Anisotropy in the hardness of single crystal tungsten before and after neutron irradiation

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Introduction

Currently, tungsten (W) has been considered as a candidate material for plasma facing components for nuclear fusion reactor. In order to evaluate the degradation of mechanical properties of tungsten after neutron irradiation, the hardness measurement for single crystal W is applied to deduce the effect related to the damage of defect-free lattice. However, the measurement of the hardness in single crystal must account for the anisotropy of the plastic slip and activation of different slip systems depending on the mutual orientation of the indented crystal and indenter. Up to now, this anisotropy effect has not been assessed for the neutron irradiated W.

Objectives

- Investigate the anisotropy of the hardness of single crystal W after neutron irradiation to 1.05 dpa at 600, 800, 900, and 1200 ºC
- Propose a simple method to deduce the hardness of single crystal tungsten, which can account for the anisotropy of hardness

Methodology

Materials

- Single crystal W is machined into disk with ~12 mm in diameter and ~0.5 mm in thickness
- The surface for indentation test is parallel to (001) crystallographic plane and is polished to mirror finish

Neutron irradiation

The disks are irradiated in Belgian Reactor 2 (BR2)

- Irradiation dose: 1.05 dpa
- Irradiation temperature: 600, 800, 900, and 1200 ºC

Micro-indentation

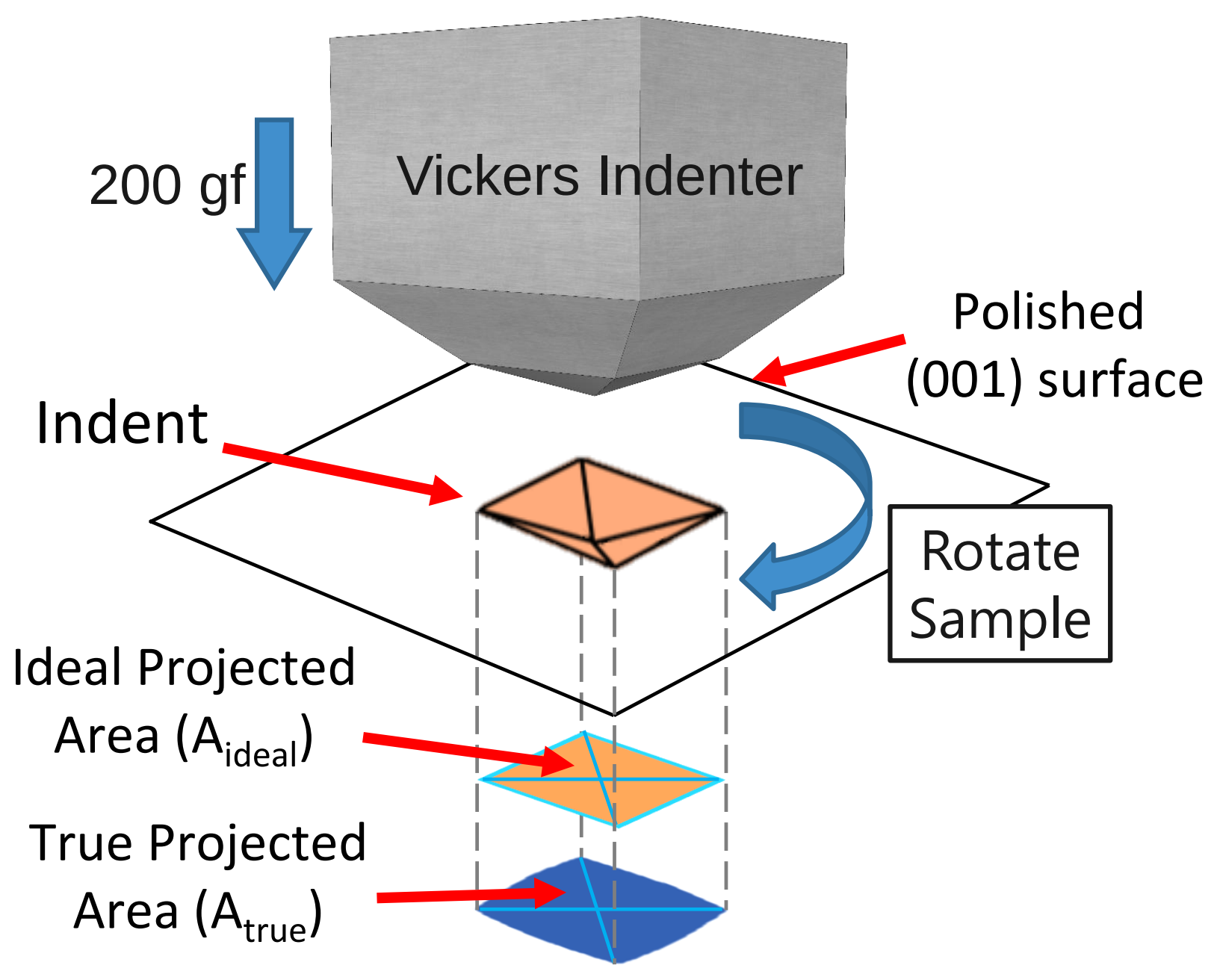
- Vickers indenter with a load of 200 gf and both the loading and holding time are 10 seconds each
- The disk is rotated with a step of 5º

Two hardness values are evaluated

$$H_{ideal} = \frac{Load}{A_{ideal}} \qquad A_{ideal} = \frac{(diagonal^2)}{2}$$

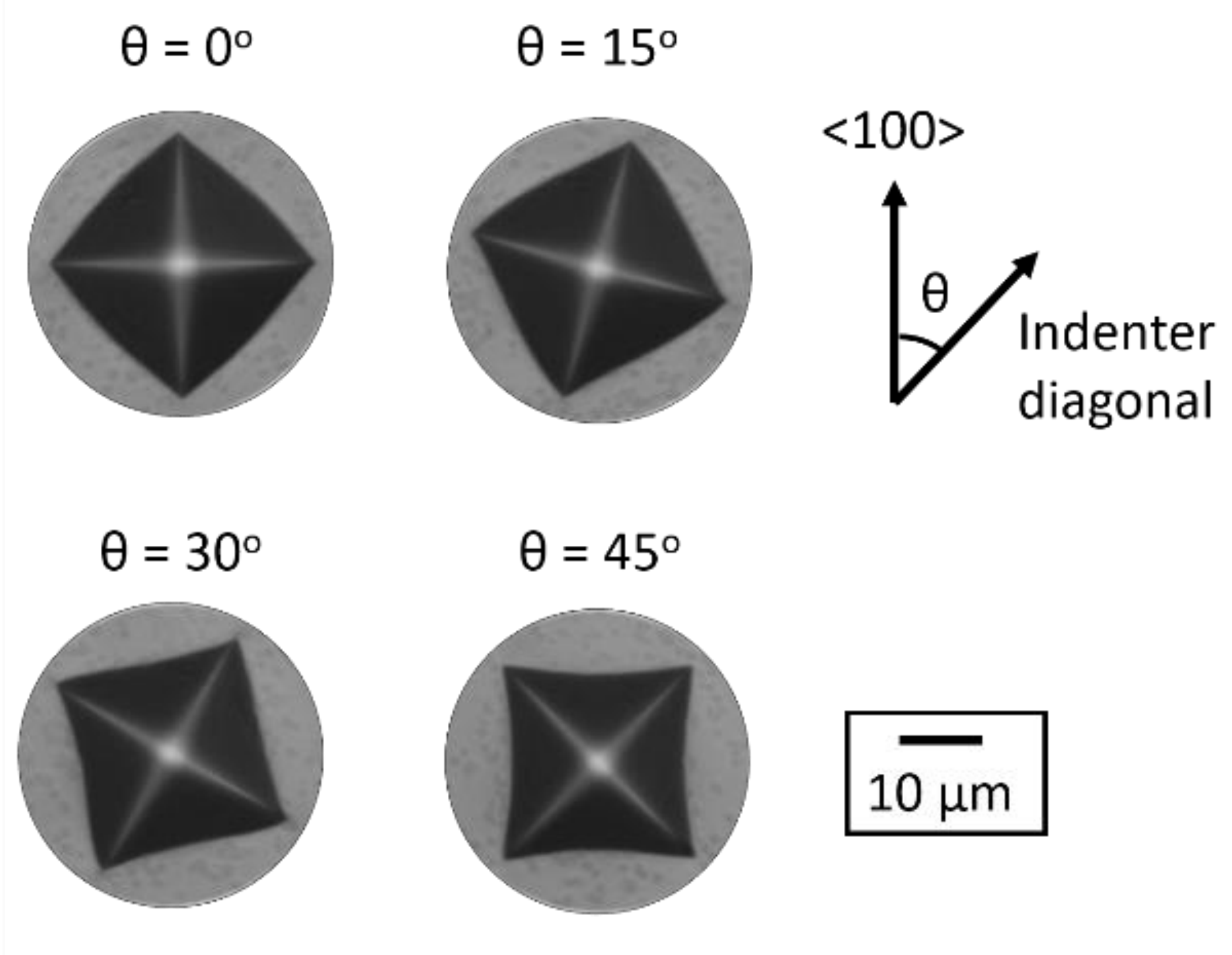
$$H_{true} = \frac{Load}{A_{true}}$$

A_{true} is measured by ImageJ software



Results and Discussion

Different ident shape at different angle



The shape of the indent various as the indenter rotates

- 0º has the largest A_{true} and the smallest A_{ideal}
- 45º has the smallest A_{true} and the largest A_{ideal}

Anisotropy in hardness (hardness as a sine function of angle)

- As indenter diagonal aligns with <100>: highest H_{ideal} and lowest H_{true}
- As indenter diagonal aligns with <110>: lowest H_{ideal} and highest H_{true}
- The variation of H_{ideal} can be explained by Schmid's law
- Combined Schmid's law and pile-up effect (ratio of A_{ideal} to A_{ture}), the variation of H_{true} is well captured

Neutron irradiation: before and after

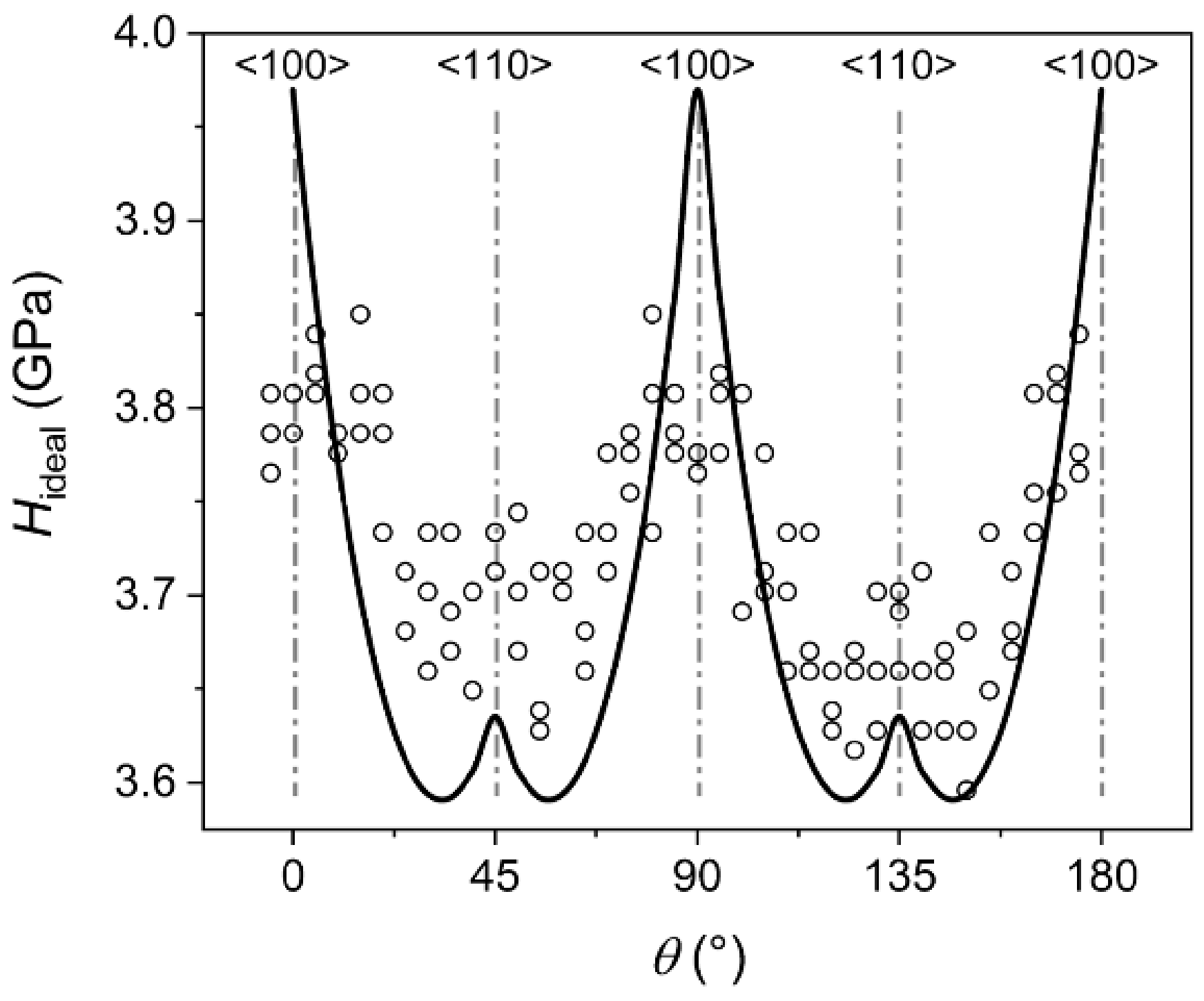
- The true hardness doubles (or more) after irradiated to 1.05 dpa
- The proposed mean hardness H_0 indicates that the irradiation hardening effect reaches its peak at irradiation temperature of 800 ºC
- The relative amplitude of hardness variation is the same for unirradiated and irradiated single crystal W, which is around 8%

Anisotropy of hardness

Schmid's law

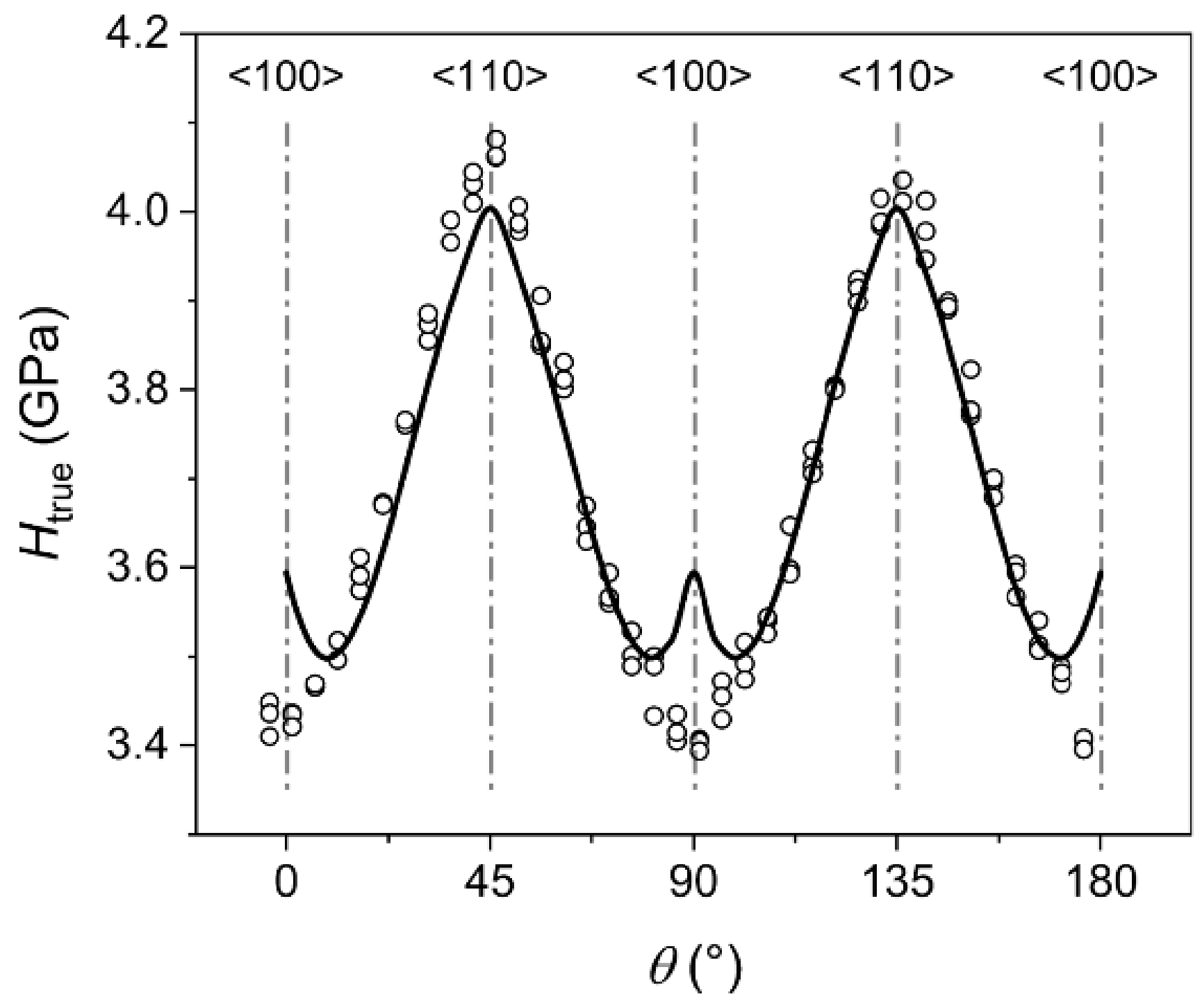
Yield strength (σ_y) is a function of Schmid factor (m), where critical resolved shear stress (τ_c) is a constant

$$H_{\text{ideal}} \sim \sigma_y = \frac{\tau_C}{m}$$

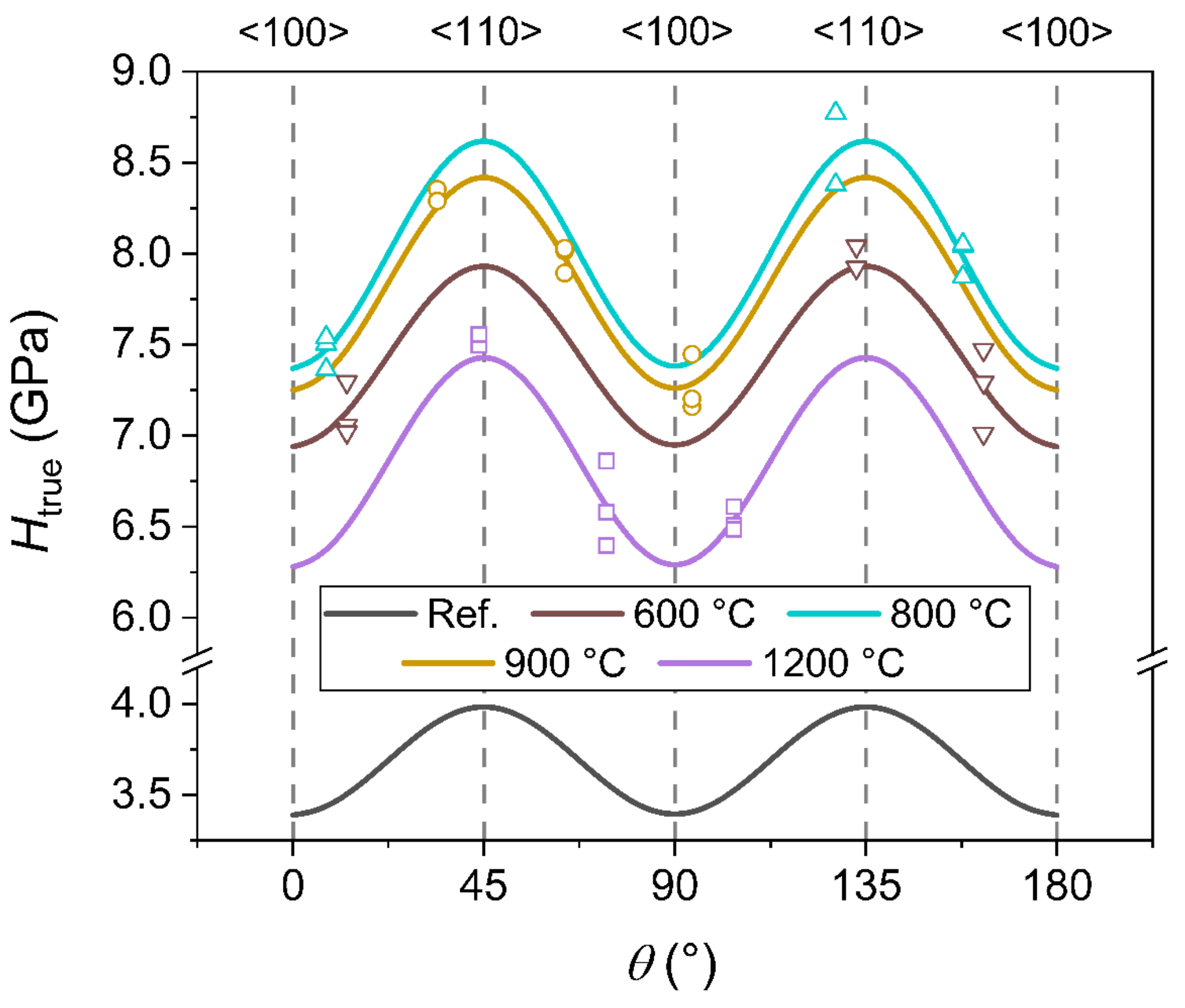


As a function of Schmid Factor (m) and Pile-up effect

$$H_{\text{true}} = \frac{A_{\text{ideal}}}{A_{\text{true}}} H_{\text{ideal}} \sim \frac{A_{\text{ideal}}}{A_{\text{true}}} \frac{1}{m}$$



Anisotropy of hardness: before and after irradiation



$$H_{\text{true}} = H_0 \left[1 + \delta H \sin\left(2\pi \frac{\theta - \theta_0}{\theta_P} \right) \right]$$

- H_0: **Unbiased mean hardness**
- δH: **Amplitude**
- θ_0: **Phase shift = 22.5º**
- θ_P: **Period = 90º**

Sample	H_0 **(GPa)**	δH **(n.u.)**
Ref.	3.69 ± 0.00	0.081 ± 0.003
600 °C	7.44 ± 0.06	0.085 ± 0.011
800 °C	8.00 ± 0.05	0.075 ± 0.009
900 °C	7.84 ± 0.04	0.079 ± 0.006
1200 °C	6.86 ± 0.05	0.085 ± 0.012

Conclusions:

- Anisotropy is observed in the hardness of single crystal W with an amplitude of ~8% for both irradiated and unirradiated materials. Thus, an uncertainty of ~8% is recommended for the absolute value of the hardness if the exact orientation of the indenter and crystallographic axes of the crystal is unknown.
- The true hardness is well described by a sine function with the maximum and minimum corresponding to the configuration of the indenter diagonal being parallel to the <110> and <100> crystal axis, respectively.
- A simple methodology to deduce the mean hardness, H_0, which can be used as an unbiased value to measure the hardness of single crystal W, is proposed.
- Neutron irradiation up to 1 dpa causes a strong increase of the hardness (more than a factor of two). The maximum hardness is attained at 800 ºC, which coincides with the temperature of the peak swelling. Only limited recovery of the irradiation-induced hardening is observed after the irradiation at 1200 ºC.