Applications of Synchrotron Radiation Scattering to Studies of Plasma Facing Components at Siberian Synchrotron and Terahertz Radiation Centre

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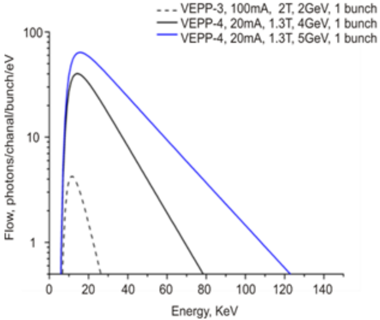
Motivation

Material erosion and degradation

- Sputtering:
  - Physical sputtering,
  - Chemical sputtering.
- Evaporation,
- Surface and structure modifications (including DPA and recrystallization),
- Impurities retention (including α-particles):
  - Bubble growth,
  - Blistering,
  - Flaking,
  - "Fuzz" growth.
- Brittle destruction:
  - Cracking,
  - Dust particles formation and ejection.
- Melting and flowing away,
- Boiling and splashing.

The most promising materials: W, C, Be, Li.

Synchrotron radiation sources

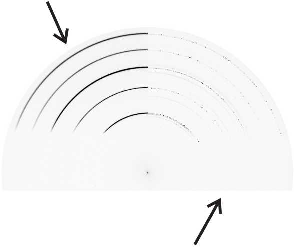


- VEPP-3 and VEPP-4 synchrotron radiation sources were used.

Overview of *ex-situ* studies

Recrystallization

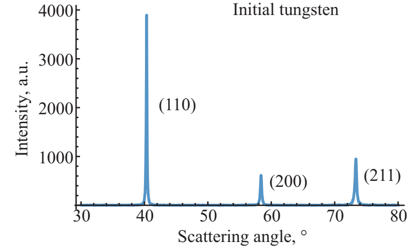
Initial tungsten
(hot-pressed tungsten powder)

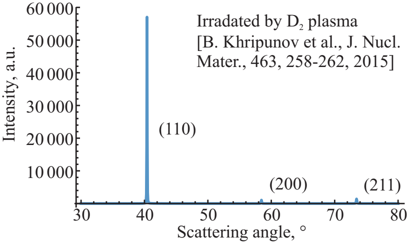


Exposed by electron beam tungsten
(electron energy of 31keV,
power density of 1.6GW m^{-2},
duration of 260μs, 1000 pulses)

- 2D diffractometry demonstrates the grain size growth.
- The growth of material grains makes material more fragile.
- Tungsten-molybdenum composite for the recrystallisation preventing was tested.
- Current status: measurements are completed, data analysis is in progress.

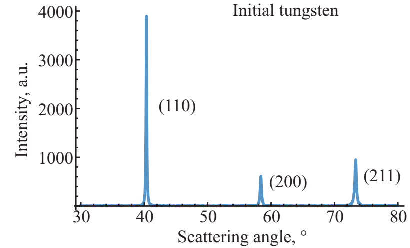
Modification of crystal structure

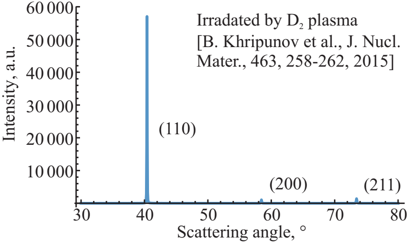




- The strong change of the diffraction intensity are measured.
- The change of the different peaks intensity ratio means that the crystal structure is oriented.
- Influence to tungsten: irradiated by deuterium plasma at room temperature (fluence of $2.3 \cdot 10^{21} cm^{-2}$).

Modification of crystal structure

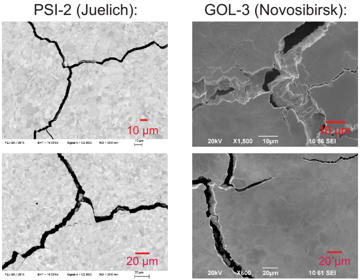




- Possible explanation: the columnar structure of molten and crystallized tungsten.
- However, the influence was inconsistent to the result.

[A.V. Argannikov et al., J. Nucl. Mater., 438, S677-S680, 2013]

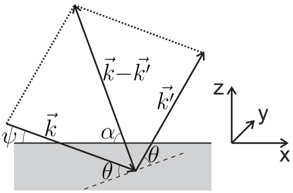
Residual stresses and deformations



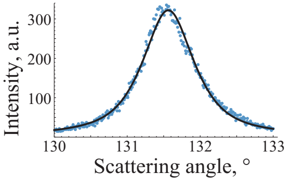
Cracks on the tungsten after pulsed heat loads

- The repetitive pulsed heat loads cause crack formation.
- The cracks are result of plastic deformation and residual stresses.

Residual stresses and deformations



Diffraction scheme



Diffraction peak

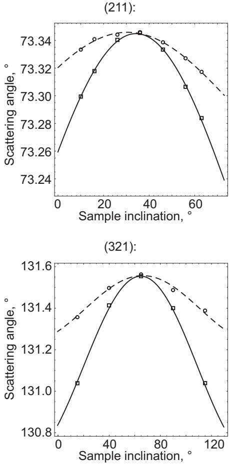
- The variation of the sample orientation changes the SR scattering angle due to residual deformation.
- Geometry:

$$n_x = \cos\alpha\cos\phi = \sin(\psi-\theta)\cos\phi,$$
$$n_y = \cos\alpha\sin\phi = \sin(\psi-\theta)\sin\phi,$$
$$n_z = \sin\alpha = \cos(\psi-\theta).$$

- Effect:

$$\frac{1}{\sin\theta} = \frac{2(d_0+\delta d)}{n\lambda} = \frac{2d_0}{n\lambda}(1- u_{xx}\sin^2(\psi-\theta)\cos^2\phi - u_{yy}\sin^2(\psi-\theta)\sin^2\phi - u_{zz}\cos^2(\psi-\theta) - 2u_{xy}\sin^2(\psi-\theta)\cos\phi\sin\phi - 2u_{xz}\sin(\psi-\theta)\cos(\psi-\theta)\cos\phi - 2u_{yz}\sin(\psi-\theta)\cos(\psi-\theta)\sin\phi).$$

Residual stresses and deformations



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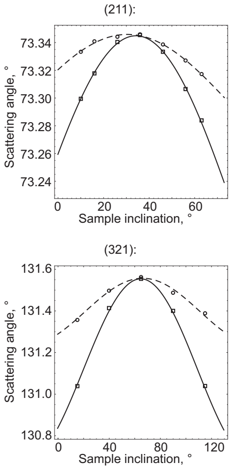
Residual stresses and deformations



- Measured stresses:
  along rolling direction 1100MPa,
  across rolling direction 400MPa.

Residual stresses and deformations

In the case of thin heated area there are simple expressions for elastic stresses and deformations:

$$u_x^e = u_y^e = 0,$$

$$u_{zz}^e = \frac{1-\sigma}{1+\sigma}\alpha\left(T(z) - T_0\right),$$

$$\sigma_{zz}^e = \sigma_{xy}^e = \sigma_{xz}^e = \sigma_{yz}^e = 0,$$

$$\sigma_{xx}^e = \sigma_{yy}^e = -\frac{\alpha E(T(z) - T_0)}{(1-\sigma)},$$

where $\vec{u}^e$ is the elastic displacements, σ_{ij}^e is the stress tensor,
α is the linear thermal extension coefficient, E is the Young's modulus, σ is the Poisson's ratio, T is the temperature., T_0 is the initial temperature.
Axis z is perpendicular to the surface,
x and y are parallel to the surface.

In-situ experiments

In-situ experiments

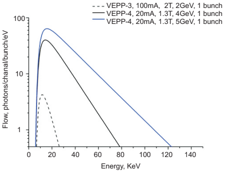
First experiment:
measurements of deformation during pulsed heat load.

Features of synchrotron radiation scattering diagnostics:

- Dynamical measurements during pulsed heating,
- Measurements inside material,
- Spatial resolution inside material.

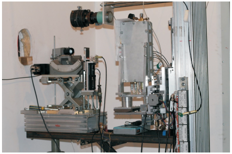
Initial conditions

VEPP-4 synchrotron radiation source



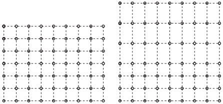
SR spectrum

1D X-ray detector



Channel width: 100μm

Model of deformation



The deformation of crystal structure

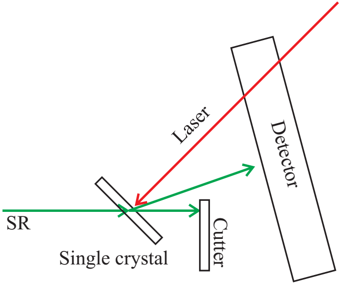
Pulsed heat load simulation

Laser:

- Energy: 1J,
- Duration: 140μs,
- Wavelength: 1064nm.

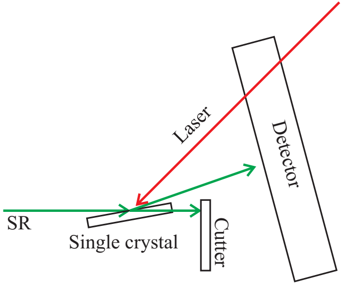
Scheme of experiment

Basic variant:



- The deep penetration into material.
- Spatial resolution.
- Thin samples.

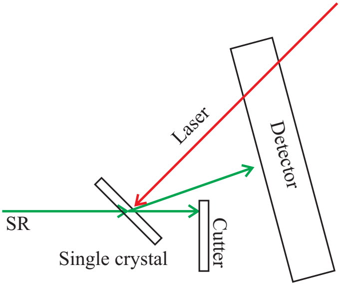
Reserve variant:

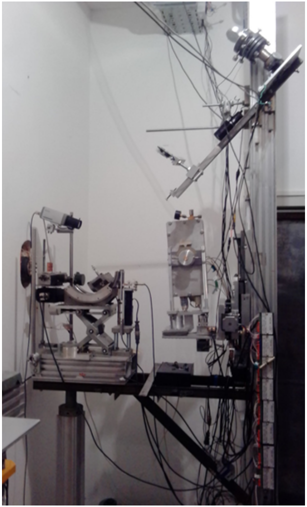


- Single crystal surface.
- Only surface measurements.
- Thick samples.

Scheme of experiment

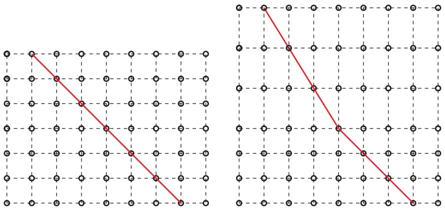
Basic variant:





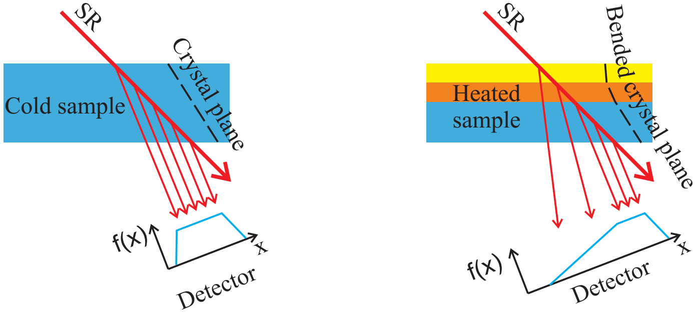
Rotation of crystal planes

Rotation of crystal planes at the heating of the surface layer:



- Compression or expansion of the surface layer result in rotation of the “reflecting” crystal plane.
- $\delta 2\theta \sim \sin(2\alpha)$

Rotation of crystal planes

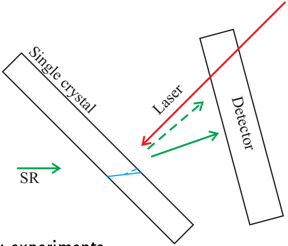


The distribution of the deformations can be calculated using the shape of the diffraction peak.

What did we expect?

Experiment parameters:

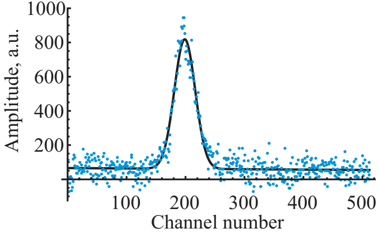
- SR cross-section: 0.5mm $\times$ 0.5mm.
- Laser diameter: 1mm.
- Laser energy: 1J.
- Laser duration: 140μs.
- Temporal resolution: 20μs.
- Single crystal thickness: 250μm.
- Distance to detector: 300mm.
- Geometry:



Consequences:

- Temperature propagation distance during irradiation: 200μm.
- Heating up to 500°C.
- Expected effect: $\delta 2\theta = \frac{1+\sigma}{4}\alpha(T - T_0) \approx 0.7\text{mrad} \approx 0.04^\circ$.
- Detector channel width: $1\text{channel} = 100\mu\text{m} \approx 0.3\text{mrad} \approx 0.02^\circ$.
- The method of the taking into account plastic deformation is under discussion.

First results

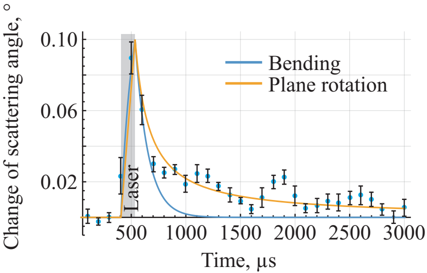


Frame obtained during 20μs.

- Frame number: 30.
- Channel number: 512.
- Frame duration: from 25ns to 200μs.

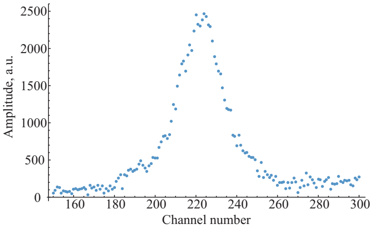
Crystal plane rotation

- The bending is proportional to temperature gradient, while the crystal plane rotation is proportional to the temperature.

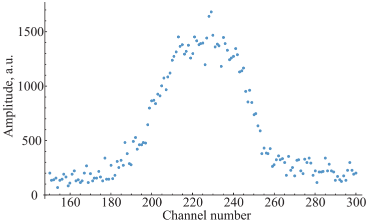


Diffraction peak shape

Diffraction peak before irradiation



Diffraction peak during irradiation



The diffraction peak shape processing is in progress.

Summary

Facility

Operable:

- Goniometers.
- Gas 1D X-ray detector.
- 1J laser.

Under construction:

- Silicon 1D X-ray detector.
- 100J laser.
- Fast pirometer.
- Vacuum vessel.

Physical results

Ex-situ:

- Recrystallization after pulsed heat loads is detected,
- Orientation of crystal structure after plasma load is measured,
- Residual deformation and stresses after pulsed heat loads are measured.

In-situ:

- Rotation of crystal plane during pulsed heating is proved.

Main result

The fast *in-situ* X-ray diffractometry of solid is demonstrated.

Thank you for attention