STEELSIM 2015
MODELLING and SIMULATION of METALLURGICAL PROCESSES in STEELMAKING

3D Numerical simulation of solidification of large size ingots of high strength steels

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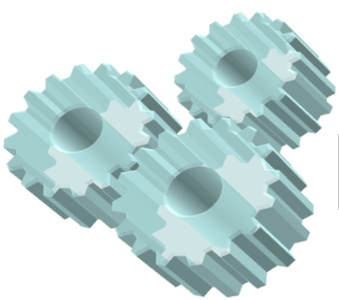
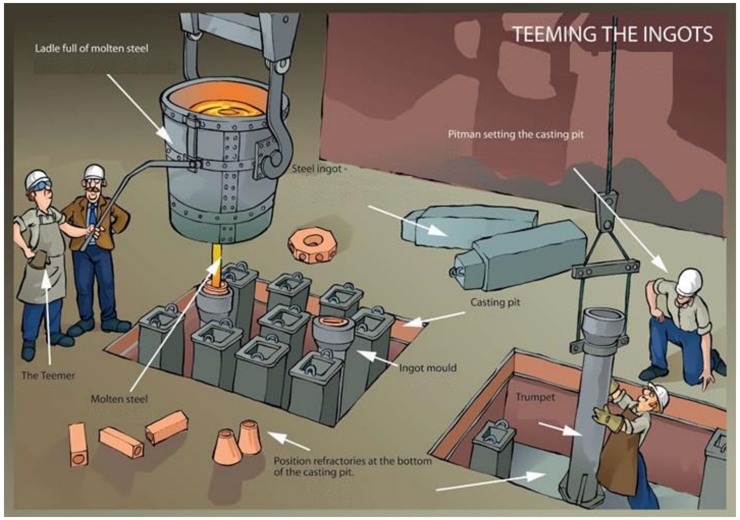
- *Objectives Of This Research*

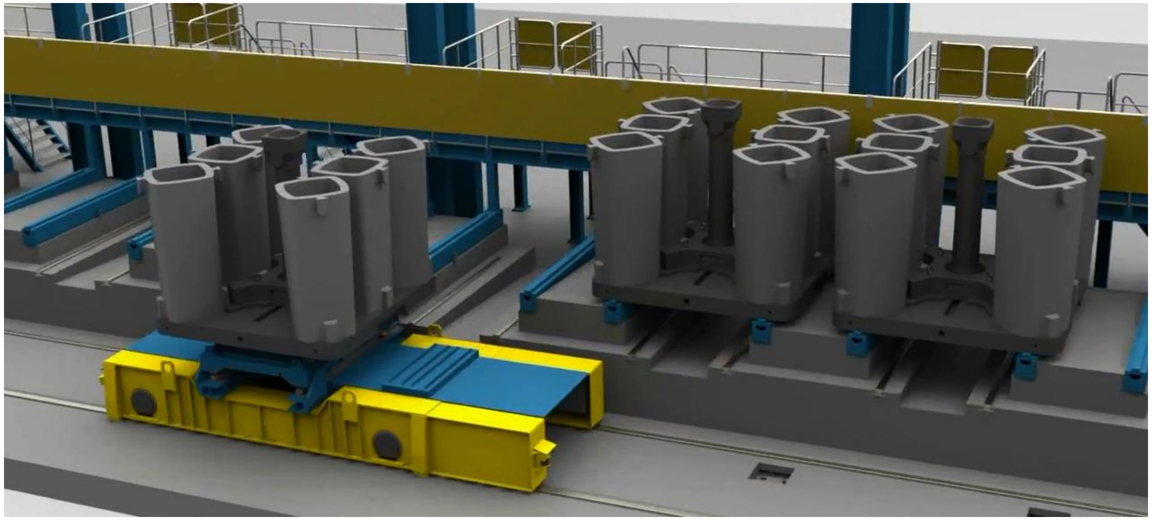
- *Numerical Simulation and Equations for Ingot Casting*
- *Flow of Steps Involved in the Large Ingot Solidification*
- *Factors Affecting Solidification Time*
- *Material Properties, Geometrical & Computational Model*

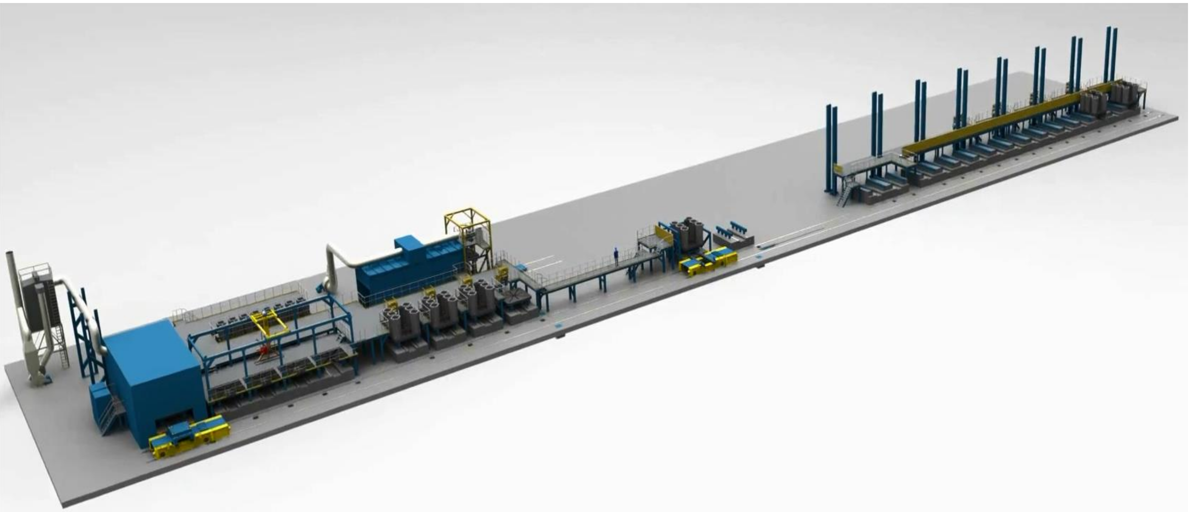


- *Setup for Computing Time*
- *Empirical Model for Solidification Time*
- *Results and Discussion*
- *Experimental Validation*
- *Conclusions*

❑ Objective of the Research



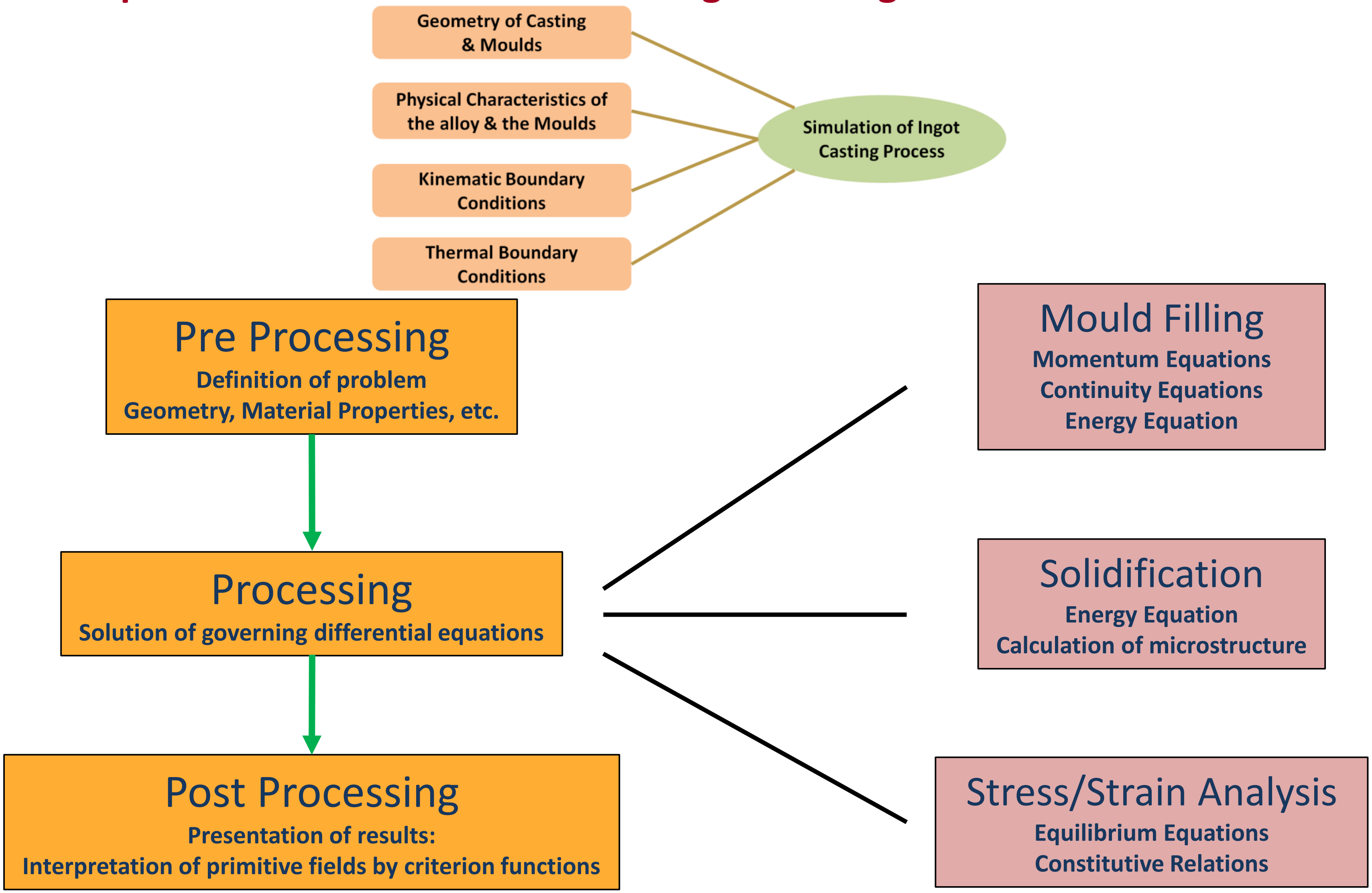




1)www.wrexham.gov.uk
2) www.svpt.se
3) www.sorelforge.com

✓ **Effects of Casting Parameters on Solidification Time of Large Size Ingot of High Strength Steels using Numerical Simulation**

❑ Concept of Numerical Simulation for Ingot Casting



Le génie pour l'industrie

Industrial Research Chair in Forming Technologies of High Strength Alloys

STEELSIM 2015 MODELLING and SIMULATION of METALLURGICAL PROCESSES in STEELMAKING

Basic Equations in Ingot Casting Simulation-Methodology for Numerical Tool Selection

Momentum Equations

Navier–Stokes equations *(general)*

$$\rho\left(\frac{\partial \mathbf{v}}{\partial t}+\mathbf{v}\cdot\nabla\mathbf{v}\right)=-\nabla p+\nabla\cdot\mathbf{T}+\mathbf{f}$$

V: flow velocity

ρ : fluid Density

P: Pressure

T: deviatoric components (stress tensor)

f: body force

$$\nabla=\left(\frac{\partial}{\partial x},\frac{\partial}{\partial y},\frac{\partial}{\partial z}\right)=\hat{\mathbf{x}}\frac{\partial}{\partial x}+\hat{\mathbf{y}}\frac{\partial}{\partial y}+\hat{\mathbf{z}}\frac{\partial}{\partial z}$$

Continuity Equations in Fluid Dynamic

$$\frac{\partial \rho}{\partial t}+\nabla\cdot(\rho\mathbf{u})=0$$

U: flow velocity

Continuity Equations for Energy Flow

$$\frac{\partial u}{\partial t}+\nabla\cdot\mathbf{q}=0$$

u: energy density

q : energy flux

✓ Heat Equation

$$\frac{\partial T}{\partial t}=\alpha\nabla^2 T$$

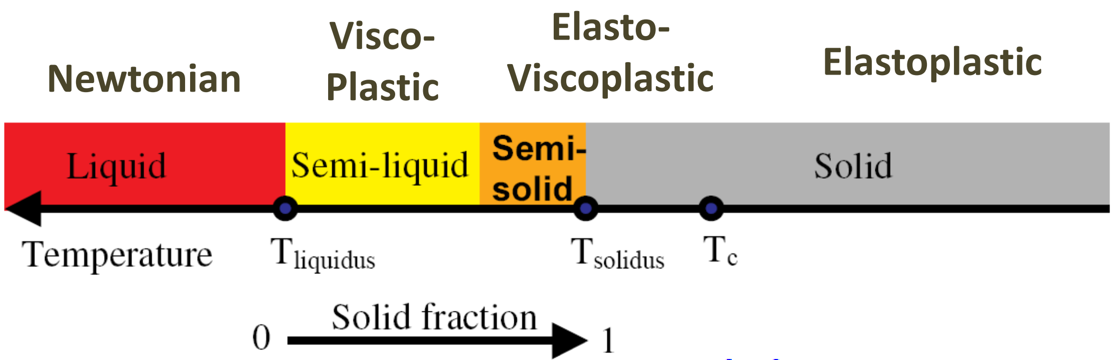
1) J.N. Reddy, An Introduction to Continuum Mechanics With Applications, Cambridge University Press, 2008.

2) P.M. Dixit, U.S. Dixit, Plasticity Fundamentals and Applications, CRC Press, Taylor & Francis Group, 2015.

3) U.S., Dixit, S. Joshi, S. N., and J.P. Davim, Incorporation of material behavior in modeling of metal forming and machining processes: A review, Materials & Design, Vol. 32, 2011, pp. 3655–3670.

Basic Equations in Ingot Casting Simulation-Methodology for Numerical Tool Selection

Material Constitutive Model



$\dot{\varepsilon} = \dot{\varepsilon}^{el} + \dot{\varepsilon}^{in} + \dot{\varepsilon}^{th}$

Ludwik Law ; $\sigma_s = \sigma_y + H\varepsilon^n$

Norton-Hoff Law ; $\sigma_{eq} = \sigma_y(T) + H(T)\varepsilon^{n(T)} + K(T)(\sqrt{3})^{m(T)+1}\dot{\varepsilon}^{m(T)}$

Perzyna Viscoplastic Law

$$\dot{\varepsilon}_{vp} = \left\langle \frac{f(\boldsymbol{\sigma}, \boldsymbol{q})}{\tau} \right\rangle = \begin{cases} \dfrac{f(\boldsymbol{\sigma}, \boldsymbol{q})}{\tau} & \text{if } f(\boldsymbol{\sigma}, \boldsymbol{q}) > 0 \\ 0 & \text{otherwise} \end{cases}$$

$$\sigma_{eq} = \sigma_y(T) + K(T)(\sqrt{3})^{m(T)+1}\dot{\varepsilon}^{m(T)}\,\varepsilon^{n(T)}$$

σ_y: Yield Stress

σ_s: Threshold stress below which no inelastic deformation occurs

H: Strain Dependency

K: Plasticity Consistency

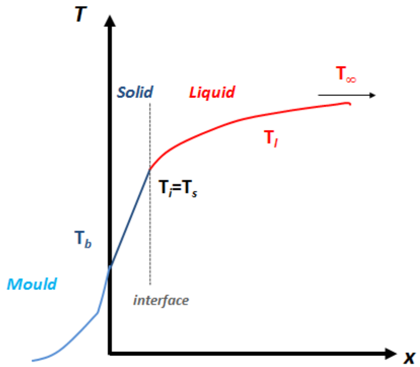
n: Strain Hardening Sensitivity

m: Strain Rate Sensitivity

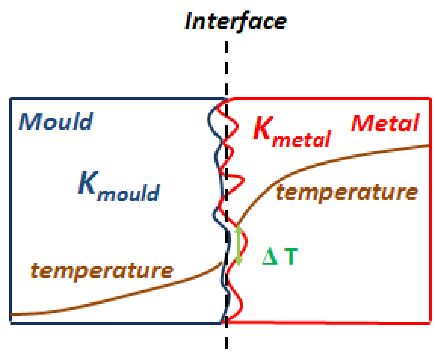
1) J.N. Reddy, An Introduction to Continuum Mechanics With Applications, Cambridge University Press, 2008.
2) P.M. Dixit, U.S. Dixit, Plasticity Fundamentals and Applications, CRC Press, Taylor & Francis Group, 2015.
3) U.S., Dixit, S. Joshi, S. N., and J.P. Davim, Incorporation of material behavior in modeling of metal forming and machining processes: A review, Materials & Design, Vol. 32, 2011, pp. 3655–3670.
4) O. Heeres, A. Suiker and R. Boster, A comparison between the Perzyna viscoplastic model and the Consistency viscoplastic model, Euro. J. Mech. A-Solid, Vol. 21, 2002, pp. 1-12

❑ Basic Equations in Ingot Casting Simulation-Methodology for Numerical Tool Selection

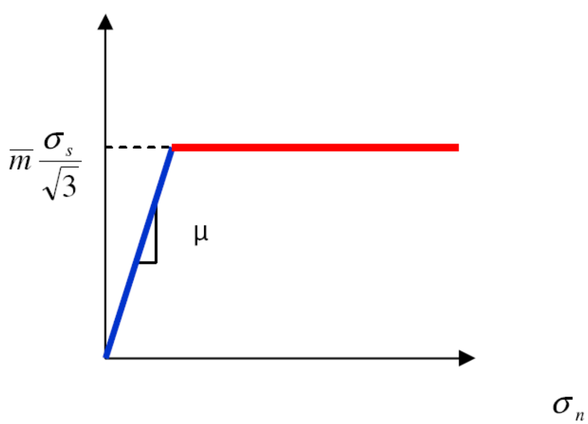
➢ Friction Model



Temperature profile during solidification



Schematic showing the temperature drop due to contact resistance at the interface



➢ Tresca 's Law $\tau = \overline{m}\frac{\sigma_{eq}}{\sqrt{3}}$

➢ Coulomb's Law $\tau = \mu\,\sigma_n$

1) J.N. Reddy, An Introduction to Continuum Mechanics With Applications, Cambridge University Press, 2008.
2) P.M. Dixit, U.S. Dixit, Plasticity Fundamentals and Applications, CRC Press, Taylor & Francis Group, 2015.
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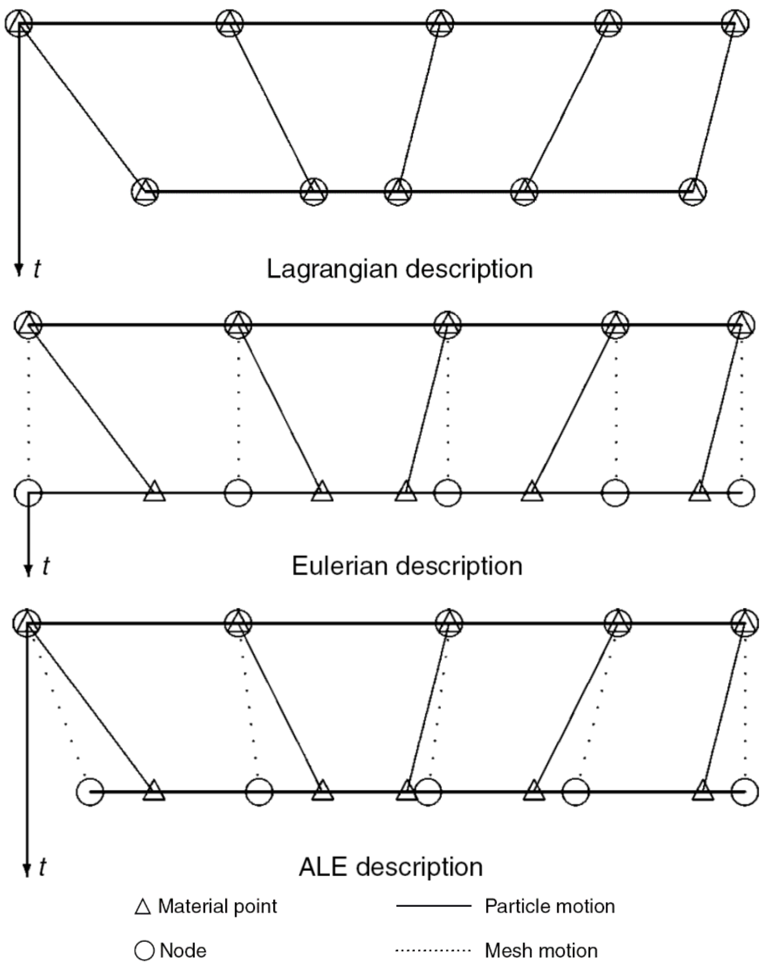
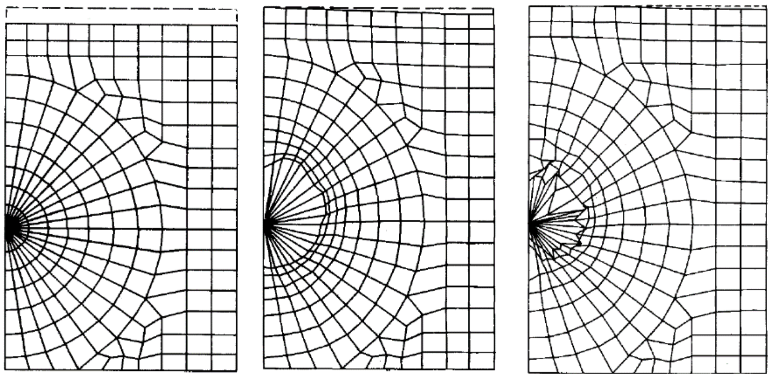
4) O. Heeres, A. Suiker and R. Boster, A comparison between the Perzyna viscoplastic model and the Consistency viscoplastic model, Euro. J. Mech. A-Solid, Vol. 21, 2002, pp. 1-12

❑ Basic Equations in Ingot Casting Simulation-Methodology for Numerical Tool Selection

➢ FEM : Algorithms of Continuum Mechanics





Initial FE Mesh | ALE Mesh | Lagrangian Mesh

- ✓ An ***ALE*** scheme is used to compute the thermal convection in liquid pool and mushy zone, taking into account the liquid contraction and the solidification shrinkage.

- ✓ The ***Lagrangian*** scheme is used to compute the deformation in solid regions, the computational grid is allowed to move with the material: this is essential to treat the air gap between mould and casting.

1) *O.C. Zienkiewicz, CBE, FRS, R.L. Taylor and J.Z. Zhu, The Finite Element Method: Its Basis and Fundamentals, Elsevier, 2005.*

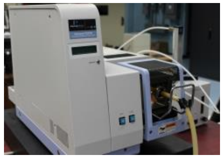
❑ Flow of Steps Involved in the Numerical Modelling and Experimental Verification for of the Large Ingot Solidification

Literature Review

Thermo-Calc Software

Thermophysical Properties

Gleeble®3800



DSC-DTA

FEG-SEM+

Material Testing — Physical Simulator

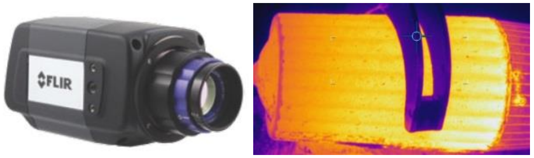
3D Modelling

Numerical Simulation

Model Determination

SOREL FORGE

Experiment

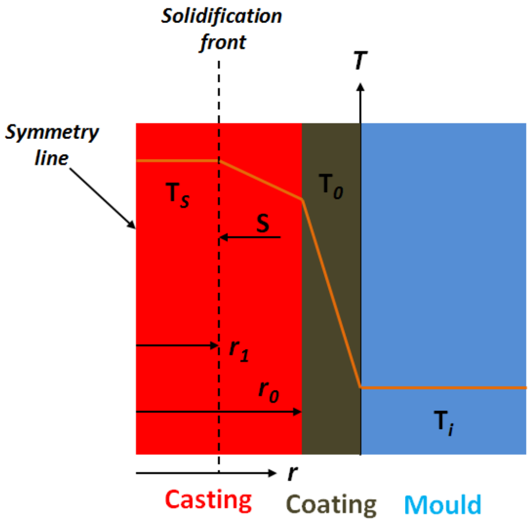


Temperature Validation

+Field Emission Gun Scanning Electron Microscopy

Factors Affecting Solidification

➢ Solidification time in cylindrical case (1D)



$$t = \frac{\rho_c\,(\Delta H_f + C_p \Delta T)}{2(T_{Solidus} - T_0)}\left[\frac{r_0^2}{K_{mold}} + \frac{r_0}{h_{mold}}\right]$$

ΔH_f [KJ/Kg] : Latent Heat

Mould Temperature (°C)	Pouring Time (min)	Pouring Temperature (°C)
T_M	t_P	T_P

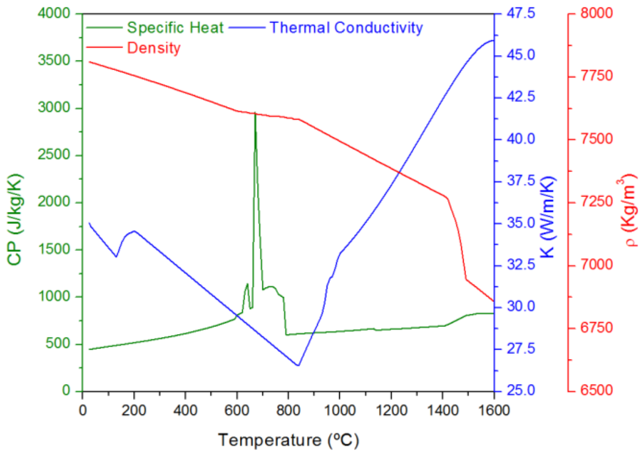
➢ $t_S = f(T_M, t_P, T_P)$

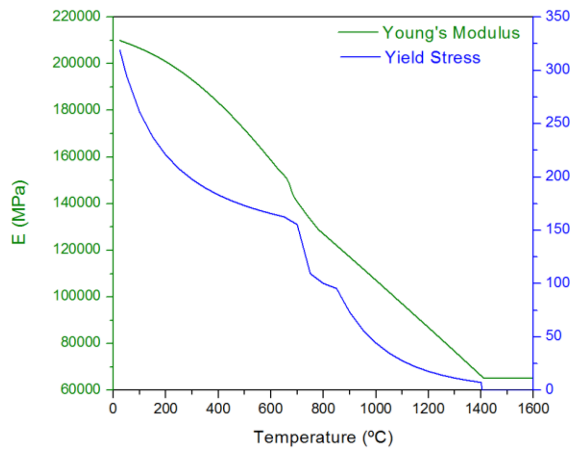
Type of Steel	T_M(°C)	t_P(min)	T_P(°C)
25CrMo4&25-20	150, 350, 550	20, 25, 30	1520, 1545, 1570

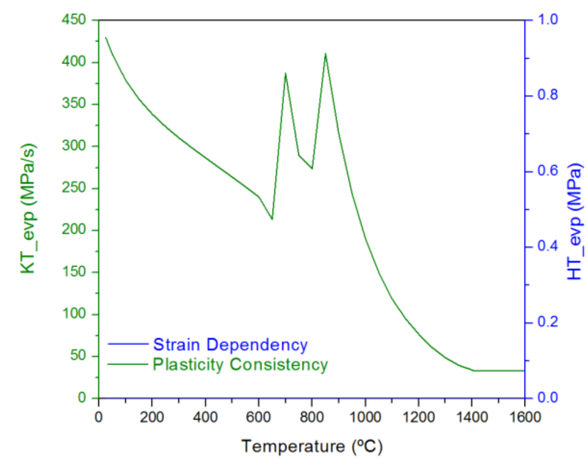
❑ Material Properties

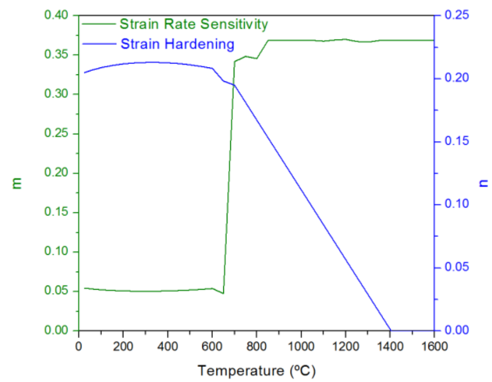
Elements	C	Mn	Ni	Cr	Mo	Cu	Si	S	P
25CrMo4 Comp.(wt.%)	0.25	0.9	0.3	1.2	0.3	0.3	0.4	0.02	0.035
25-20 Comp.(wt.%)	0.08	0.79	20	25	5	1.8	0.075	0.015	0.04

➢ **25CrMo4**

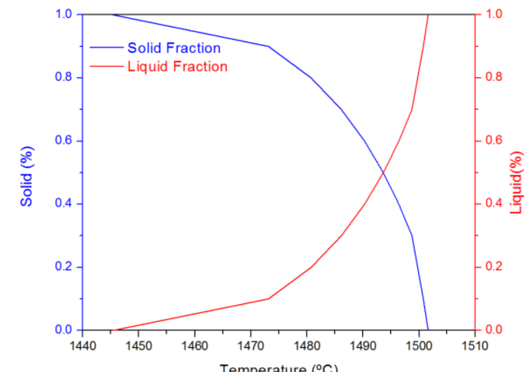




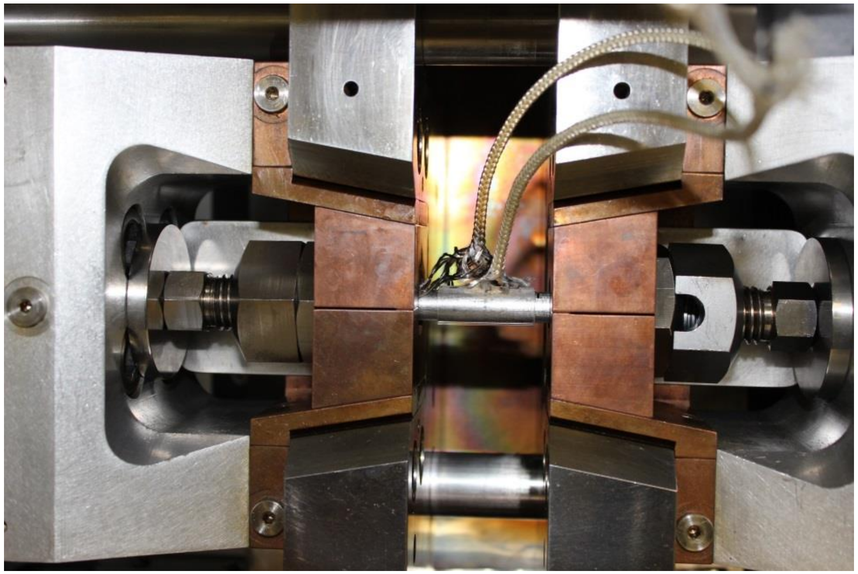


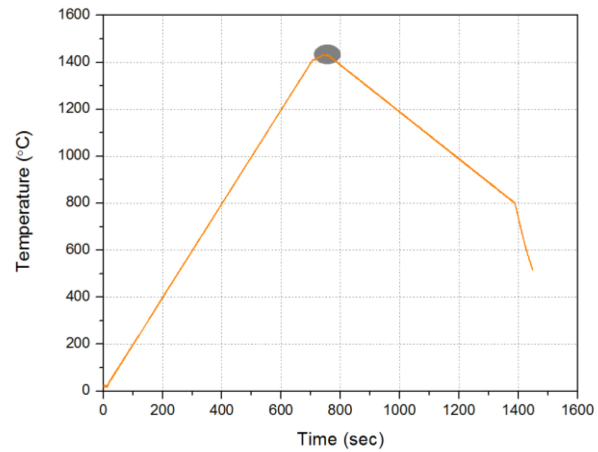


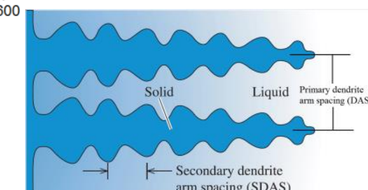
	25CrMo4	25-20
Emissivity	0.8	0.8
Poisson Coefficient	0.3	0.3
Solidification Shrinkage Factor	-0.0385	-0.03
Latent Heat *(KJ/Kg)*	265	309

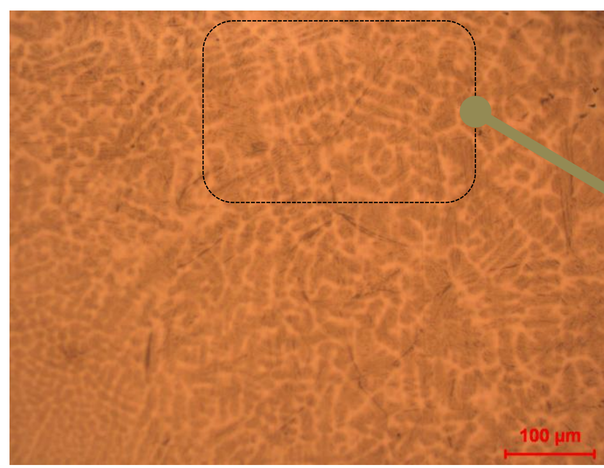


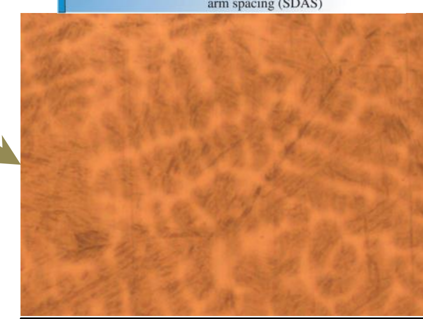
❑ Material Properties-Material Testing & Physical Simulator









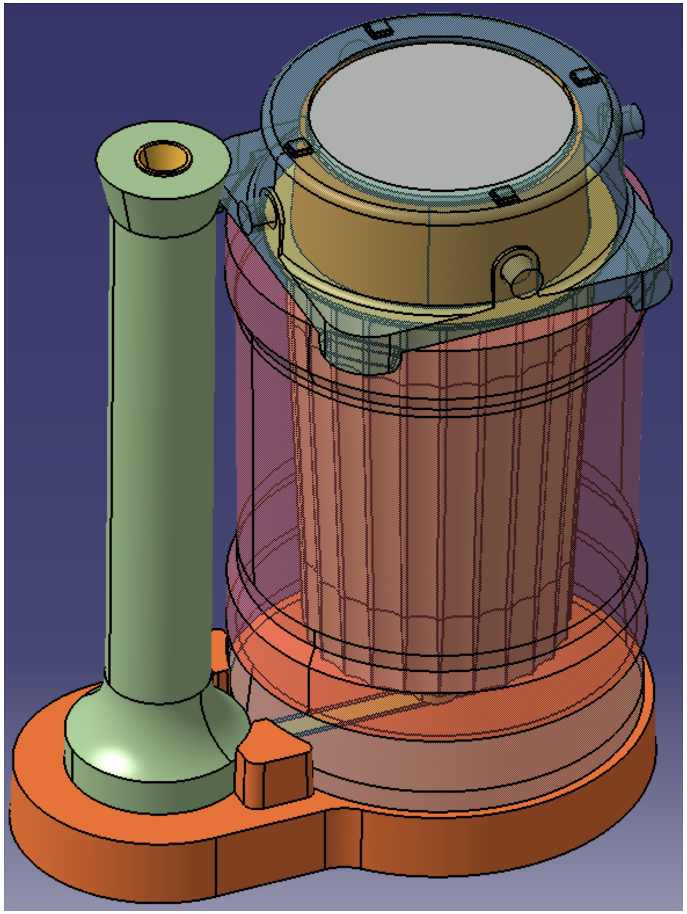


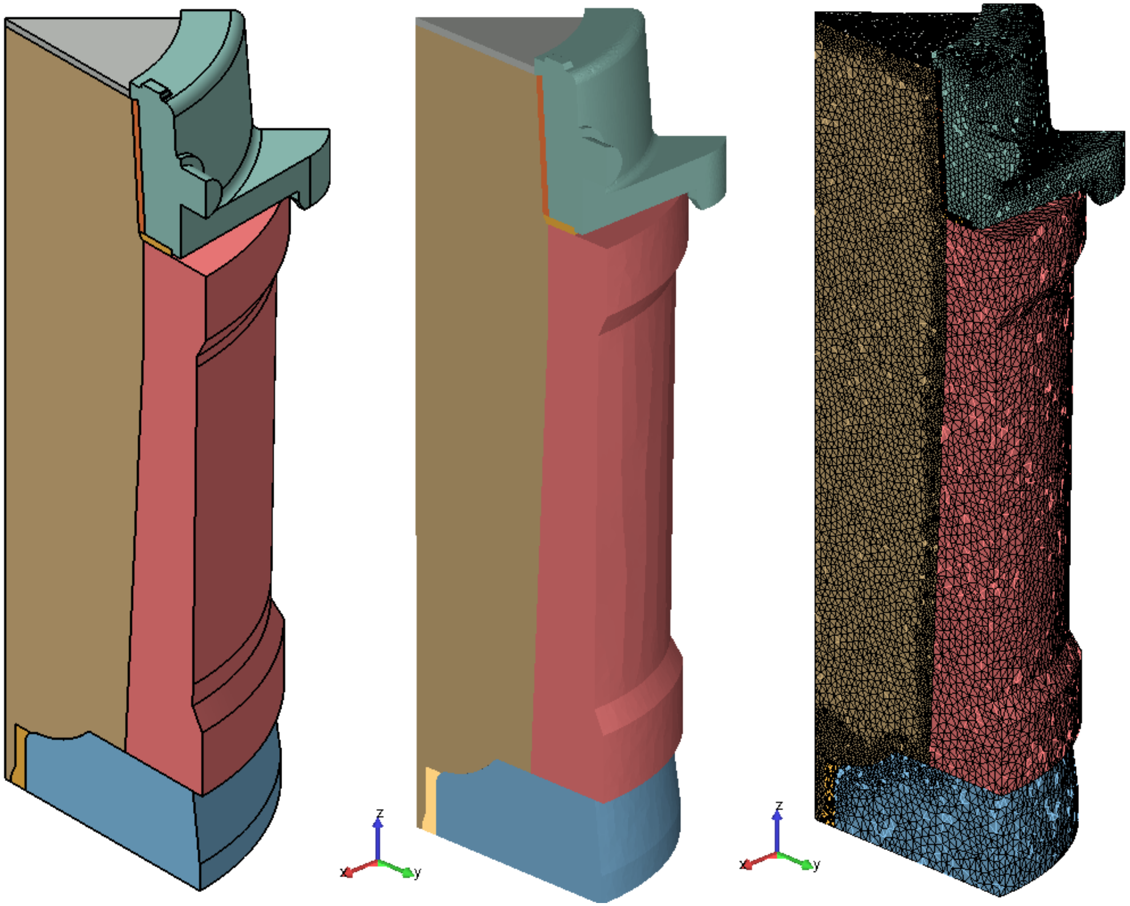
$\lambda_{SDAS} = 14 \pm 4\ \mu m$

The characteristic terms of a dendrite: primary and secondary dendrite arm spacing

Geometrical Modelling and Computational Mesh Generation

40 MT Ingot





3D Geometrical Models in Catia

3D Computational Mesh in Thercast

❑ Setup Numerical Simulation on CLUMEQ

➢ **The CLUMEQ High Performance Computing Center at ÉTS**

✓ **Top 35 worldwide**

✓ **5,000 square-feet of IT space and 5 PB of attached parallel storage at ÉTS with 1570 nodes (20400 cores) IBM cluster**

✓ **Compute Partitions: High Bandwidth(400nodes), Large Memory (346 nodes) and *Serial Workload(824 nodes)* .**

❑ Empirical Model for Solidification Time

- **A first-order response surface model is:**

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \epsilon$$

- **A second-order model is usually obtained by adding quadratic terms:**

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} {x^2}_1 + \beta_{22} {x^2}_2 + \beta_{33} {x^2}_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3 + \epsilon$$

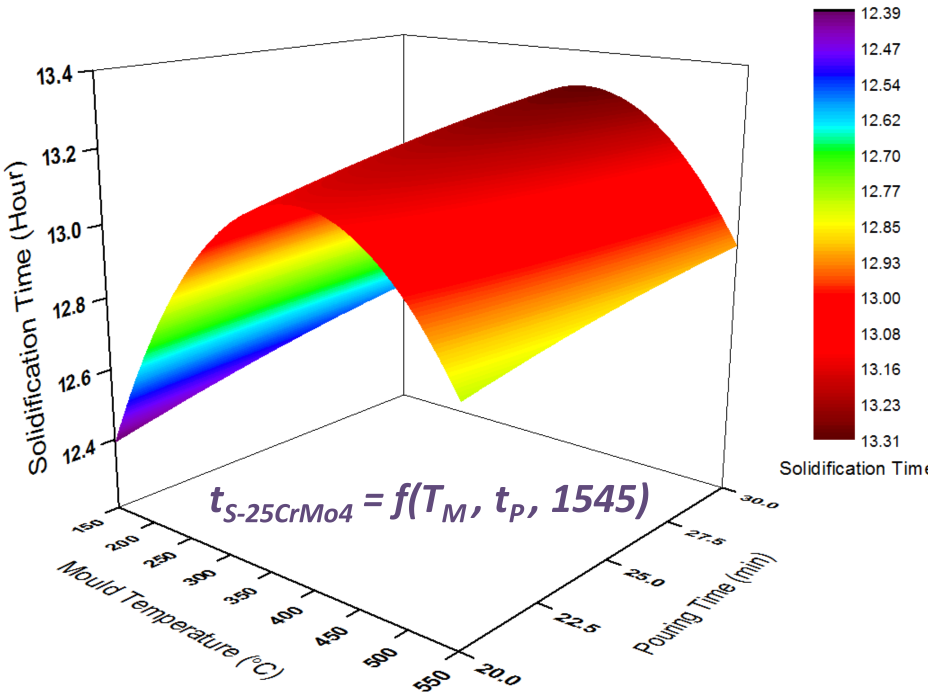
$$\therefore \ \hat{y} = y - \epsilon$$

✓ **The actual response model, $\hat{y}$,based on the observations of y_i ,from *27 simulation results for each material*, may be expressed as:**

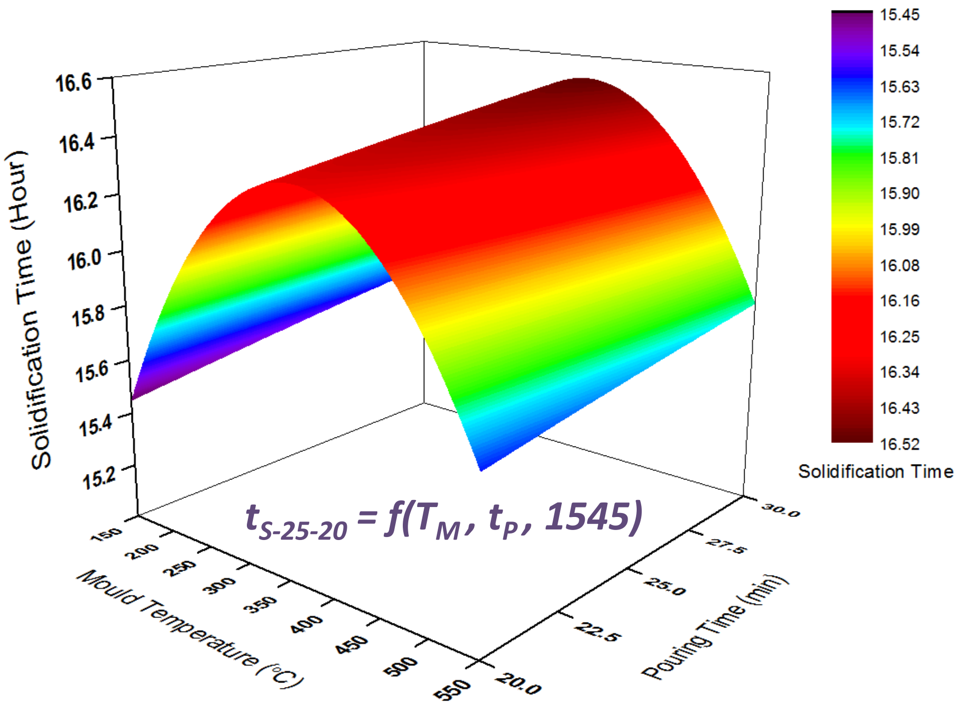
$$\hat{y} = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \beta_3 x_3 + \beta_{11} {x^2}_1 + \beta_{22} {x^2}_2 + \beta_{33} {x^2}_3 + \beta_{12} x_1 x_2 + \beta_{13} x_1 x_3 + \beta_{23} x_2 x_3$$

❑ Results and Discussion

➢ 25CrMo4

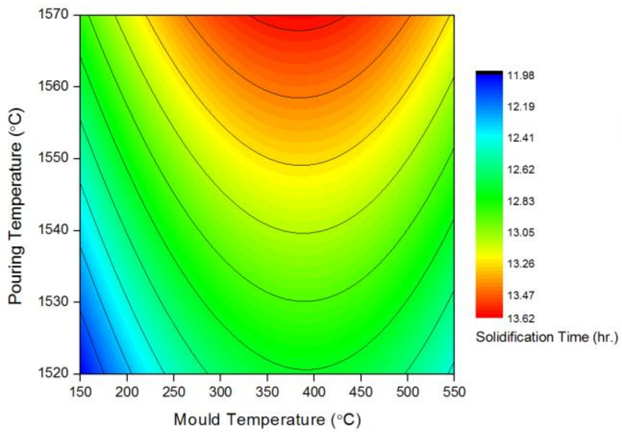


➢ 25-20

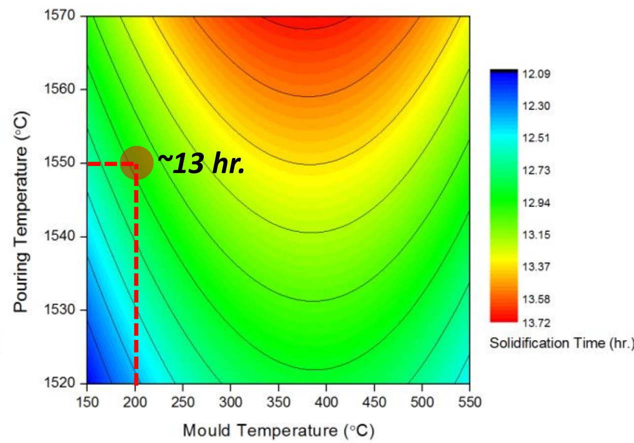


Results and Discussion

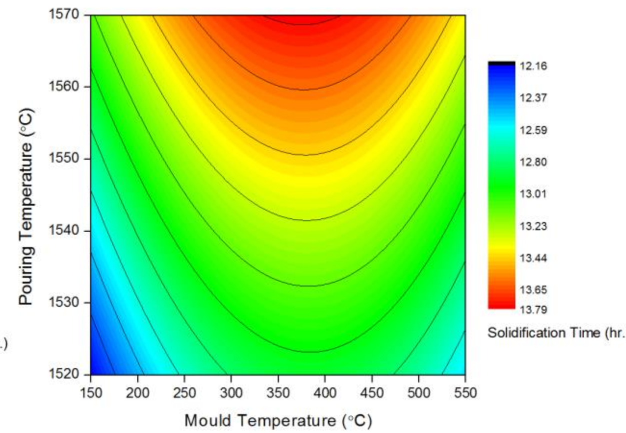
➢ 25CrMo4



$t_{S\text{-}25CrMo4} = f(T_M, 20, T_P)$

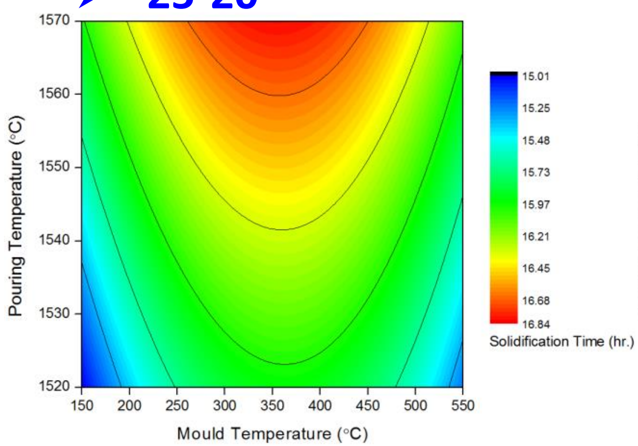


$t_{S\text{-}25CrMo4} = f(T_M, 25, T_P)$

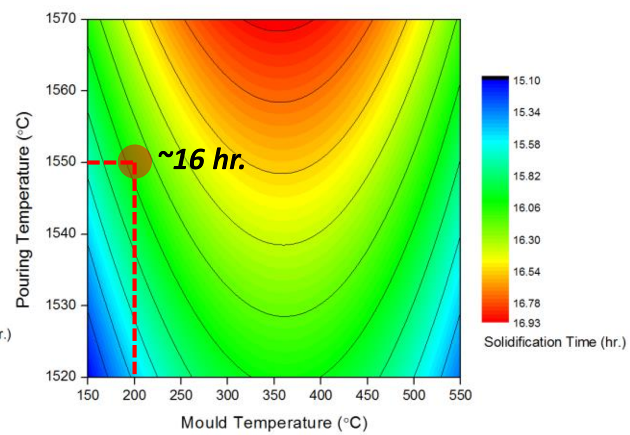


$t_{S\text{-}25CrMo4} = f(T_M, 30, T_P)$

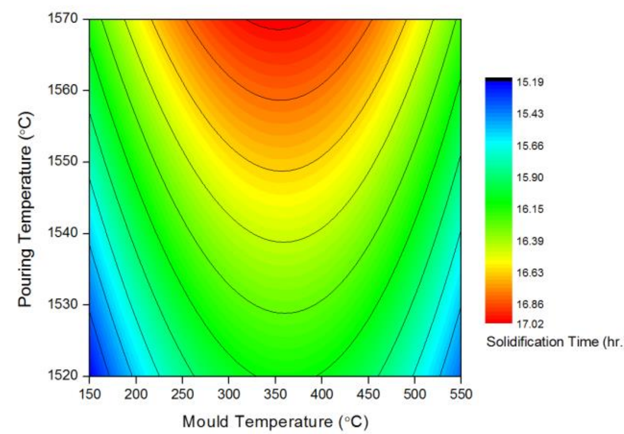
➢ 25-20



$t_{S\text{-}25\text{-}20} = f(T_M, 20, T_P)$



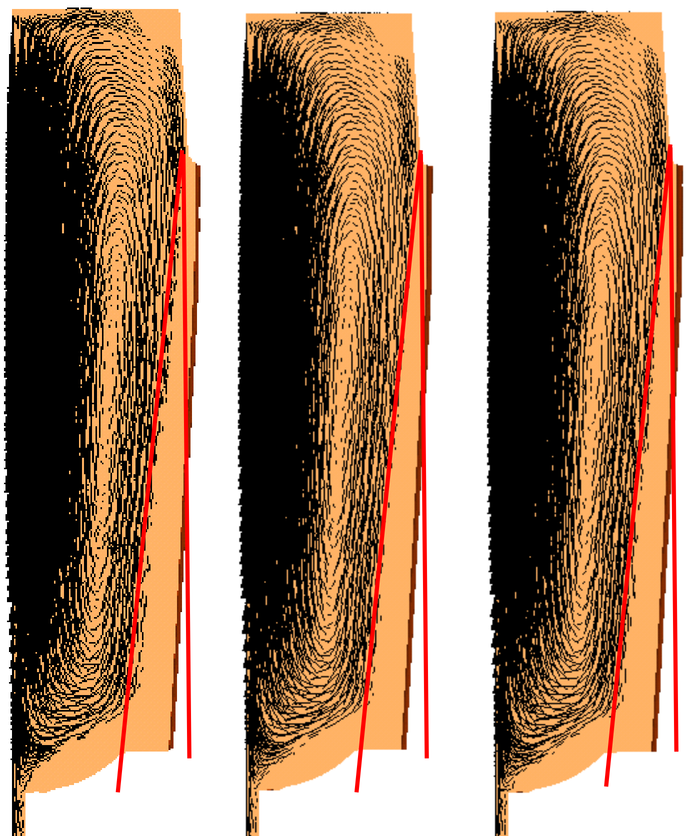
$t_{S\text{-}25\text{-}20} = f(T_M, 25, T_P)$



$t_{S\text{-}25\text{-}20} = f(T_M, 30, T_P)$

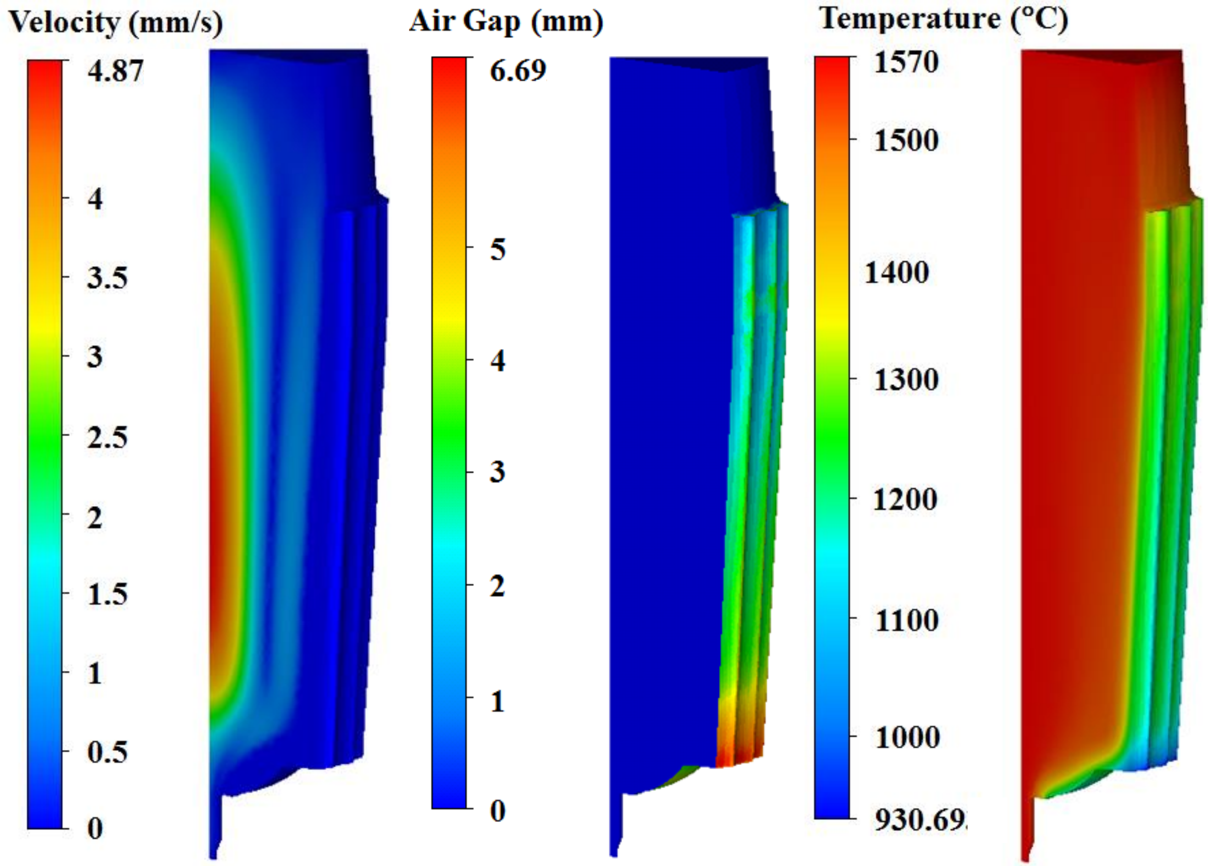
❑ Results and Discussion

➢ 25CrMo4



$T_M = 150\,^{\circ}C$ $T_M = 350\,^{\circ}C$ $T_M = 550\,^{\circ}C$

Fluid Flow Pattern at the end of Pouring

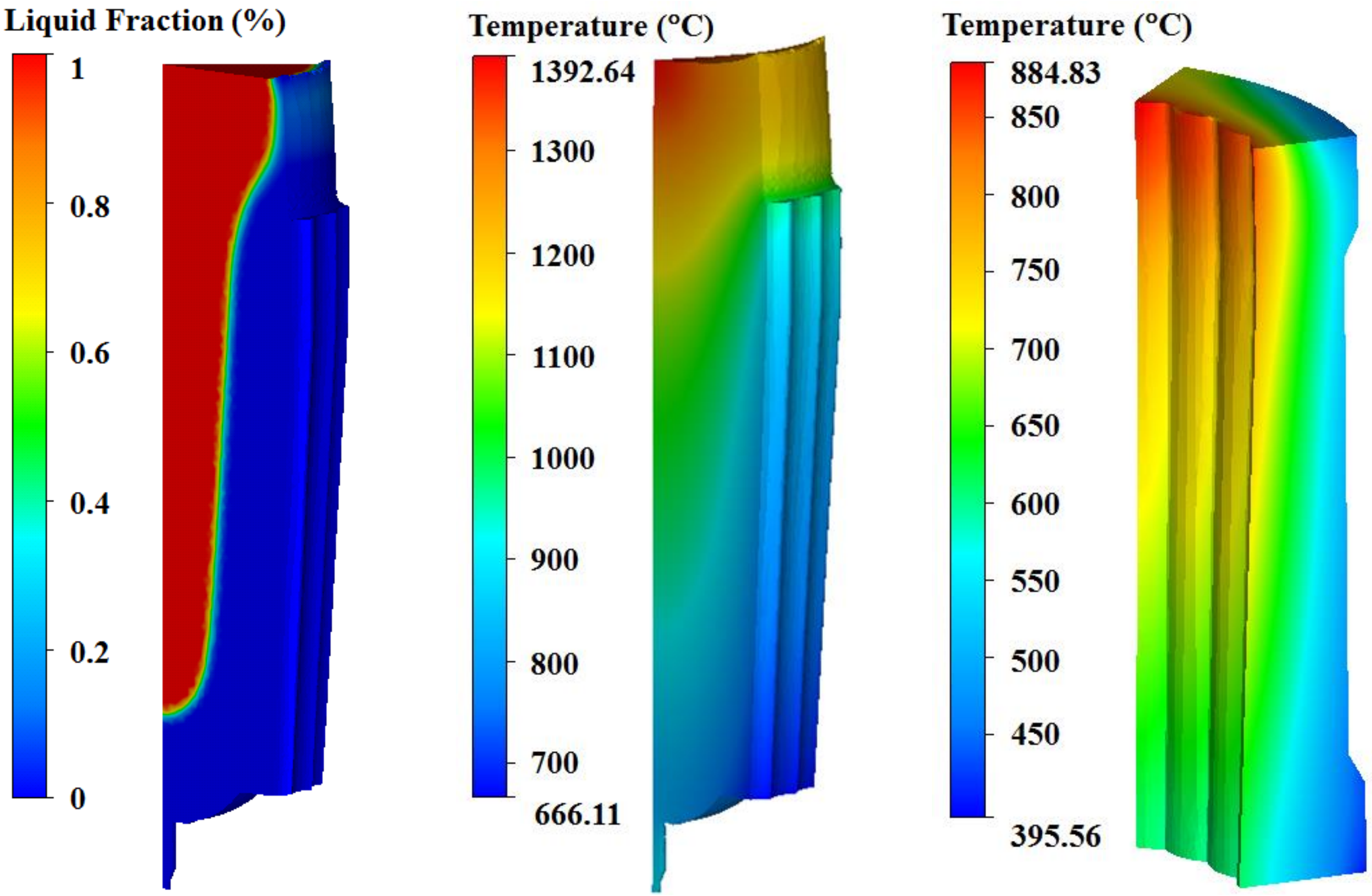


T_M(˚C)	t_P (min)	T_P (˚C)
350	30	1570

Velocity, Air Gap and Temperature Patterns at the end of Pouring

Results and Discussion

25CrMo4

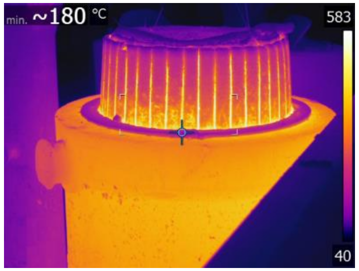


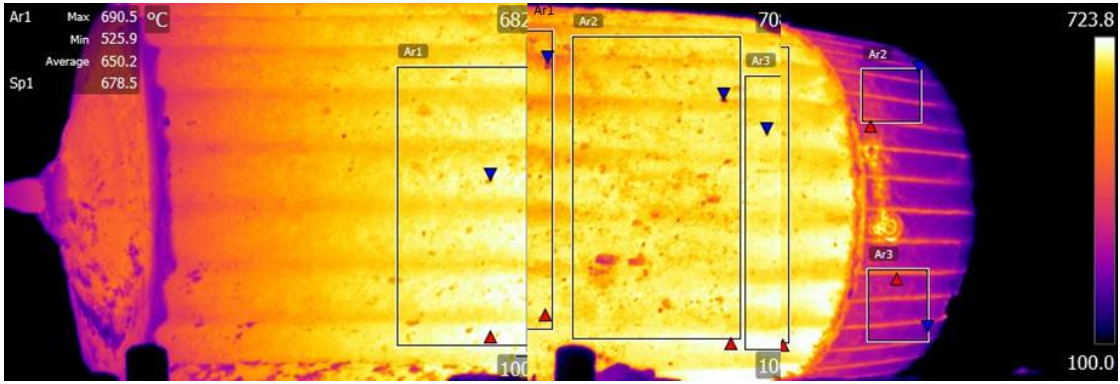
after 50% Solidification

Ingot & Mould Temperature Patterns after 100% Solidification

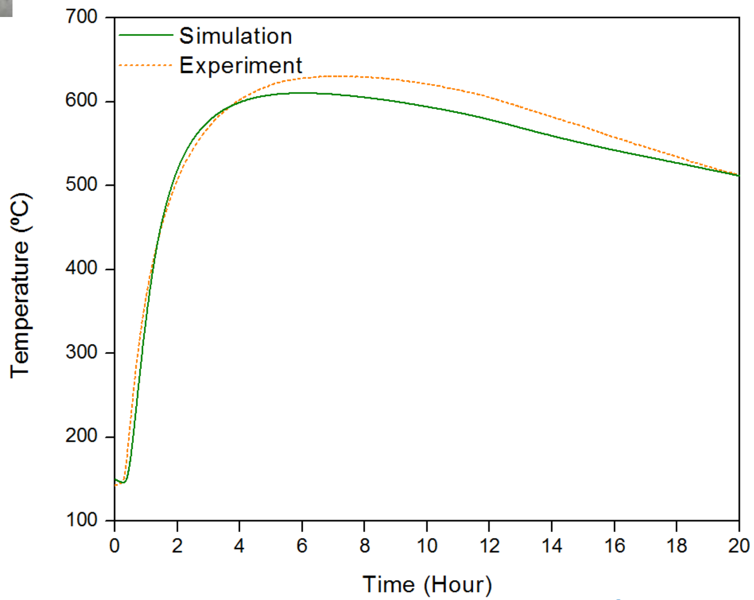
❑ Experimental Validation

Thermocouples data Recording





Infrared Radiation Thermography Camera



❑ Conclusions

- ✓ **The effect of critical process parameters on the solidification behaviour of two different steels were studied.**
- ✓ **The predictive models for the solidification time of the two steels were obtained.**
- ✓ **The obtained results were validated against actual experimental data and showed very good agreement.**

❖ **Mathematical models are used for proper selection of ingot casting parameters.**

Acknowledgments

ÉTS Le génie pour l'industrie
TRANSVALOR AMERICAS
SOREL FORGE
Calcul Québec
CLUMEQ
NSERC CRSNG Natural Sciences and Engineering Research Council of Canada

Thanks for Your Attention

- ***Any Question?***