TUNGSTEN

An overview of production, basic properties, processing and divertor applications in fusion power plants

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- **Intro: Tungsten basics & production**
  - **+ PIM (Steffen)**
  - **+ Oxidation (Lorelei)**
- **Machining & Processing**
  - **Mechanical**
  - **Electro-chemical**
- **Divertor design**
  - **Armor**
  - **Water cooling**
  - **He cooling**
- **Summary and path forward**

Divertor Workshop KIT
& nächstes Germ. DEMO meeting

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Tungsten Basics

REACTIONS

$W^{183.85}_{74}$

Reactions with Non-metals

C	>800 °C	W_2C, WC
O	>400 °C	WO_3 → sublim. at 800 °C
S	>400 °C	WS_2
F	>RT	WF_6 (volatile)
F+O	>RT	WOF_4
Cl	>250 °C	WCl_6

Reactions with Compounds

H_2O	>RT	$WO_2(OH)_2$ (volatile)
H_2S	>350 °C	$WS_2 + 2H_2$
SO_2	300 °C	$WO_3 + S_2$
CO	80-200 °C	tungsten hexacarbonyl
	>1000 °C	$W_2C + CO_2$
SiC	>1100-1900 °C	WC and WSi
SiO_2	>2000 °C	slight oxidation
Al_2O_3	<1900 °C	compatible in vacuum
BeO	<2000 °C	compatible in vacuum
MgO	<1500 °C	compatible in vacuum
ZrO_2	<1600 °C	compatible in vacuum
Glass	<1400 °C	stable

Alloying Elements / Phases

(W rich side in the phase diagram at room temperature)

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M_2W Be	Mg	MW B	MW_2 C $M_{1-x}W$	M_4W Al		Y	La	
Ti >3wt.% >300°C	V	MW_3 Cr	Mn	MW, M_7W_6 Fe	M_7W_6 Co	MW Ni	Cu	
MW_2 Zr	Nb	Mo		Ru < 3 wt. %	Rh < 2 wt. %	M_3W Pd	Ag	Cd
MW_2 Hf	Ta		MW Re < 26 %	Os < 5 %	MW Ir	MW Pt	Au	

Insoluble | Intermetallic Phases | Line Compounds | Solid Solution

POWDER-METALLURGICAL PRODUCTION ROUTES

Industrial Route
- Blending
- Pressing
- Sintering
- Hot forming

+ Cost effective
+ Large quantities/ Semi-finished products
+ High density

± Specific, anisotropic micro-structure

Mass Fabrication
- Blending (+Binder)
- Injection Molding
- Debindering/Sintering
- HIP (optionally)

+ Mass production of near net-shaped parts

± Homogenous microstructure

\- Rest porosity

Mechanical Allyoing
- Blending
- Ball Milling
- Encapsulation
- HIP or hot forming

+ Higher ductility possible

\- Small scale production route

Tungsten Materials (beside pure W & WC)

Grain Stabilized Tungsten „ODS Tungsten“

Potassium Doping (ppm range)

WVM, WVMW, AKS, etc.
→ Bulb Wire

Oxides & Carbides

- La_2O_3 (e.g. WL10, WL15, WL20)
- CeO_2 (e.g. WC20)
- ThO_2 (e.g. WT20)

→ Weld Electrodes

- Y_2O_3, ZrO_2, TiC, HfC, etc.

„W Heavy Metals“ (liquid phase sintered)

- W-Ni-Fe (e.g. Densimet, Inermet)
- W-Cu

→ Functional Applications

Solid Solution Alloys

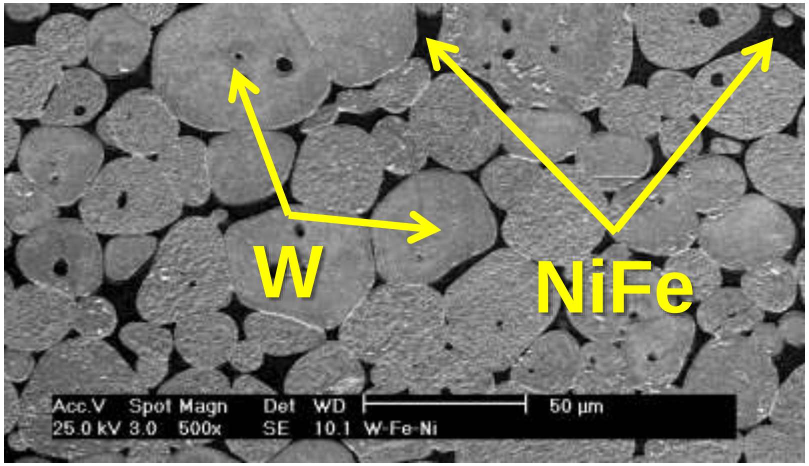
- W-Re (<26%)

→ commercial alloy

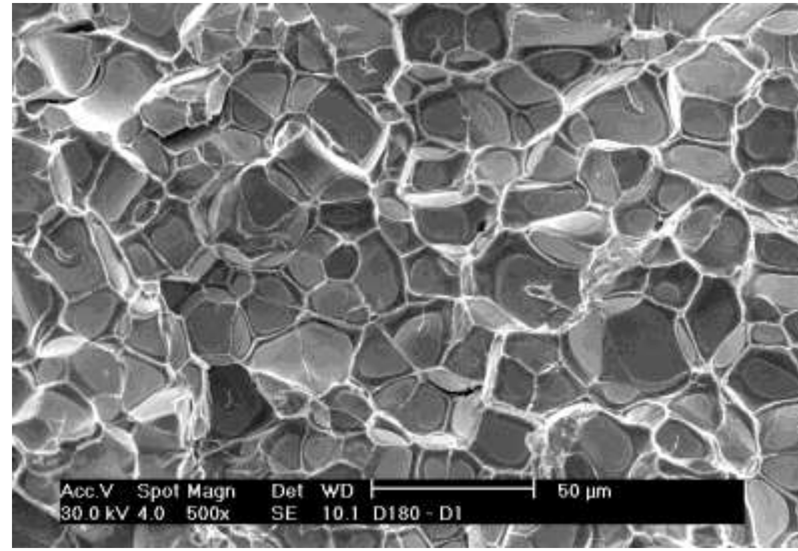
- W-V
- W-Ta
- W-Mo
- W-Ti
- W-Nb

MICROSTRUCTURE OF "W HEAVY METALS"

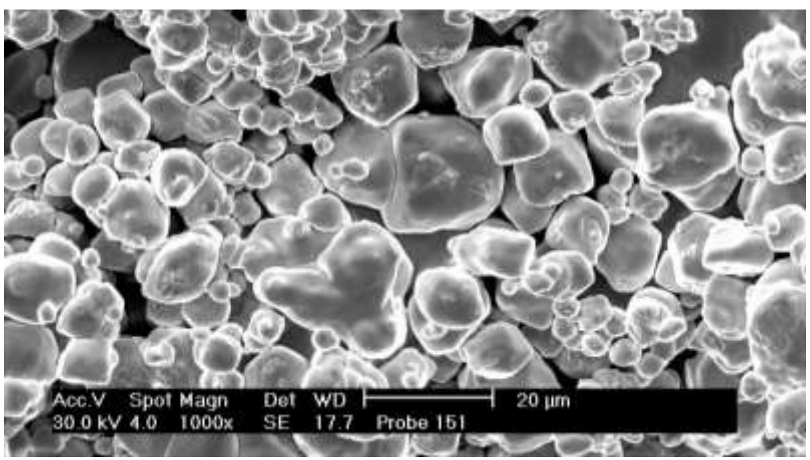
DENSIMET D180, W-3.5Ni-1.5Fe



Cold fracture surface



W-Cu, hot fracture surface

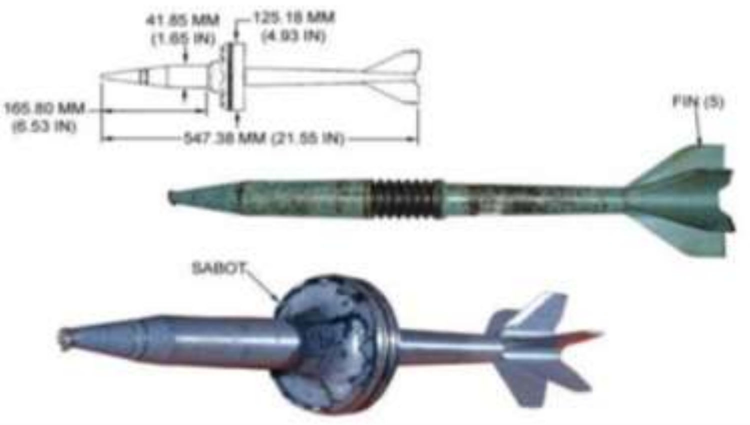


DENSIMET D180

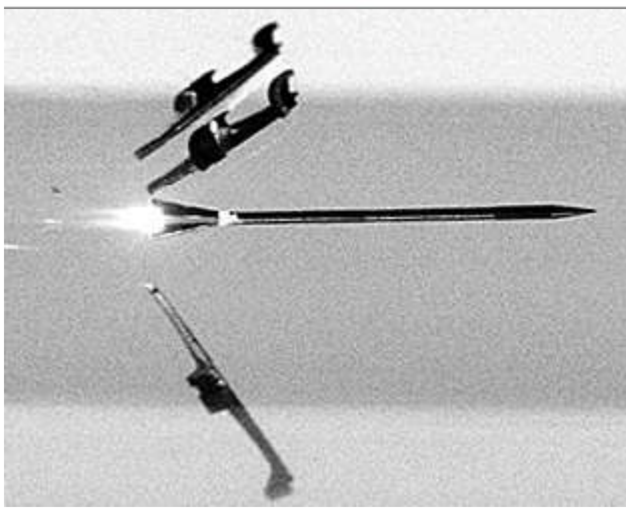
Density	18 g/cm³
Young's mod.	380 GPa
Therm. Cond.	83 W/mK
Therm. Exp.	$5.5x10^{-6}$/K
ferromagnetic	

APPLICATIONS

Heavy Metal



…d ailerons in modern aeroplanes (indicated by the arrows); the weights are made of tungsten … up to 850kg of counterweights are used in a Boeing 747



…ent kinds of "green" ammunition for waterfowl and game hunting

Polymer-tungsten sheet with a density of $11 g/cm^3$. It is used as a substitute for lead.

APPLICATIONS

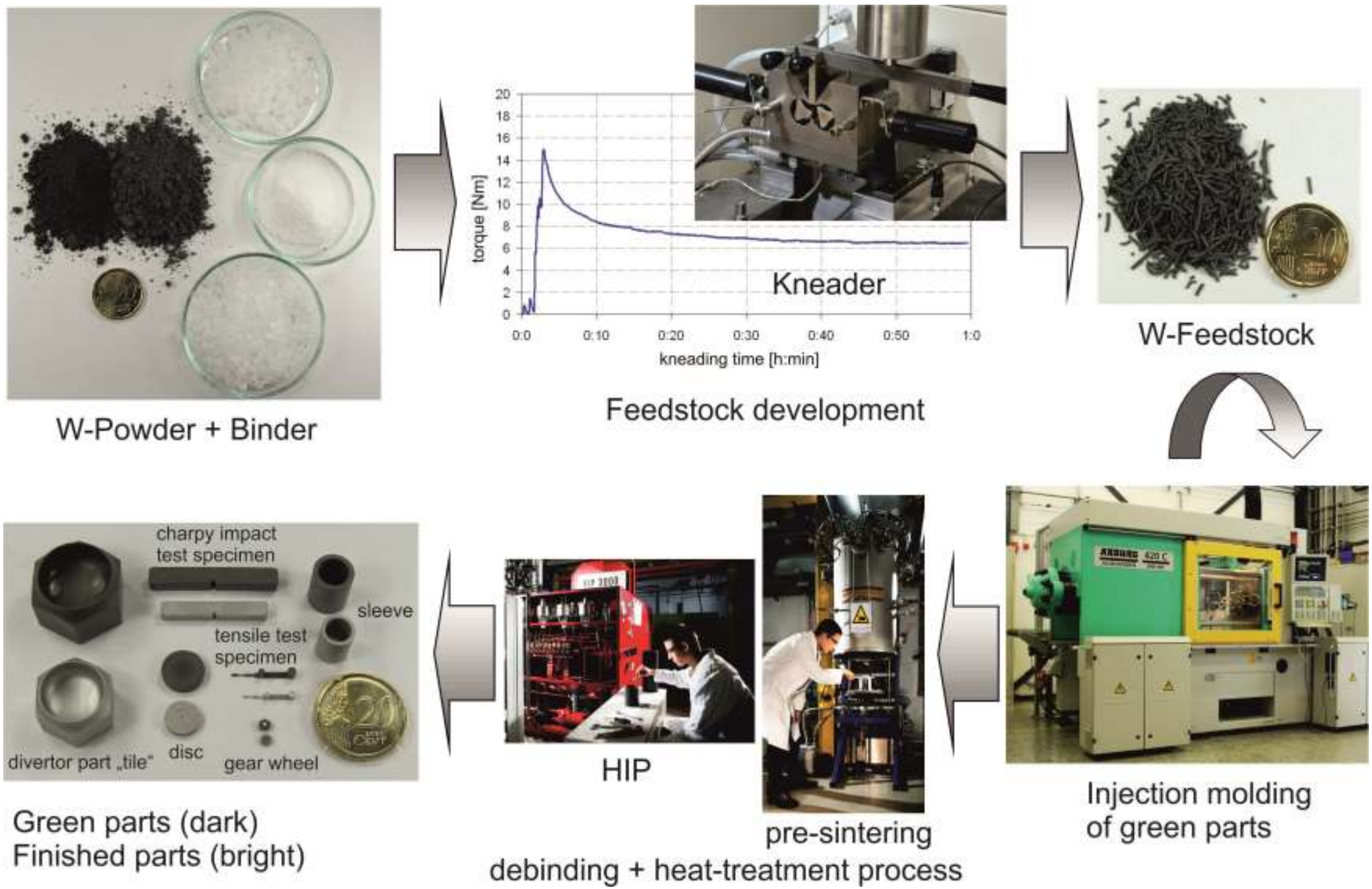
Cemented Carbides

Roadheader for underground mining

Indexable inserts

Coated inserts indicating the manifold geometries which exist to different cutting operations

The KIT PIM process for tungsten



The KIT PIM process for tungsten

The KIT PIM process for tungsten

green parts

debinding +
heat-treatment-process

finished parts

Summary (wrt Divertor Applications)

- **Preferred Production Routes**
  - Industrial Sintering & Hot Forming
  - Powder Injection Moulding → mass fabrication of near net-shaped parts

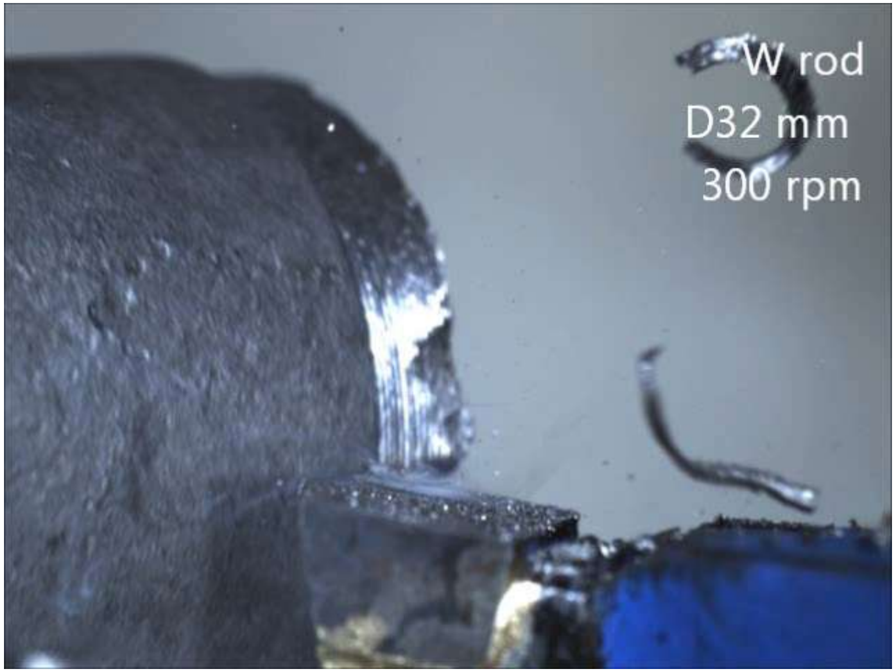
- **Potential Tungsten Materials**
  - Pure W and Potasium doped W
  - W Solid Solutions → W-V, W-Ti, W-Ta
  - Grain Stabilised W → La_2O_3, Y_2O_3, TiC (& other carbides)
  - W Heavy Metals → only W-Cu

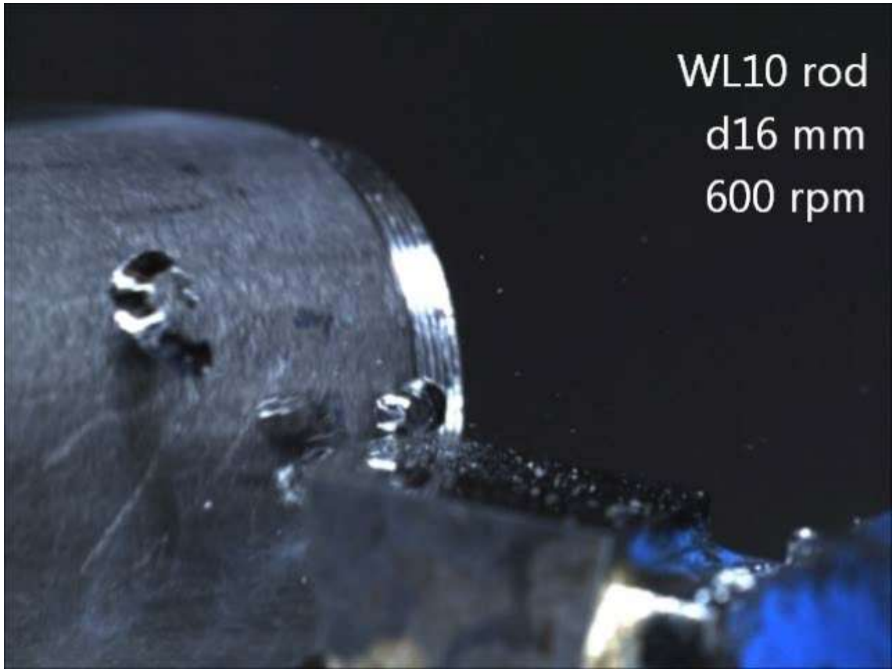
- **Perfect Tool for W Materials Development**
  - PIM → “Rapid Prototyping of W Alloys”

2 MACHINING

Mechanical Machining

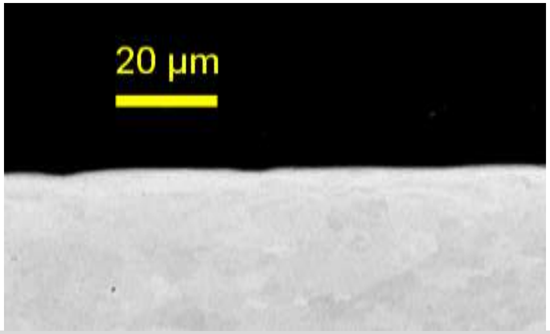
- Turning





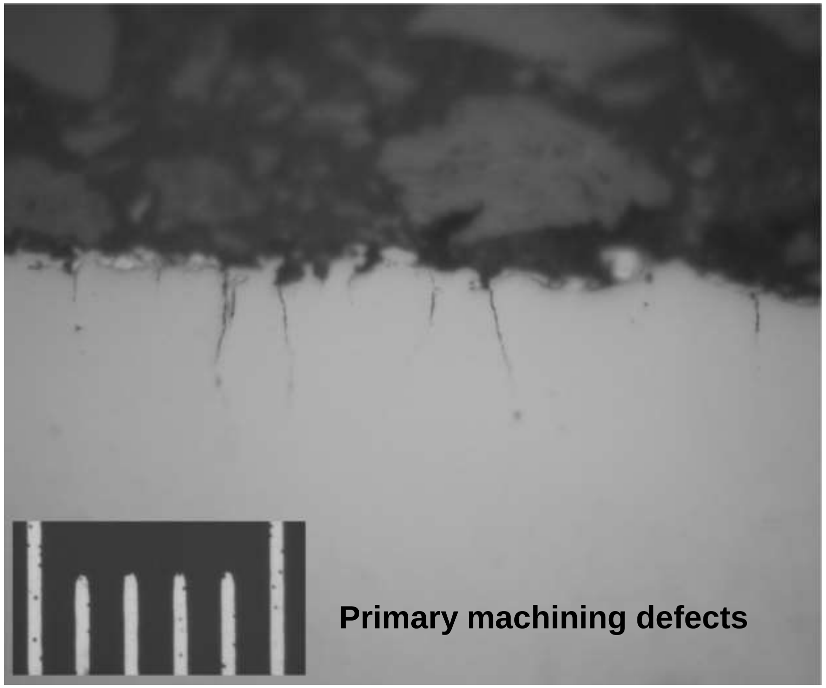
- Milling
- Grinding

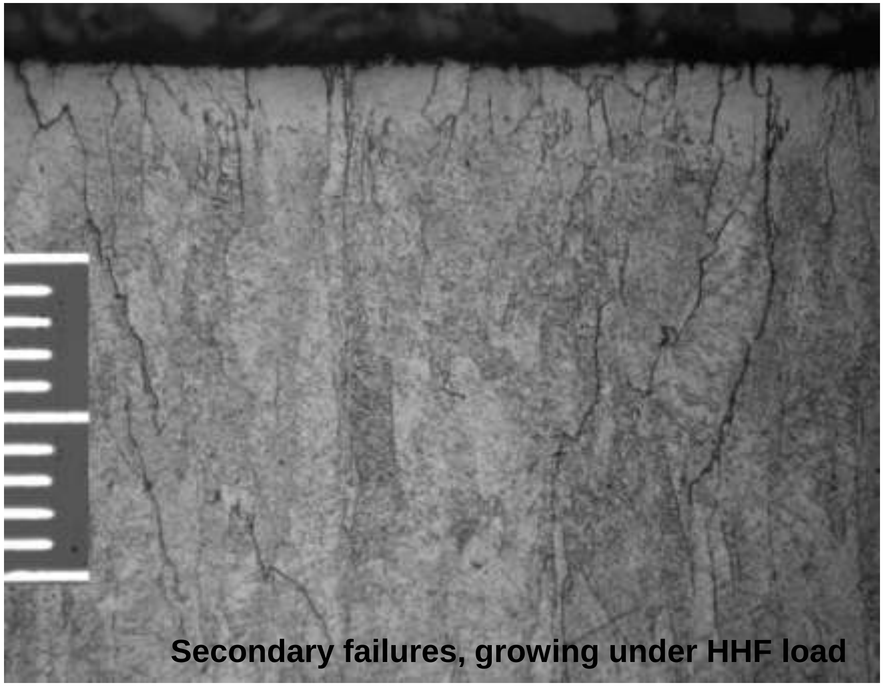
→Possible with acceptable surface quality
→Pure W is harder to machine



Electro-Discharge Machining

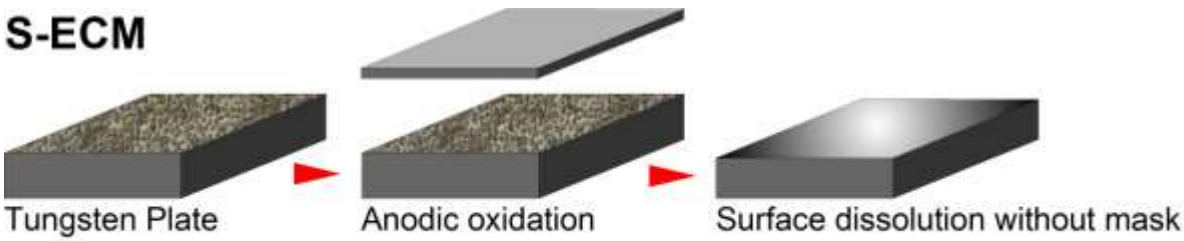
- No problem
- BUT: Surface crack formation

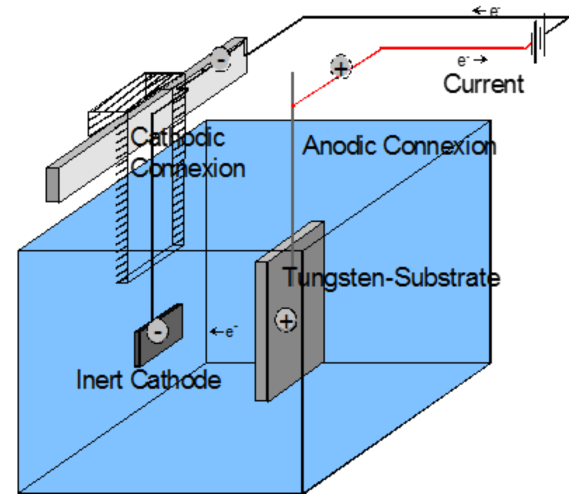




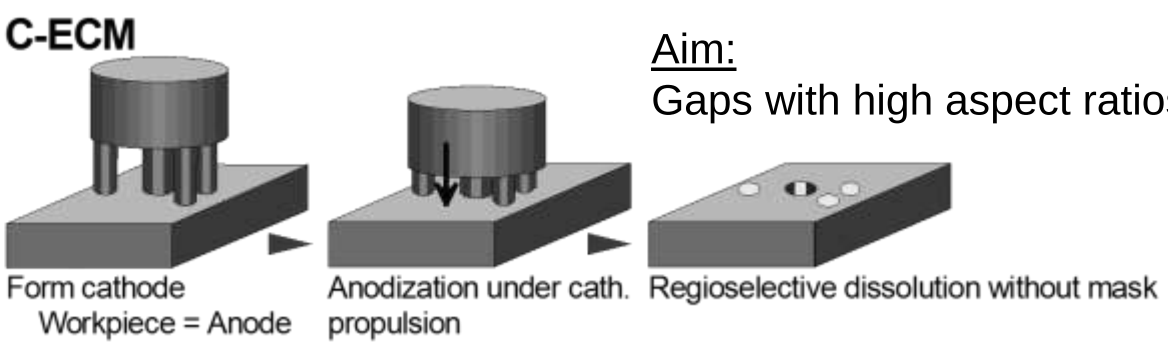
Electro-Chemical Machining

- Surface finishing on the micron scale → S-ECM

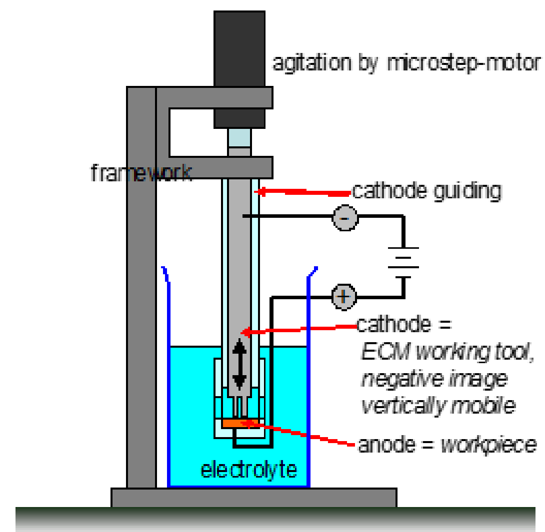




- Bulk structuring → C-ECM

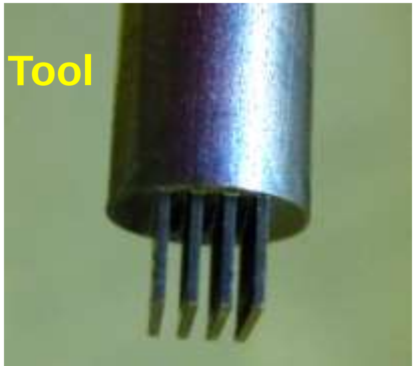


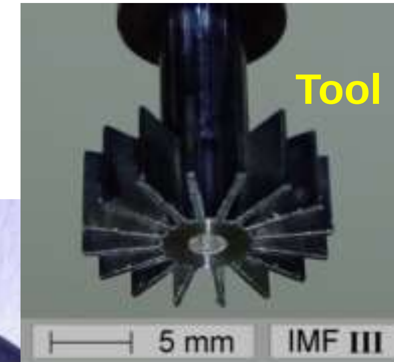
<u>Aim:</u>
Gaps with high aspect ratios

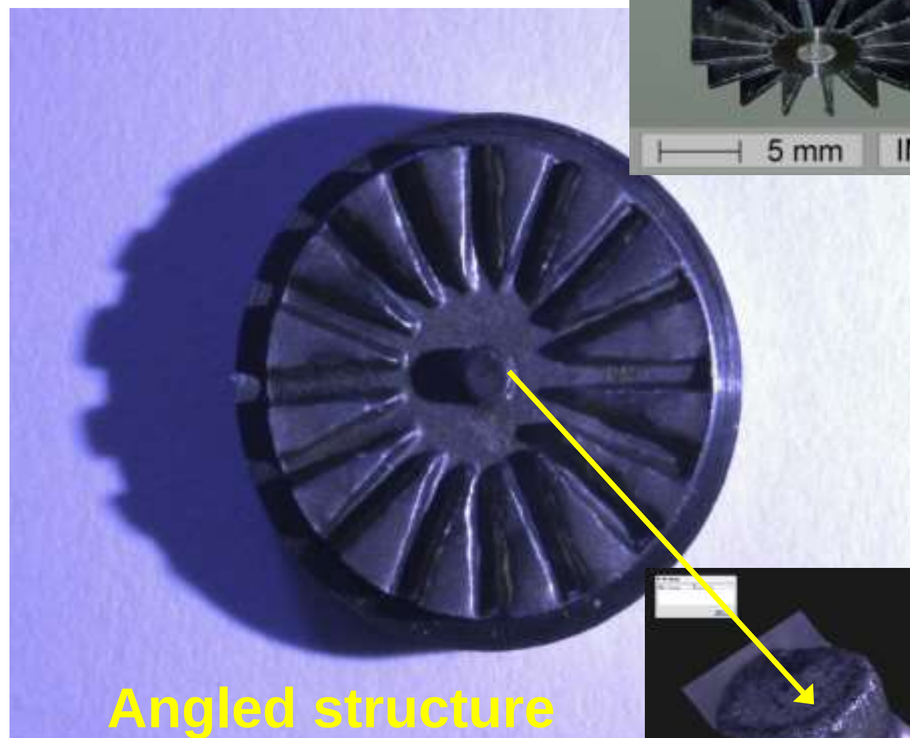


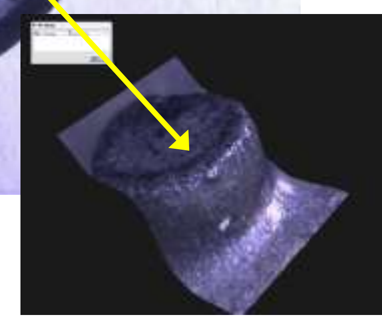
Electro-Chemical Machining

Some Examples



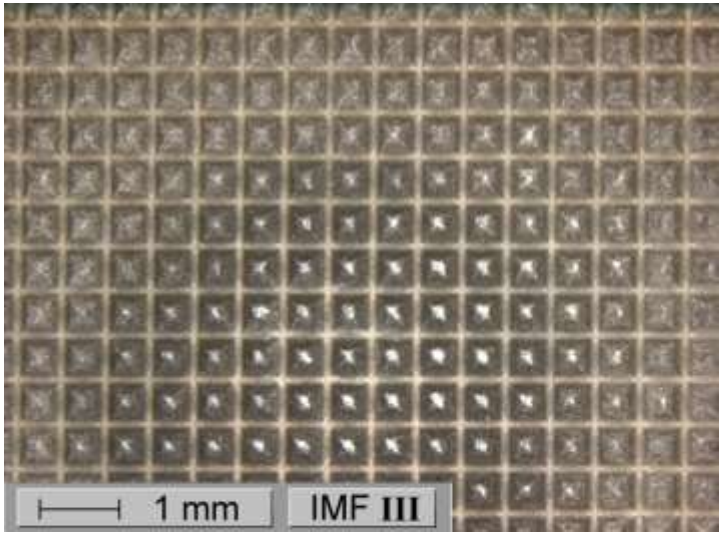




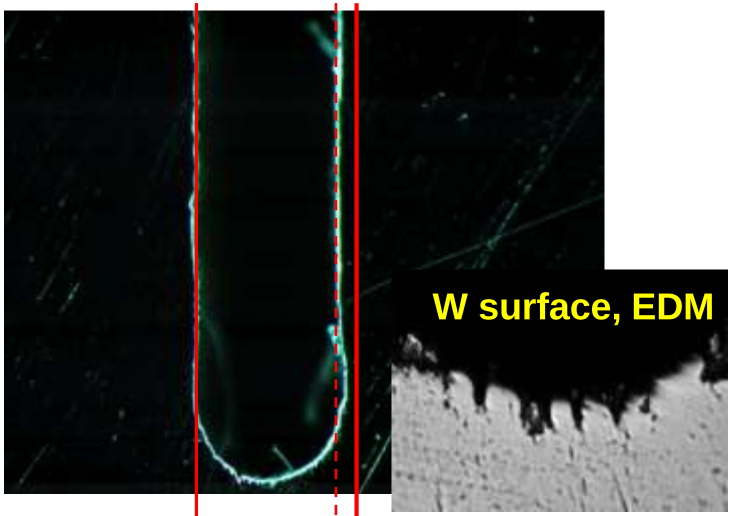


Electro-Chemical Machining

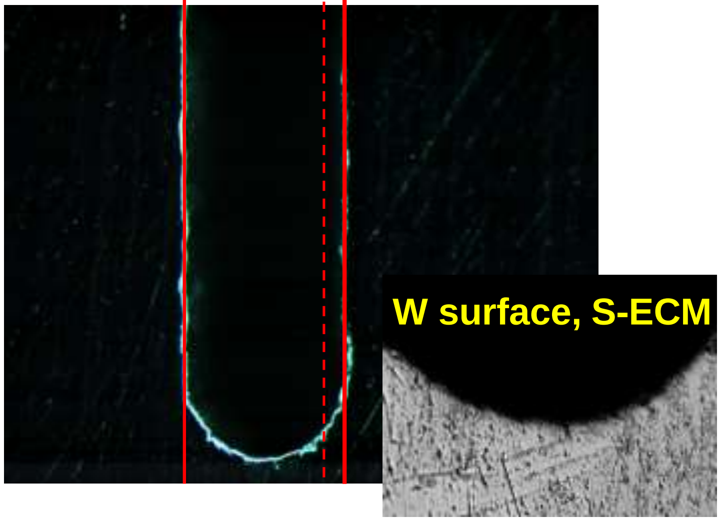
Surface treatment:
Electro-polishing



Electro-discharge machining



Electro-chemical machining



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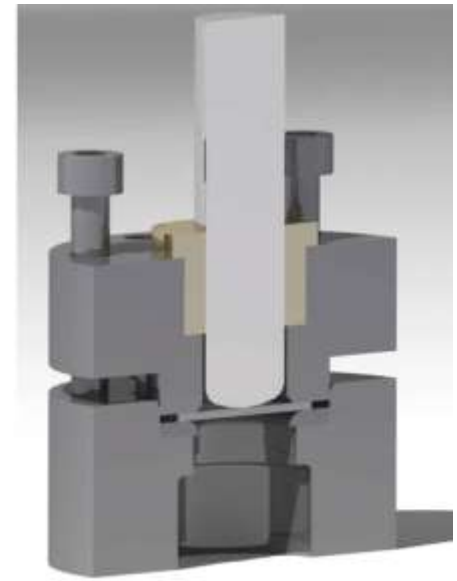
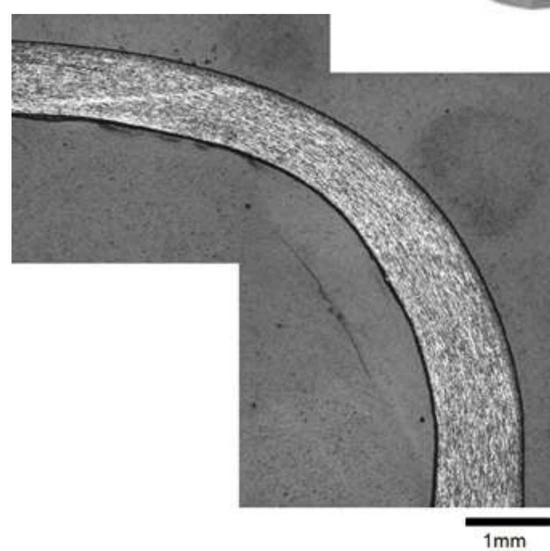
PROCESSING

Deep Drawing & Bending

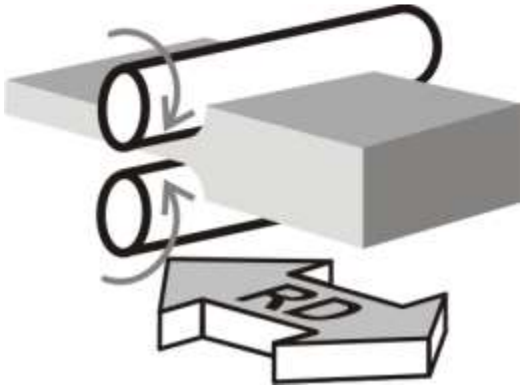


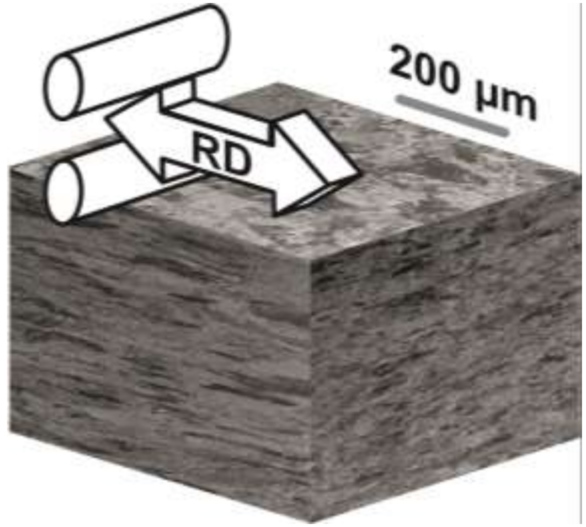


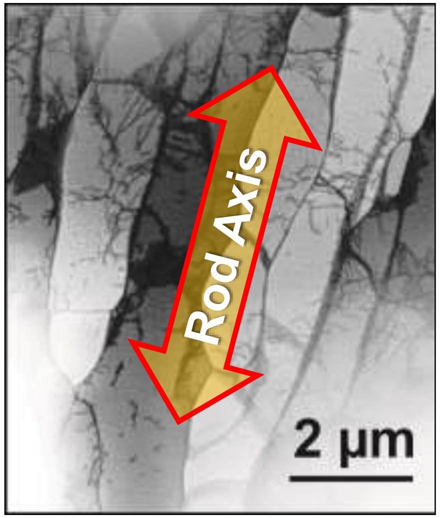
→ **Possible at 600 °C with very low strain rate (in vacuum)**

Hot Forming

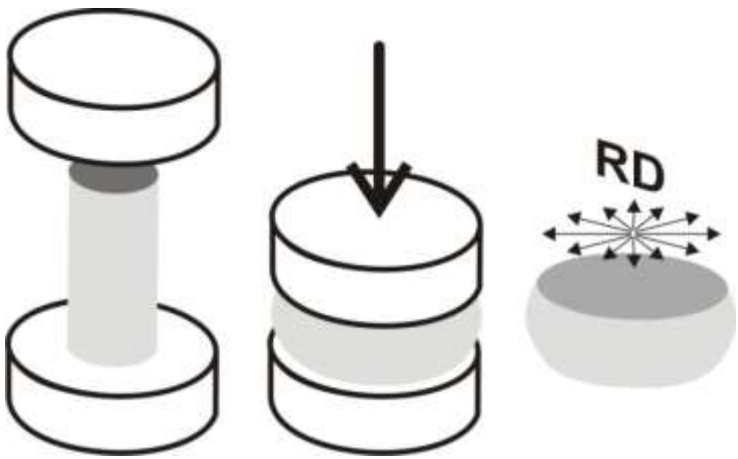
Rolling Plates



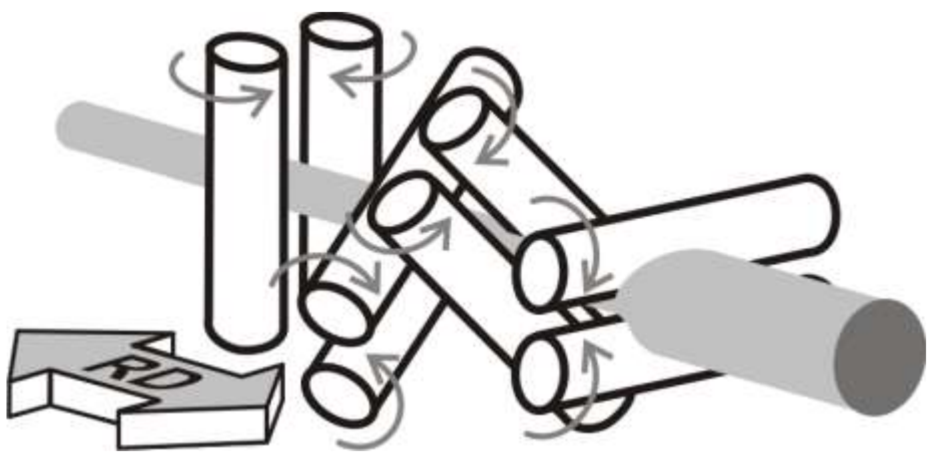




Forging Round Blanks



Rolling/Swaging Rods



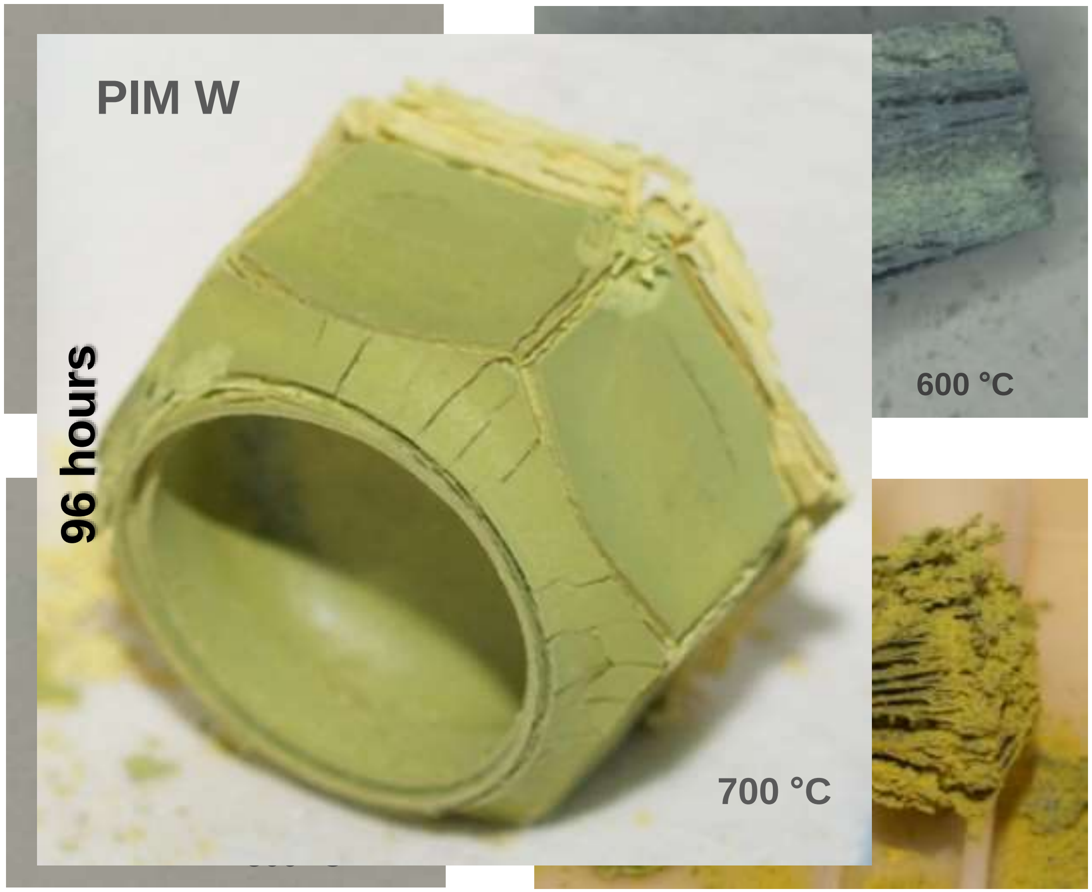
Hot Forming

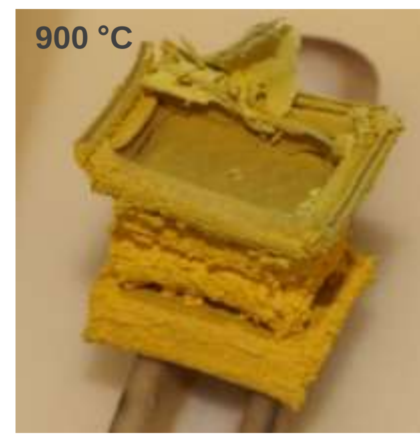
OXIDATION IN AIR

W plates

24 hours

48 hours

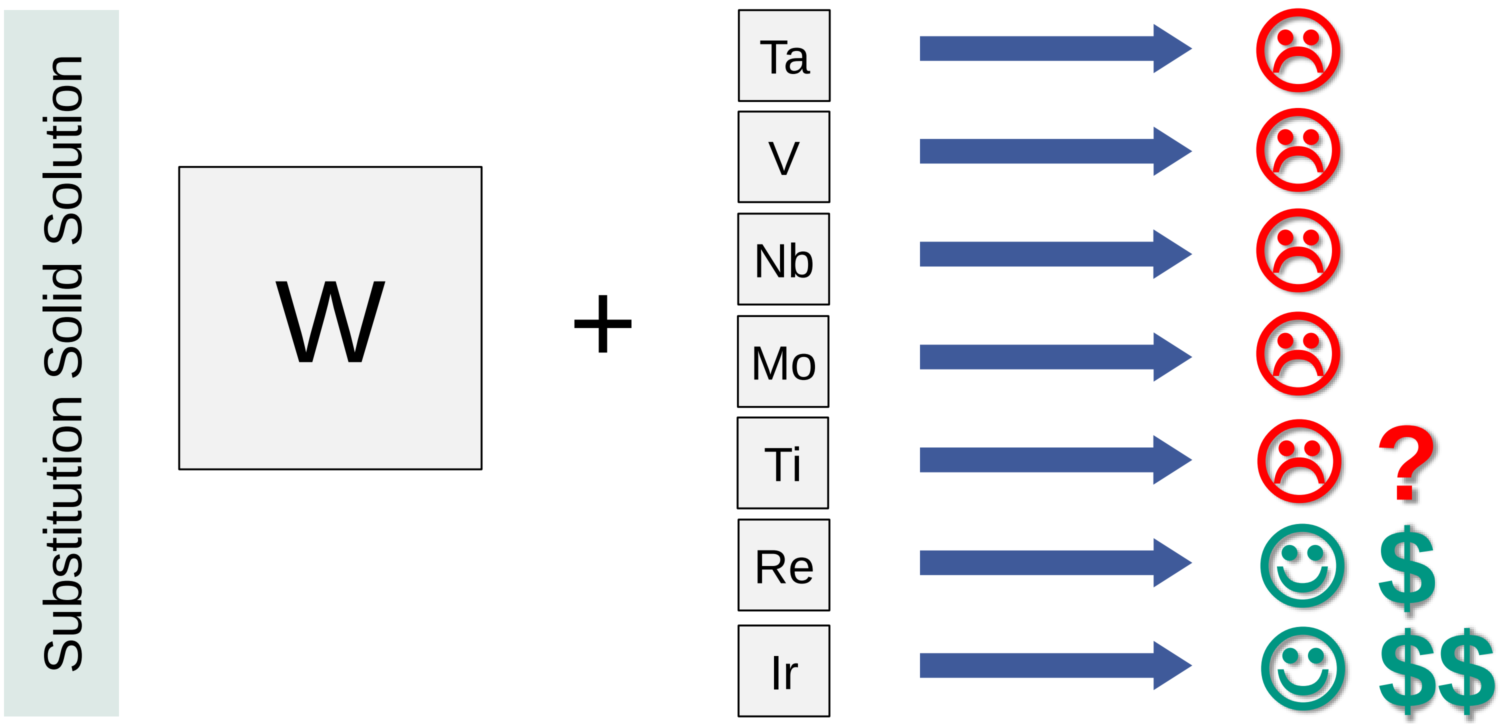




Ductilisation

Known Strategies

1. Nanostructuring → **Small quantities only!**
2. Composites → **Not yet commercially available!**
3. Alloying



Conclusion**: For large-scale applications we have to live with the intrinsic brittleness of tungsten materials!**

MICROSTRUCTURE

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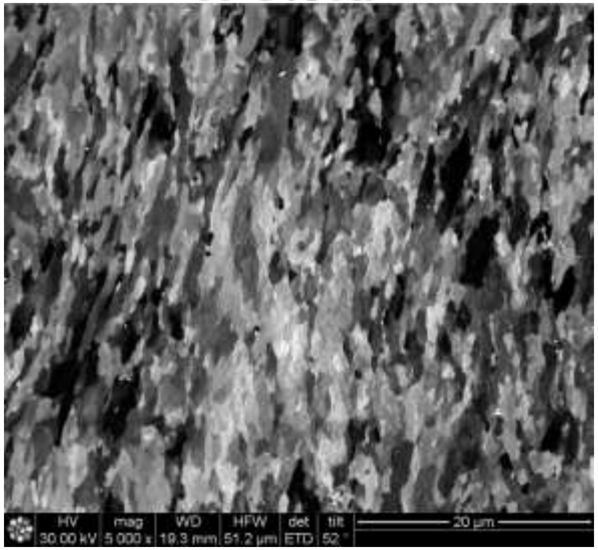
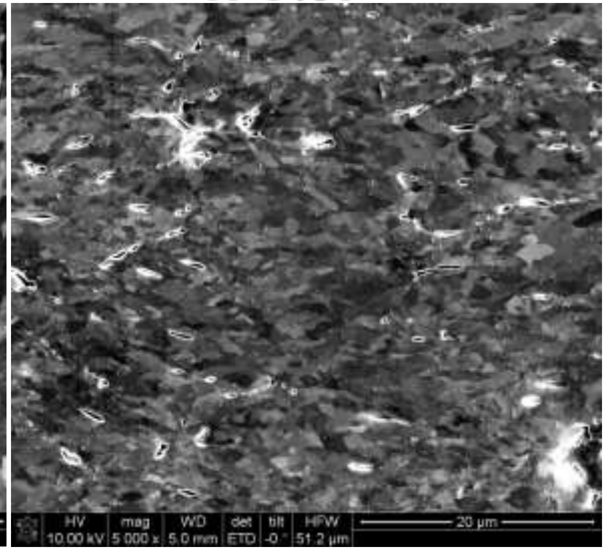
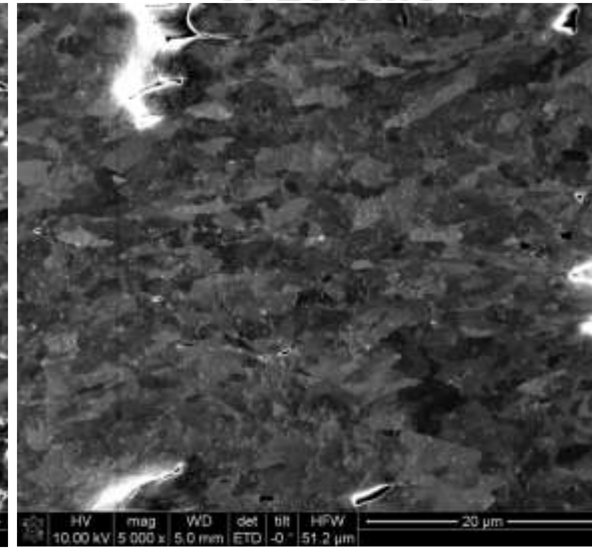
W-5%Ta

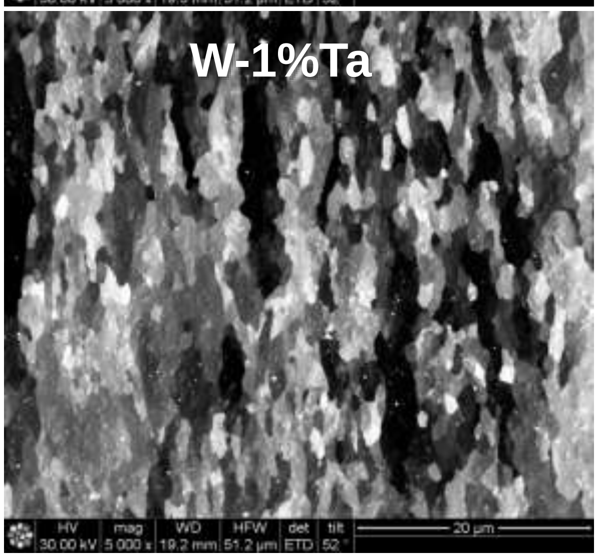


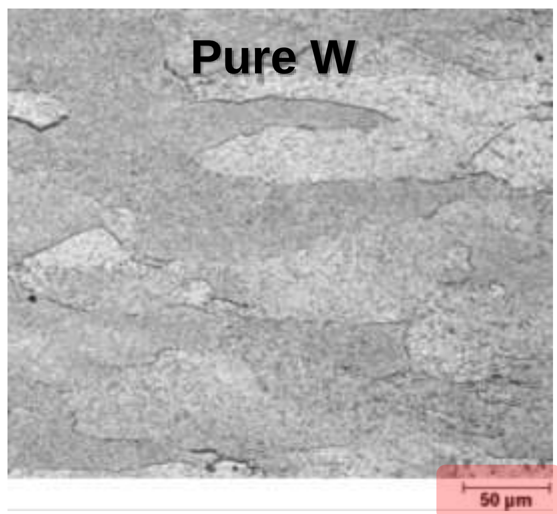
W-5%V



W-20%Mo

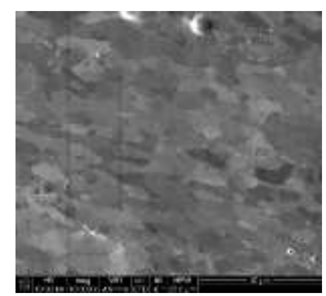




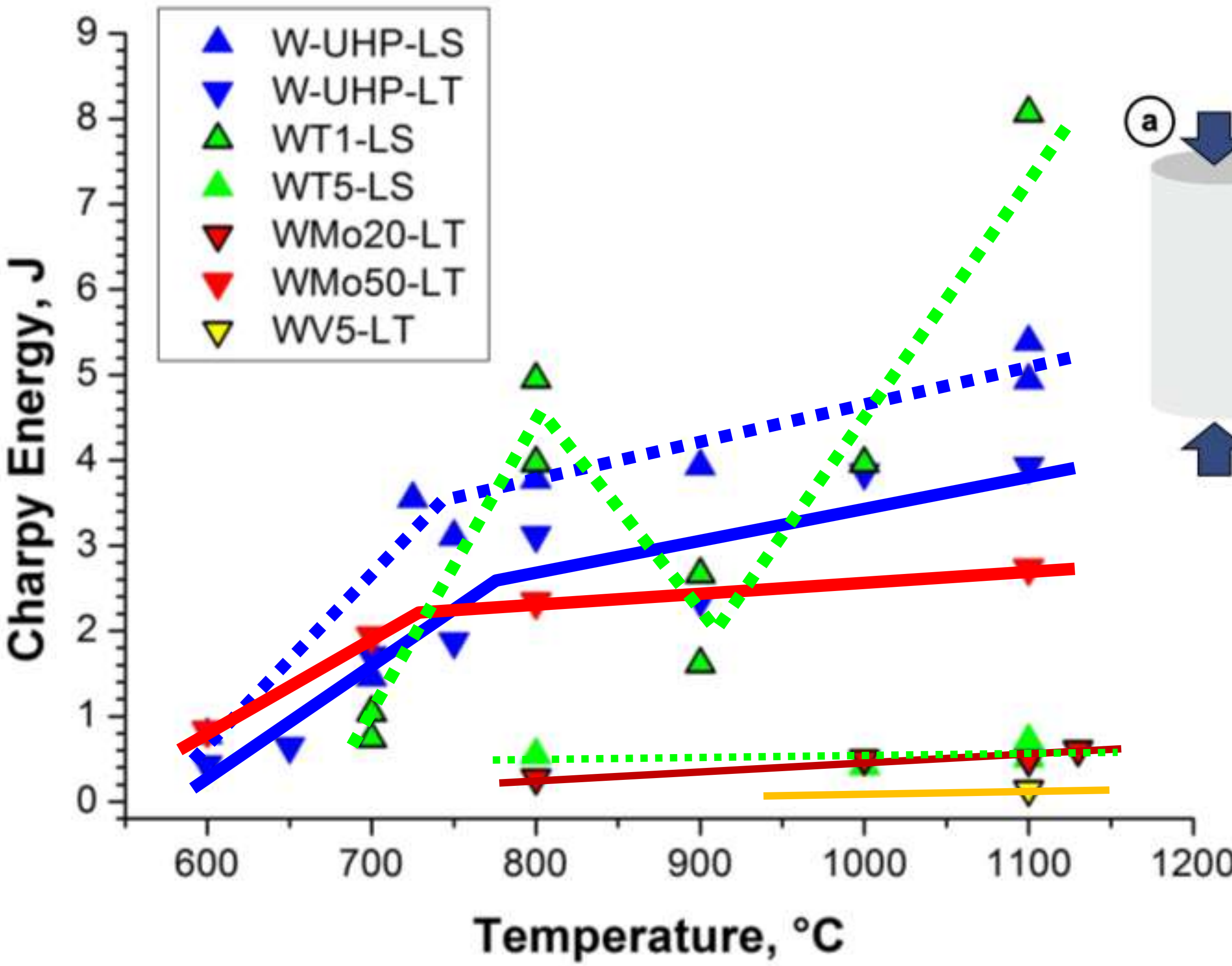


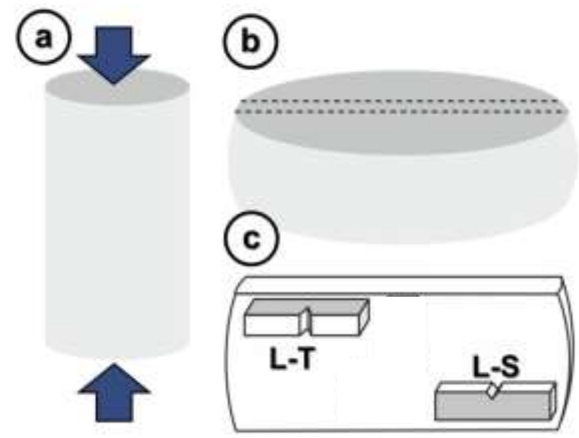
20 µm

W-50%Mo



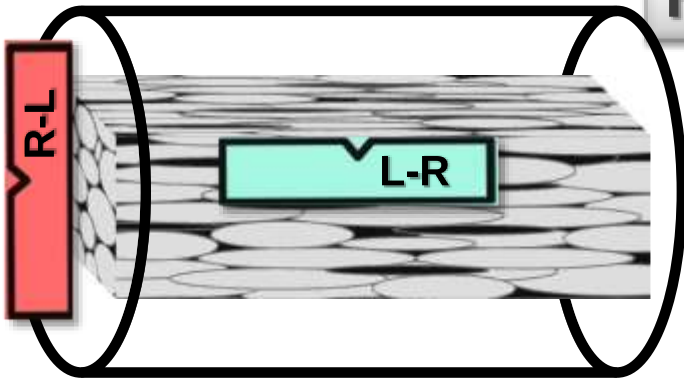
ALLOYING EFFECT (ON DUCTILITY)





Microstructure and Related Properties

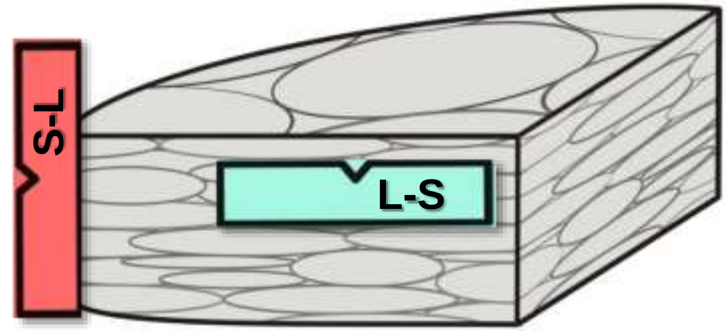
Rods



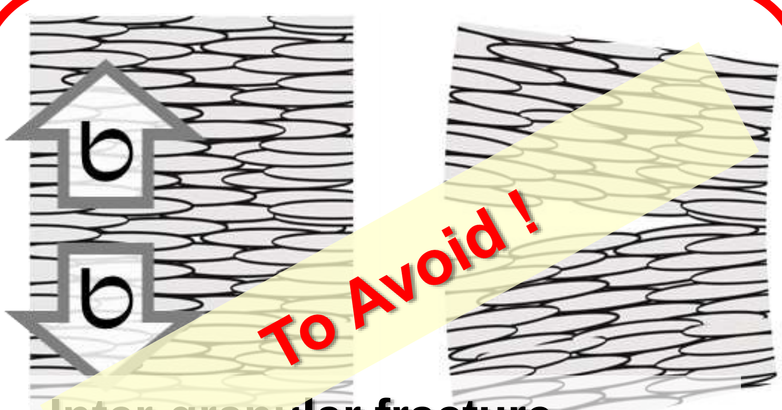
Bundle of „Fibres“

Plates

Round Blanks



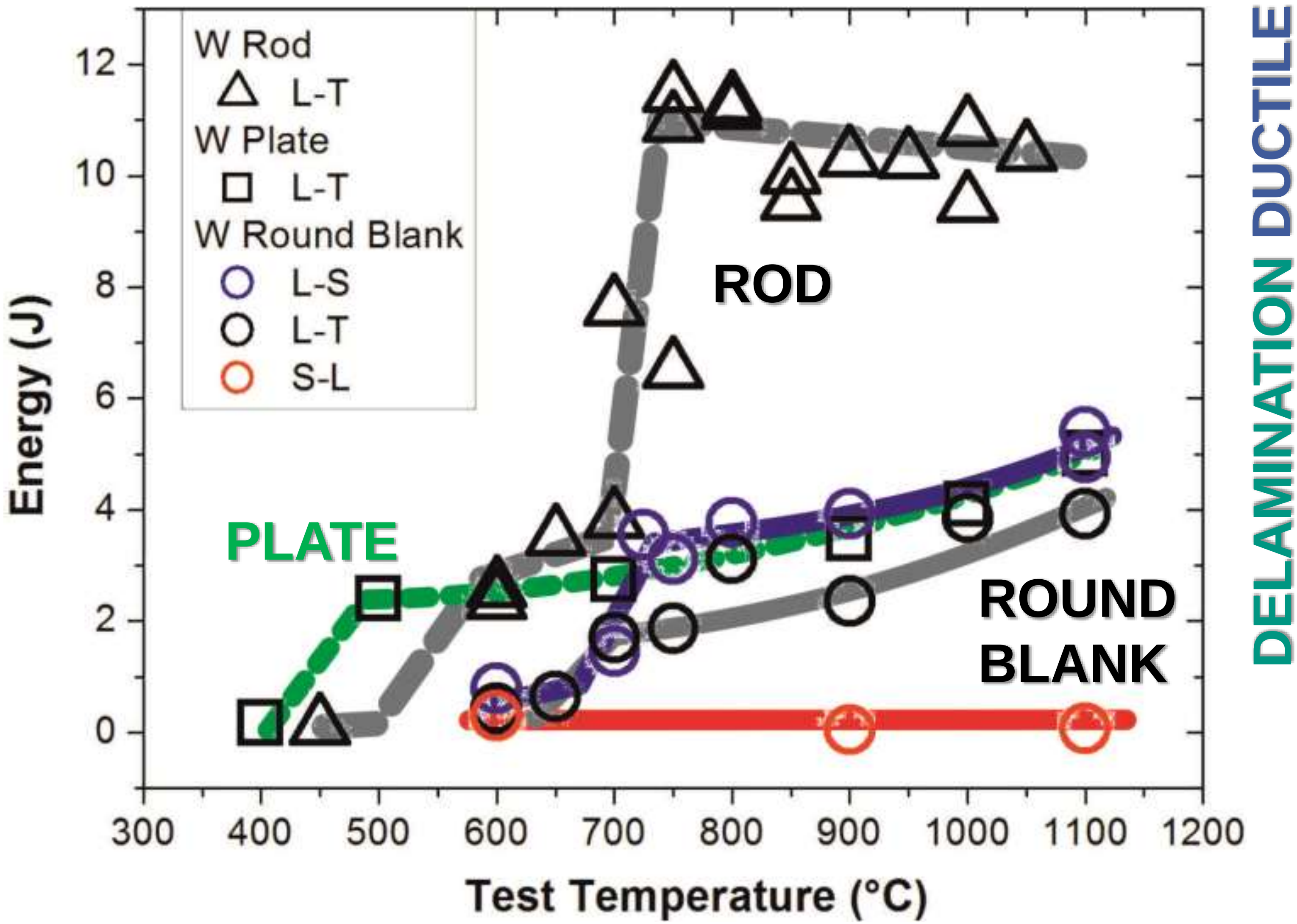
Stack of „Pancakes“



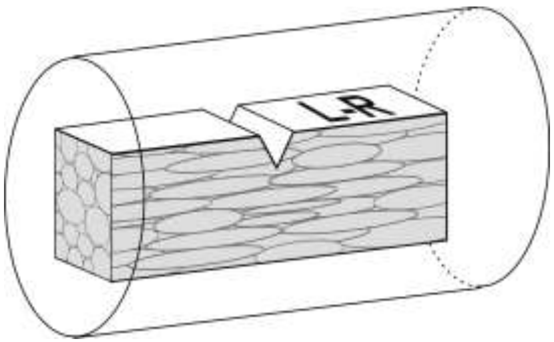
Inter-granular fracture,
enhanced by oxide particles !

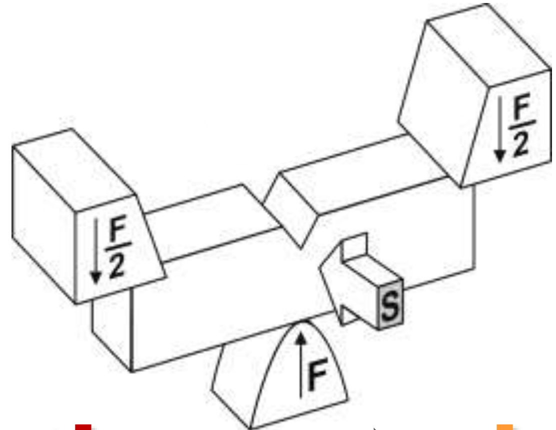
Partly ductile fracture,
improved by deformation !

Impact on Toughness

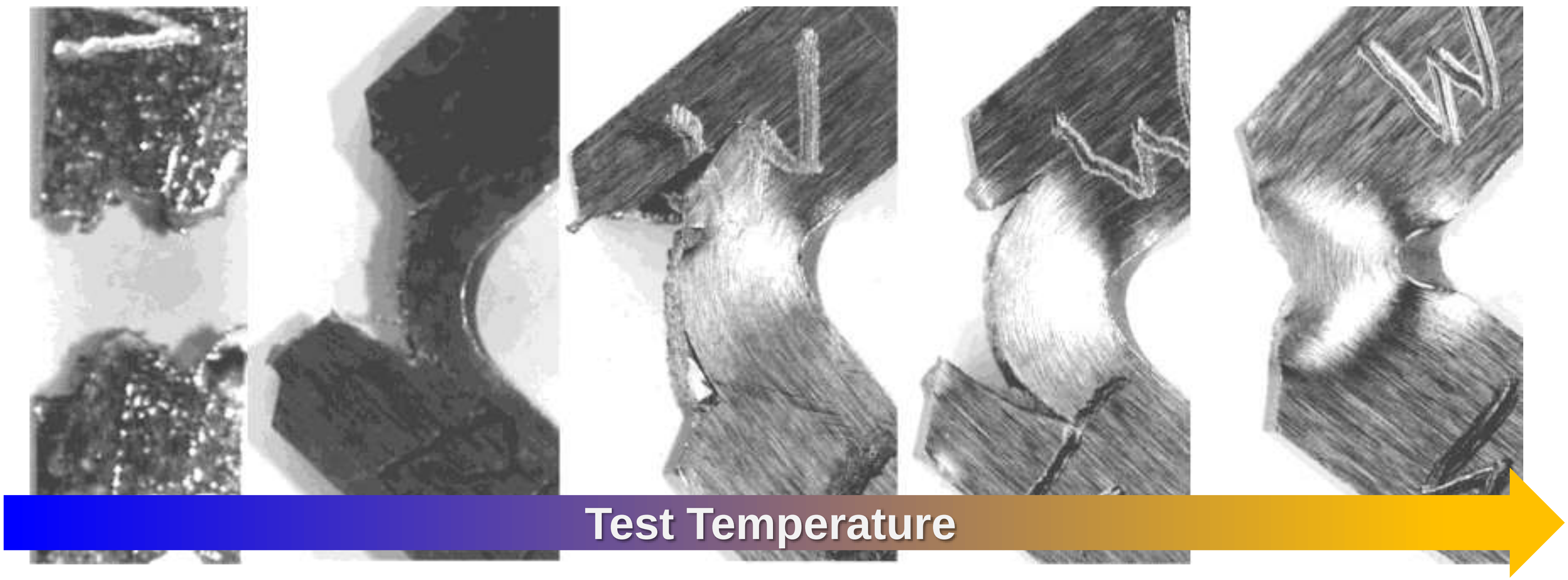


Delamination Fracture



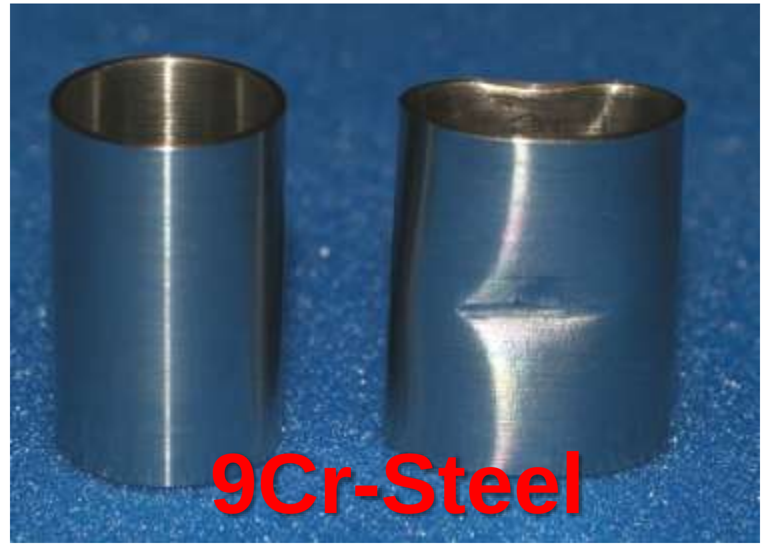


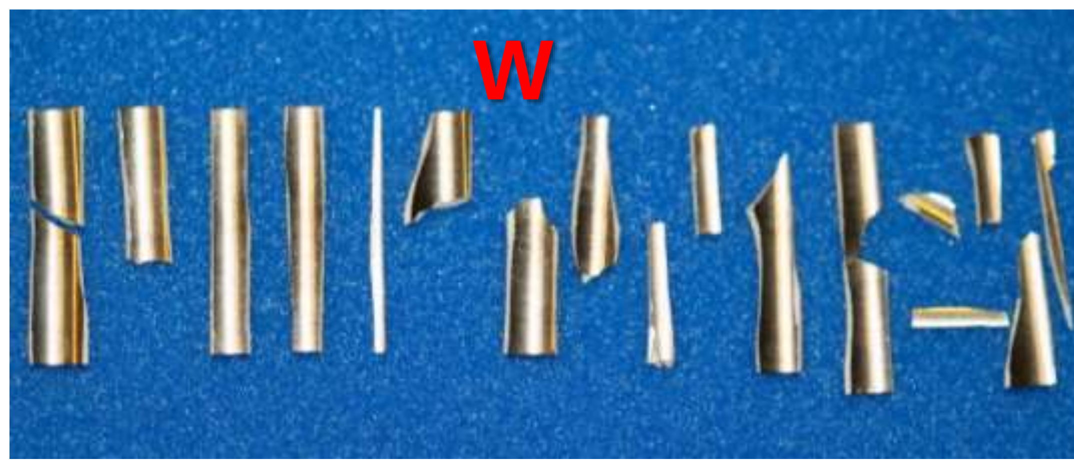
brittle → delamination → ductile



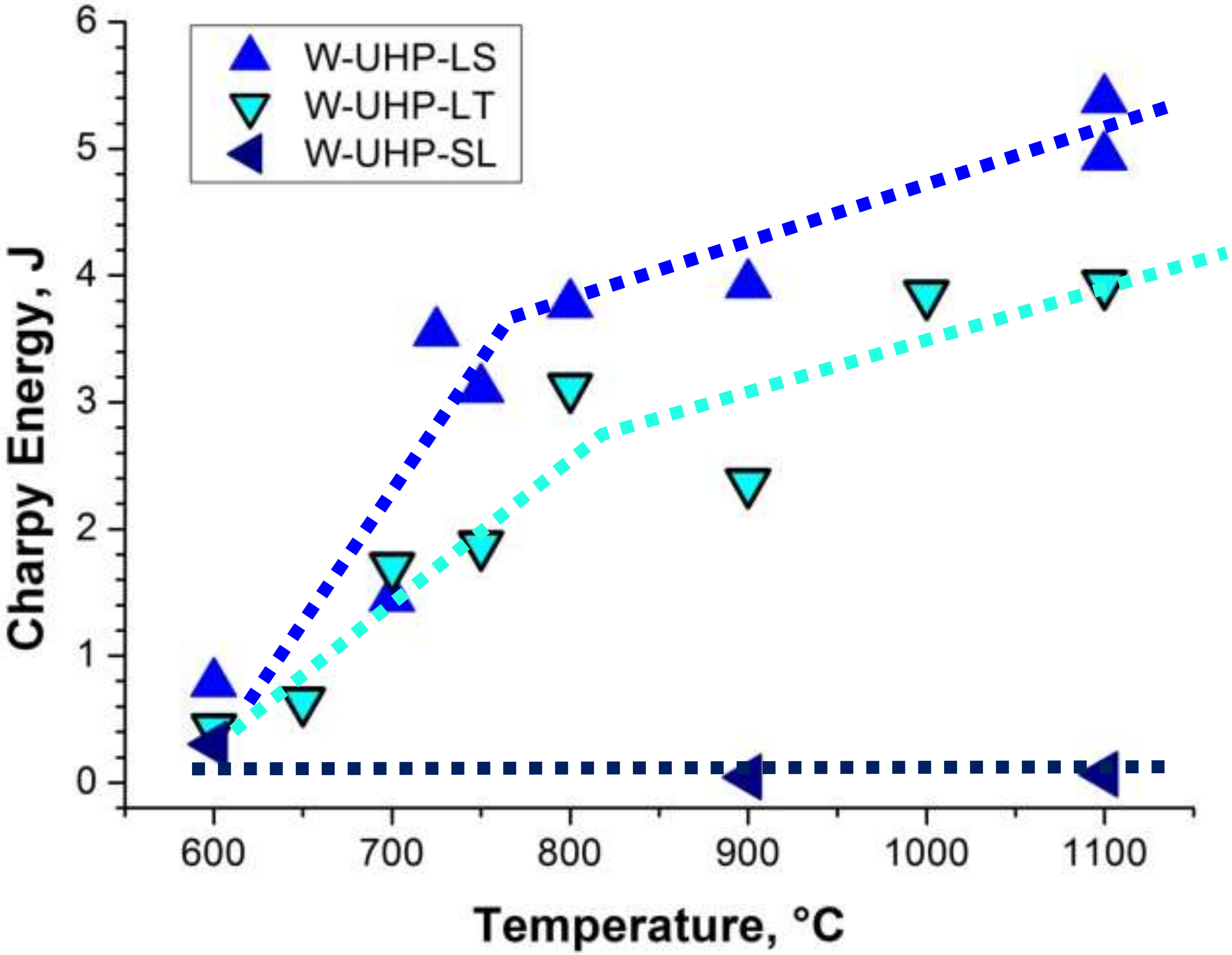
Problem of Microstructure Orientation

Pipe Impact Test

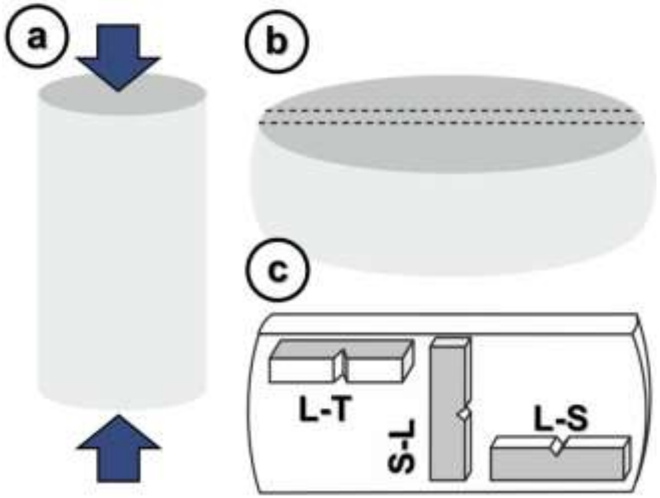


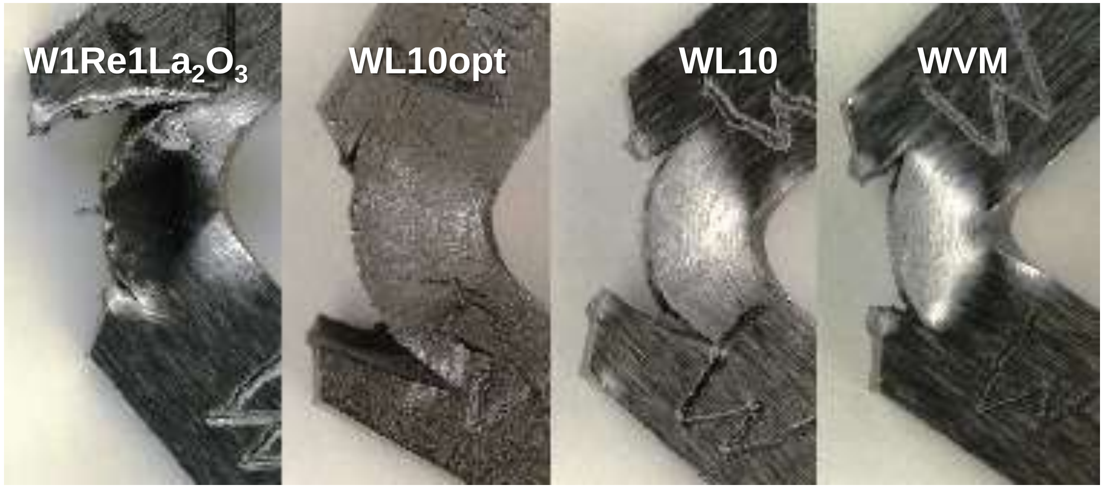


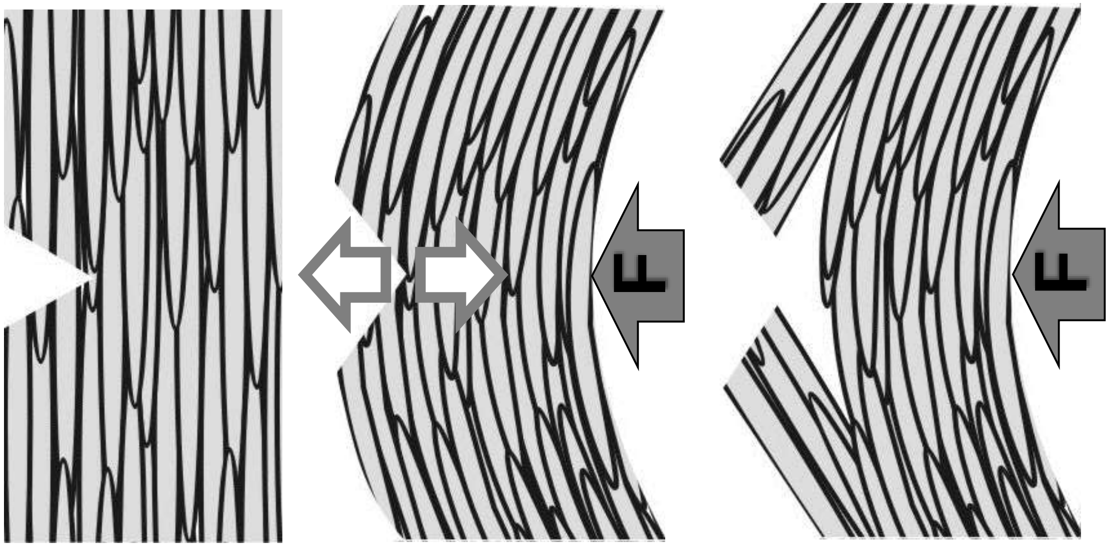
ORIENTATION EFFECT (ANISOTROPY) IN PLATES



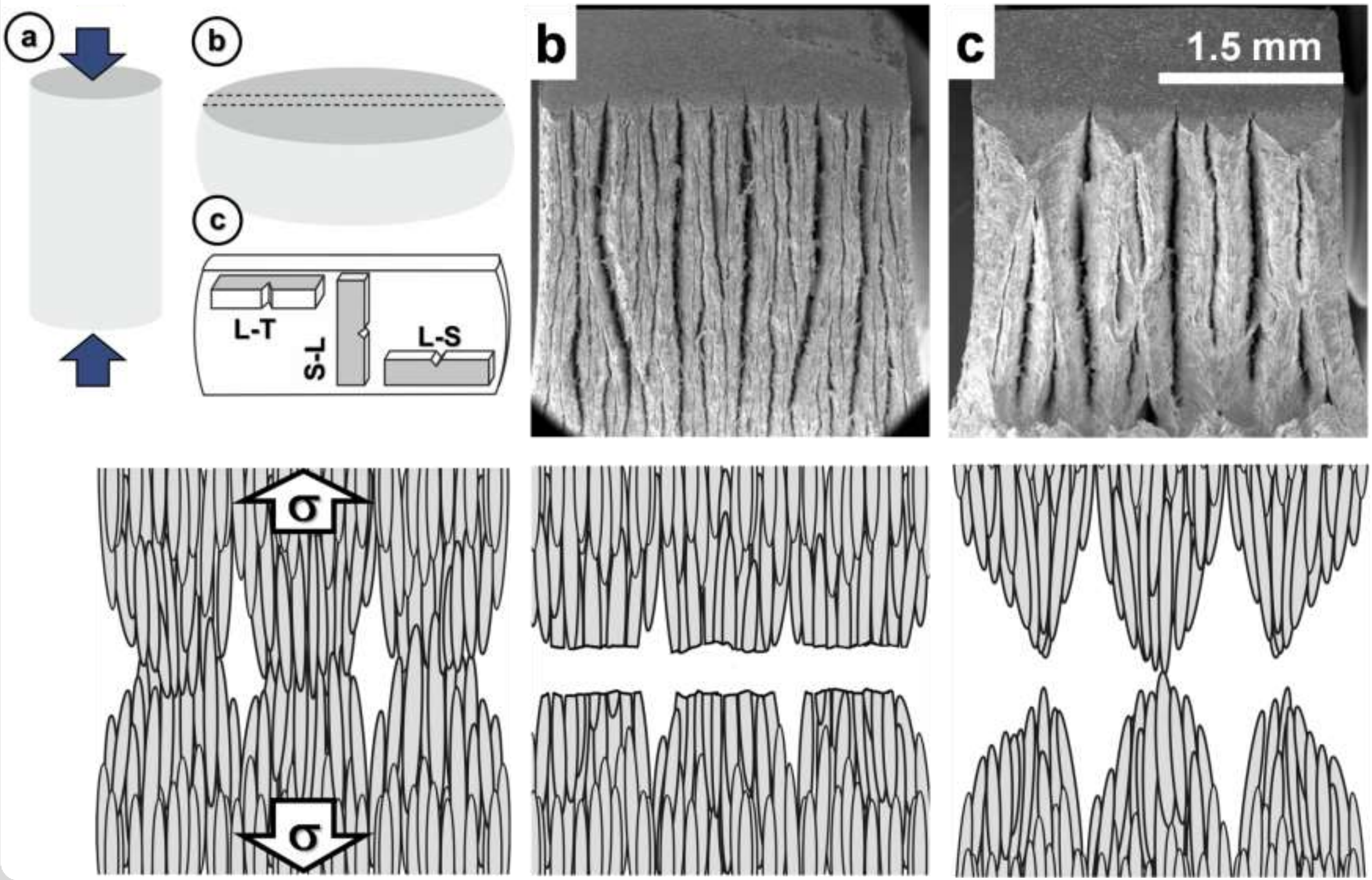
Delamination Fracture (L-S)







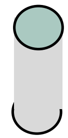
Delamination Fracture (L-T)

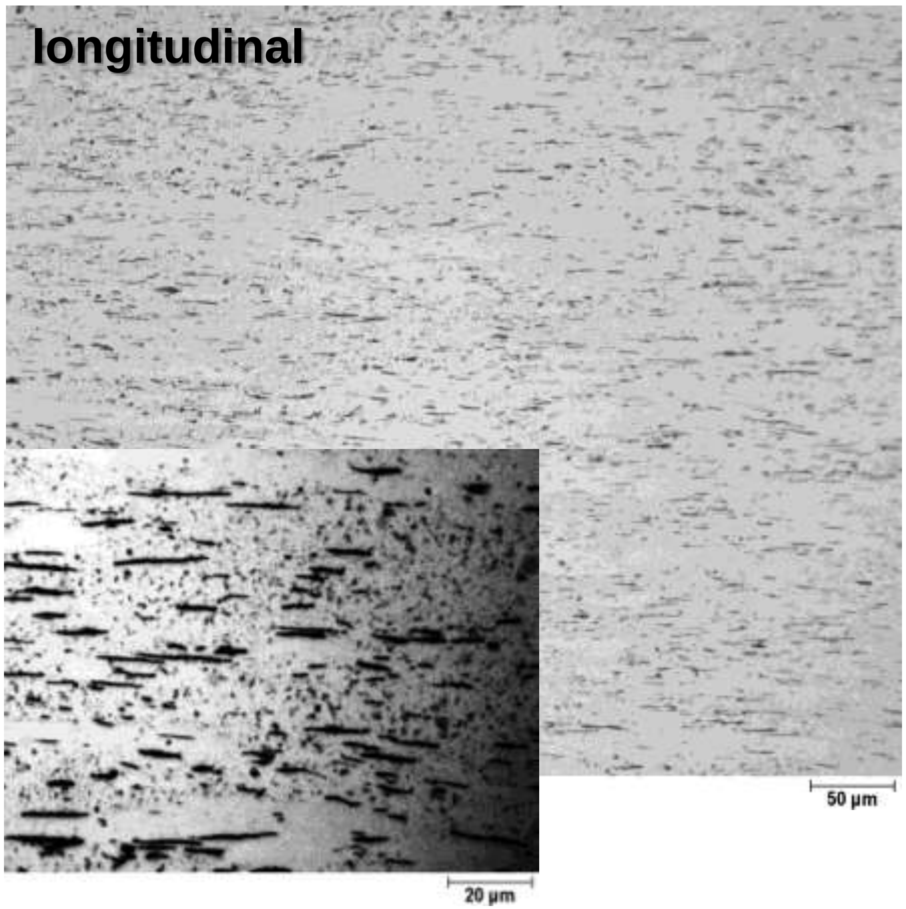


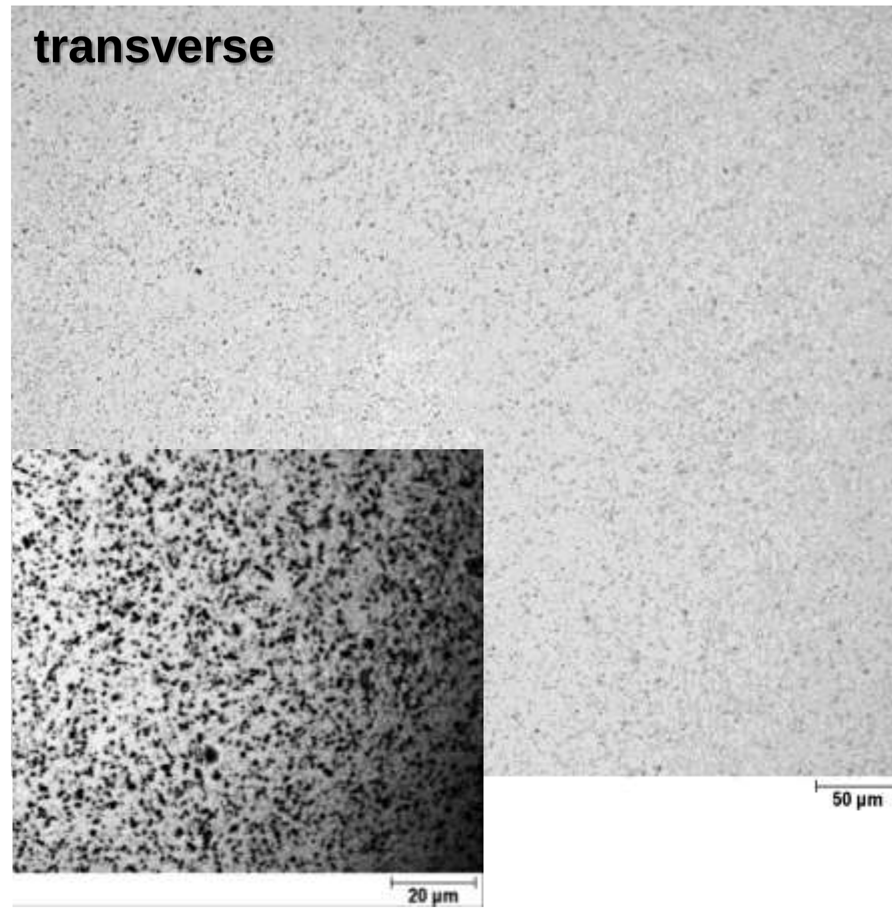
Effect of ODS particles in W

WL10 Rod, Ø7 mm

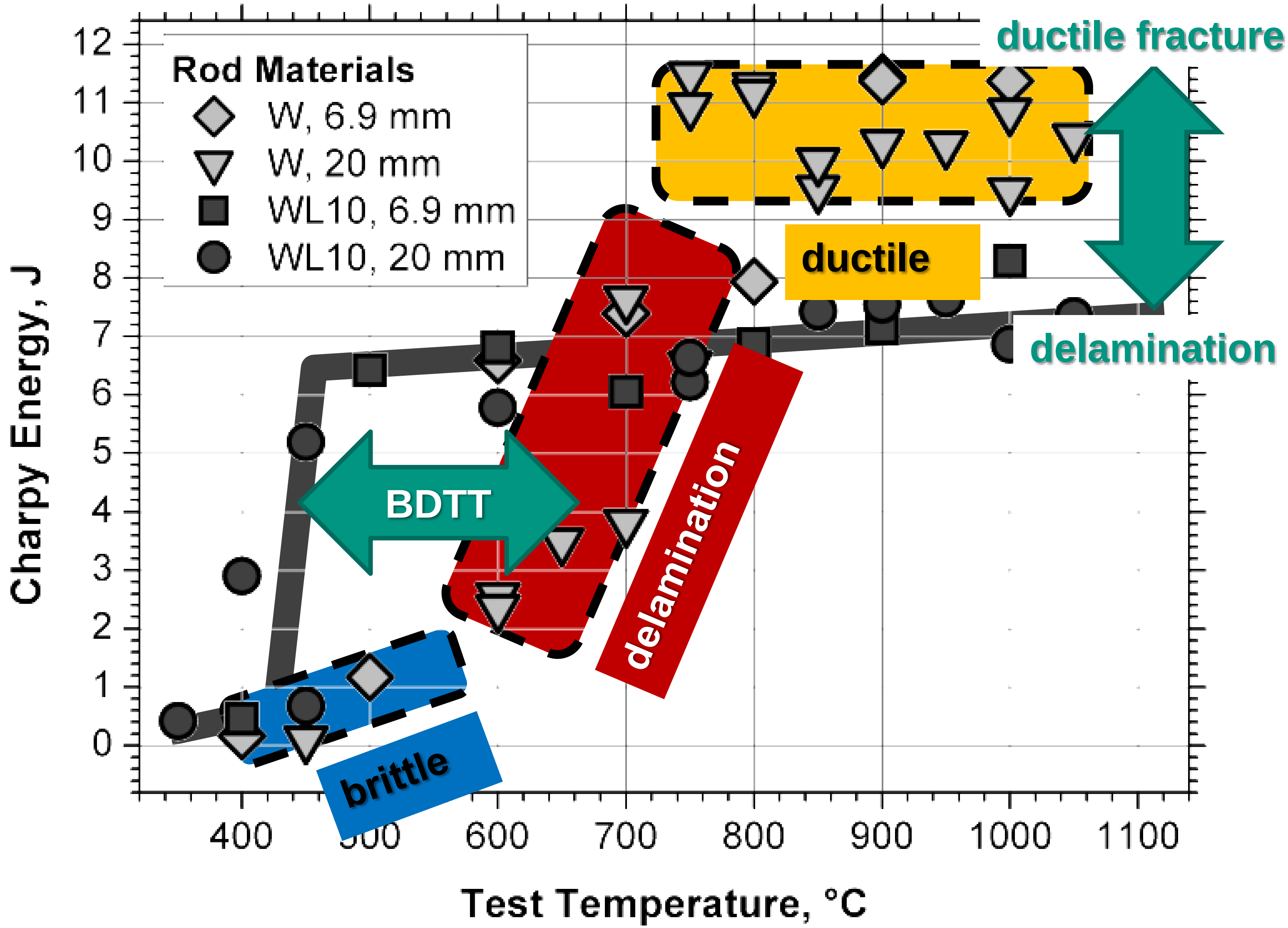
Rods: Metallography







Effect of ODS particles in W



STRUCTURAL TUNGSTEN MATERIALS SUMMARY

So far, the best suitable tungsten materials for structural applications (divertor or other large scale components) are

Thin Plates, Thickness < 4 mm

Produced by Sintering (Hydrogen Atmosphere) and Cross-Rolling

Pure Tungsten (maybe small amounts of grain stabilizers, like La_2O_3)

4 HELIUM COOLED DIVERTOR DESIGNS

Tungsten and its Use as Armor Material

KIT Karlsruher Institut für Technologie

The expected life time of a power plant divertor is TWO years !?

High heat flux

→ High operating temperatures (peaks>1800°C)
→ Microstructural stability, aging, …
→ Thermo-shocks, cyclic loading, fatigue, …

Heavy ion bombardment

→ Sputtering, cracking/fracturing
→ Surface interactions and modifications
→ Microstructural changes

Neutron load 15 dpa/year (in W)

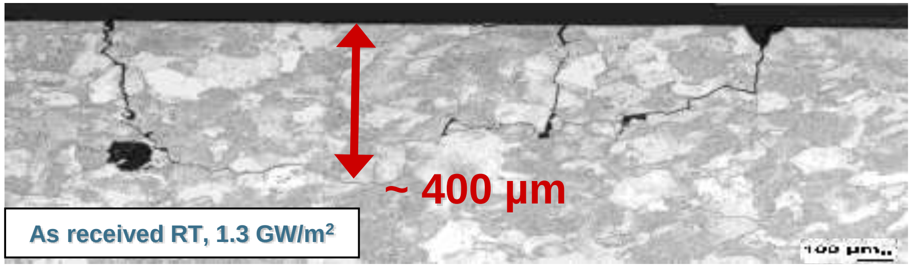
→ 30 dpa (in W) until end of service
→ Transmutation effects (Re, Os)
→ Swelling (order of magnitude: 3% for pure W)

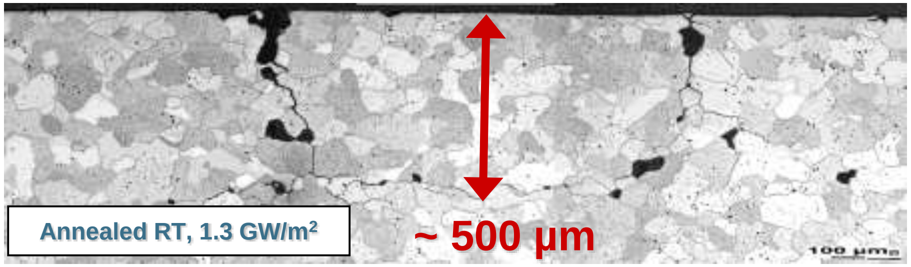
QUESTION: What can we do about this? How can we improve **ARMOR** materials?

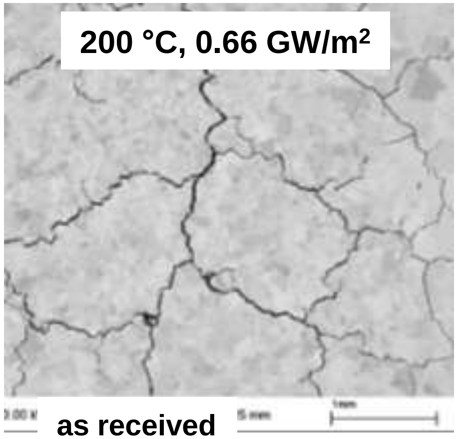
ANSWER: There is not much we can do now! We have to live with most properties and effects. A final assessment would require real in-service conditions.

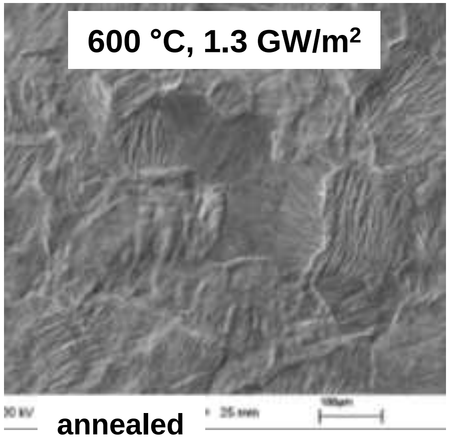
HIGH HEAT FLUX EFFECTS

Electron Beam



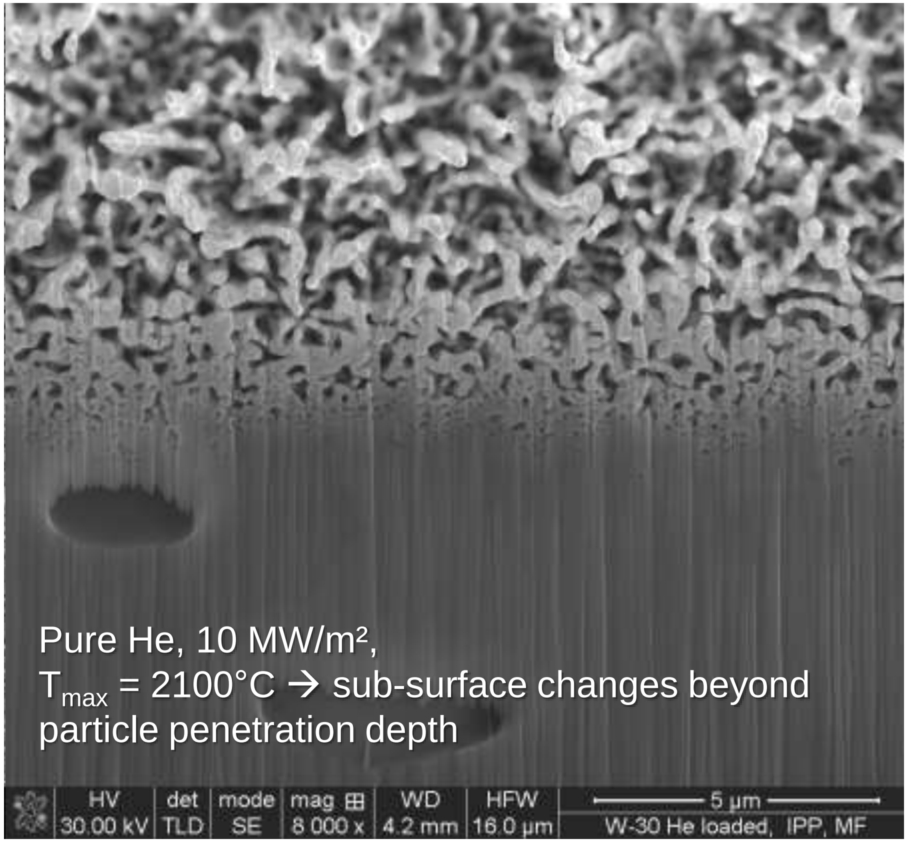






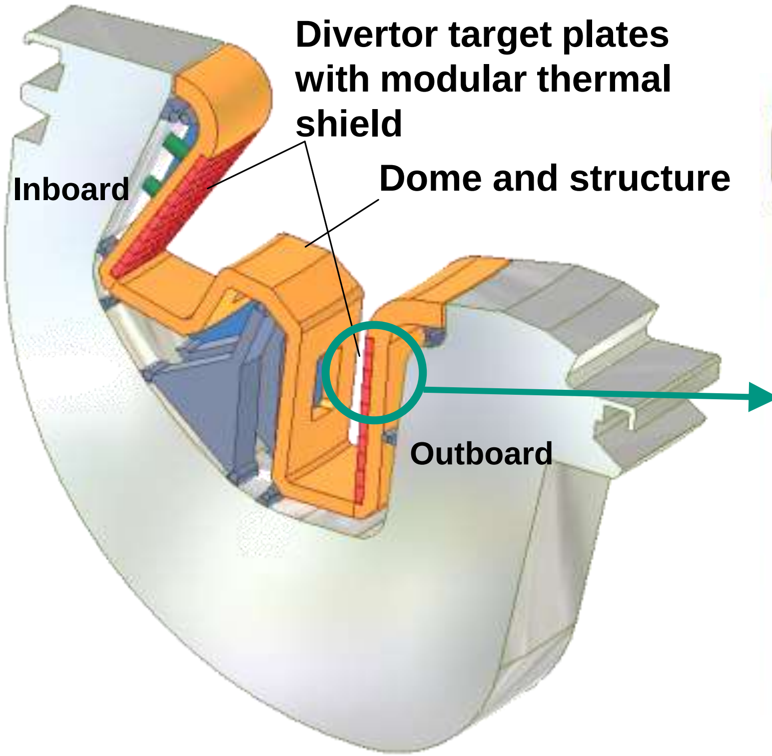
→ G. Pintsuk, J. Linke, et al., FZJ

Hydrogen/Helium Ion Beam

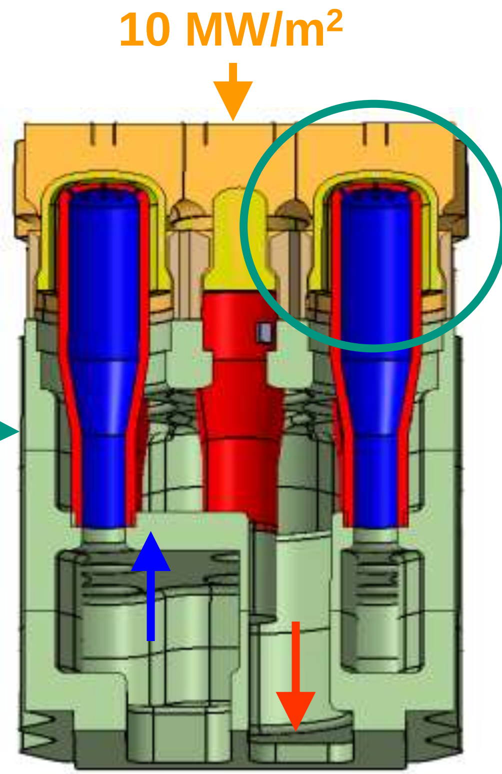


→ H. Maier, H. Greuner, M. Rasinski, Ch. Linsmeier, IPP

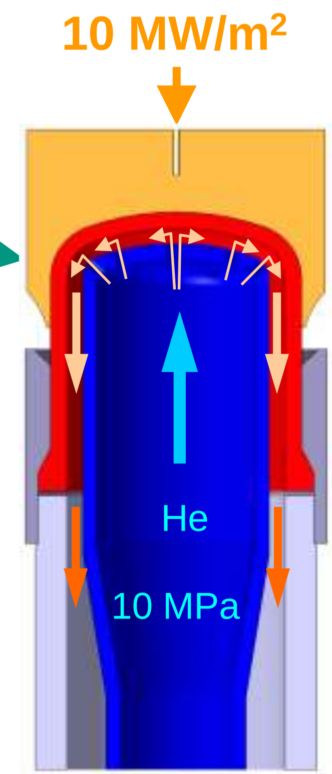
FINGER DESIGN, JET COOLING



Divertor Cassette



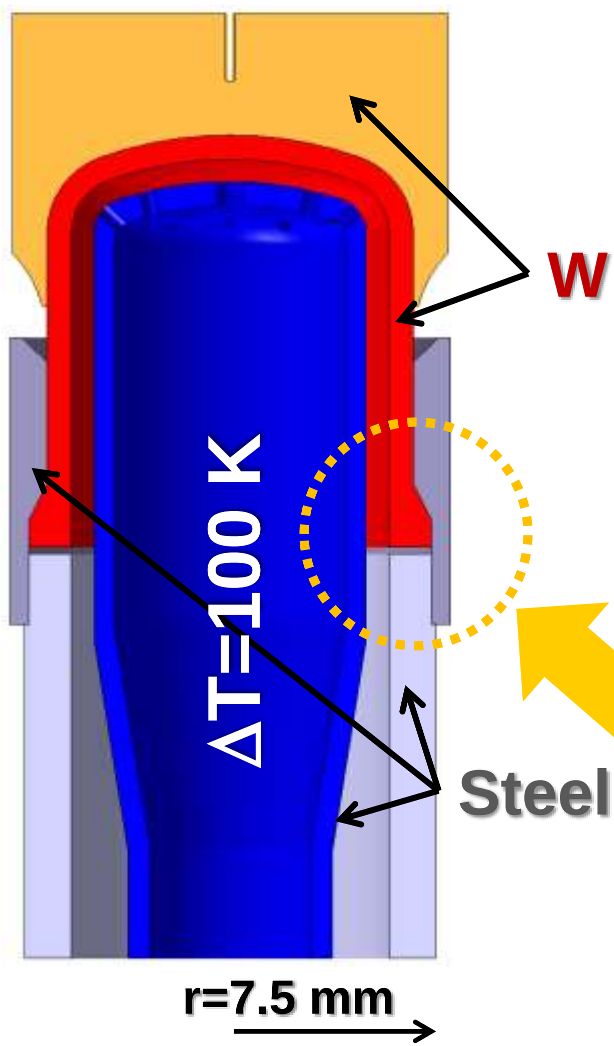
9-Finger Module



Finger

→ P. Norajitra, T. Ihli *et al.*, 2003-2009

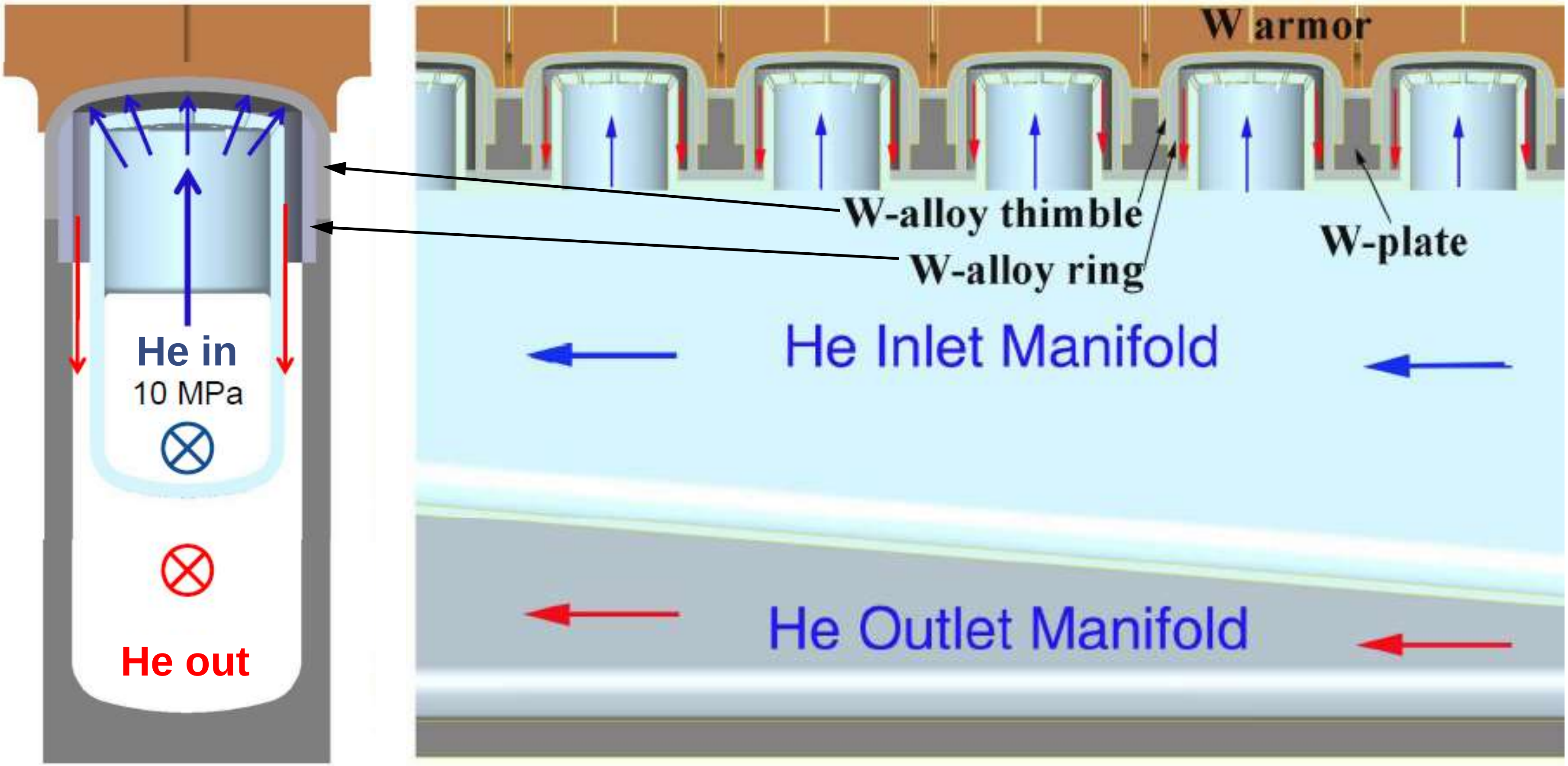
FINGER DESIGN, JET COOLING



+ High heat flux: >10 MW/m²
+ Small Size, Thin Walls
– Large Numbers: ~500 000
– Joints between W and Steel

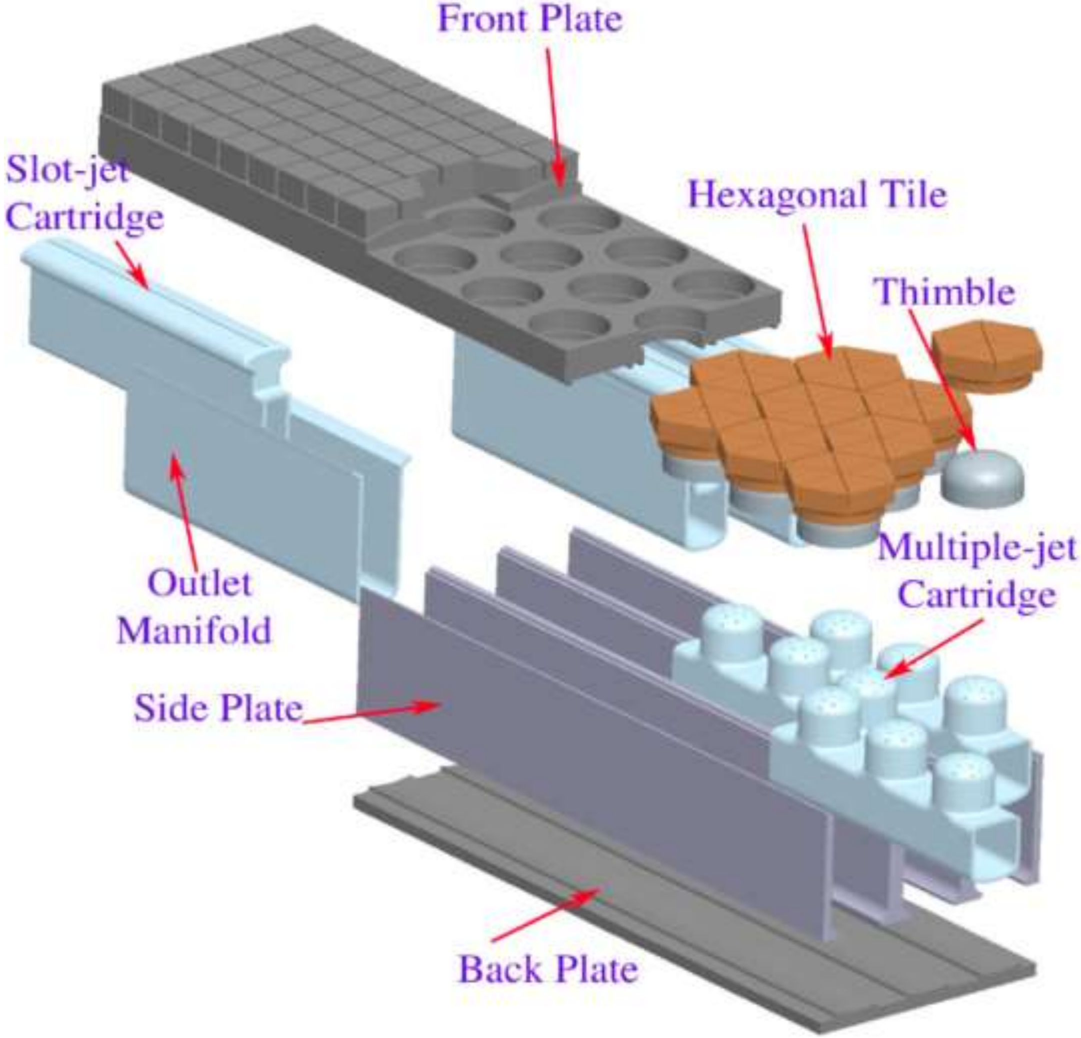
He and W temperature limited by steel
Ferritic ODS → 750°C ???
Eurofer ODS, 9Cr ODS → 650°C
Eurofer 97, F82H → 550°C

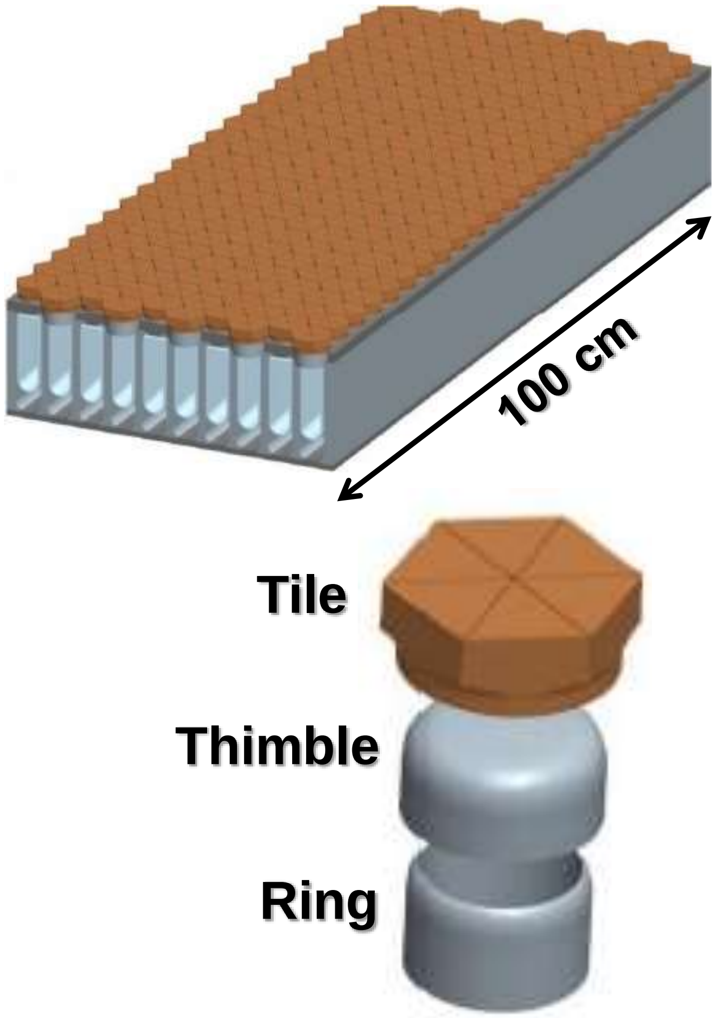
Plate Design (ARIES), Jet Cooling



X.R. Wang, S. Malang, M.S. Tillack & ARIES Team, 2008-2011

PLATE DESIGN (ARIES), JET COOLING

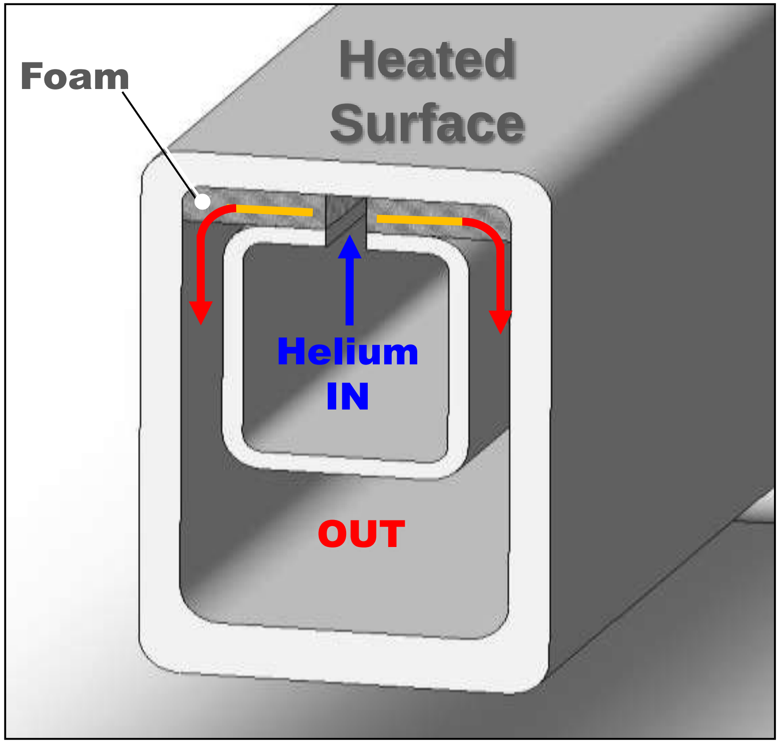


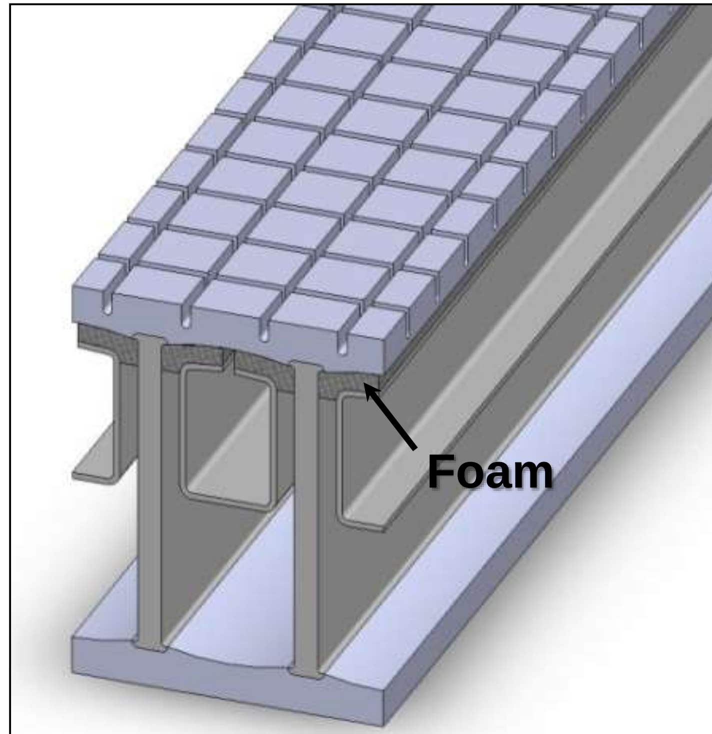


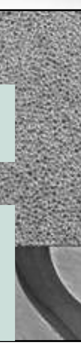
X.R. Wang, S. Malang, M.S. Tillack & ARIES Team, 2008-2011

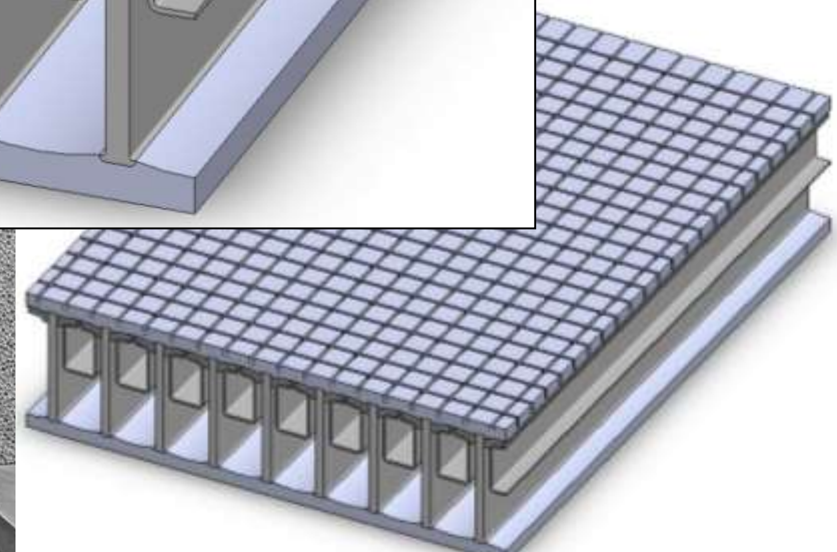
PLATE DESIGN, FOAM PROMOTER

Karlsruher Institut für Technologie





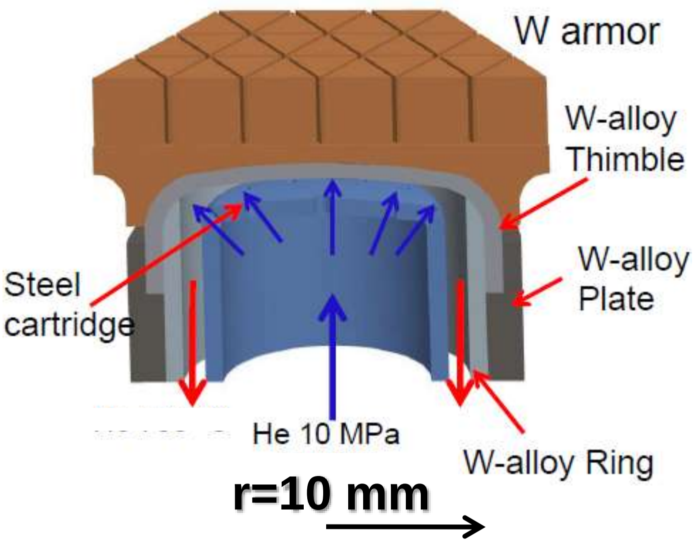




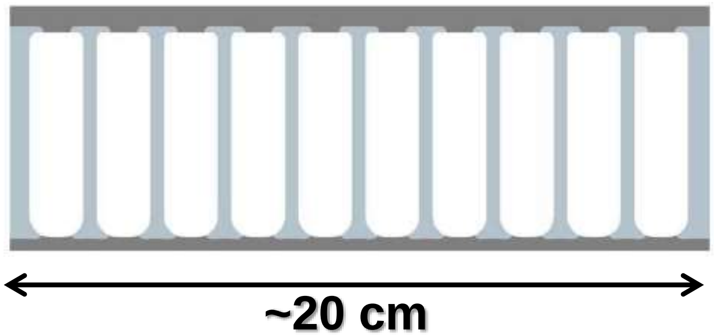
→ S. Sharafat *et al.*, UCLA, 2005-2009

→ Mo, Nb, SiC Foam:
D. Youchison *et al.*, SNL,2011

PLATE DESIGN (ARIES), JET COOLING

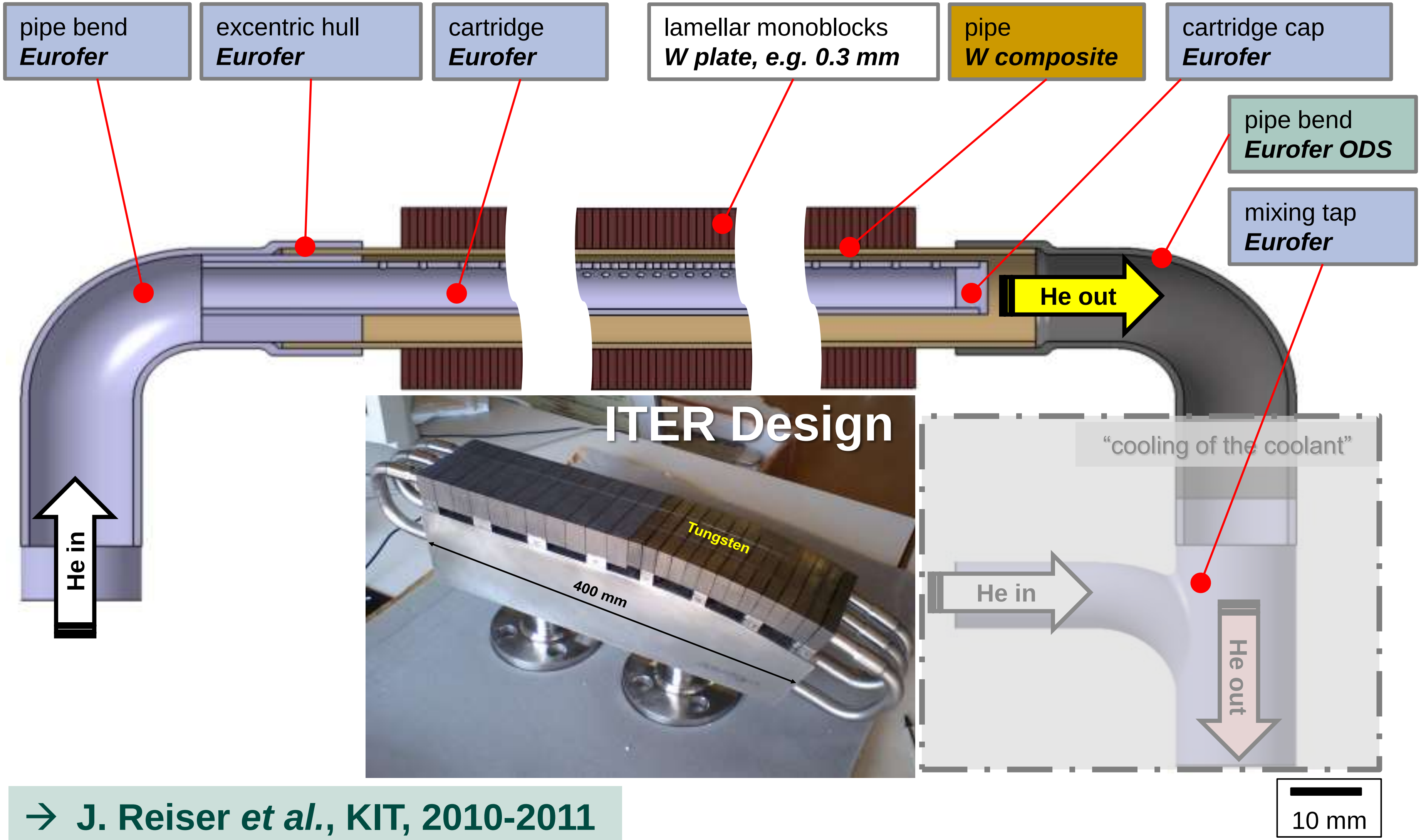


- + High heat flux: ~15 MW/m²
- + Small Size, Thin Walls
- + "Double Containment"
- − Large Numbers: ~300 000
- − Many/Long Struct. W-W Joints



He temperature limited by steel (multiple jet cartridges)
Ferritic ODS → 750°C ???
Eurofer ODS, 9Cr ODS → 650°C
Eurofer 97, F82H → 550°C

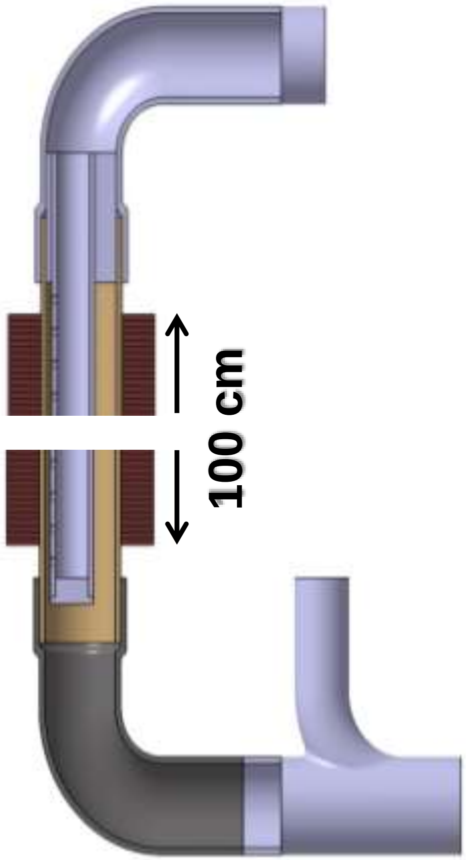
PIPE/MONOBLOCK DESIGN, JET COOLING



→ **J. Reiser *et al.*, KIT, 2010-2011**

PIPE/MONOBLOCK DESIGN, JET COOLING

Karlsruher Institut für Technologie



- + Simple Design
- + "Easy Joints"
- + "Small Number of Parts"
- + Inexpensive
- – Low Temperatures for W
- – Low Performance
- – Speculative Pipe Material

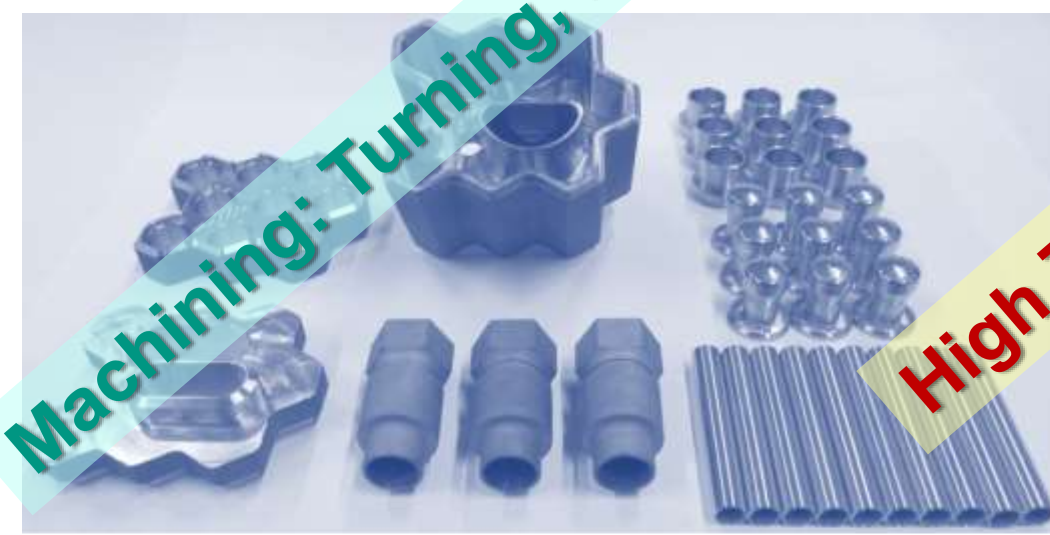
He temperature limited by steel
Eurofer ODS → 650°C (upper)
Eurofer 97 → 350°C (lower)

5

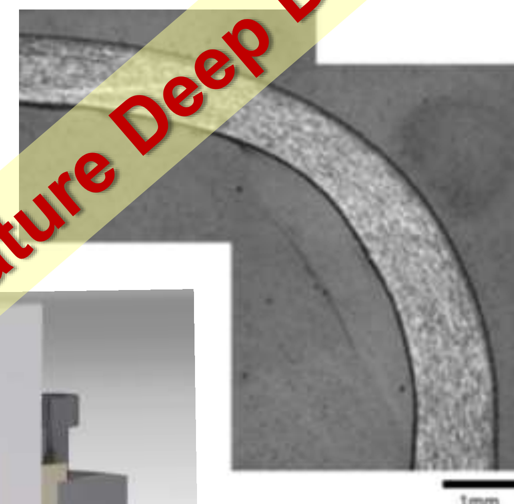
DESIGN ANALYSIS

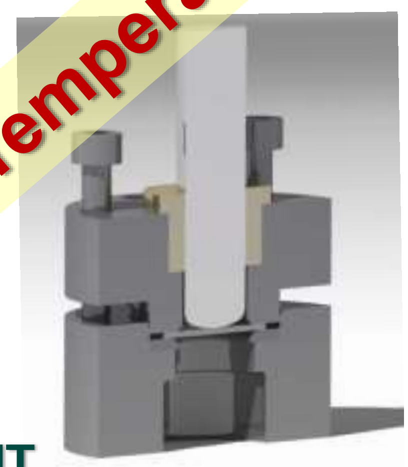
FABRICATION

Karlsruher Institut für Technologie



Machining: Turning, Milling, Grinding, ...

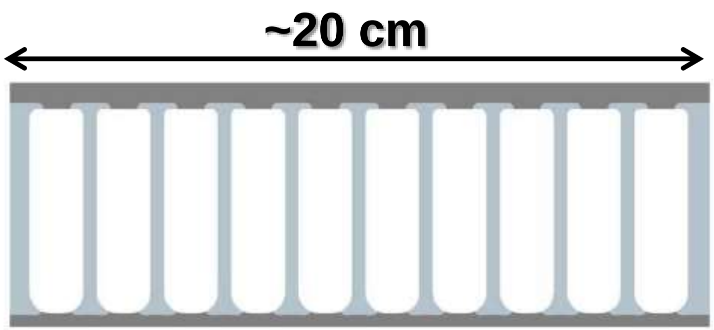


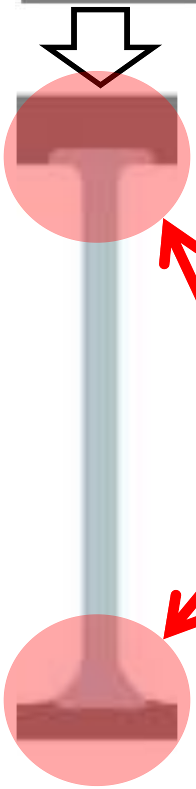


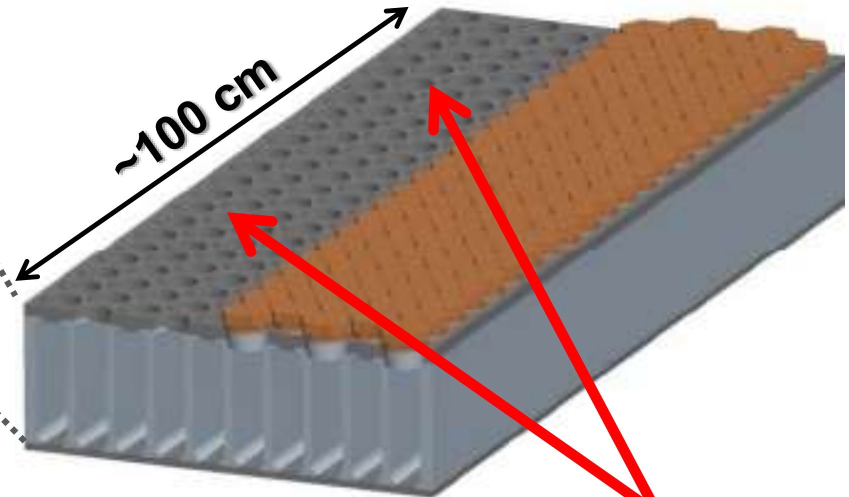
High Temperature Deep Drawing

P. Norajitra, J. Reiser, S. Baumgärtner *et al*., KIT

FABRICATION







High Temperature Plate Pressure-Forging → to be developed

Drilling Holes in 10 mm Plate → standard

JOINING → BRAZING

IMPORTANT: We have to consider joints for STRUCTURAL applications!!!
Joining W tiles to W timbles is NOT considered as structural application!

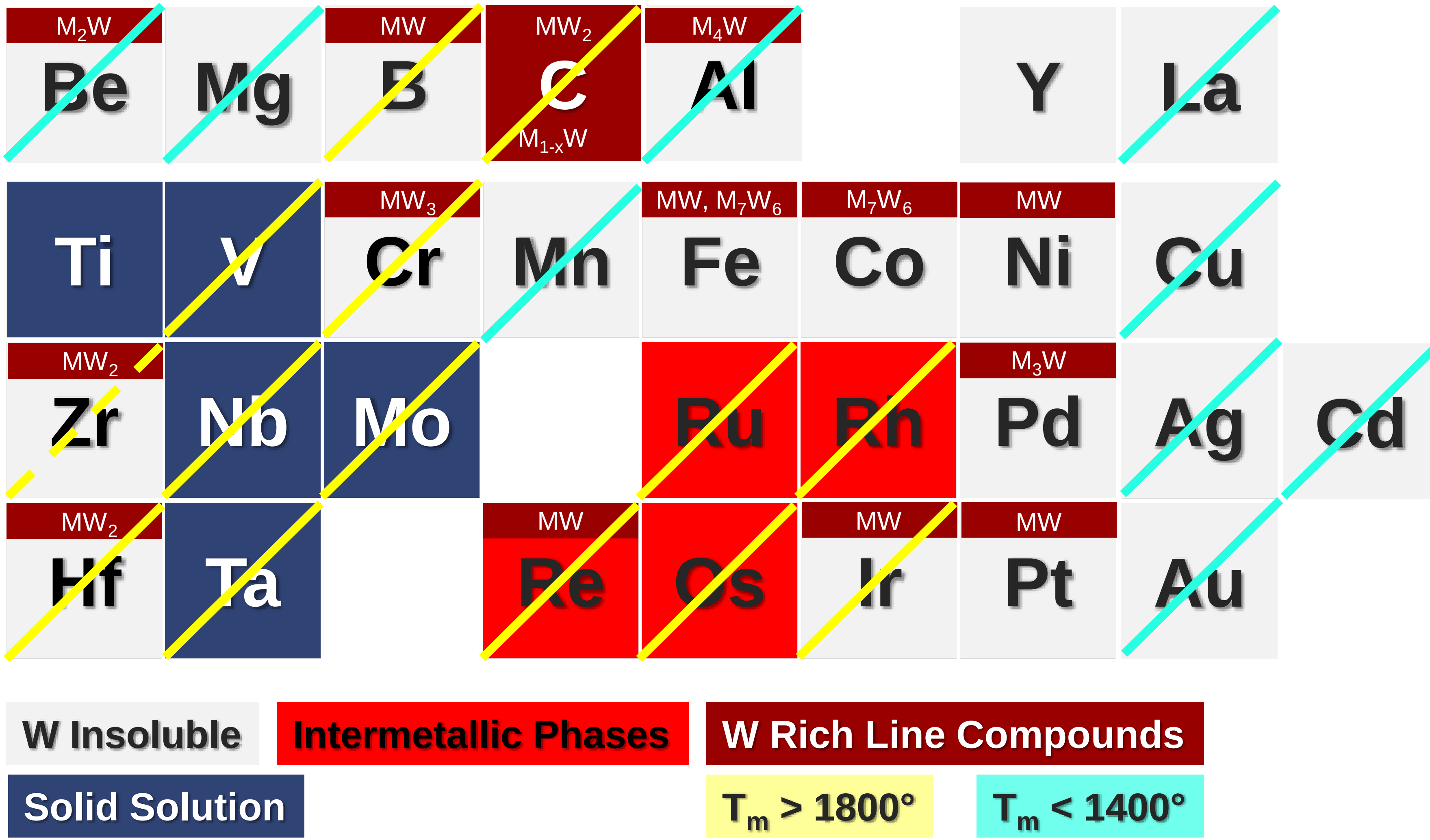
Brazing Material for W-W Joints

- Brazing temperature must be >>900-1200 °C (operating temp.)
- Brazing temperature must be <1800 °C → Grain growth
- Formation of brittle compounds cannot be tolerated

Brazing Material for W-Steel Joints

- Brazing temperature <1100 °C → Grain growth (in steel)
- Brazing temperature must be >>550-750 °C (operating temp.)
- Formation of brittle compounds cannot be tolerated

BRAZING W→W

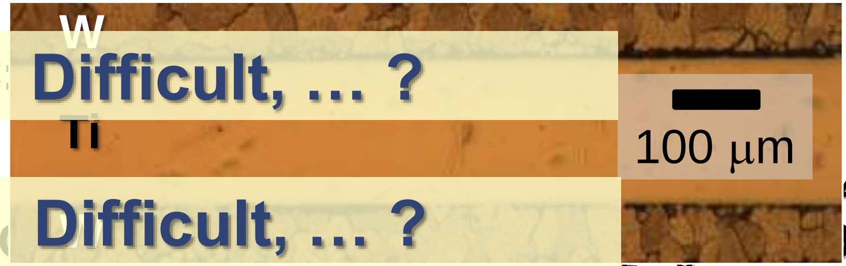


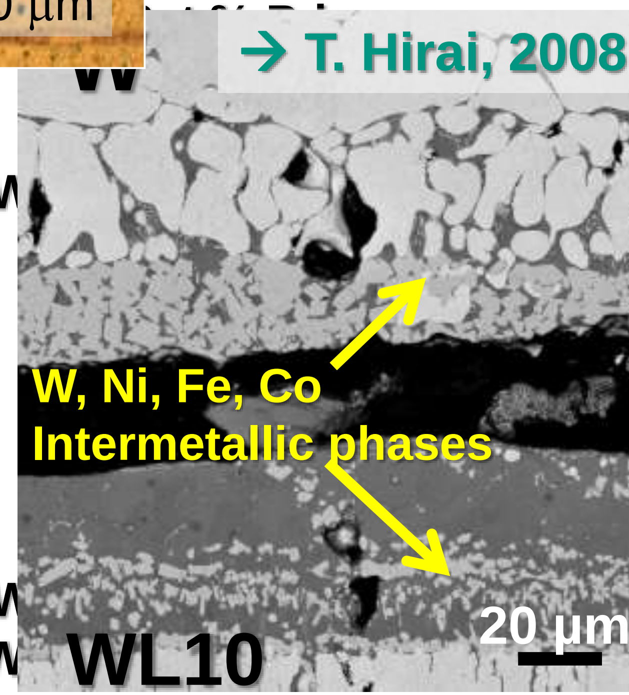
M2W
Be
Mg
MW
B
MW2
C
M1-xW
M4W
Al
Y
La
Ti
V
MW3
Cr
Mn
MW, M7W6
Fe
M7W6
Co
MW
Ni
Cu
MW2
Zr
Nb
Mo
Ru
Rh
M3W
Pd
Ag
Cd
MW2
Hf
Ta
MW
Re
Os
MW
Ir
MW
Pt
Au
W Insoluble
Intermetallic Phases
W Rich Line Compounds
Solid Solution
Tm > 1800°
Tm < 1400°

BRAZING MATERIALS, W→W

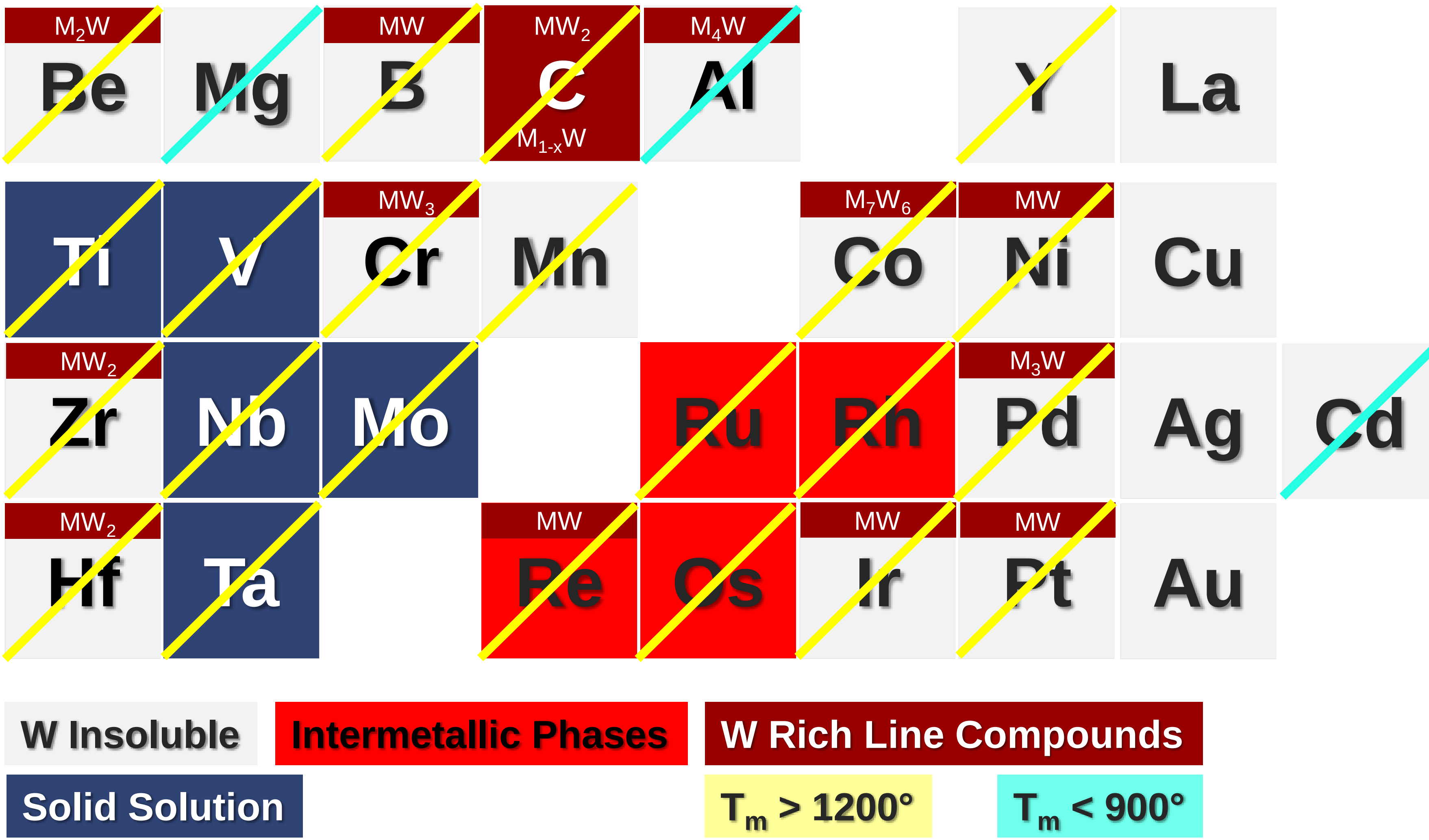
1670°C	Ti	<740°C: Difficult, … ?
1520°C	Y	Strong <1570°C: Difficult, … ? …40°C …00°C: alpha-Y + Y_2O_3
1850°C	Zr	<2160°C: W→ ZrW_2 <1700°C: Brittle Joint …% intermetallic ZrW_2 <860°C: Zr→ ZrW_2 …tallic ZrW_2
1550°C	Pd	<1800°C: W→ ZrW_2 Expensive, … ? <900°C: intermetallic Pd_3W ???
1770°C	Pt	<24…°C: peritectic gamma phase Pt_3W Very expensive, … ?
1540°C	Fe	<1700°C: µ phase $Fe_7W_6(Fe,W)_4$ <1000°C: Laves phase Fe_2W
1500°C	Co	<1700°C: µ phase $Co_7W_6(Co,W)_4$ <1000°C: Laves phase Co_3W
1450°C	Ni	<1000°C: peritectoid intermetallics NiW <950°C: peritectoid intermetallic Ni_4W

Brittle Joints



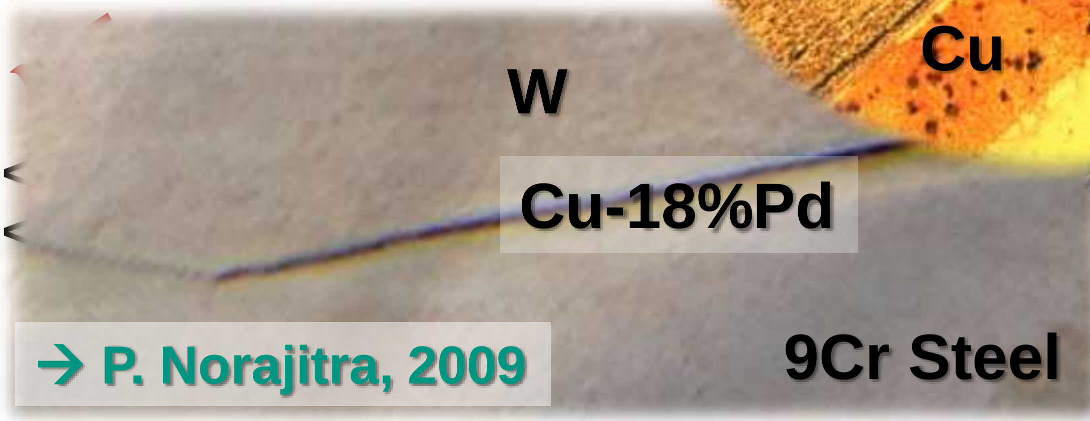


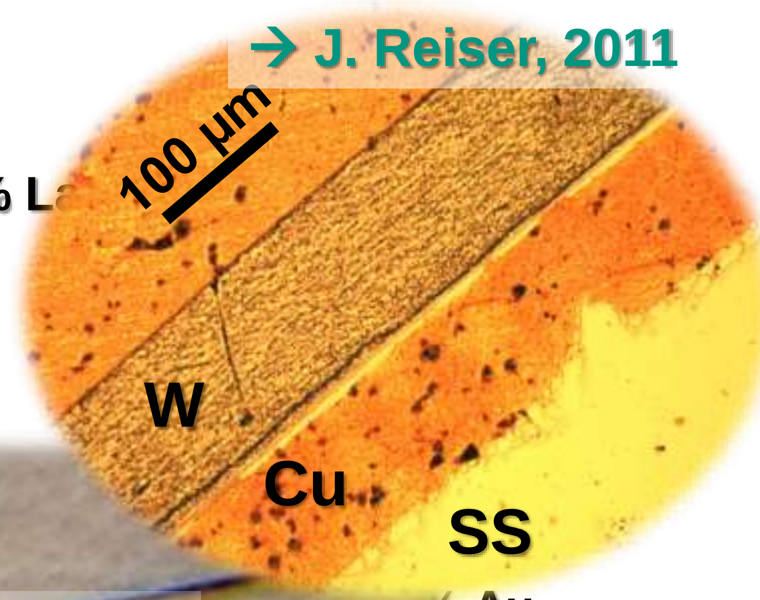
BRAZING W→STEEL



BRAZING MATERIALS, W→STEEL

920°C	La	<790°C: eutecticum → 93at.% La
1080°C	Cu	✓ … but strength ???
960°C	Ag	
1060°C	Au	% Au

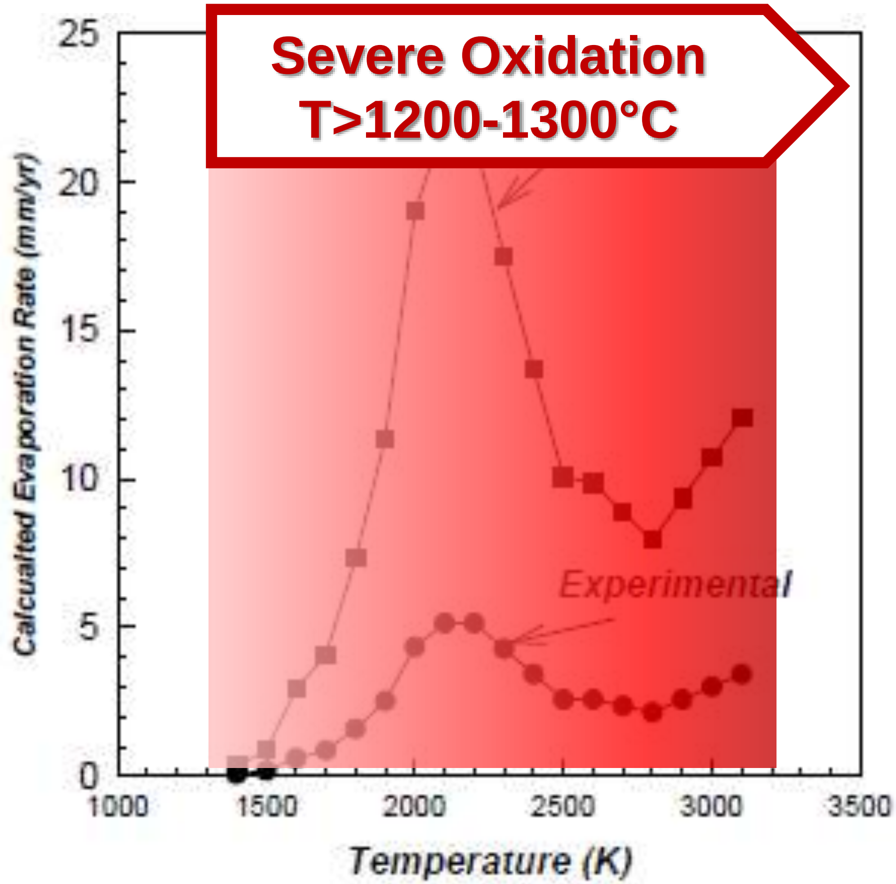




CONCLUSION: Copper has to be used as sealing rather than as a braze material !!!

ENVIRONMENT → OXIDATION

WO_3 yellow, T_m=1470°C, 7200 kg/m³, volatile in vacuum

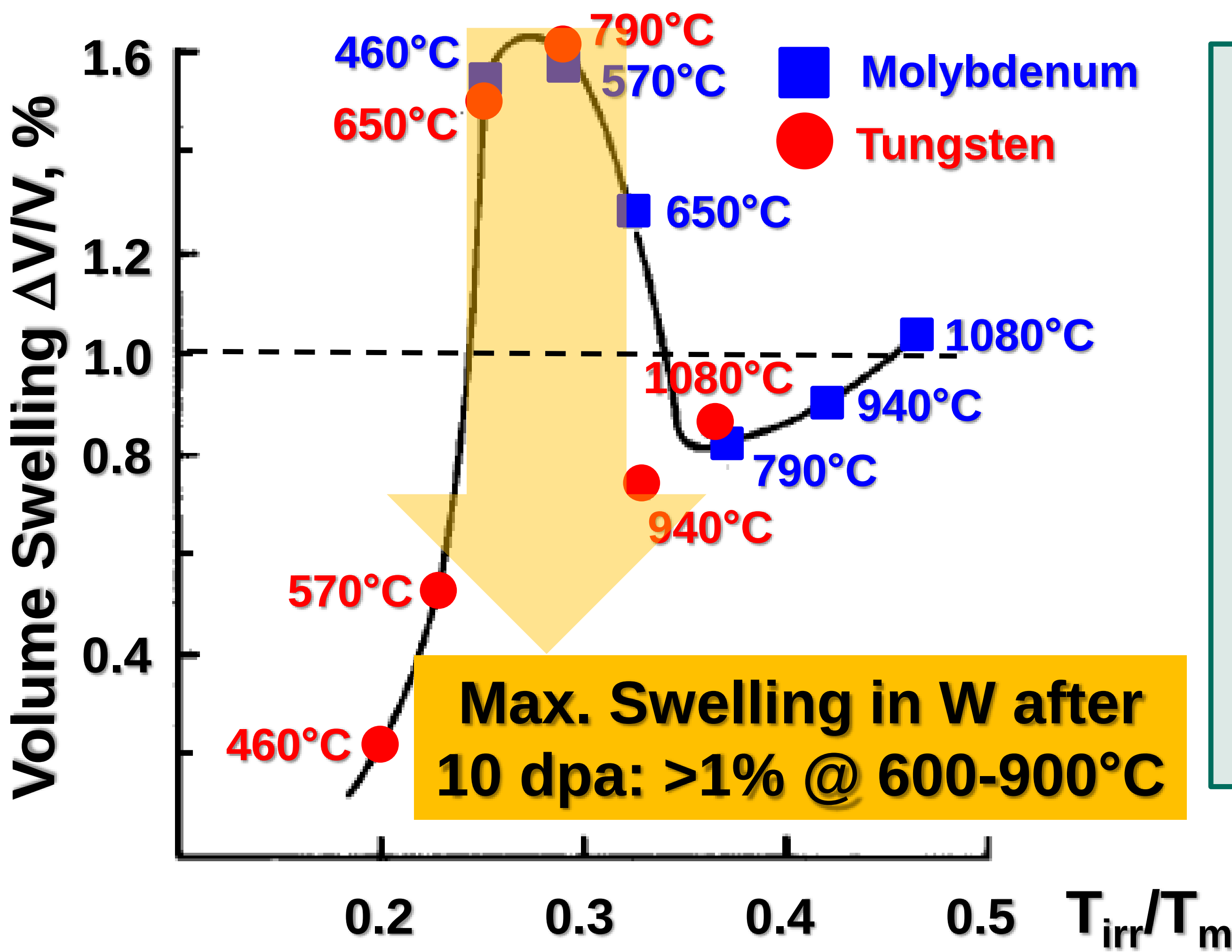


CONCLUSION

For tungsten operating at 50 atm. He coolant, at 0.1 ppm oxygen, the upper temperature is estimated at 1200-1300°C.

→ N.M. Ghoniem, 1998

IRRADIATION EFFECTS → SWELLING



EBR-II

E_n > 1 MeV
1 x 10^{22} n/cm²

E_n > 0.1 MeV
1.6 x 10^{22} n/cm²

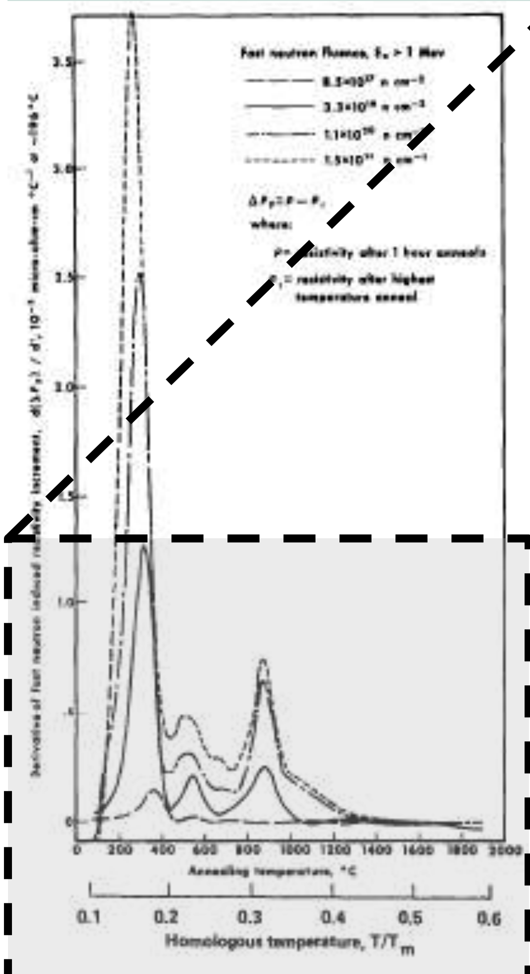
→ **29 dpa in Mo**

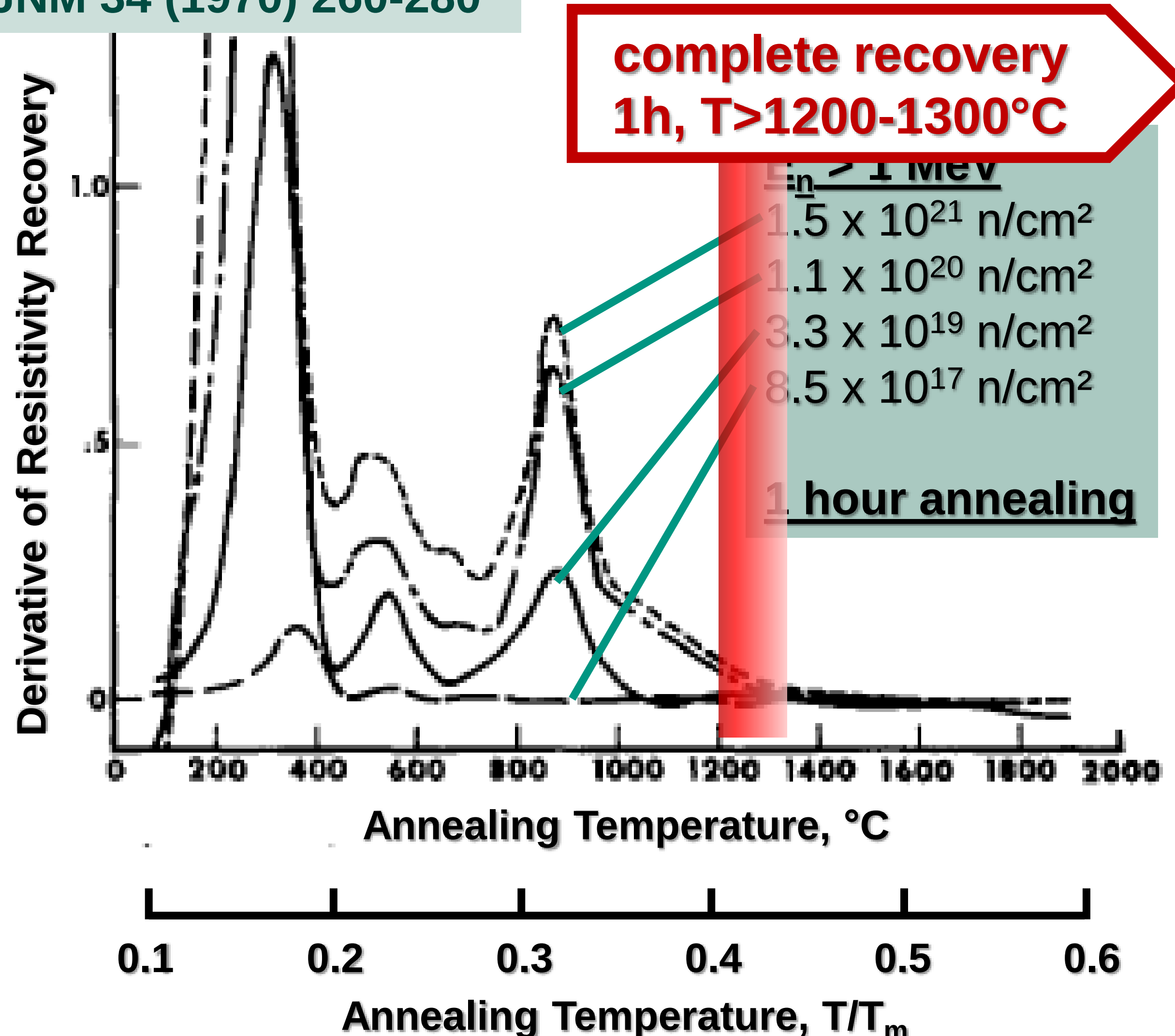
→ **9.6 dpa in W**

→ F. Lee, J. Matolich, J. Moteff, JNM 62 (1976) 115-117

IRRADIATION EFFECTS → RECOVERY

→ L.K. Keys, J. Moteff, JNM 34 (1970) 260-280

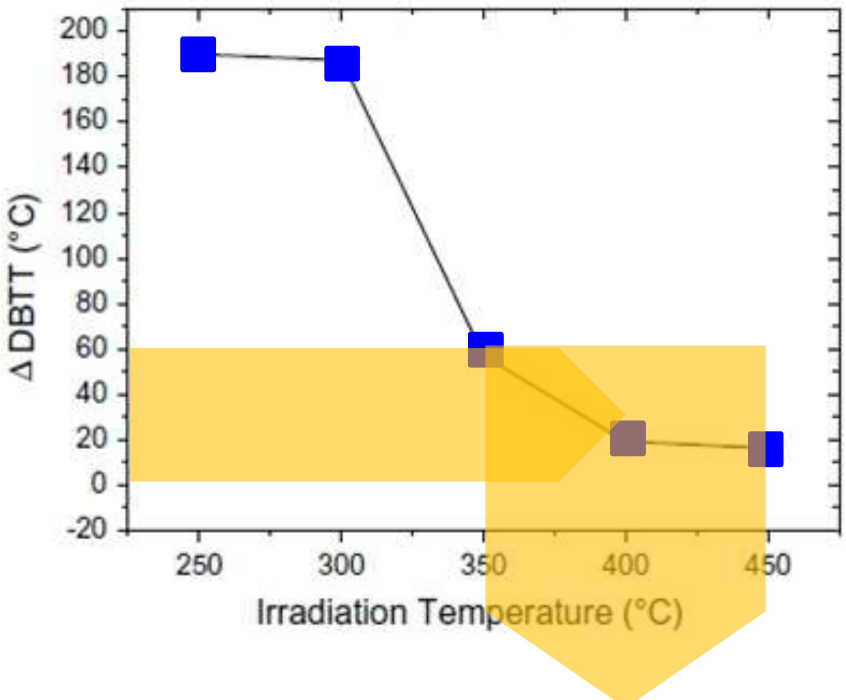




IRRADIATION EFFECTS → EMBRITTLEMENT

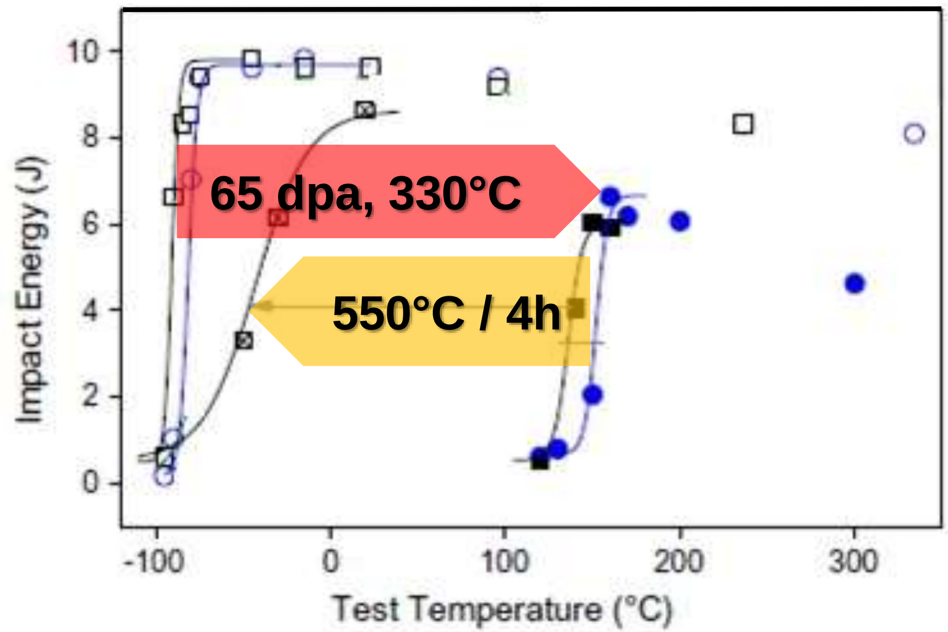
Karlsruher Institut für Technologie

EUROFER: In-service irradiation embrittlement after ~10 dpa



Possible Operating Temperature T_{op} > 350°C

EUROFER: Recovery of 65 dpa irradiation embrittlement

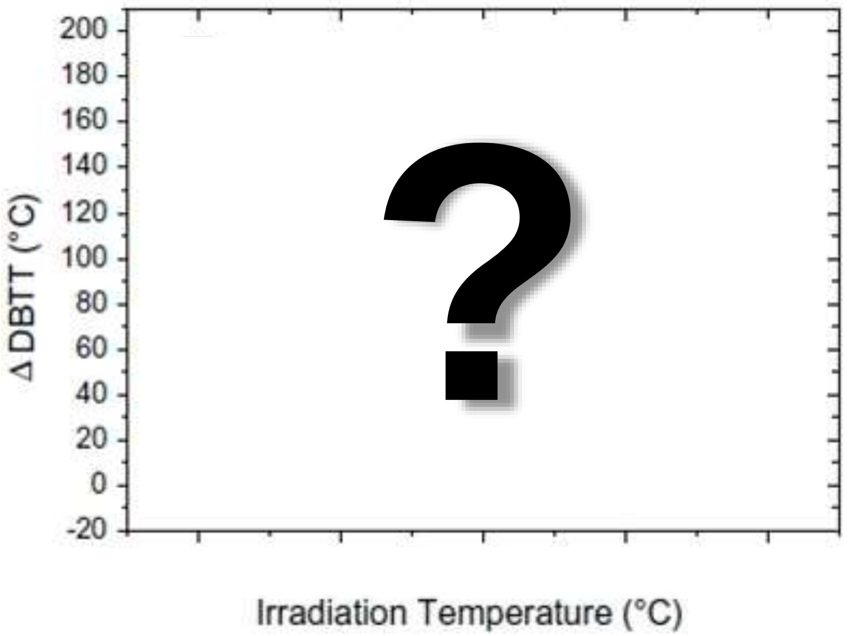


Possible Recovery Temp. T_{rec} > 550°C

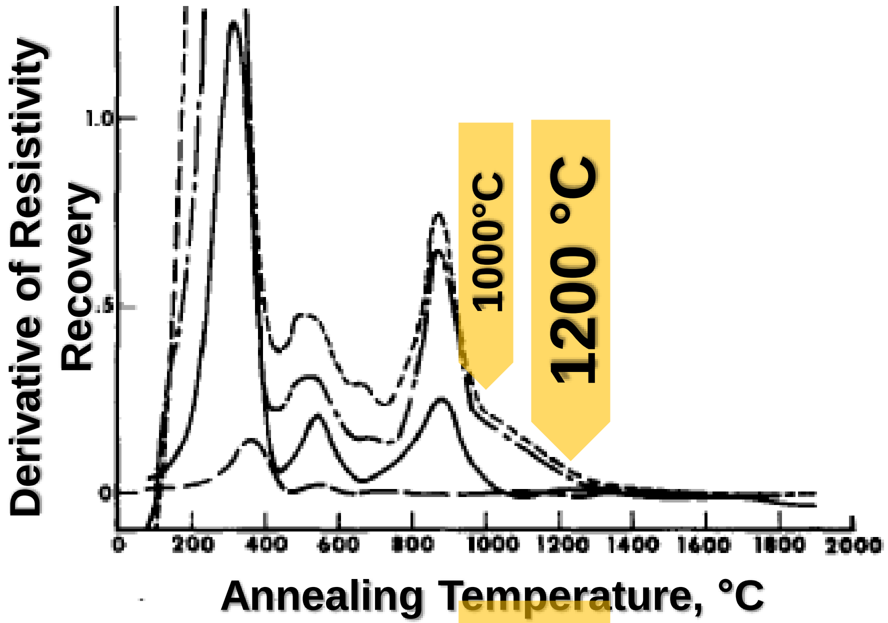
→ E. Gaganidze *et al.*, KIT

IRRADIATION EFFECTS → EMBRITTLEMENT

TUNGSTEN: In-service irradiation embrittlement after 10-20 dpa



Tungsten: Recovery of ~2 dpa stage IV irradiation hardening

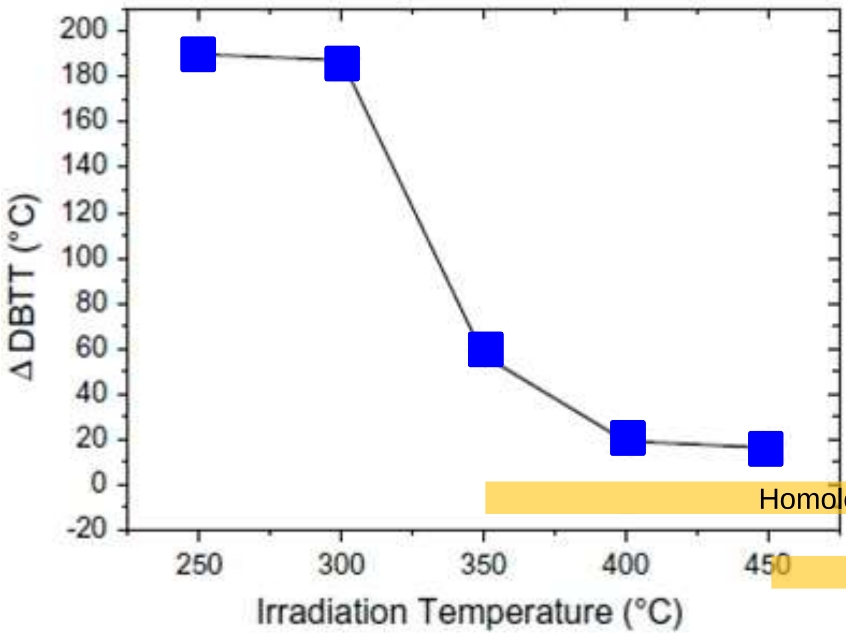


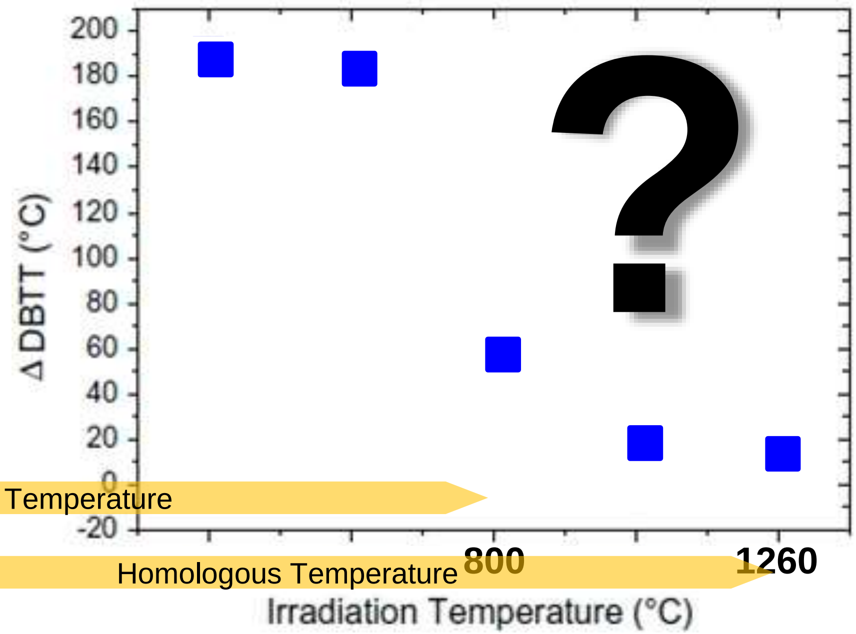
Possible Operating Temp.
T_{op} > 800°C … 1000°C

IRRADIATION EFFECTS → EMBRITTLEMENT

EUROFER: In-service irradiation embrittlement after ~10 dpa

TUNGSTEN: In-service irradiation embrittlement after ??? dpa





Fe9Cr: Possible Operating Temperature T_{op} > 350°C !!!

W: Possible Operating Temperature T_{op} > 800°C ???

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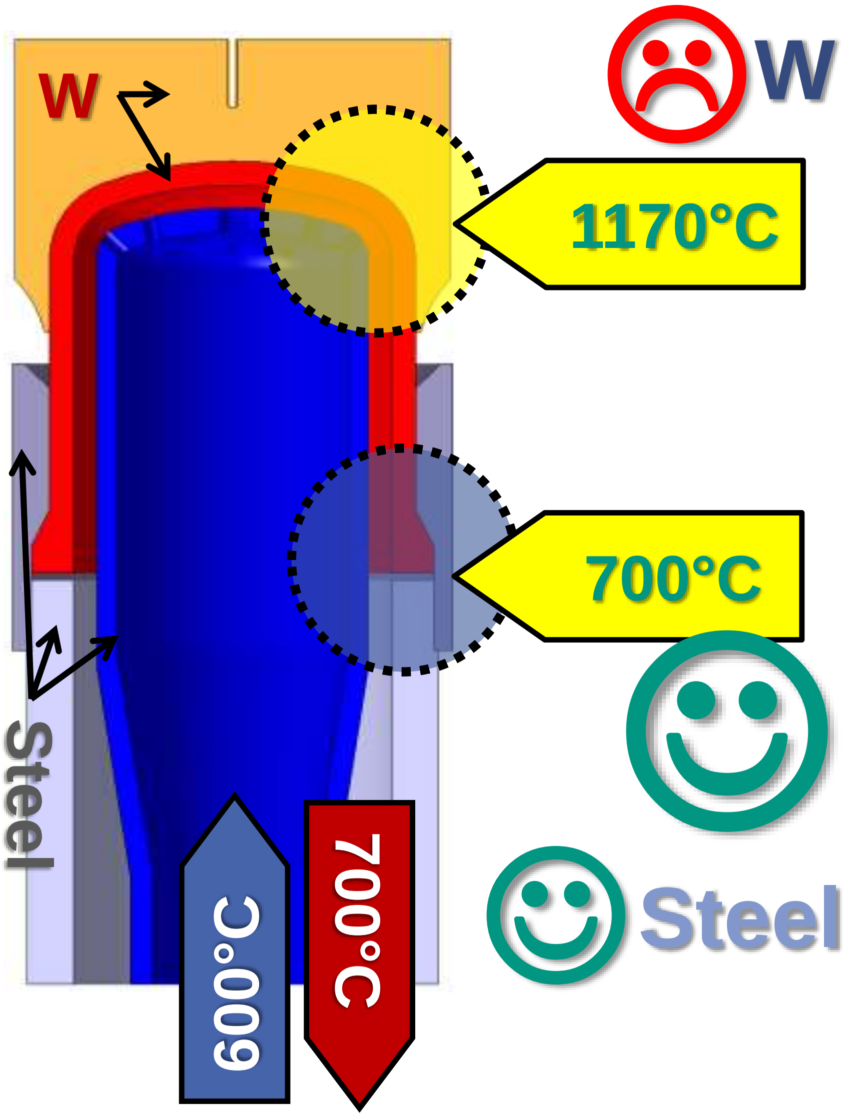
DESIGN ASSESSMENT

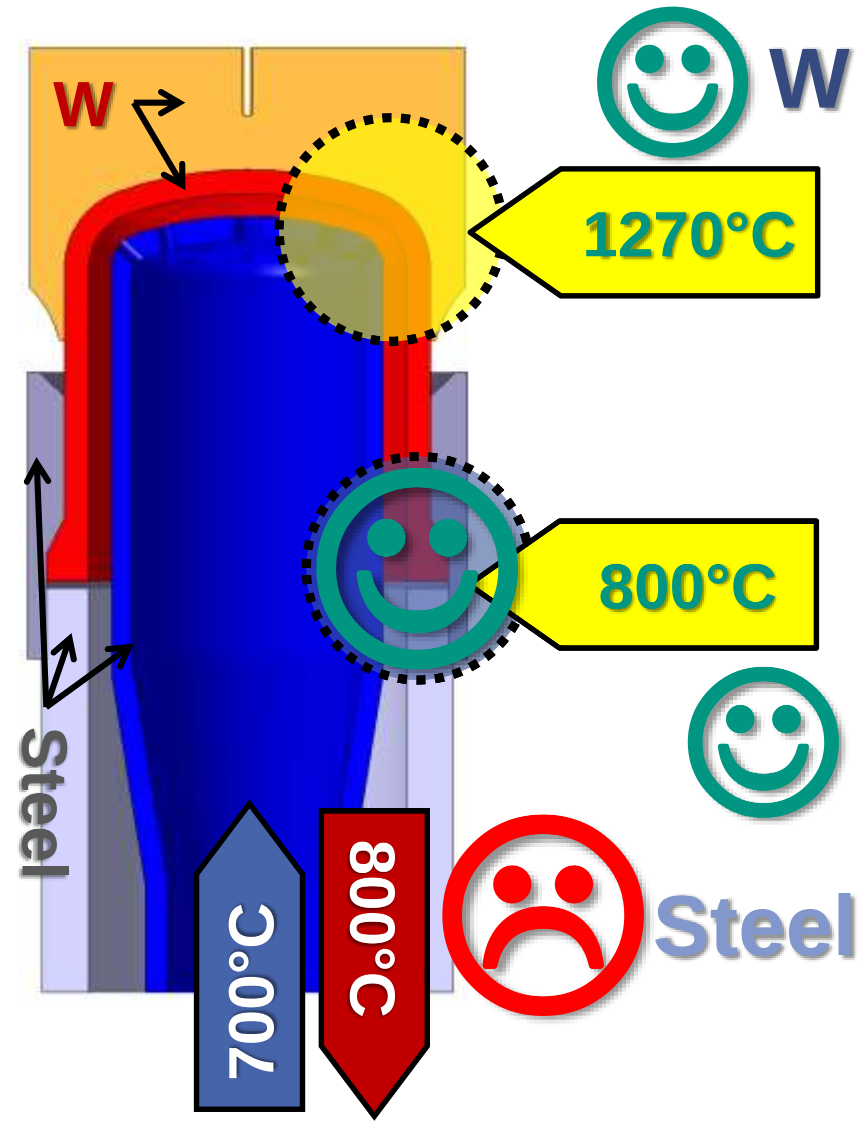
Materials / Design Window → Finger



Oxidation →	OK
Swelling ~3% →	?
Embrittlement →	OK
Grain Growth →	? (ODS)

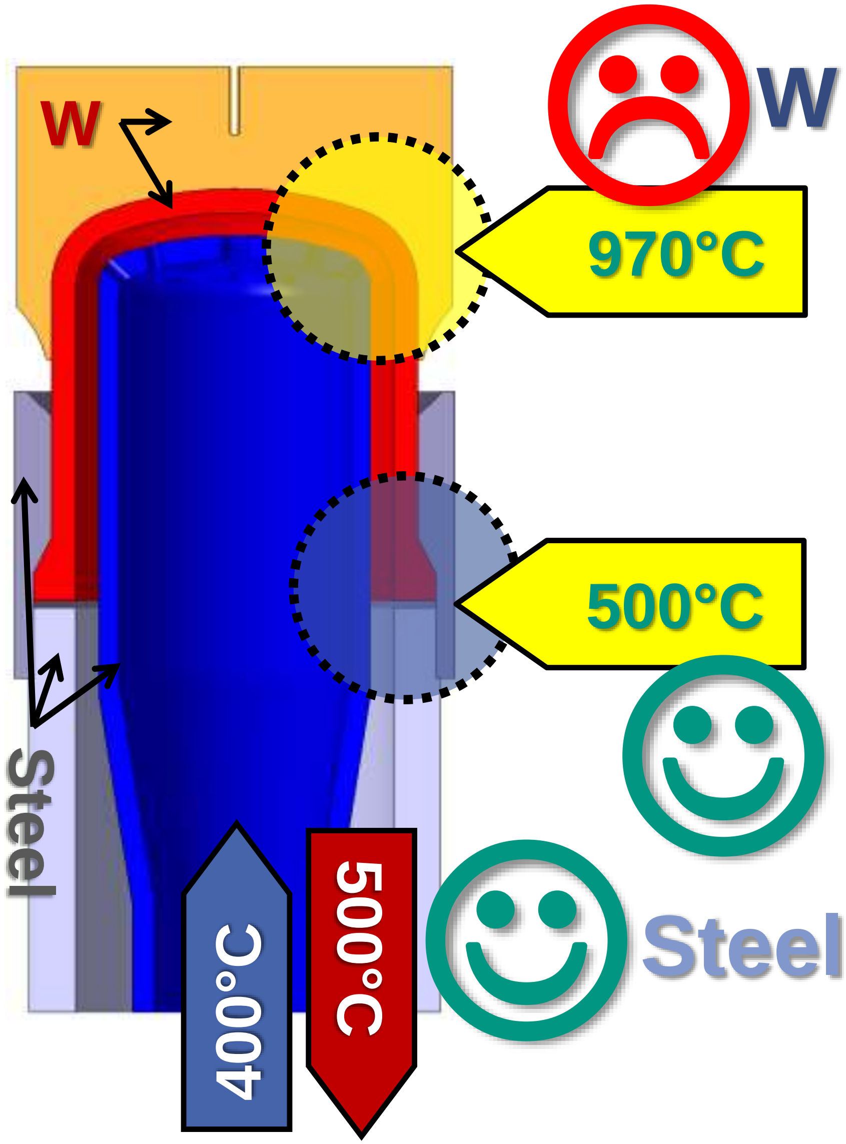
Swelling ~5% →	?
Embrittlement →	NO GO (?)
Brazing (Cu) →	OK (…)
Embrittlement →	OK
Strength, … →	? (ODS)

Materials / Design Window → Finger



Oxidation	→	OK
Swelling ~3%	→	?
Embrittlement	→	OK
Grain Growth	→	ODS
Swelling ~5%	→	?
Embrittlement	→	OK (tbc)
Brazing (Cu)	→	OK (…)
Embrittlement	→	OK
Strength, …	→	ODS ???

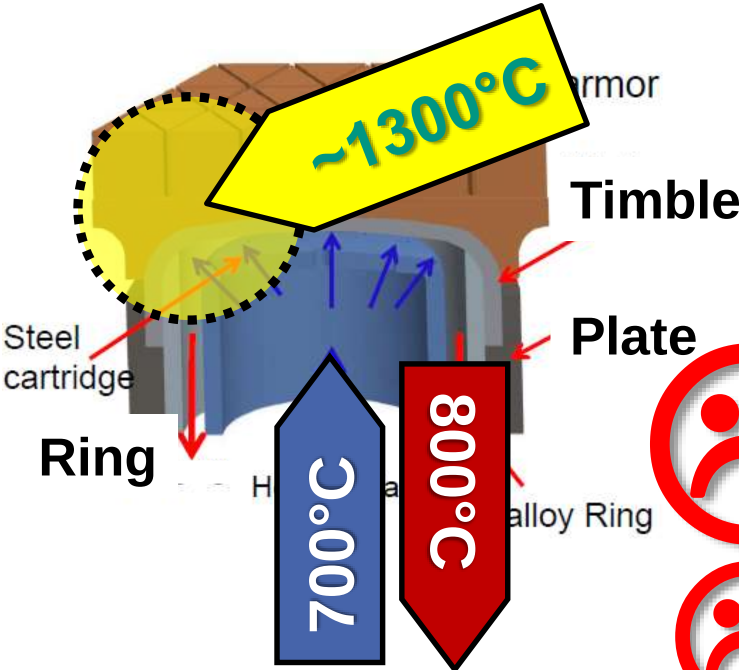
MATERIALS / DESIGN WINDOW → FINGER

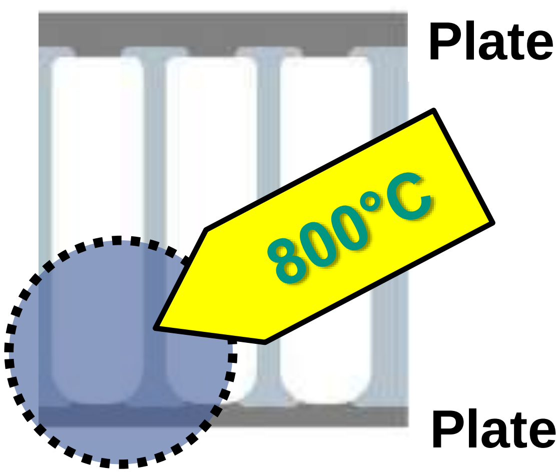


Oxidation →	OK
Swelling <3% →	OK (?)
Embrittlement →	OK
Grain Growth →	OK

Swelling <2% →	OK (?)
Embrittlement →	NO GO
Brazing (Cu) →	OK (…)
Embrittlement →	OK
Strength, … →	OK

MATERIALS / DESIGN WINDOW → PLATE





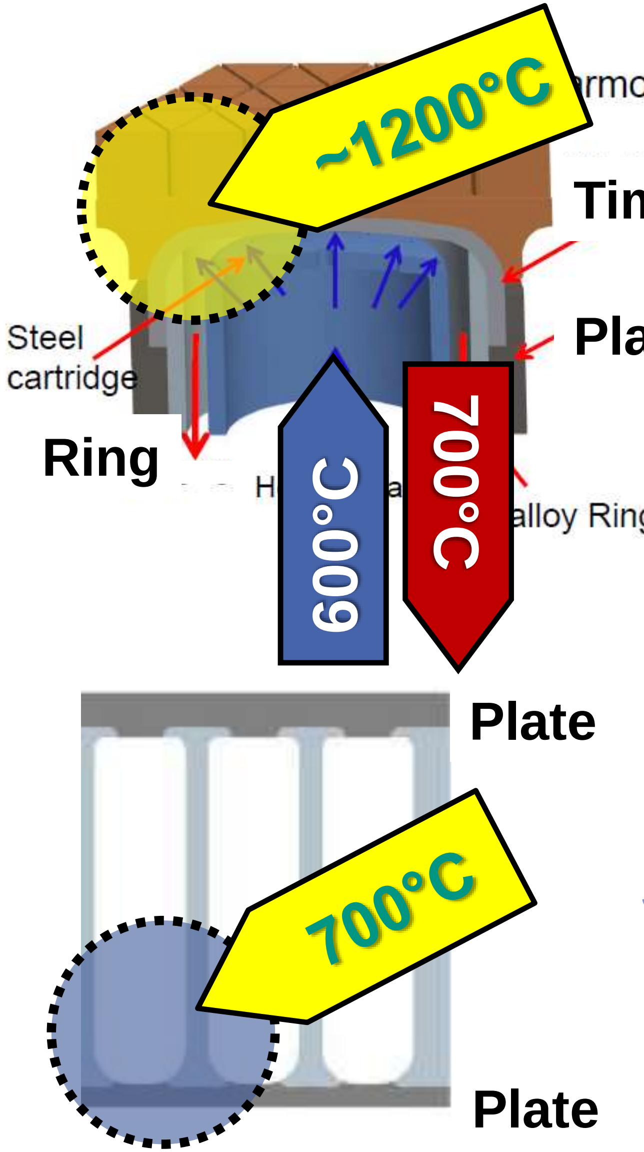
W

Oxidation →	OK
Swelling ~3% →	???
Embrittlement →	OK
Grain Growth →	ODS
Brazing W→W →	Pd, Pt ???
Swelling ~5% →	?????
Embrittlement →	OK (tbc)

Steel

Embrittlement →	OK
Strength, … →	ODS ???

MATERIALS / DESIGN WINDOW → PLATE



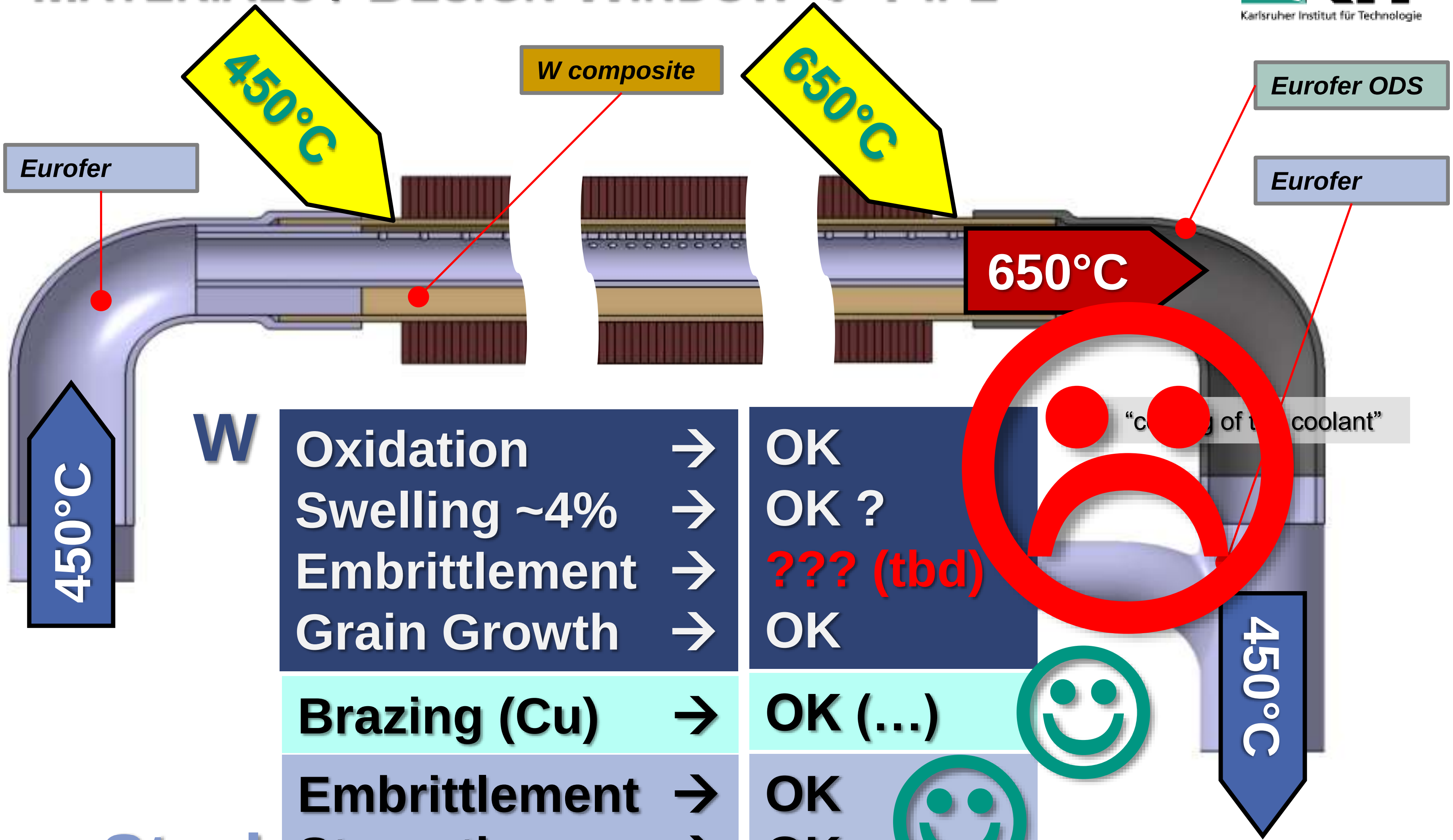
W

Oxidation →	OK
Swelling ~3% →	???
Embrittlement →	OK
Grain Growth →	? (ODS)
Brazing W→W →	**Pd, Pt ???**
Swelling ~5% →	?????
Embrittlement →	NO GO (?)

Steel

Embrittlement →	**OK**
Strength, … →	**? (ODS)**

MATERIALS / DESIGN WINDOW → PIPE



W	Oxidation	→	OK
	Swelling ~4%	→	OK ?
	Embrittlement	→	??? (tbd)
	Grain Growth	→	OK
	Brazing (Cu)	→	OK (…)
Steel	Embrittlement	→	OK
	Strength, …	→	OK

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SUMMARY AND PATH FORWARD

SUMMARY

→ Thin plates (<4 mm) of pure W (including small amounts of grain stabilizers, if necessary) are the most suitable sem… d products for structural applications !

→ The microstructure … contour of the accordi… ome fabrication pr… be developed) !

→ Co… can be used as brazing material for W-steel joints, but needs additional strengthening by desing !

Specific Design Rules for Structural Tungsten Components

→ Suitable structural W-W joints are not yet demonstrated and characterized ! → Pt, Pd, …?

→ W irradiation data needed for design (determination of lowest possible operating temperature) !!!