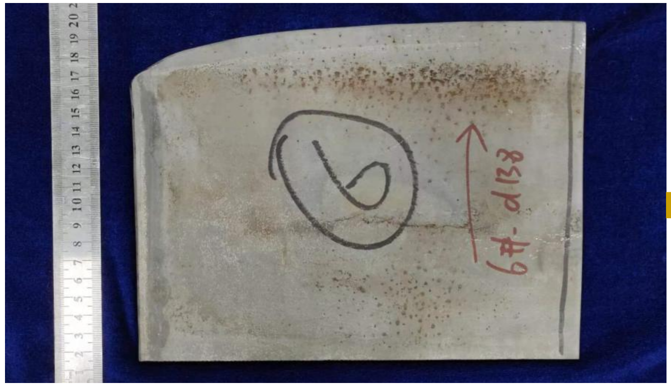


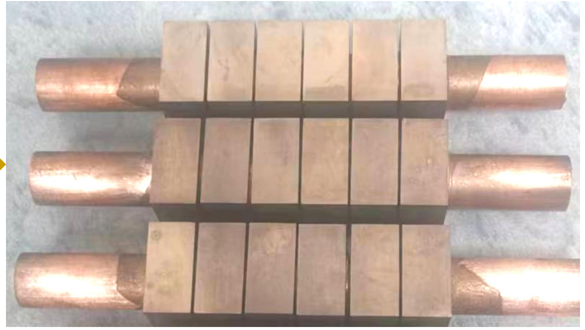
W-Y_2O_3　　W-Y_2O_3

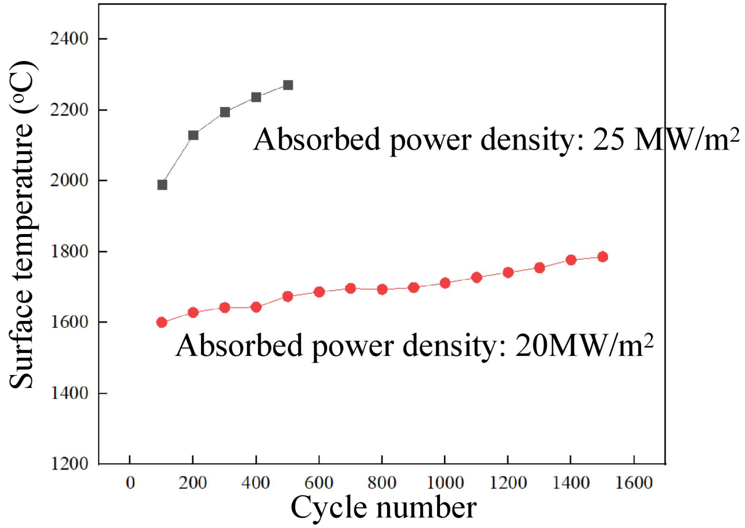
Surface modification of the HHF tested mockup

4. W/Cu mock-ups and components

3 mockups with the rolled W-K plate (T: 13.8mm)







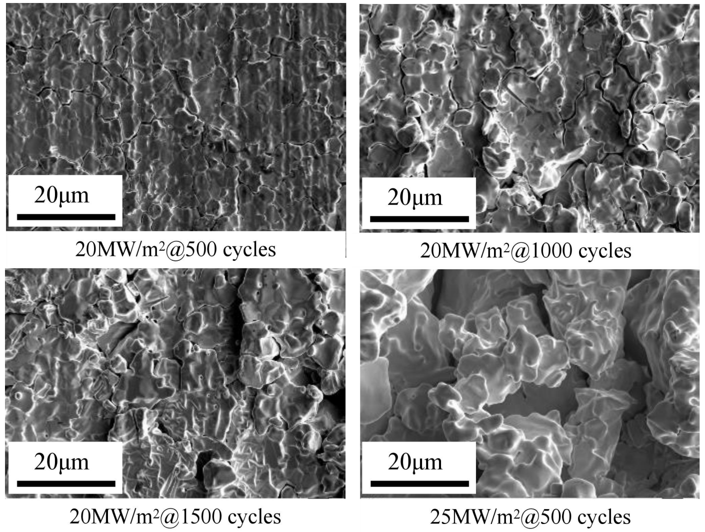
High heat flux performance

Rolled W-K: 24*26*12 mm， armor thickness: 5mm

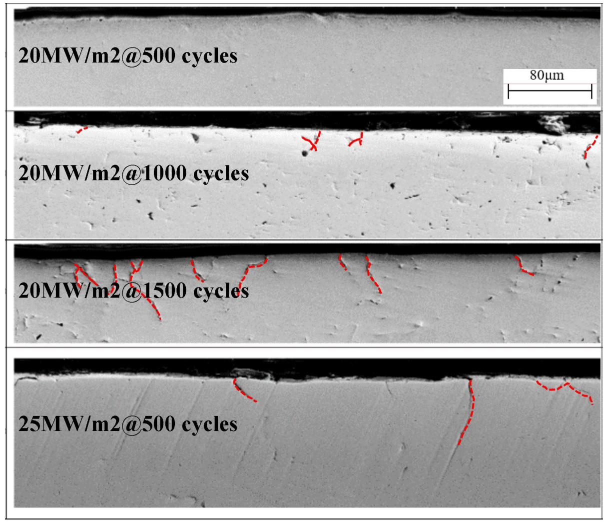
Cooling water: 25±5 °C； 1.5m³/h；

Thermal fatigue： 10-25MW/m² ， 15s on/ 15s off

20MW/m² @500-1500cycles; 25MW/m² @500cycles



Surface modification



Cracks propagation

4. W/Cu mock-ups and components

- Manufacturing of components with the advanced W materials

Vacuum casting
+
Vacuum brazing

Vacuum casting
+
HIP

5. Summary

- Divertor high heat flux materials (W base PFMs and Cu base heat sink) have been prepared by industrial technology route and hot plastic-deformation technology, which is the standard process for bulk production and has large-scale production potential.
- The developed large scale W base PFMs exhibite high thermal conducitvity, high recrystallization temperature, and high strength/ductility. Especially, the swaged W-Y_2O_3 and W-K has excellent room-temperature ductility.
- ODS-Cu heat sink with high-temperature microstructure stability and mechanical properties has also been prepared by induction melting and plastic deformation.
- Divertor mockups with advanced W alloys have been prepared by vacumm casting and vacuum brazing methods.The advanced W alloys has been tested at 10 - 25 MW/m^2. The results show that the swaged and rolled W-K materials have no obvious damage after tested at 25 MW/m^2 for 300-500 cycles .
- Based on the developed W PFMs and joining technologies, large components have also been successfully prepared.

Thanks!