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Qualification of W heavy alloys as plasma facing material

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Introduction

Motivation:

Areas with steady-state heat fluxes up to 10 MW/m² allow to consider W heavy alloys for fusion experiments with limited neutron-fluence, which allow to reduce the material and manufacturing costs. Beside improving the mechanical properties, the Ni/Cu or Ni/Fe matrix limits the thermal performance. Selected results of a series of experimental investigations on the thermomechanical and plasma physical suitability performed on W heavy alloy materials are presented.

Material	Melting temperature [°C]	Thermal conductivity [W/(m·K)]	Supplier / Product name
W95Ni3.5Cu1.5	~1380 (Ni-Cu matrix)	≥ 85	HC Starck Hermsdorf / HPM 1801
		≥ 105	Plansee SE / Inermet® 180
		105	WHS Sondermetalle / WSM-W95NiCu
W97Ni2Fe1	~1440 (Ni-Fe matrix)	≥ 75	HC Starck Hermsdorf / HPM 1850
		≥ 85	Plansee SE / Densimet® 185
W	3420	164	MG Sanders
			Plansee SE

Important material properties and suppliers of investigated W heavy alloy materials and bulk W.

Outline of the paper

- Introduction
- Characterisation of W-Ni-Cu heavy alloy
  - Measurement of thermal conductivity
  - Change of microstructure and mechanical properties as result of heat treatment
- Results of high heat flux tests
  - Adiabatic loading of W, W-Ni-Cu and W-Ni-Fe samples
  - Steady-state loading of W, W-Ni-Fe and W-Ni-Cu material
- D retention measurement of W-Ni-Cu
- Conclusions

High heat flux test facility GLADIS

Beam parameters:
- Hydrogen neutral beam,
- Heat flux: 2 – 45 (90) MW/m², 150 mm FWHM, Ø 50 mm (95% q'_{max})
- Pulse length: 1 ms – 45 s

Target cooling
- T_{in} 20 – 230 ± 0.5 °C, T_{out} max. 250 °C

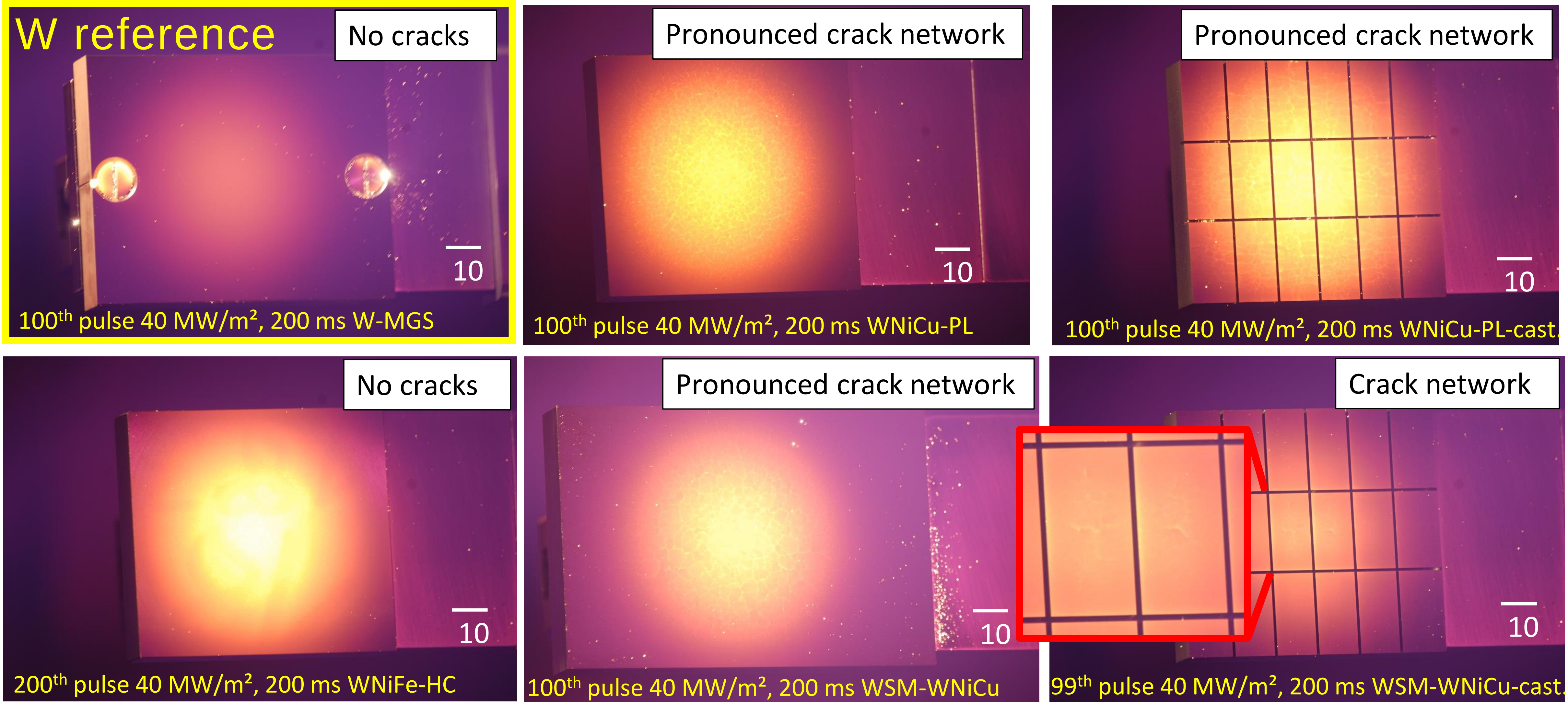
Target diagnostics
- Water calorimetry, thermocouples
- Fast one-and two-colour pyrometers
- High-resolution CCD & IR cameras

Adiabatic loading of W, W-Ni-Cu and W-Ni-Fe samples (1)

Sample/ Supplier material	Geometry (length x width x height)	Loading / maximum surface temperature	Results
W95NiCu WHS WSM-W95NiCu	115 x 79 x 17 [mm^3]	100 x 40 MW/m^2, 200 ms $T_{surface\ max.}$ = 1180 °C	Pronounced crack network
W95NiCu WHS WSM-W95NiCu	80 x 74 x 15 [mm^3] castellated	100 x 40 MW/m^2, 200 ms $T_{surface\ max.}$ = 1130 °C	Crack network
W95NiCu Plansee INERMET® 180	80 x 74 x 15 [mm^3]	100 x 40 MW/m^2, 200 ms $T_{surface\ max.}$ = 1270 °C	Pronounced crack network
W95NiCu Plansee INERMET® 180	80 x 74 x 17 [mm^3] castellated	100 x 40 MW/m^2, 200 ms $T_{surface\ max.}$ = 1250 °C	Pronounced crack network
W97NiFe Plansee DENSIMET® 185	80 x 74 x 15 [mm^3]	100 x 40 MW/m^2, 200 ms $T_{surface\ max.}$ = 1280 °C	Some cracks on different areas of the surface
W97NiFe HC Starck HPM 1850	80 x 74 x 15 [mm^3]	200 x 40 MW/m^2, 200 ms $T_{surface\ max.}$ = 1300 °C	No cracks, roughening of surface in the center
W MG Sanders bulk W	95 x 75,8->77 x 15 [mm^3]	100 x 40 MW/m^2, 200 ms $T_{surface\ max.}$ = 1130 °C	No cracks

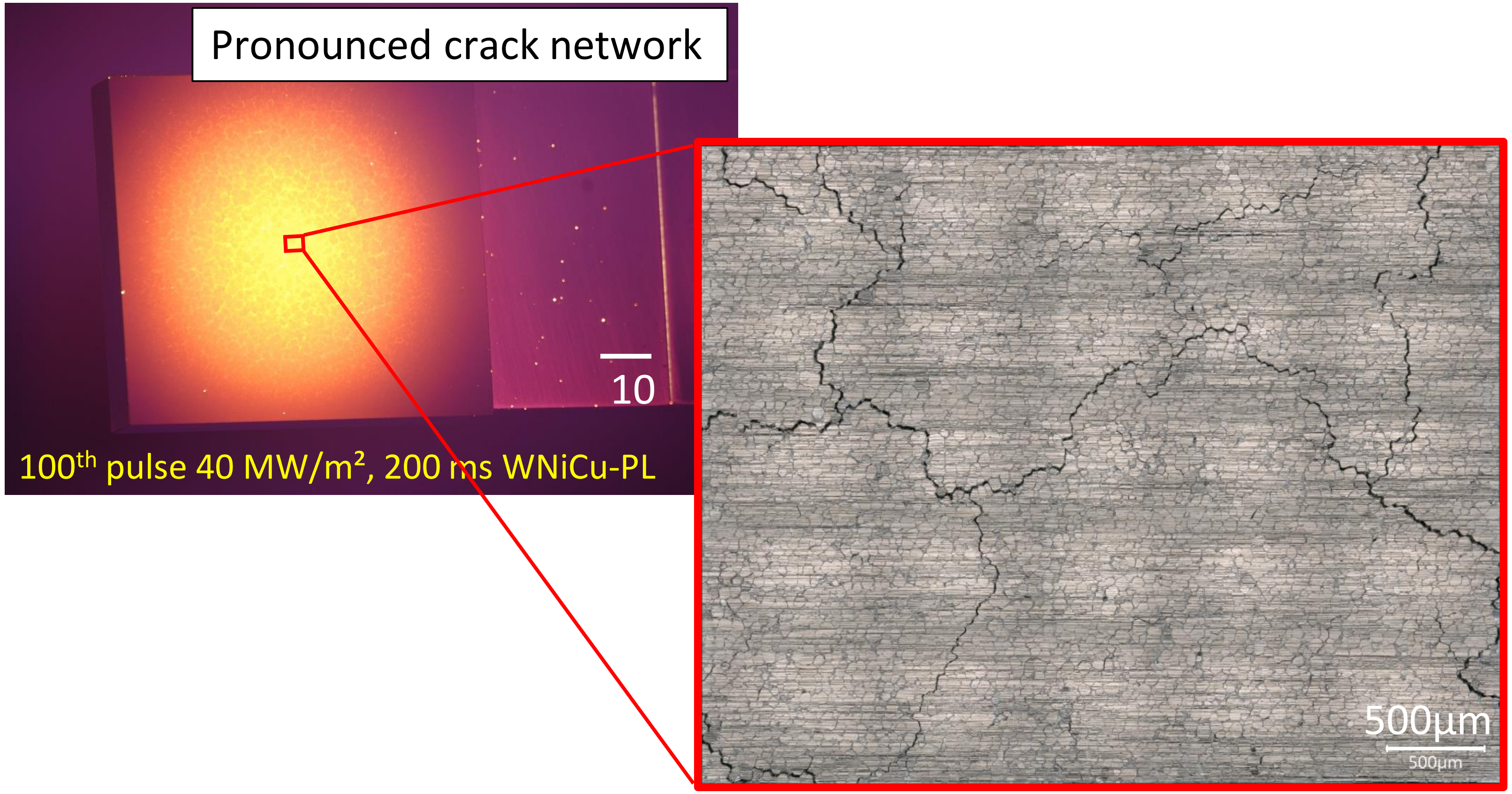
Table of selected test parameters and results for adiabatic loading experiments at GLADIS.

Adiabatic loading of W, W-Ni-Cu and W-Ni-Fe samples (2)



CCD camera images for different samples of one of the last cycles at end of pulse.

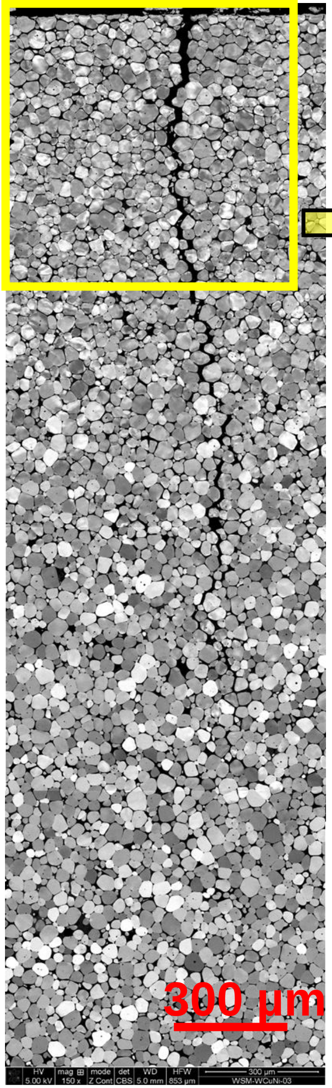
Adiabatic loading of W, W-Ni-Cu and W-Ni-Fe samples (2)

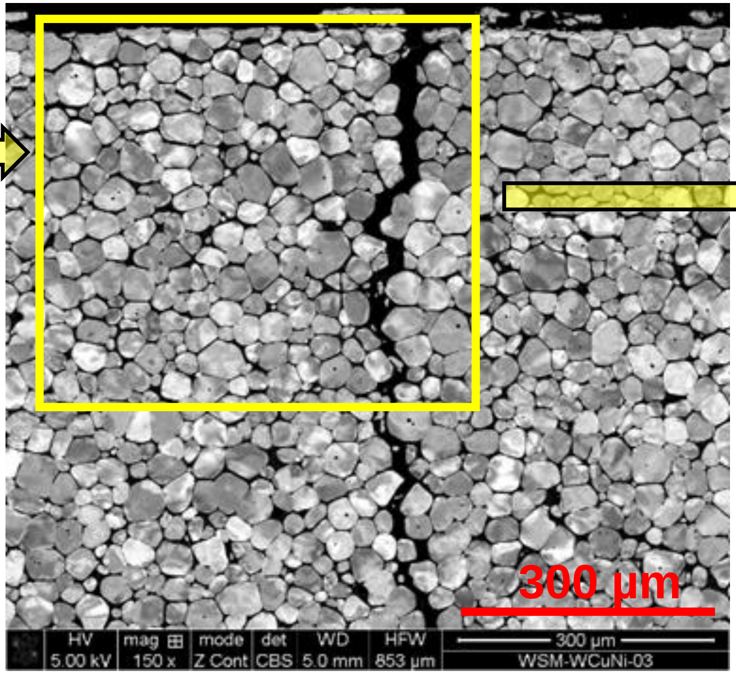


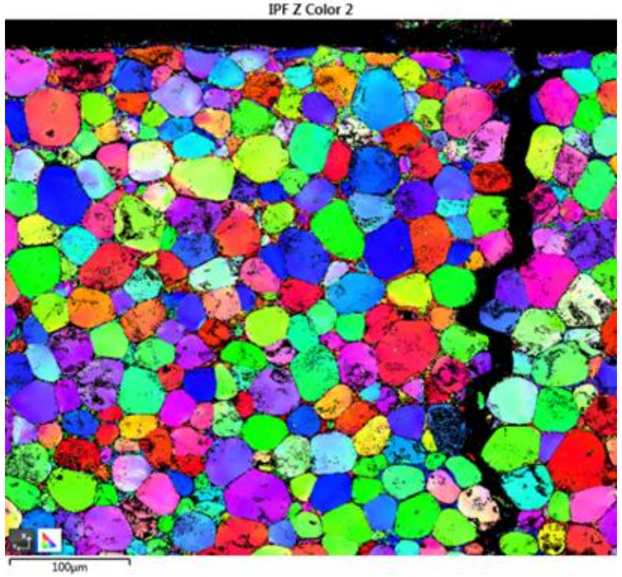
Microscopical image after GLADIS loading.

SEM cross section and EBSD scan of a W-Ni-Cu sample

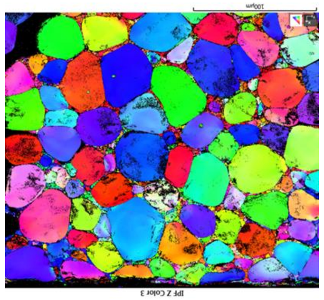
loaded surface

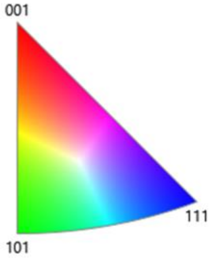






100 µm



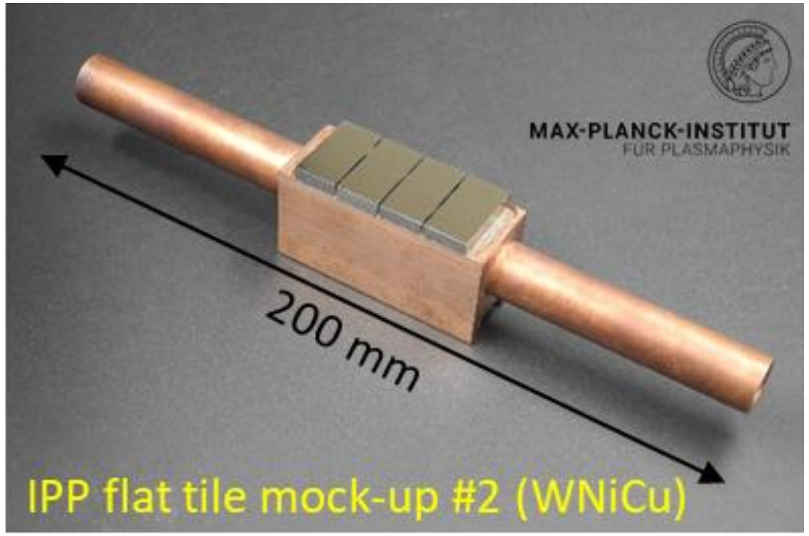


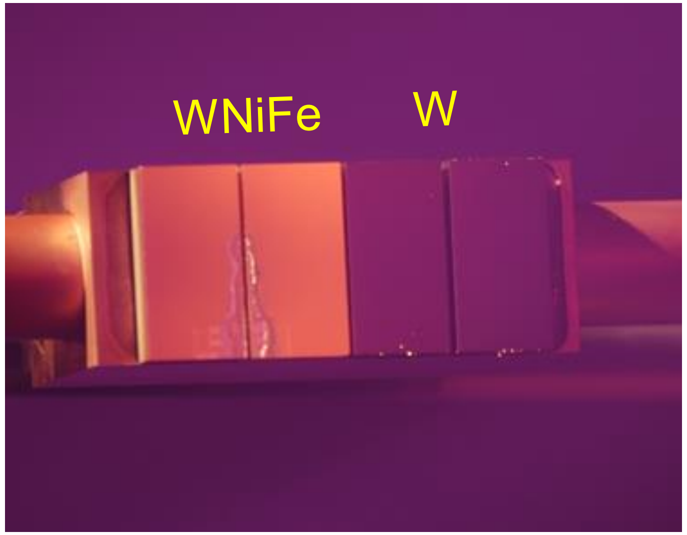
tile bottom

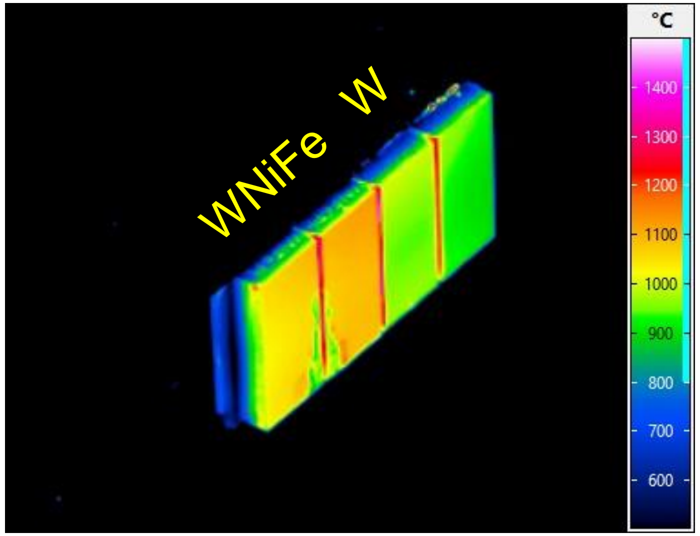
SEM cross section image of electron microscopy and EBSD scan (IPFZ) of WSM-WNiCu after GLADIS loading.

Steady state loading of W heavy alloy flat tile mock-ups (1)

Mock-up	tile dimensions	Result screening	Result cycling
#1 W/WNiFe (4 tiles)	23 * 12 * 5 [mm³]	up to 12 MW/m^2 ok, ✓	100 x 10 MW/m^2, ok, ✓ 100 x 12 MW/m^2, ok, ✓
#2 WNiCu (4 tiles)	23 * 12 * 5 [mm³]	up to 12 MW/m^2 ok, ✓	100 x 10 MW/m^2, ok, ✓ 100 x 12 MW/m^2, ok, ✓ small bonding defects

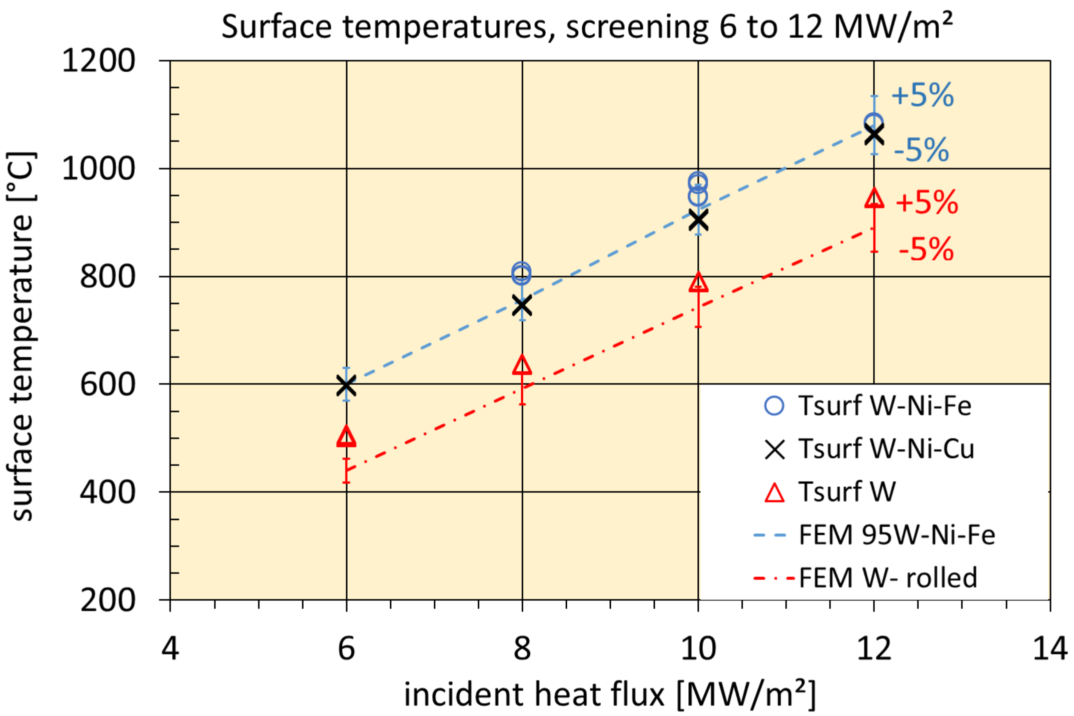


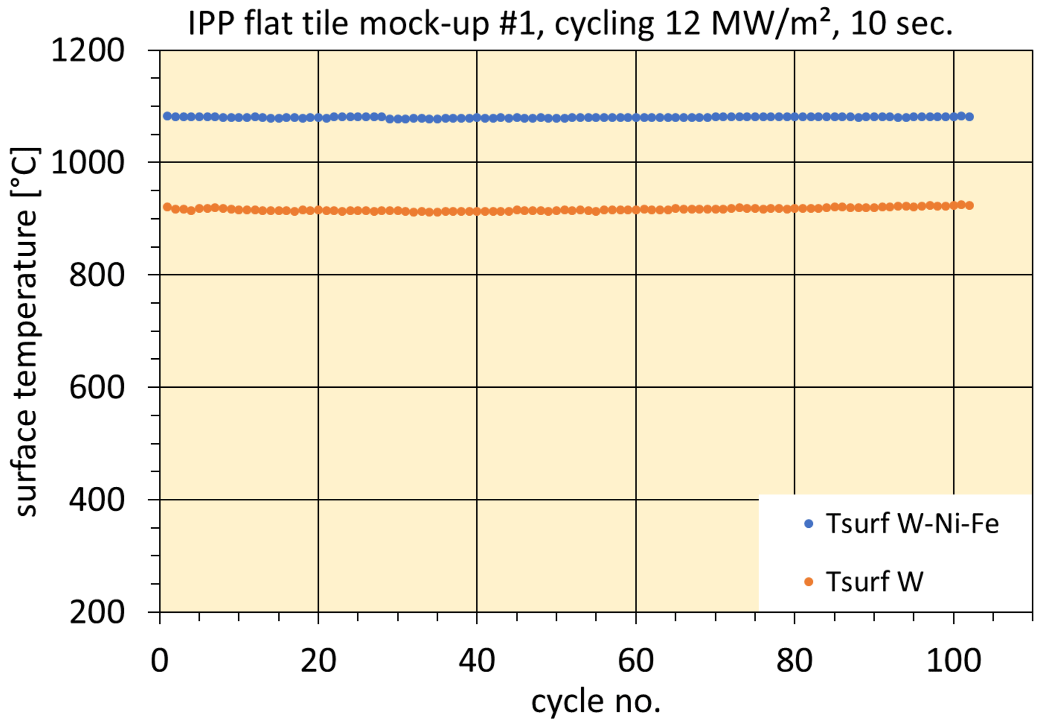




CCD image and infrared image of 100th pulse 12 MW/m^2 on flat tile mock-up #1.

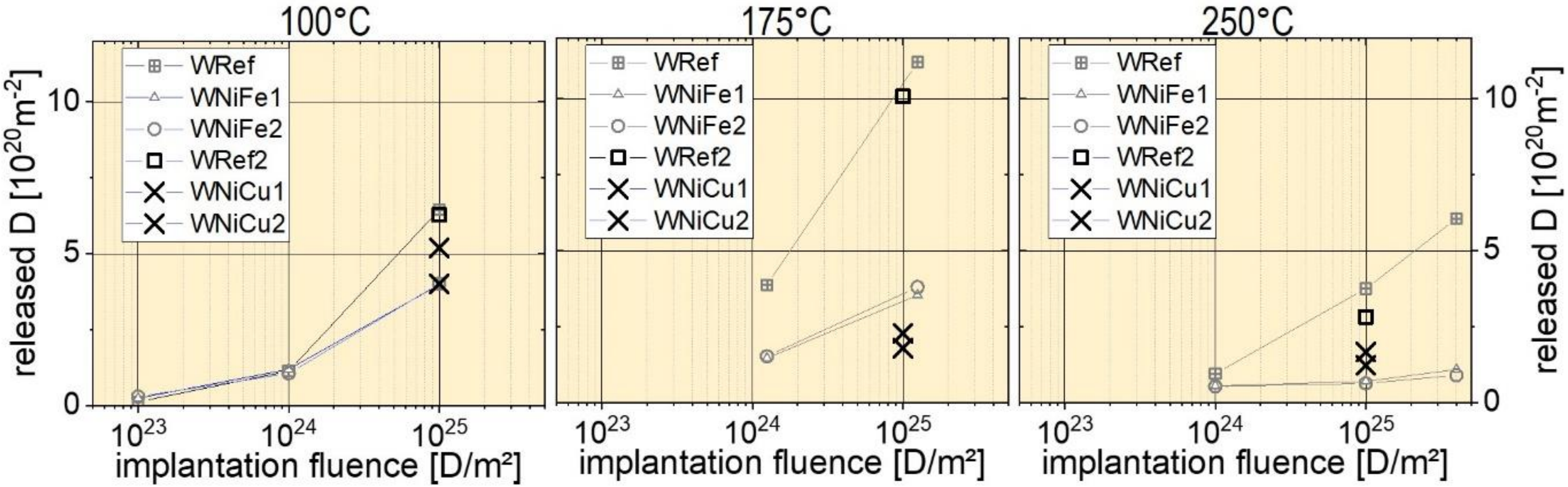
Steady state loading of W heavy alloy flat tile mock-ups (2)





Thermal screening of both flat tile mock-ups (left figure). Mock-up #1 is equipped with W, W-Ni-Fe tiles, mock-up #2 is equipped with W-Ni-Cu tiles.
The right figure shows the low cycle fatigue loading at 12 MW/m², 10 s, of flat tile mock-up #1 equipped with W, W-Ni-Fe tiles.

D retention measurement of W-Ni-Cu



Thermal desorption deuterium release from implanted W-Ni-Fe as a function of the implanted D fluence for three implantation temperatures [H. Maier et al., Nucl. Fusion 60, 126044 (2022)]. The data for W-Ni-Cu were acquired with an implantation fluence of 10^{25} m^{-2}. As in the case of W-Ni-Fe, the amount of stored D in the W-Ni-Cu samples is always lower than that of the corresponding bulk W reference sample.

Conclusions

The results from the HHF tests as well as those from the complementary D retention measurements confirm the previous results on the potential of W heavy alloys as plasma-facing material.

- The cracks developed at the adiabatic loading, especially for the W-Ni-Cu alloys, do not affect the heat transfer into the material.
- No damage of the material was visible after the cyclic steady state loading. Nevertheless, the joining of the W heavy alloy tiles and the cooling structure has to be improved.
- Depending on the design of a component, a limited number of short transient events up to a temperature of about 100 K below matrix melting could be accepted.
- Cyclic steady-state operation up to 1100 °C in the case of W-Ni-Fe, respectively 900 °C for W-Ni-Cu should be achievable.
- The D retention measurement of the W-Ni-Cu material confirmed the favourable behaviour of W heavy alloys.