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

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1. Advanced Brazing Technique (ABT)
   - Idea of the microstructural manipulation for the W/ODS-Cu joint
   - Joint mechanism

2. Advanced Multi-Step Brazing (AMSB)
   - Requirement for the new type divertor heat removal component
   - Four conditions for obtaining the joint structure of the new type divertor heat removal component
   - Development of the AMSB and fabrication procedures of the new type divertor heat removal component
   - Heat removal capability of the new type divertor heat removal component
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Reliable joint is required between “W” and “Cu alloy” however, joint procedure is difficult. Large deviation of the CTE

- W: 4.3 μ/K
- Cu alloy: 16.5 μ/K

To absorb the large deviation of the CTE

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.

We challenged Direct brazing (this study)
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.
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Requirement for the "new type divertor heat removal component"

Ideal cooling structure

1. Rectangular-shaped cooling flow path
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"

Longitudinal cross-section

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

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

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


Flow path model

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

GlideCop®

GlideCop®

GlideCop®

80
48
50

SUS bolts
Carbon springs
Carbon flanges (t=25mm)

Sample

UT image

“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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Leak tight joint in an areal condition was achieved.

Quality of the leak-tight sealing joint

1. GlidCop® / GlidCop®

2. SUS/GlidCop®

(a) Three-point bending test

- 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

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Breakthrough: cleared the four conditions

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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

Type I

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

Advanced brazing

Three-step brazing

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

Patented:
No. 6528257
No. 6606661

Advanced Multi-Step Brazing (AMSB) was developed. Two-step brazing, the "new type divertor heat removal component" was successfully fabricated.

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
- Rectangular-shaped cooling flow path
- V-shaped staggered rib structure

Type II

V-shaped staggered rib structure

GlidCop®

SUS

Rectangular shape fluid flow path

Swirling turbulent flow is generated

Water velocity:

Velocity u [m/s]

- 27
- 16
- 5
- 0
- -6
- -17

Heat load [MW/m²]

W

Heat removal performance

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/m² steady state heat loading.
An overview of thick tungsten coating prepared by chemical vapor deposition and manufacture of relevant mockup

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

- Controllable preparation of CVD-W coatings on different substrates has been achieved.
- Comparable thermal conductivity (TC) to the theoretical value of W.
- \( \geq 670^\circ C \), lower coefficient of thermal expansion (CTE) vs forged-W.
- Purity \( \geq 99.99\% \)

Tungsten (2020) 2:83–93
Thermal stability, transient heat flux, permeability

Annealing: 1200–2300 °C, 3 h

- Excellent recrystallization resistance.

Disruption-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.

ELM-like thermal loading

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

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

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

Thermal fatigue

CVD-W/FGM/CuCrZr component

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

CVD-W/FGM coatings → Polishing (1.8mm) → Mock-up

Brazing with CuCrZr with FGM, 950°C, 20min

Cross-section

Thermal conductivity

Vickers hardness

Power density: 11.7MW/m²
15s on/15s off 1000 cycles

• Good thermal fatigue performance

30s on/15s off, 2 cycles


China National Nuclear Corporation
Steady-state: H plasma, 8.6 MW \cdot m^{-2}

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

@Magnum-PSI

Commercial pure W

Forged-W

CVD-W

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

CVD-W: smoother surface

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