POWDER INJECTION MOLDING (PIM) – A MULTI-PUPOSE PROCESS FOR ARMOR PART FABRICATION AND MATERIALS DEVELOPMENT

Karlsruhe Institute of Technology (KIT)
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University of Oxford
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Outline

- **Motivation**
- **What is Powder Injection Molding (PIM)?**
- **The PIM process for tungsten developed at KIT**
- **Material development for PIM**
- **Producing of 2-Component W PIM divertor parts**
- **Summary & Outlook**

- **Motivation**
- What is Powder Injection Molding (PIM)?
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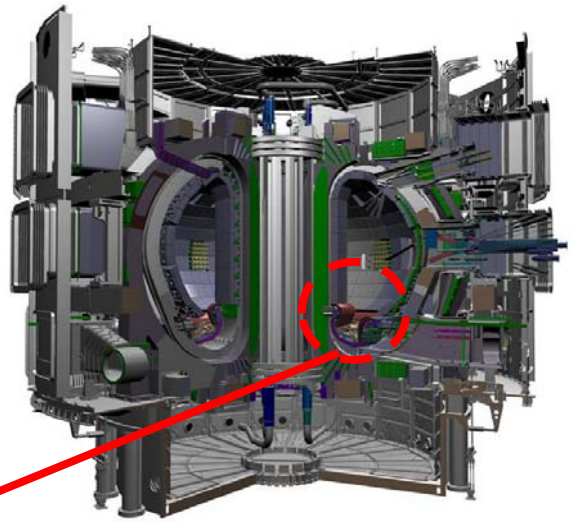
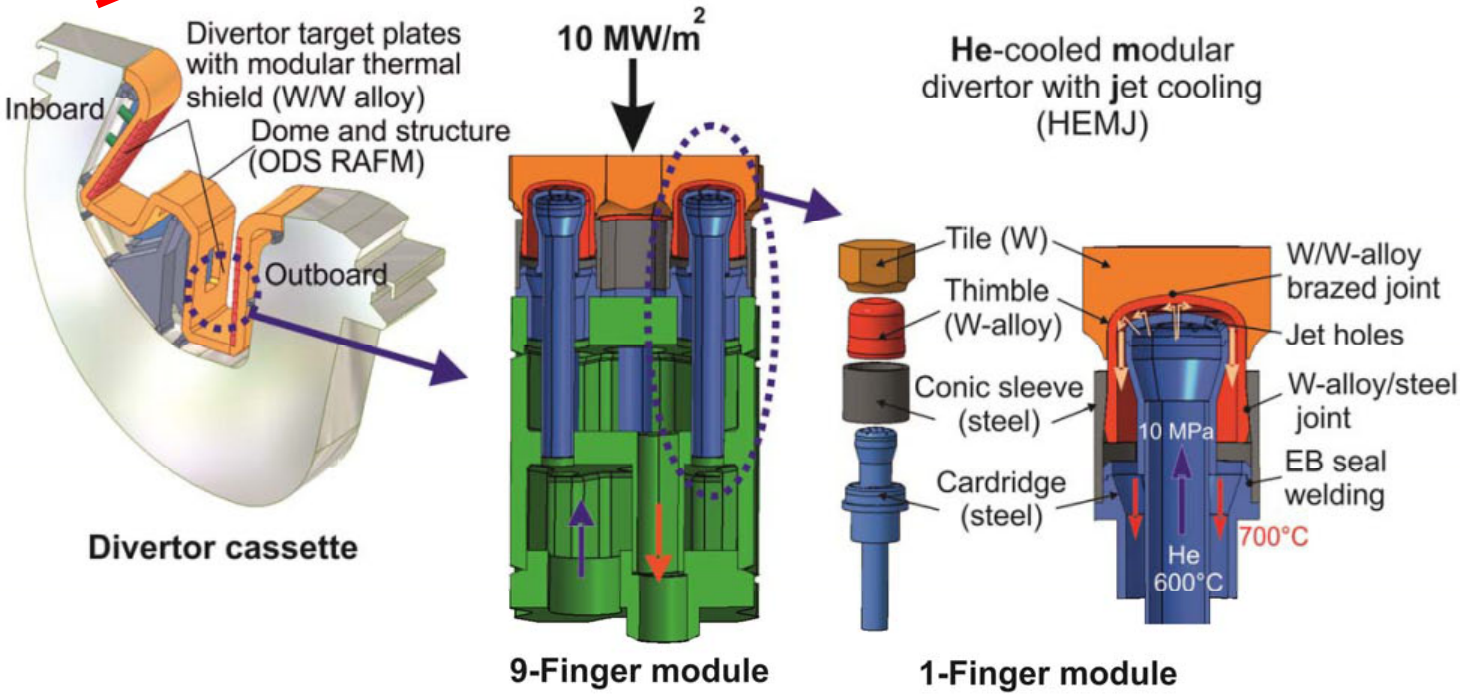
- Producing of 2-Component W PIM divertor parts
- Summary & Outlook

Motivation



Future fusion power reactor DEMO

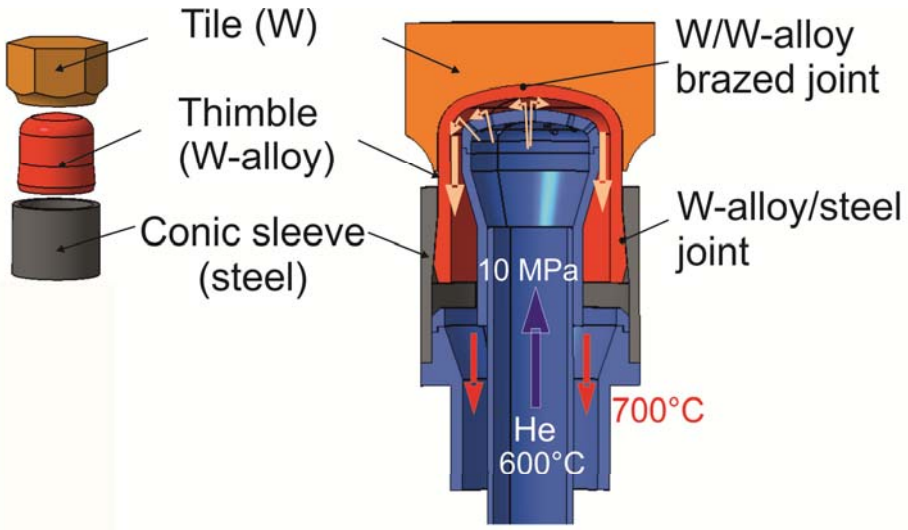
One promising divertor design – developed at KIT



P. Norajitra et al., KIT.

Motivation

⇒ 1 Finger-mockup – 3 main parts
⇒ 2 – 3 several materials
⇒ 2 brazed joints
⇒ assembling, adjustment…



1-Finger-Mockup

⇒ DEMO: nearly 300.000 mockups
⇒ lifetime nearly 2 years

⇒ **Reasonable manufacturing method?**

- Motivation
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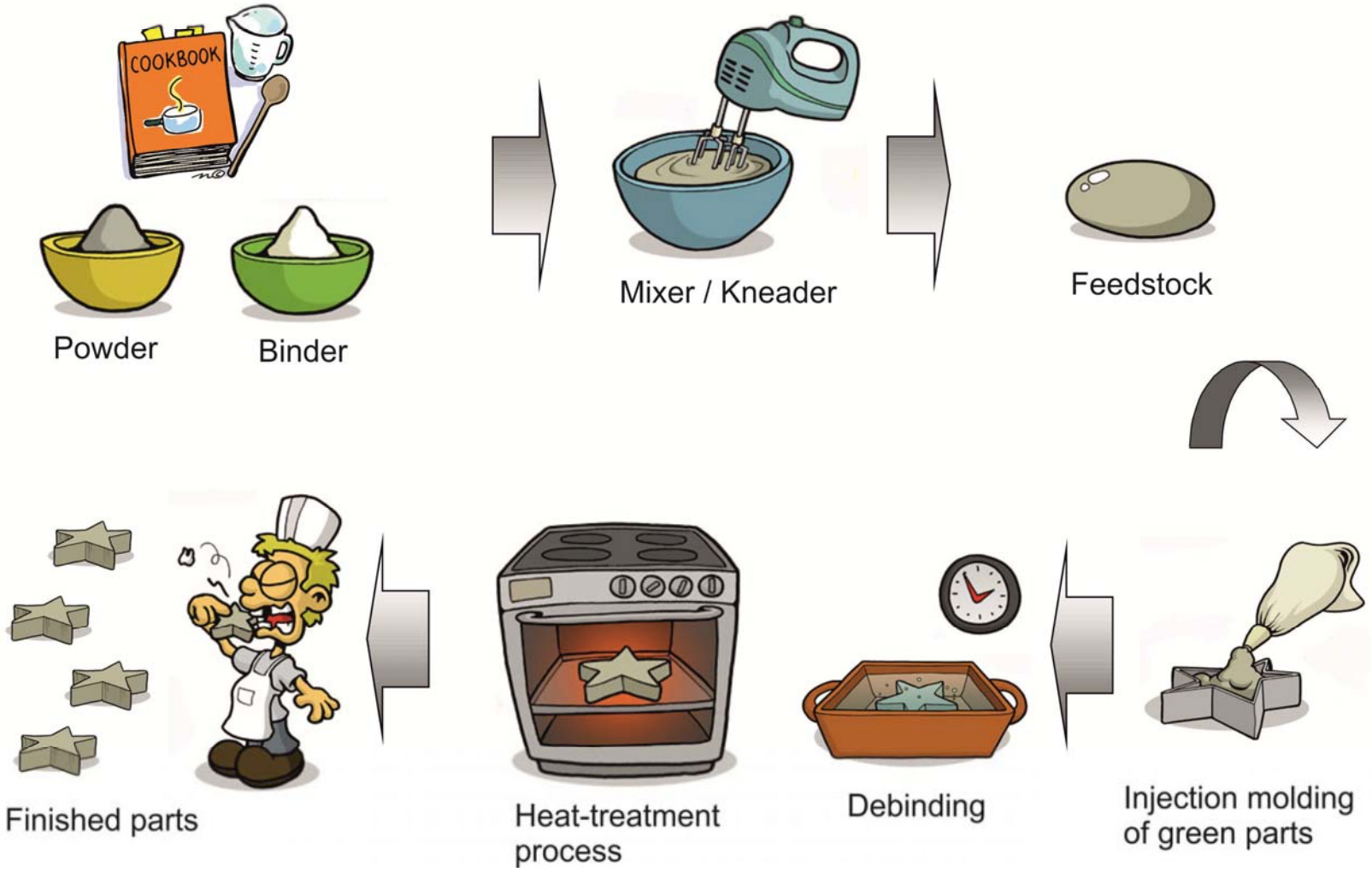
What is Powder Injection Molding (PIM)? …manufacturing technology…

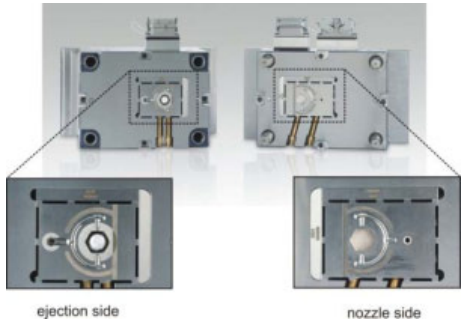
source: http:\\pim-technologies.com



What is Powder Injection Molding (PIM)?
…manufacturing technology…

…a little bit more technical…

Feedstock



Injection Molding tool

Injection Molding machine

Green parts

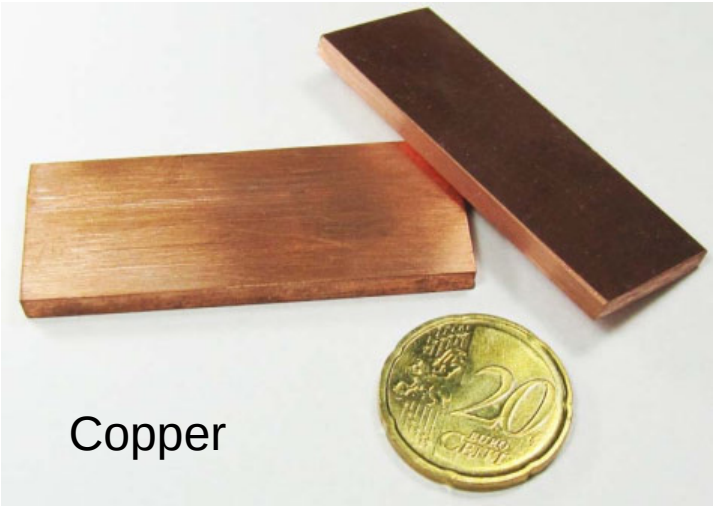
What is Powder Injection Molding (PIM)? …manufacturing technology…

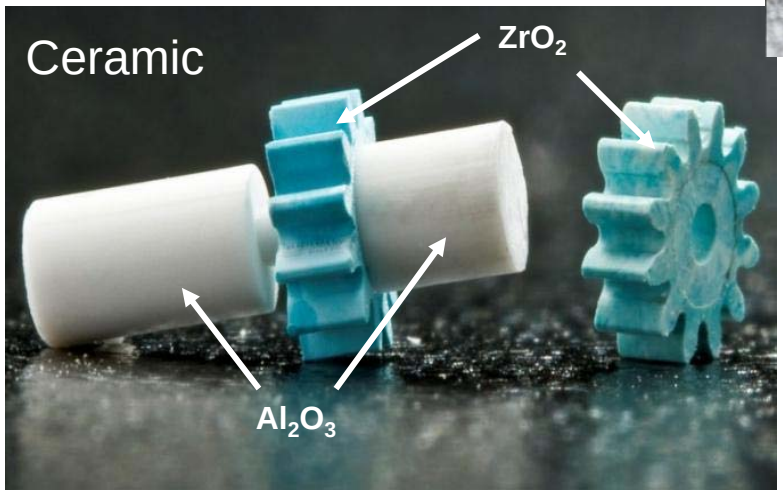
Powder Injection Molding (PIM)

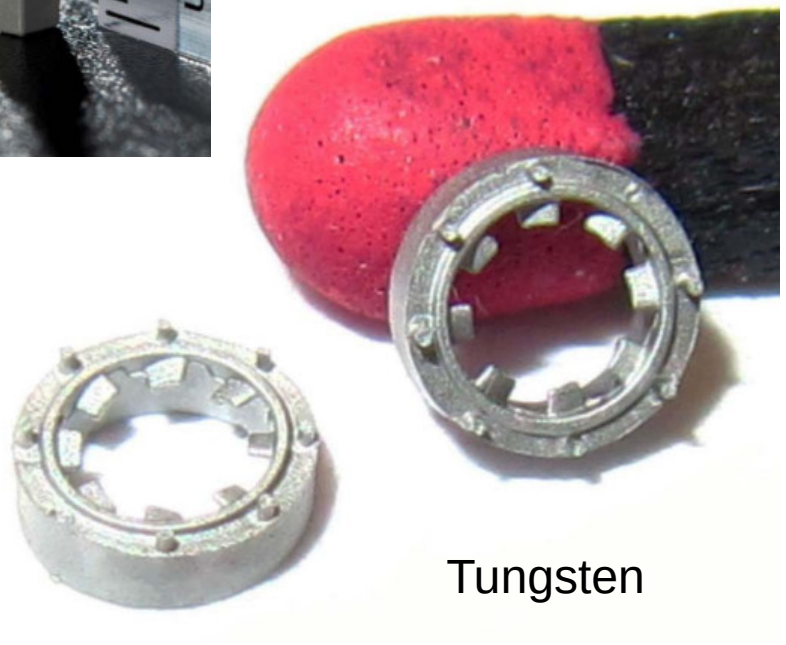
Metal Injection Molding (MIM)

Ceramic Injection Molding (CIM)

What is Powder Injection Molding (PIM)?
…parts produced at KIT…







Smallest ZrO_2 gear wheel of the world:
outer-∅ 275 µm

What is Powder Injection Molding (PIM)? …tungsten PIM…

Advantages

⇒ Cost-effective mass production

⇒ Producing of 3D-parts

⇒ Metal forming of tungsten based materials complicated

Challenges

⇒ Adequate powders / powder mixtures

⇒ preparation / feedstock development

⇒ Heat-treatment process

⇒ High density

⇒ Low porosity

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- What is Powder Injection Molding (PIM)?
- **The PIM process for tungsten developed at KIT**
- Material development for PIM
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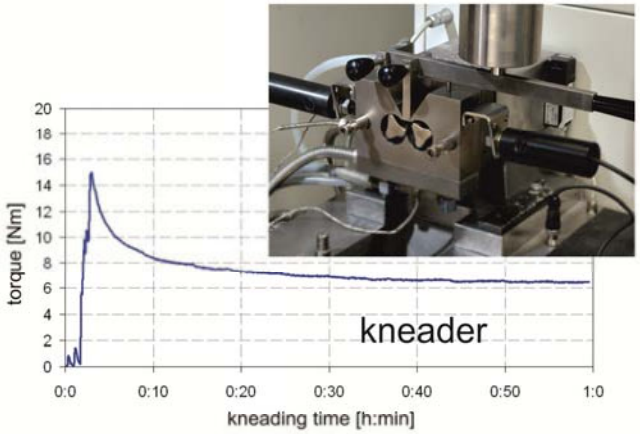
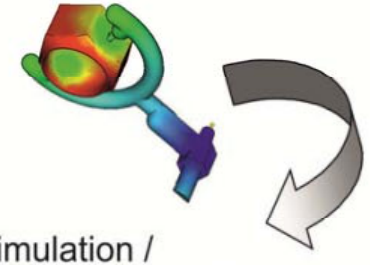
The PIM process for tungsten developed at KIT

W-powder + binder

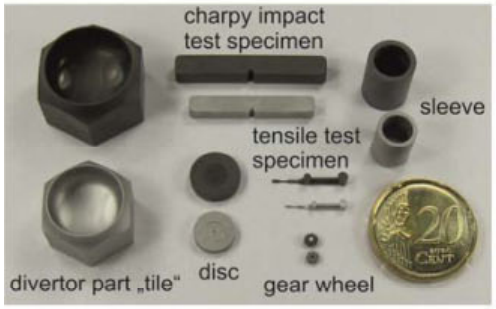


feedstock development

W-feedstock



filling simulation /
design+engineering of a tool



green parts (dark)
finished parts (bright)

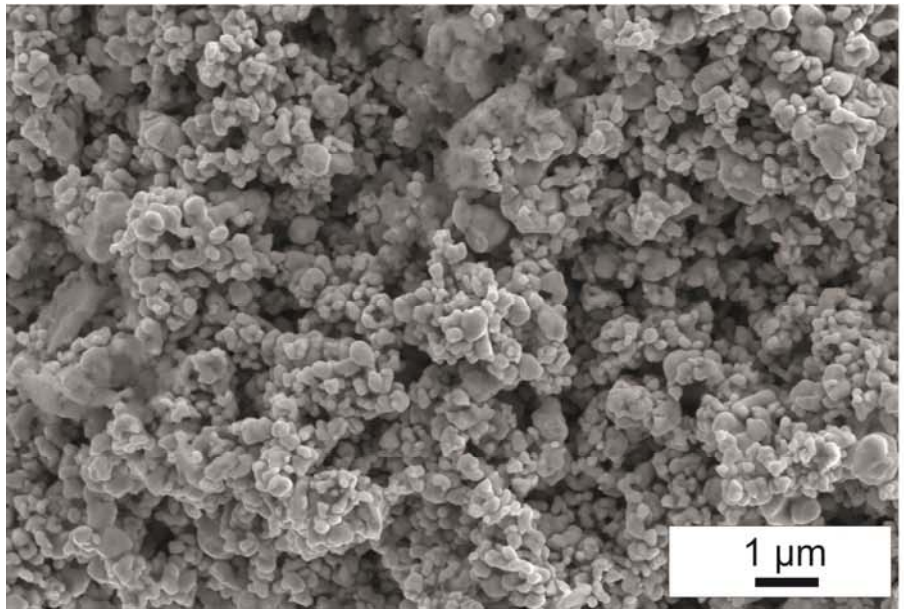
HIP

pre-sintering

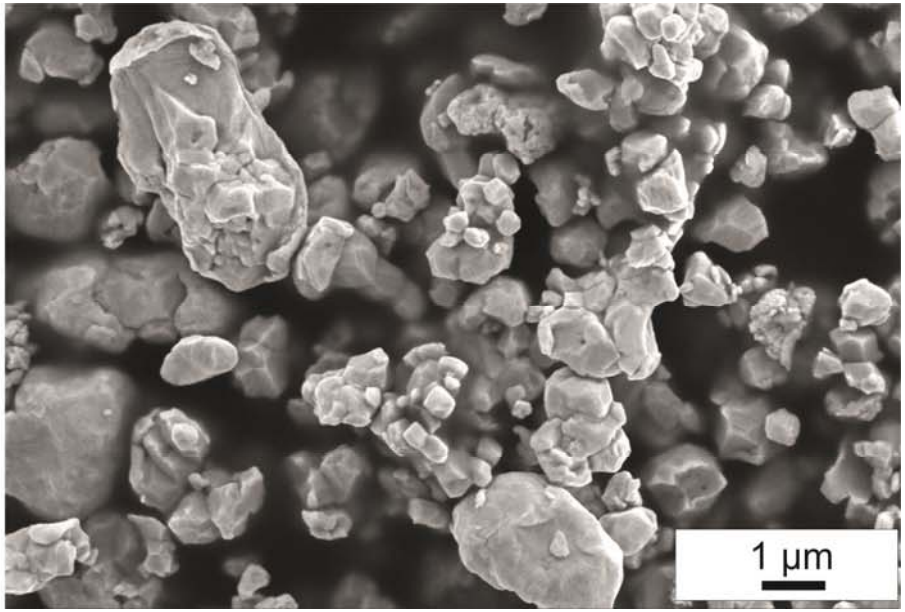
debinding + heat-treatment process

injection molding
of green parts

The PIM process for tungsten developed at KIT
1. Powder



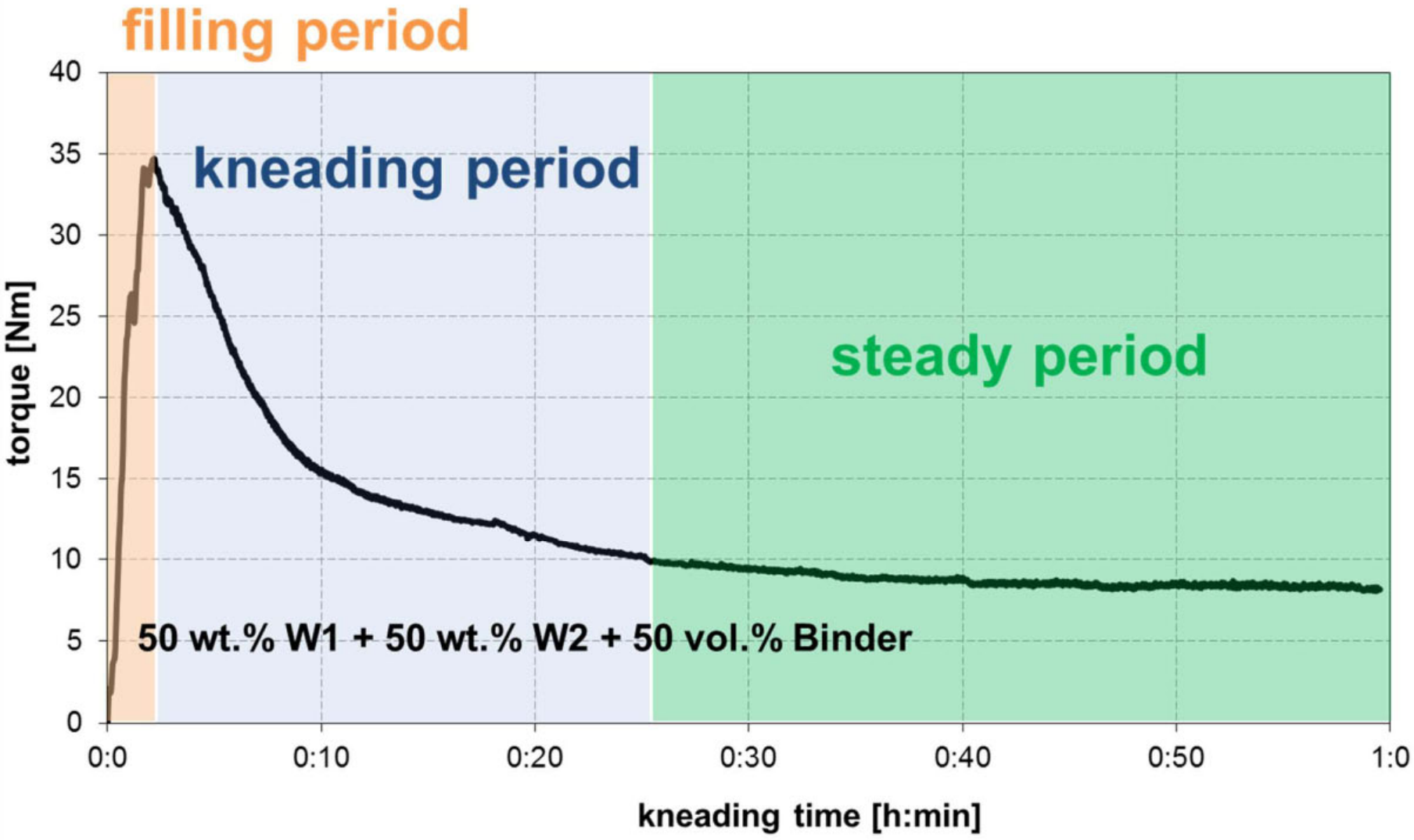
SEM Microstructure tungsten powder W1



SEM Microstructure tungsten powder W2

W powder	Particle size [µm FSSS]	D10 [µm]	D50 [µm]	D90 [µm]	BET [m²/g]
W1	0.70	0.14	0.47	1.25	1.27
W2	1.70	0.55	1.80	4.91	0.43

The PIM process for tungsten developed at KIT
2. Feedstock development - kneading



The PIM process for tungsten developed at KIT
…steps for developing of a new PIM tool…

Needful knowledge about:
- Powder properties (size, shape, surface,…)
- Powder / Binder relationship
- Shrinkage (green part – finished part)

pretests + analyzes

Filling simulation:
- Define gating system parameters (position, size, shape)
- Problems (air inclusions, mold filling, premature setting)

6 month

+

Construction of the tool
- Running-in tests – maybe subsequent improvement

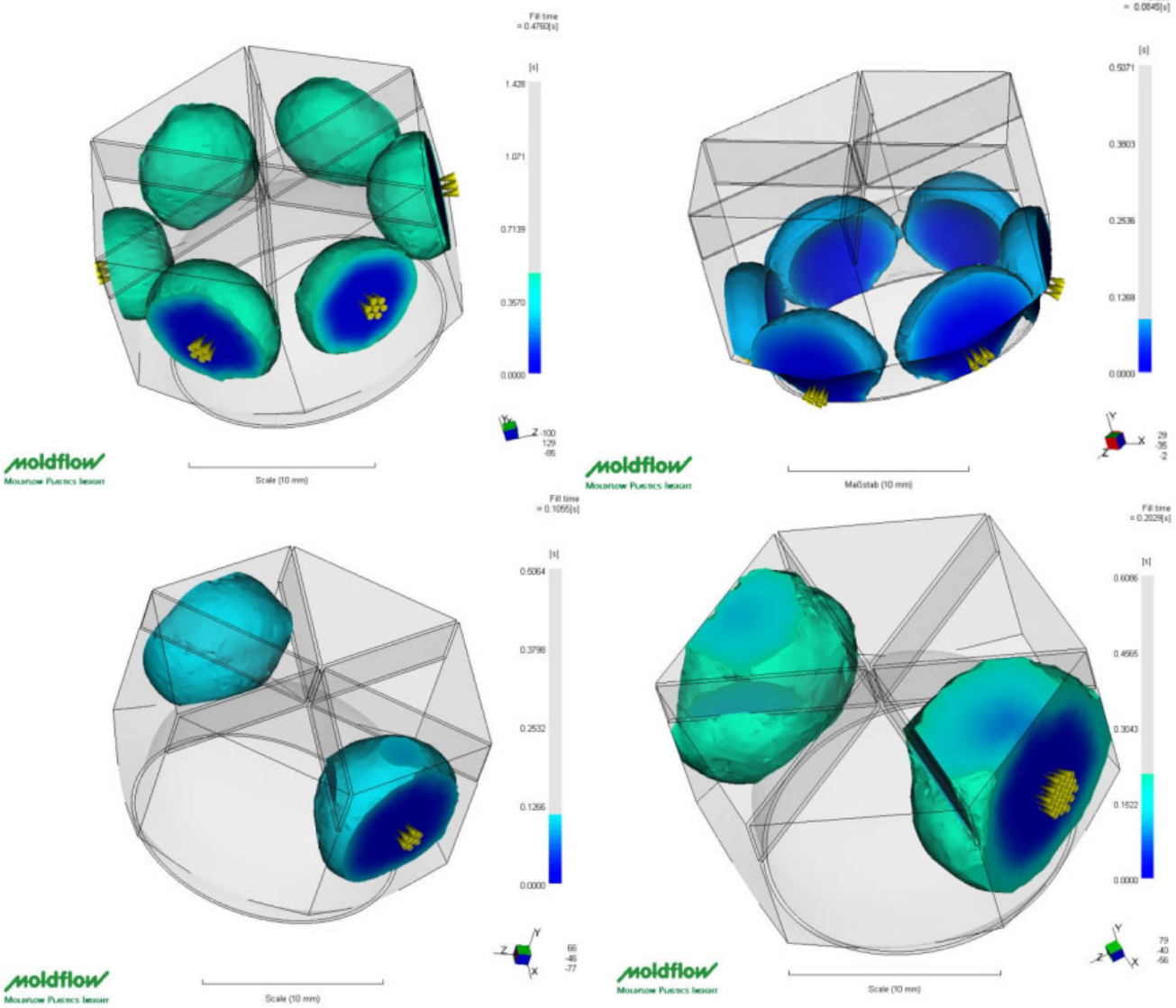
6 month

The PIM process for tungsten developed at KIT
…filling simulation…

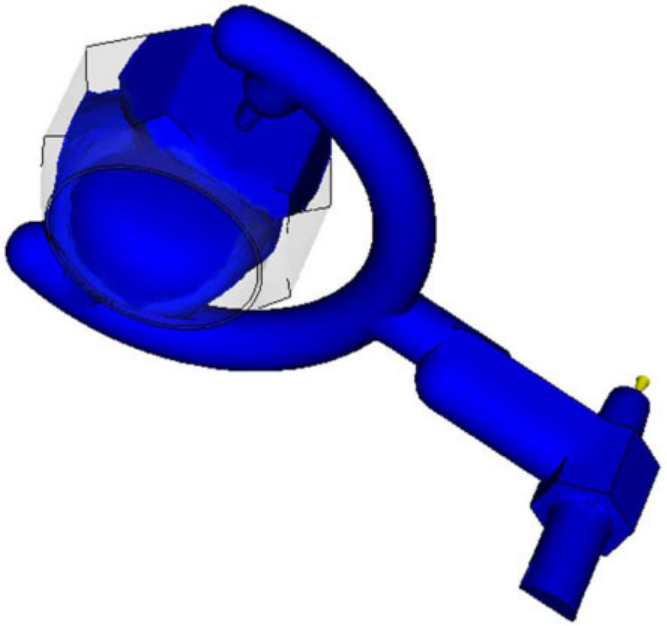
Information about the gating system:

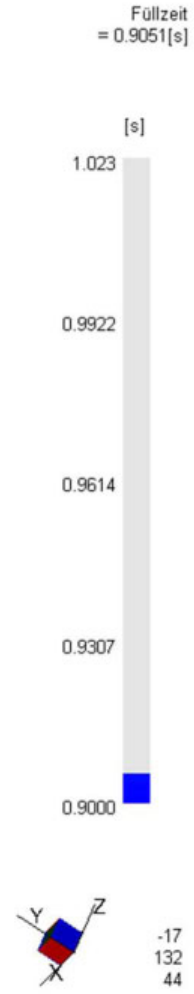
-position

-size



The PIM process for tungsten developed at KIT
…filling simulation…

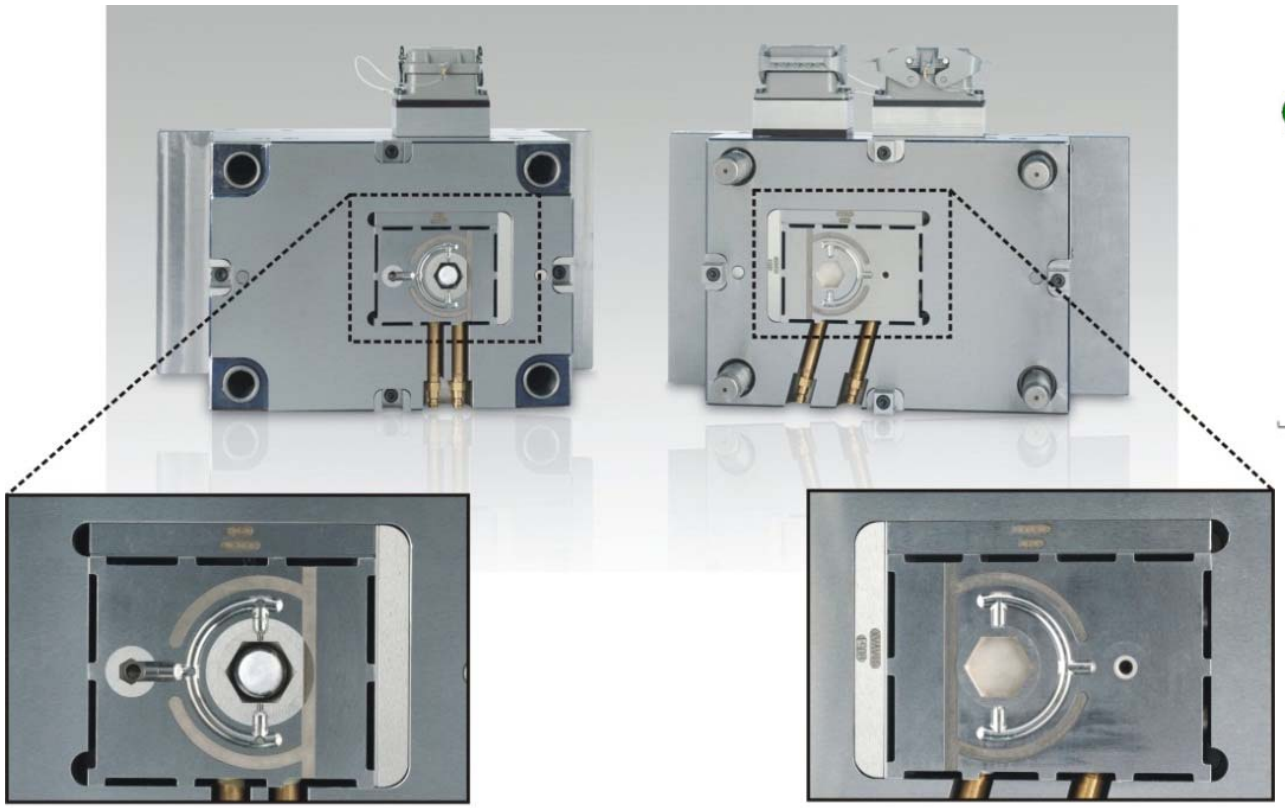


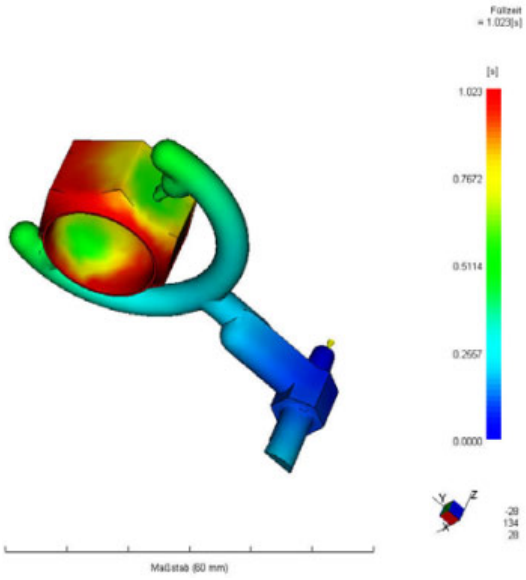


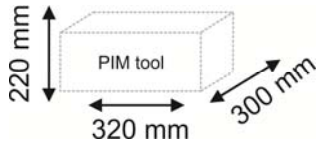
moldflow
Moldflow Plastics Insight

Maßstab (50 mm)

The PIM process for tungsten developed at KIT …The divertor W PIM part „tile“…

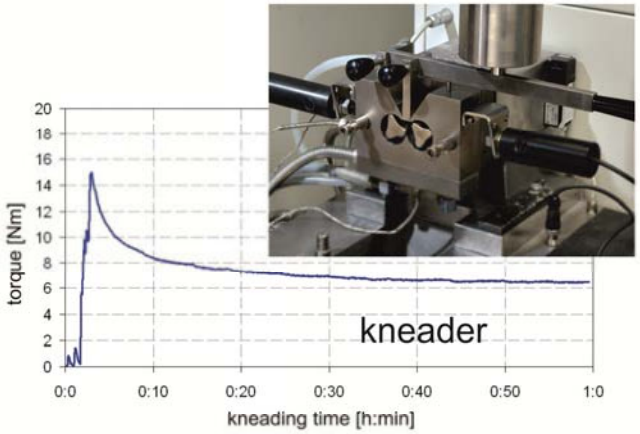






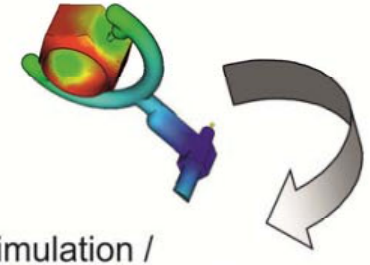
The PIM process for tungsten developed at KIT

W-powder + binder



feedstock development

W-feedstock



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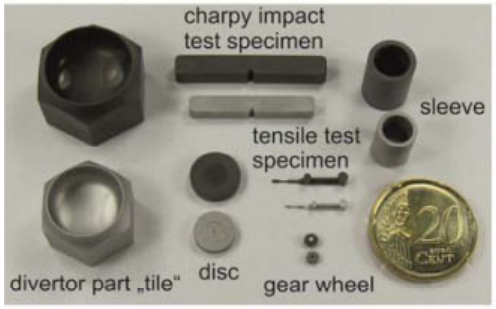


green parts (dark)
finished parts (bright)

HIP

pre-sintering

debinding + heat-treatment process

injection molding
of green parts

The PIM process for tungsten developed at KIT
…Injection Molding of green parts…

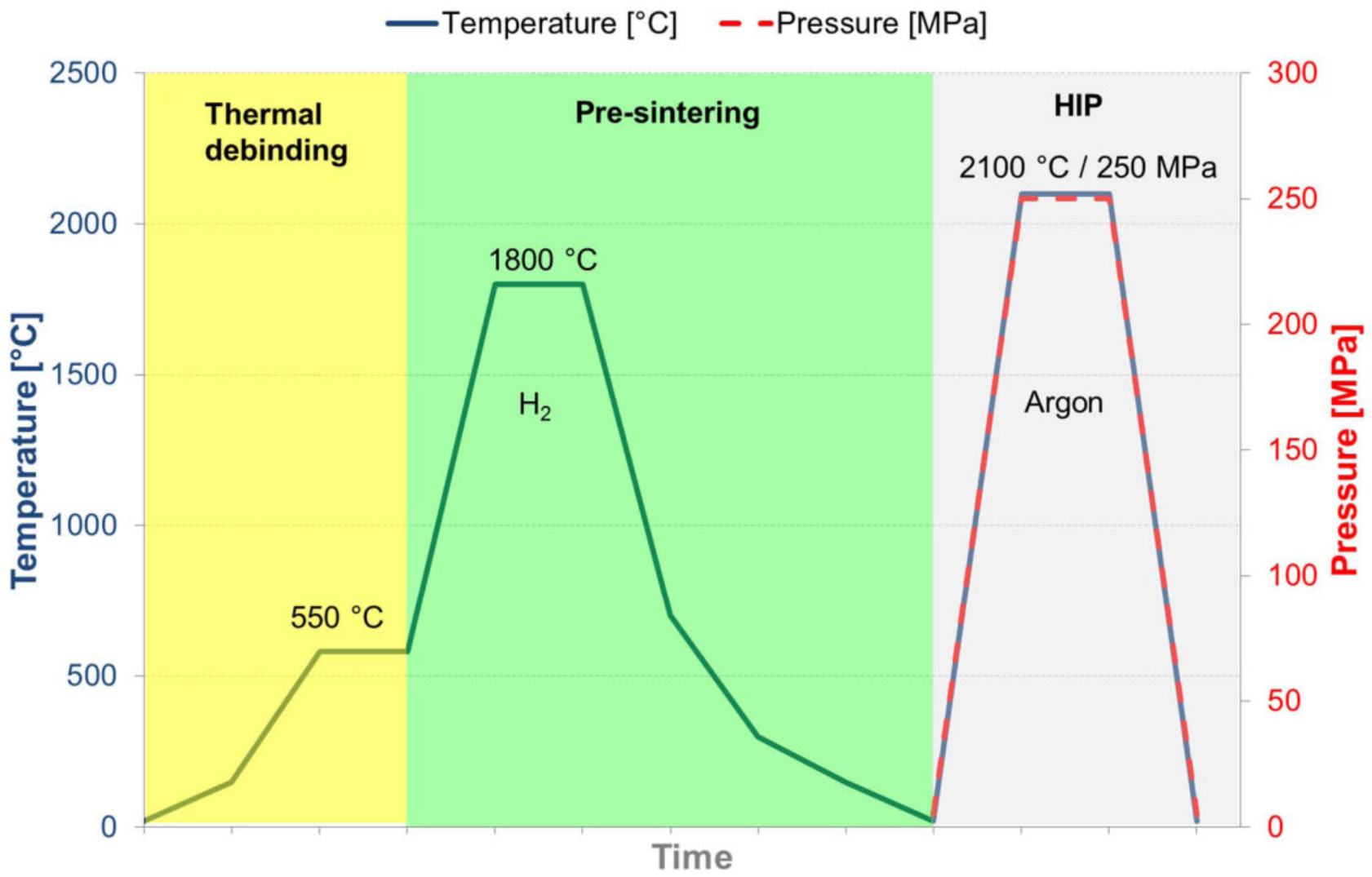
The PIM process for tungsten developed at KIT

green parts

debinding +
heat-treatment-process

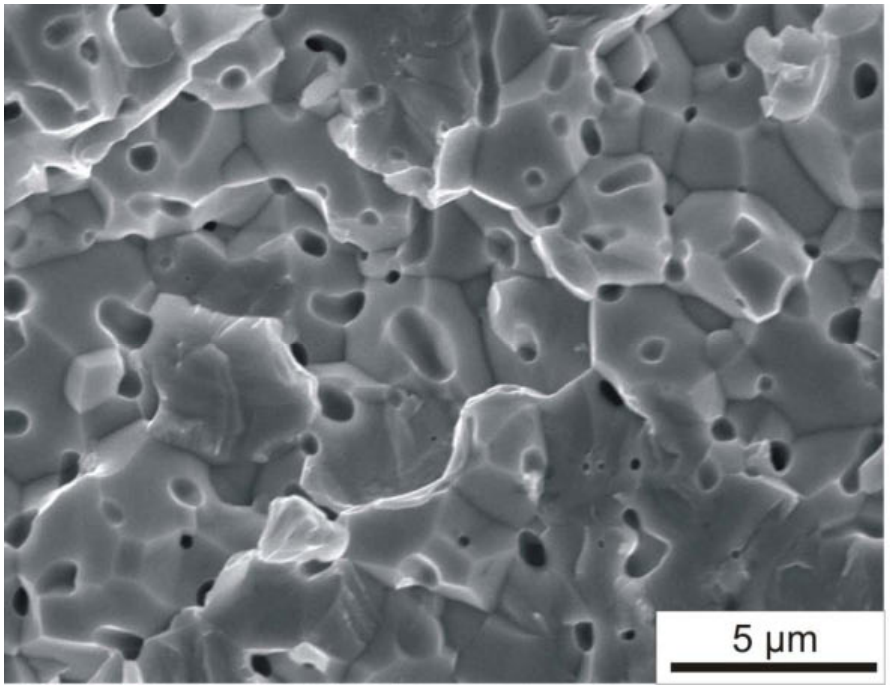
finished parts

The PIM process for tungsten developed at KIT …Heat-treatment process…



The PIM process for tungsten developed at KIT …Heat-treatment process…

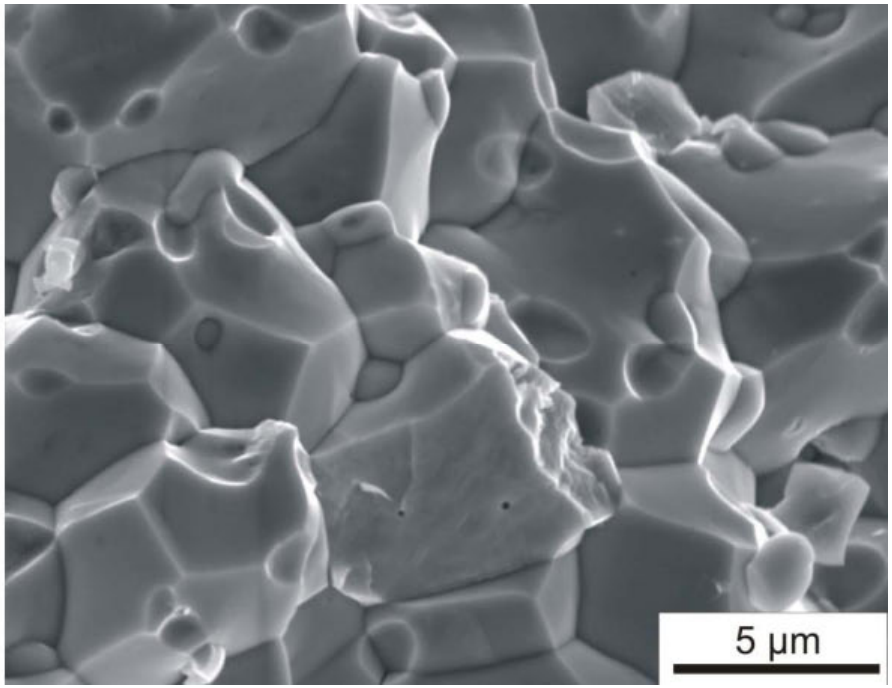
only pre-sintering



SEM Microstructure pre-sintering W

Density >95% - closed porosity!!!
Vickers-hardness 420 HV0.1

pre-sintering + HIP

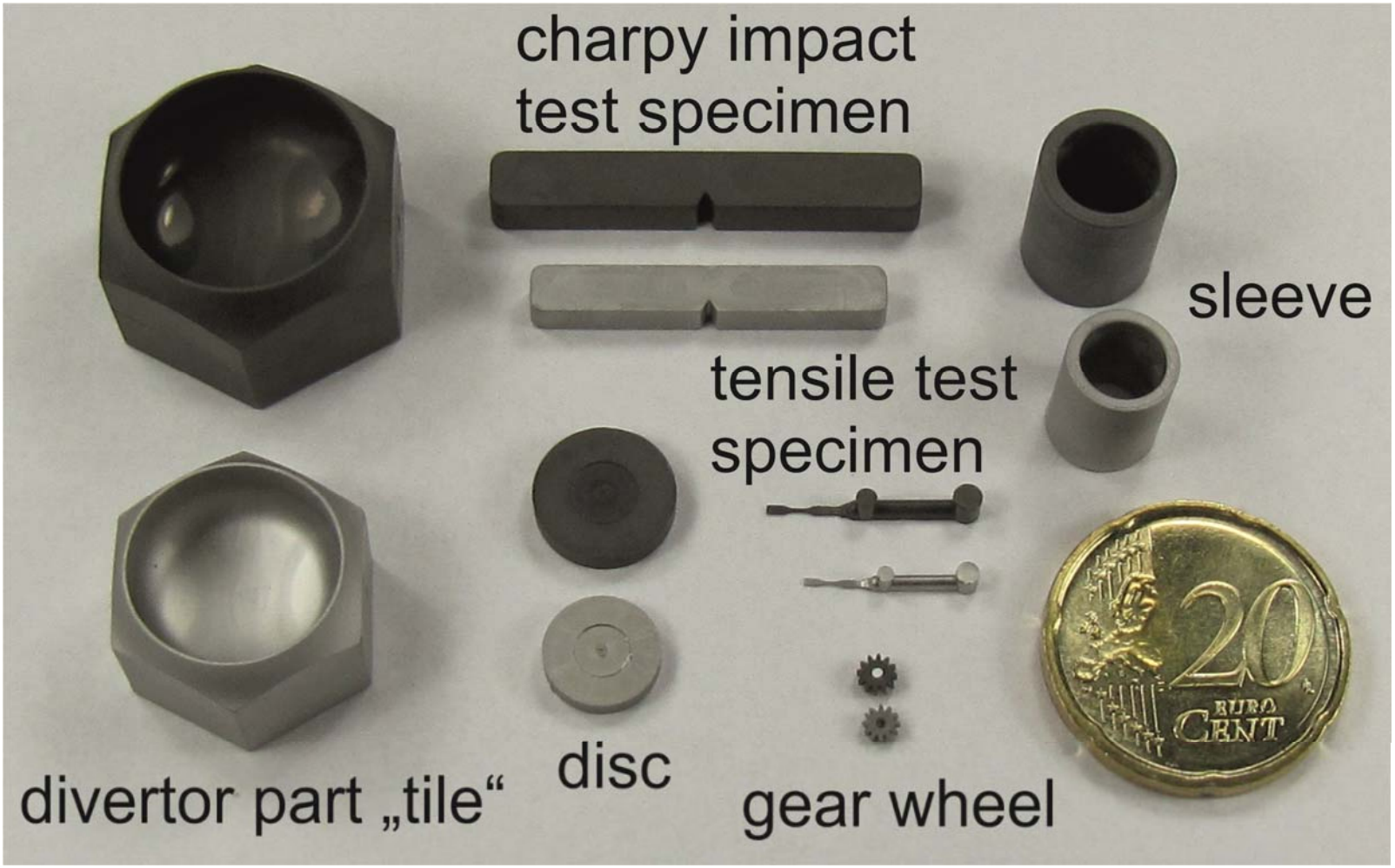


SEM Microstructure pre-sintering +HIP W

Density >98%
Vickers-hardness 457 HV0.1

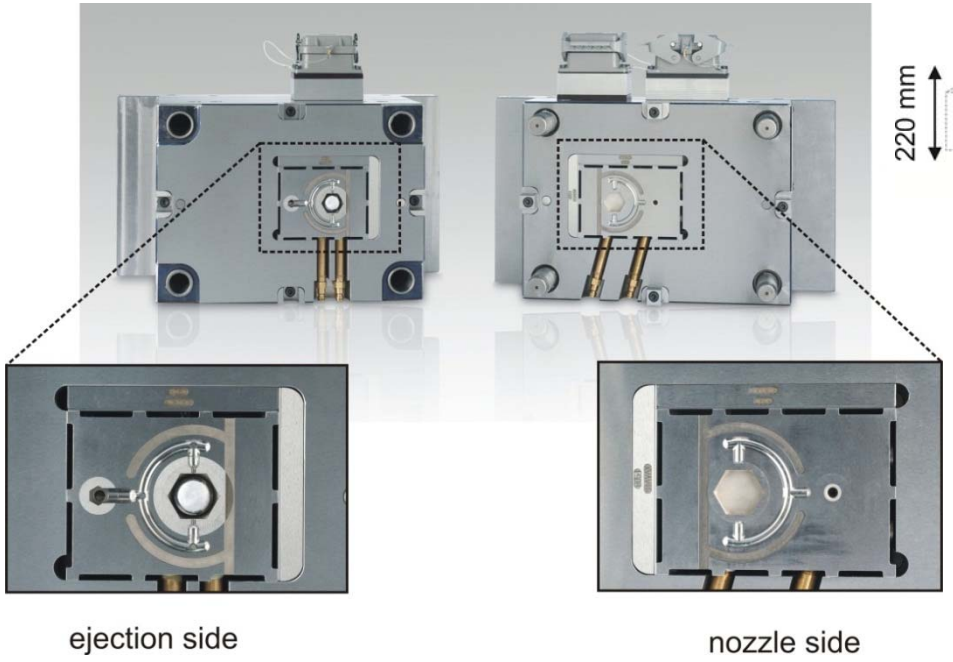
S. Antusch et al., J. Nucl. Mater. 417 (2011) 533-535.

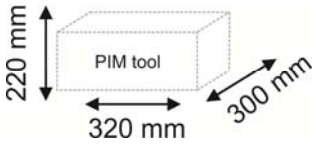
The PIM process for tungsten developed at KIT
…Tungsten PIM samples…

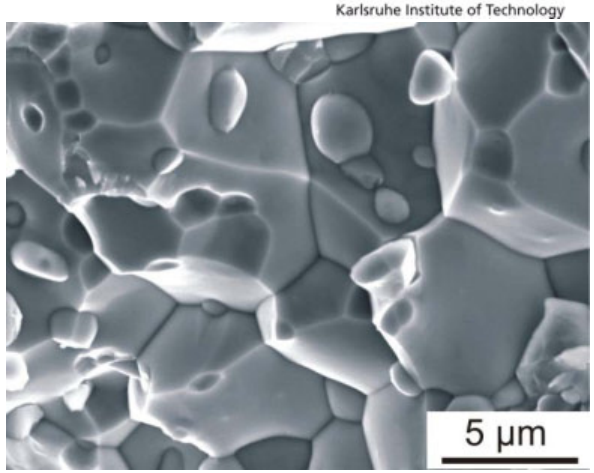


Green parts (dark) and finished parts (bright)

The PIM process for tungsten developed at KIT …The divertor W PIM part „tile“…



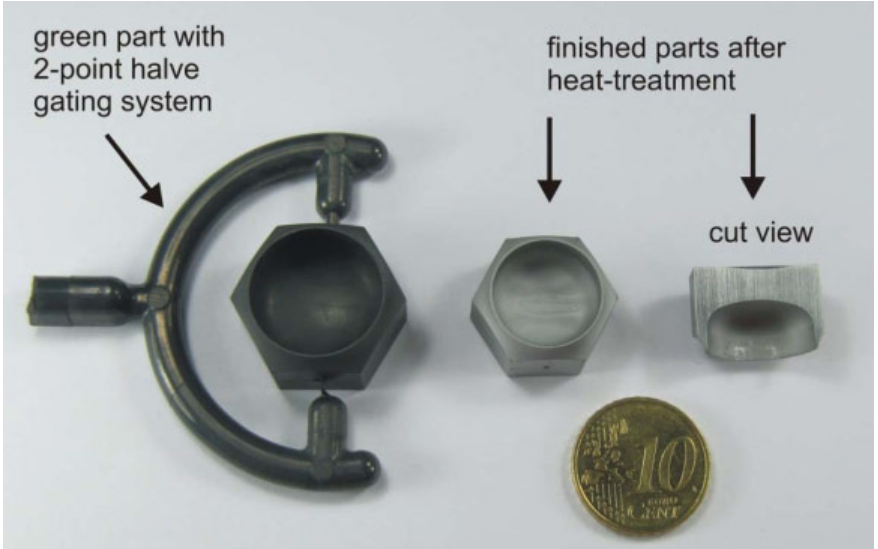




SEM image of the fracture surface: no porosity or cracks

Heat-treatment process:
- pre-sintering (1800 °C, 2 h, H_2) +
- HIP (2100 °C, 3 h, Ar, 250 MPa)

Properties of the finished material:
Vickers-hardness: 457 HV0.1
Density: 98.6 – 99 % TD

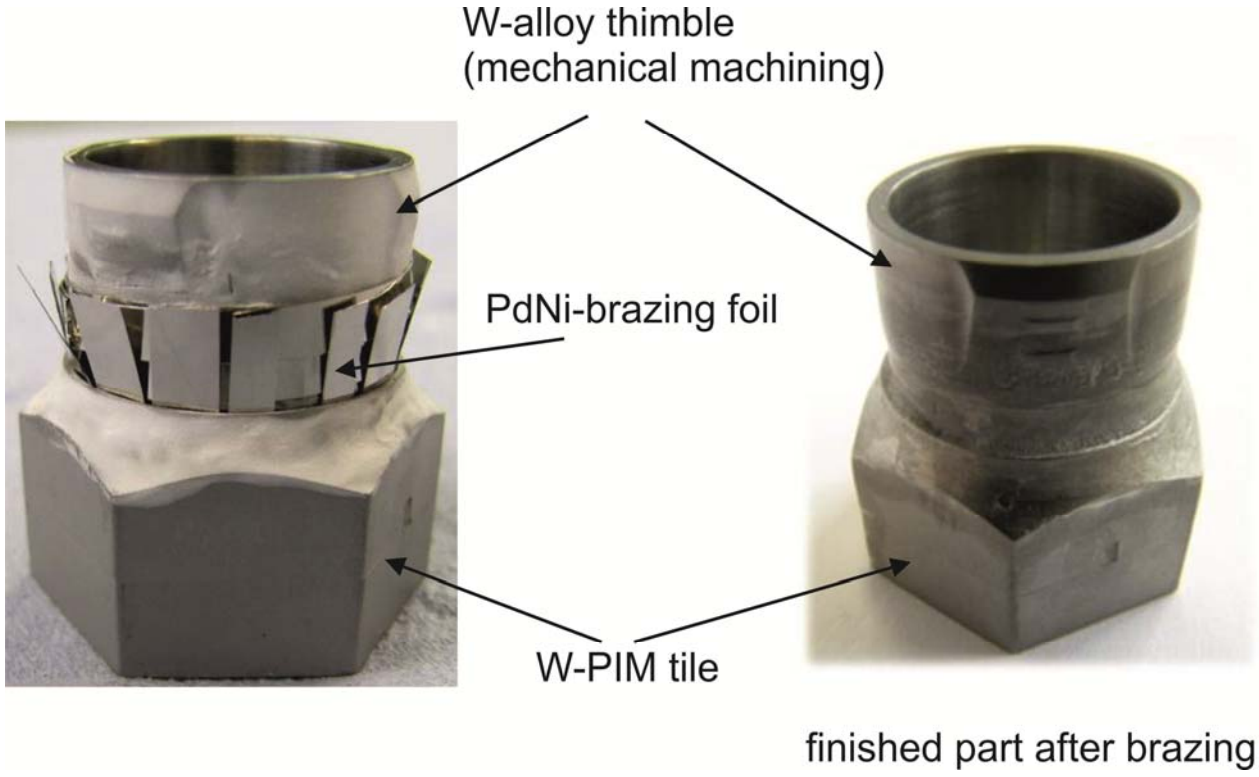


S. Antusch et al., Fusion Engineering and Design, 86 (2011) 1575-1578.

The PIM process for tungsten developed at KIT …joining…

→ Fabrication of the W PIM tile successful

→ Joining via brazing of W PIM tile and W-alloy thimble (produced by mechanical machining)



→ **Mass production process?**

Courtesy of L. Spatafora (Bachelor Thesis 2010)

- Motivation
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- Producing of 2-Component W PIM divertor parts
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Material development for PIM

⇒ Material produced by mechanical alloying

(2 h, n-Hexane, ZrO_2 balls + bowl)

⇒ **W-2La_2O_3**

⇒ **W-2Y_2O_3**

PIM parts (small discs) produced

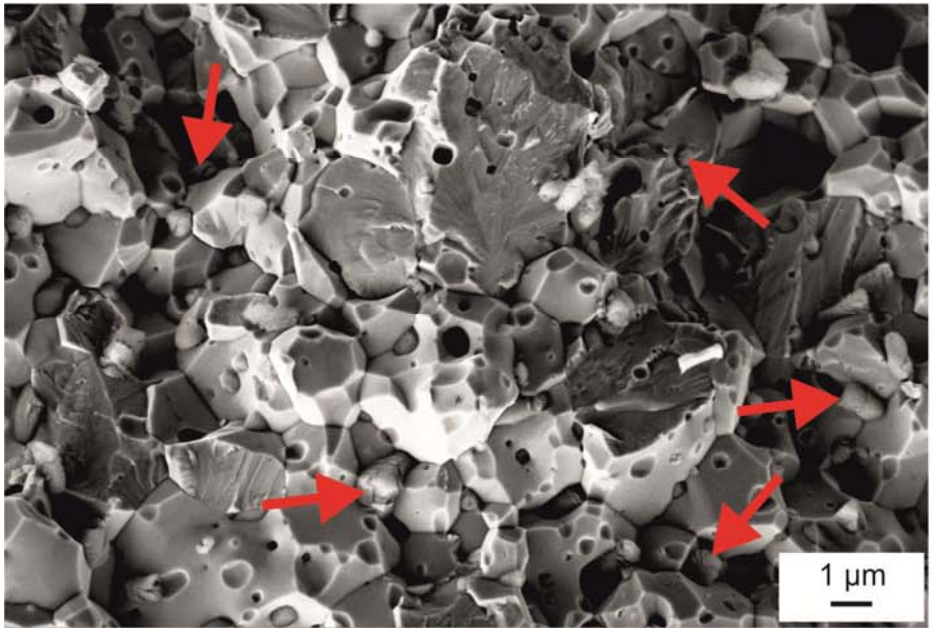
Heat-treatment:
- pre-sintering (1800 °C, 2 h, H_2) +
- HIP (2100 °C, 3 h, Ar, 250 MPa)

Mill and equipment

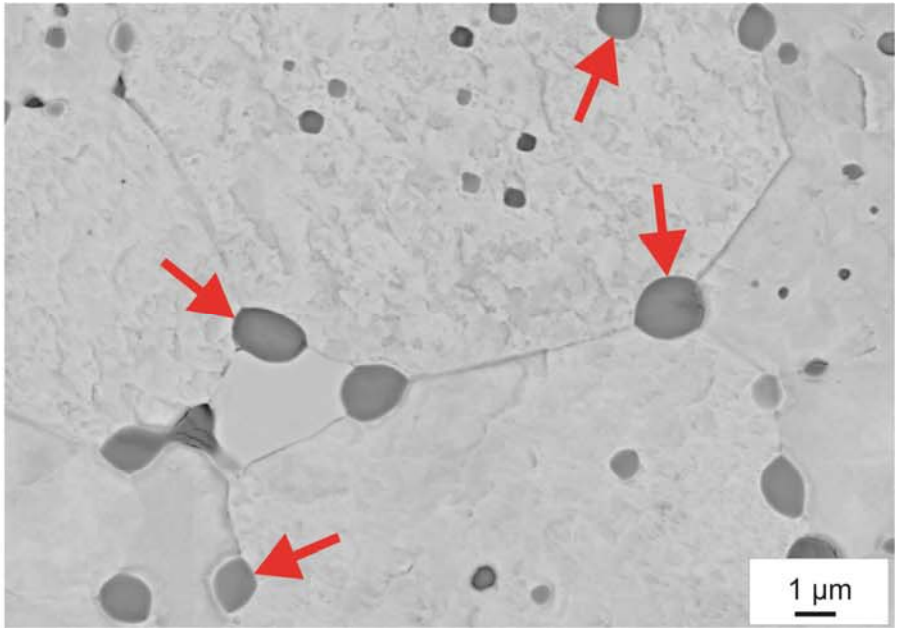
Material	Theoretical density (% TD)	Vickers-hardness (HV0.1)	Grain size (µm)
W	98.6 - 99.0	457	5 - 7
W-2La_2O_3	96.5 - 97.2	586	>3
W-2Y_2O_3	96.3 - 97.1	617	<3

Material development for PIM

$\Rightarrow$ **W-2La_2O_3**



SEM Microstructure (fracture surface)

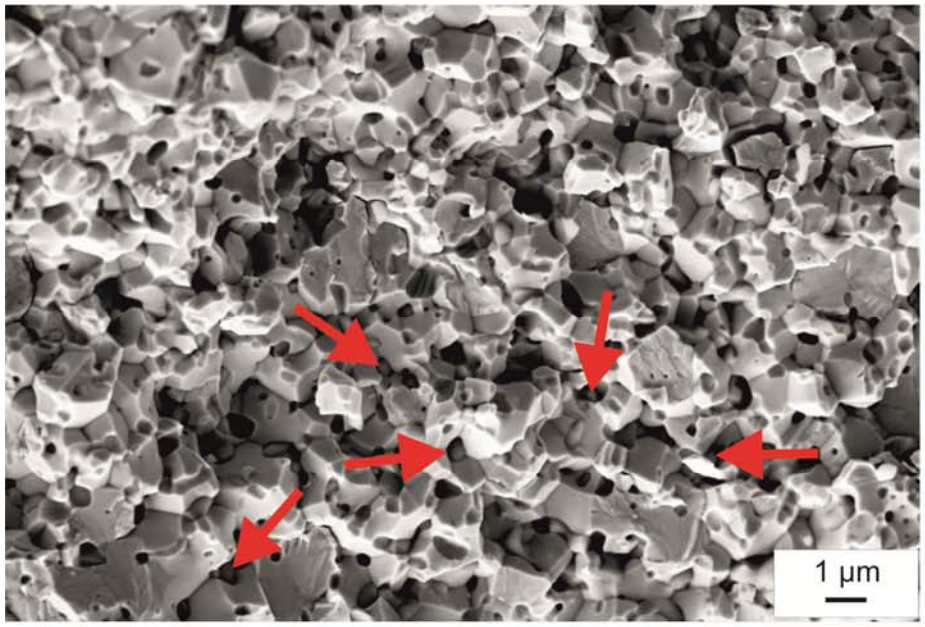


SEM Microstructure (metallographic section)

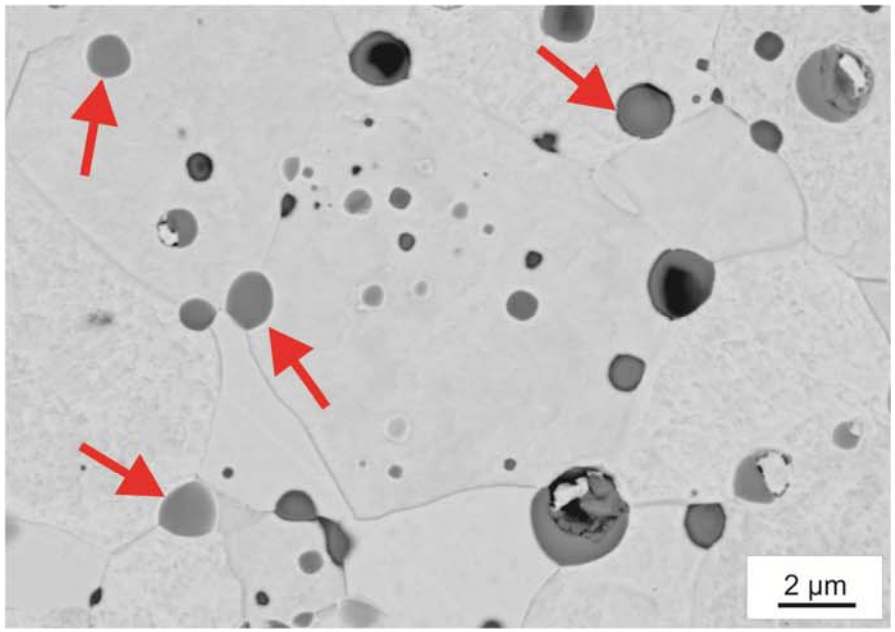
A selection of La_2O_3-particles is marked by arrows...

Material development for PIM

$\Rightarrow$ **W-2Y_2O_3**



SEM Microstructure (fracture surface)



SEM Microstructure (metallographic section)

A selection of Y_2O_3-particles is marked by arrows...

- Motivation
- What is PIM?
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- **Producing of 2-Component W PIM divertor parts**
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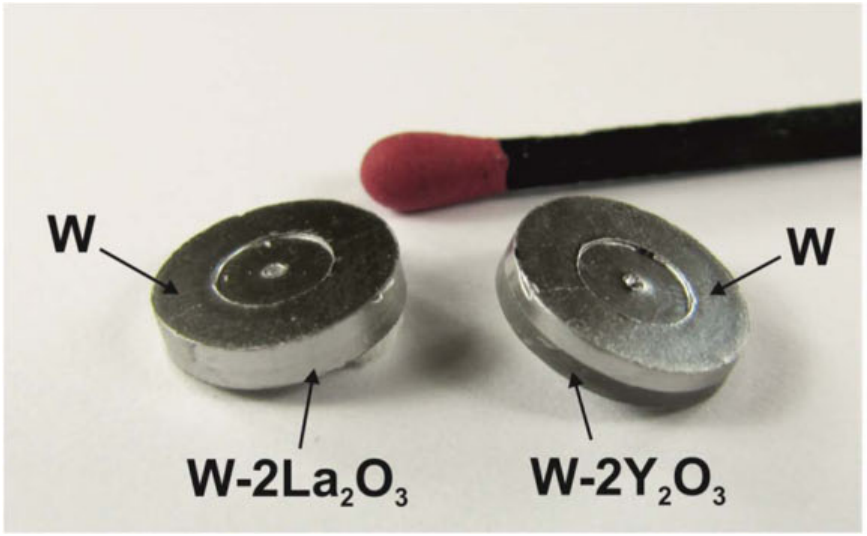
Producing of 2-Component W PIM divertor parts

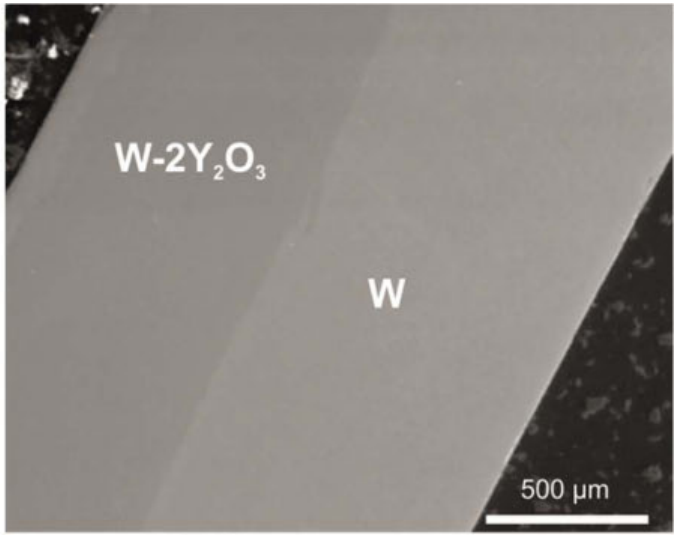
Pretests via insert 2-Component PIM:

Material produced by mechanical alloying

Heat-treatment:
- pre-sintering (1800 °C, 2 h, H_2) +
- HIP (2100 °C, 3 h, Ar, 250 MPa)

⇒ **W + W-2La_2O_3 / W + W-2Y_2O_3** PIM samples produced + characterized





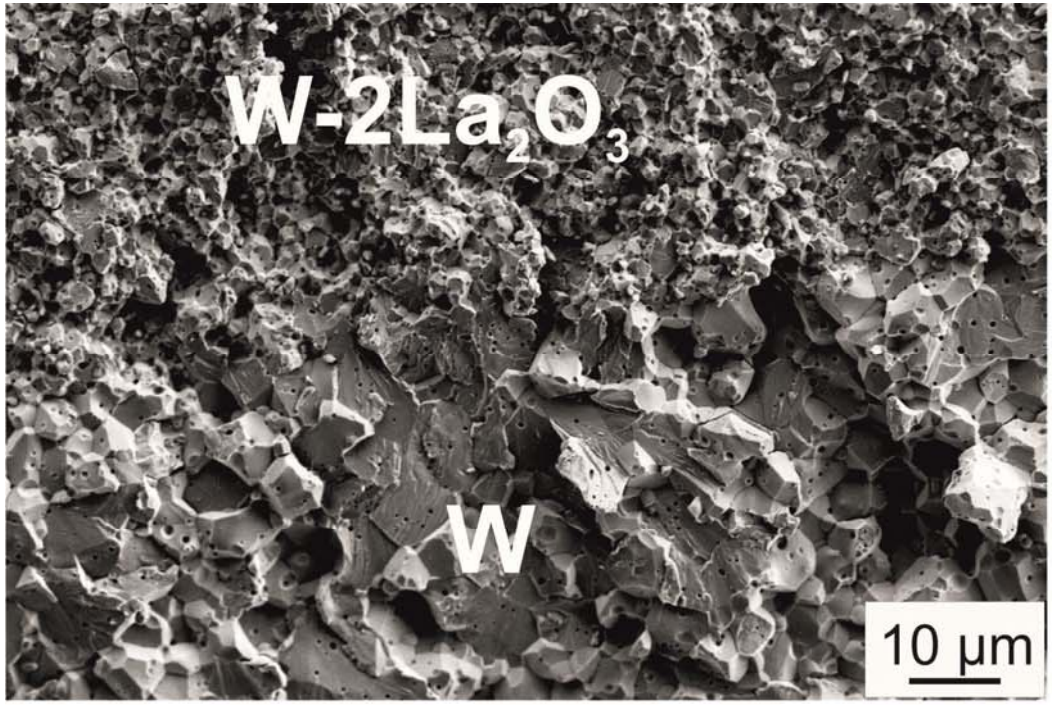
S. Antusch et al., Fusion Science and Technology (2012) submitted.

Producing of 2-Component W PIM divertor parts

Pretests via insert 2-Component PIM:

⇒ **W + W-2La$_2$O$_3$**

⇒ Joining seam: without cracks or gaps
⇒ Material connecting successful



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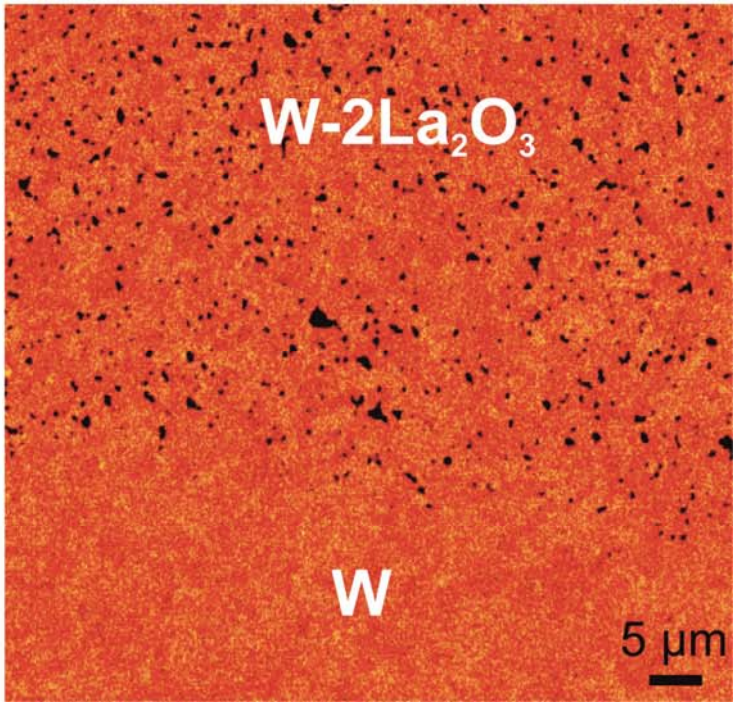


AES Map (metallographic section)

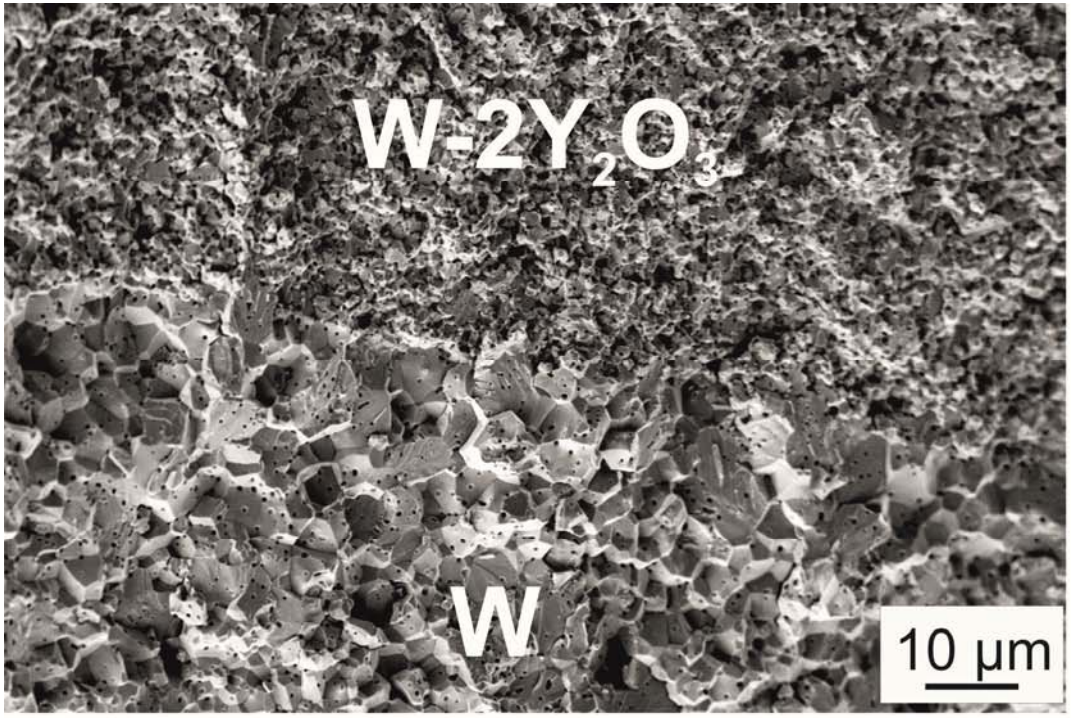
black: La$_2$O$_3$
red: W

Producing of 2-Component W PIM divertor parts

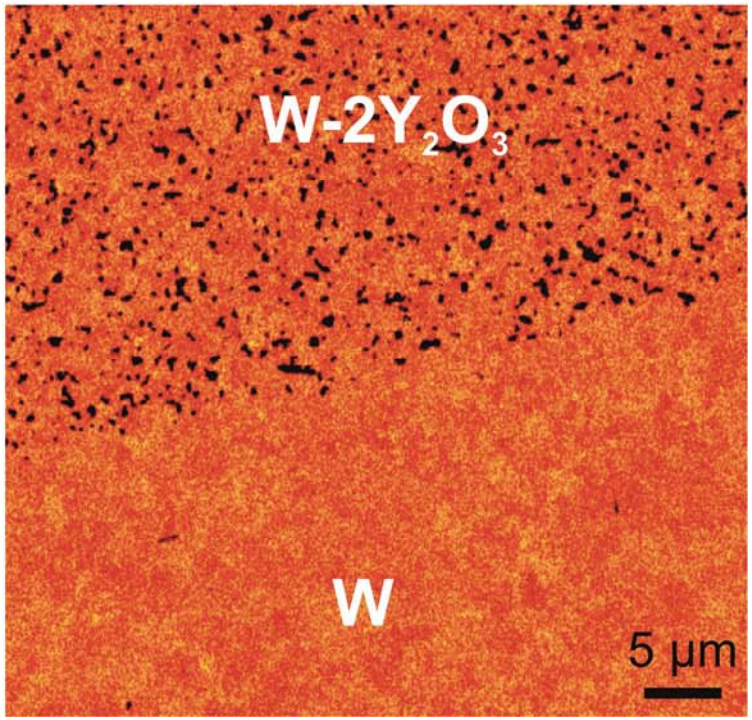
Pretests via insert 2-Component PIM:

⇒ **W + W-2Y_2O_3**

⇒ Joining seam: without cracks or gaps
⇒ Material connecting successful



SEM Microstructure (fracture surface)



AES Map (metallographic section)

black: Y_2O_3
red: W

Producing of 2-Component W PIM divertor parts

W PIM parts – material development – insert 2-C PIM pretests

Knowledge transfer –
from pretests to real 2-Component Powder Injection Molding process:
material combination, heat-treatment process, shrinkage, filling simulation…

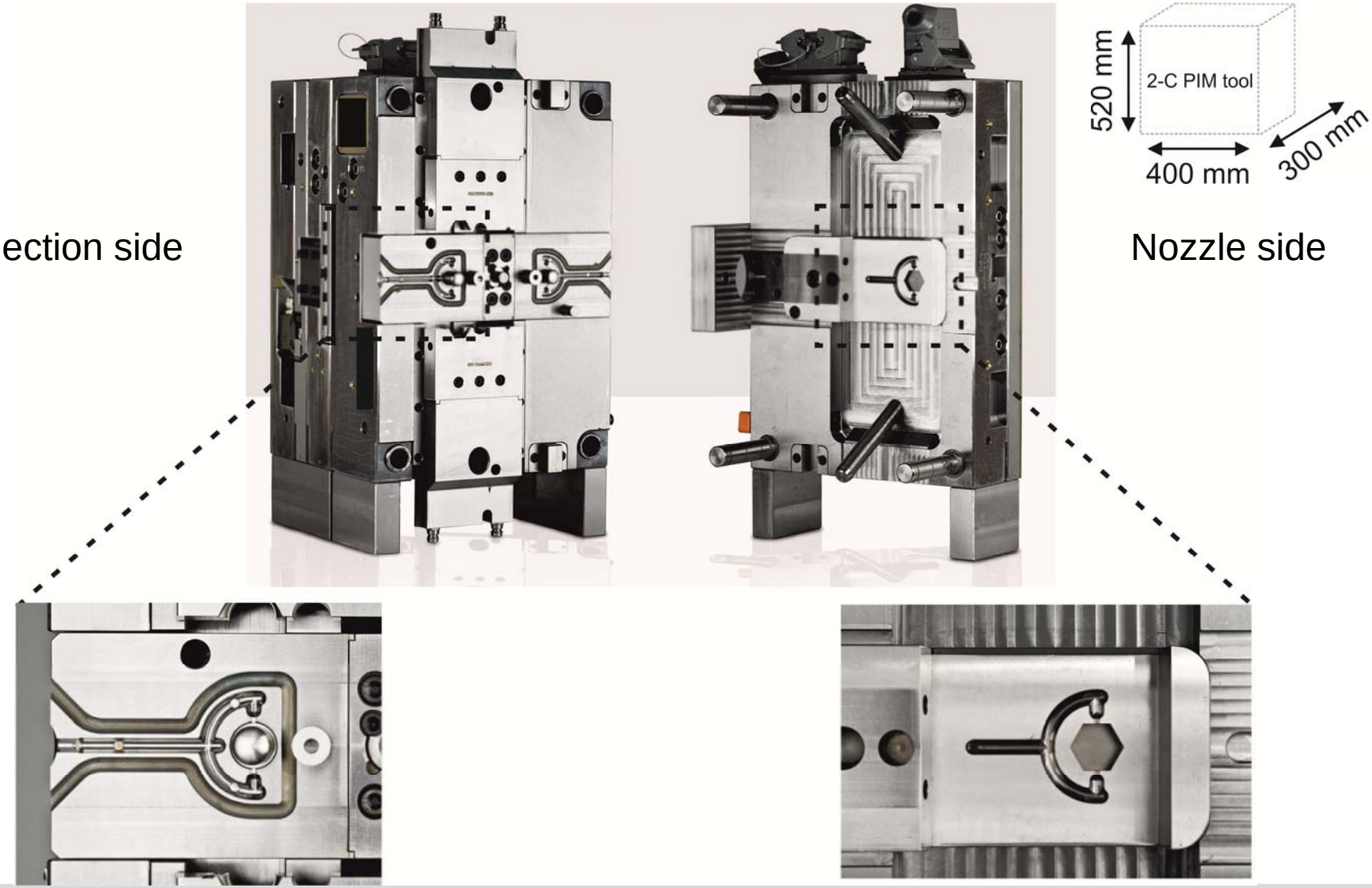
⇒ **Design and Engineering of a fully automatic 2-Component PIM tool**

Goals:

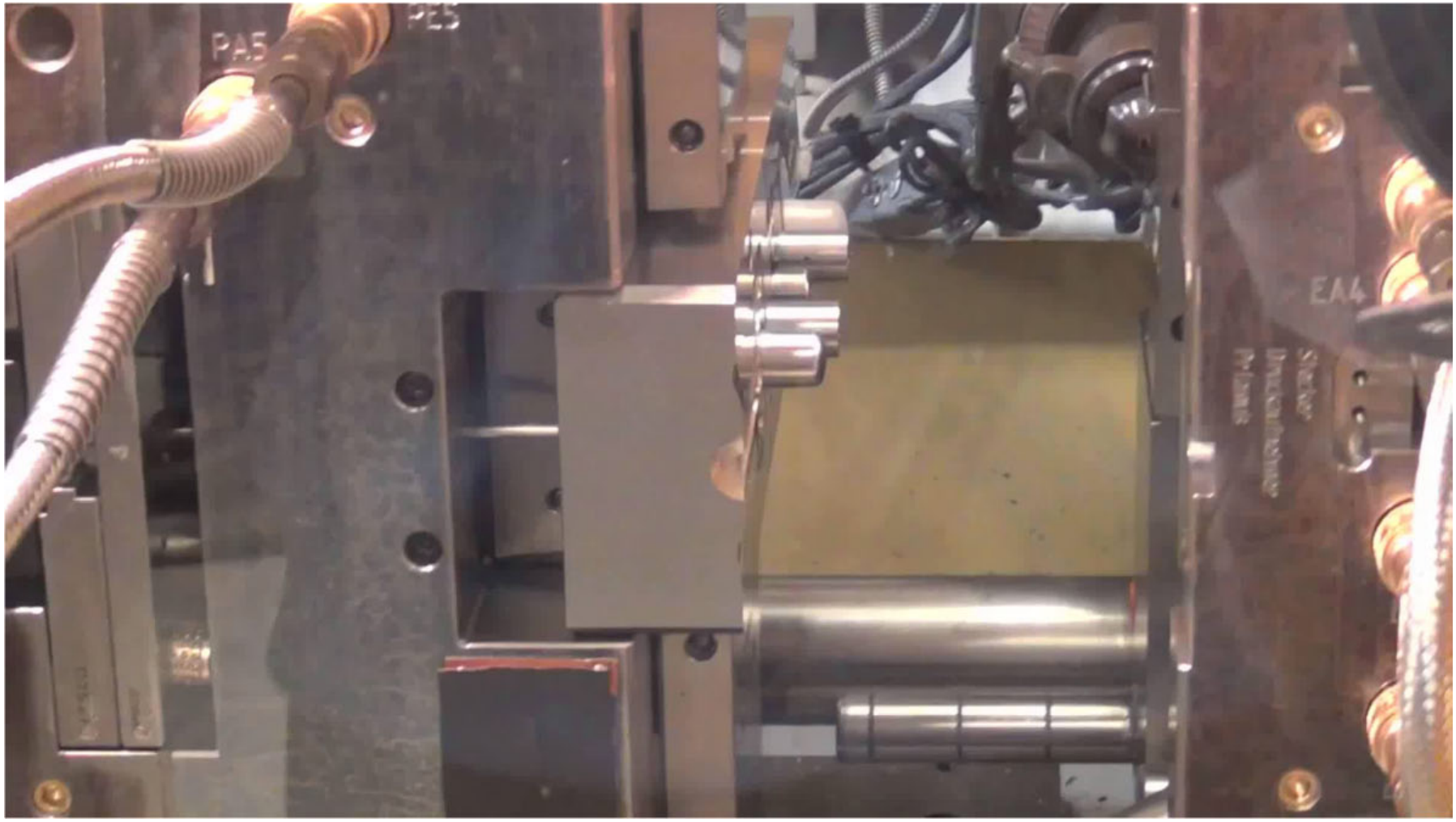
⇒ Tile and thimble in one unit with / without joining layer

⇒ Joining of 2 different materials without brazing in 1 process step

Producing of 2-Component W PIM divertor parts …The new fully automatic 2-C-W-PIM tool…



Producing of 2-Component W PIM divertor parts



Producing of 2-Component W PIM divertor parts …first samples…

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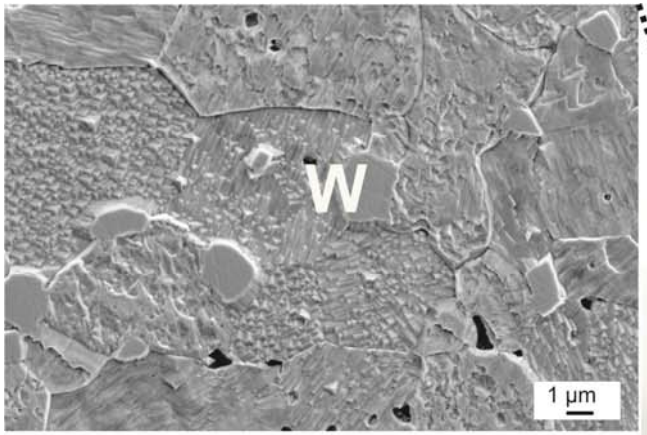
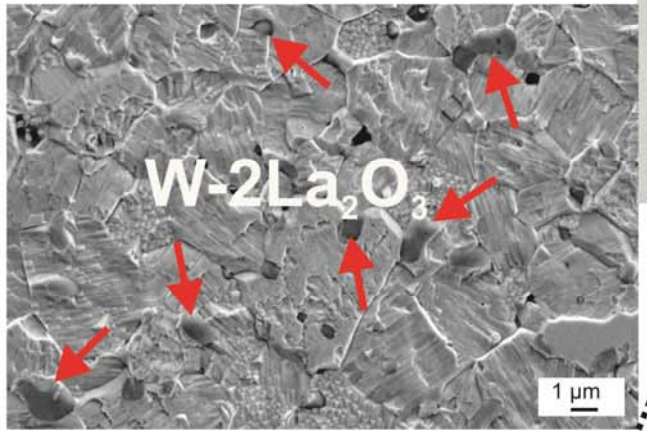
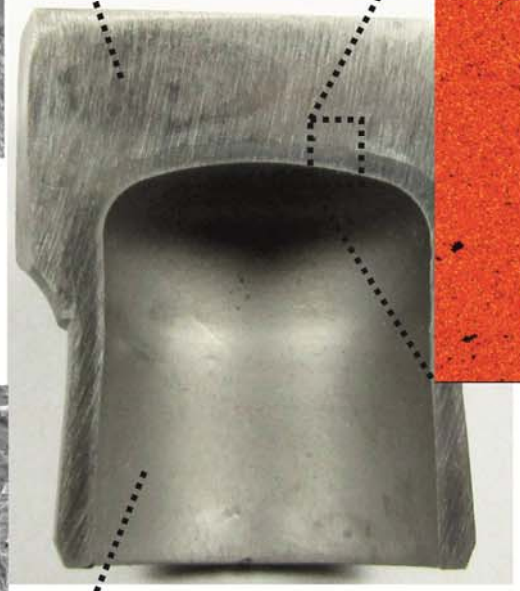
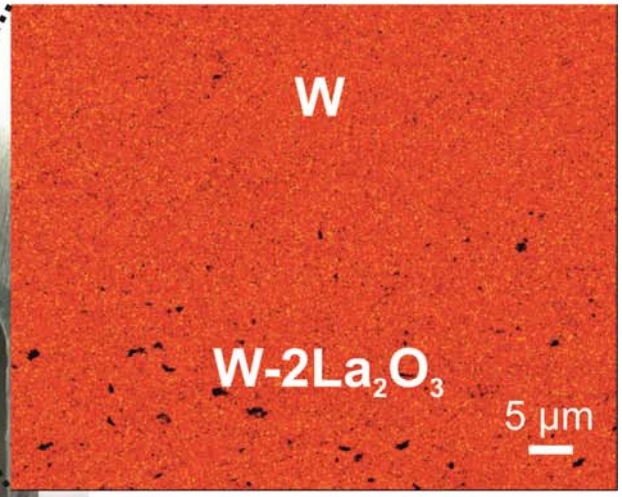






$W + W2La_2O_3$



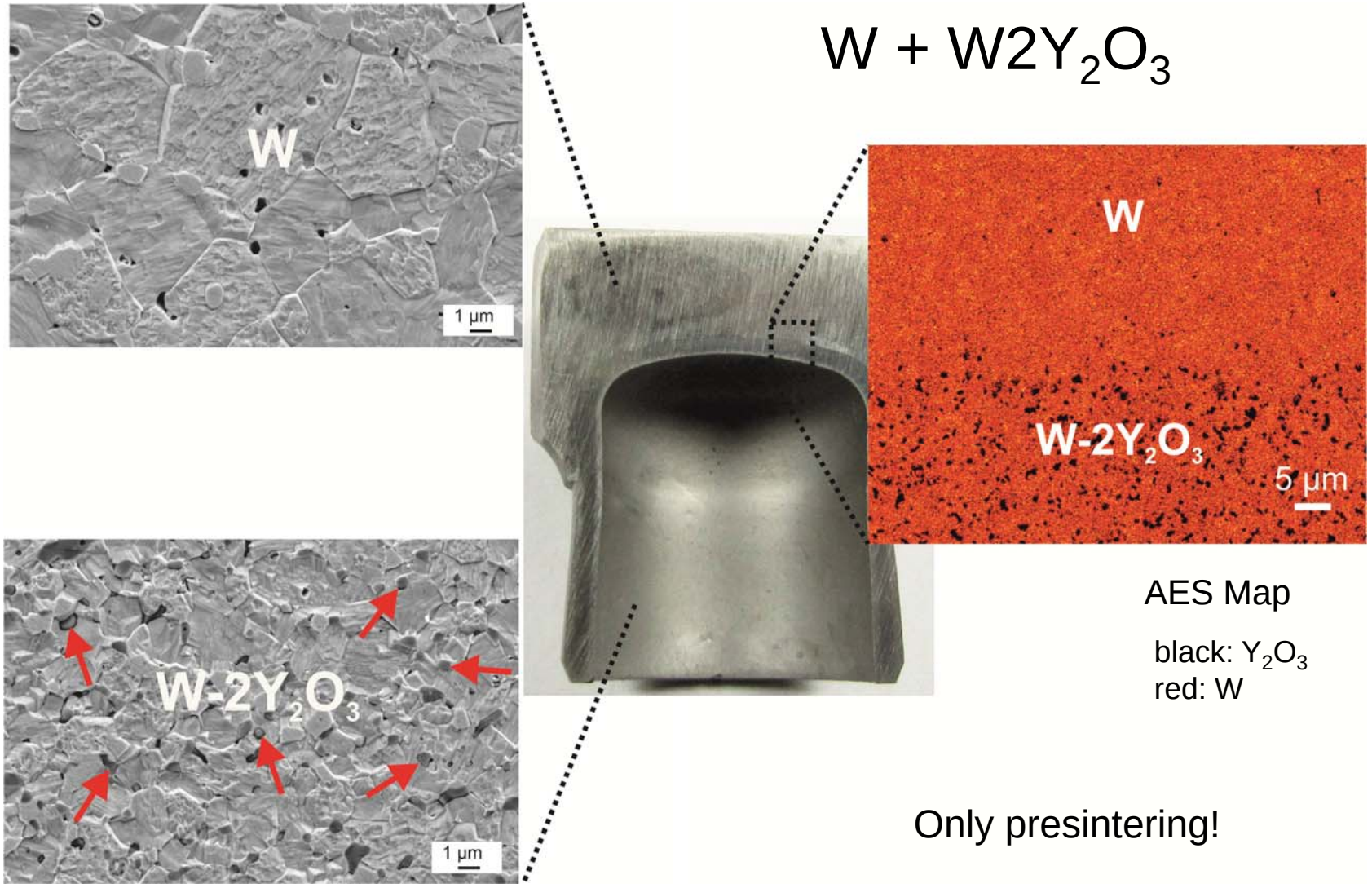
AES Map

black: La_2O_3
red: W

Only presintering!

S. Antusch et al., J. Nucl. Mater. (2012) submitted.

Producing of 2-Component W PIM divertor parts …first samples…



AES Map

black: Y_2O_3
red: W

Only presintering!

- Motivation
- What is PIM?
- The PIM process for tungsten developed at KIT
- Material development for PIM
- Producing of 2-Component W PIM divertor parts
- **Summary & Outlook**

Summary

- **Material & process development for W PIM at KIT**

  - Development of a suitable **W feedstock**: W1 + W2 (50:50) 50 vol.%

  - Optimization of the **heat-treatment process**: pre-sintering + HIP

  - Producing of W PIM parts
    → Properties of the finished **divertor part W tile**:
    → Density: 98.6 – 99 % T.D.
    → Vickers-hardness: 457 HV0.1
    → Microstructure without porosity or cracks

  - Development of **new W PIM materials**:
    → W-2La_2O_3
    → W-2Y_2O_3

  - Pretests via **insert 2-Component W PIM** / Investigation of the joining zone quality:
    → Joining seam: without cracks or gaps
    → Material connecting successful

  - Design & Engineering of a new **fully automatic 2-Component W PIM tool**:
    → **First 2-Component W PIM divertor parts successful produced!**

Summary

Powder Injection Molding:

→Mass production & joining process

→Time & cost effective near-net-shape forming process

→Shape complexity and high final density

→Create new materials / Investigation of properties

Outlook

Material development, e.g.:

- W-2Y_2O_3: mixing only
- W-2Y_2O_3: mixing + MA 24h
- W-2Y_2O_3: mixing + MA 48h
- …other possible material combinations…

Material characterization:

- Charpy tests (KIT)
- Tensile tests (KIT)
- High Heat Flux Tests (IPP Garching, FZ Jülich)

Producing of PIM plates:

W-PIM plate (55 x 22 x 4 mm)

- **Options of scientific cooperation:**

→ 4 point bending tests
→ Structure analysis: FIB, SEM, EBSD

Thank you very much!