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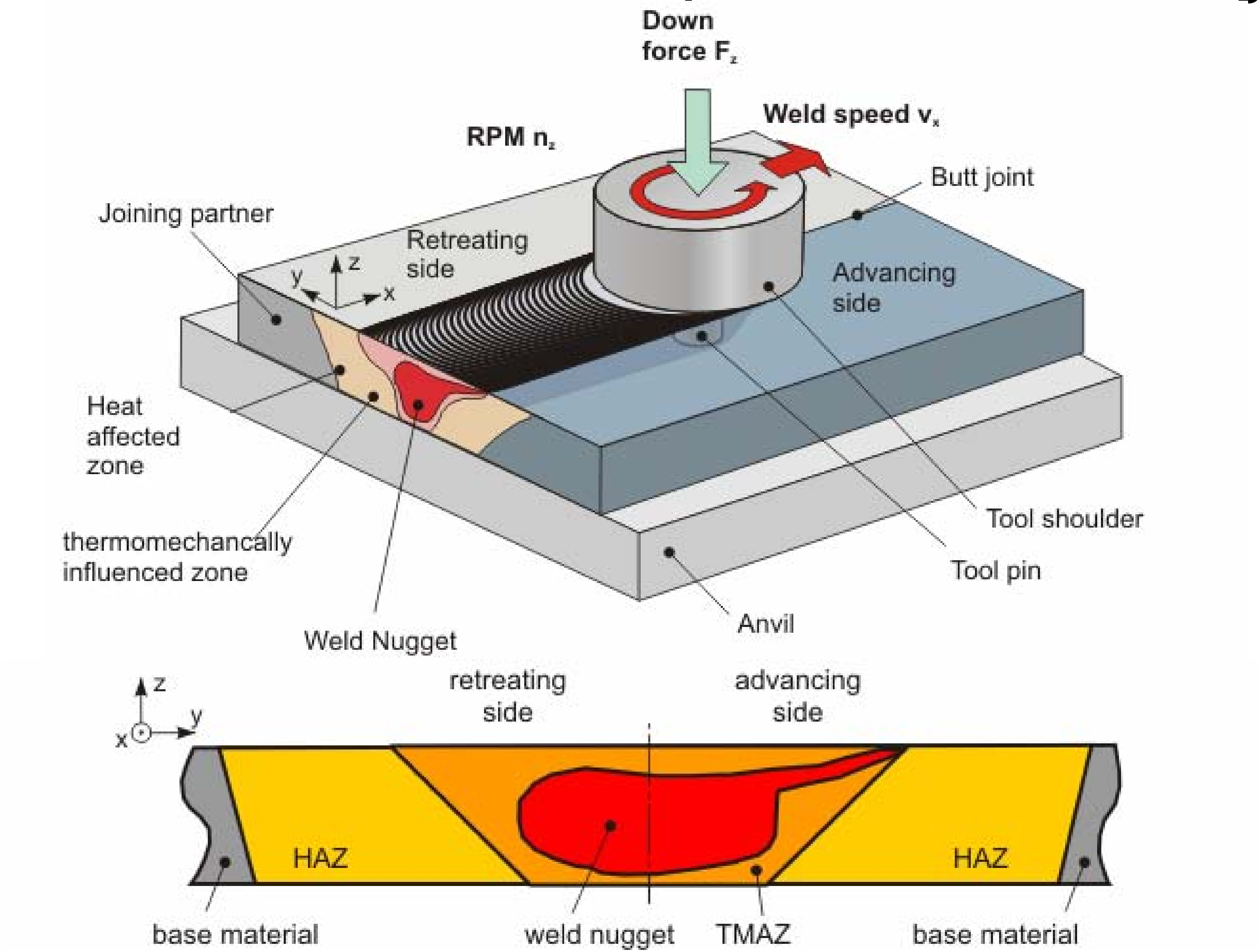
Advanced Modeling of Friction Stir Welding – Improved Material Model for Aluminum Alloys and Modeling of Different Materials with Different Properties by Using the Level Set Method

- Introduction to Friction Stir Welding
- Motivation and target of presented work
- Model setup
    - Metallic material modeling in CFD – empirical material model for Aluminum Alloys and it´s implementation
    - Introduction of the level set method to FSW-Modelling
- Results Modelling FSW
- Results Modelling Extrusion Process
- Conclusion

GRONBACH Process Principle - Friction Stir Welding



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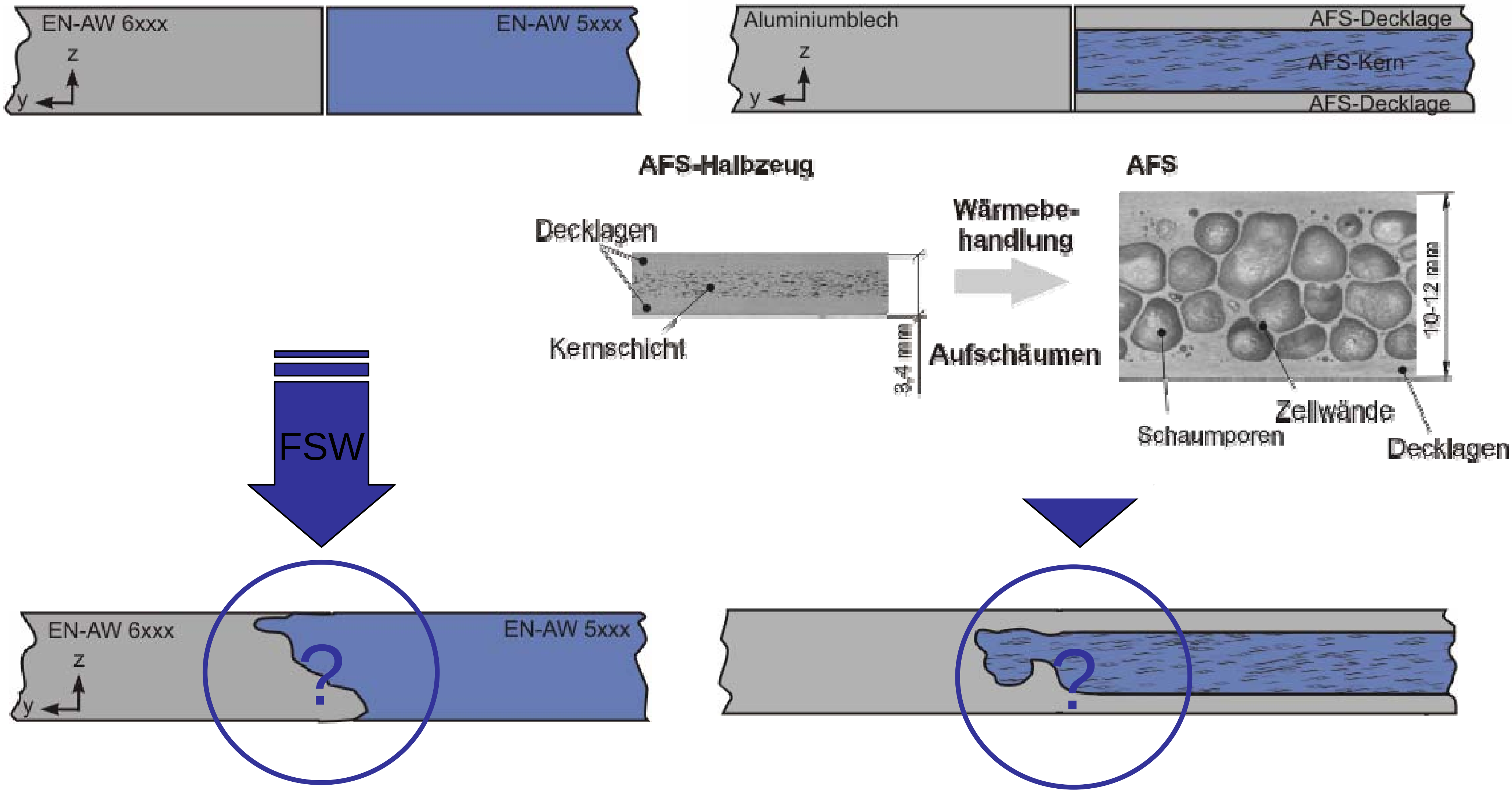
Motivation and target of this work



Modelling challanges

FSW properties:

- Very high plastic strains within the weld nugget
- Great variety of strain rates, strains and temperature
- Ususally joining two different materials with different properties

Use of CFD – Model
Extension of the State of the Art by

- Adapted material model for Aluminium alloys (modelling temperature and strain rate dependency of yield stress)
- Using level-set method for integration of two different material models

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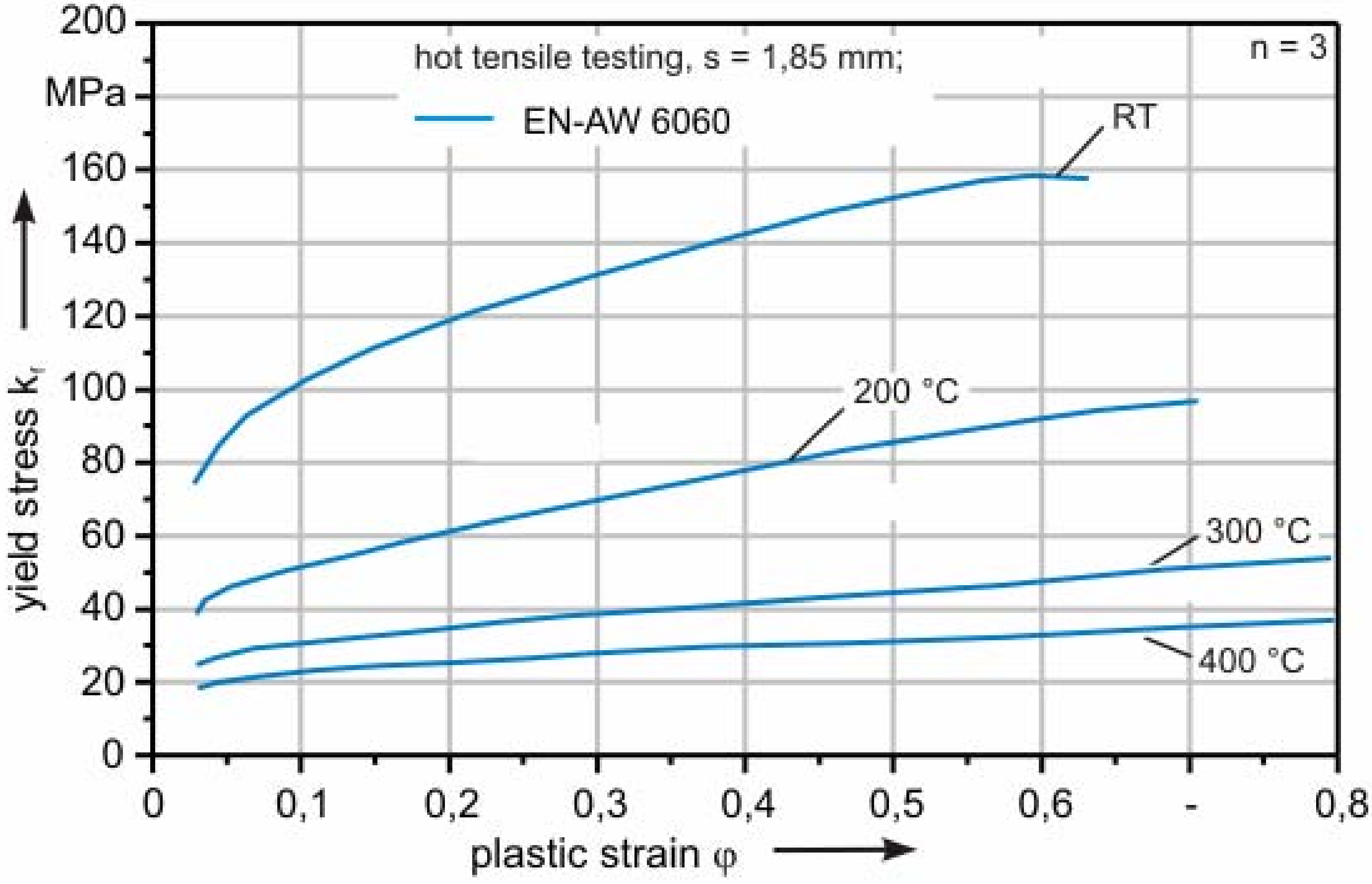
Yielding behavior of Aluminium alloys at high strains and elevated temperatures



[Akeret78]

Material model

To cope with specific behavior of aluminum alloys at elevated temperatures and high strains, a new, empirical material model is proposed:

Basic concept:

$$k_f(T) = a - b \cdot \ln(\dot{\varphi} + c)$$

Introducing temperature dependency of a, b and c:

$$a = a_a + b_a \cdot T + c_a \cdot T^2$$

$$b = a_b \cdot (T - b_b)$$

$$c = a_c + b_c \cdot T + c_c \cdot T^2$$

Results in empirical material model [Doerfler08]:

$$k_f(\dot{\varphi}, T) = \underbrace{a_a + b_a \cdot T + c_a \cdot T^2}_{a} - \underbrace{a_b \cdot (T - b_b)}_{b} \cdot \ln(\dot{\varphi} + \underbrace{a_c + b_c \cdot T + c_c \cdot T^2}_{c})$$

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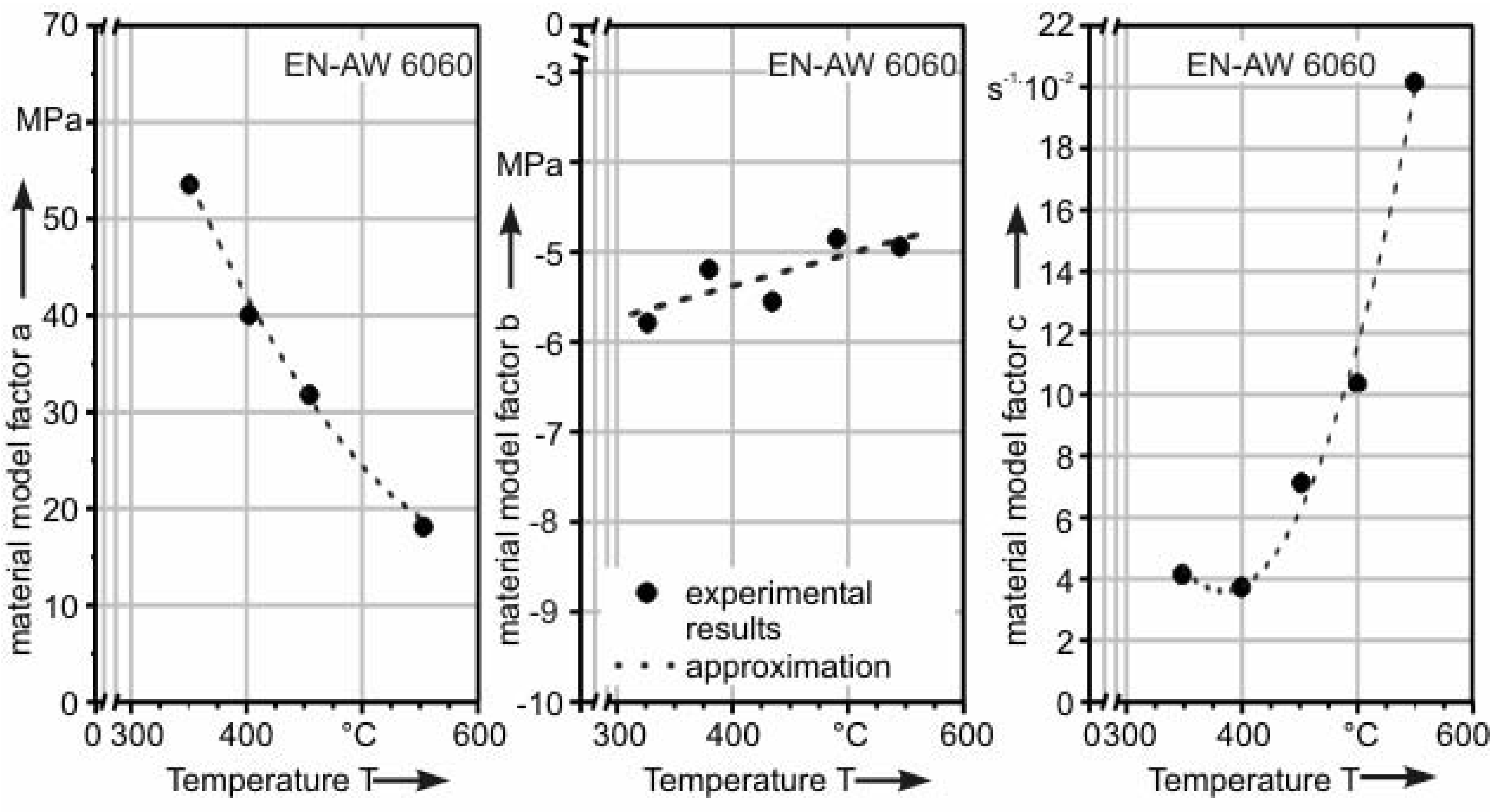
Model factors for different alloys



Model factor	Unit	EN-AW 3103	EN-AW 6060
aa	MPa	624,16	401,53
ba	MPa K^{-1}	-1,4096	-0,8465
ca	MPa K^{-2}	8,20E-04	4,60E-04
ab	MPa K^{-1}	0,02872	3,97E-03
bb	K	958,3	2041,3
ac	s^{-1}	0,084	2,62
bc	s^{-1} K^{-1}	-6,02E-05	-7,86E-03
cc	s^{-1} K^{-2}	1,44E-07	5,97E-06

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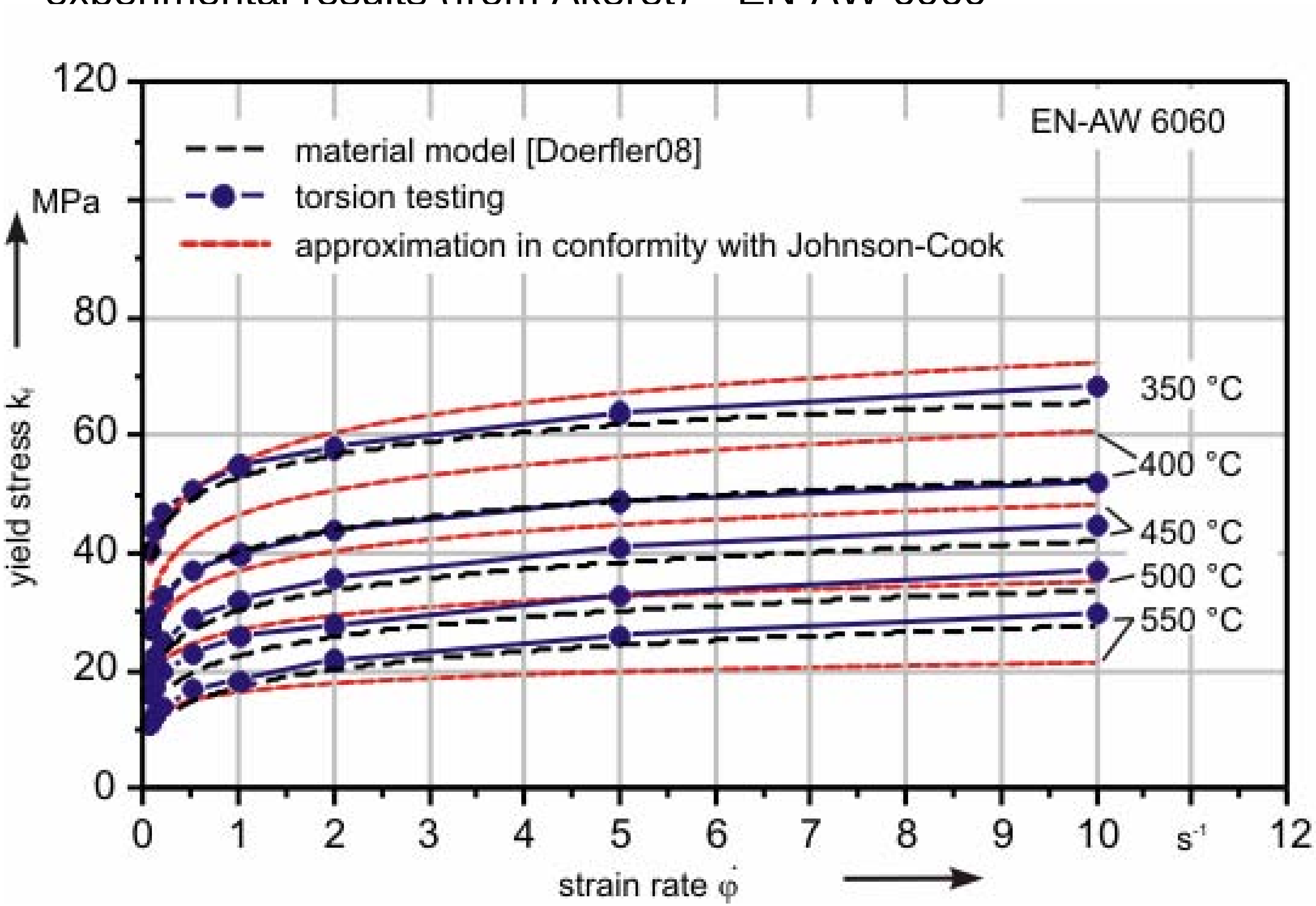
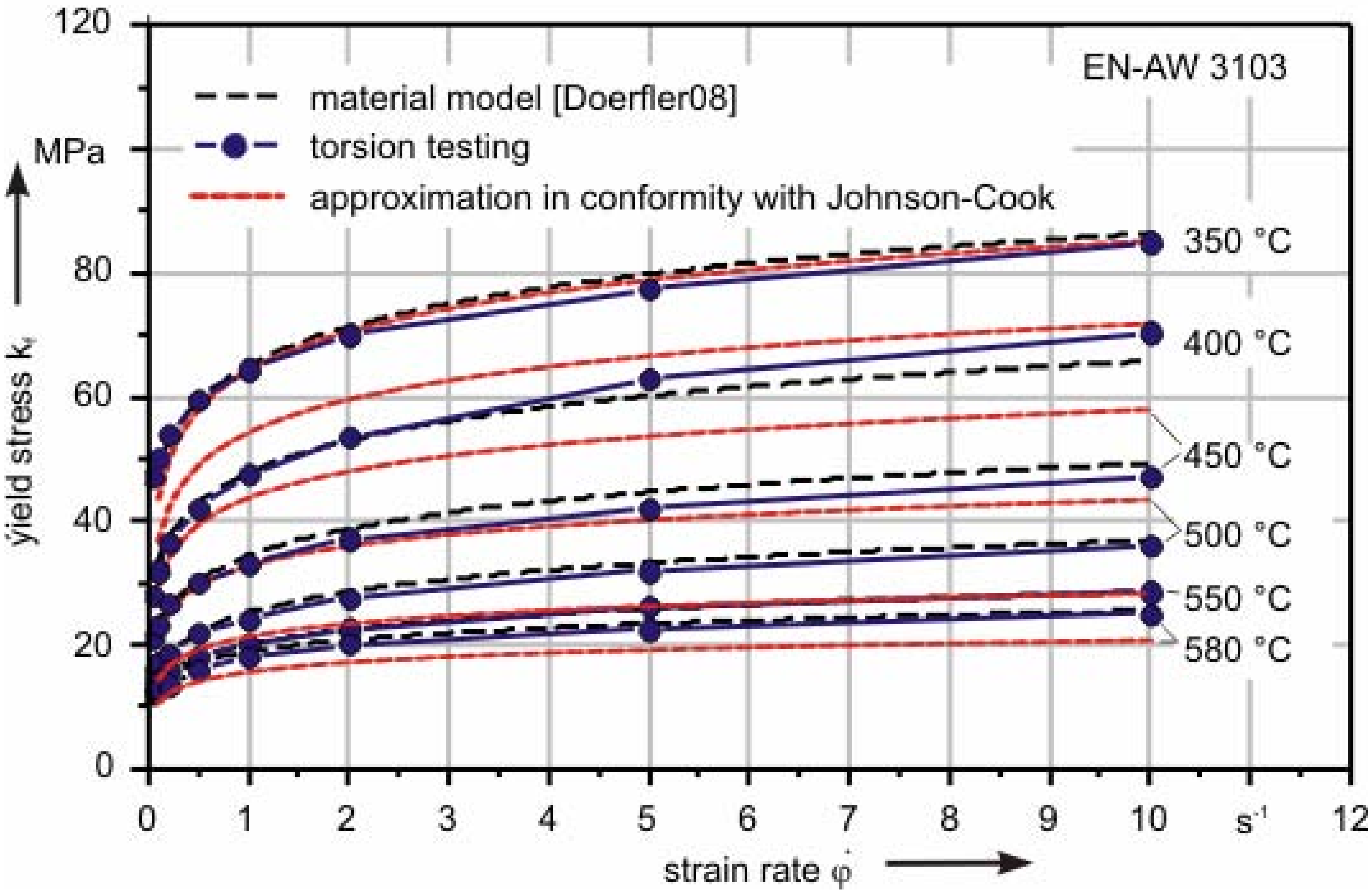
Material model quality I

Material model in comparison to Johnson-Cook (best fit) and experimental results (from Akeret) – EN-AW 6060



Material model quality II

Material model (Doerfler) in comparison to Johnson-Cook (best fit) and experimental results (from Akeret) – EN-AW 3103



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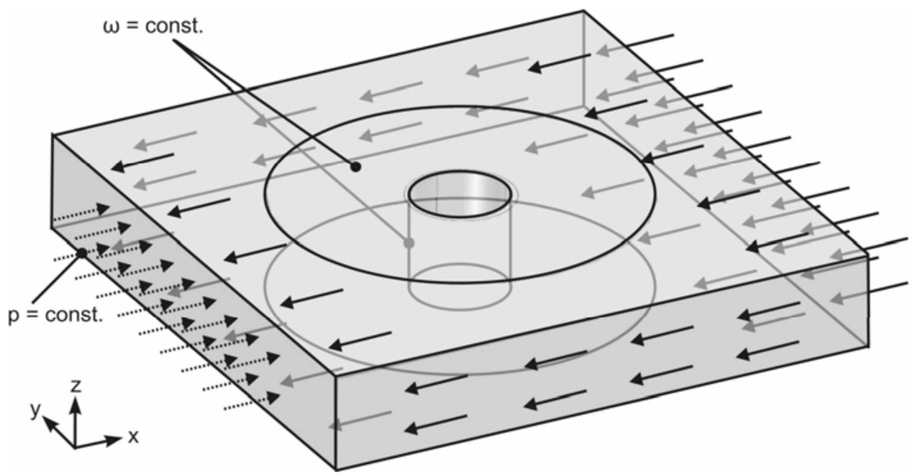
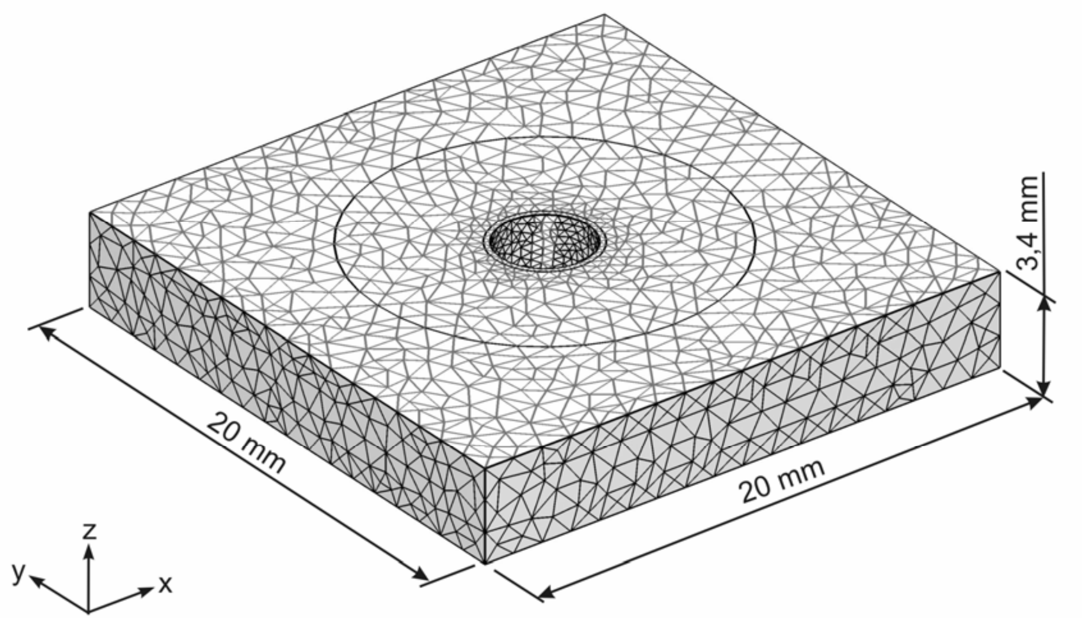
Model concept





- CFD-Model (non-newtonian fluid dynamics mode from Comsol Chemical Engineering Module)
- Material flow through model domain
- Thermal boundary conditions in conformity to experimental measurements (tool and material boundaries)
- Constant material speed at inlet
- No slip condition at tool pin

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Material model implementation in momentum equations

Bingham-Fluid

$$\begin{cases} \bar{\tau} < \tau_0 : \dot{\bar{\gamma}} = 0 \\ \bar{\tau} \geq \tau_0 : \bar{\tau} = (\frac{\tau_0}{\dot{\gamma}} + \eta) \cdot \dot{\bar{\gamma}} \end{cases}$$

-> you`d need to know, where yield stress is reached and where not

$$\bar{\tau} = (\frac{\tau_0 (1 - e^{-m\dot{\gamma}})}{\dot{\gamma}} + \eta) \cdot \dot{\bar{\gamma}}$$

Solution from Papanastasiou for above problem (approximation)

$$\bar{\tau} = (\frac{\tau_{kf}(\dot{\gamma}, T)(1 - e^{-m\dot{\gamma}})}{\dot{\gamma}}) \cdot \dot{\bar{\gamma}}$$

Modification for strain rate and temperature sensitive materials that won´t converge

$$\bar{\tau} = (\frac{\tau_{kf}(\dot{\gamma}, T)^m}{(\dot{\gamma} + h)^m}) \cdot \dot{\bar{\gamma}}$$

Own, converging approach using the convergence parameter m together with a small constant h

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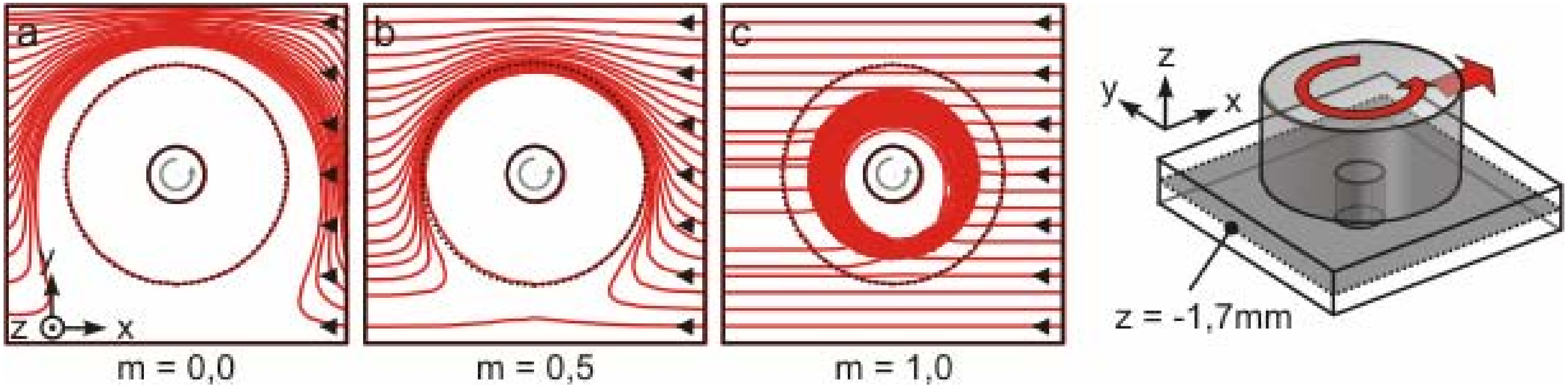
Material model implementation in momentum equations

$$\bar{\tau} = \begin{cases} \dot{\gamma} > 0 : (\dfrac{\tau_{kf}(\dot{\gamma},T)^m}{(\dot{\gamma}+h)^m}) \approx (\dfrac{\tau_{kf}(\dot{\gamma},T)^m}{(\dot{\gamma})^m}) \\ \dot{\gamma} = 0 : (\dfrac{\tau_{kf}(0,T)^m}{(h)^m}) \end{cases}$$

h is used to prevent instability due to shear rates near or equal zero (h<<1)

m is increased from 0 to 1 using the parametric solver to determine plastisiced and solid areas within the domain



Newtonian fluid s.th. in between yielding material

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Introduction of level set approach to FSW-model

- Introduction of convection and diffusion equations to the model (level-set-method)
- Sign of virtual concentration c‘ determines, where which material is

Implementation:

$$k_f = k_f(T, \dot{\varphi}, sign(c'))$$

$$k_f = k_{f1} + \frac{1}{2}(1 + sign(c')) \cdot (k_{f2} - k_{f1})$$

Convergence is reached by using smoothing function and another convergence factor:

$$k_f = \left[\frac{\frac{1}{2}(1 + sign(c'))(k_{fKern} - k_{fAl}) + k_{fAl}}{k_{fAl}} \right]^{m_c} \cdot k_{fAl}$$

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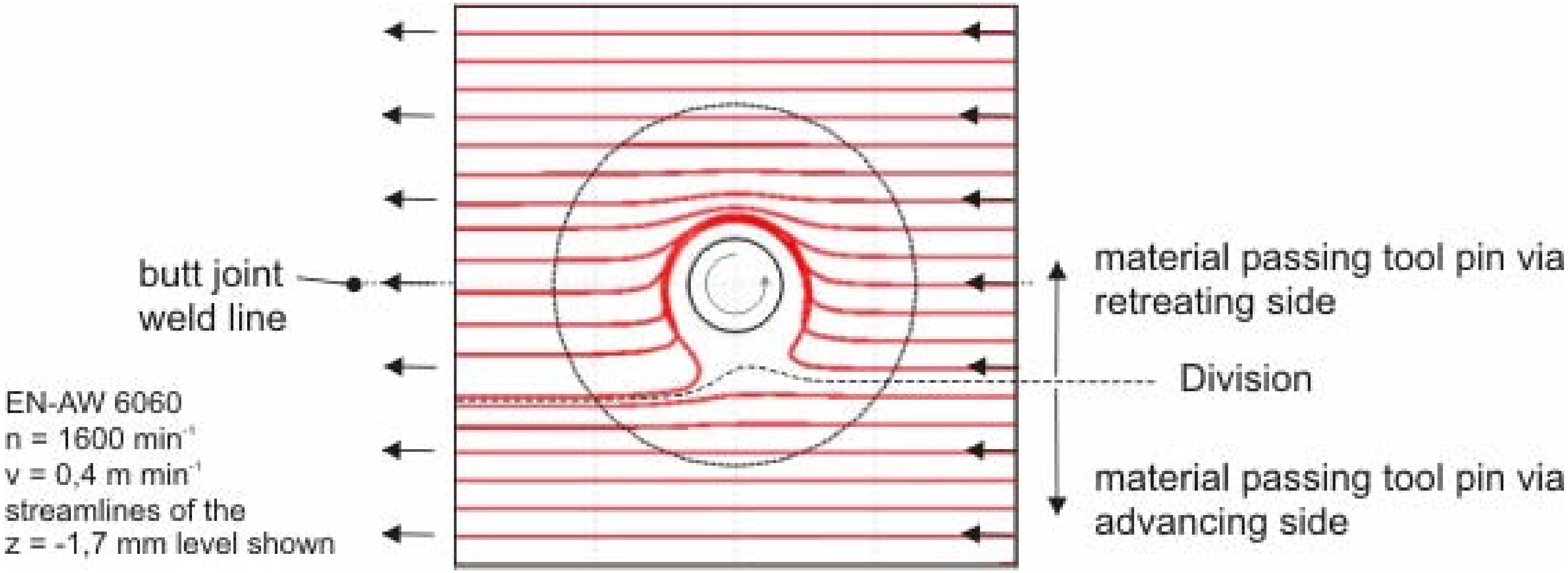
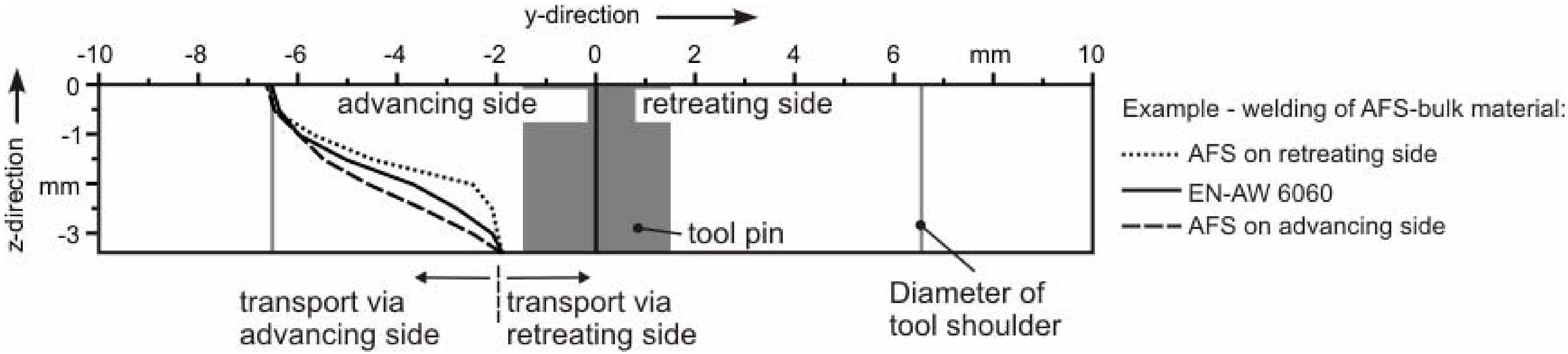
Results: Determination of the material division on retr. and adv. side





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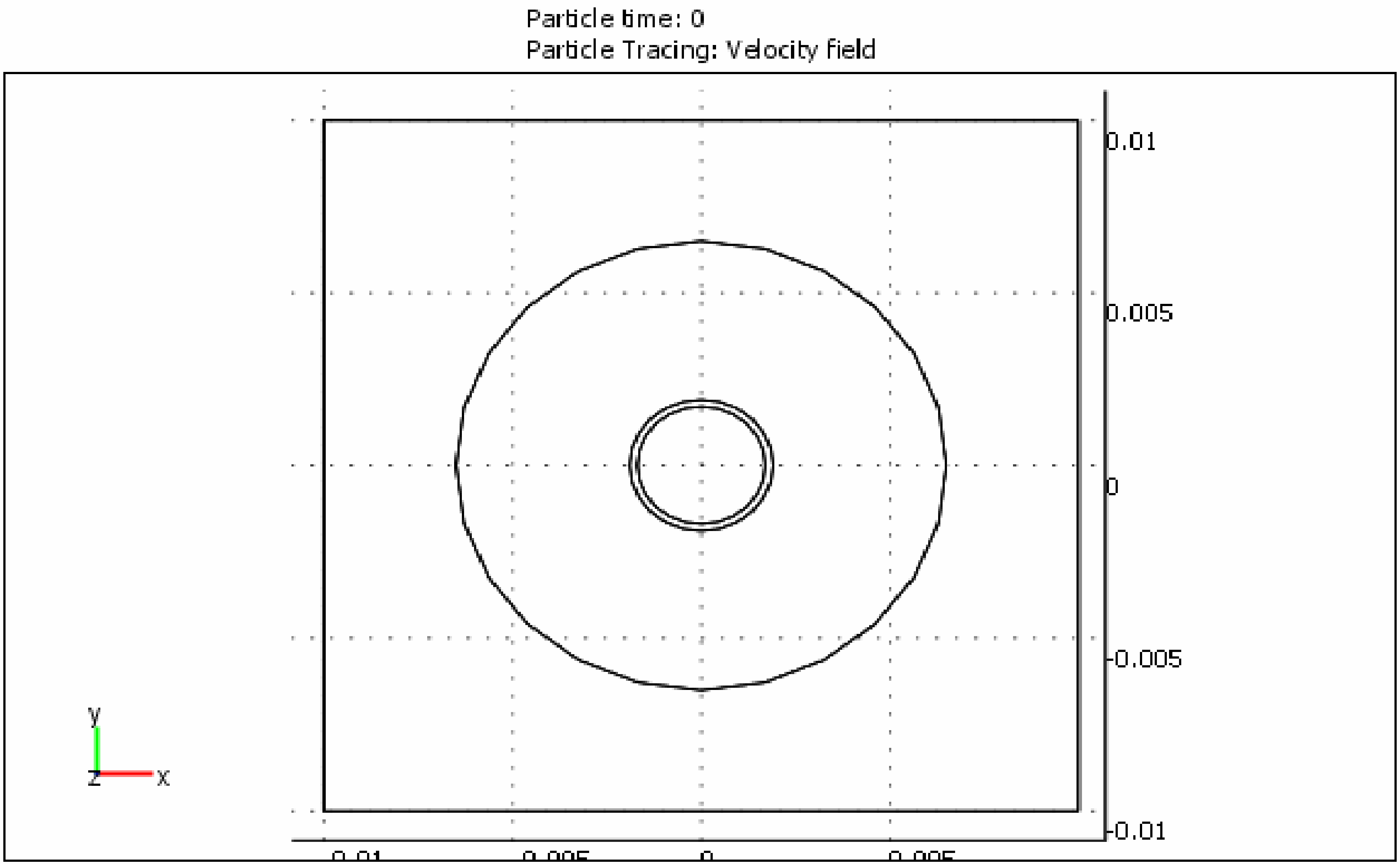
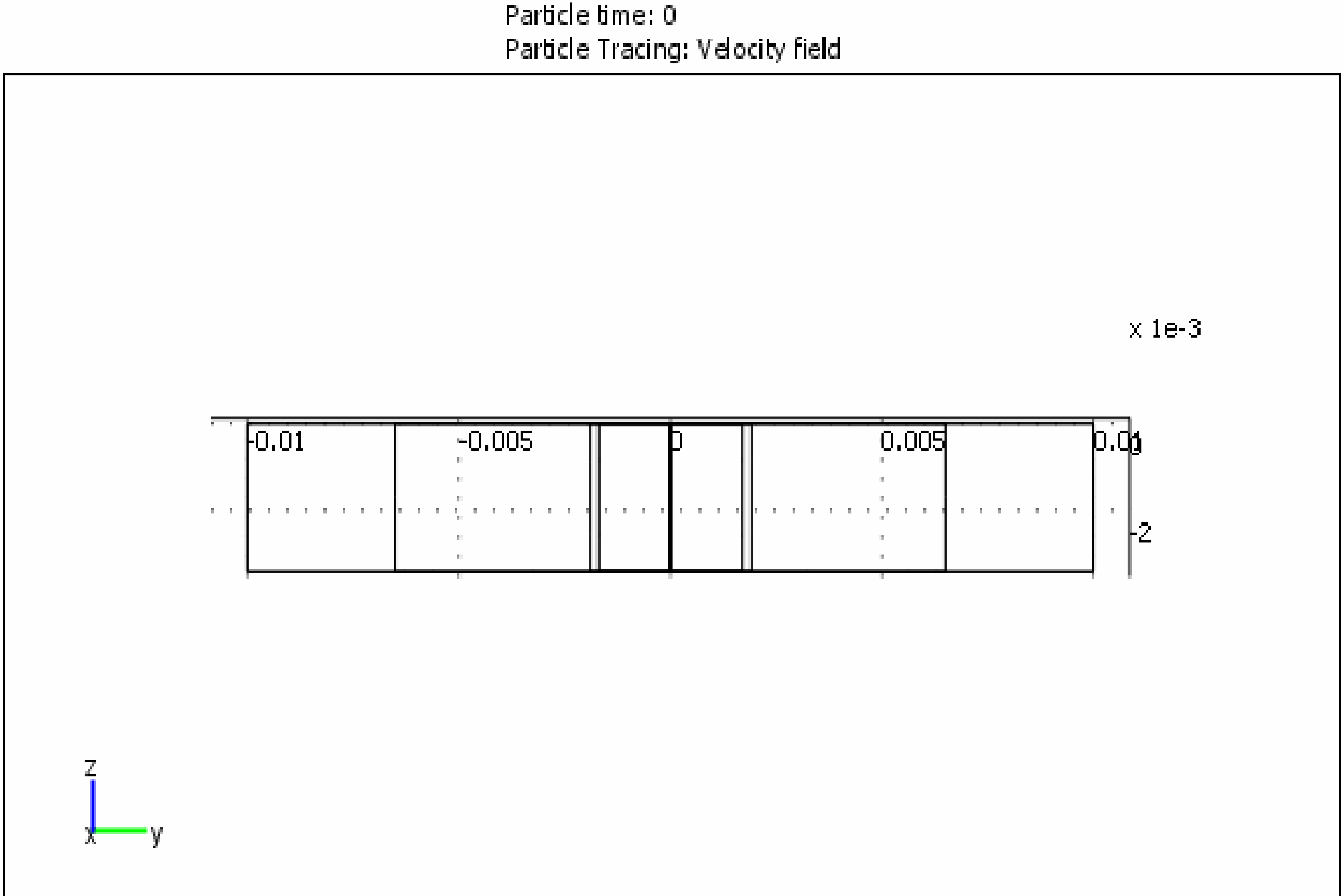
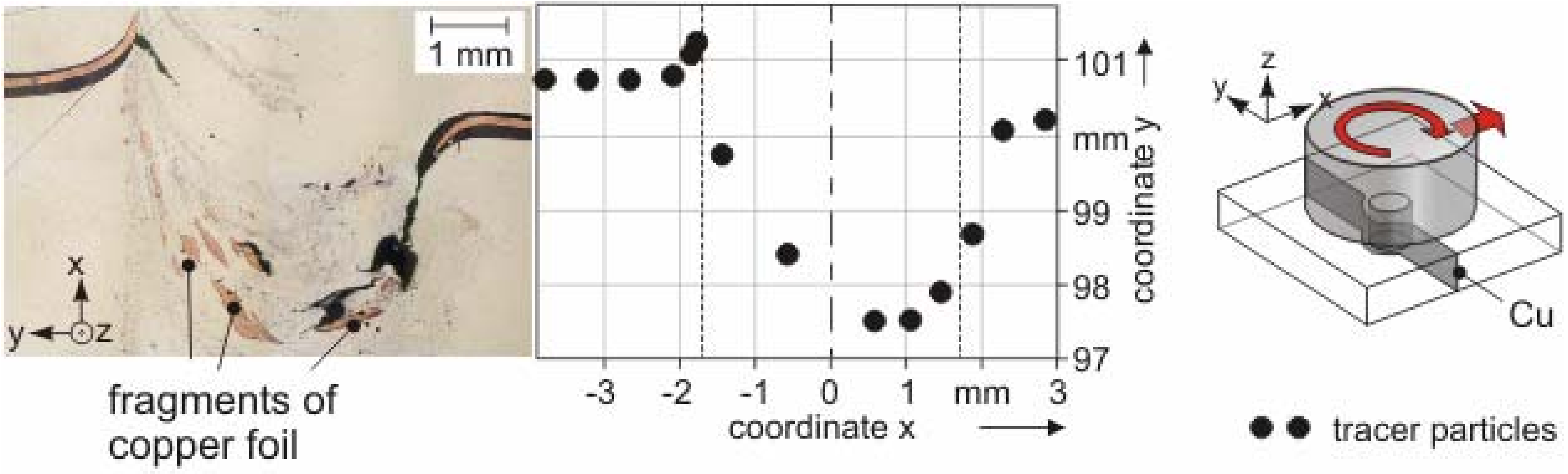
Results: Particle tracing



Results: Particle tracing II



Verification experiment - simulation



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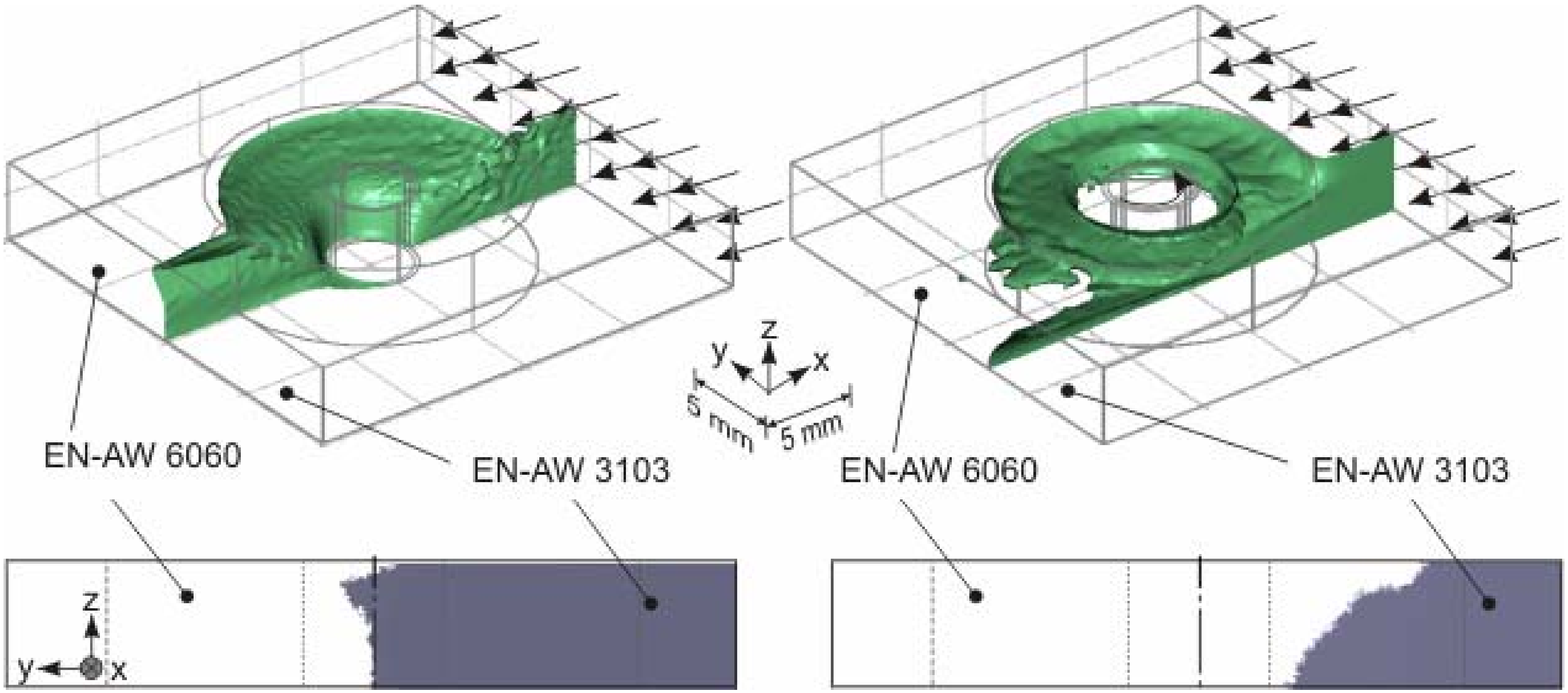
Resulting material distribution of two different alloys due to welding process



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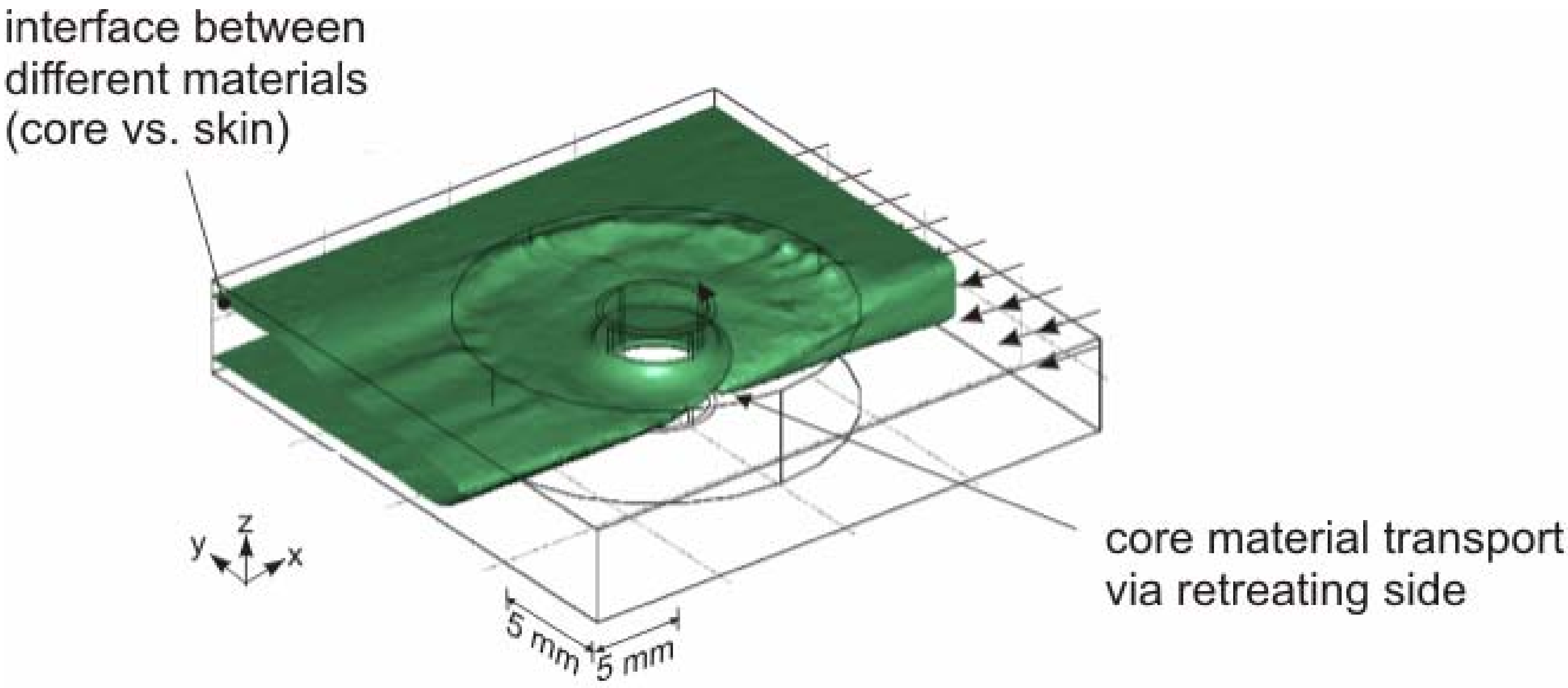
Material distribution for special aluminum material AFS



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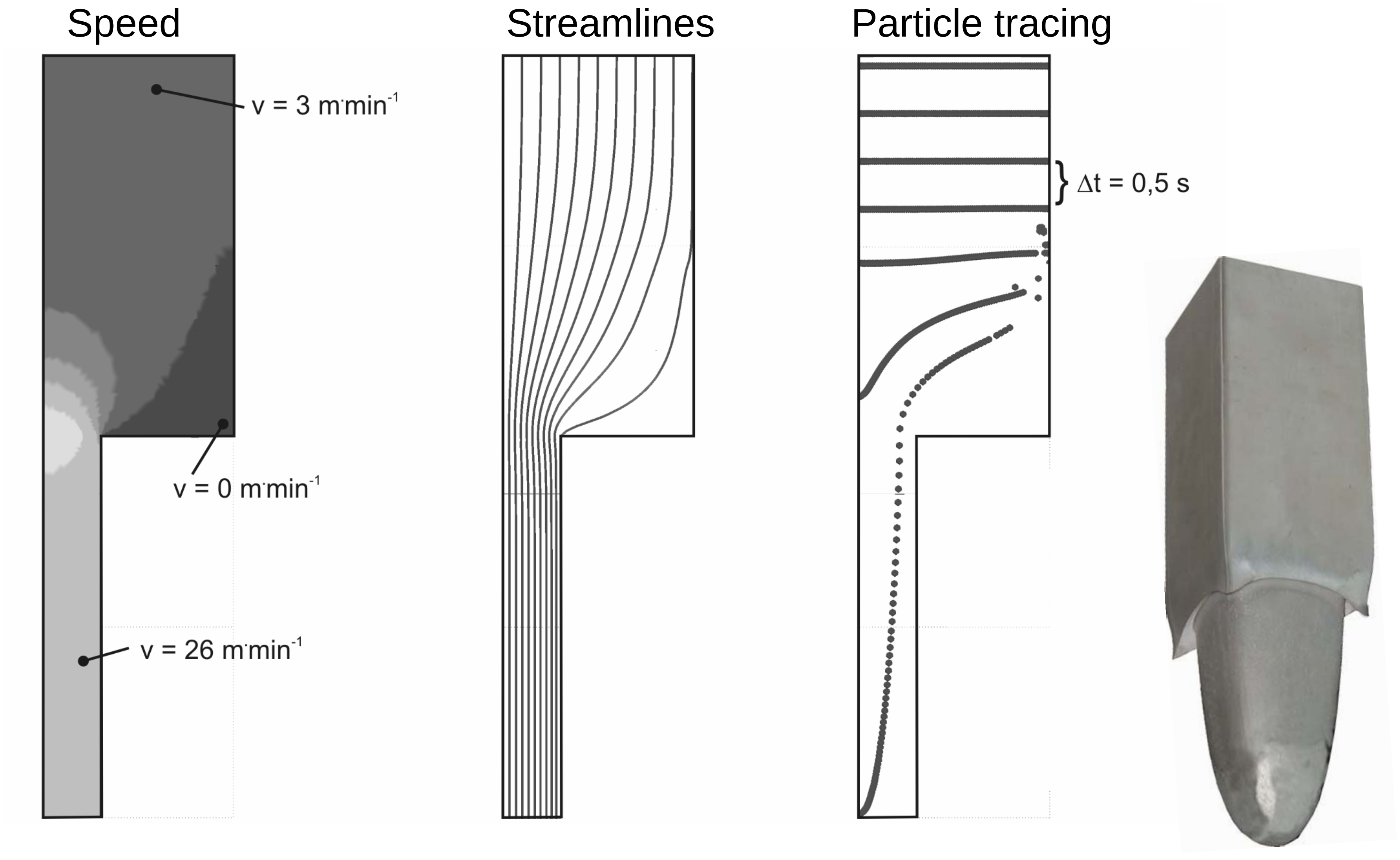
Results: Modeling of extrusion process



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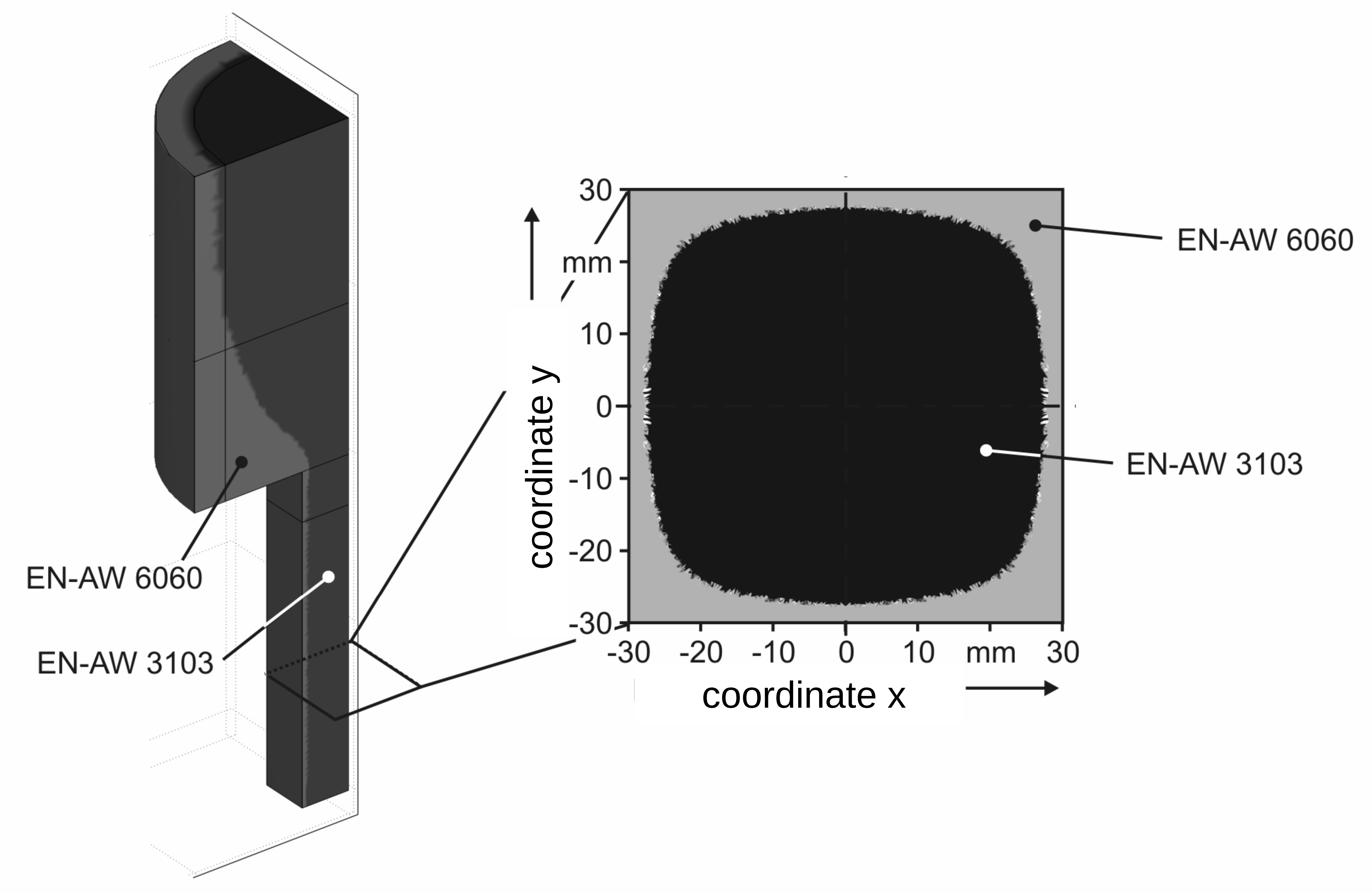
Simulation of material distribution for the coextrusion process



Summary and conclusion

- **Modelling of aluminum alloys by empirical material model leads to improved implementation of material behavior for high temperatures and strain rates**
- **Special measures for the implementation of the constitutive law are necessary**
- **Implementation of the level set method features two improvements**
  - Different properties of different materials can be implemented
  - Prediction of material distribution after welding becomes possible
- **With the improved modeling it becomes possible not only to simulate friction stir welding, but also similar processes (extrusion/ coextrusion)**

Acknowledgements

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Many thanks for this kind support…

… and many thanks for your kind attention!