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AMERICAN METALCASTING CONSORTIUM

Modeling of Reoxidation and Inclusions in Steel Castings

University of Iowa

Innovative Casting Technologies (ICT)

AMC Technology Review

August 17-18, 2022

Chicago, IL

The University of Iowa

SFSA

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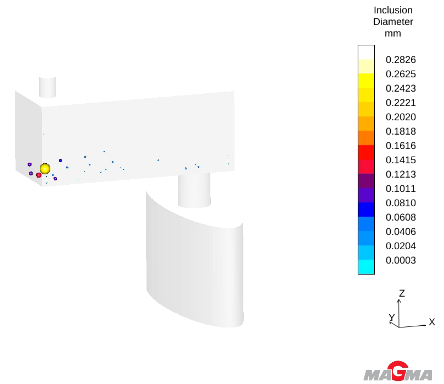
Overview

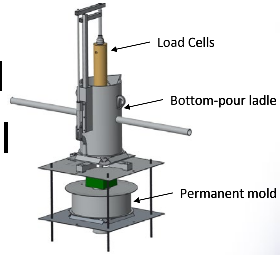
Duration

1	2	3	4	5

- Needs and Benefits Related to Inclusion Defects in Castings
  - ✓ Need - Decrease part reliability, defects not found until part fails
  - ✓ Need - Cause failures in service, costs can exceed the casting itself
  - ✓ Need - Adversely affects quality and procurement costs
  - ✓ Benefit - Reducing manufacturing costs and lead times
  - ✓ Benefit - Improving product quality
  - ✓ Benefit - Increasing component and system reliability



- Progress
  - ✓ Developed and implemented air entrainment and inclusion formation model
  - ✓ Performed first ever air entrainment experiments in liquid aluminum and steel
  - ✓ Performed inclusion generation and tracking experiments for validating model



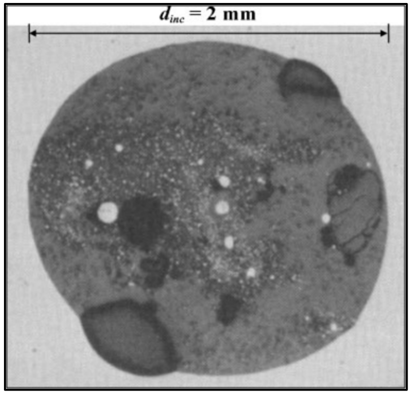
- Transition
  - ✓ Air entrainment inclusion model implemented in software used in steel foundries
  - ✓ Experiment results and models published in the open literature
  - ✓ Perform case studies to demonstrate technology to SFSA and DoD partners

DISTRIBUTION A. Approved for public release.

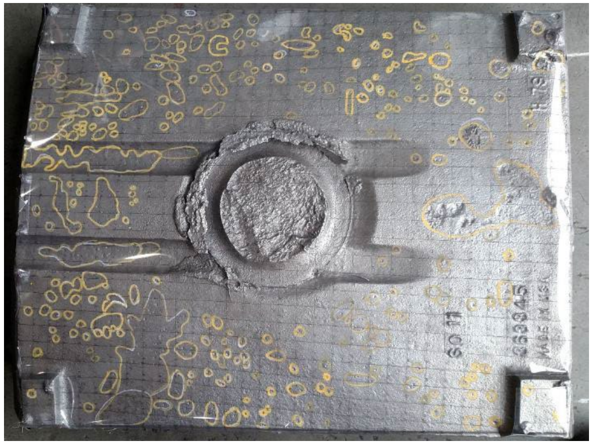
MAGMA
Committed to Casting Excellence

Objective

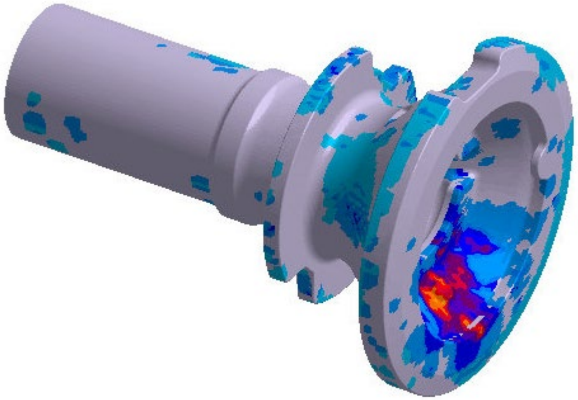
- ***Problem:*** Non-metallic inclusions are troublesome, severe defects in steel casting
- Form when liquid metal interacts with oxygen
- Reoxidation inclusions generated during pouring: a common type, entrained air a driving formation mechanism
- Inclusions cause poor surface quality; Reduced mechanical properties, service performance, machinability and yield



Round Inclusion in Steel Casting (Griffin and Bates, 1991)



Inclusions Marked for Repair on Casting Cope Surface



Measured Inclusion Concentration from 30 Castings

- ***Solution:*** Develop computational simulation model to predict the formation and locations of inclusions during the pouring of steel castings
  - Advection and buoyant movement of inclusions, their characteristics and locations in the casting.

Objective

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- ***<u>Technology Delivered:</u>*** Model for air entrainment in casting processes, inclusion formation and transport - incorporated in casting simulation software
  - Air entrainment and inclusion formation model and experiment results.
  - Model tested and calibrated using experimental data.
  - Steel casting trials and inclusions analysis to validate model.
  - Case study of production steel casting.

Entrained Air, Inclusions Generated and Their Transport

Key Technology:	**Current Deficiency:**	**Solution:**
Model for air entrainment in free surface flows and inclusion transport	Inclusions cause reduced service performance of steel castings and failures, weld repairs, rejection of castings, and reduced machinability and casting yield.	Apply models to reduce inclusions in steel casting, design improved pouring systems, demonstrate benefits to DLA and the industry

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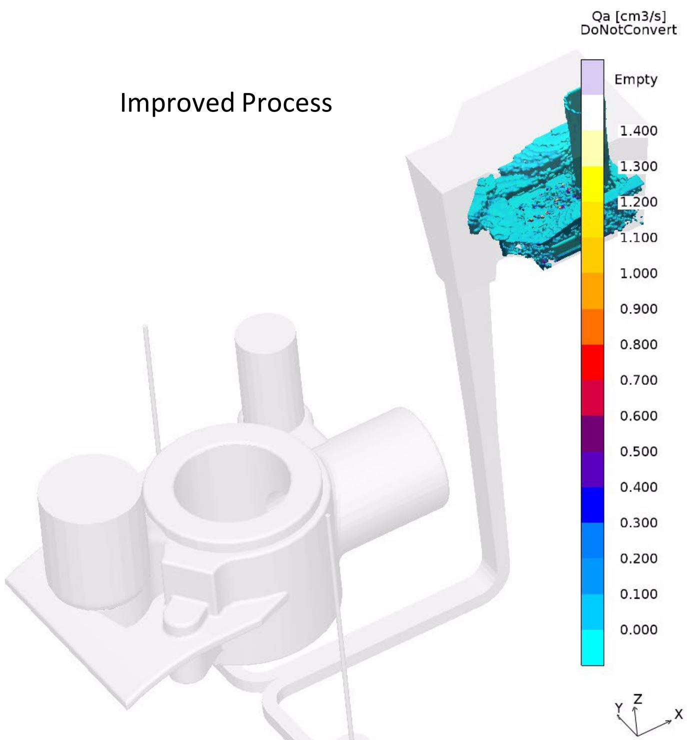
Needs and Benefits

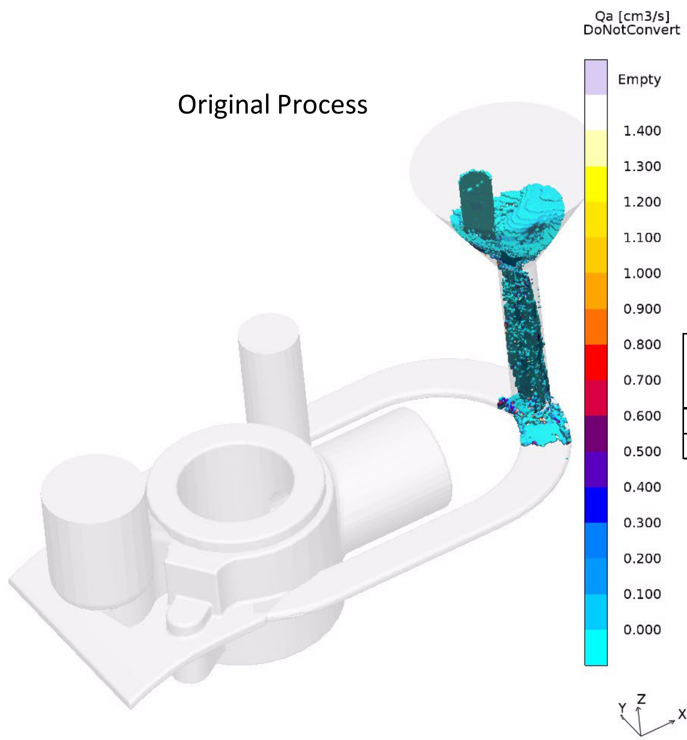
DoD Needs Addressed

- DoD and DLA benefit from steel foundries reducing inclusion defects
  - reducing manufacturing and procurement costs
  - reducing lead times
  - improving product quality and performance
  - increasing component and system reliability
  - reducing failures in service

Improved Process



Original Process



Summary of Comparisons

Version	Total Casting System Volume (cm^3)	Air Entrainment Ratio	Fill Time (s)
Original	19,302	0.1383	8.7
Improved	23,256	0.0246	23.8

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Needs and Benefits

For Foundry / Casting Supplier / Industry …

– Surface inclusions inspected and repaired at the foundry

– 20% of the direct cost of casting production lies in removing inclusions, refilling defect areas with weld metal.[1]

– Subsurface inclusions cause serious and expensive problems in subsequent machining operations.[1]

[1]M. Blair, Steel Founders' Society of America Research Report No. 104, 1991.

Inclusions Marked for Repair

"Reoxidation products in steel are one of the primary concerns in steel casting quality. Inclusions result in reduced mechanical properties, increased lead time to the customer, and overall increased cost of manufacturing."

-Shawn C. Martin, Melt and Lab Operations Manager, Harrison Steel Castings

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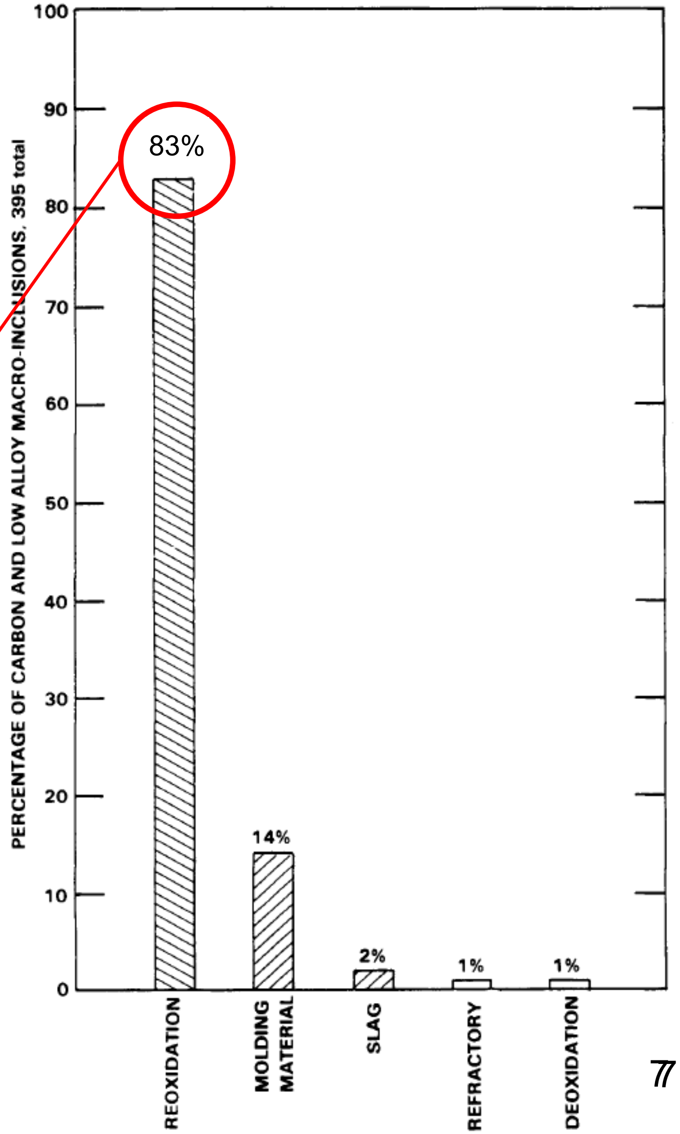
Needs and Benefits

Predict and Avoid Air Entrainment and Reoxidation Inclusions

- Reoxidation inclusions form when deoxidized steel comes into contact with oxygen during mold filling.
- Primary oxygen source is from air
  - entrained air in particular
- Ability to predict air entrainment will directly affect our ability to design better mold filling systems and reduce reoxidation inclusions
- 83% of inclusions in **carbon and low alloy steel castings** are produced by reoxidation[1]
- 48% of inclusions in **high alloy steel castings** are produced by reoxidation[1]

[1]M. Blair, Steel Founders' Society of America Research Report No. 104, 1991.

Distribution of Inclusion Sources in Carbon and Low Alloy Steel Castings[1]



"Understanding how filling systems contribute to air entrainment is likely to be very similar in aluminum and steel."

"The work being done by the University of Iowa in both alloy systems could lead to better performance of castings through reduction of defects and better mechanical performance. "

-David Weiss, Vice President Engineering / R&D, Eck Industries, Inc.

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Technical Progress

Technical Approach to Reducing Reoxidation Inclusions

- Simulations predict air entrainment and inclusion formation, apply model developing production processes minimizing inclusion defects
- Model advection and buoyant movement of the inclusions, and their final characteristics (size, number density, etc.) and locations in the casting, implemented in *MAGMAsoft*
- Calibrate and validate model with experimental data, test castings poured and measured

Model of Inclusion Generation from Entrained Air and Their Transport **Implemented in *MAGMAsoft***

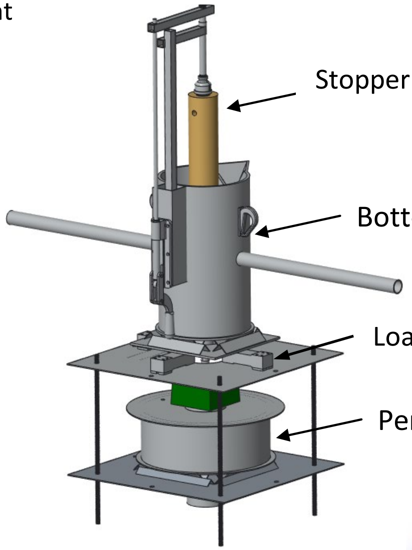
Air Entrainment Rate

Inclusion Size and Motion

Water-Air Entrainment Experiments

Metal Experiment Development

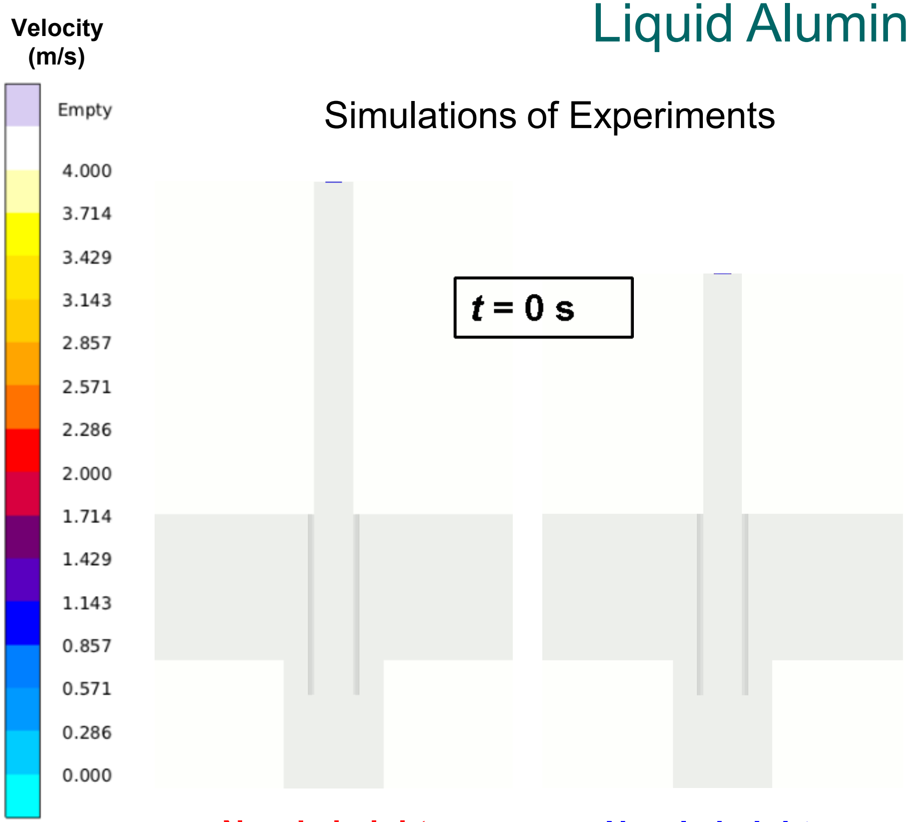
Air Entrainment Measurement System for Liquid Metals



Technical Progress

Performed First Ever Air Entrainment Experiments in Liquid Aluminum and Steel

Simulations of Experiments

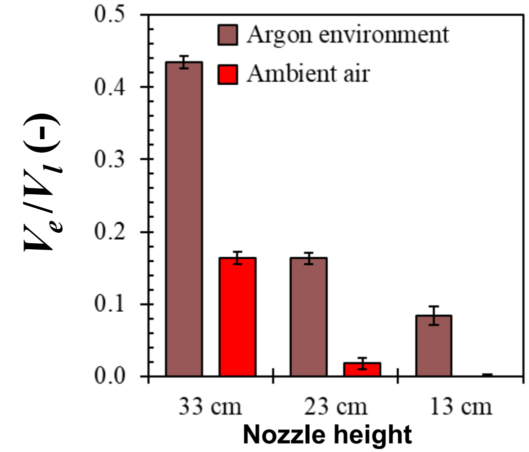


Nozzle height: 33.0 cm

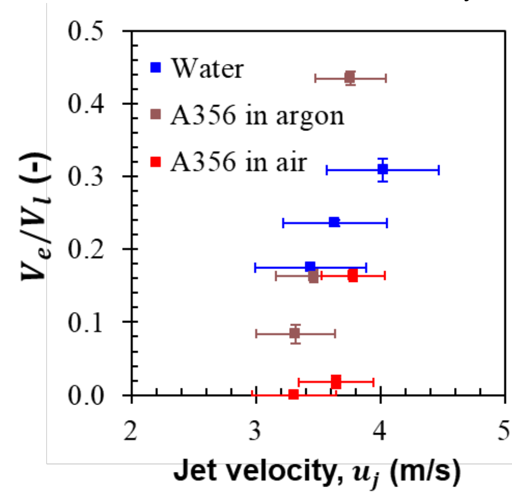
Nozzle height: 23.0 cm

Experiment Results

Average Air Entrainment Ratios for Aluminum Experiments



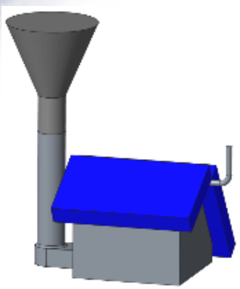
Air Entrainment Ratio vs. Jet Velocity at Impact

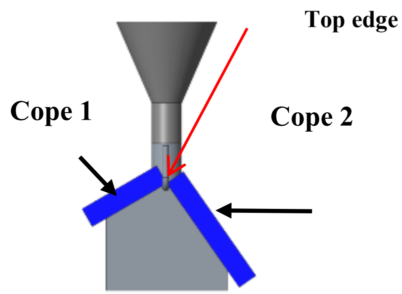


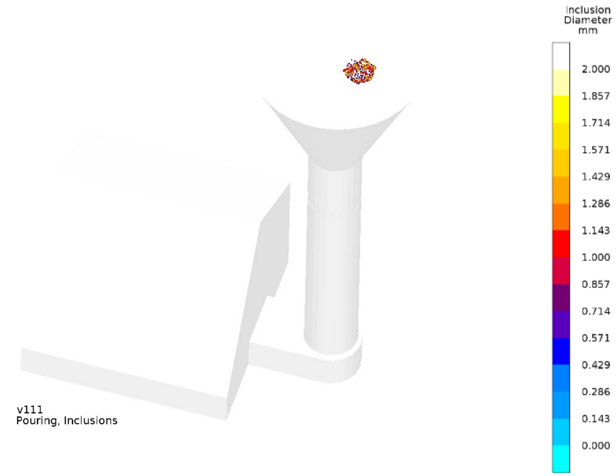
- The critical velocity for A356 in air is estimated to be 3.7 m/s, much higher than ~1 m/s reported for water
- The critical velocity for A356 in argon is 3.4 m/s
- Experiments with steel gave similar critical velocity

Technical Progress

Test Castings for Inclusion Model Validation: Examples



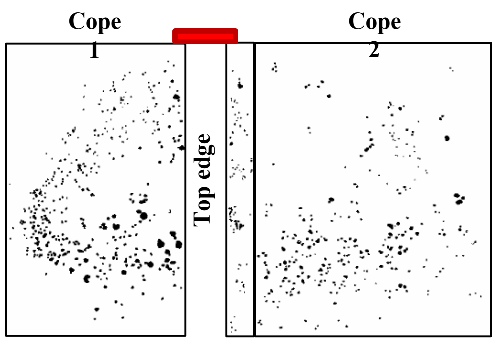




Measured Inclusions
Cope 1
Inclusion area: 4.0%
Inclusion count: 345
Average diameter: 1.27 mm

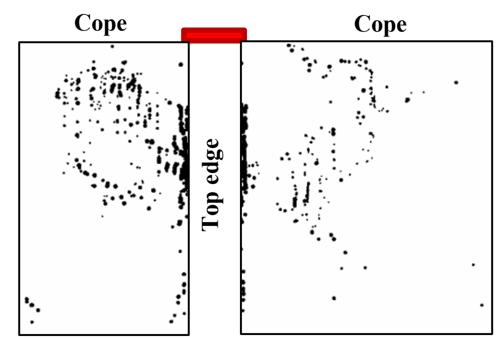
Measured Inclusions
Cope 2
Inclusion area: 2.0%
Inclusion count: 280
Average diameter: 1.13 mm

Measured



Simulated

Cope 1
Inclusion area: 4.39%
Inclusion count: 156
Average diameter: 1.97 mm



Cope 2
Inclusion area: 2.17%
Inclusion count: 129
Average diameter: 1.75 mm

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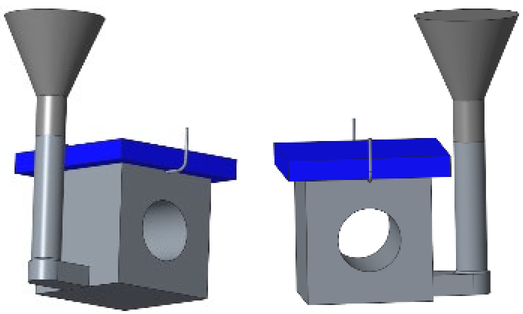
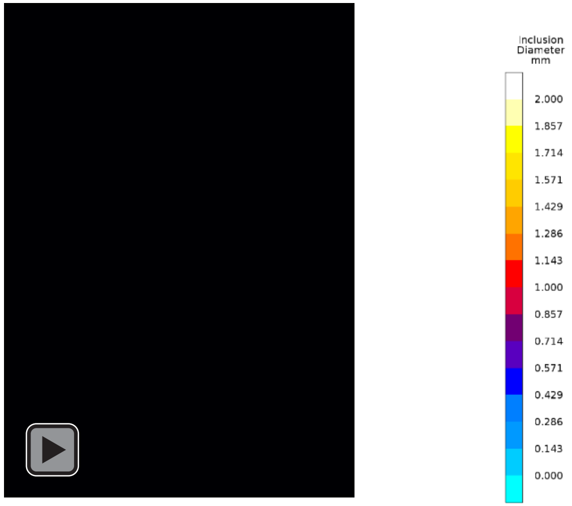
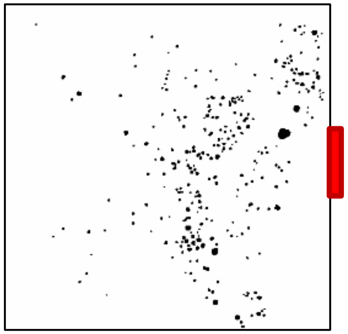
Test Castings for Inclusion Model Validation: Examples



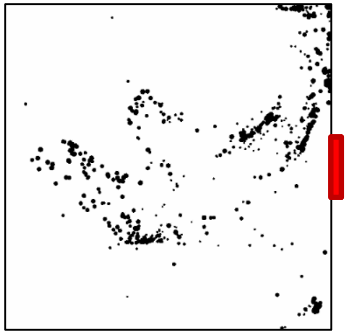


Measured



Inclusion area: 2.1%
Inclusion count: 272
Average diameter: 1.38 mm

Simulated



Inclusion area: 3.98%
Inclusion count: 220
Average diameter: 1.96 mm

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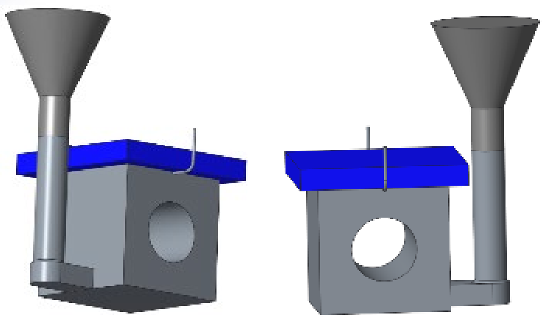
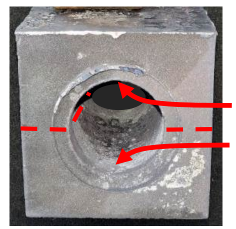
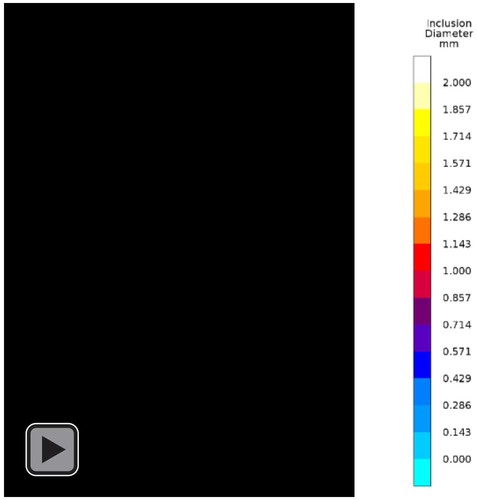
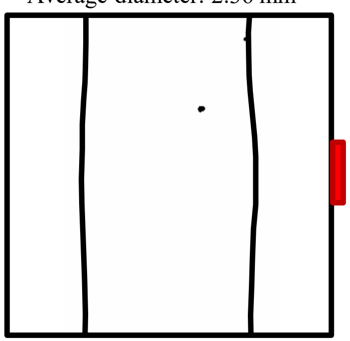
Test Castings for Inclusion Model Validation: Examples



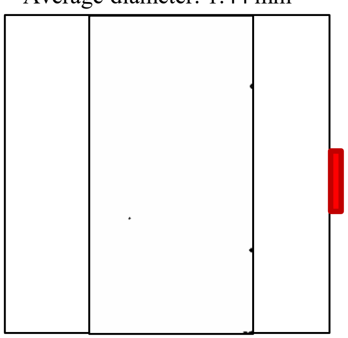




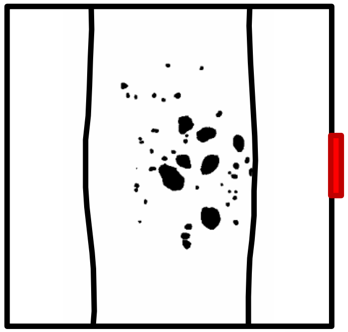
Measured Inclusions - Top
Inclusion area: 0.05%
Inclusion count: 2
Average diameter: 2.36 mm



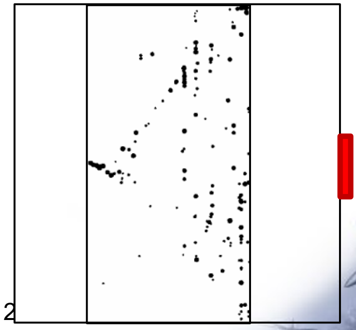
Predicted Inclusions - Top
Inclusion area: 0.05%
Inclusion count: 5
Average diameter: 1.44 mm



Measured Inclusions - Bottom
Inclusion area: 3.2%
Inclusion count: 45
Average diameter: 3.19 mm



Predicted Inclusions - Bottom
Inclusion area: 1.72%
Inclusion count: 105
Average diameter: 1.77 mm



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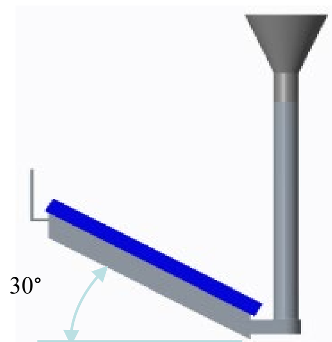
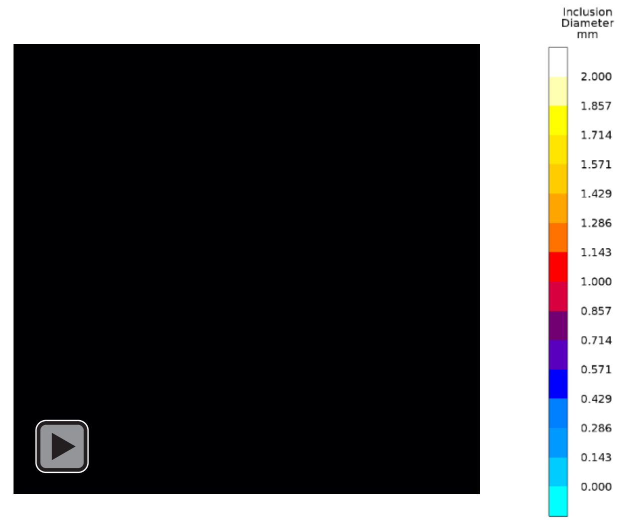
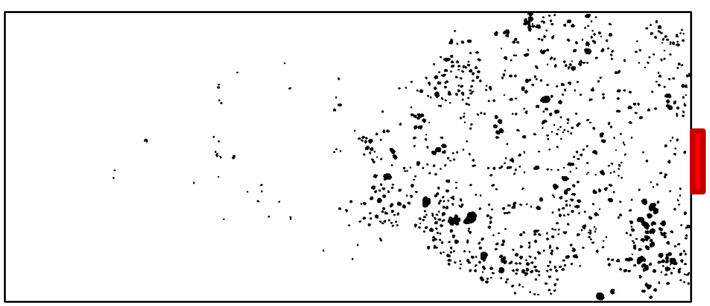
Test Castings for Inclusion Model Validation: Examples

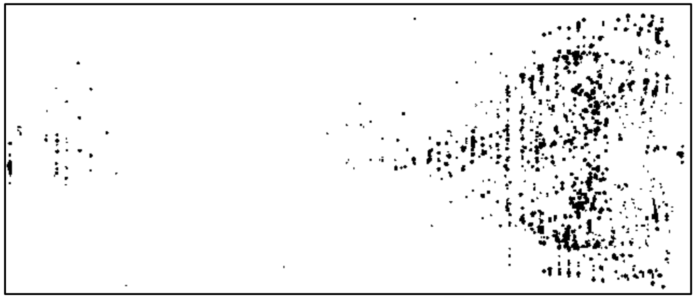




Measured: Inclusion area: 3.6%
Inclusion count: 837
Average diameter: 1.55 mm



Simulated: Inclusion area: 3.86%
Inclusion count: 483
Average diameter: 1.99 mm



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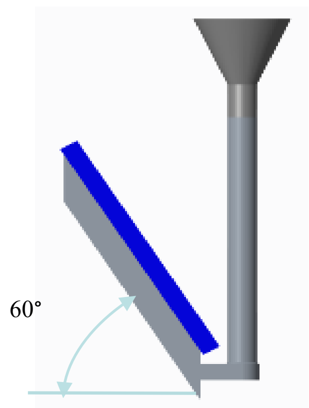
Test Castings for Inclusion Model Validation: Examples



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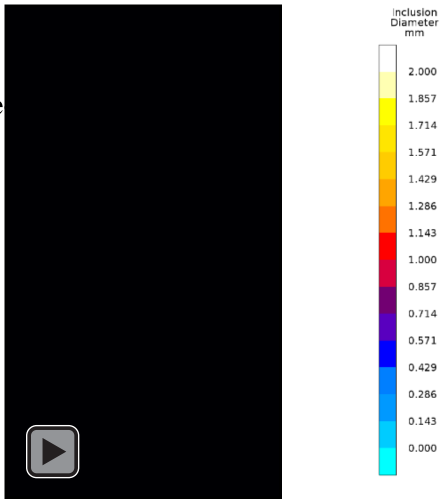
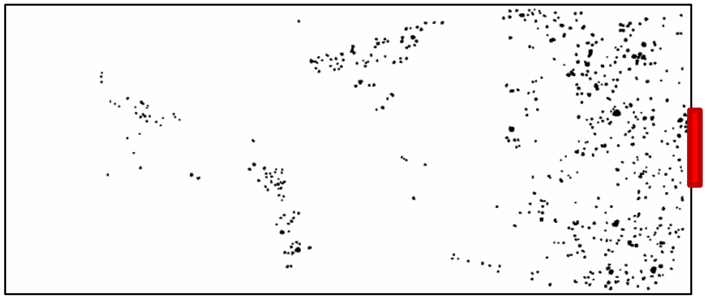
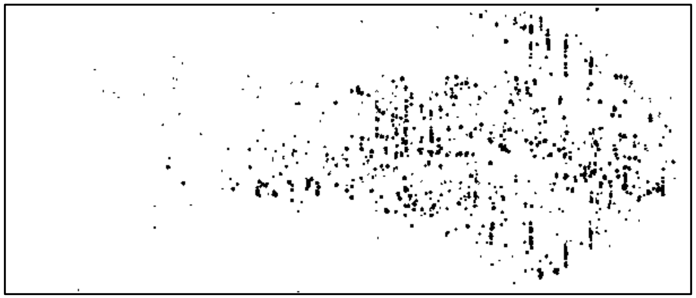


Measured: Inclusion area: 1.9%
Inclusion count: 496
Average diameter: 1.54 mm



Simulated: Inclusion area: 3.4%
Inclusion count: 506
Average diameter: 2.00 mm



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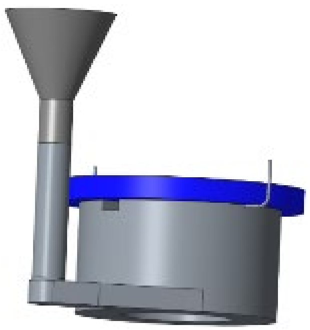
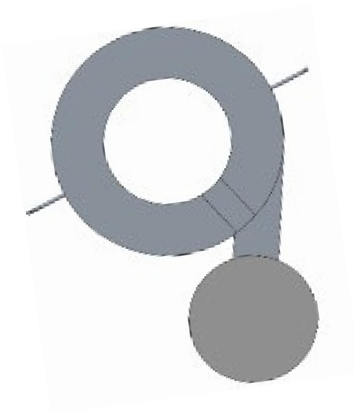
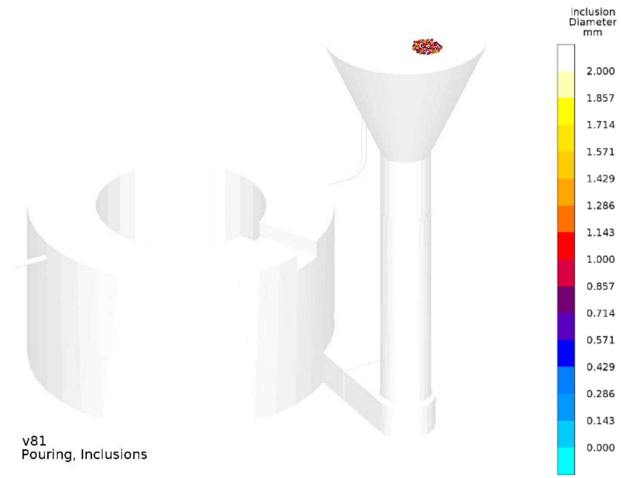
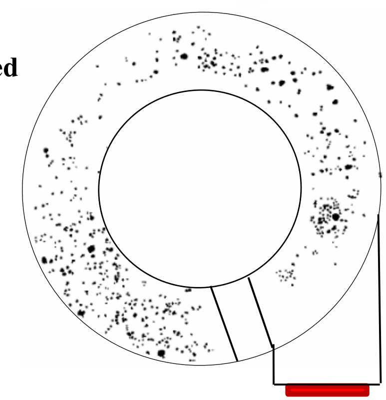
Test Castings for Inclusion Model Validation: Examples





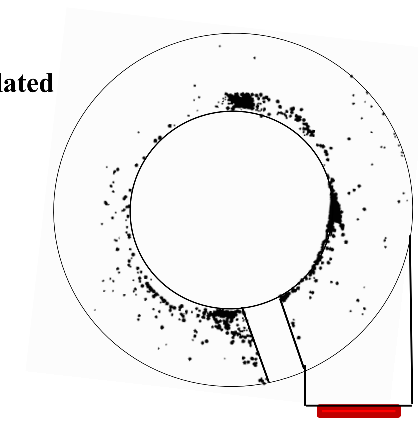


Measured



Inclusion area: 3.6%
Inclusion count: 498
Average diameter: 1.51 mm

Simulated



Inclusion area: 4.78%
Inclusion count: 199
Average diameter: 2.18 mm

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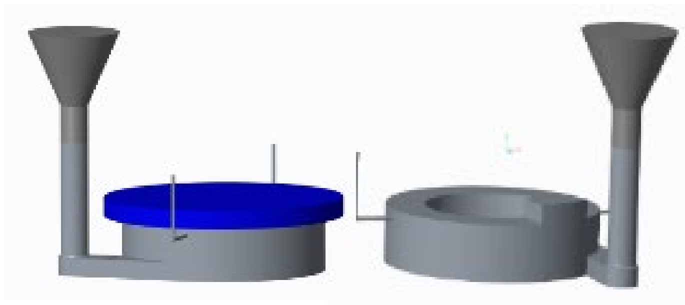
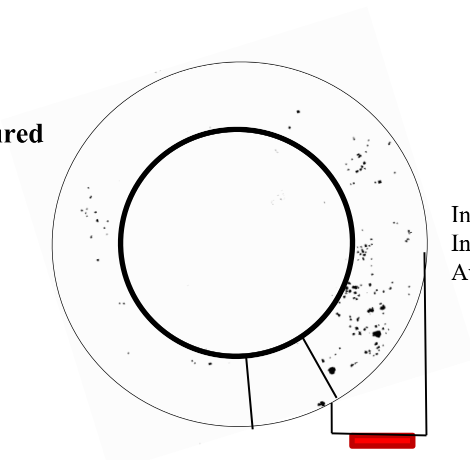
Test Castings for Inclusion Model Validation: Examples

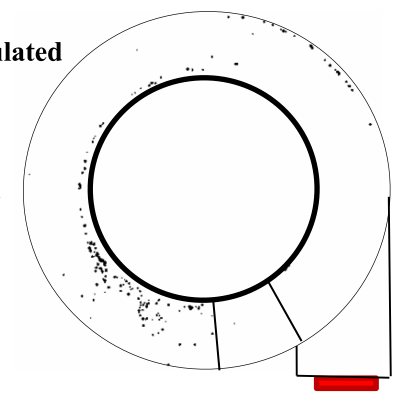


Measured



Inclusion area: 0.82%
Inclusion count: 131
Average diameter: 1.53 mm

Simulated



Inclusion area: 1.13%
Inclusion count: 122
Average diameter: 1.91 mm

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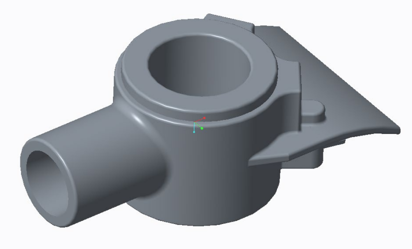
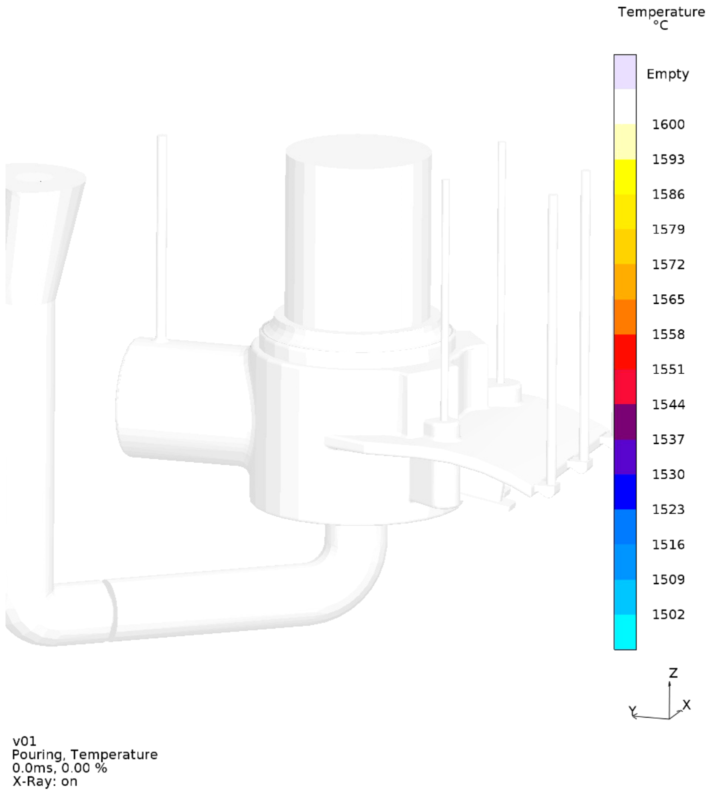
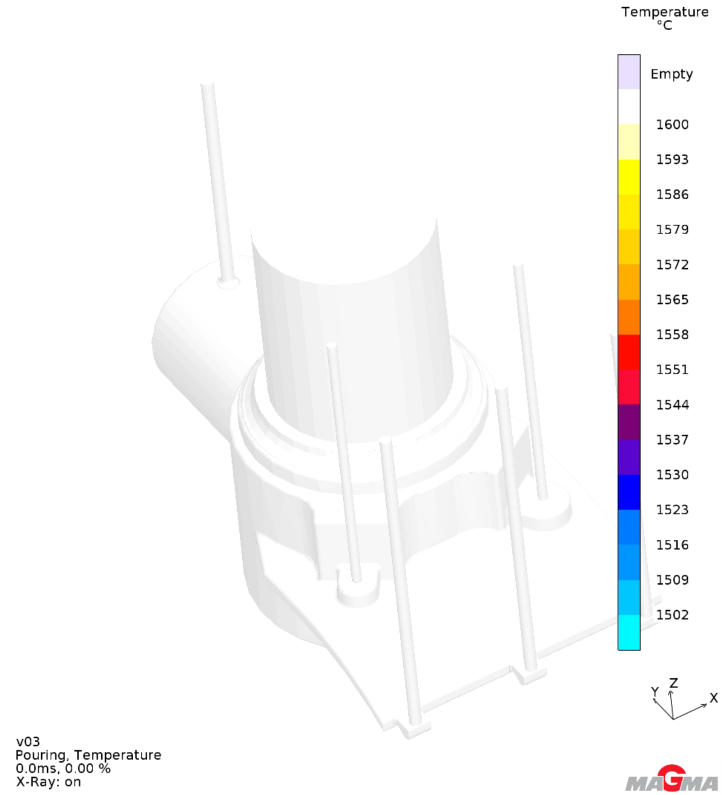
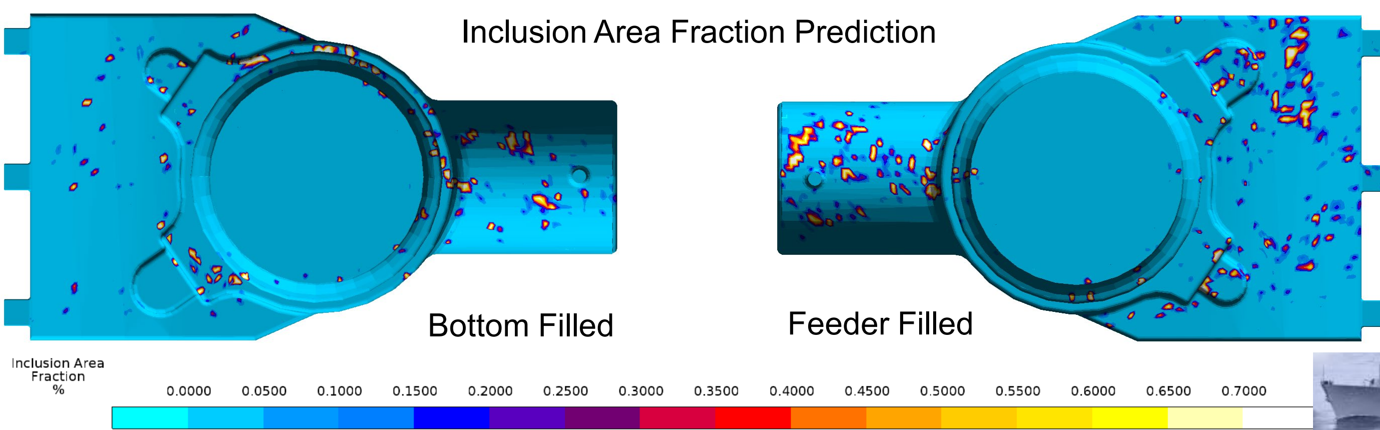
Case Study Involving a Production Steel Casting



- Seven “platypus” castings poured at SFSA member foundry
- Four poured with bottom filled gating system
- Three poured directly into feeder
- Interesting features: cores and surfaces







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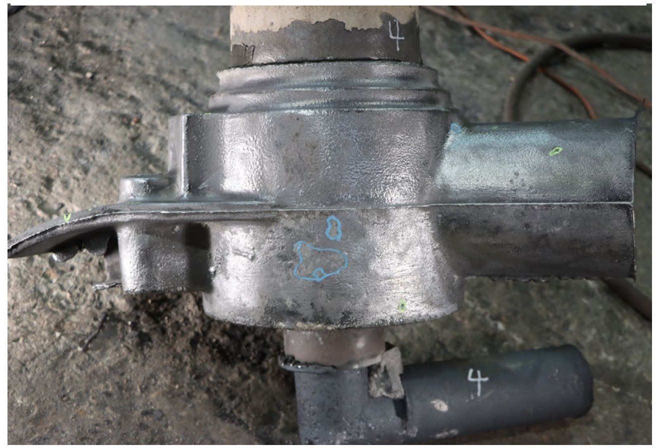
Technical Progress

Case Study Involving a Production Steel Casting

- Castings cleaned, inspected and marked up - yellow regions are inclusions, blue are deox deposits

Castings After Markup – Photo Lighting

Castings After Markup – Example View of Results



Castings After Markup – Example View of Results

Castings After Markup – Example View of Results

Castings After Markup – Example View of Results

Castings After Markup – Example View of Results

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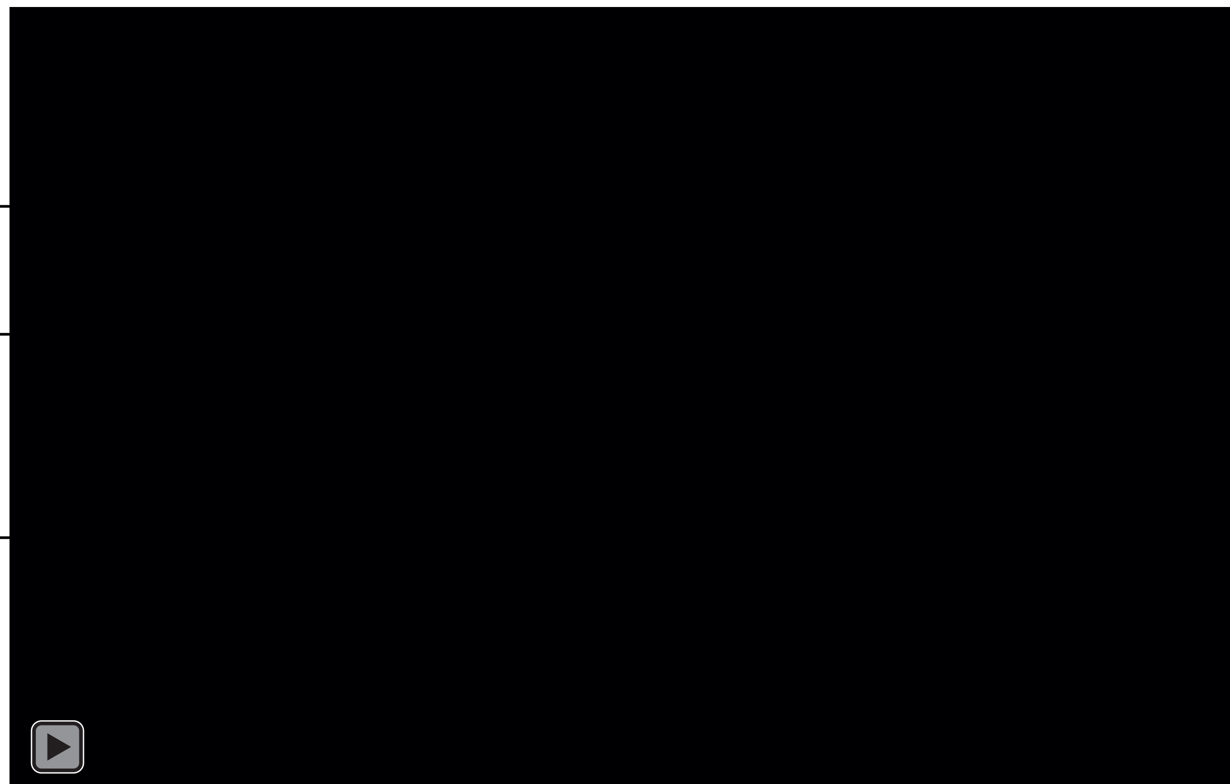
Completion Plans

Key Accomplishments Needed to Complete the Project

- Complete case study comparing observed and predicted inclusions - **Ongoing**
- Report on experiments of air entrainment and inclusion formation - **Done**
- Development of a computational model for air entrainment during pouring and transport of oxide inclusions - **Done**
- Implement model in commercial casting simulation software – **Done**

Model of Inclusion Generation from Entrained Air and Their Transport **Implemented in *MAGMAsoft***



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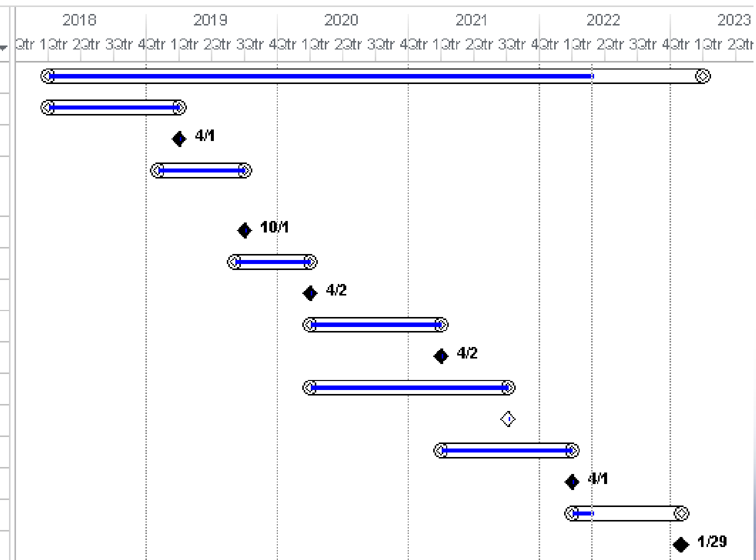
Completion Plans

Key Accomplishments Needed to Complete the Project

- Model validation using data from casting trials – **Completed 5/22**
- Report on validation – **Completed 5/22**
- Case study involving a production steel casting – **Ongoing 4/22 to 1/23**
- Final report on production steel casting case study – **Complete by 1/23**
- Draft of Final Project Report due to ATI by **10/29/22**

WBS	Task Name	Start	Finish	% Complete
0	MODELING OF REOXIDATION AND INCLUSIONS IN STEEL CASTINGS	Mon 4/2/18	Thu 3/30/23	83%
1	Experiments to measure entrainment and inclusion formation	Mon 4/2/18	Mon 4/1/19	100%
1.1	Report on experiments for studying air entrainment and inclusion formation	Mon 4/1/19	Mon 4/1/19	100%
2	Development of a computational model for air entrainment during pouring and transport of oxide inclusions	Fri 2/1/19	Tue 10/1/19	100%
2.1	Model for air entrainment in free surface flows and inclusion transport developed	Tue 10/1/19	Tue 10/1/19	100%
3	Model testing and calibration using experimental data	Mon 9/2/19	Thu 4/2/20	100%
3.1	Report on validation of model.	Thu 4/2/20	Thu 4/2/20	100%
4	Model implemented in commercial casting simulation software	Thu 4/2/20	Fri 4/2/21	100%
4.1	Implemented model	Fri 4/2/21	Fri 4/2/21	100%
5	Casting trials and inclusion analysis in solidified steel	Thu 4/2/20	Mon 10/4/21	100%
5.1	Final report on casting trials and inclusion analysis	Mon 10/4/21	Mon 10/4/21	100%
6	Model validation using data from casting trials	Fri 4/2/21	Fri 4/1/22	100%
6.1	Report on validation	Fri 4/1/22	Fri 4/1/22	100%
7	Case study involving a production steel casting	Fri 4/1/22	Sun 1/29/23	20%
7.1	Final report on case study involving a production steel casting	Sun 1/29/23	Sun 1/29/23	0%



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Transition Plan

- Model for air entrainment and inclusion transport is implemented in commercial casting simulation software for use by foundries, experiment results and methodology published
  - Partnering with MAGMA, implemented in *MAGMAsoft*
  - Published methodology in the open literature, all software vendors can implement
  - Model completed, only calibration and validation left to accomplish
- Perform case study to demonstrate technology with SFSA, industry and DoD partners
  - Air entrainment model applied to DoD Applications: track shoe gating system designs for Bradley and M1, and foundry improvement project with Newport News Shipbuilding
  - Casting Trials and Case Studies with Industry

"Predicting the amount and location of reoxidation products due to gating and risering choices shrinks the learning curve, improves material performance, and reduces lead time to end user."

-Shawn C. Martin, Melt and Lab Operations Manager, Harrison Steel Castings

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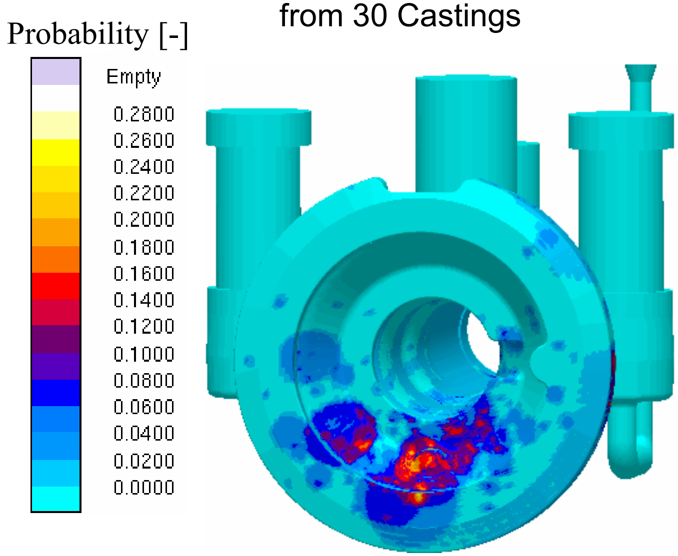
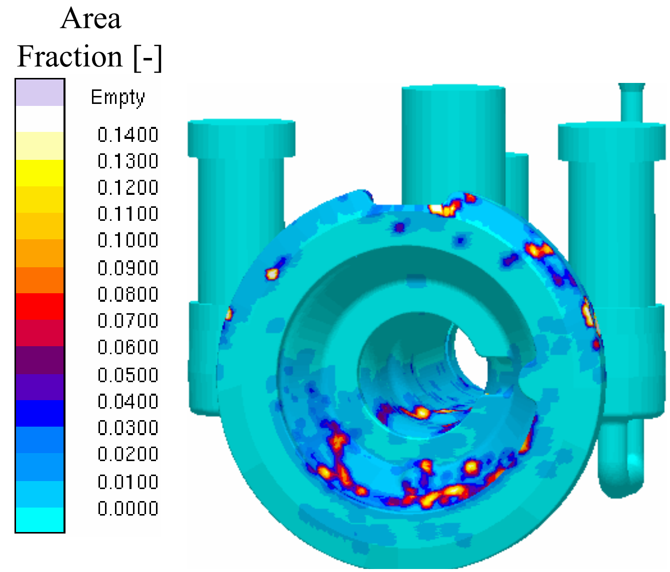
Leveraging

- Project uses expertise, methods and experiments developed through Iowa Energy Center funded work

Measured Inclusion Probability Map
from 30 Castings



Predicted Inclusion Area Fraction



- Project leveraging from SFSA Clean Steel research at UI funded under the DLA Digital Innovative Design (DID) program, experimental data and modeling experience

- Additional experience and technology development from foundry improvement project with Newport News Shipbuilding in reduction of reoxidation inclusions

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Project Metrics

Description	Baseline	Threshold	Goal	How Measured	Target Date	Progress	How Demonstrated
Agreement Between Measured and Predicted Inclusions in Test Castings	No Agreement	50% Agreement in Size and Amount	90% Agreement in Size and Amount	Quantitative Measurement of Inclusion Amount and Size	April 2022	100%, Measured and Simulated Inclusion Area, Count and Size Data	Result Agreement (Average, Best): Inclusion Area (66%,100%) Inclusion Diameter (60%,75%) Inclusion Count (54%,98%)
Reduce Inclusions in Production Case Study Casting	Current Production Data	40% Reduction in Inclusions	80% Reduction in Inclusions	Casting Inspection, Markup And Photographs	January 2023	70%, Castings poured, inspected and recorded. Measurement and image analysis ongoing.	Degree of Inclusion Reduction in Area, Count and Diameter of Inclusions
Reduction in Weld Repair and Yield Improvement	Current Production Data	Reduce Repair, Scrap and Improve Casting Yield by 5%	Reduce Repair, Scrap and Improve Casting Yield by 10%	Production Data	January 2023	10%, Case Study Started, castings produced.	Degree of Repair Reduction, and Yield Improvement

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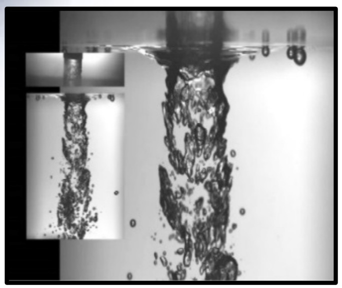
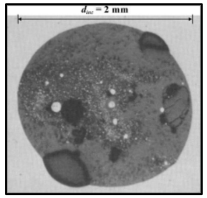
Modeling of Reoxidation and Inclusions in Steel Castings

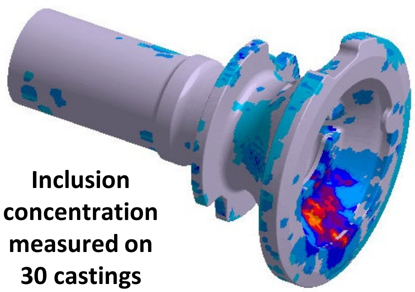
DLA - POC: DLAR.DPR@dla.mil



Entrained air bubbles for a plunging water jet



Reoxidation inclusion in a steel casting



Inclusion concentration measured on 30 castings

Problem

- Non-metallic inclusions are one of the most prevalent and severe defects present in steel castings.. Inclusions limit the casting yield, resulting in the need for weld repair, extra machining, possible rejection, and poor service performance.

Objectives

- Improve ductility and fatigue life, and reduce weld repairs, machining, and scrap by developing a computational simulation model to predict the formation of inclusions during the pouring of steel castings.

Benefits to Warfighter

- Improved lead times resulting from reduction of weld repairs and machining (fewer inclusions)
- Reduced costs from improved yields due to superior gating systems and fewer casting rejections
- Enhanced service performance from improvements in ductility and fatigue life

Description of Project:

This project will develop a computational simulation model to predict the formation of reoxidation inclusions during the pouring of steel castings, the subsequent advection and buoyant movement of inclusions, and their final characteristics and location in the solidified casting.

Team:

University of Iowa, SFSA, ATI

The University of Iowa   SFSA   ATI Advanced Technology International

Milestones / Deliverables

- Model for air entrainment in free surface flows and inclusion transport developed
- Model tested and calibrated using experimental data
- Model implemented in casting simulation software
- Steel casting trials completed and inclusions analyzed
- Model validated using data from casting trials
- Case study involving production steel casting