Alternative Modelling Tools and Techniques in Continuous Casting

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European Commission

Research Fund for Coal & Steel

Introduction

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MSc.
KTH, Royal Institute of Technology
Materials Science

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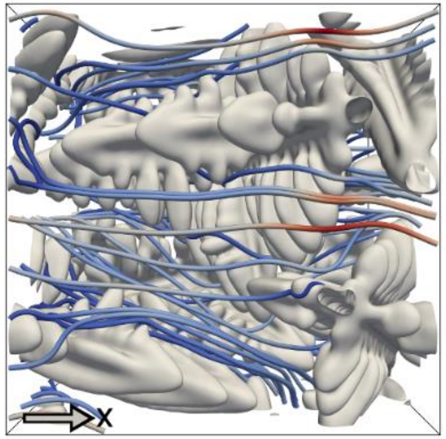
Iran

BSc.
Azad University (IAU)
Industrial Metallurgy

Engineering Applications

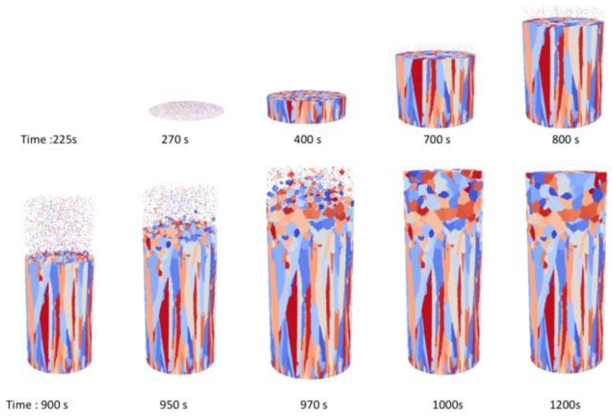
Microstructure



Phase-field & cellular automaton models: MICRESS, OpenPhase, CAFE, … .

- High resolution in prediction of microstructures formed during solidification.
- Coupled with thermodynamic databases e.g. Thermo-Calc or JMatPro.
- Small computational domain.
- High computational cost.

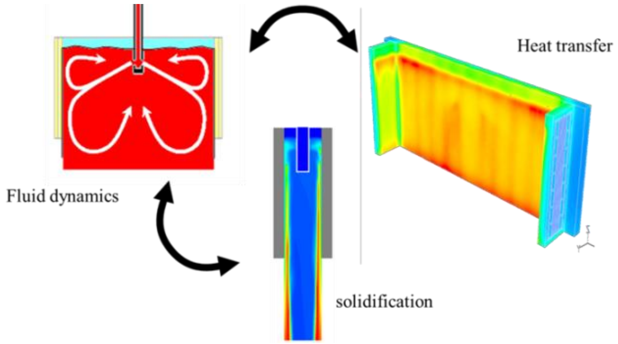
Meso-Scale Models



Coupled macro scale models with e.g. direct grains envelopes tracking technique: Sprime, Thercast-CAFE, … .

- Prediction of fluid flow as well as solidification including a simplified microstructure & segregation model.
- Potential to be applied to industrial scale problems.
- Moderate computational cost.
- The model lacks the microstructure features from MICRESS and CAFE models.

Macroscale



Macroscale computational codes based on CFD, FEM, etc numerical methods: FLUENT, OpenFOAM, THERCAST, MAGMA, … .

- Applicable to 2D-3D industrial scale problems.
- Lower computational cost.
- Coupled multiphase approach (steel-slag-argon gas)
- Possible coupling of slag-metal reactions through thermodynamic data bases.
- Coupled multiphysics e.g. EMS and EMBr applications.
- The model lacks accurate prediction of microstructure and segregation.

µm mm cm/m m

Length Scale

Outlines

I. Open source CFD

- OpenFOAM

II. Commercial codes FEM and FDM

- THERCAST
- Abaqus
- Tempsimu
- castManager

III. Meso-scale and micro-scale models

- Sprime
- MICRESS
- OpenPhase Solution

Open Source CFD

https://fluidityproject.github.io/

OpenFOAM

The OpenFOAM Foundation

https://openfoam.org/

Open Source
Computational Fluid Dynamics
Software

https://www.openfoam.com/

https://su2code.github.io/

https://palabos.unige.ch/

Have you heard or had any experience with the below open source software?

a) OpenFOAM

b) Palabos

c) SU2

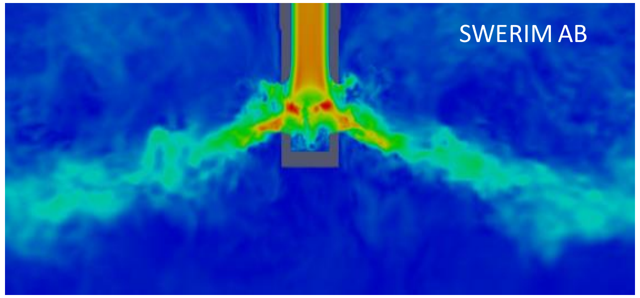
d) Fluidity

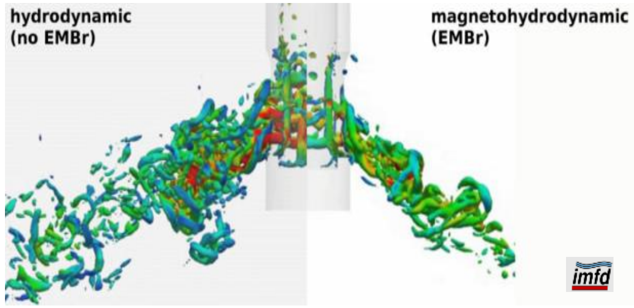
e) none

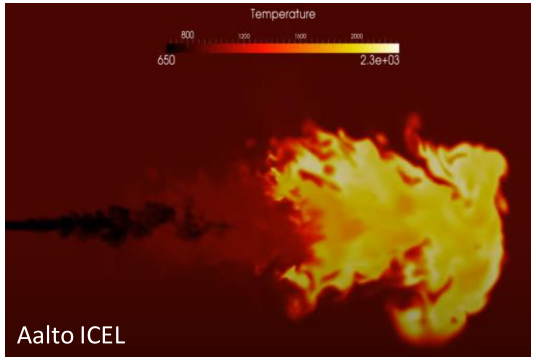
What is OpenFOAM?

OpenFOAM (**Open**-source **F**ield **O**peration **A**nd **M**anipulation) is a C++ toolbox for the development of customized numerical solvers for the solution of continuum mechanics problems, most prominently including computational fluid dynamics (CFD).

It is free, open source toolbox released and developed primarily by OpenCFD Ltd since 2004. It has a large user base across most areas of engineering and science, from both commercial and academic organizations. It addresses complex fluid flows involving chemical reactions, turbulence and heat transfer, to acoustics, solid mechanics and electromagnetics.







Why Open Source?

OpenFOAM

Customization

The capability to modify the program according to the needs is the major difference among closed source and open source software.

Pre-Post Analysis

Free built-in and third-party pre-post processing tools e.g. blockMesh, snappyHexMesh and ParaView (https://www.paraview.org/).

Freely Obtainable

It is published under General Public License (GNU) which means no licensing costs and freely obtainable.

Big Community

Generally, such popular programs are supported by a big community of program developers.

What are disadvantages?

Lack of Graphical User Interface (GUI)

It can be less “user-friendly” and not as easy to use because less attention is paid to developing the user interface. However, there are commercialized GUIs available in the market which are bounded to the original OpenFOAM solvers e.g. :

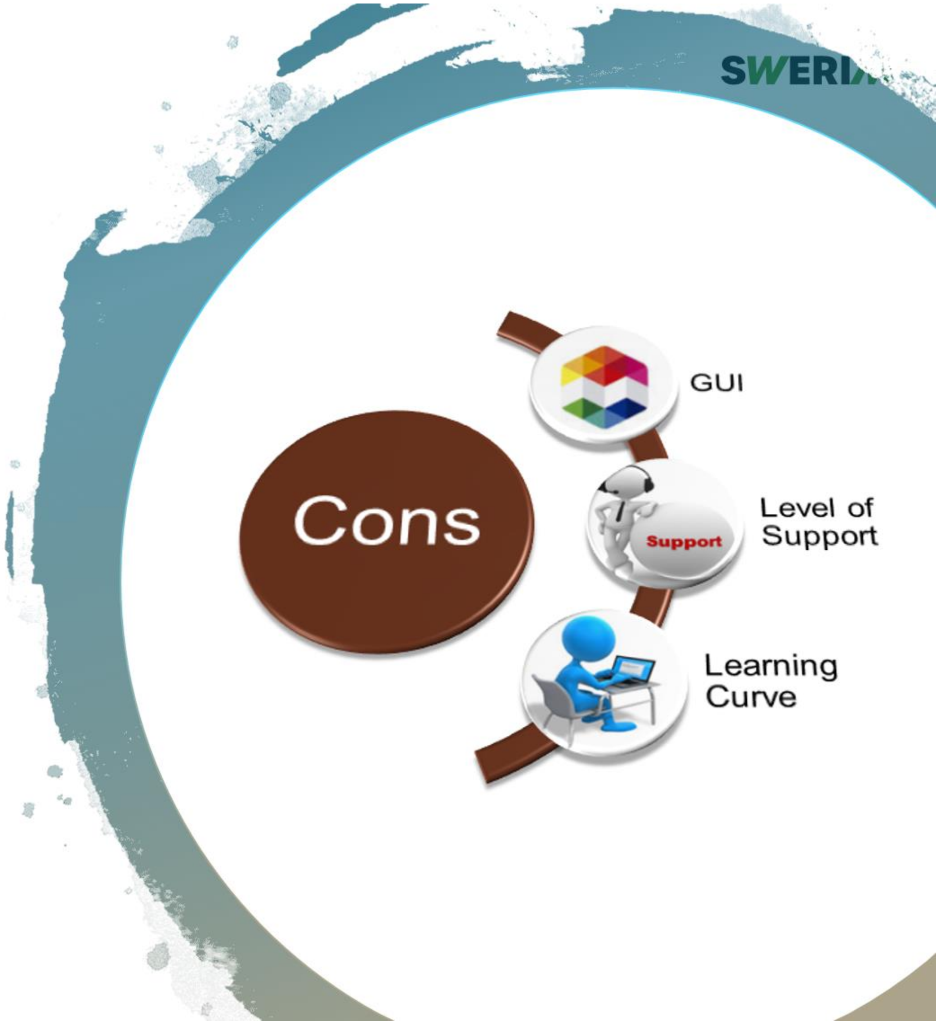
- HELYX-OS (https://engys.com/products/helyx-os)
- simFlow (https://sim-flow.com/)

Level of Support

You can’t necessarily find well documented help or get support on the phone for your feature of interests.

Long Learning Process

It needs primary investment to create the necessary technical knowledge to use the software.



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Mould Flow, Heat Transfer and Solidification Examples

Mould & SEN Fluid Flow

The model is based on the solution of Navier-Stokes equations using Volume of Fluid (VOF) interface tracking technique and includes the effect of:

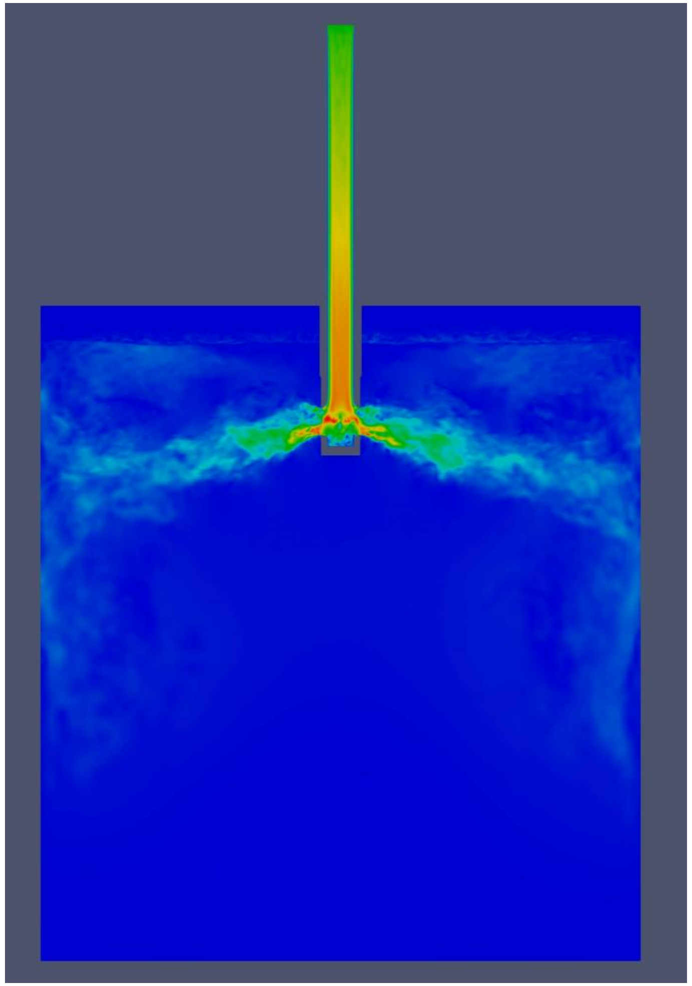
I. **Casting parameters**

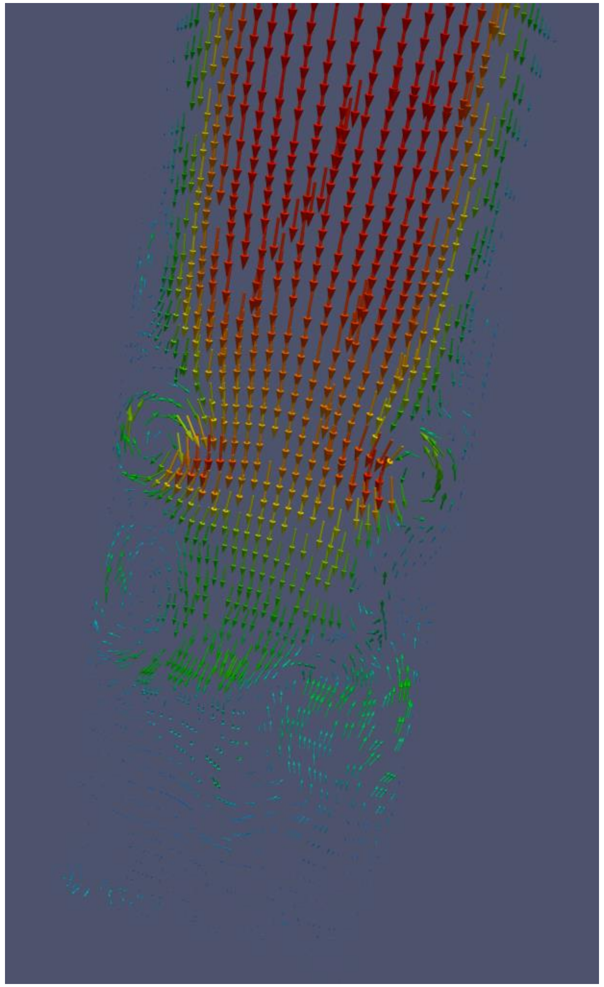
II. **SEN design parameters and type**

- SEN shape (Cup, Flat, Mountain)
- SEN immersion depth
- Port dimension
- Port angle

III. **Mould design and dimension**

on the mould-SEN flow and frequencies, free surface instabilities, etc.

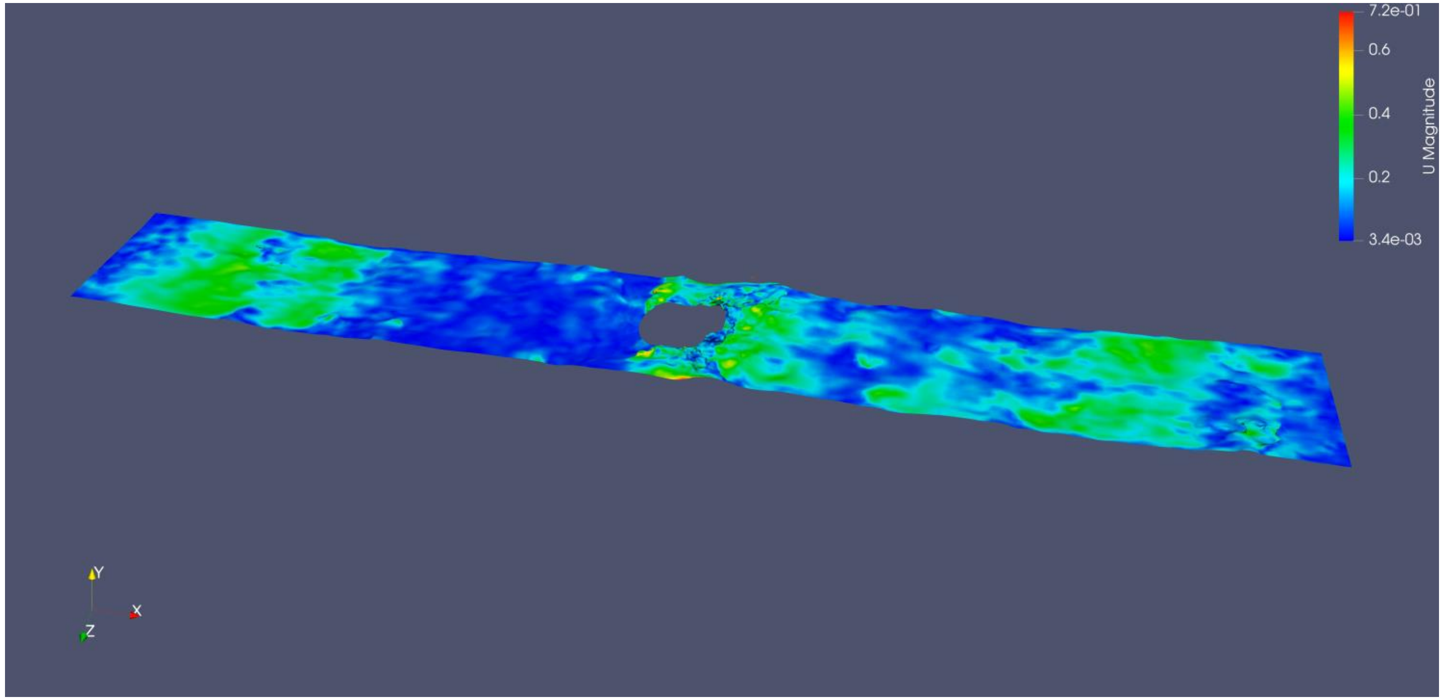




Free Surface Dynamics

The model predicts:

I. Standing wave hight
II. Surface waves
III. Von Karman vortex formation around SEN
IV. Bias free surface instabilities

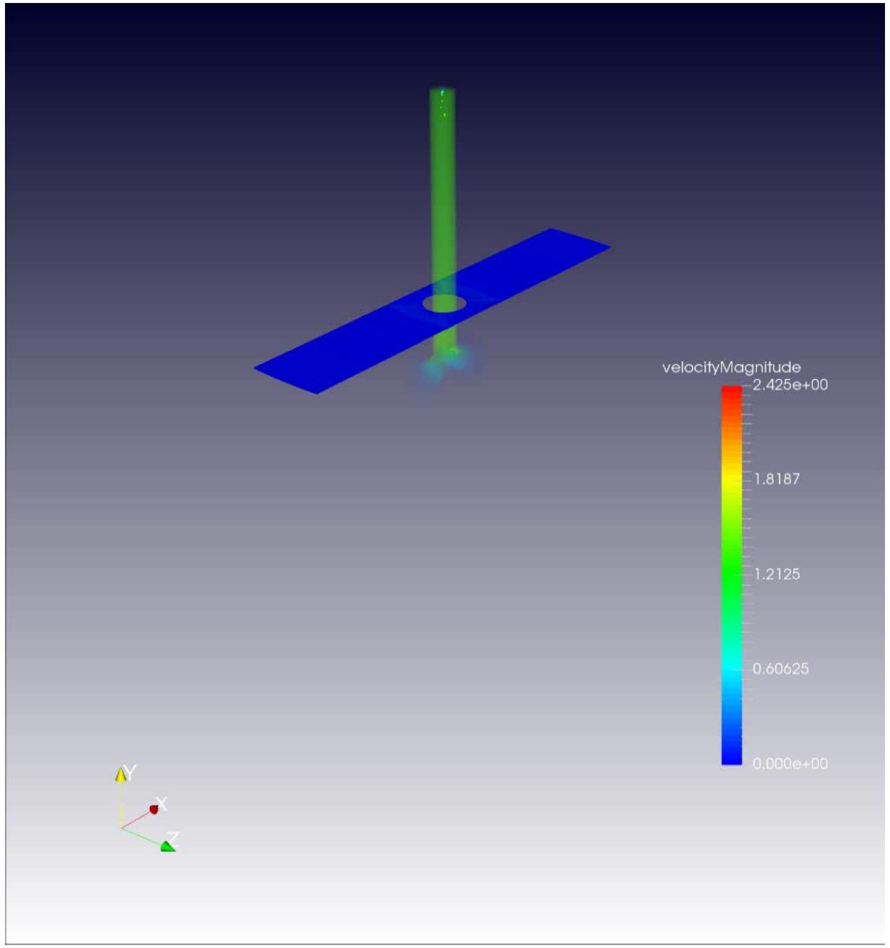


Argon gas injection

Coupled interFOAM solver with basicKinematicCloud

The model is based on:

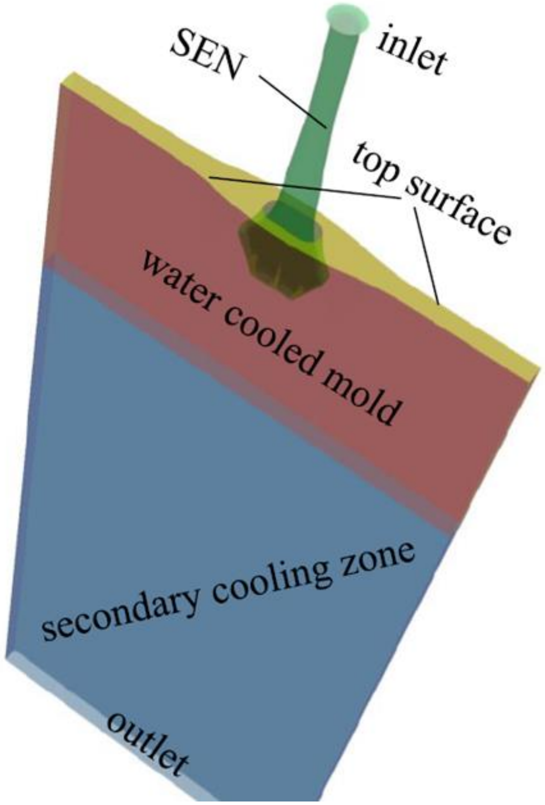
- Solution of Navier-Stokes equations
- Volume of Fluid (VOF) interface tracking technique for interface tracking.
- Large Eddy Simulation (LES) turbulence model to investigate transient behaviour of the meniscus and metal level.
- Gas bubbles through Lagrangian Particle Tracking (LPT) to assess-optimise argon injection flow rate to obtain a stable casting sequence.

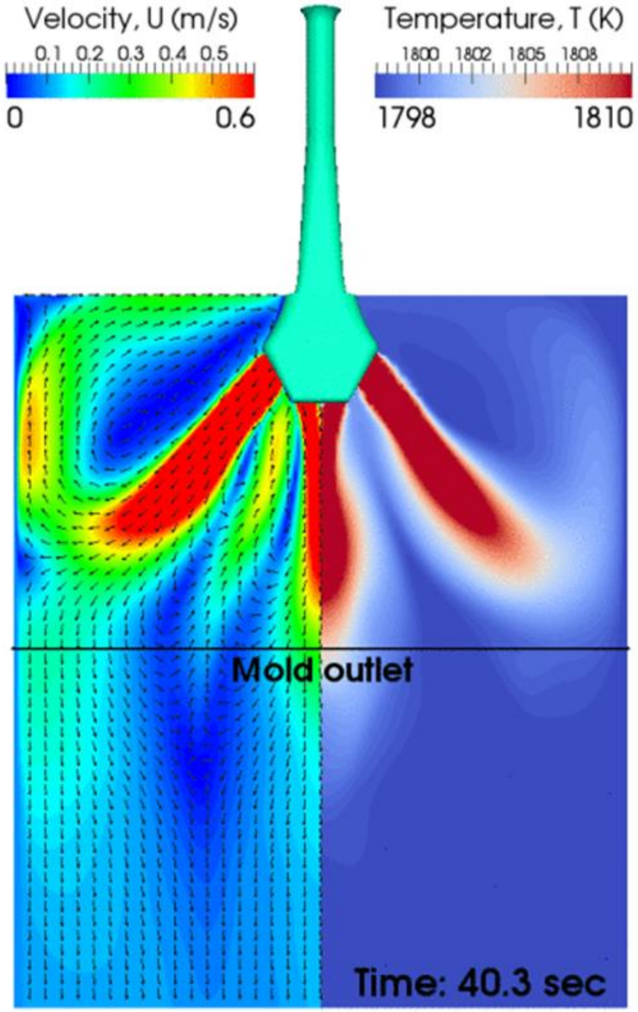


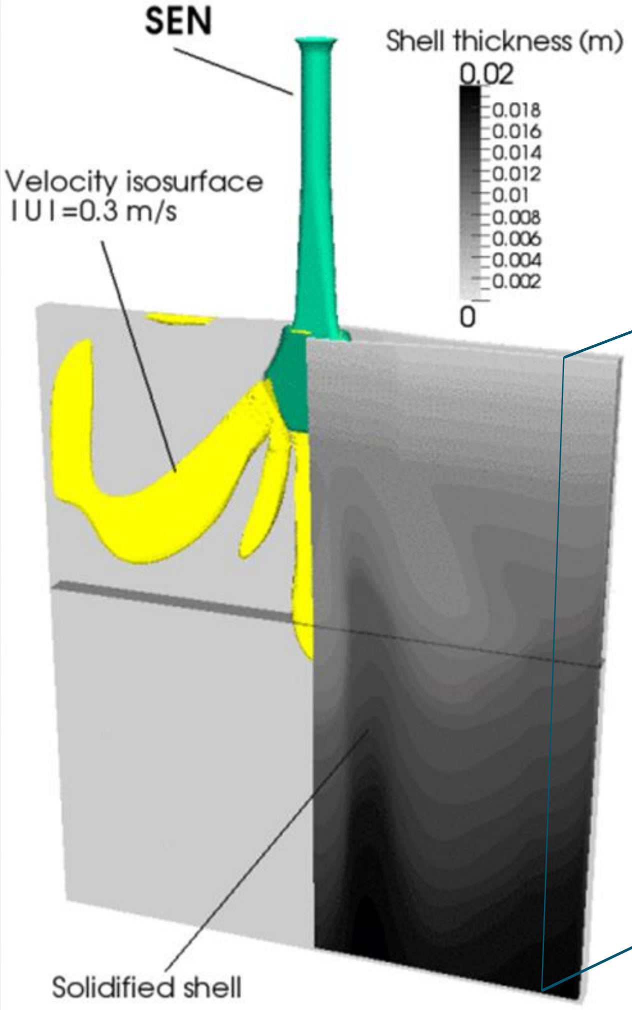
Shell formation in thin slab casting

Simulation results: melt flow & solidification

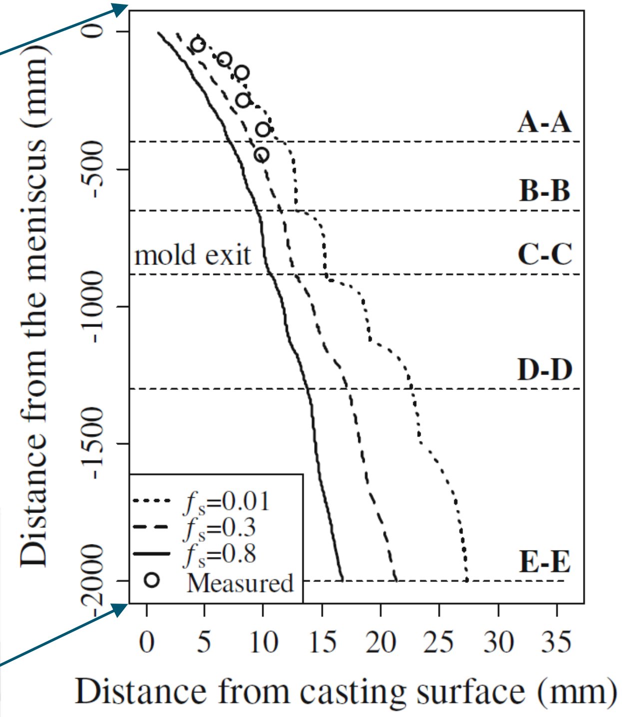
Model setup







Solid shell growth

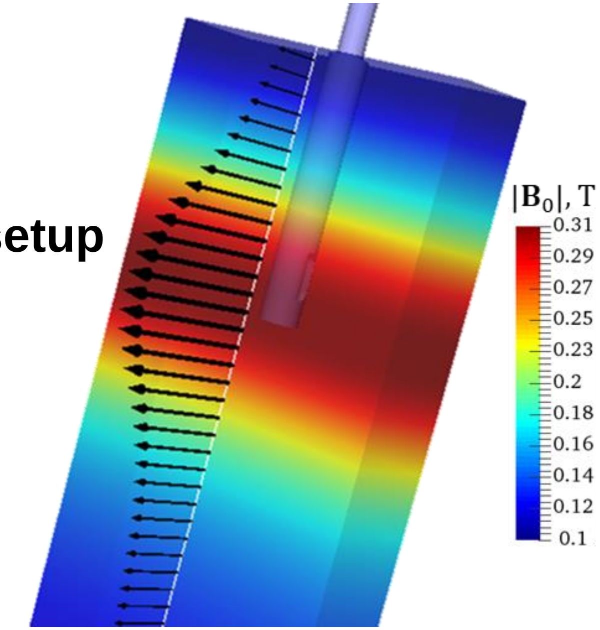


Vakhrushev A, Wu M, Ludwig A, Tang Y, Hackl G, Nitzl G, MMTB, 2014, 1024-1037

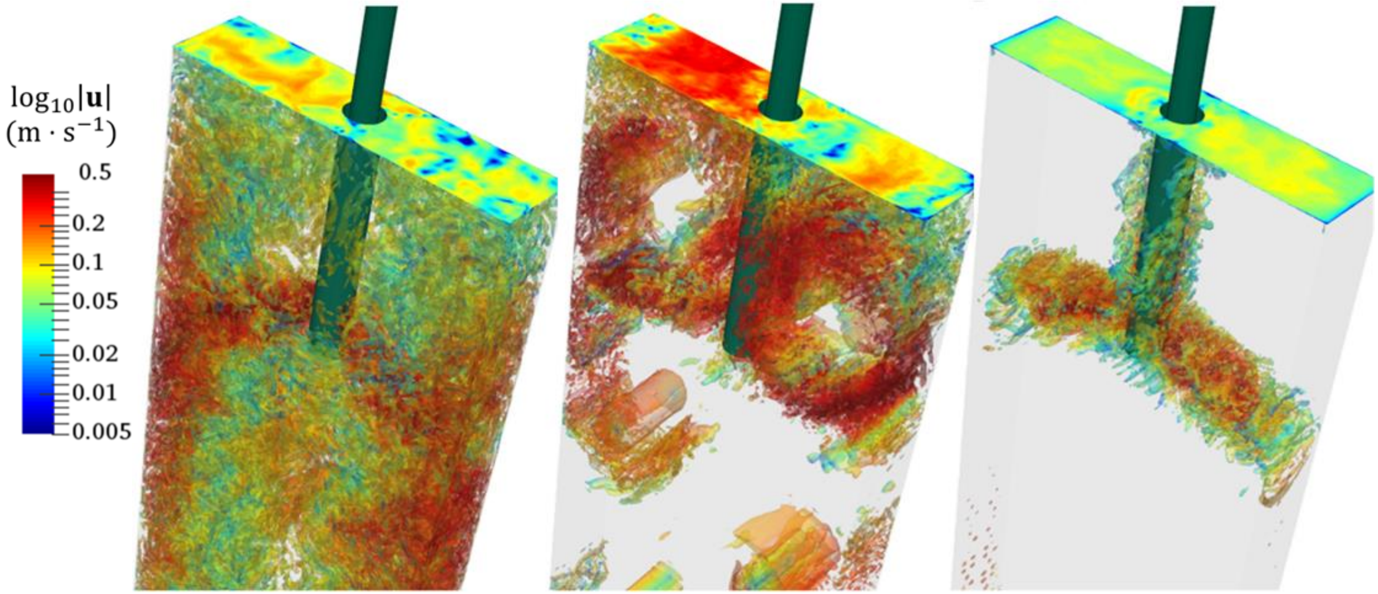
EMBr in continuous casting

Christian Doppler Forschungsgesellschaft
RHI MAGNESITA
PRIMETALS TECHNOLOGIES
MONTAN UNIVERSITÄT

EMBr setup



Flow structure

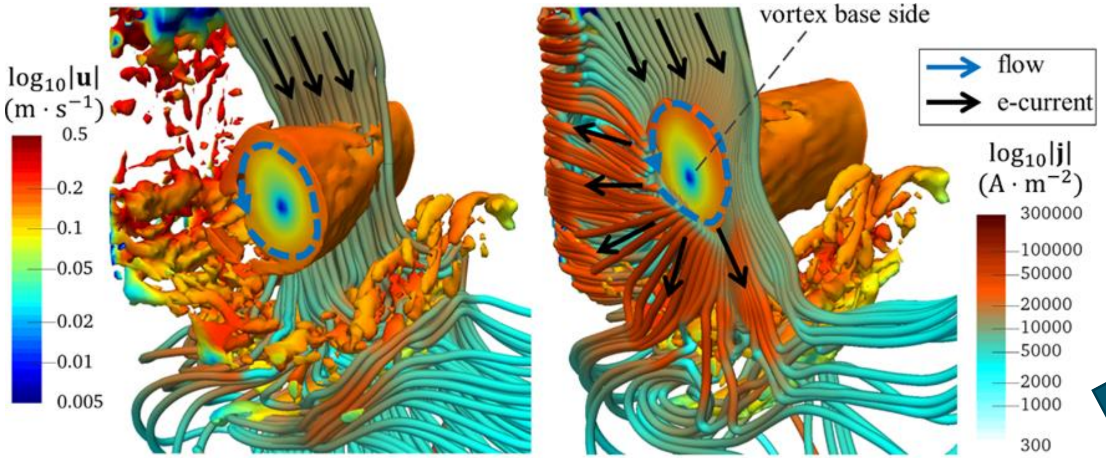


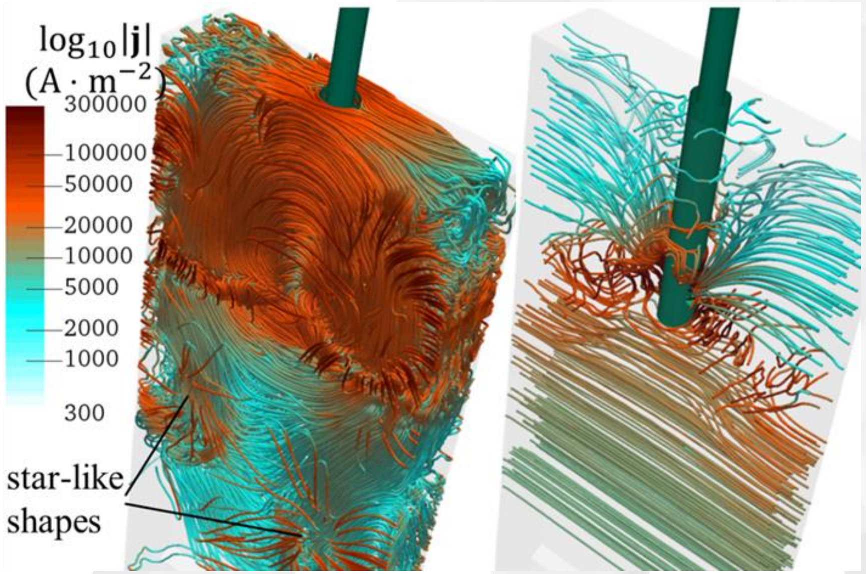
no EMBr

insulated mold

conductive mold

Induced e-current





Vakhrushev A, Kharicha A, Liu Z, Wu M, Ludwig A, Nitzl G, Tang Y, Hackl G, Watzinger J, MMTB, 2020

Finite Element Method (FEM)

Aalto University

THERCAST®

https://www.transvalor.com/en/thercast

get it right®

ProCAST

https://myesi.esi-group.com/products/casting

Computational FEM Software

SIMULIA ABAQUS

https://scanscot.com/products/simulia/abaqus

MAGMA

Committed to Casting Excellence

https://www.magmasoft.de/

Full 3D CC Model

THERCAST®

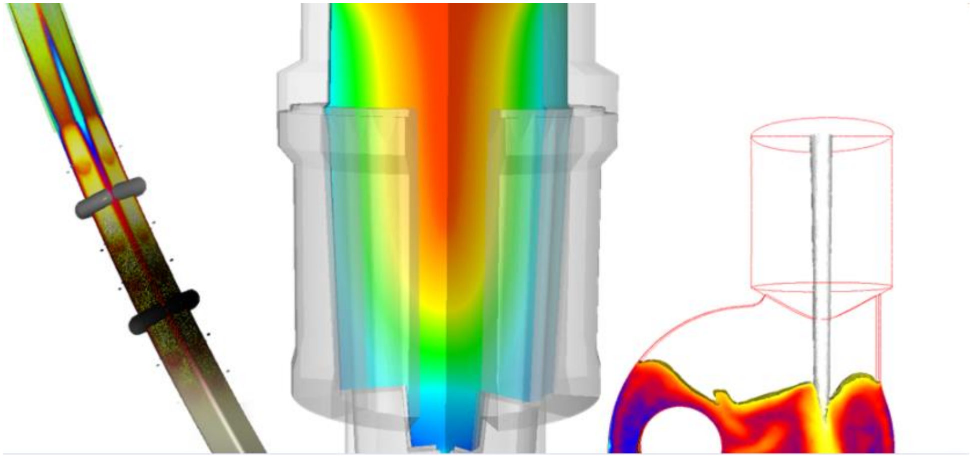
THERCAST is a 3D thermo-mechanical FEM software for foundry processes, continuous and ingot casting processes. It includes both primary and secondary cooling zones in a modular manner.

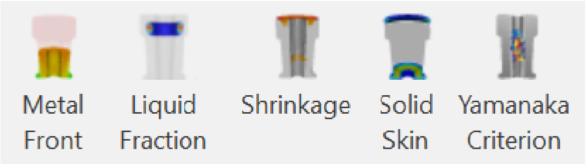
Primary Cooling: It can take any parameters of the caster into consideration e.g. :

- The design of the molds with the taper
- The design of the water channels or water box
- The air gap created during metal shrinkage

Secondary Cooling: it takes any modification of each single spray nozzle and roll into consideration e.g. what happens if one or several nozzles get clogged?

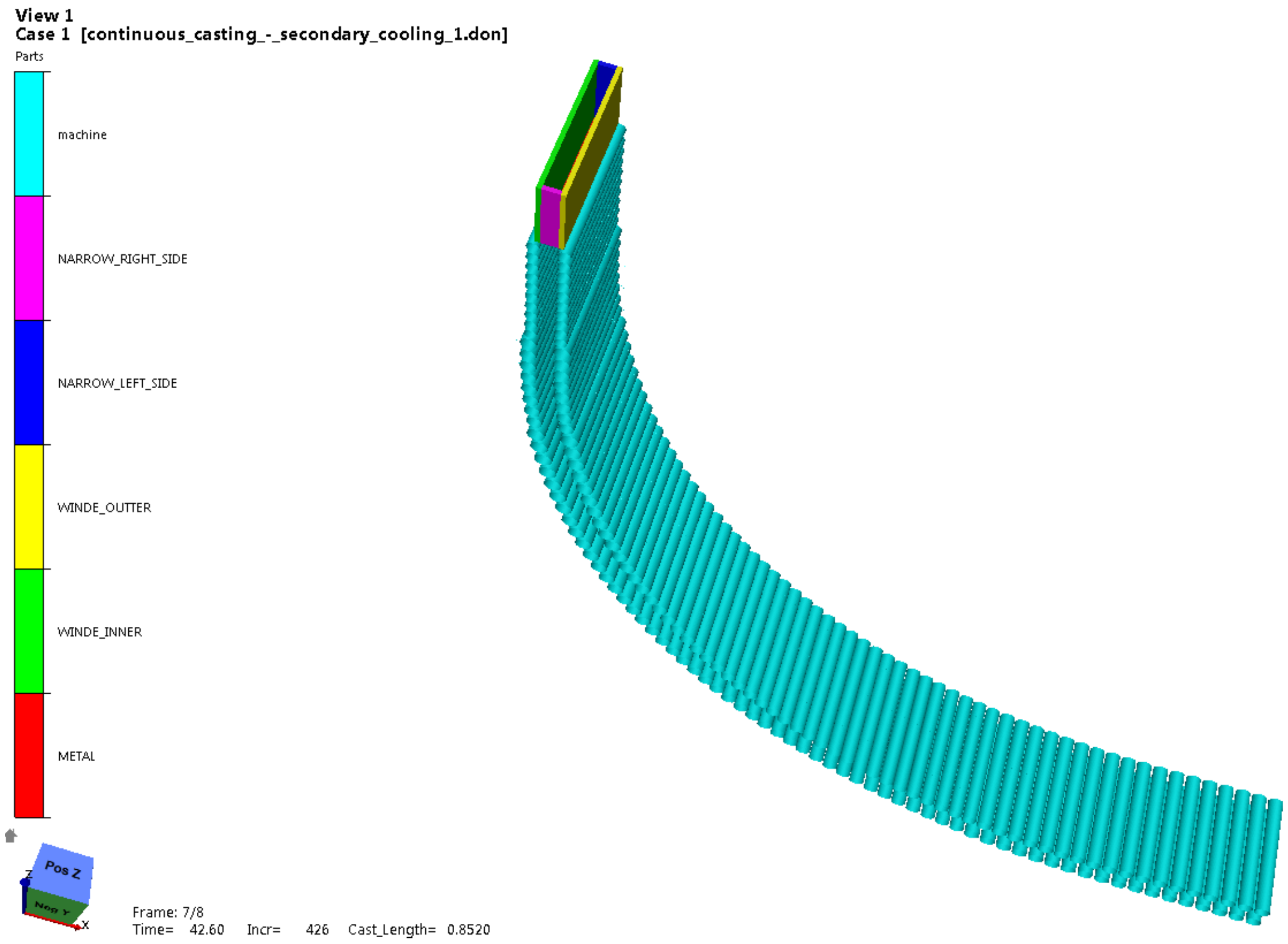
It also offers a graphical module dedicated to the material specifications representing the thermo-physical data and the associated laws of behavior.

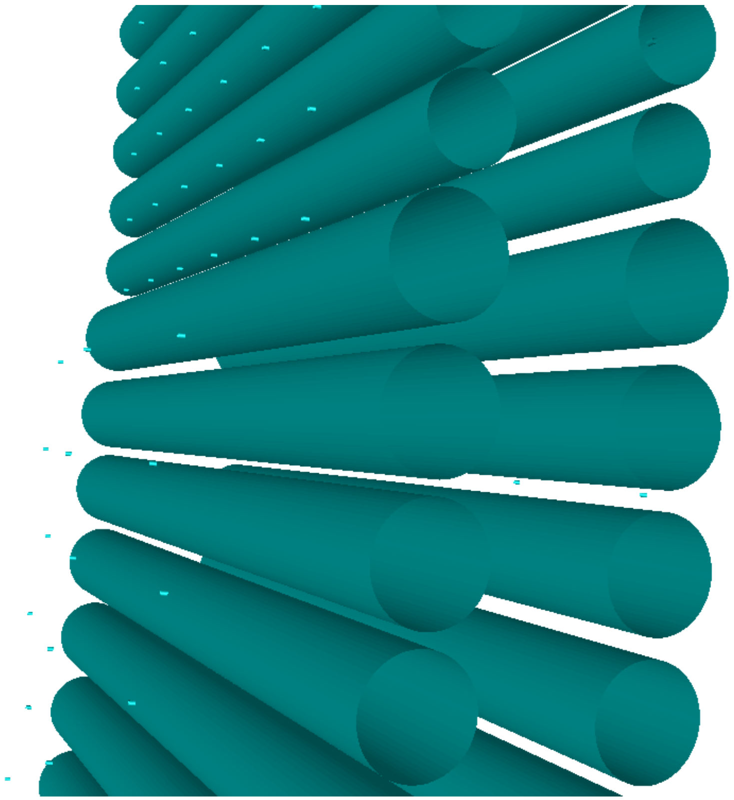




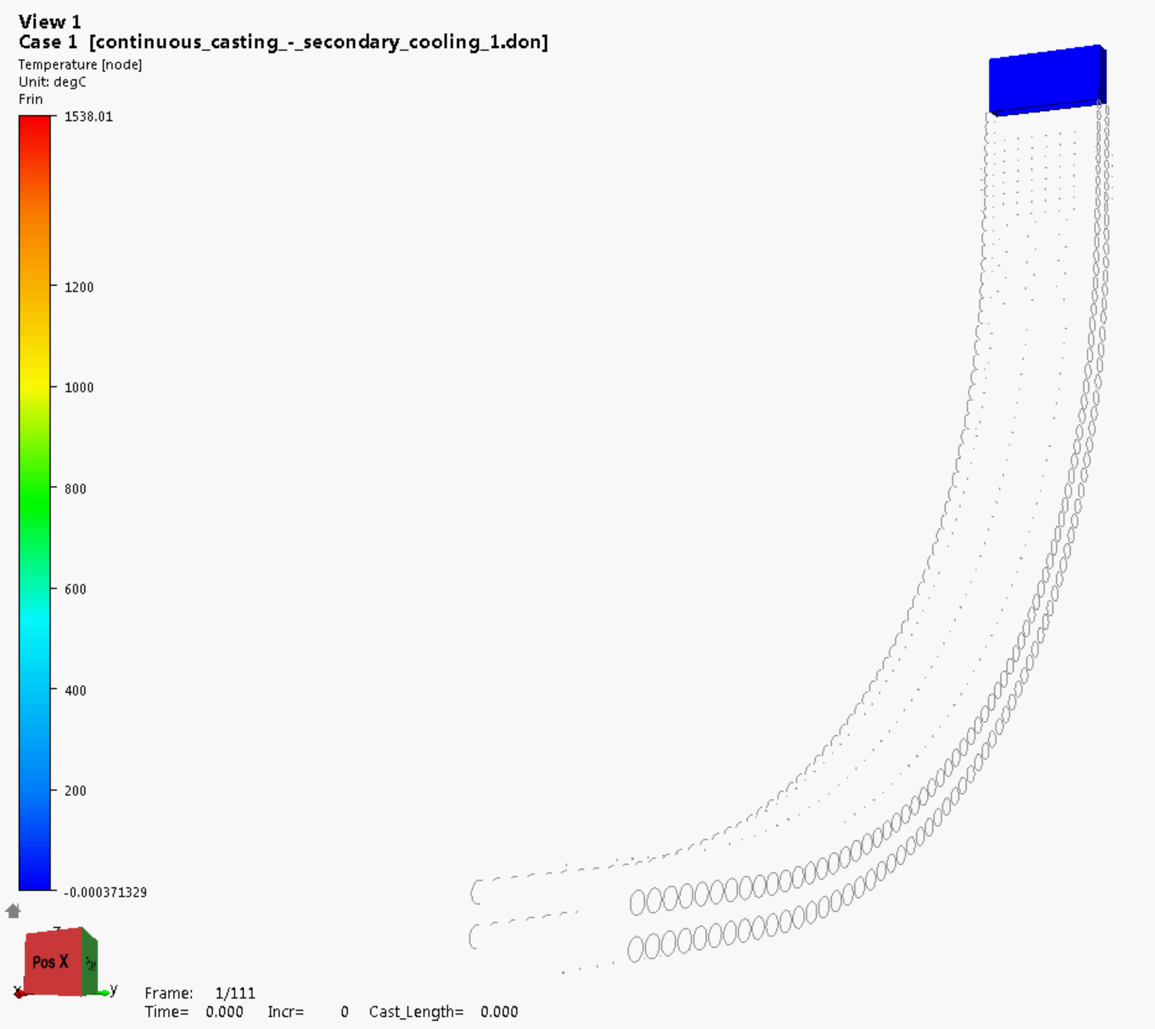
Custom actions available in THERCAST® software

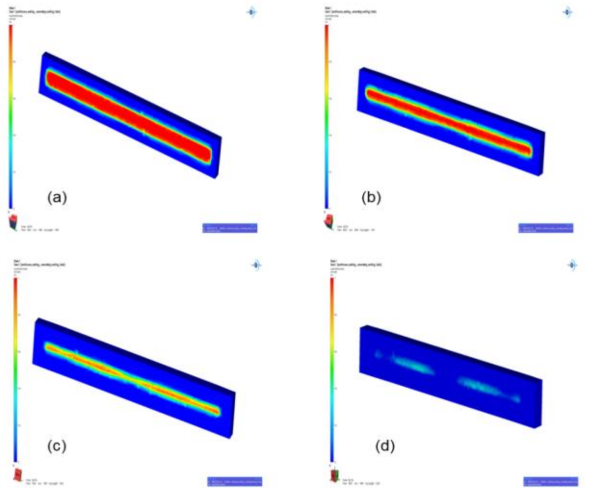
Secondary Cooling Modelling

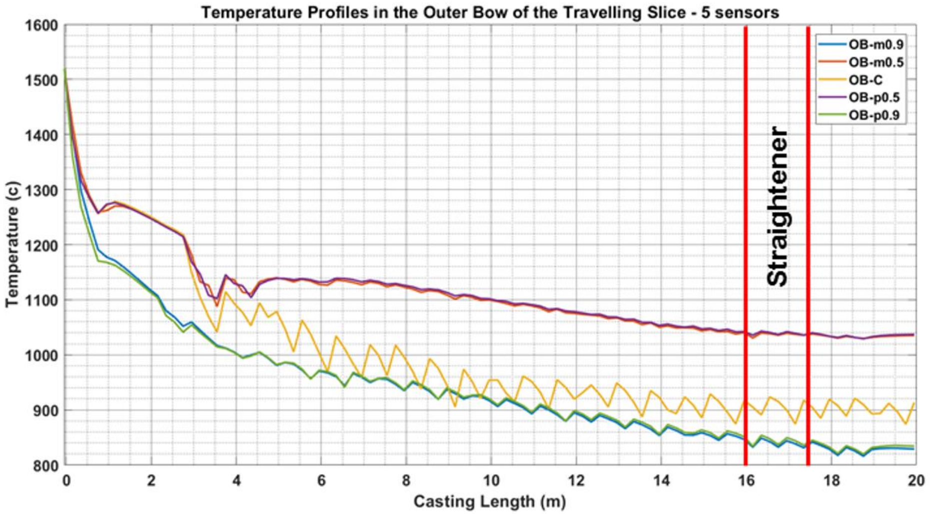




Travelling Slice



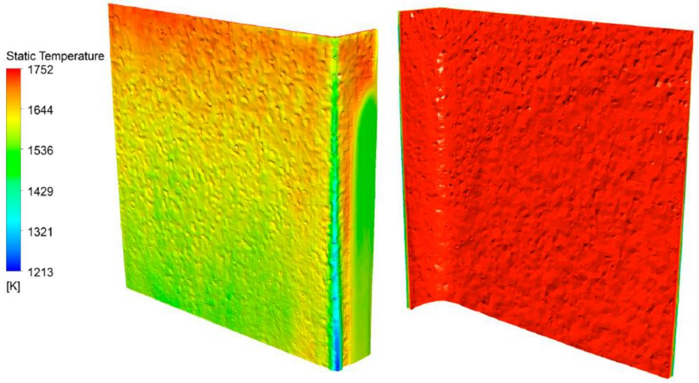


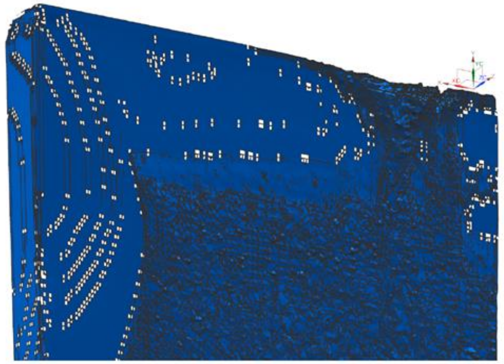


CFD-FEM Coupling

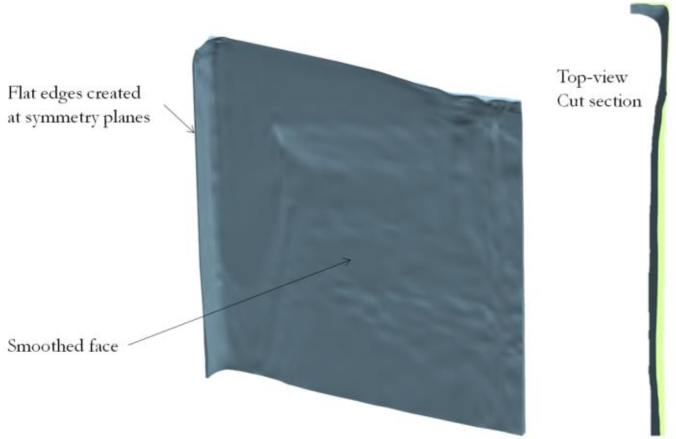
ABAQUS

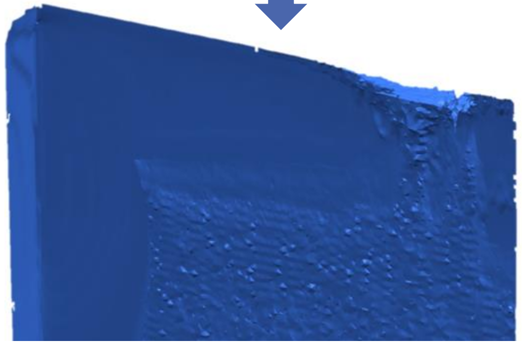
CFD results





FEM model



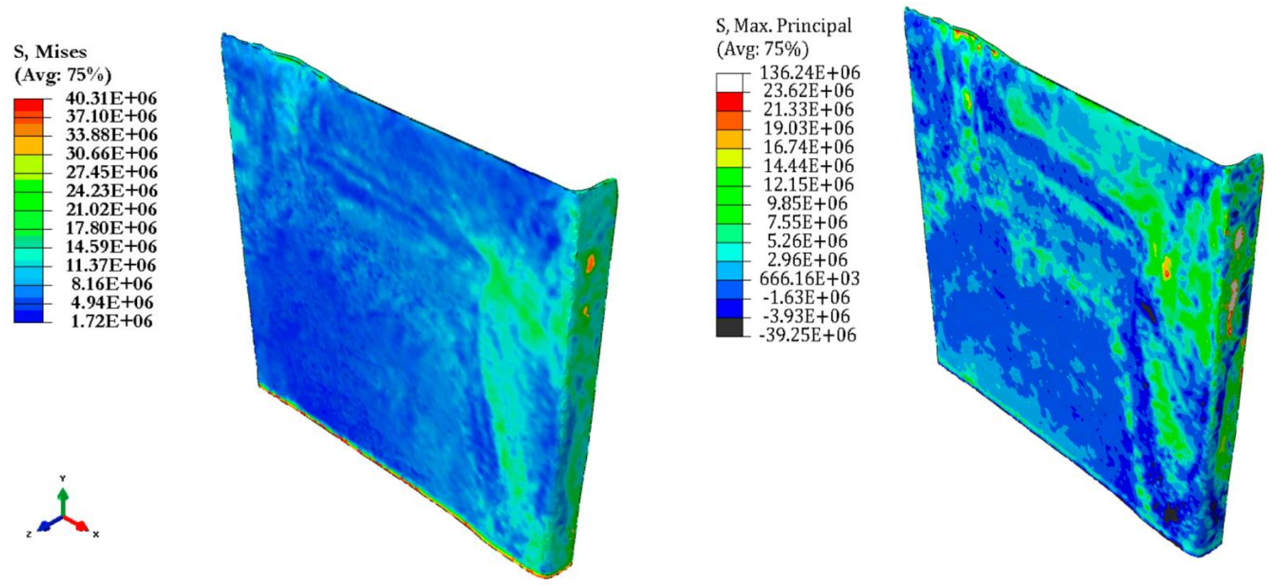


CFD-FEM Coupling

Stress Calculation

The magnitude of von Mises stresses indicates higher strains compared with the two-dimensional cases. However, the maximum stresses are limited to a few nodes, where the shell is thin and at the mould exit, where translation was fixed.

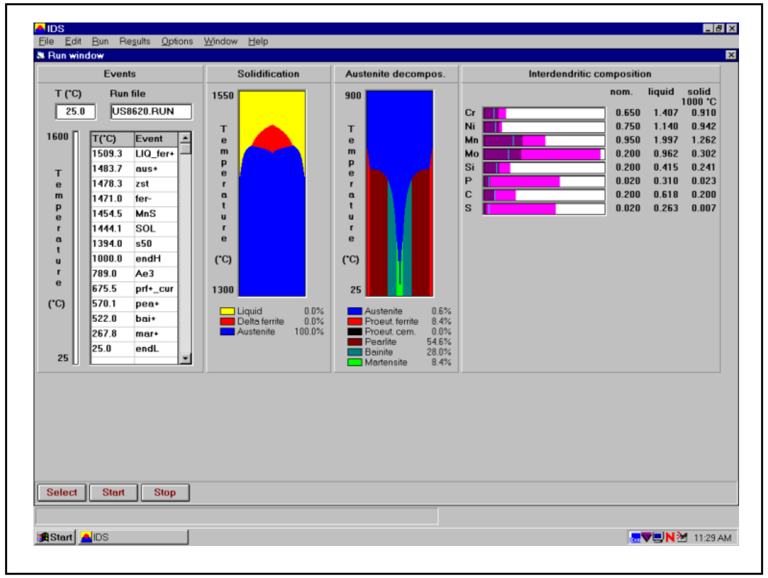
This should be corrected in future cases by a slip condition. The maximum von Mises stress read is 40.31 MPa and is found at a position in the narrow face close to the tip, where the shell is very thin. Results show that the shell is both in compression and tension for this case. Preliminary results indicate compressive stresses at the exterior and tensile at the interior.



https://www.diva-portal.org/smash/get/diva2:1018796/FULLTEXT02

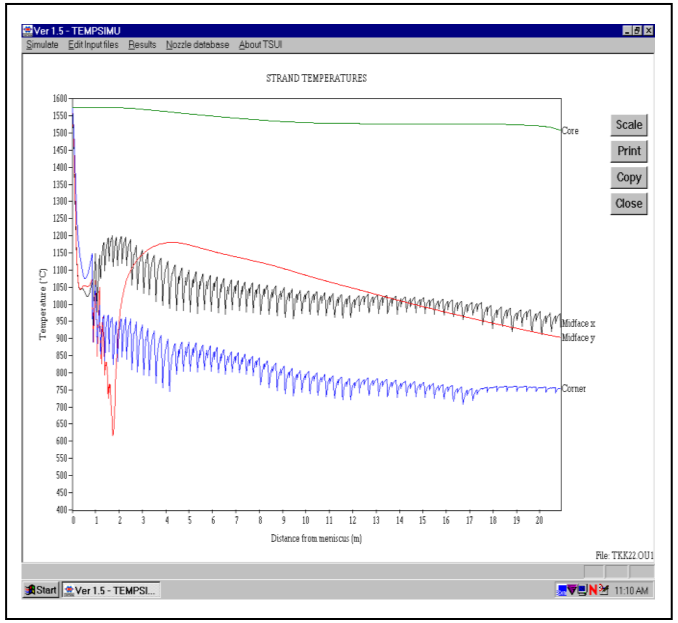
CC Models Developed by Aalto University

IDS



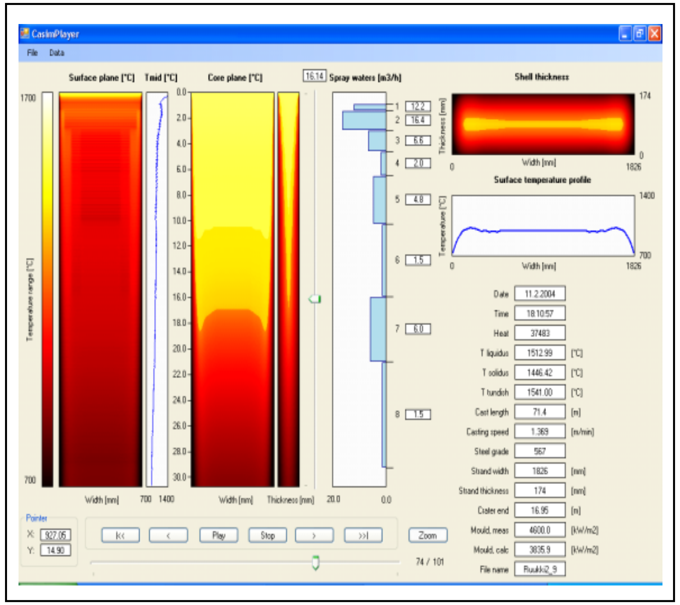
Thermodynamic-kinetic-empirical tool for solidification and micro-structure evolution from CC to hot rolling.

TEMPSIMU3D



Steady state heat transfer model for CC based on FDM

CastManager



Transient heat transfer model for CC (on-line/off-line) based on FDM

IDS (InterDendritic Solidification)

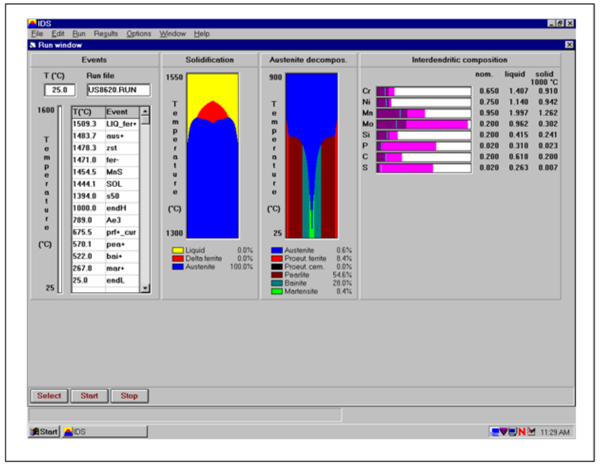
Aalto University

IDS (InterDendritic Solidification) is a thermodynamic–kinetic–empirical tool for simulation of solidification phenomena of steels including phase transformations from melt down to room temperature. The model has been developed in the Laboratory of Metallurgy, Helsinki University of Technology, Finland, since 1984. It includes:

- Calculation of important thermophysical material properties such as enthalpy, thermal conductivity, density, etc.
- IDS module to simulate the solidification phenomena from liquid down to 1000◦C.
- ADC (AusteniteDeComposition) module to simulate austenite decomposition down to room temperature. Both modules have their own recommended composition ranges.

INPUT

Steel composition
Cooling rates



OUTPUT

Solidification phenomena
Phase transformations
Micro-segregations
Microstructure evolution
Inclusions
Precipitates
Pore formation, etc.

Thermophysical material properties (H, k, C_p, L,..)
Thermal contraction
Density
Liquid viscosity
Liquid/air surface tension
Solid/liquid interface energy
Hardness, etc.

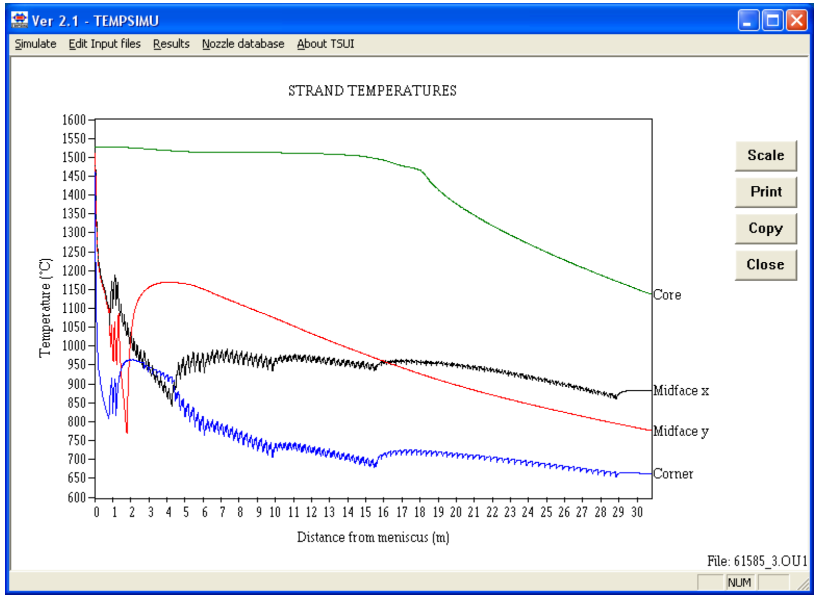
Tempsimu

3D Steady state heat transfer model for CC

Strand dimensions, locations of rolls and spray nozzles and types, zone waters, casting speed, etc.

TEMPSIMU

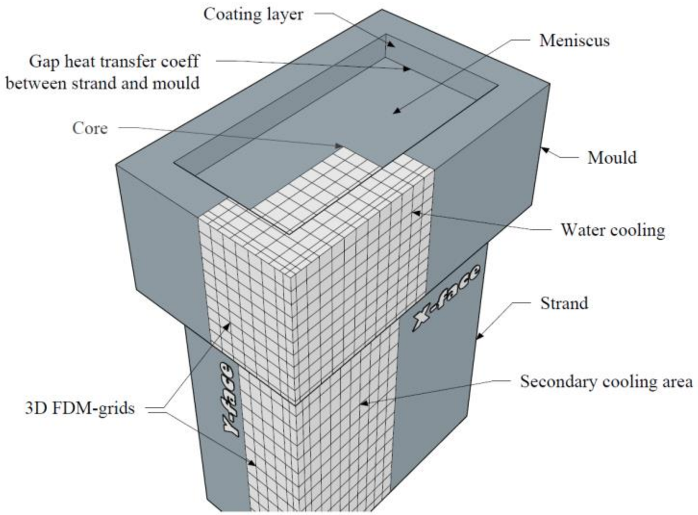
IDS: Material data



Strand temperature, shell thickness, etc.

Aalto University

Heat transfer model based on Enthalpy formulation and Kirchhoff' function



CastManager

Dynamic 3D heat transfer model for CC (transient process data is needed)

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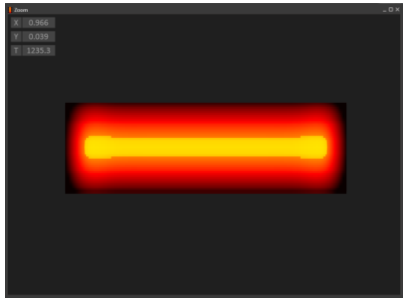
$$\rho c\frac{\partial T}{\partial t} = \frac{\partial\left(k_{eff}\frac{\partial T}{\partial x}\right)}{\partial x} + \frac{\partial\left(k_{eff}\frac{\partial T}{\partial y}\right)}{\partial y} + \frac{\partial\left(k_{eff}\frac{\partial T}{\partial z}\right)}{\partial z} + \frac{\partial v\rho c T}{\partial z} + Q$$

Enthalpy formulation

$$H(T) = \rho\int_0^T c(\xi)d\xi + \rho L(1 - f_s(T)),$$

Kirchhoff's function

$$K(T) = \int_0^T k_{eff}(\xi)d\xi.$$



$$\frac{\partial H}{\partial t} + v\frac{\partial H}{\partial z} = \Delta K(T), \qquad \frac{\partial H(T)}{\partial t} = \Delta K(T)$$

Transient 3D heat transfer and solidification

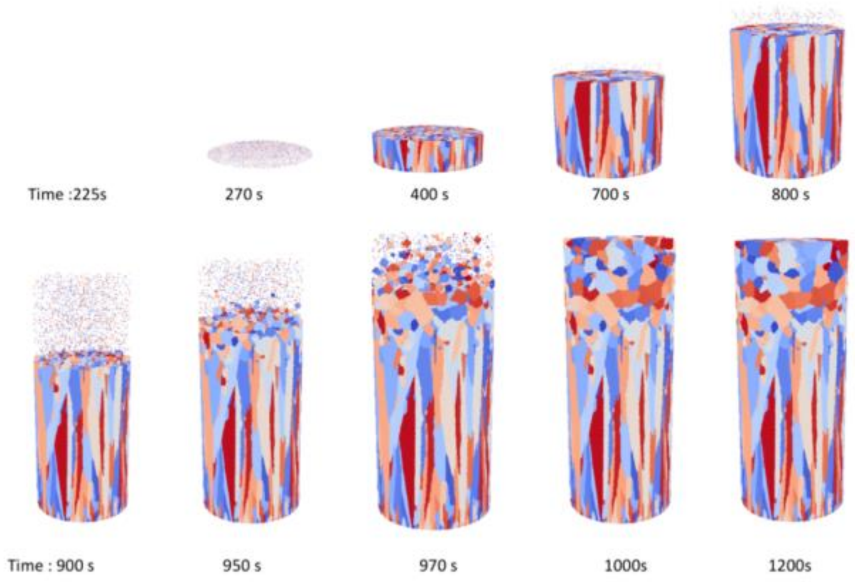
Computational Meso-Scale Models

SPrime

SPrime code is a proprietary solidification grain structure modeling algorithm developed by Think Solidification company based OpenFOAM code. It was designed for direct grains envelopes tracking and it can be applied for the prediction of metallic alloys solidification.

The original code is designed for ingot casting where SWERIM and Think Solidification are collaborating to adapt the code for CC process. The model includes:

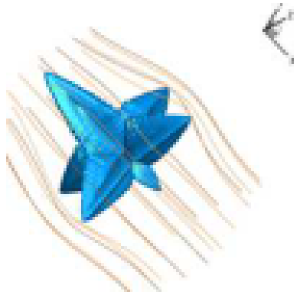
- Fluid flow, heat transfer and solidification.
- Microstructure modelling through grain envelop tracking
- Possibility to be coupled with Lagrangian Particle Tracking (LPT)
- Possibility of EMS application through source term manipulation.



Phase Field Microstructure Modelling

https://micress.rwth-aachen.de/

µMatIC



https://www.imperial.ac.uk/engineering-alloys/research/software/

http://openphase-solutions.com/

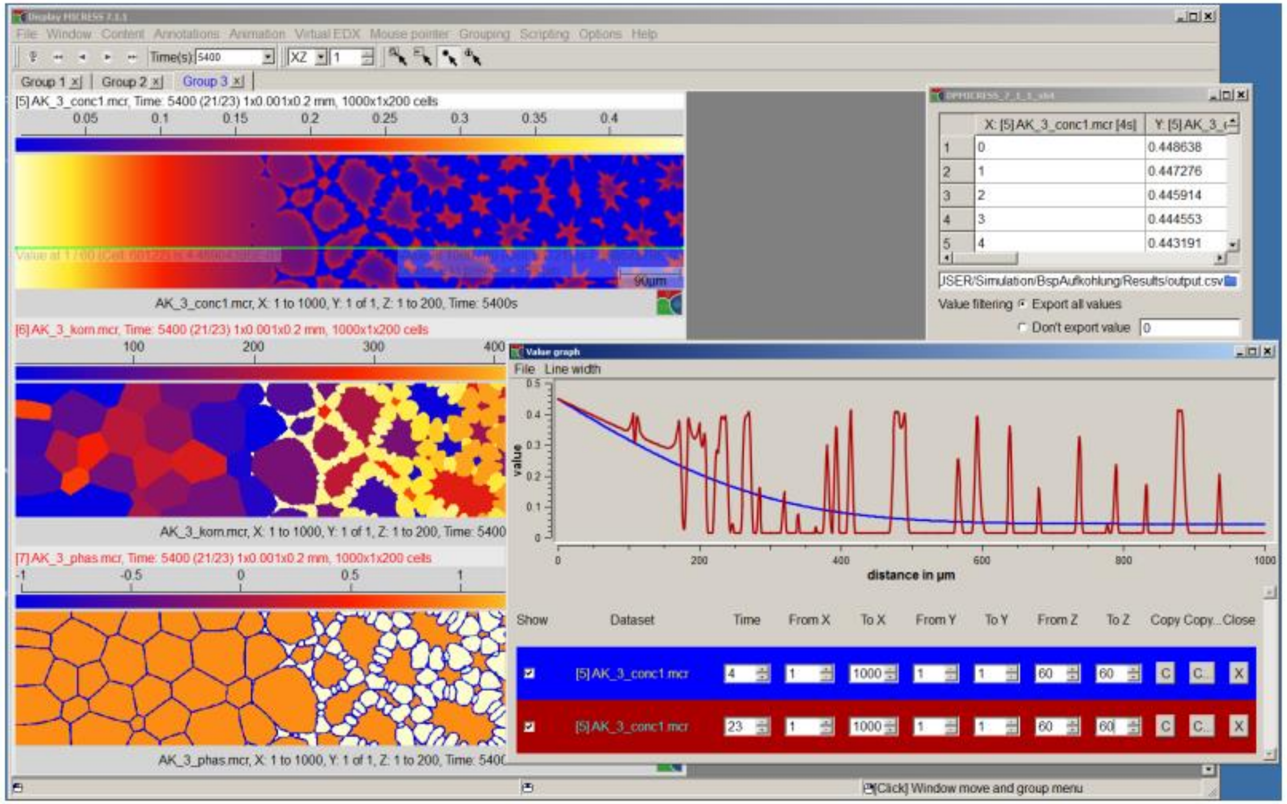
Phase Field Modelling

MICRESS (The Microstructure Evolution Simulation Software)

MICRESS is a software package that enables the calculation of microstructure formation during phase transformations.

It is maintained and distributed by ACCESS e.V., a non-profit research center at the Aachen University of Technology (RWTH).

The software is based on the multiphase-field concept where the evolution of a microstructure is essentially governed by thermodynamic driving forces, diffusion and interfacial curvature.



Phase Field Modelling

MICRESS

The backbone of MICRESS® is the multiphase field method for multicomponent alloys and enables the treatment of multiphase, multigrain and multicomponent problems. The code includes different modules as follow:

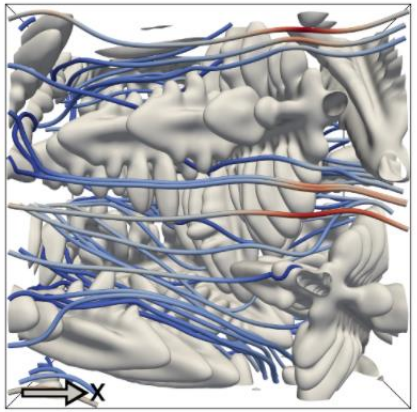
TQ module: The MICRESS® TQ module allows to interface to commercially available thermodynamic and mobility datasets being provided by ThermoCalc.

Elastic module: This module allows the calculation of elastic stresses originating form phase-transformations and also the influence of elastic stresses and strains on phase formation. Examples are the formation of cubic γ' and rafting in superalloys.

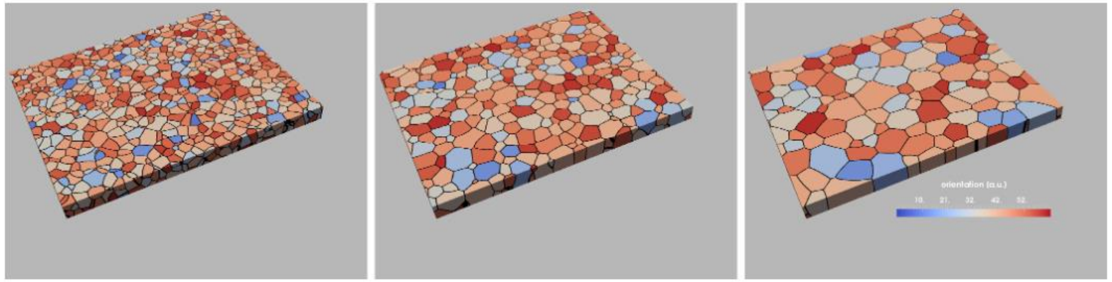
Flow module: This module allows investigating the effect of flow on phase formation and the effect of moving boundaries on evolving flow patterns. Typical applications of this module are the determination of the permeability of mushy zones or dendritic growth in a flowing liquid.

Equiaxed and Directional Solidification of a AlSi7Mg03 Alloy

CFD simulation of melt flow through a microstructure



Grain growth and re-crystallization



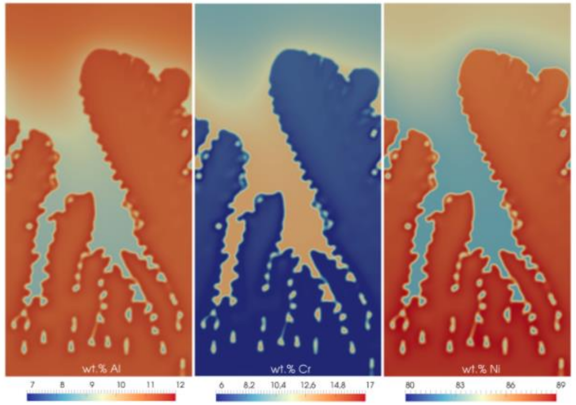
Phase Field Modelling

OpenPhase Solution

OpenPhase is a microstructure simulation suite made for metallic materials, ceramics and minerals. Using multi-physics models embedded in the phase-field method.

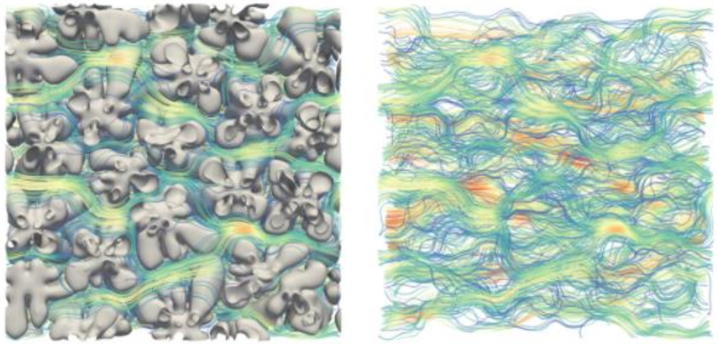
- **Dendritic solidification** simulation could be conducted with OpenPhase. The focus is on **the transport of alloying elements** by means of **fluid flow and diffusion** in liquid, as well as solid.

- Thermodynamic and kinetic data can be obtained from Thermo-Calc®, OpenCALPHAD or supplied directly by the user.



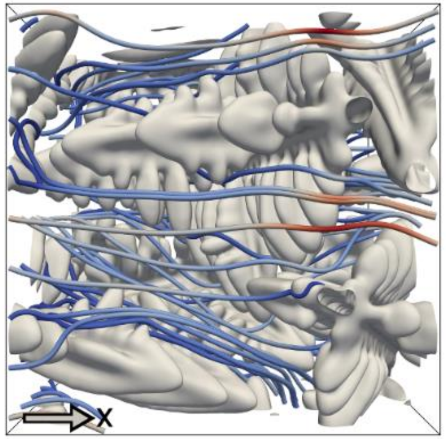
- OpenPhase includes a **Lattice-Boltzmann solver**, which can be used concurrently with the phase-field simulation or sequentially.

- In this example here, a dendrite forest was obtained from a Mg-5%Al-cast alloy solidification simulation. Then, the permeability of this dendrite forest for the melt was evaluated using the Lattice Boltzmann solver.



Engineering Applications

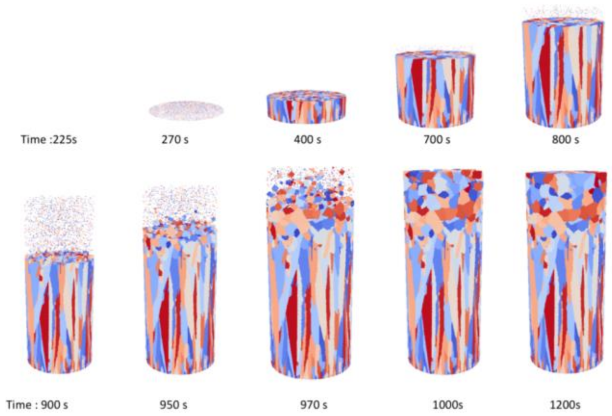
Microstructure



Phase-field & cellular automaton models: MICRESS, OpenPhase, CAFE, ...

- High resolution in prediction of microstructures formed during solidification.
- Coupled with thermodynamic databases e.g. Thermo-Calc or JMatPro.
- Small computational domain.
- High computational cost.

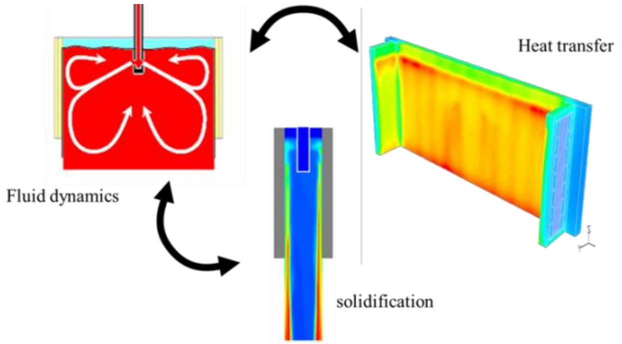
Meso-Scale Models



Coupled macro scale models with e.g. direct grains envelopes tracking technique: Sprime, Thercast-CAFE, … .

- Prediction of fluid flow as well as solidification including a simplified microstructure & segregation model.
- Potential to be applied to industrial scale problems.
- Moderate computational cost.
- The model lacks the microstructure features from MICRESS and CAFE models.

Macroscale



Macroscale computational codes based on CFD, FEM, etc numerical methods: FLUENT, OpenFOAM, THERCAST, MAGMA, … .

- Applicable to 2D-3D industrial scale problems.
- Lower computational cost.
- Coupled multiphase approach (steel-slag-argon gas)
- Possible coupling of slag-metal reactions through thermodynamic data bases.
- Coupled multiphysics e.g. EMS and EMBr applications.
- The model lacks accurate prediction of microstructure and segregation.

μm mm cm/m m

Length Scale

Thanks for the attention!

Stay informed

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