Recent progress in the assessment of irradiation effects for in-vessel fusion materials: tungsten and copper alloys

Materials for plasma-facing components

- Baseline design:
  - Tungsten block
  - Copper pipe

- Ageing under nuclear operation:
  - Embrittlement of tungsten
  - Softening of copper
  - Strength of W-Cu joint

- Materials & bonding => **Lifetime** of PFC unit

10-20 MW/m² + 14.1 MeV neutrons

1200°C on surface

-10¹⁴ n/cm²/sec
PFC materials: EU programme 2014-2020

Plasma facing materials: decrease of DBTT, recrystallization resistance, oxidation resistance

Heat sink materials: high temperature performance (≤ 500-600°C)

Interlayers & Joints: closing of operational temperature gap, stress reduction (e.g. FGMs, alternative concepts)

Improvement Strategies:
- **Plasma facing materials**
  - CuCrZr
  - Safe operation T
  - Recrystallization

- **Heat sink materials**
  - Baseline & advanced tungsten alloys
  - Safe operation T

- **Interlayers & Joints**
  - Closing of operational temperature gap
  - Stress reduction (e.g. FGMs, alternative concepts)

Irradiation dose [dpa]

- **ITER 0.1 dpa**
  - Phase I DT-operation

- **ITER 0.4 dpa**
  - PFC replacement

- **ITER 1 dpa**
  - End of life

- **DEMO 5 dpa**
  - Phase I
Strategy to test materials for nuclear fusion environment

- Neutron irradiation at BR2
  - 3-5 dpa(Fe)/year
- Testing in Hot Cells
  - Tensile, bending, fracture toughness
  - Microstructural analysis
- Development of materials & test techniques (SSTT)
  - High temperature testing
  - Small-scale test techniques to enable high flux irradiation
- Accounting for Re/Os transmutation
  - 2 at.%Re / dpa

1) Neutron Irradiation exposure

2) Post-irradiation examination

3) Design rules assessment
Advanced W alloys: additive manufacturing

- Powder Injection Molding (PIM)
  - Strengthening by ODS or TiC particles
  - Mass production of final-shaped components
  - Fully isotropic material properties
  - Recrystallization-resistant preserving fine-grain size

![Diagram of powder injection molding process](image1)

- Fabrication of green parts
- Heat-treatment at ~2000 °C
Advanced W alloys: fiber composites

- W fiber-reinforced
- Enables usage of brittle matrix

As fabricated

![Graph showing load vs. displacement](image)

Matrix failure = bulk material failure

Multi-fibre sample, 3-point bending

Reference: [Chawla 1993]
Advanced W alloys: alloyed/doped rolled plates

- Rolled K-Re doped plates
  - Reduction in DBTT / increase in strength
  - Mature fabrication technology
  - Screening irradiation is already performed
Advanced Cu alloys reinforced by W

- Option 1: Particle-reinforced W-Cu composites
- Option 2: Fiber-reinforced W-Cu composites
  - Enhanced strength and thermal conductivity
  - Cost-effective solution
  - Good potential for industrial upscaling
Advanced Cu alloys: Vanadium/ODS/W laminates

• Option 3: Strengthened by Vanadium & ODS-particles
• Option 4: W-Cu laminates: strong & ductile

Ductile W thin foil

Joining technology

Final product: pipe or tile

Tests are performed on reference samples used for neutron irradiation
Irradiation effects in W ITER spec.: 1 dpa @ 800°C

- Large shift in Ductile to Brittle Transition Temperature
- $\Delta$DBTT = 600-625°C
- Irradiation below 800°C embrittles W

DBTT defined at the onset of non-linear load-displacement response.
Irradiation effects in W ITER spec.: 1 dpa @ 900-1200°C

- Irradiation at 900-1200°C @ 1dpa still leads to DBTT shift > 200°C
- Irradiation at 600°C @ 0.1 dpa causes ΔDBTT ~ 150°C
- Irradiation enhances transgranular cleavage
Irradiation effects in W alloys: 1 dpa @ 600-1100°C

- Severe embrittlement in PIM alloys
- Pronounced hardening even after high temperature irradiation
- Irradiation hardening alters in Re-added alloy (transmutation to Os)
Irradiation effects in W alloys: 1 dpa @ 600-1100°C

- $\Delta DBTT$ of rolled plates is lower by 50-150°C than in ITER spec. W
- $T_{irr}=1100°C$, $\Delta DBTT$ is ~250-400°C for rolled and forged W plates
- At $T_{irr}=600°C$, Re alloying increase DBTT shift

DBTT defined at the onset of flexural strain exceeding 5%

Promising results for rolled plates
Microstructural studies: single crystal vs. rolled plate

• Irradiation hardness ($\Delta H$) is much lower in rolled plate compared to single crystal
• Transmission microscopy and positron spectroscopy proved the reduced void growth in the rolled plate
• High density of dislocations and grain boundaries operate as defect sinks

Fully consistent with theoretical expectations
Irradiation effects in Advanced Cu alloys & composites

- W-Cu Laminates: strong impact on ductility (= embrittlement)
- W-fiber composites: reduction in total elongation & hardening
- W-particle composite: reduction of elongation, minor hardening/softening
- V-alloyed CuCrZr: softening after irradiation at 450°C
- ODS-CuCrZr: reduction of uniform & total elongation
Irradiation effects in Fiber-reinforced composites

- **W-fiber composites:**
  - Some fibers fracture brittle
  - Matrix remains ductile

Promising results

Engineering stress [MPa] vs Engineering strain [-]
Irradiation effects in W-Cu laminates

- **W-Cu laminates:**
  - Fully brittle fracture
  - Cracks initiate near interfaces

![Graph showing engineering stress vs. engineering strain for CuCrZr-W laminate at different irradiation and test temperatures.]

- Unexpected results
Irradiation effects in Advanced Cu alloys & composites

- Irradiation softening is observed in: V-alloyed CuCrZr
- Complete loss of ductility is observed in: W-Cu laminates
- Reduction of elongation & hardening (= embrittlement):
  - Moderate in W-fiber and -particle reinforced composites
  - Considerable in ODS-CuCrZr
Summary & conclusions

• ITER specification W irradiated at ~1 dpa (W):
  • (1) Ductile operation is 900-1100°C range
    • DBTT (T_{irr}=800°C) = 1100°C; DBTT (T_{irr}=1100°C) = 800°C

• Advanced W-alloys irradiated at ~1 dpa (W):
  • (2) Ductile threshold can be reduced to 600°C or even lower
    • Application rolling/forging reduces DBTT and irradiation embrittlement
    • Re alloying increases DBTT shift (transmutation)

• Advanced Cu alloys irradiated at ~2.5 dpa (Cu):
  • (3) Unexpected embrittlement of W-Cu laminates
    • Strength of W-Cu interface
  • (4) Softening of V-alloyed CuCrZr above 350°C
    • Stability of V-precipitates under irradiation
  • (5) Promising results for fiber-reinforced composites
    application window might be extended above 450°C
    • W fibers preserve ductile deformation in a wide T_{irr} range
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