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MPT/1-4

Neutron Irradiation Effects on Grain-refined W and W-alloys

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Outline

1. Introduction

2. Summary of neutron irradiation effects of Tungsten based on previous data.

3. Prediction of microstructural development of tungsten under fusion reactor irradiation conditions.

4. Tungsten alloys development by grain refining and alloying for fusion application.

5. Current status of material evaluation of unirradiated state.

Tungsten in Fusion Reactor

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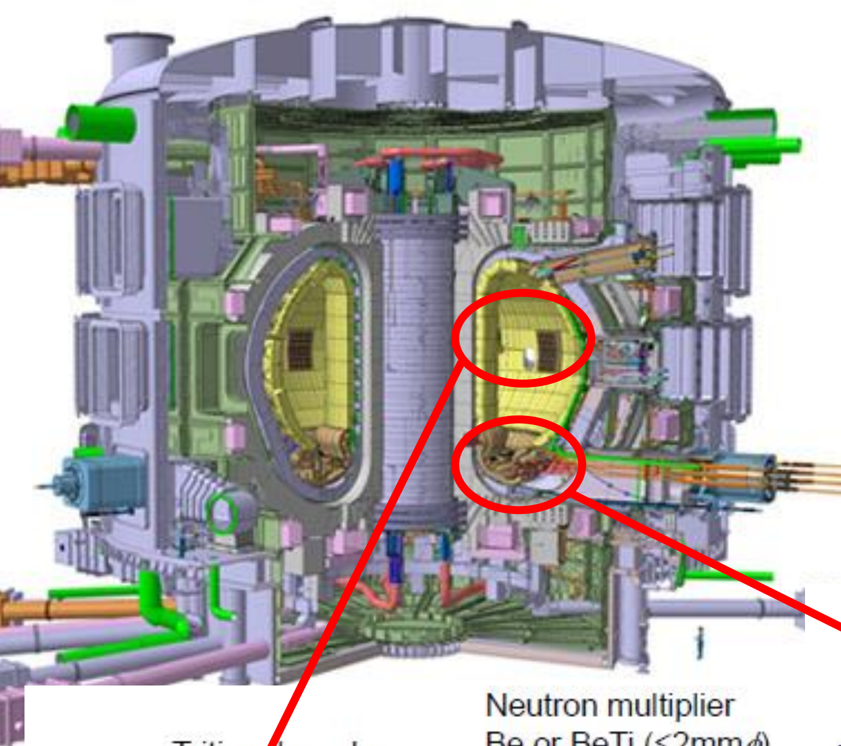
・Tungsten is candidate material for first wall and divertor components in fusion reactor.

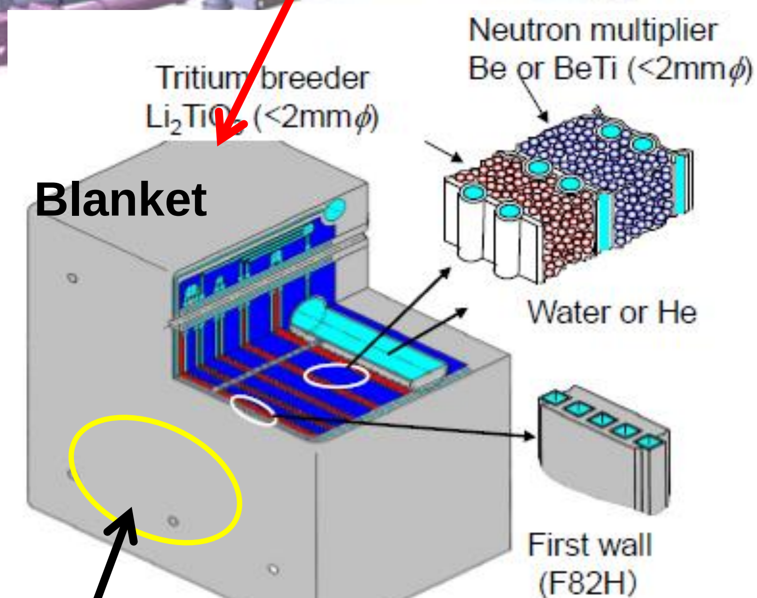
Resistance to High-Hear-Load and High-Density-Particle Irradiation

→ High melting temperature

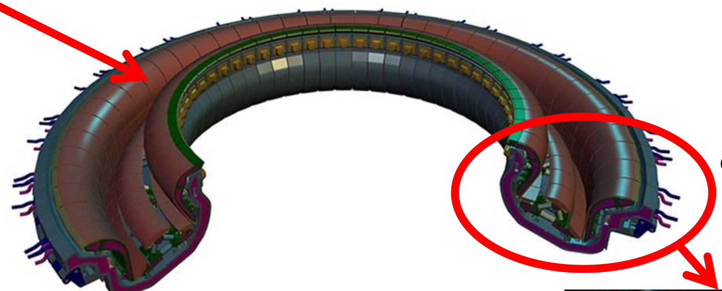
→ High resistance to sputtering

→ Low hydrogen retention

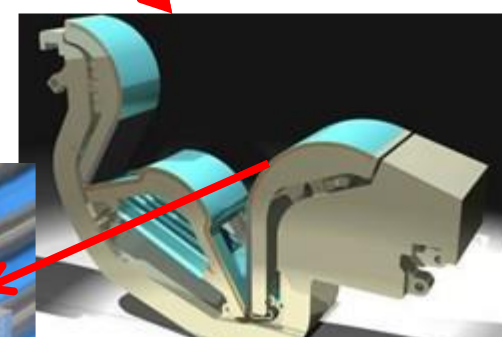




Coating on plasma facing surface
(Thickeness:1mm for TBR)



Divertor :
Impurity exhaust apparatus



Cooling Block

Cooling component

Temperature Dependence on Microstructure and Physical Properties of Tungsten

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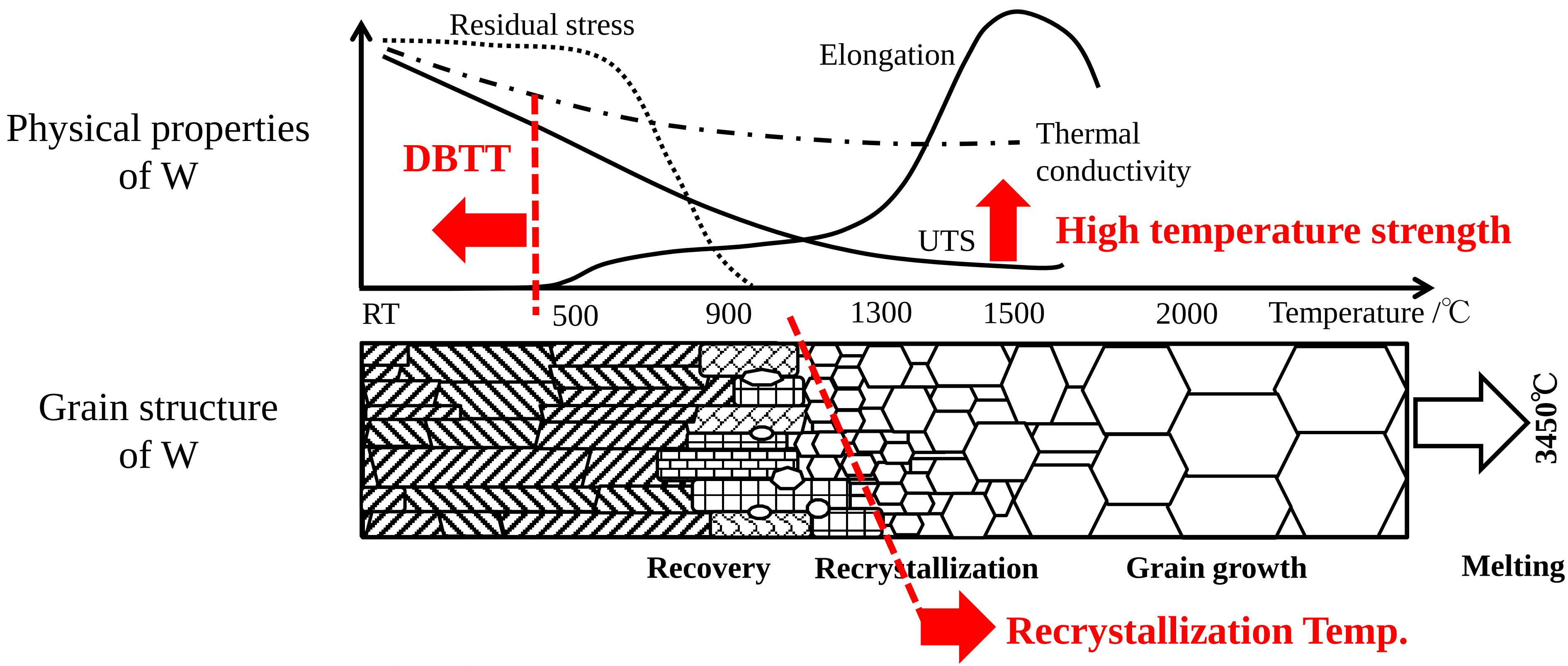

Strategy of material development of Tungsten

- Decrease DBTT (Ductile-Brittle-Transition- Temperature)
  Improve low temperature embrittlement.
- Increase recrystallization temperature.
- Increase high temperature strength.

Improvement of Mechanical Properties by Microstructure Control

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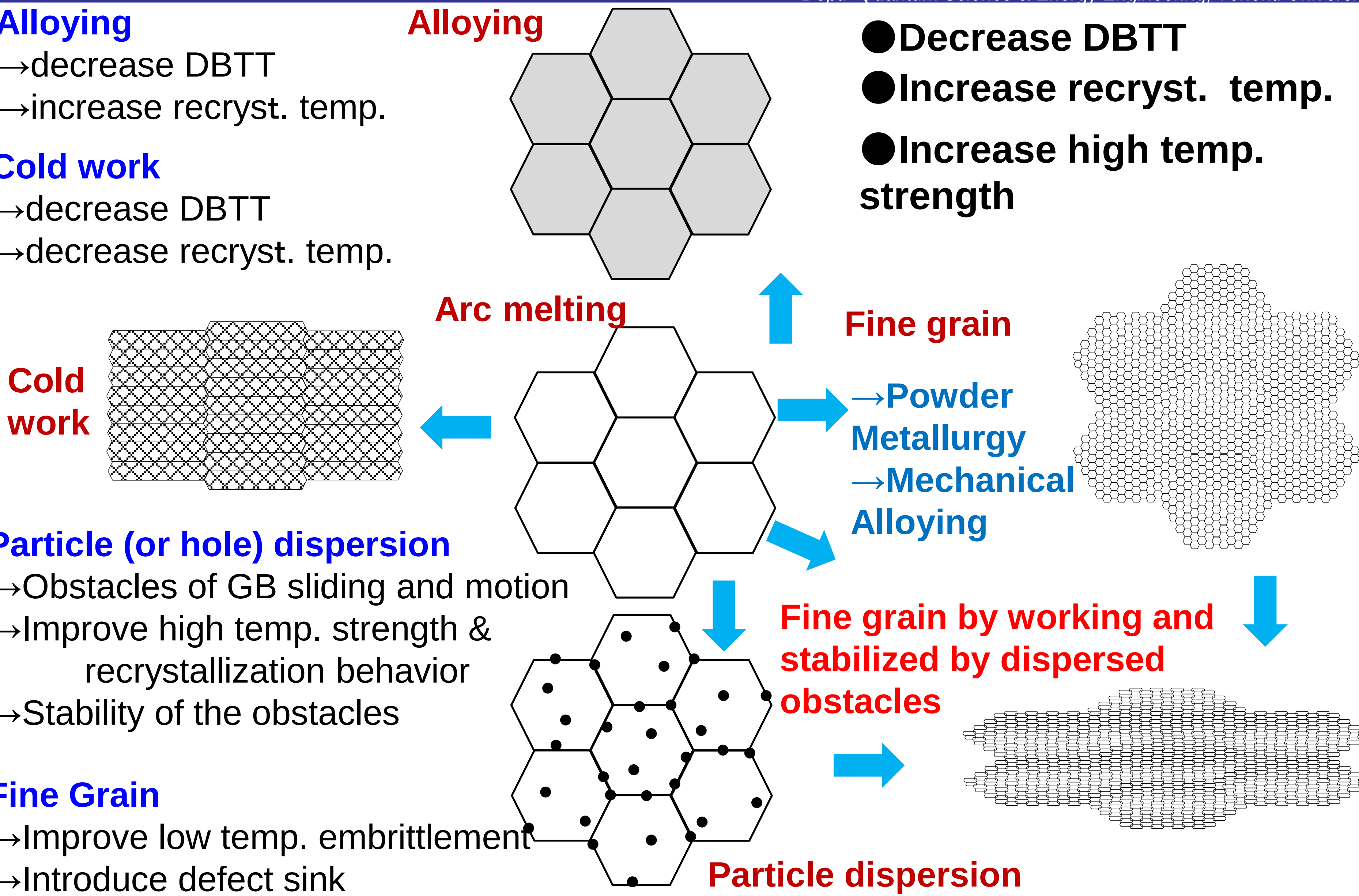
Alloying
→decrease DBTT
→increase recryst. temp.

Cold work
→decrease DBTT
→decrease recryst. temp.

Particle (or hole) dispersion
→Obstacles of GB sliding and motion
→Improve high temp. strength & recrystallization behavior
→Stability of the obstacles

Fine Grain
→Improve low temp. embrittlement
→Introduce defect sink

- ●Decrease DBTT
- ●Increase recryst. temp.
- ●Increase high temp. strength



Examples of Microstructure Control of W

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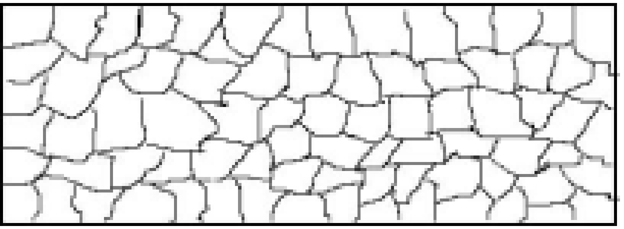
PM W

Full Recrystallize (R)

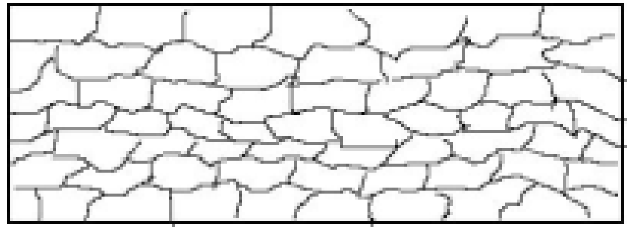


Coarse Grain

Grain size 100x100μm

PM W

Recrystallize (R)

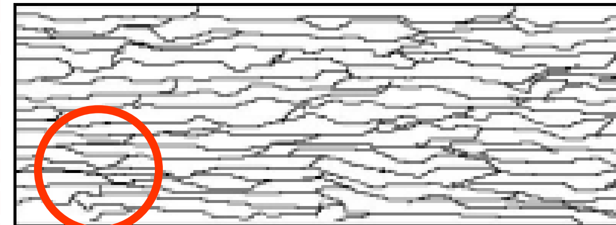


Coarse Grain

Grain size 100x50μm

PM W

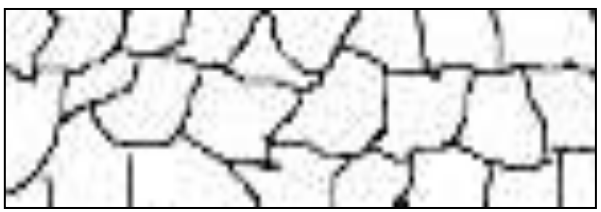
Stress Relief (SR)



Layered Structure

Layer thickness<10μm

Arc Melt W(as-cast)



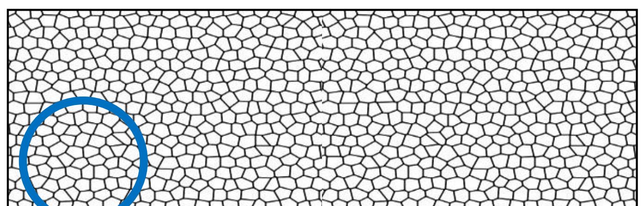
Coarse Grain

Grain size ～1mm

CVD W

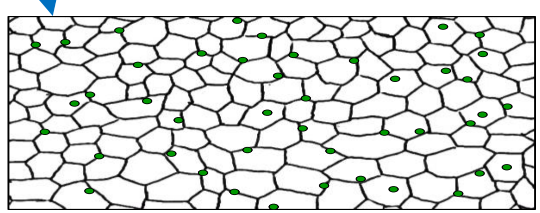
Columnar 100nm x 1μm

MA W-TiC UFG



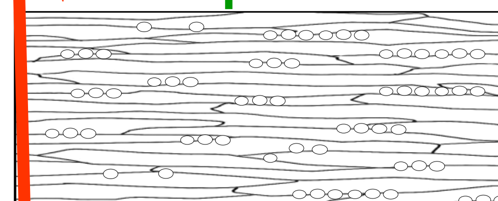
Ultra fine grain

Grain size 70-100nm



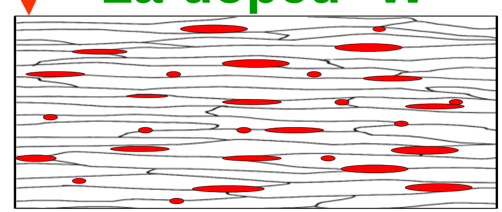
Ultra Fine Grain (<100nm) with Carbide precipitates on GB

K-doped W



Dope hole dispersion

La-doped W



La_2O_3 particle dispersion

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Summary of Damage Structure Map of W

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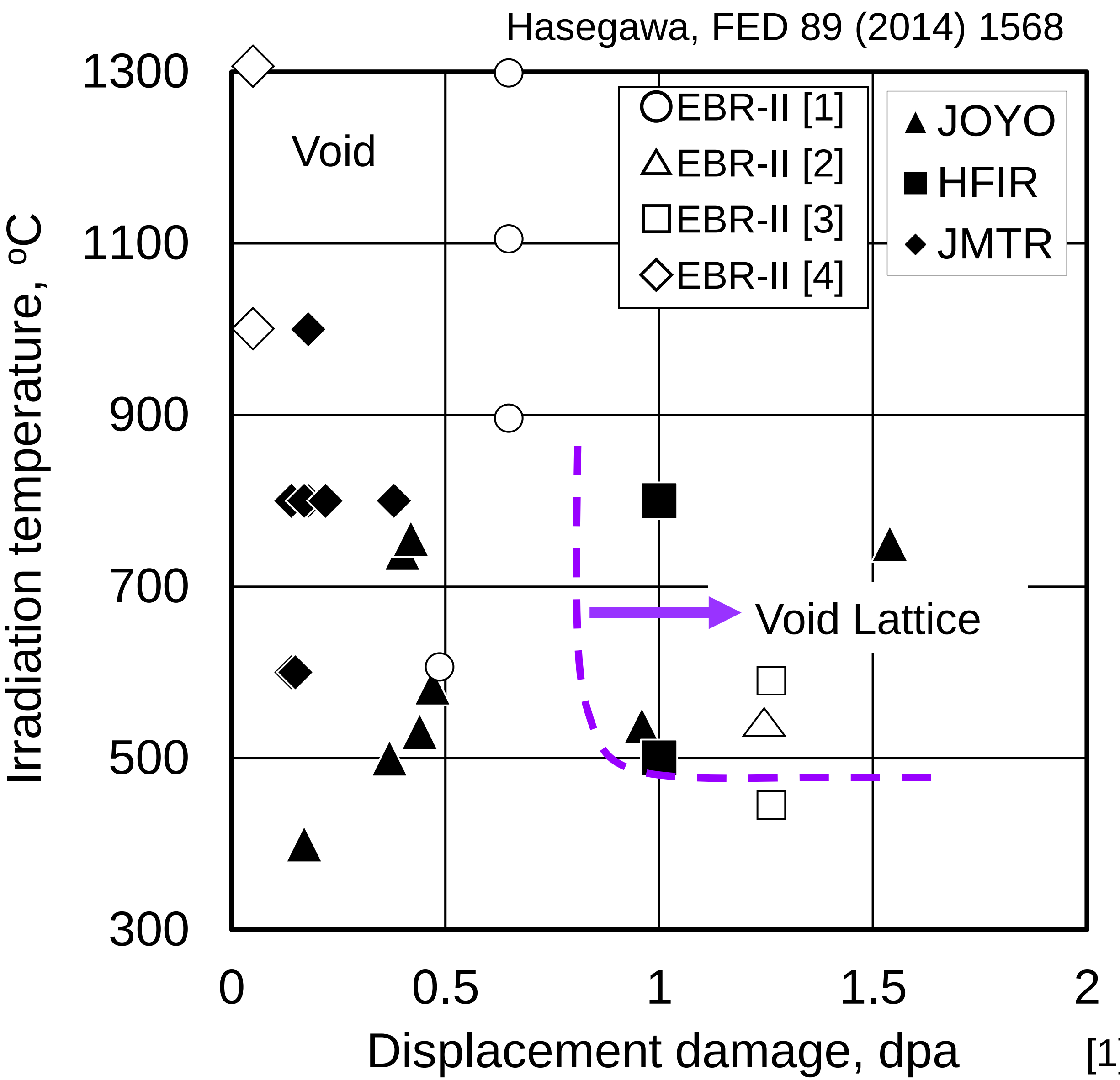

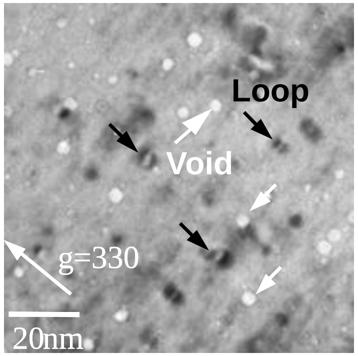

538 ℃
0.96dpa
In JOYO

#Void was observed above 0.1dpa irradiation, above 400 ℃ up to 1300 ℃ .

#Loop was also observed above 400 ℃ . Upper limit of loop formation could not be confirmed.

#Void lattice formed after higher level irradiation (>1dpa).

[1] Williams(1983), [2] Sikka(1972), [3] Sikka(1973),[4] Rau (1969)

Damage Structure of W and W-Re Alloys

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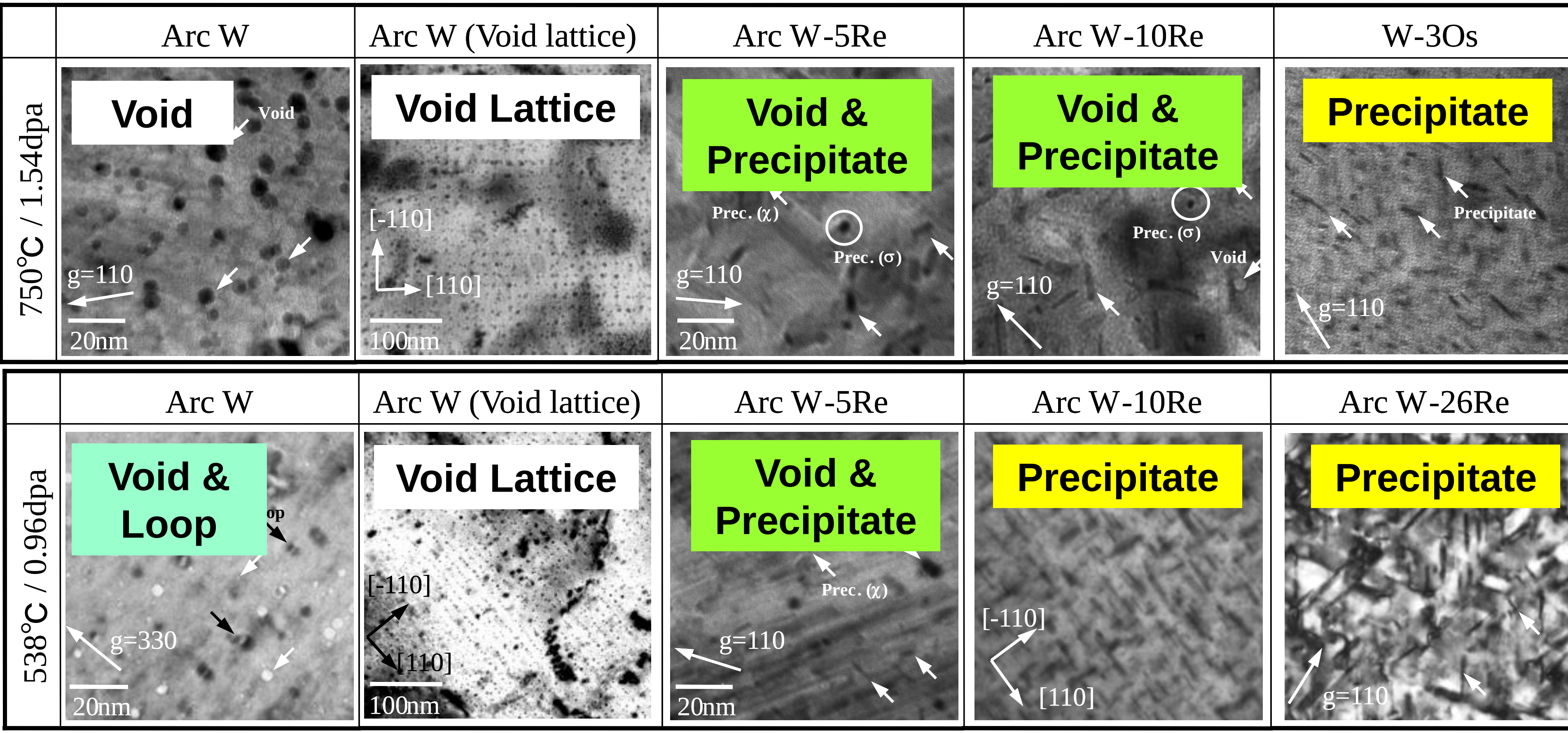
Irradiated in JOYO (first neutron spectrum reactor)



Void lattice were observed in pure W. (pure W → W-1.5Re-0.05Os after 1.5dpa)

Void formation was drastically suppressed in W-Re and acicular precipitates were observed above 5%Re.

T. Tanno, Mater. Trans 52 (2011) 1447

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Summary and Prediction of Microstructural Development of W

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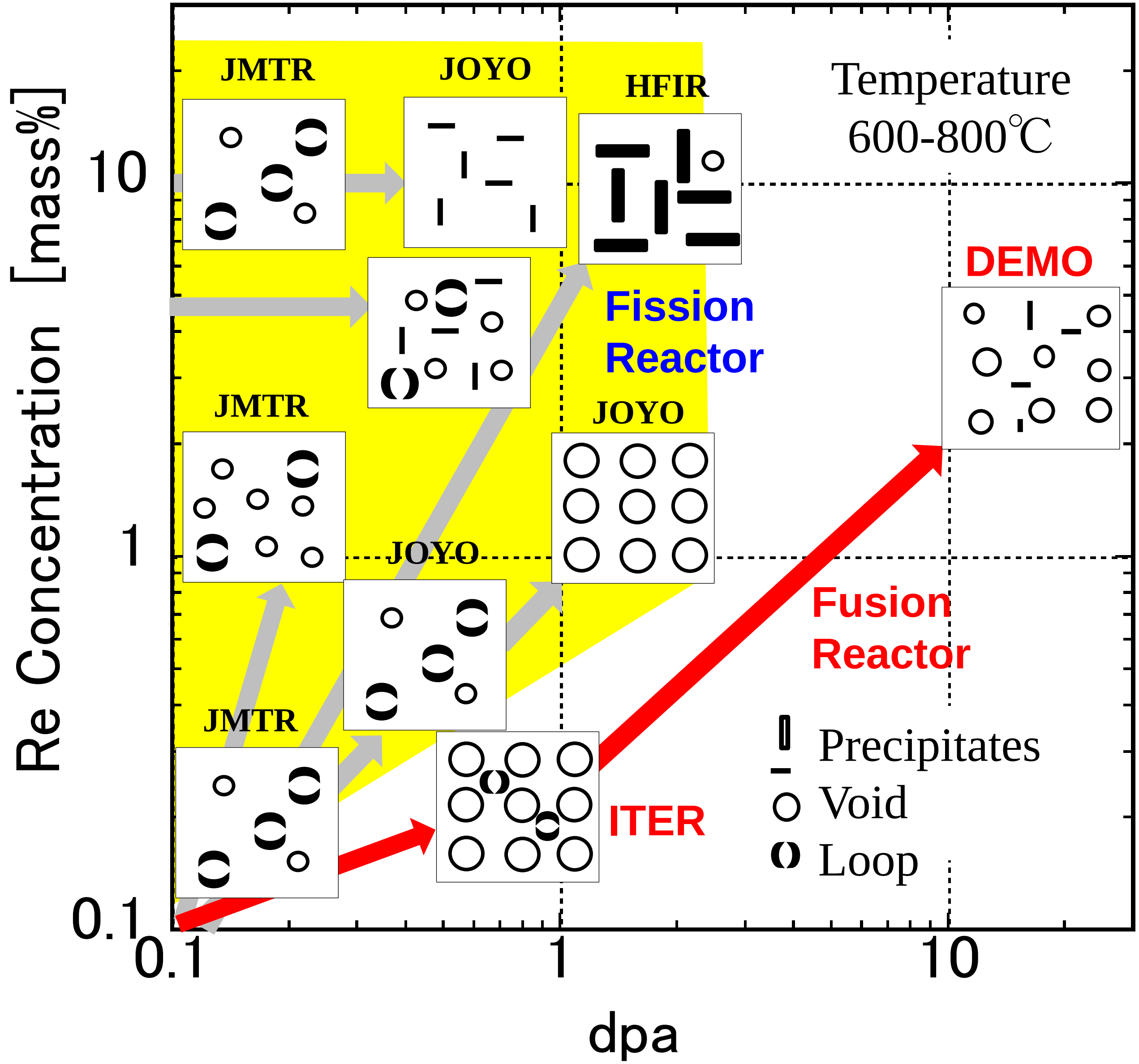

DEMO
3-6%Re
15-30dpa
→Void+Precipitate

ITER
Below 1%Re
Around 1dpa
→ Void (Lattice?)

Hasegawa, FED 89 (2014) 1568

Background of Grain Refined W Development

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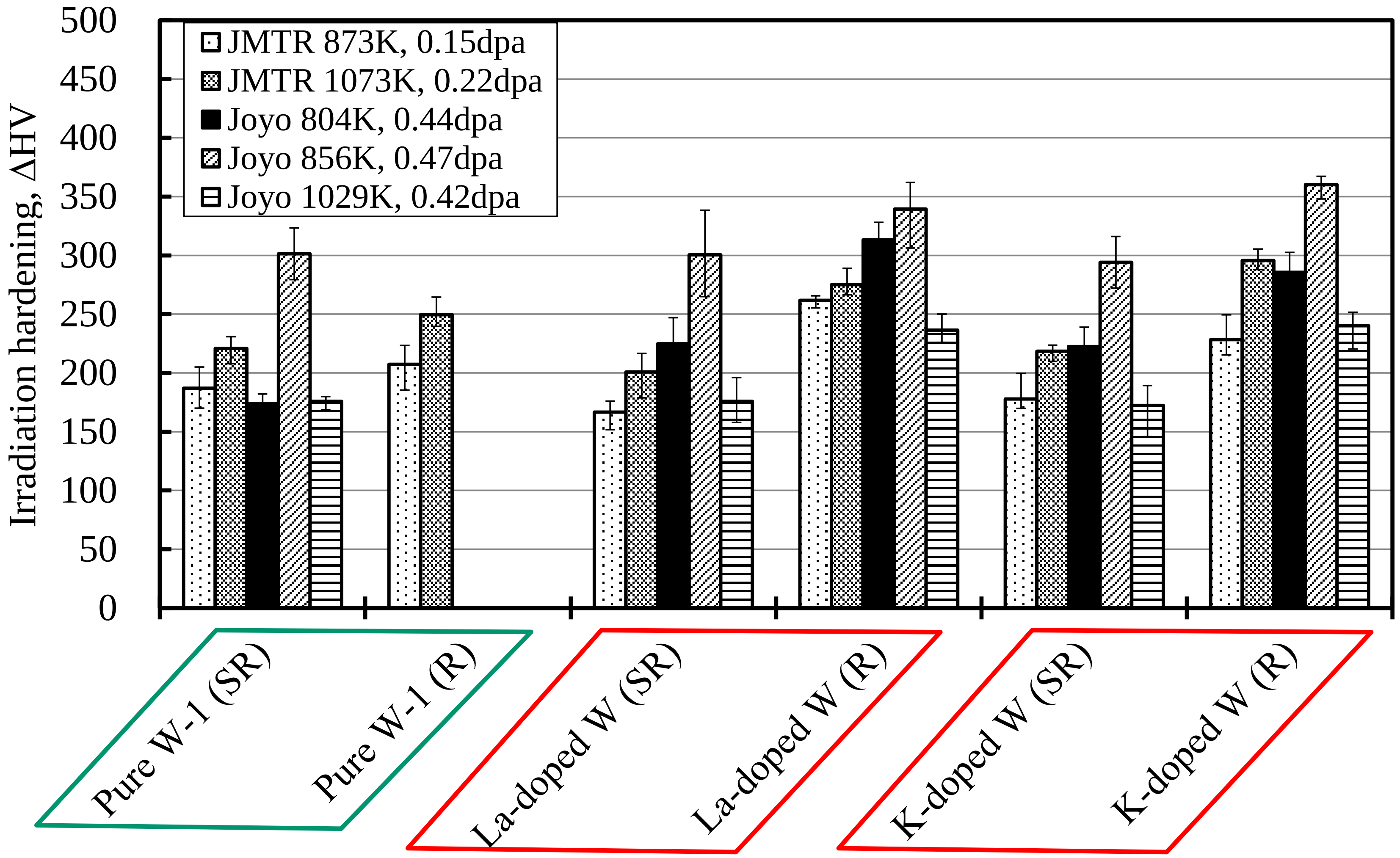
Irradiation hardening of advanced W alloys.



Fukuda, JNM 442 (2013) S273-S276

Defect Clusters in Matrix after JOYO Irradiation

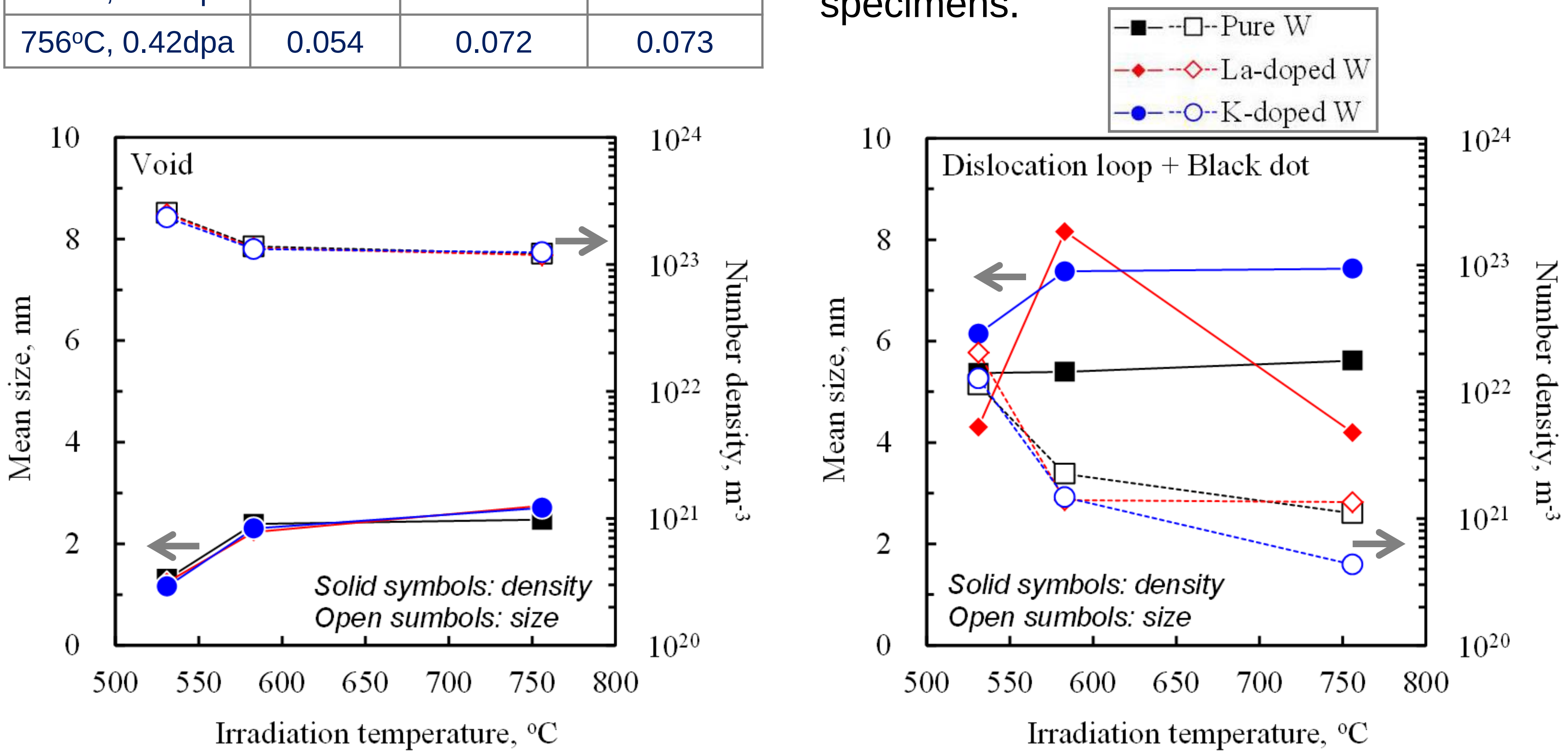
Dept. Quantum Science & Energy Engineering, Tohoku University

Fukuda, JNM 442 (2013) S273-S276

Calculate void swelling (%)

Irradiation conditions	Pure W	La-doped W	K-doped W
531°C, 0.44dpa	0.017	0.014	0.011
583°C, 0.47dpa	0.056	0.044	0.047
756°C, 0.42dpa	0.054	0.072	0.073

- Irradiation response of the advanced W alloys were almost the same as pure W.
- Matrix condition for defect clustering were considered to be similar between these specimens.



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Fabricated W and W-alloys in LHD Project

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- **Name of fabricated alloys**

By A.L.M.T. Corp.

- **Pure W**
- **W–1%Re**
- **K–doped W**
- **W–3%Re**
- **K–doped W–3%Re**
- **La–doped W–3%Re**

} ①

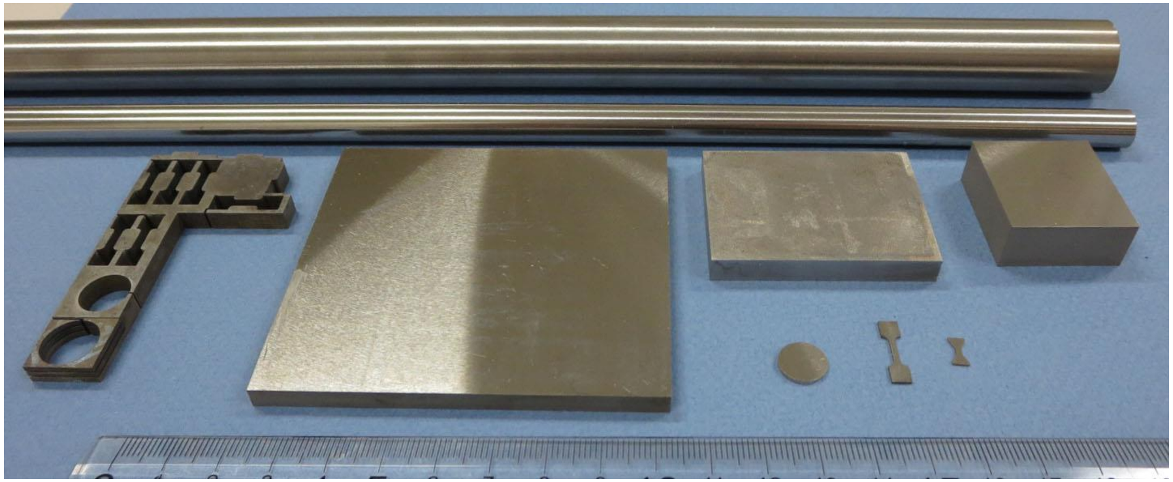
- **Pure-W**
- **K–doped W**
- **K–doped W–3%Re**

} ②

▪ Pure W 13mmt

①PM and hot rolled plates 5mmt or 7mmt

②PM and swaged rod 20mmφ,10mmφ



- Example of impurities

	C [ppm]	O [ppm]	N [ppm]	Re [%]	K [ppm]	Al [ppm]	Si [ppm]
Pure W	10	< 10	< 10	–	< 5	< 2	< 5
W-1%Re	10	< 10	< 10	0.98	< 5	< 2	< 5
K –doped W	10	< 10	< 10	–	30	15	17

- Relative density

▪Pure W : 99.0%
▪W–1%Re: 99.1%
▪K–doped W: 99.1%

ρ_0 : 19.1 g/cm^3

Grain Structure (As received)

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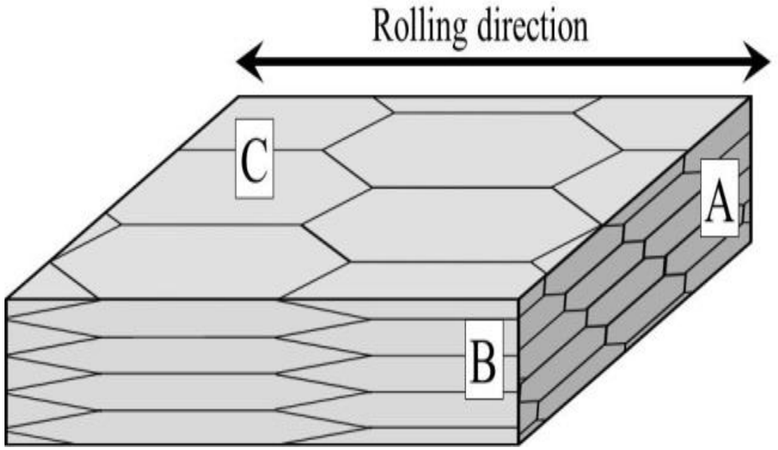
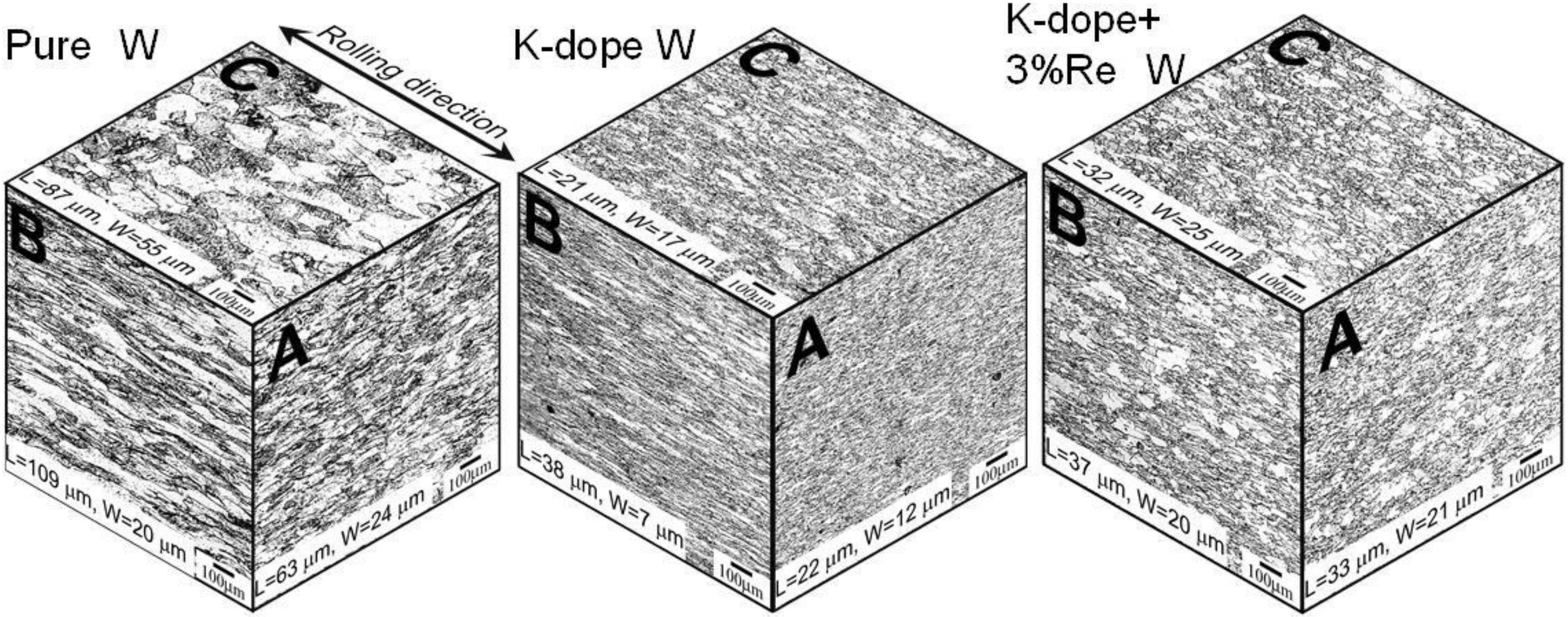
As received：

Heat treated at 900℃ for 20min



- Hot rolled structure

  Layered structure



Recrystallized Behavior of Rolled Plate

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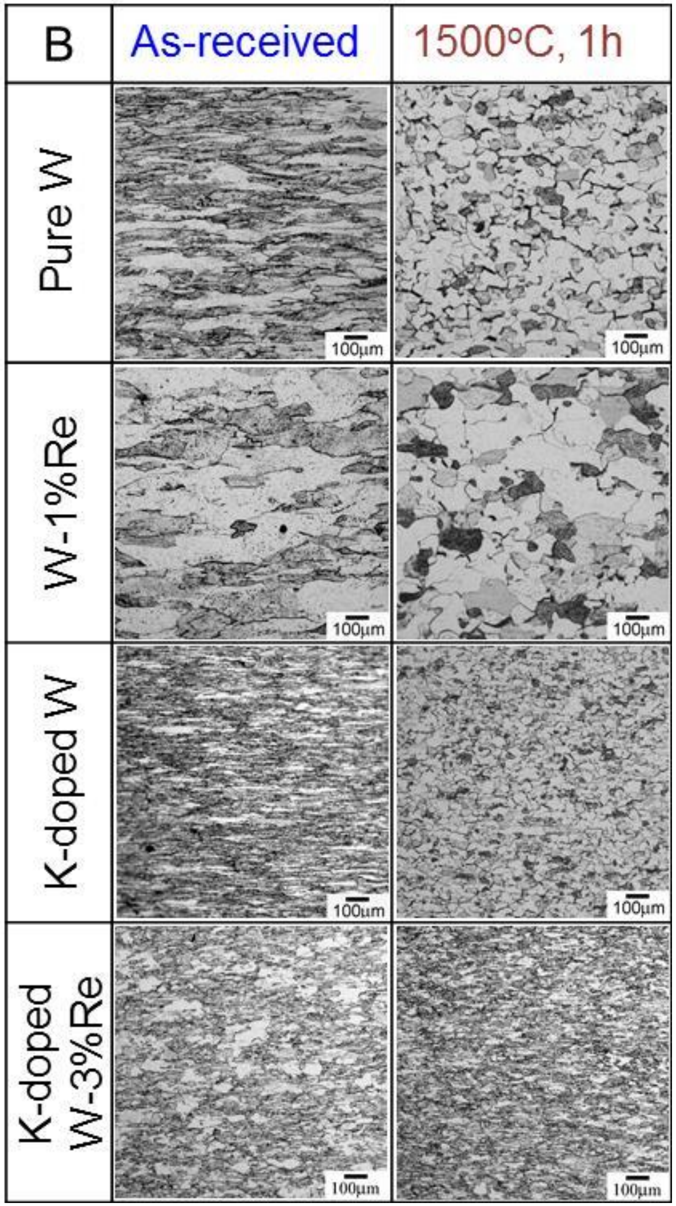

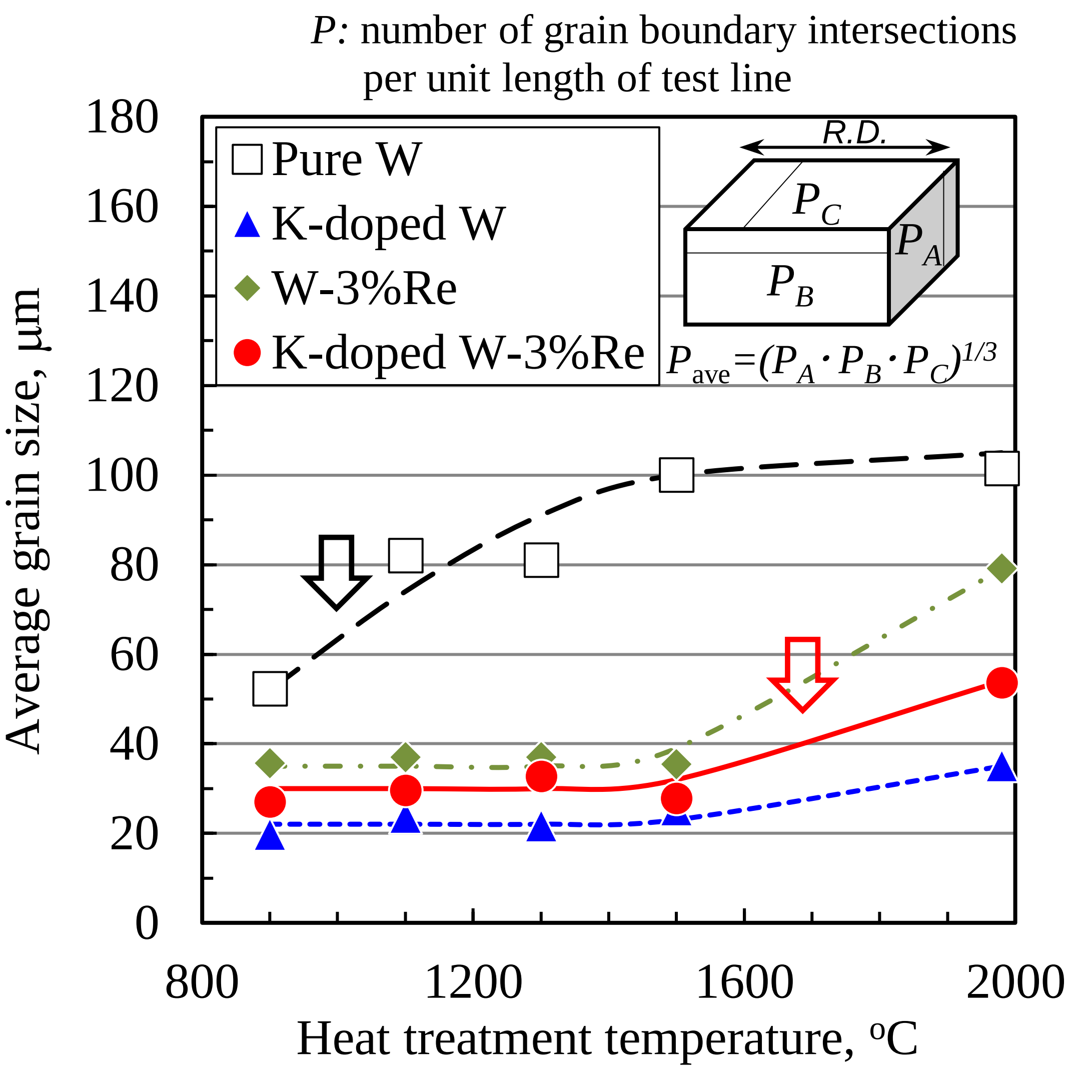

Temperature Dependence of Strength

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- Strength increase by K-dope（at RT: 64% up, 1500℃: 36% up)
- Strength increase above 900℃ by Re addition to K-dope W.

K-doping

・Fine grain size

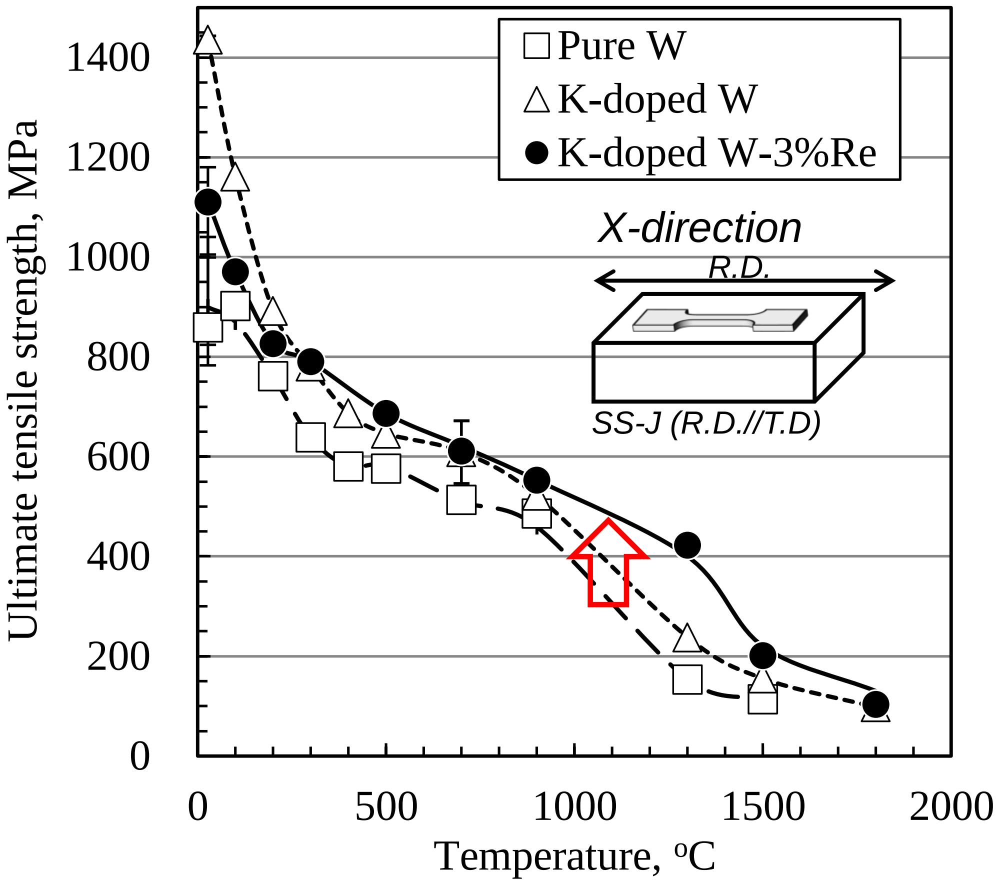
・Obstacles for dislocation and GB sliding, and recrystallization

Re addition

Solute Re

・Solution softening（<900℃）

・Solution hardening（>900℃）



Anisotropic Tensile Strength

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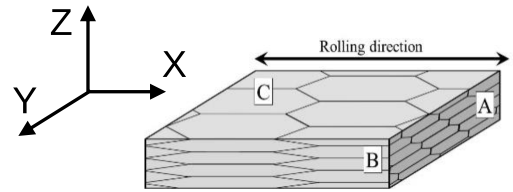
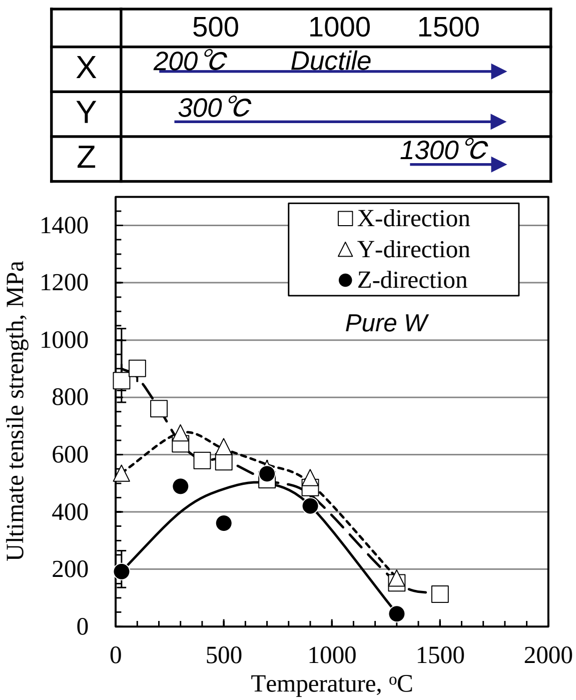
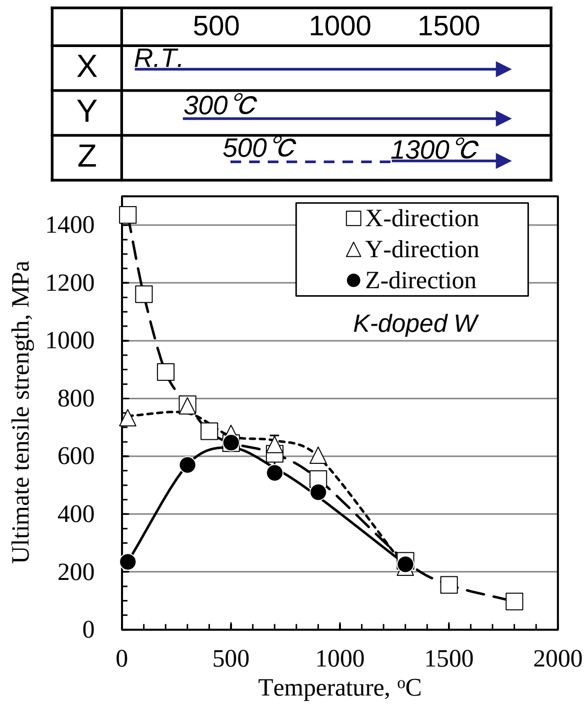
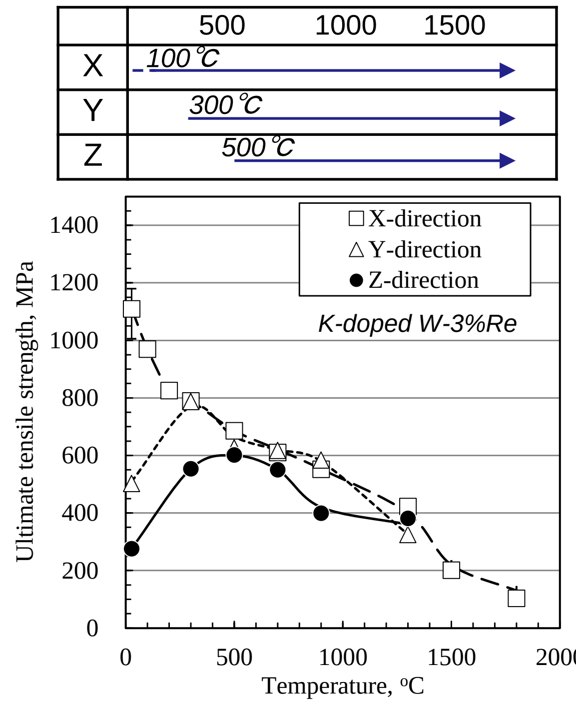
- Anisotropy was observed in the temperature range of R.T. - 500 ºC.









Fukuda, to be presented in TOFE (2014)

Strain Rate and Temperature Dependence of Strength

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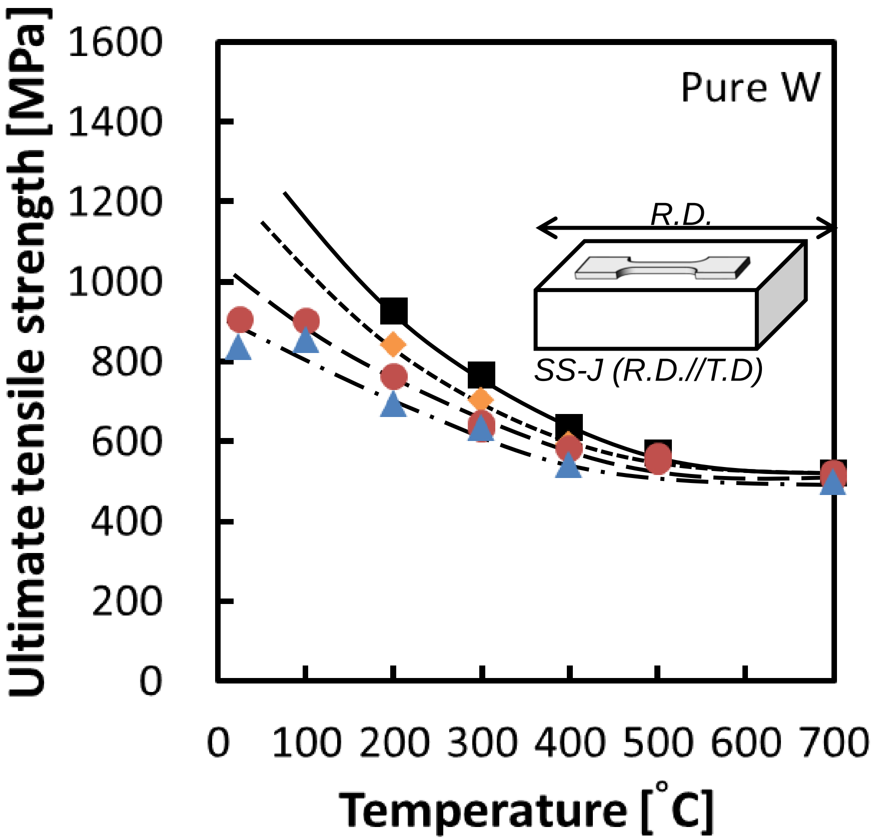
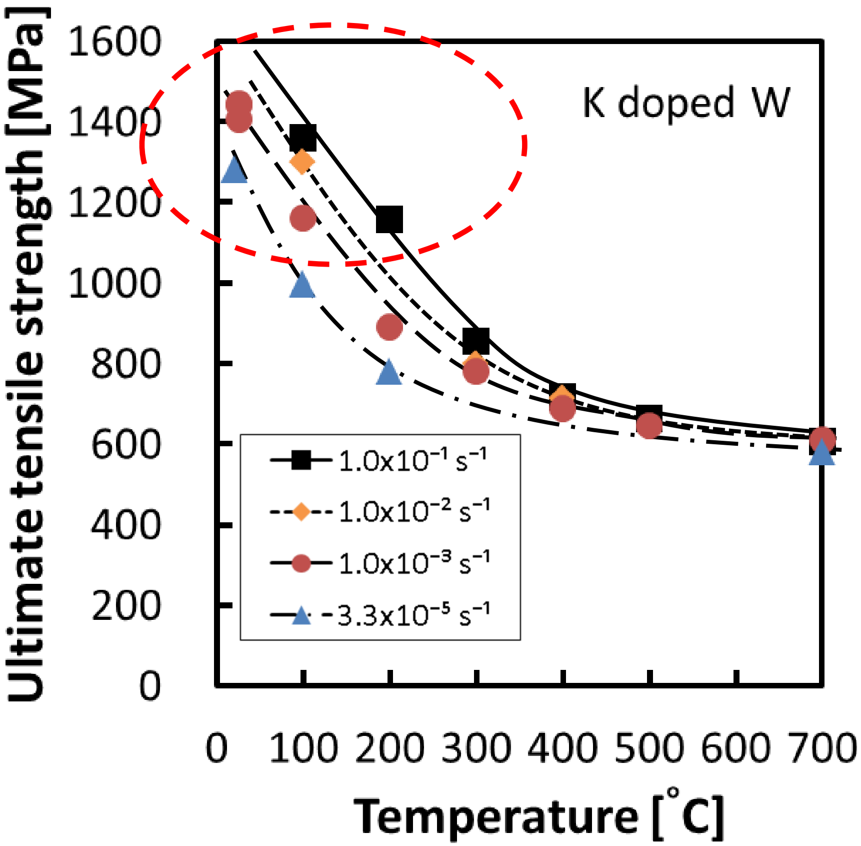
Time dependent mechanical properties





Fukuda, to be presented in TOFE (2014)

Strain Rate Dependence of Tensile Behavior

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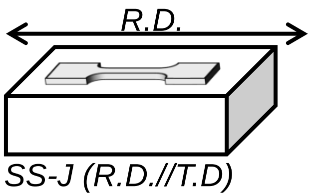
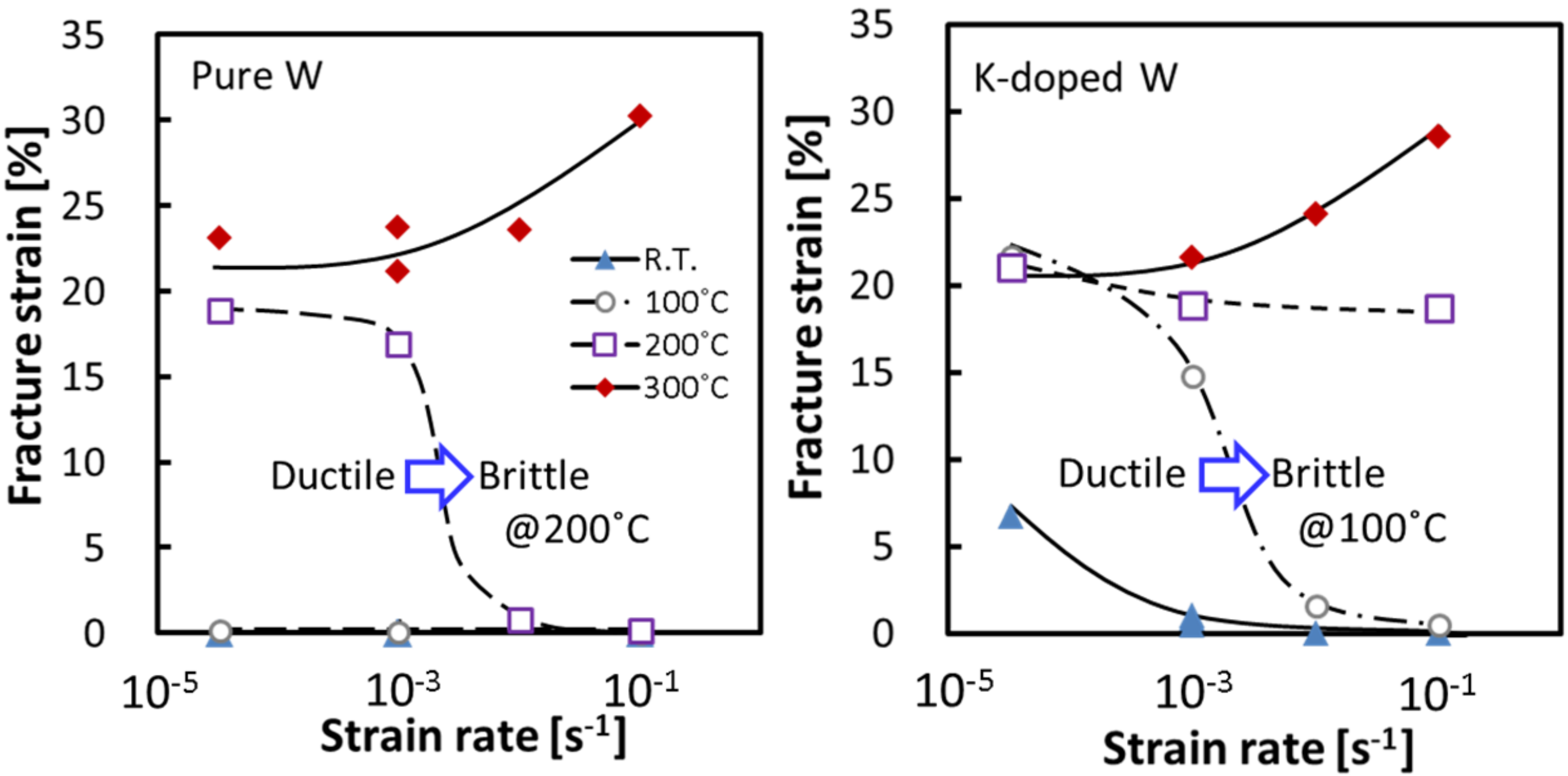
Time dependent mechanical properties

- DBTT of tensile deformation is decreased about 100 ℃ by K-dope process.





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Thermal Diffusivity

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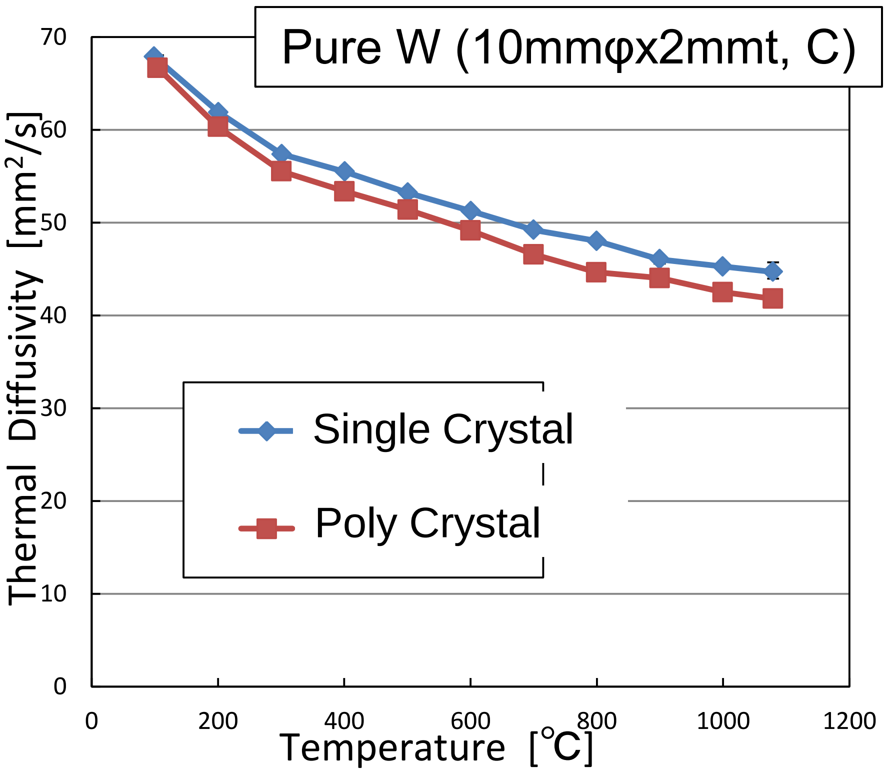
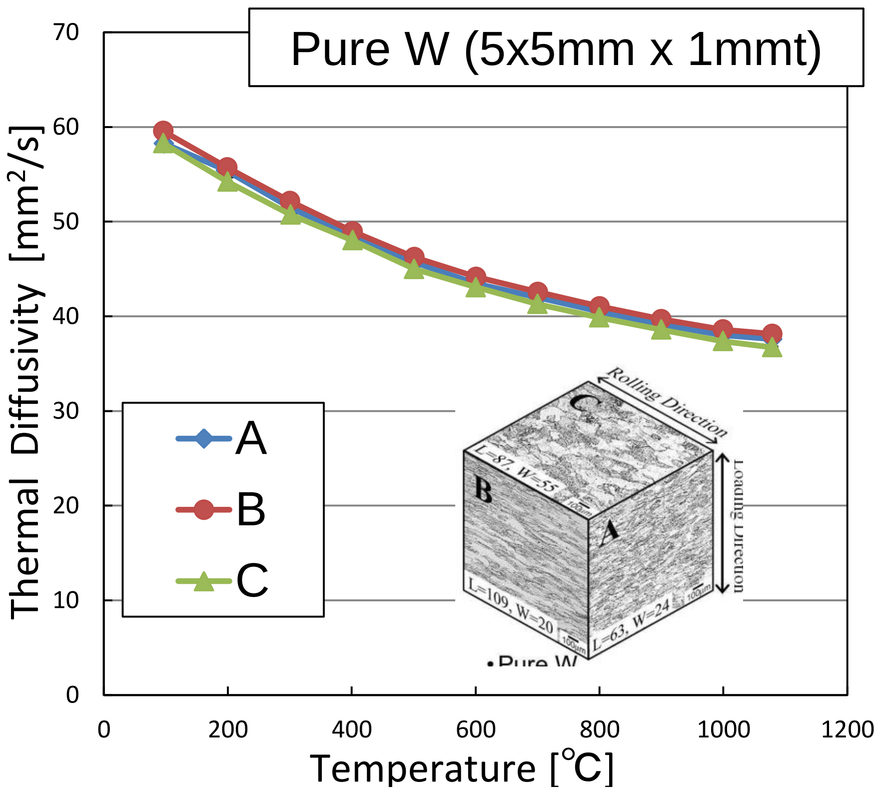
Effects of grain boundary and microstructure anisotropy.

Evaluated by Laser flash method.





- TD of poly crystal is lower than TD of single crystal, but difference is small.
- Anisotropy of TD of pure W(poly-X) is not observed.

Thermal Diffusivity of W and W alloys

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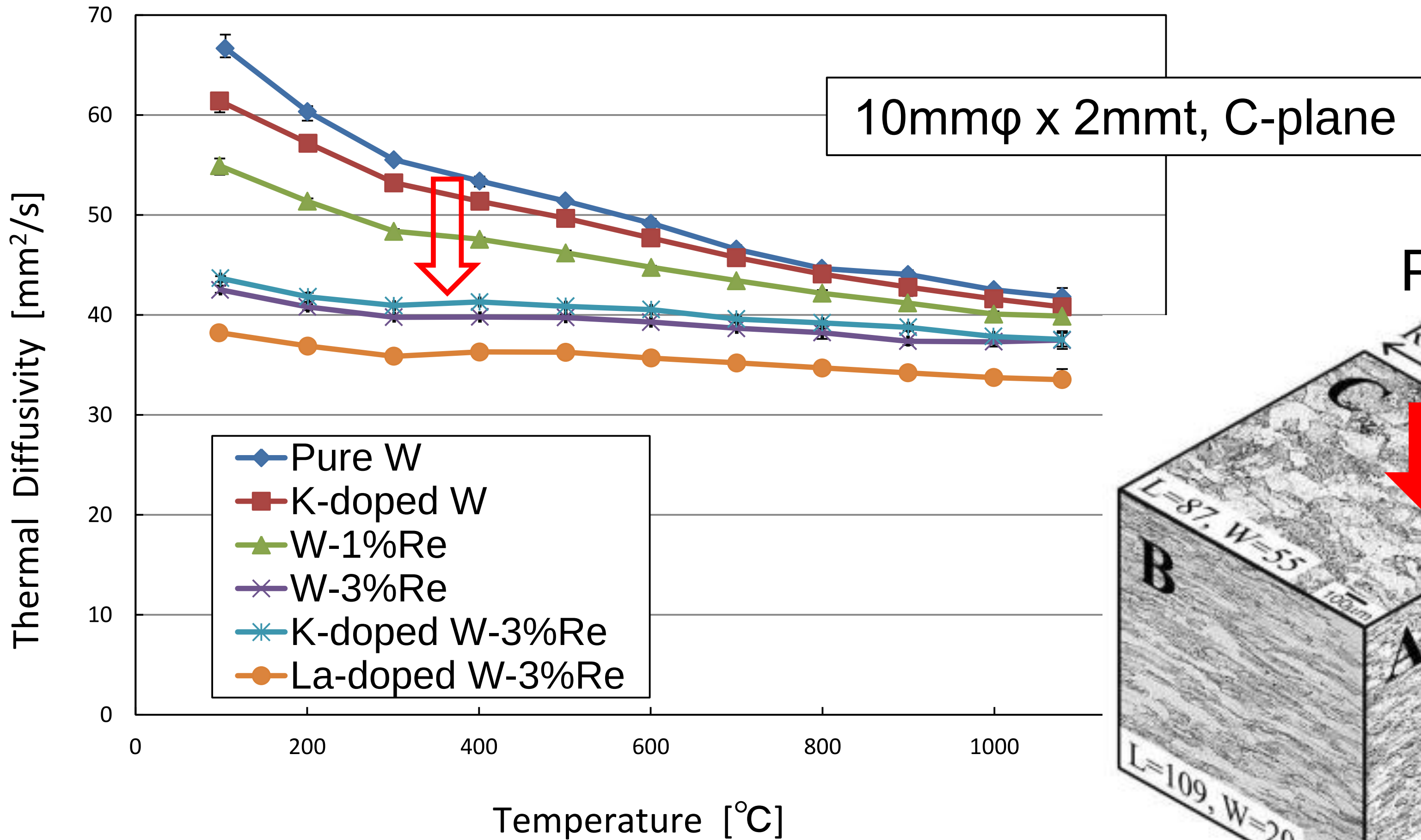
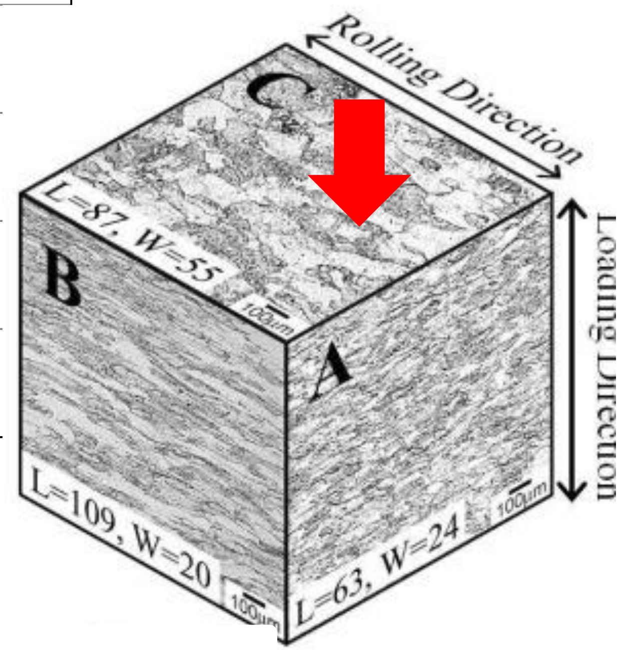


Pure W



- TD of W alloys are lower than pure W.
- Temperature dependence of TD was not significant by 3%Re addition.

Thermal Conductivity of W and W alloys

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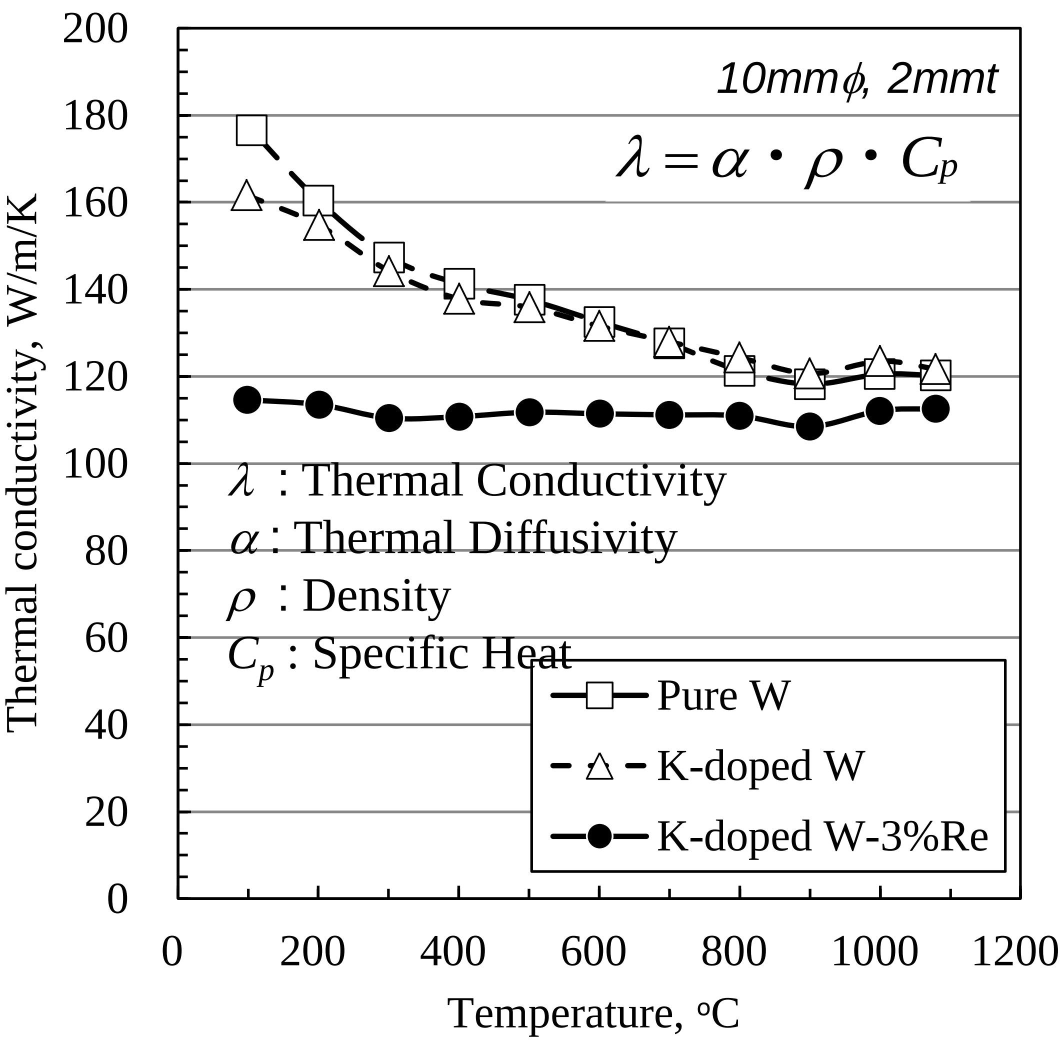

$$\lambda = \alpha \cdot \rho \cdot C_p$$

λ : Thermal Conductivity
α : Thermal Diffusivity
ρ : Density
C_p : Specific Heat

Trend is the same as thermal diffusivity

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Thermo-mechanical Analysis

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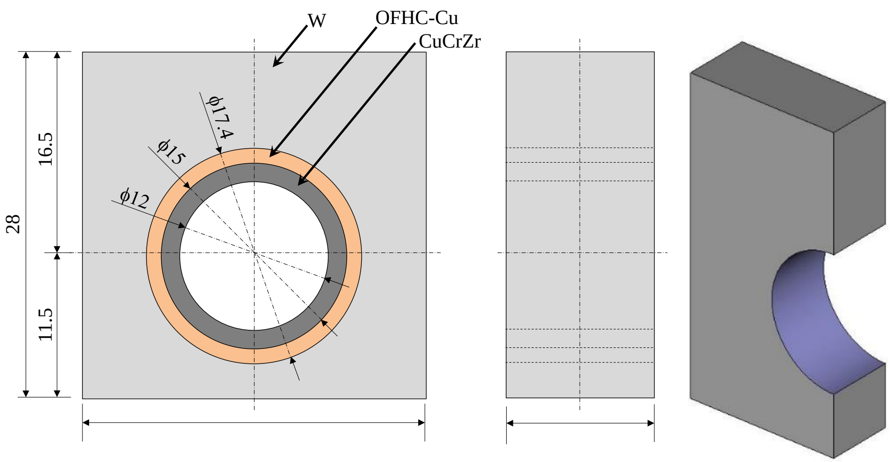
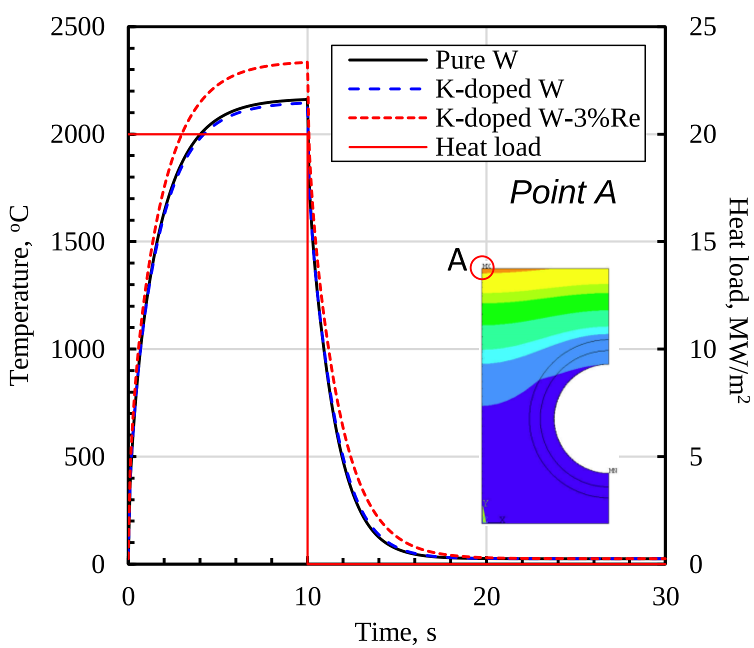
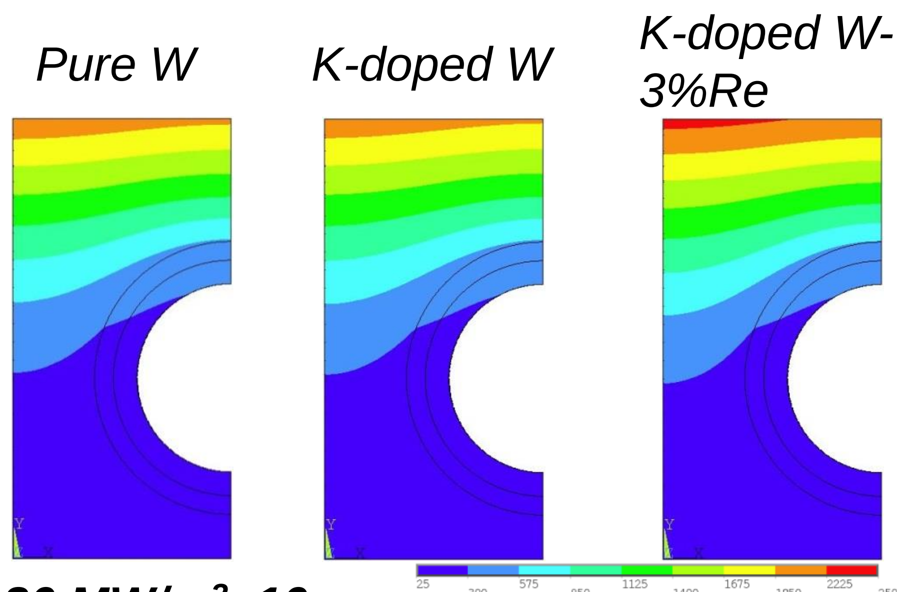


Thermo-mechanical analysis of the W and its alloys mono-block tile under heat load using FEA is now in progress.





20 MW/m² 10 s

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Recrystallization

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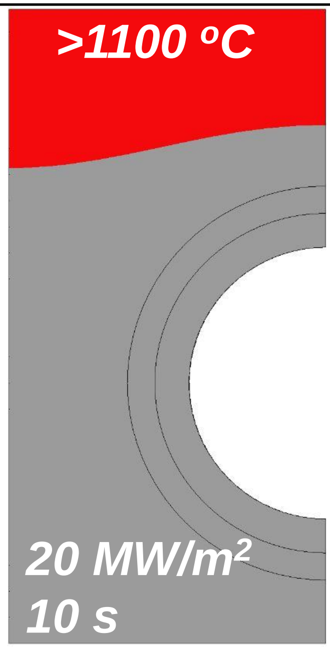
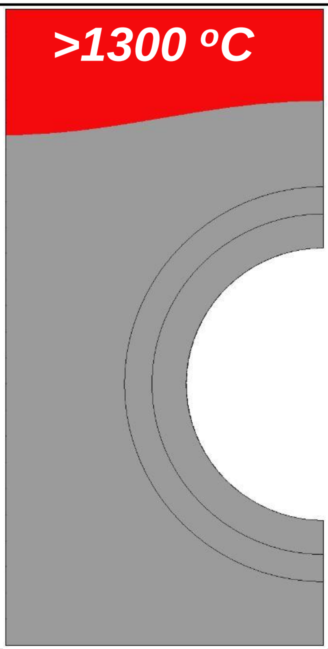
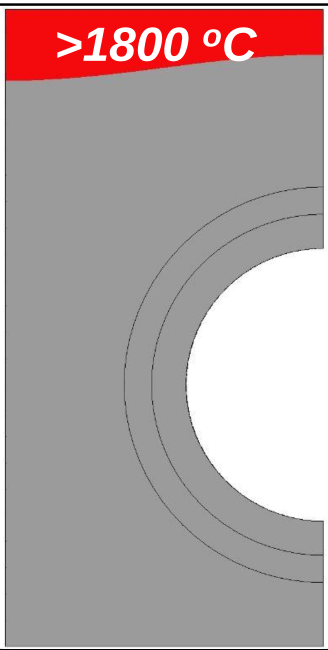
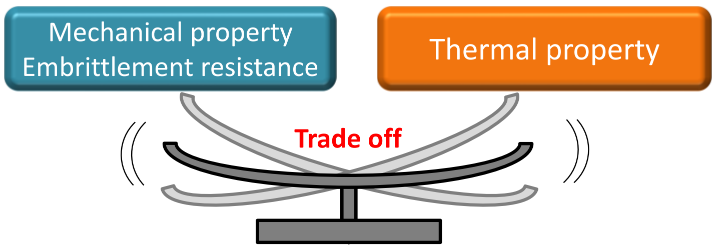
- In the case of pure W, the depth of the recrystallized area was ~8 mm from the top surface.
- The depth of the recrystallized area were 6 and 3 mm from the top surface for K-doped W and K-doped W-3%Re, respectively.

  →Increase in recrystallization temperature by K and Re dope decreased recrystallized depth.

Pure W	K-doped W	K-doped W-3%Re
		

Recrystallization

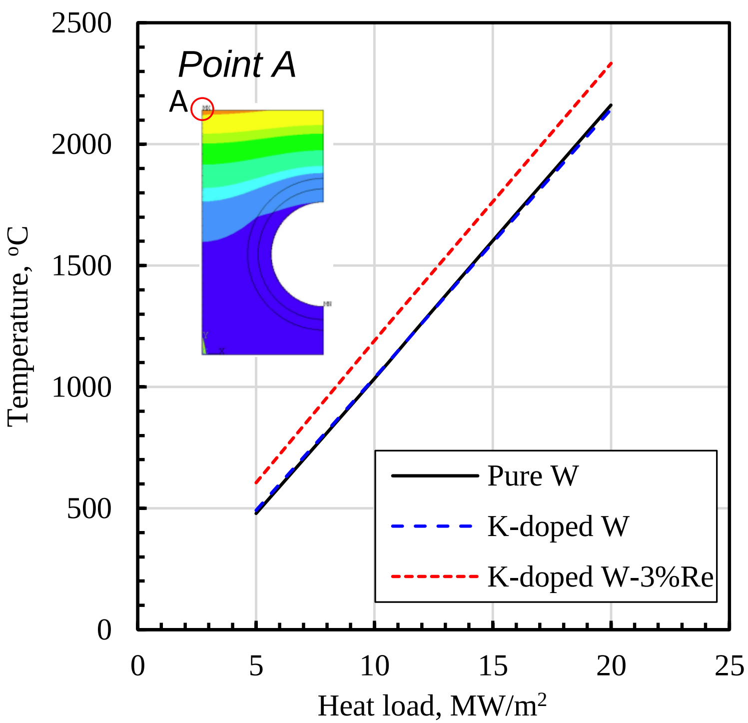
- The threshold temperature of the recrystallization was estimated as ~11, ~12, and 15 MW/m^2 for pure W, K-doped W, and K-doped W-3%Re, respectively.
- The recrystallization depth was linearly increased with increasing heat load.

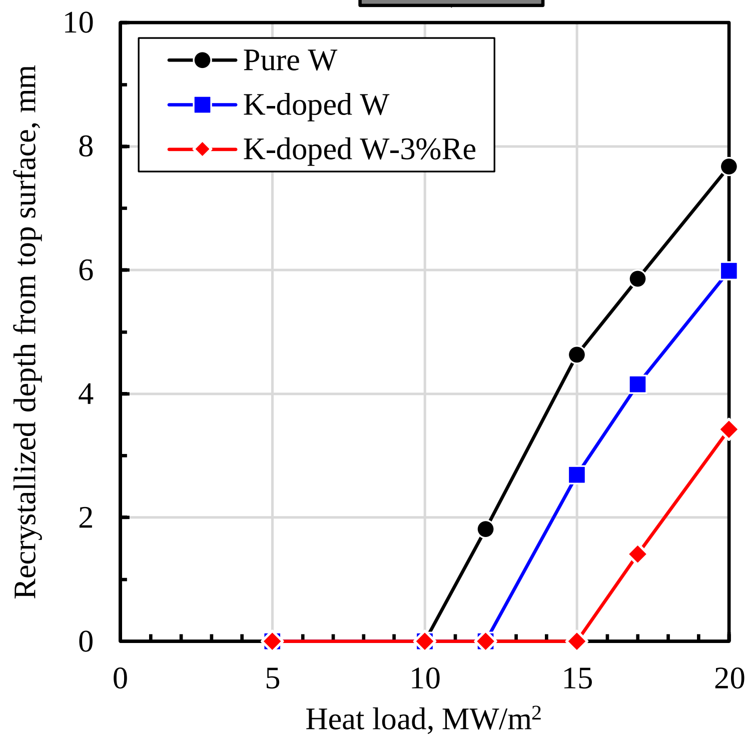


Thermal conductivity decrement

∧

Recrystallization temperature increment





Summary

Microstructural data of neutron irradiated Tungsten (W) obtained by neutron irradiated W up to 1.5dpa irradiation in the temperature range of 400-800°C were compiled quantitatively. Nucleation and growth process of these defects were clarified and a qualitative prediction of the damage structure development and hardening of W in fusion reactor environments were made taking into account the solid transmutation effects for the first time.

Powder metallurgically processed pure W and W-alloys were fabricated to improve mechanical properties, recrystallization behavior and radiation resistance of W by grain refining and alloying processes.

Mechanical property and thermal property of the alloys were obtained. Improvement of strength, low temperature embrittlement and recrystallization behavior of the W-alloys compared to pure W were demonstrated. Neutron irradiation experiment of these materials using a fission reactor (HFIR) will start during 2014.

Trade-off between the thermal conductivity and mechanical property, embrittlement resistance by the structural control must be considered quantitatively to design diverter cooling component. The thermo-mechanical analysis of the diverter block made of the alloys considering thermal diffusivity and recrystallized temperature were performed by finite element analysis.

Thank you for your attention.