Heat Sink Materials for the Plasma-facing Components of Fusion Devices

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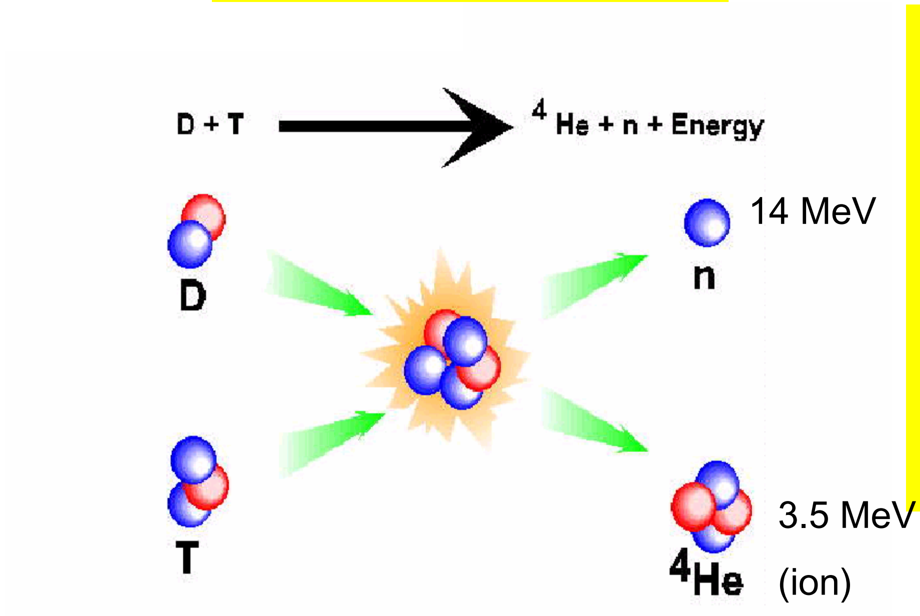
contents

- Fusion
- ITER: divertor requirements
  heat sink material: CuCrZr
- Reactor: divertor requirements →
- Cu-SiC MMC development
- Conclusions

Part of the work has been supported by the European Commission in the frame of the ExtreMat Integrated Project

Fusion reaction, fusion power

D-T Fusion



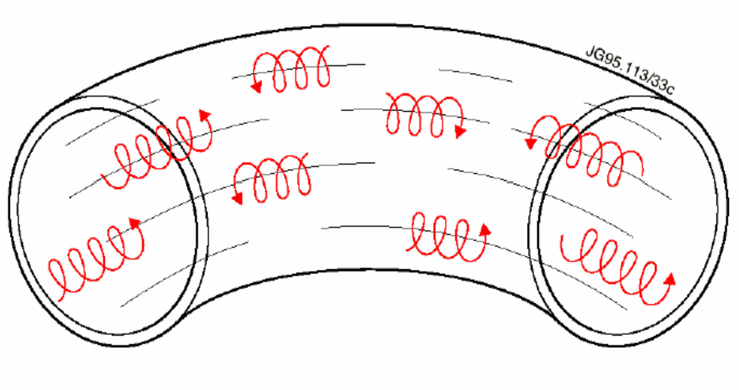
Parameter field for a fusion reactor

plasma density (**n**): $>10^{20}$ m^{-3}
plasma temperature (**T**): 18 keV
(equ. 200 Mio. deg.)
energy confinement time (τ): >1 s

plasma volume: approx. 1000 m^3
fusion power: 2 GW

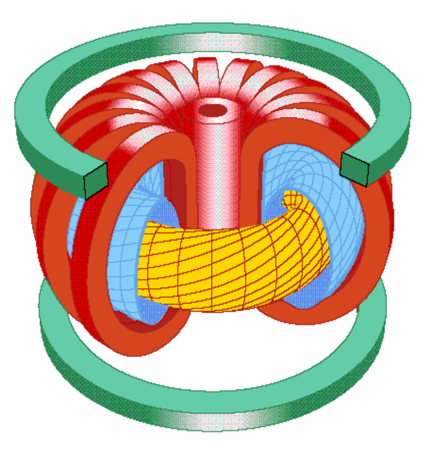
Magnetic confinement, tokamak, stellarator

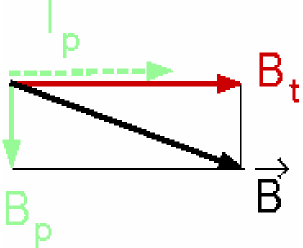
principle of toroidal magnetic confinement



- **magnetic field confines ions,electrons**
- **balances the plasma pressure (10 atm)**
- **thermal insulation (200 Million K)**

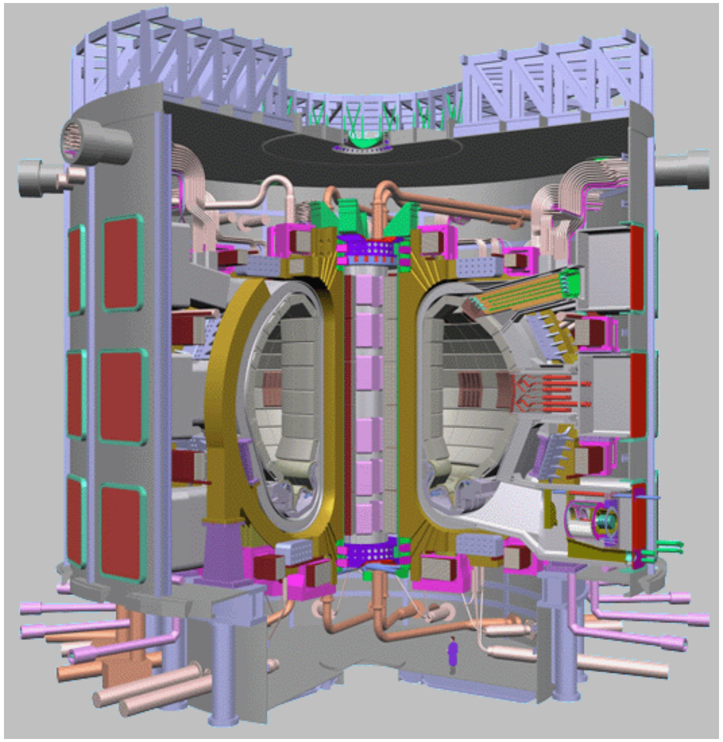
Tokamak





Next step: ITER

ITER Design Parameters



Fusion Power	500 MW
Plasma Volume	837 m^3
Plasma Surface	678 m^2
Heat flux on Divertor	10 (20) MW/m^2
Pulse length	400 s
Number of pulses	~ 30.000

ITER goals:

- **Show scientific and technological feasibility of fusion energy for peaceful purposes.**
- **Test essential technologies in reactor-relevant physics and technology environment.**
- **Demonstrate safety and environmental acceptability of fusion.**

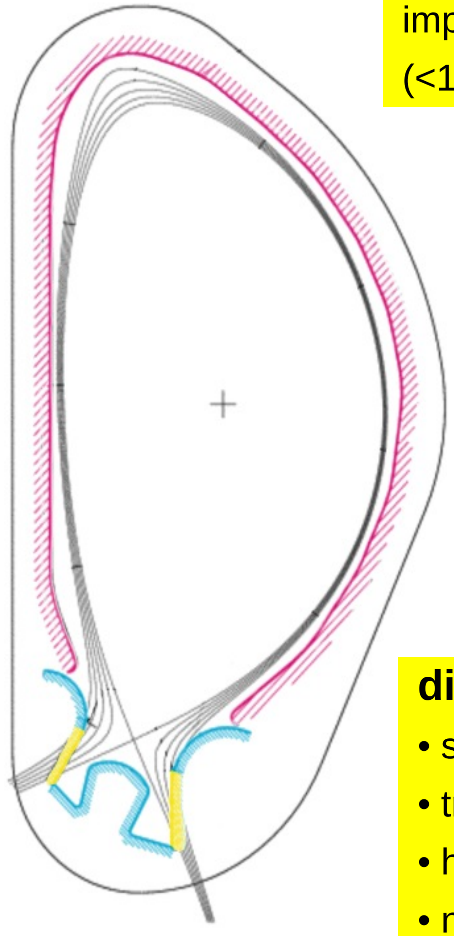
Loading of materials in a fusion device

structural materials

- *thermomechanical loads*
- *electromagnetical loads*
- *neutron irradiation*

plasma facing materials

heat sink materials



bulk plasma:

impurity tolerance

(<10^{-5} W, 10^{-2} Be, C)

tritium inventory:

- to be kept low (safety)

divertor target:

- stationary high heat flux 10 (20) MW/m^2
- transient heat loads: e.g. disruptions
- highly loaded surface approx. 50 m^2
- neutron damage: < 0.5 dpa

Materials for the ITER Plasma Facing Components

Plasma facing materials

first wall: beryllium: *low Z*

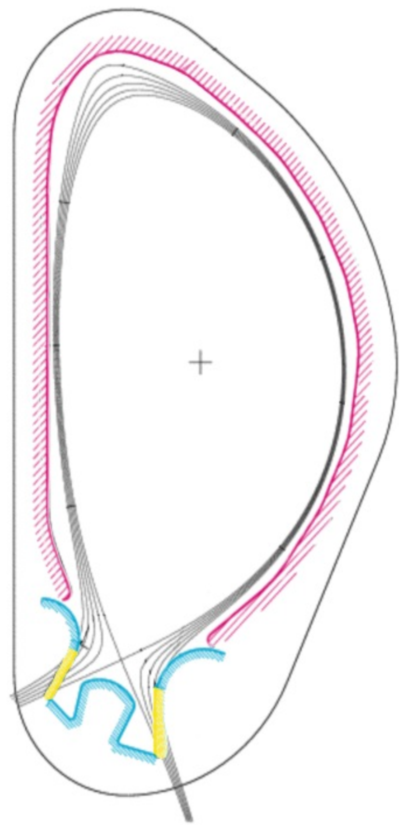
divertor: 3d C-C composite:

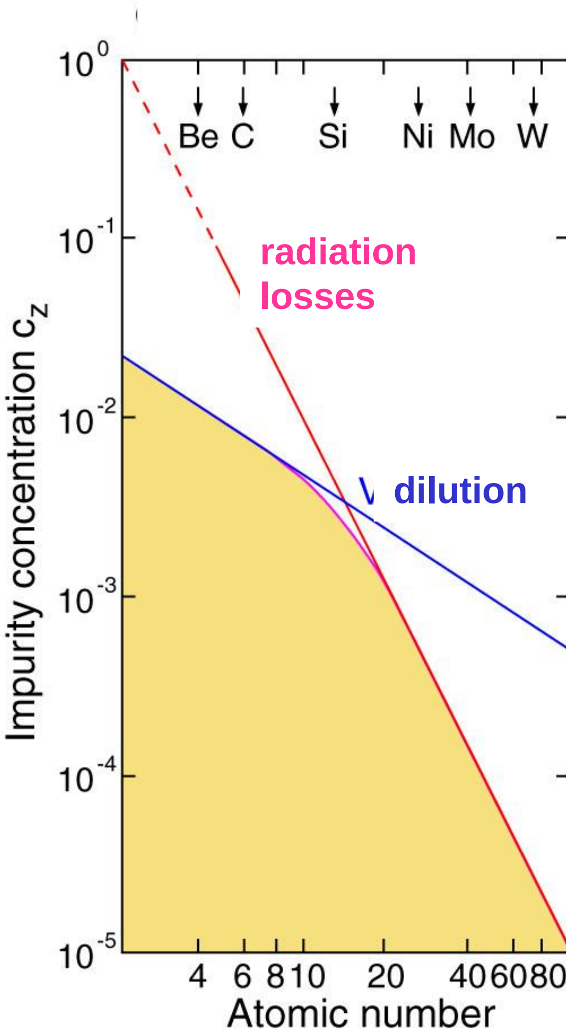
thermal shock resistance

tungsten:

high temp. resistance

→ materials selection driven by T-codeposition and thermal transients

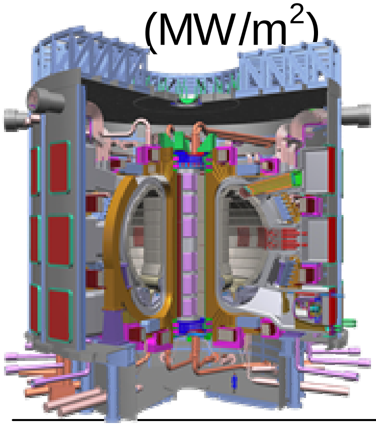




Heat sink material CuCrZr

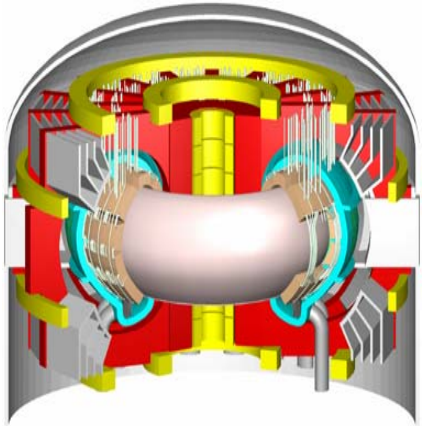
Loading conditions for the divertor

	Divertor target **ITER**	Divertor target **Reactor (DEMO)**
component replacements	up to 3	5 year cycle
av. neutron fluence (dpa)	max. 0.5	30
Normal operation		
No. of cycles	10000?	<1000
coolant temperature (°C)	100	300 (600, He)
Surface heat flux (MW/m^2)	10 (20)	10...15



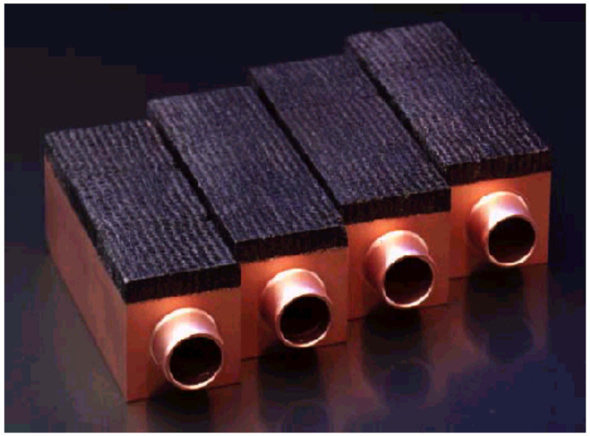
ITER

Reactor

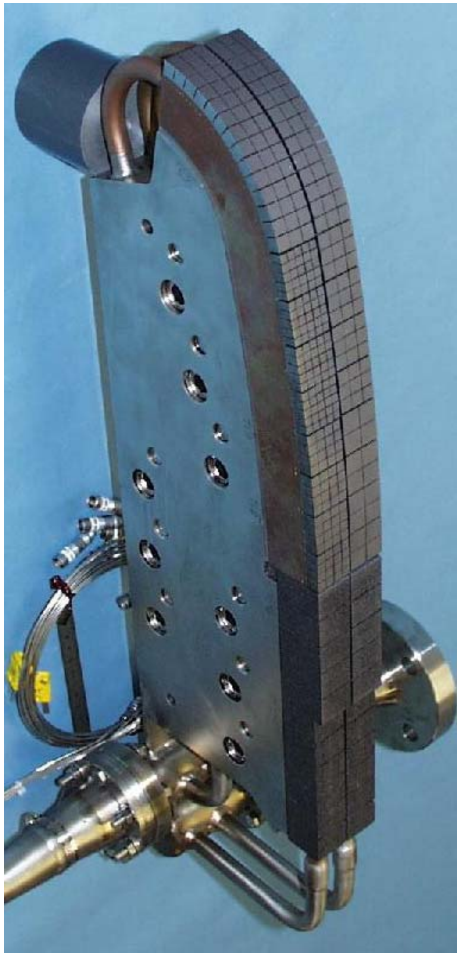


ITER Divertor cassette

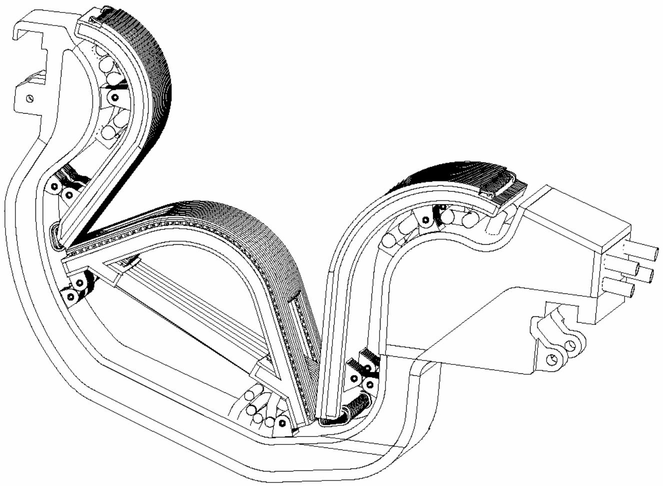
Plasma facing armour:
Tungsten and CFC



25 mm

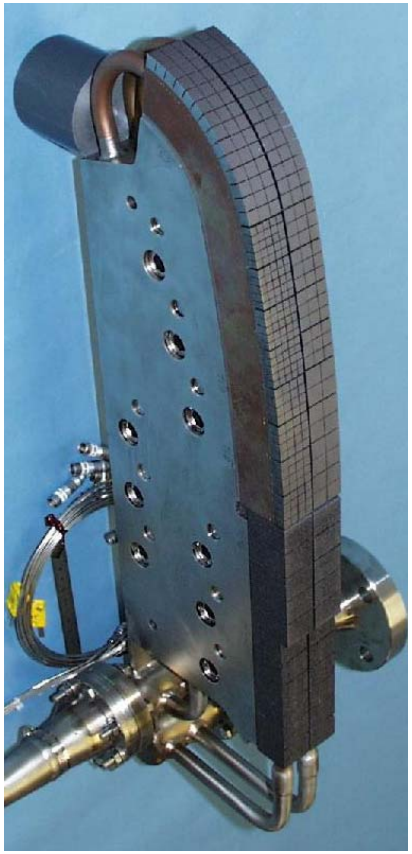


150 mm

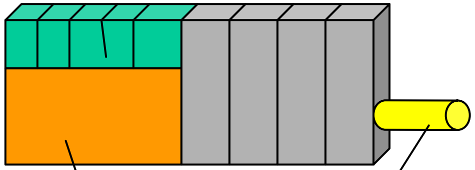


400 mm

ITER: Two designs: „Flat tile“ and „Monoblock“



W flat tiles



CFC monoblocks

Heat sink material CuCrZr (ITER)

ITER Database – Heat sink material

CuCrZr alloy:

- properties depend largely on heat treatment (manufacturing of components).

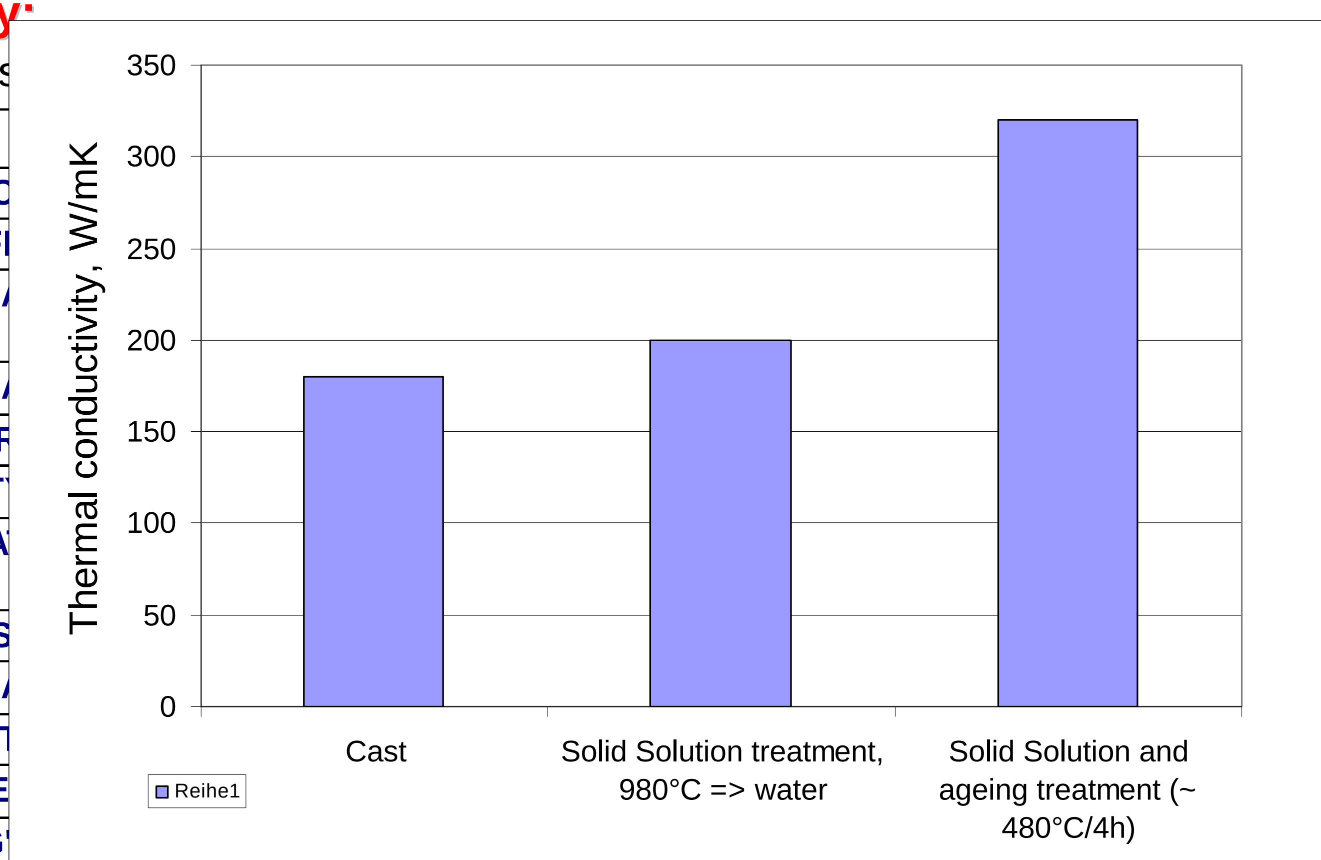
CuCrZr	*Comments*
CHEMICAL COMPOSITION	Detail from Industry
SPECIFIC HEAT	Generally OK
THERMAL CONDUCTIVITY	Generally OK, depends on thermal treatment
THERMAL EXPANSION	Well documented
ELECTRICAL CONDUCTIVITY	Well documented
DENSITY	Well documented
ULTIMATE TENSILE STRENGTH	Generally OK, depends on thermal treatment
YIELD STRENGTH	- " -
ELONGATION	- " -
REDUCTION OF AREA	- " -
ENGINEERING STRESS-STRAIN	- " -
YOUNG'S MODULUS	Well documented
STRESS RUPTURE	Some data exists
CREEP AT 1%	Some data exists
FATIGUE	Some data exists, depends on creep
FRACTURE TOUGHNESS	Some data, better than DS Cu

Data: ITER Materials Data Handbook

ITER Database – Heat sink material

CuCrZr alloy:

- properties



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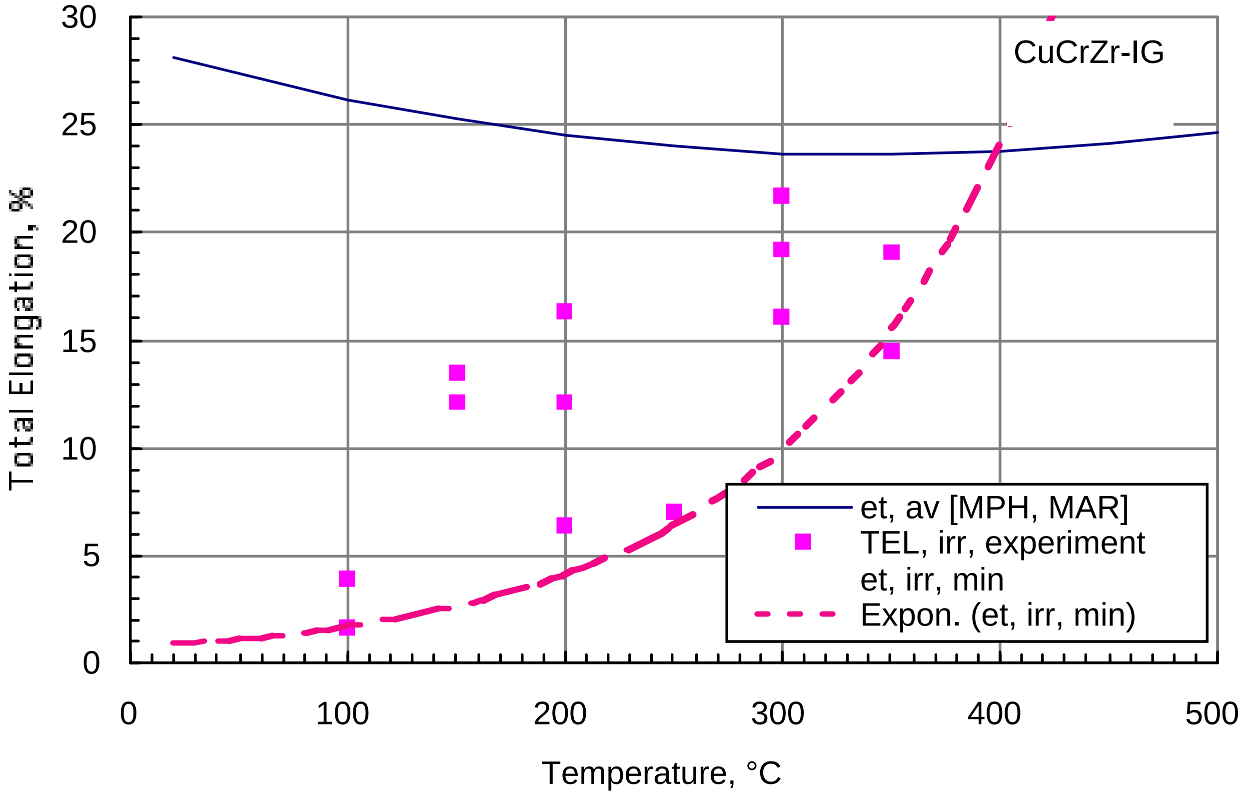
ENGINE	
YOUNG'	
STRESS RUPTURE	Some data exists
CREEP AT 1%	Some data exists
FATIGUE	Some data exists, depends on creep
FRACTURE TOUGHNESS	Some data

Data: ITER Materials Data Handbook

ITER Database – Heat sink materials

CuCrZr Alloy, Neutron effects

- For ITER conditions: no change of thermal properties,
- However, loss of ductility is main concern for ITER (low operation temperature), but should pose no problem for reactor conditions (high operation temperature)



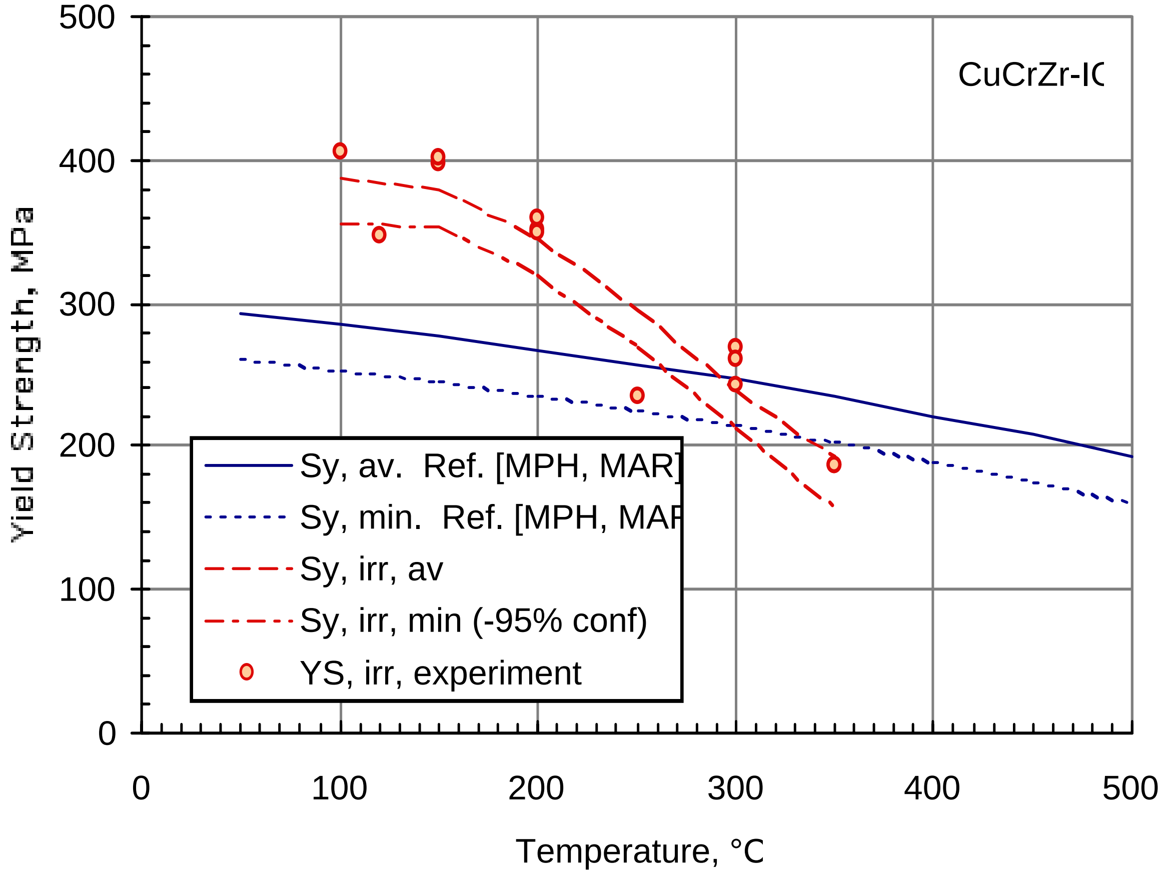
Dose - 0.3 - 5 dpa, Tirr =Ttest

Data: ITER Materials Data Handbook

ITER Database – Heat sink materials

CuCrZr Alloy, Neutron effects:

- For **reactor conditions** irradiation induced creep is main issue

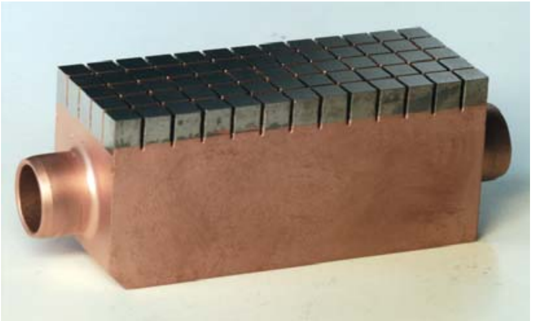


Dose - 0.3 - 5 dpa,
Tirr = Ttest

Data: ITER Materials Data Handbook

Performance of components under irradiation EUROMAT C33

Tungsten Macrobrush Mock-Ups



Unirradiated

- 1000 cycles x 8 MW/m^2 – no failure
- 1000 cycles x 14 MW/m^2 – no failure

200°C, PARIDE 4 (0.5 dpa in tungsten)

- 1000 cycles x 10 MW/m^2 – overheating
- 1000 cycles x 14 MW/m^2 – loss of tiles

CFC Monoblock Mock-Ups

Unirradiated

- 1000 cycles x 19 MW/m^2 – no failure
- 700 cycles x 23 MW/m^2 – no failure,

200°C, 0.2 dpa (in carbon)

- 1000 cycles x 10 MW/m^2 – no failure
- 1000 cycles x 12 MW/m^2 – no failure
- screening at 14 MW/m^2 – surface erosion

Activity: FZ Juelich and HFR, Petten

Data: J. Linke, M. Roedig, FZ Juelich

Comparison of PH alloys and DS Cu

PH Cu alloys	DS Cu alloys
Thermal stability	
Above ageing temperature overageing: significant decrease of strength. Overageing affects also the thermal conductivity by the dissolution of precipitates.	Inert alumina particles are not prone to coarsening or to dissolution, keeping their hardening effect up to very high temperatures. Properties strongly depend on the production route and are less sensitive to heat treatments.
Fracture toughness	
FT of unirradiated and irradiated materials decreases with increasing temperature, but remains at a relatively high level.	Very low above 200°C in the unirradiated condition. Fracture toughness of irradiated GlidCop Al25 decreases 2-3 times compared to unirradiated material.
Isotropy	
Isotropic mechanical properties.	The short-transverse ductility and fracture toughness is less than in the other two directions.
Weldability	
Can be welded by TIG and EB and then solution annealed and aged without cold work, recovering 50-70% of the full hardened strength.	Not suitable for structural/leak tight fusion welds. Microstructure is completely destroyed in this case, with unrecoverable loss of strength of the joint. Non-fusion weld should be applied (friction, explosion, etc.).
Neutron irradiation resistance at high temperature	
The PH alloy microstructure is less stable under irradiation, due to radiation enhanced coarsening of the Cr/Zr precipitates. Irradiation induced creep at >350°C.	DS alloys have a higher stability range, but are also expected to show irradiation induced creep at high temperature.

Requirements for reactor PFCs

Most important: efficient energy conversion

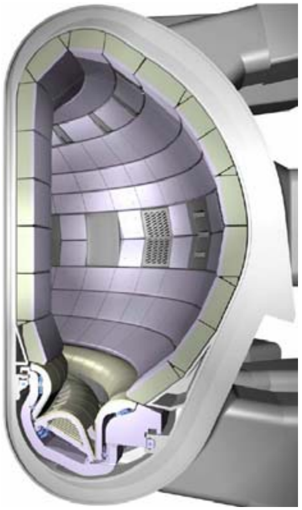
- **Water cooled** divertor: close to PWR conditions,
  water at 300°C, 10 MPa:
  new heat sink materials needed

Attractive, higher thermal efficiency:

- **He-gas cooled** W-based divertor:
  advanced technology (min. 600°C He at 10 MPa)
  open materials questions

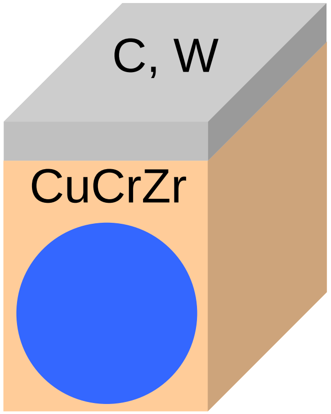
Heat sink materials: ITER – reactor (DEMO)

ITER - Divertor

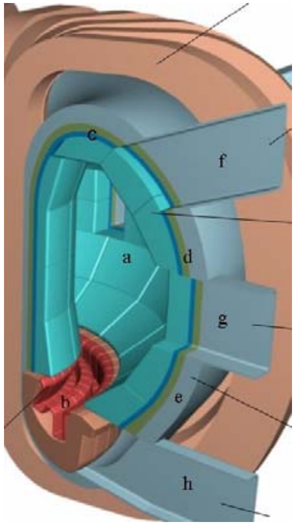


- divertor: 10-15 MW/m²
- coolant: water 80°C
- no energy production
- neutron irradiation
  ≤ 0.5 dpa
- use of available materials

Heat sink:
CuCrZr
max. operation temperature:
350-400°C

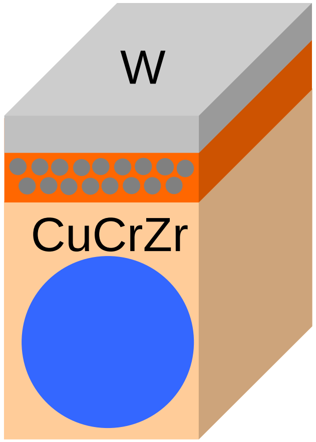


DEMO - Divertor



- divertor: 10-15 MW/m²
- coolant: water ≥ 300°C or
  helium ~ 600°C
- energy production
- neutron irradiation ~ 30 dpa
- development of new materials

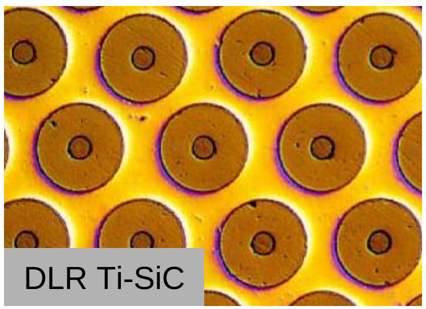
Heat sink:
SiC fibre reinforced copper
operation temperature:
~ 550°C



Motivation: Cu-SiC MMCs

aim: composite tensile strength 600-800 MPa at room temperature

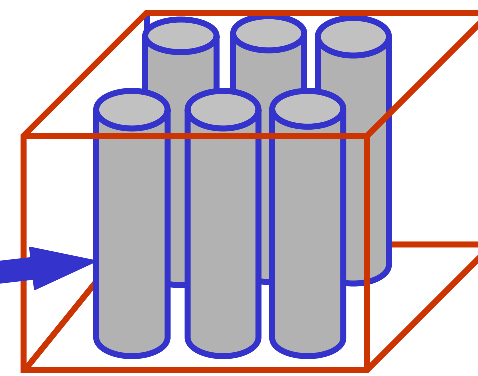
important: optimised bonding between the fibre and matrix



- e.g. DLR: titanium matrix composite reinforced with SiC long fibres for aeroplane engines
- interf. shear strength in the range of 70-80 MPa

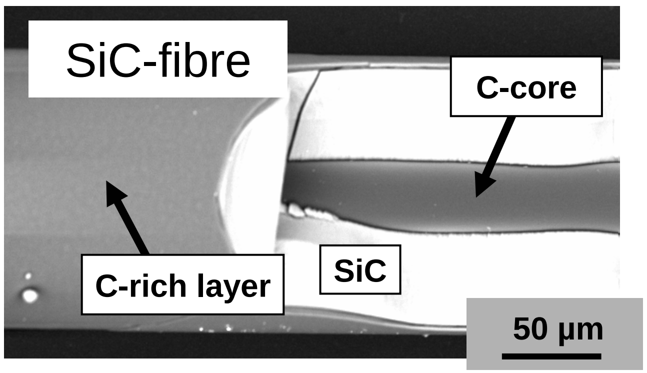
problem: adhesion between SiC/C and copper

solution: titanium interface layer between SiC fibre and copper matrix

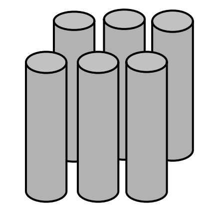


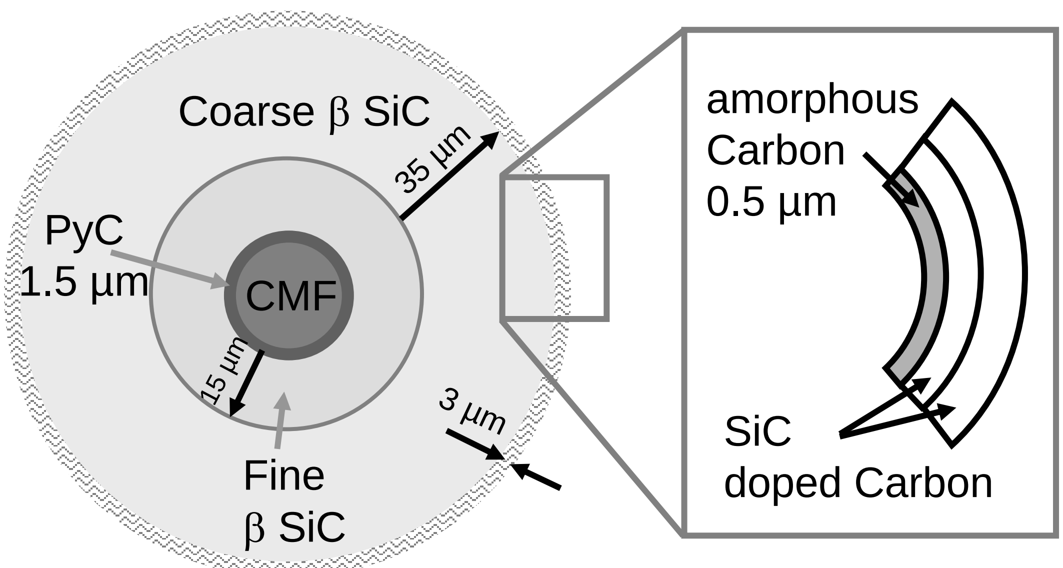
MMC – SiC Fibres

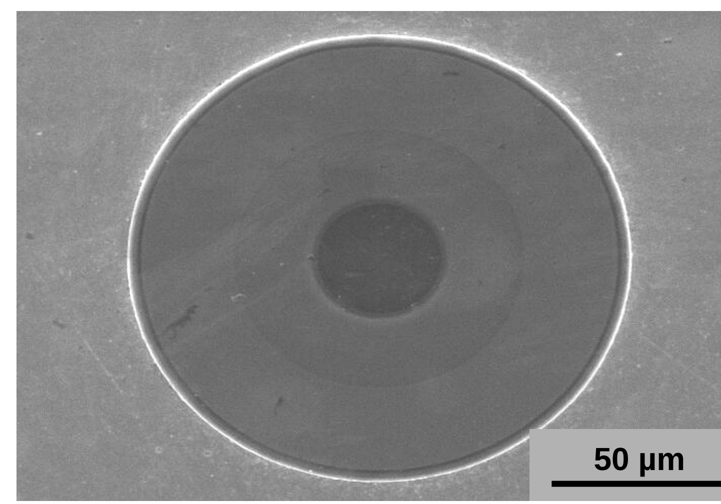
SiC fibre SCS6 (Specialty Materials) Ø 140 µm



- commercially available SiC fibre
- with carbon rich layer at the surface for protection during handling
- optimised for titanium matrix





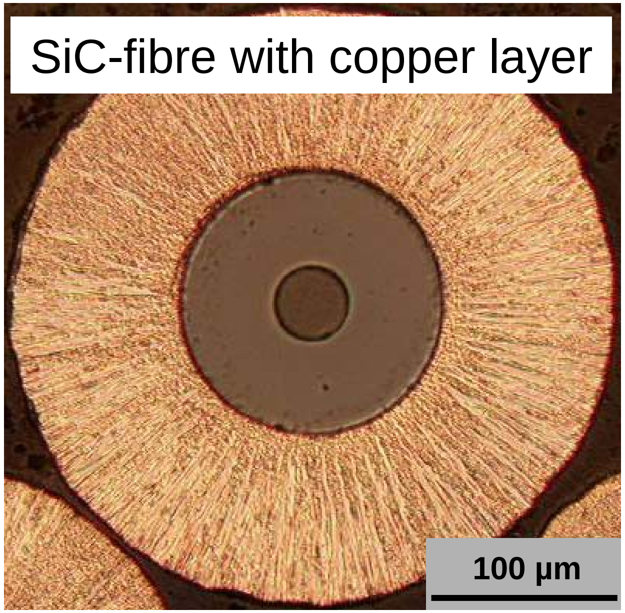


CMF - Carbon Mono Filament

Processing of MMC - Matrix

Electroplating of copper

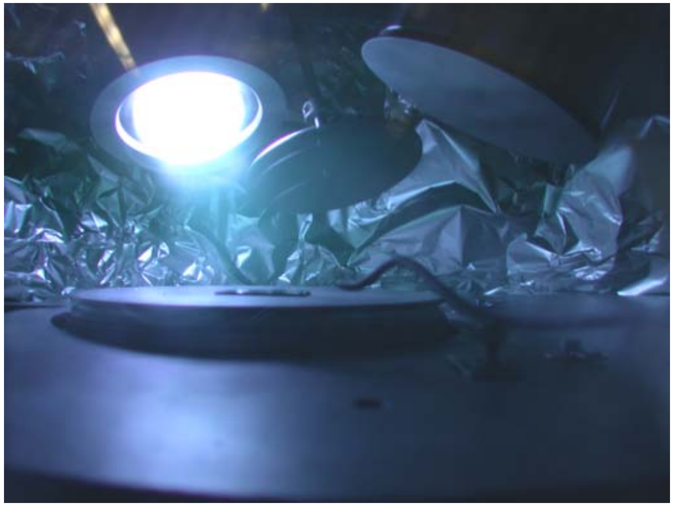
- $CuSO_4$ bath
- room temperature
- 4,5 V
- 8 hours
- fibre volume fraction v_f = 20 %



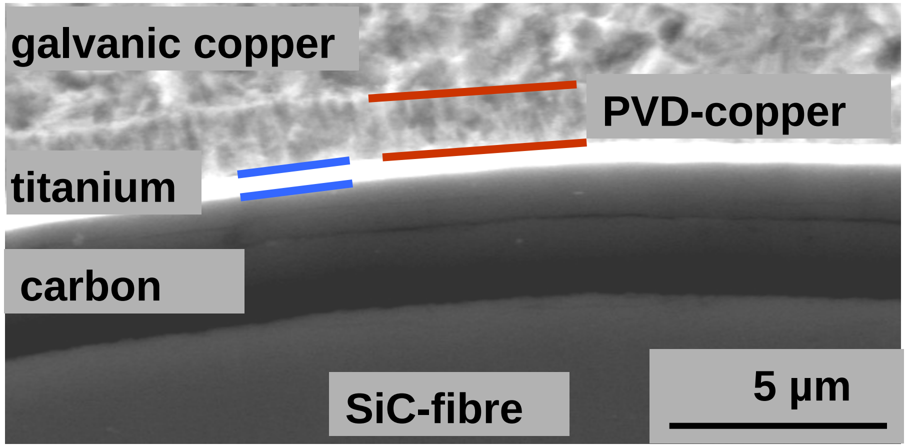
galvanic deposition of a 80 µm thick copper layer as matrix

Processing of MMC – Interlayer

Magnetron sputter device

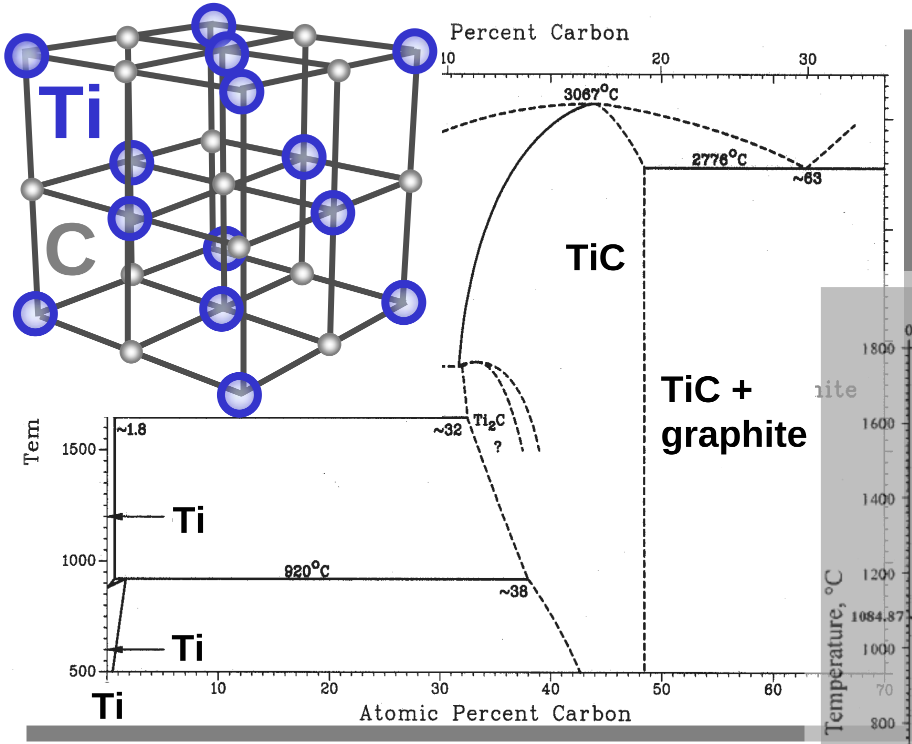


SEM



- sputter deposition of titanium interlayer
- layer thickness 100-200 nm
- deposition of copper layer - protective coating (500 nm)

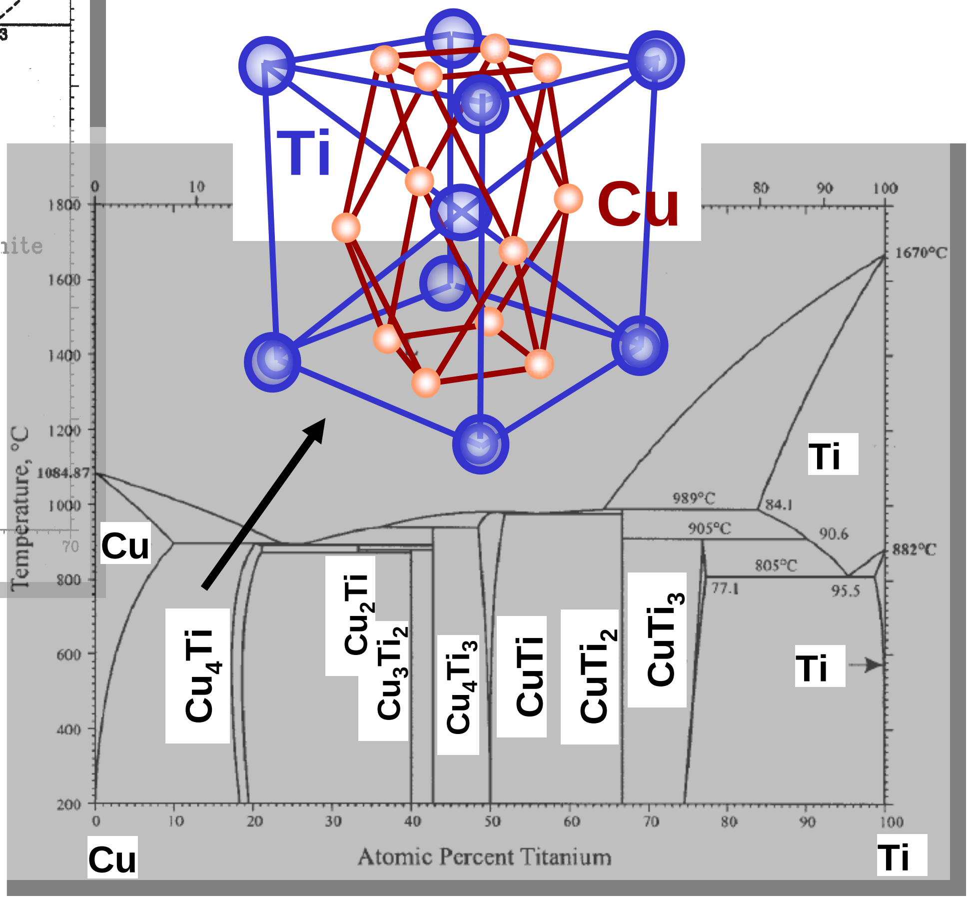
Phase diagrams



Titanium and Carbon

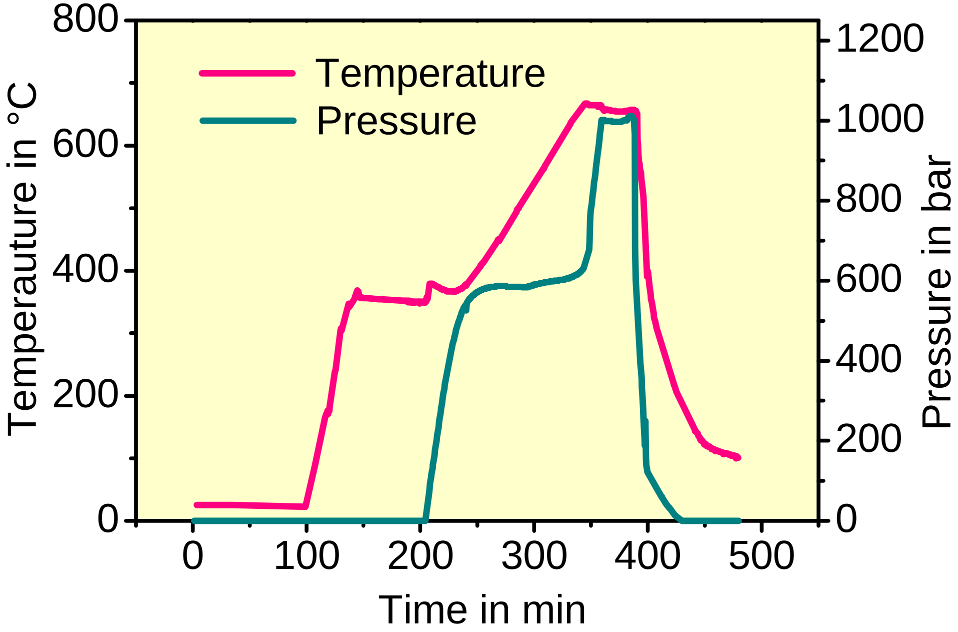
Ti + C → TiC above 350°C

Copper and Titanium

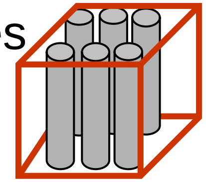


Processing of MMC - HIP

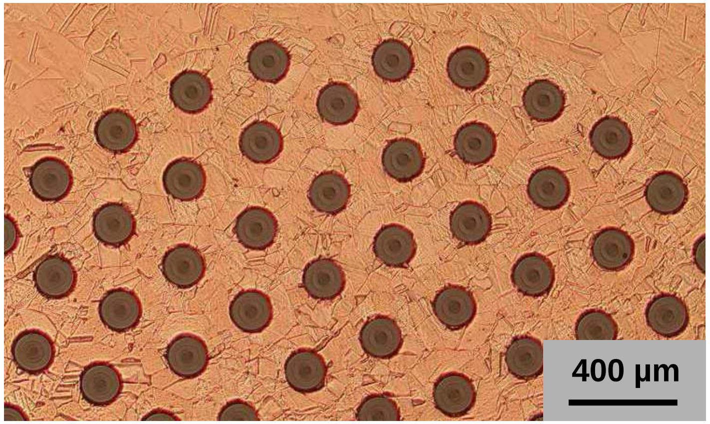
Hot-isostatic pressing (HIP)

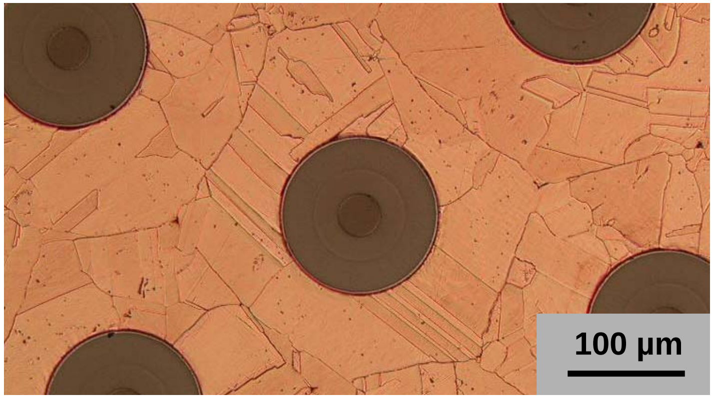


- coated fibres were consolidated in a copper capsule by hot-isostatic pressing at 650°C for 30 minutes
- maximum pressure 100 MPa

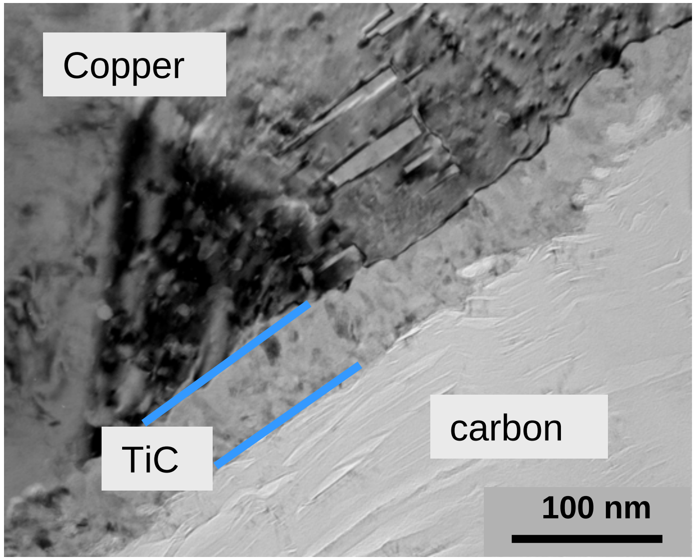


Composite





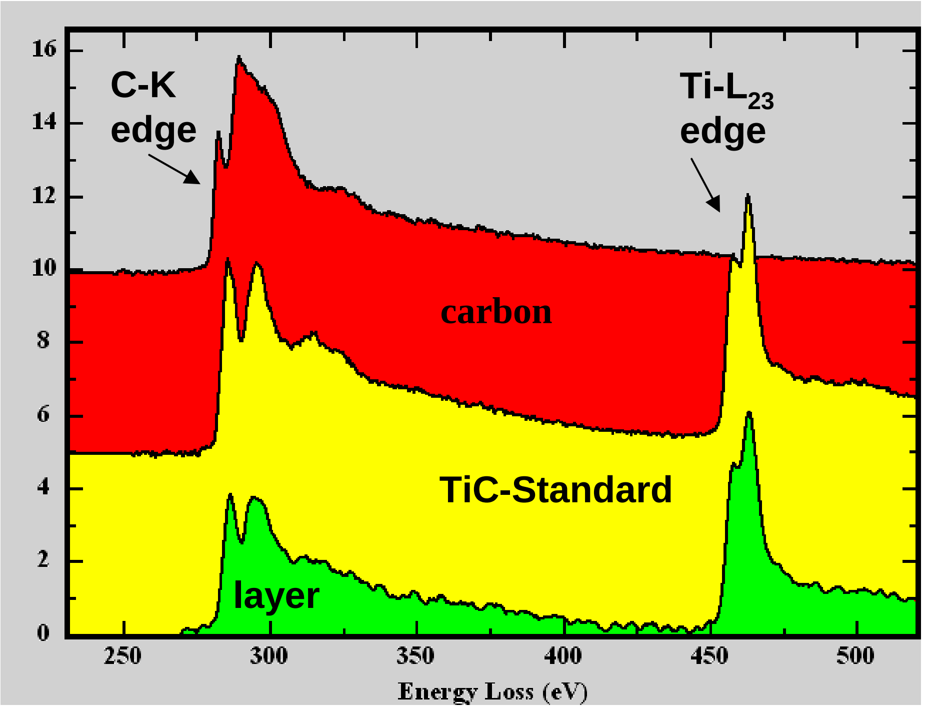
TEM investigation



TEM image of interface (PyC)

- plane pyrolytic carbon substrate (PyC)
- 100 nm Ti + 500 nm Cu
- heat treatment at 650°C/ 1h

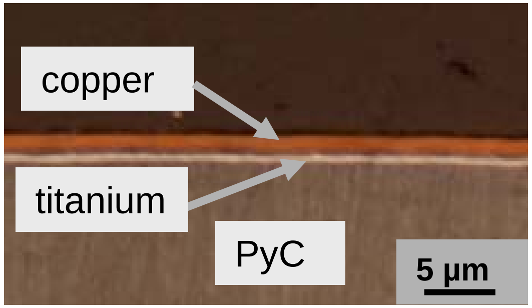
EELS (electron energy-loss spectroscopy)

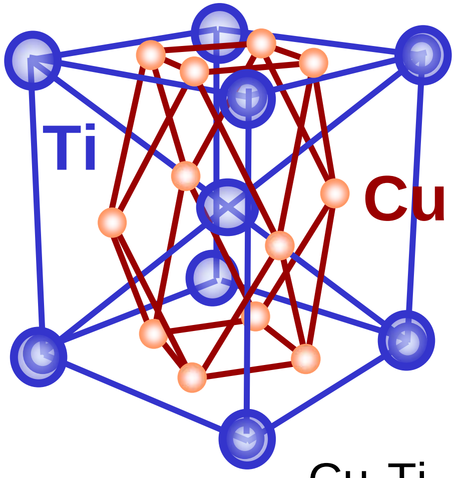


- EELS: formation of TiC
- formation of a rough interface
- chemical and mechanical bonding between C and Cu

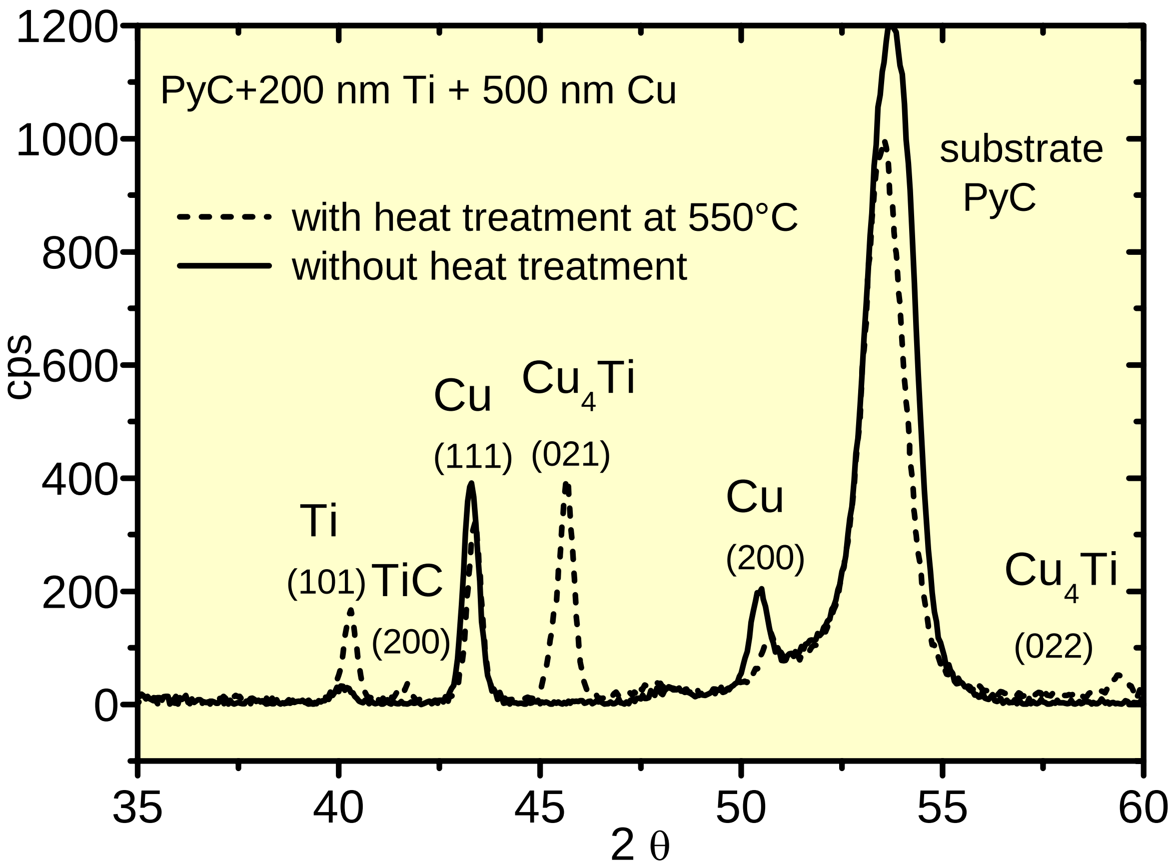
See also Poster by MPI Halle (Woltersdorf, Pippel, Brendel, Bolt), C11

XRD Investigations

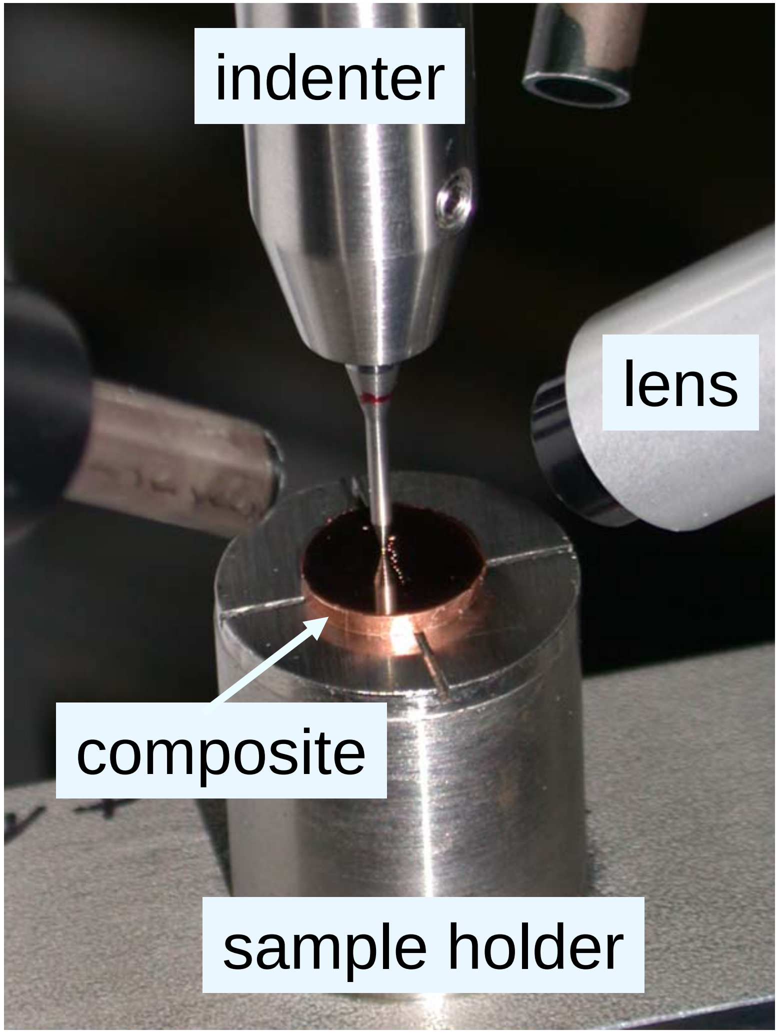


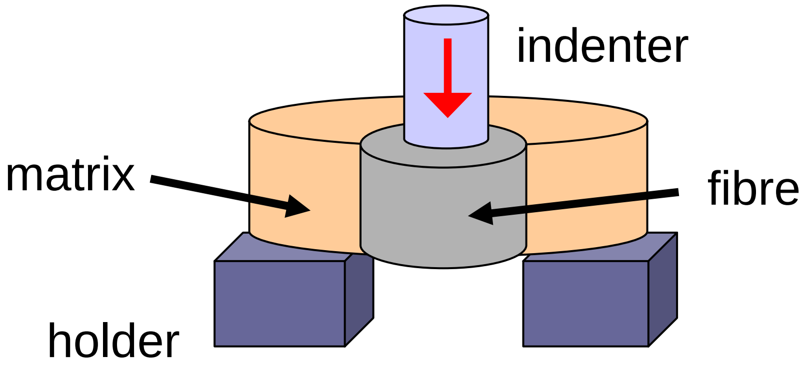


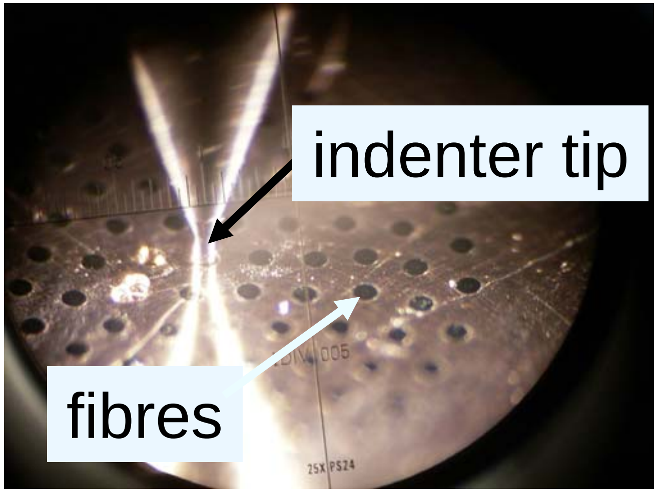
Cu_4Ti



Push-Out Test





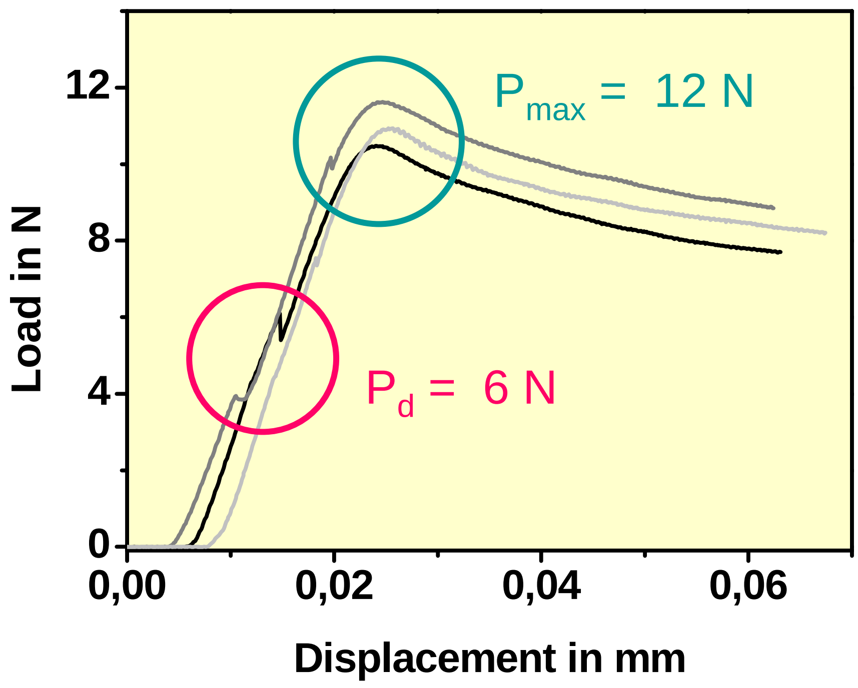


view through magnifying glass

Push-Out Test

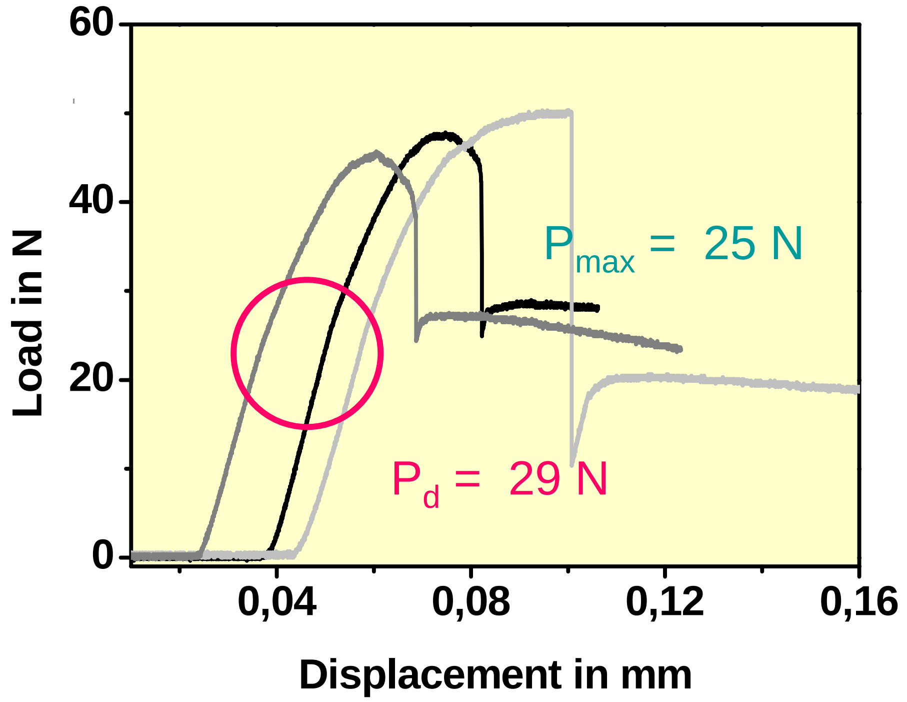
SiC fibre reinforced copper **without** titanium interlayer

Sample thickness 2.4 mm



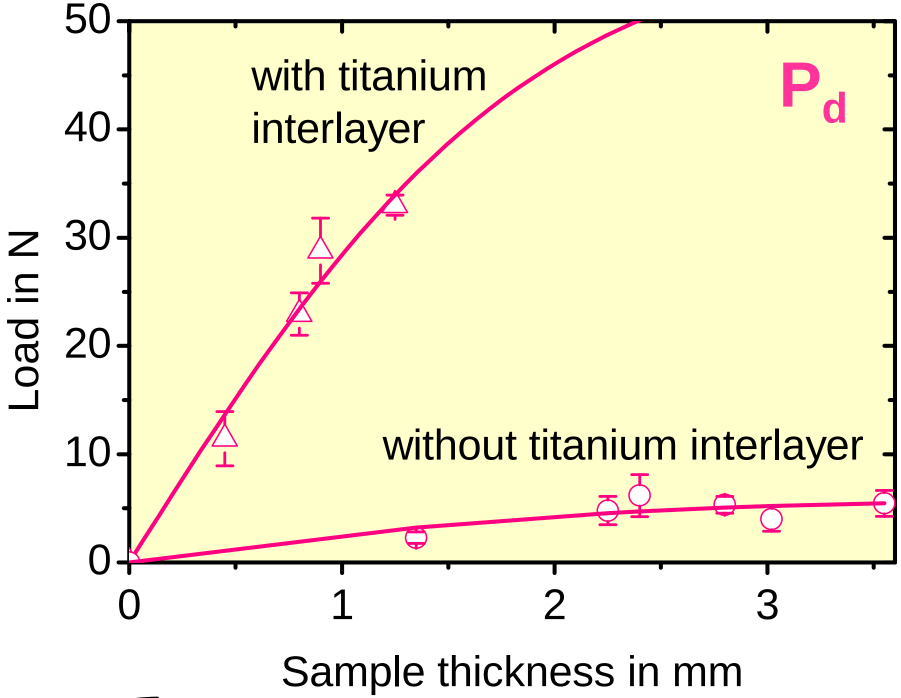
SiC fibre reinforced copper **with** titanium interlayer

Sample thickness 0.9 mm

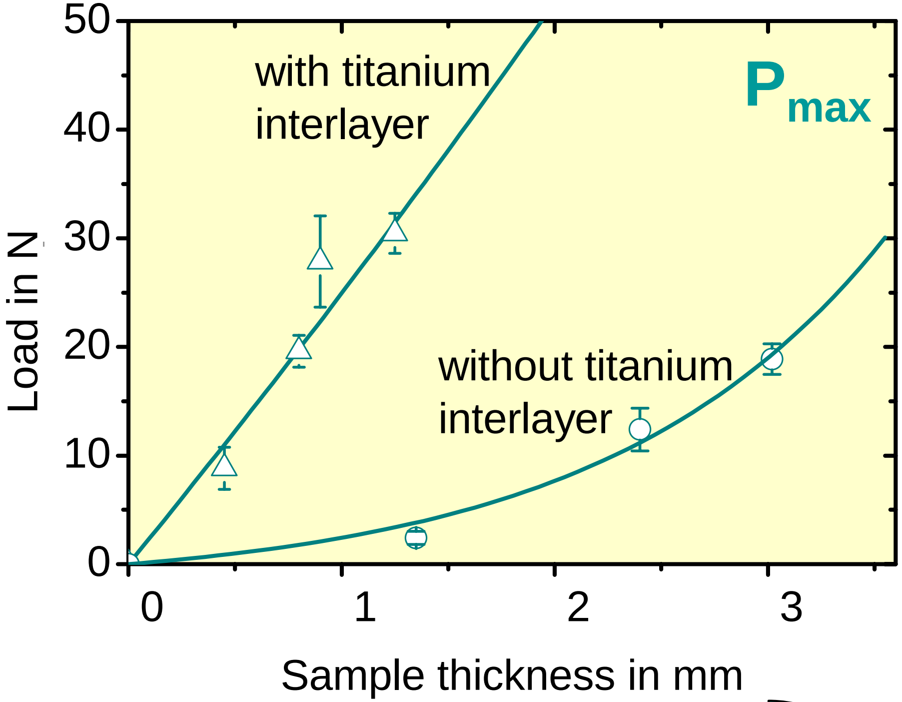


Push-Out Test

Interfacial shear strength



Interfacial friction stress



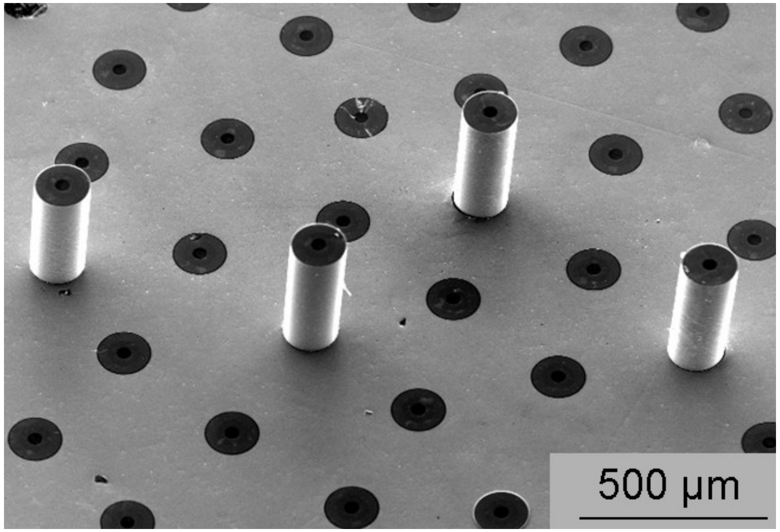
τ_d = 6 MPa without titanium interlayer **τ_f = 4 MPa**

τ_d = 70 MPa with titanium interlayer **τ_f = 54 MPa**

Evaluation acc. to: Rausch, Meier & Grathwohl, *Journal of the European Ceramic Society* **10** (1992) 229-235

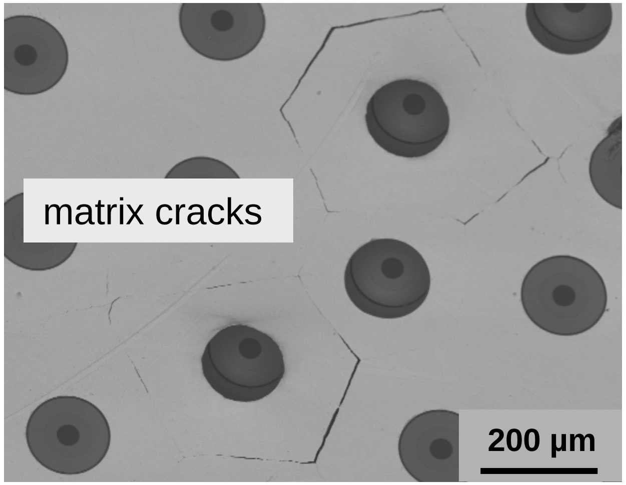
Push-Out Test - SEM

without titanium interlayer

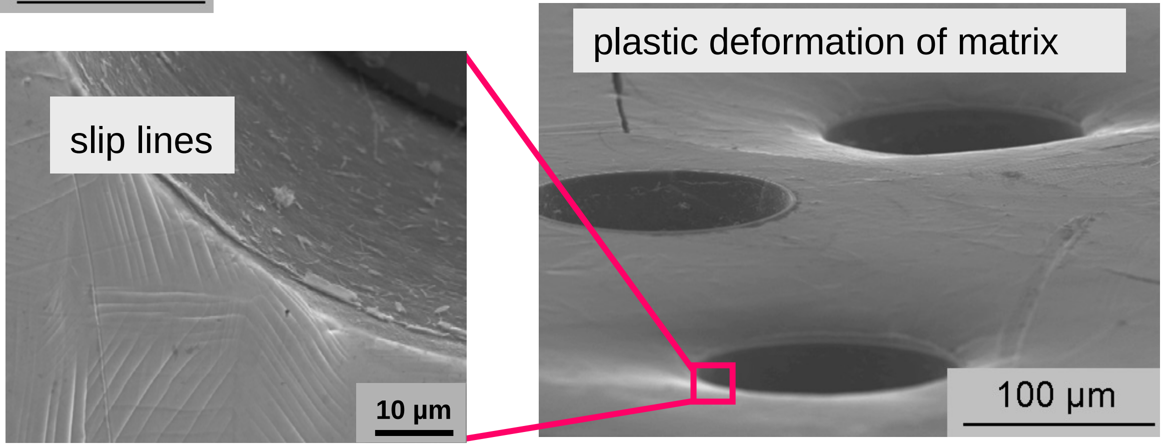


no plastic deformation of matrix after push-out test

with titanium interlayer

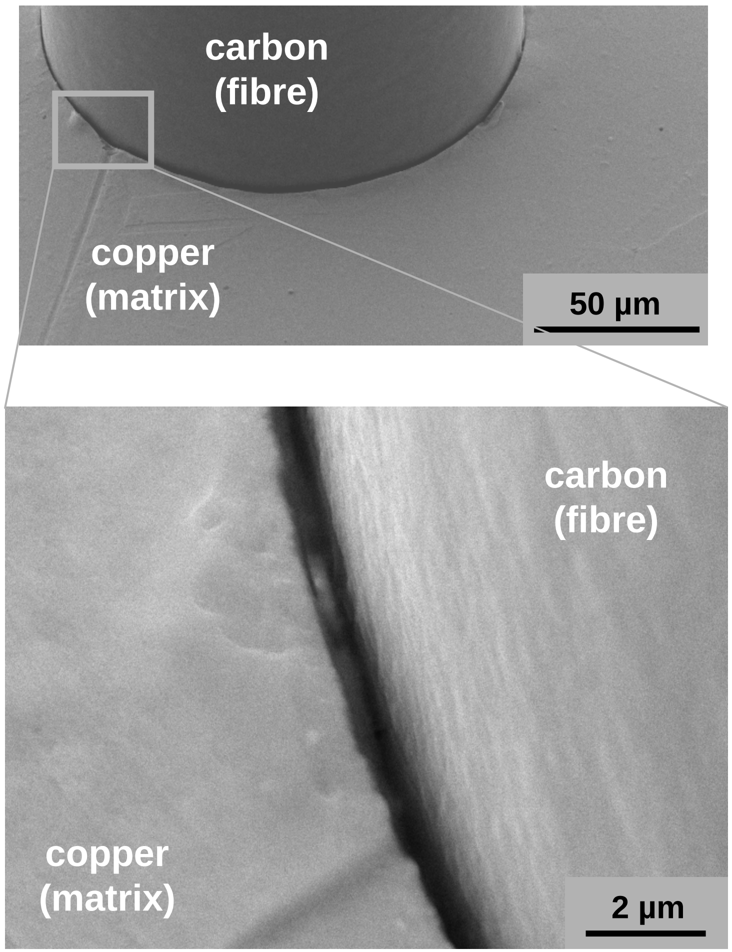


front side after push-out test

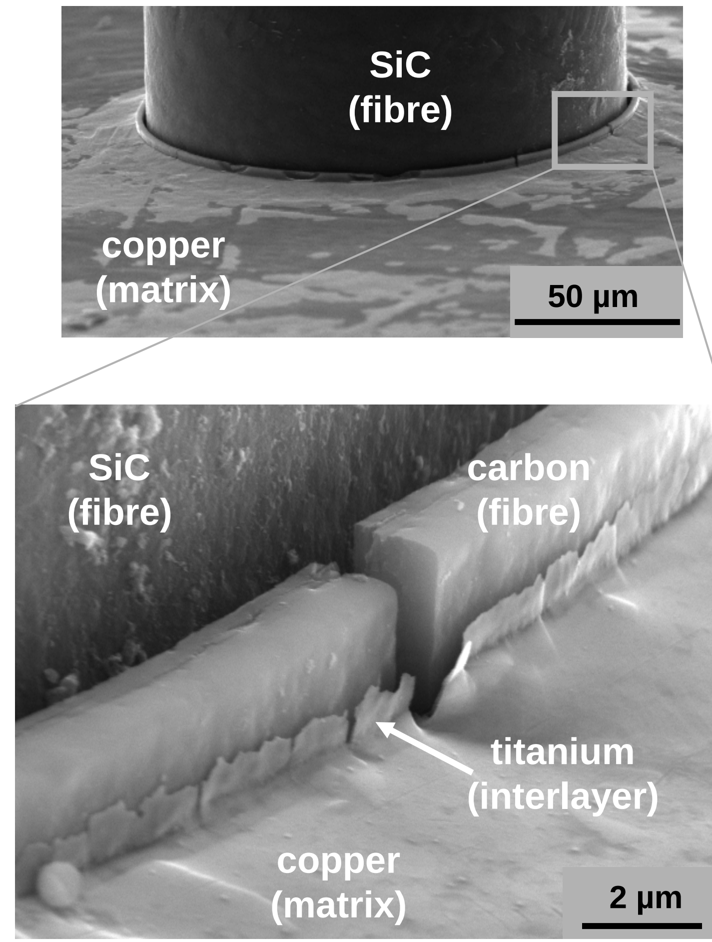


Push-Out Test - SEM

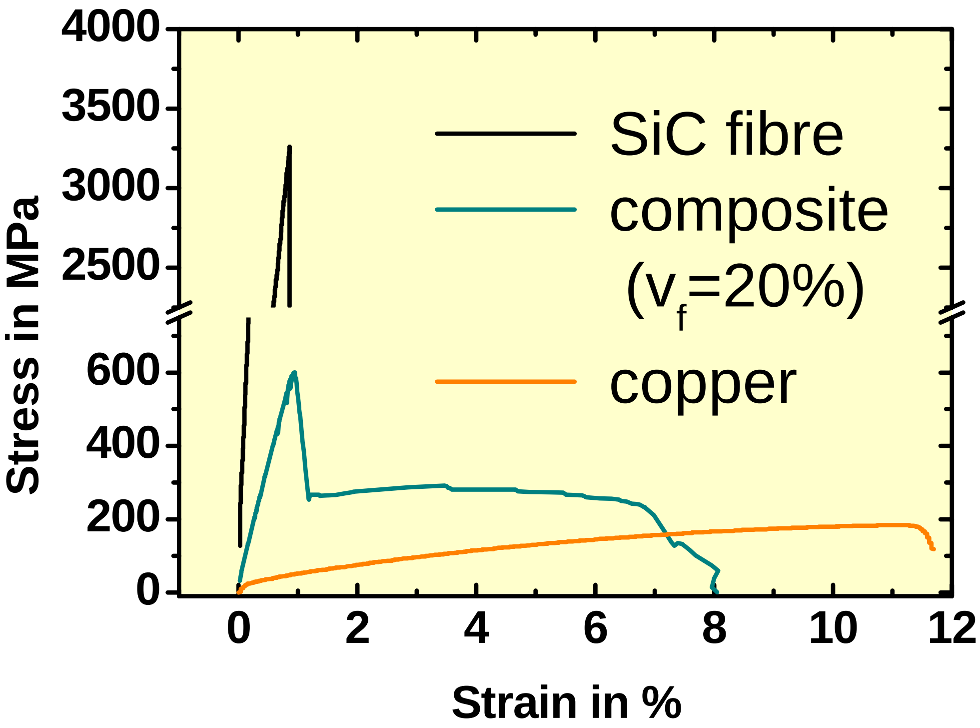
without titanium interlayer



with titanium interlayer



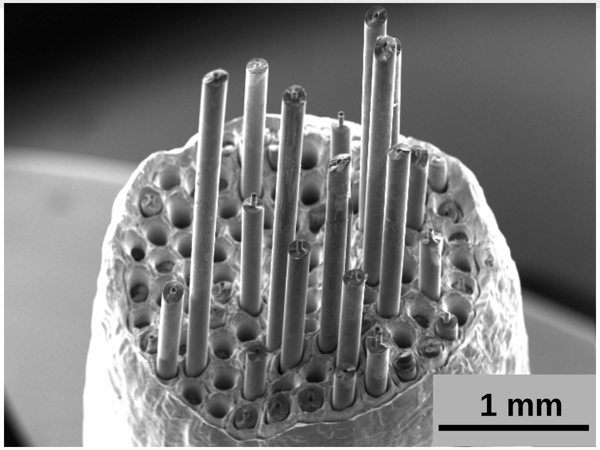
Tensile Test



- sample length 70 mm with thread at the ends
- gauge length 10 mm
- diameter in gauge length 3.5 mm (fibre reinforced zone)

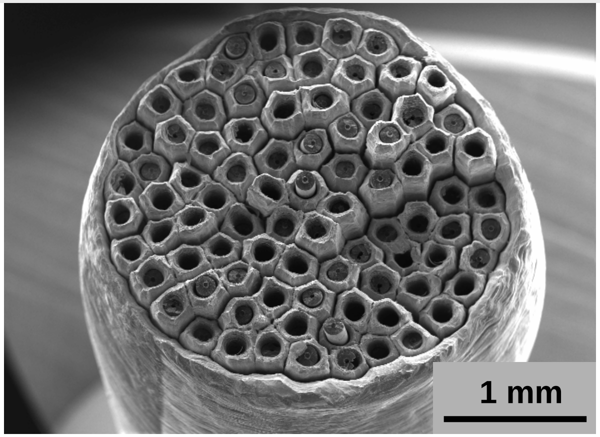
Tensile Test - SEM

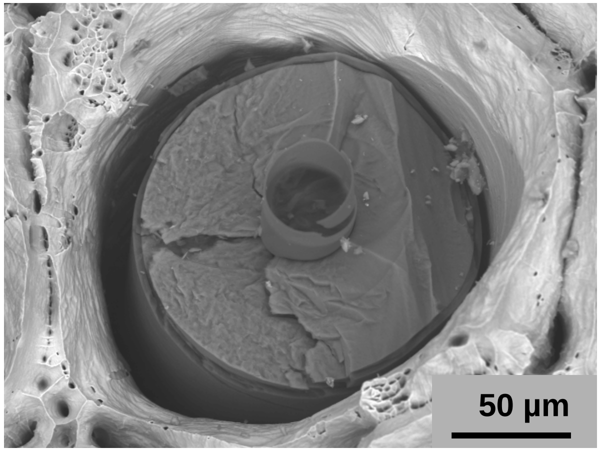
Composite without titanium



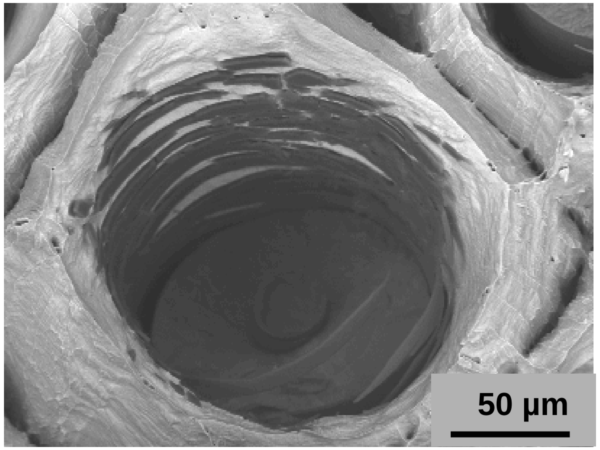
Fibre pull out in the composite without titanium interlayer indicates a weak bonding between fibres and matrix.

Composite with titanium

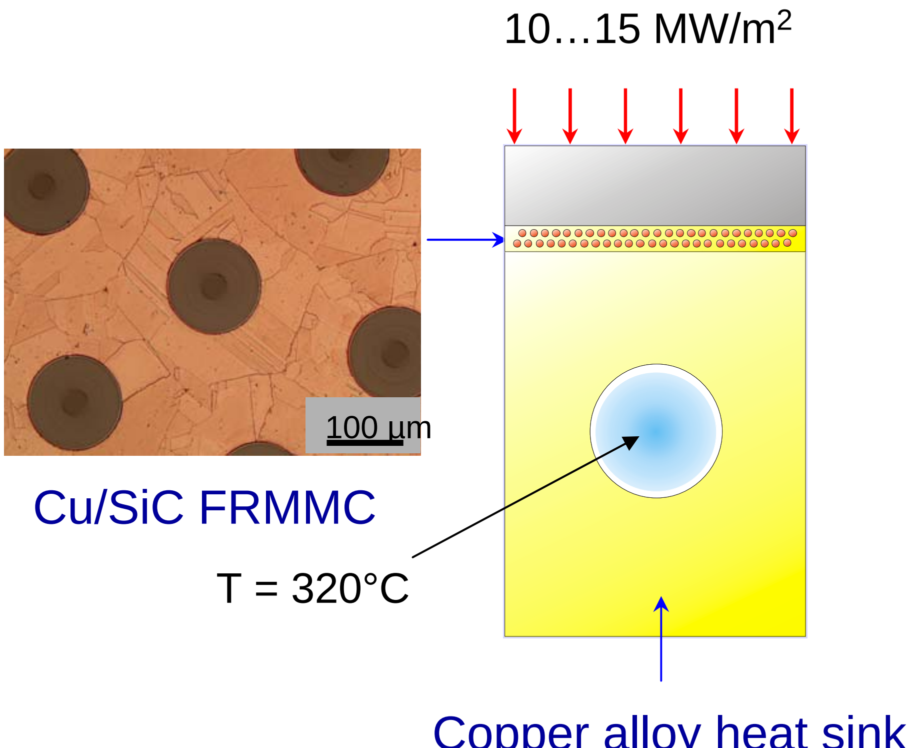




Analysis of back scattered electrons shows carbon at the matrix for composites with titanium after tensile test.



Thermomechanics of Cu-SiC FRMMCs



- Open question:
  plastic stability of the FRMMC under cyclic heat flux loads ?
- Investigation issue:
  determination of loading limit for plastic instability (shakedown / ratchetting)
- Shakedown analysis;
  SD limit as design criterion?
- Implications on design

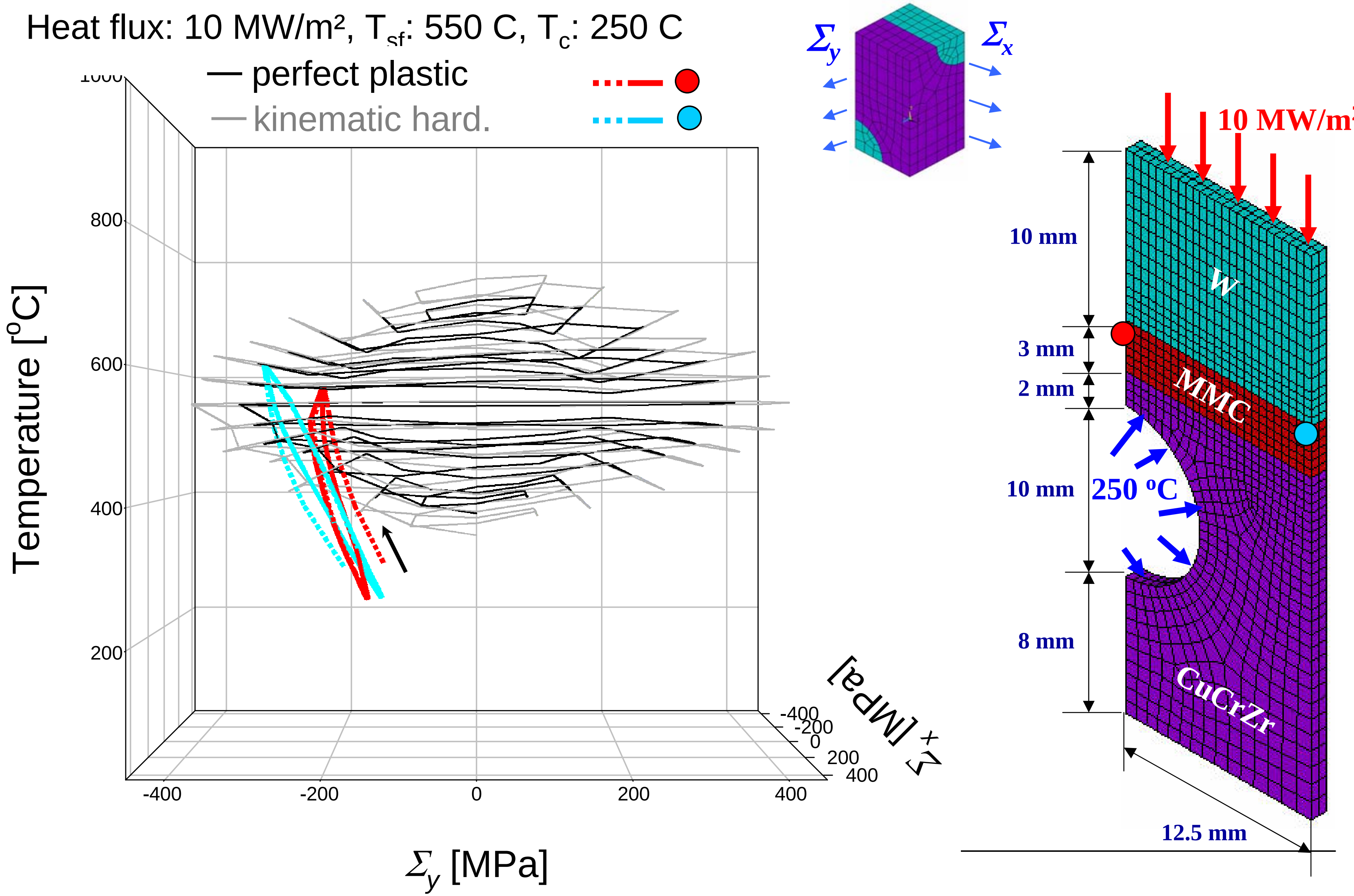
Tensile strength (MPa)
FMMC laminate: 600 (//)
CuCrZr: 400 at RT

CTE ($\times 10^{-6}$)
W: 3.9
FMMC laminate: 12.4 (//)
CuCrZr: 15.5

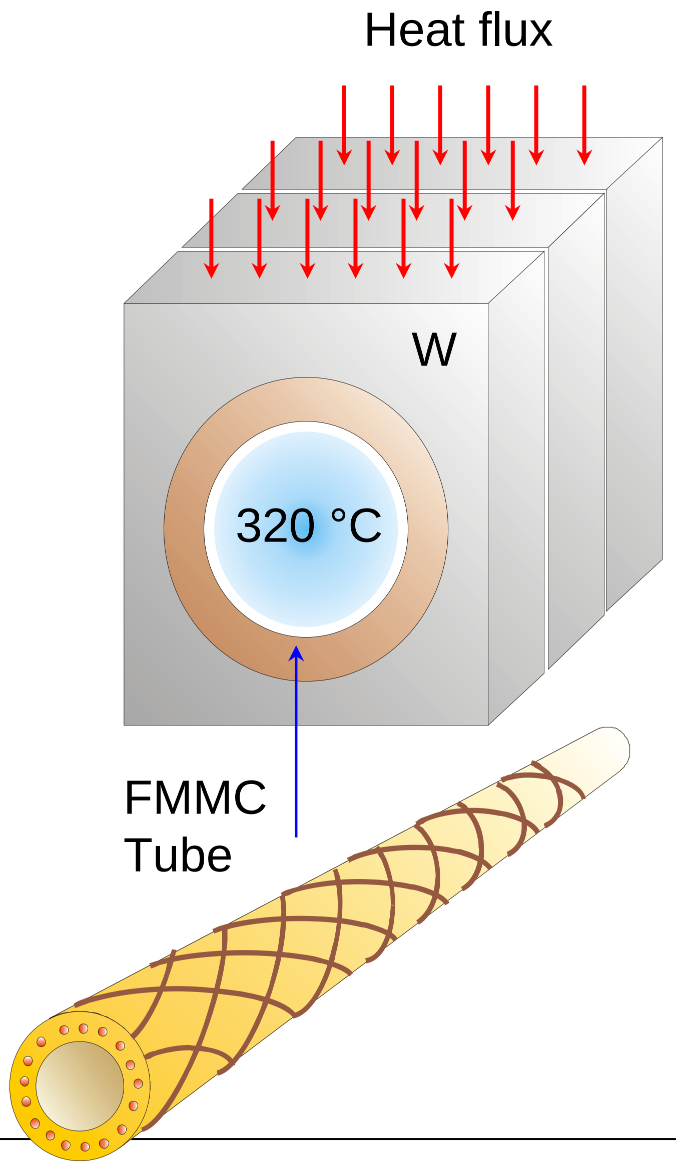
Young's modulus (GPa)
W: 398
FMMC laminate: 165 (//)
CuCrZr: 128

Component thermomechanics under high heat flux loading

Heat flux: 10 MW/m², T_{sf}: 550 C, T_c: 250 C



Alternative design: Composite coolant tubes



- Merits of this design
- works with CuCrZr tube for cold ITER loading conditions
- basic component fabrication technology already developed

- Motivation
- strengthen the tube for coolant temperature up to 320 °C
- reduce the thermal stress

- Issues:
- fabrication of fiber-reinforced composite tubes
- simulation techniques for ‘design by analysis’

Summary: Heat sink materials for fusion

<u>Divertor</u> (high thermal conductivity needed):

- CuCrZr: (irrad. data up to 10 dpa)
  temperature window:
  200°C...350°C
  (<200°C: hardening; >350°C: softening)
- DS Cu similar, max. 400°C

↓

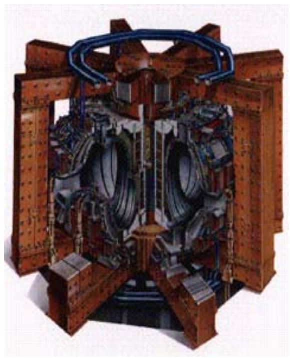
<u>New class of heat sink materials needed</u>
<u>and the respective component technology</u>

Cu-SiC MMC | Bonding technologies

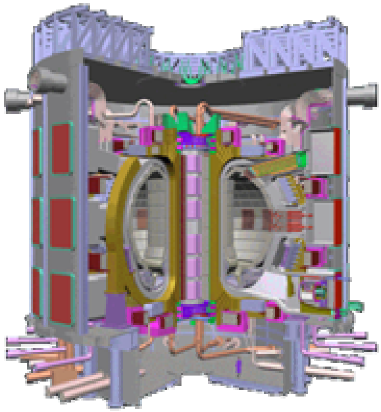
Adequate component design

Summary: New materials are needed for fusion

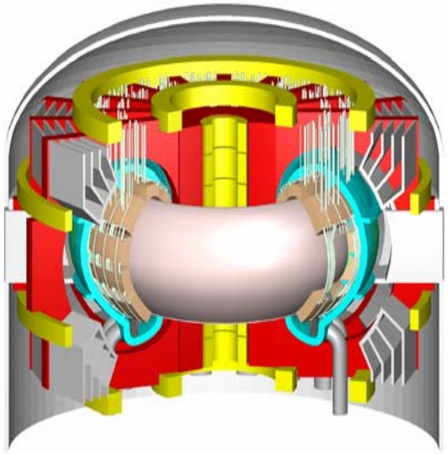
JET
(fusion power 16 MW, 2 s)



ITER
(fusion power 500 MW, 400 s)



reactor (DEMO)
(fusion power >2000 MW, stationary)

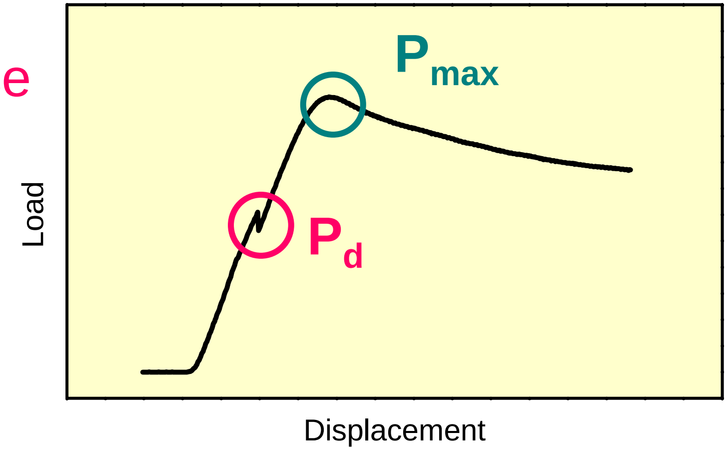


	ITER	**power reactor**
relative size	1	1...1.2
fusion power (MW)	500	2000
power to He-ions (MW)	100	400
total thermal power (MW)		2600
electric power (MW)		1000
efficiency (%)		38
neutron damage (dpa)	5	120 in 5y

Push-Out-Test

P_d – debonding force

Interfacial shear strength τ_d



P_{max} - maximum force

Interfacial friction stress τ_f

$$P_d = \frac{\tau_d \cdot 2\pi R}{\alpha} \cdot \tanh(\alpha \cdot L)$$

$$P_{\max} = \frac{\pi R^2 \sigma_0}{k}\left[\exp\left(\frac{2\mu k}{R} L\right) - 1\right]$$

○ Fit parameter

$$\alpha = \sqrt{\frac{2G_i}{b_i R E_f}}$$

$$\tau_f = \mu \cdot \sigma_0$$

$$k = \frac{\upsilon_f E_m}{E_f(1+\upsilon_m)}$$

P_d, P_{max} debonding, maximum force
R fibre radius
L specimen thickness

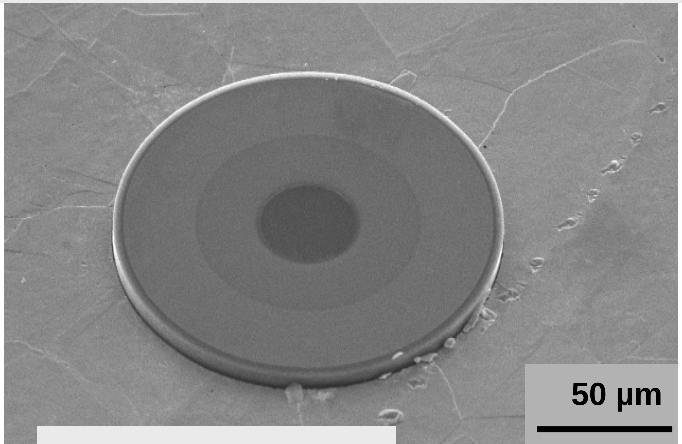
G_i shear modulus
b_i interface thickness
E_f, E_m Young's moduli of fibre and matrix

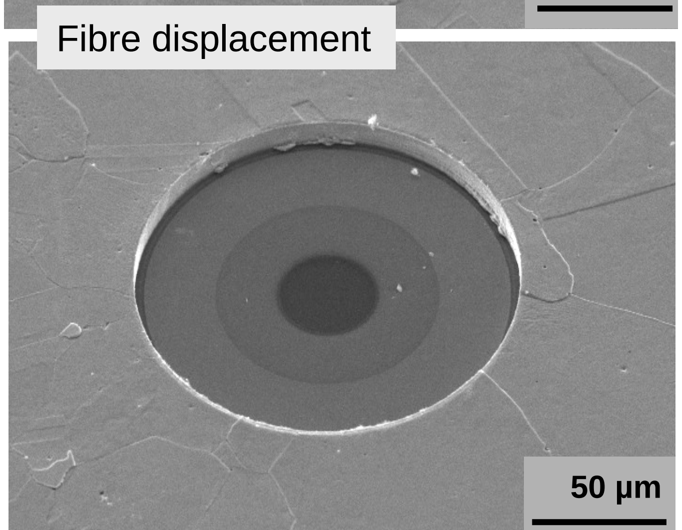
σ_0 radial residual stress
μ friction coefficient
ν_f, ν_m Poisson's ratio of fibre and matrix

Ref.: Rausch, Meier & Grathwohl, *Journal of the European Ceramic Society* **10** (1992) 229-235

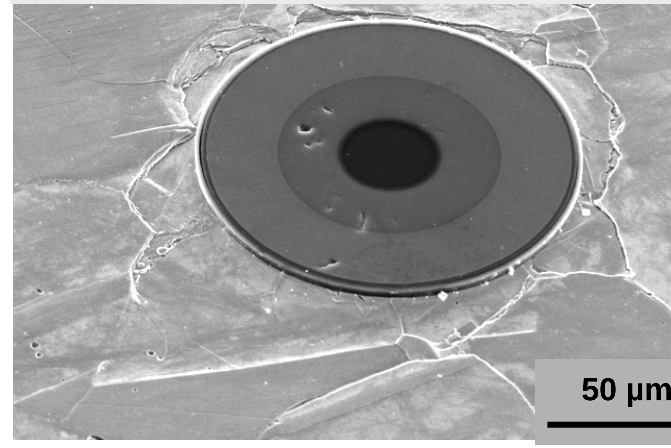
Thermal cycling

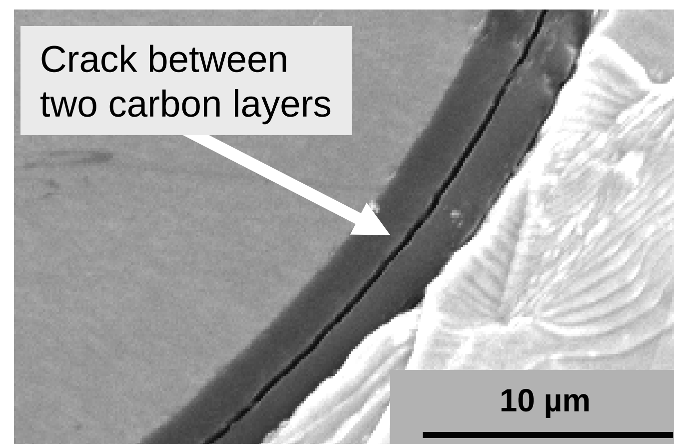
Composite without titanium





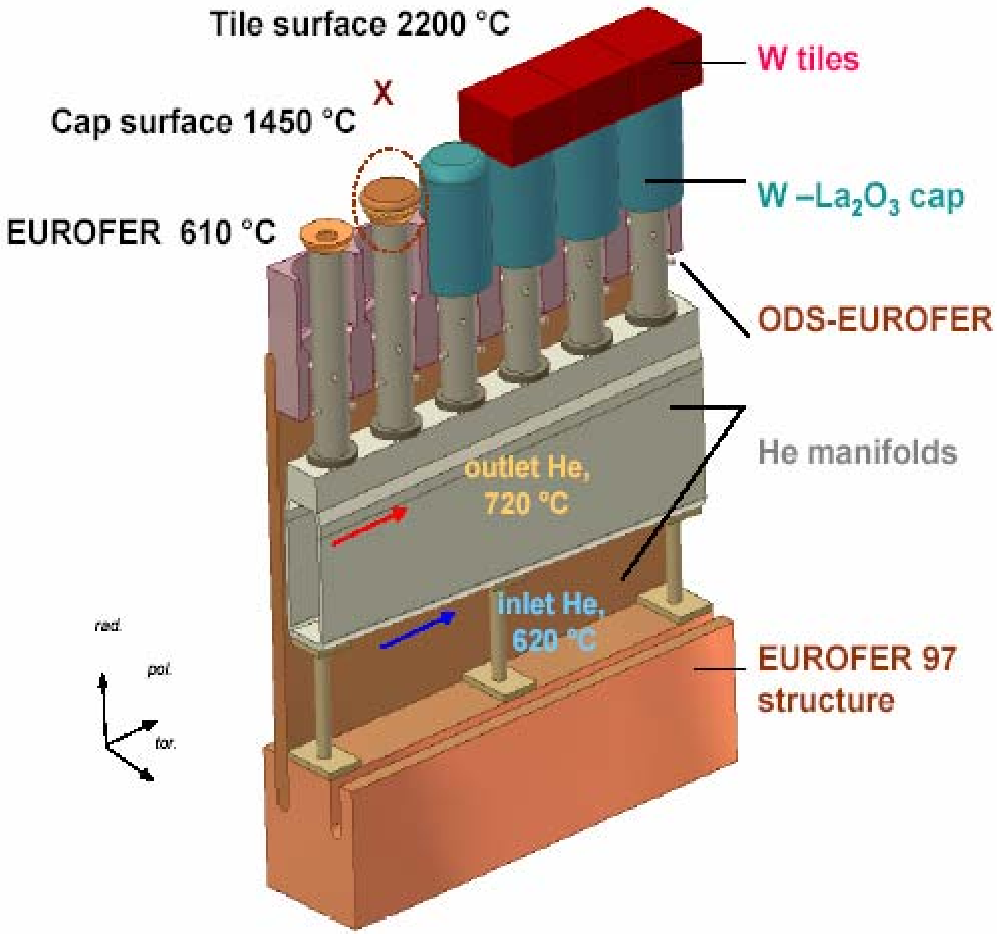
Composite with titanium





120 cycles between 350°C and 550°C

Design of Cooling Fingers in He-cooled Divertor Development



Detail X: Pin plate with outlet tube.