Perspectives of chemical vapour deposition for the fabrication of tungsten fibre-reinforced composite components

Johann Riesch, J.W. Coenen, A. Lau, L. Raumann, D. Schwalenberg, A. Feichtmayer, B. Curzadd, M. Fuhr, H. Gietl, H. Greuner, T. Höschen, Y. Mao, A. von Müller, Ch. Linsmeier, and R. Neu

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Idaho National Laboratory — H. Gietl

WISCONSIN UNIVERSITY OF WISCONSIN–MADISON — J.W. Coenen

Tungsten the ideal plasma-facing material?

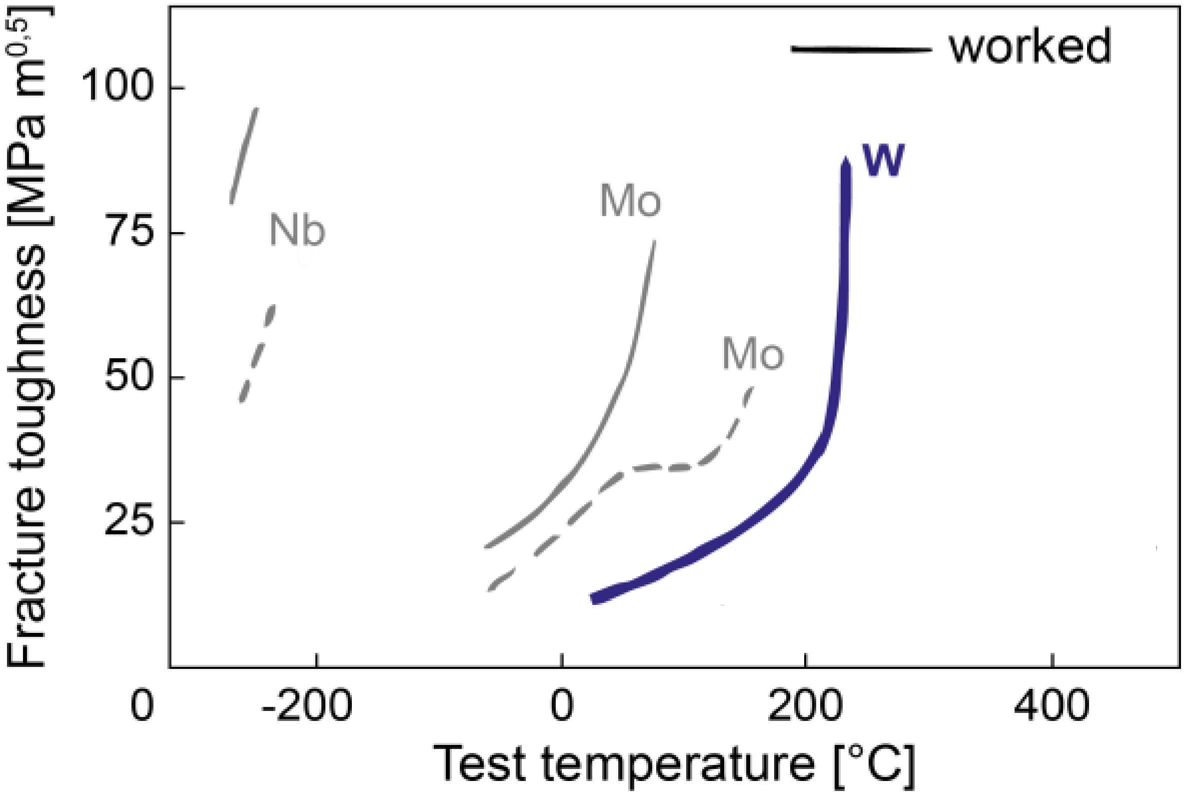
Tungsten features unique property combination

- T_{melt} = 3380 °C, λ = 167 W/mK, high temperature strength and creep resistance, high erosion resistance

Tungsten has a brittleness problem

- Inherent brittleness below temperature threshold
- Toughness strongly related to microstructure
- Susceptible to embrittlement

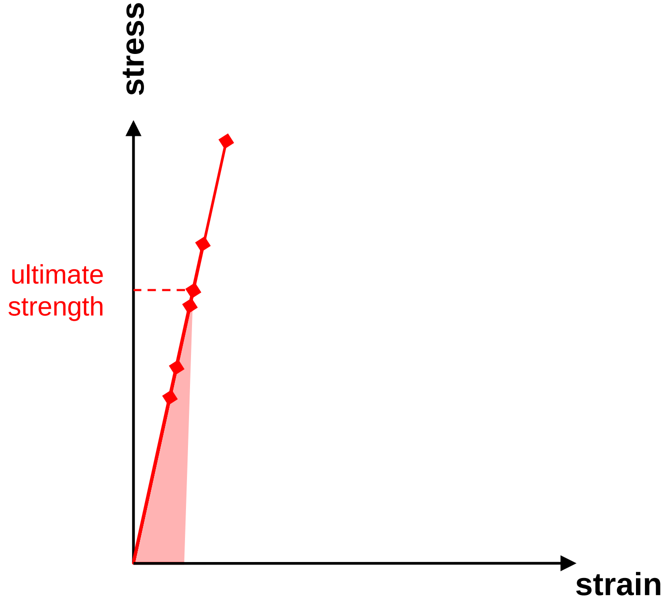
[Marshall and Holden in High Temperature Refractory Metals, Gordon and Breach, New York (1966)]



Why do we want tough tungsten

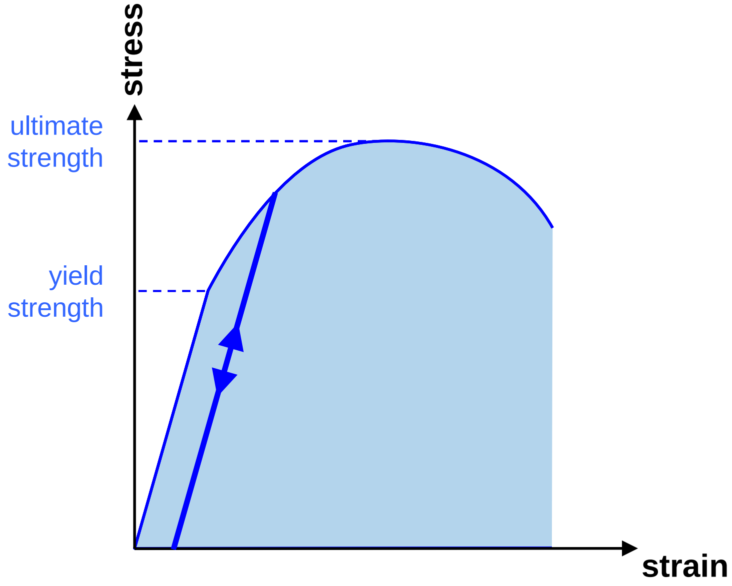
Reality: Brittle tungsten

(Below DBTT)



- No stress redistribution → Catastrophic failure, no damage tolerance (notch sensitivity)
- High scatter → weakest link scaling
- Limited fracture energy

Request: Tough tungsten



- Stress redistribution by plastic deformation
- High fracture energy
- Cyclic loading possible after damage → damage tolerance

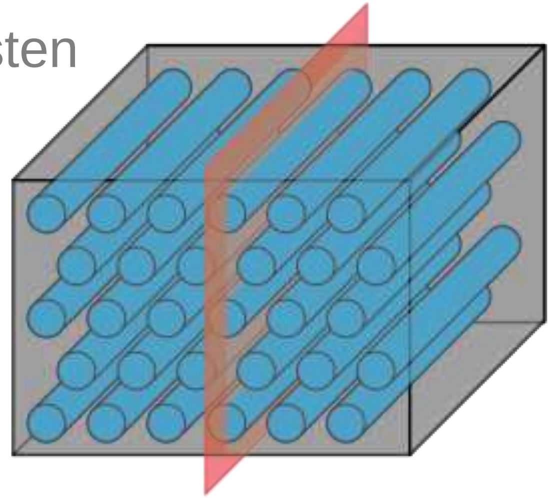
Tungsten fibre-reinforced tungsten composites produced by chemical vapour deposition

Toughening by extrinsic mechanisms

Toughening as in ceramic fibre-reinforced ceramics

Tungsten fibre-reinforced tungsten composite (W_f/W)

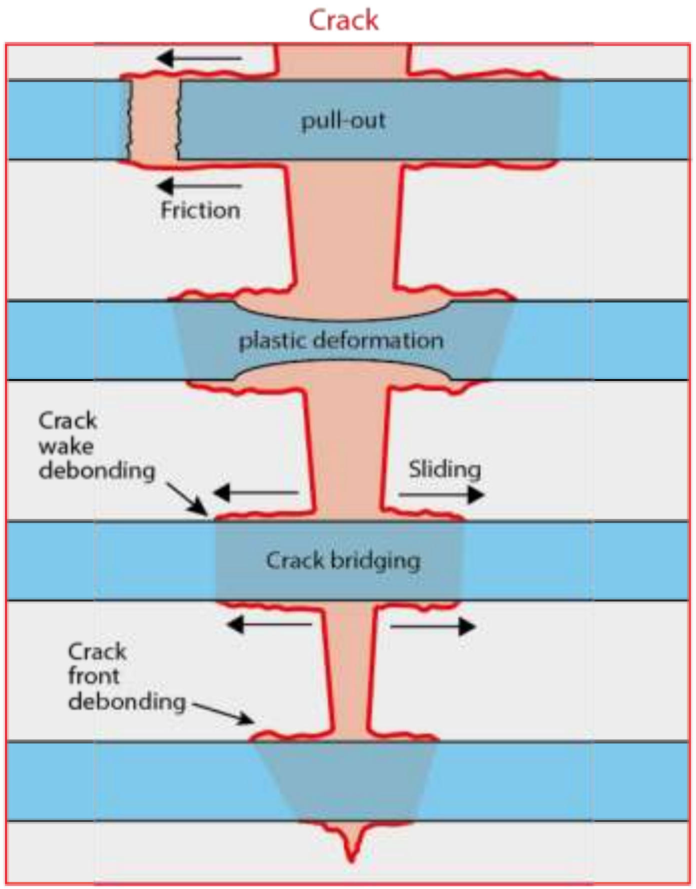
pure tungsten



Cross section

Tungsten fibres

based on A. Evans



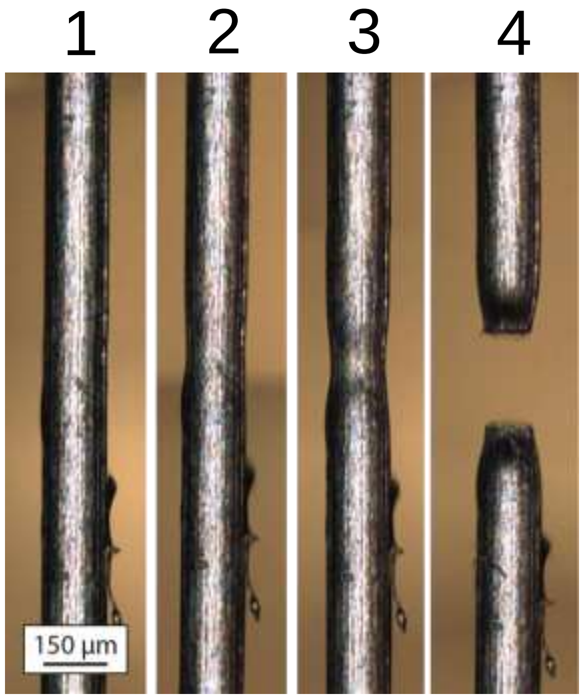
[Riesch et al., Physica Scripta, T167 (2016) 014006]

Extrinsic toughening mechanisms

Stress redistribution by local energy dissipation

W wire features high strength and ductility

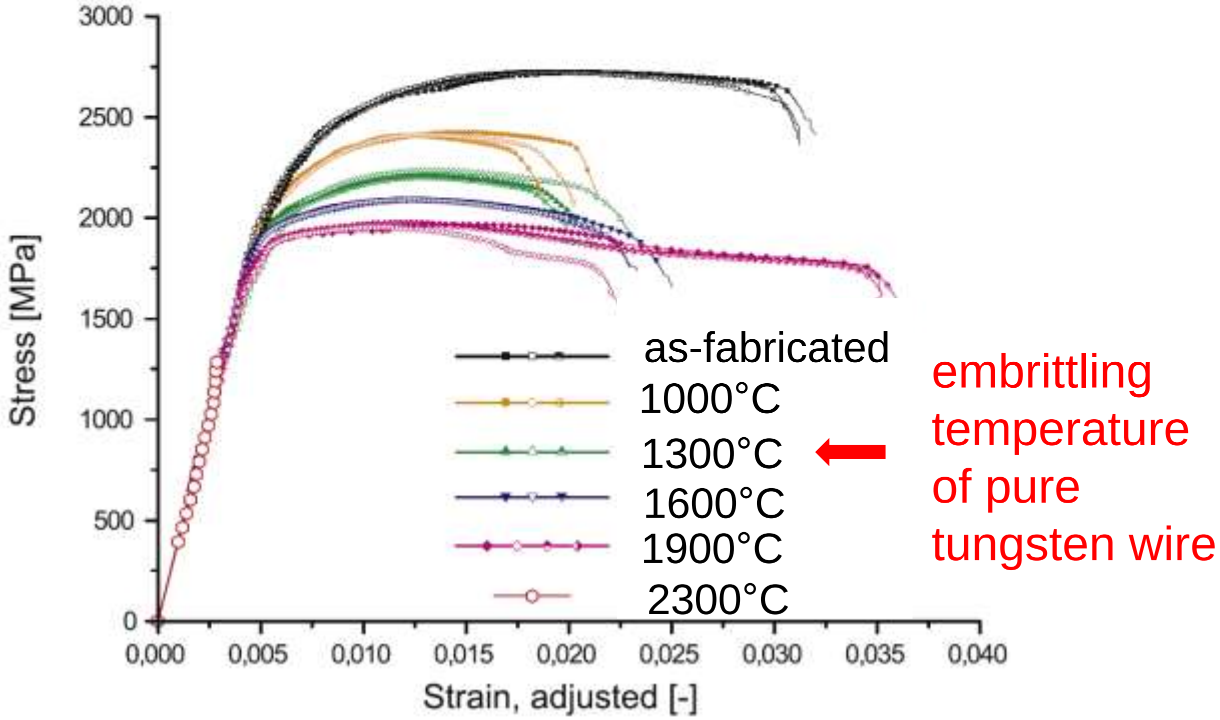
Large energy consumption by ductile deformation



Single fibre tensile test

[Riesch et al. IOP Conf. Series: Mat. Sci. & Eng., Vol. 139 (2016) 9pp]

High strength and temperature stability



[Riesch et al., Physica Scripta, T167 (2016) 014006-]

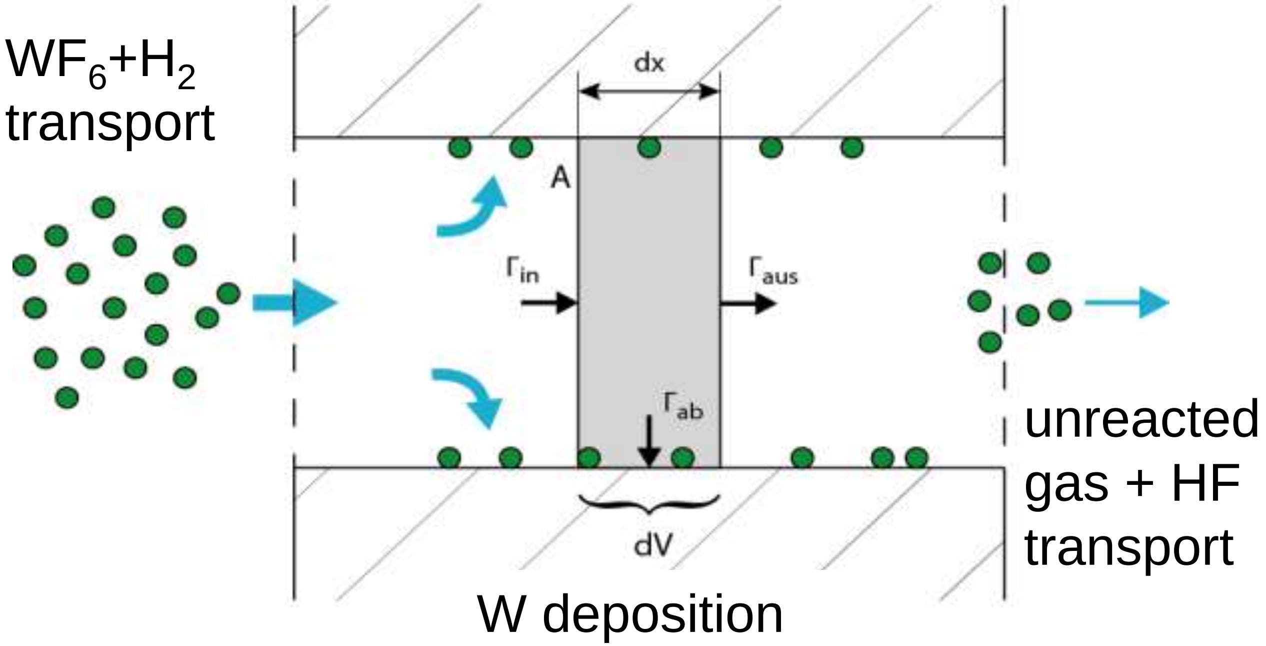
Matrix production

Chemical vapour deposition (CVD)

Surface process or infiltration mechanisn

+ Low temperature process (300 – 700 °C)
+ Load free production
  – Preservation of interface/ fibre integrity
- Low experience in W bulk production
- Complex process

$$WF_6 + 3H_2 \xrightarrow{300°C-700°C} W + 6HF$$



Powder metallurgy (PM)

more details in next talk by **Y. Mao**

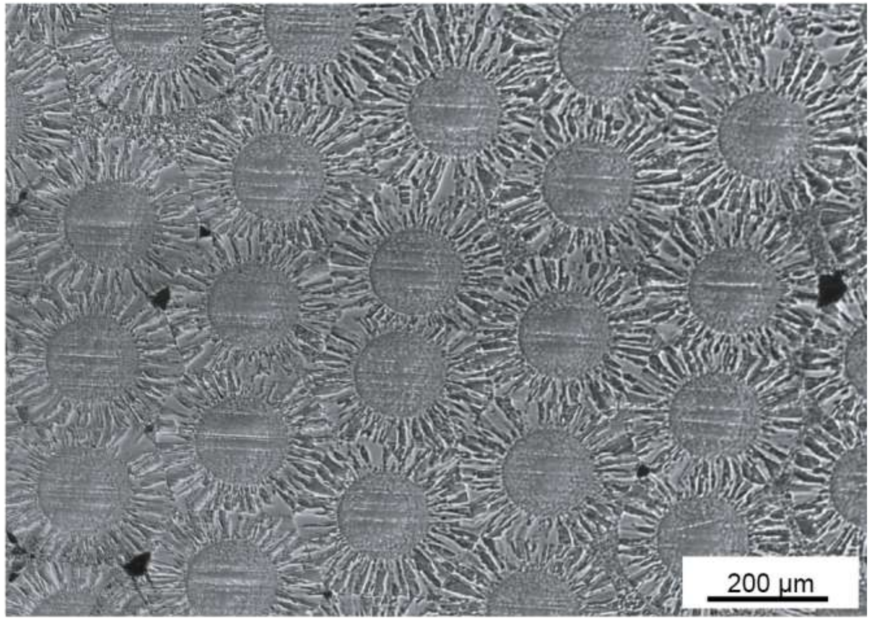
Infiltration vs. surface process
Proof of principle and larger samples

Duel step infiltration

Step 1: transversal infiltration to create freestanding preform

Step 2: longitudinal infiltration to have thermal gradient parallel to gas flow

Density >95%



[Riesch et al., Phys. Scr. T159 (2014) S. 14031]

Infiltration vs. surface process
Proof of principle and larger samples

Duel step infiltration

Step 1: transversal infiltration to create freestanding preform

Step 2: longitudinal infiltration to have thermal gradient paralell to gas flow

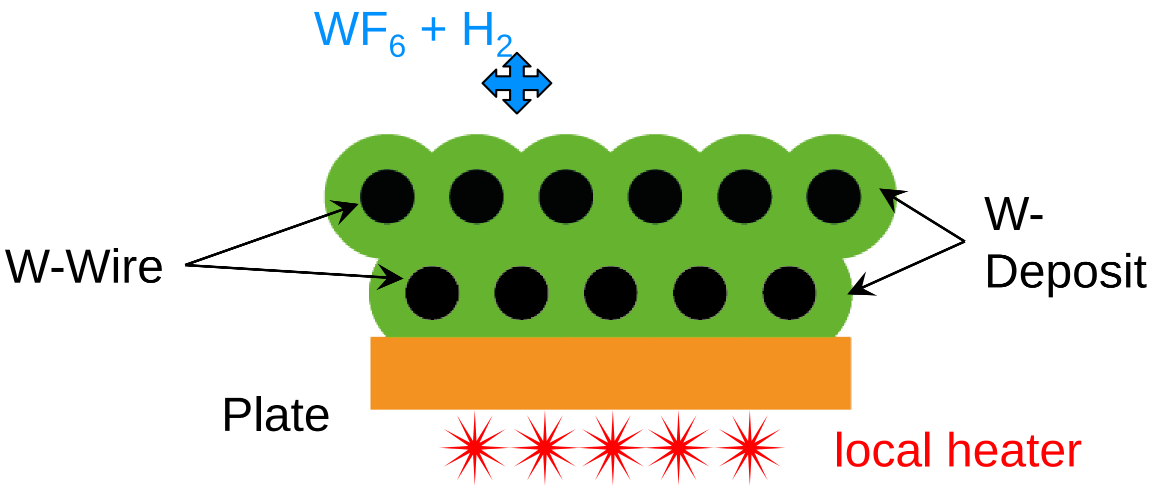
Layered deposition (LD)

Step 1: put single fibre layer on heated plate

Step 2: deposit tungsten layer on that

Step 3: put next fibre layer on top of ingrown first layer

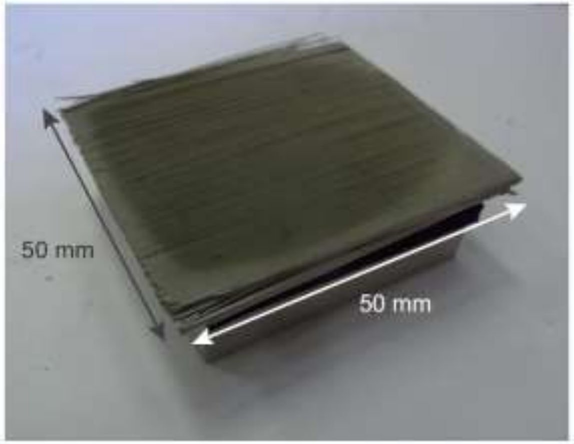
and so on



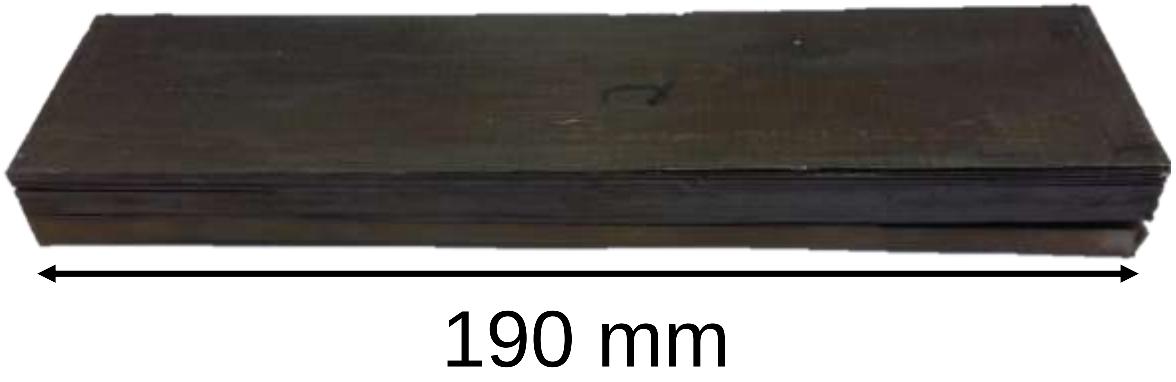
[Riesch et al., Nuclear Materials and Energy 9 (2016) S. 75–83]

Upscaling of layered deposition

- 50 x 50 x 3.5-4 mm^3, 194 g
- 10 Layers, fibre volume fraction ≈ 0.3, unidirectional
- 93 – 98 % density depending on location



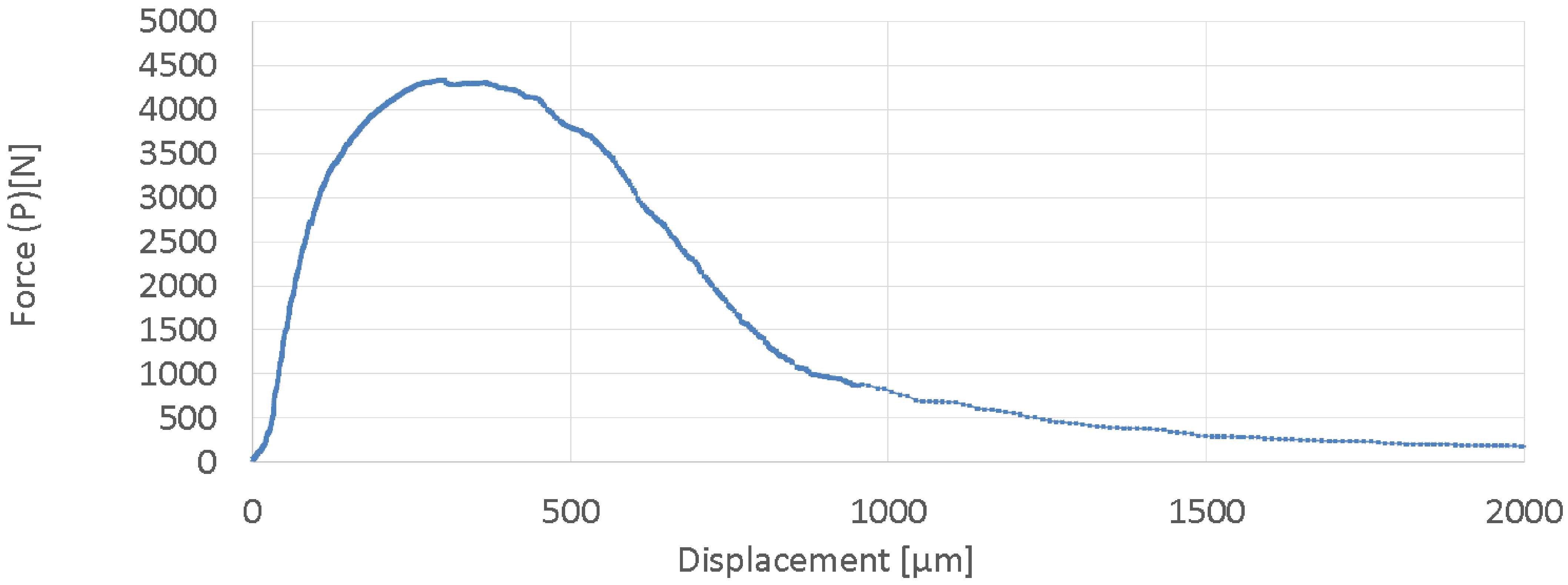
- 190 x 50 x 10 mm^3,
- 23 layers, fibre volume fraction ≈ 0.1, unidirectional
- 88-93 % density depending on location



[Schwalenberg et al., J. Nucl. Eng., (2022) accepted]

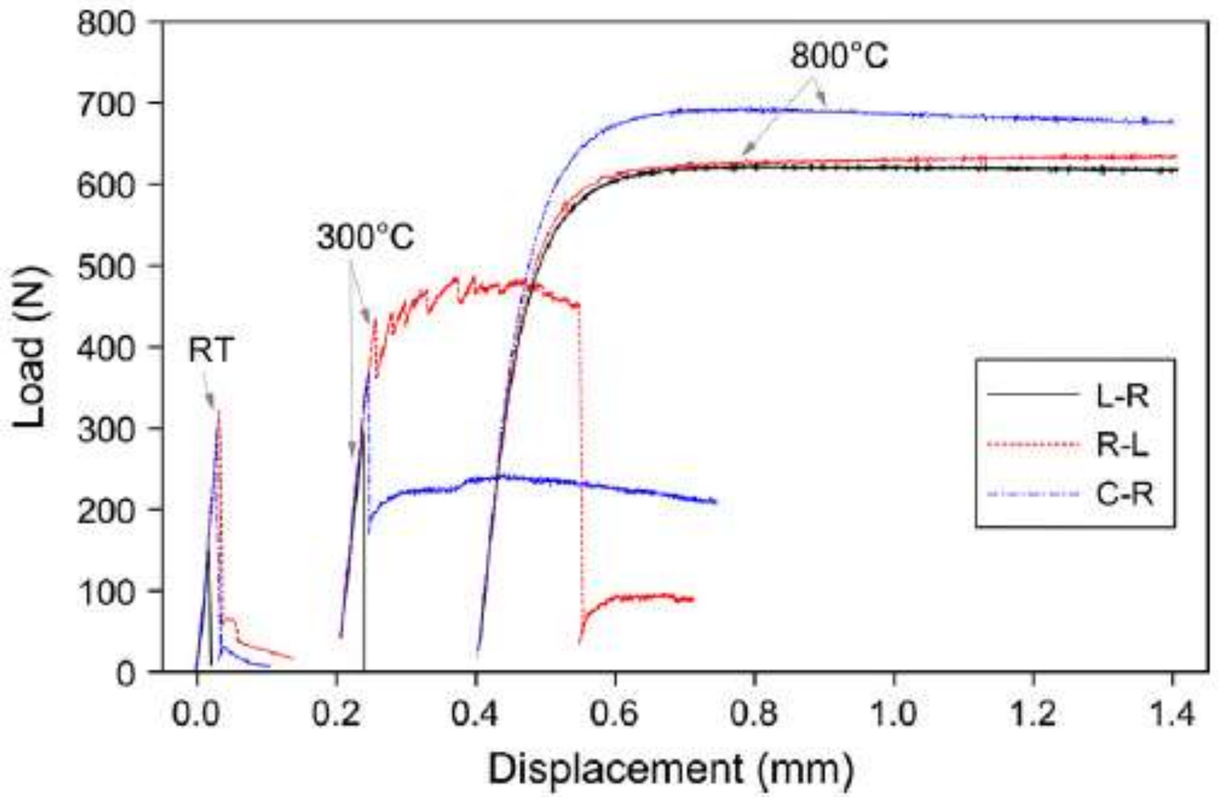
High toughness even at room temperature

Stable crack propagation and rising load bearing capacity



[Schwalenberg et al., J. Nucl. Eng., (2022) accepted]

High toughness even at room temperature
Comparison to „ITER – grade“ W



[Gaganidze et al., J. Nucl. Mat., 446 1-3 (2014) 240-254]

Fracture toughness at room temperture according to ASTM E399

	K_Q in $MPam^{0.5}$
ITER grade L-R	7
ITER grade R-L/C-R	15
W_f/W - small	188±43*
W_f/W – medium	143±46*
W_f/W – large	347*
*) only provisional	

[Schwalenberg et al., J. Nucl. Eng., (2022) accepted, Gietl et al., Engineering Fracture Mechanics, 232 (2020) 107011, Gaganidze et al., J. Nucl. Mat., 446 1-3 (2014) 240-254]

Why we still need advanced materials

WPDIV (J.H. You, PFMC 2021)

Summary & Conclusions

ITER-like baseline
- the structural integrity verified under all types of specified HHF loads

Armour blocks
- commercial tungsten materials qualified for the specified HHF loads
- seem to afford irradiation embrittlement

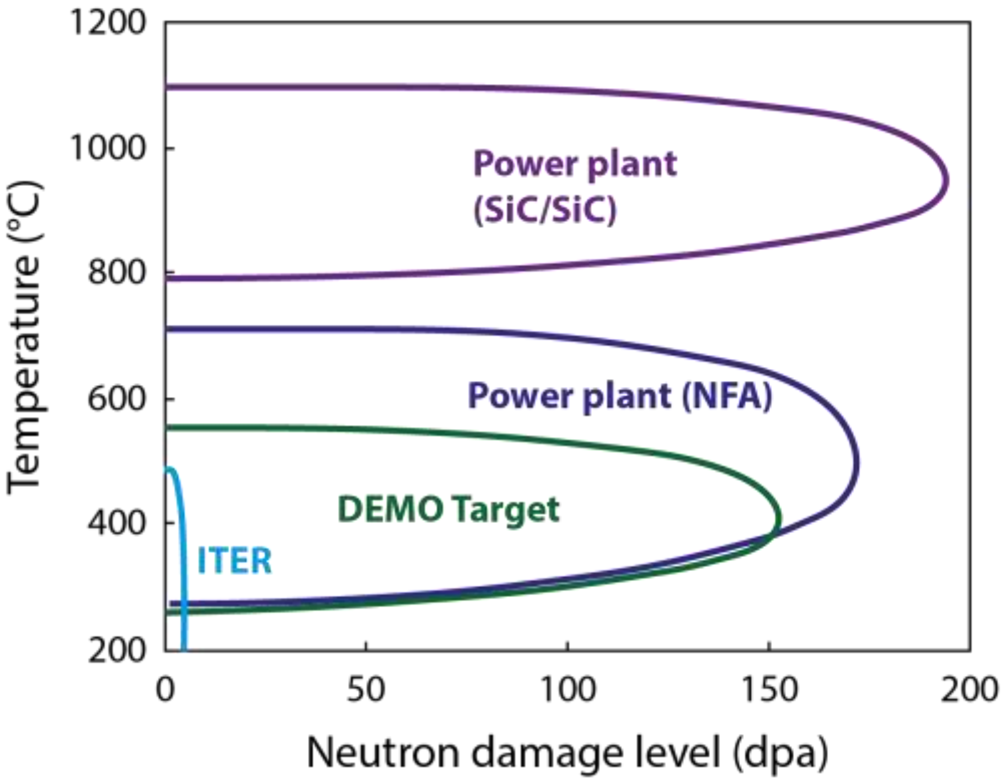
Cooling pipe
- exhaustion of ductility due to irrad. embrittlement seems to be a critical design issue

Cu interlaye
- irradiation em

Standard design for DEMO is for brittle W – “not too bad”

Why do we still need advanced materials?
Identify possible risks

- **Mono block is not scalable**
- **DEMO → Fusion power plant**
  - increase of dose
  - higher demands on lifetime
- **uncertainties in performance after irradiation (delay in IFMIF)**
- **… (to be discussed)**



[Zinkle et al., Nucl. Fusion 53, (2013) 104024]

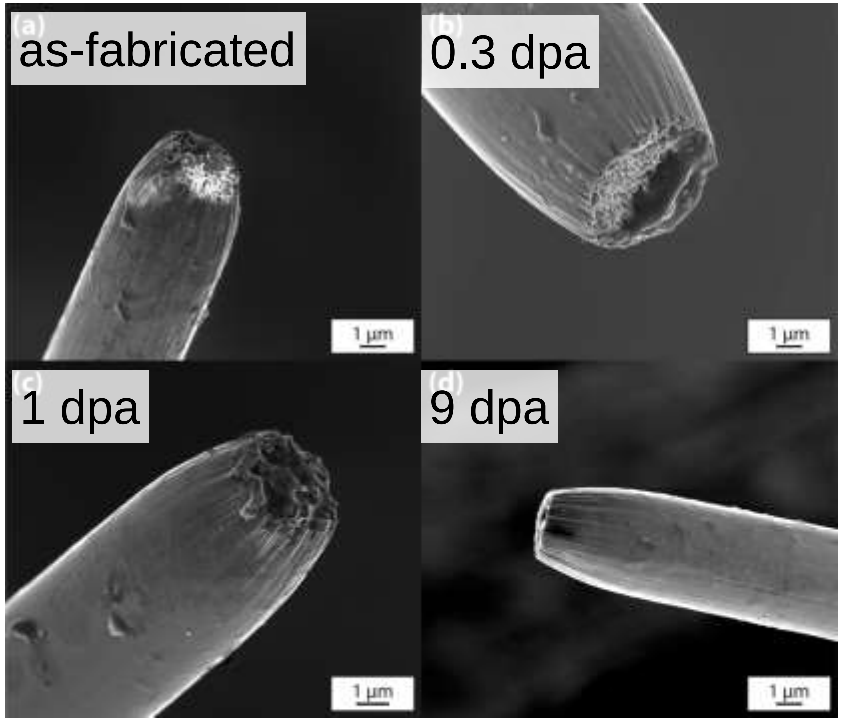
Why do we still need advanced materials?
Possible benefits of tungsten fibre-reinforced composites

- **Joining Cu and W is still a weak point**
  - Is a joint fibre preform possible?
- **Reduce complexity**
  - Larger components → fewer elements, easier alignment, fewer edges
    → see talk of Y. Mao
- **Be more resilient to irradiation**
  - W fibres show so far promising resistance to irradiation degradation
  - Can the composite concept contribute to the good performance (keyword: embrittlement of fibre)?
- **Enable higher surface temperature/heat loads**
  - Fibres are very temperature stable: recrystallisation & grain growth only >2300 °C
- **…**

Effect of irradiation damage

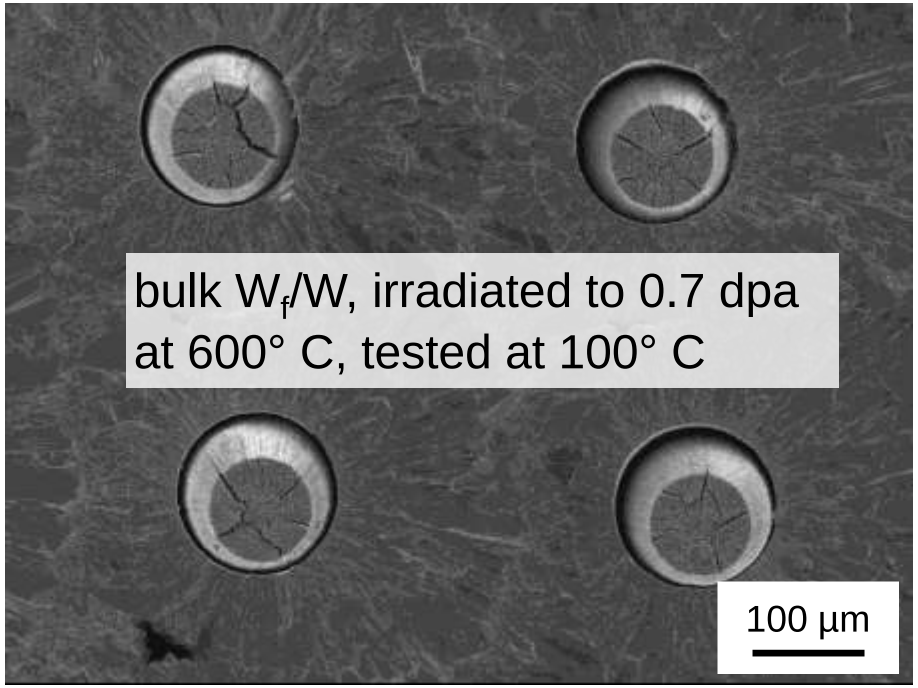
Wire shows good resilience in first experiments

Tensile tests of single fibre after irradiation by 20.5 MeV W^{6+} in particle accelerator



[Riesch et al., Nuclear Materials and Energy 30, 2022, S. 101093]

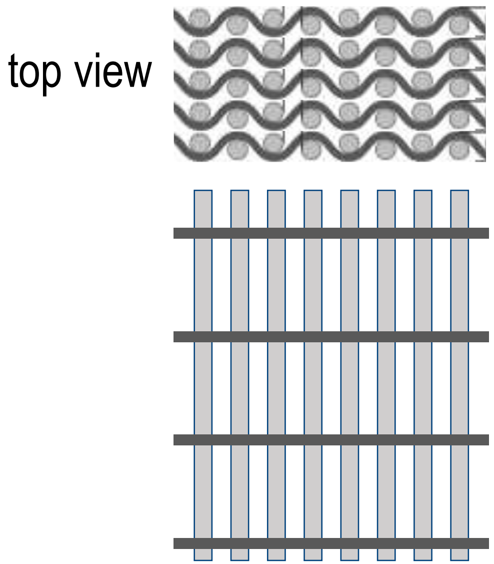
Fracture tests of bulk material after irradiation in fission reactor up to 1 dpa (see also talk by **Y. Mao**)



W_f/W – W_f/Cu hybrid plasma facing component (PFC)

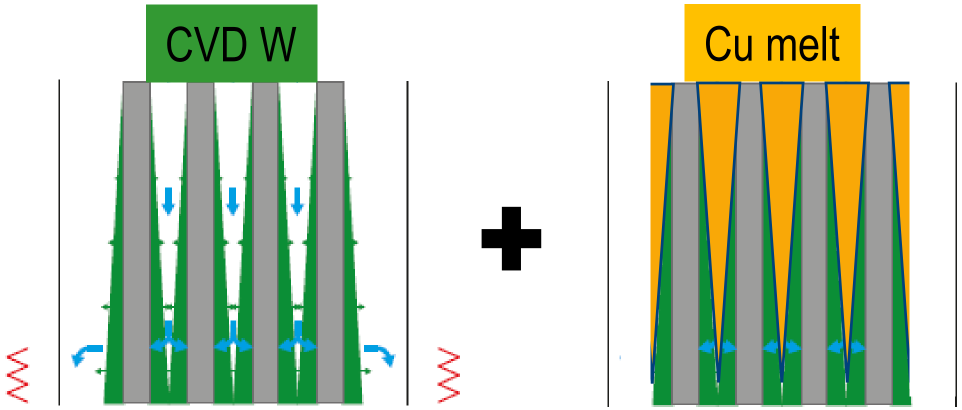
A possible solution to joining problems

textile techniques
using W wire yarns



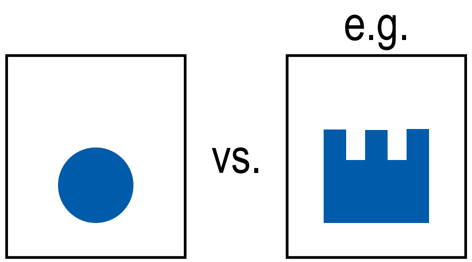
[Gietl et al., J. Compos. Mater. 52 (28) (2018) 3875-3884]

W-CVI and Cu melt infiltration
→ joint W fibre preform



[Riesch et al., Phys. Scr. T159 (2014) S. 14031]

Manny more questions:
e.g. how to design and create a cooling channel?
→ „standard" vs. alternative design (use of **additive manufacturing**?)



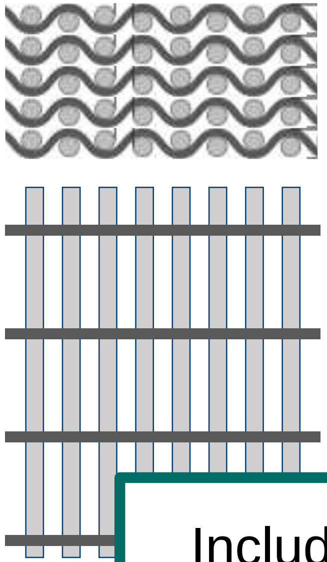
[Chen et al., Fusion Eng. Des. 172 (2021) 112919]

W_f/W – W_f/Cu hybrid plasma facing component (PFC)

A possible solution to joining problems

textile techniques
using W wire yarns

top view



W-CVI and Cu melt infiltration
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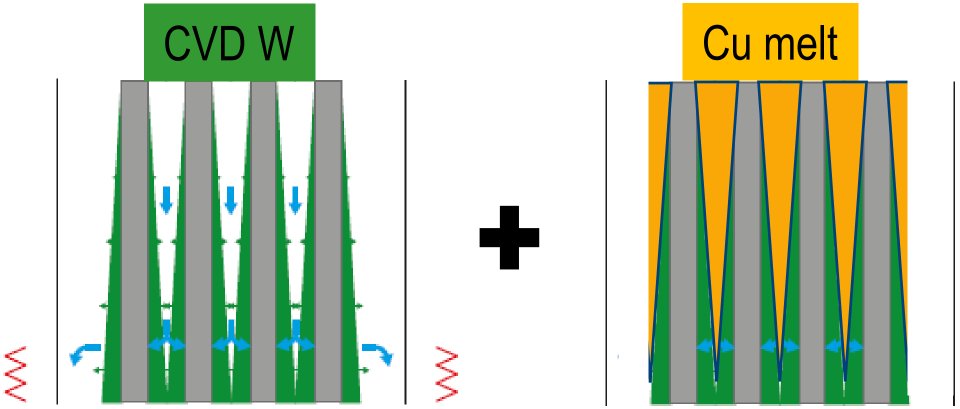

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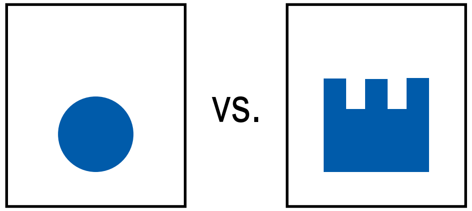
e.g.



n Eng. Des.
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Includes so far only the view of the material scientist and the design engineer
→ talk to the plasma exhaust experts

[Gietl et al., J. Compos. Mater. 52 (28) (2018) 3875-3884]

Summary

Tungsten fibre-reinforced tungsten features high toughness even at room temperature

Chemical vapour deposition allows the fabrication of W_f/W and offers some design freedom

- Duel step infiltration and layered deposition
- Infiltration for more complex materials e.g. a W_f/W – W_f/Cu hybrid

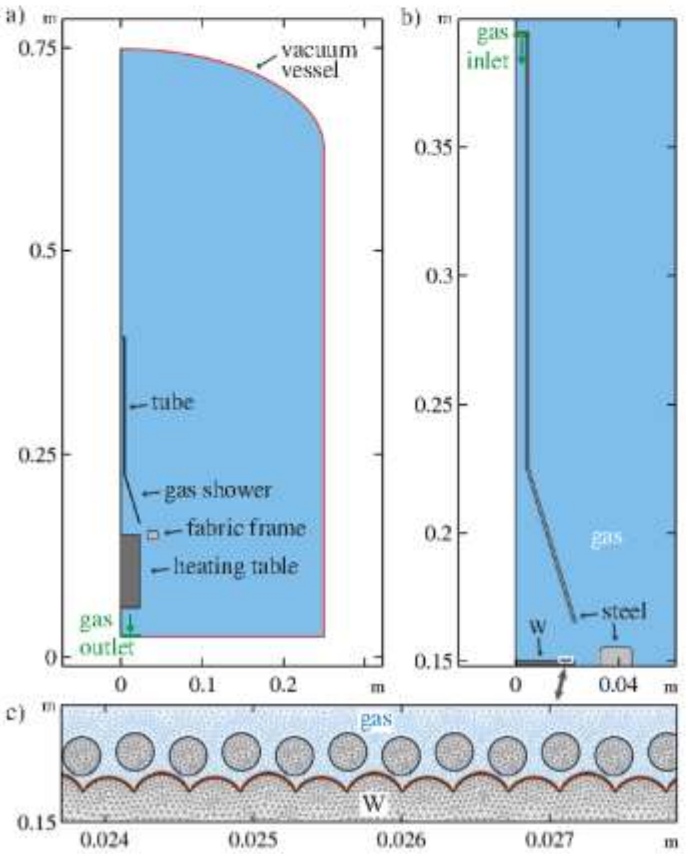
DEMO design works but advanced materials may help to mitigate possible risks

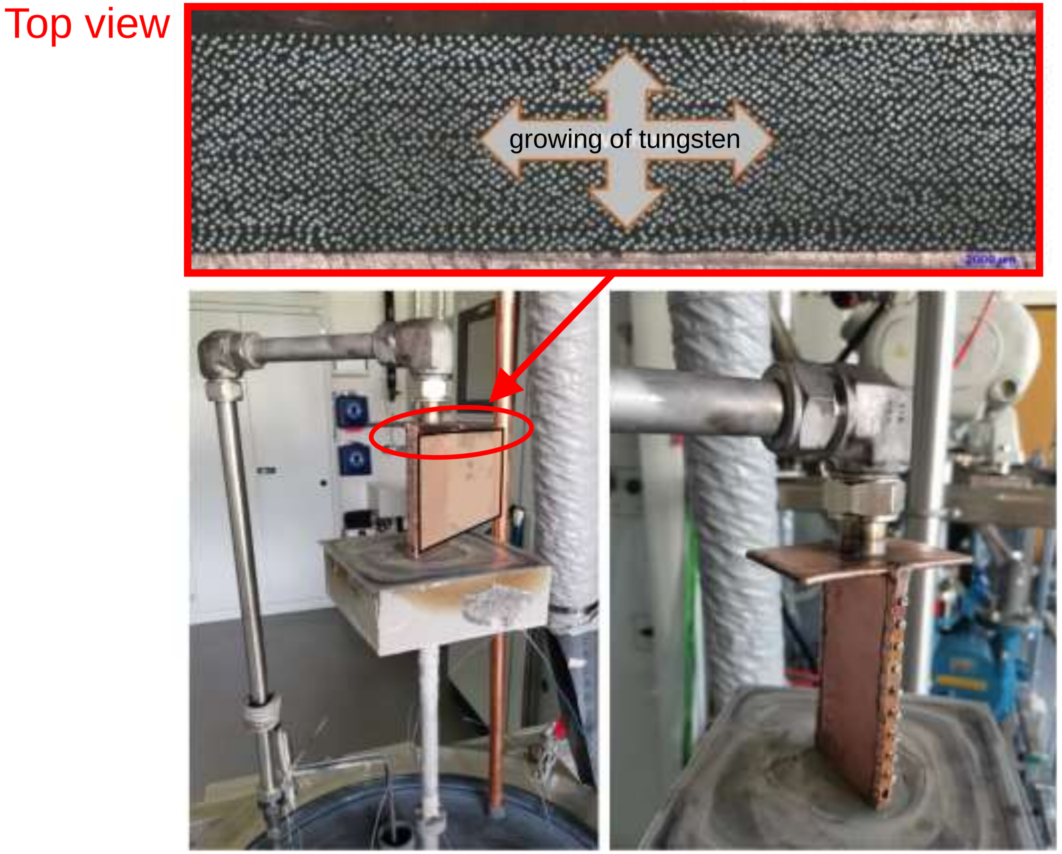
- W_f/W – W_f/Cu hybrids to improve the joining
- Possible improve of irradiation stability due to W wire and composite approach

W_f/W composites can be useful for the development of new PFCs but their application needs a highly integrated approach between material scientists, design engineers and power exhaust experts

Outlook: W_f/W-W_f/Cu Hybrid – going back to infiltration

New capabilities in textile techniques +
Large experience in machine handling & modelling



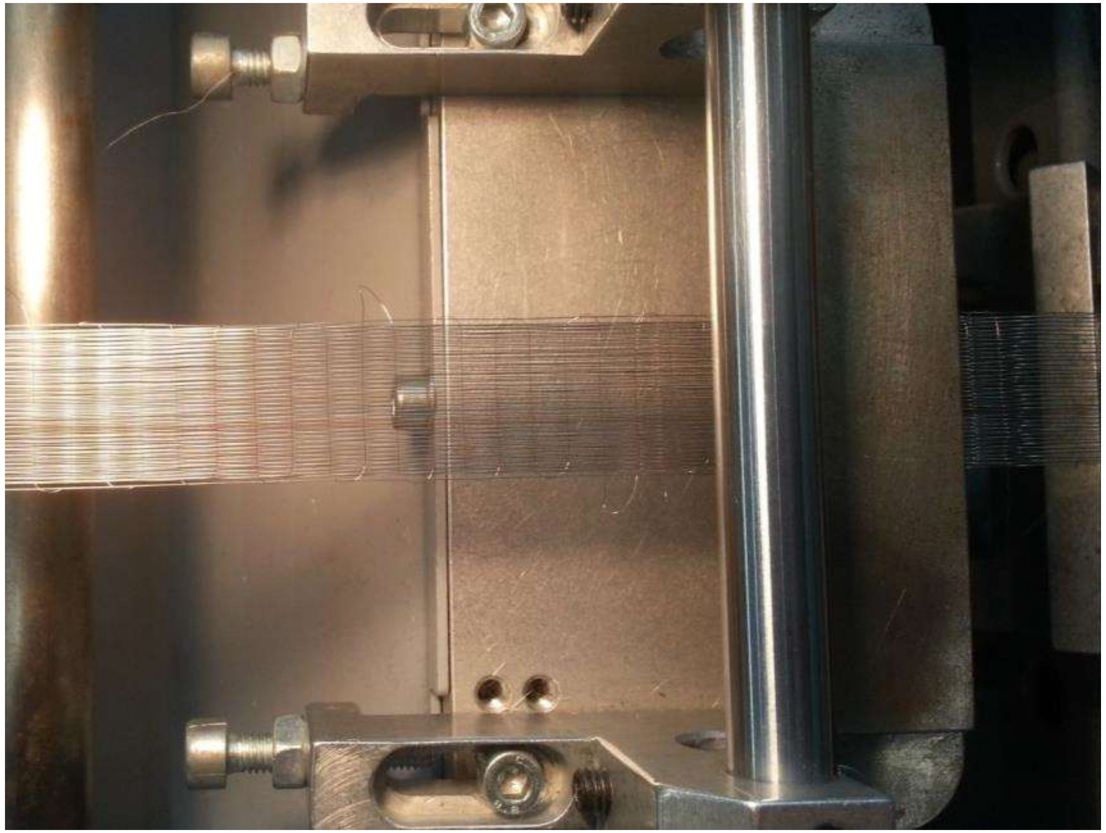


[Raumann, L et al.., Metals 11 (7), 2021, S. 1089.]

Thank you for your attention

WILMA: W Infiltration Machine
Setup for the chemical deposition of W installed at Forschungszentrum Jülich
[Riesch et al., Nuclear Materials and Energy 9 (2016) S. 75–83]]

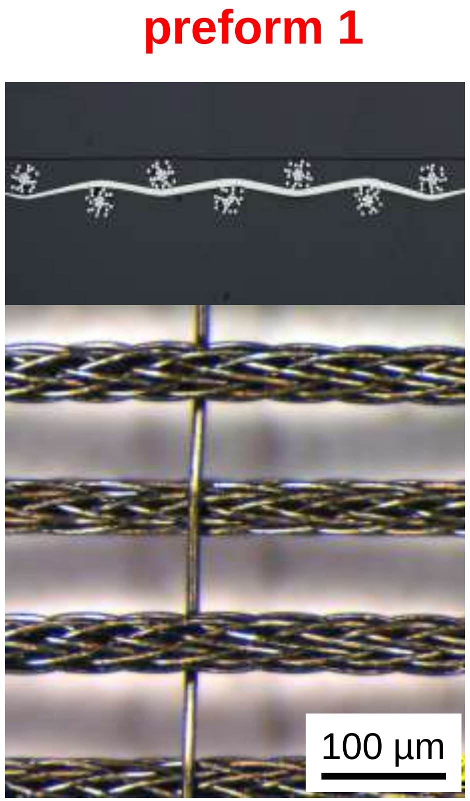
Textile techniques

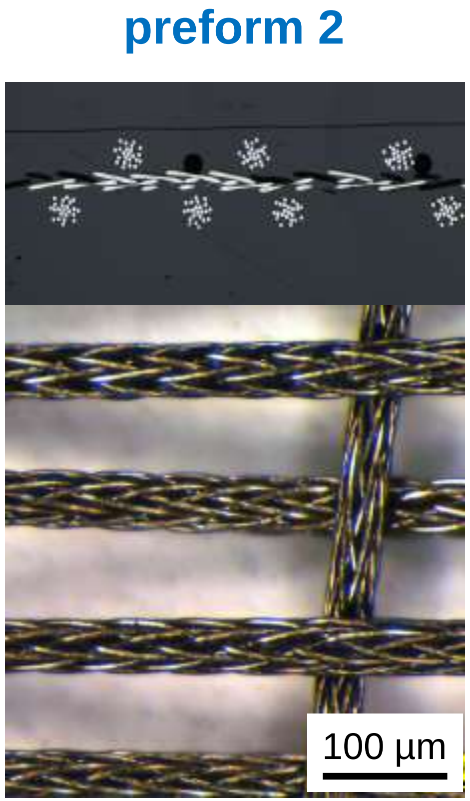


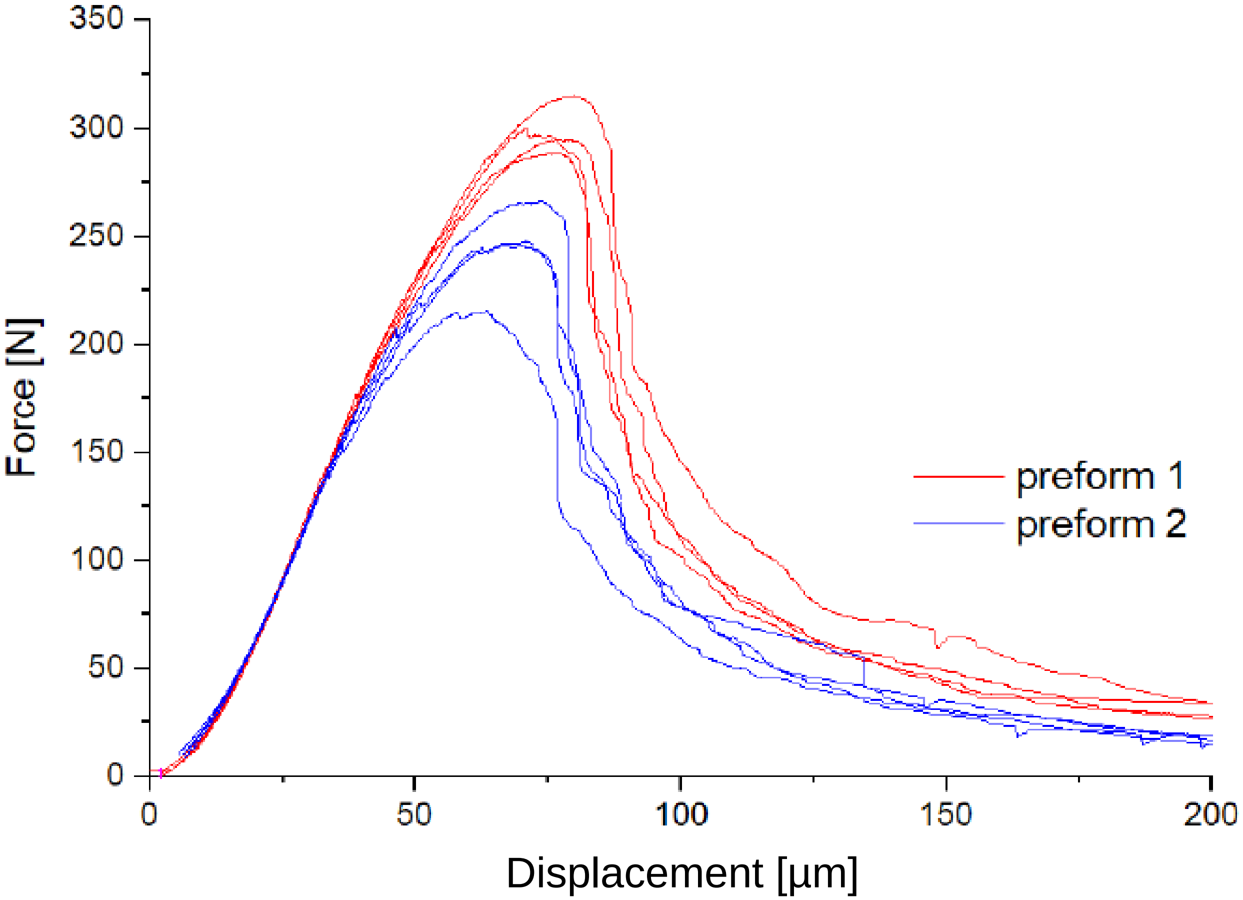
[Gietl et al., J. Compos. Mater. 52 (28) (2018) 3875-3884]

Development of W wire textiles and yarns

Significant increase of performance and reproducibility







[Lau et al., 32nd Symposium on Fusion Technology, 2022]