28th IAEA Fusion Energy Conference, Virtual Event, 10-15 May 2021

TECH/3

Advanced Multi-Step Brazing (AMSB) for Fabrication of the Divertor Heat Removal Component

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[a] National Institute for Fusion Science
[b] Okayama University of Science
[c] Nagoya University

Contents

1. Advanced Brazing Technique (ABT)

- Idea of the microstructural manipulation for the **W/ODS-Cu** joint
- Joint mechanism

2. <u>A</u>dvanced <u>M</u>ulti-<u>S</u>tep <u>B</u>razing (<u>AMSB</u>)

- Requirement for the <u>new type divertor heat removal component</u>
- Four conditions for obtaining the joint structure of the <u>new type divertor heat removal component</u>
- Development of the **AMSB** and fabrication procedures of the <u>new type divertor heat removal component</u>
- Heat removal capability of the <u>new type divertor heat removal component</u>

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"W/Cu alloy" divertor heat removal component

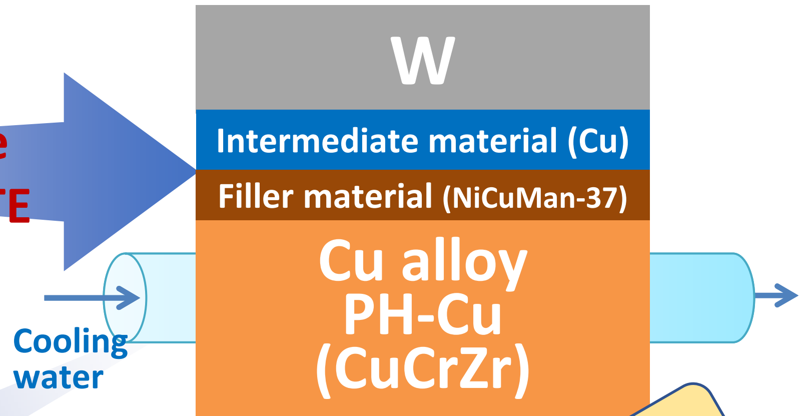
Reliable joint is required between "W" and "Cu alloy"
However, joint procedure is difficult

Reason

Large deviation of the CTE
W: 4.3 μ/K
Cu alloy：16.5 μ/K

To absorb the large deviation of the CTE

Conventional structure (e.g., ITER)



Including many issues

There are a lot of disadvantages

- Degradation of the physical and mechanical properties of Cu inter layer by the neutron dose.
- Degradation of the thermal conductivity due to the multiple interface between dissimilar materials.
- High manufacturing costs.

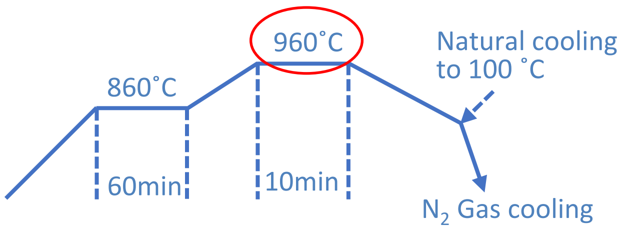
Direct brazing (this study)

Ideal structure

We challenged

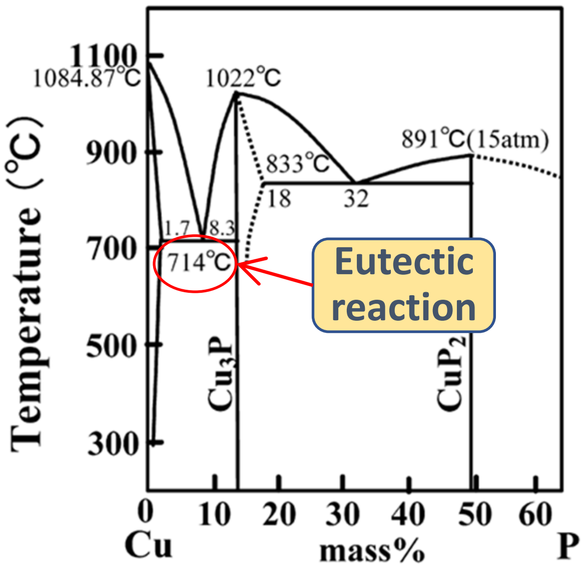
Direct brazing

Advanced brazing technique (ABT)

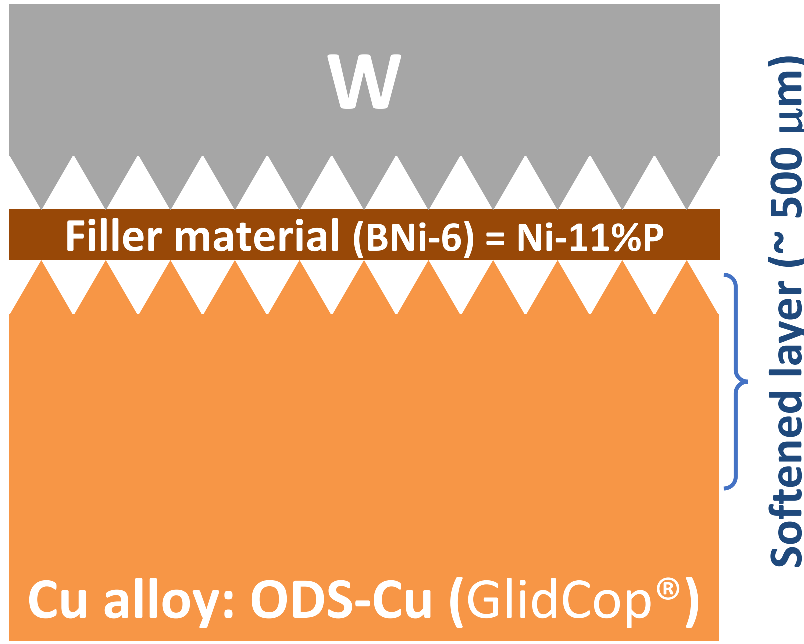


Feature 1: Very narrow joint like a microscale welding

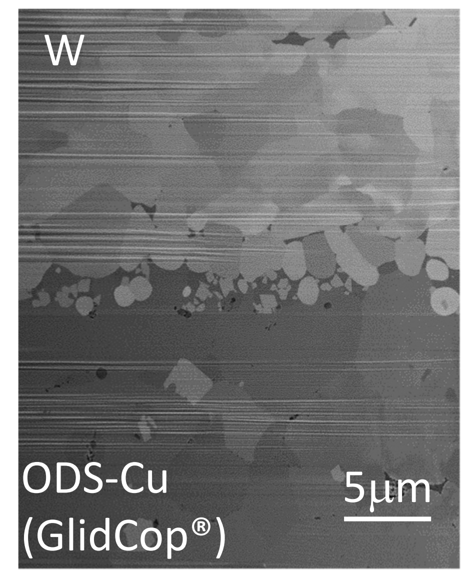
Feature 2: Softened layer is spontaneously created



I. Shoji et al., Surface Technol., Vol.58, No.12, (2007) 133-137



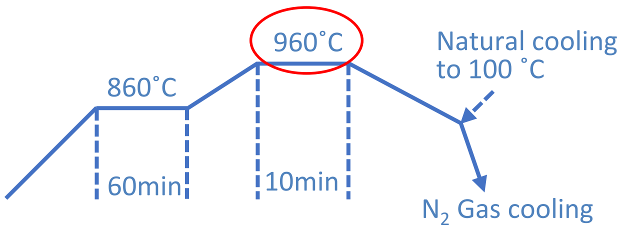
Cross-sectional SEM image



M. Tokitani et al., Nucl. Fusion 57 (2017) 076009.

1. **During the bonding heat treatment with 960˚C, the ODS-Cu (GlidCop®) bulk only near the bonding surface satisfies the eutectic reaction (Cu-P) for a short time.**
2. **The surface of the ODS-Cu (GlidCop®) bulk is melted, and melted material tightly sticks to the W bulk through the anchor effect.**

Advanced brazing technique (ABT)



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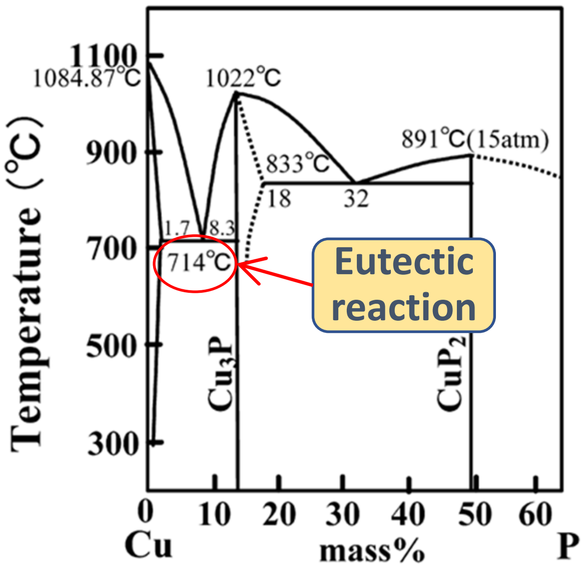

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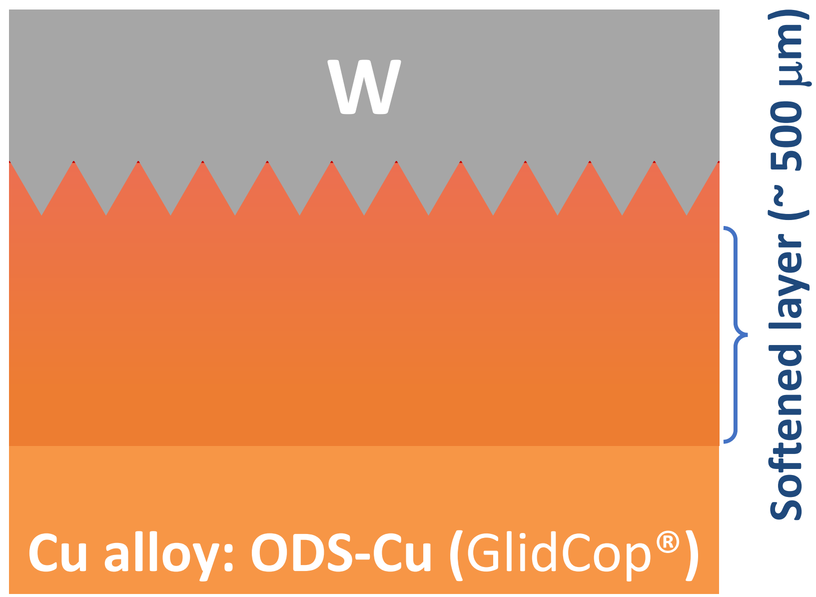

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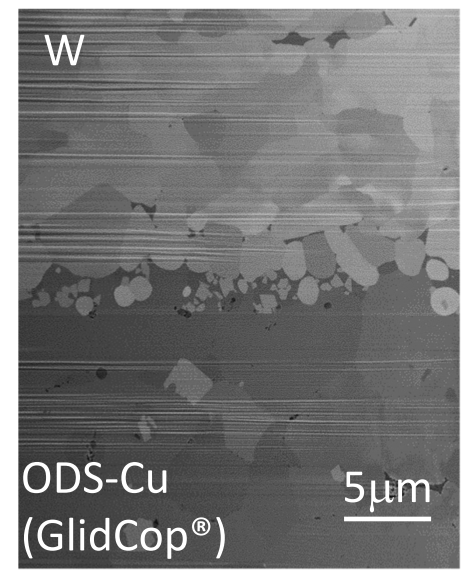

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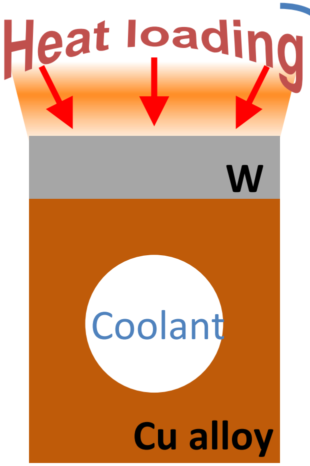
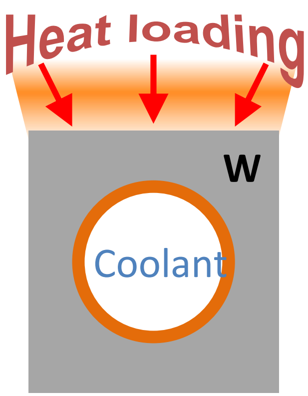
Requirement for the "new type divertor heat removal component"

Structural limit to heat removal



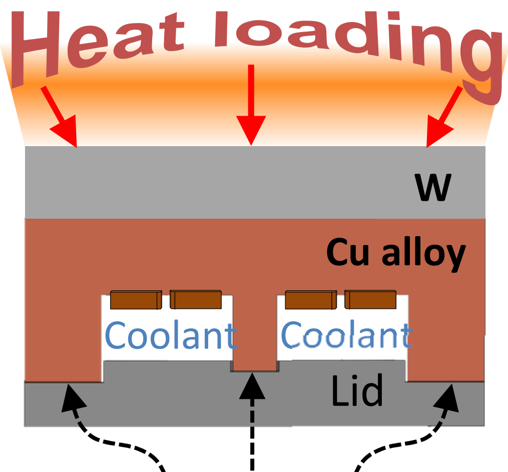


The leak-tight joint is difficult to create in the conventional technologies.

❑ Ideal cooling structure

T. Tsuneyoshi et al., JSFM 2015, C11-1.

(1) Rectangular-shaped cooling flow path



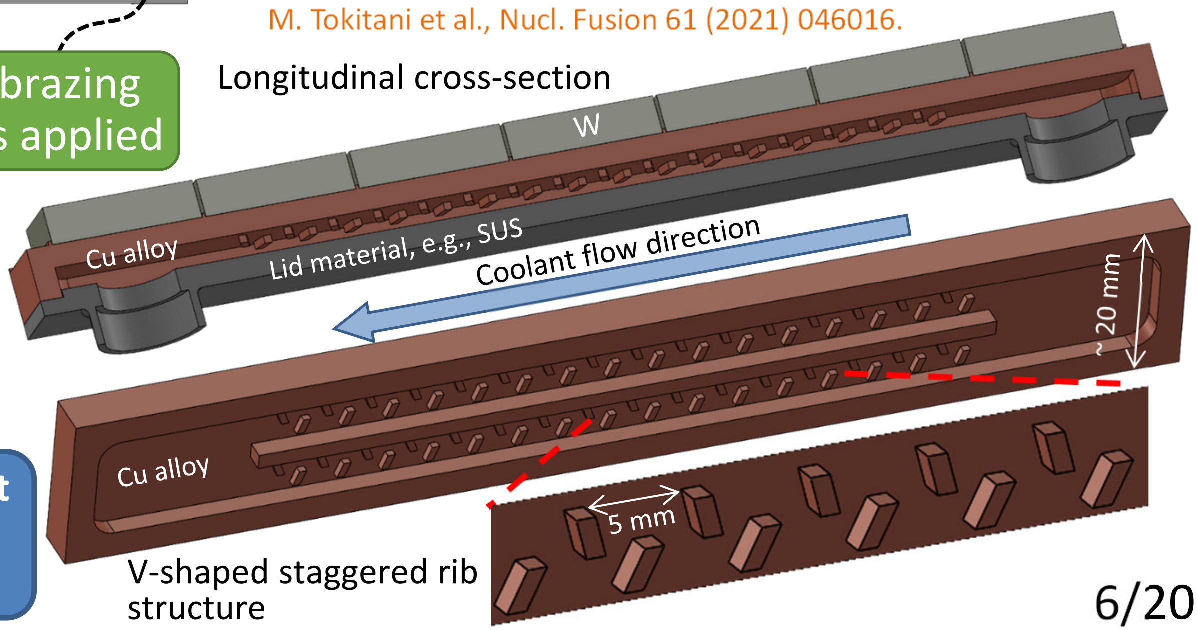
"Advanced brazing technique" is applied

(2) V-shaped staggered rib structure

- **Industrially applied technology, e.g., gas turbine blade etc.**
- **The swirling turbulent flow is generated due to the effect of the V-shaped rib structure.**

"New type divertor heat removal component"

M. Tokitani et al., Nucl. Fusion 61 (2021) 046016.



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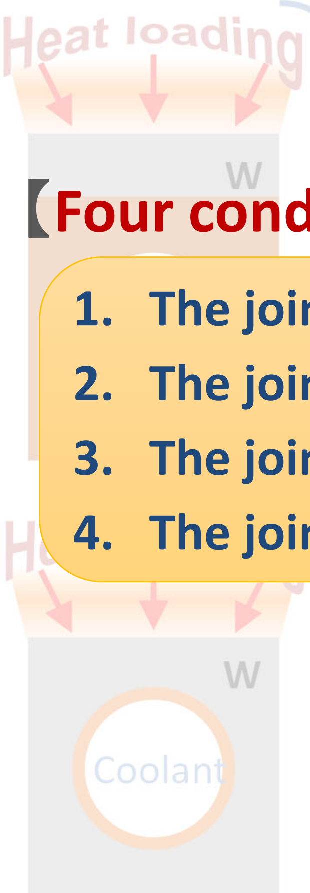

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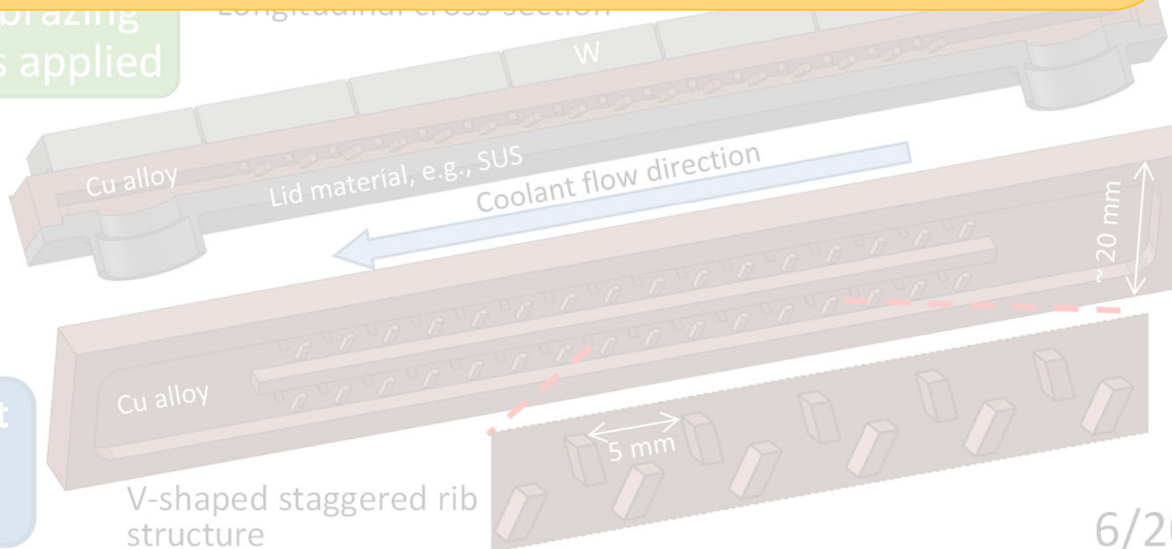
- Industrially applied technology, e.g., gas turbine blade etc.
- The swirling turbulent flow is generated due to the effect of the V-shaped rib

【Four conditions】

1. The joints are completely leak-tight.
2. The joints have areal contact, not line- or spot-like contact.
3. The joints withstand against "thermal stress" and "water pressure".
4. The joints do not degrade even after a repetitive (brazing) heat treatment.

"Advanced brazing technique" is applied



The leak-tight joint is difficult to create in the conventional technologies.

Leak tight joint method by applying the advanced brazing

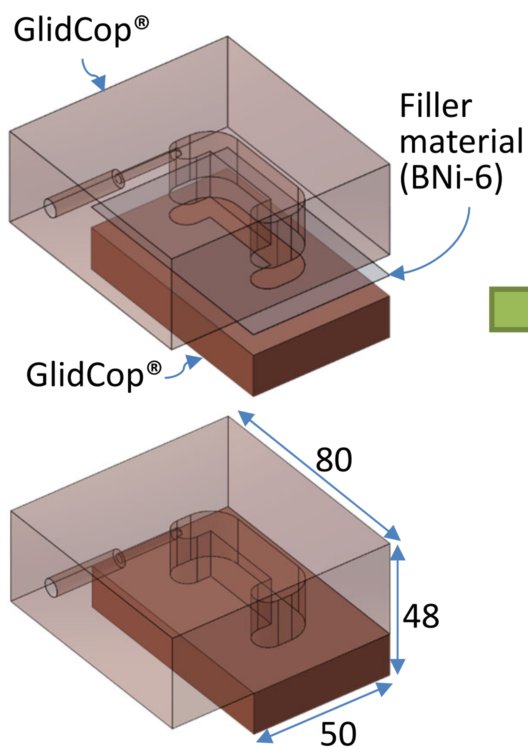
① GlidCop®/GlidCop® ② SUS/GlidCop® → **Same method is applied**

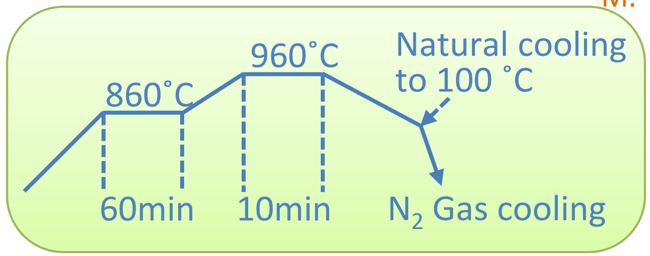
Uniform compressive load: 0.54 MPa + **Developed heat treatment**

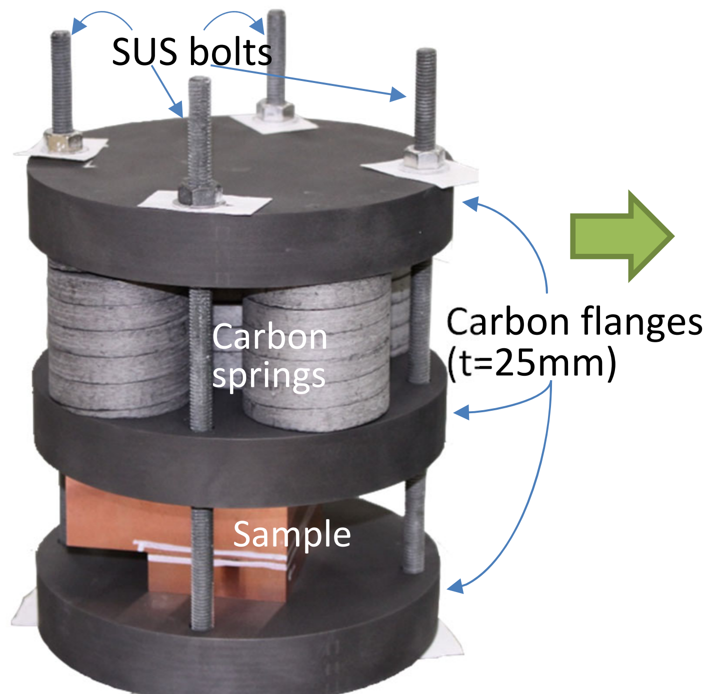
M. Tokitani et al., Fusion Eng. Des. 148 (2019) 111274.

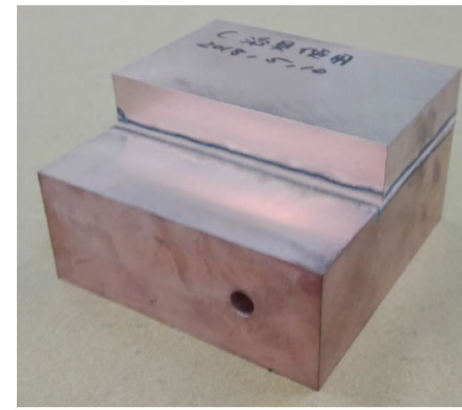
Flow path model

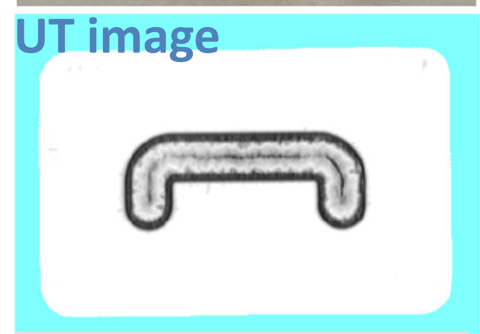
Filler material:
BNi-6 (Ni-11%P) t=38μm











"Defects free joint" with wide area

Leak tight joint in an areal condition was achieved.

Leak tight joint method by applying the advanced brazing

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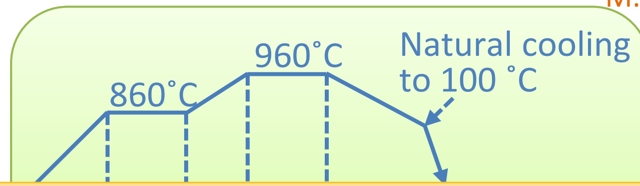

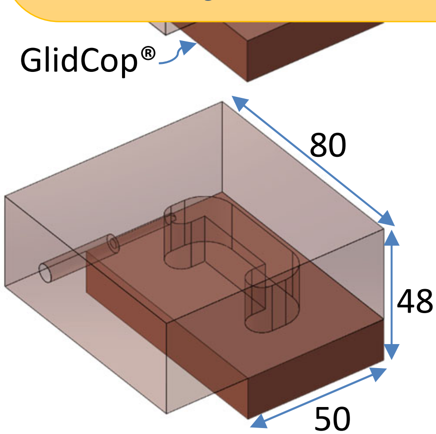

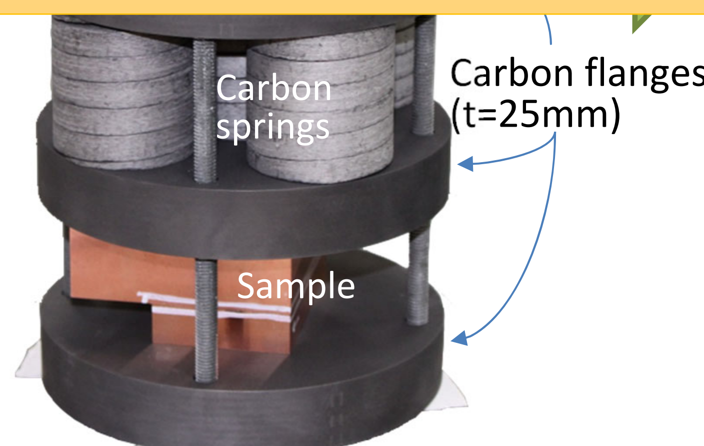

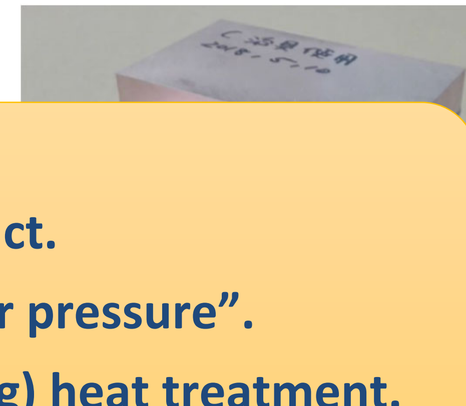

1. **The joints are completely leak-tight.**
2. **The joints have areal contact, not line- or spot-like contact.**
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4. **The joints do not degrade even after a repetitive (brazing) heat treatment.**

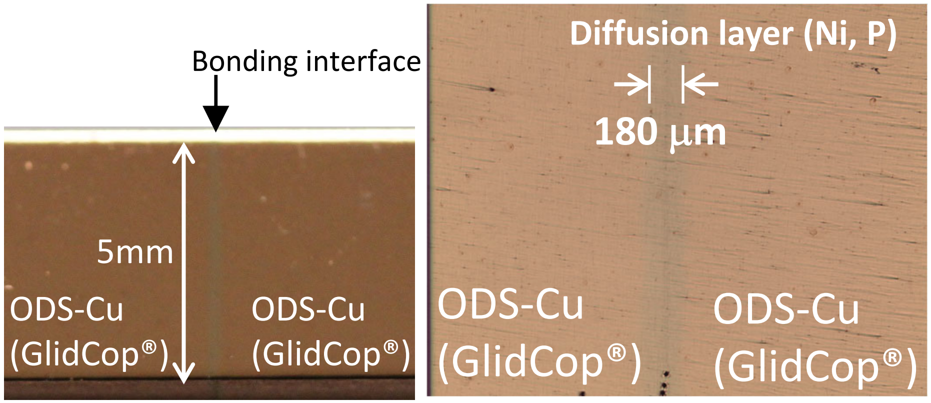
“Defects free joint”
with wide area

Leak tight joint in an areal condition was achieved.

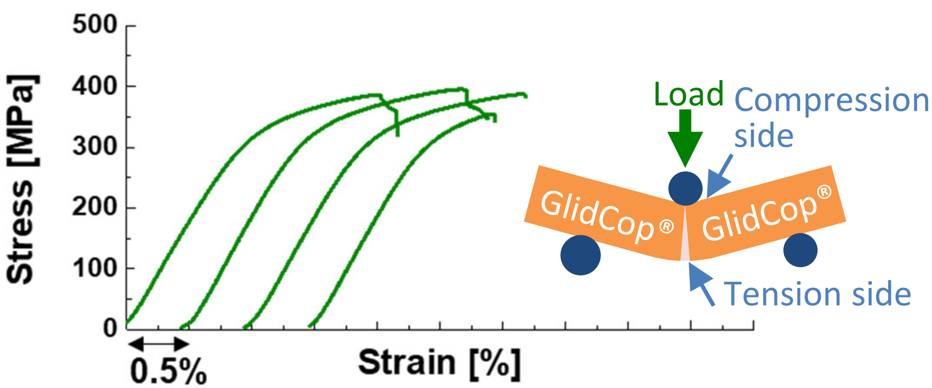
Quality of the leak-tight sealing joint

① GlidCop® / GlidCop®

M. Tokitani et al., Fusion Eng. Des. 148 (2019) 111274.

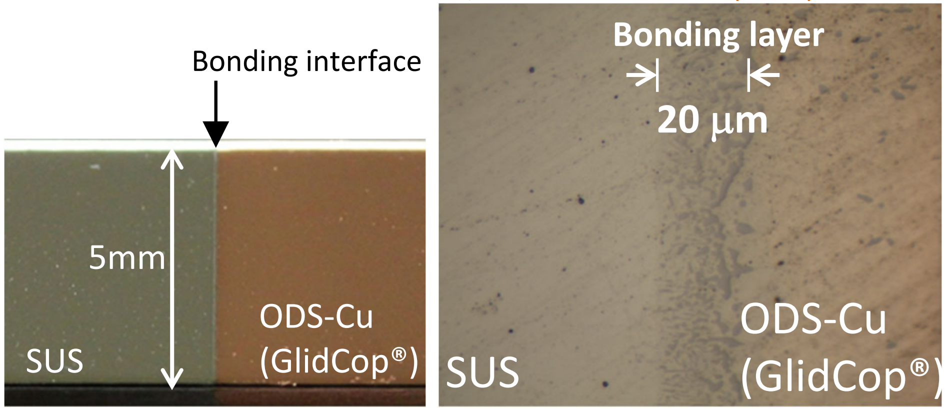


(a) Three-point bending test



② SUS/GlidCop®

M. Tokitani et al., J. Nucl. Mater. 538 (2020) 152264.



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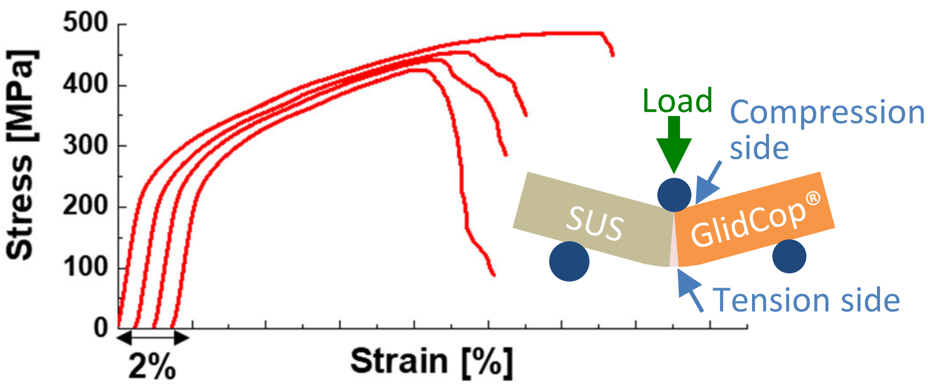
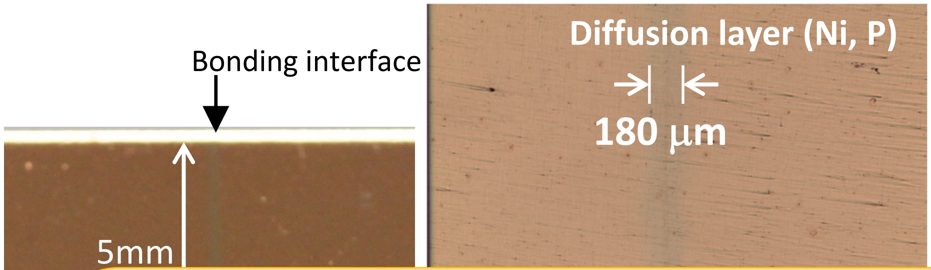


- **Very narrow bonding layers of ODS-Cu/ODS-Cu and SUS/ODS-Cu were obtained.**
- **Strength of the bonding layers were as high as the original ODS-Cu (GlidCop®).**
- **Microstructures and joint strength does not show any sign of the degradation even after the 2nd time heat treatment.**

Quality of the leak-tight sealing joint

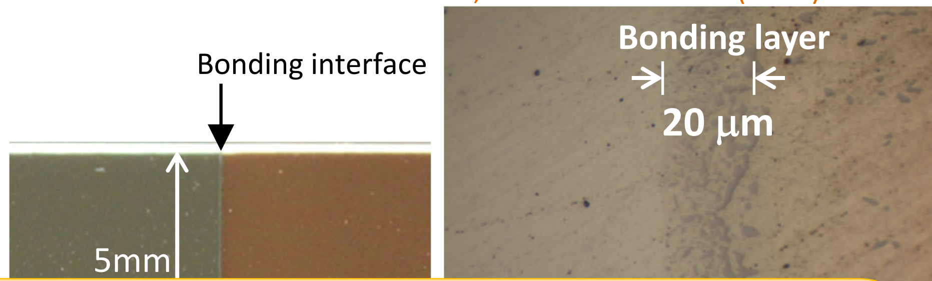
① GlidCop® / GlidCop®

M. Tokitani et al., Fusion Eng. Des. 148 (2019) 111274.



② SUS/GlidCop®

M. Tokitani et al., J. Nucl. Mater. 538 (2020) 152264.



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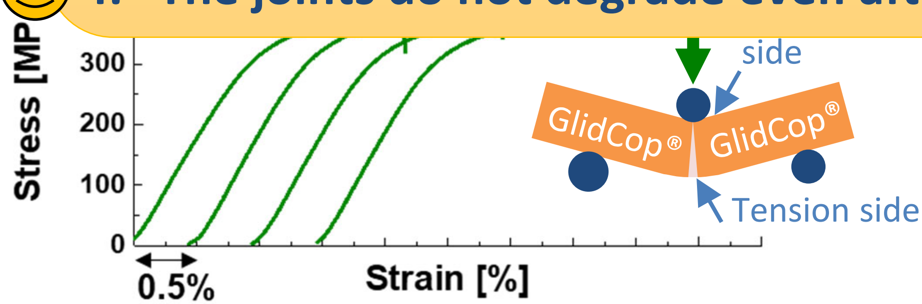

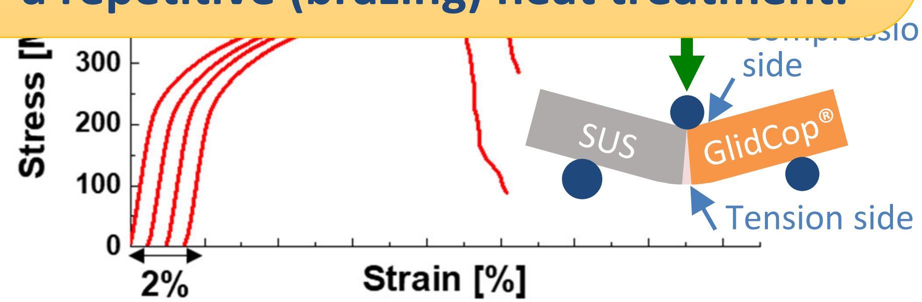

- ➢ **Very narrow bonding layers of ODS-Cu/ODS-Cu and SUS/ODS-Cu were obtained.**
- ➢ **Strength of the bonding layers were as high as the original ODS-Cu (GlidCop®).**
- ➢ **Microstructures and joint strength does not show any sign of the degradation even after the 2nd time heat treatment.**

Breakthrough: cleared the four conditions

1. The joints are completely leak-tight.
2. The joints have areal contact, not line- or spot-like contact.
3. The joints withstand against “thermal stress” and “water pressure”.
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– Judgement:

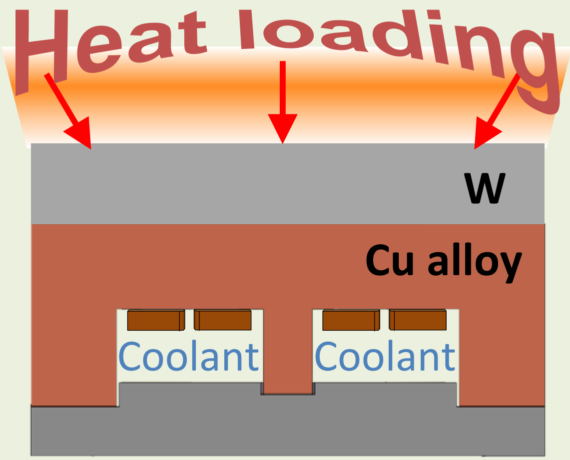
The “new type divertor heat removal component”

□ Ideal cooling structure

(1) Rectangular-shaped cooling flow path

\+

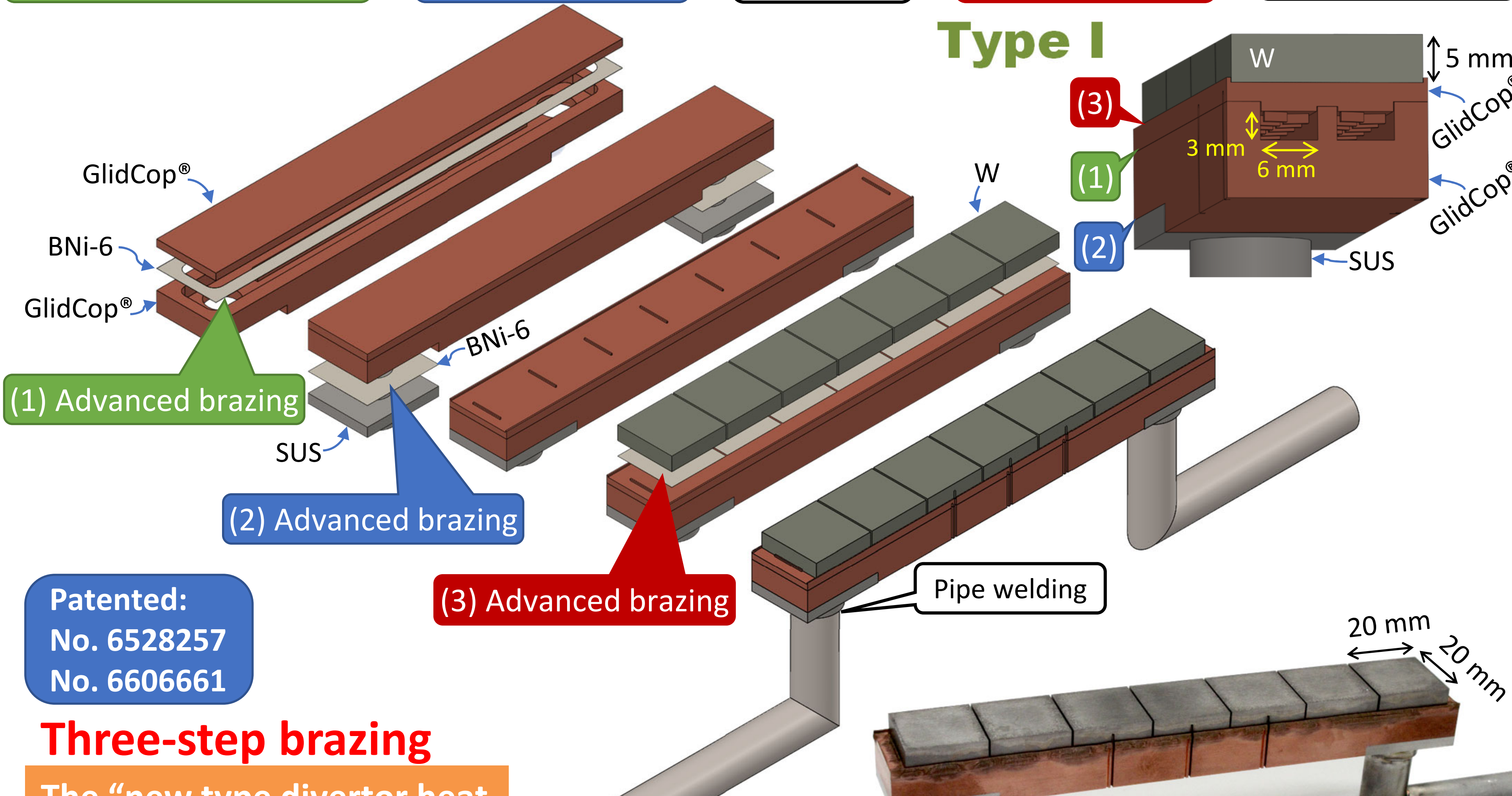
(2) V-shaped staggered rib structure

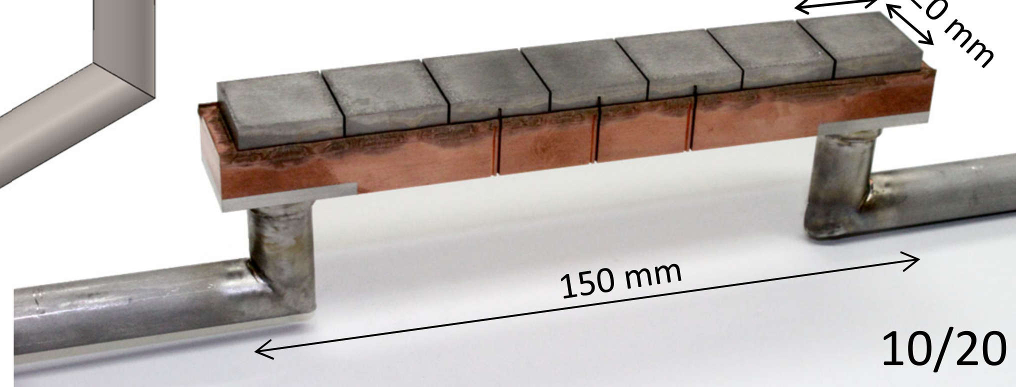


→ can be fabricated

Advanced Multi-Step Brazing (AMSB) was developed

(1) GlidCop®/GlidCop® → (2) SUS/GlidCop® → Machining → (3) W/GlidCop® → SUS pipe welding





Patented:
No. 6528257
No. 6606661

Three-step brazing

The "new type divertor heat removal component" was successfully fabricated.

M. Tokitani et al., Nucl. Fusion 61 (2021) 046016.

Advanced Multi-Step Brazing (AMSB) was developed

(1) ~~GlidCop®/GlidCop®~~ → (2) SUS/GlidCop® → Machining → (3) W/GlidCop® → SUS pipe welding

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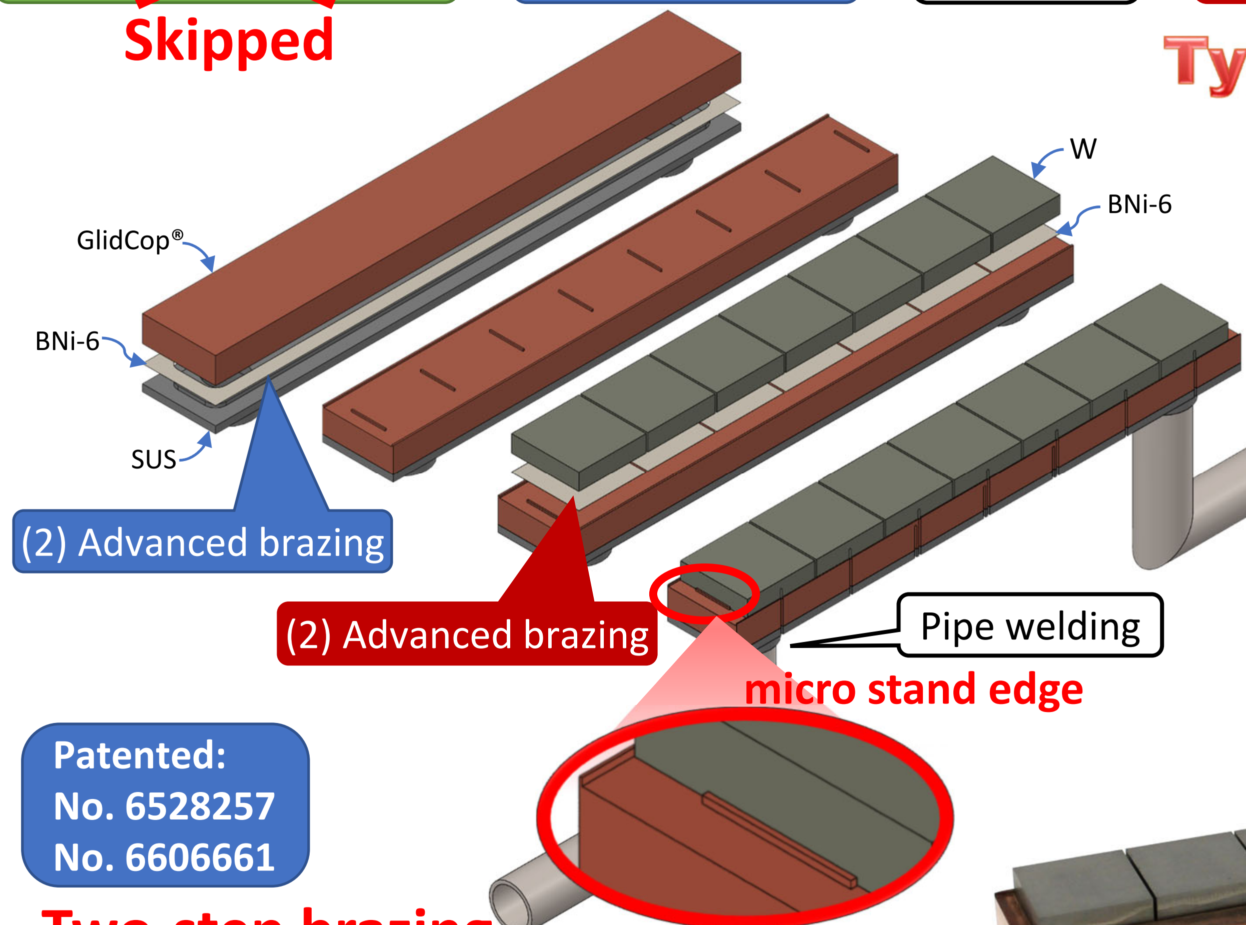
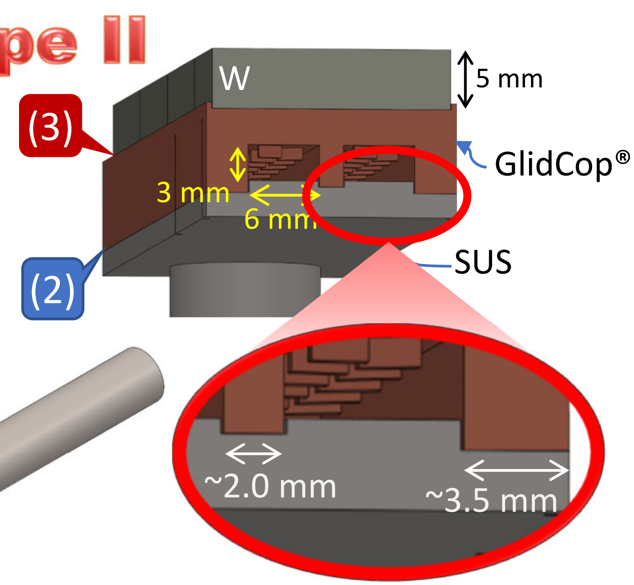


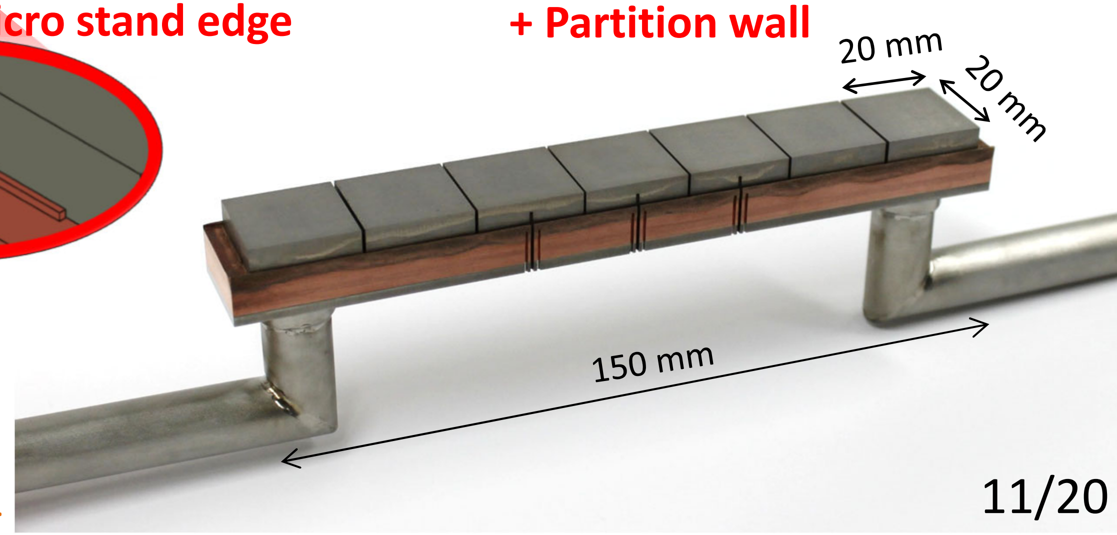


Narrow joint width (~3.5 mm) + Partition wall

Patented:
No. 6528257
No. 6606661

Two-step brazing

The “new type divertor heat removal component” was successfully fabricated.



M. Tokitani et al., Nucl. Fusion 61 (2021) 046016.

Advantages of AMSB

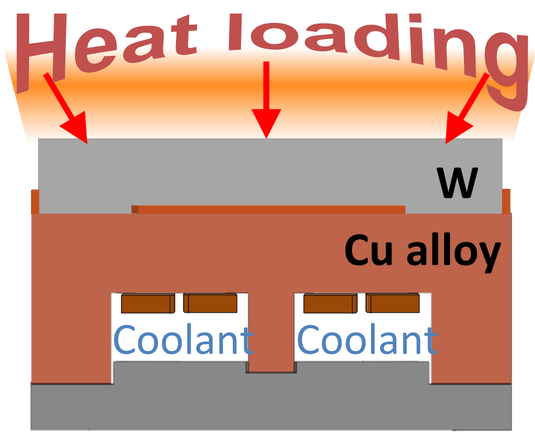
– Manufacturing advantages:

1. The joints are completely leak-tight.
2. The joints have areal contact, not line- or spot-like contact.
3. The joints withstand against “thermal stress” and “water pressure”.
4. The joints do not degrade even after a repetitive (brazing) heat treatment.

“Structural advantages” can be realized by “Manufacturing advantages”

– Structural advantages:

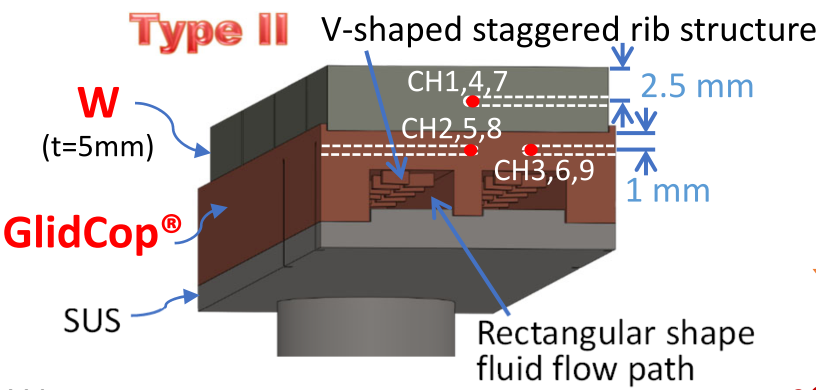
1. Rectangular-shaped cooling flow path + V-shaped staggered rib structure
2. Micro stand edge structure
3. Narrow joint width (~3.5 mm) + Partition wall

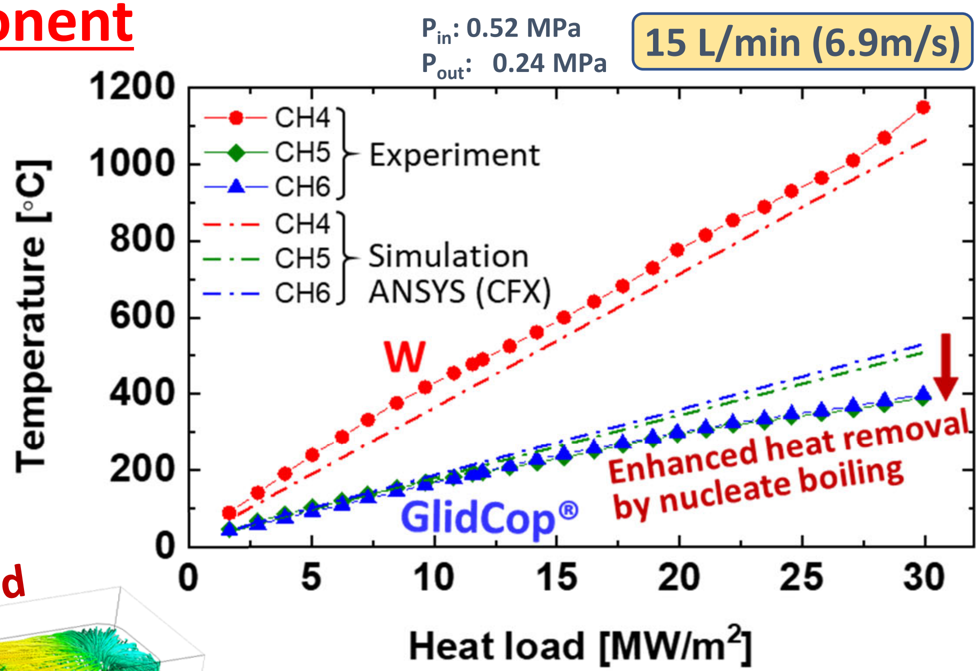


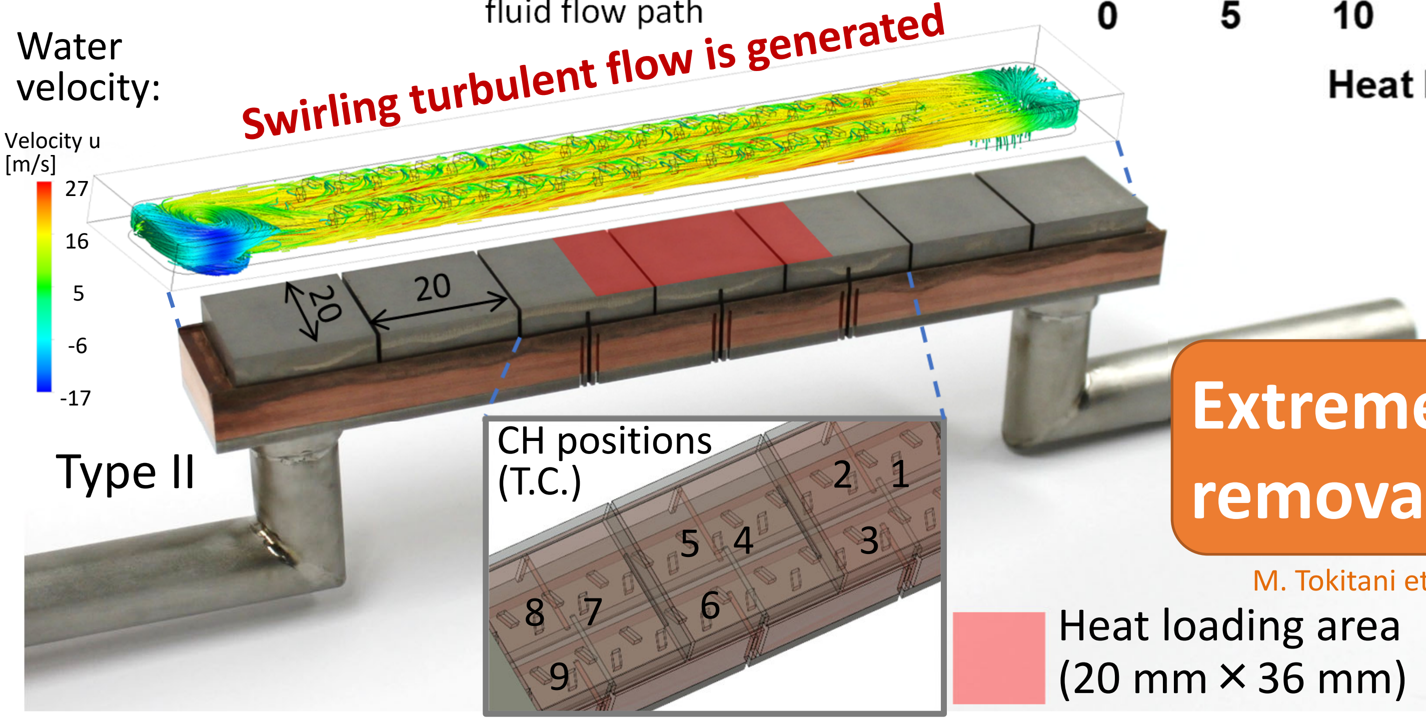
Extremely high heat removal capability: ~30MW/m²

New type AMSB divertor component

(1) Rectangular-shaped cooling flow path
(2) V-shaped staggered rib structure







Extremely high heat removal performance

M. Tokitani et al., Nucl. Fusion 61 (2021) 046016.

Summary (1)

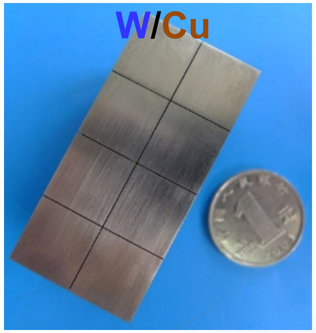
1. The concept of the new type divertor heat removal component was proposed.
2. The leak-tight joint method of GlidCop®/GlidCop® and SUS/GlidCop® was developed by applying the advanced brazing technique (ABT).
3. Advanced Multi-Step Brazing (AMSB) was developed, and the new type divertor heat removal component was successfully produced. (Patented: No. 6528257, 6606661)
4. The new component demonstrated an extremely high heat removal capability under the ~30 MW/m^2 steady state heat loading.

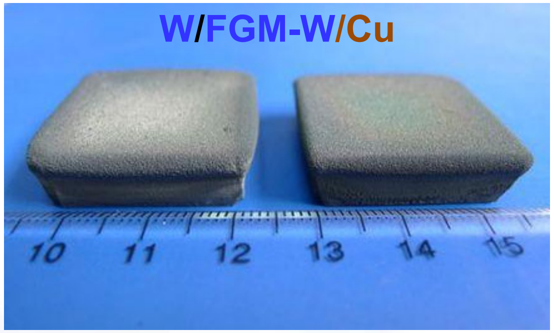
An overview of thick tungsten coating prepared by chemical vapor deposition and manufacture of relevant mockup

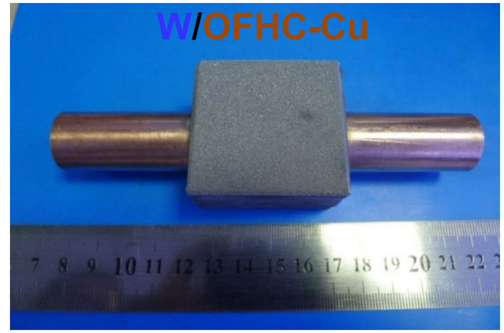
Z. Chen[1], Y. Li[2], L. Cheng[3], Y.Y. Lian[1], X. Liu[1], F. Feng[1], J.B. Wang[1], Y. Tan[1], T.W. Morgan[2], B.Y. Yan[4], J.P. Song[4], Z.L. Wang[5], X.Q. Ye[5]

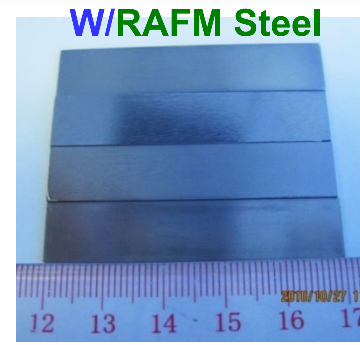
[1]Southwestern Institute of Physics
[2]DIFFER—Dutch Institute for Fundamental Energy Research
[3]Beihang University
[4]Xiamen Tungsten Co., Ltd.
[5]Science and Technology on Surface Physics and Chemistry Laboratory

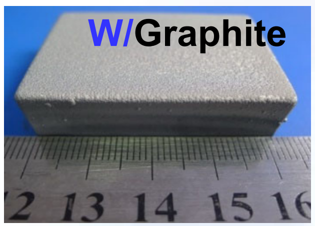
CVD-W: preparation, purity, TC, and CTE

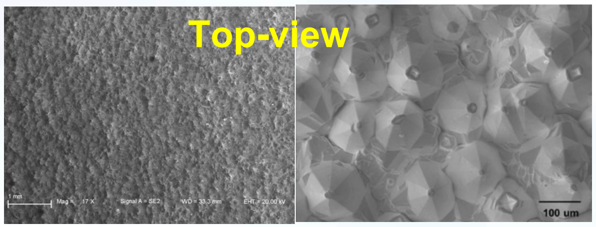


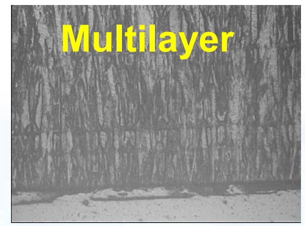


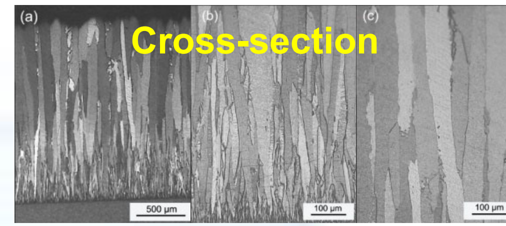




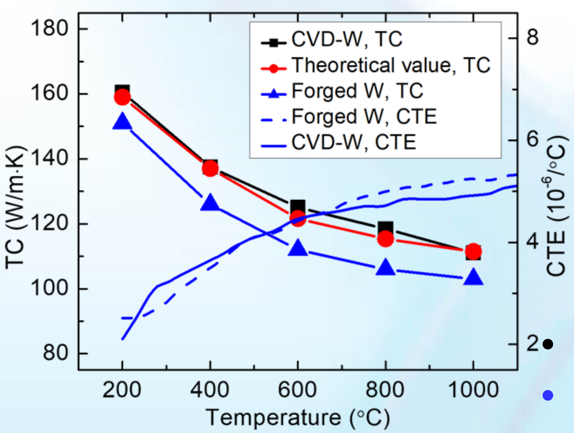








- Controllable preparation of CVD-W coatings on different substrates has been achieved.



Element	C	Element	C	Element	C	Element	C
C	<5	Al	0.03	Cr	0.08	Ni	0.02
O	<10	S	0.02	Fe	0.01	Zn	0.02
N	<5	Ca	0.03	Ti	0.002	Co	0.008
Ta	<1	Hg	<0.1	Re	<0.05	F	<0.01
Th	<0.0001	U	<0.0001	Others	<0.38	W	Matrix

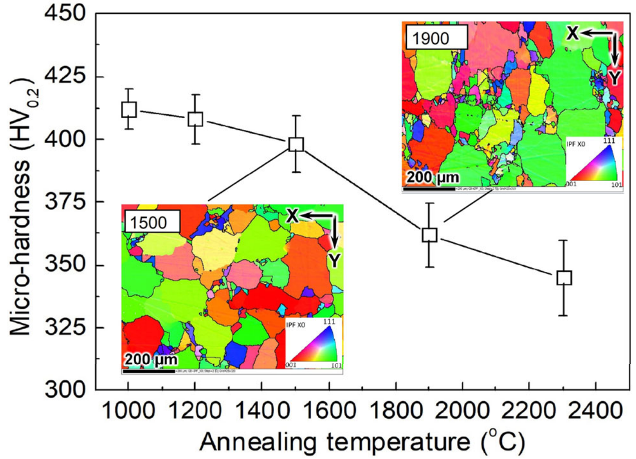
C is the concentration of an element with a unit in wt. 10^{-4}%

- Purity ≥99.99%

- Comparable thermal conductivity (TC) to the theoretical value of W.
- ≥670℃, lower coefficient of thermal expansion (CTE) vs forged-W

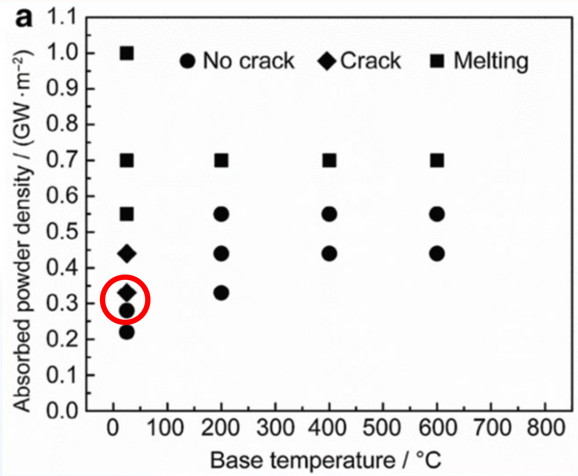
J. Nucl. Mater. 457 (2015) 317 *Tungsten (2020) 2:83–93*

Thermal stability, transient heat flux, permeability

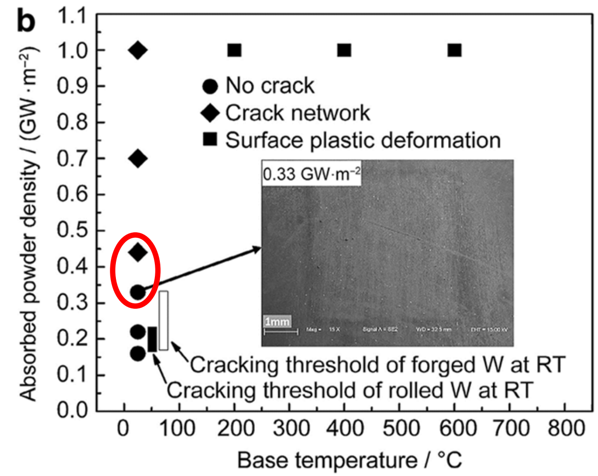


Annealing: 1200–2300 ℃, 3 h

- Excellent recrystallization resistance.

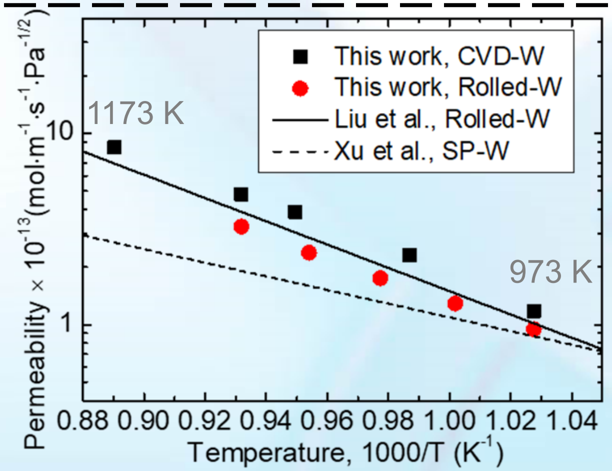


Disruption-like thermal loading



ELM-like thermal loading

- CVD-W: cracking threshold at RT, 0.28–0.33 GW·m^{-2}.
- CVD-W: cracking threshold at RT, 0.33–0.44 GW·m^{-2}.



$$\Phi_{CVD-W} = 1.44 \times 10^{-7} \exp\left(-\frac{1.17eV}{kT}\right), \mathrm{mol \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1/2}}$$

$$\Phi_{rolled-W} = 7.14 \times 10^{-8} \exp\left(-\frac{1.14eV}{kT}\right), \mathrm{mol \cdot m^{-1} \cdot s^{-1} \cdot Pa^{-1/2}}$$

- D permeability of the CVD-W was higher than commercial pure W, while their activation energy values were almost the same.

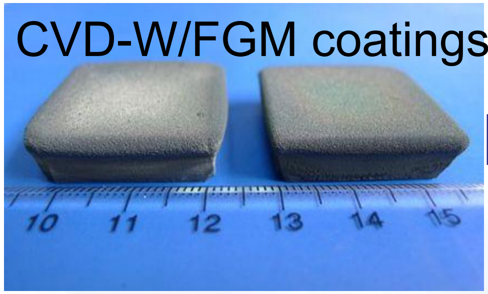
Appl. Surf. Sci. 390 (2016) 167–174; J. Nucl. Mater. 455 (2014) 371-375

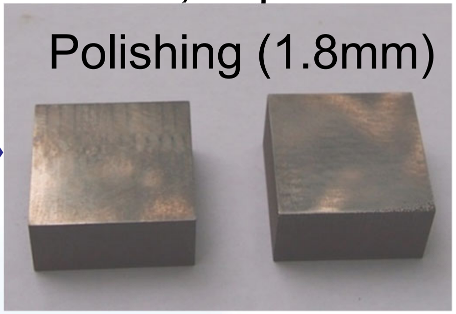
Thermal fatigue

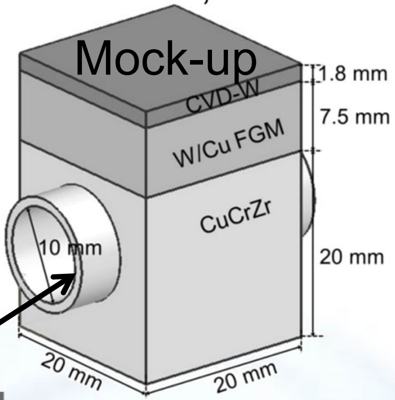
CVD-W/FGM/CuCrZr component

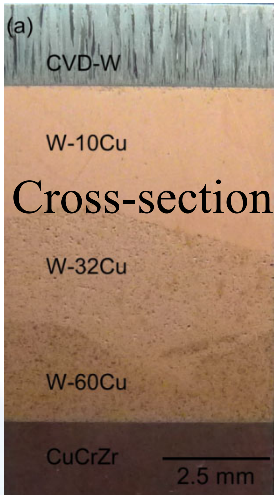
Fusion Eng. Des. 88 (2013) 1694-1698

Deposition temperature: 580℃, deposition rate: 0.7mm/h, thickness: 2mm

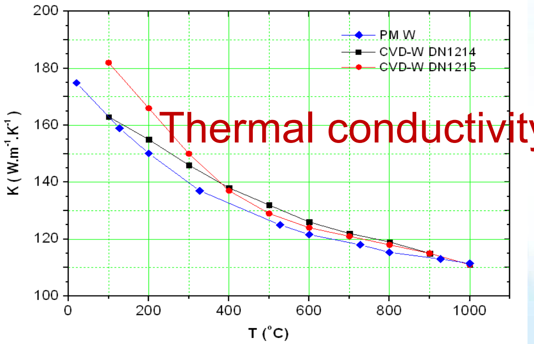


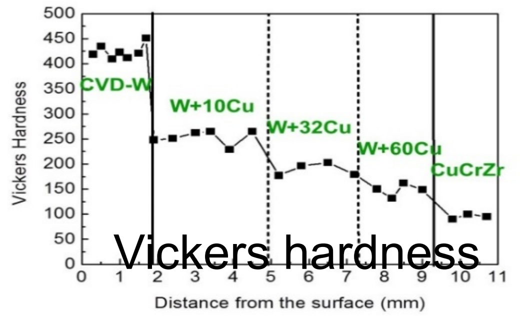


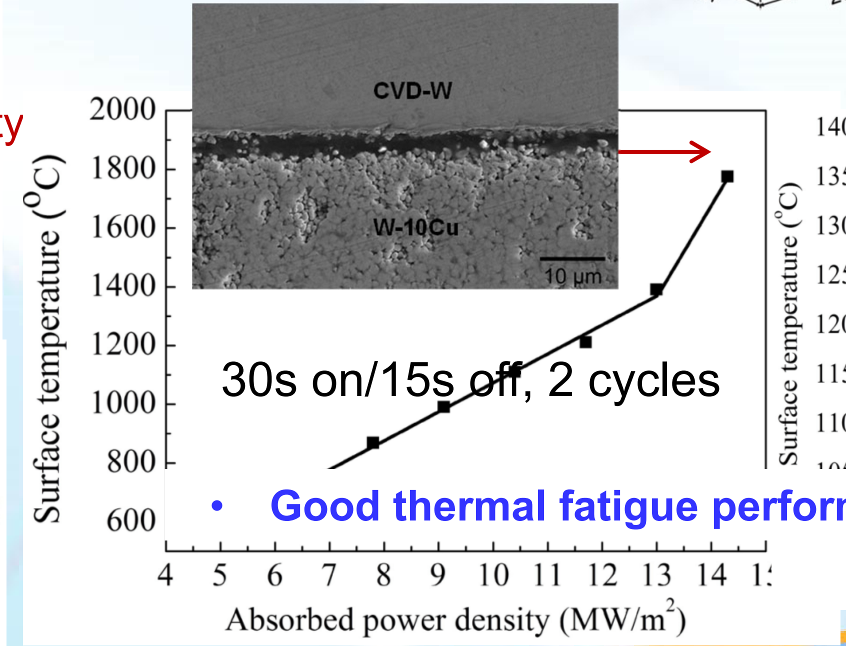


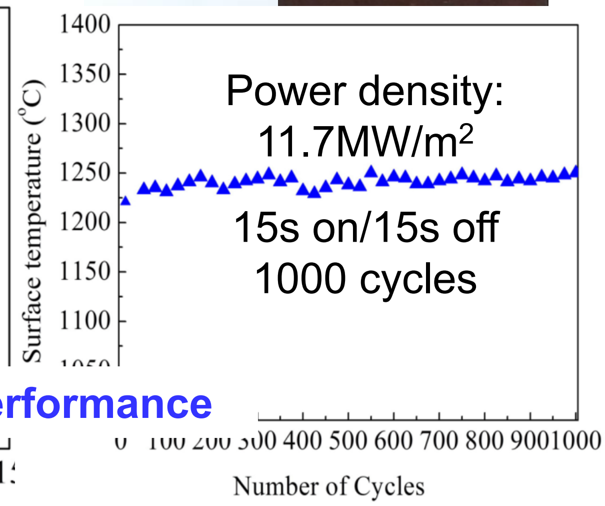


Brazing with CuCrZr with FGM, 950℃, 20min





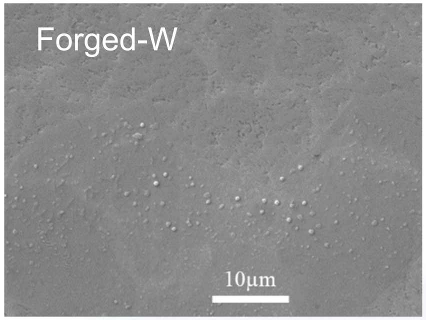


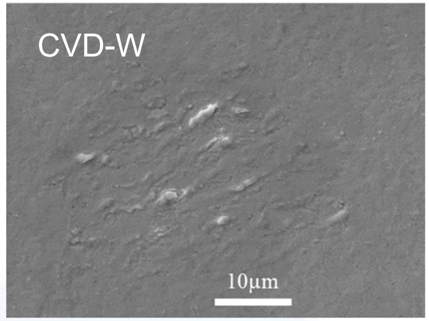


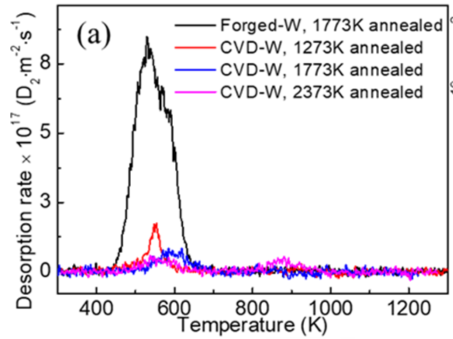
- **Good thermal fatigue performance**

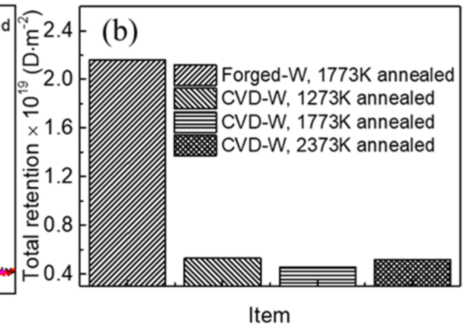
D plasma exposure, steady-state and transient, mockups

@Magnum-PSI, 50 eV, 823 K, Te=1.65 eV, ne = $4.73\times10^{19}m^{-3}$, Fluence=1.02×10^{26} m^{-2}

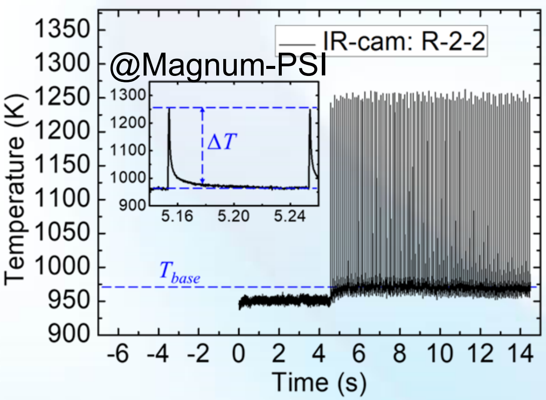






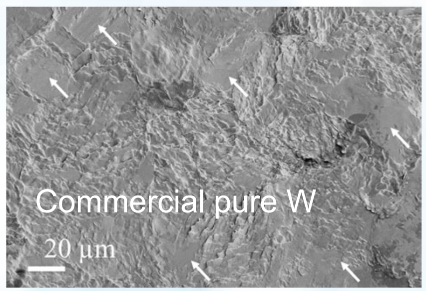


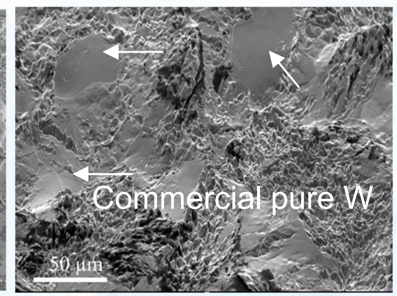
- **CVD-W: a mitigated blistering behavior, lower D retention VS the forged-W.**

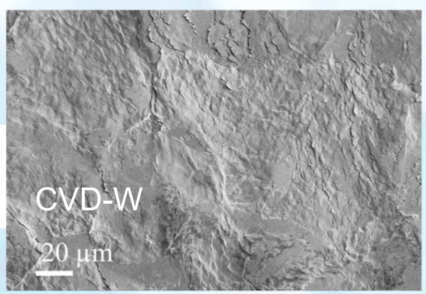


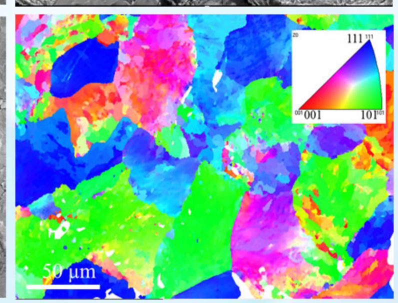
Steady-state: H plasma, $8.6MW\cdot m^{-2}$

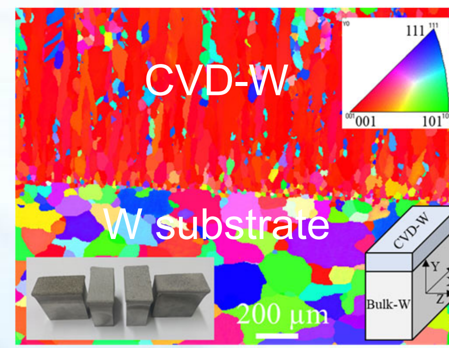
Transient: laser beam, $4MW\cdot m^{-2}\cdot s^{0.5}$











CVD-W: smoother surface

- **Strong grain orientation dependence of surface degradation**
- **Degradation preferentially occurred on the planes close to (101)**

Summary (2)

1. CVD (chemical vapor deposition)-W on different substrates including Cu, RAFM steel, and graphite are successfully prepared.
2. The CVD-W showed an excellent recrystallization resistance and a good thermal fatigue performance. In addition, a mitigated blistering and low D retention characteristics were confirmed. The CVD-W showed a higher D permeability compared to the commercial pure W counterpart.
3. The surface degradation induced by steady-state and transient heat flux exhibited a strong grain orientation dependence.
4. The large-scale CVD-W/CuCrZr mockups have also been developed. The preparation and heat loading tests of the CVD-W based water-cooled mono-block are undergoing.