EUROfusion

Thermal stability of differently rolled pure tungsten plates in the temperature range from 1125 °C to 1250 °C

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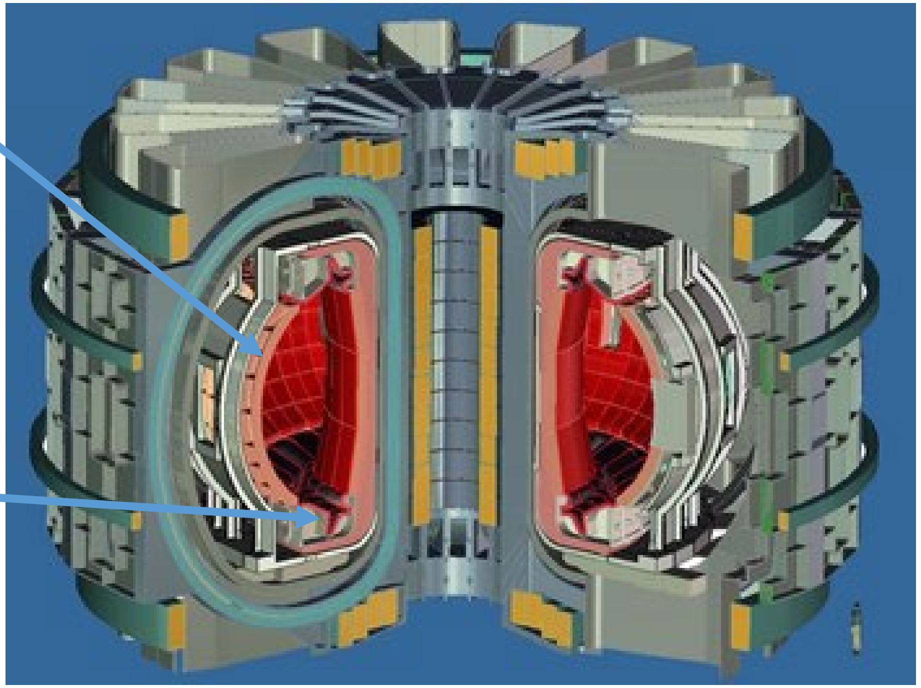
Motivation

Blanket (First wall)

- 150 dpa / 5 y
- 2.5 MW/m²
- 350 °C–550 °C (800 °C)
- 85% power

Divertor (Armor)

- 30 dpa / 2 y
- 10 MW/m²
- 350 °C–1300 °C (1100 °C)
- 15% power



Tungsten	
High melting point (3695 K)	✔
High thermal conductivity	✔
Good creep resistance	✔
Resilience to thermal shocks	✘
Resistance to radiation damage	✔

Mechanical properties
Pure tungsten: ductile at RT
Minor impurities: hard, brittle
Deformation reduces DBTT

74
W
Tungsten
3695 K

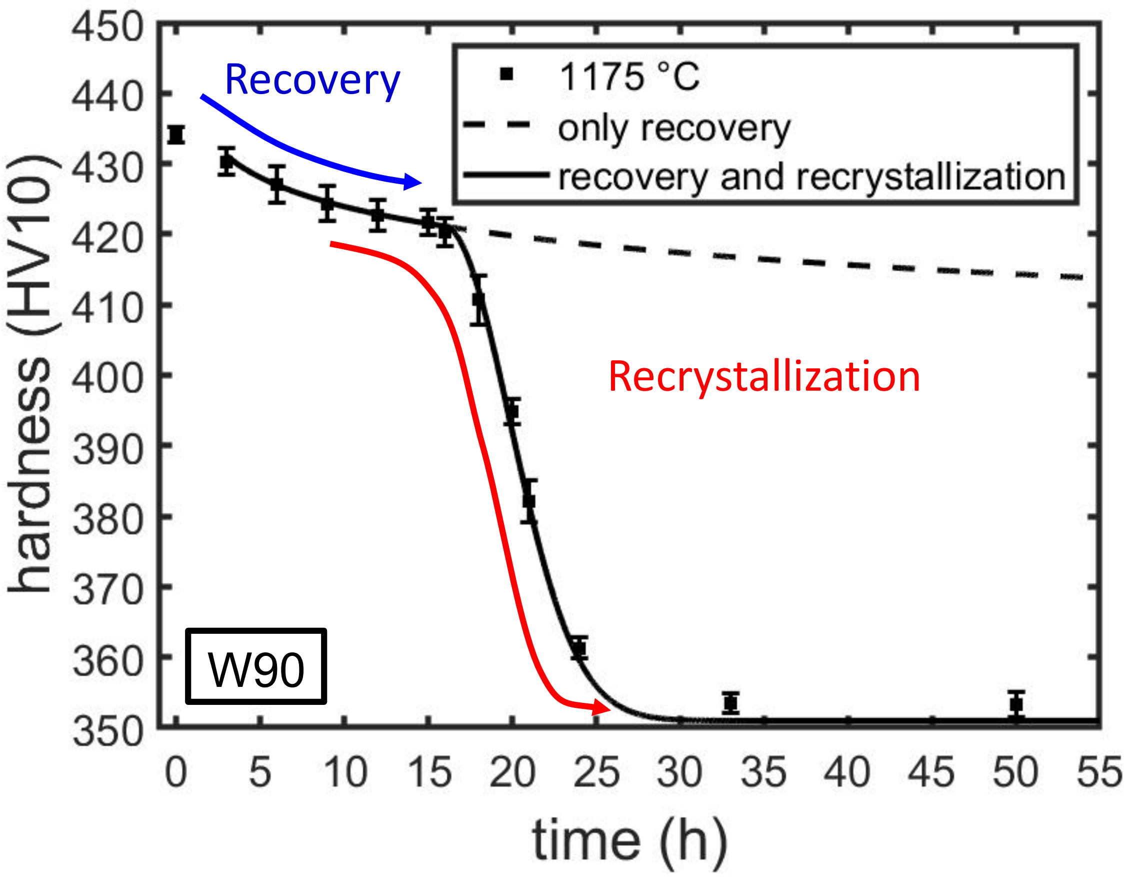
Plastically deformed tungsten

W ≠ W

Degradation during operation

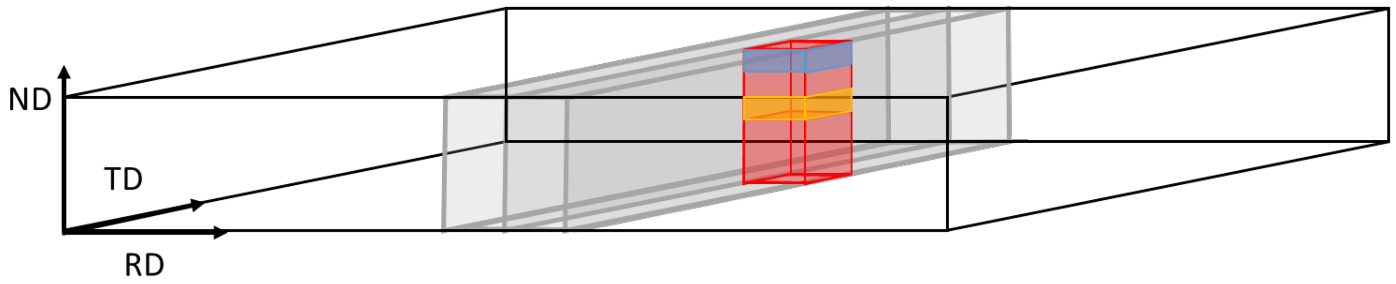
Thermal stability of tungsten - degradation

- Annealing of tungsten plate warm-rolled to 90% reduction



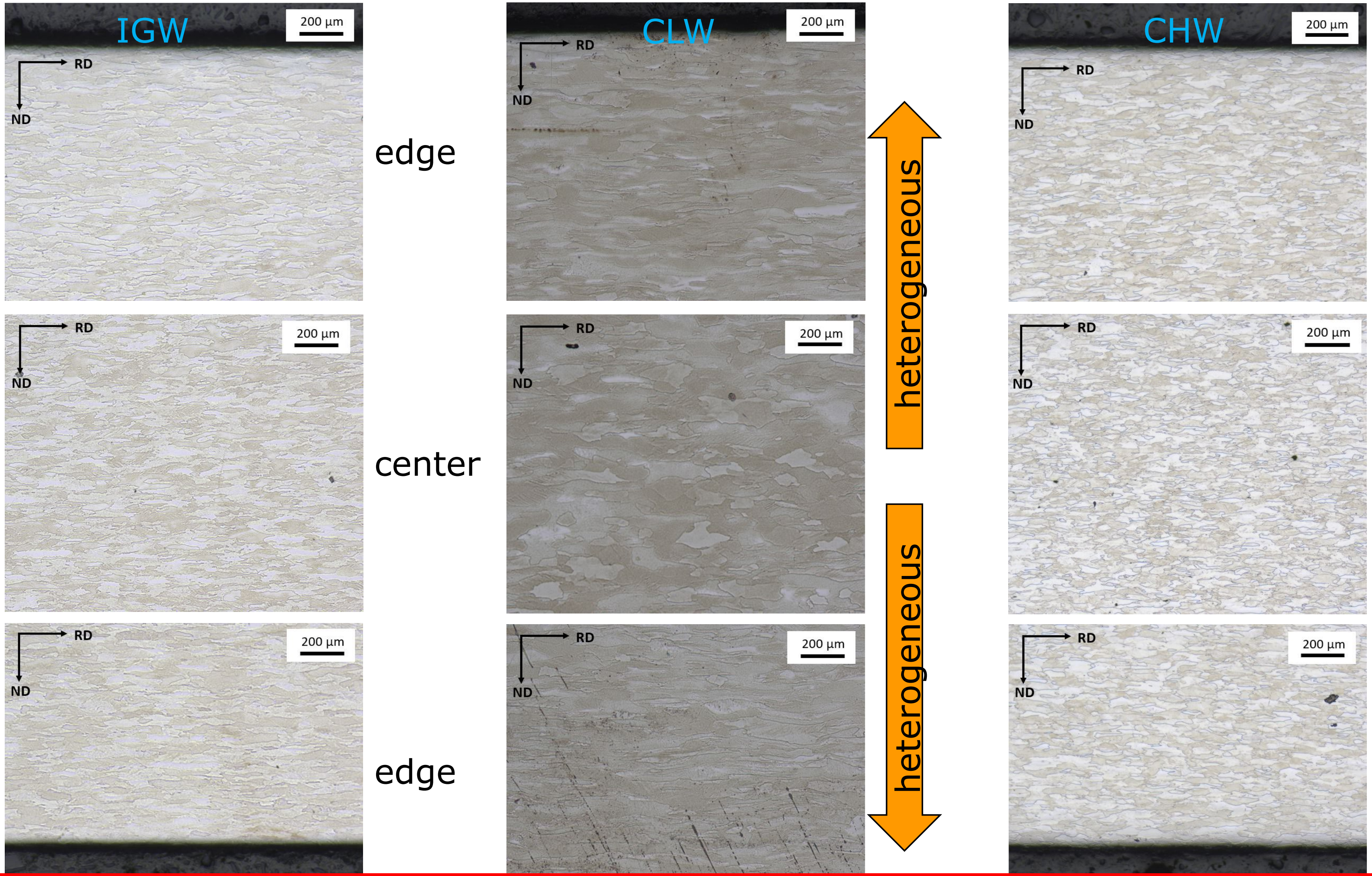
- Restoration of properties: removal of defect content
- Recovery: dislocation annihilation and rearrangement
- Recrystallization: dislocation removal by boundary motion
- Competition about driving force

- Differently rolled W plates from A.L.M.T. Corp. Japan
- Complying with ITER grade specifications
  (Yu et al. Fusion Engng. Des. 157 (2020) 111679)
  - IGW (ITER)   unidirectionally rolled
  - CLW   cross-rolled with low/moderate cross rolling ratio?
  - CHW   cross-rolled with high cross rolling ratio?
- Geometry with edge core



Macro hardness rather homogeneous 440 HV10

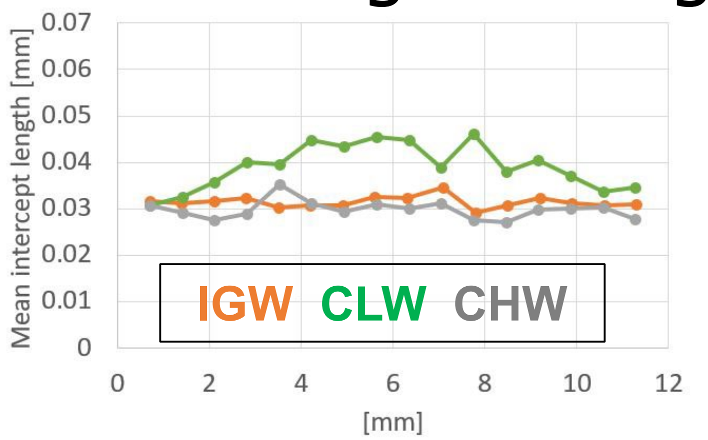
Microstructural investigations – light optical microscopy



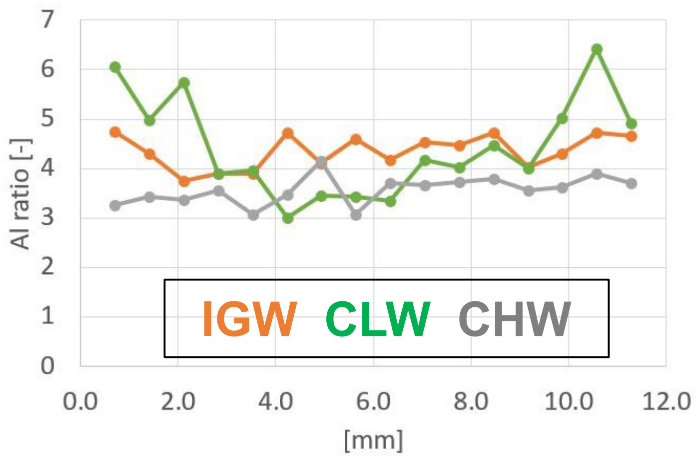
Discrepancy with results from Yu et al. Fusion Engng. Design 157 (2020) 111679

Microstructural analysis – quantitative LOM

- Chord length along ND



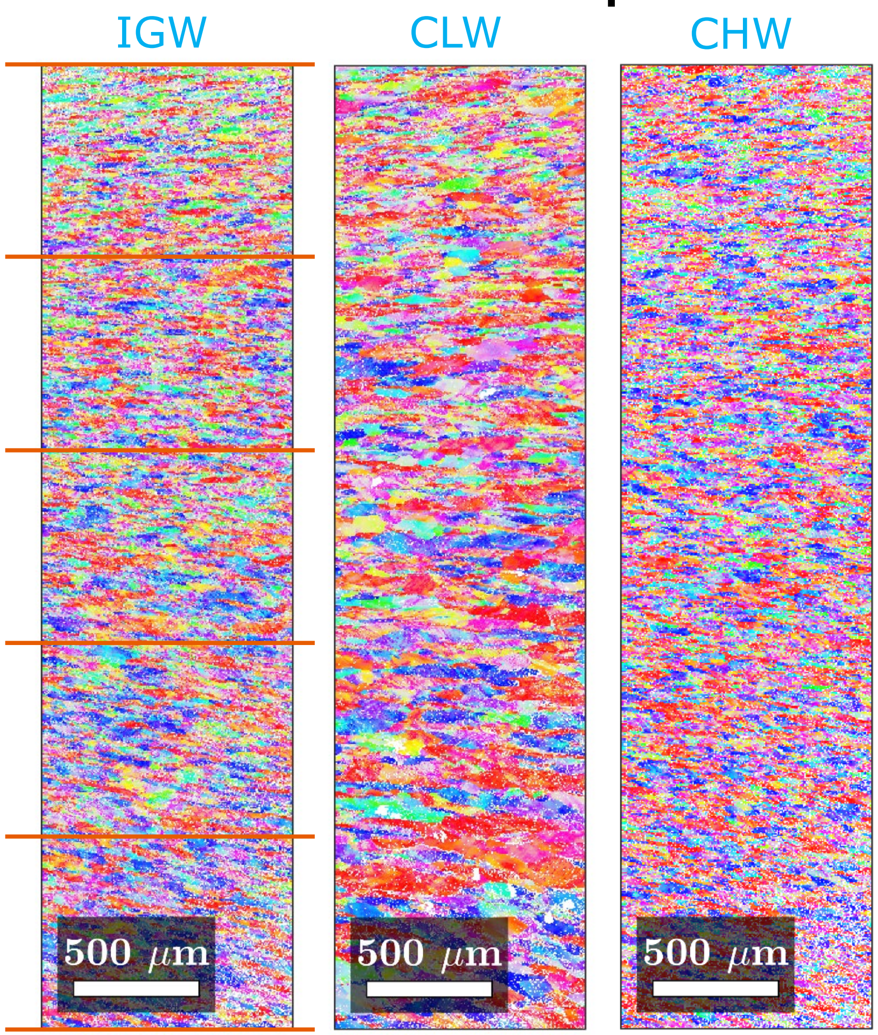
- Aspect ratio



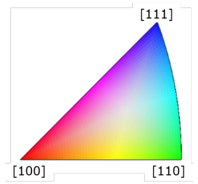
- Mean chord length
  - Similar for IGW and CHW
  - Larger for CLW
- Through thickness variation of chord length
  - Insignificant for IGW and CHW
  - For CLW large grains in core, small at edge

Microstructural investigation - EBSD

- Orientation maps IPF ND

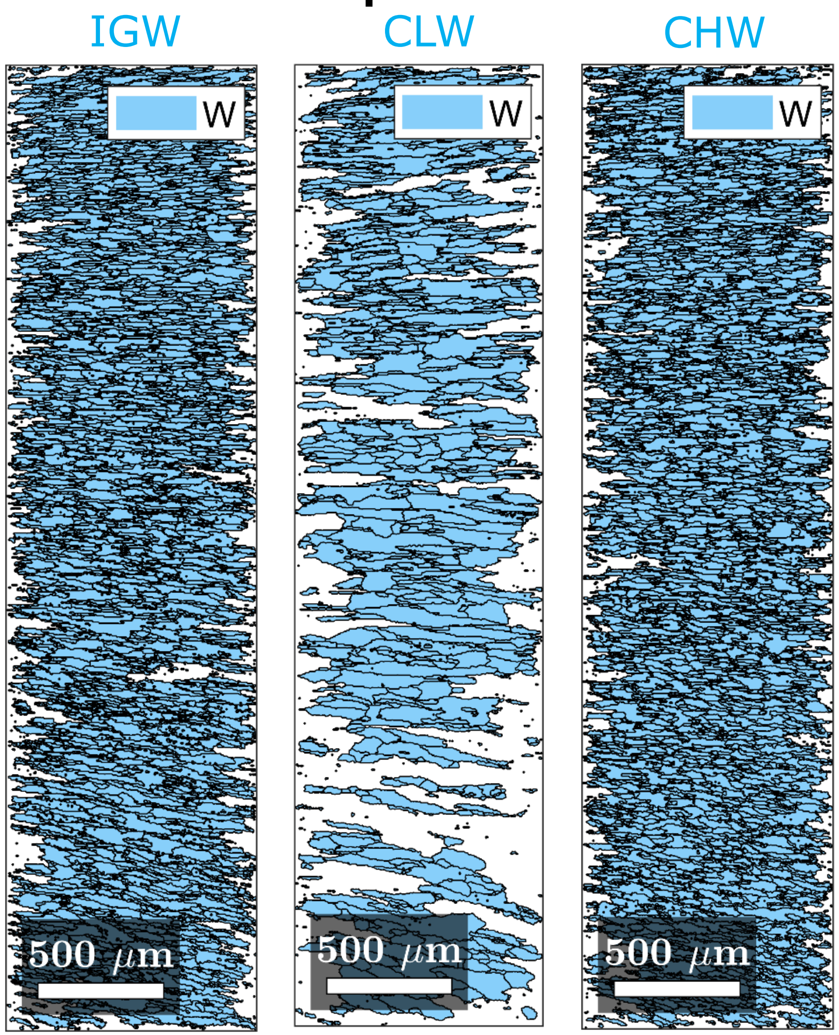


Edge



Core

- Grain maps

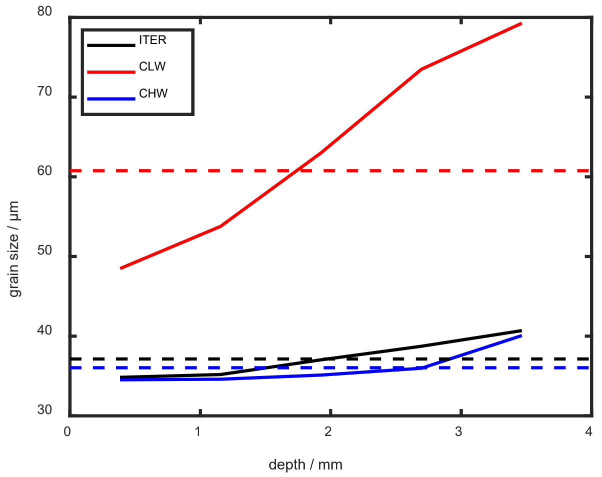


Microstructural analysis - EBSD

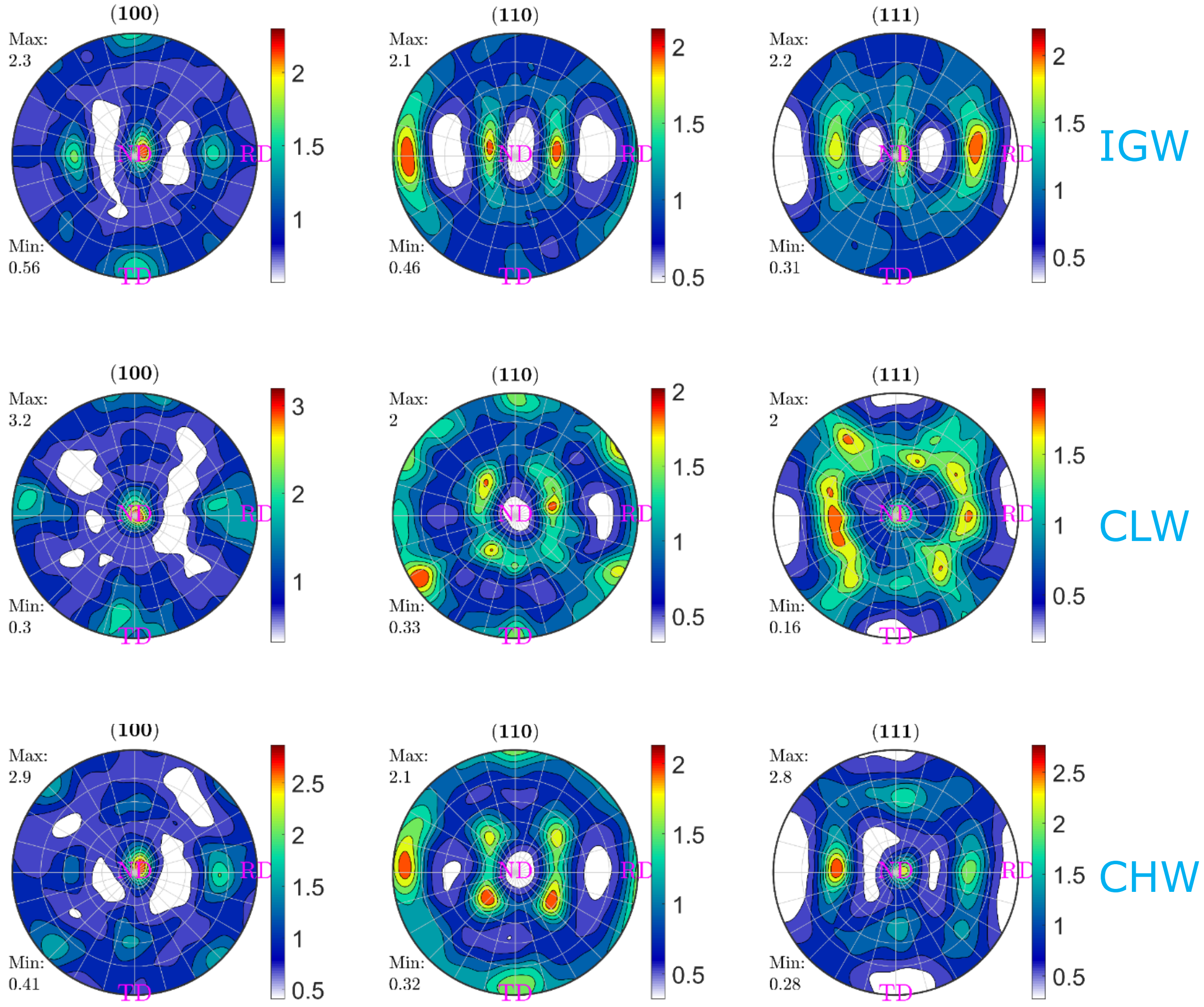
• Grain size

As-received	Number	ECD [µm]	ASTM
IGW	3308	37	6.9
CLW	1176	61	5.5
CHW	3565	36	7.0

ITER spec: ASTM grain size number of 3 or larger



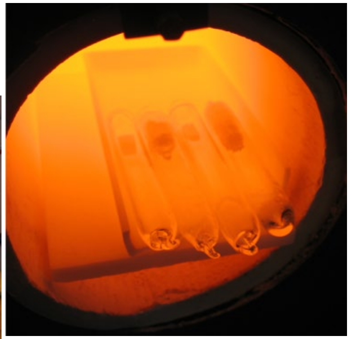
• Pole figures

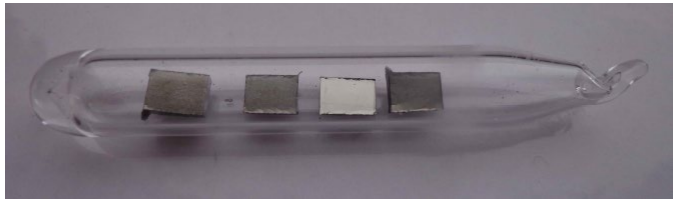


- Annealing at six different temperatures up to 42 d

Annealing temperatures
1125 °C
1150 °C
1175 °C
1200 °C
1225 °C
1250 °C

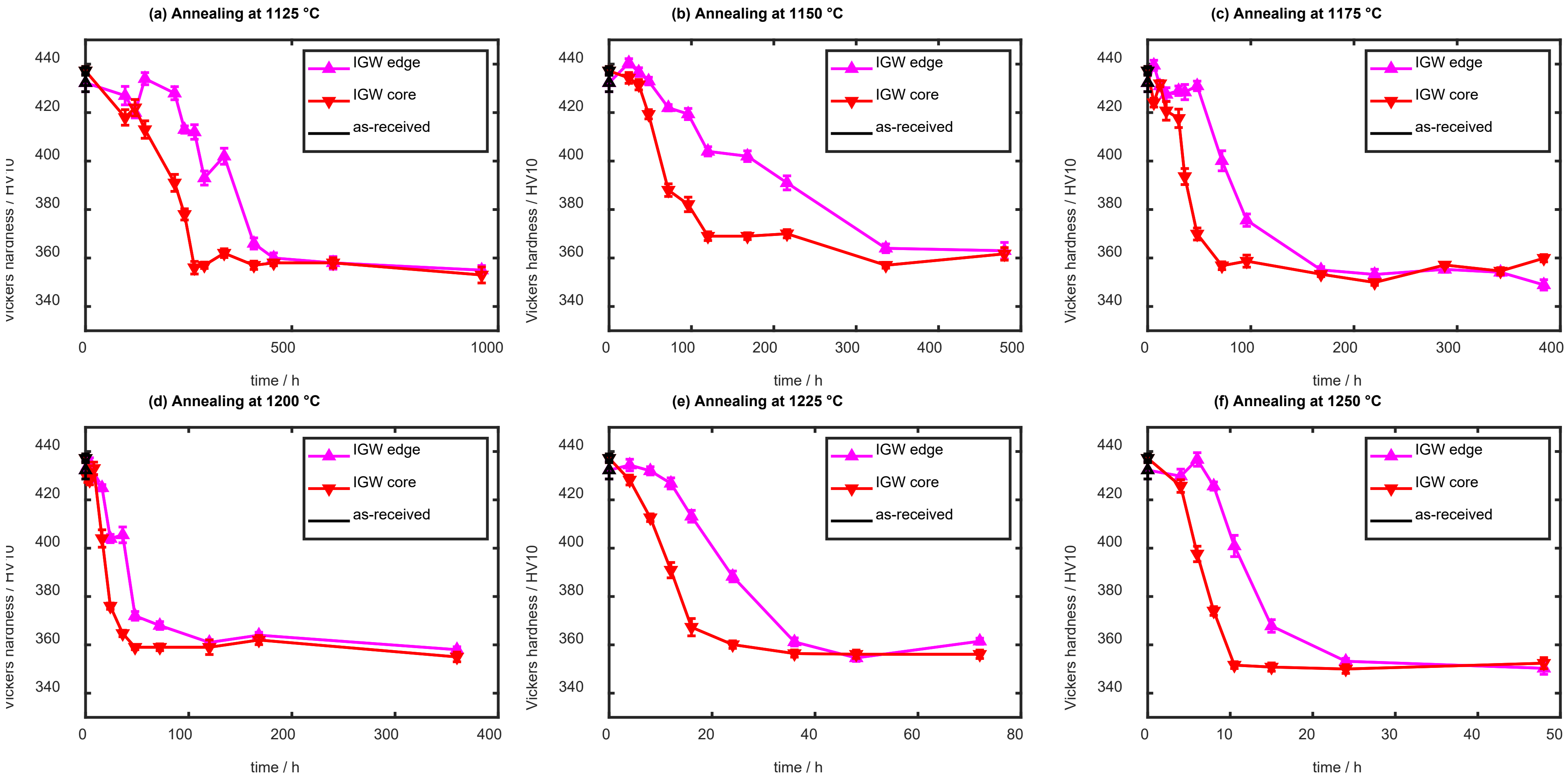
- Kinetics and temperature dependence





Hardness evolution IGW 1125 °C to 1250 °C

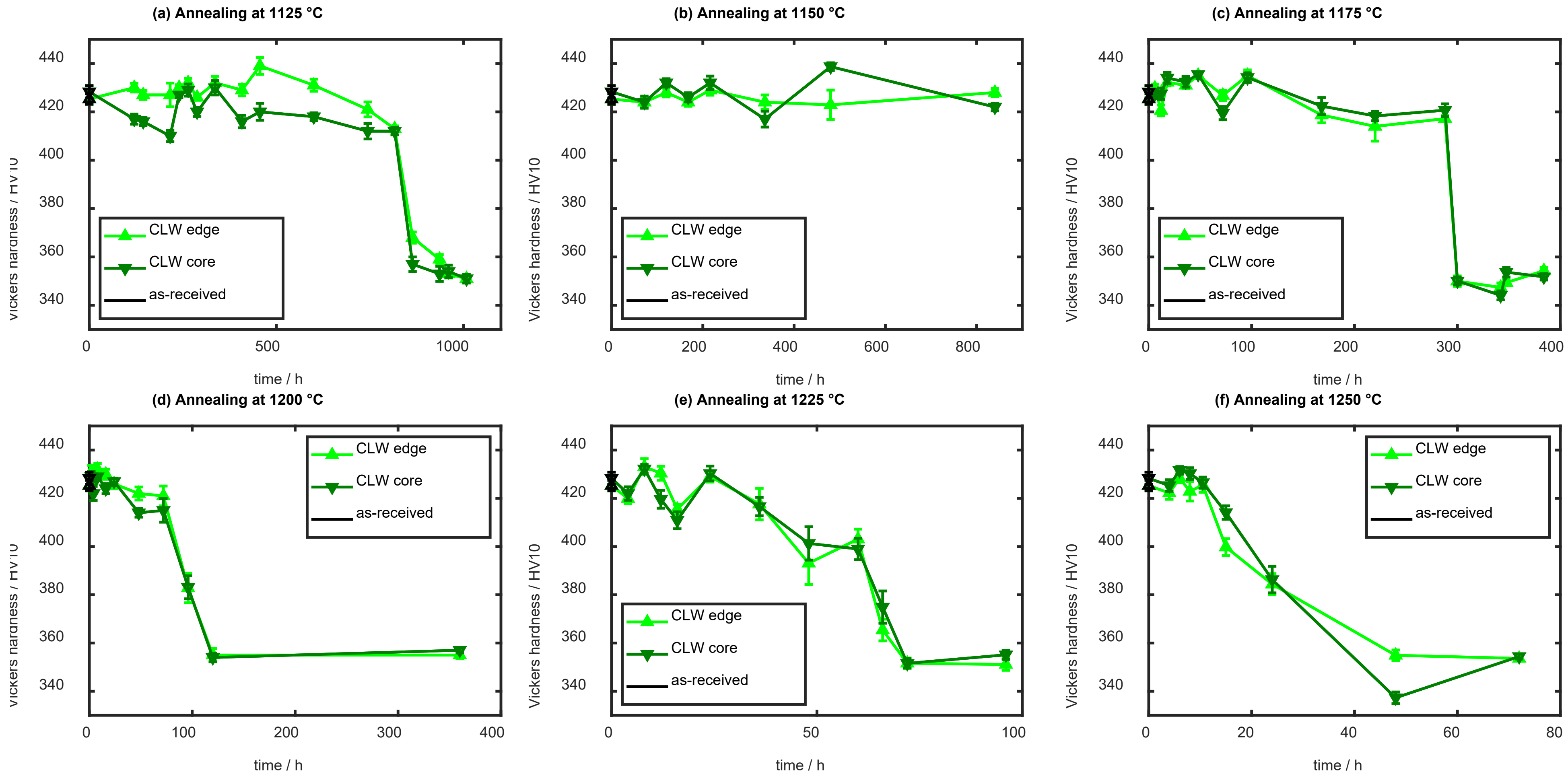
- IGW



Edge slower than core

Hardness evolution CLW 1150 °C to 1225 °C

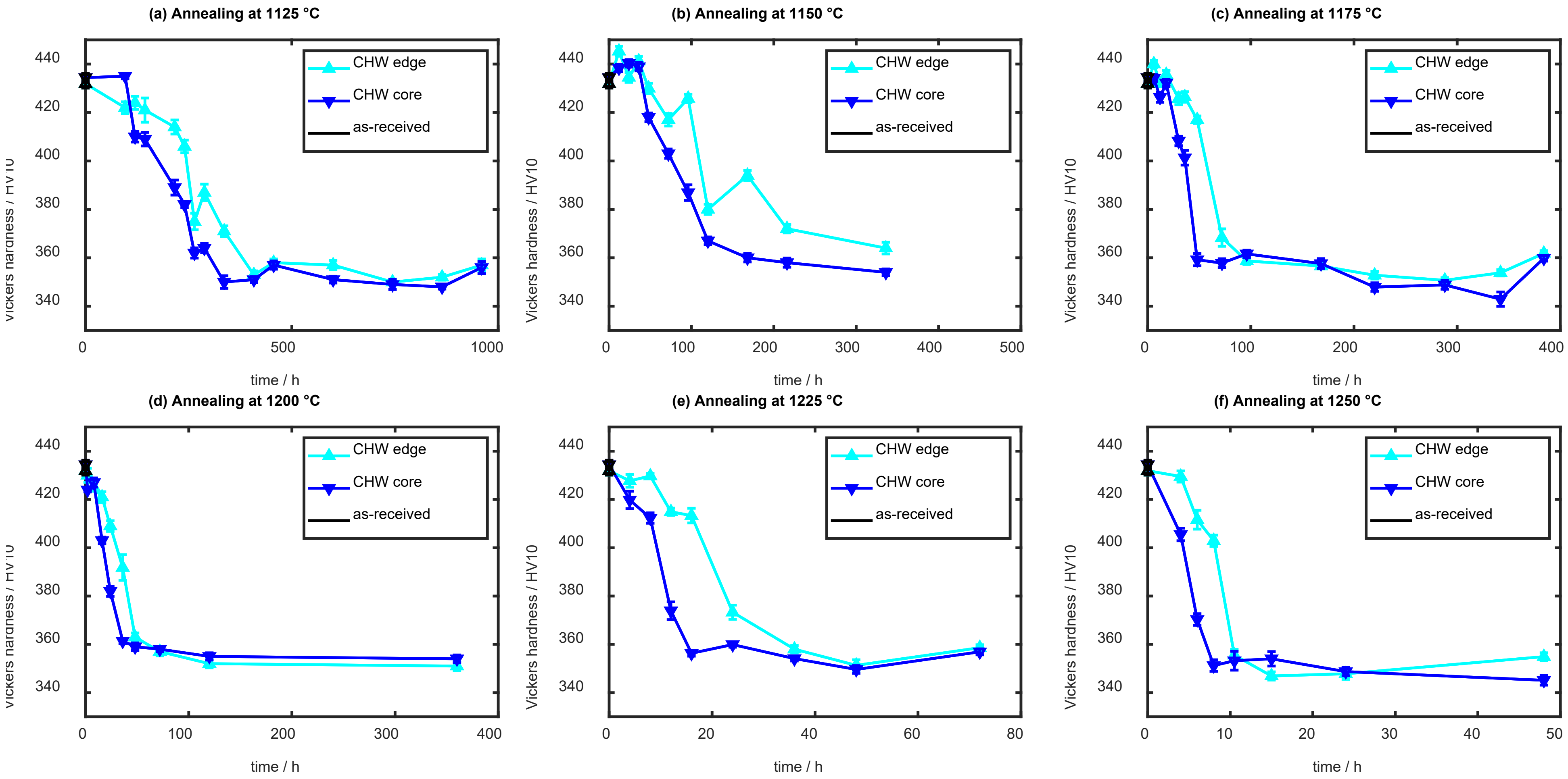
- CLW



Edge as slow as core

Hardness evolution CHW 1150 °C to 1225 °C

- CHW

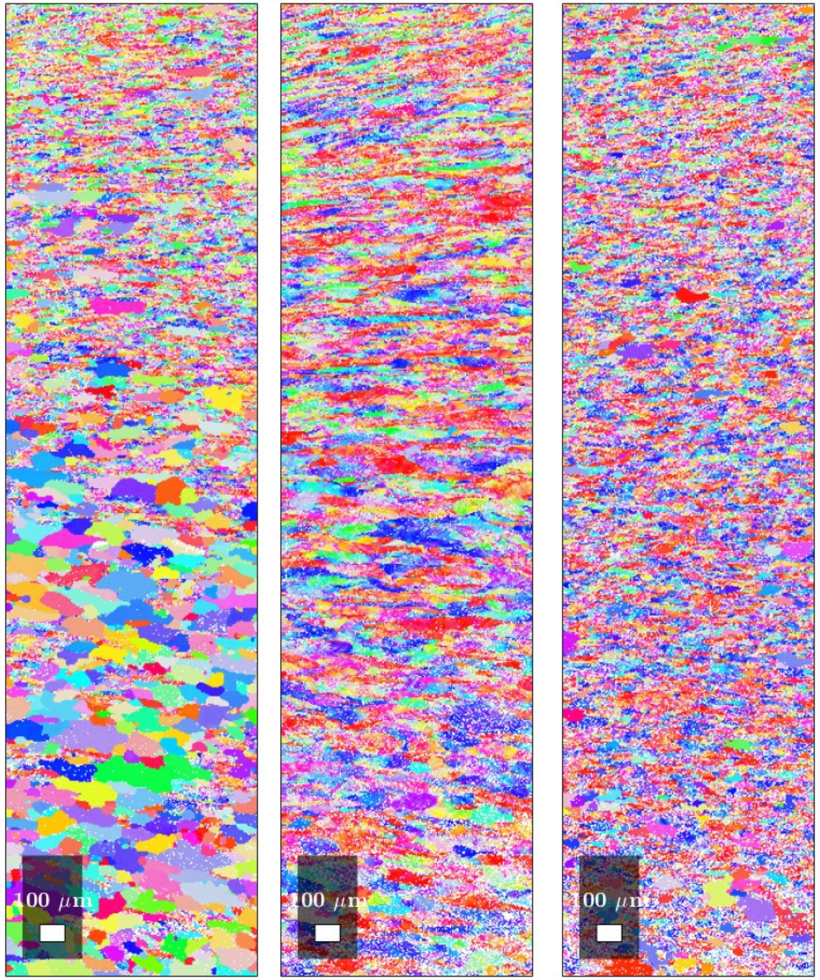


Edge slower than core

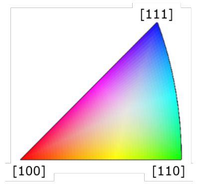
Microstructural investigation – EBSD at 1175 °C

- 2 d (partially recrystall.)

IGW CLW CHW



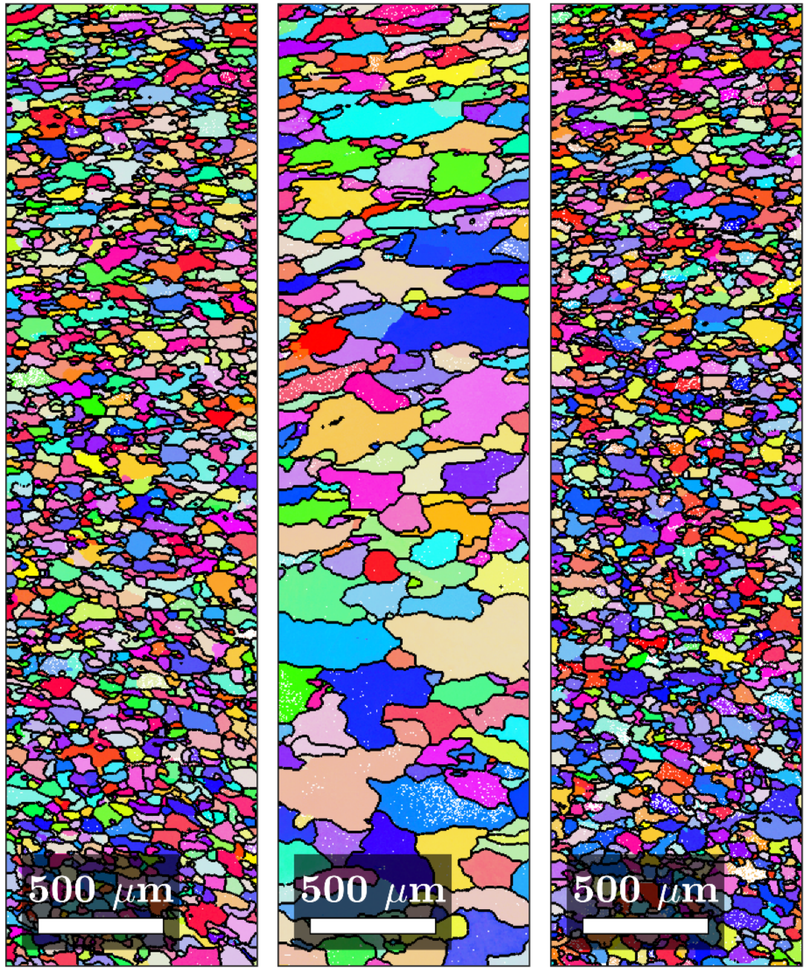
Edge



Core

- 16 d (full recrystallized)

IGW CLW CHW

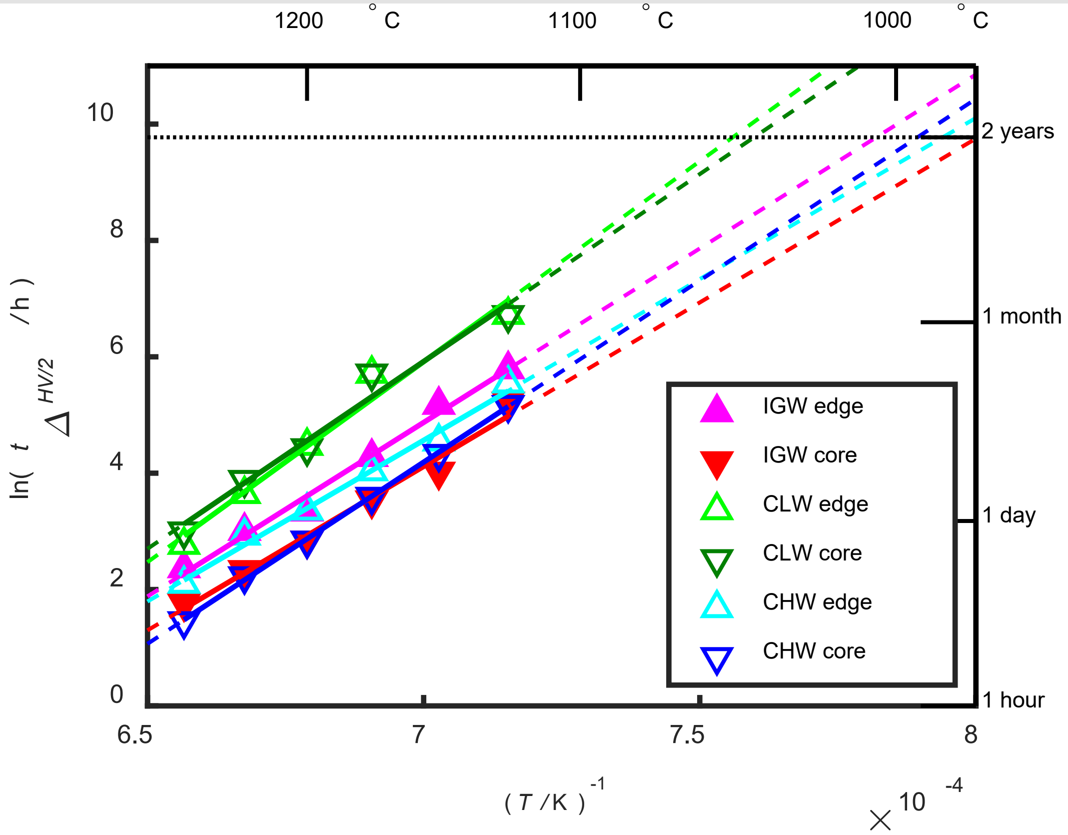


Annealing kinetics – half hardness loss

- Time to half of the entire hardness loss
- Thermal activated process

$$t_{\Delta HV/2} = t^*_{\Delta HV/2} \exp\left(Q/RT\right)$$

- Activation energy
- Maximal temperature for two years of operation



Half hardness	IGW Edge	IGW Core	CLW Edge	CLW Core	CHW Edge	CHW Core
Q / kJ/mol	497	468	573	535	497	519
T (2 y)	1006 °C	976 °C	1050 °C	1043 °C	986 °C	994 °C

Annealing kinetics

- Hardness drop indicates occurring recrystallization
- Hardness determined by recrystallized fraction X

$$HV = X\,HV_{rex} + (1 - X)\,HV_{rec}$$

- Johnson Mehl Avrami Kolmogoroff kinetics

$$X = 1 - \exp\left(-b^n\,(t - t_{inc})^n\right)$$

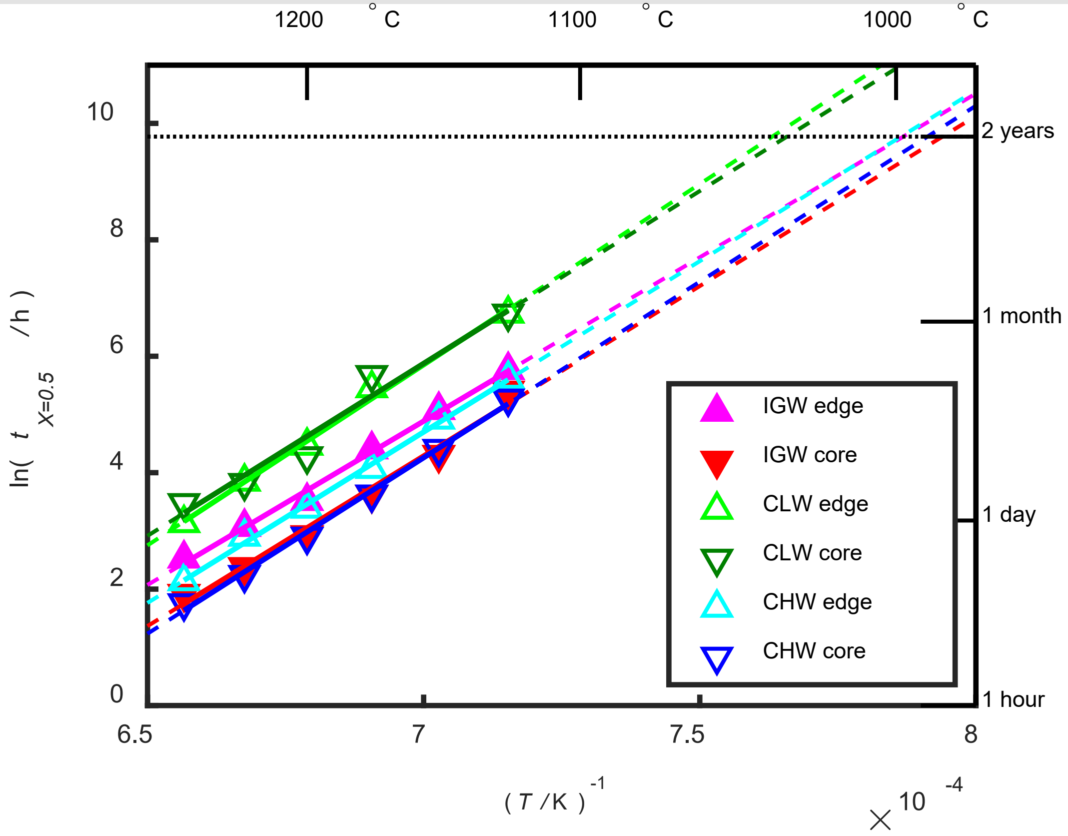
- Avrami exponent $n = 2$
- Time to half recrystallization

Annealing kinetics – half recrystallization

- Time to recrystallization of half of the local volume
- Thermal activated process

$$t_{X=0.5} = t^*_{X=0.5} \exp\left(Q/RT\right)$$

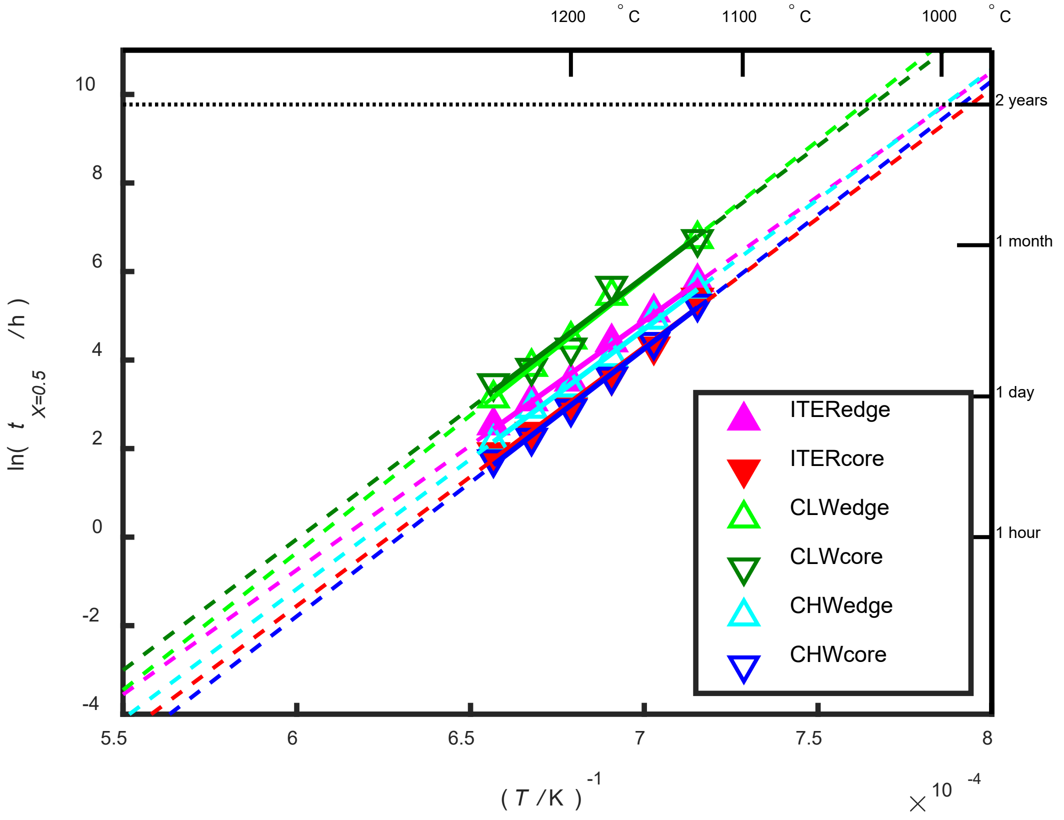
- Activation energy
- Maximal temperature for two years of operation

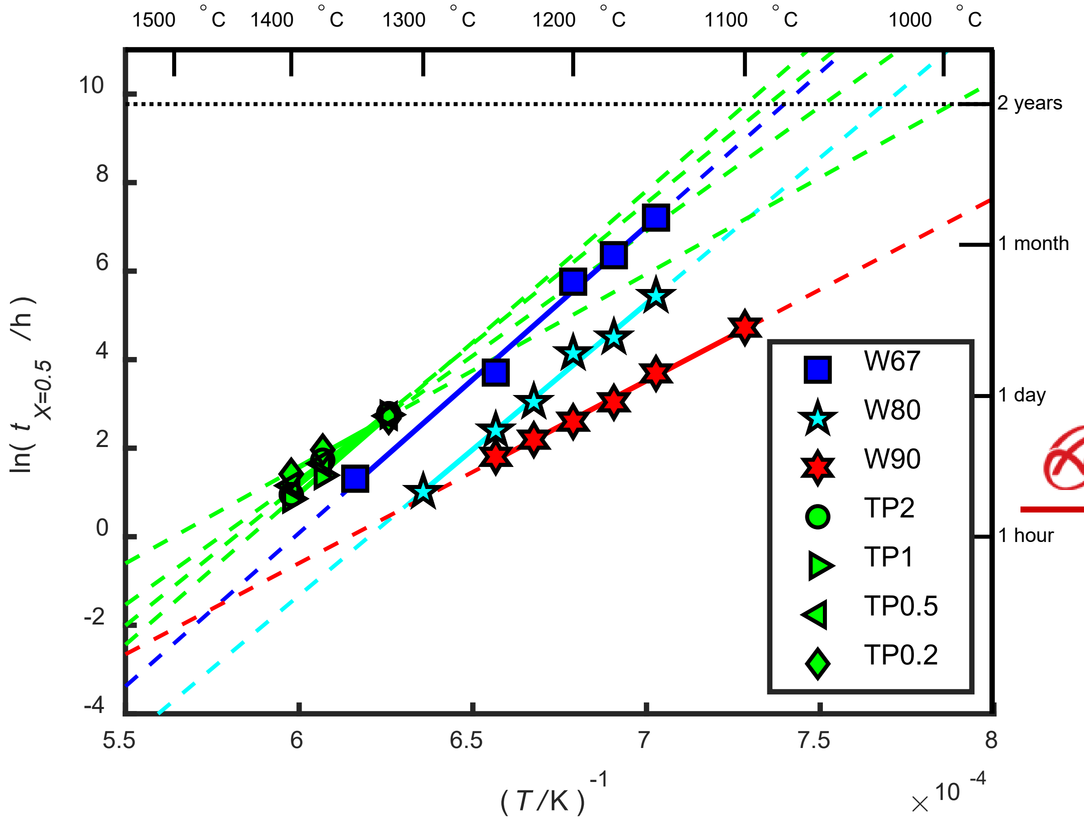


Half recryst.	IGW Edge	IGW Core	CLW Edge	CLW Core	CHW Edge	CHW Core
Q / kJ/mol	468	486	516	492	467	503
T (2 y)	998 °C	987 °C	1037 °C	1033 °C	999 °C	991 °C

Annealing kinetics – comparison with other plates

- Inferior to other plates (W67 AT&M or TP2/TP1 Plansee)





Conclusions

- Annealing kinetics of three differently rolled W plates: IGW, CLW and CHW received from A.L.M.T. Corp.
- Core recrystallizes faster than edge for IGW and CHW (despite homogeneous hardness and grain size, stored energy difference? strong texture gradient!)
- No kinetics difference between core and edge for CLW
- Recrystallization slower in CLW than IGW or CHW
- Activation energies quantified: highest for CLW
- Extrapolation of degradation to 2 lower temperatures: maximal operation temperature for 2 fpy 1030 °C
- Inferior to other plates (W67 AT&M or TP2/TP1 Plansee)