Issues of tungsten as a plasma facing material for ITER and DEMO

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Outline

☐ Introduction (W as plasma facing materials)
☐ Pulsed heat load effects
  ■ Melting and cracking: experiments and simulations
☐ Helium effects
  ■ Nano-structure: formation mechanism and its effects
☐ Tritium behavior
  ■ Role of surface mixing layers
☐ Neutron effects
  ■ Synergism of radiation damage and transmutation
☐ Concluding remarks
Tungsten as plasma facing materials

- **Advantages of tungsten as PFM’s**
  - High melting point (3693 K)
  - High thermal conductivity
  - Low sputtering yield (high threshold energy for light ion bombardment)
  - Low tritium retention

- **Critical Issues**
  - Avoidance of material degradation under complex fusion environments
    - Steady-state heat load
      - 400s, $10^4$ cycles for ITER W, used below DBTT*
    - Pulsed (Transient) heat load (ELM’s, disruptions, etc.)
    - Plasma Irradiation (D/T, He ions)
    - Neutron irradiation
      - Radiation damage, transmutation
  - Avoidance of core plasma accumulation
  - Safety operation (Dust)

*DBTT (Ductile Brittle Transition Temperature)
Pulsed heat load effects
Summary of pulsed load effects

VDE - Be
60 MJm\(^{-2}\)
100 / 300 ms

Disruption - W

Disruption - PS-W

Increasing power density

Additional crack formation during cool-down

Cracking roughening
Homogeneous melting
Melt ejection
Boiling and droplet formation

ELMs vertical displacement events / plasma disruptions

Melting threshold

From J. Linke
Surface morphology changes by pulsed load

Nd/YAG laser
(effective pulse length: ~100µs)
Base temp.: 500°C

Surface Melting

*Heat flux factor (MW m⁻² t⁻¹/₂)

Roughening, Cracking

Melting Threshold

~1/4 of Melting Threshold

Even ~1/4 of melting threshold pulse energy causes surface damage after large cycles of ELMs

*energy absorption ~0.3 is considered.
Concerns of melting

- Erosion enhancement and dust formation
  - Cracking and rapture
  - Dust release

- Formation of brittle solidified layers
  - Cracking and rapture
  - Dust release
  - Leading edge grows in the next melt event.

- Formation of leading edge
  - Further melting of leading edge (ITER limit: 0.3 mm)
  - Leading edge grows in the next melt event.

- Bridging between adjacent monoblocks
  - Stress to cooling tube
    - May cause Rapture of cooling tube

Excessive melting must be avoided.
What is the acceptable limit?
Simulation of Melt layer dynamics (pulsed plasma)

- **Base equations**
  - Navier–Stokes equations
  - Heat conduction equation

- **Material parameters** *(given)*
  - Thermal conductivity, viscosity, surface tension, etc.

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**Before**

**after**

\[ E = 1.0 \text{ MJm}^{-2} \quad \Delta t = 500 \mu s \quad 100 \text{ pulses} \]

**Plasma Gun exp. (QSPA)**

**Surface morphology (MOMOS code)**

Coupling with plasma

- **Vapor shielding, surface instability** (plasma pressure driven)
- Very few well controlled benchmark experiments.

*Presented at PSI2012*

G. V. Miloshevsky
A. Hassanein

Surface instability modeling

- Kelvin–Helmholtz instability
  - **Acting Force**: Plasma pressure (Plasma flow), Vapor recoil, Magnetic force


J. W. Coenen et al., Nucl. Fusion 51 (2011) 083008

Resolidified layer (TEXTOR exp.)

Figure 9. Fields of volume fraction for plasma–liquid tungsten flow at different times. Twenty wavelengths with $\lambda = 0.5$ mm were initially excited at $t = 0.3$ $\mu$s.
Simulation of cracking

- **Simulation code (PEGUSUS-3D)**
  - Simulates heating and heat conduction in the sample
  - Calculates thermal stress
  - Cracks formation and propagation
  - Dust particles splitting
  - Material properties (given)
  - Phenomenological approach

Experimental results (plasma gun)

Comparison between experiments and simulation

Cross section

Simulation results (PEGASUS-3D)

Top surface
Future direction: Combination of micro- (MD) and macro-(CIP) simulations to for PFM evaluation

Benchmark experiments (pulsed laser, E-beam, confinement devices)

Molecular Dynamics (MD)
Expanded ensemble MD for rare event

Material properties
from atomic dynamics
- viscosity coefficient
- surface tension
- equation of state
- diffusion coefficient

from electronic state
- Thermal conductivity
- electric conductivity
- energy of alloy, vacancy, and so on.

Exam.) DFT energy v.s. new potential for W-He-Ar system.

High quality potential
Density Functional Theory (DFT)
Exam.) DFT energy v.s. new potential for W-He-Ar system.

CIP sim.
for Melting and evaporation behavior

Interaction with plasma (vapor shielding, etc.)
Solidified material performance

Cubic Interpolated Propagation (CIP)
Helium Effects
Low energy* He effects on W

- **High temperature**
  - Large He bubbles formation with recrystallization
  - Degradation of mechanical and thermal properties

- **Medium temperature**
  - Nano-structure (fuzz) formation
  - Porous structure
  - Low thermal conductivity

- **Low temperature (< ~900 K)**
  - Small He bubble formation (a few nm)
  - Degradation of mechanical and thermal properties
  - Affects D/T retention

*Low energy*: around 100 eV or less

- **NAGDIS (Nagoya Univ.)**
  - $T \sim 2,100$ K

- **PISCES (UCSD)**
  - $T \sim 1,120$ K
  - $T \sim 1,400$ K
  - $T \leq 773$ K
He irradiated W in NAGDIS-II at 1400 K and 50 eV.

Many nanometer sized helium bubbles are formed on the surface by the exposure to helium plasmas. With the help of an active surface diffusion, pinholes, dips, and protrusions are formed on the surface. The shape of structure becomes complicated ones such as plain-like or pillar-like structures.

S. Kajita, N. Yoshida et al. JNM 418 (2011) 152–158

Surf. temp.: 1400 K, Ion energy: 50 eV

(a) Surf. temp.: 1400 K, Ion energy: 50 eV

(b) Surf. temp.: 1400 K, Ion energy: 50 eV
Layer growth follows kinetics that are controlled by a diffusion like process.

- Observed $t^{1/2}$ proportionality.
- The thickness of the nanostructured layer, $d$, agrees well with

$$d=(2Dt)^{1/2},$$

with,

$$D_{1120\ K} = 6.6 \pm 0.4 \times 10^{-16} \text{ m}^2\text{s}^{-1}$$
$$D_{1320\ K} = 2.0 \pm 0.5 \times 10^{-15} \text{ m}^2\text{s}^{-1}$$

- Overall process is consistent with an activation energy of $\sim 0.7$ eV.
To understand tungsten nano-bubble and fuzz structure formations, multi-simulation process is three phases

1. **penetration**: range (depth) v.s. sputtering
   - Depending on injection energy

2. **diffusion**: He diffusion, thermal vacancy, He-v traps.
   - Depending on trap energy and temperature

3. **growth**: growth to bubble and fuzz (sub micro meter)

A. Ito et al., Physical society meeting, March 2012
Growth mechanism of fuzz

- **Key physics necessary to understand**
  - Tungsten atom diffusion to tips of nano-structure
  - Role of He bubbles
  - Role of ion bombarding energy (≥ 20 eV)

- **Viscoelastic model**
  - Viscose flow of W to the tip of the fiber due to the force caused by the pressure of He in the growing fiber.

Present understandings on W nano-structure

- W fuzz looks common for all high density plasma devices (linear plasma & magnetic confinement plasma).
  - Alcator C-Mod (Magnetic confinement device)
  - Pilot-PSI (High flux device relevant to ITER)

- W fuzz has advantages and disadvantages for fusion reactors
  - Advantages
    - Low physical sputtering yield (1/5~1/10 of flat surface)
    - Mitigation of pulsed heat load (no cracking)
    - Thermal annealing (> 1400 K) → extinction without release to plasma
  - Disadvantages
    - Unipolar arcing → still under discussion
Nanostructured W formed in the NAGDIS-II was installed in LHD. Arcing was initiated by the exposure to the LHD plasma, the duration of which was 2s. Since the magnetic field direction was almost normal to the target, the motion was Brownian-like. This results strongly suggest that arcing can be easily initiated when the nanostructure is formed on the surface.

Tritium Behavior in tungsten
Tritium issues for DEMO

- Neutron irradiated W
  - It was believed that T retention is low for W.
  - However, neutron irradiated W has deep traps and uniform trap site distribution.
  → Need more investigation and proper modeling

- Dynamic behavior of T
  - Dynamic retention in blanket and divertor and permeation of T to bulk materials and coolant are important to control T in fusion reactors.
  - One of the important issues for dynamic T behavior is effects of surface conditions on T behavior.
Suppression of D retention by He

SR-W, $5 \times 10^{25}$ D/m$^2$, @573K

Pure-D

$D$ retention
$\sim 9.4 \times 10^{20}$ D/m$^2$

D retention
less than detection limit

M. Miyamoto et al., Nucl. Fusion 49 (2009) 065035 (7pp)
He/D mixed ion driven permeation

- Addition of He (2%) greatly reduces permeation flux.
- Saturation time almost corresponds to He bubble formation time.

Detailed studies showed increase in effective diffusion of D to ion implantation surface.

Ion driven permeation model (Brice & Doyle)

- **Penetration**
  \( \phi_i (1 - R_e) \)

- **Recombination (recycling)**
  \( J_1 = 2 k_1 C_1^2 \)

- **Diffusion**
  \( J_1 = \frac{D_1}{R} (C_R - C_1) \)

- **Recombination (Permeation)**
  \( J_2 = \frac{D_2}{x_0 - R} (C_R - C_2) \)

- **Incident flux** \( \phi_i \)
- **Permeation flux** \( \phi_p \)
- **PLASMA**
- **COOLANT**
- **IRRADIATION SURFACE**
- **PERMEATION SURFACE**
- **Solute hydrogen concentration**

(a) **Recombination limited condition**:
\[
\phi_p = \frac{D_2}{x_0 \sqrt{k_1}} \sqrt{\alpha \phi_i}
\]

(b) **Diffusion limited condition**:
\[
\phi_p = \frac{R D_2}{x_0 D_1} \alpha \phi_i
\]

Incident flux dependence

- $\phi_p \sim \phi_i$ (D only irradiation)
- $\phi_p \sim \phi_i^{1/2}$ (D/He irradiation)

  $\phi_p$ : Permeation flux
  $\phi_i$ : Incident flux

- Change of flux dependence suggests D release from the front surface could change from diffusion limited (D) to recombination limited (D/He).

  Front surface diffusion increased.

Permeation flux $\phi_p$ vs. Incident flux $\phi_i$
Enhanced D desorption by He bubble layer

- He bubble layer was observed up to the depth of about 20 nm.
- Thickness of He bubble layer was larger than ion range (~10 nm).
- He bubbles could be interconnected to form pores to the surface.

Possible Mechanism for decrease in permeation

Necessary to make proper modeling and simulation!
Neutron Effects
Neutron effects of tungsten

- Neutron irradiation damage effects
  - Increase in DBTT (Ductile Brittle Transition Temperature)
  - Reduction in thermal conductivity due to lattice damage
  - Void swelling
  - Increase in T trapping

- Transmutation (W \( \rightarrow \) Re (\( \rightarrow \) Os)) effects
  - Mainly, neutron capture reaction (\(^{184}\text{W}(n, \gamma)\) and \(^{186}\text{W}(n, \gamma)\))
  - Increase in impurity elements concentration reduces thermal conductivity.
  - Increase in embrittlement (especially Os)

- For DEMO
  - Up to 15 to 20 dpa \( \rightarrow \) both damage and transmutation are important.

- For ITER
  - Even for low dpa (up to 0.7 dpa), damage effects (T retention) needs to be taken care of.
Transmutation of W

  - W: 5% Re: 0.02% Os (3 MW y/m²)
  - W: 10% Re: 0.1% Os (6 MW y/m²)
  - W: 25% Re: 1.0% Os (15.5 MW y/m²)

- Thermal diffusivity of W decreases with the increase in Re

- Neutron load (3 MW/m²)
  - Pure W
  - W95Re5%: ~1 year
  - W90Re10%: ~2 years
Void and loop formation were suppressed by Re and Os addition and fine and dense precipitates were formed after irradiation in the alloys.  


Synergistic effects of radiation damage and transmutation elements
Concluding remark

- Melting and roughening by pulsed heat load
  - Acceptable surface damage level by pulsed heat load is still not clear. Experiments and proper modeling need to be done to understand and evaluate W performance under complex fusion plasma environments.

- He surface effects
  - Surface damage and new structure (nano-structure) are developed by He ion irradiation. Whether its effects are serious or not, is under discussion.
  - Modeling of nano-structure is in progress.

- Tritium behavior in tungsten
  - Effects of surface modified layers (He bubble, material mixing layer) need to be understood. Dynamic processes will become more important for DEMO.

- Material modeling and simulation
  - Microscopic (MD, DFT) and macroscopic simulation (Hydrodynamics, CIP, rate process) are in progress. Combined simulation of microscopic and macroscopic models could be a new direction in fusion science and engineering.