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Fraunhofer-Institut für Werkstoffmechanik IWM

Mean-Field simulation of microstructure evolution during forging using FORGE® and DynamiX GUI

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Transvalor International Simulation Days
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Funded by the European Union

- **Motivation and objectives**
- Material characterization
- Material modelling
- Forging simulation
- Microstructure simulation
- Summary and outlook

EU Horizon Project AID4GREENEST

AI powered characterization and modelling for green steel technology

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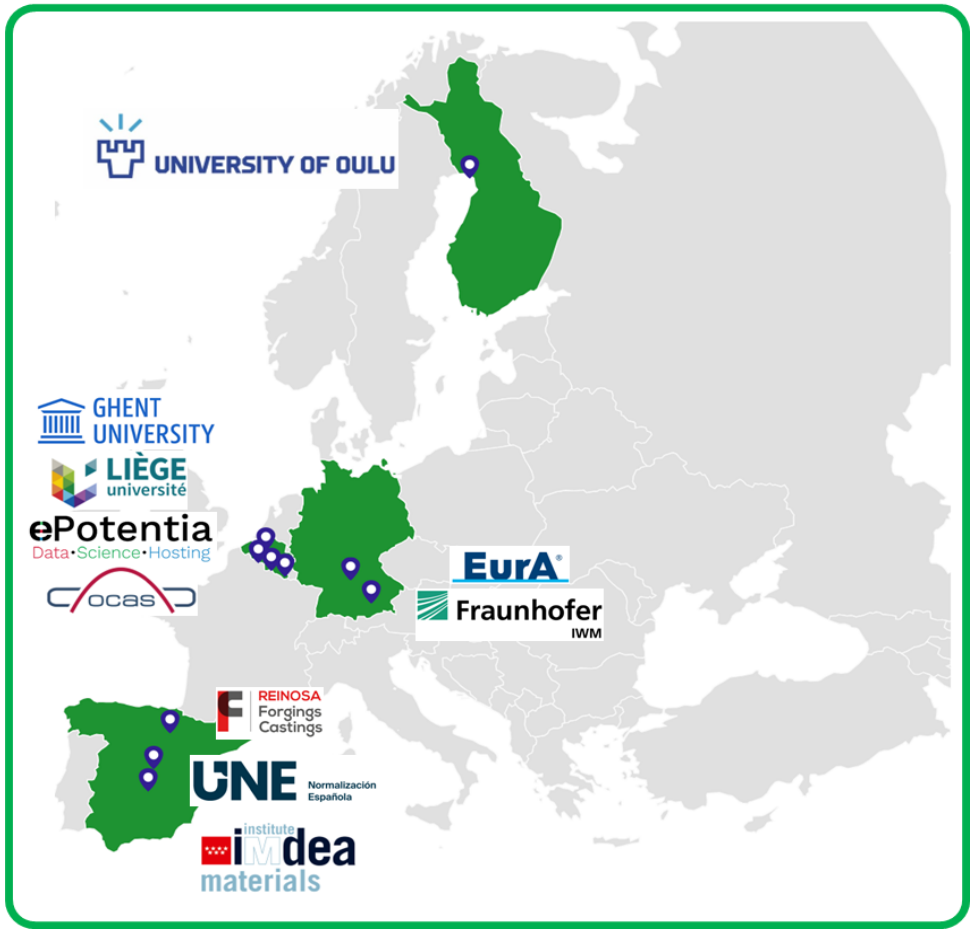

AID4GREENEST (GA 101091912)

- **Call**: HORIZON-CL4-2022-RESILIENCE-01
- **Topic**: HORIZON-CL4-2022-RESILIENCE-01-19 Advanced materials modelling and characterisation (Research and Innovation Action)
- **Start date**: 01.09.2023
  End date: 31.08.2026
- **Total budget**: € 4,946,876.25
- **Consortium:** 10 partners from 4 countries
  3 companies + 3 universities + 2 research organizations + 1 standardization body + 1 consulting company

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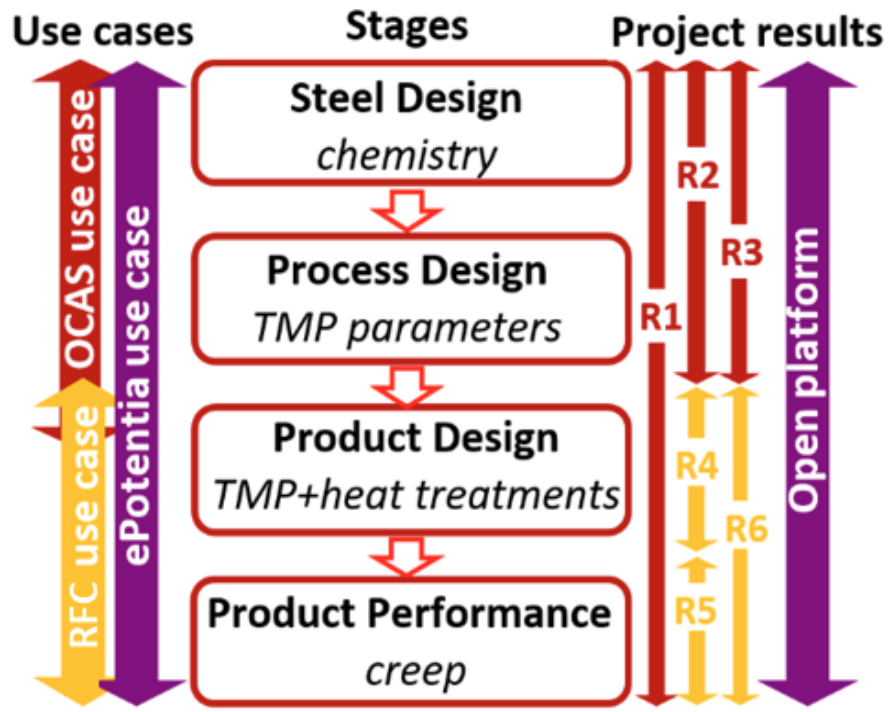

Six AI-powered tools / methods (results)

R1. A model-enabled method for rapid characterization of steel microstructure
R2. AI-based computational screening tool "Process → Microstructure"
R3. AI-based computational screening tool "Microstructure → Process"

R4. Sequential computational model predicting microstructure during forging and quenching of meter-scale parts
R5. A ML-based tool predicting creep life of heat-resistant steels
R6. A model-enabled method for accelerated creep testing

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REINOSA Forgings Castings

Six AI-powered tools / methods (results)

R1. A model-enabled method for rapid characterization of steel microstructure

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REINOSA Forgings Castings

R4. Sequential computational model predicting microstructure during forging and quenching of meter-scale parts

R5. A ML-based tool predicting creep life of heat-resistant steels

R6. A model-enabled method for accelerated creep testing

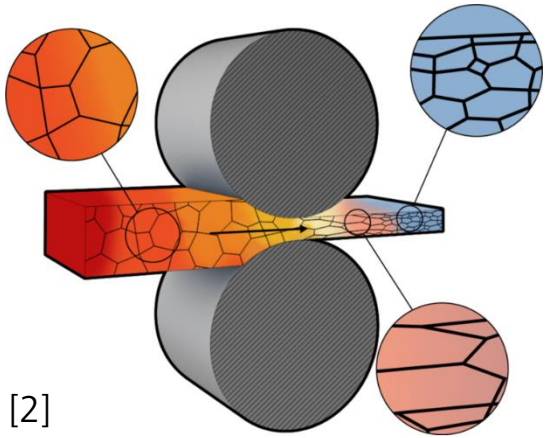
Motivation and objectives

Material phenomena in thermo-mechanical processing of metallic materials

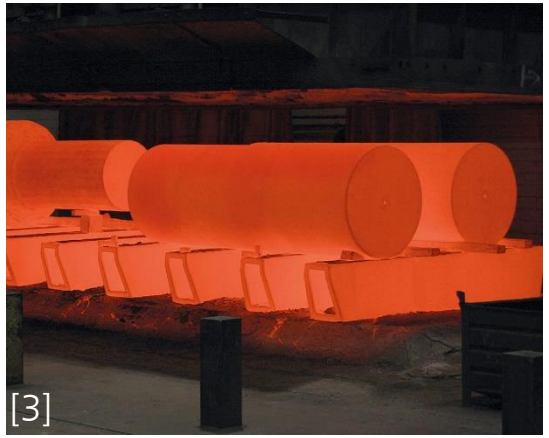
Viscoplasticity
Thermo-elasticity


[1]

Recovery, Recrystallization


[2]

Grain coarsening
Precipitation


[3]

Phase transformation


[4]

+ Energy storage/release

+ Energetic coupling phenomena

[1] https://www.metal-i-cast.com/images/forging/forging-img-6.jpg
[2] https://www.manufacturingguide.com/en/hot-rolling-sheets
[3] https://dirostahl.com/portfolio/fertigung/waermebehandlung
[4] https://www.hawcoindia.com/manufacturer-supplier-polymer-quenching-oils.php

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Material characterization
Methods

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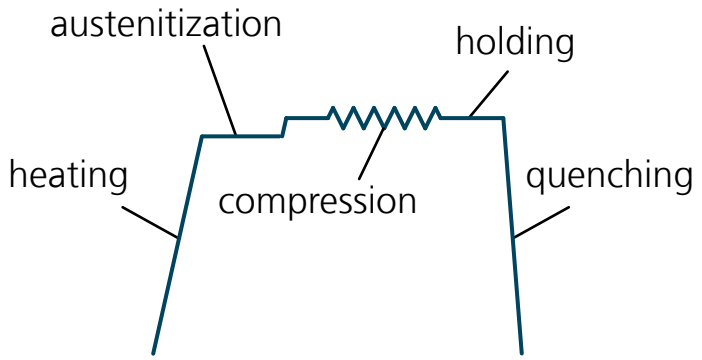
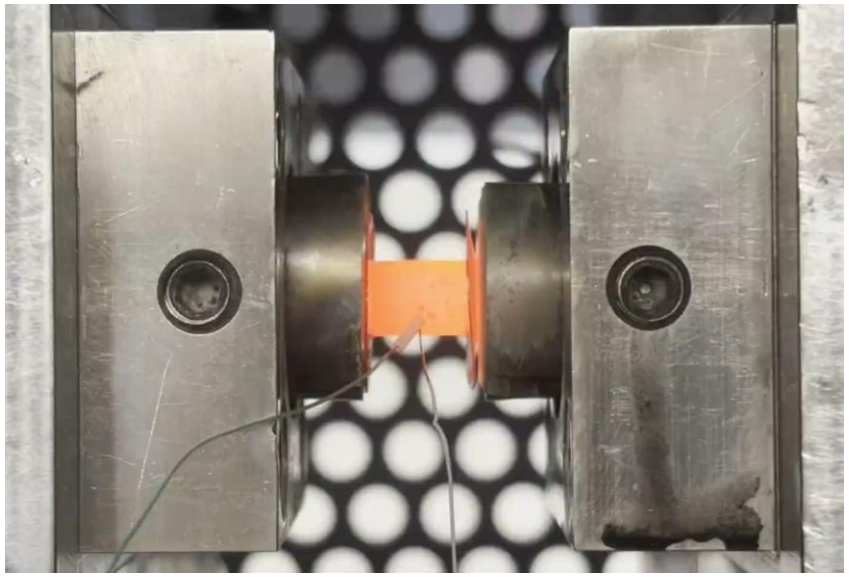
Creep-resistant steel 30CrMoNiV5-11

	C	Si	Mn	Cr	Mo	Ni	V	Cu	S	P
wt.%	0.28	0.10	0.65	1.37	1.08	0.63	0.29	0.10	0.01	0.009

- Thermo-mechanical testing (Gleeble 3150)





Variables
- Deformation temperature
- Strain rate
- Total strain
- Holding time

Results
- Flow curves
- Deformed/DRX/PDRX microstructures

- Metallography

Material characterization

Thermo-mechanical testing

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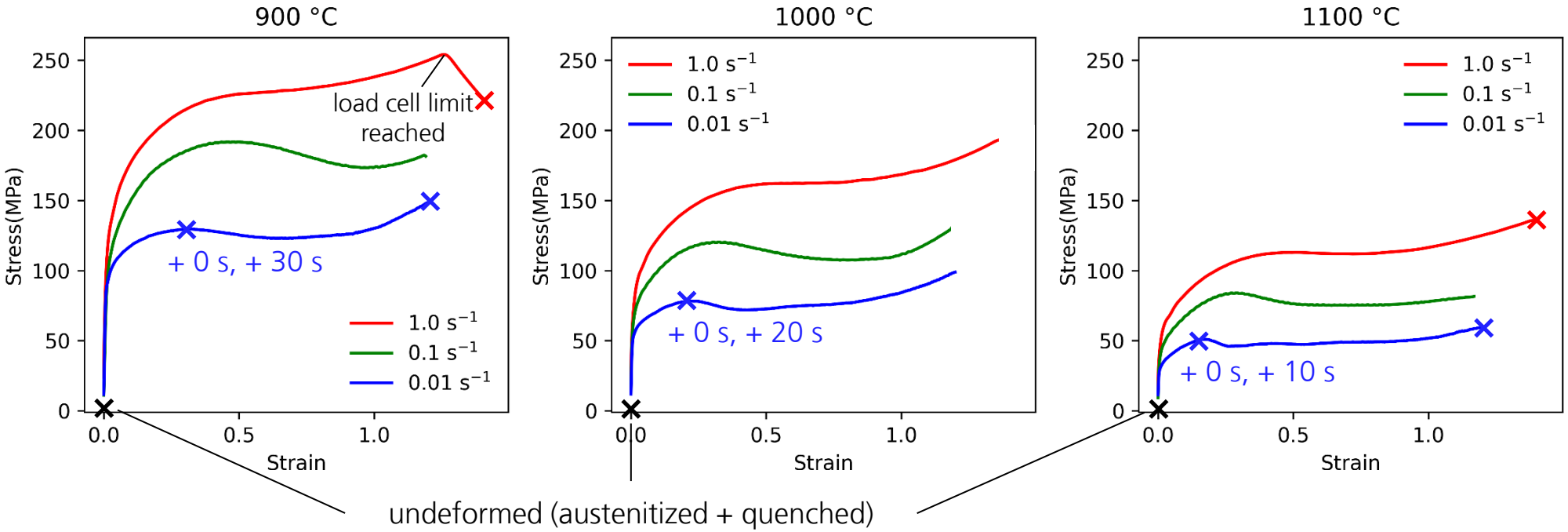
Flow curves

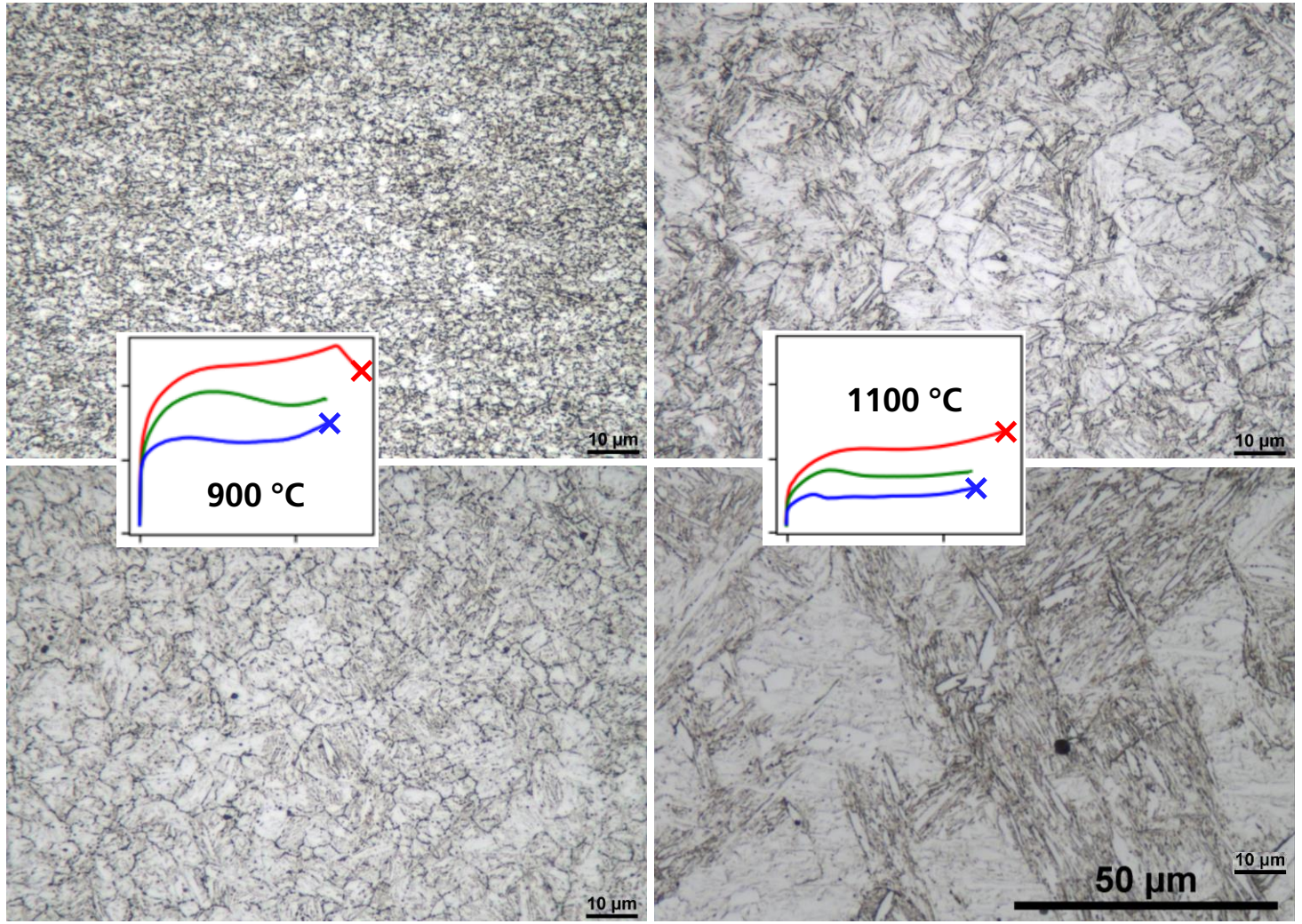


Metallography after various process histories ✕ to reveal deformed and recrystallized microstructures

Material characterization

Metallography

Etched to reveal the prior austenite grain boundaries



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Material characterization

Metallography

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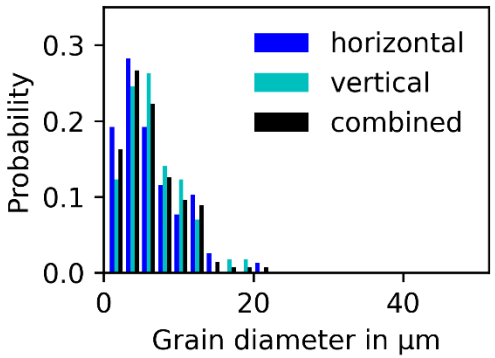
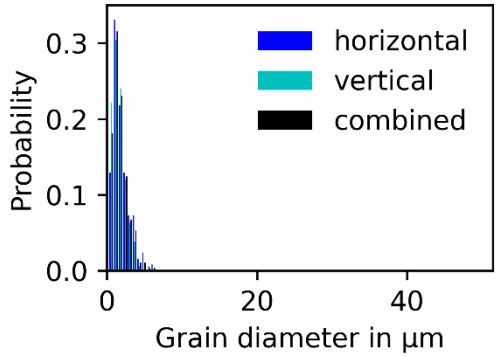
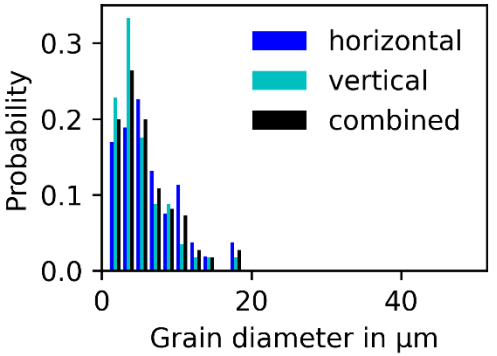
Grain size distributions

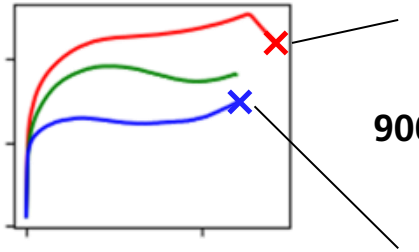
undeformed



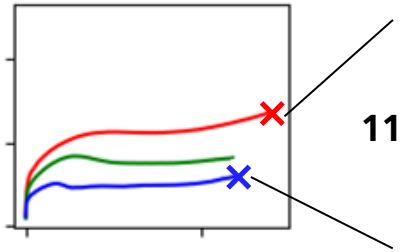


1 s^{-1}

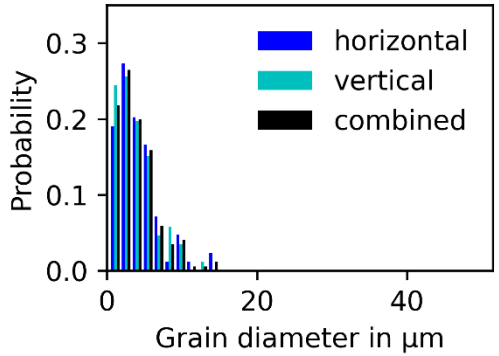




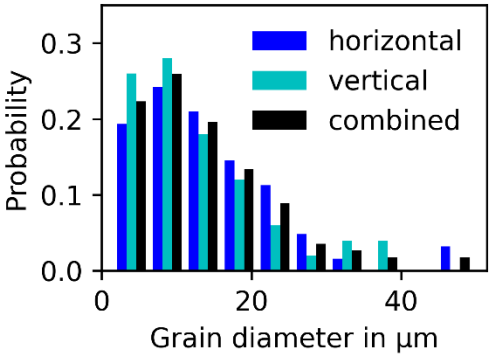
900 °C



1100 °C



0.01 s^{-1}



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Material modelling

General structure of the mean-field model[1,2] developed at Fraunhofer IWM

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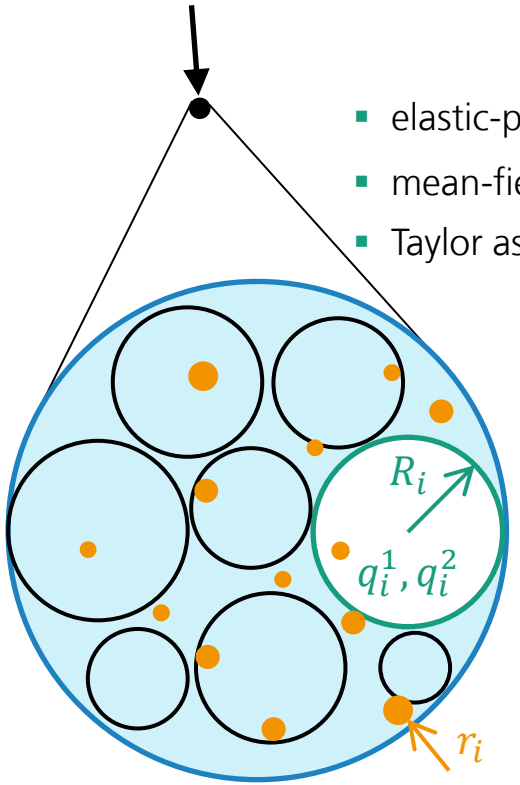
Loads at a material point
Deformation $\mathbf{F}$, temperature T



- elastic-plastic split $\mathbf{F} = \mathbf{F}_\mathrm{e}\mathbf{F}_\mathrm{p}$
- mean-field approach
- Taylor assumption

- **Mean-field approach**
  - N grains with equivalent radii $R_1, \dots R_N$ and hardening variables $q_1^1, q_1^2, \dots, q_N^1, q_N^2$
  - M precipitate particles with equivalent radii $r_1, \dots, r_M$
- **Thermodynamic framework**
  - Thermodynamic potential: Free energy $\psi = \psi_\mathrm{e} + \psi_\mathrm{p} + \psi_\mathrm{chem} + \psi_\mathrm{gb} + \psi_\mathrm{pb}$
  - Conservation of energy, momentum, mass + 2. law
- **Model equations**
  - Evolution equations: plasticity, work hardening, grain and precipitate sizes, nucleation
  - Microstructure-property-relations: flow stress, grain boundary mobility, diffusivity, … as functions of microstructure and temperature

1) L. Kertsch: *Modellierung des thermomechanischen Materialverhaltens und der Gefügeentwicklung mikrolegierter Stähle*. Dissertation, KIT, Karlsruhe, 2022
2) L. Kertsch, D. Helm: International Journal of Solids and Structures 152–153 (2018) 185–195

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Forging simulation

Process overview

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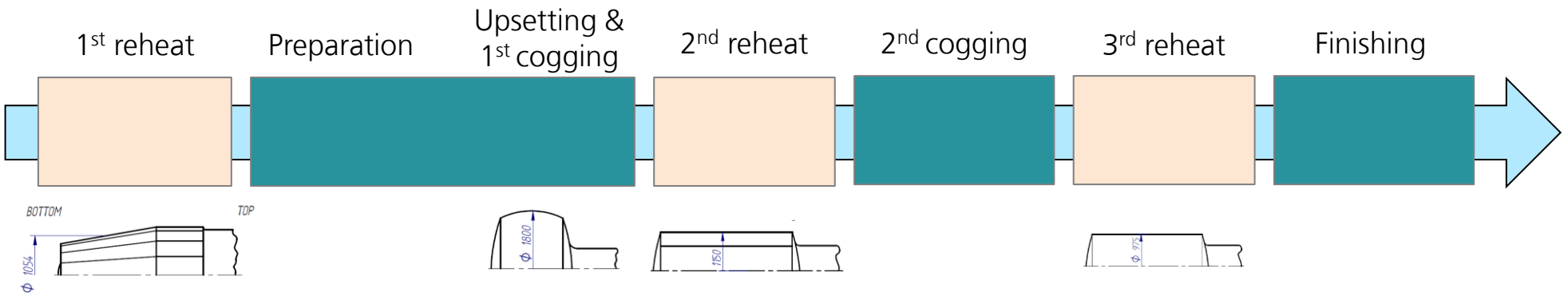
- Simulation of the entire forging process with FORGE® NxT 4



- Results: strain and temperature field within the workpiece as functions of time
- Needed to predict the microstructure evolution during forging

Forging simulation

Preliminary results for the 1st reheat

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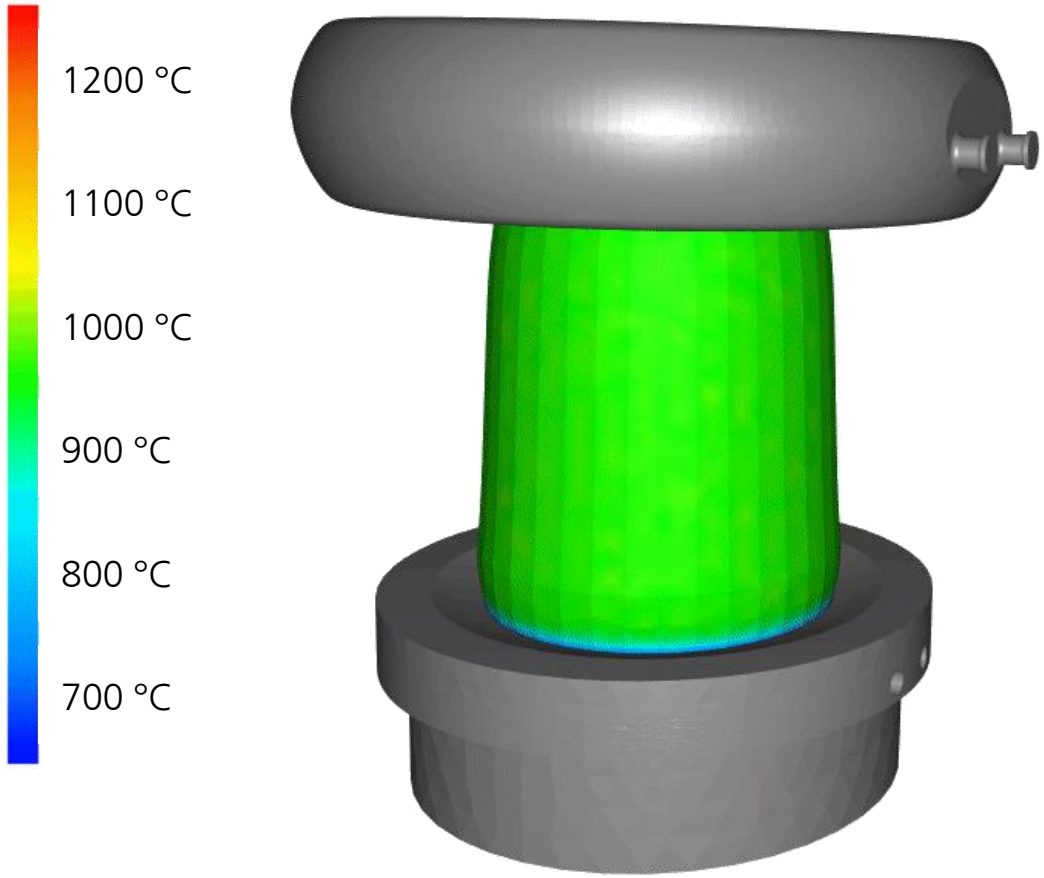

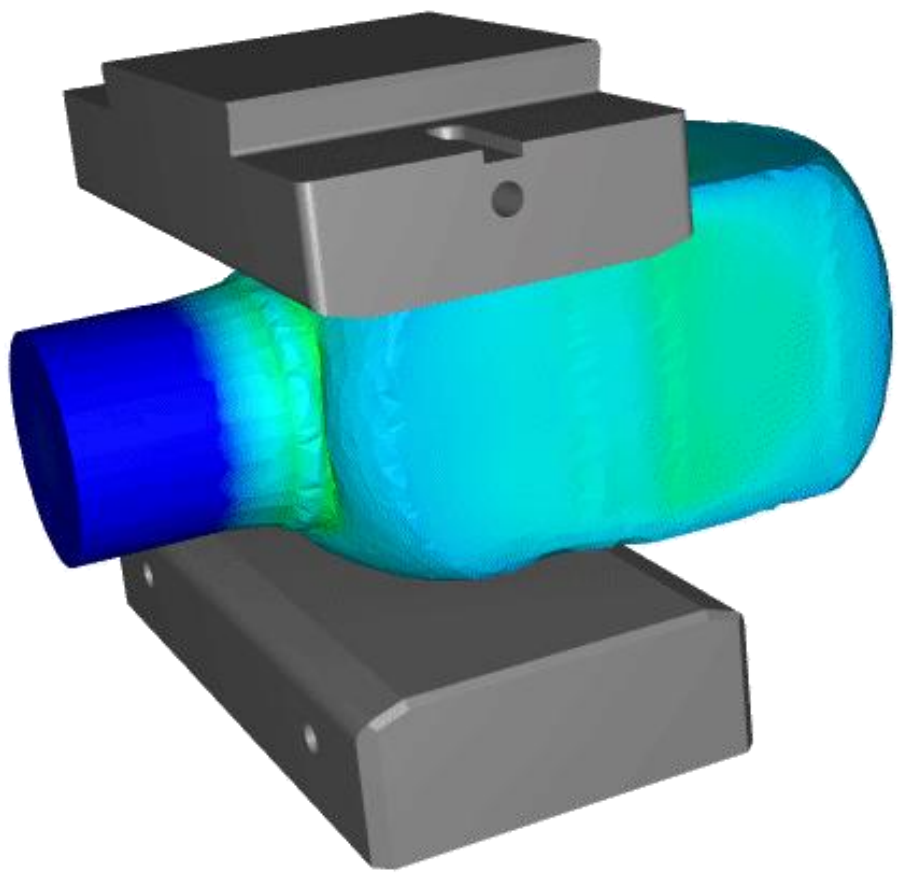

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Microstructure simulation

Working with DynamiX GUI

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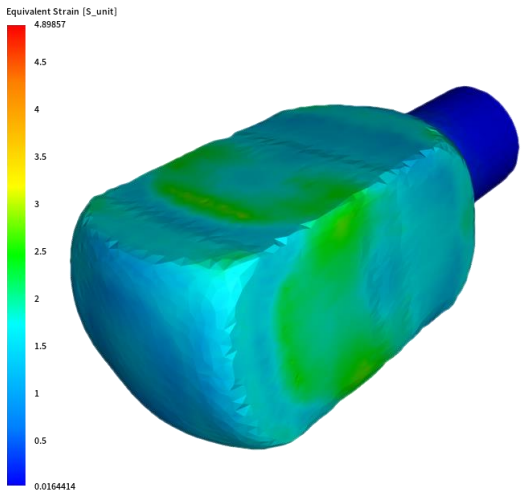
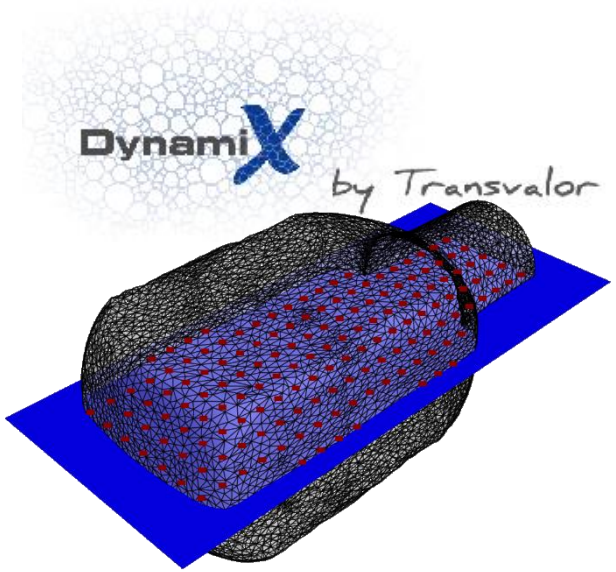
Finite element simulation



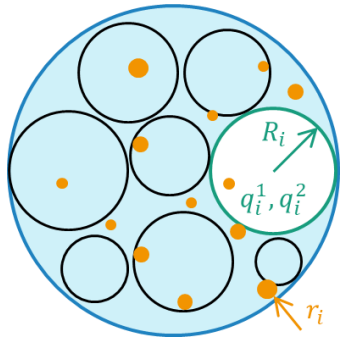
Strain and temperature evolution in the workpiece

DynamiX GUI

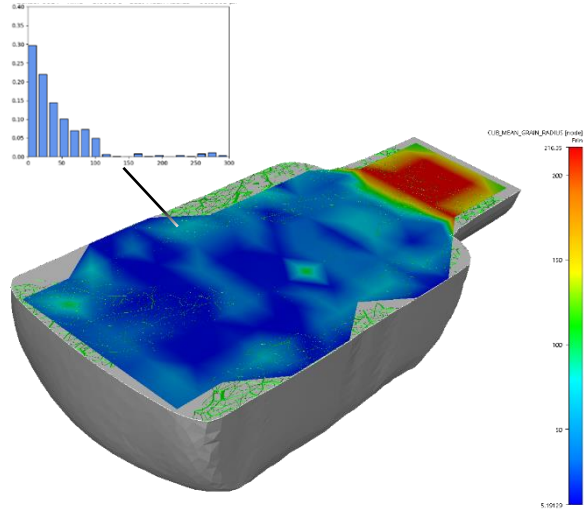


Strain and temperature evolution on a point grid

Microstructure model



Microstructure prediction



e.g. grain size, recrystallized fraction

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Summary and outlook

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Summary

- Simulation of the multi-stage open-die forging process of a large turbine shaft
- Experimental characterization of the used steel
- Calibration of a physics-based model for the thermo-mechanical material behavior and microstructure evolution
- Prediction of microstructure evolution using DynamiX GUI

Outlook

- Integration into the toolchain within the AID4GREENEST project:
  - Prediction of phase transformation and microstructure evolution during quenching
  - Correlation of final microstructure and creep life during service
- Contribution to product, process, and material design
- Reduction of time, cost, energy, and material consumption,
  both in manufacturing and in product and process development

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