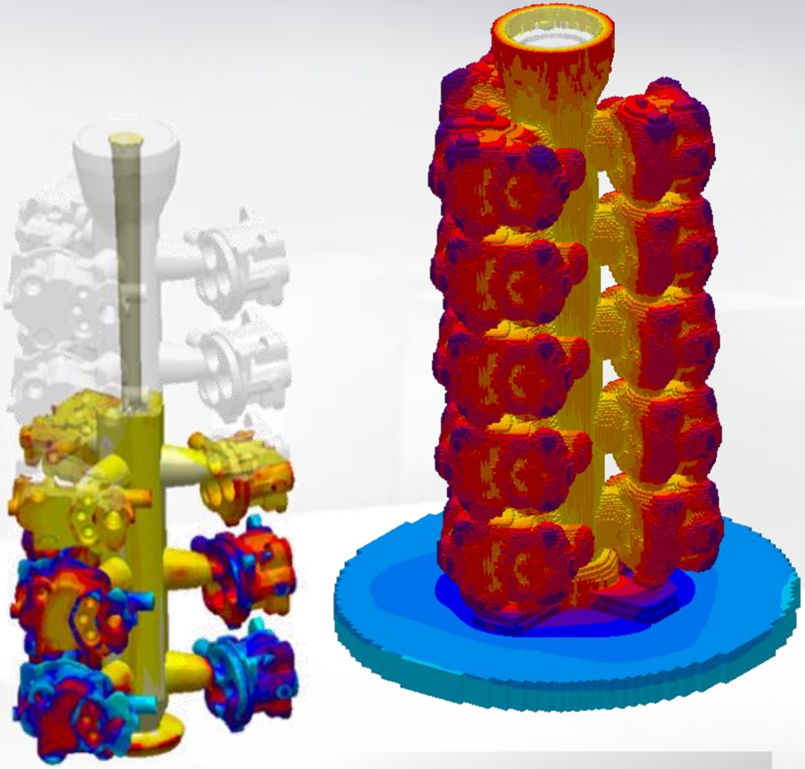
Autonomous Engineering Applied to Investment Casting Process



ICI Conference
October 15-18, 2017

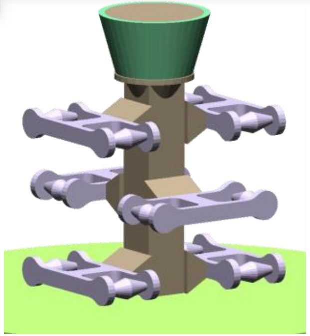
Overview

- What is Autonomous Engineering?
  - Traditional simulations vs new approach
- Case Study #1
  - Using Autonomous Engineering to evaluate two pattern layouts
- Case Study #2
  - Adjusting Thermal Property datasets for Investment Casting Shells
- Case Study #3
  - Evaluating a gating approach using Autonomous DoE

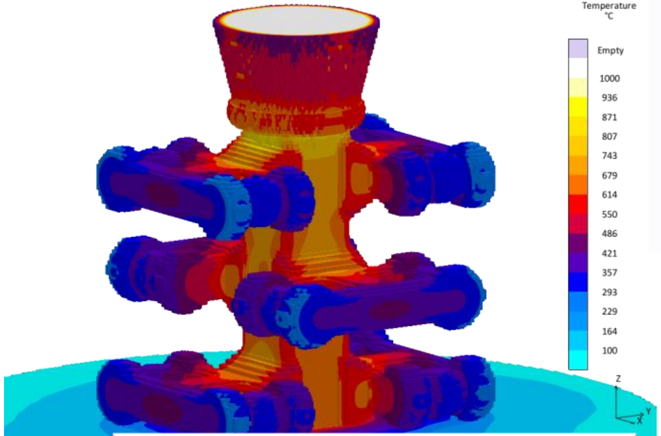
From Simulation to Autonomous Engineering

Investigating Solidification

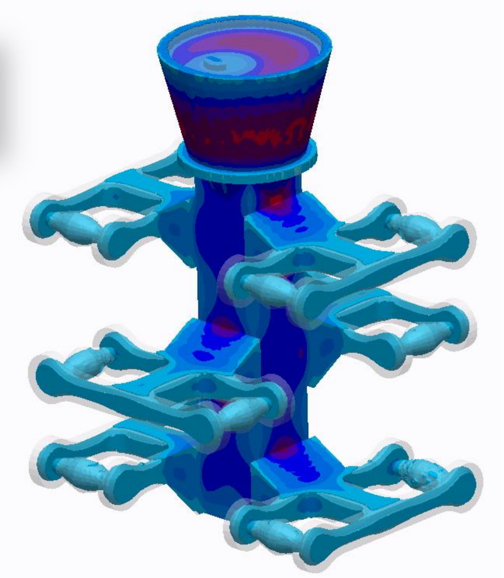
MetalTek International (US)



Casting geometry with premanufactured cone (Shell hidden)

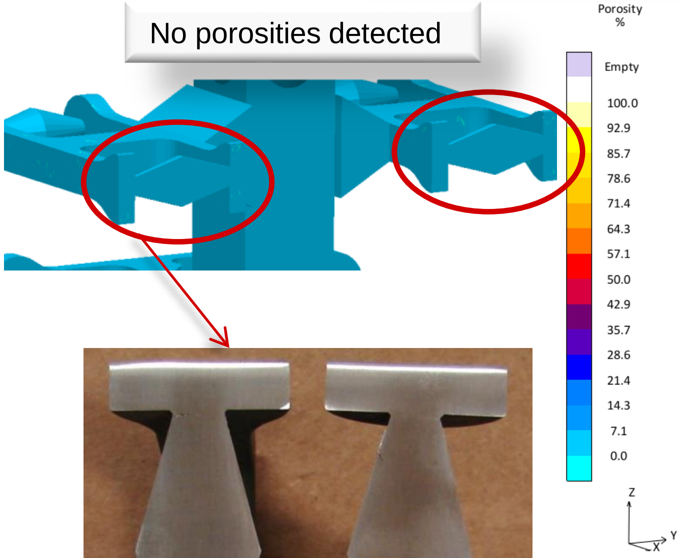


Shell surface temperatures after ~ 21min (end of solidification)

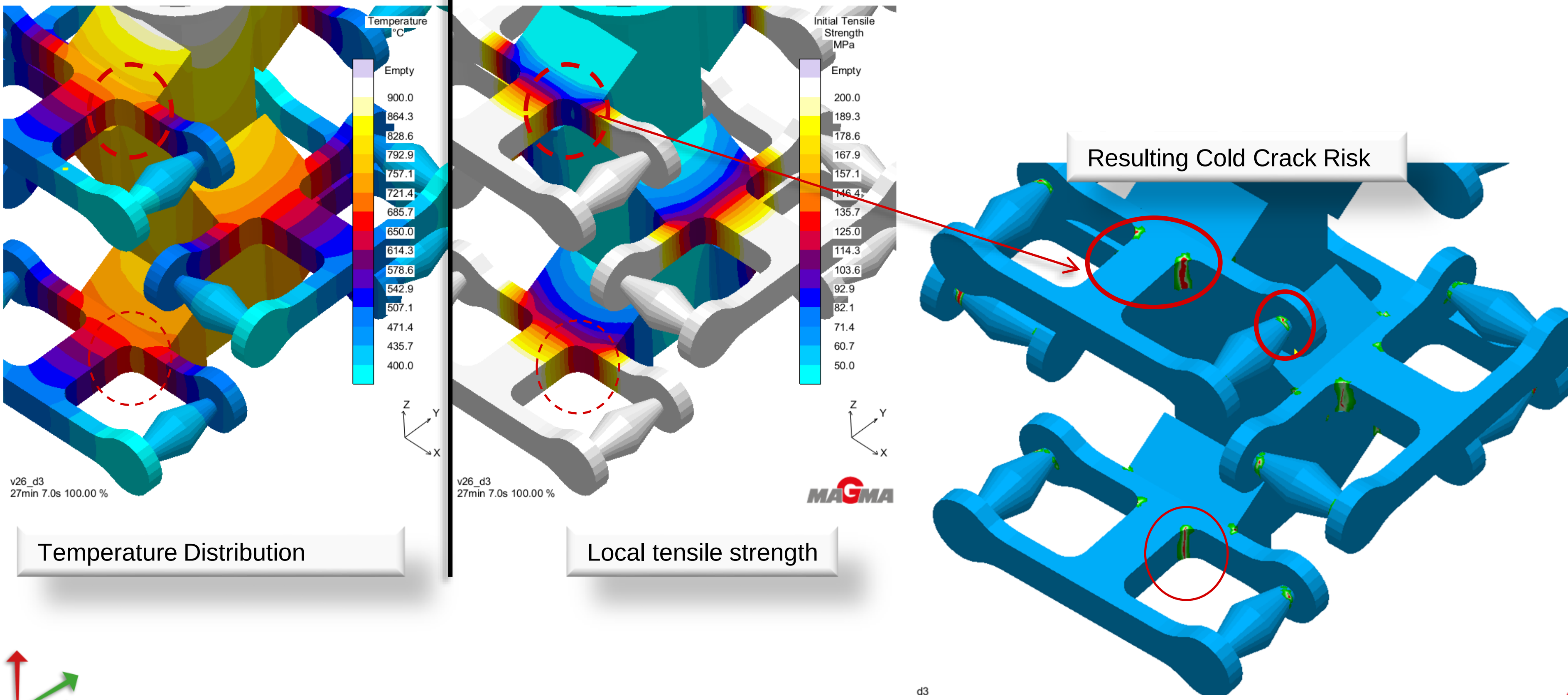


solidification pattern Indicating feeding paths

No porosities detected

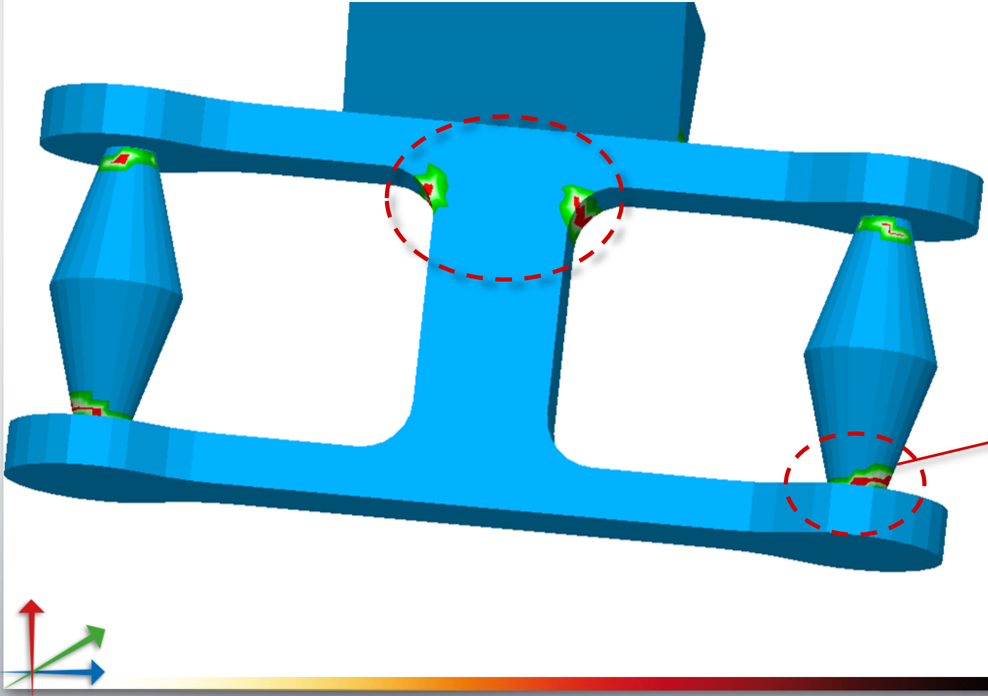


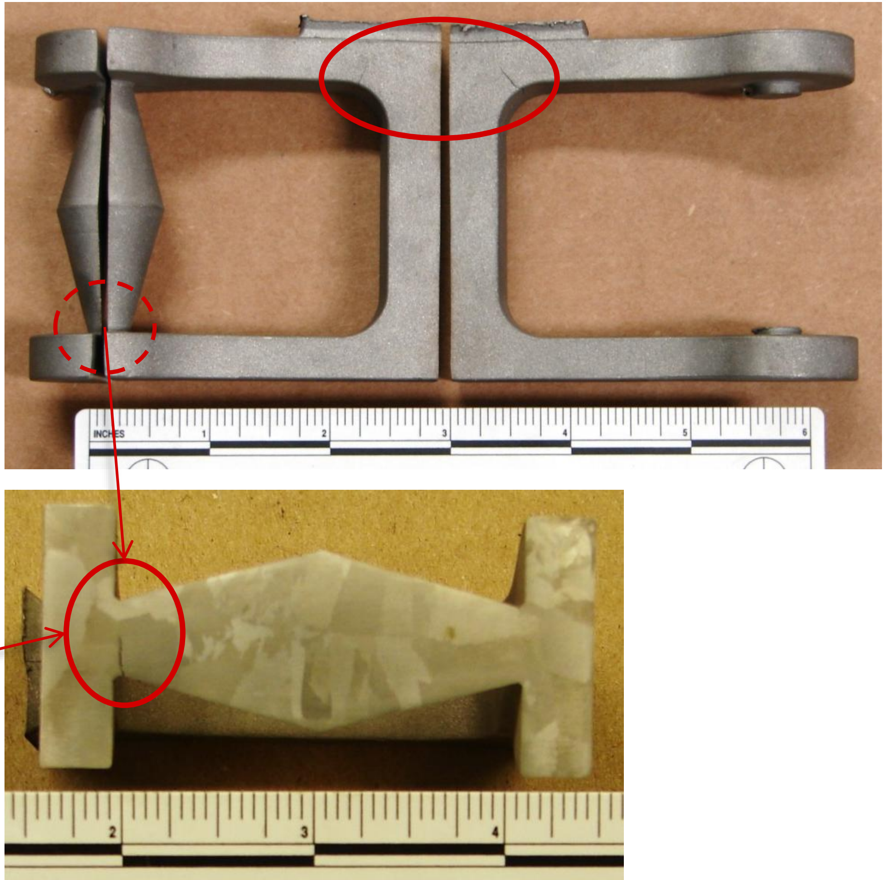
Investigating Stresses and Cracks



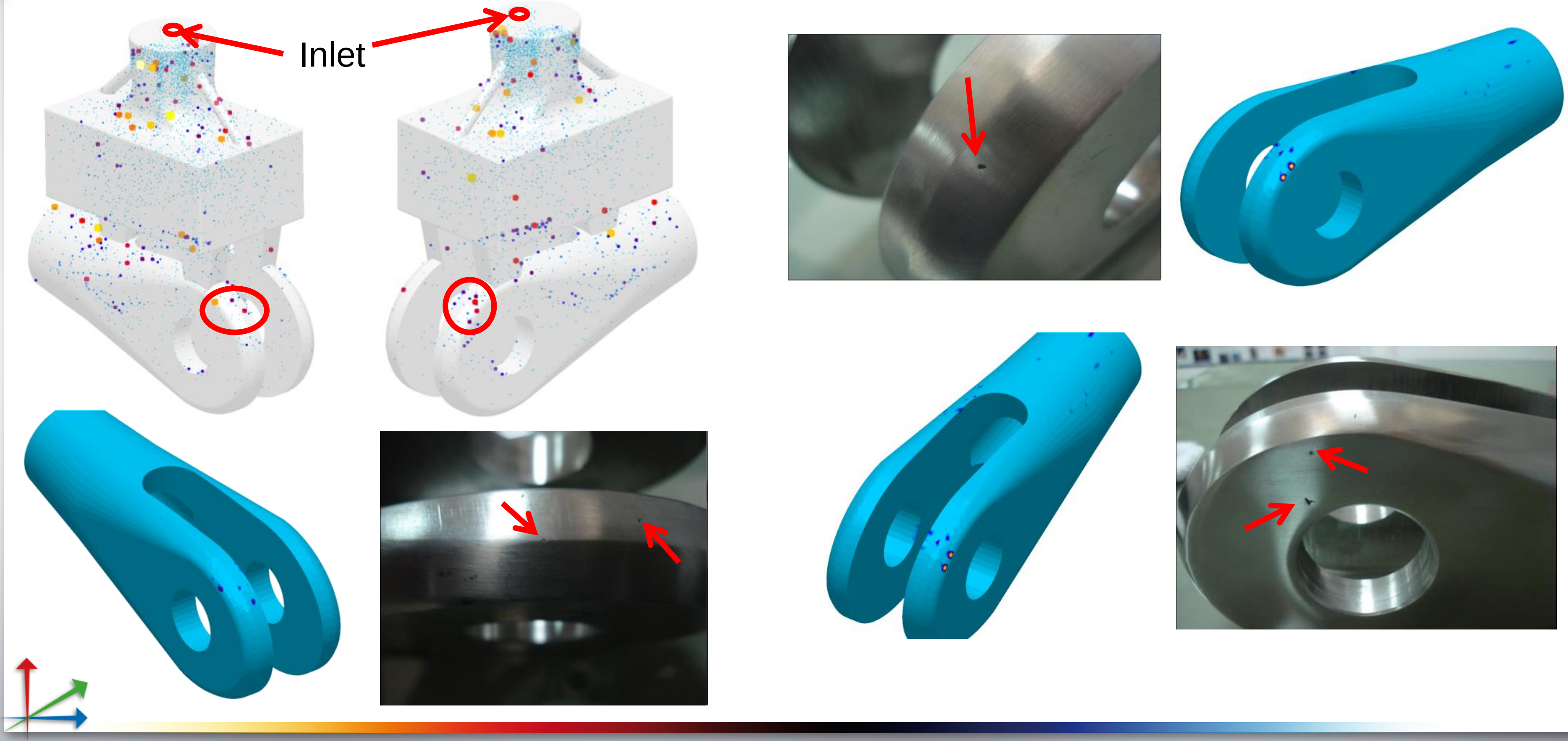
Investigating Stresses and Cracks

Cold Crack Result



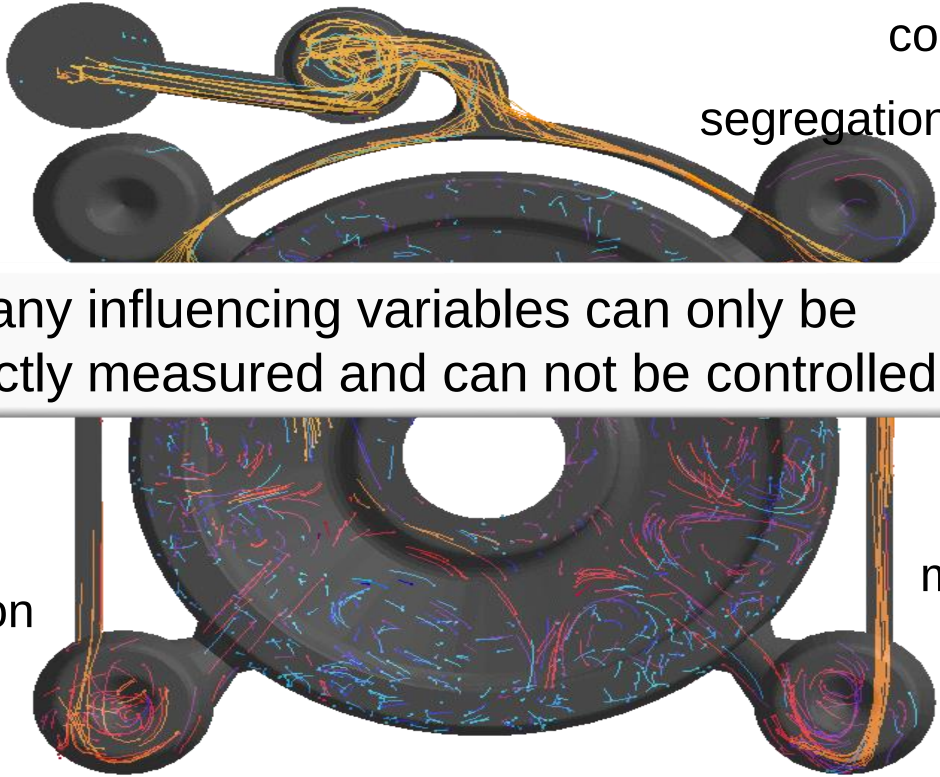


Reoxidation inclusions in steel alloys



Robust Casting Designs and Processes – a Black Box ?

... everything happens at the same time



flow

heat flow

cooling

gas

convection

segregation

composition

Many influencing variables can only be indirectly measured and can not be controlled

processing

solidification

stresses

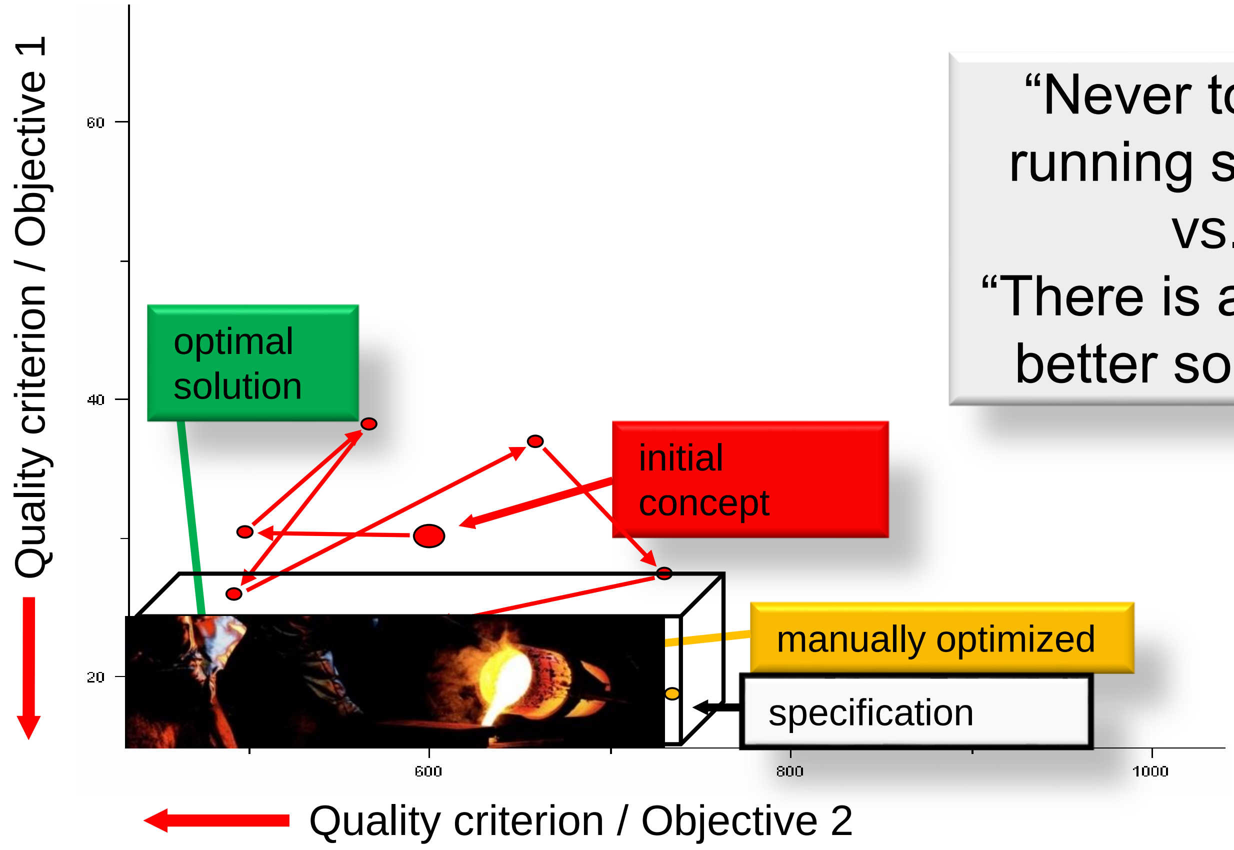
metallurgy

distortion

heat treatment

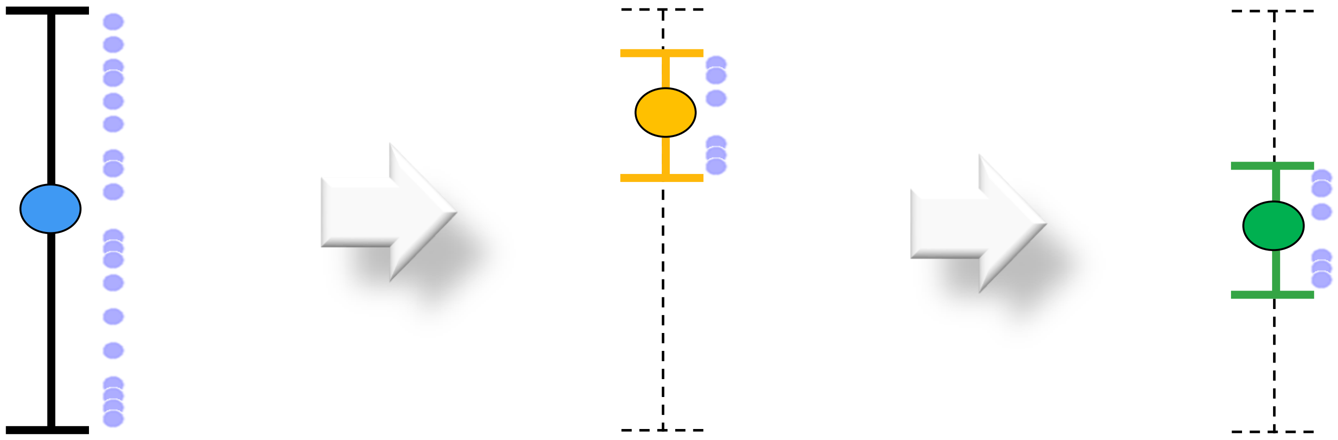
Why autonomous engineering?

“Improve the solution”



“Never touch a running system”
vs.
“There is always a better solution!”

Why autonomous engineering?
“Support continuous improvement processes”



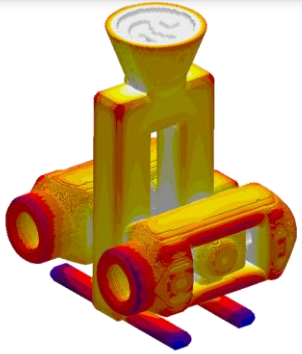
SOP:
large process
variation

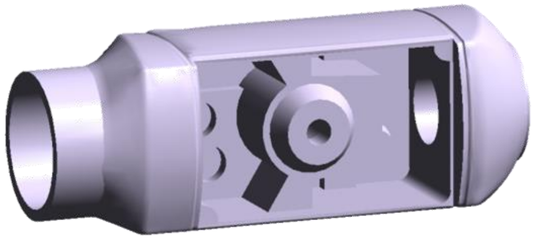
running production:
process variation reduced
(process robustness)

running production:
robust process
+
optimized operating point
(quality, costs, productivity)

Case Study #1

Autonomous Engineering applied to two pattern layouts

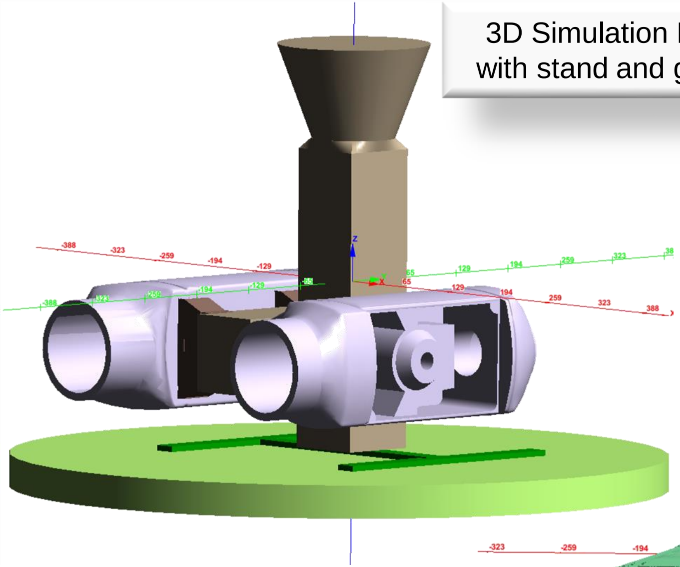


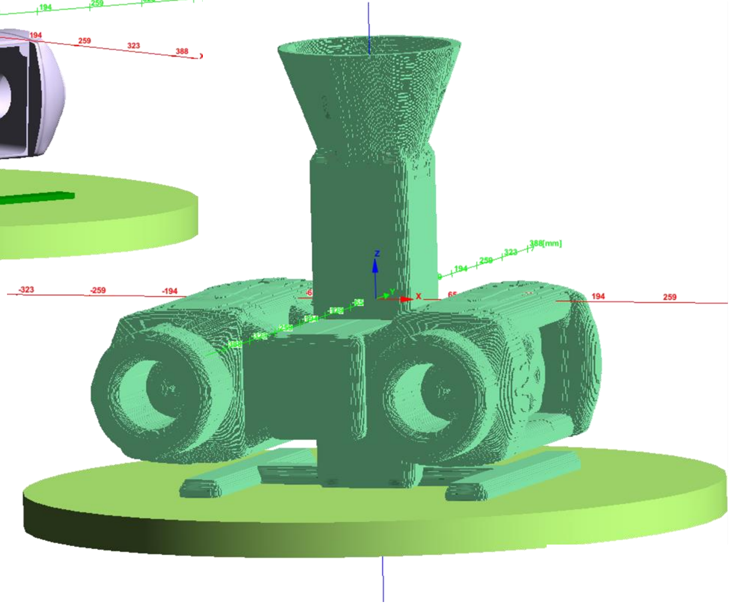


Wax model and simulation setup

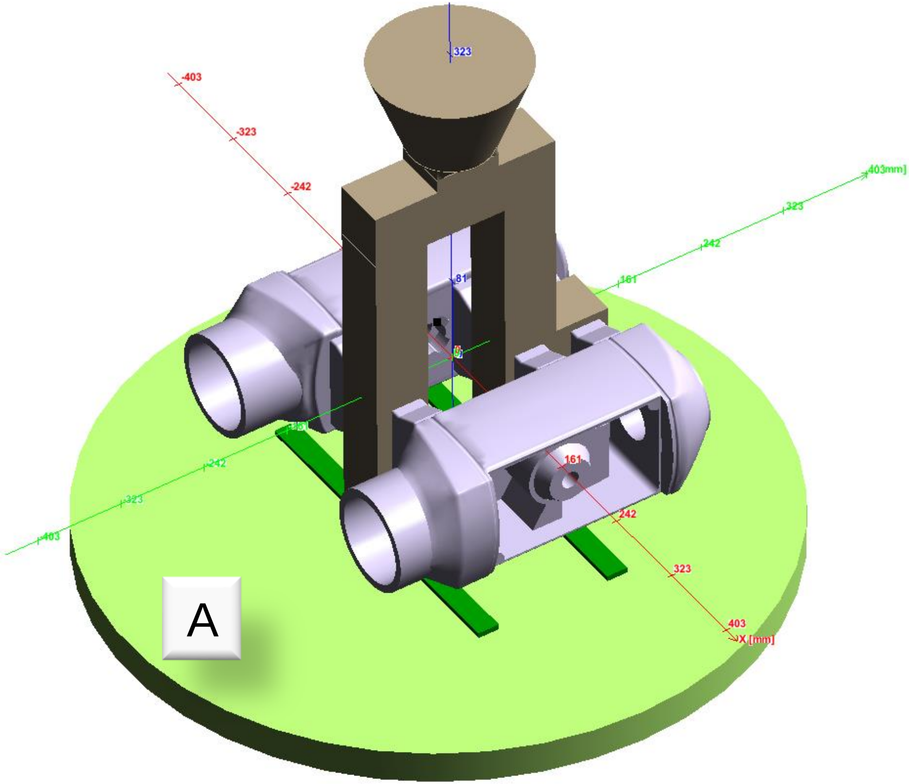
Wax Model Layout of Customer (Upside Down)

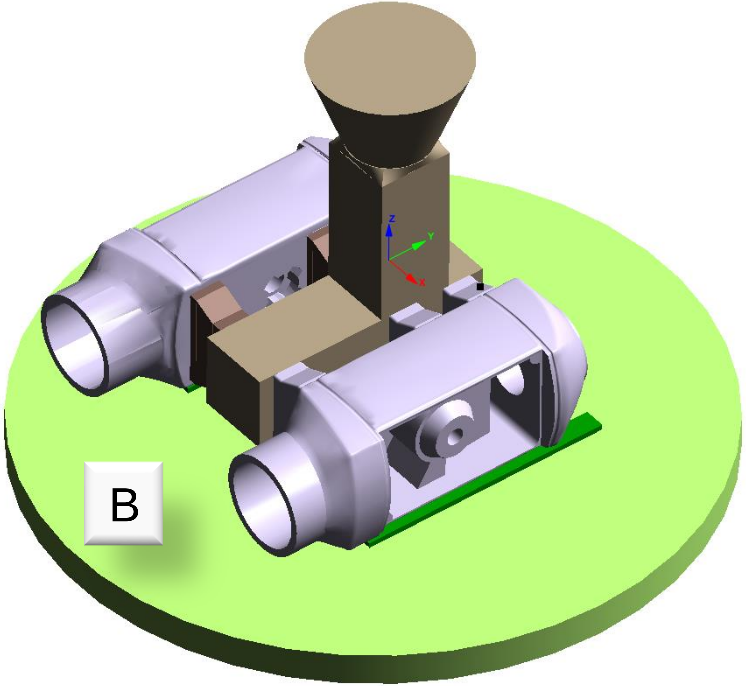
3D Simulation Model with stand and ground





Runner/Feeder Layouts A and B



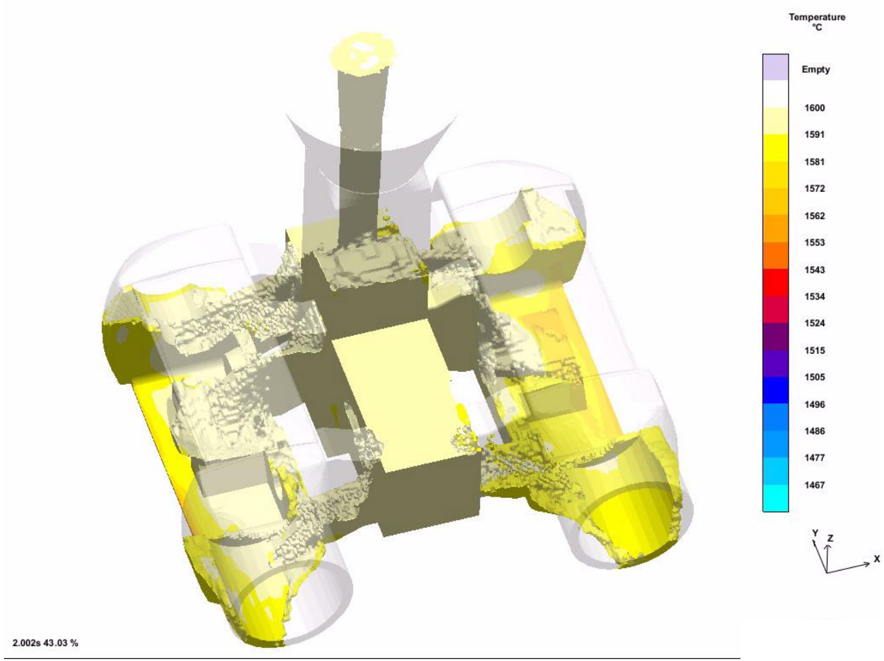


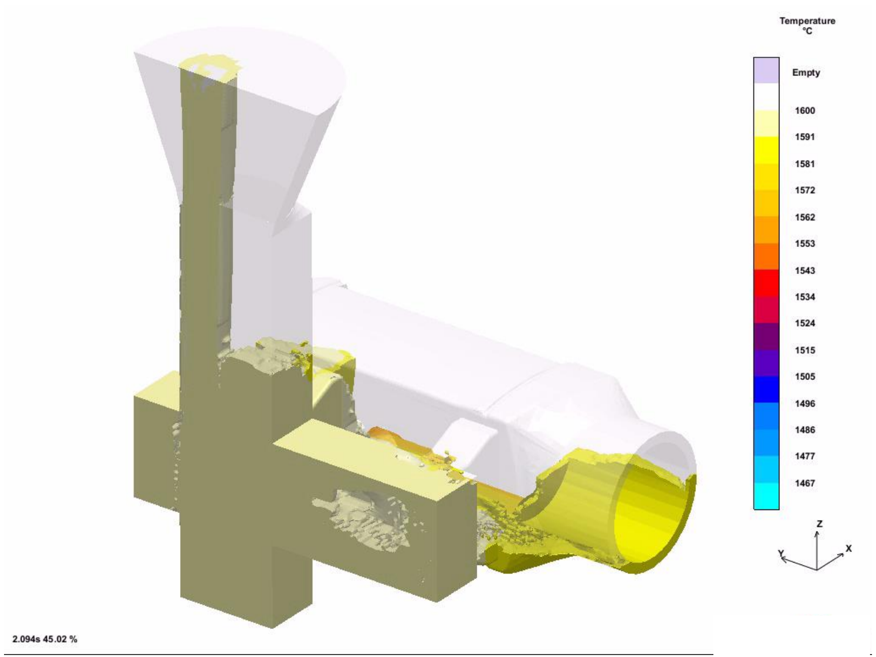
Process Parameters

- Cast Material: High-Alloy CrNi-Steel
- Pouring Temperature: 1600°C
- Pouring Time: ~ 5s
- Ceramic Shell preheated at 850°C
- Cast in ambient environment
- Down sprue isolated through topping

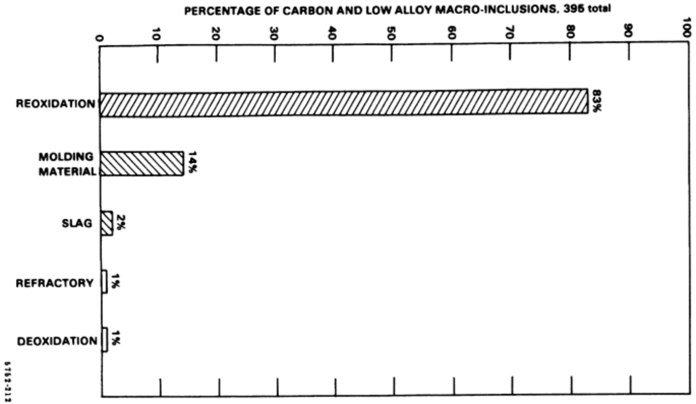
Filling Simulation Results

Metal flow and temperatures during filling



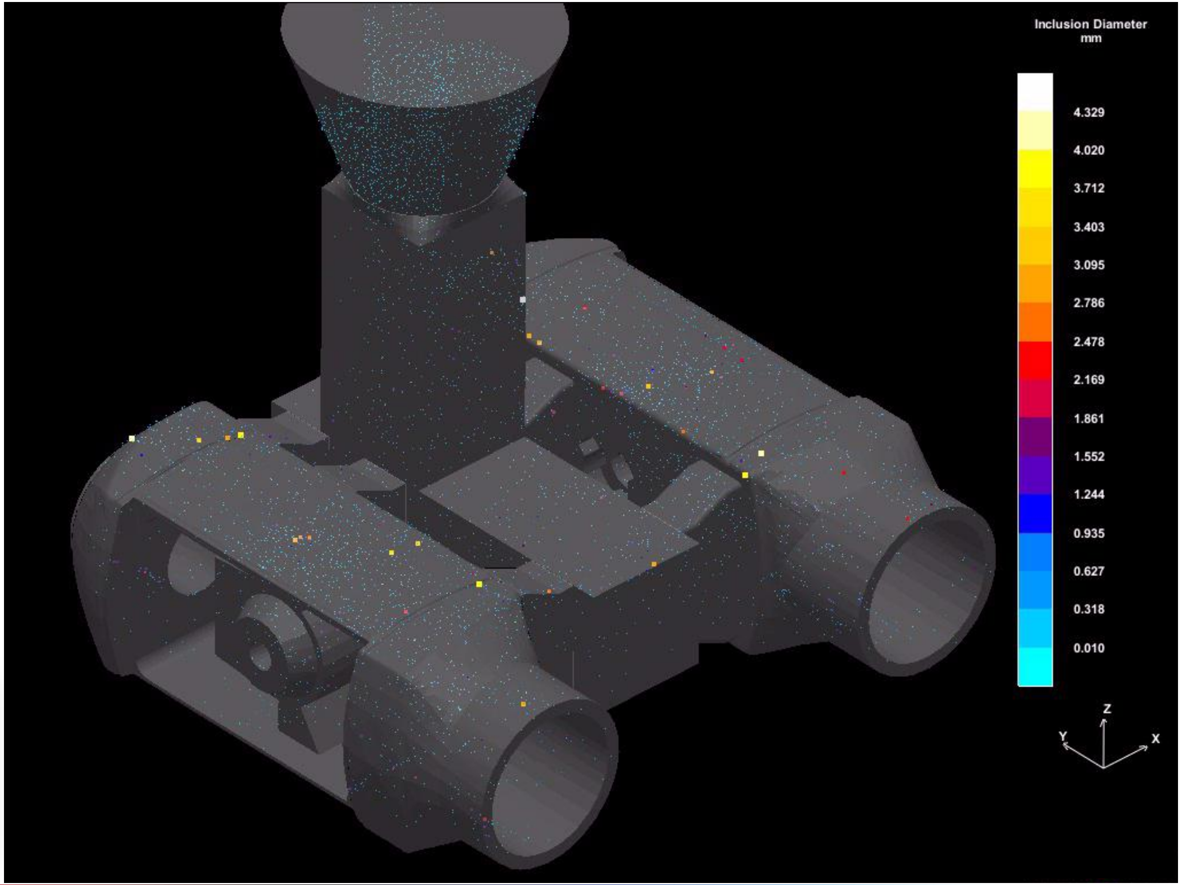


Re-oxidation inclusions

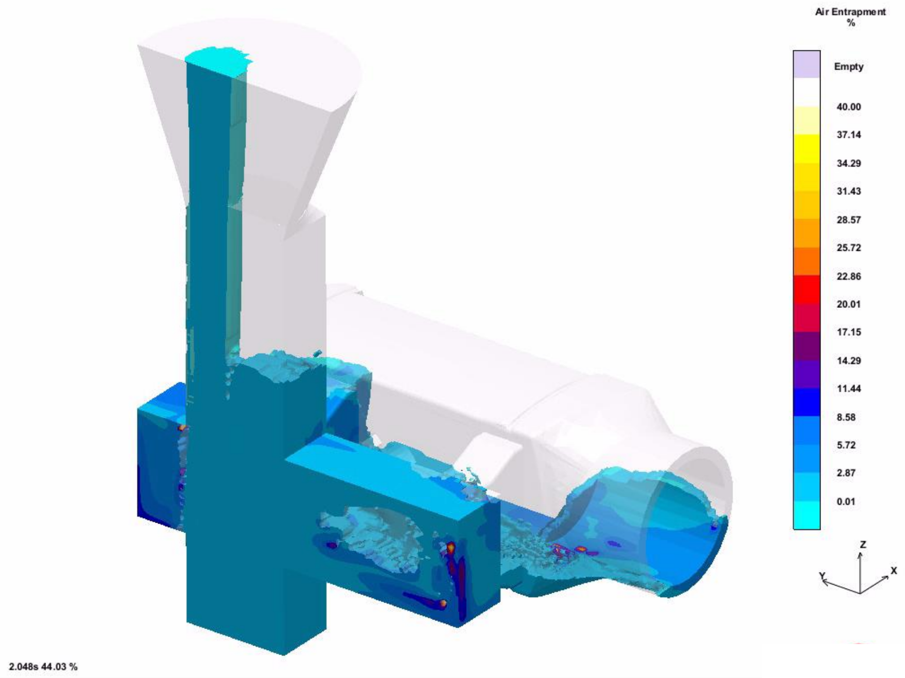


Svoboda, J.M., et al., “Appearance and Composition of Oxide Macroinclusions in Steel Castings,” AFS Transactions vol. 95, 1987, pp. 187-202

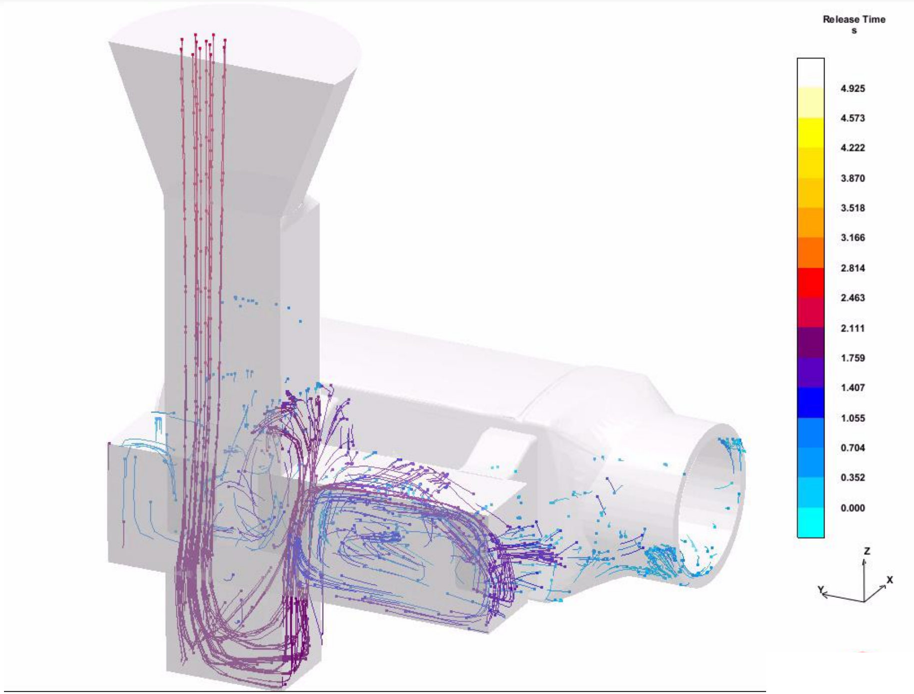
The majority of inclusions in steel castings result from reoxidation and turbulence during mold filling



Other Filling Results



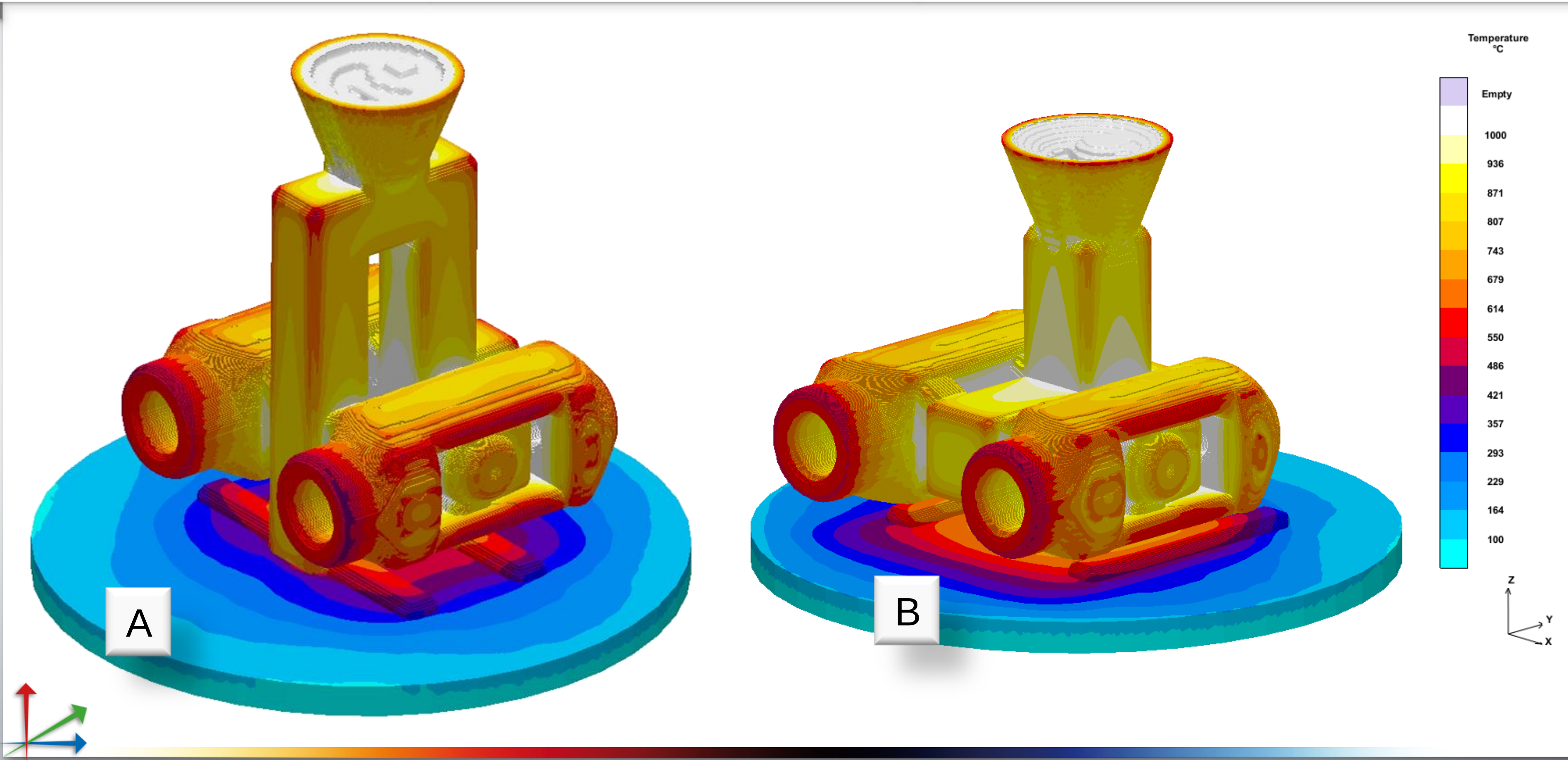
Air entrapped by the metal front



Massless particles showing flow patterns

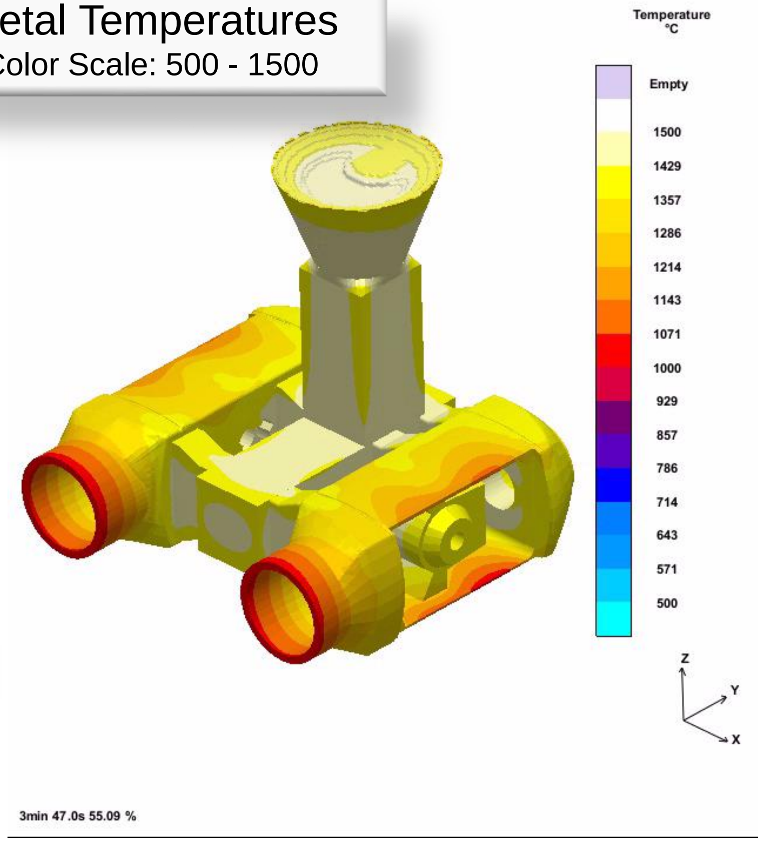
Solidification Simulation Results

Radiative Heat Exchange

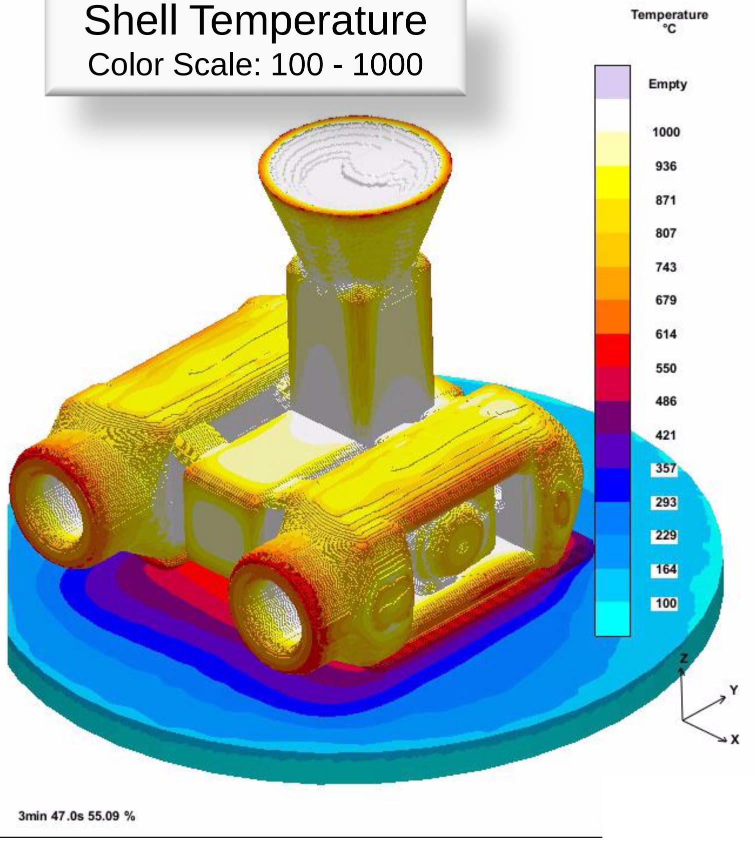


Temperatures during Solidification

Metal Temperatures
Color Scale: 500 - 1500



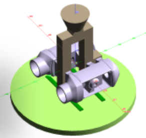
Shell Temperature
Color Scale: 100 - 1000

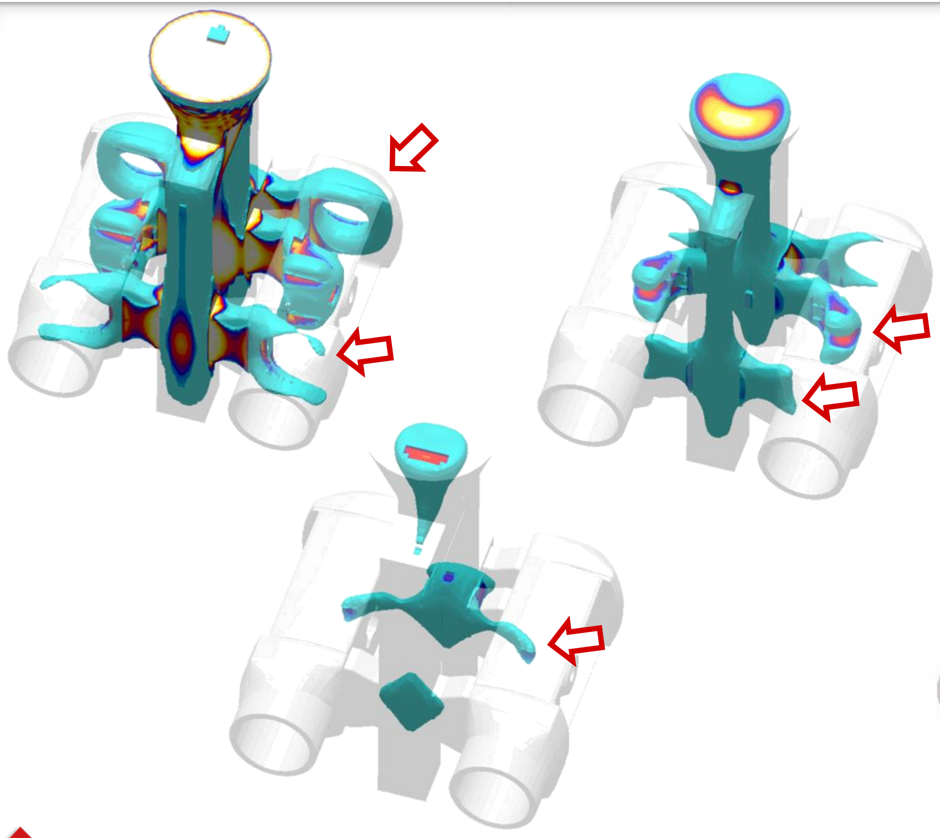


B

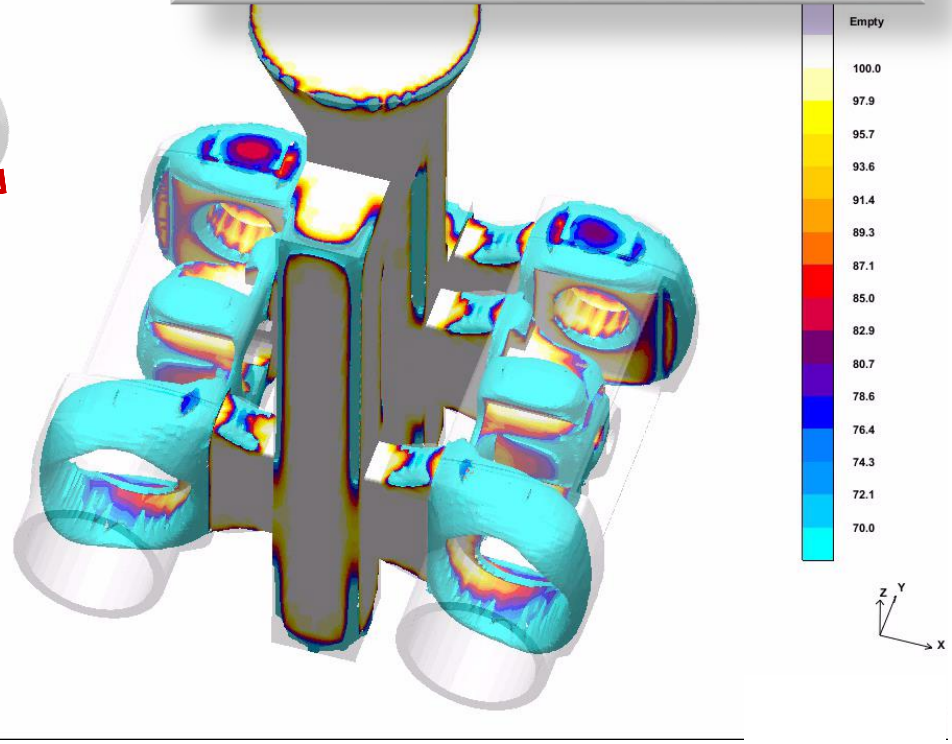
Solidification Path of Layout A

A



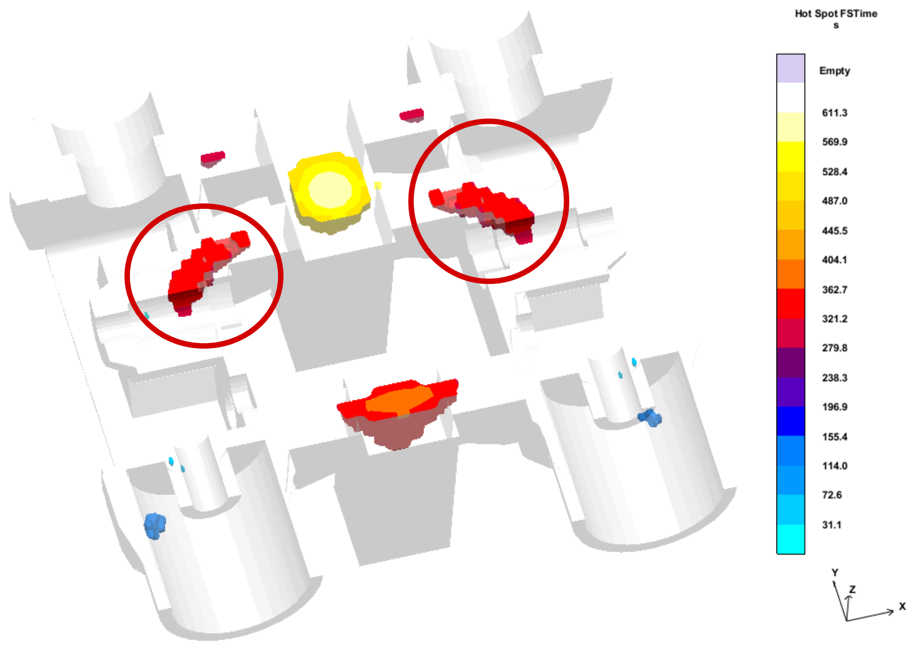


Fraction Liquid with areas which no longer can be fed are shown invisible

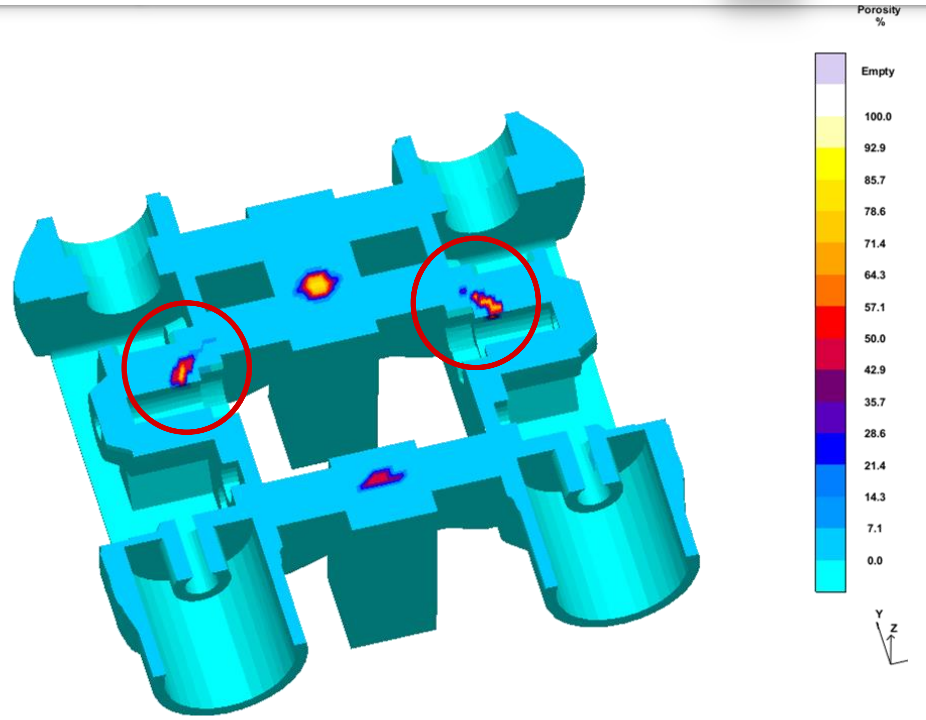


Critical Areas during Solidification Layout A

A



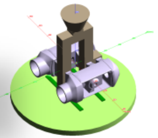
Regions isolated from feed paths



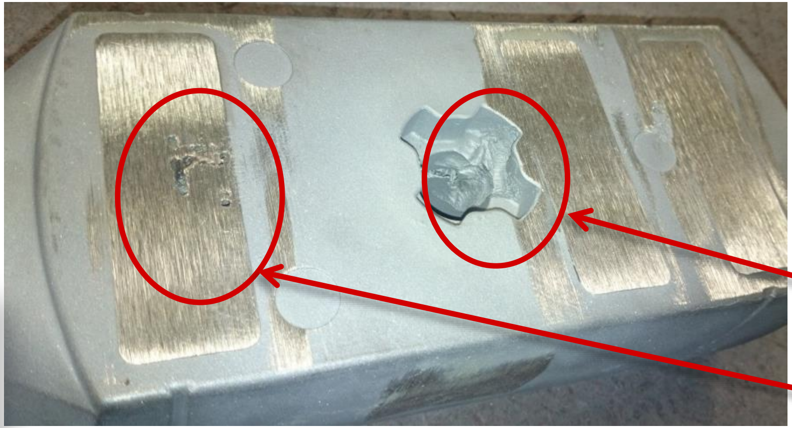
Areas with macroscopic shrinkage

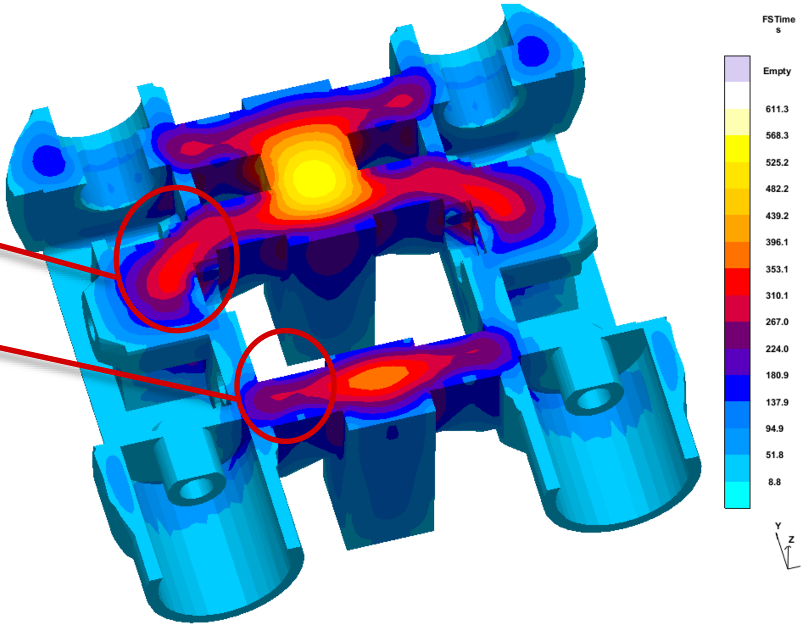
Actual Defects and Feeding Paths Layout A

A



Casting defects

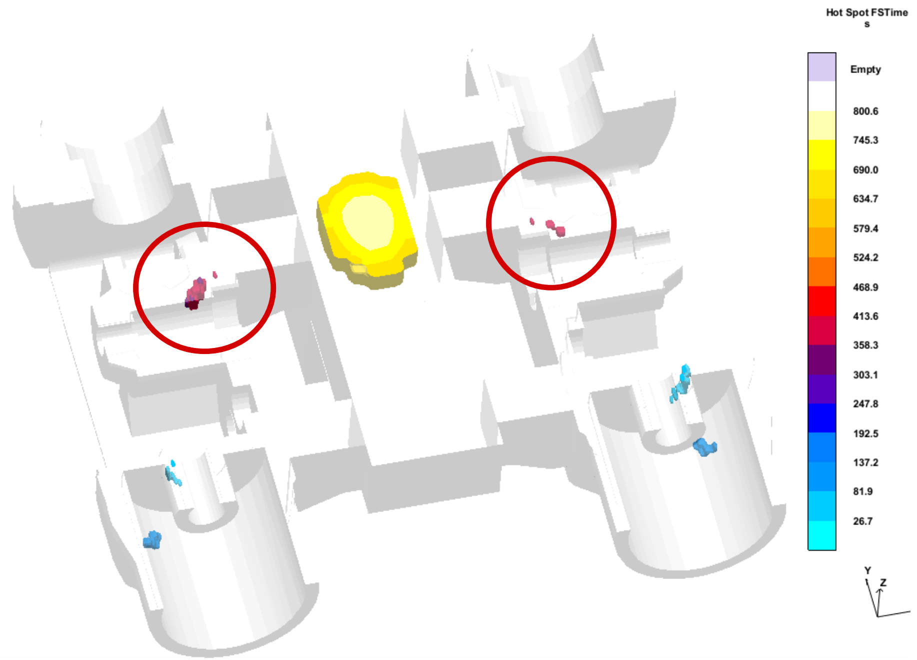




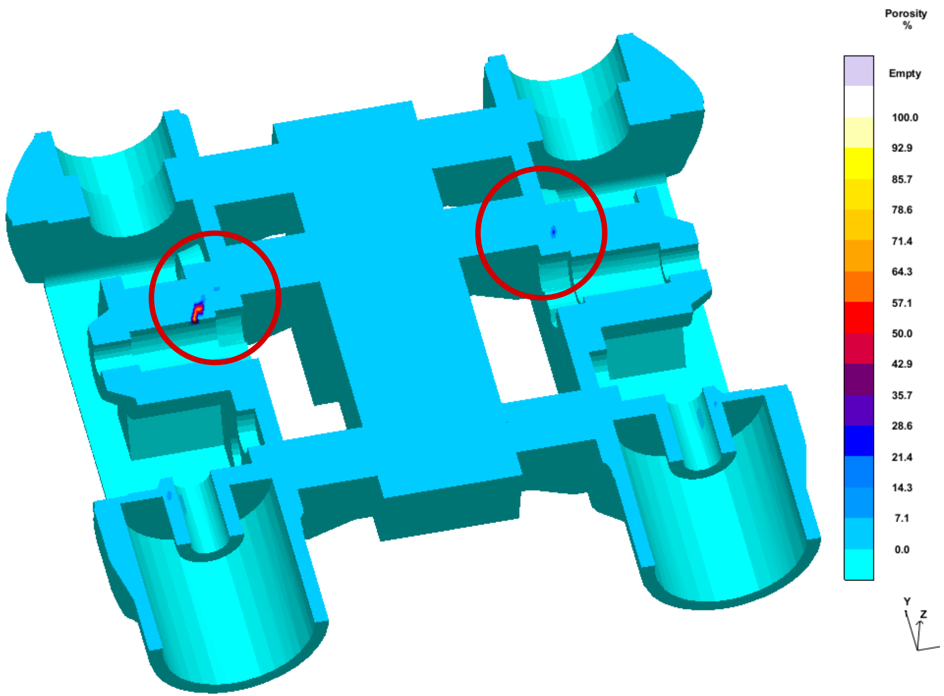
Insufficient feed paths

Critical Areas during Solidification Layout B

B



Regions isolated from feed paths

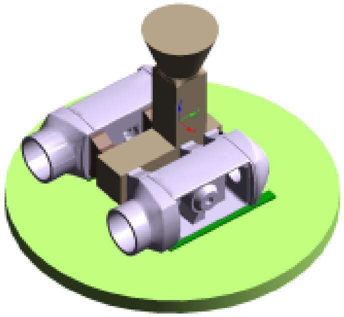


Areas with macroscopic shrinkage

Summary

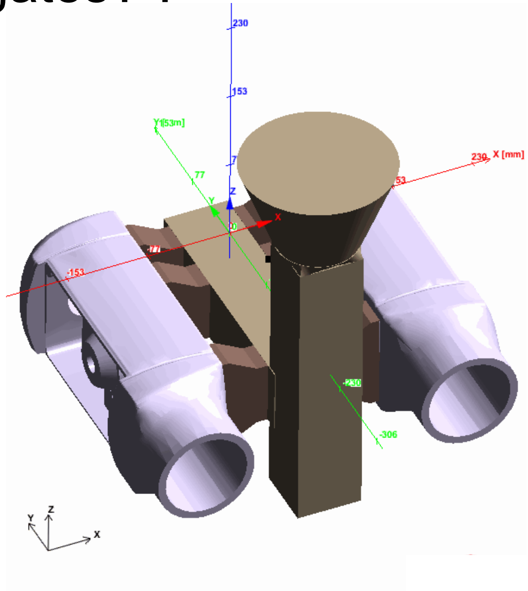
- Runner/Feeder Layout ‚A‘ does not provide feeding paths which result in a sound part
- Layout ‚B‘ shows improvements concerning tendency to form porosity, but some indications remain
- To get a casting whose quality is robust in spite of process fluctuations, and to better understand the influence of geometrical changes on feeding, it is decided to perform a set of virtual experiments with different parameter variations
- Casting Layout ‚B‘ is the subject of the further investigation

Autonomous Engineering through virtual Design of Experiments for Layout B



Parameter Variations in Layout B

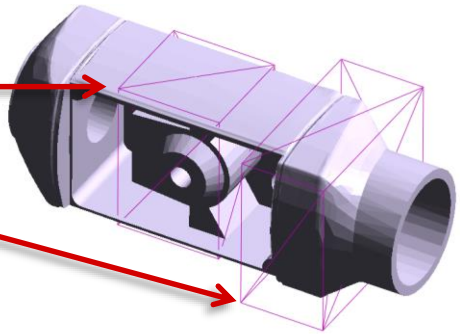
- **DoE 1:** „Influence of changing process parameters on solidification?“
  - Delayed pouring:
    - Wait time: 10s , 65s, 120s
  - Shell preheat temperature:
    - 800°C, 900°C, 1000°C
  - Pouring temperature:
    - 1500°C – 1650°C, step 50°C
  - Geometry as before
- **DoE 2:**„Support feeding by changing dimensions of runner and gates?“:



- Process parameters fixed.

Design of Experiments 1, „Changing Process Variables“

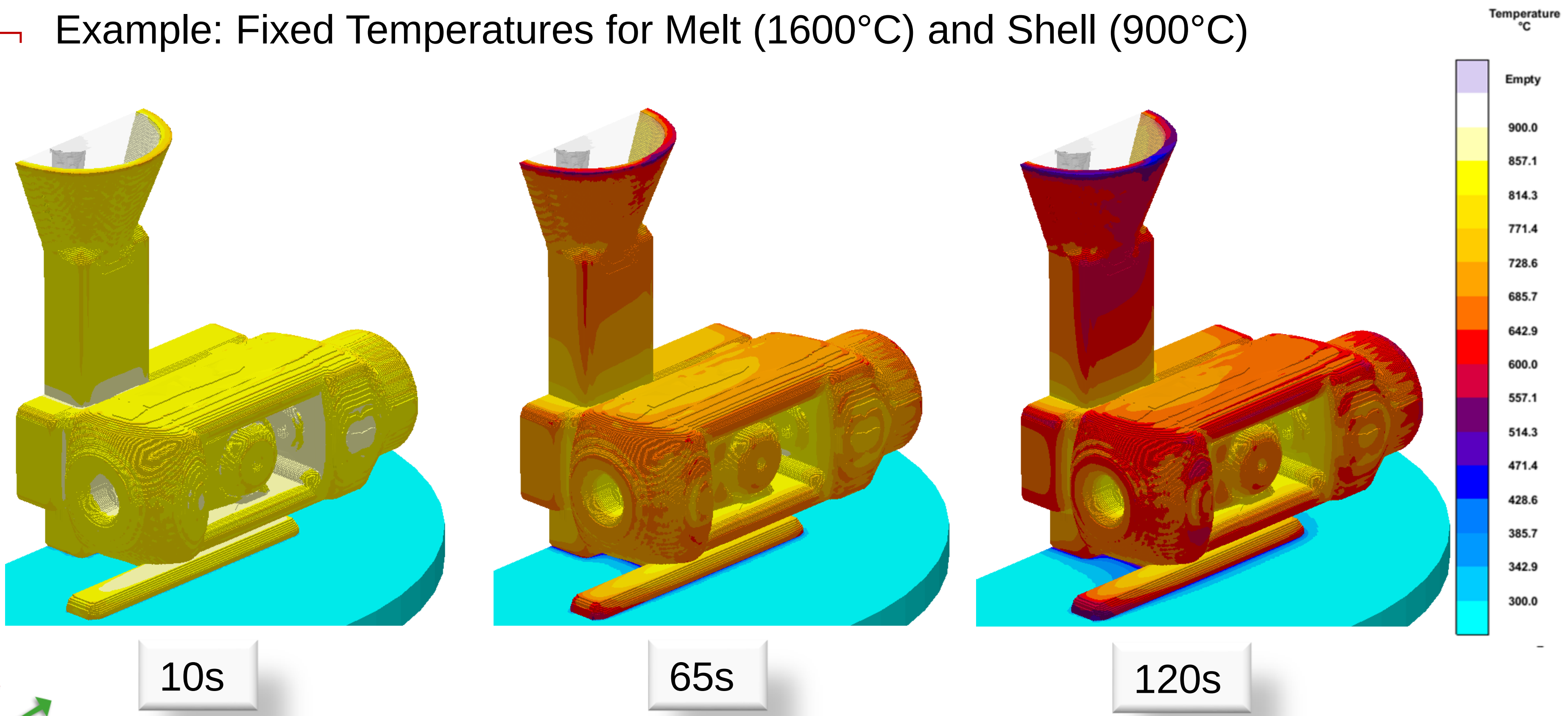
- Goal is to examine influencing process parameters on the critical areas during solidification



- Calculation covers all 36 possible combinations
- Comprehensive comparison and utilization of all simulation results
- Quantitative assessment in charts and tables

DoE1: Effect of Pouring Delay on shell temperature

- Example: Fixed Temperatures for Melt (1600°C) and Shell (900°C)



DoE 1: Assessment of Virtual Experiments

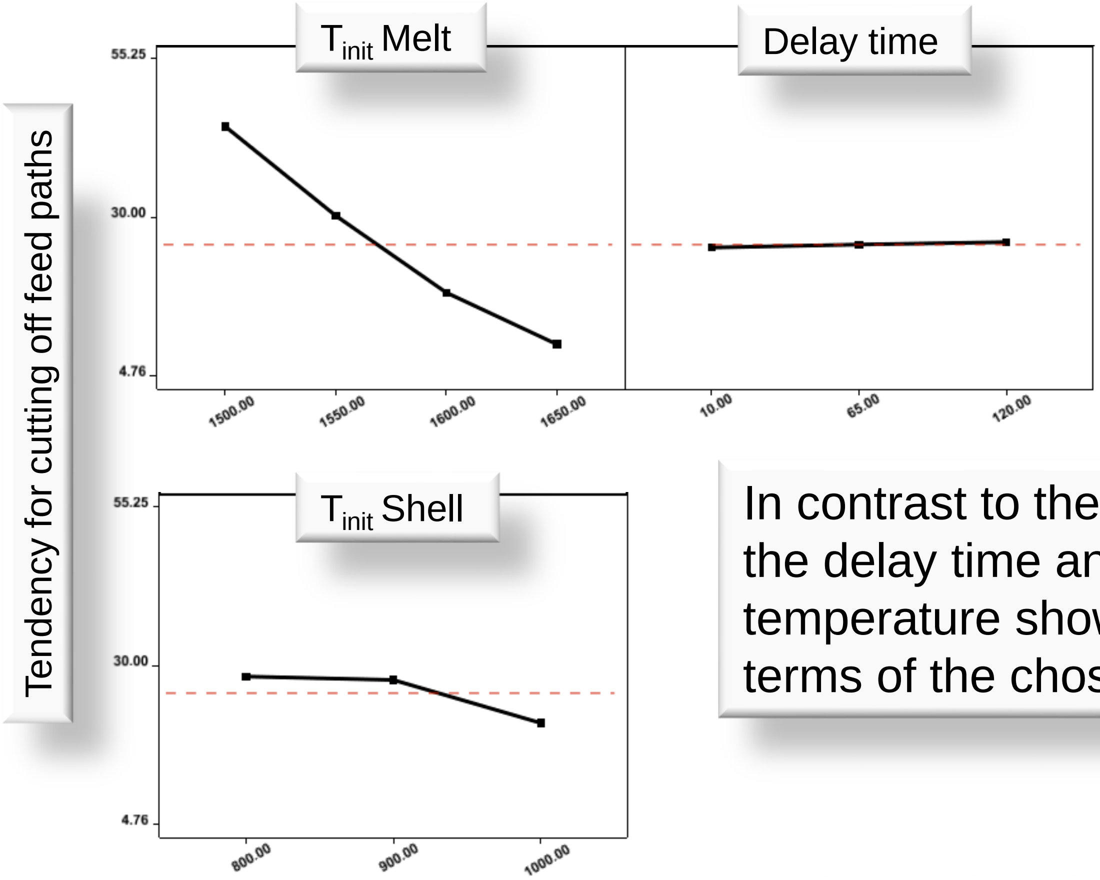
Melt 1600 and 1650°C

Shell 900 and 1000°C

- Ranking according to chosen result values
- Experiments with higher Melt Temperatures (red, pink) show less tendency for cutting off feed paths
- Experiments using higher shell preheating (greenish) show both good and bad tendencies. No obvious effect.

Rank	Design	Critical Solid Area1 (-)	Critical Solid Area2 (-)
Rank 1	Design 24	0.0	4.76
Rank 2	Design 36	0.0	6.14
Rank 3	Design 12	0.0	6.63
Rank 4	Design 32	0.0	8.97
Rank 5	Design 8	0.0	9.3
Rank 6	Design 20	0.0	9.5
Rank 7	Design 35	0.0	9.89
Rank 8	Design 16	0.0	11.43
Rank 9	Design 23	0.0	11.93
Rank 10	Design 4	0.0	15.04
Rank 11	Design 11	0.0	16.45
Rank 12	Design 28	0.0	16.51
Rank 13	Design 19	0.0	16.71
Rank 14	Design 31	0.0	17.97
Rank 15	Design 7	0.0	19.26
Rank 16	Design 15	0.0	22.13
Rank 17	Design 3	0.0	23.89
Rank 18	Design 27	0.0	24.03
Rank 19	Design 22	0.0	24.5
Rank 20	Design 10	0.02	26.65
Rank 21	Design 34	0.0	27.37
Rank 22	Design 2	1.49	28.13
Rank 23	Design 14	1.78	28.89
Rank 24	Design 30	0.23	31.26
Rank 25	Design 6	0.0	33.21
Rank 26	Design 18	0.16	33.75
Rank 27	Design 26	1.86	38.63
Rank 28	Design 33	14.52	34.93
Rank 29	Design 21	12.07	39.71
Rank 30	Design 9	12.63	41.81
Rank 31	Design 5	36.56	48.09
Rank 32	Design 29	38.75	49.6
Rank 33	Design 17	39.84	55.25
Rank 34	Design 1	76.37	33.84
Rank 35	Design 13	71.08	49.51
Rank 36	Design 25	75.32	47.39

DoE 1 Assessment using Main Effects diagram

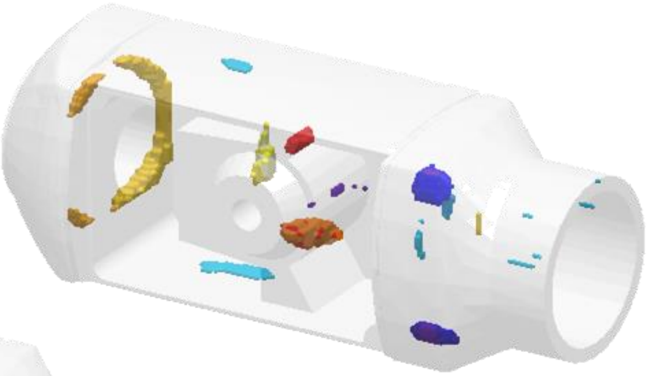


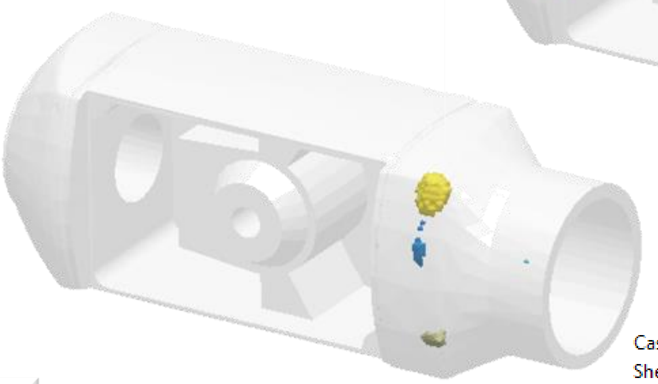
In contrast to the melt temperature, the delay time and the shell preheat temperature show no significancy in terms of the chosen quality criterion

DoE1: Selected Results of virtual Experiments

Cast Alloy Class - Initial Temperature 1550.0
Shell All - Initial Temperature 800.0
Pouring - Pouring Rate Parametric Function, Interval 1, 10.0

Cast Alloy Class - Initial Temperature 1500.0
Shell All - Initial Temperature 800.0
Pouring - Pouring Rate Parametric Function, Interval 1, 120.0



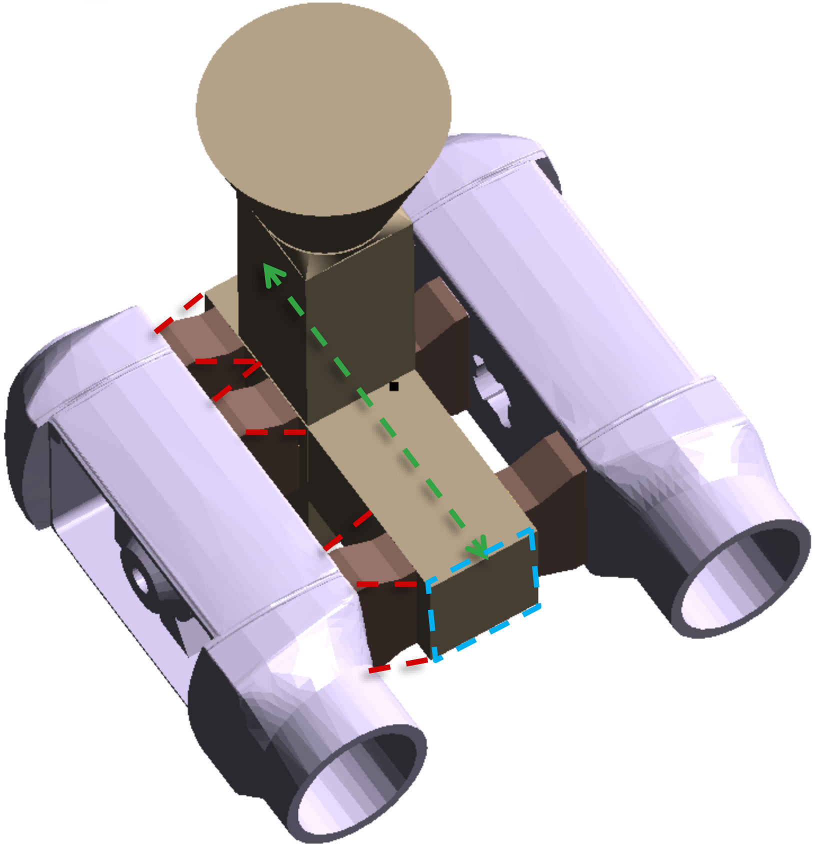


Cast Alloy Class - Initial Temperature 1600.0
Shell All - Initial Temperature 800.0
Pouring - Pouring Rate Parametric Function, Interval 1, 120.0

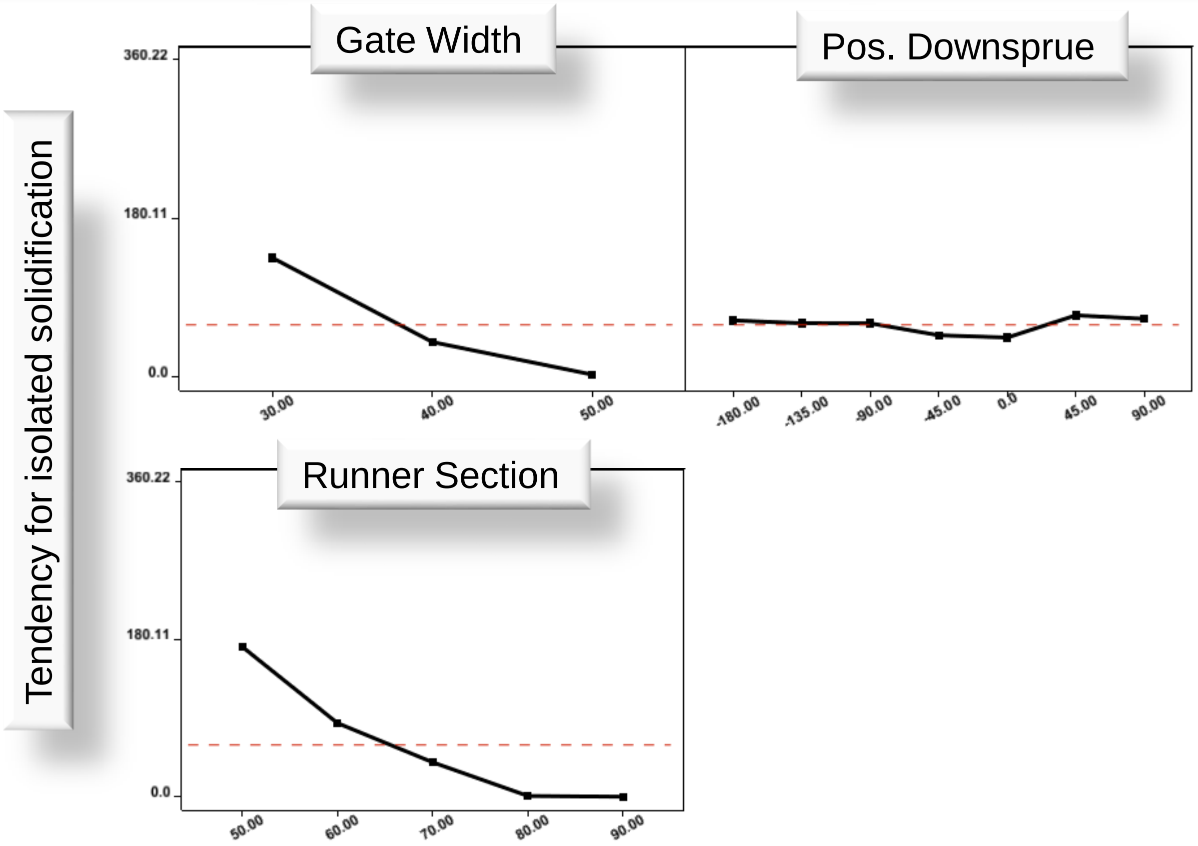
Areas isolated from feed paths

Design of Experiments 2: „Geometry Variation“

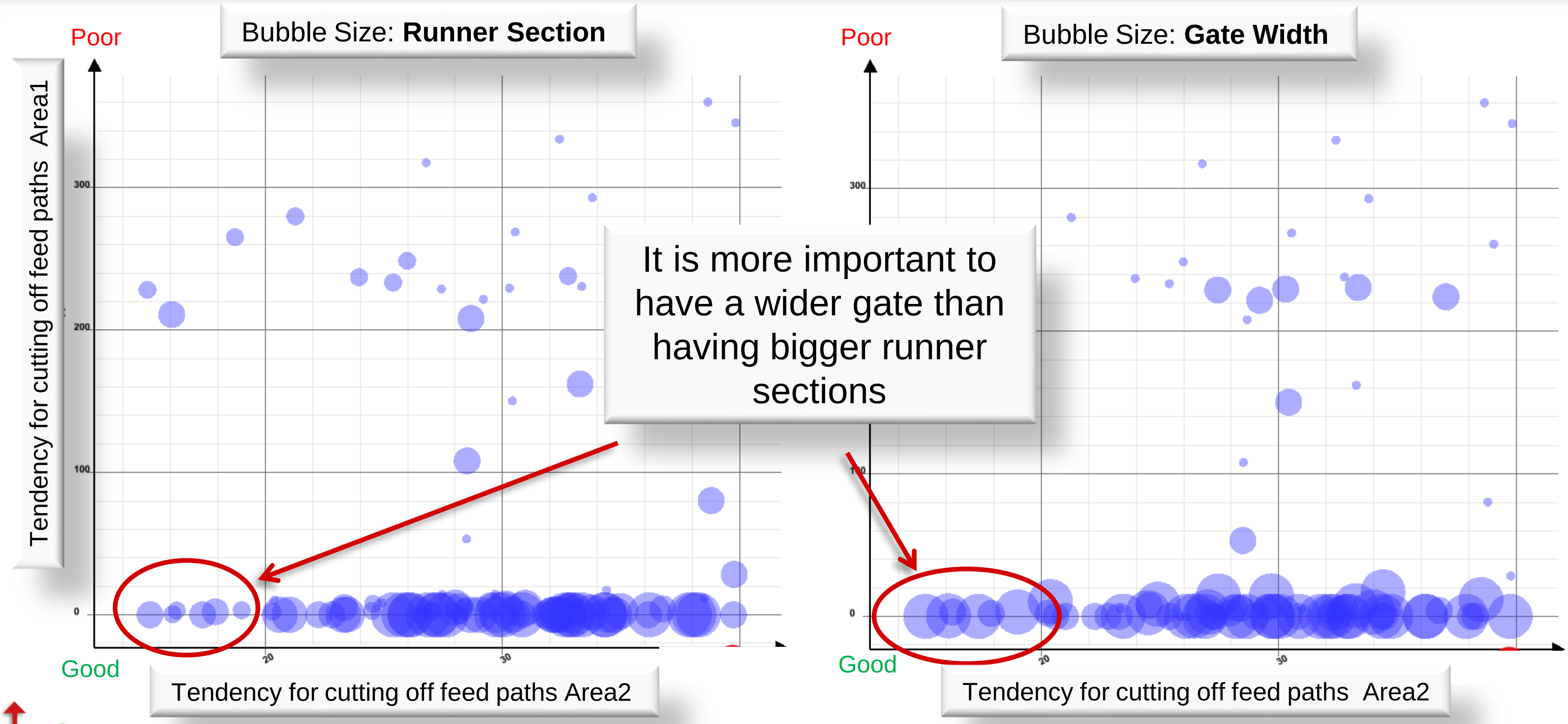
- Objective is to improve feeding paths into the casting by the following variables:
  - Widening gates
  - Varying runner section
  - Changing down sprue position



DoE 2, Assessment using Main Effects Diagrams

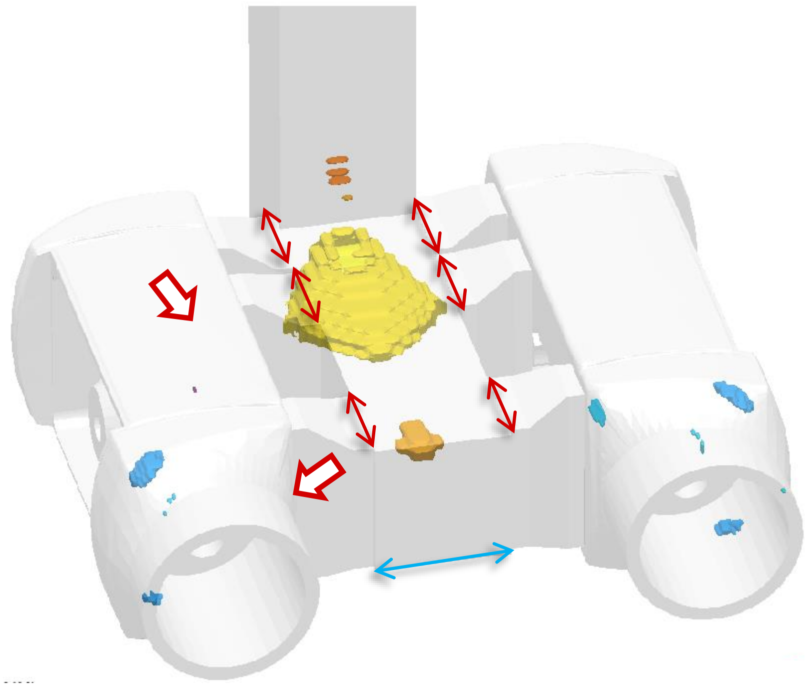


DoE 2, Assessment using Scatter charts



DoE 2: Best Compromise

- Widening the gates prevents the separation of the feeding paths
- The runner section can be reduced -> better yield
- Down sprue position has only minor influence



Summary of DoE 1 and DoE 2

- Virtual Experimentation delivered insight and revealed influencing process parameters

- For the considered Investment Casting and with respect to the examined criteria (Cutting off of Feed Paths -> Porosity), the process parameter which is most important is the Melt Temperature. The variation of the Delay Time as well as the Shell Temperature is almost negligible

- The results of geometrical variation shows that as long as the gates are widened, the runner section and the down sprue position have almost no impact

Case Study #2

Adjusting Thermal Property Datasets of Investment Casting Shells

Introduction

Using Simulation for Investment castings.

1. New Jobs where gating needs to be cut into the die before the die is shipped.
2. Prototype jobs where the gating needs to be printed on the part.
3. Old problem jobs to reduce the amount of post processing such as welding.

How can we increase the accuracy of our simulations?

- X-ray results vs. Simulation results.
- Study input variables.
- No general dataset can be used to describe every foundries Ceramic Shell.
  - *shell compositions*
  - *particle size distribution*
  - *processing parameters*

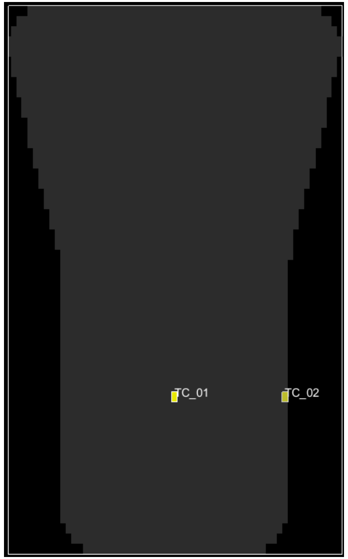
Dip #	Slurry	Stucco
1	Primary Zircon/Silica	Zircon
2	Intermediate Silica	50/100
3	Back up silica	30/50
4	Back up silica	30/50
5	Back up silica	30/50
6	Back up silica	10/30
7	Back up silica	10/30

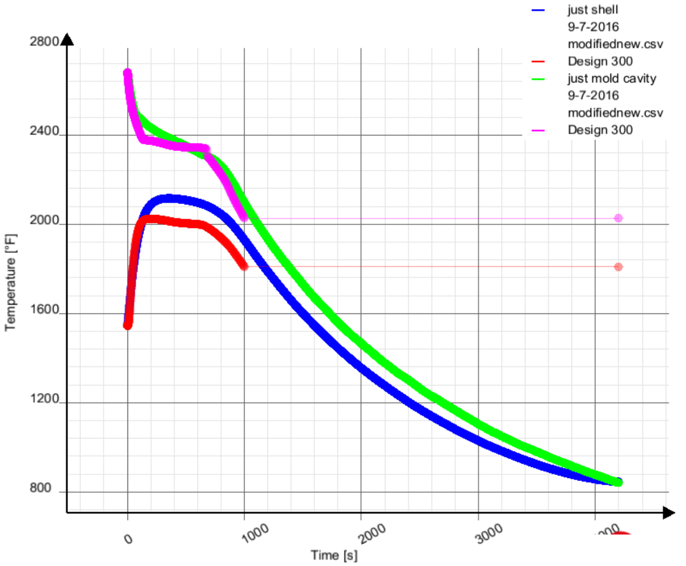
Experiment introduction

Matching Cooling Curves

<u>In the Foundry</u>: We will measure the temperature inside the mold cavity and outside the shell to see how heat passes through the shell.

<u>In Simulation</u>: We will use inverse optimization to incrementally change thermal conductivity and specific heat of our shell until our temperature vs. time curves match that produced in the foundry.





Design of Experiment

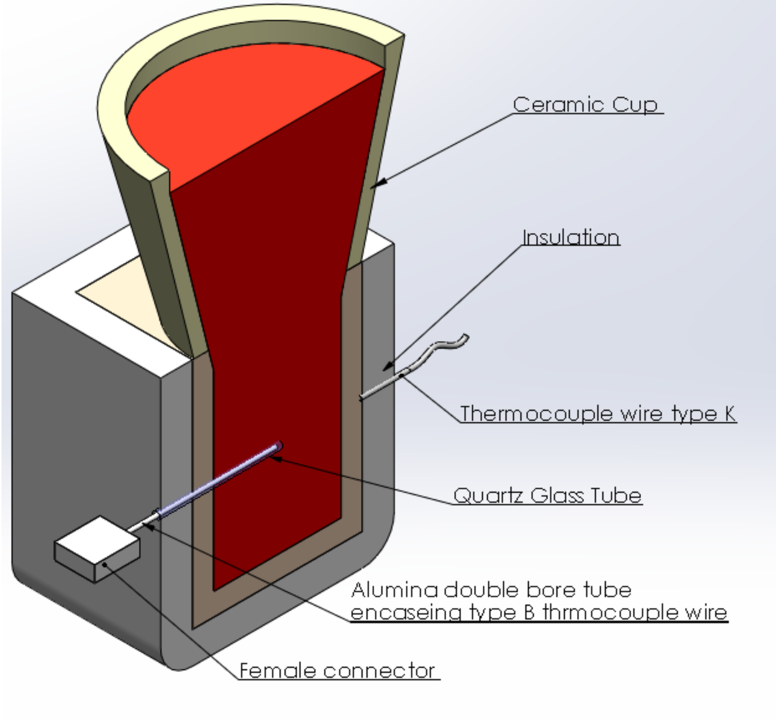
Thermocouple setup

Materials:

- K, B, and S type thermocouple wire
- Quartz Glass Tube
- Alumina Double Bore tube
- Mini connectors

Steps:

- Mold in a Quartz glass tube
- Build Shell
- Autoclave
- Drill and Place K type wire just under shells outside surface
- Attach insulation to the outside of the shell
- Fire shell and observe shell temperature
- Remove shell from oven
- Insert thermocouple probe into glass tube
- Pour the shell and record the data.

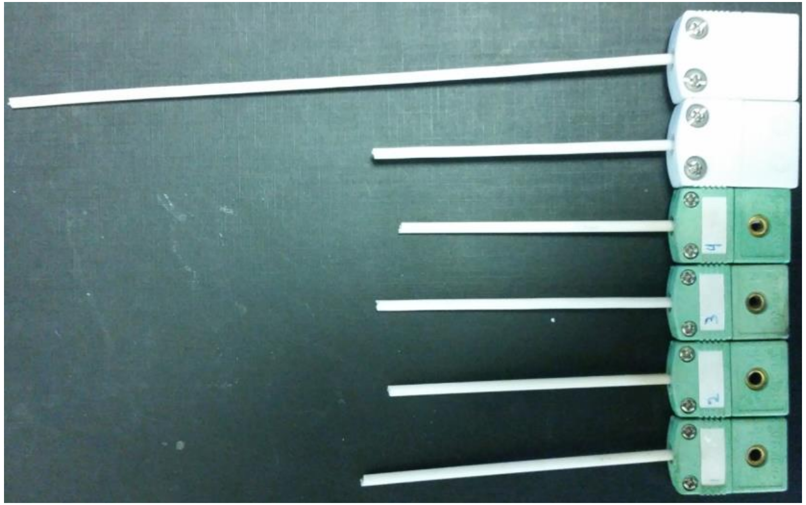


Molding in Glass Tube

Thermocouple Probe

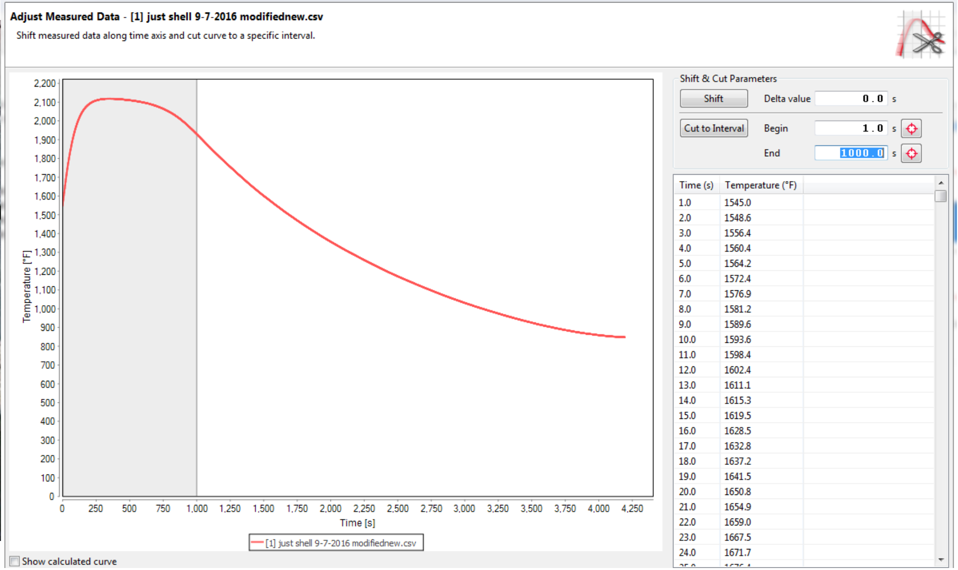
Materials

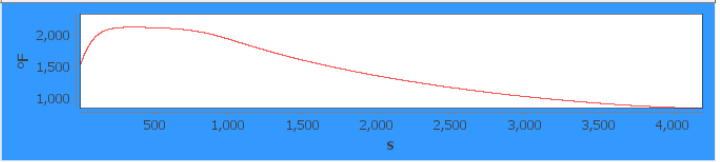
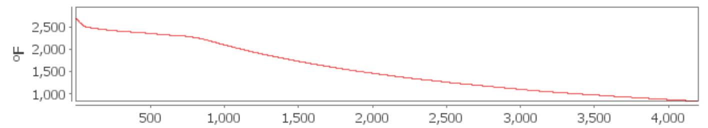
- S and B type wire
- S and B type extension wire
- Quartz glass tube
- Alumina double bore tube
- Connectors based on your data logger



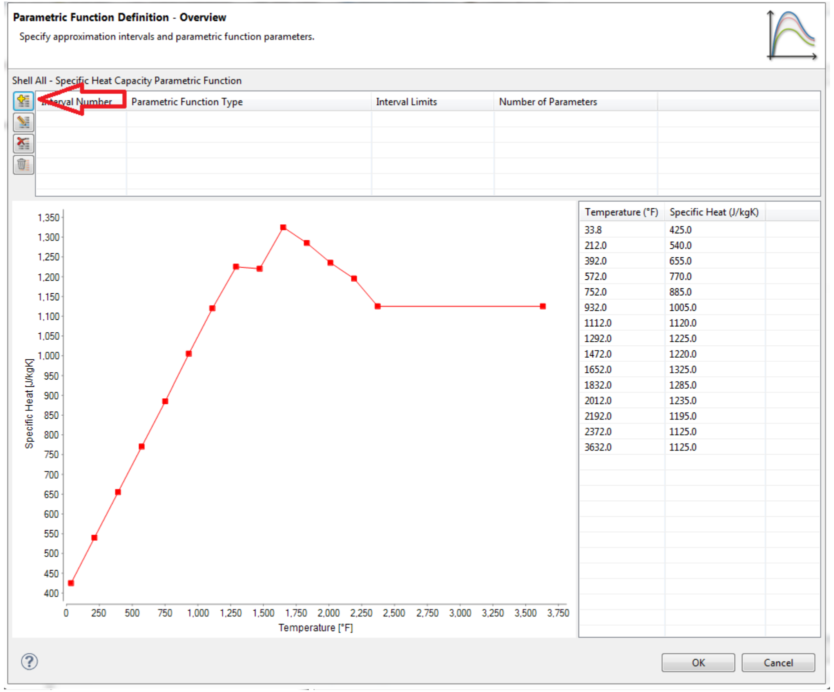
Inserting K type wire and Insulation

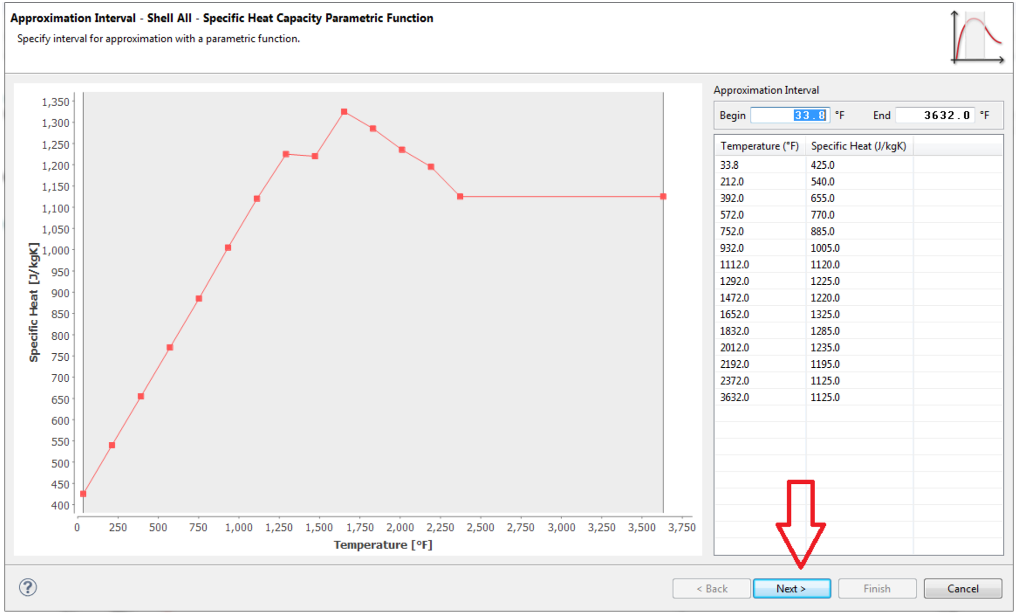
Collecting Data



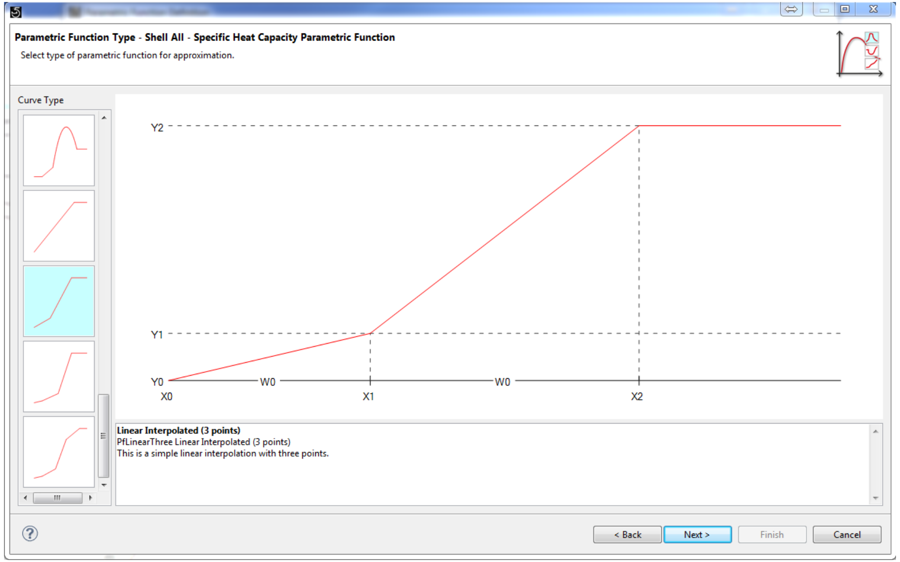
Index	Simulated Curve	Comparison Interval(s)	Name	Data
1	Solidification & Cooling,Temperature Curve - Thermocouple TC_02	[1.0,4197.0]	just shell 9-7-2016 modifiednew.csv	
2	Solidification & Cooling,Temperature Curve - Thermocouple TC_01	[1.0,4197.0]	just mold cavity 9-7-2016 modifiednew.csv	

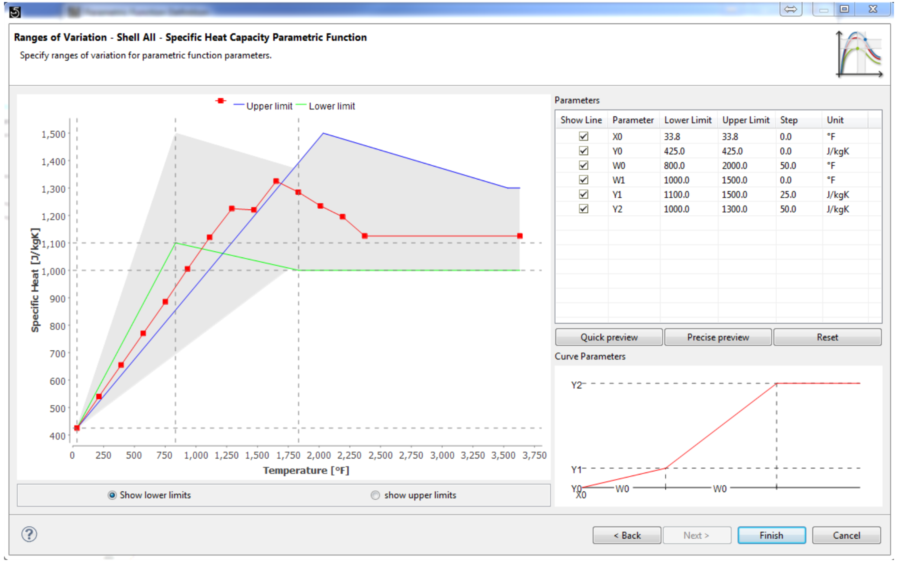
Inverse Optimization: Setting Design Variables



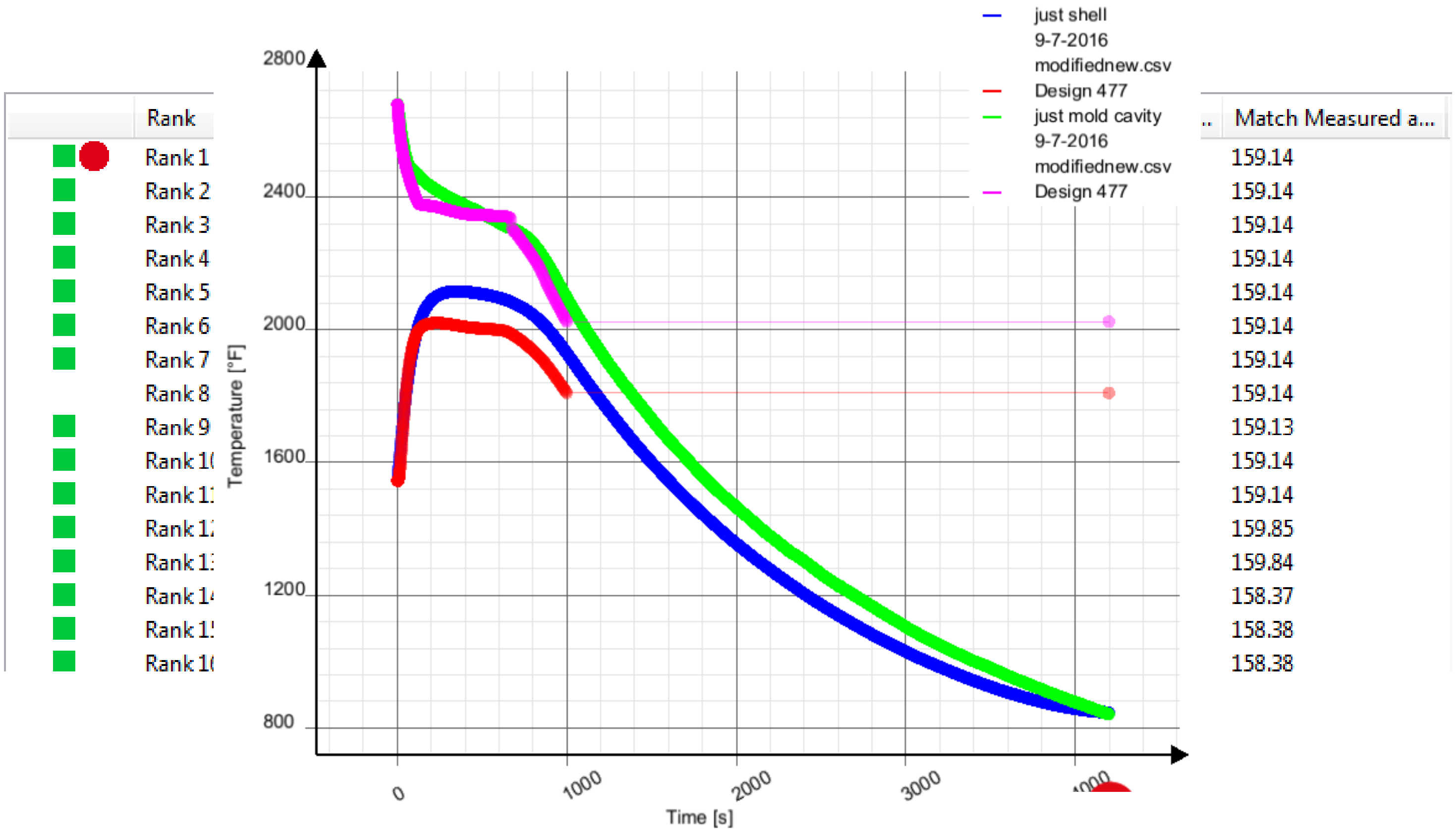


Inverse Optimization: Setting Design Variables





Assessment: Curve Comparison

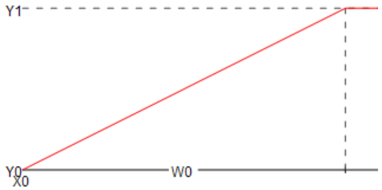


Assessment: Main Effects Plot

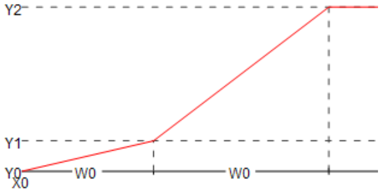
Based on Gradient objective

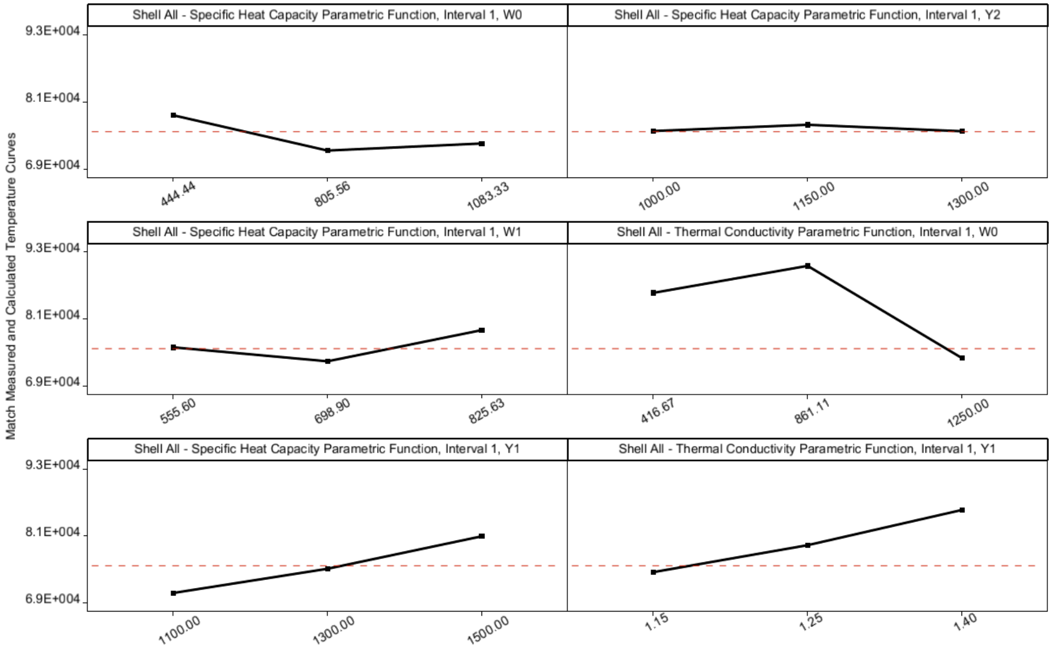
Based on Integral objective

Thermal Conductivity

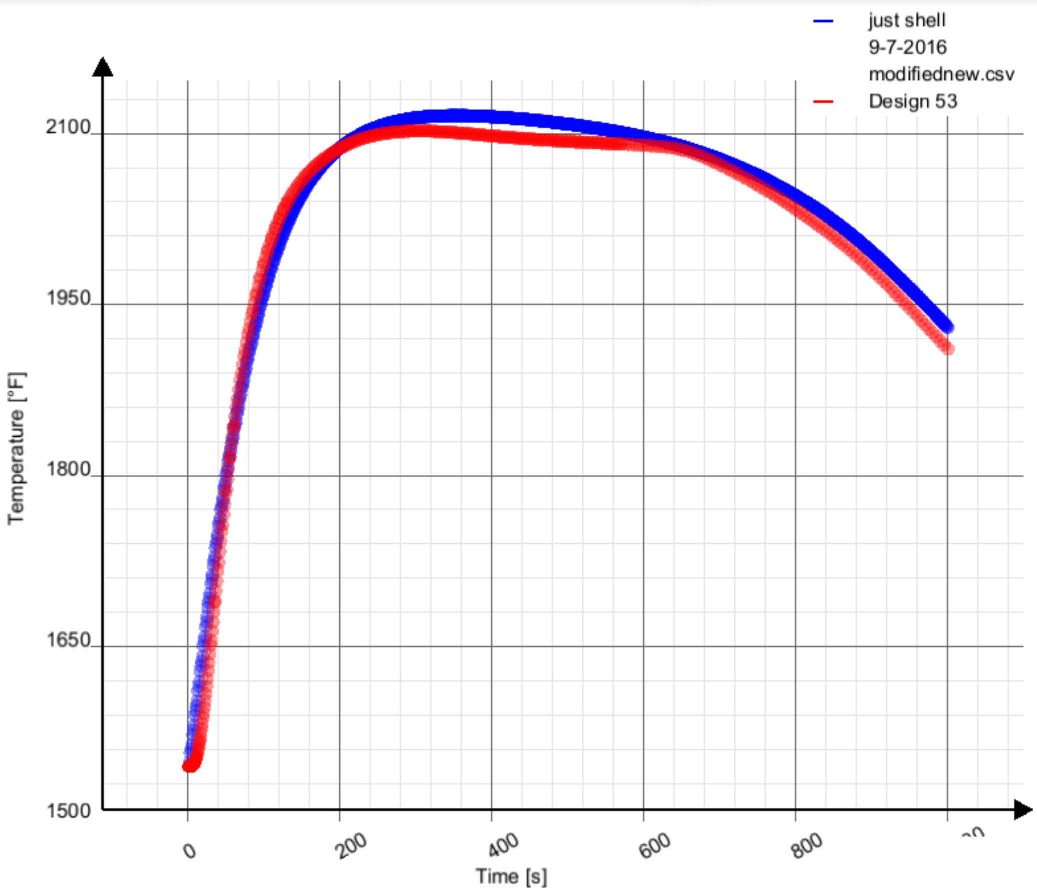


Specific Heat Capacity

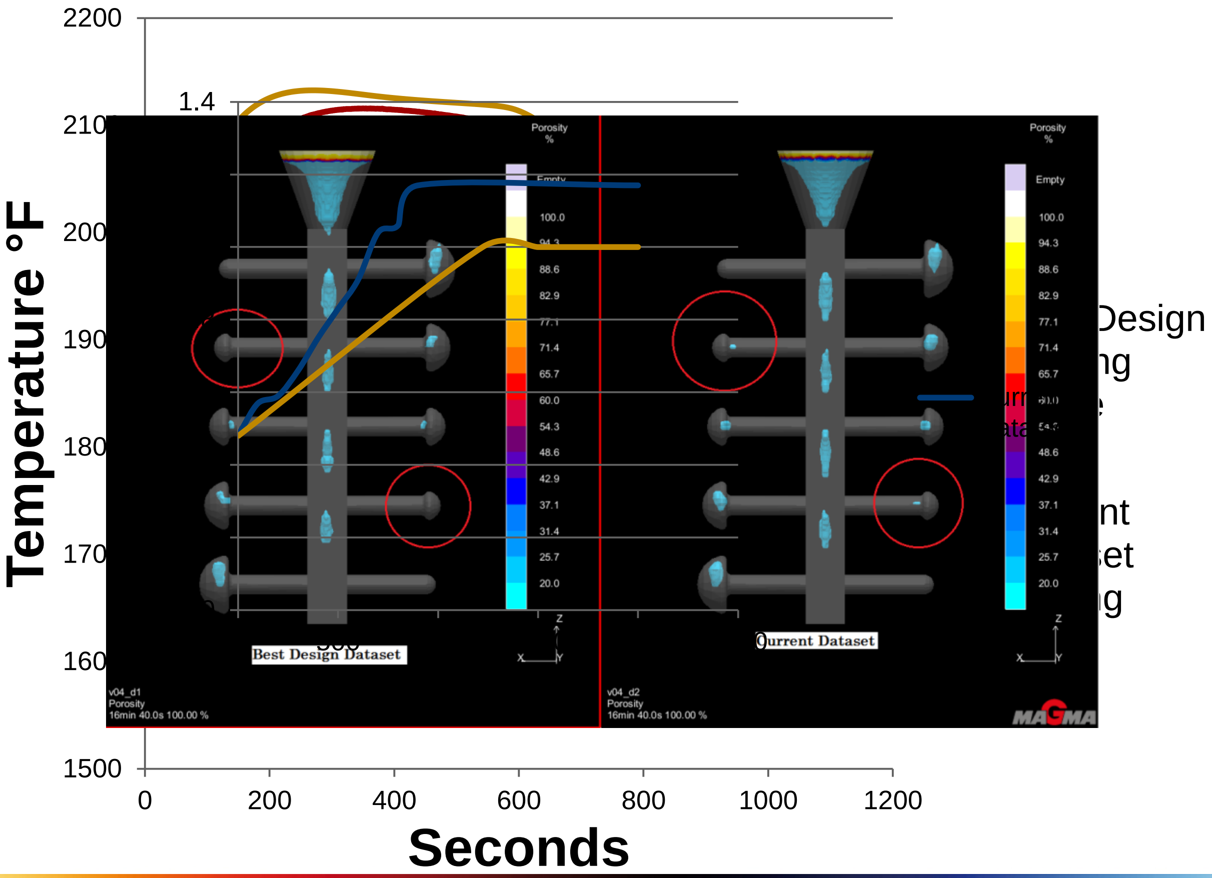




Assessment: Curve Comparison



Simulation Results



Summary

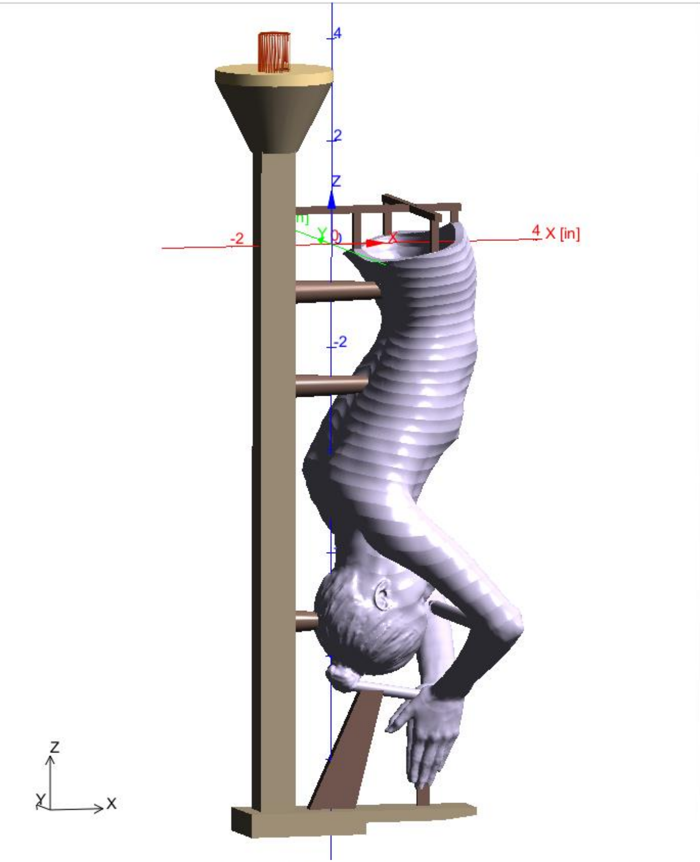
- The Main Effects Plot quickly showed that the thermal conductivity and the specific heat capacity had the biggest impacts on matching the simulated cooling curves with the measured cooling curves
  - Fine tuning those properties provided simulated curves to match measured data
- The porosity prediction more closely matched what was seen in production once the proper thermophysical properties we determined using inverse optimization
  - This provided more confidence in the simulated results and reduced sampling time

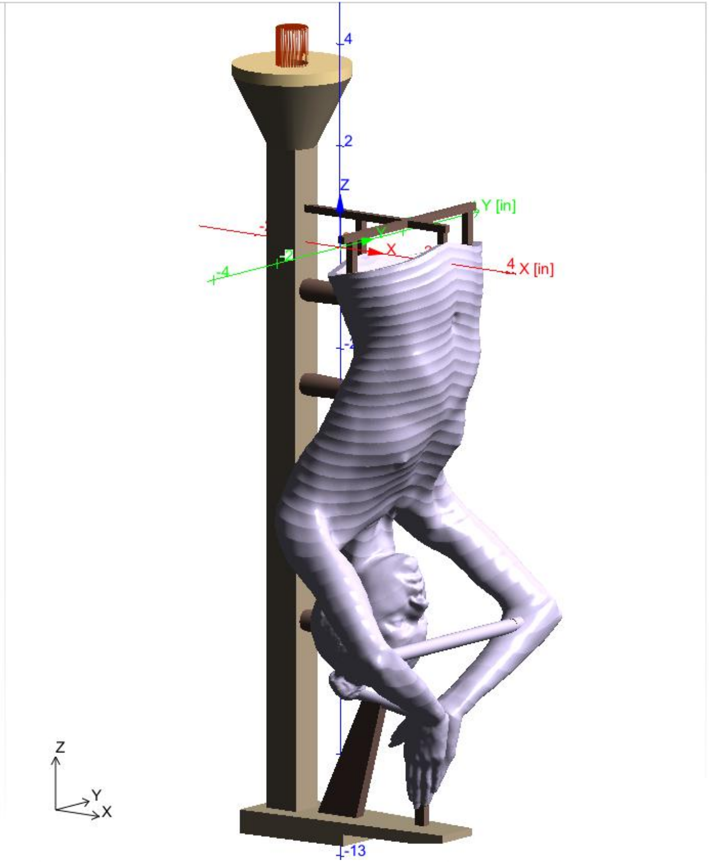
Case Study #3

Evaluating a gating approach using Autonomous DoE

Gating System/Casting Layout

The goal is to achieve smooth filling that will produce good surface finish and eliminate repairs





Process Parameters

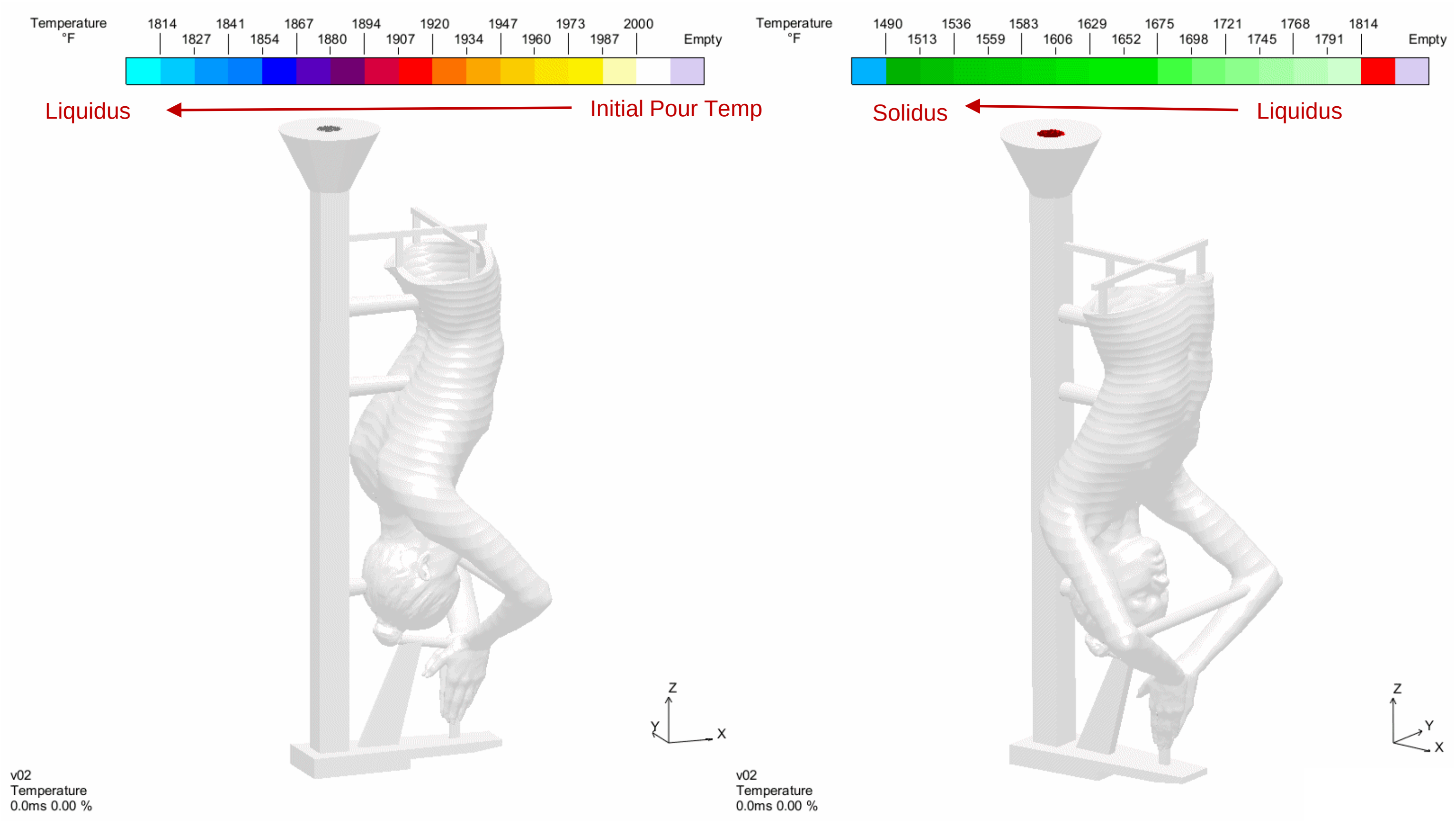
Defined variables that can be changed

- Cast Material: CuSn12 Tin bronze
- Pouring Temperature: 2000°F
- Pouring Time: ~ 2s
- Ceramic Shell preheated at 800°F

Filling Simulation Results

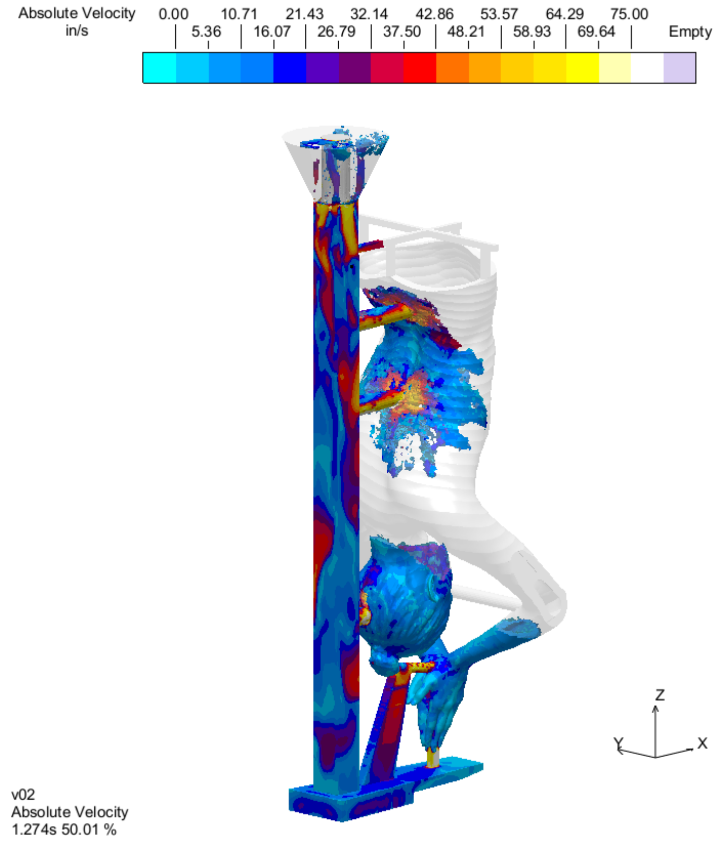
Metal Temperatures During Filling

the objective is to track metal front temperatures to avoid misruns or cold laps

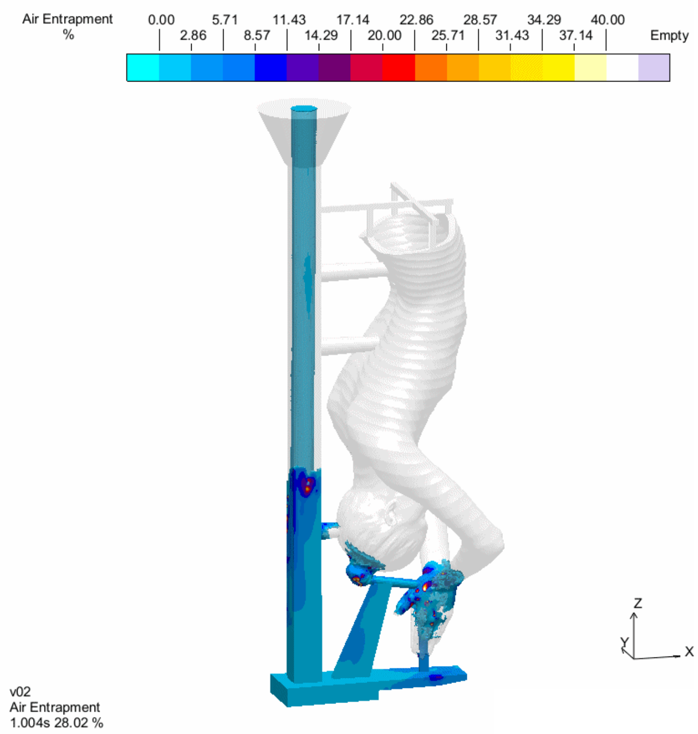


Metal Front Velocities During Filling

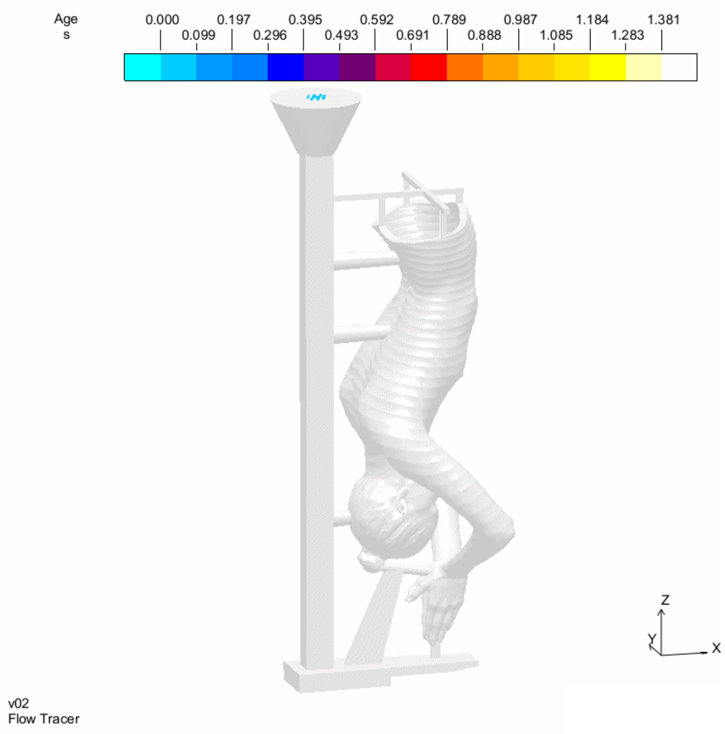
the objective is to track metal velocities to reduce turbulence and inclusions



Other Filling Results



Air entrapped by the metal front

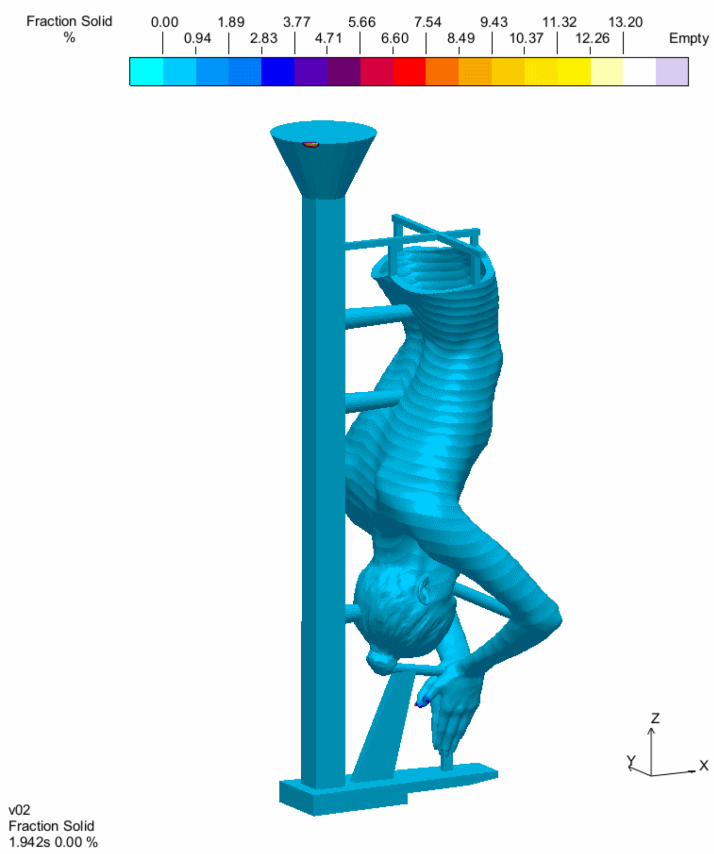


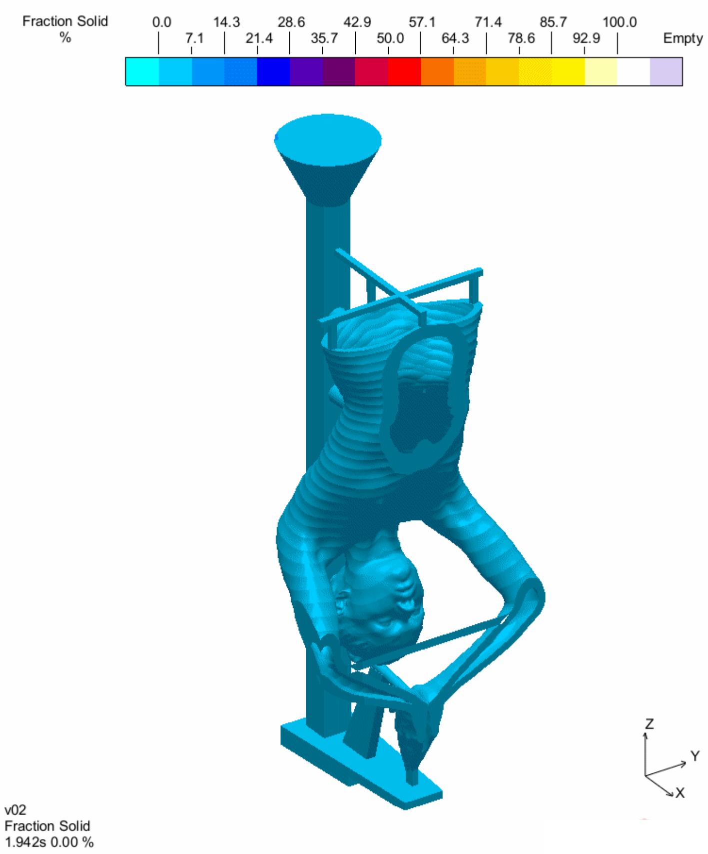
Weightless particles showing flow patterns

Solidification Simulation Results

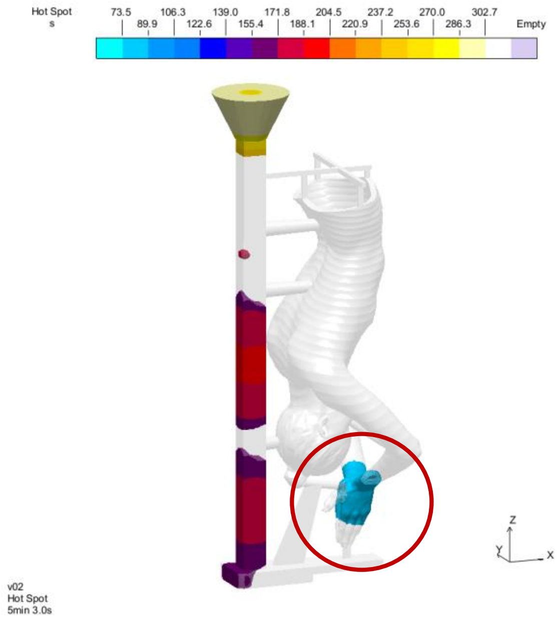
Solidification Path – Fraction Solid Result

Transparent areas are no longer open to feeding

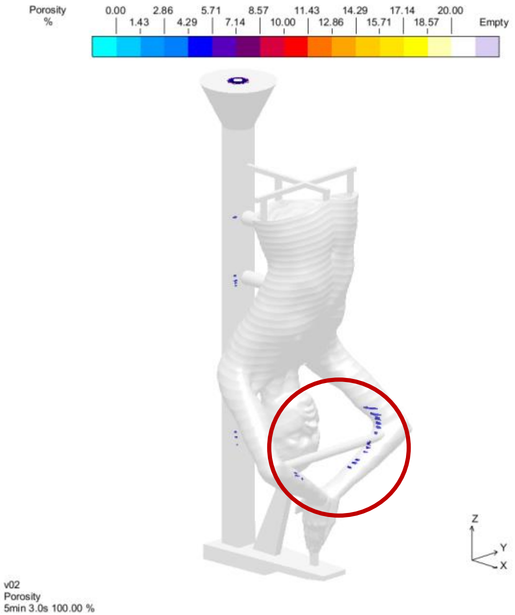




Locations of Significant Themal Centers



Regions isolated from feeding through the gating system



Areas with macroscopic shrinkage porosity

Virtual Experimentation through Design of Experiments

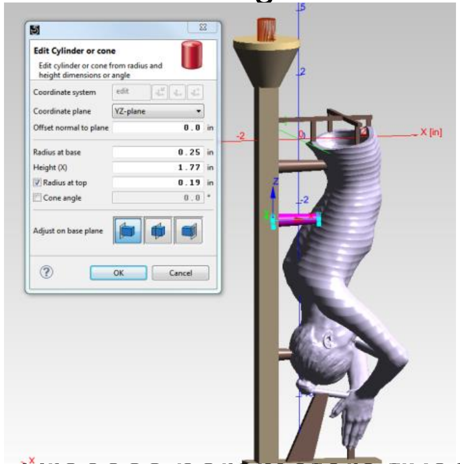
Parameter Variation

Design of Experiment setup parameters

Possible optimization paths:

- **DoE 1:** Influence of changing process parameters on solidification?
  - Pouring speed:
    - Ladel height: 3, 6, 9
  - Shell preheat temperature:
    - 500°F, 600°F, 800°F
  - Pouring temperature:
    - 1800°F – 2250°F, step 20°F
  - Baseline geometry

- **DoE 2:** Gating modifications?:



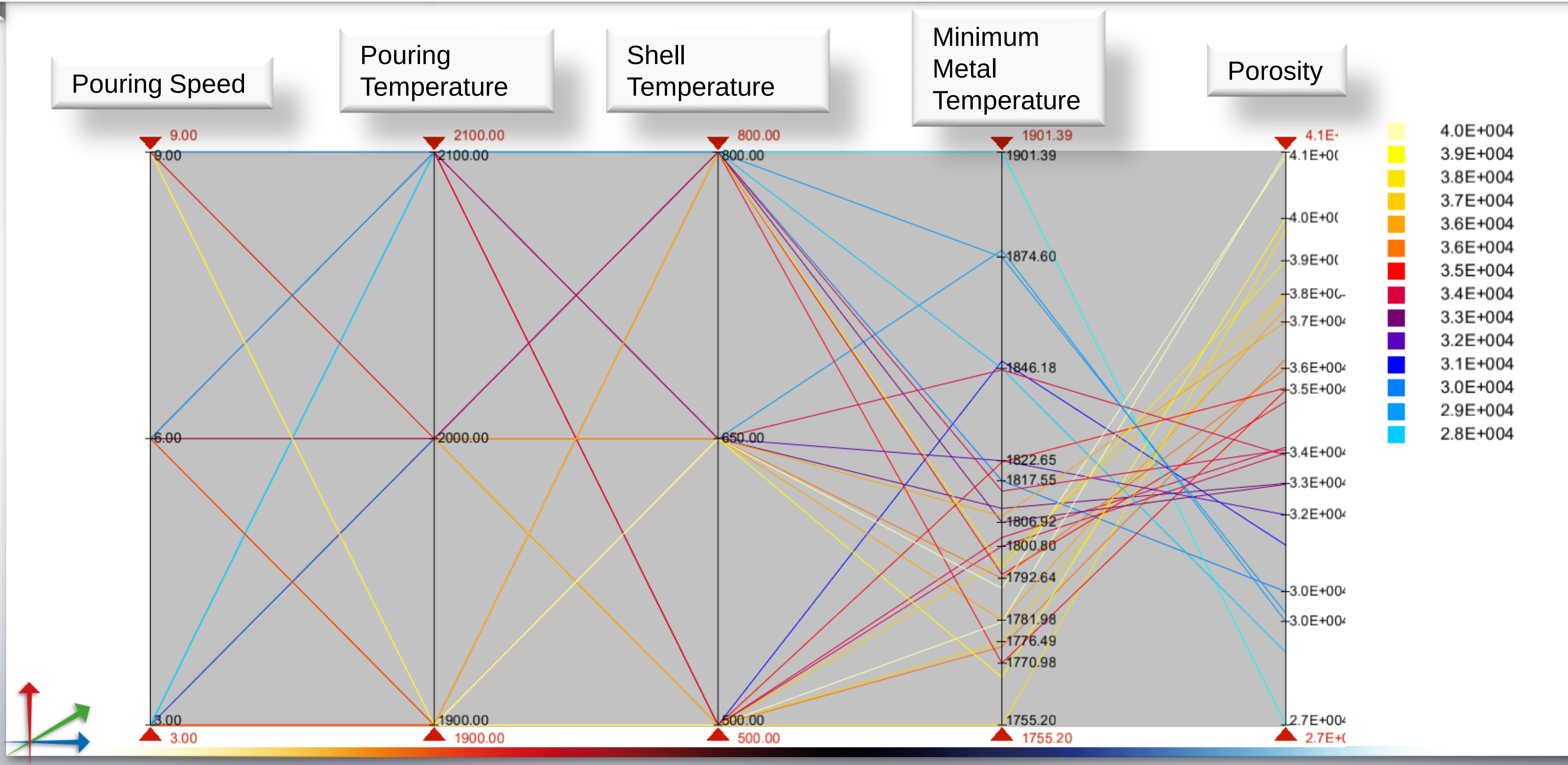
- Process parameters fixed

Goal is to examine the influence of process parameters

on the critical areas during filling and solidification

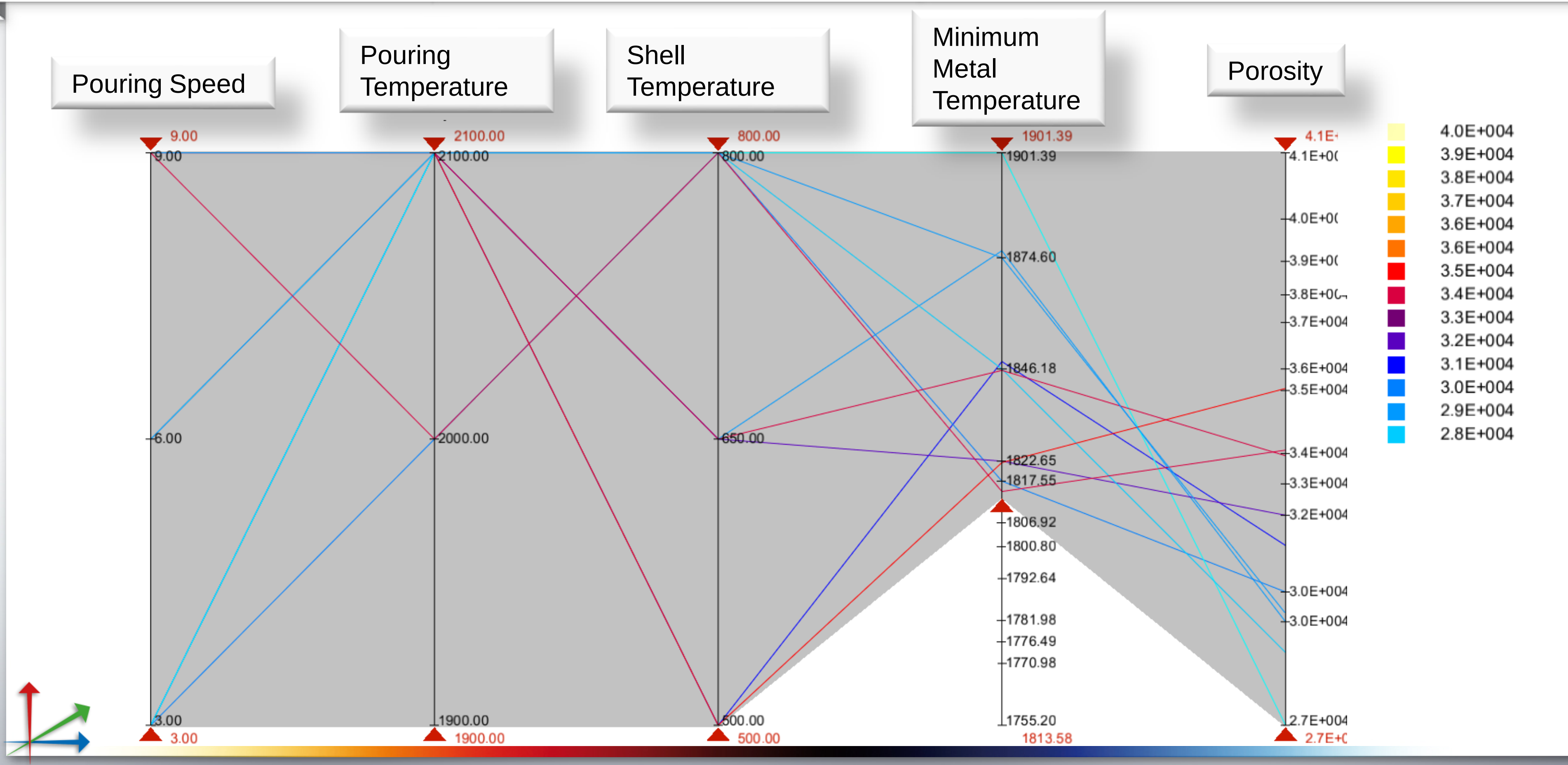
Parralell Coordinates

Each line represents a design that has been run



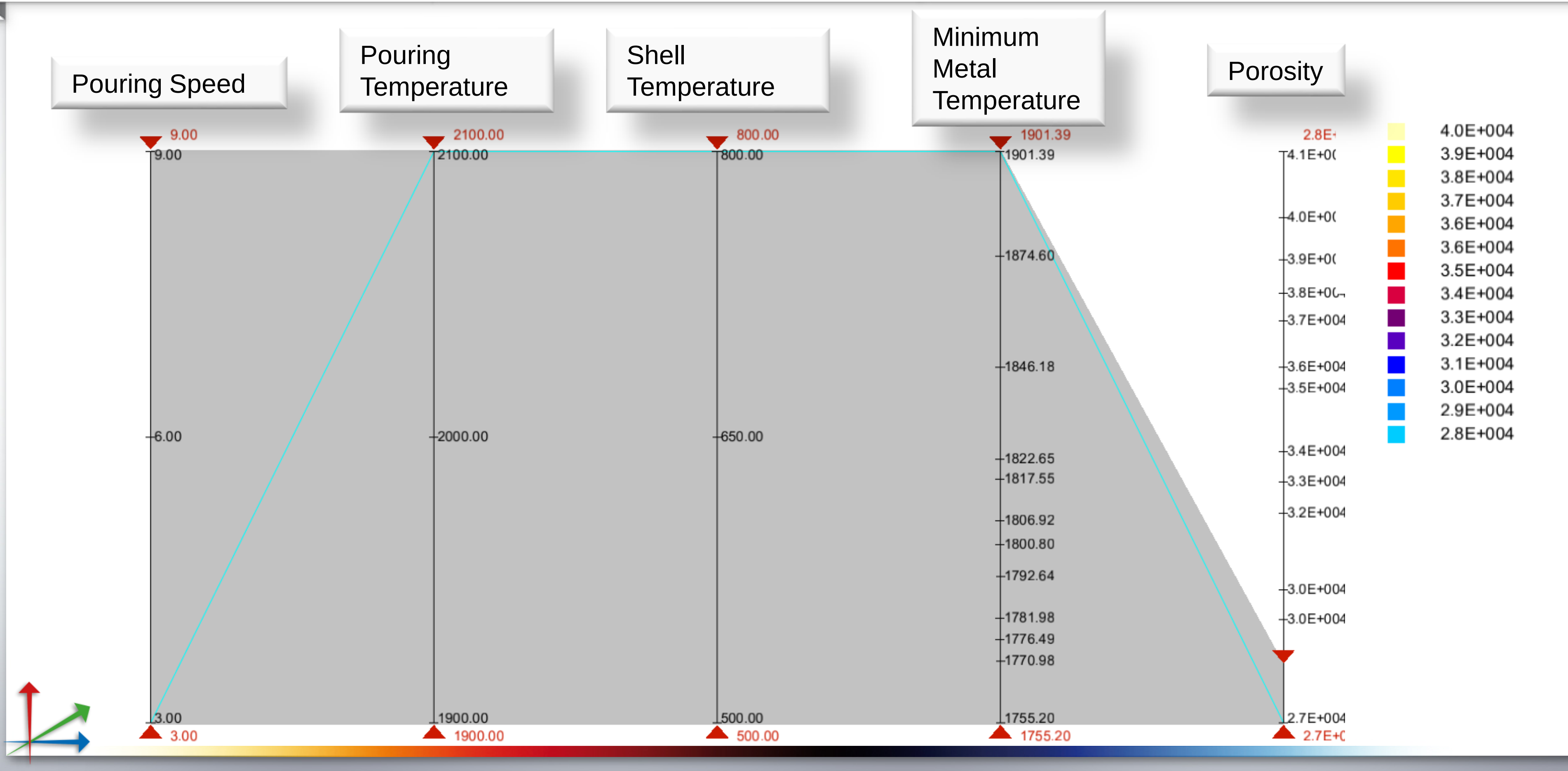
Parralell Coordinates

We want to look at designs whos minumum temperature exeeds the liquidus



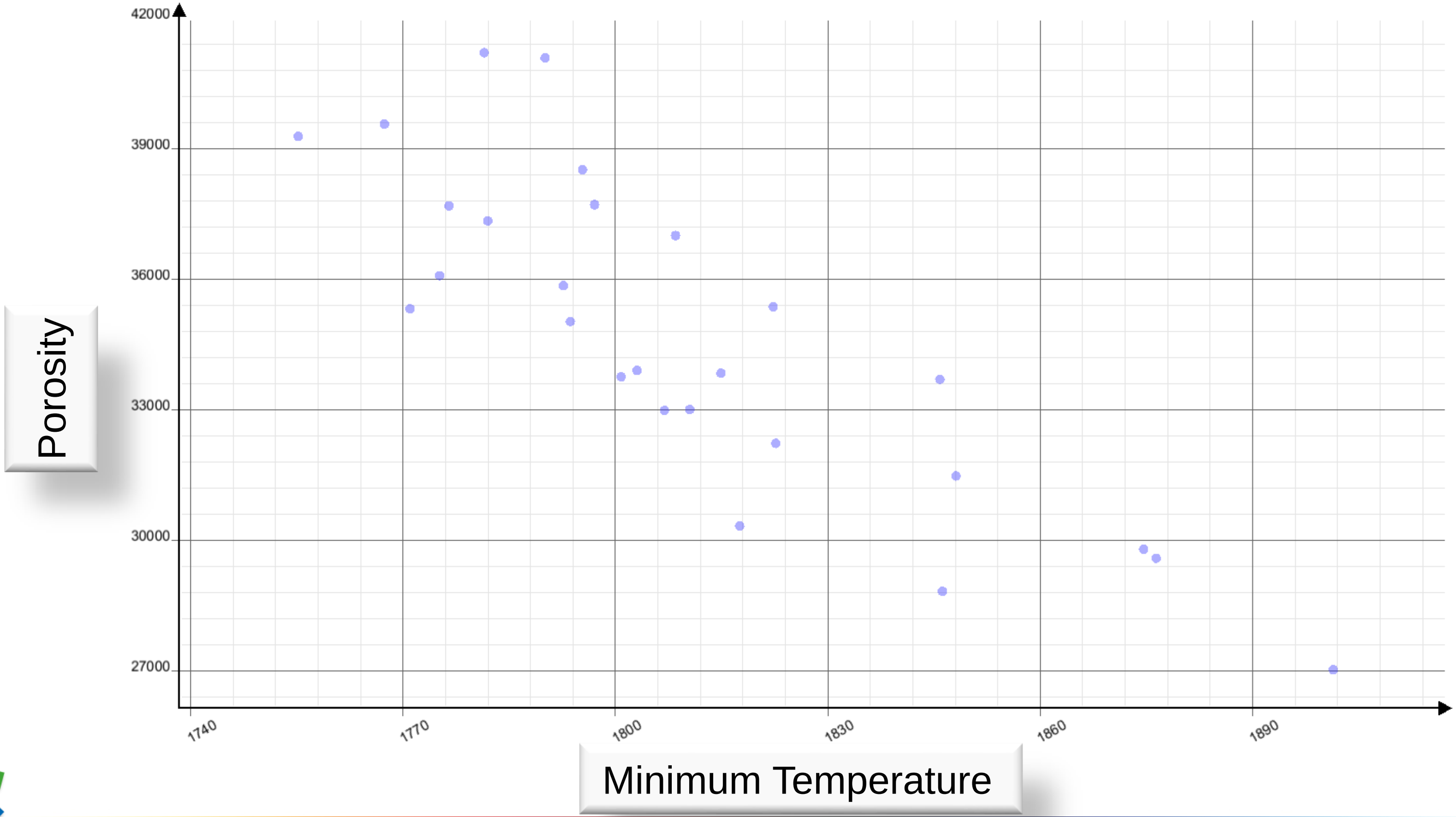
Parralell Coordinates

Which designs have the lowest porosity



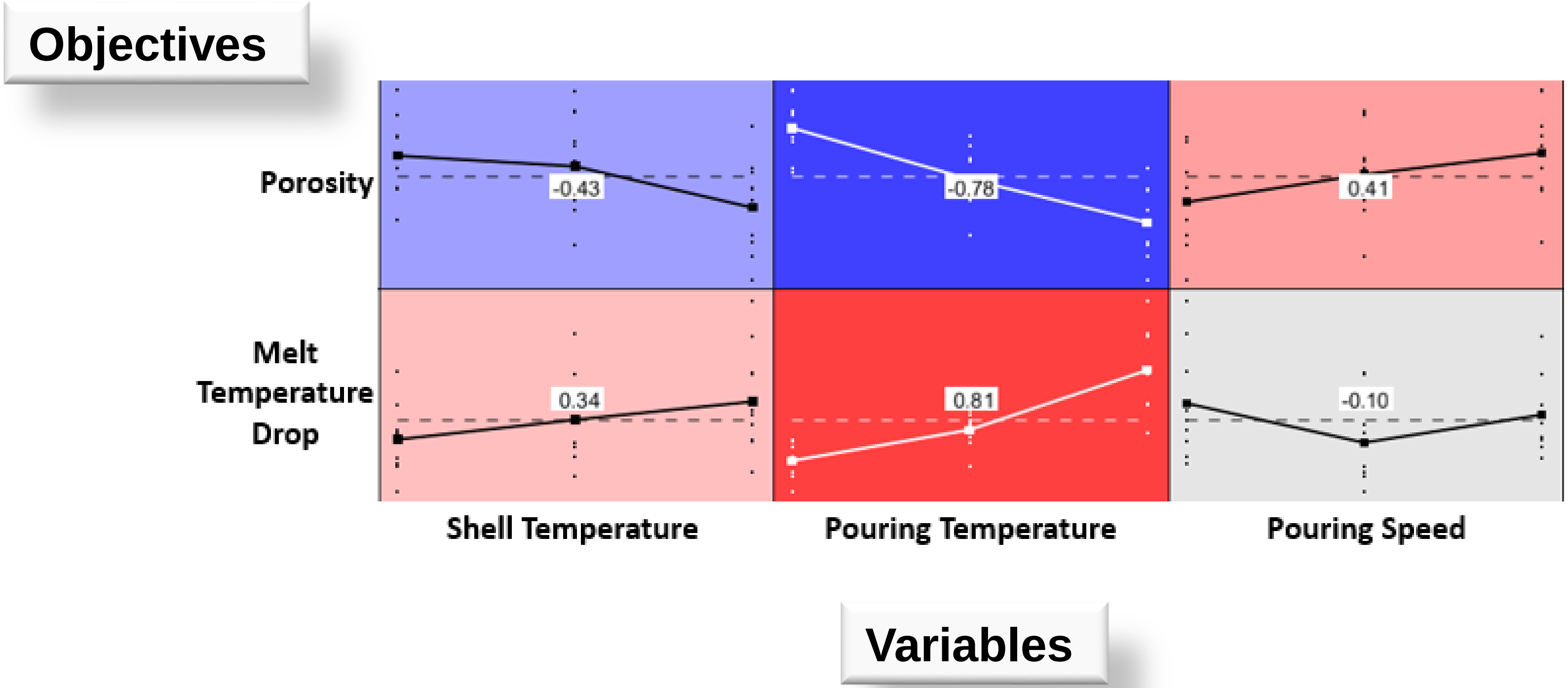
Scatter Plot

Porosity vs Minimum Metal Temperature



Correlation Matrix

Shows how variables impact the objective



Summary

- The DoE showed that a slower pouring speed and a higher pouring temperature was needed to produce a part with the lowest porosity
  - Porosity will likely increase if multiple parts are poured in the same heat
- The shell temperature also had an impact on the porosity, but the impact was less than the pouring speed and pouring temperature
- The information gained from running an Autonomous DoE can assist in establishing a process window to ensure consistent quality from the process

Conclusion

- Data driven decision making capabilities available using Autonomous Engineering allows the engineer to increase the quality and consistency of their products while having the ability to focus on reducing cost through inventive design considerations

- Using the capability to autonomously run virtual designs of experiments optimizations to find optimal casting process parameters and design feature combinations to make quality castings at minimal costs is the core benefit of autonomous engineering methodology integrated into the casting process simulation software

Thank you