TUNGSTEN

Properties, possible and impossible applications

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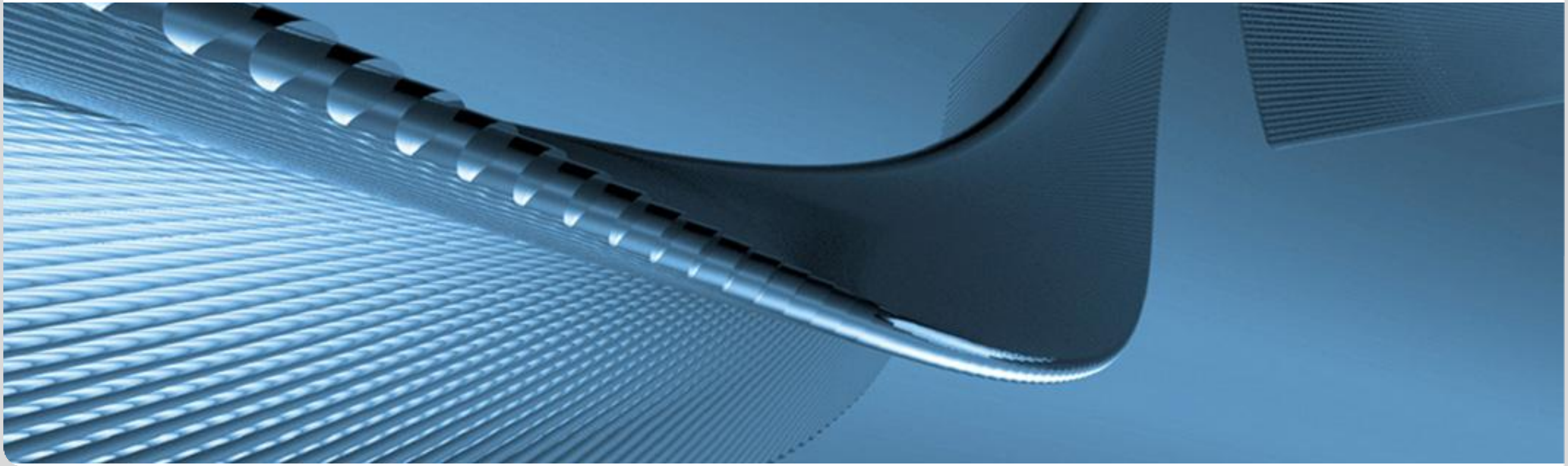

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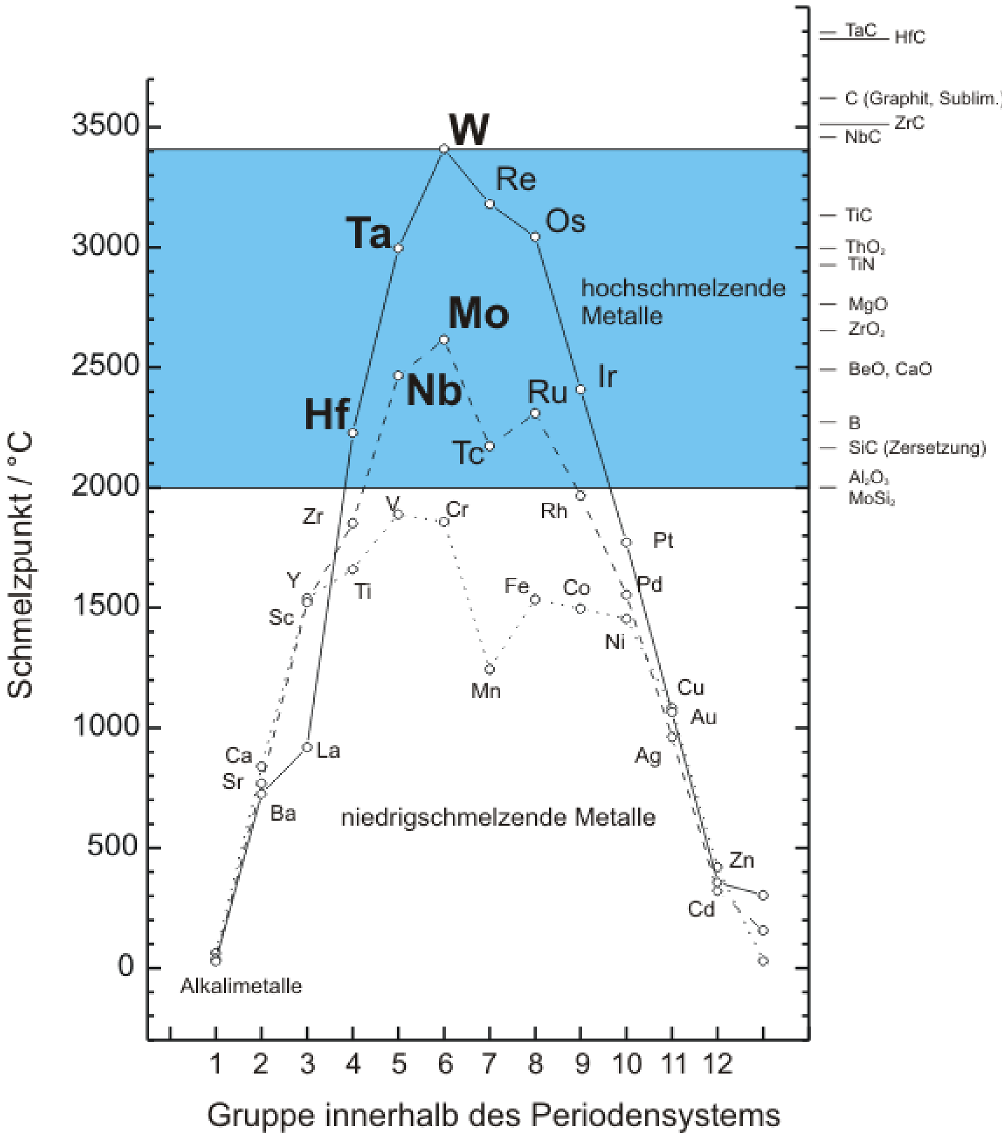
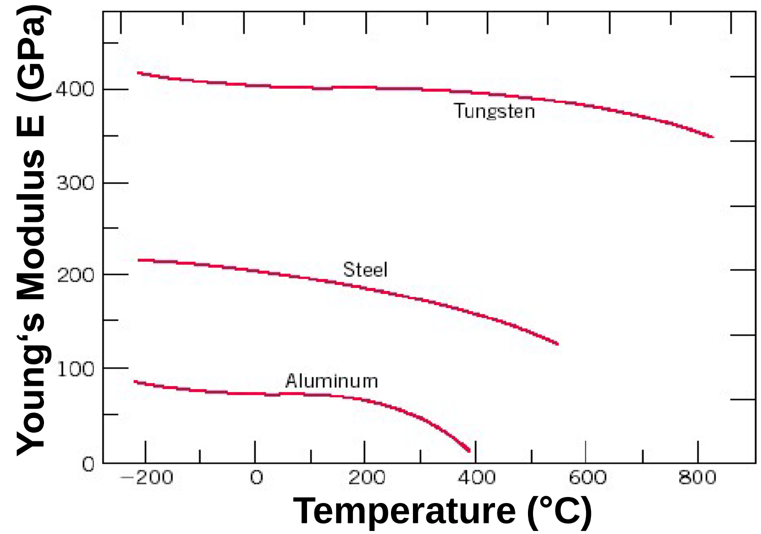
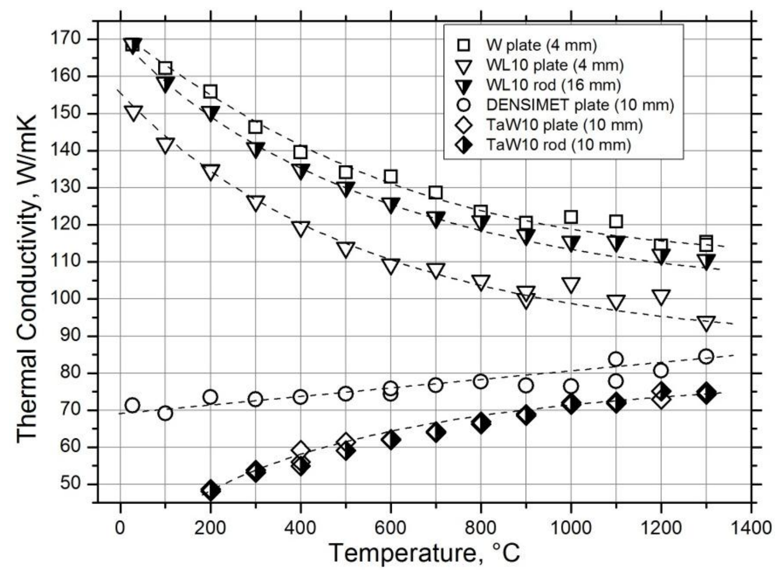
Tungsten Basics

BASIC PROPERTIES







BASIC PROPERTIES

$^{183.85}_{74}W$

Stable isotopes	W182, 183, **184**, 186, (180)
Density	19.3 g/cm³
Crystal structure	body centered cubic (bcc)
Super conductor	T_j = 15 mK

Reactions with Non-metals

C	>800 °C	W_2C, WC
P	>700 °C	WP_2
As	>600 °C	WAs_2
O	>400 °C	WO_3 (sublim. at 800 °C)
S	>400 °C	WS_2
Se	>480 °C	WSe2 (exothermic)
F	>RT	WF_6 (volatile)
F+O	>RT	WOF_4
Cl	>250 °C	WCl_6 ($WOCl_4$, WO_2Cl_2)
Br	>450 °C	$WBr_{6,5,4}$
I	>550 °C	W_6I_{12}

Reactions with Acids/Alkalis

Reagent	20 °C	100 °C
HF	none	none
HNO_3	slight attack	oxidation
H_2SO_4	none	slight attack
HCl	none	slight attack
H_3PO_4	none	slight attack
H_2O_2	none	dissolution
NH_4OH	none	none
KOH	none	none
NaOH	none	none
HCl+HNO_3	oxidation	dissolution
HF+HNO_3	dissolution	dissolution
KOH+H_2O_2	slight attack	dissolution

Basic Properties

Reactions with Compounds

H_2O	>RT	$WO_2(OH)_2$ (volatile)
NH_3	>600 °C	>3.5wt.% N → fcc W_2N, γ-W_3N_4
HF	<600 °C	only little corrosion
	>600 °C	volatile WF_6
HCl	<700 °C	stable
H_2S	>350 °C	$WS_2 + 2H_2$
SO_2	300 °C	$WO_3 + S_2$
CO	80-200 °C	tungsten hexacarbonyl
	>1000 °C	$W_2C + CO_2$ (bulk tungsten)
SiO_2	>2000 °C	slight oxidation
SiC	>1100-1900 °C	WC and WSi
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

"REASONABLE" ALLOYING ELEMENTS FOR W

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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

Tungsten Materials

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Pure Tungsten

Grain Stabilized Tungsten „ODS Tungsten“

Potassium Doping

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.

„Heavy Metals“ (Two Phases)

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

→ Functional Applications

Alloys (Solid Solution)

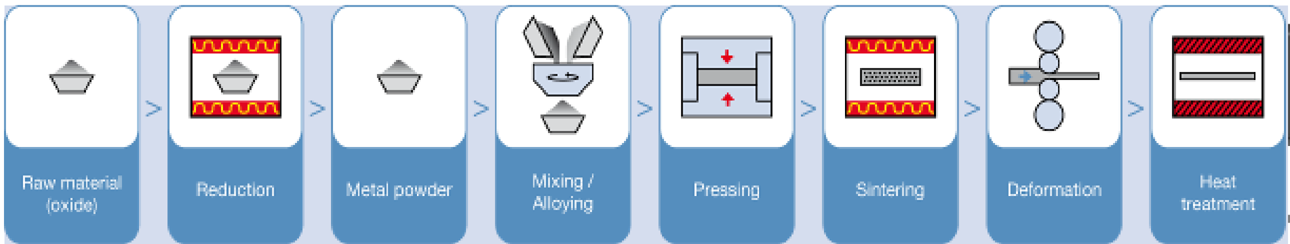
- W-Re (<26%)

→ only commercial alloy

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

→ Even more brittle as pure tungsten !!!

PRODUCTION ROUTES



- Blending
- Pressing
- Sintering
- Hot Forming

This is so far the only large-scale production route which could handle <u>500 tons of W</u> (or more) needed for power plant applications.

- Blending with Binder
- Injection Molding
- Debindering/Sintering
- HIP

+ Mass Production
+ Nearly Finished Products
+ Homogenous Microstructure

→ *S. Antusch, KIT*
→ *J. Opschoor, ECN*

- Ball Milling
- Encapsulat
- HIP/Hot Formir

+ Na cture
+ D y

all Scale
roduction Route

only in very small amounts

→ *H. Kirushita, IMR*
→ *N. Baluc, PSI*
→ *A. Muñoz, CIEMAT*

COMMERCIAL PRODUCTION ROUTE

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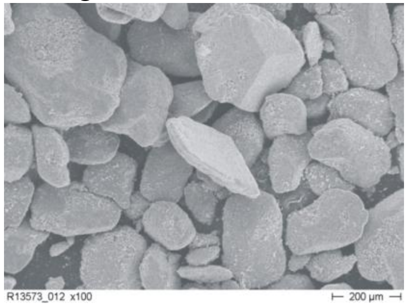
WO_3 powder



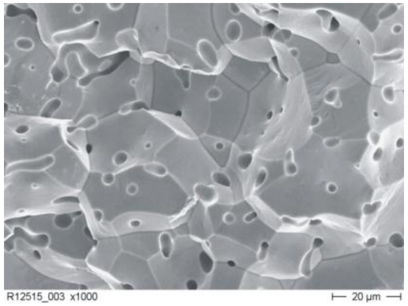
powder reduction

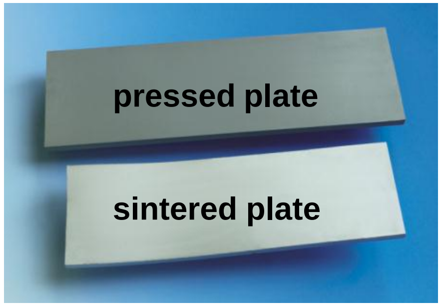
W powder

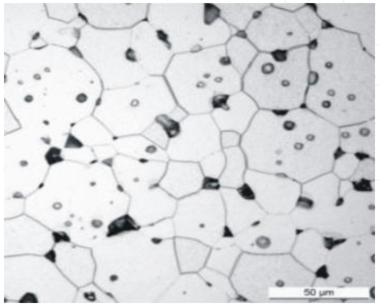
pressing sintering

sintered W part
(fracture surface)

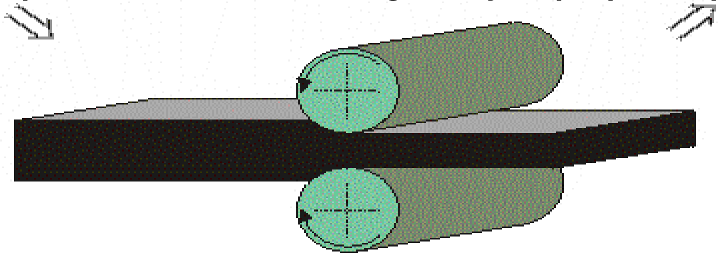
PLANSEE



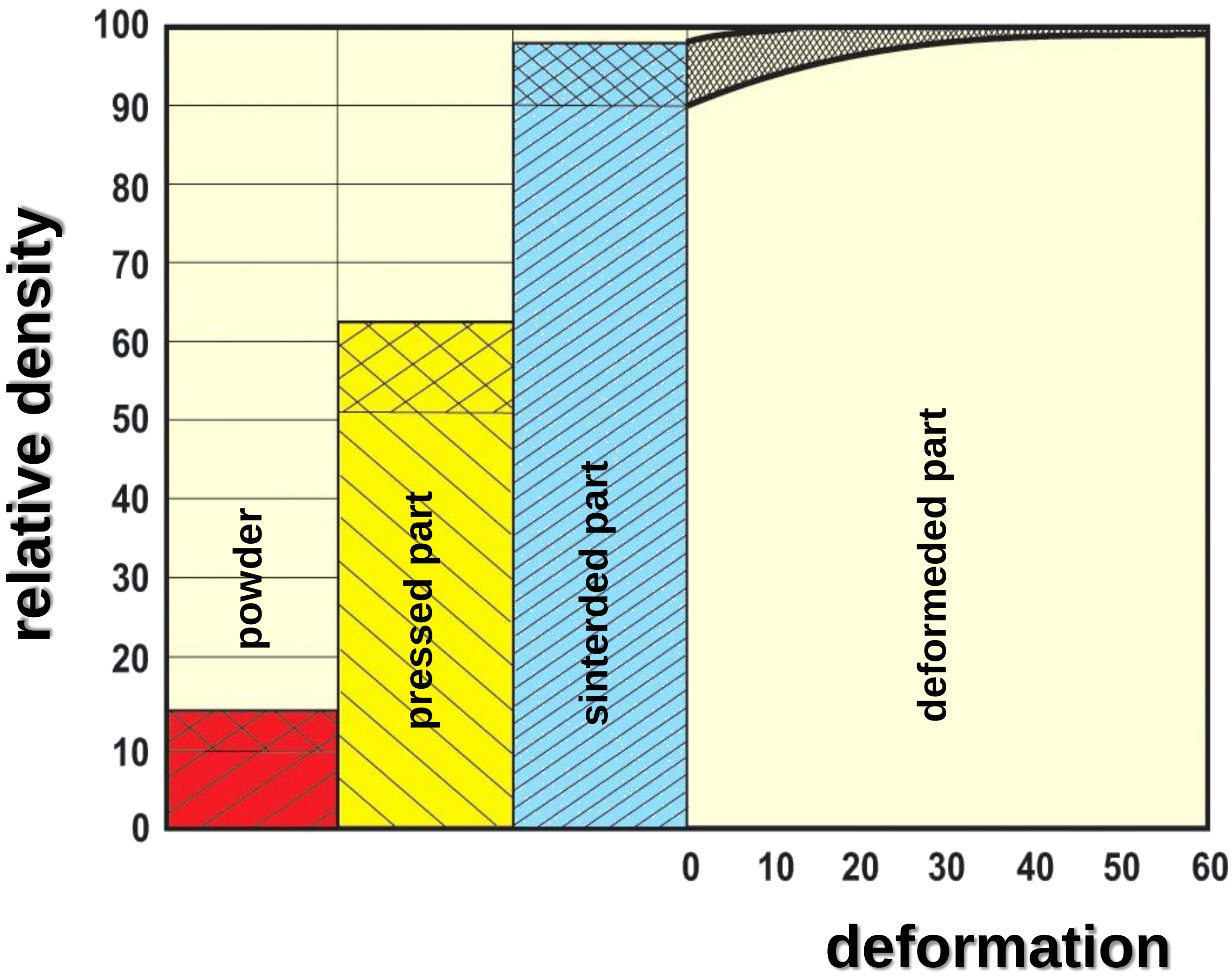




thermomechanical treatment
(deformation & annealing to adjust properties)



COMMERCIAL PRODUCTION ROUTE



COMMERCIAL SEMI-FINISHED W PRODUCTS

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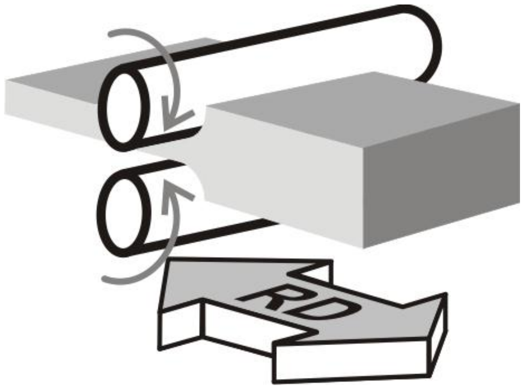
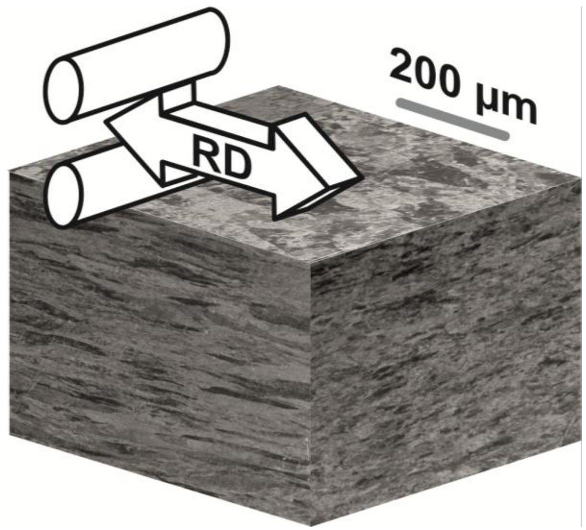
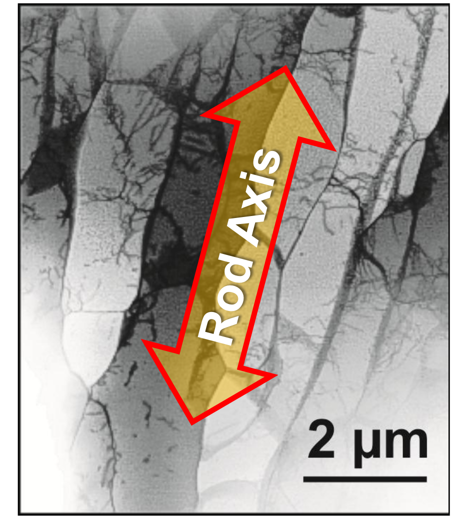
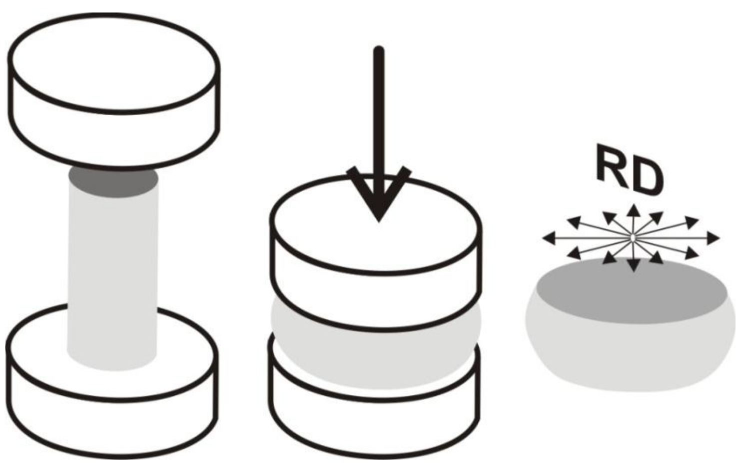
Rolling Plates



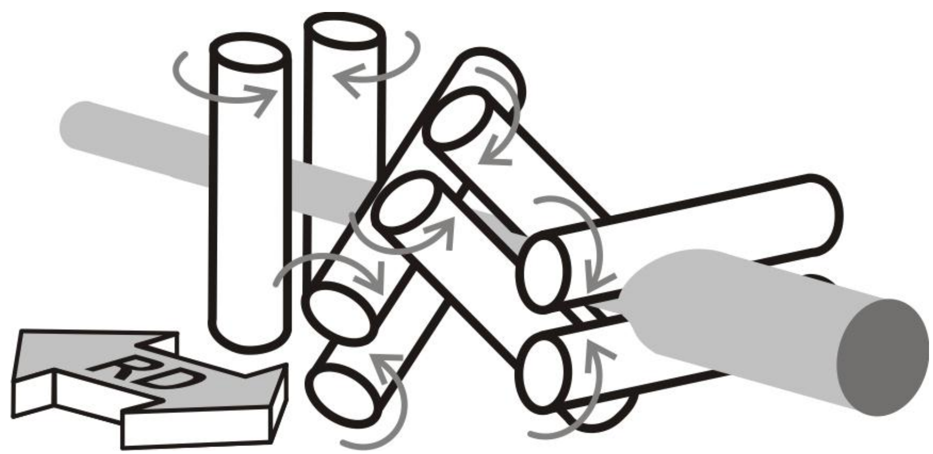




Forging Round Blanks



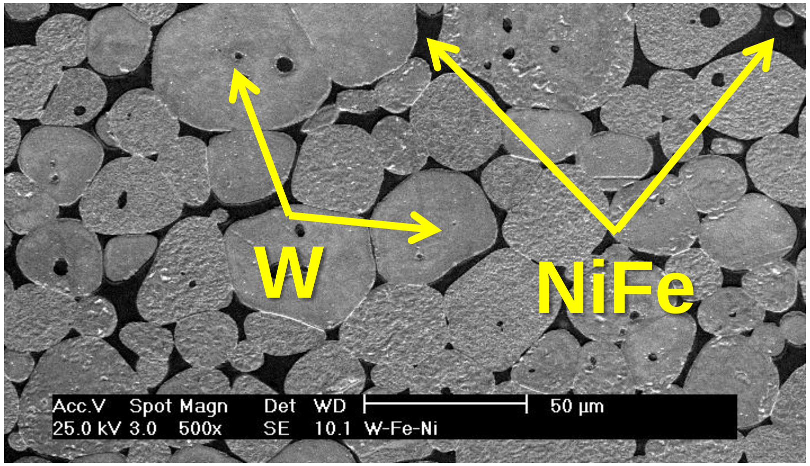
Rolling/Swaging Rods



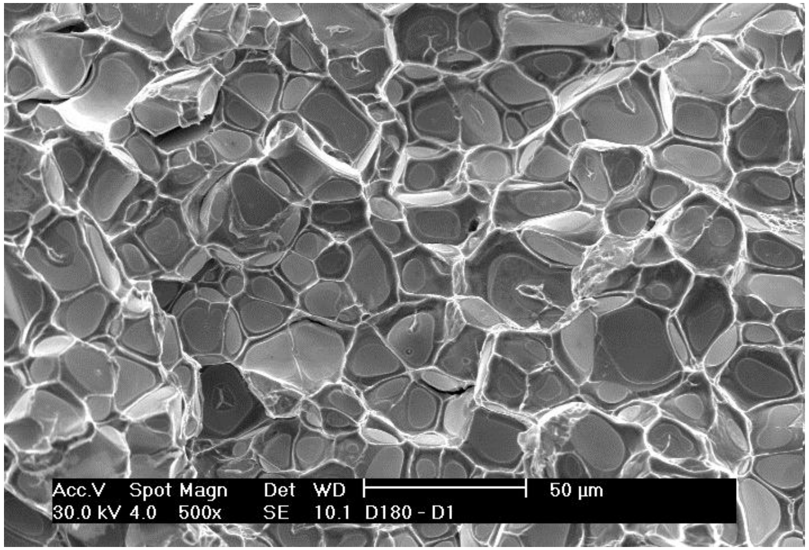
MICROSTRUCTURE OF "HEAVY METALS"

KIT
Karlsruher Institut für Technologie

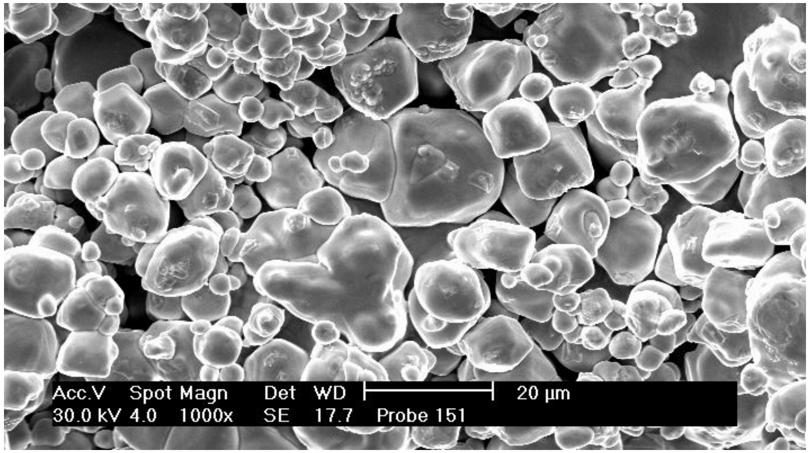
DENSIMET D180, W-3.5Ni-1.5Fe



Cold fracture surface



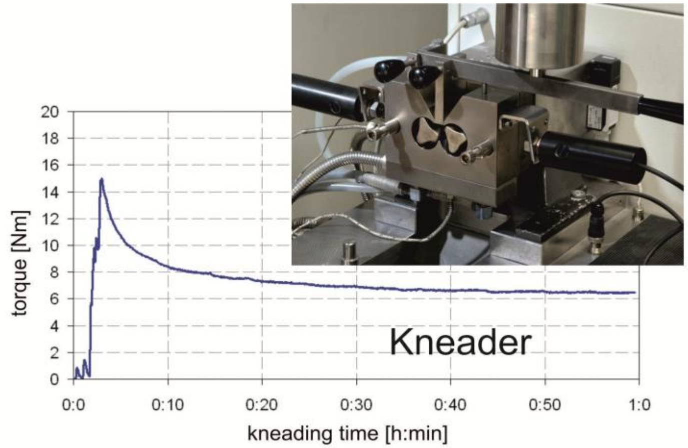
W-Cu, hot fracture surface



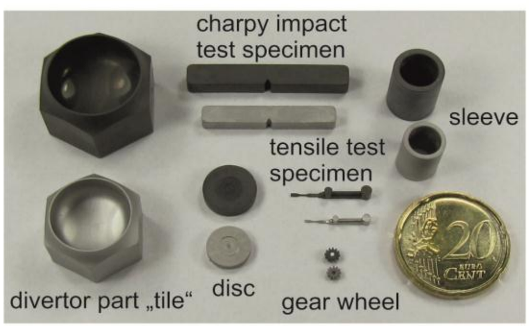
DENSIMET D180	
Density	18 g/cm³
Young's mod.	380 GPa
Therm. Cond.	83 W/mK
Therm. Exp.	$5.5x10^{-6}$/K
ferromagnetic	

POWDER INJECTION MOLDING

Powder + Binder



Feedstock



Green parts (dark)
Finished parts (bright)

debinding; pre-sintering + HIP

Injection molding of green parts

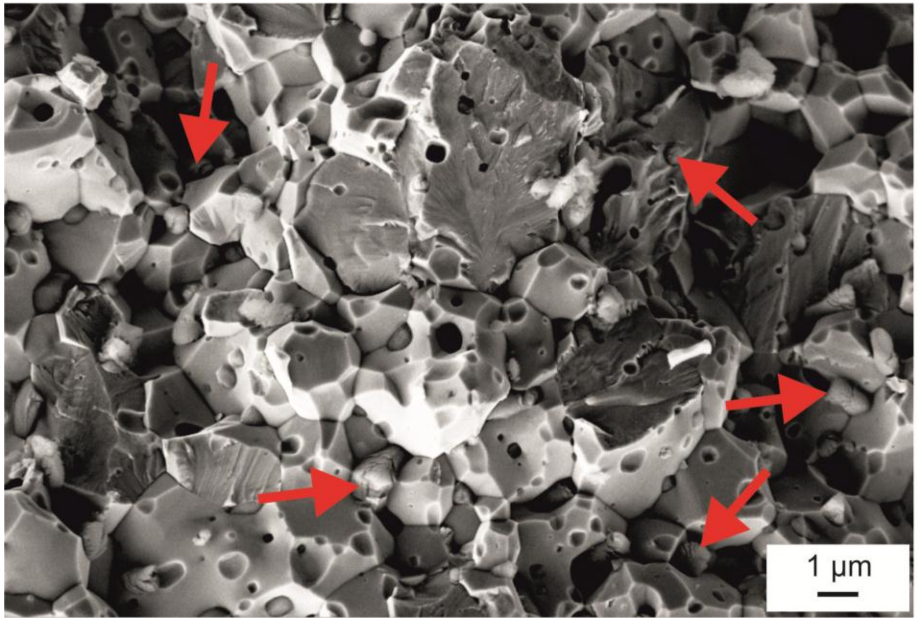
→ S. Antusch, IAM-WPT, 2011

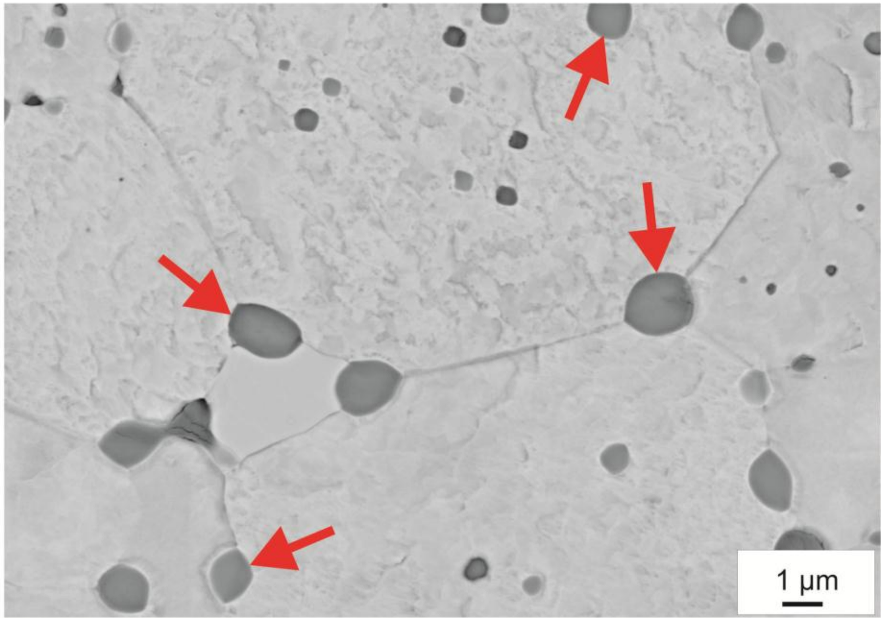
POWDER INJECTION MOLDING

Materialherstellung:
Mechanisches Legieren (Dotieren)
- 2 h / n-Hexan / ZrO_2 Kugeln/Becher

Thermische Prozessführung:
- Vor-Sintern (1800 °C, 2 h, H_2) **+**
- HIP Prozess (2100 °C, 2500 bar, 3 h, Ar)

W-2La_2O_3 / W-2Y_2O_3 / W-1TiC…





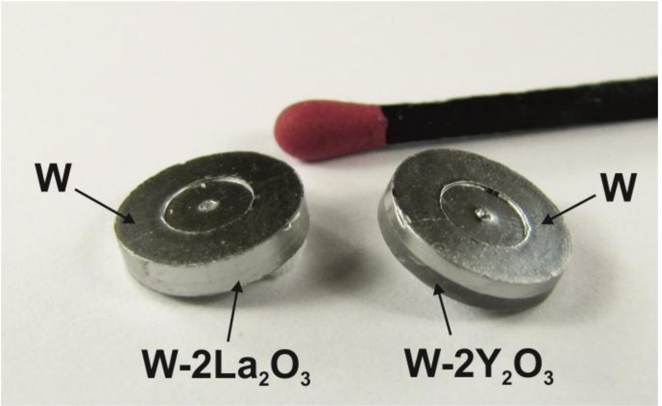
SEM Mikrostruktur (Bruchfläche) und Schliffbild für W-2La_2O_3, die Pfeile zeigen La_2O_3-Partikel

Material-Eigenschaften:
Vickers-Härte: 586HV0.1
Dichte: 96.5 – 97.2 % TD

→ **S. Antusch, IAM-WPT, 2011**

Powder Injection Molding

Materialherstellung:
Mechanisches Legieren (Dotieren)
- 2 h / n-Hexan / ZrO_2 Kugeln/Becher



$W+W-2La_2O_3$ / $W+W-2Y_2O_3$ / W+W-1TiC…

Thermische Prozessführung:
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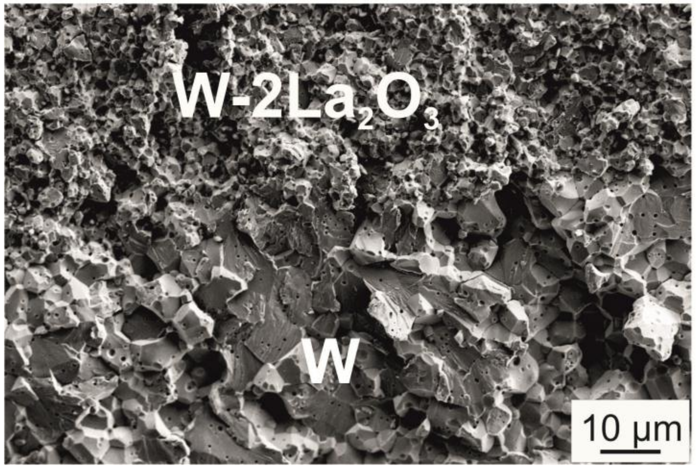
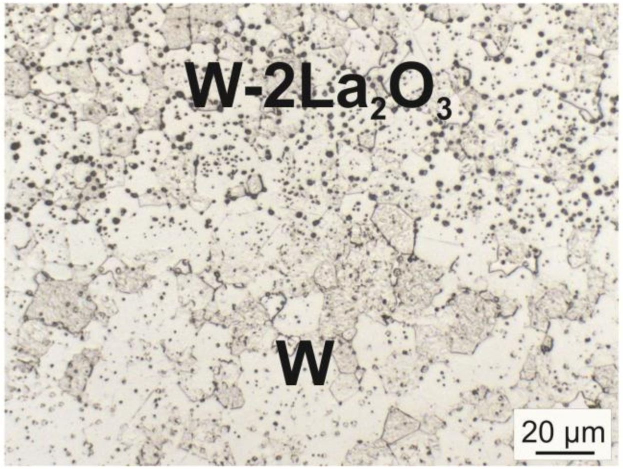
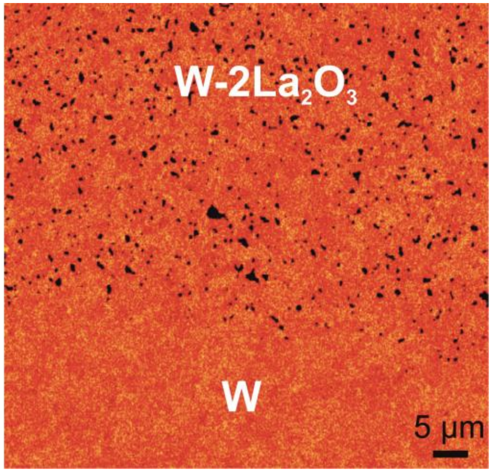






SEM Mikrostruktur (Bruchfläche) $W+W-2La_2O_3$

SEM Mikrostruktur (Schliff) und AES-Map $W+W-2La_2O_3$

Rot: W
Schwarz: La_2O_3

⇒ Fügezone: frei von Rissen und Spalten √

⇒ Materialverbund erfolgreich √

→ S. Antusch, IAM-WPT, 2011

2

PRODUCTION, RESOURCES, APPLICATIONS

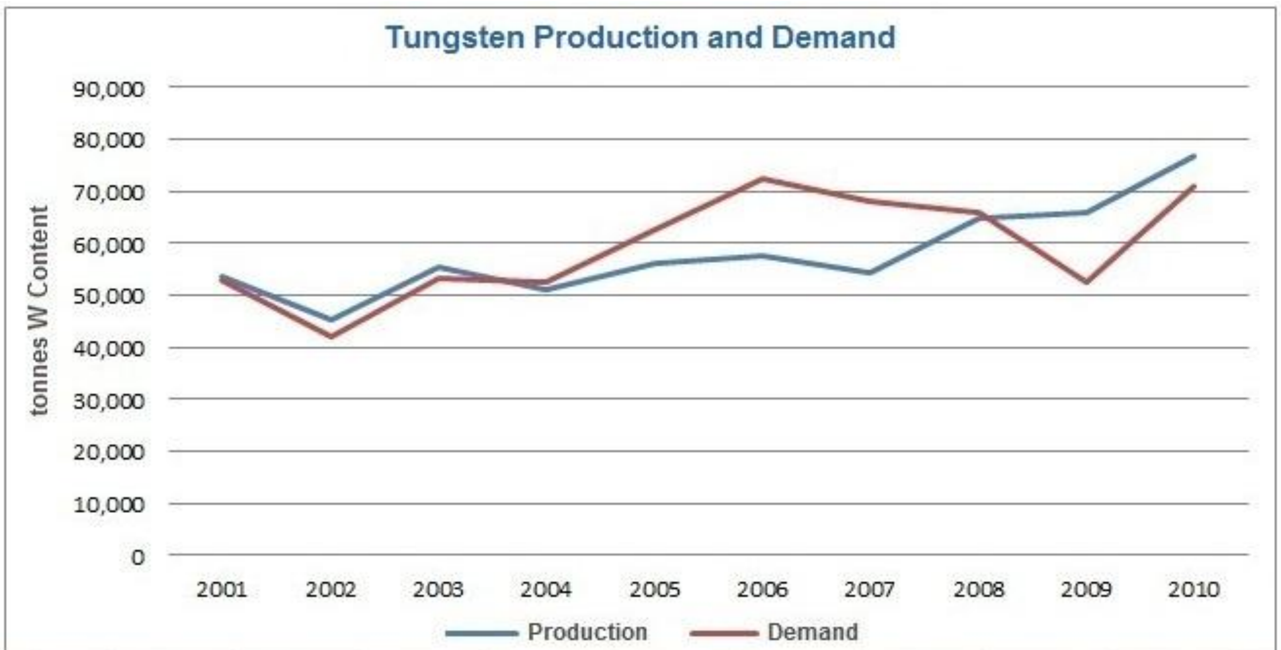
PRODUCTION

Country/Continent	Production (tonne W)	Country/Continent	Production (tonne W)
China	67,000	Peru	550
Russia	2,800	Canada	400
Bolivia	1,200	Thailand	250
Vietnam	1,150	Brazil	250
Austria	1,000	Spain	250
Portugal	800	Mongolia	200
Africa	800	Other	200

Source: ITIA

鎢

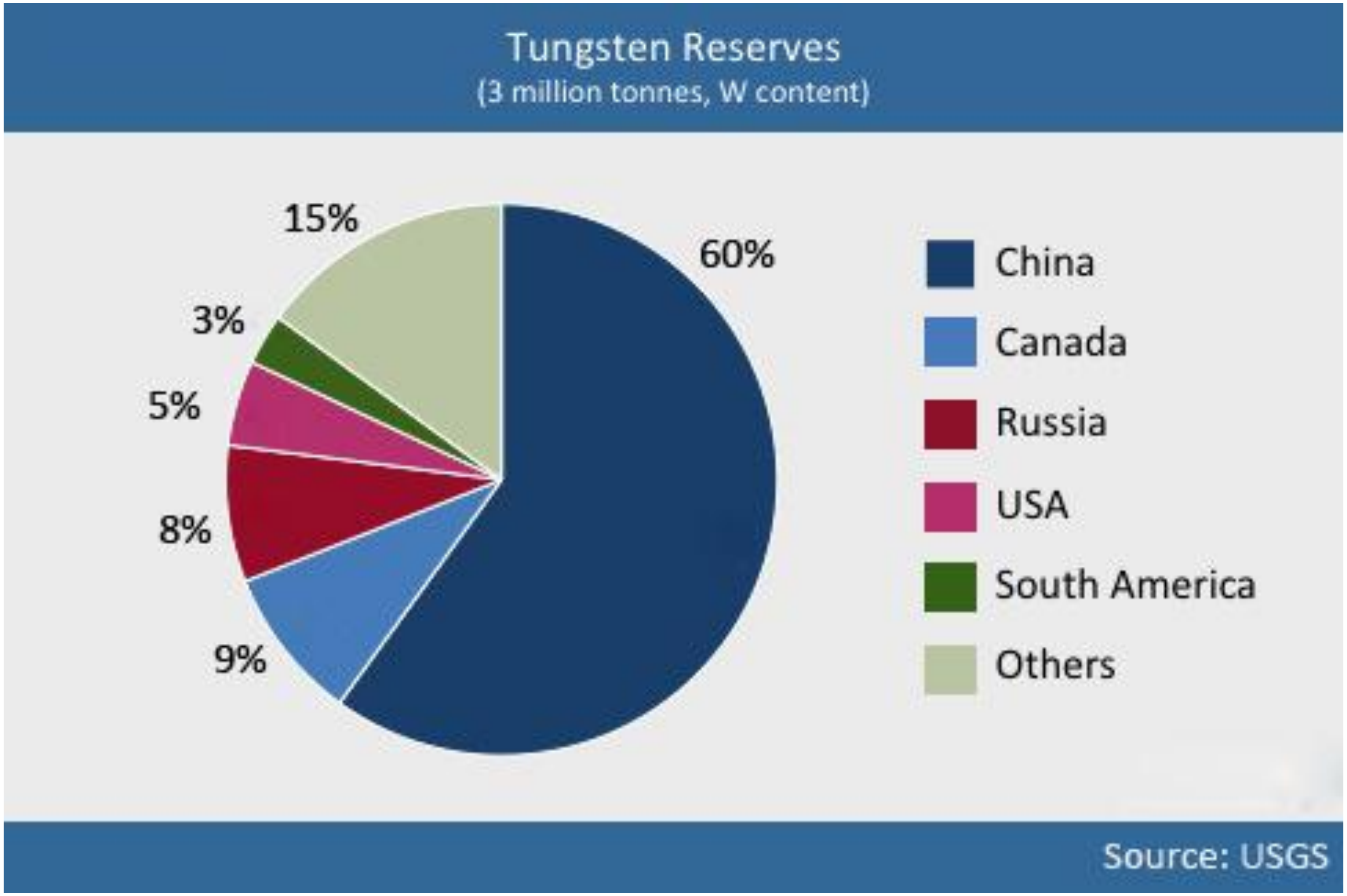
Chinese character for tungsten



Source: ITIA

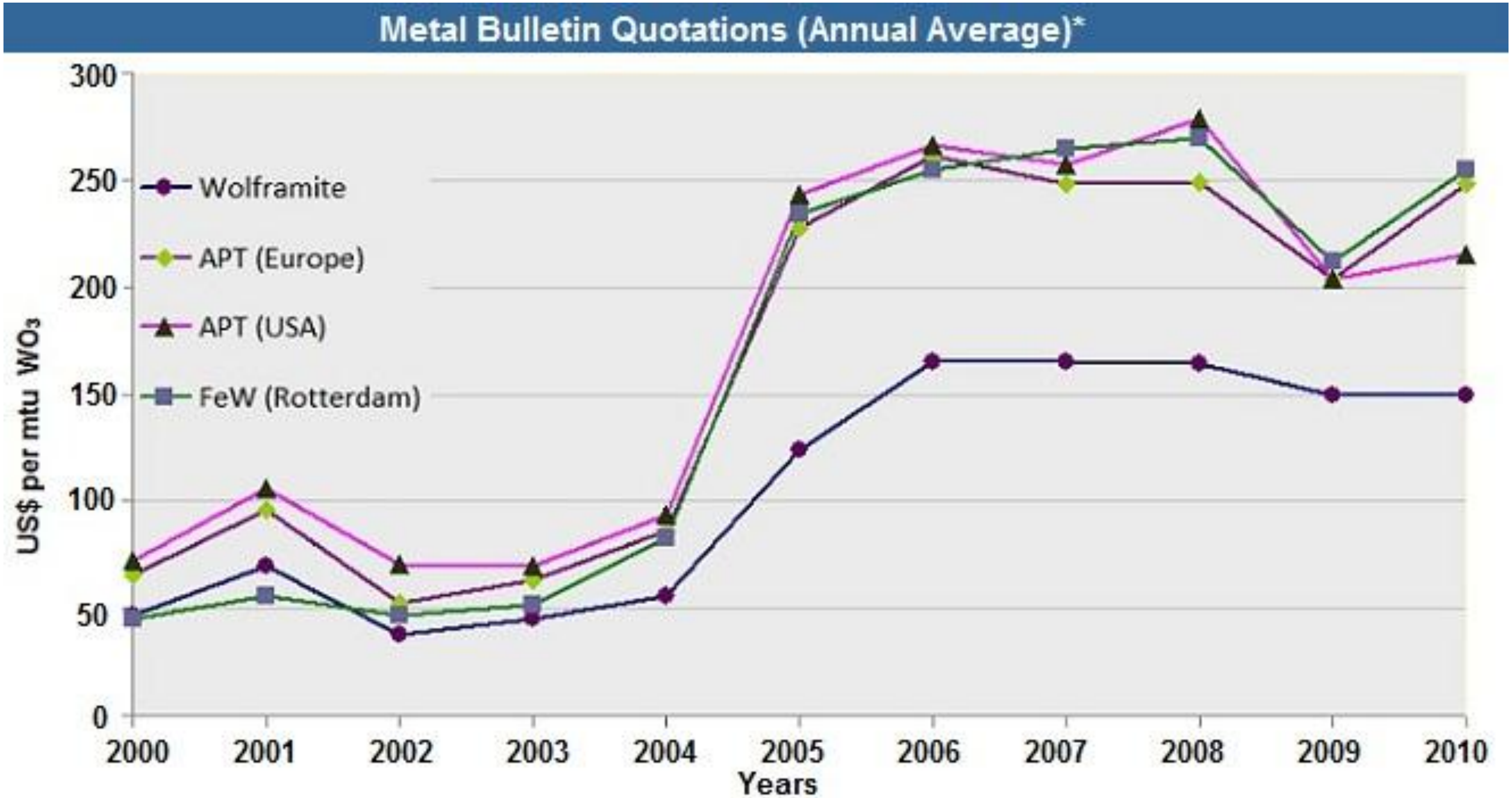
INTERNATIONAL TUNGSTEN INDUSTRY ASSOCIATION

RESERVES



U.S. Geological Survey

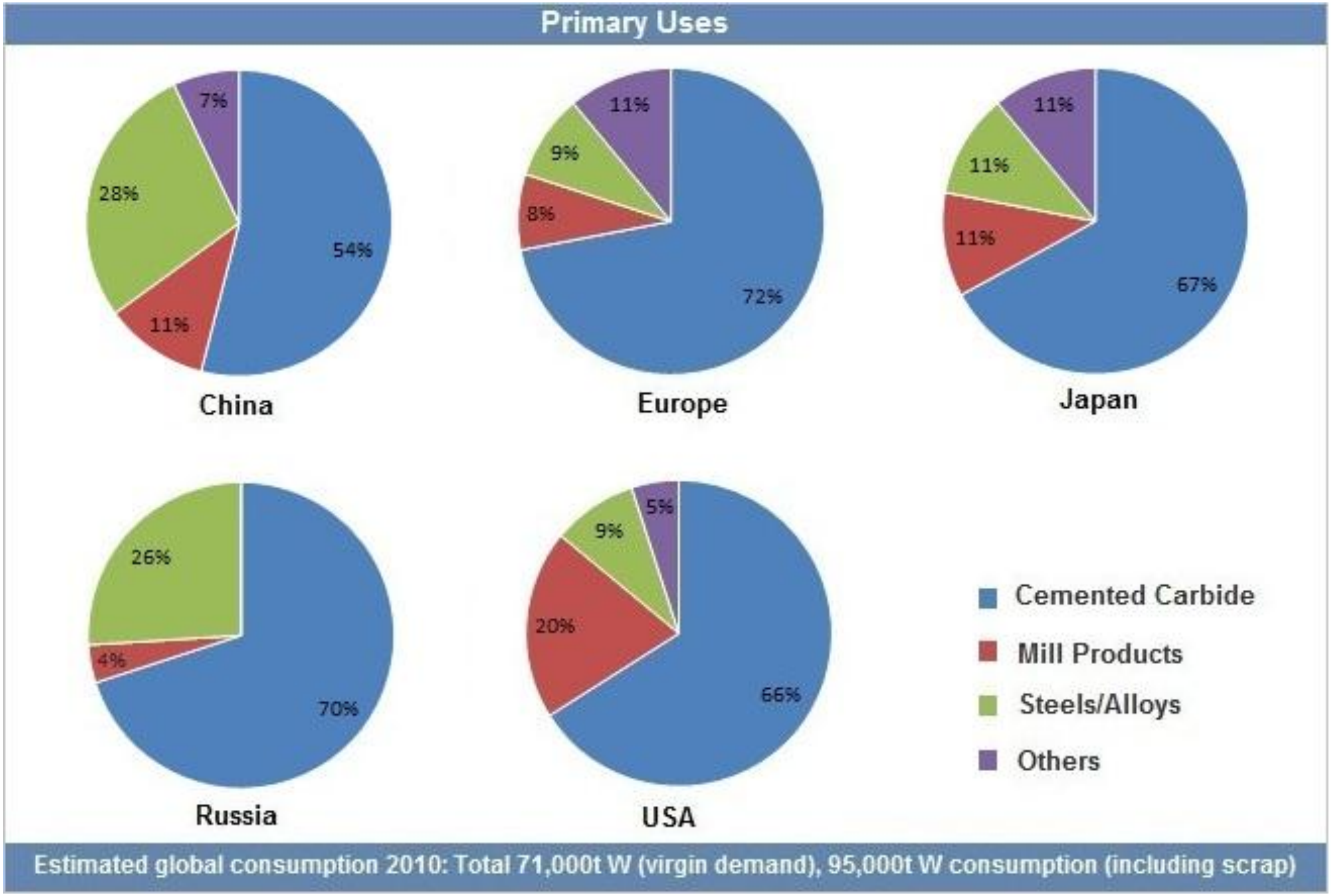
PRICING



- ***A metric ton unit (mtu) is 10 kg***
- ***A metric ton unit of tungsten trioxide (WO_3) contains 7.93 kg of tungsten***

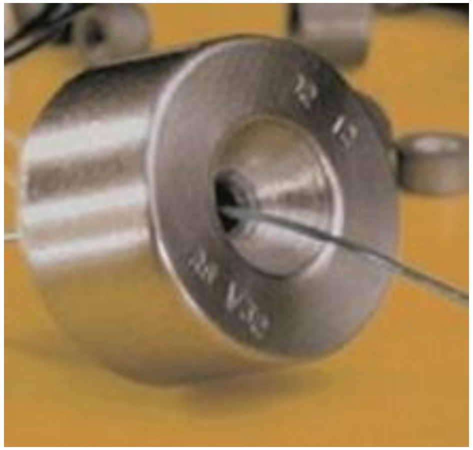
INTERNATIONAL TUNGSTEN INDUSTRY ASSOCIATION

APPLICATIONS



APPLICATIONS

Cemented Carbides



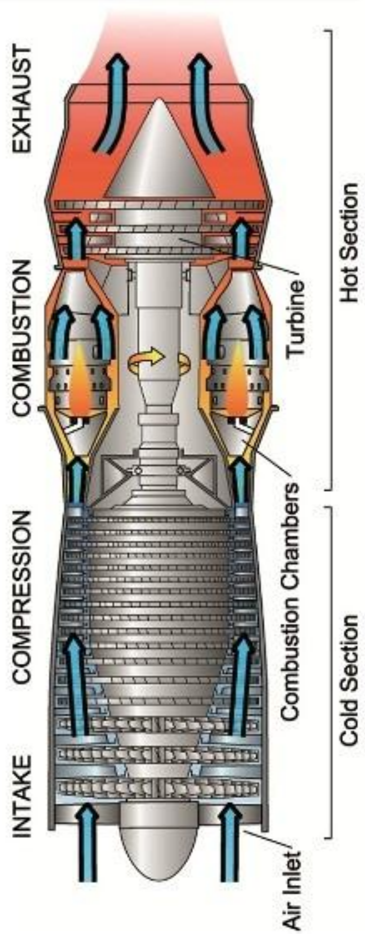
Roadheader for underground mining

Indexable inserts

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

Applications

Steel & Superalloys



Design of a typical gas turbine jet engine. Turbine blades are made of tungsten-containing superalloys

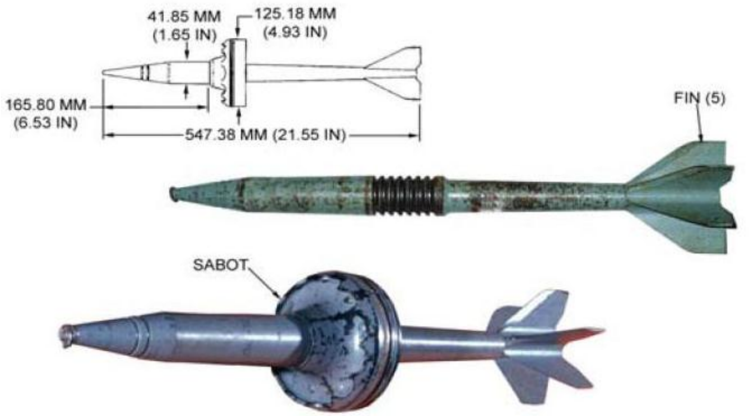
Typical Compositions of Selected High Speed Steels (%)

Grade	C	Cr	Mo	W	V	Co
T-1	0.75	-	-	18.0	1.1	-
M-2	0.95	4.2	5.0	6.0	2.0	-
M-7	1.00	3.8	8.7	1.6	2.0	-
M-42	1.10	3.8	9.5	1.5	1.2	8.0

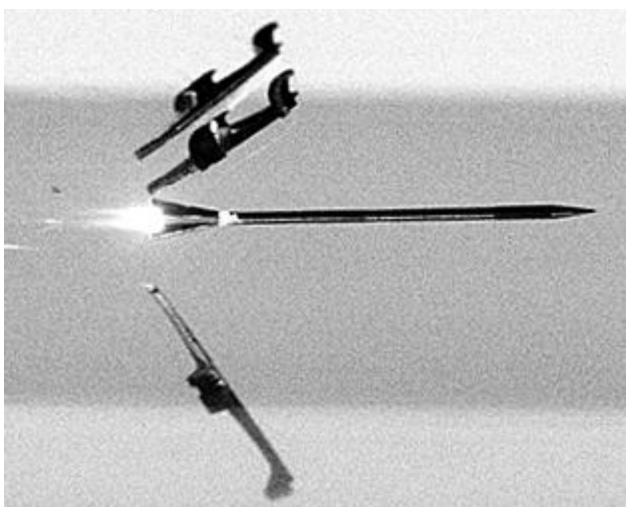
Turbine rotor and compressor rotor disk of a gas turbine ready for installation

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 11g/cm^3. It is used as a substitute for lead.

APPLICATIONS

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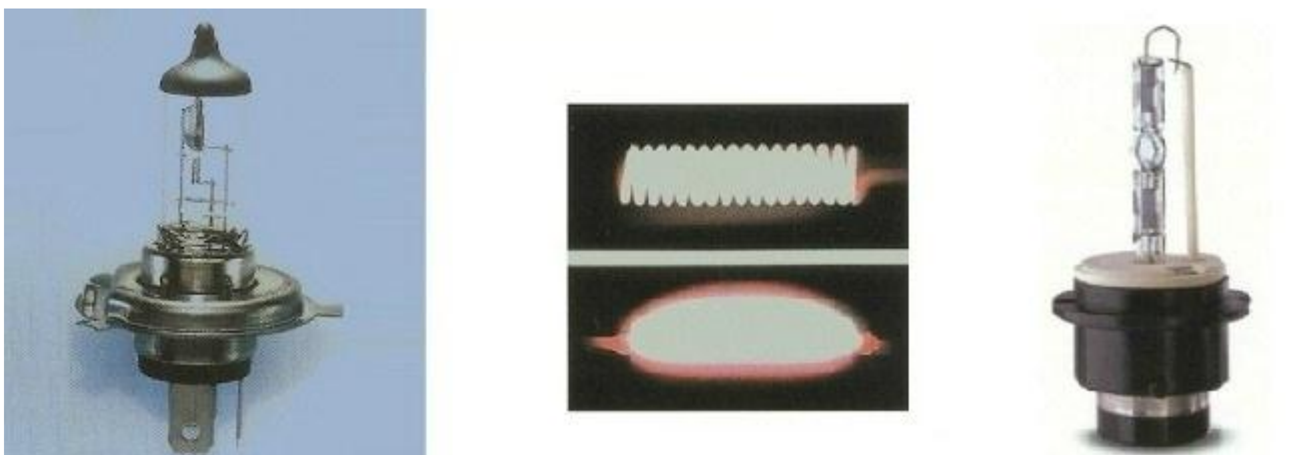
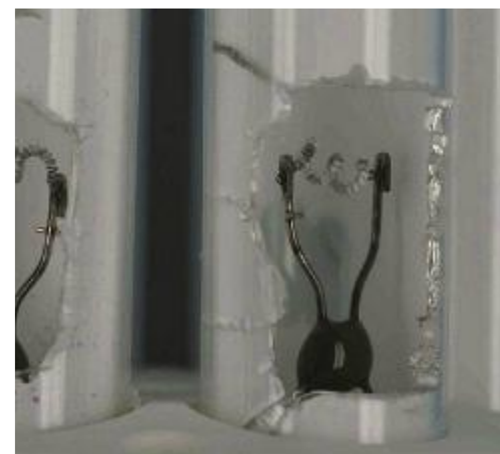
Lamp Industry

New generation of energy saving halogen lamps have an Infrared Coating (IRC)



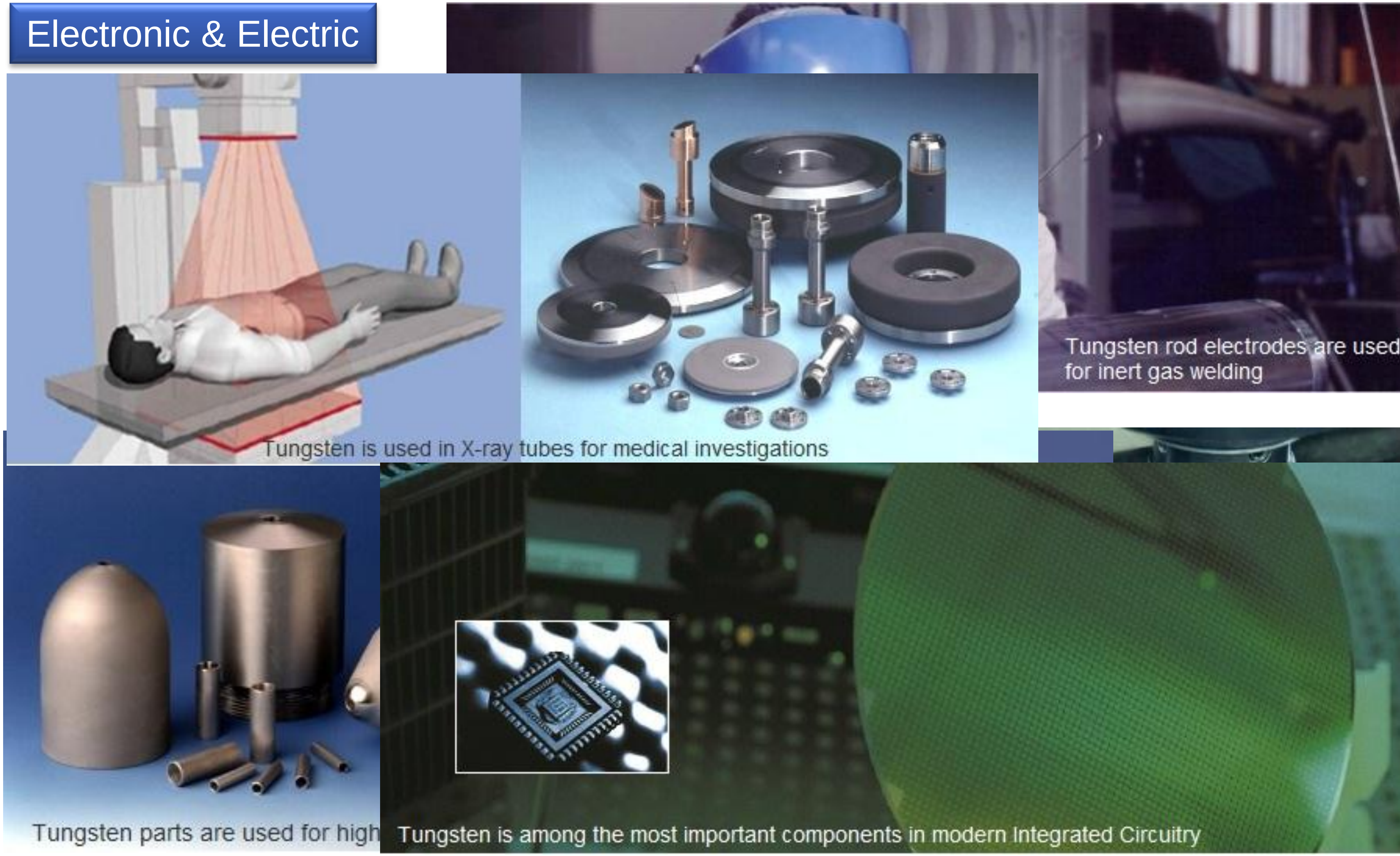
Modern automotive lighting - comparison of halogen lamp (left) and discharge lamp (right)



lectrodes

APPLICATIONS

Electronic & Electric



Tungsten rod electrodes are used for inert gas welding

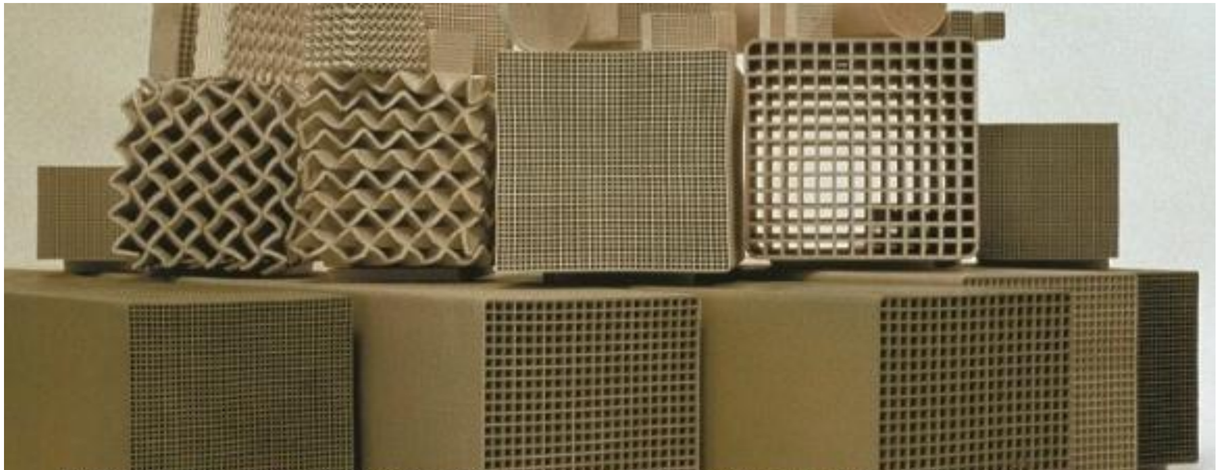
Tungsten is used in X-ray tubes for medical investigations

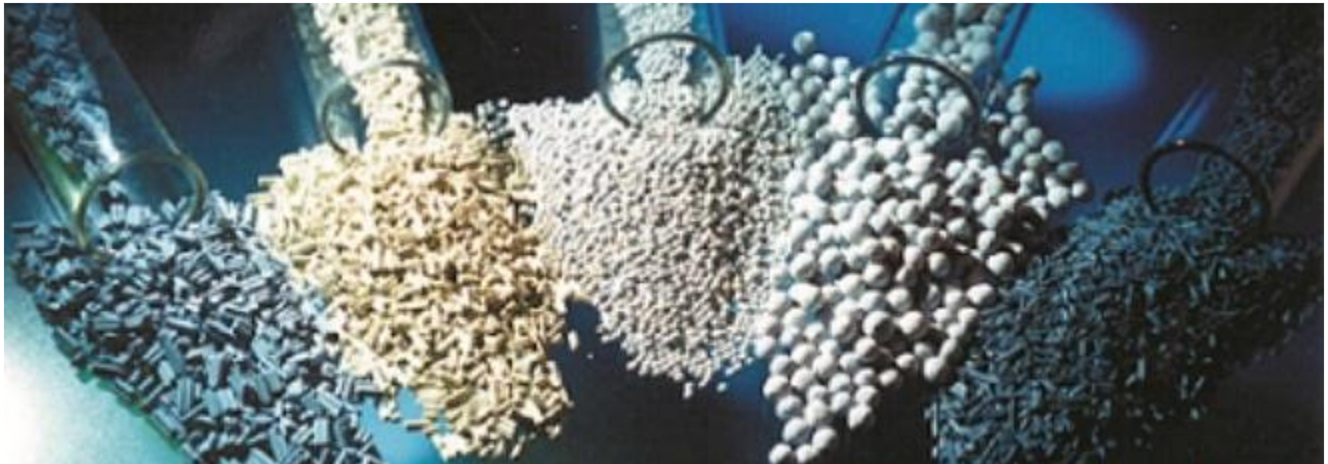
Tungsten parts are used for high

Tungsten is among the most important components in modern Integrated Circuitry

Applications

Chemistry

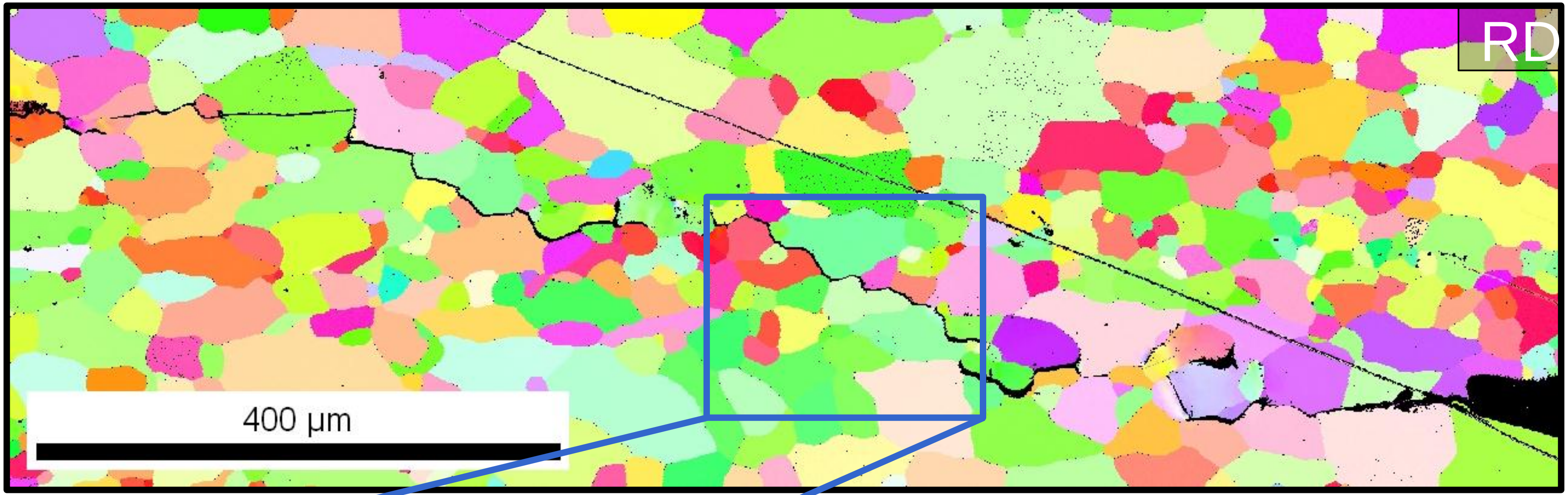

DeNOx catalysts are used for the removal of nitrogen oxides from stack gases


HDS, HDN and HAD catalysts containing W-Ni and Mo-Ni in sulfided form

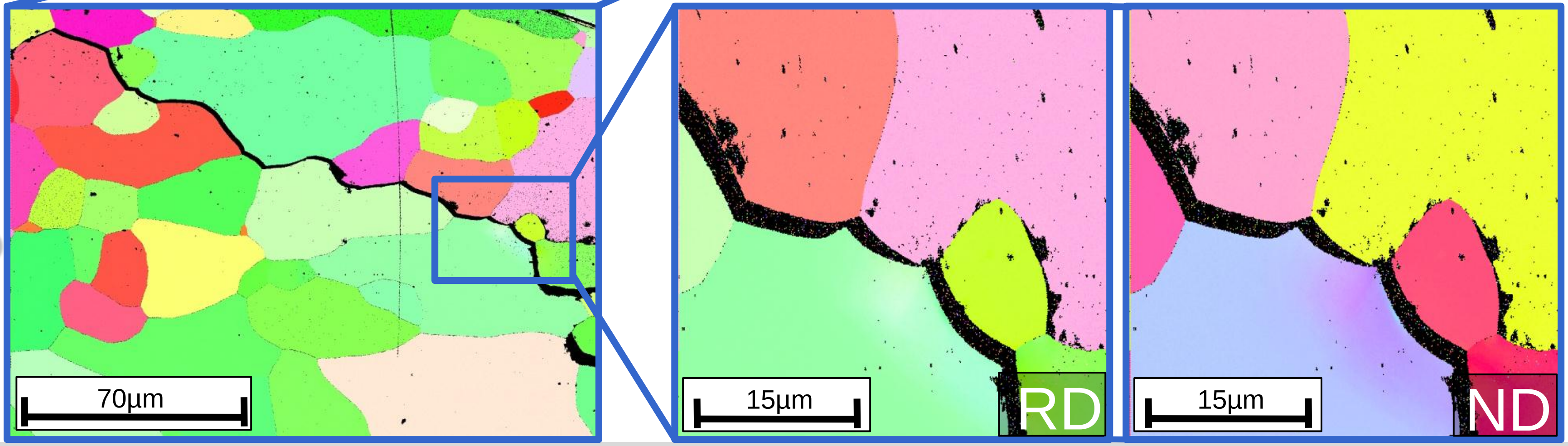
3

MECHANICAL PROPERTIES

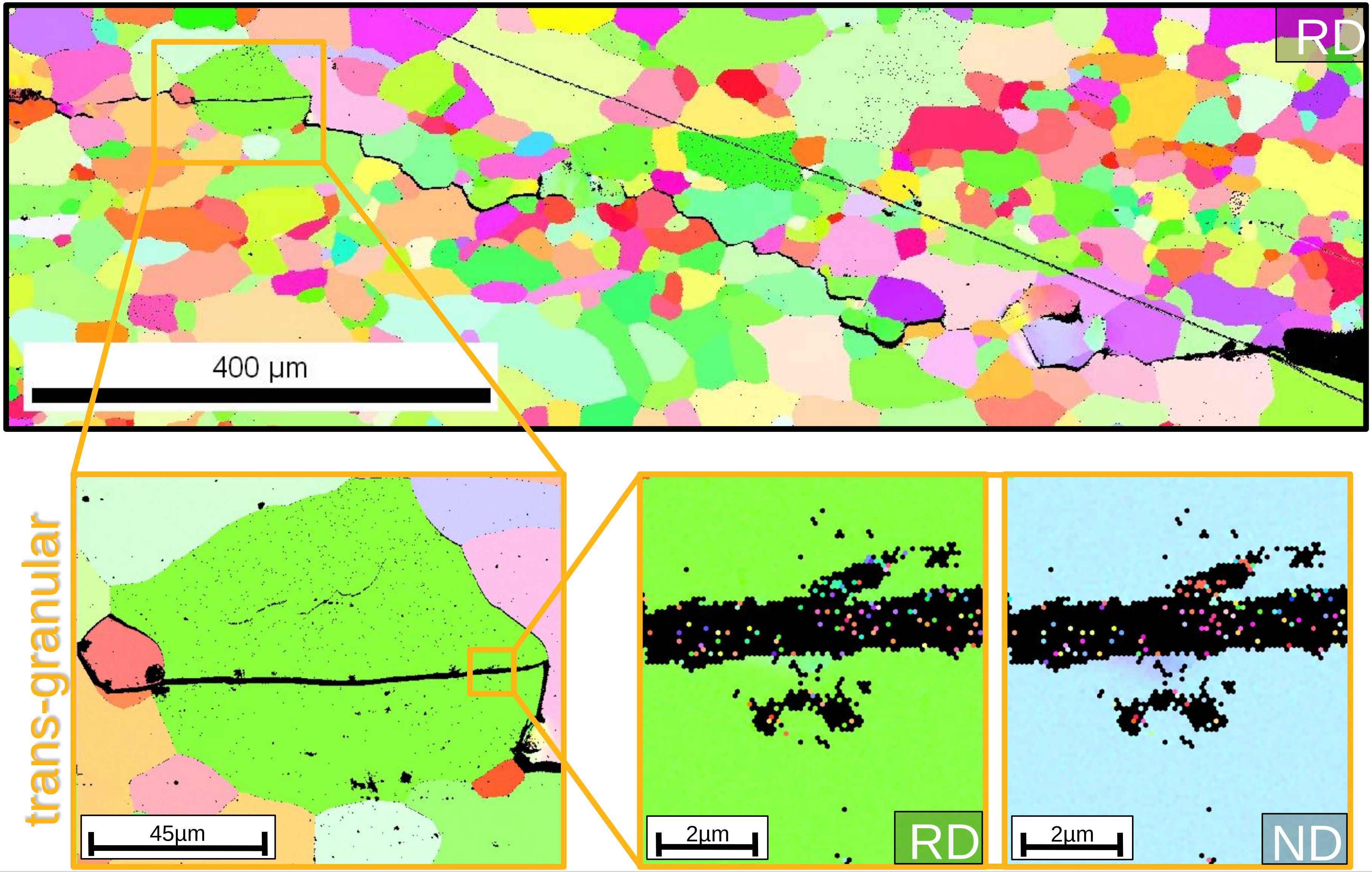
Fracture Behaviour/Ductility/Brittleness



inter-granular

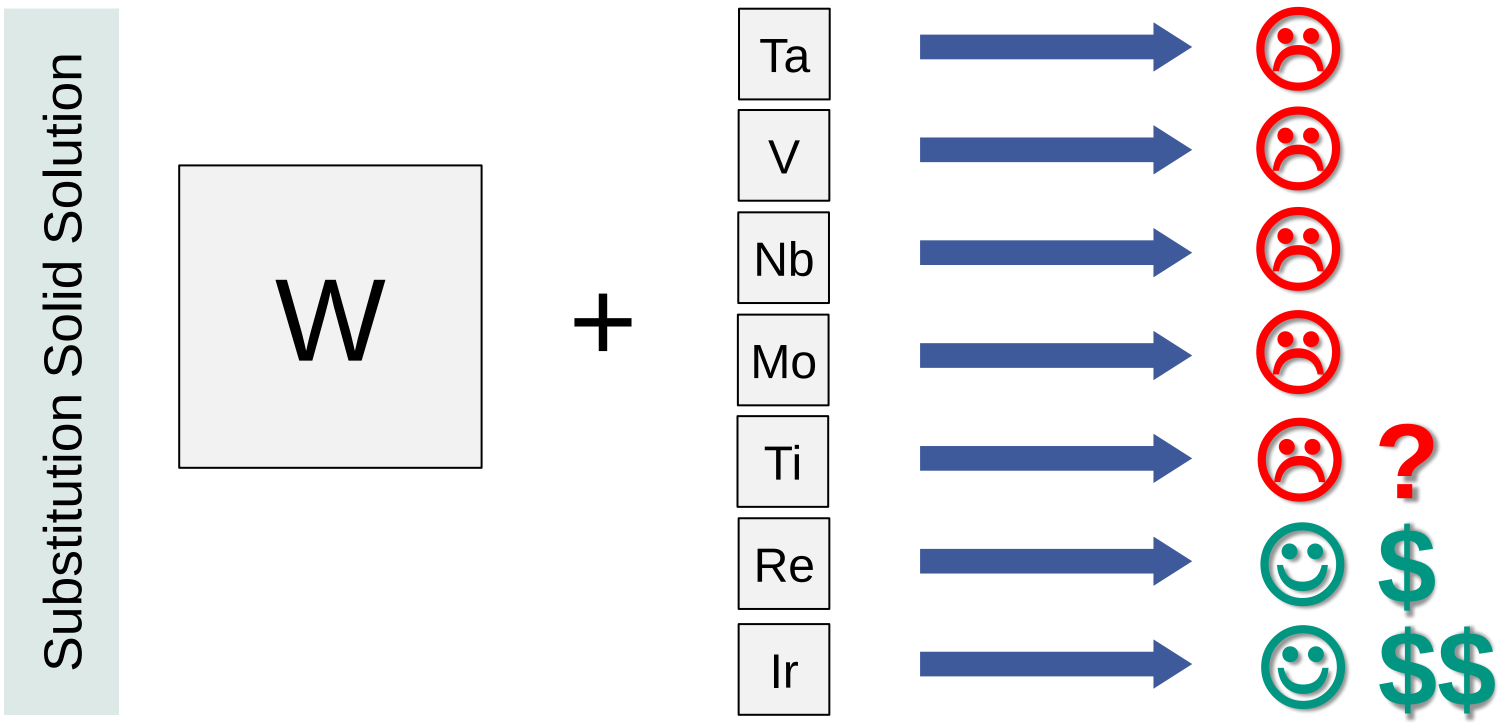


FRACTURE BEHAVIOUR/DUCTILITY/BRITTLENESS



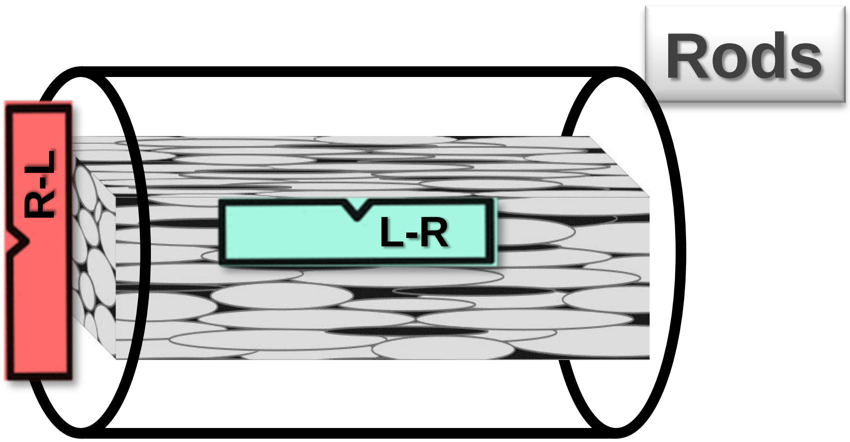
DUCTILISATION

Known Strategies
1. Nanostructuring → **Small quantities only!**
2. Composites → **Not yet availlable!**
3. Alloying

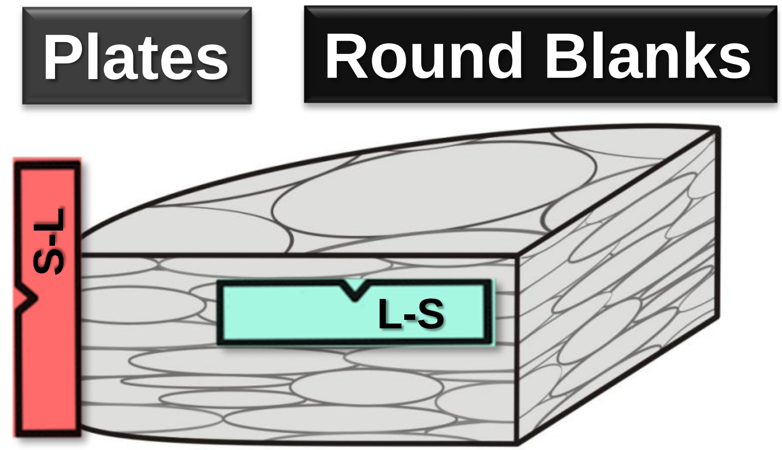


***Conclusion*: For large-scale applications we have to live with the intrinsic brittleness of tungsten materials!**

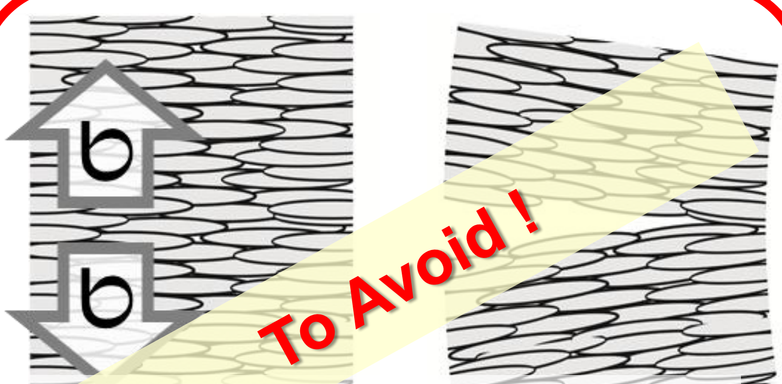
MICROSTRUCTURE AND RELATED PROPERTIES



Bundle of „Fibres“



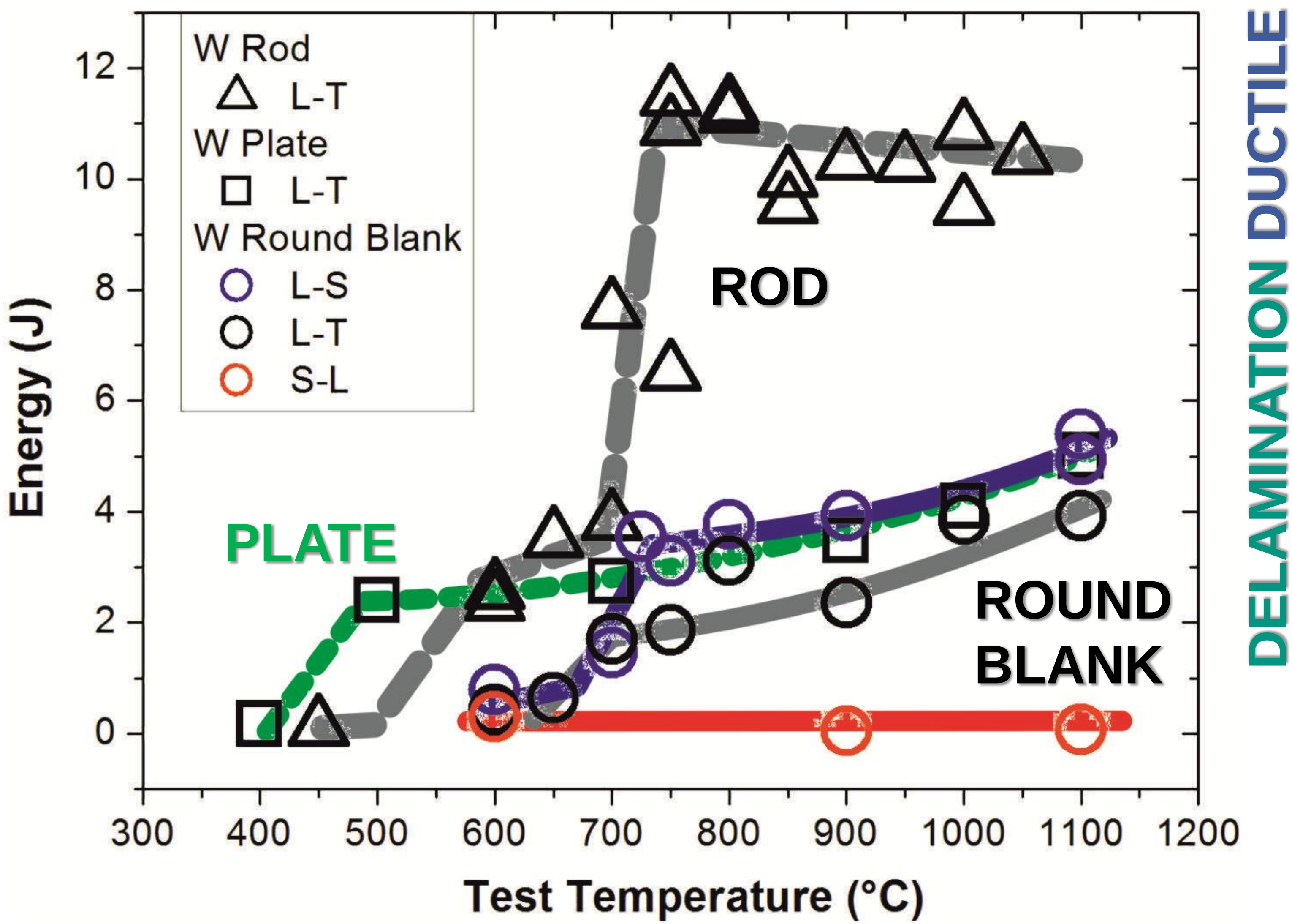
Stack of „Pancakes“



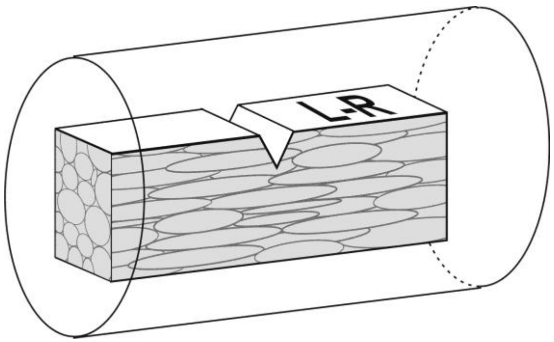
Inter-granular fracture, enhanced by oxide particles !

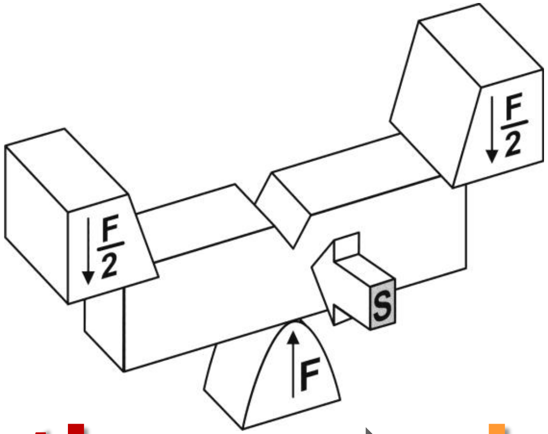
Partly ductile fracture, improved by deformation !

Impact on Toughness

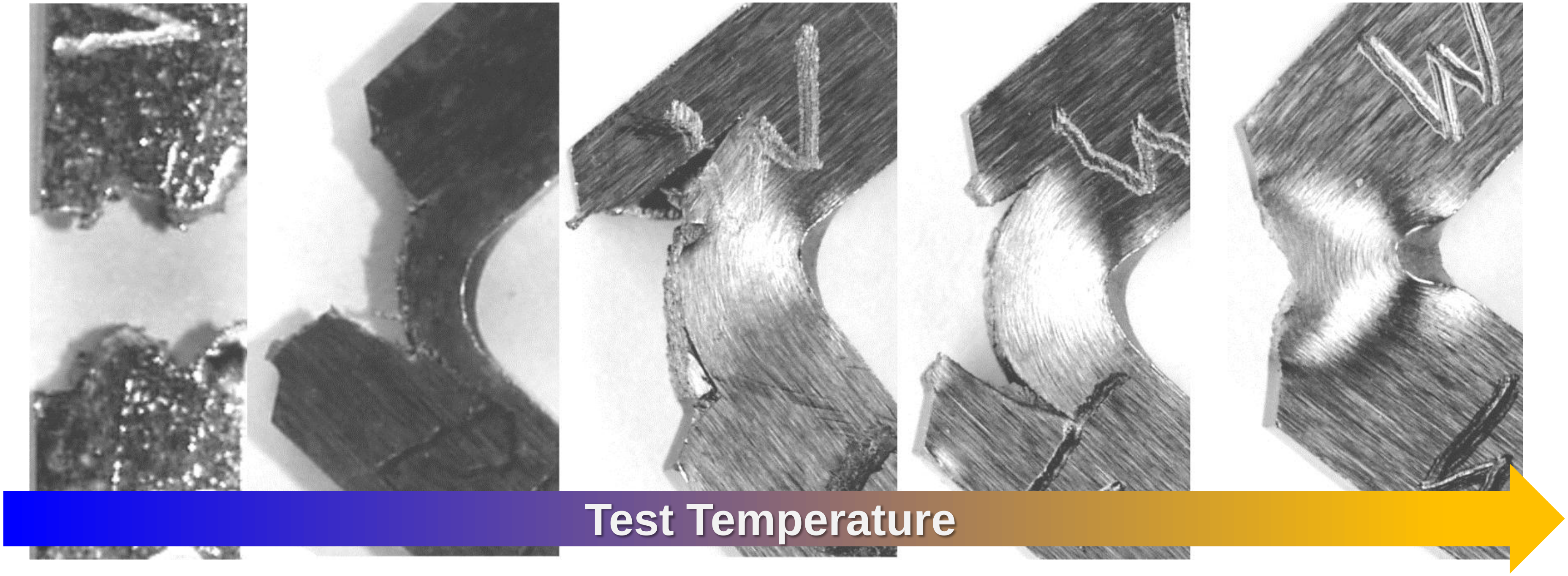


Delamination Fracture





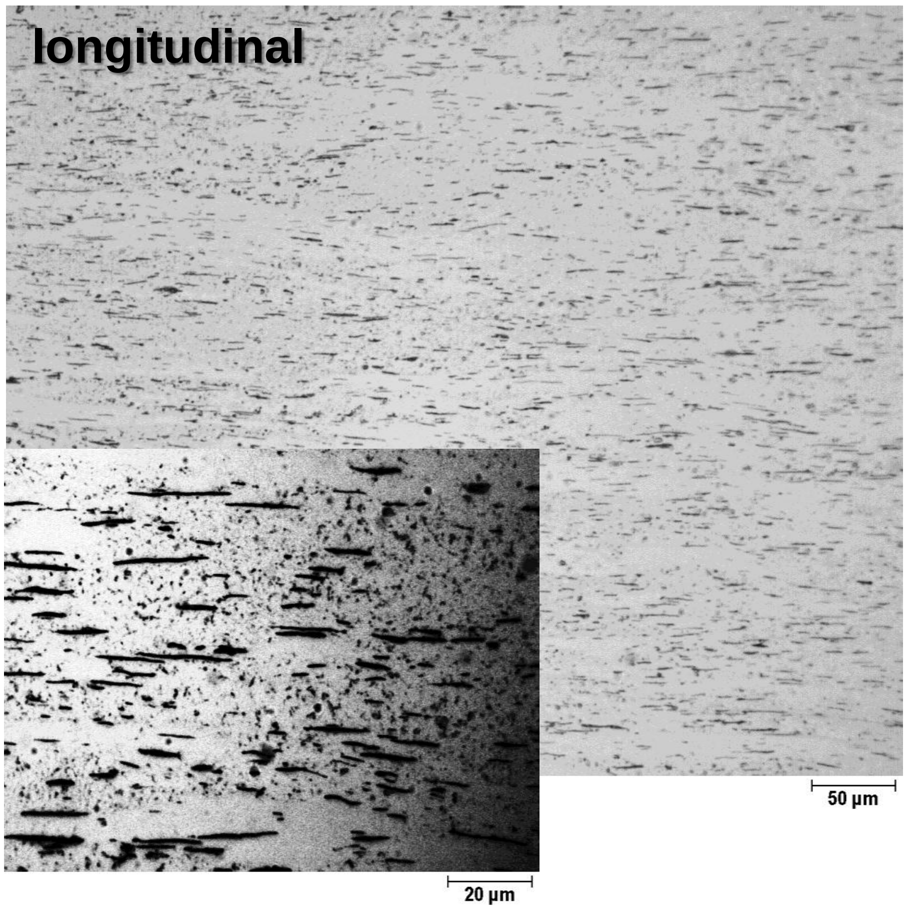
brittle → delamination → ductile

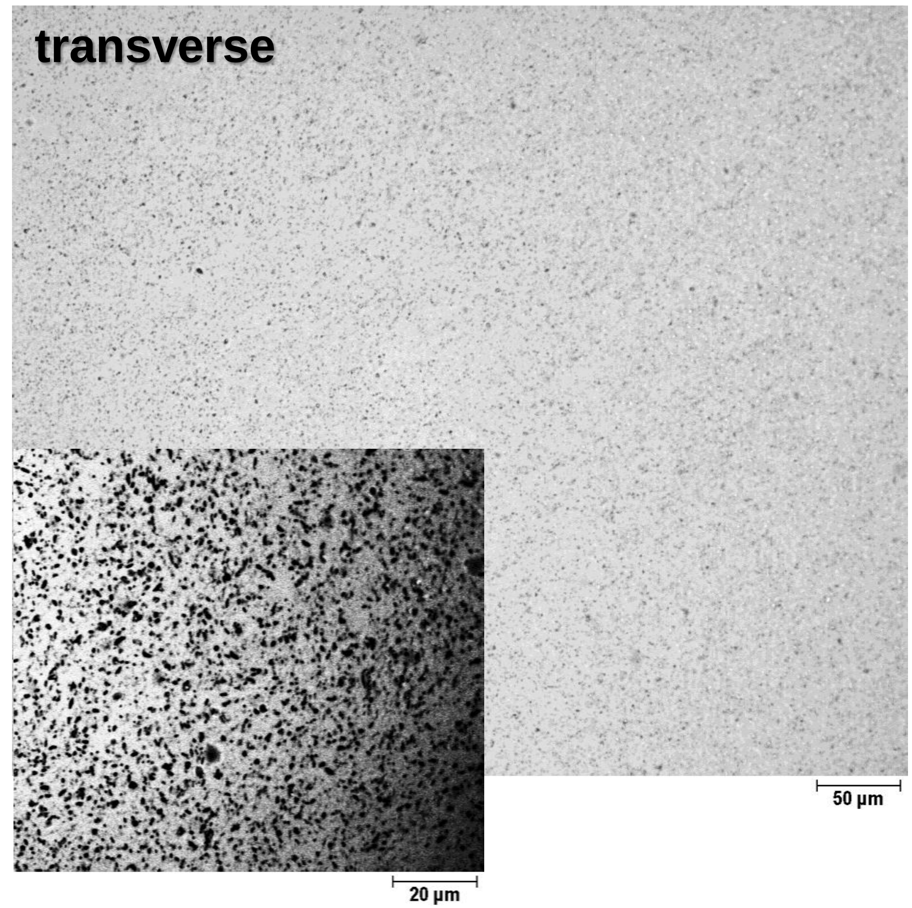


Effect of ODS particles in W

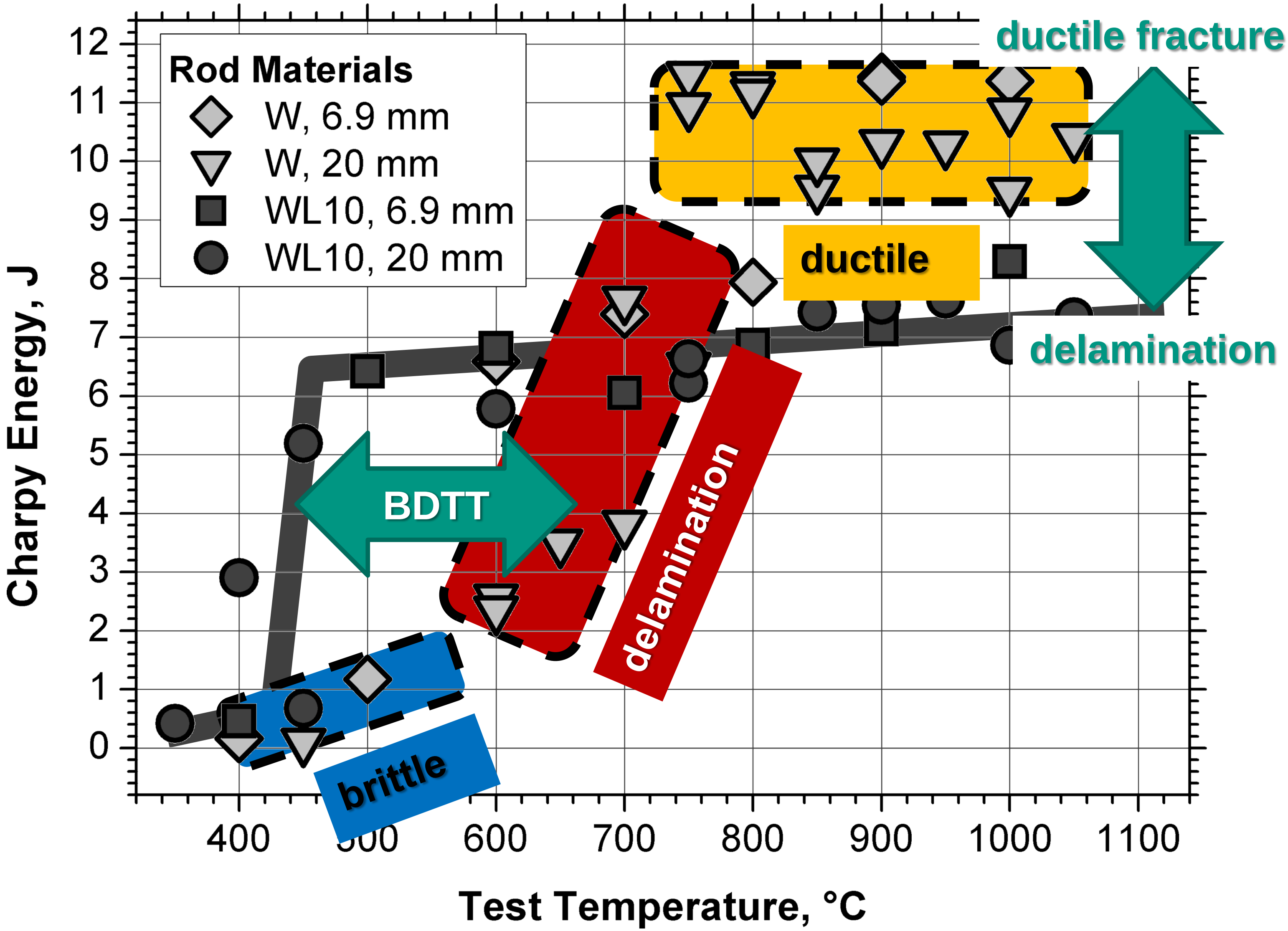
WL10 Rod, Ø7 mm

Rods: Metallography



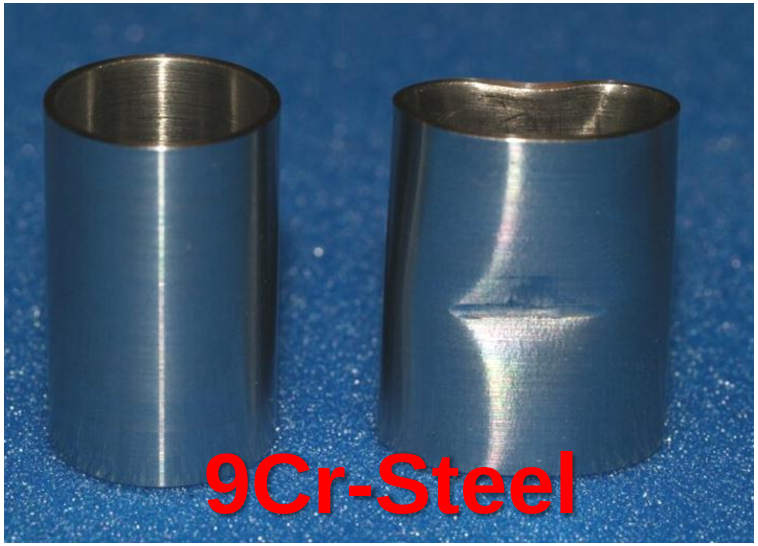


Effect of ODS particles in W



Problem of Microstructure Orientation

Pipe Impact Test



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

Karlsruher Institut für Technologie

The life time of a power plant divertor is TWO years – hopefully!

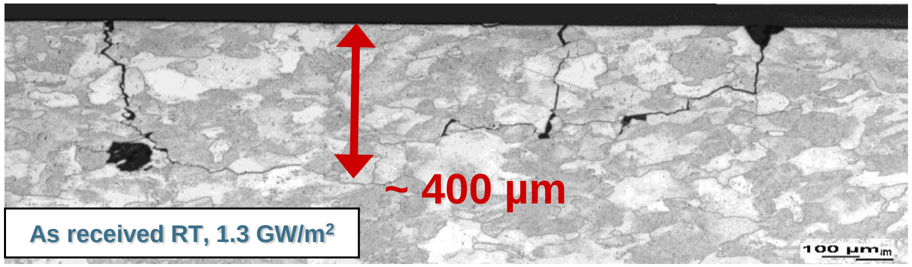
High heat flux	→ High operating temperatures (peaks>1800°C) → Microstructural stability, aging, … → Thermo-shocks, cyclic loading, fatigue, …
Heavy ion bombardment	→ Sputtering, cracking/fracturing → Surface interactions and modifications → Microstructural changes
Neutron load 15 dpa/year (in W)	→ 30 dpa (in W) until end of service → Transmutation effects (Re, Os) → Swelling (order of magnitude: 3% for pure W)

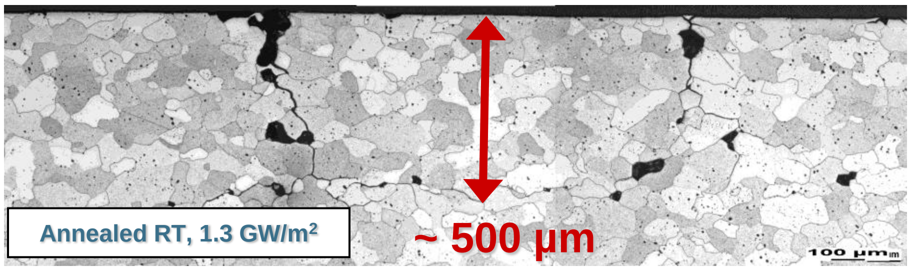
QUESTION: What can we do about this? How can we improve **ARMOR** materials?

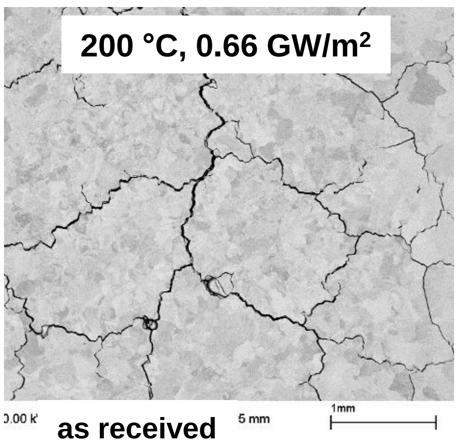
ANSWER: There is not much we can do now! We have to live with most properties and effects. A final assessment would require real in-service conditions.

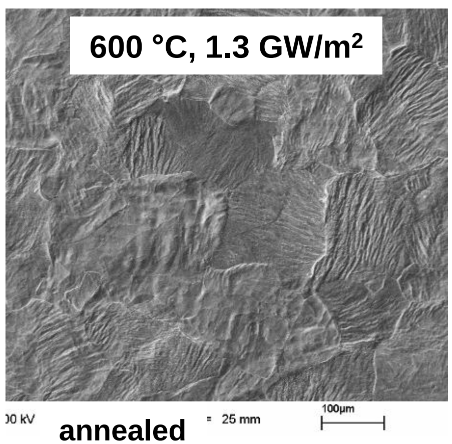
High Heat Flux Effects

Electron Beam



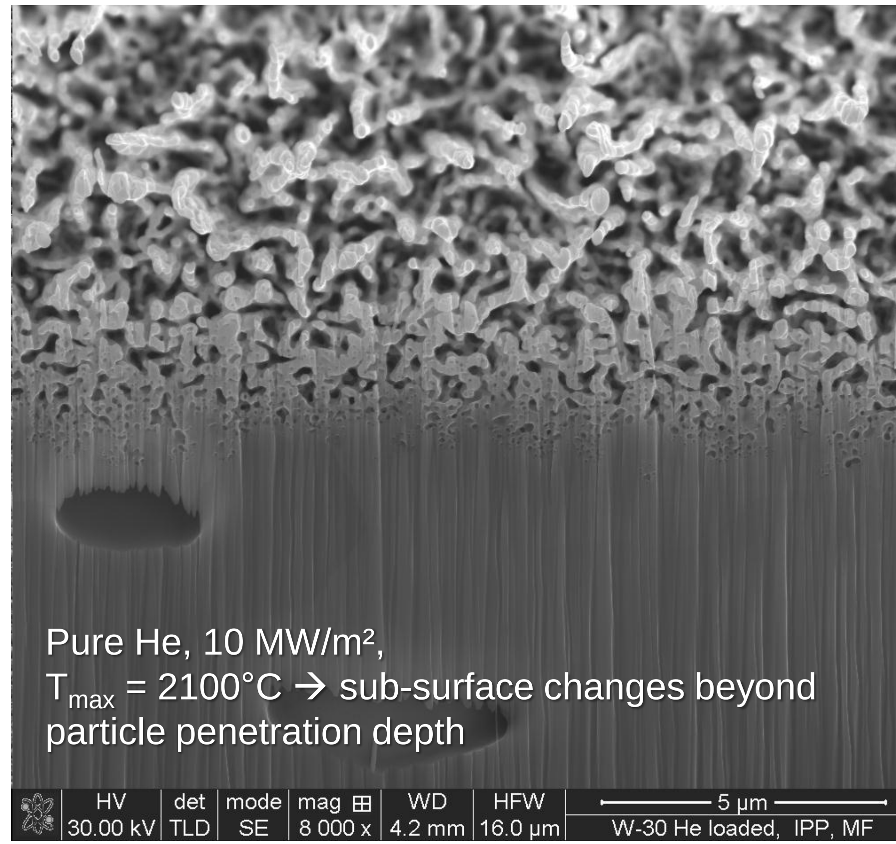






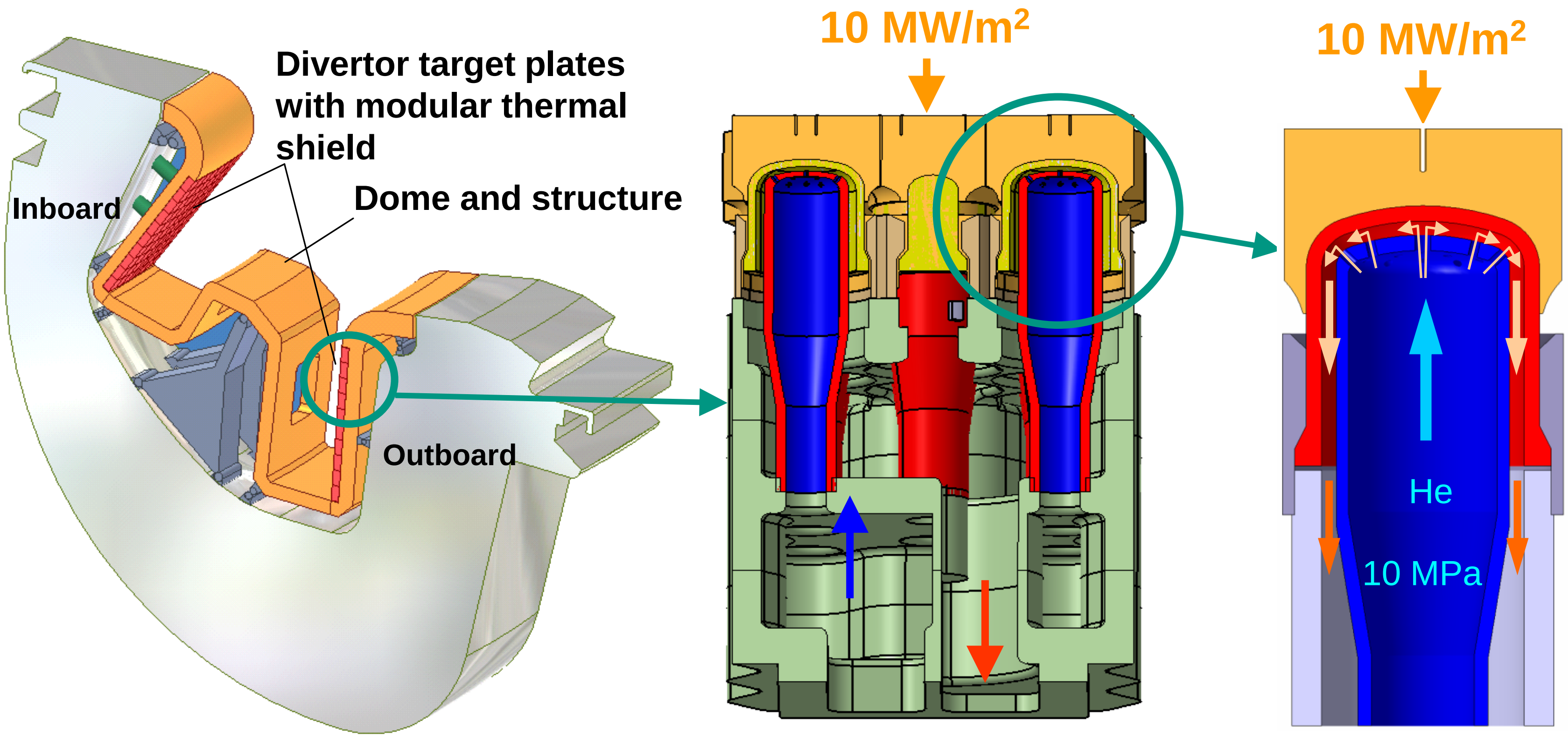
→ G. Pintsuk, J. Linke, et al., FZJ

Hydrogen/Helium Ion Beam



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

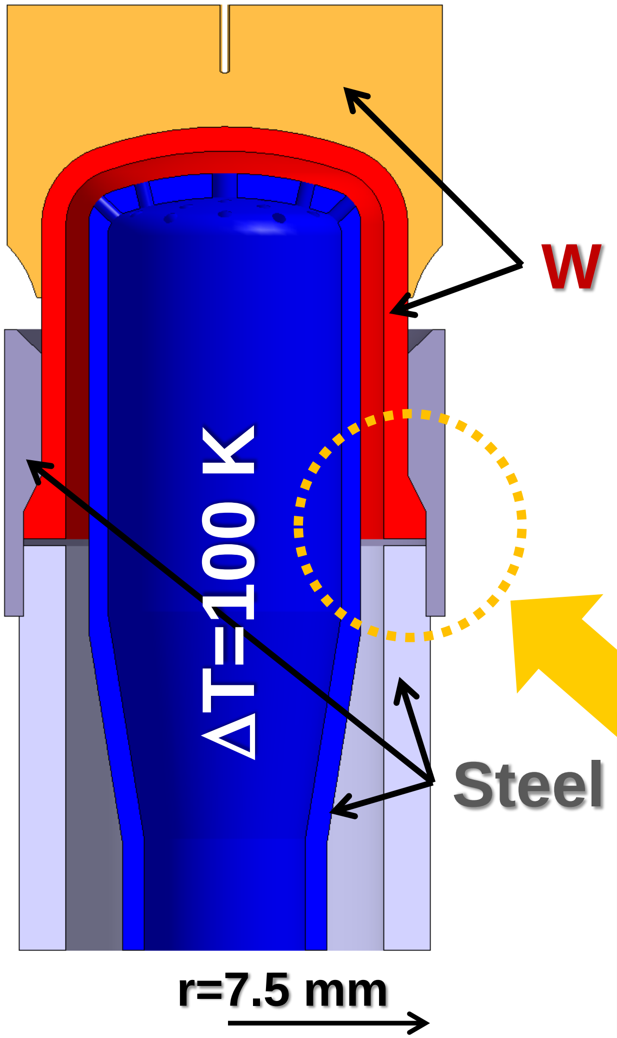
Finger Design, Jet Cooling



Divertor Cassette — **9-Finger Module** — **Finger**

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

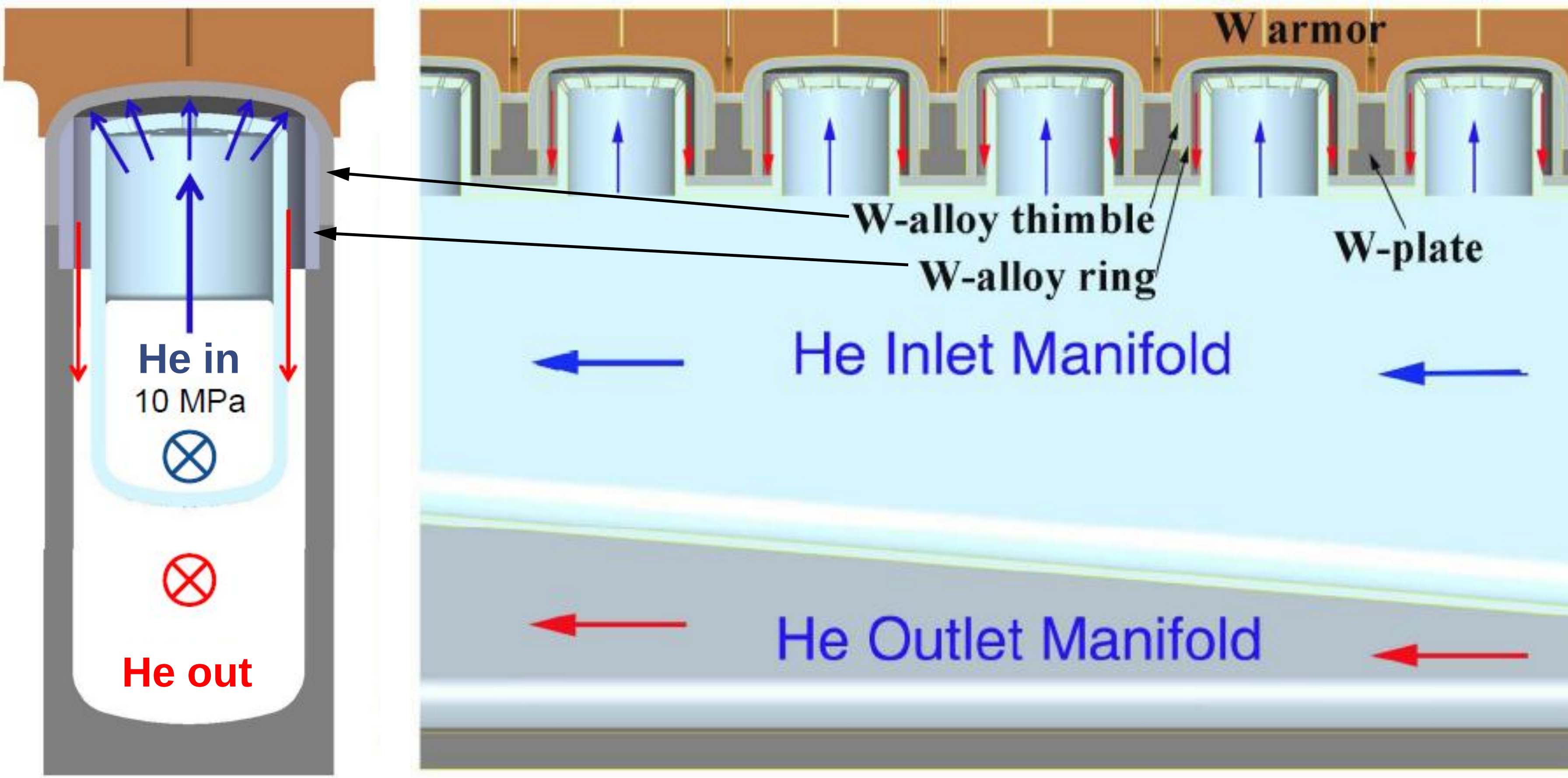
Finger Design, Jet Cooling



- **+ 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

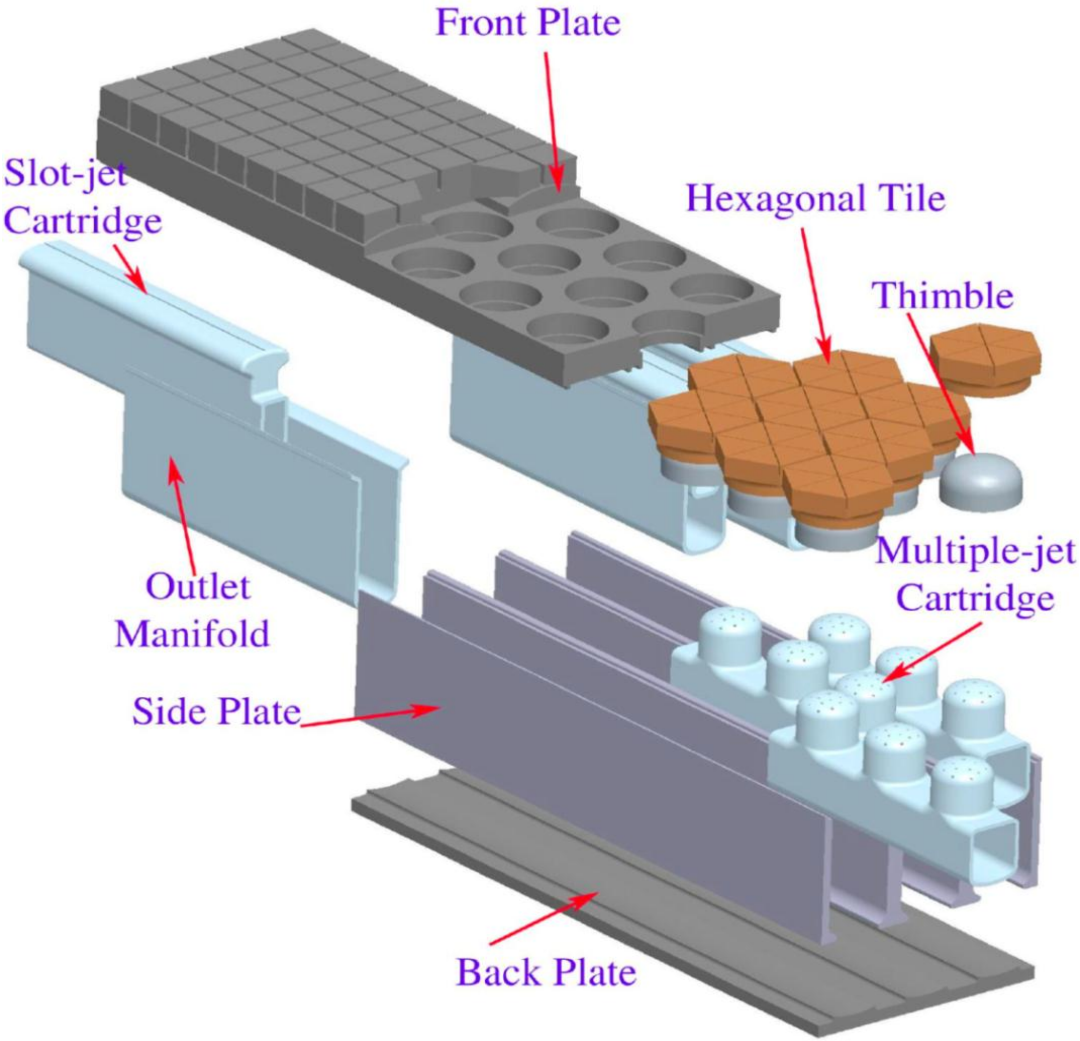
Plate Design (ARIES), Jet Cooling

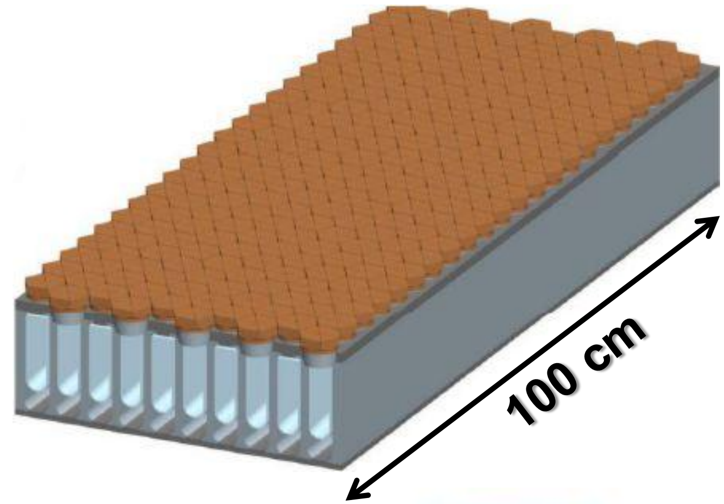


X.R. Wang, S. Malang, M.S. Tillack & ARIES Team, 2008-2011

PLATE DESIGN (ARIES), JET COOLING

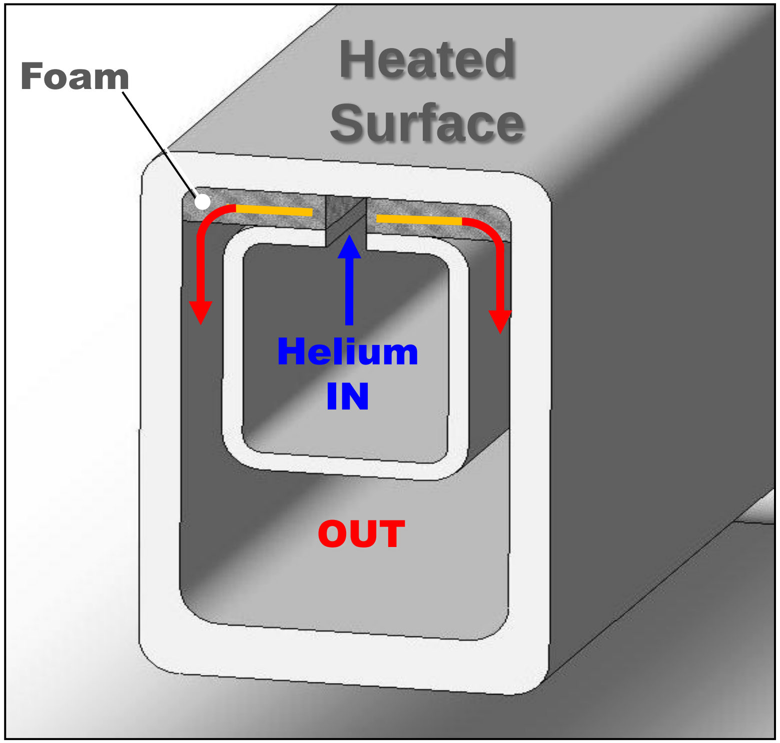
Karlsruher Institut für Technologie

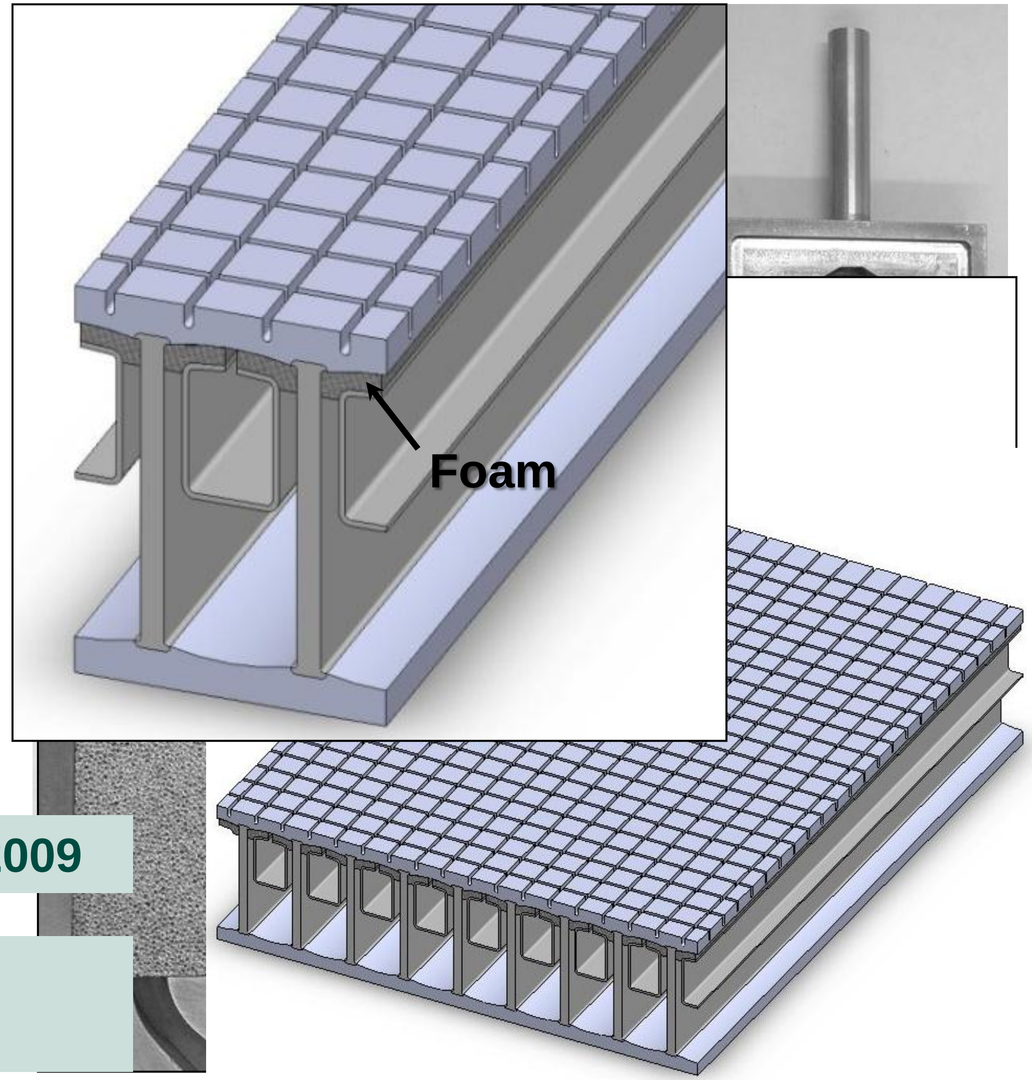




X.R. Wang, S. Malang, M.S. Tillack & ARIES Team, 2008-2011

PLATE DESIGN, FOAM PROMOTER

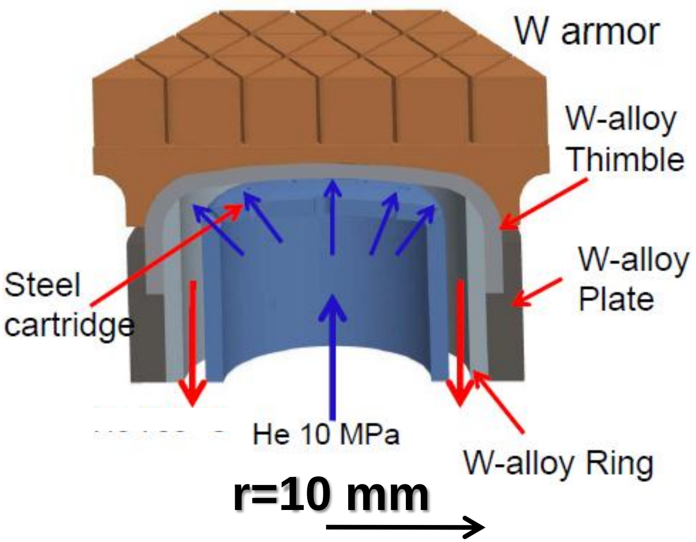




→ S. Sharafat *et al.*, UCLA, 2005-2009

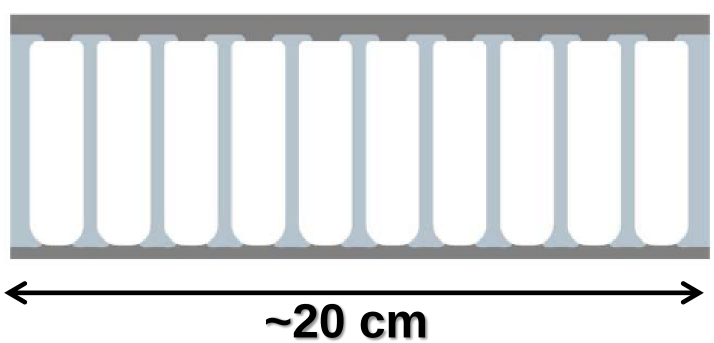
→ Mo, Nb, SiC Foam:
D. Youchison *et al.*, SNL,2011

PLATE DESIGN (ARIES), JET COOLING



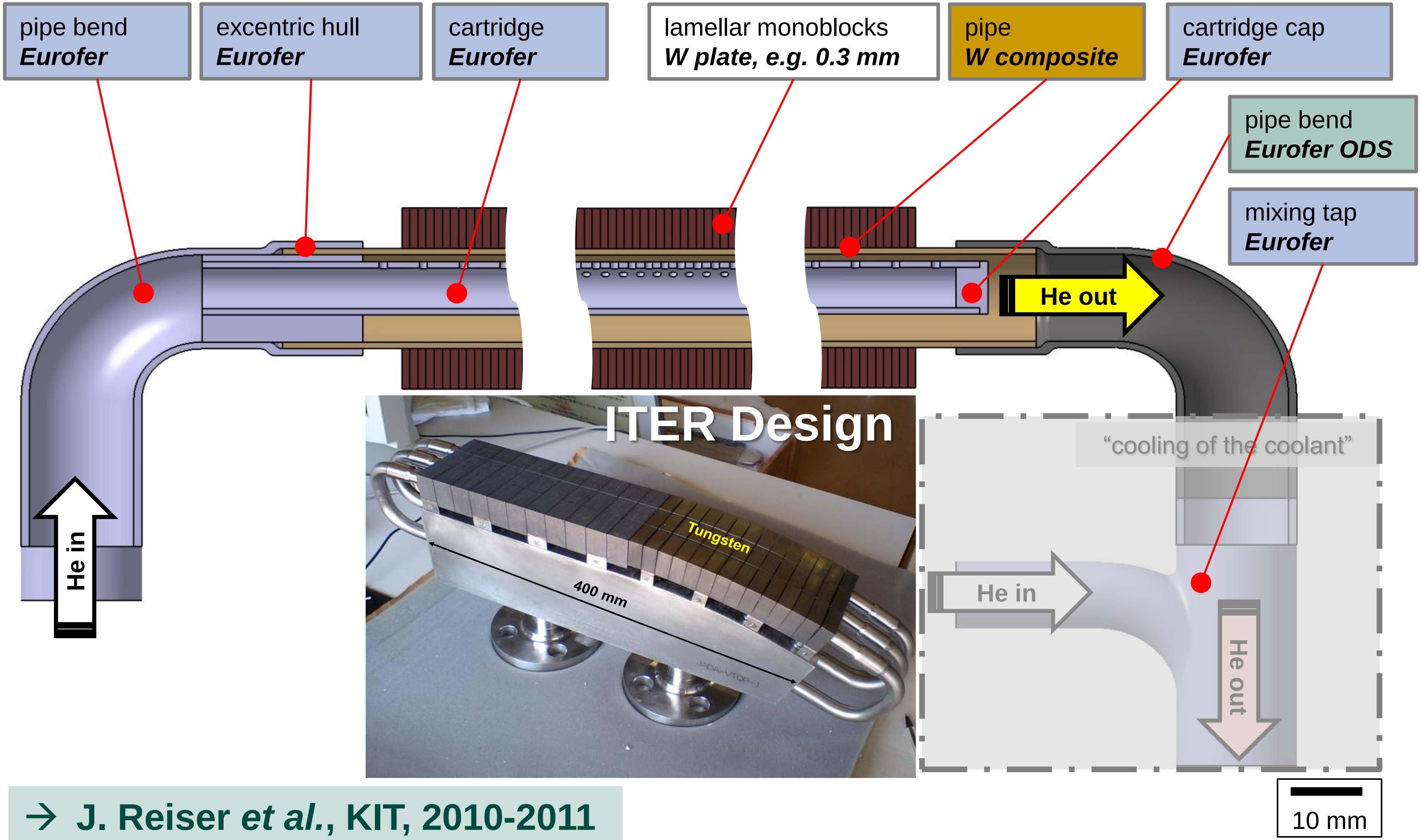
+ High heat flux: ~15 MW/m²
+ Small Size, Thin Walls
+ "Double Containment"

− Large Numbers: ~300 000
− Many/Long Struct. W-W Joints



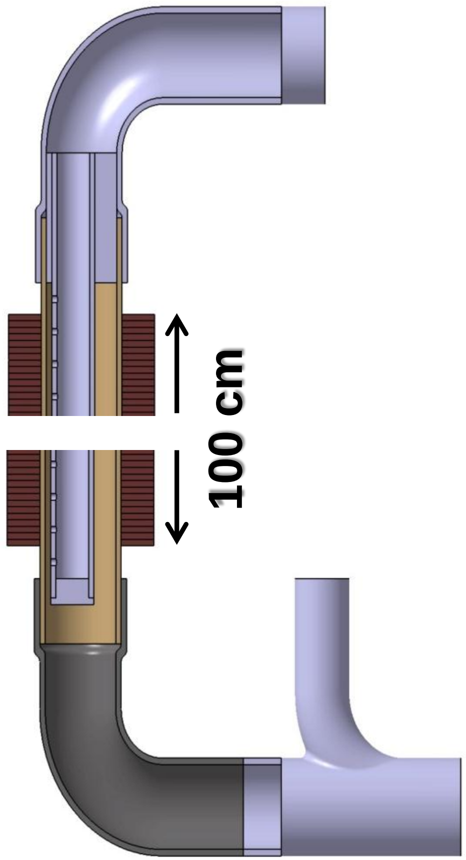
He temperature limited by steel (multiple jet cartridges)
Ferritic ODS → 750°C ???
Eurofer ODS, 9Cr ODS → 650°C
Eurofer 97, F82H → 550°C

PIPE/MONOBLOCK DESIGN, JET COOLING



→ J. Reiser *et al.*, KIT, 2010-2011

PIPE/MONOBLOCK DESIGN, JET COOLING



+ Simple Design
+ "Easy Joints"
+ "Small Number of Parts"
+ Inexpensive

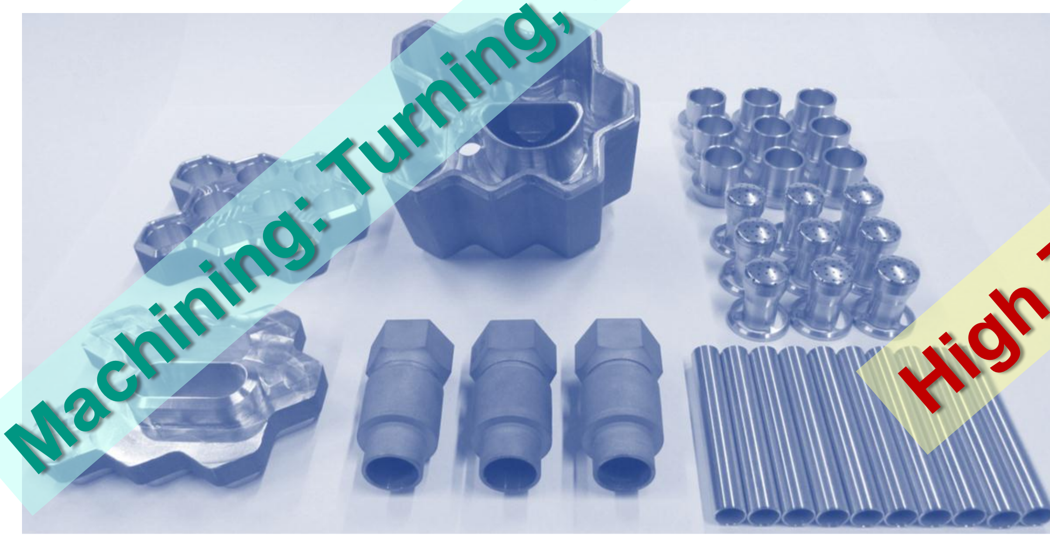
− Low Temperatures for W
− Low Performance
− Speculative Pipe Material

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

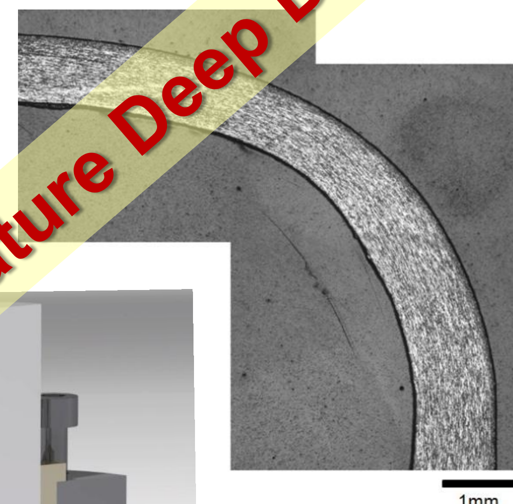
5

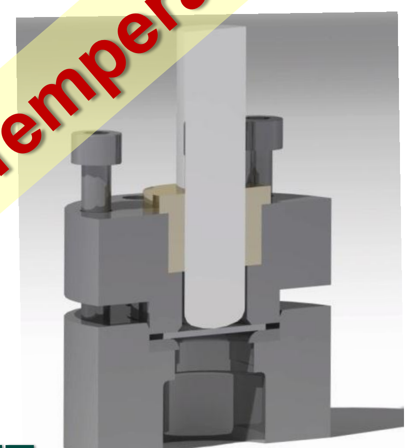
DESIGN ANALYSIS

Fabrication



Machining: Turning, Milling, Grinding, …

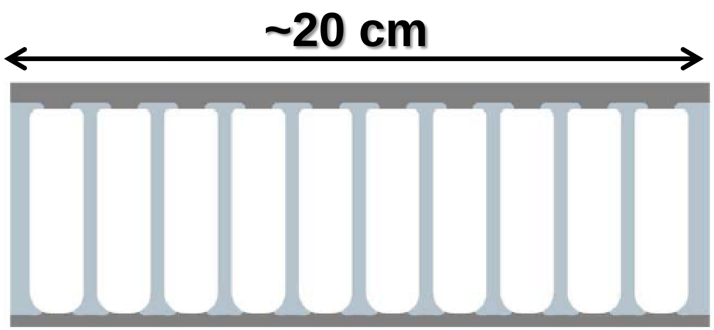


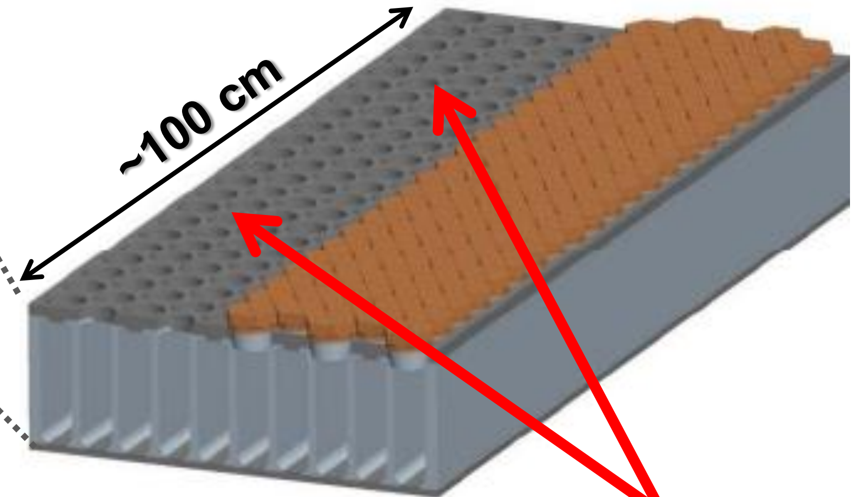


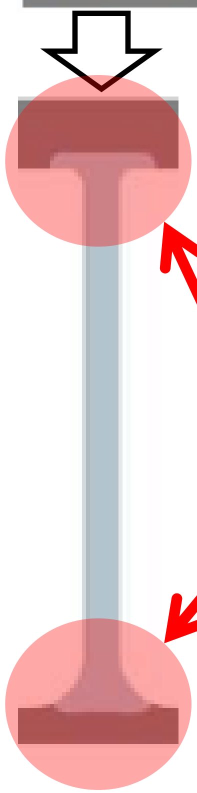
High Temperature Deep Drawing

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!

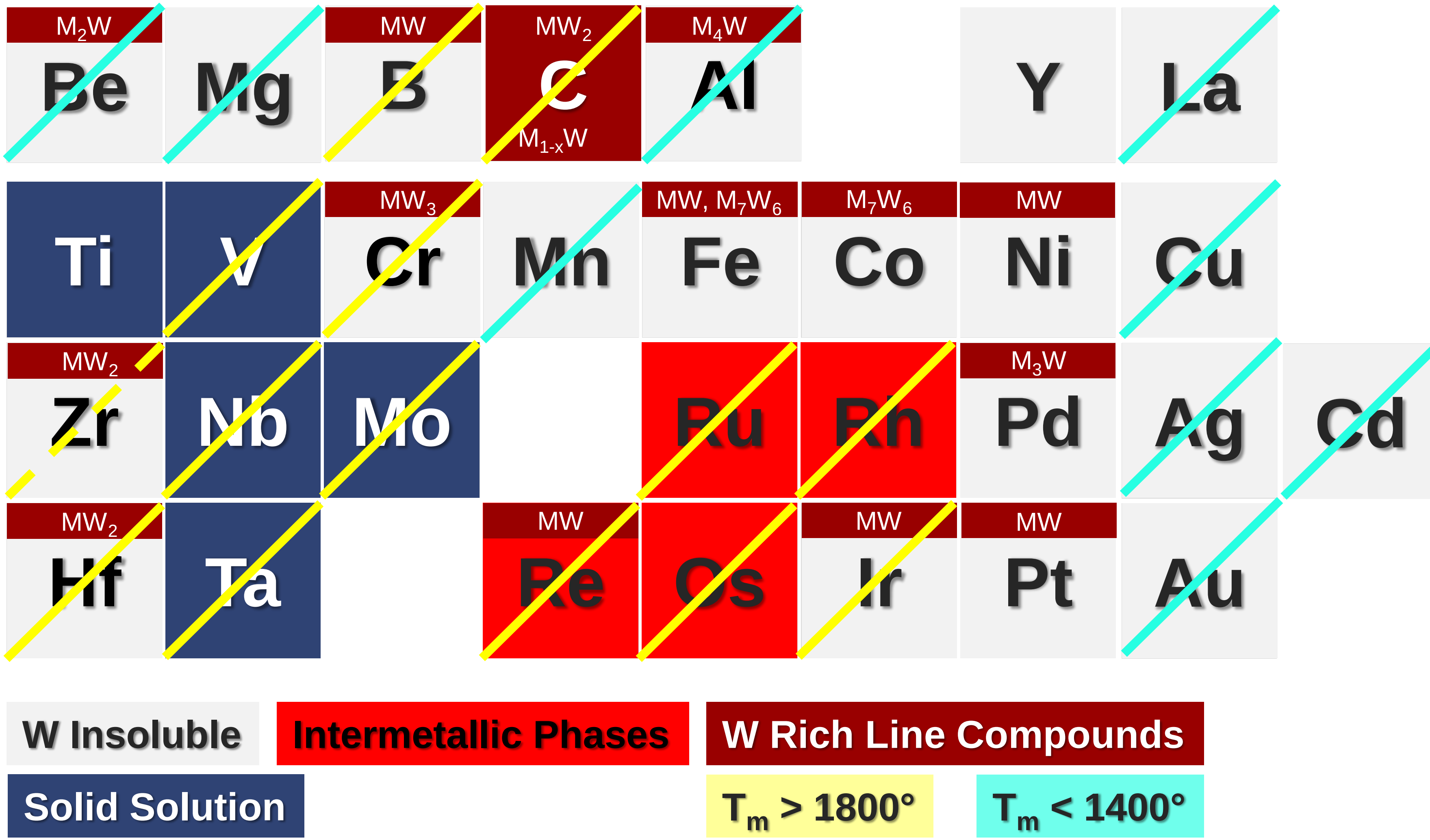
Brazing Material for W-W Joints

- 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


M_2W
Be
Mg
MW
B
MW_2
C
$M_{1-x}W$
M_4W
Al
Y
La
Ti
V
MW_3
Cr
Mn
MW, M_7W_6
Fe
M_7W_6
Co
MW
Ni
Cu
MW_2
Zr
Nb
Mo
Ru
Rh
M_3W
Pd
Ag
Cd
MW_2
Hf
Ta
MW
Re
Os
MW
Ir
MW
Pt
Au
W Insoluble
Intermetallic Phases
W Rich Line Compounds
Solid Solution
$T_m > 1800°$
$T_m < 1400°$

Brazing Materials, W→W

1670°C	Ti	<740°C: …
1520°C	Y	Strong … <1570°C … 40°C … 00°C: alpha-Y + Y_2O_3
1850°C	Zr	<2160°C: W→ ZrW_2 <1700°C … % intermetallic ZrW_2 <860°C: Zr→ ZrW_2 … etallic ZrW_2
1550°C	Pd	<1800°C: W→ ZrW_2 <900°C: intermetallic Pd_3W ???
1770°C	Pt	<24…°C: peritectic gamma phase Pt_3W
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

Difficult, … ?

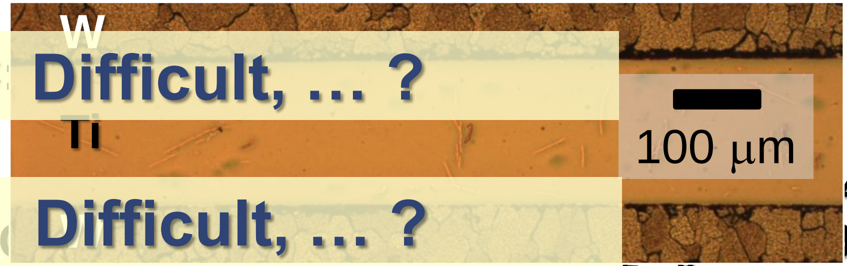
Difficult, … ?

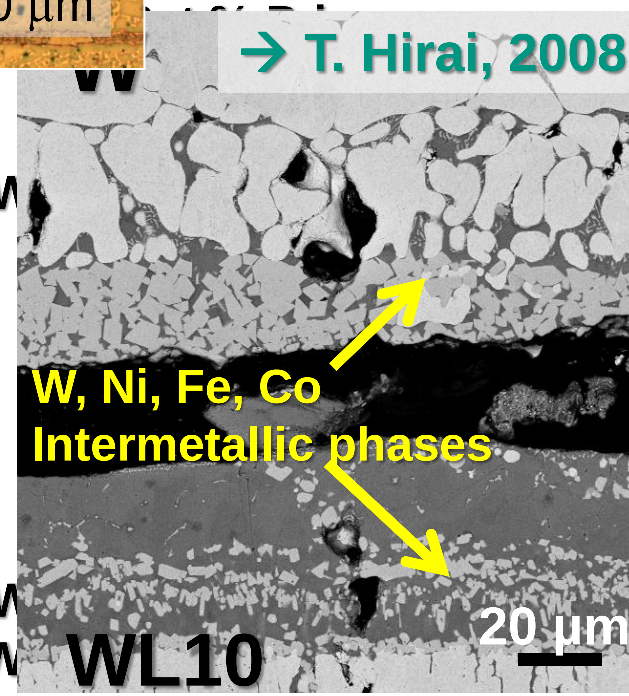
Brittle Joint

Expensive, … ?

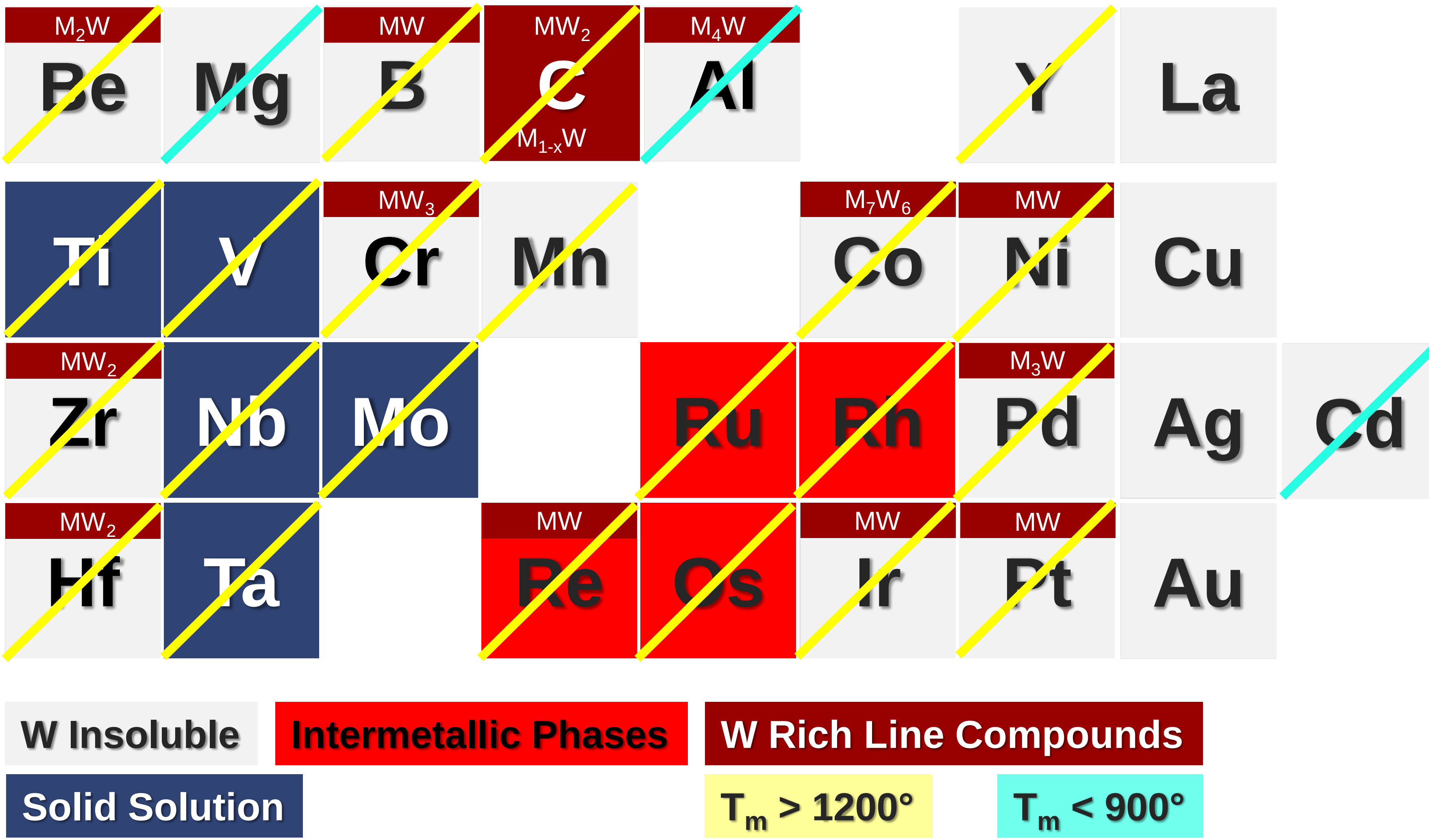
Very expensive, … ?

Brittle Joints



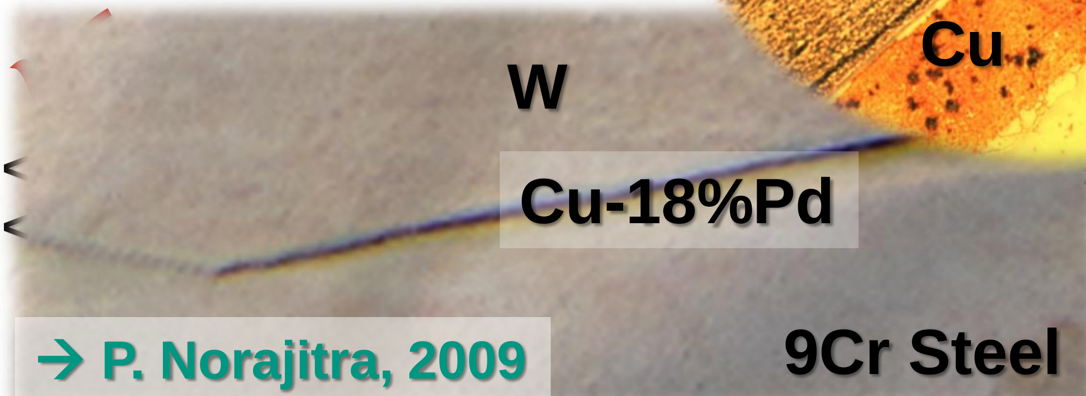


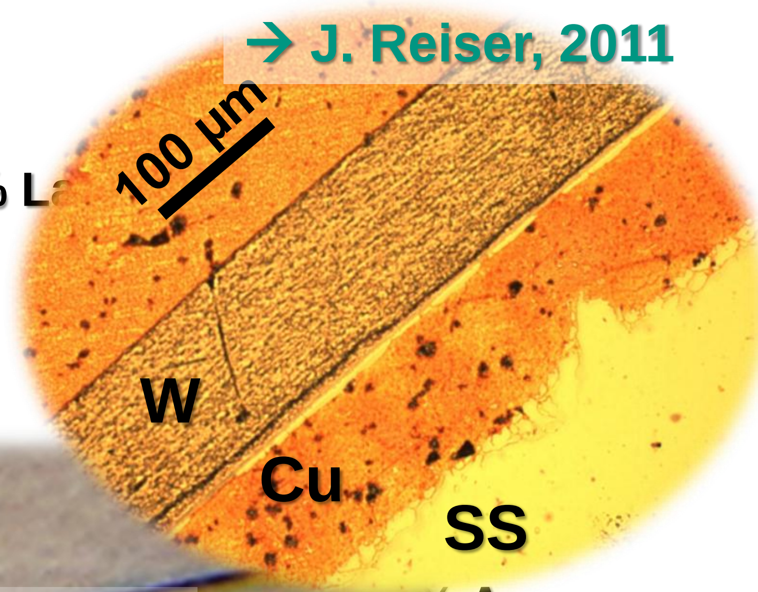
Brazing W→Steel



BRAZING MATERIALS, W→STEEL

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

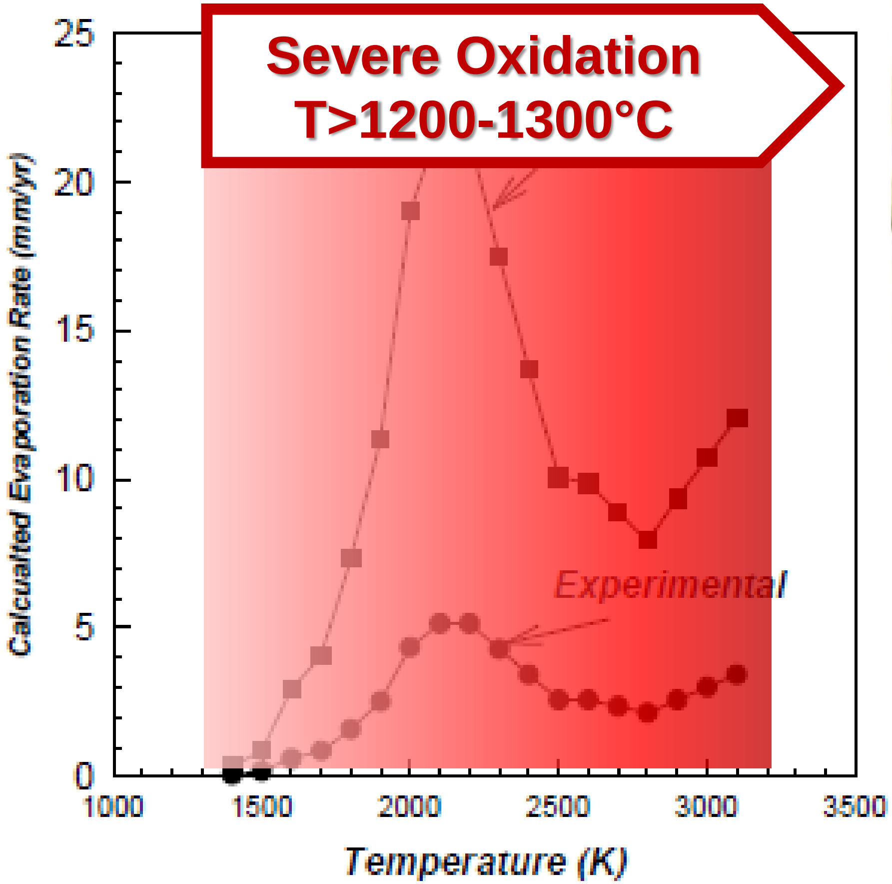




CONCLUSION: Copper has to be used as sealing rather than as a braze material !!!

Environment → Oxidation

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

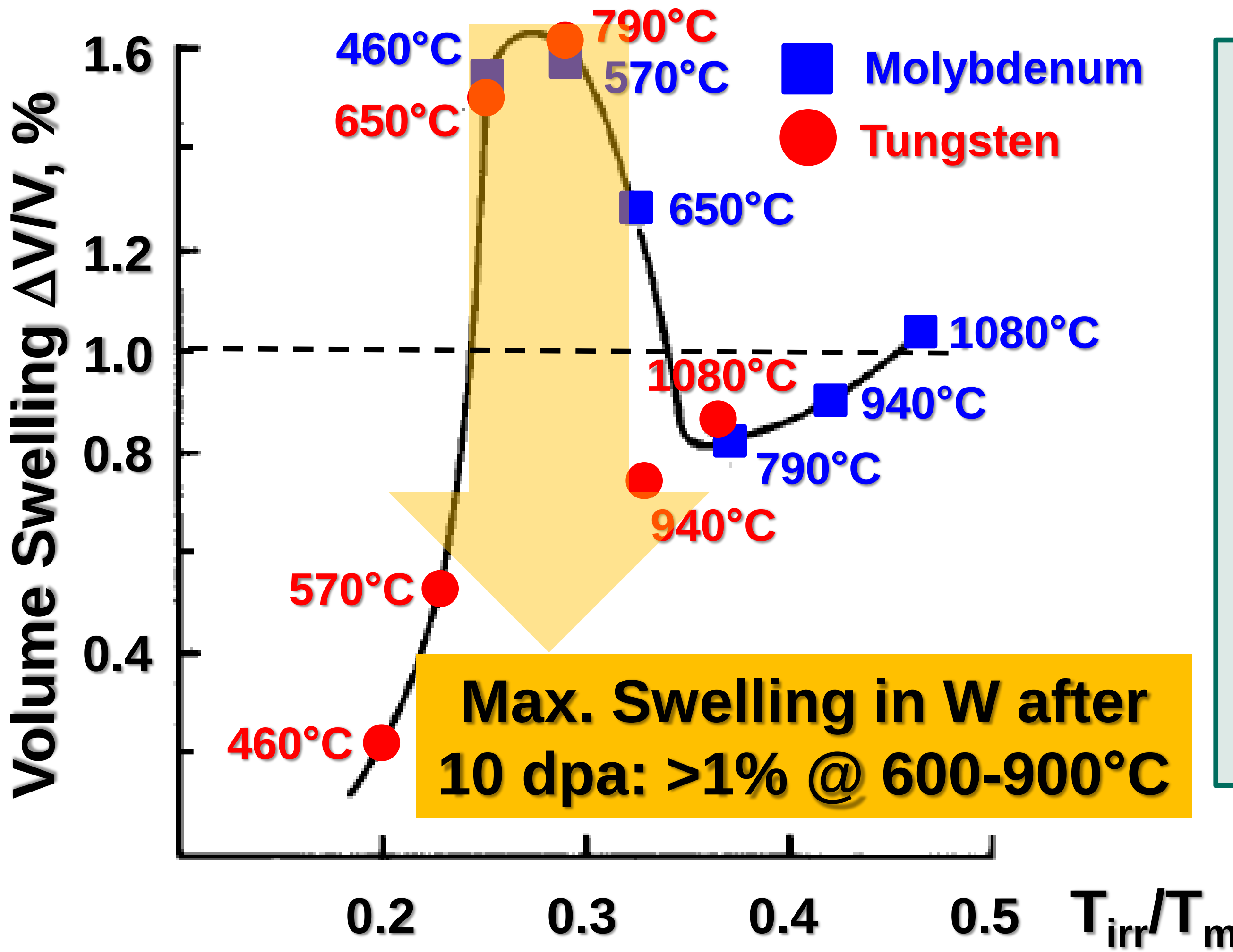


→ N.M. Ghoniem, 1998

CONCLUSION

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

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

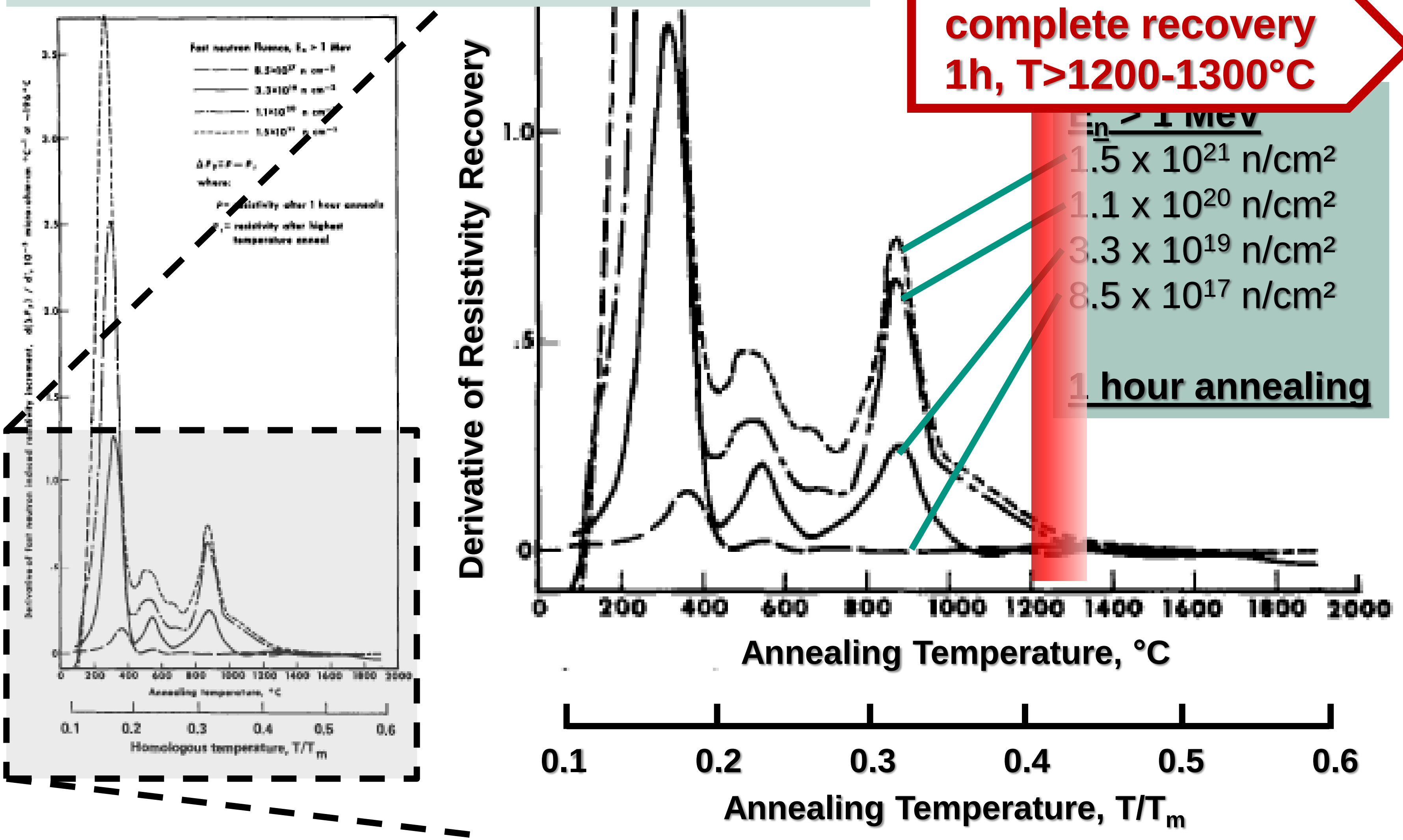
→ **29 dpa in Mo**

→ **9.6 dpa in W**

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

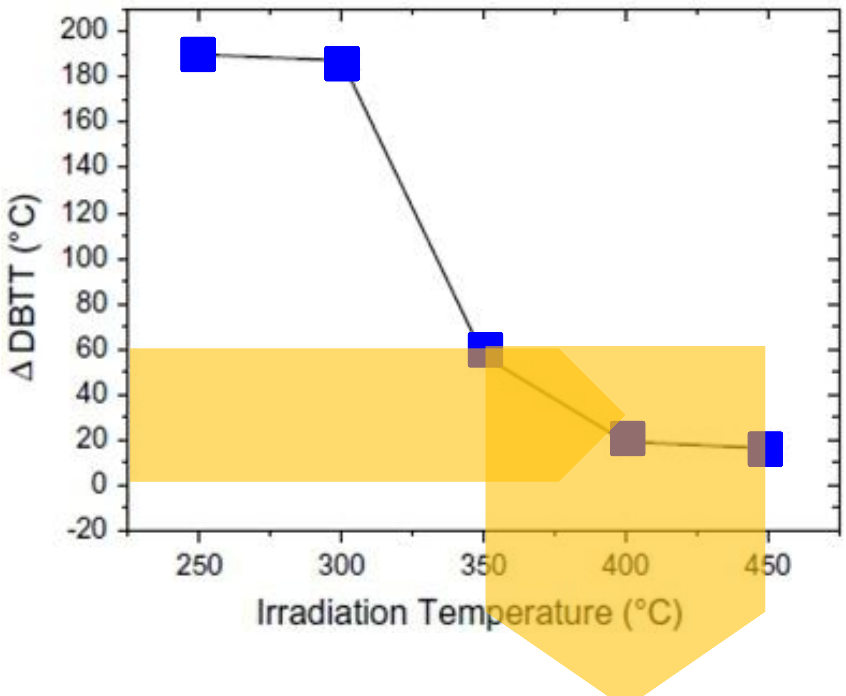
IRRADIATION EFFECTS → RECOVERY

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



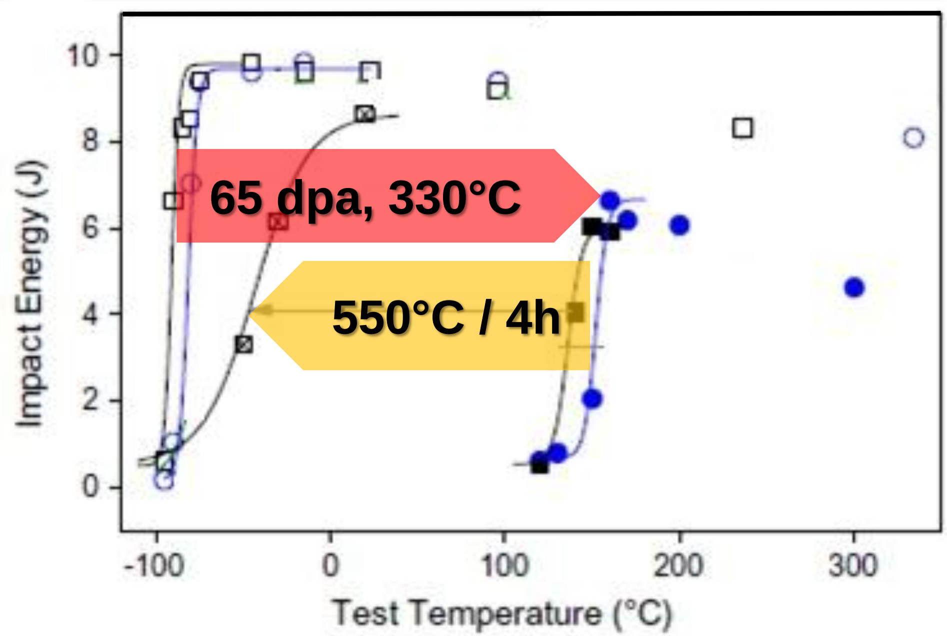
IRRADIATION EFFECTS → EMBRITTLEMENT

EUROFER: In-service irradiation embrittlement after ~10 dpa



Possible Operating Temperature T_{op} > 350°C

EUROFER: Recovery of 65 dpa irradiation embrittlement



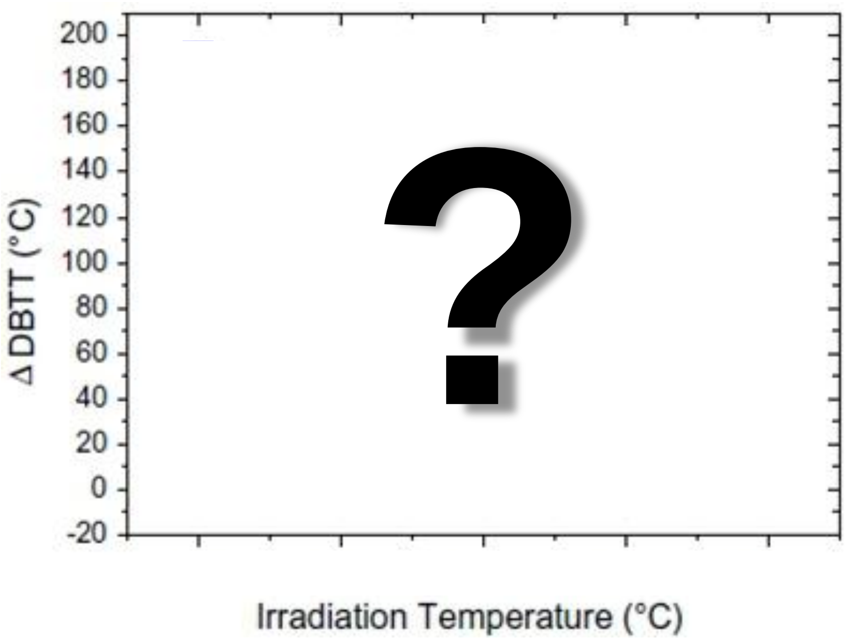
Possible Recovery Temp. T_{rec} > 550°C

→ E. Gaganidze *et al.*, KIT

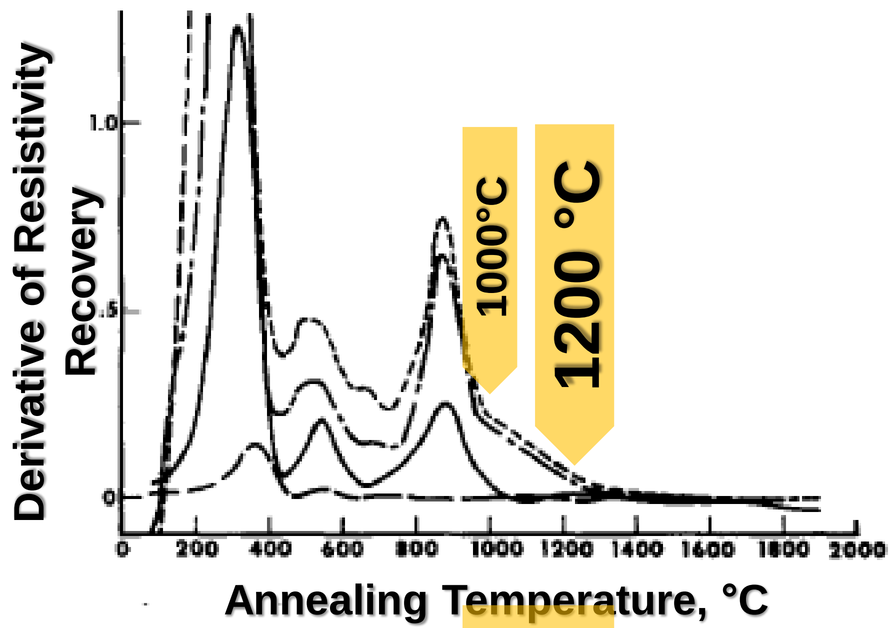
IRRADIATION EFFECTS → EMBRITTLEMENT

Karlsruher Institut für Technologie

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



Tungsten: Recovery of ~2 dpa stage IV irradiation hardening

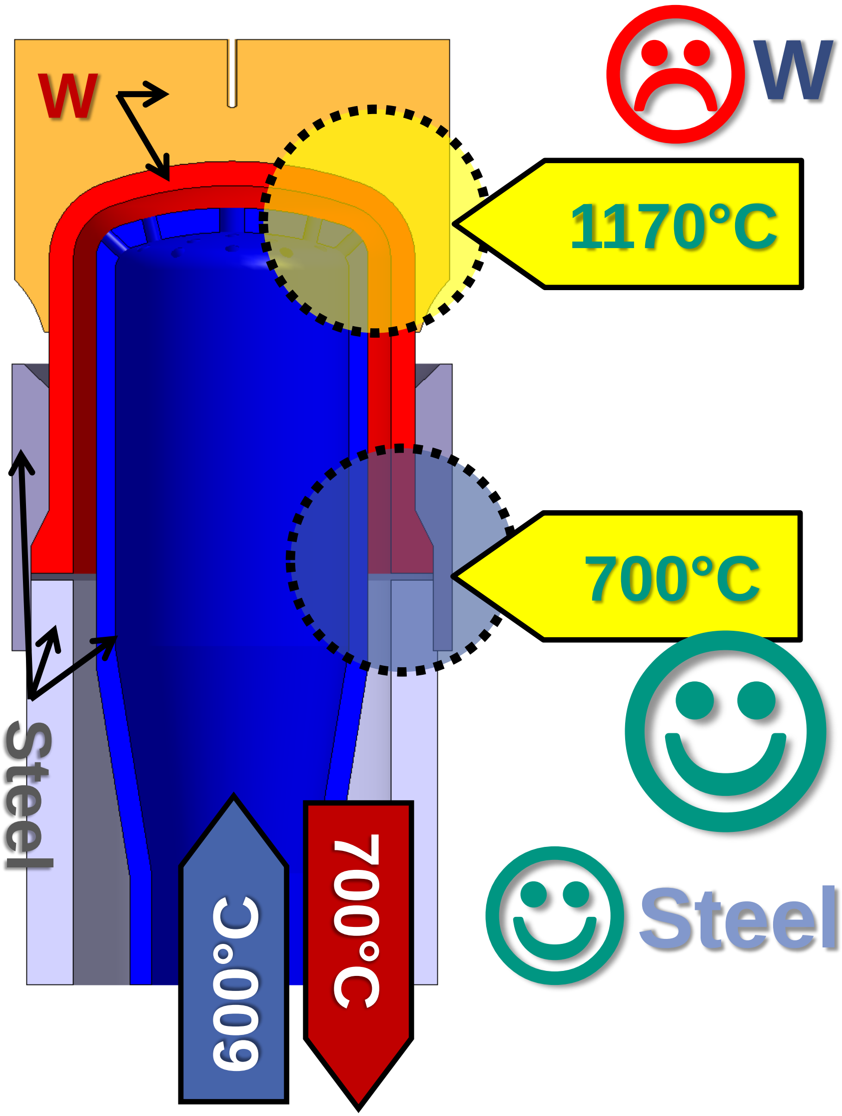


Possible Operating Temp.
T_{op} > 800°C … 1000°C

6

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

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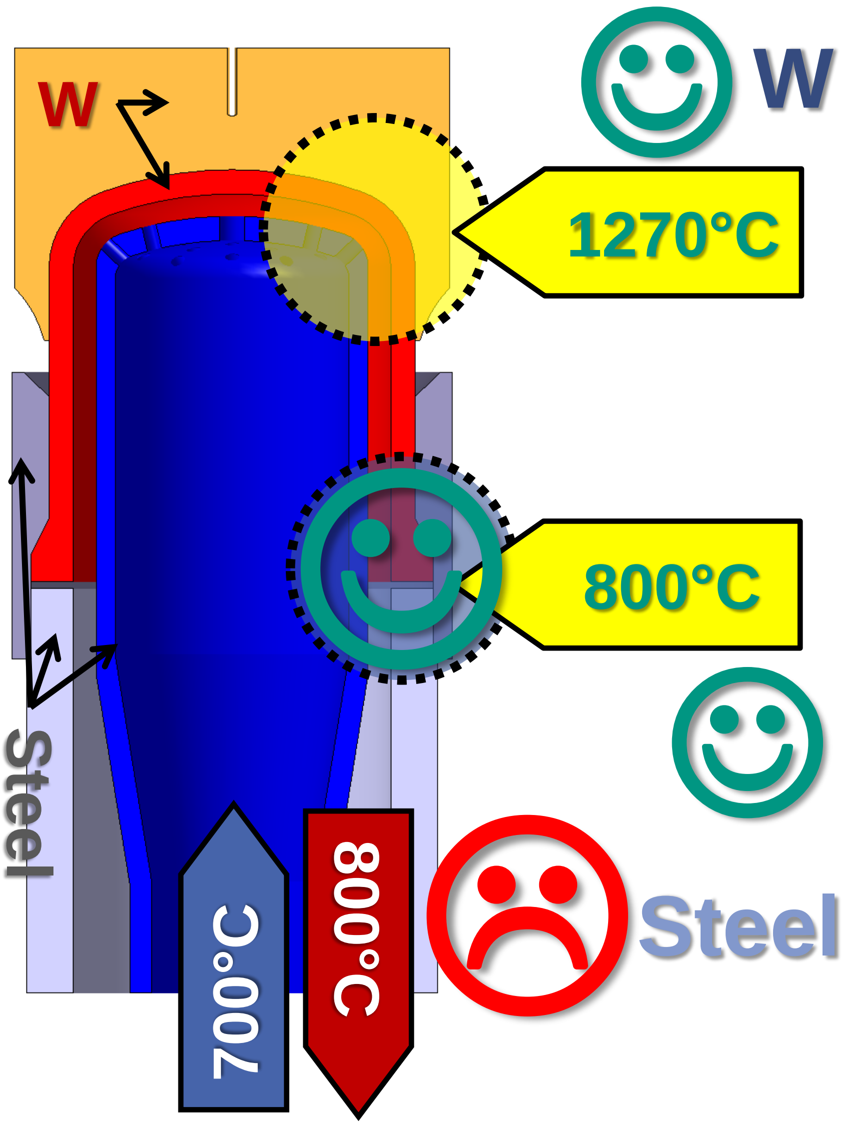
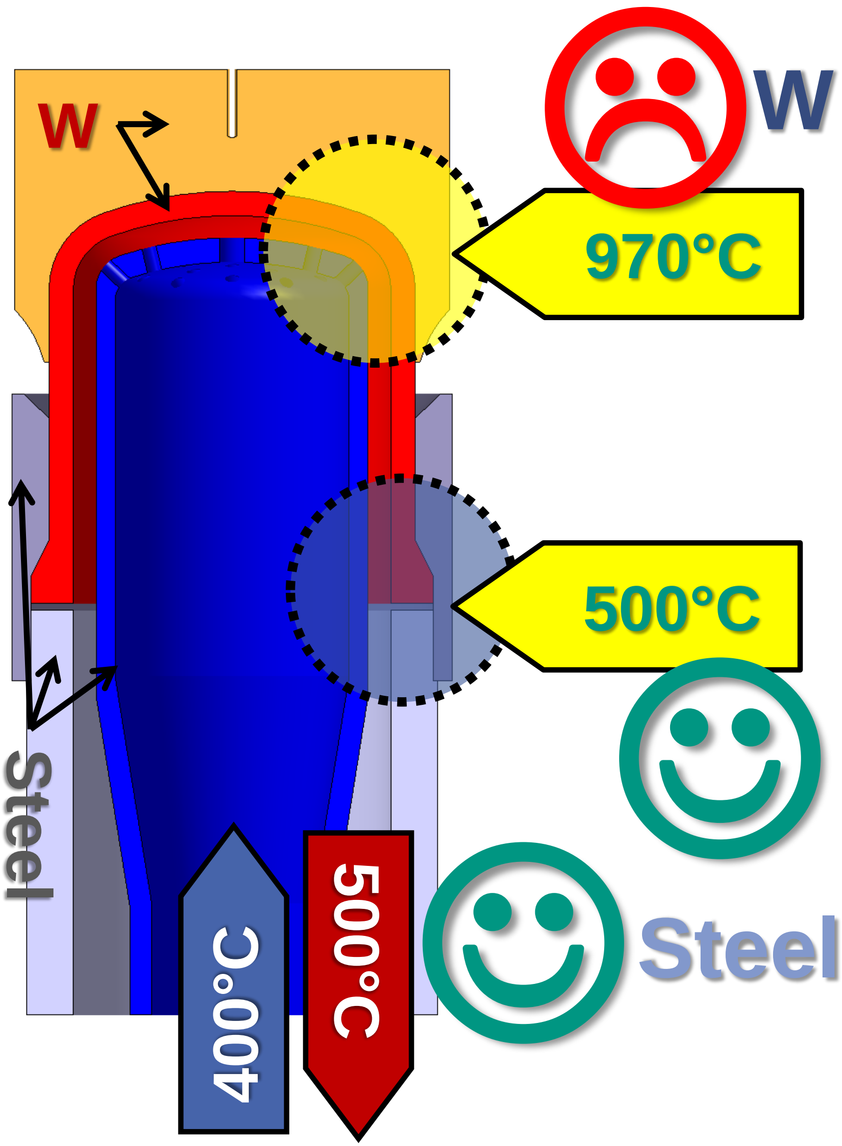


Oxidation →	OK
Swelling ~3% →	?
Embrittlement →	OK
Grain Growth →	ODS

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

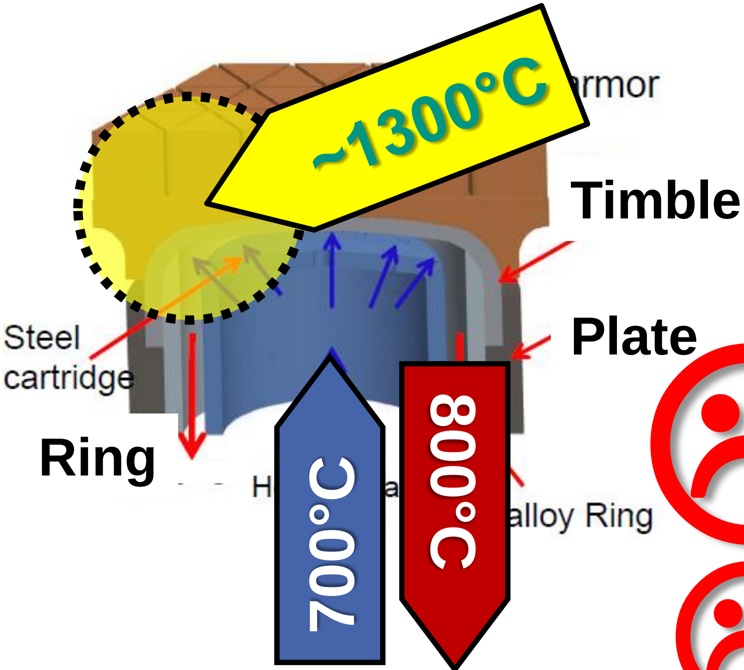
Materials / Design Window → Finger

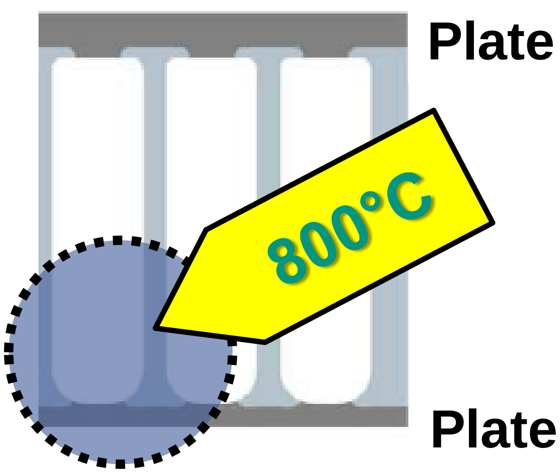


Oxidation	→	OK
Swelling <3%	→	OK (?)
Embrittlement	→	OK
Grain Growth	→	OK

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

Materials / Design Window → Plate





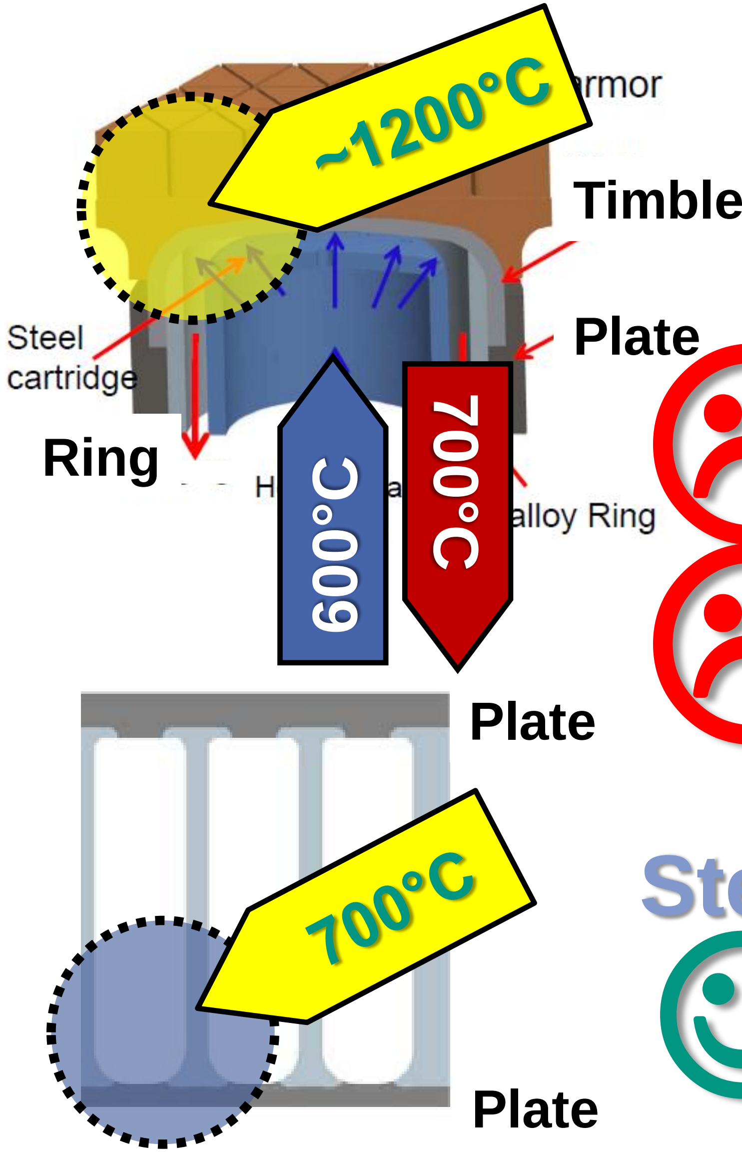
W

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



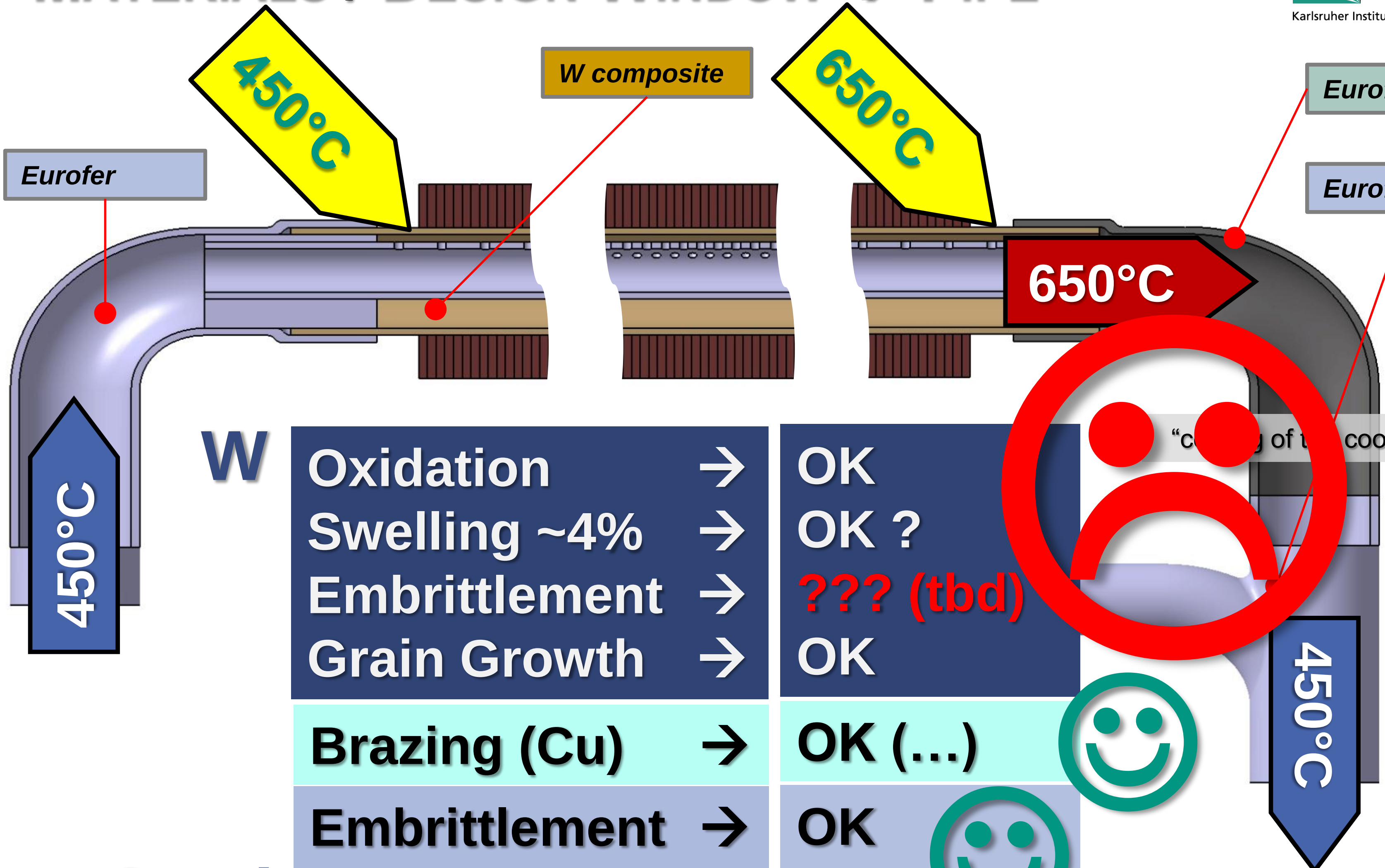
W

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**

7 Summary and Path Forward

SUMMARY

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

Specific Design Rules for Structural Tungsten Components

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

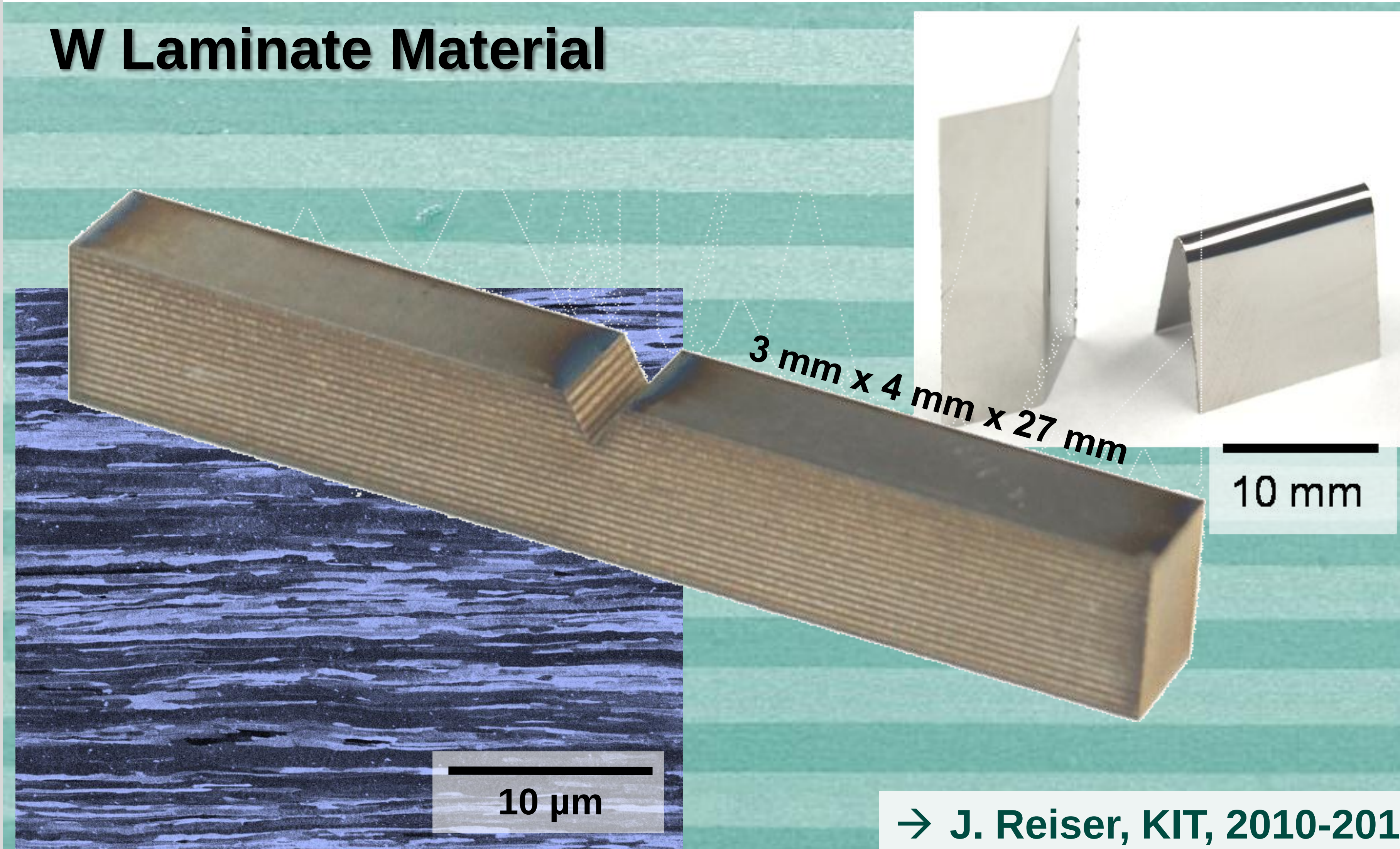
→ Co… an be used as brazing material for W-steel joints, but needs additional strengthening by desing !

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

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

PATH FORWARD → TUNGSTEN ALTERNATIVES

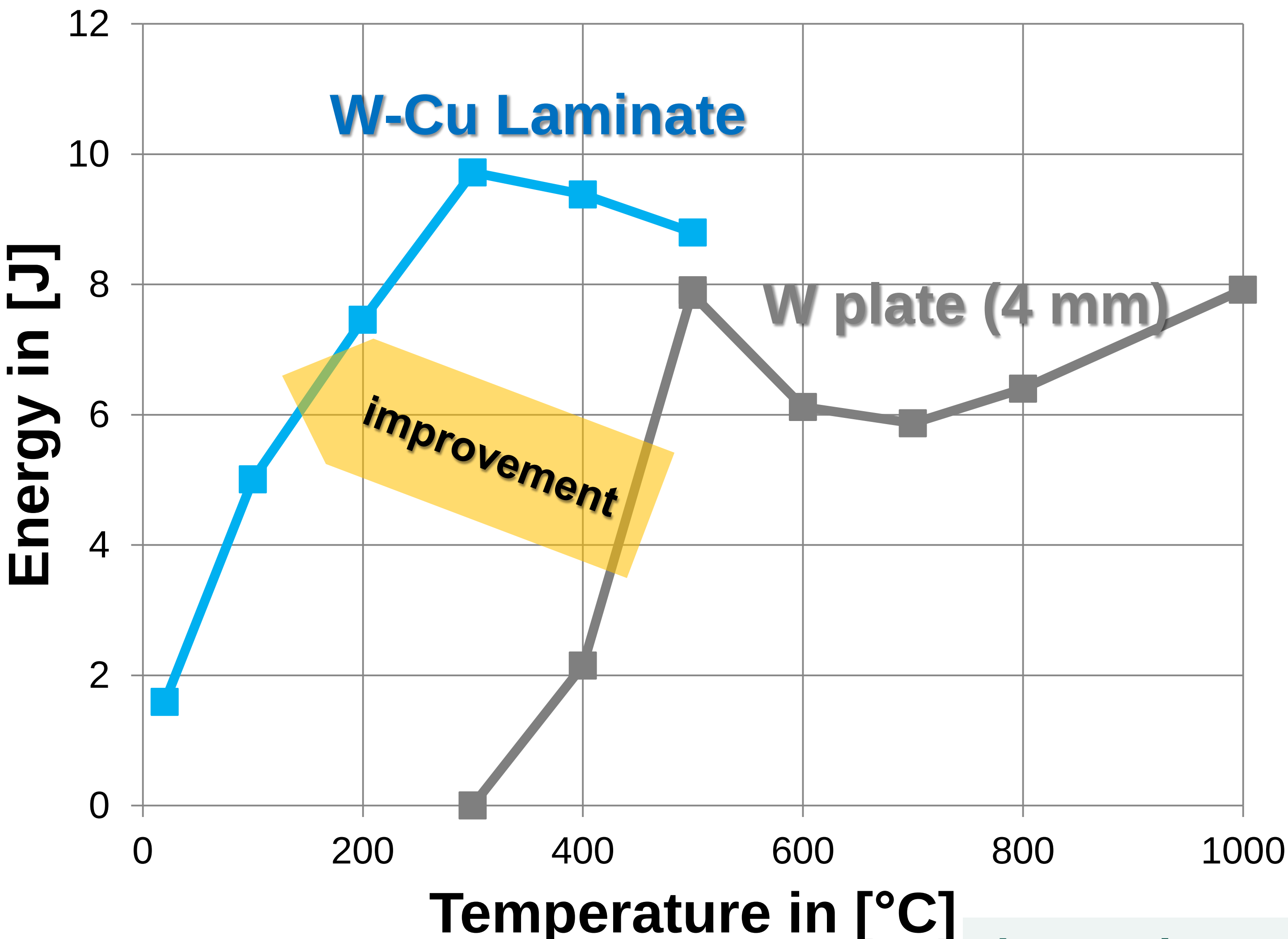
W Laminate Material



→ J. Reiser, KIT, 2010-2011

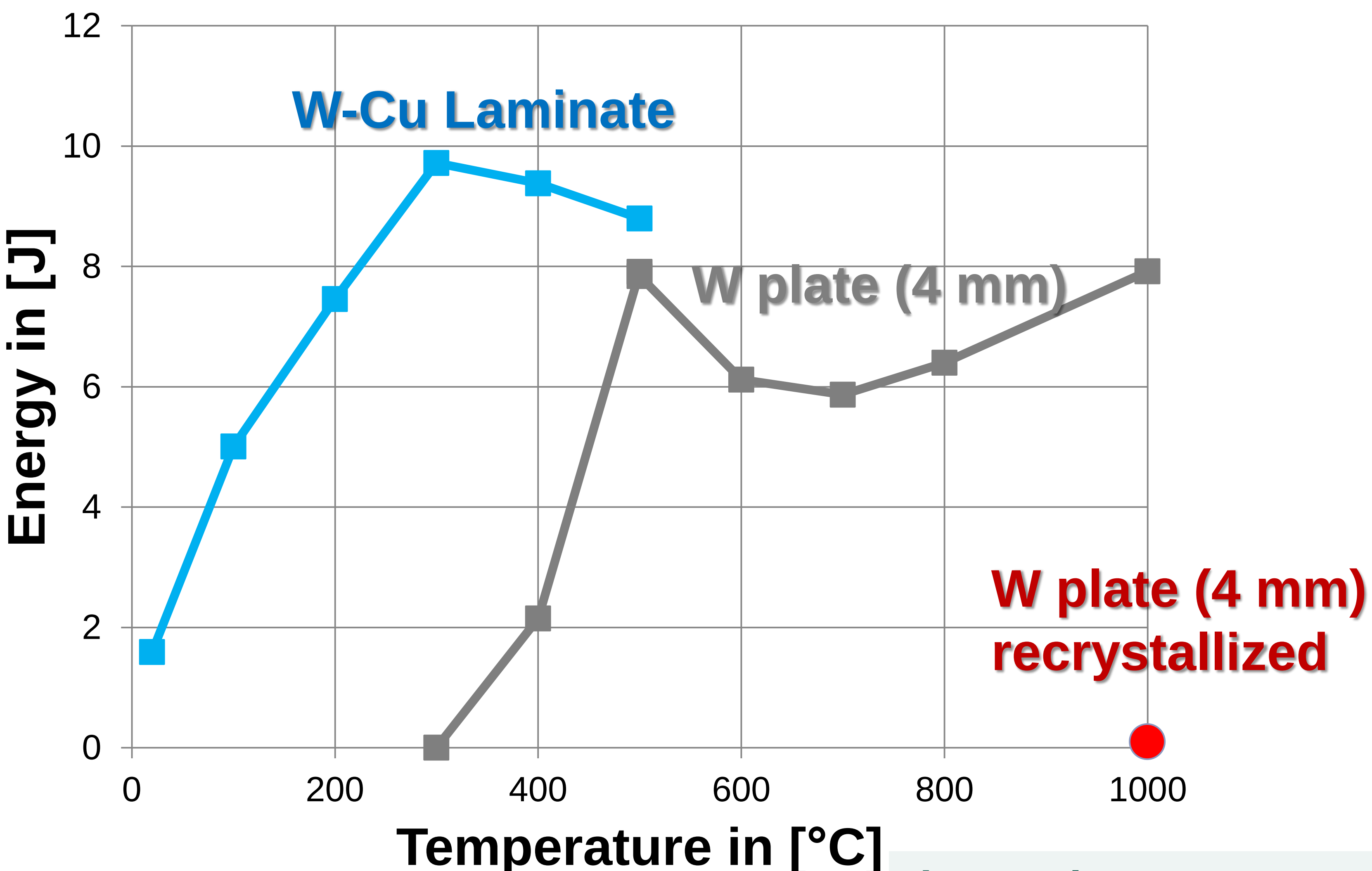
PATH FORWARD → TUNGSTEN ALTERNATIVES

KIT Karlsruher Institut für Technologie



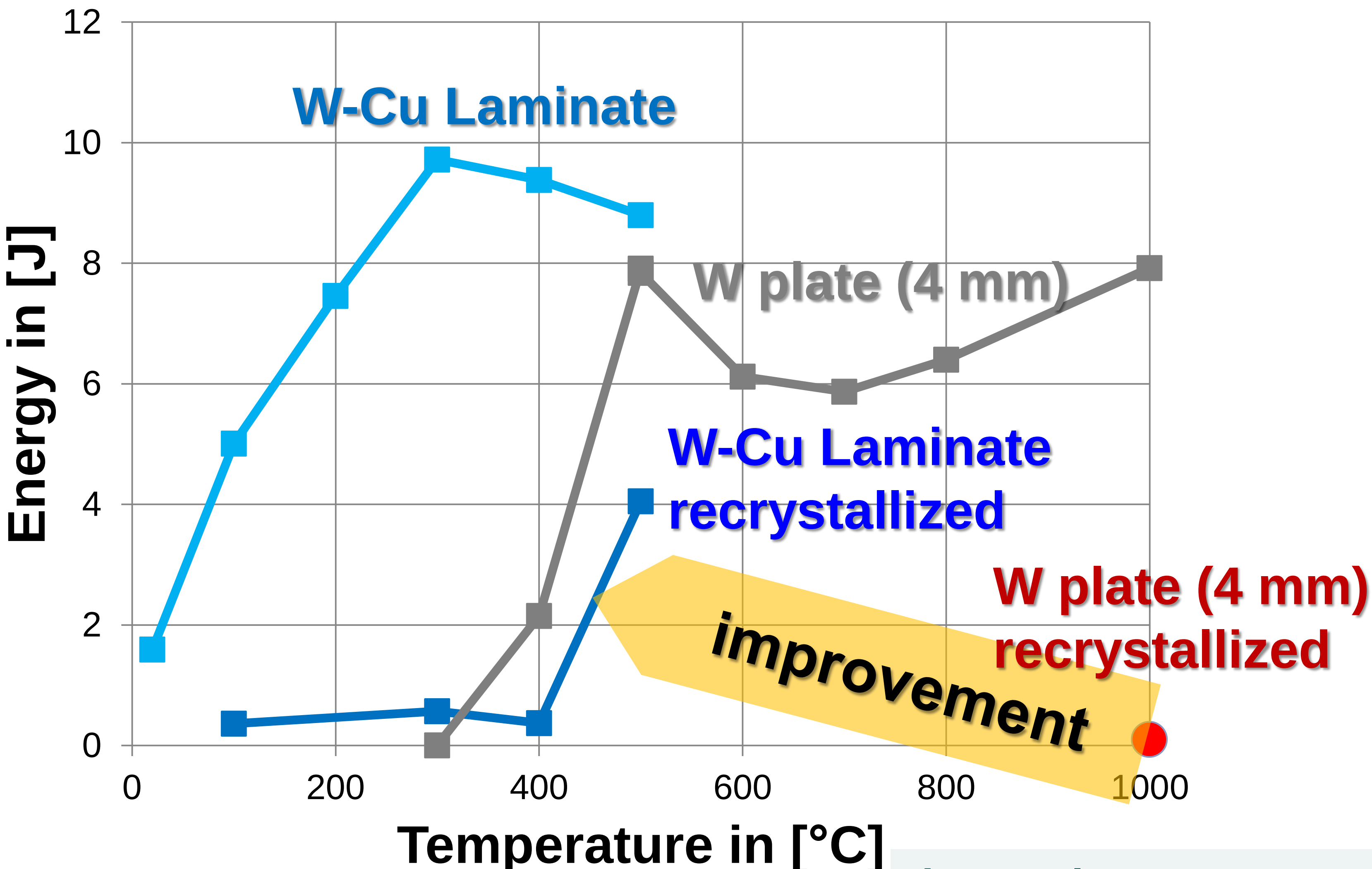
→ J. Reiser, KIT, 2010-2011

Path Forward → Tungsten Alternatives



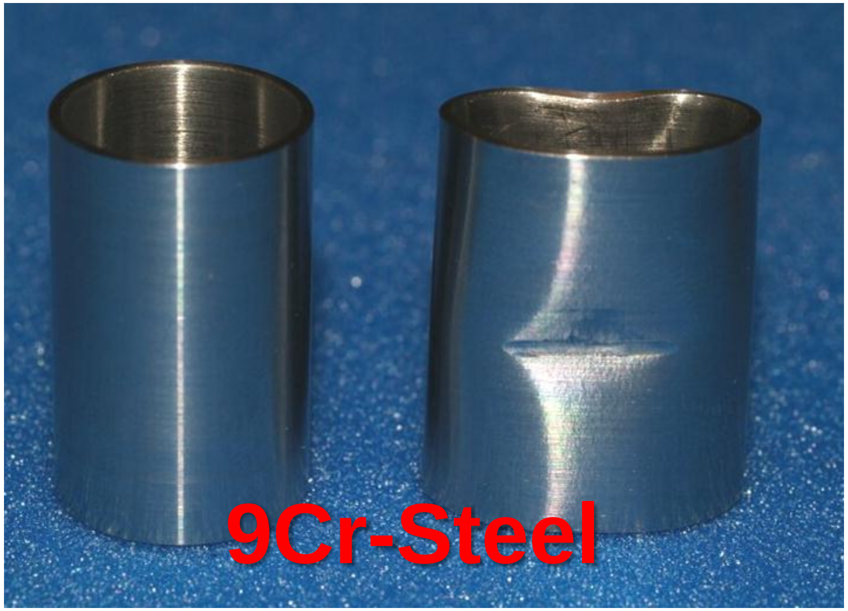
→ J. Reiser, KIT, 2010-2011

PATH FORWARD → TUNGSTEN ALTERNATIVES



→ J. Reiser, KIT, 2010-2011

PATH FORWARD → TUNGSTEN ALTERNATIVES



→ J. Reiser, KIT, 2010-2011

THE ULTIMATE DIVERTOR → GENERIC DESIGN