CFD Modeling and Simulation of Macro-Shrinkage and Micro-shrinkage for A356 alloy using ExOne's RCT 3D Digital Mold Printing Process

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PROMETAL RCT™ AN EX ONE COMPANY

Outline

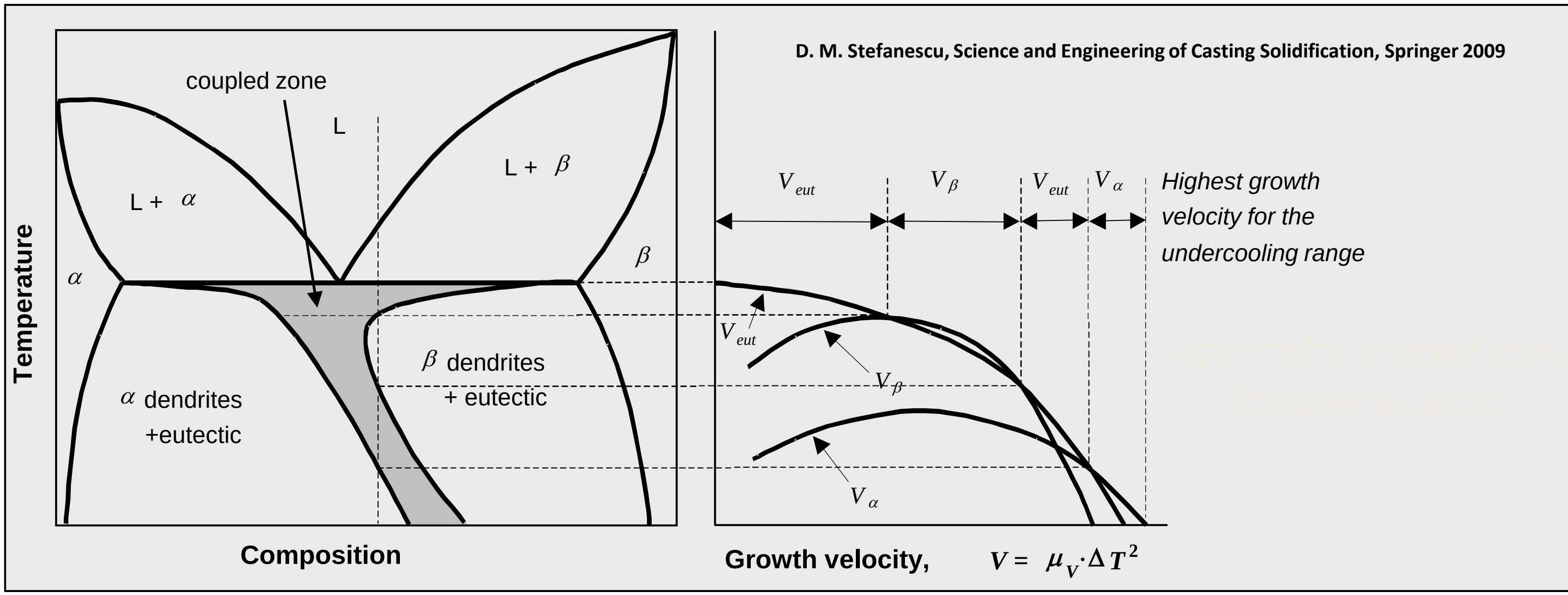
- Main Objective
- Background
- CFD Model Description
- Experimental Procedure
- Simulation Results
- Calibration Procedure and Validation for Macro-Shrinkage and Shrinkage Porosity Models
- Conclusions and Future Work

Main Objective

- The main objective of this paper is to develop a calibration procedure and then validate a casting simulation software (NocaFlow&Solid) for quantitative prediction of macroshrinkage and shrinkage porosities in A356 sand mold castings (Obiectivul principal - dezvoltarea unei proceduri de calibrare si validare a Soft-ului “Novacast” pentru prezicerea cantitativa a macroretasurilor si microretasurilor in aliajul A356 turnat in forme de nisip folosind tehnologia de printare RCT)
  - A356 plates cast in furan-silica sand molds using the Prometal Rapid Casting Technology (RCT) mold printing technology.

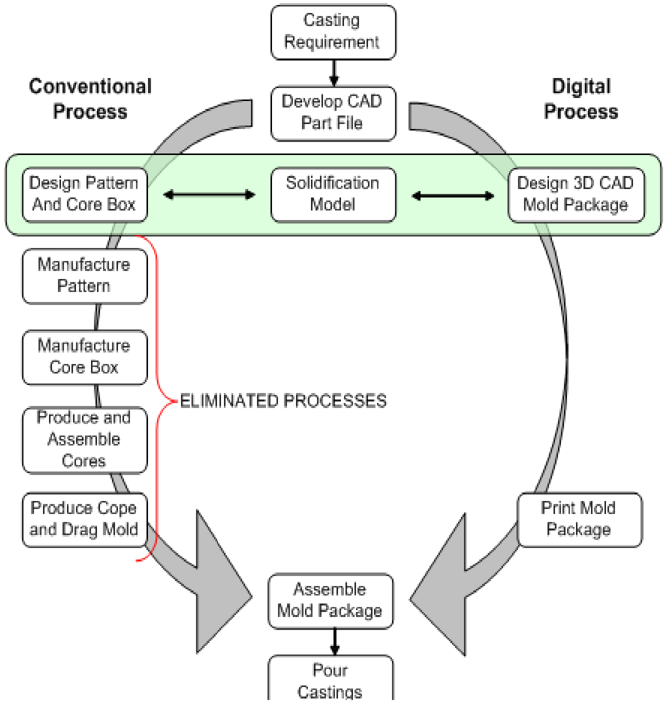
Introduction

Competitive growth of eutectics and dendrites

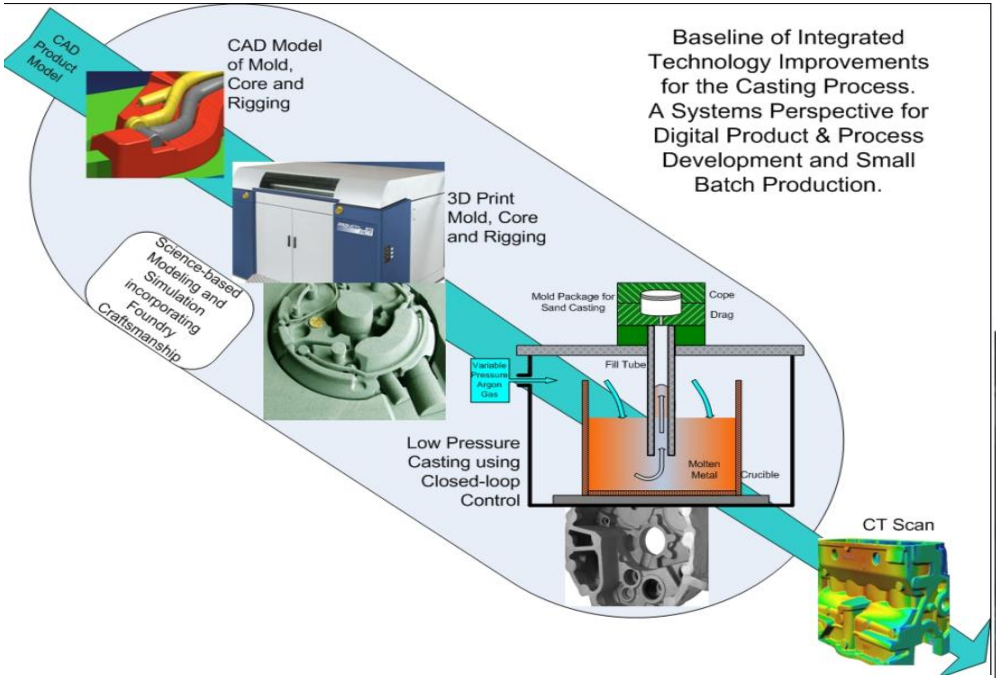


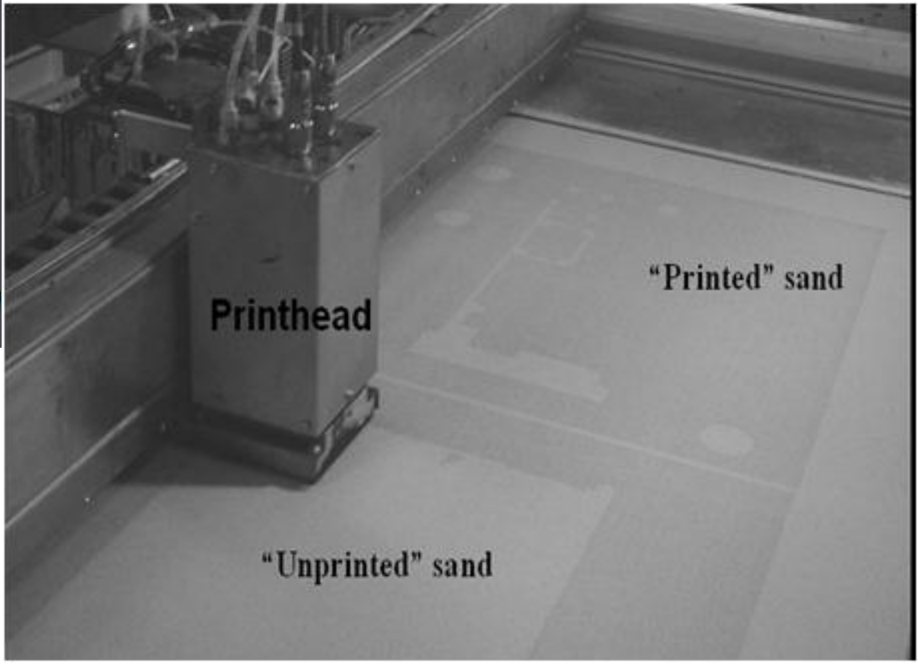
Macro-shrinkage and Shrinkage Porosity (A356)

ProMetal Rapid Casting Technology (RCT)



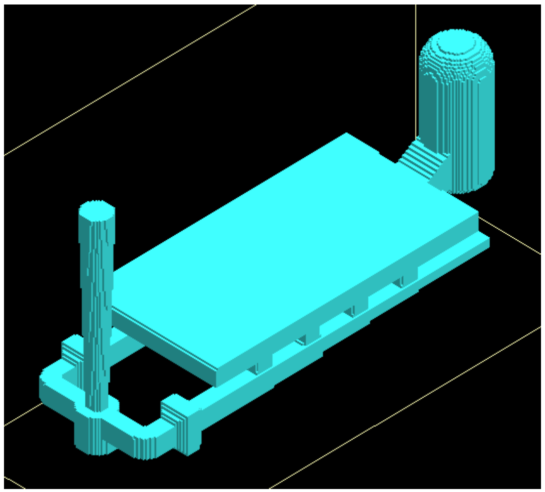
Details of the ProMetal RCT Process



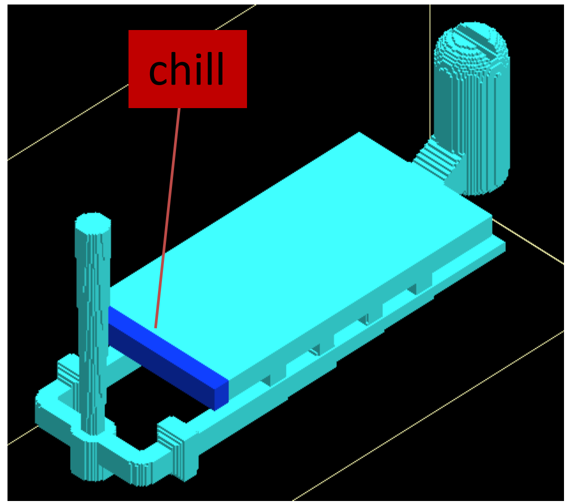


S15 Process Station Printhead

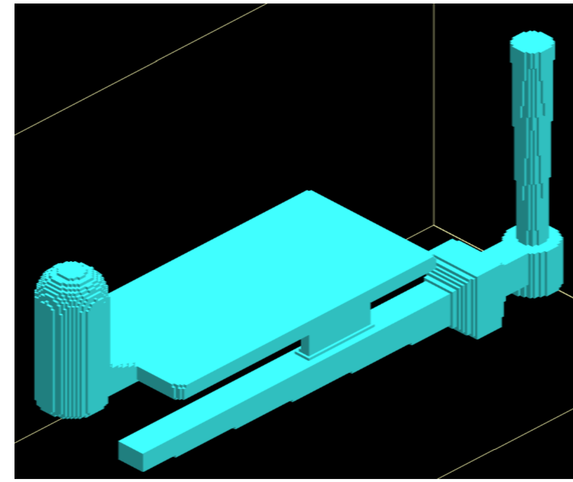
Geometries of the A356 plates with the rigging system



Rigging system type A



Rigging system type B



Rigging system type C

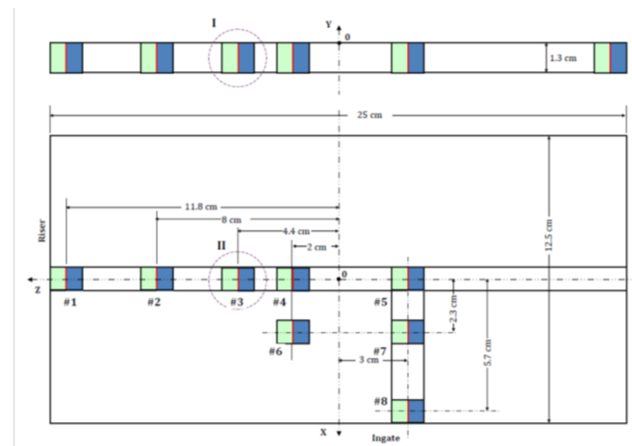


Plate thicknesses: 25 mm and 12.5 mm

Simulation Parameters

Simulation parameters	Material type /Value
Mold	Silica Sand/Furan binder
Mold thickness	Minimum 50 mm
Initial Mold and Ambient Temperature	20 °C
Pouring time (ladle pouring-over lip)	~ 3 s
Pouring Temperature	740 °C
A356 (7.0 wt. % Si and 0.35% Mg)	T_L = 622 °C, T_S = 571 °C

Calibration Procedure (A356)

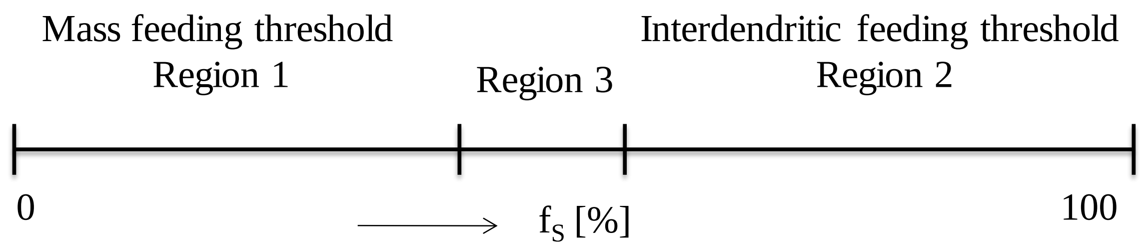
Purpose	Experimental results	Parameter changed in NovaCast
Determine amount and location of macro-shrinkage and porosities	Visually quantify location, amount and distribution of macro-shrinkage CT X-ray scans - micro-shrinkage	Niyama threshold Mass feeding threshold Interdendritic feeding threshold Density curve Niyama scale

Niyama threshold is the volume of liquid fraction where the temperature gradient (G) and cooling rate (CR) are computed – Niyama = G x $CR^{-0.5}$

Niyama values vs. porosity severity level : <0.1 severe; 0.1-0.3 moderate; 0.3-0.5 less severe; 0-1.5 least severe

Niyama scale: 1.0-1.5 → pores <10 microns (not visible at X-ray)

Threshold regions for shrinkage prediction



- Three regions/parameters are defined:
  - **Mass feeding threshold** – based on dendrite coherency solid fraction:
    - Value of solid phase fraction below which the Navier Stokes equations are applicable.
    - Equiaxed crystals can nucleate in the melt and then grow and flow freely in the melt.
    - Fluid flow is by mass feeding.
  - **Interdendritic feeding threshold**:
    - Value of solid phase above which melt flow is insignificant without plastic deformation.
    - Fluid flow is by interdendritic feeding.
    - Burst and solid feeding may also occur.
  - **Mass feeding threshold – Interdendritic feeding threshold region**:
    - Darcy’s law applies in this zone.
    - A fraction of solid phase network becomes rigid and opposes resistance to melt flow.

Calibration Results for A356 alloy

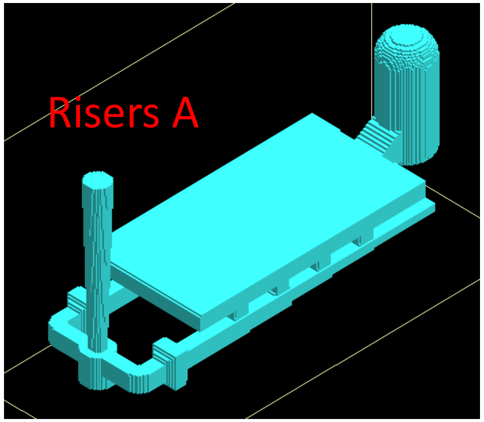
Parameter changed in NovaCast	Studied values (Solid fraction, %)	Calibration values (Solid fraction, %)
Niyama threshold	90-97%	95%
Mass feeding threshold	20-50%	35%
Interdendritic feeding threshold	50%-80%	65%
Density curve	Ref. [1, 2]	Ref. [2]
Niyama scale	0-1.5	0-0.3

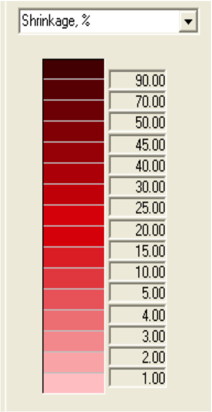
[1] Novaflow&Solid™ (Novacast AB, Sweden, www.novacast.se)

[2] A. Sabau, Met Tran B, Vol. 37 B, 2006, pp. 131-139

Macro-Shrinkage Validation: A356 plate A

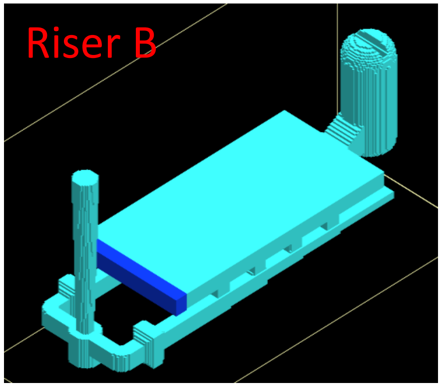
A356 (gravity pouring)

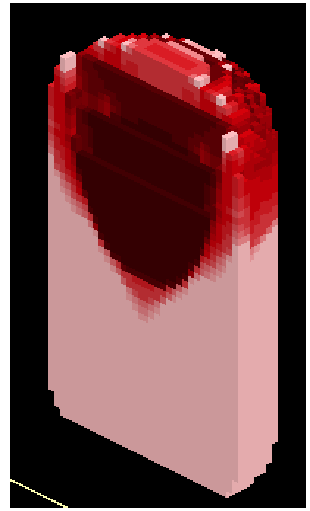


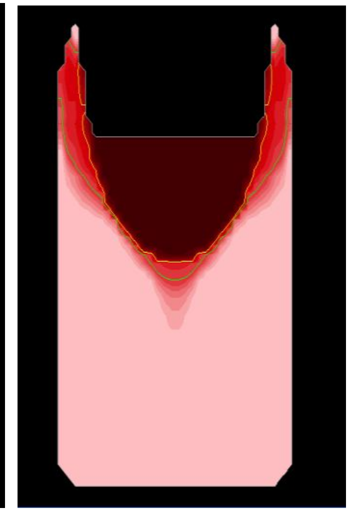


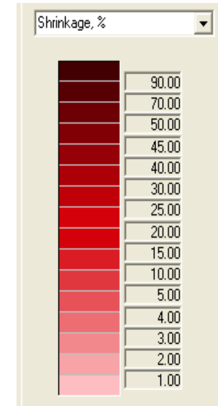
Macro-Shrinkage Validation: A356 plate B

A356 (gravity pouring)



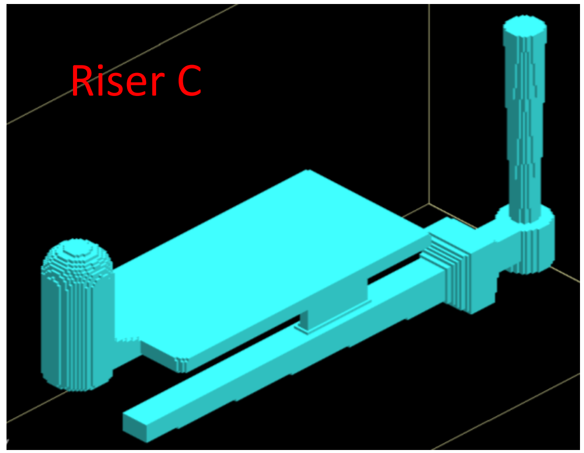


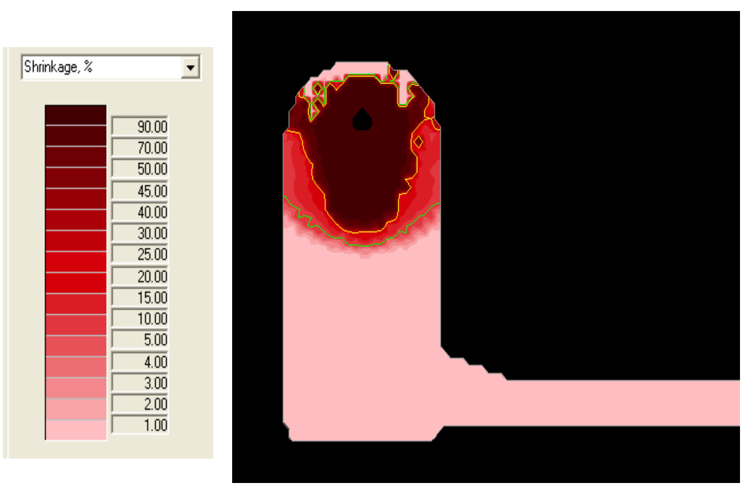




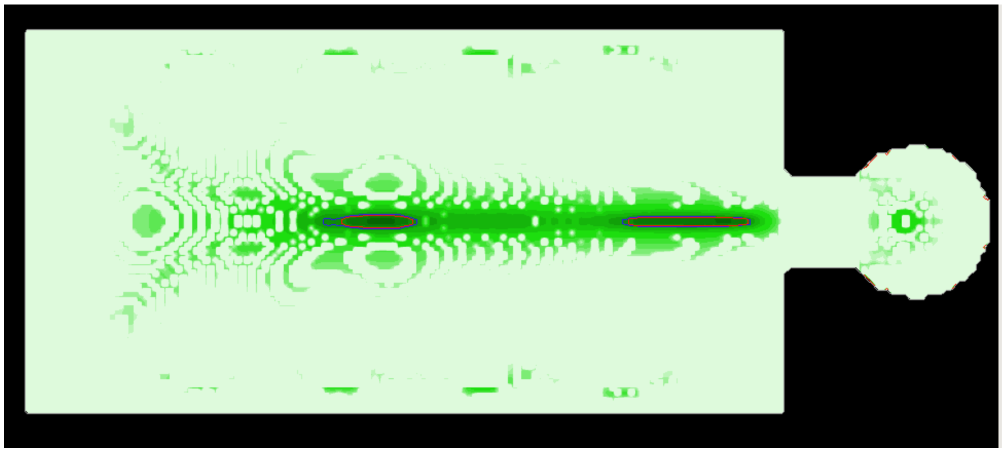
Macro-Shrinkage Validation: A356 plate C

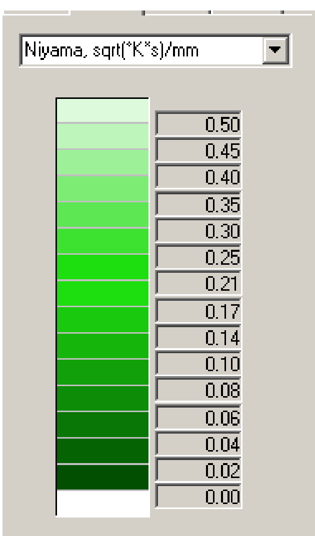
A356 (gravity pouring)

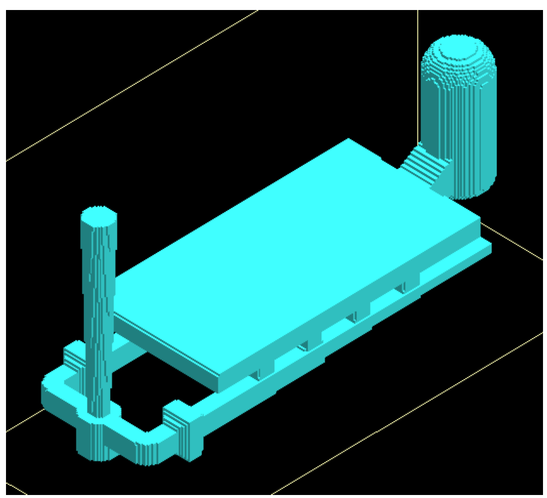


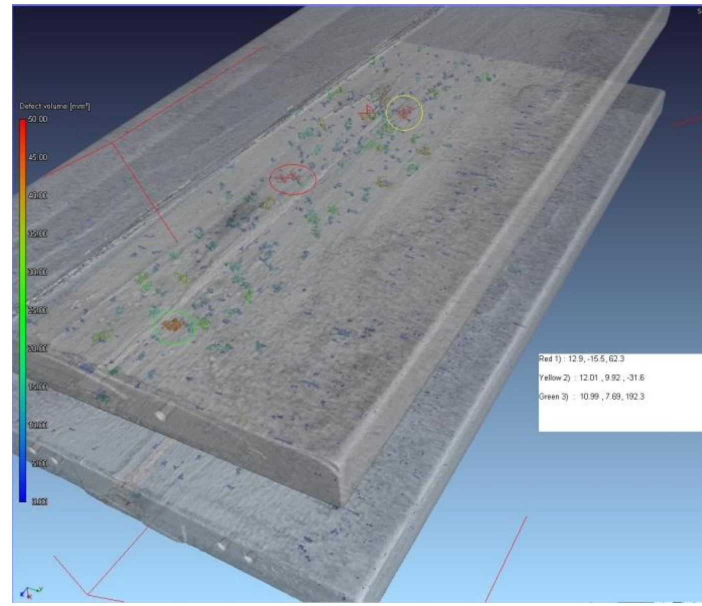


Shrinkage Porosity Validation: A356 - 25 mm Thick Plate A



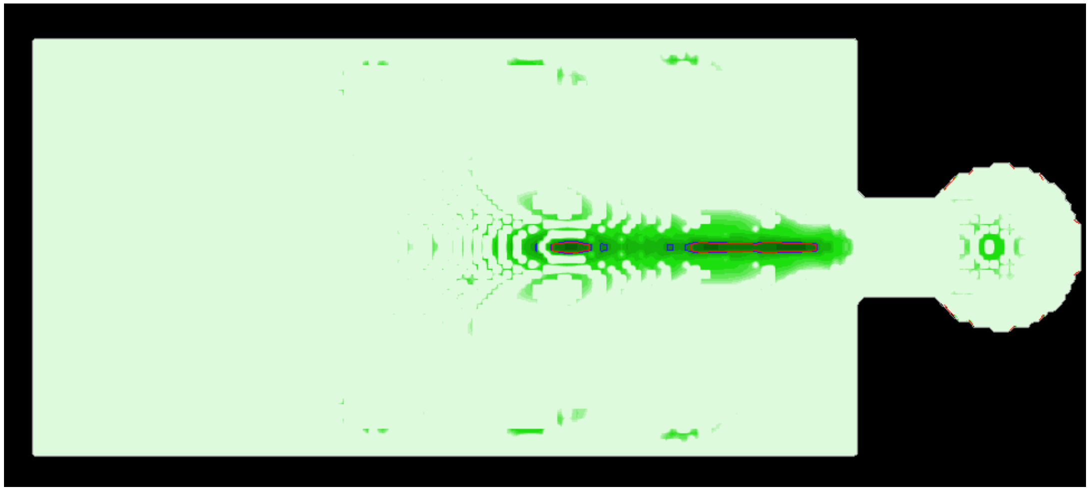


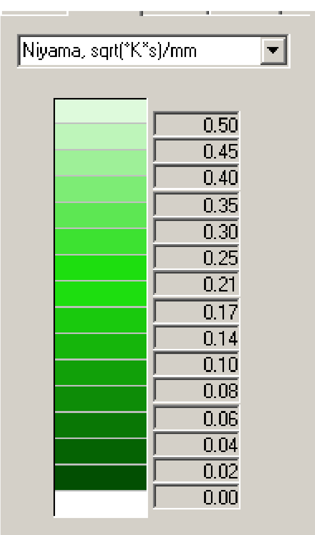


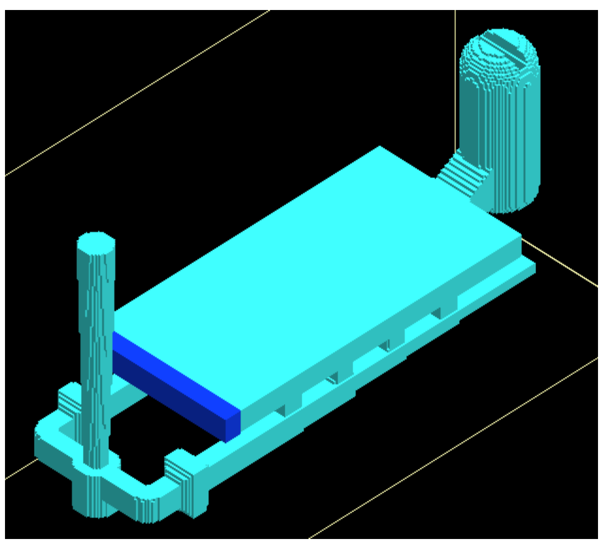


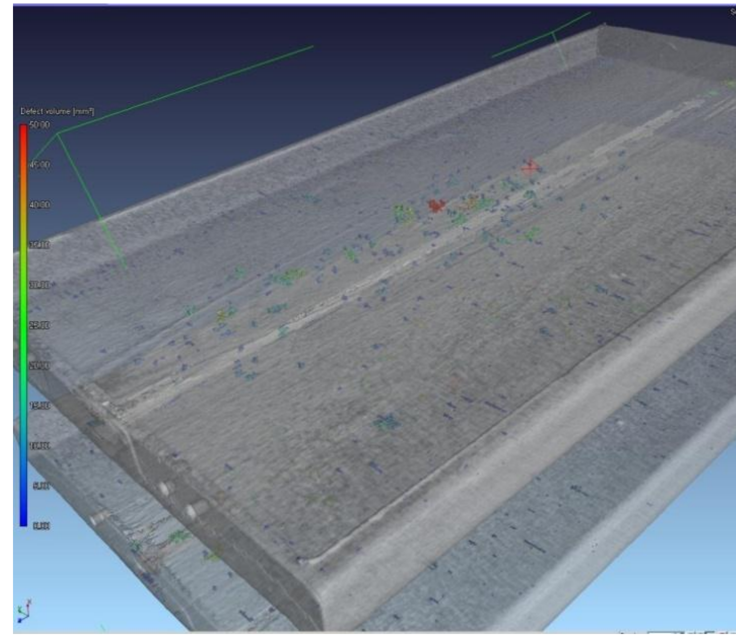
Computer tomography (CT) scan showing volume of defects per mm^3

Shrinkage Porosity Validation: A356 - 25 mm Thick Plate B



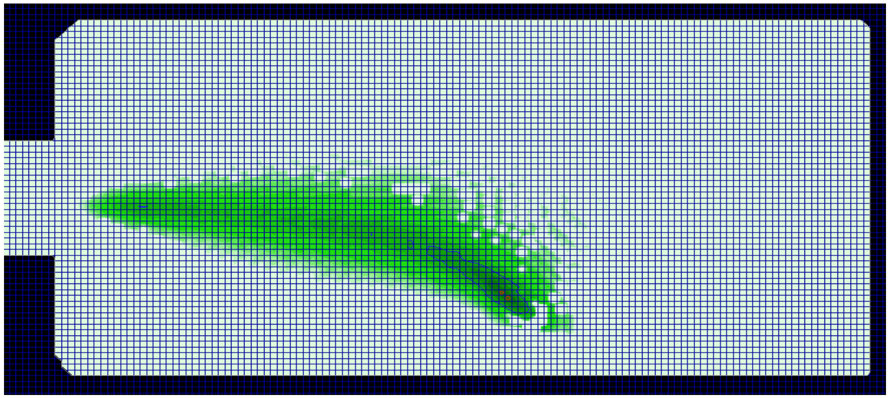


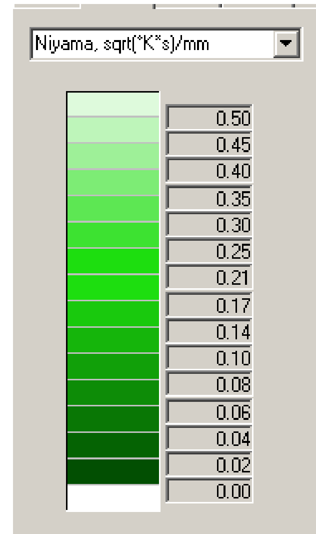


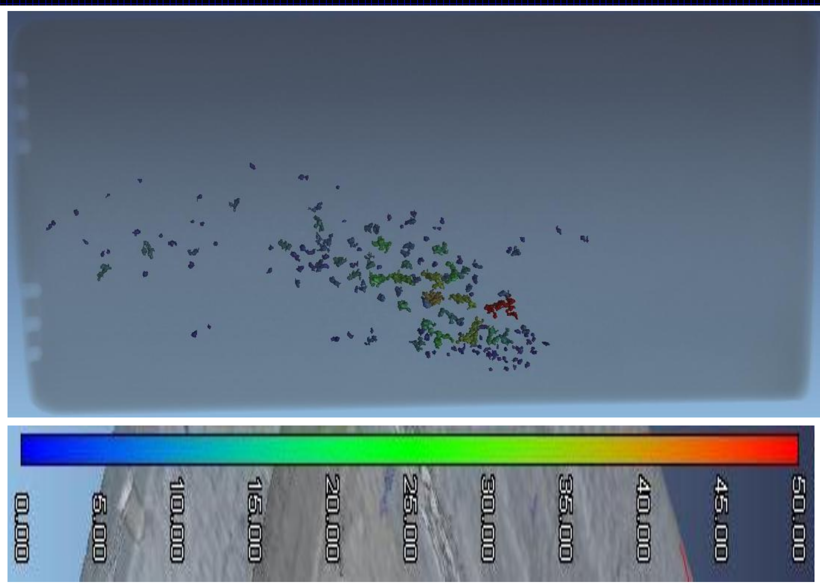


Computer tomography (CT) scan showing volume of defects per mm^3

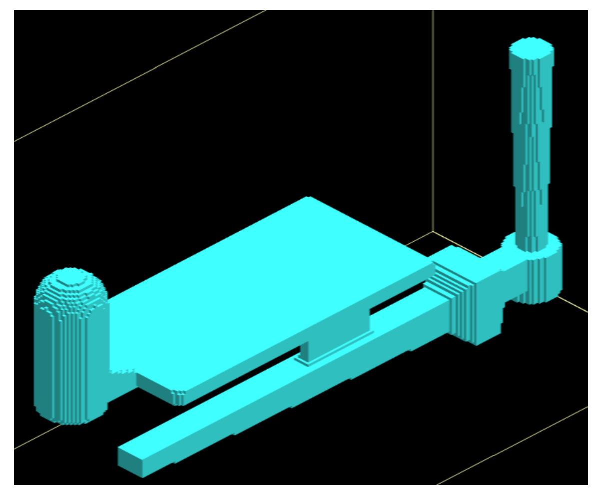
Shrinkage Porosity Validation: A356 - 12.5 mm Thick Plate C



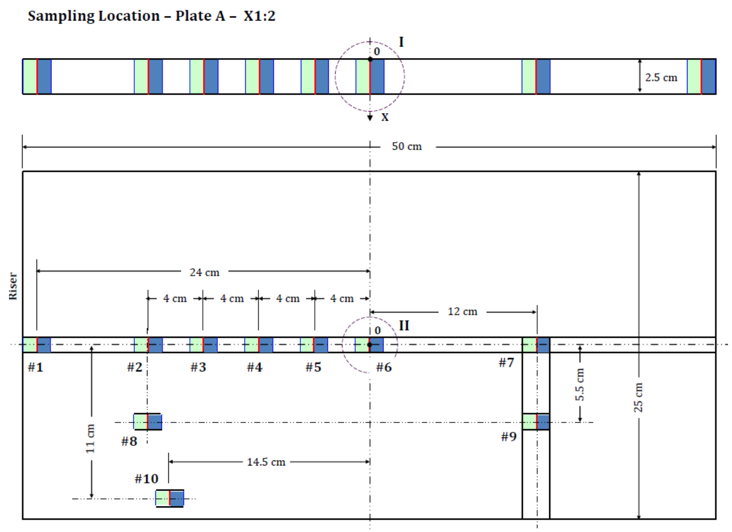




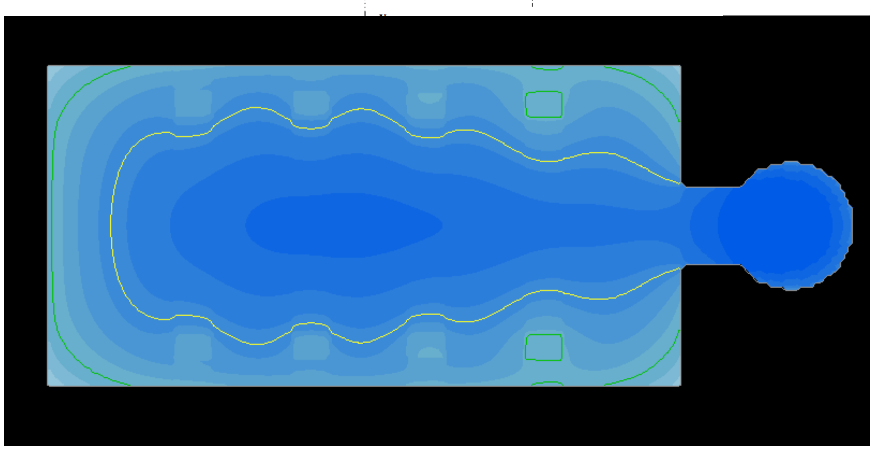
Computer tomography (CT) scan showing volume of defects per mm^3

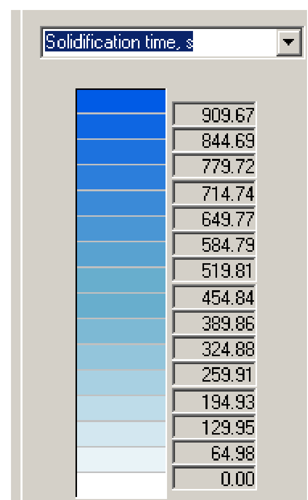


Shrinkage Porosity Calibration: A356 plate A (25 mm)



Sample	Pore%	Niyama	t_s (s)	CR (K/s)
#1	0.875	0.229	801	0.217
#2	1.614	0.050	796	0.219
#3	1.862	0.133	813	0.214
#4	1.314	0.119	839	0.207
#5	1.554	0.114	854	0.204
#6	**2.221**	**0.058**	870	0.200
#7	**1.754**	**0.321**	823	0.211
#8	0.487	1.278	715	0.243
#9	**1.009**	**0.516**	776	0.224
#10	0.455	1.553	475	0.366

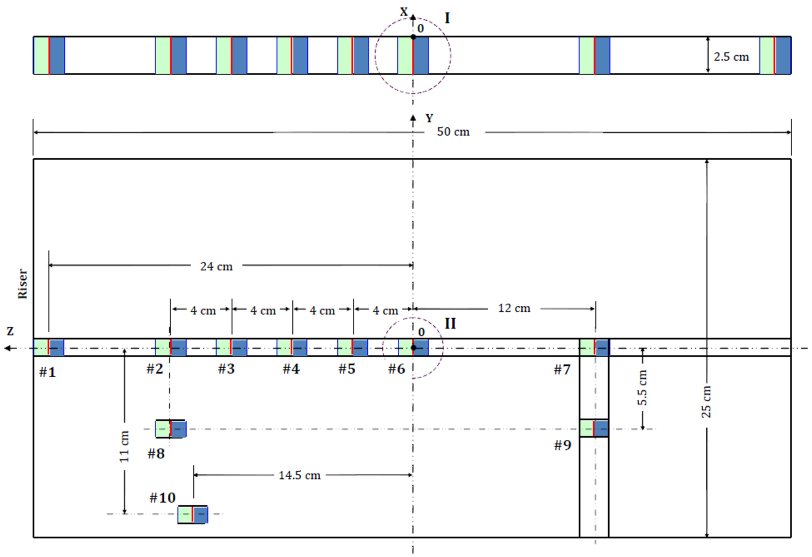




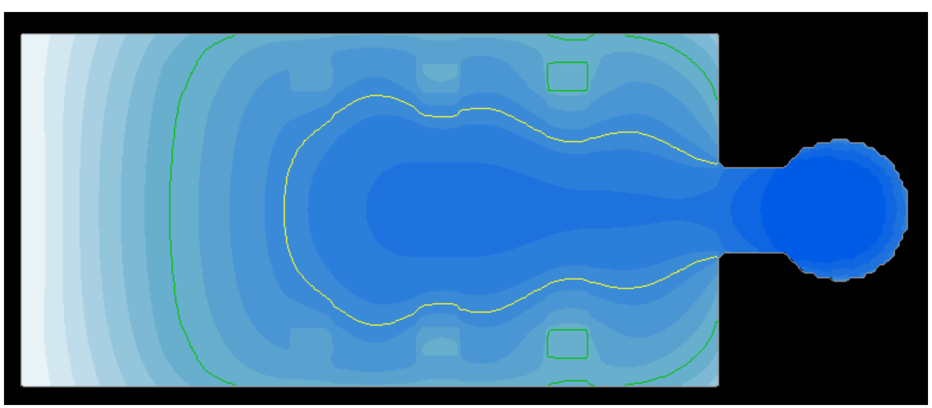
Solidification time

Shrinkage Porosity Calibration: A356 plate B (25 mm)

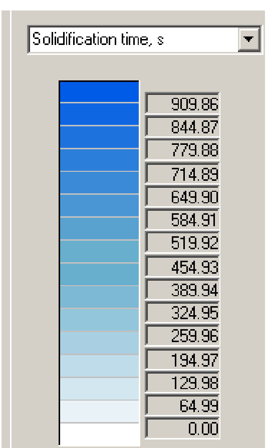
Sampling Location – Plate B – X1:2



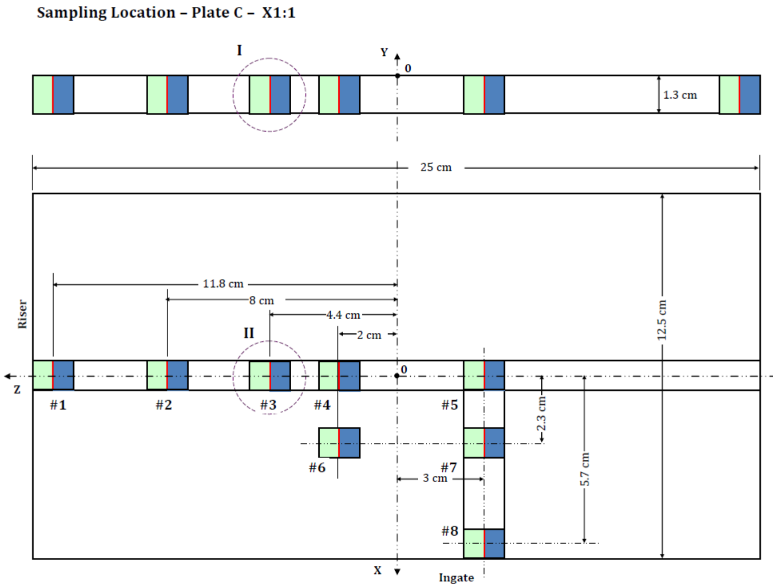
Sample	Pore%	Niyama	t_s (s)	CR (K/s)
#1	0.845	0.277	793	0.219
#2	1.678	0.041	791	0.222
#3	1.220	0.137	822	0.212
#4	2.370	0.039	815	0.213
#5	2.042	0.144	790	0.221
#6	**1.459**	**2.515**	783	0.222
#7	**0.754**	**7.995**	530	0.328
#8	0.632	5.469	675	0.258
#9	**0.664**	**7.814**	517	0.337
#10	0.552	8.028	471	0.369



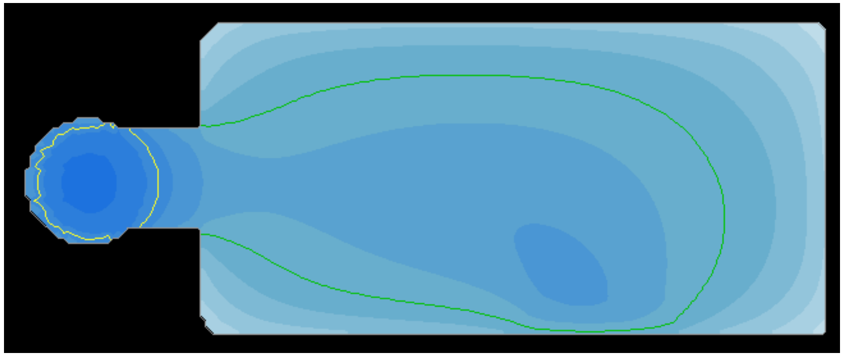
Solidification time



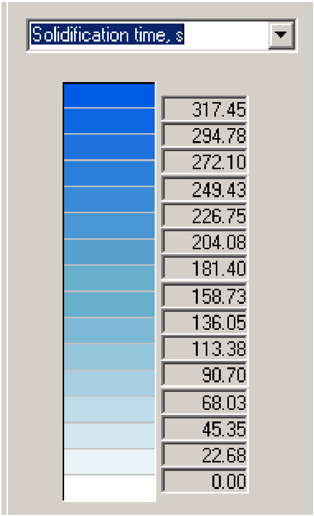
Shrinkage Porosity Calibration: A356 plate C (12.5 mm)



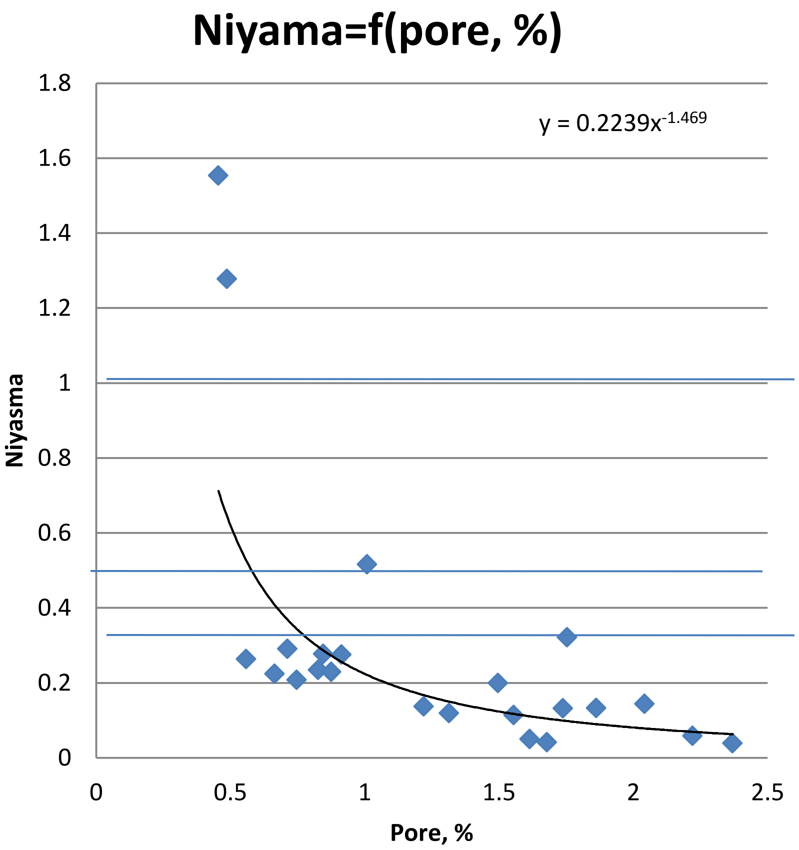
Sample	t_s (s)	CR(K/s)	Pore%	Niyama
#1	192	0.703	0.712	0.291
#2	184	0.784	0.747	0.208
#3	191	0.763	0.665	0.224
#4	193	0.755	1.496	0.199
#5	187	0.722	0.913	0.275
#6	196	0.732	1.738	0.132
#7	198	0.654	0.558	0.263
#8	187	0.832	0.827	0.234

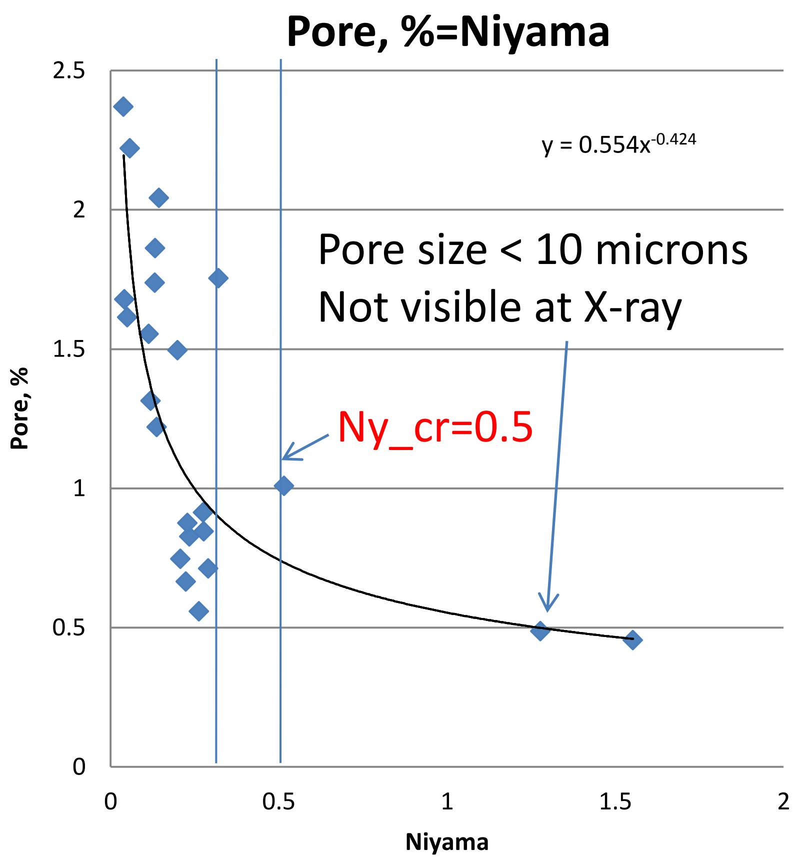


Solidification time



Niyama vs. Pore% (A356)





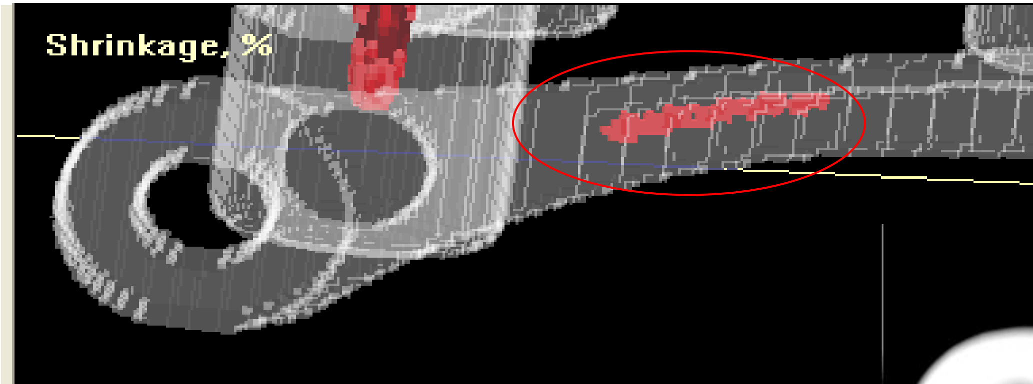
Concluding Remarks and Future Work

- **Conclusions:**
  - A comprehensive validation/calibration for predictions of macro-shrinkage and shrinkage porosities was performed
  - Experimental measurements for A356 plate sand mold castings at ExOne/Prometal RCT.
  - Predictions are compared reasonably with macro-shrinkage and shrinkage porosity measurements.
  - For A356 and the foundry practice in in the current work, the critical Niyama number is 0.5.
  - It was also demonstrated that Niyama criterion correlates reasonable well with pore percent in A356 plate castings.
- **Future work:**
  - Developing an improved criterion to account for the nucleation and growth of shrinkage porosities

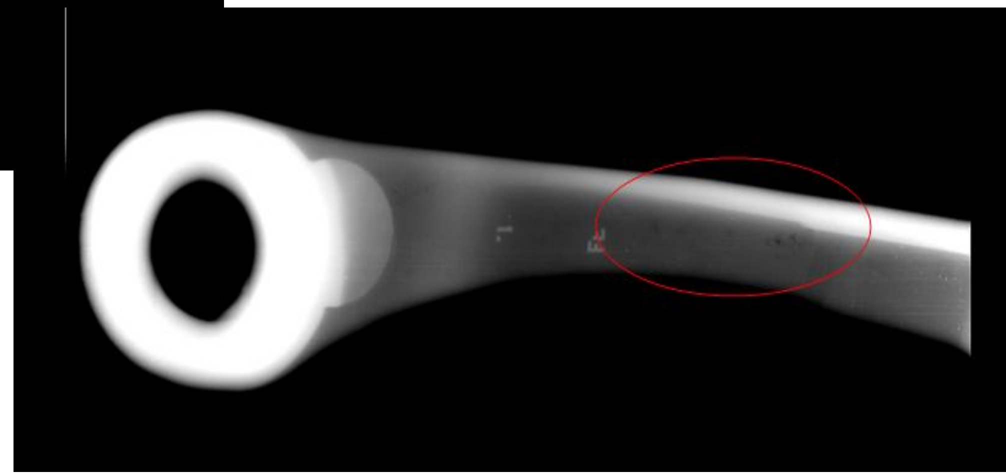
Acknowledgement

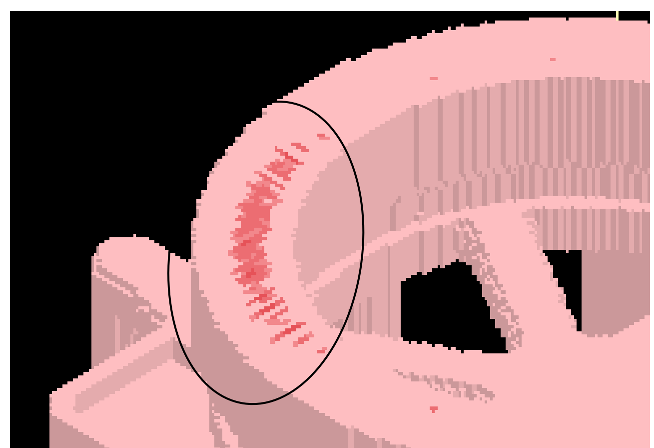
- The authors would like to acknowledge ExOne-Prometal RCT for their continuous support and useful comments and suggestions in developing this article.

Macro-Shrinkage Validation



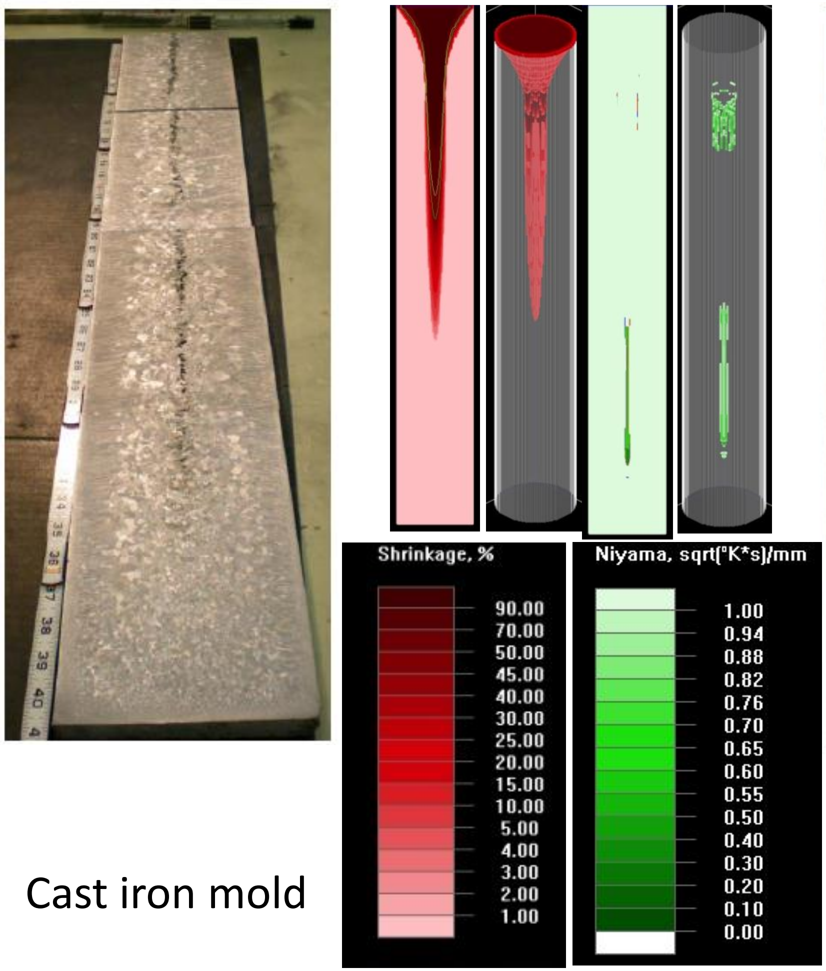
Steel (Gravity Pouring)



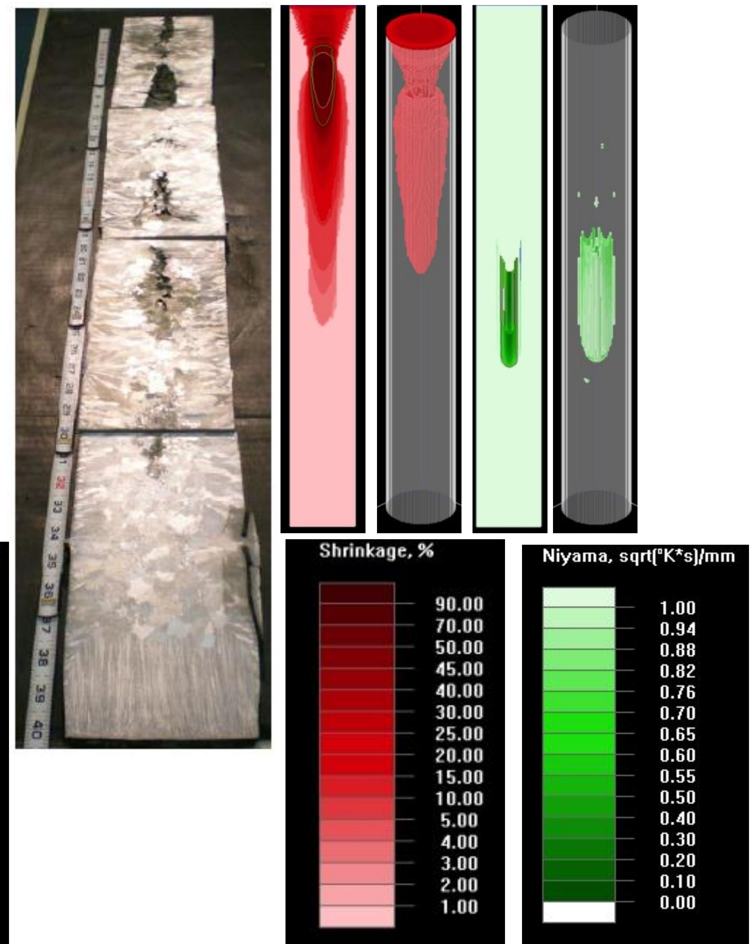


A356 (Low Pressure)

Prediction of Shrinkage and Porosities in a 6-in Diameter Ingot (IN718)



Cast iron mold

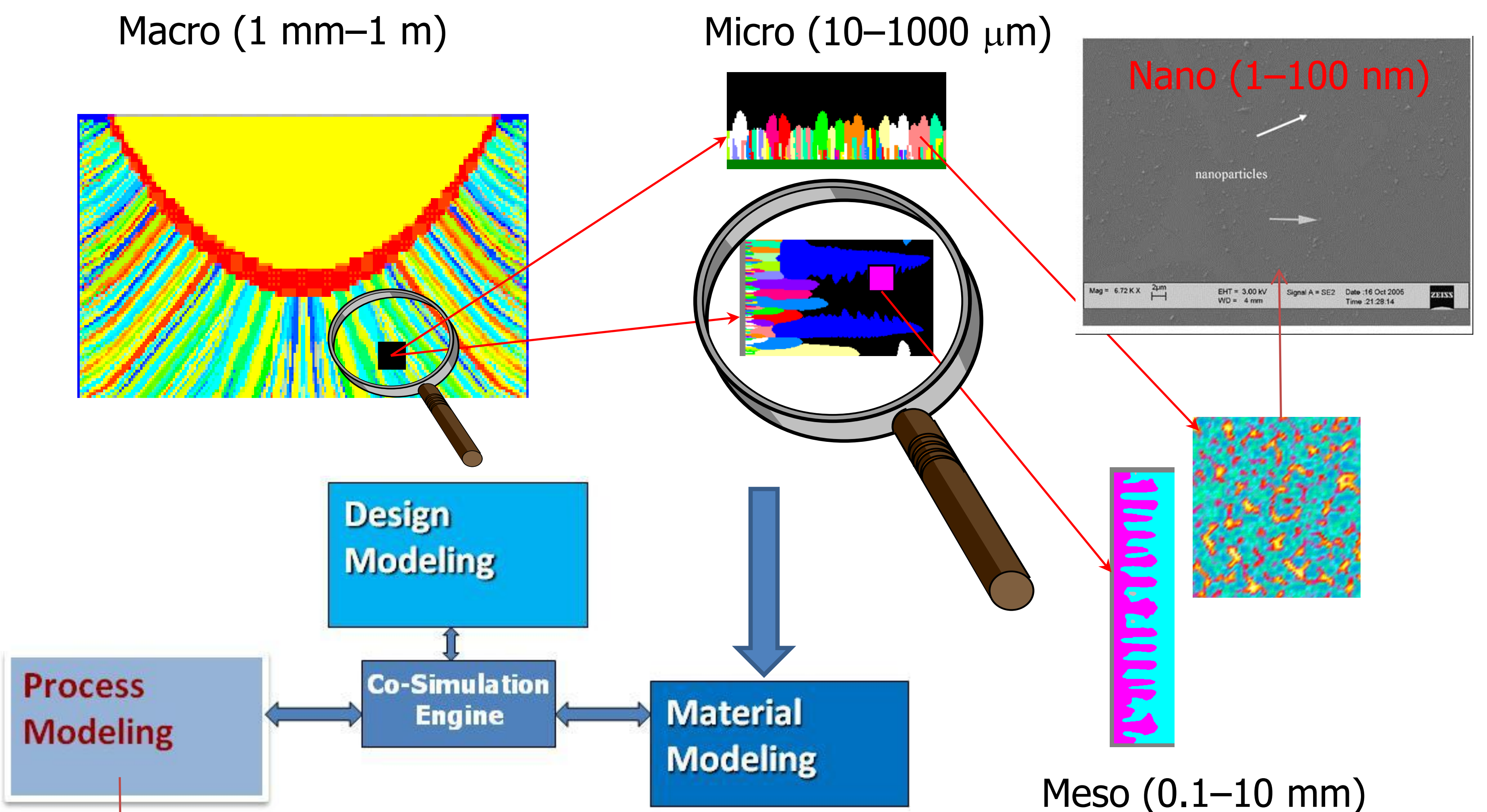


Cast iron mold with 12 mm insulation

Parametric Study: Macro-Shrinkage and Shrinkage Porosities (IN718)

- Studied variables were:
  - Ingot diameter and taper
  - Sleeve length
  - Hot top vs. radiation
  - Alloy type
- Main findings:
  - For sleeve and cast iron cases, shrinkage length increase and porosity length decreases with ingot diameter
  - For full insulation case, porosity length increase and shrinkage length decreases with ingot diameter
  - Sleeve length and use of hot top vs. radiation are important factors.
  - Ingot D=12-in case study:
    - A small-size insulation sleeve with hot top material show lowest predicted levels of shrinkage
    - Without hot top (e.g., radiation), a larger insulation sleeve is required

What's next? Solver Length Scales for Multi-Scale Modeling*



Ultrasonic Technology, MHD processing: controlled solidification, minimize macro-segregation
New high temperature alloys: Nucleation and growth kinetics of in-situ nano-phases

*Laurentiu Nastac, "Modeling and Simulation of Microstructure Evolution in Solidifying Alloys," Springer Verlag, 2004, 305 pages.