Recent Progress of Tungsten R&D for Fusion Application in Japan

Y. Ueda, H. T. Lee, H. Y. Peng (Osaka Univ.)
N. Ohno, S. Kajita (Nagoya Univ.)
A. Kimura, R. Kasada (Kyoto Univ.)
T. Nagasaka (NIFS)
Y. Hatano (Toyama Univ.)
A. Hasegawa, H. Kurishita (Tohoku Univ.)
Y. Oya (Shizuoka Univ.)

13th International Workshop on Plasma-Facing Materials and Components for Fusion Applications and 1st International Conference on Fusion Energy Materials Science

May 09th - 13th, 2011 in Rosenheim, Germany
Outline

- **Tungsten Materials Development**
  - TFGR (Toughened, Fine-Grained, Recrystallized) W-1.1%TiC
    - H. Kurishita (Tohoku Univ.), et al.
  - W coating on reduced activation materials
    - A. Kimura, R. Kasada (Kyoto Univ.), et al.

- **Neutron Effects**
  - Retention in neutron damaged W
    - Y. Hatano (Toyama Univ.) et al. (J-US collaboration project TITAN)
  - Mechanical and electrical properties of neutron irradiated W alloys (W-Re, W-Re-Os)
    - A. Hasegawa (Tohoku Univ.), et al.

- **Surface Modification Effects by Mixed Plasma Exposure**
  - D permeation by mixed ion exposure
    - H.T.Lee, Y. Ueda (Osaka Univ.), et al.
  - Mechanism of He induced nano-structure formation
    - N. Ohno, S. Kajita (Nagoya Univ.), et al.

- **Summary and issues**
Tungsten Material Development
Conversion of UFG W-1.1TiC to TFGR W-1.1TiC by SPMM process

UFG W-1.1TiC compacts

SPMM process for significantly strengthening weak, high-energy grain boundaries (GBs) in UFG W-1.1TiC compacts

SPMM (SuperPlasticity-based Microstructural Modification)

TFGR W-1.1TiC compacts

TFGR (Toughened, Fine-Grained, Recrystallized) W-1.1%TiC Compacts

- Equiaxed grain structures with mostly random GBs and TiC dispersoids
- Very high fracture strength and appreciable bend ductility even at RT (DBTT: around RT)

H. Kurishita et al., JNM. 398 (2010)
Effects of SPMM temperature on microstructures

W-1.1TiC/Ar-UH
As-HIPed → SPMM: 1650 C

- Recrystallized grain structures
- Mostly high-energy random GBs

Grain size: 60 nm

W-1.1TiC/H₂-NH
As-HIPed → SPMM: 1650 C

Random (Mackenzie curve)

Grain size: 90 nm

T. Sakamoto et al.

S. Tsurekawa et al.
Effect of SPMM temp. on TiC dispersoid size

- The size of TiC dispersoids in grain interior and GBs increases with increasing SPMM temperature.
- W-1.1TiC/Ar exhibits much lower TiC growth rate than W-1.1TiC/H₂.
The samples exposed to 1850 and 2000C still exhibit slight ductility at RT and much higher strength than the as-HIPed, UFG sample.
W coating on reduced activation materials by VPS (vacuum plasma spray)

- Higher temperature is better for VPS coating
- Process temperature is limited by substrate materials

VPS-W coating was successful for F82H, ODS, and NH2 (V-alloy).

Cross section of VPS-W coating

Hardness of cross section
Neutron Effects
**TDS Results**

Comparison of TDS spectra from unirradiated, neutron-irradiated, and 2.8 MeV Fe$^{2+}$ ion-irradiated W specimens after plasma exposure at 200 °C.

**Difference between Neutron and Ion Irradiation**
- Distribution of defects (uniform vs. near surface)
- PKA energy spectrum (uniform vs. exponential)
- Damage rate ($10^{-7}$ vs. $10^{-4} – 10^{-3}$ dpa s$^{-1}$)

Broad peak for the n-irradiated sample suggests presence of several kinds of trapping sites ($1 – 2$ eV binding energy).

Simulation study is required to understand the difference between neutron and ion irradiation.
**NRA Results** (Neutron-irradiated & unirradiated W)

Good quantitative agreement between TDS and NRA results.

Trap density: 0.2-0.3 at% at 0.025 dpa.

Strong trapping even at 500 °C.

**M. Shimada, Poster Presentation, P50B (Today)**

Depth profiles of deuterium measured by NRA after TPE plasma exposure at indicated temperatures.
Irradiation effects of W-Re alloys, W-Re-Os alloys

Hasegawa (Tohoku Univ.)

Irradiation Hardening of W-Re alloys
Dept. Quantum Science & Energy Engineering, Tohoku University

- Lower dpa region (<0.37 dpa):
  - Irradiation hardening ($\Delta H_v$) of W-Re alloys was smaller than that of W.
  - Re concentration dependence on $\Delta H_v$ was not significant.

- Medium dpa region:
  - (about 1 dpa):
    - The irradiation hardening became larger.
    - The magnitude of the hardening depended on Re content.

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[16] Ueda et al. Unpublished data
Hasegawa et al. ICFRM-14 (to be published in J.N.M)
Void and loop formation were suppressed by Re and Os addition and fine and dense precipitates were formed after irradiation in the alloys.

Effects of Re and Os Contents on Change of Electrical Resistivity of W by Irradiation

W and W-Re alloys
- JOYO Irradiation:
  Significant change by irradiation was not observed.
- HFIR Irradiation:
  Increase of resistivity was observed.
  → Re production effects

W-Re-Os alloys
- JOYO Irradiation:
  Decrease of resistivity was observed.
  → Reduction of solute elements in the matrix by precipitation.

[14] Tanno et.al. J.N.M. 386-388(200) 218
Hasegawa et.al. ICFRM-14(to be published in J.N.M)
Surface Modification effects by Mixed Plasma Exposure
pure D permeation study in tungsten

Microstructure dependence

--Steady state permeation--

- Weak grain boundary dependence (factor of two)
- Peak in permeation flux observed $T \approx 800$ K

$\phi_i = 1.5 \times 10^{20}$ D m$^{-2}$s$^{-1}$

Normalized thickness: 25 $\mu$m
pure D permeation study in tungsten

Microstructure dependence
--Effective diffusivity--

- Effective diffusivity values determined from lag time measurements.
- Thickness dependence was observed.
- The activation energy was ~0.65 eV for “thick” samples (50 and 75 µm) with difference only in the diffusion constant.

He effects on permeation

- D permeation greatly reduced with He (5%) in ion beam.
- $\phi_p \sim \phi_i$ (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).

TEM picture (cross section)

He bubble layer and pores

Surface

Flux dependence of D permeation

H.T. Lee et al. JNM in print (2011)
Carbon effect on D permeation

- D permeation greatly increased with C (>0.9%) in ion beam.
- Strong temperature dependence.
- Surface elemental composition shows little dependence on temperature (C:1.4%).

Energy: 1 keV D, Ion flux ~10^{20} m^{-2}s^{-1}

Temperature dependence of permeation

Near surface atomic composition

H.Y. Peng, Poster Presentation, P44B (Today)
Solute D behavior in tungsten

Mixed irradiation (D/C, D/He) greatly changed diffusion and recombination near surface area

- Addition of C → Recombination or diffusion reduced: under investigation
- Addition of He → Effective diffusion near surface area increased.

D: diffusion limited
R: recombination limited

Ion implantation
Sample thickness

Depth

 Ion implantation

C

D density

D-only

+ C

~10^2

+ He

~10^-1

~10^3 difference in permeation flux (solute D density) (at 700~800 K)
Summary of W fuzz formation condition

N. Ohno, S. Kajita (Nagoya Univ.)

Surface Temp: $1000 \, \text{K} < T < 2000 \, \text{K}$
Ion Incident Energy $> 20 \, \text{eV}$

Growth of protrusions by helium irradiation

Irradiation were performed in the divertor simulator NAGDIS-II. The samples were analyzed FIB-TEM analysis.

Sample: W, 1400K, 50eV-He plasma

Thickness $\propto (\text{fluence})^{1/2}$

Summary and future directions

- **Development of TFGR W-1.1TiC**
  - Superplasticity based process (SPMM) successfully demonstrated
  - High fracture strength and ductility even at RT
  - **Issues**: large size specimen, retention

- **W coating on reduced activation materials**
  - VPS-W successfully demonstrated on RAM
  - **Issue**: optimization of process, retention, heat flux

- **Neutron irradiation effects on T retention**
  - Difference from ion damaged W
  - **Issues**: trap site characterization, T behavior modeling
Summary and future directions 2

- **Property change of W alloys due to neutron irradiation**
  - Hardening: void formation (W), radiation induced precipitation (W alloy)
  - Electrical resistivity (thermal conductivity) change:
    - low dpa $\rightarrow$ damage, high dpa $\rightarrow$ transmutation
  - **Issues**: more database, modeling

- **D permeation by mixed ion irradiation**
  - Weak dependence of SS permeation on microstructure
  - **D/C** mixed irradiation *increases* permeation
  - **D/He** mixed irradiation *reduces* permeation
  - **Issues**: parameter dependence, modeling

- **He induced nano-structure**
  - Detailed formation mechanism
  - **Issues**: impact on plasma operation