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PSI

Microstructures, strengths of **Al6061-T6** after irradiation in SINQ Target-13

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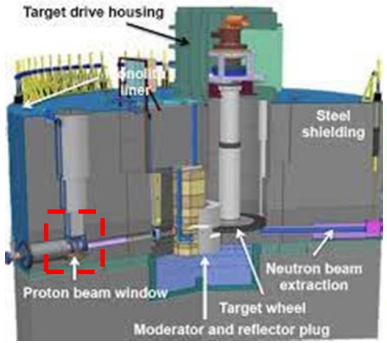
HPTW2023, RIKEN, Wako, Japan 09.11.2023

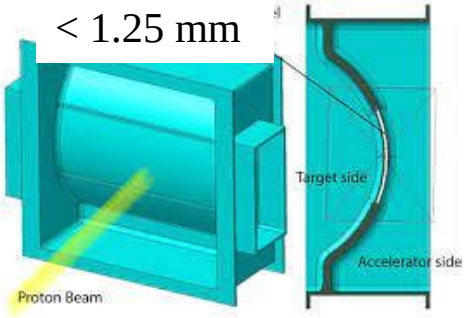
Content

Background

Europe Spallation Source (ESS)



Thickness:
< 1.25 mm



Proton Beam Window (PBW)*:

1. Suffer from high-fluence protons (2 GeV)
2. Low scattering of proton beam (< 1%)
3. Thickness less than 1.25 mm

**R. Vivanco, et al. IOP Conf. Series: Journal of Physics: Conf. Series 1021 (2018) 012065*

Materials applied to PBW

Requirements :

1. Good radiation tolerance
2. Good thermal conductivity
3. Light atoms
4. Good strength

Al alloys:

Al6061-T6 for ESS (5 MW)

$AlMg_3$ for SINQ (1.4 MW)

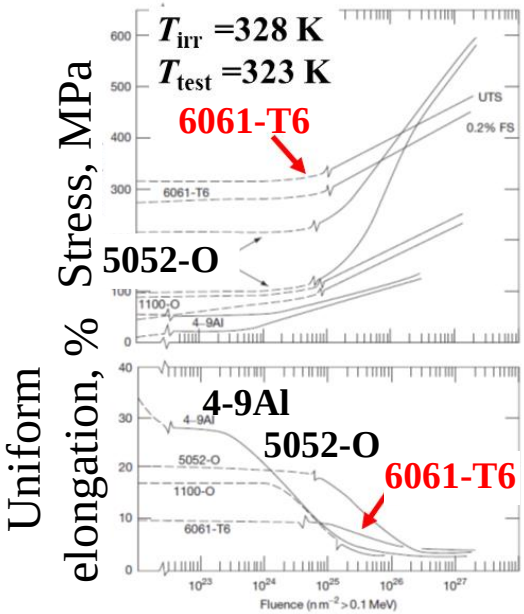
Al5083 for MLF (1 MW)

$AlMg_3$

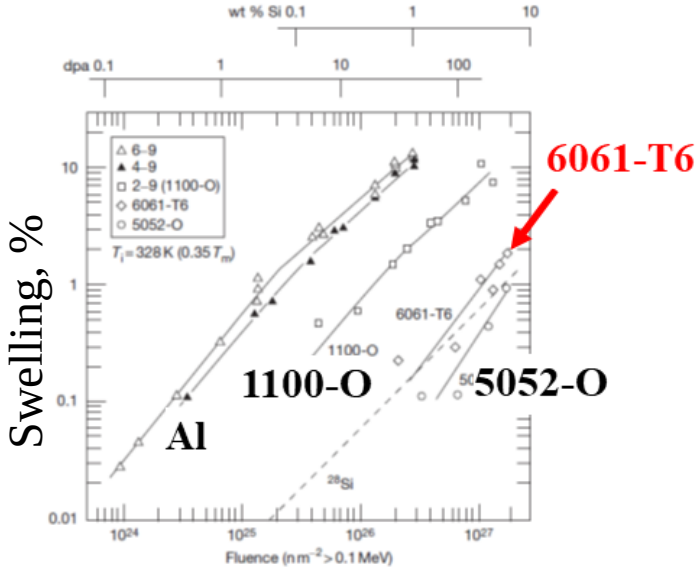
Max. p-fluence:
8.6×10^{25} p/m^2
Max. 8.5 dpa

Objective

Radiation-induced changes in tensile properties of Al alloys*



Radiation-induced swelling as a function of Fast fluence



**Performance of Aluminum in Research Reactors, K. Farrel, Oak Ridge*

Objective: Microstructures of **Al6061-T6** after neutron or proton irradiation?

Content

Material:Al6061-T6

Chemical Composition

wt.%	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti	**Al**
Max.	0.8	0.7	0.4	0.15	1.2	0.35	0.25	0.15	**Bal.**

Thermal treatments

Heat treatment at 530 °C

⇩

Water quenching

⇩

Aging at 158 – 177 °C for 8 – 18 hours

Possible second phases*

SSSS: Supersaturate solid solution

⇩

Mg, Si, Cu atomic enriched clusters

⇩

GP-zones (Pre-β''):
e.g. Mg_5Si_6, Al_5Si_6, $AlMg_4Si_6$

⇩

β'', Q', S, L, C, QP, QC
β'': e.g. Mg_5Si_6, Al_5Si_6, $AlMg_4Si_6$
Q': $Mg_9Al_3Si_7Cu_2$

⇩

β' ($Mg_{1.8}Si$), Q'

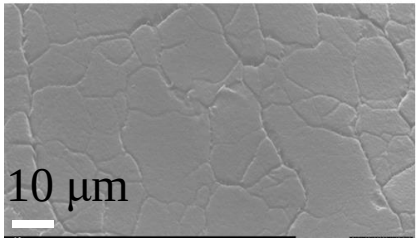
⇩

β (Mg_2Si)

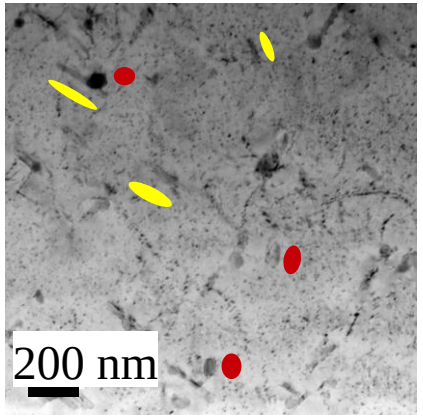
**Acta Materialia 132 (2017) 209-221.*

Grain morphology

Averaged grain size: ~10.4 μm

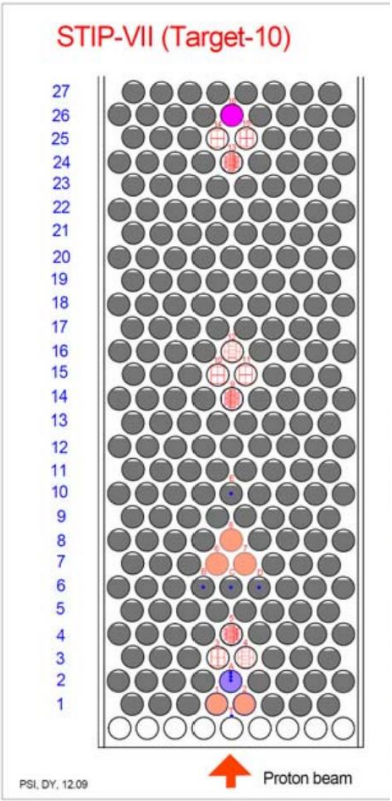


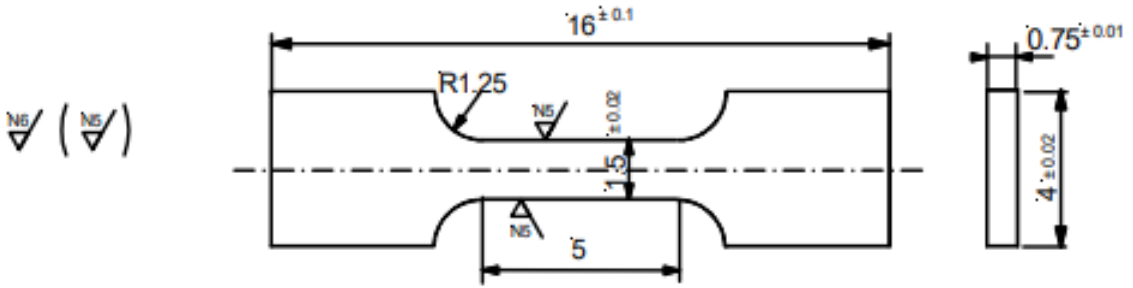
General microstructures



Irradiation conditions

SINQ at PSI





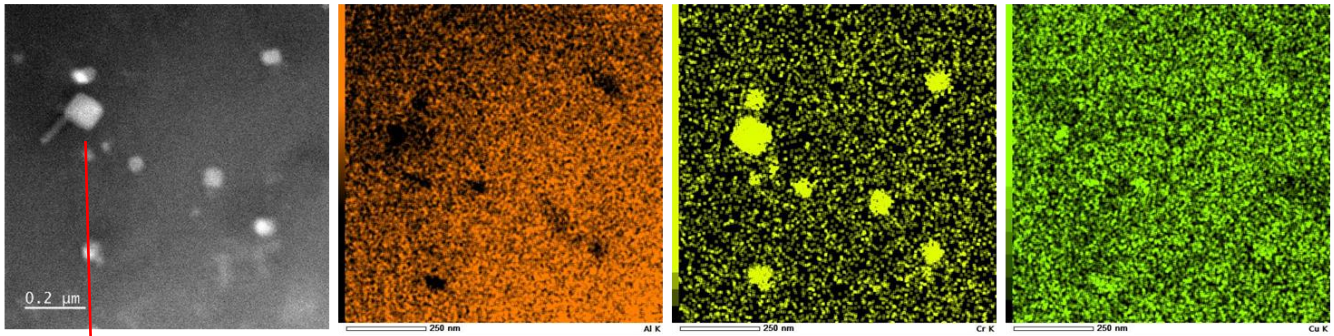
Specimen	Irrad. T (°C)	Dose (dpa)	He (appm)	H (appm)	Test T (°C):
7-LT-N20	~ 62	10.1	455	1095	~ 32
7-LT-N19	~ 62	10.1	455	1095	~ 152

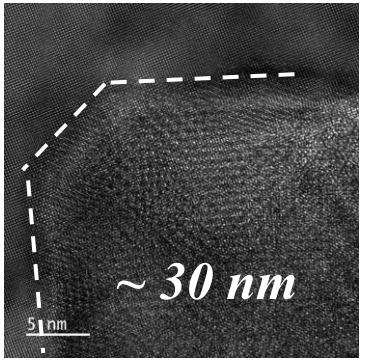
7-LT-N20: **As-irradiated**

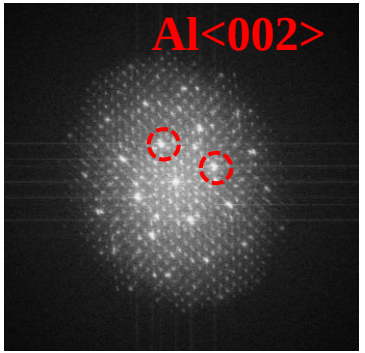
7-LT-N19: **Irradiation + annealed (Irrad.+ ann.)**

Content

Microstructures *before irradiation*: big precipitates





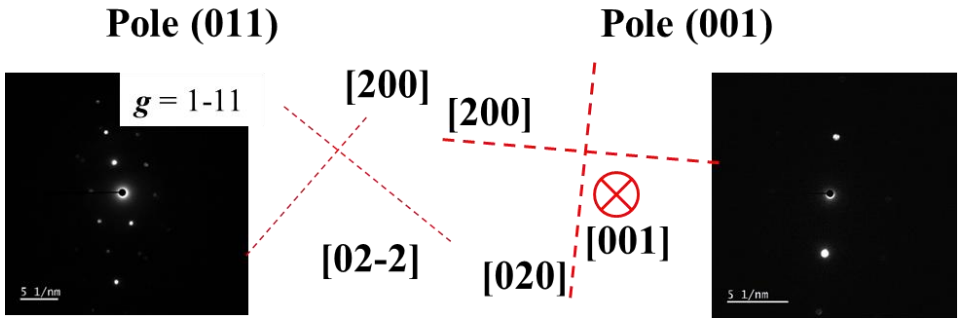


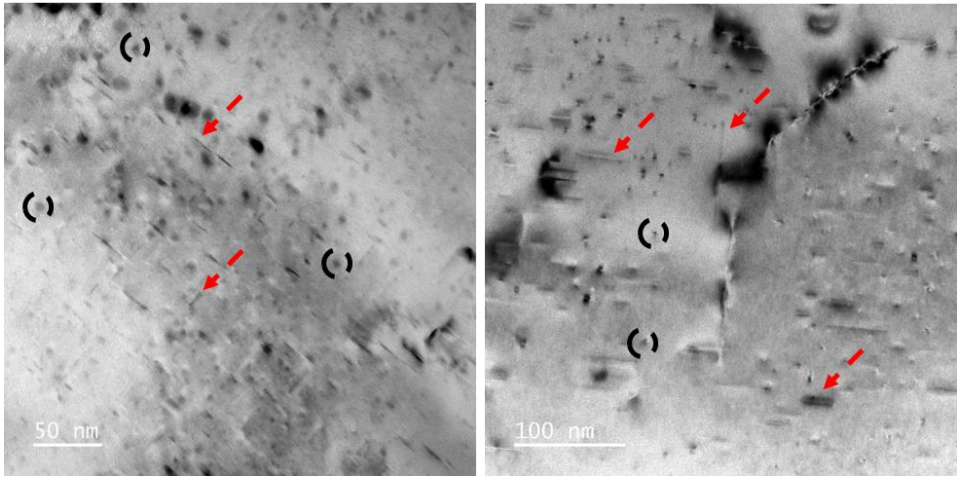
Si, Fe (Mn, Cr), Mg, Al

Mg, Si, Al

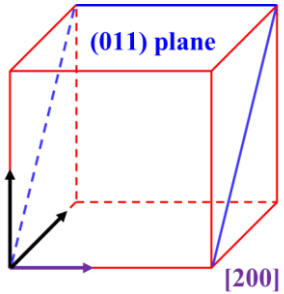
π-phase $Al_9FeMg_3Si_5$

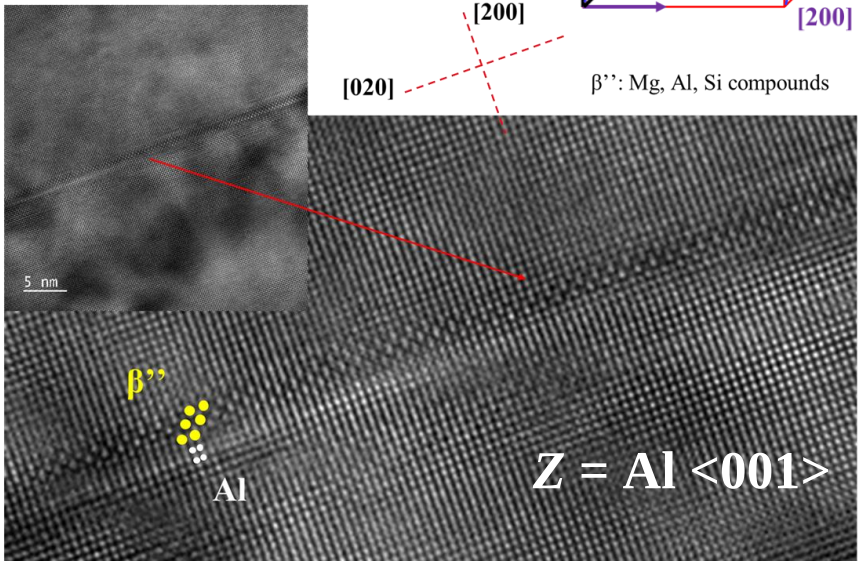
Microstructures *before irradiation*: Needle-shaped





Needle-shaped precipitates // Al <001>





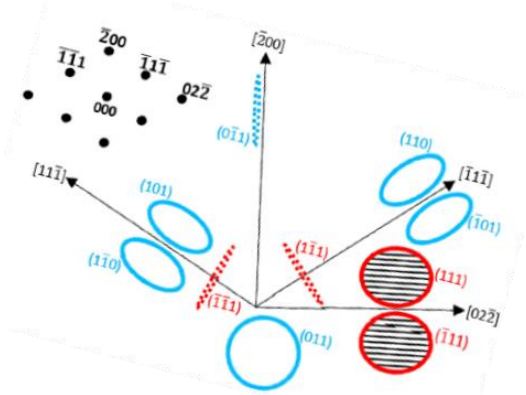
Averaged length: 22.1 ± 10.3 nm

Number density: (1.7 ± 0.8) × 10^{22} m^{-3}

Microstructures *after irradiation*: general view

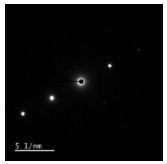
Perfect type: ½<110>

Faulted frank type: 1/3<111>



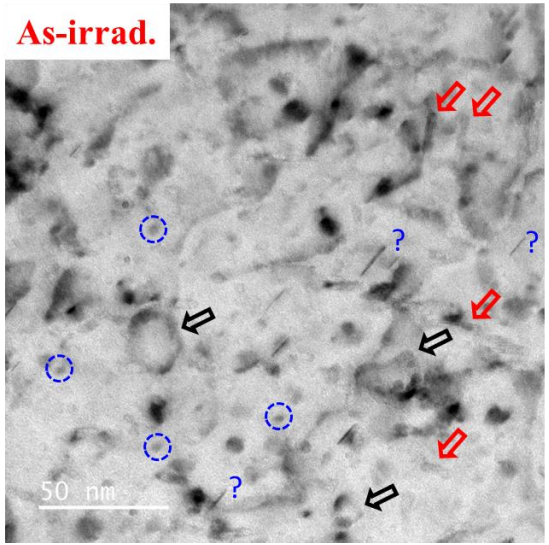
Project plane: fcc Al (110)

pole 110 g = [-1 1 -1]

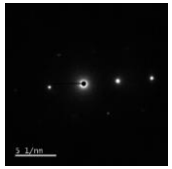


g220

g200

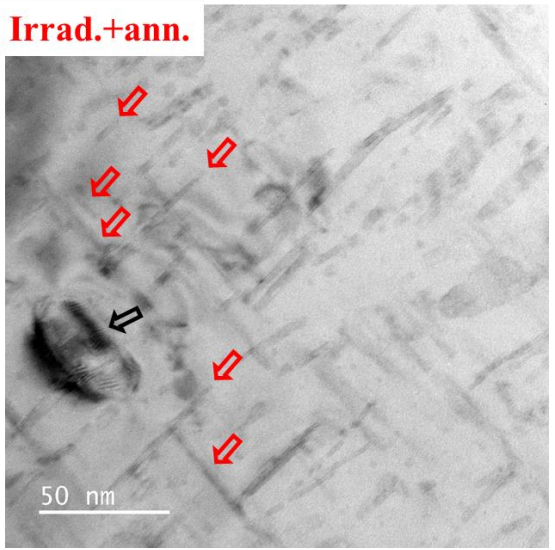


pole 110 g = [-1 1 -1]



g220

g200

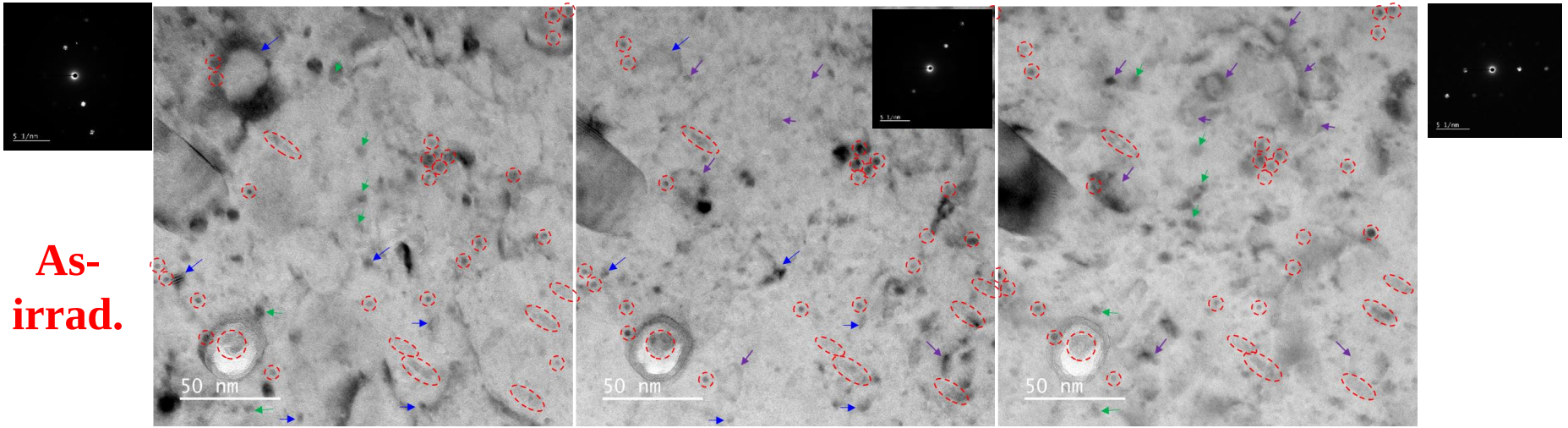


Microstructures *after irradiation*: loops & precipitates

g/B vectors	1/2[1 1 0]	1/2[-1 1 0]	1/2[0 1 1]	1/2[0 1 -1]	1/2[1 0 1]	1/2[-1 0 1]
[1 1 -1]	2	0	0	2	0	-2
[-2 0 0]	-2	2	0	0	-2	2
[-1 1 -1]	0	2	0	2	-2	0

pole 011 ***g = 11-1*** *pole 011* ***g=-200*** *pole 011* ***g=-11-1***

As-irrad.



Microstructures *after irradiation*: faulted frank loops

$Z = (011)_{Al}$

B vectors:

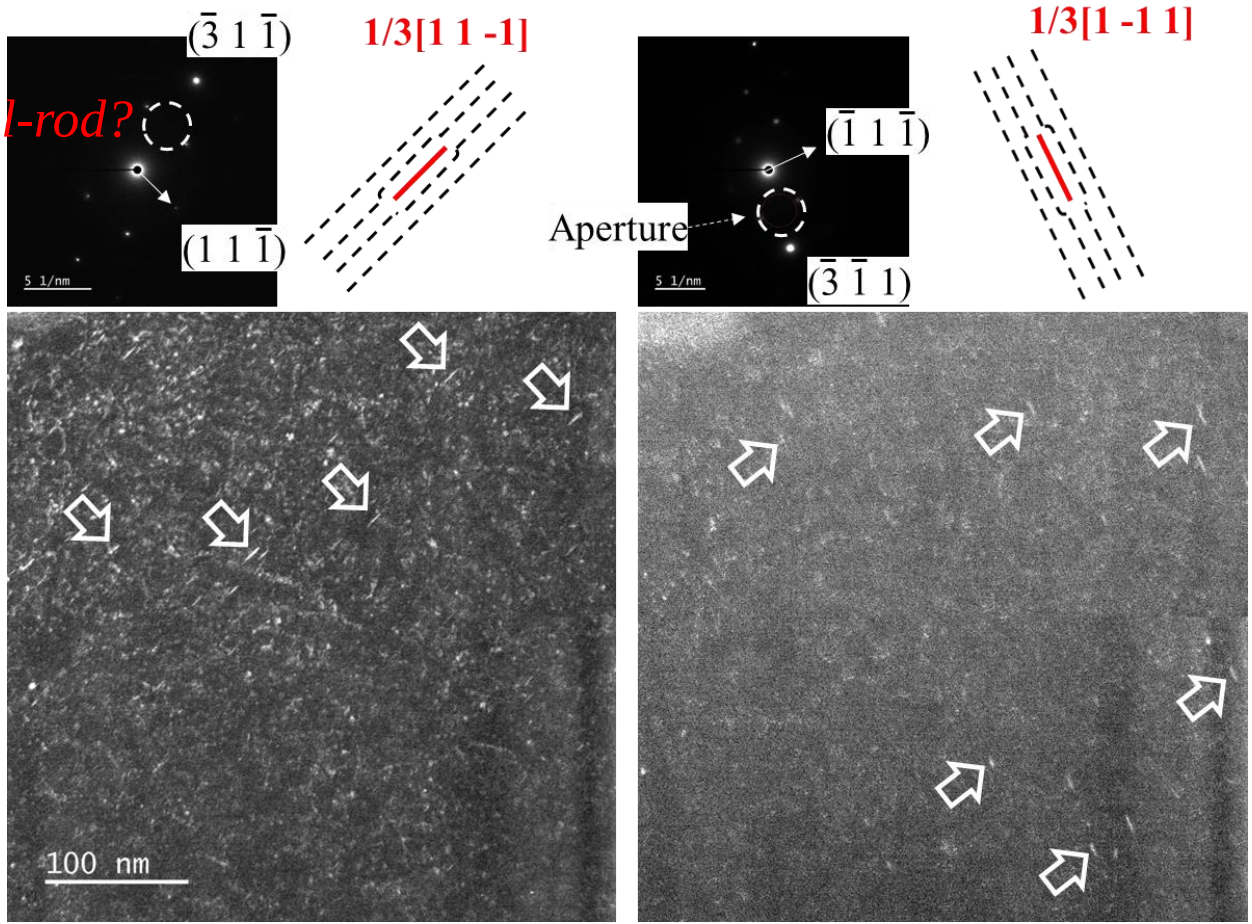
1/3[1 1 1]

1/3[1 1 -1]

1/3[1 -1 -1]

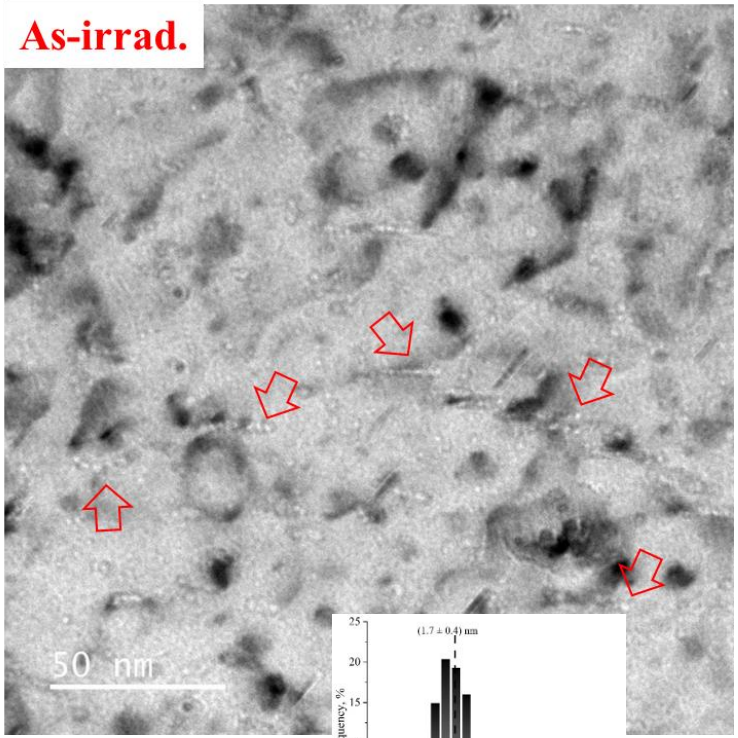
1/3[1 -1 1]

As-irrad.



Microstructures *after irradiation*: bubbles inside grain

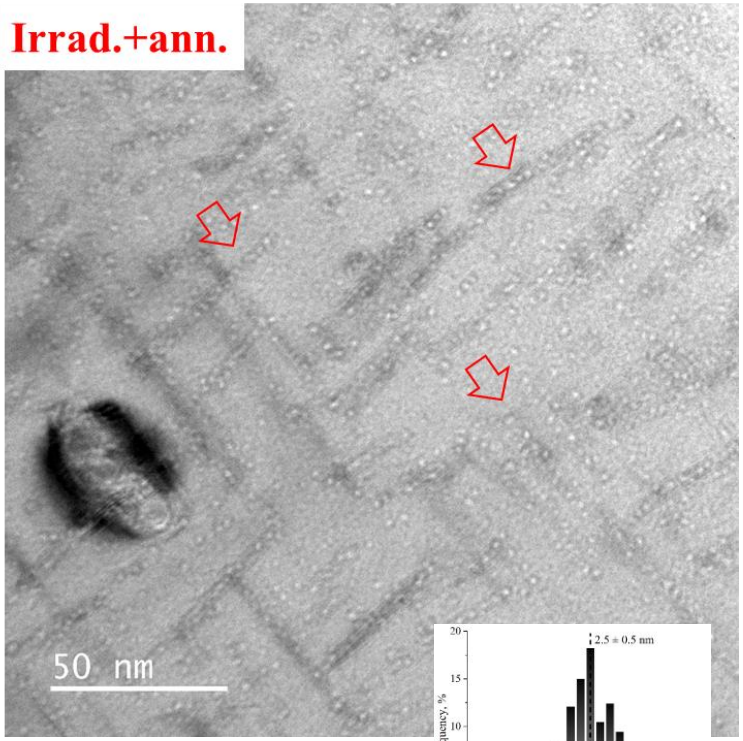
Under focus ~ -640 nm



1.7 ± 0.4 nm

~ 2.6 × 10^{23} m^{-3}

Under focus ~ -750 nm

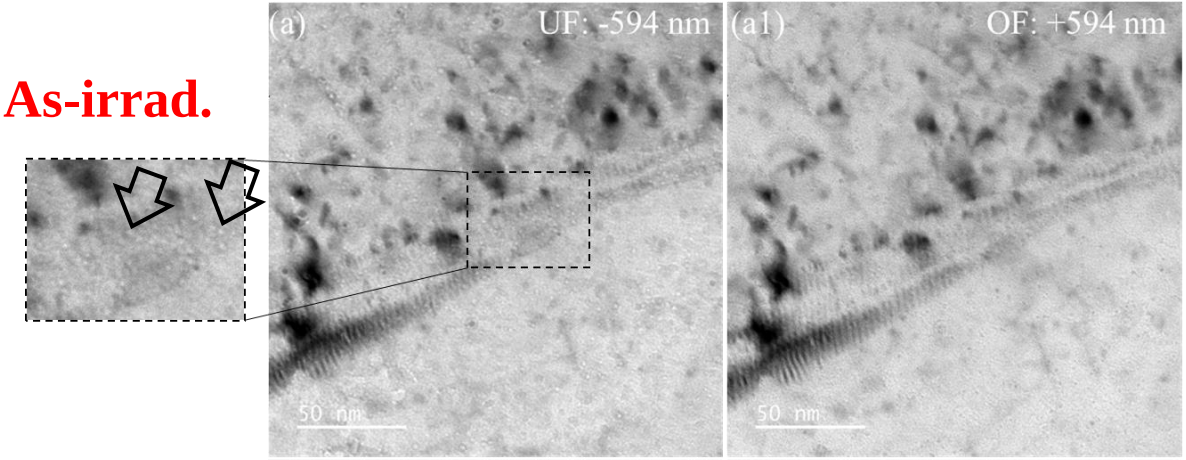


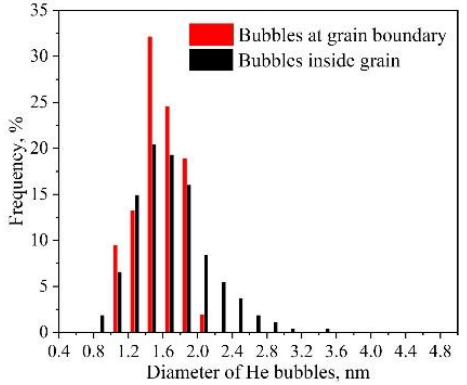
2.5 ± 0.5 nm

~ 1.7 × 10^{23} m^{-3}

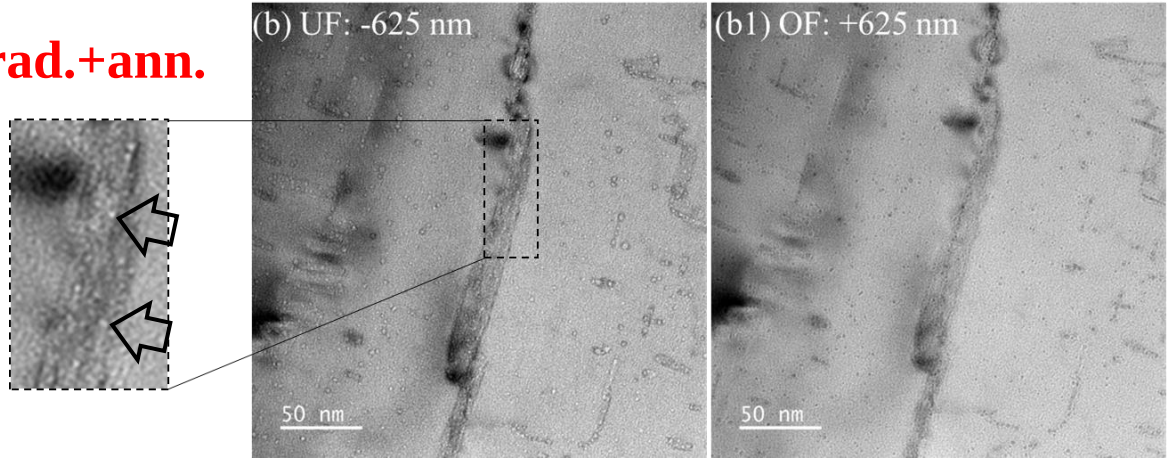
Microstructures *after irradiation*: bubbles at GBs

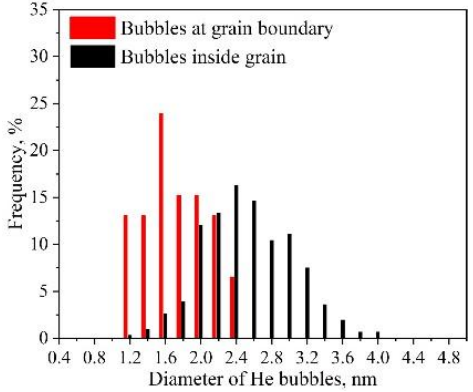
As-irrad.



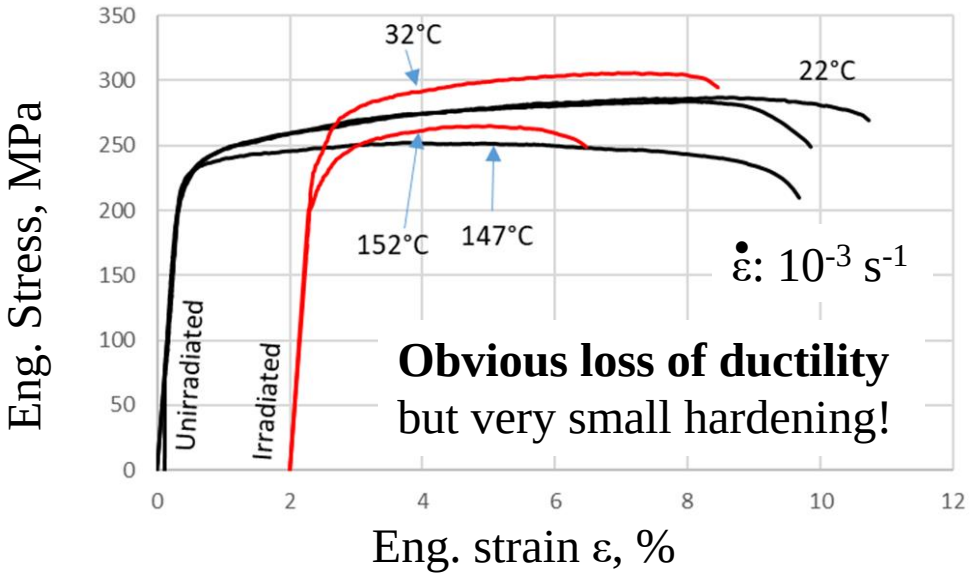


Irrad.+ann.





Tensile test results



- **As-received:**

$$\sigma_{y1} = \sqrt{\sigma_{solute}^2 + \sigma_{grain}^2 + \sigma_{needle}^2 + \sigma_{dislocations}^2}$$

- **As-irradiated:**

$$\sigma_{y2} = \sqrt{\sigma_{solute}^2 + \sigma_{grain}^2 + \sigma_{dislocations}^2 + \sigma_{loops}^2 + \sigma_{round}^2 + \sigma_{bubbles}^2}$$

- **Irradiated+annealed:**

$$\sigma_{y3} = \sqrt{\sigma_{solute}^2 + \sigma_{grain}^2 + \sigma_{dislocations}^2 + \sigma_{needls}^2 + \sigma_{bubbles}^2}$$

- **Strengthening of barriers** based on the Orowan model:

$$\Delta\sigma = M\alpha\mu b(Nd)^{0.5}$$

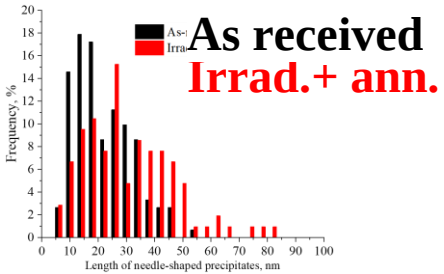
N and d: the number density and mean diameter of the barriers, respectively.

	As-received @ 22 °C	As-received @ 147 °C	As-irradiated @ 32 °C	As-irradiated @ 152 °C
Yield stress, MPa	230	230	260	227

Conclusions

		Needle-shaped	Small round	Frank loops	Perfect loops
As-received	Size, nm	22.1 ± 10.3	6.0 ± 1.2	×	×
	Density, m^{-3}	(1.7 ± 0.8) × 10^{22}	(6.6 ± 4.5) × 10^{21}	×	×
As-irradiated	Size, nm	11.6 ± 3.8	**4.8 ± 1.9**	7.9 ± 2.8 nm	**19.7 ± 8.6 nm**
	Density, m^{-3}	~4.3 × 10^{21}	**~9.6 × 10^{21}**	(6.3 ± 1.5) ×10^{21} m^{-3}	**~1.0 × 10^{22}**
As-irradiated + annealing	Size, nm	30.8 ± 15.9	4.1 ± 0.9	×	56 ± 20
	Density, m^{-3}	(2.5 ± 0.1) × 10^{22}	(4.2 ± 0.7) ×10^{21} m^{-3}	×	~9.9×10^{19}

Length distribution of needle-shaped precipitates



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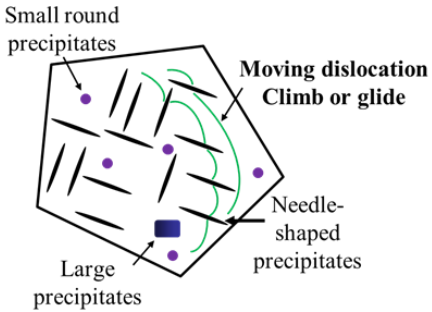
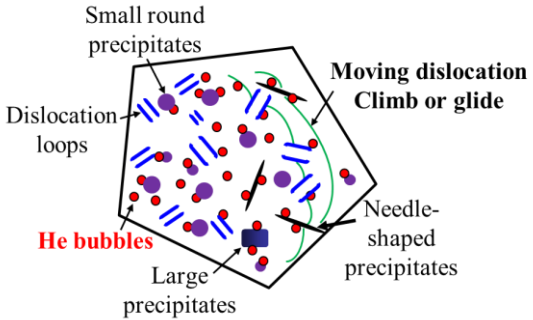
Thanks a lot for your attention!

Discussion

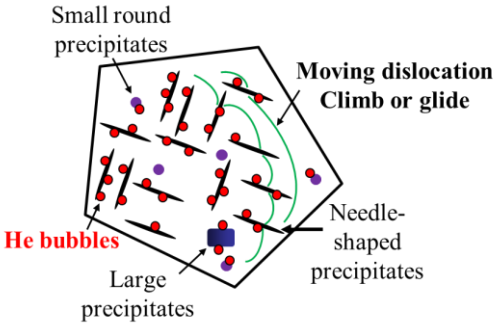
As-received

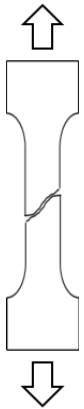


As-irradiated



Irradiated + annealed





- **As-received:**

$$\sigma_{y1} = \sqrt{\sigma_{solute}^2 + \sigma_{grain}^2 + \sigma_{needle}^2 + \sigma_{dislocations}^2}$$

- **As-irradiated:**

$$\sigma_{y2} = \sqrt{\sigma_{solute}^2 + \sigma_{grain}^2 + \sigma_{dislocations}^2 + \sigma_{loops}^2 + \sigma_{round}^2 + \sigma_{bubbles}^2}$$

- **Irradiated+annealed:**

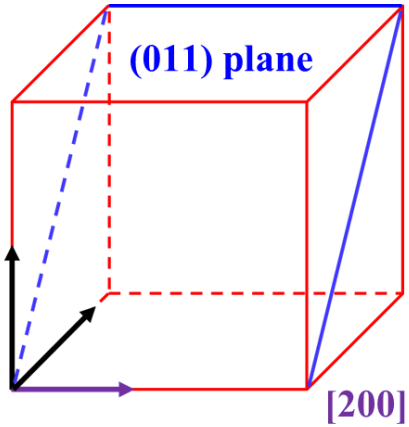
$$\sigma_{y3} = \sqrt{\sigma_{solute}^2 + \sigma_{grain}^2 + \sigma_{dislocations}^2 + \sigma_{needls}^2 + \sigma_{bubbles}^2}$$

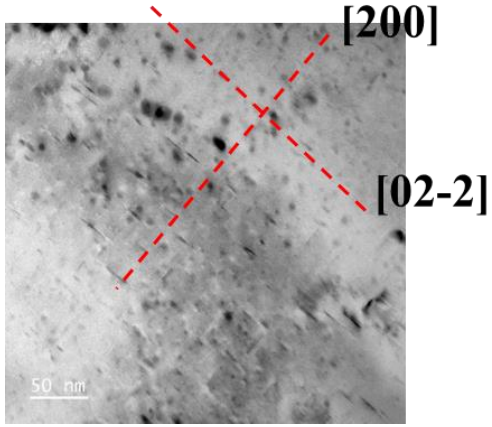
- **Strengthening of barriers** based on the Orowan model:

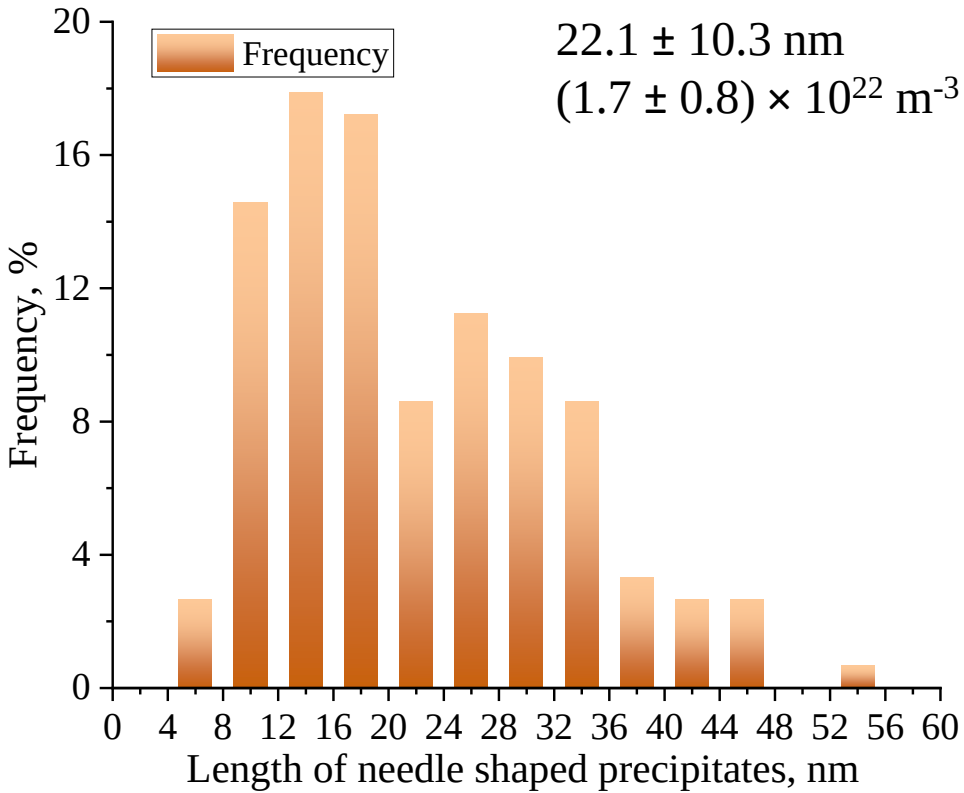
$$\Delta\sigma = M\alpha\mu b(Nd)^{0.5}$$

N and d: the number density and mean diameter of the barriers, respectively.

Size distribution of needle-shaped precipitates

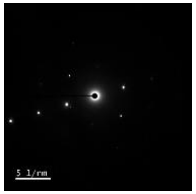


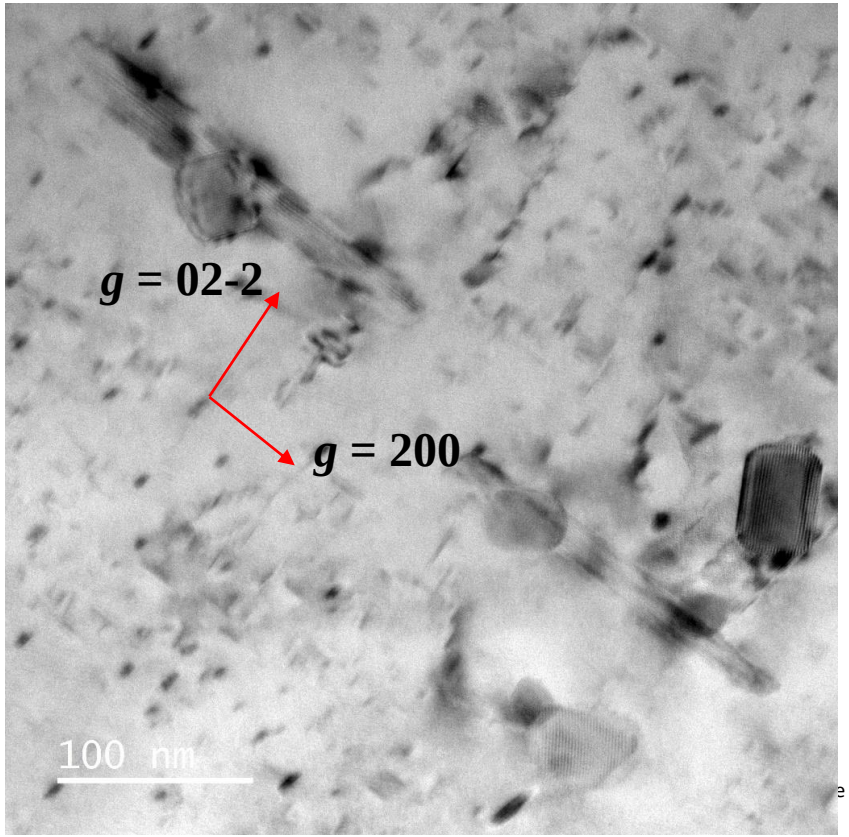


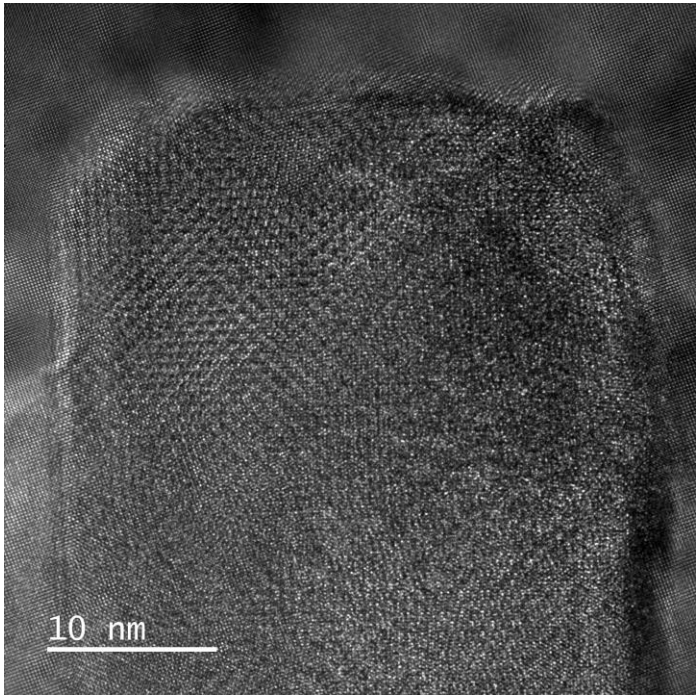


Microstructures before irradiation

Pole 110
g = [1-11]
3*g* excited



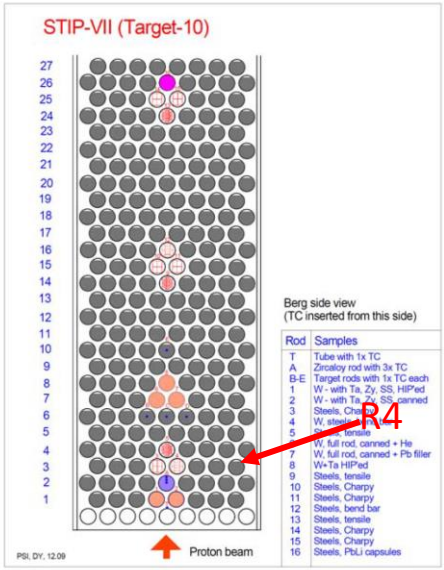




Al-alloys for PBW applications

Al-alloy: Al 6061-T6

Irradiation in STIP-7 (Target-10, 2013-14)



Inconel 718 (for LANSCE, SNS)

Al alloys (for ESS, SINQ, MLF)

Ti-Al-V alloys

High Entropy Alloys (HEAs)

n-flu.	9.5×10^{25} n/m^2
p-flu.	1.6×10^{25} p/m^2
Dose	10.1 dpa
He	455 appm
H	1095 appm
T_{irr}	62°C

to be finalized