Cooling and hardening during injection molding of field joint coatings for deep sea pipelines

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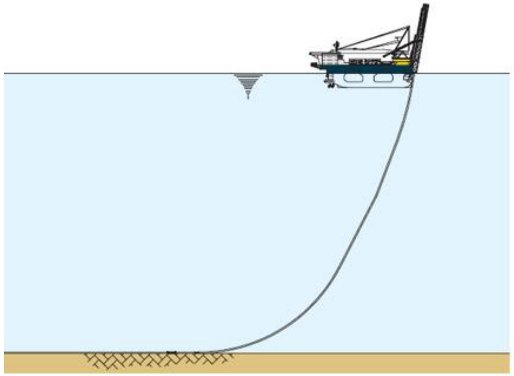
Field joint coatings for deep sea pipelines



Field joint coating application process

Pipe sections
Welded together

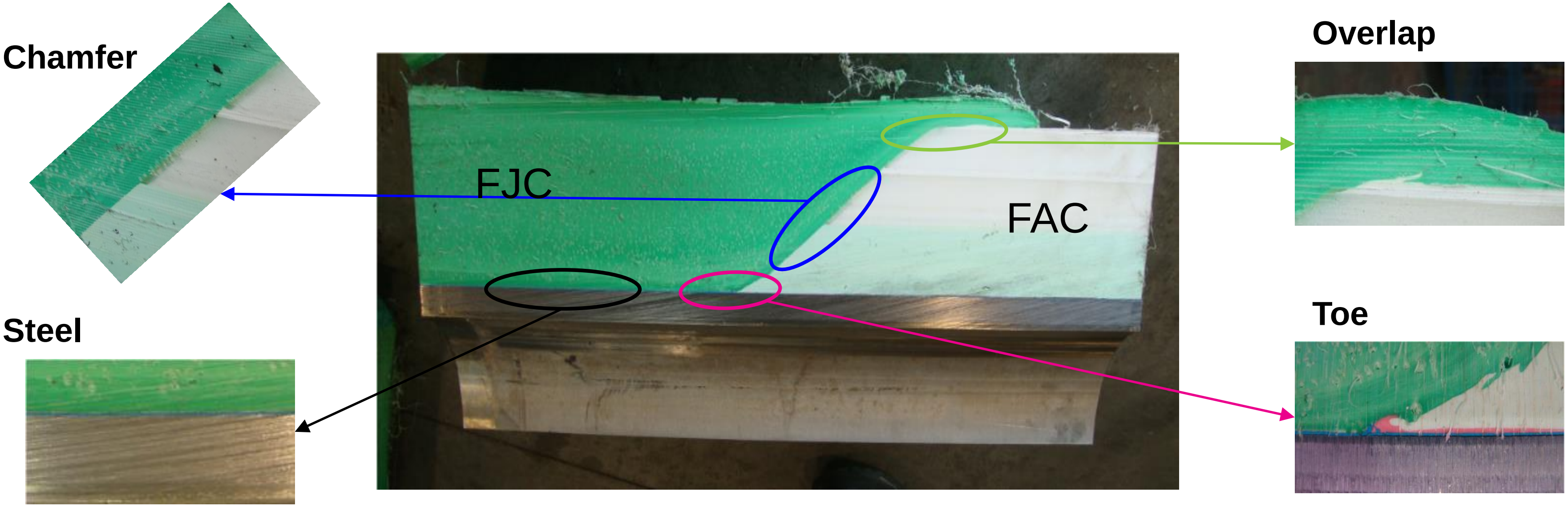
Surface cleaning
Grit blasting

FBE application
Corrosive protection

Injection moulding
Thermal insulation

Field joint
Needs cooling

Field joint coatings for deep sea pipelines



Challenges:

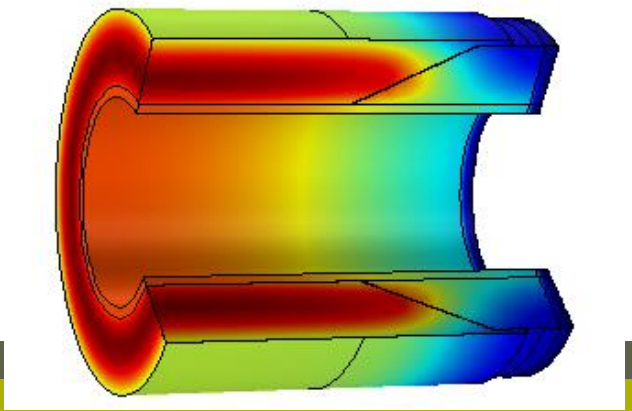
- Insufficient bonding and cracks
- Processing optimization

Aim:

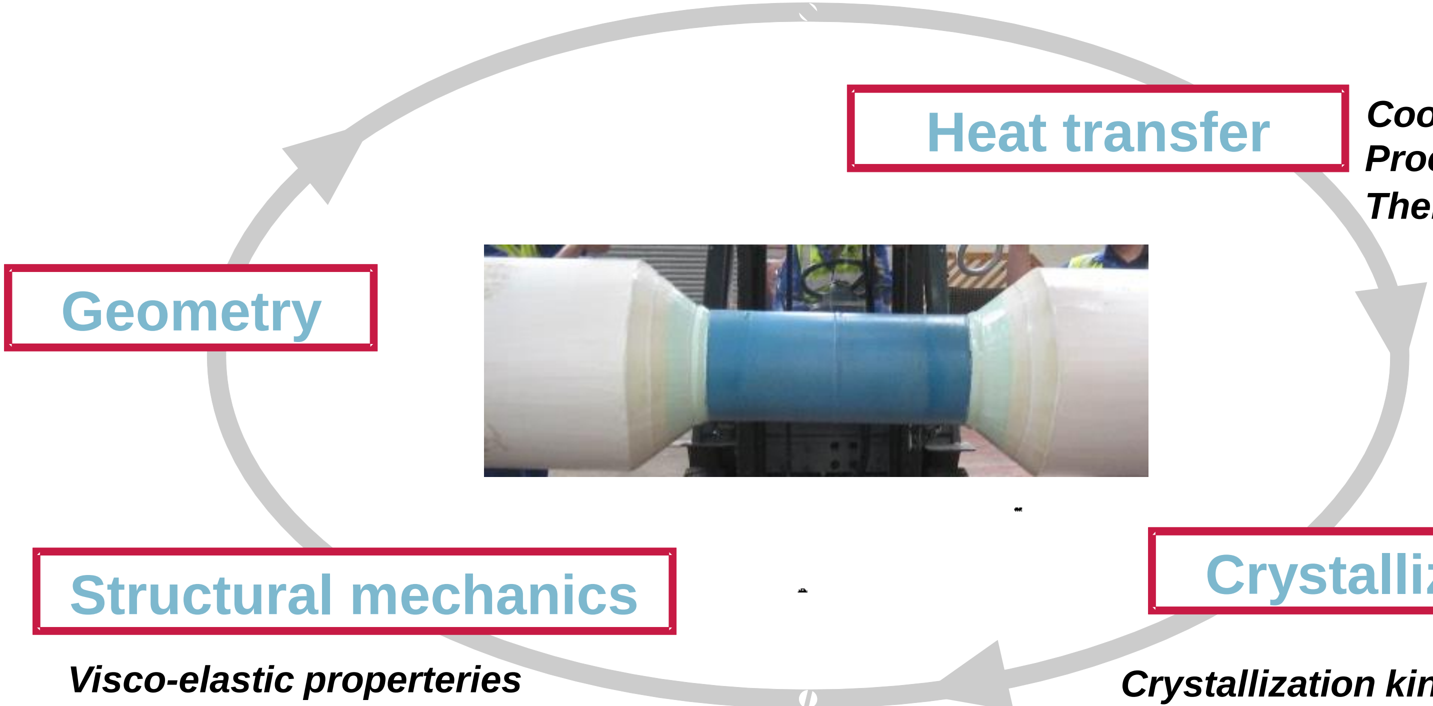
1. Understanding FJC process
2. Support optimization FJC process:
   - Materials
   - Process conditions

Approach:

1. Build a FEM model
2. Acquire experimental data



Physicochemical aspects of the FJC process



Heat transfer

Cooling rates
Process conditions
Thermal shrinkage

Geometry

Crystallization

Crystallization kinetics
Crystallization shrinkage

Structural mechanics

Visco-elastic properteries
Stress calculation

Multiphysics problem:
- Heat transfer
- Crystallization
- Structural mechanics

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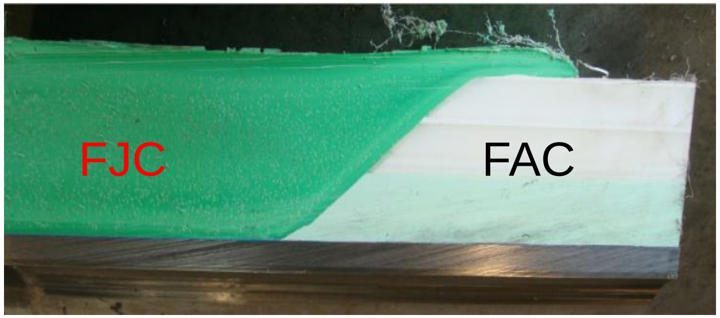
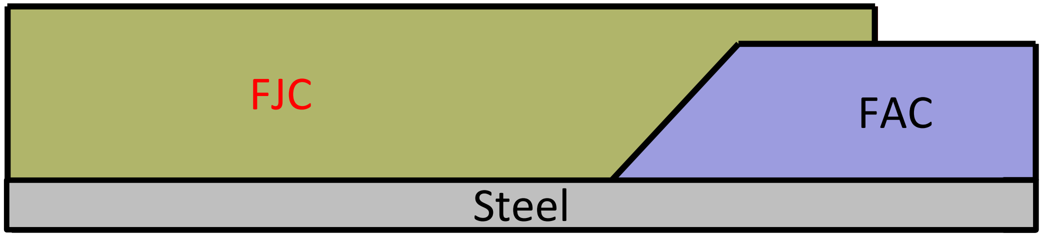
Model: geometry and process steps

Geometry



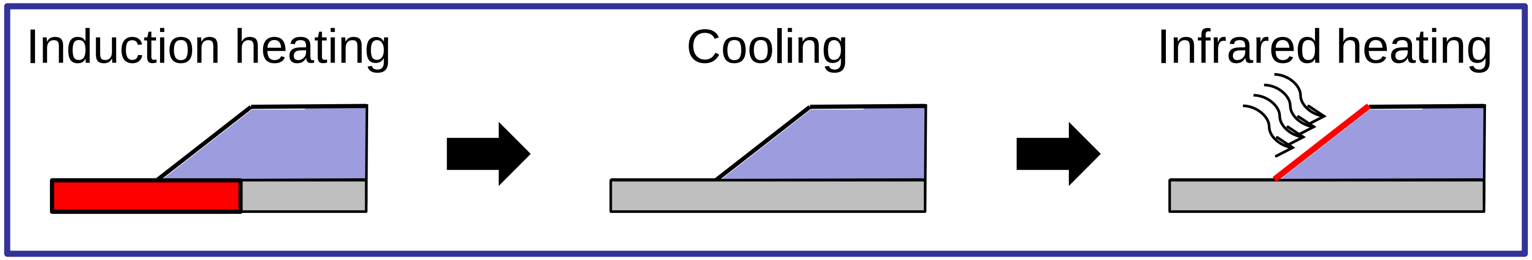
Field joint coating (FJC)



Factory applied coating (FAC)

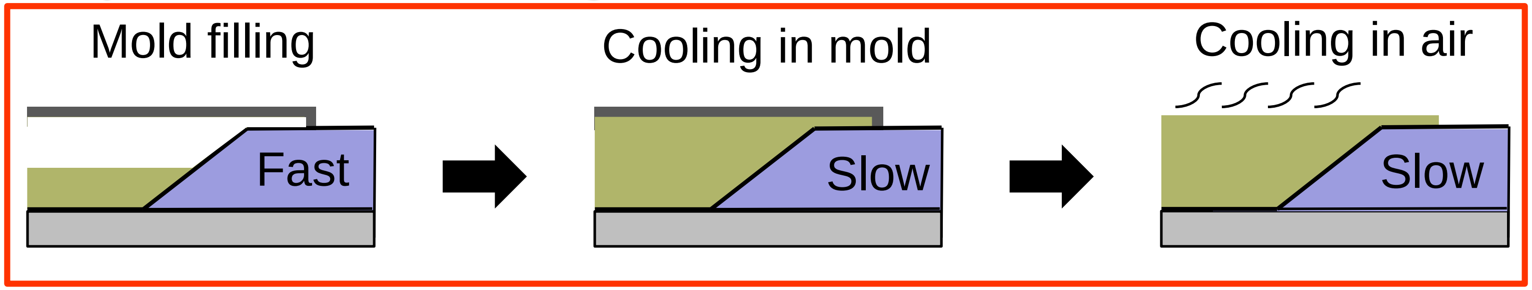
Process steps

Pretreatment



Induction heating → Cooling → Infrared heating

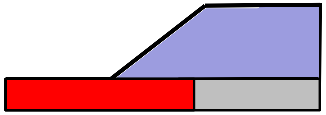
Crystallization and cooling



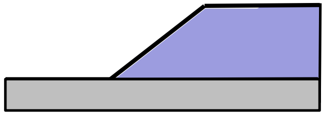
Mold filling → Cooling in mold → Cooling in air

Simulation pretreatment steps

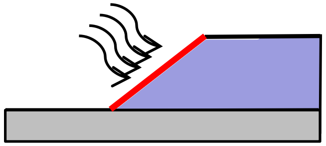
Purpose: obtain realistic T-distributions for cooling and crystallisation



1. Induction heating



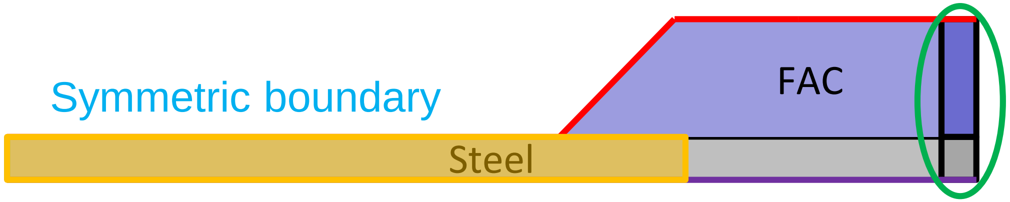
2. Cooling



3. Infrared heating

1. Induction heating

- Domain heat scource
- T_{max} steel reached 260°C

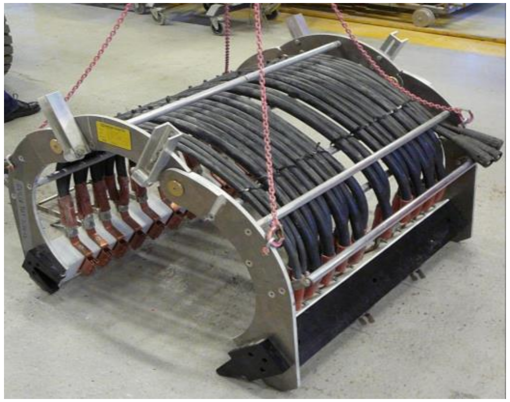


Natural convection: long horizontal cylinder

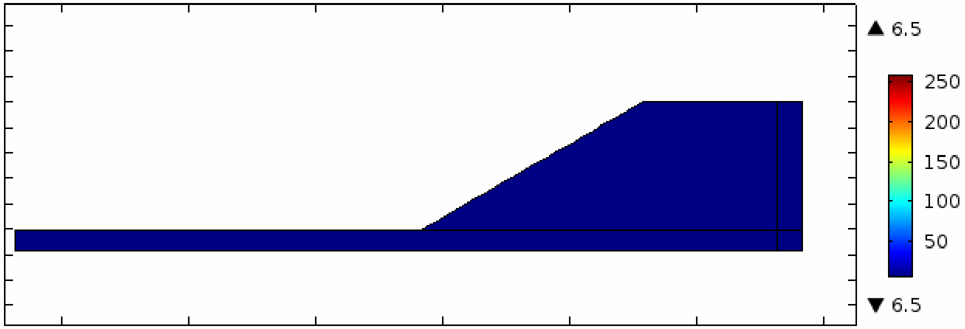
Symmetric boundary

Convective cooling

Infinite element domain



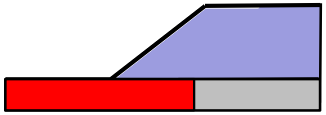
Temperature



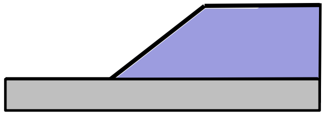
Potential degradation polymer at toe

Simulation pretreatment steps

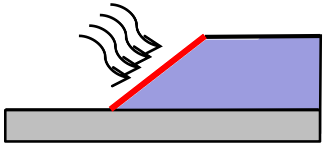
Purpose: obtain realistic T-distributions for cooling and crystallisation



1. Induction heating



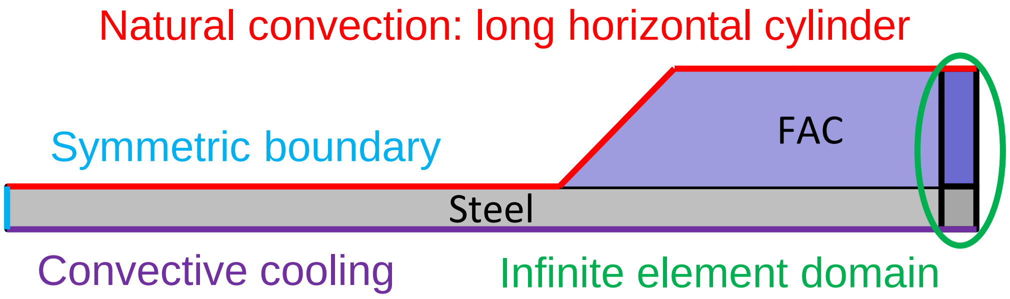
2. Cooling



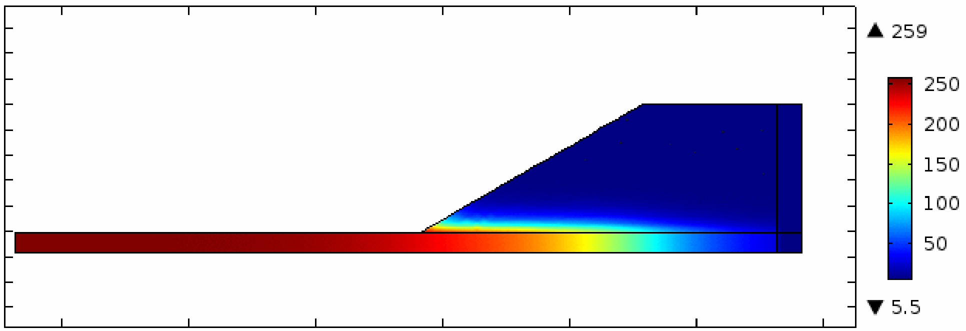
3. Infrared heating

2. Cooling + FBE application

- FAC acts as heat sink
- T_{max} steel 235°C

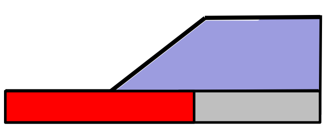


Temperature

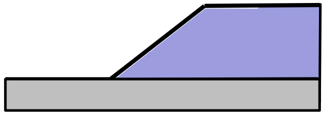


Simulation pretreatment steps

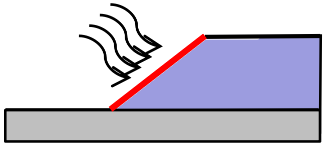
Purpose: obtain realistic T-distributions for cooling and crystallisation



1. Induction heating



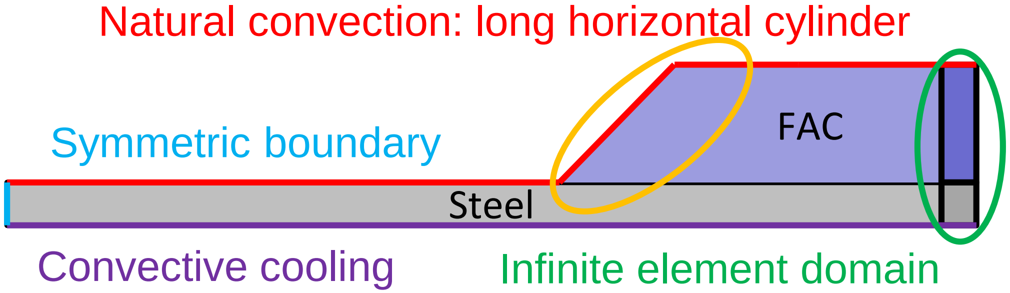
2. Cooling



3. Infrared heating

3. Infrared heating chamfers

- Domain heat scource
- Beer-Lambert law
- T_{max} at middle chamfer 100°C



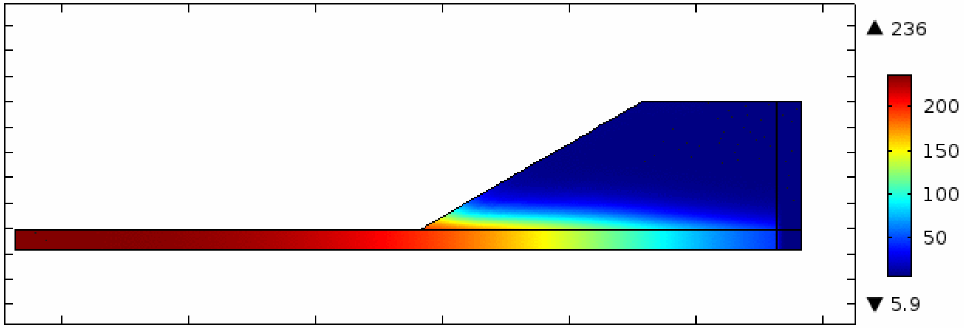
Natural convection: long horizontal cylinder

Symmetric boundary

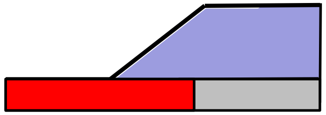
Convective cooling

Infinite element domain

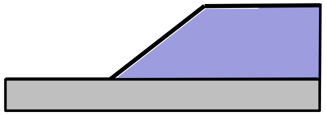
Temperature



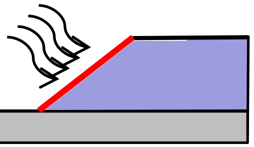
Simulation pretreatment steps vs. experimental data



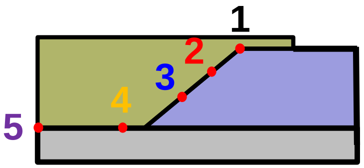
A. Induction heating



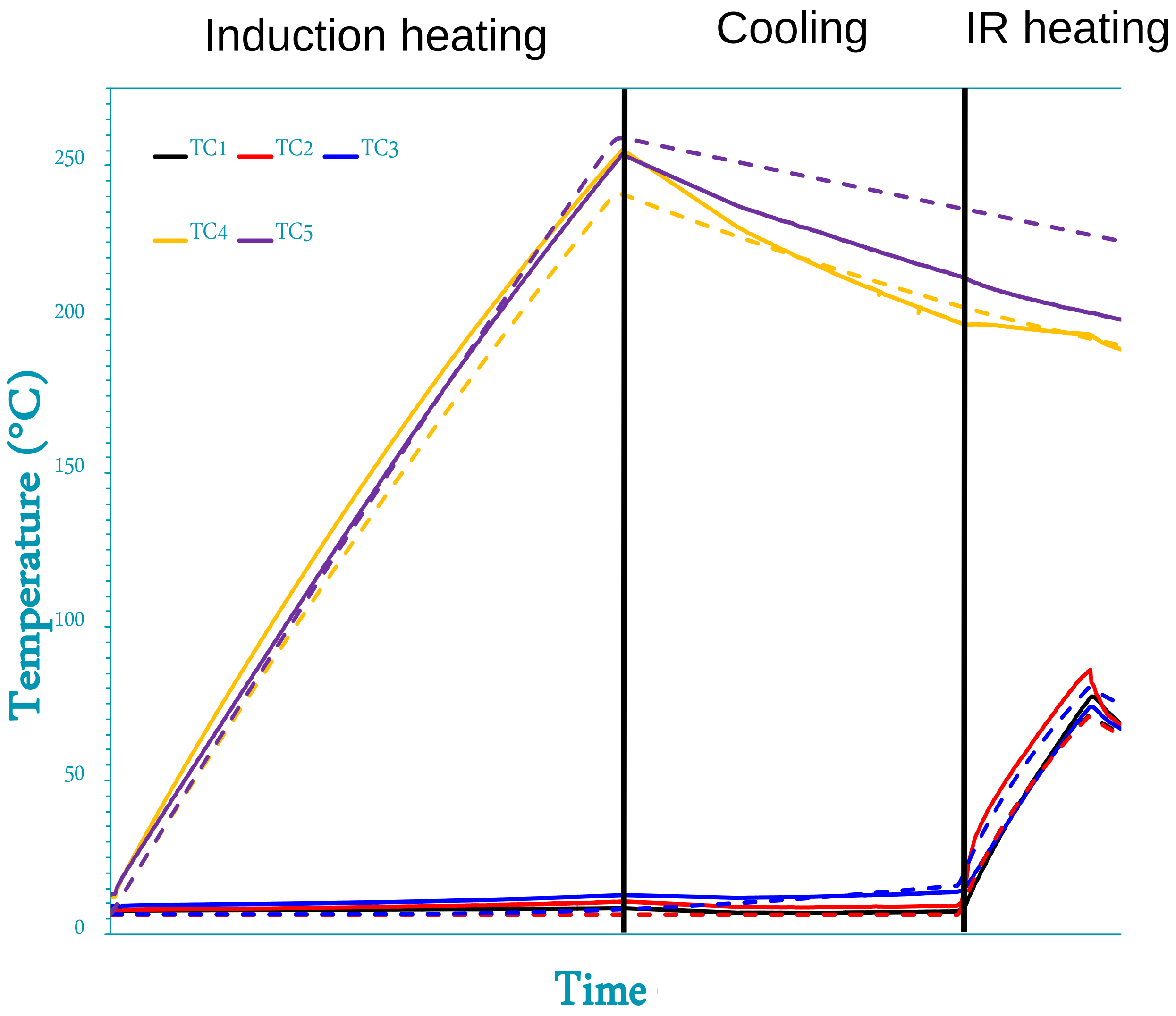
B. Cooling



C. Infrared heating



Locations thermocouples

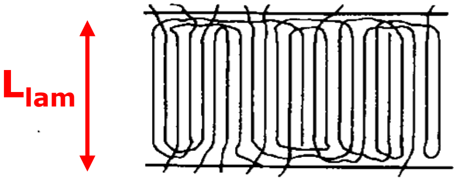


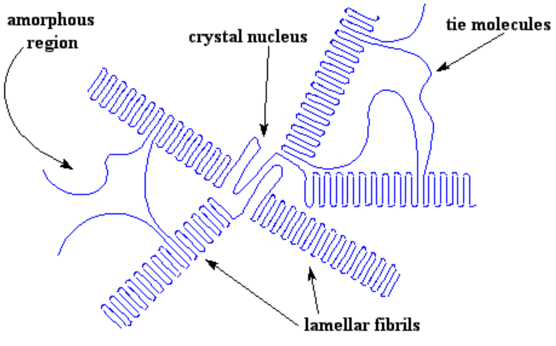
Experimental (Solid) Model (Dashed)

Cooling and crystallization: principles polymer crystallization

Polymer crystal morphology

- Folded chain lamellar (single) crystals
- Lamellar thickness L_{lam}:
  - $L_{\mathrm{lam}} \div 1/(T_M - T_C) \div 1/\Delta T$

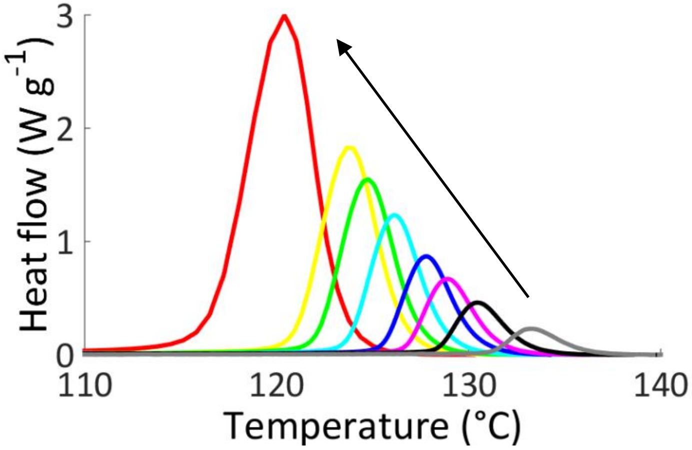




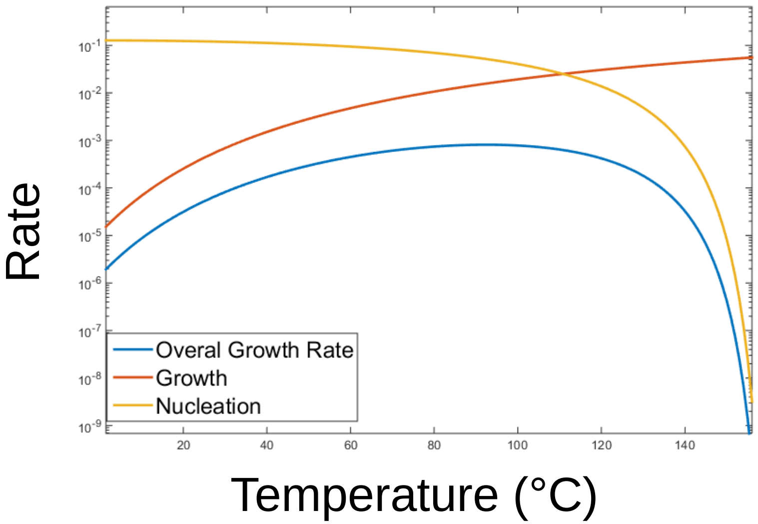
a polymer crystalline spherulite

Formation spherulites

Differential scanning calorimetry in cooling



Polymer crystallization kinetics



Crystallization kinetics model: description

Haudin & Chenot model[1]:

Nucleation

$$\frac{dN}{dt} = -N\left(q + \frac{1}{1-\alpha}\frac{d\alpha}{dt}\right) + (1-\alpha)\frac{dN_0(T)}{dT}\frac{dT}{dt}$$

N number of potential nuclei

$$\frac{dN_a}{dt} = qN \qquad \frac{d\tilde{N}_a}{dt} = \frac{qN}{1-\alpha}$$

N_a number activated of potential nuclei

Growth

$$\frac{d\alpha}{dt} = 4\pi(1-\alpha)G(F^2\tilde{N}_a - 2FP + Q)$$

α relative crystallinity

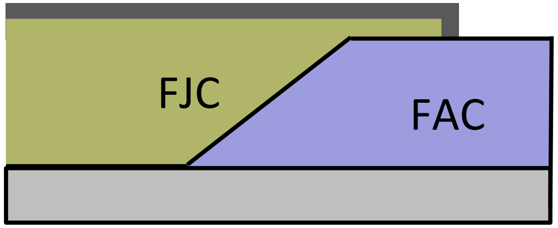
Aid functions

$$\frac{dF}{dt} = G \qquad \frac{dP}{dt} = F\frac{d\tilde{N}_a}{dt} = F\frac{qN}{1-\alpha} \qquad \frac{dQ}{dt} = F^2\frac{d\tilde{N}_a}{dt} = F^2\frac{qN}{1-\alpha}$$

Implemented in COMSOL using domain ODEs

Domain heat source for crystallization heat:

$$Q_0 = \Delta H_{cryst}\rho\frac{d\alpha}{dt}$$



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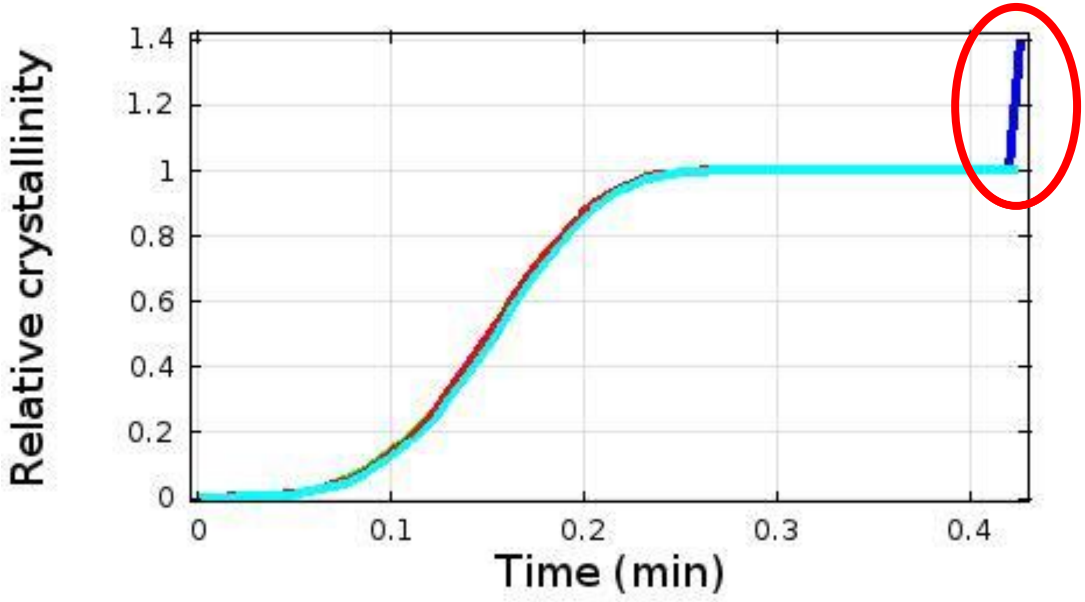
[1] *J.-M. Haudin, J.-M. Chenot, Intern. Polym. Process, XIX (2004) 3 267-274*

Crystallization kinetics model: instabilities



Relative crystallinity α:

Numerical calculation
out of limits [0,1]

Instability

Avoided by
transformation function

Stable solution:

b [-∞, +∞]

a [0,1]

$$\alpha = \frac{\mathrm{erf}(b)}{2} + \frac{1}{2}$$

$$\frac{d\alpha}{dt} = 4\pi(1-\alpha)G(F\tilde{N}_a - 2FP + Q)$$

$$\frac{db}{dt} = 4\pi G\left(F\tilde{N}_a - 2FP + Q\right) * \frac{1}{2} erfcx(b)$$

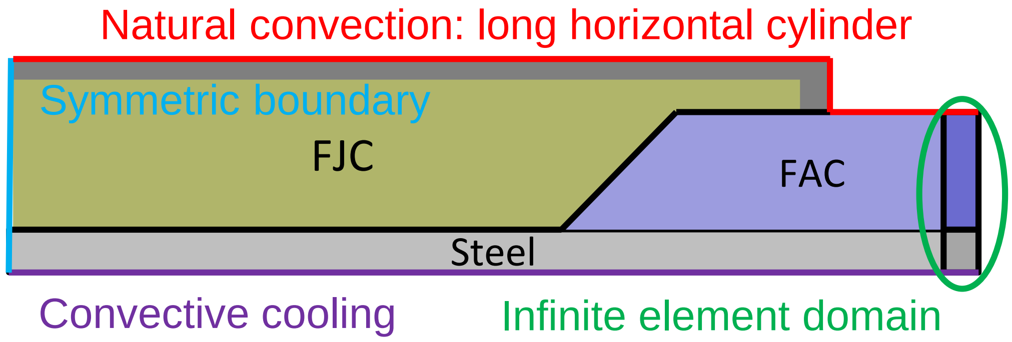
Cooling and crystallization: **in mold**

Short injection time

T_{mold} =15°C
T_{FJC} =220°C
} Large ΔT

⬇

Mesh refinement at boundaries
DOF: 290571



Natural convection: long horizontal cylinder

Symmetric boundary

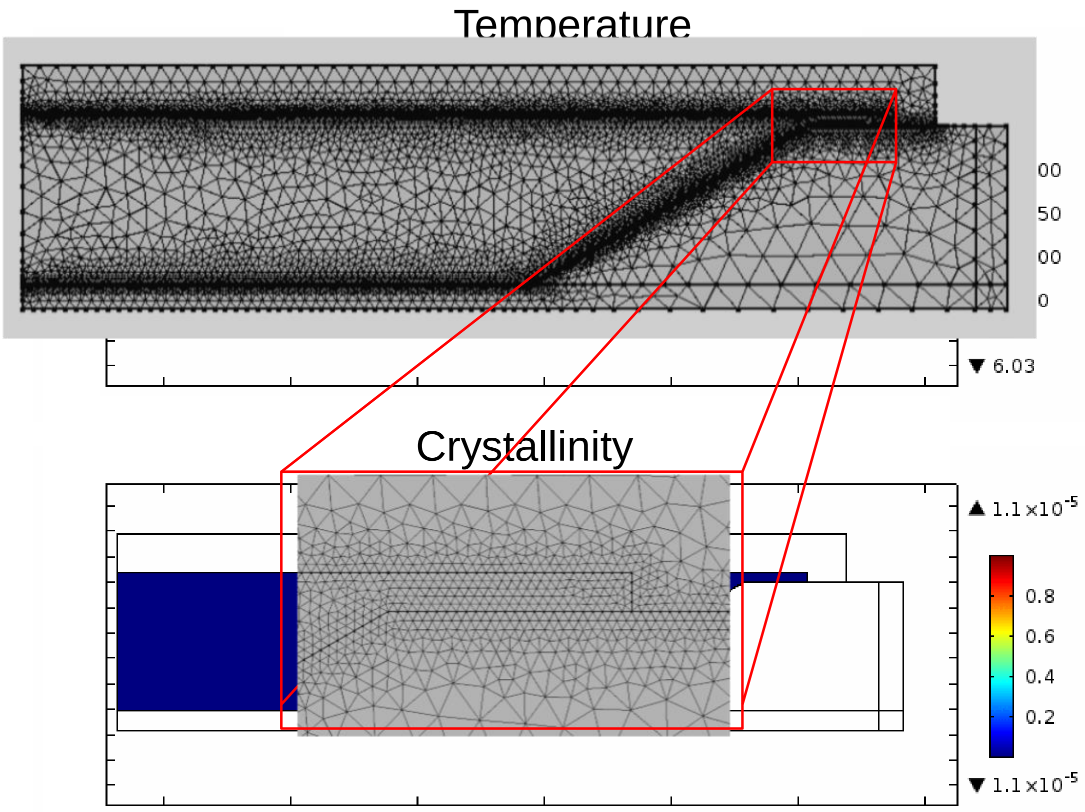
FJC

FAC

Steel

Convective cooling

Infinite element domain



Temperature

Crystallinity

Cooling and crystallization: **in air**

Short injection time

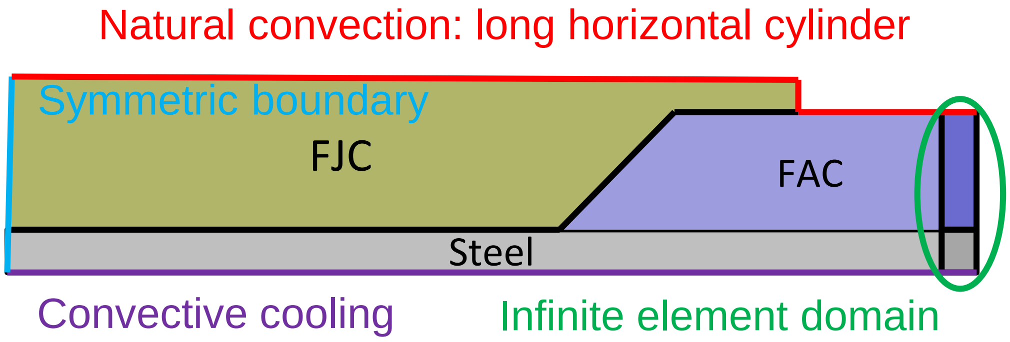
T_{mold} =15°C
T_{FJC} =220°C

Large ΔT

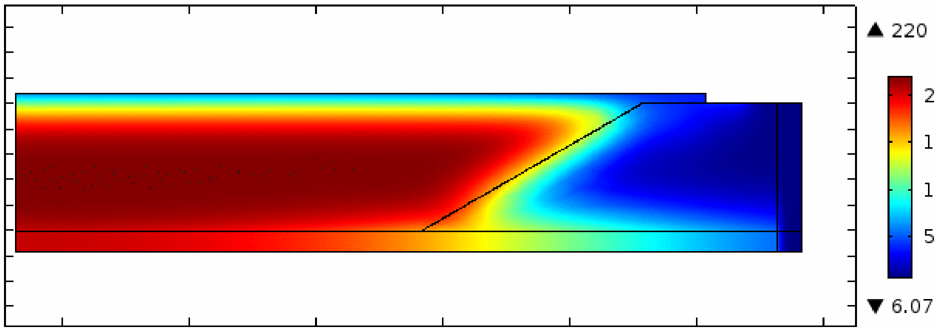
↓

Mesh refinement at boundaries
DOF: 290571
Demold after minutes

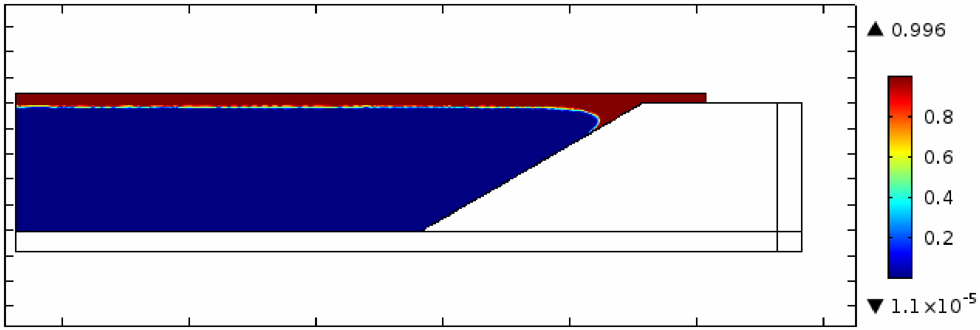
After hours still liquid in center
Thickness of the crystallized layer compares favorably to experiment



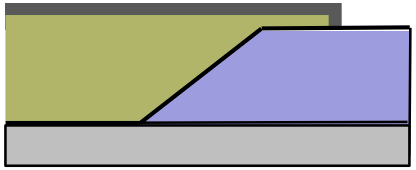
Temperature



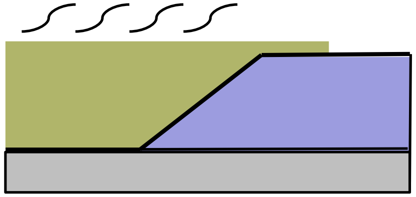
Crystallinity



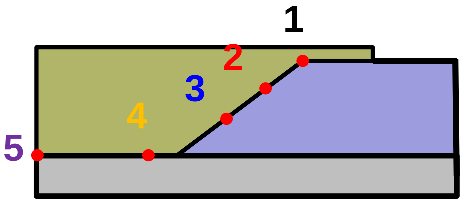
Cooling and crystallization: model vs. experimental



A. Cooling in mold



B. Cooling in air



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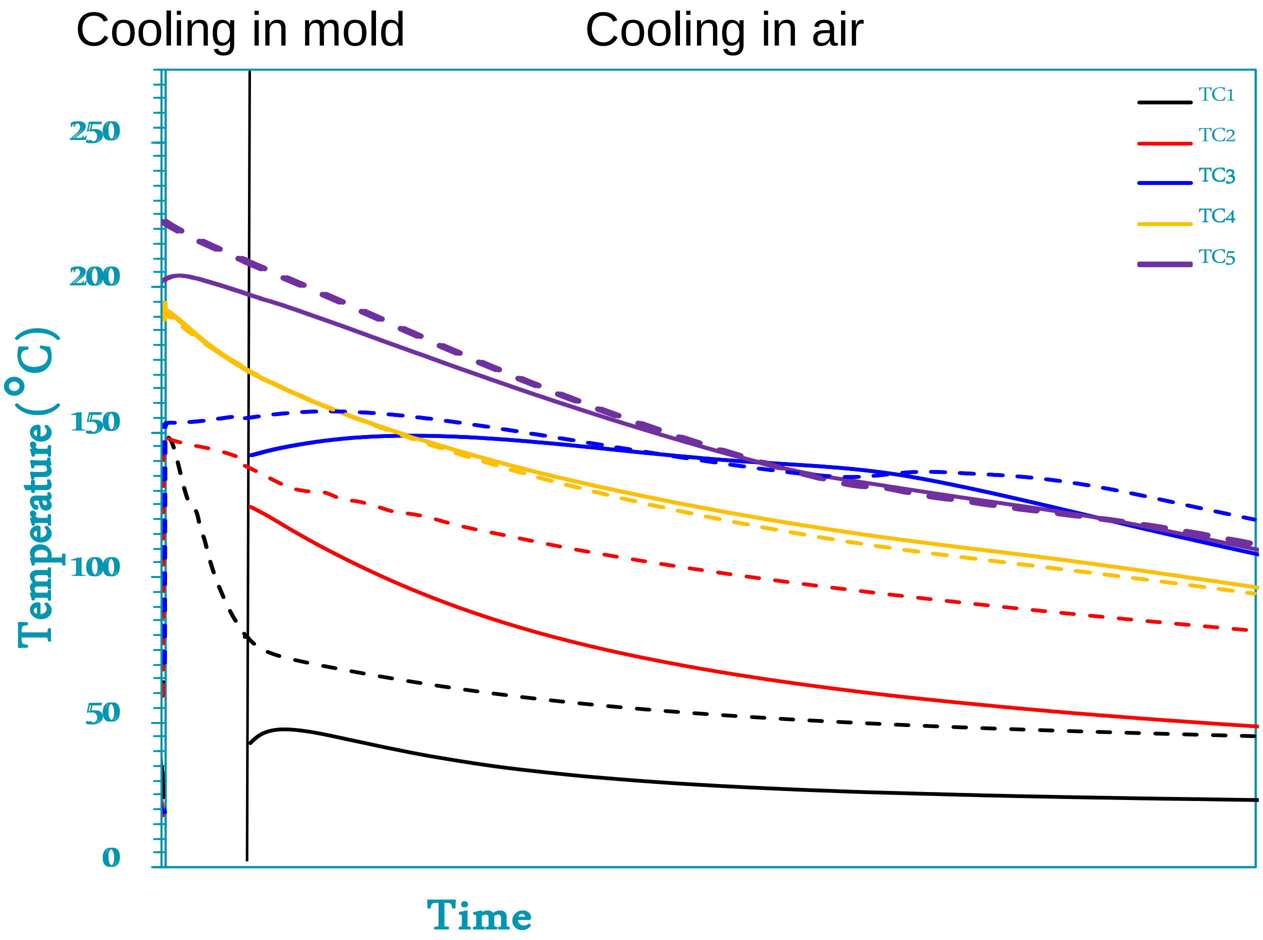


Experimental (Solid) Model (Dashed)

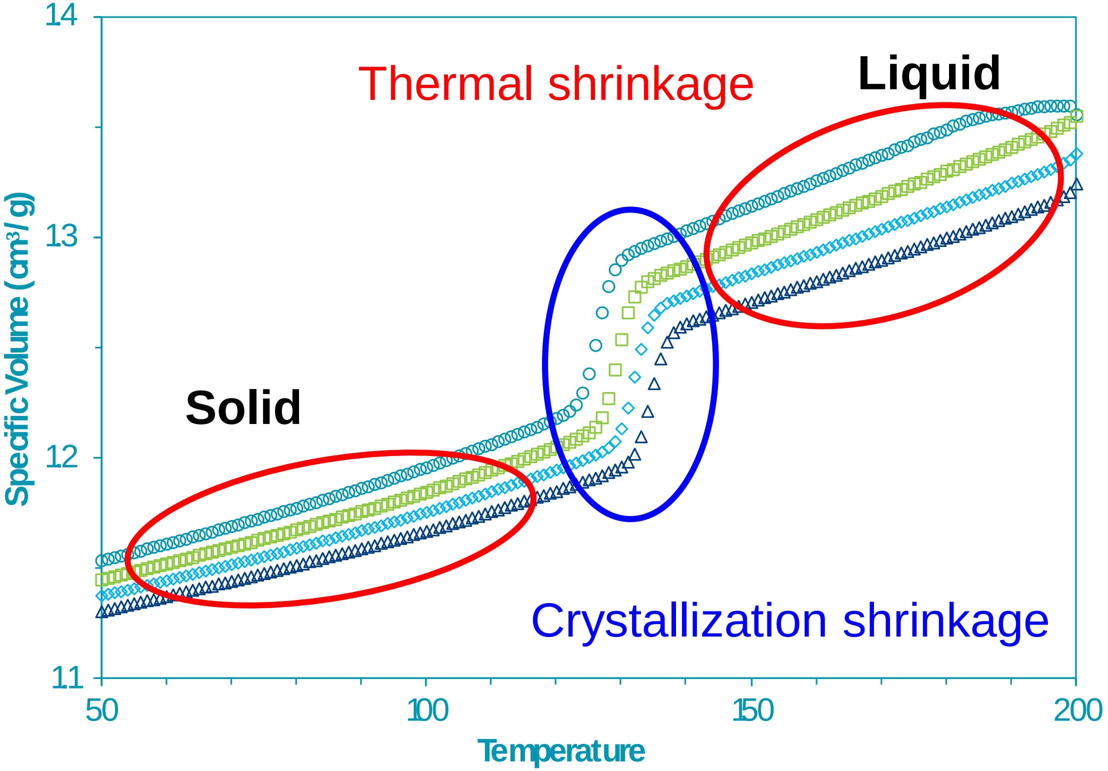
Extension of the Model: Estimation Stresses

Heat transfer
Thermal shrinkage

Crystallization
Crystallization shrinkage

→ Structural mechanics → Stress calculations

Implementation Comsol



Modules:
- Heat transfer
- Structural Mechanics

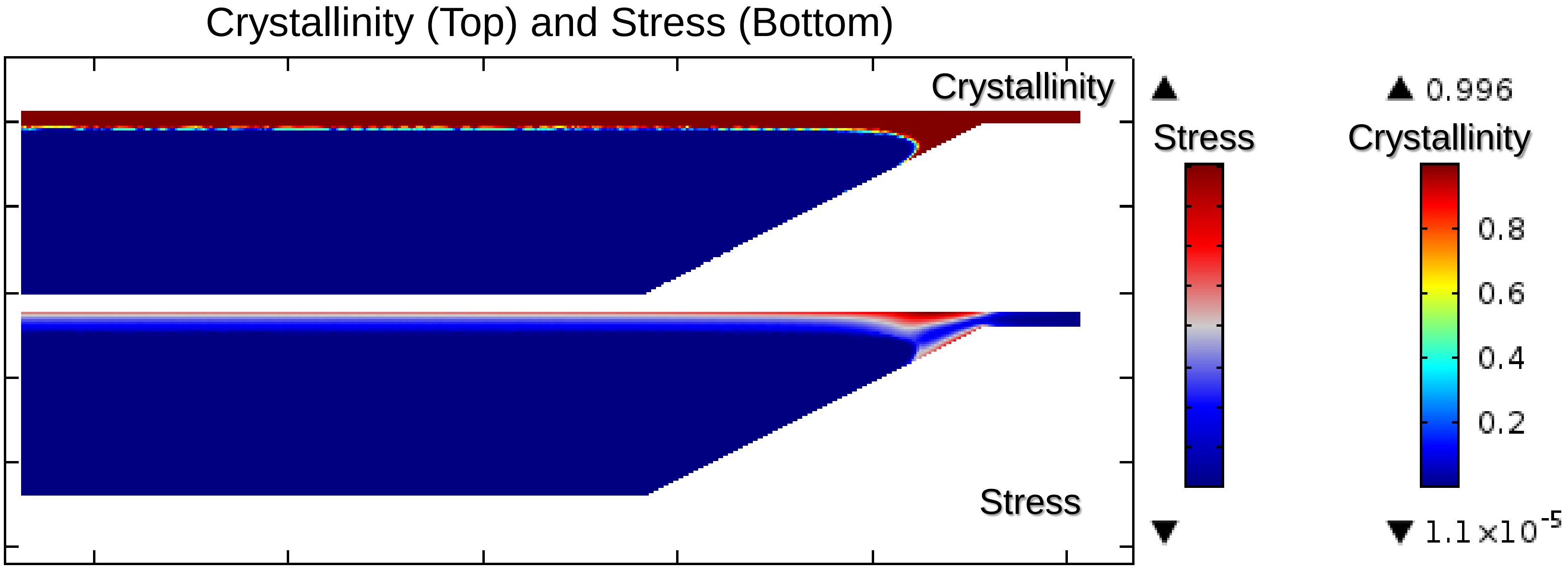
Thermal expansion

Linear elastic material:
Polymer: modulus
T and α dependent

Crystallization shrinkage via α dependent initial strain

Extension of the Model: Estimation Stresses

Crystallinity (top) and stress (bottom) distributions upon demolding



Approximation:

Future

Linear elastic material → Visco-elastic material

Extension of the model: reactive systems

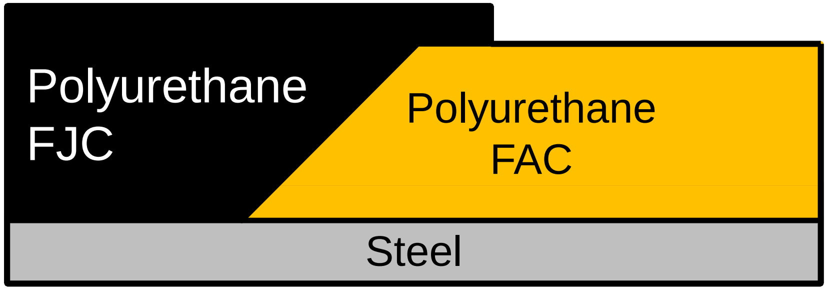
Curing polymer systems: polyurethanes

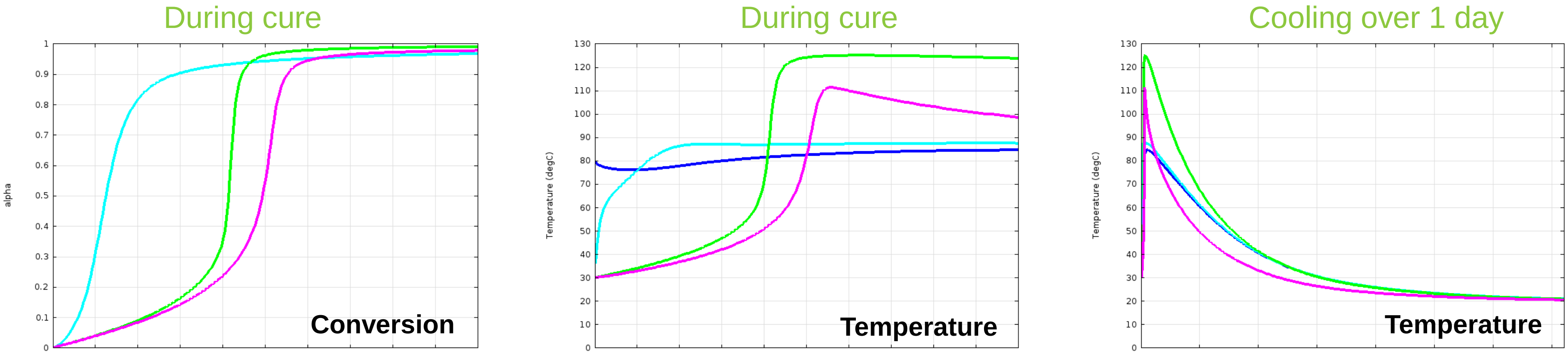
Cure kinetics – autocatalytic model with diffusion control

$$\frac{dx}{dt} = k_{overall}(1-x)^n \quad \text{with} \quad \frac{1}{k_{overall}} = \frac{1}{k_{chemical}} + \frac{1}{k_{diffusion}}$$

$$k_{chemical} = k_1 + k_2 x^m \qquad k_i = A_i \exp\left\{-\frac{E_i}{RT}\right\}$$

$$k_{diffusion} = Z_D \exp\left\{-\frac{E_D}{RT} + \frac{C_1(T - T_g(x))}{C_2 + T - T_g(x)}\right\}$$




During cure

During cure

Cooling over 1 day

Middle of the FJC (weld): steel pipe, IMPU inner skin (1 mm), center, IMPU outer skin (1 mm)

Observation: (nearly) adiadiabatic temperature rise in center

Conclusions

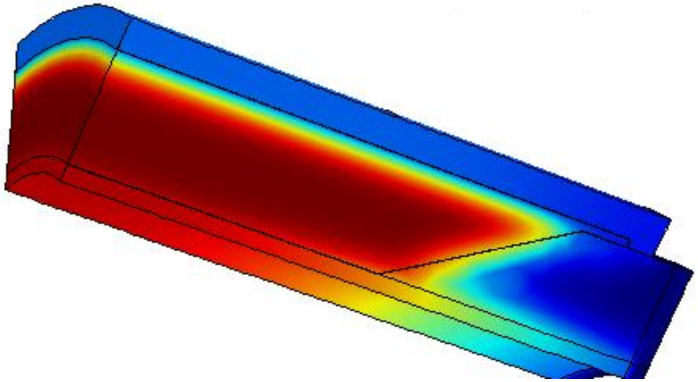
Heat transfer and phase change model

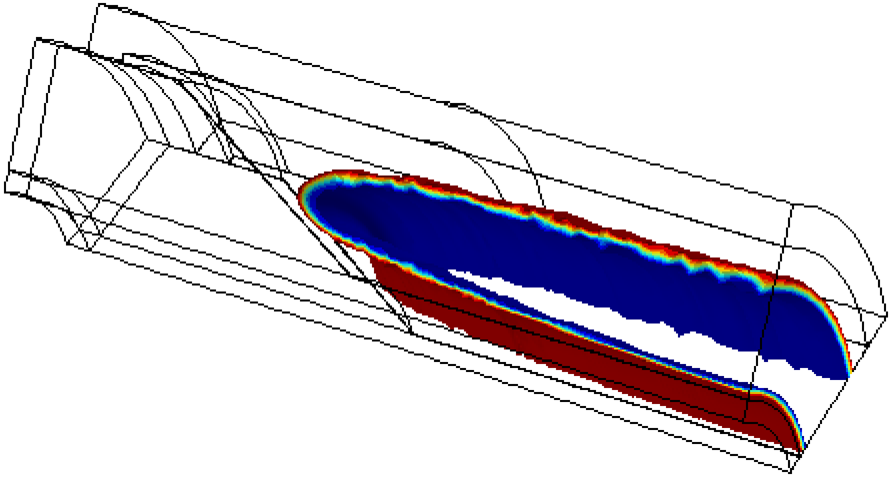
- ***Crystallization kinetics model***

  T-dependent nucleation and growth

  Variable transformations to avoid numerical errors

- ***Start of induced stress calculations***





Modelling opportunities

Optimisation

- Process
  - pretreatment steps
  - injection moulding
- Material
- Geometry

Acknowledgements

MARINE CONTRACTORS

M2i

HUNTSMAN

Enriching lives through innovation

FYSC

COMSOL

Vrije
Universiteit
Brussel