Modeling of Oxide Films in High Alloy Steel Castings

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Emergent Metal Casting Technologies (EMCS)

AMC Technology Review

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Overview

- Needs and Benefits
  - **Need/Problem** - **Oxide film defects** in high alloy castings reduce casting performance and mechanical properties, increase production costs and lead times.
  - **Benefits** - Generate experimental data and validated simulation tools, guidance to engineers designing pouring and gating systems, minimizing the presence of oxide films in high alloy castings.
- Progress
  - Completed measurement and analysis of oxide film casting experiments.
  - Developed and demonstrated oxide film transport and breakup model.
  - Developed and applied oxide defect modeling methods to casting experiments.
  - Applied oxide film transport models in *Flow-3D* and *MAGMAsoft* to casting experiments and an industry case study.
  - Ongoing work - additional casting experiments, case studies of industry castings, testing and improving models in commercial software.
- Transition
  - Oxide film formation and transport model available in foundry software.
  - Results and models published in the open literature.
  - Perform case studies to demonstrate technology to SFSA and DoW partners.
- Cost Share-$145,200

Needs

- **Reduce oxide films** in high alloy steel castings or **eliminate special measures to reduce them**.
- Oxide film defects degrade casting performance, increase cost and lead times.
- Special precautions required, casting without oxygen.

- Oxide films form in nonferrous metal casting: Ni-based, aluminum, magnesium and Ni-Al bronze.
- Impacts more than high alloy steel castings.

Needs: Reducing Oxide Film Defects

Oxide Film Defects on a Ni-based Alloy Casting

- Special precautions required in this case - use an inert gas environment or in vacuum.

Dye Penetrant Testing Results

Needs: Reducing Oxide Film Defects

- Research program SFSA project A-54 - Oxide films in high alloy steels (CF8M)
- Two related types of oxide films found: Surface Films and Fold Films, described as tenacious.
- Oxide films and folds are mainly eutectic oxides “primarily of chromium and manganese with minor amounts of silicon, and $MnCrO_4$. No iron was found in these fold films.”
- Iron oxides were found at the mouths of these folds - evidence of a reaction between the oxide and the metal during filling.
- Thickness of films estimated to range from 10 to 100 µm.

1. Roach D. B. and Hall A. M. ,“Summary Report on Project 54 - Investigation of Surface Defects Associated with Tenacious Surface Films on High Alloy Castings,” Alloy Casting Institute Division Steel Founders' Society Of America, 1973.

Benefits

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- Benefits to DLA from Reducing Oxide Film Defects
  - Improving cast product quality and performance
  - Controlling oxide films increase component and system reliability
  - Reducing scrapping, failures and leaks in service, uncertain performance due to oxide films
  - Reducing lead times by eliminating rework and repairs
  - Lower manufacturing and procurement costs

- Foundry / Casting Supplier / Industry Benefits
  - Modeling enables foundry engineers to design pouring and gating systems that minimize presence of oxide films in high alloy steel castings.
  - Design reliable casting processes with shorter development times.
  - Model applicable to nonferrous metal casting processes that form oxide films: aluminum, magnesium and Ni-Al bronze alloys.

Milestones/Tasks

- Completed
  - Task 1.1 Literature search, identify and organize industry partners
  - Task 1.2 Design, plan and organize experiments
  - Task 1.3 Pour CY40 Ni-based alloy (Inconel 600) experiments
  - Task 2 Develop model for predicting oxide films
    - Developed and demonstrated oxide film transport and breakup model.
    - Completed analysis of oxide film casting experiments.
    - Compare experiment results to existing oxide inclusion modeling methods.
    - Calibrated and applied oxide film transport models in *Flow-3D* and *MAGMAsoft* to casting experiments and industry case study.
    - Developed methods to apply oxide defect modeling to casting experiments.

- In Progress
  - Task 3 Implement oxide film model in casting simulation software
  - Task 3.1 1st round of modifications to casting simulation software
  - Task 4.1 Casting experiments to test and calibrate model, first round

- Planned
  - Task 5 Case studies involving production high alloy steel castings

Technical Progress

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Technical Progress in Modeling Oxide Films in Castings over Last 12 Months

- Task 2 Developed methods and completed analysis of oxide film casting experiments.
- Task 2 Compared experiment results to existing oxide inclusion modeling methods.
- Task 2 Developed methods to apply oxide defect modeling to casting experiments.
- Task 2 Calibrated and applied oxide film transport models in *Flow-3D* and *MAGMAsoft* to casting experiments.
- Task 5.1 Application of oxide film models to casting experiments and a case study of an industrial casting process.
- Task 4.1 Designing casting experiments to test and calibrate modeling, first round

Technical Progress

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Task 2 Analysis of Oxide Film Experiments

- Four cases developed; molds printed
- Weights of rigging, total including pouring cup and fill gage
- Pouring cup and fill gage
- Pour two of each case, A and B
- Total weight poured 522 pounds of Ni-based CY40 alloy
- Chill plates used on the blocks
- Pouring order, fill time

    1 Case 4 Puzzle B with filter, 8 s

    2 Case 4 Puzzle A with filter, 12 s

    3 Case 2 B no filter, 13 s

    4 Case 2 A no filter, 7 s

    5 Case 1 A no filter, 7 s

    6 Case 1 B with filter, 9 s

    7 Case 3 A no filter, 13 s

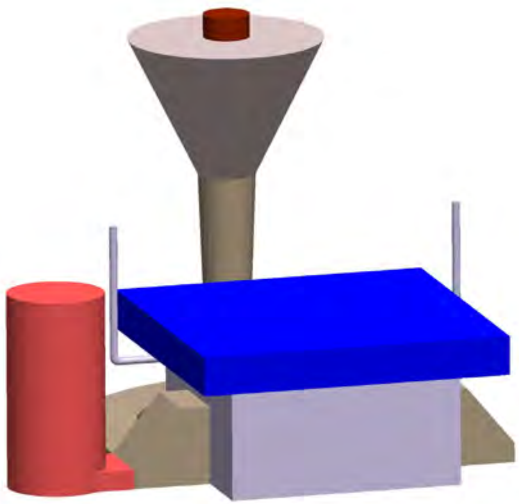
    8 Case 3 B no filter, 13 s

Technical Progress

Task 2 Analysis of Oxide Film Experiments

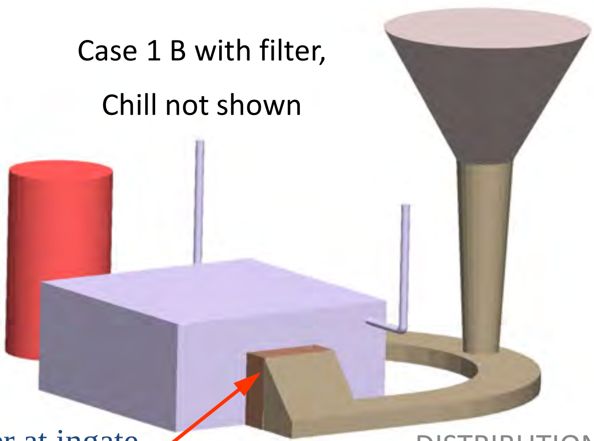
Case 1 A with no filter,

Chills used in Case 1, 2 and 3



Case 1 B with filter,

Chill not shown



Filter at ingate

- Result for Case 1 B with filter
- Casting surfaces were shot blasted

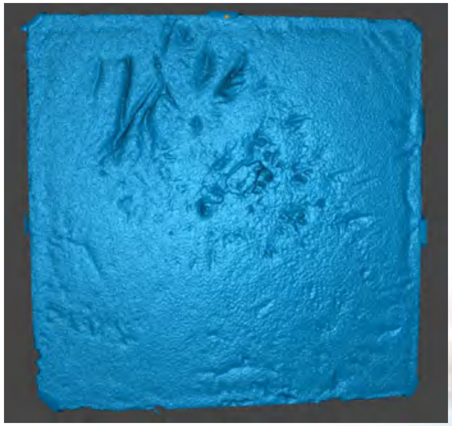
Technical Progress

Analysis of Oxide Film Experiments - Comparison to CLA Oxide Inclusions

CLA Inclusion Experiment Media Blast Surface Inspection

High Alloy Oxide Film Surfaces Dye Penetrant Inspection

High Alloy Oxide Film 3D Surface Scan Model

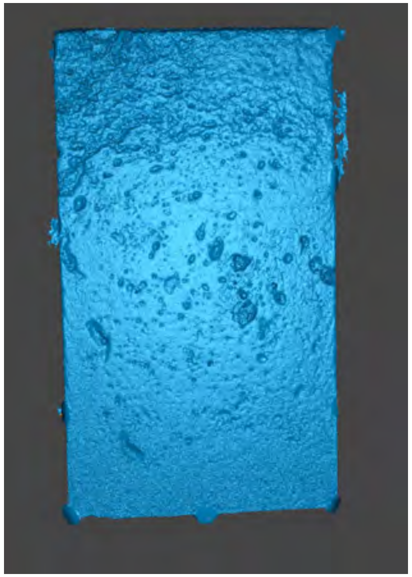


Technical Progress

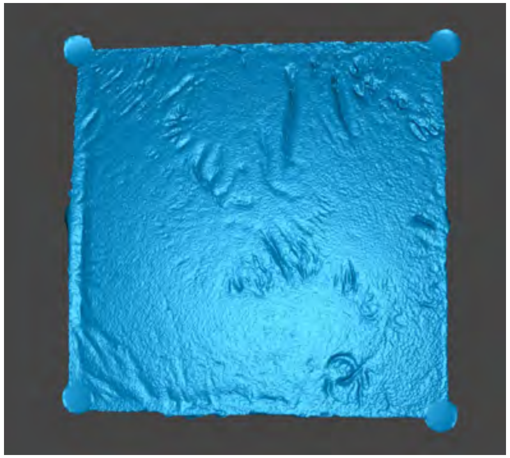
Analysis of Oxide Film Experiments - Comparison to CLA Oxide Inclusions

- Oxide inclusion surface from carbon low alloy casting compared to oxide film surface from high alloy casting
- First step in the analysis are creating 3D surface scans of casting surfaces, and models of casting surfaces
- 0.1 mm resolution used

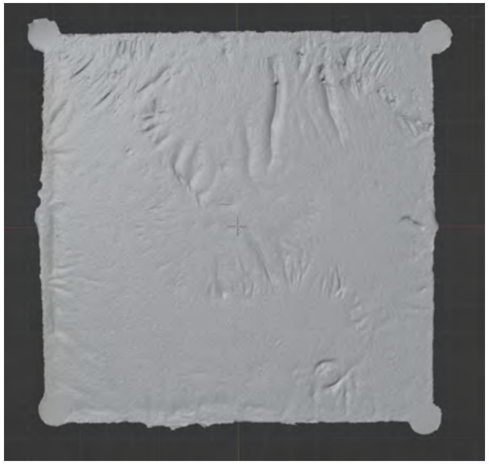
3D scanned cope surface model from a carbon low-alloy casting experiment



3D scanned cope surface point cloud of the oxide film casting experiment Case 1 B

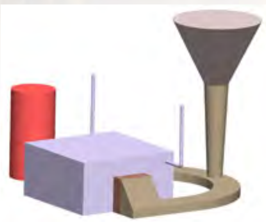


Surface model (.stl format) developed from the 3D point cloud



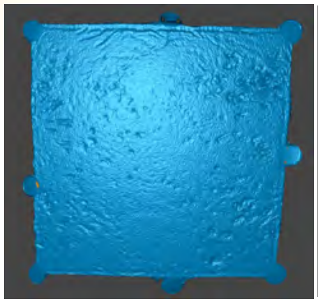
Technical Progress

Task 2 Analysis of Oxide Film Experiments – Surface Models

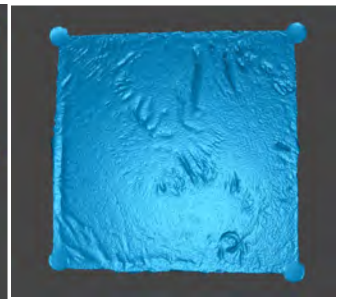


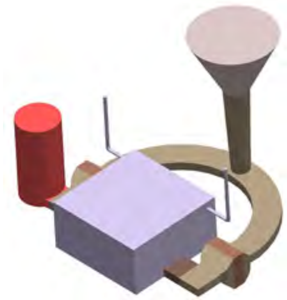
Case 1 = 52 pounds

Case 1 A No Filter



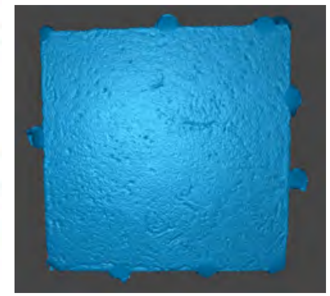
Case 1 B with Filter



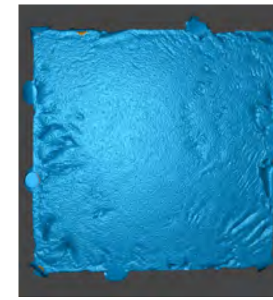


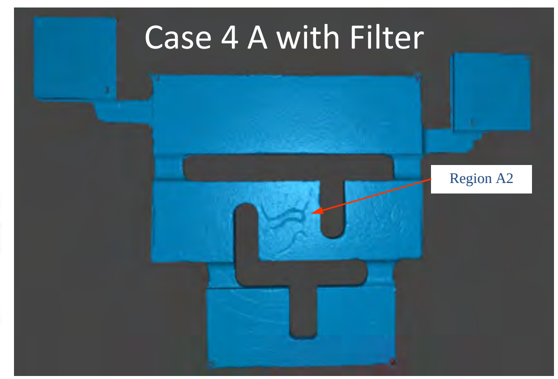
Case 2 = 54 pounds

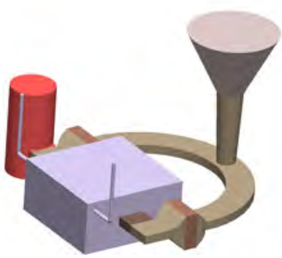
Case 2 A No Filter



Case 2 B No Filter

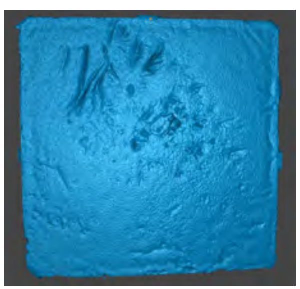




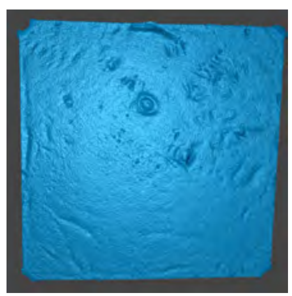


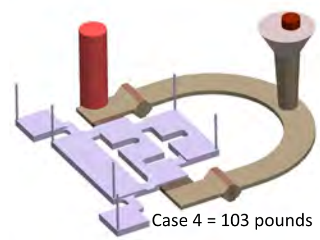
Case 3 = 52 pounds

Case 3 A No Filter

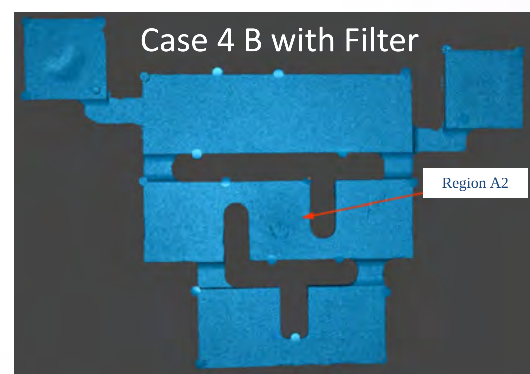


Case 3 B No Filter





Case 4 = 103 pounds



Technical Progress

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Task 2 Analysis of Oxide Film Experiments – Surface Measurements

- Analysis of surface oxide film folding
- Used software for the visualization and analysis of data from scanning probe microscopy and profilometry
- Surface model imported into software

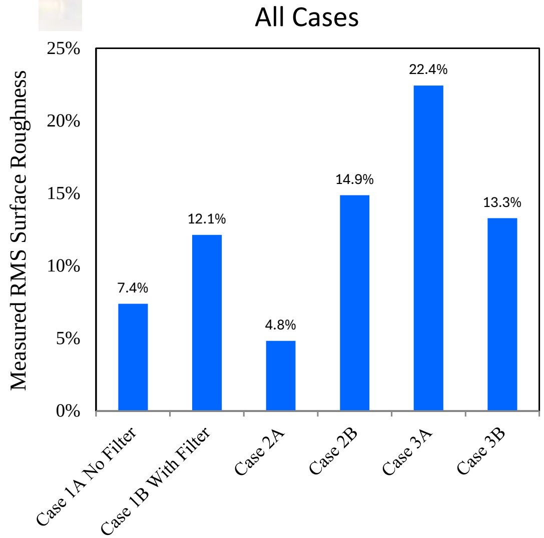
- Surface is not perfectly flat
- Film fold features lie on "background" surface
- Background surface subtracted from the data using a leveling algorithm

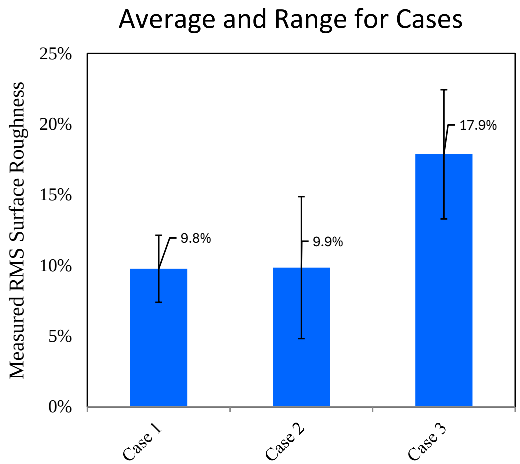
- Measurements are quantitative evaluations of the oxide film experiments
  - surface roughness measurements using **RMS roughness** analysis method
  - **fold feature surface area ratio:** projected area A_P (planform area) and surface area A_S (surface area features) analysis methods. The ratio is calculated from $(A_S - A_P)/A_P$.

Technical Progress

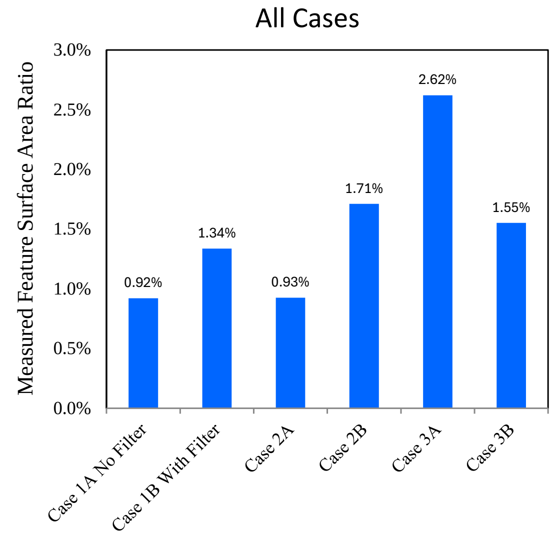
Task 2 Analysis of Oxide Film Experiments – Cases 1, 2 and 3 Surface Measurements

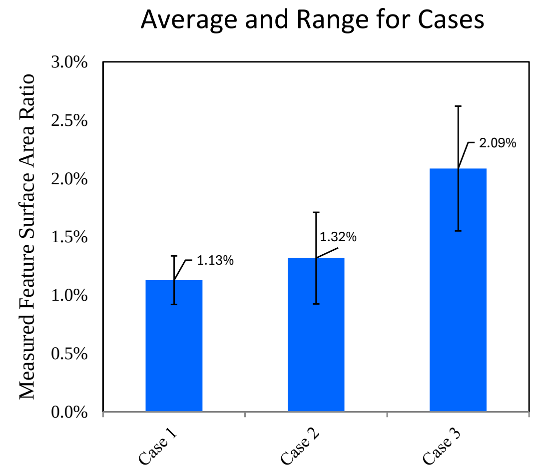
Surface Roughness Measurements





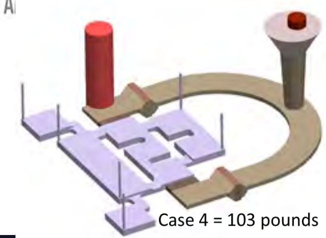
Feature Surface Area Ratio Measurements



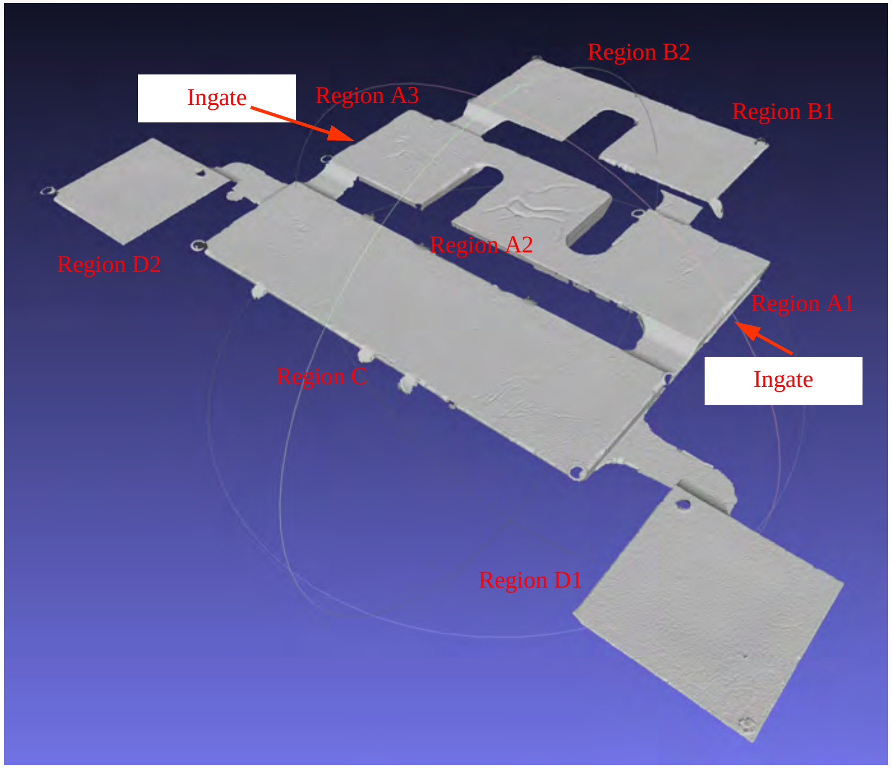


Technical Progress

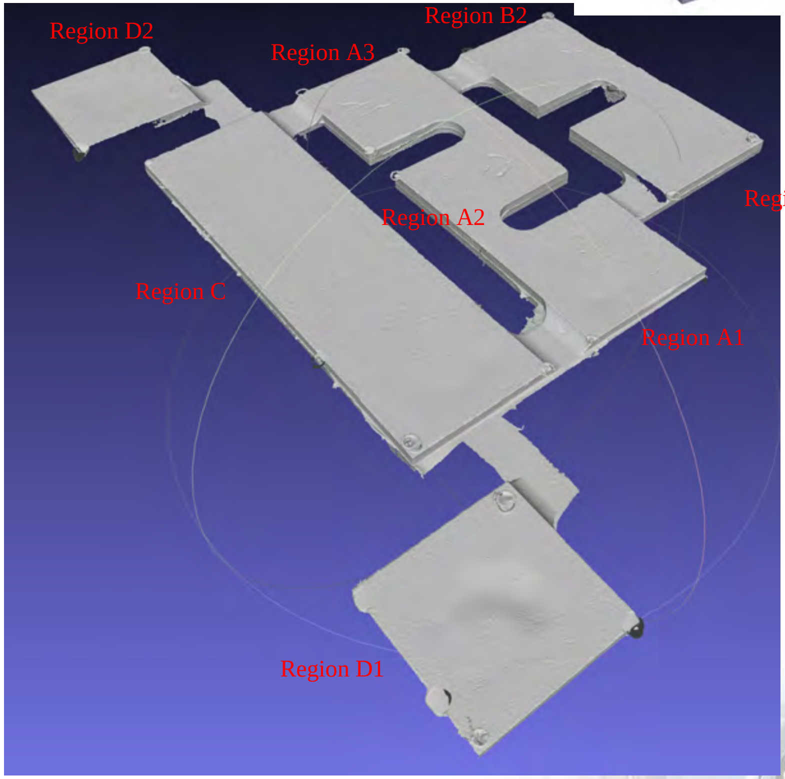
Task 2 Analysis of Oxide Film Experiments – Puzzle Casting Region Results



Case 4 A



Case 4 B

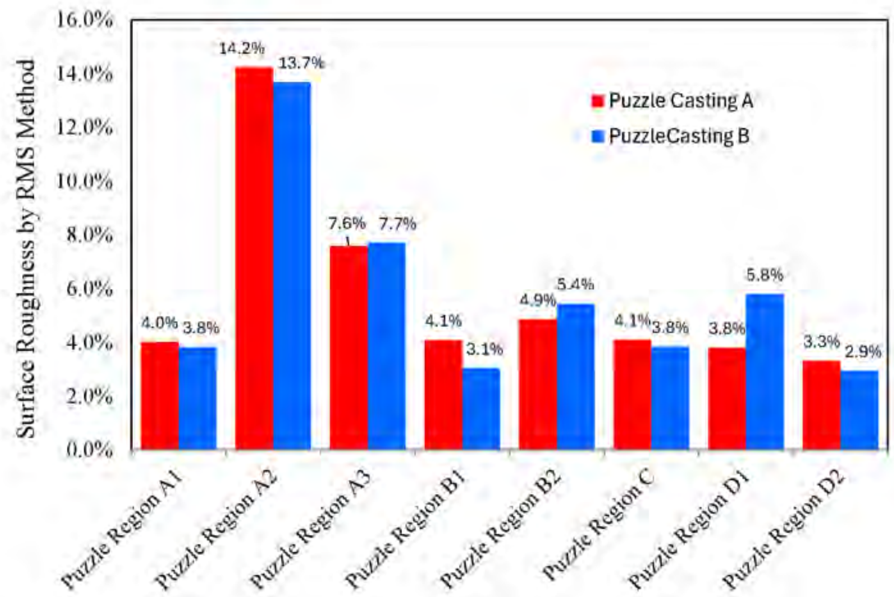


- Subdivide the puzzle casting into regions and analyze the regions

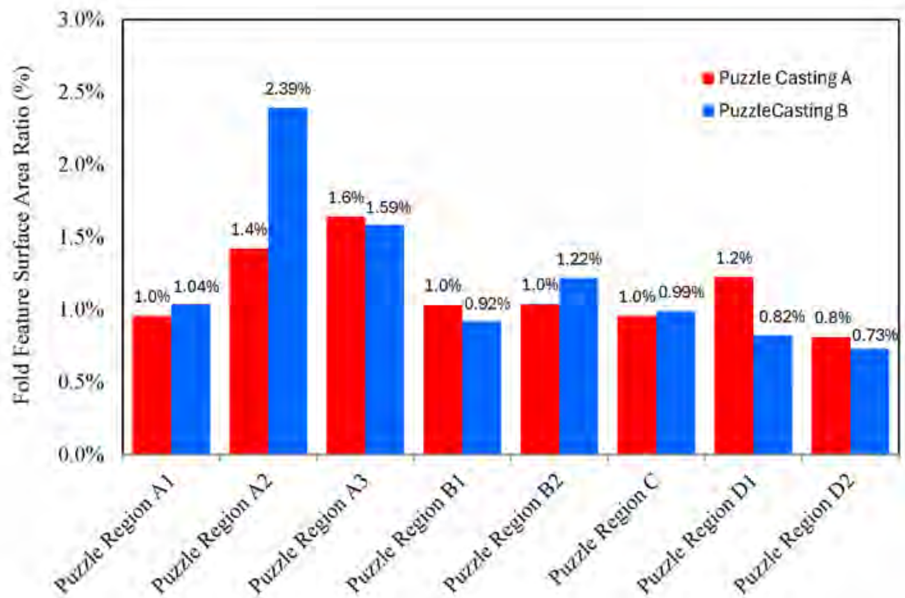
Technical Progress

Task 2 Analysis of Oxide Film Experiments – Puzzle Casting Region Results

Surface Roughness Measurements



Feature Surface Area Ratio Measurements



Technical Progress

Task 2 Modeling of Oxide Film Experiments - Results

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- Casting simulation results using ***MAGMAsoft*** and ***FLOW-3D CAST*** compared to the experiments.
- ***Flow3D-CAST*** result “free surface defect concentration.” *Free surface defect concentration FSDC model*: concentration of oxides *FSDC*, having units kg/m^3, accumulated in a cell calculated by

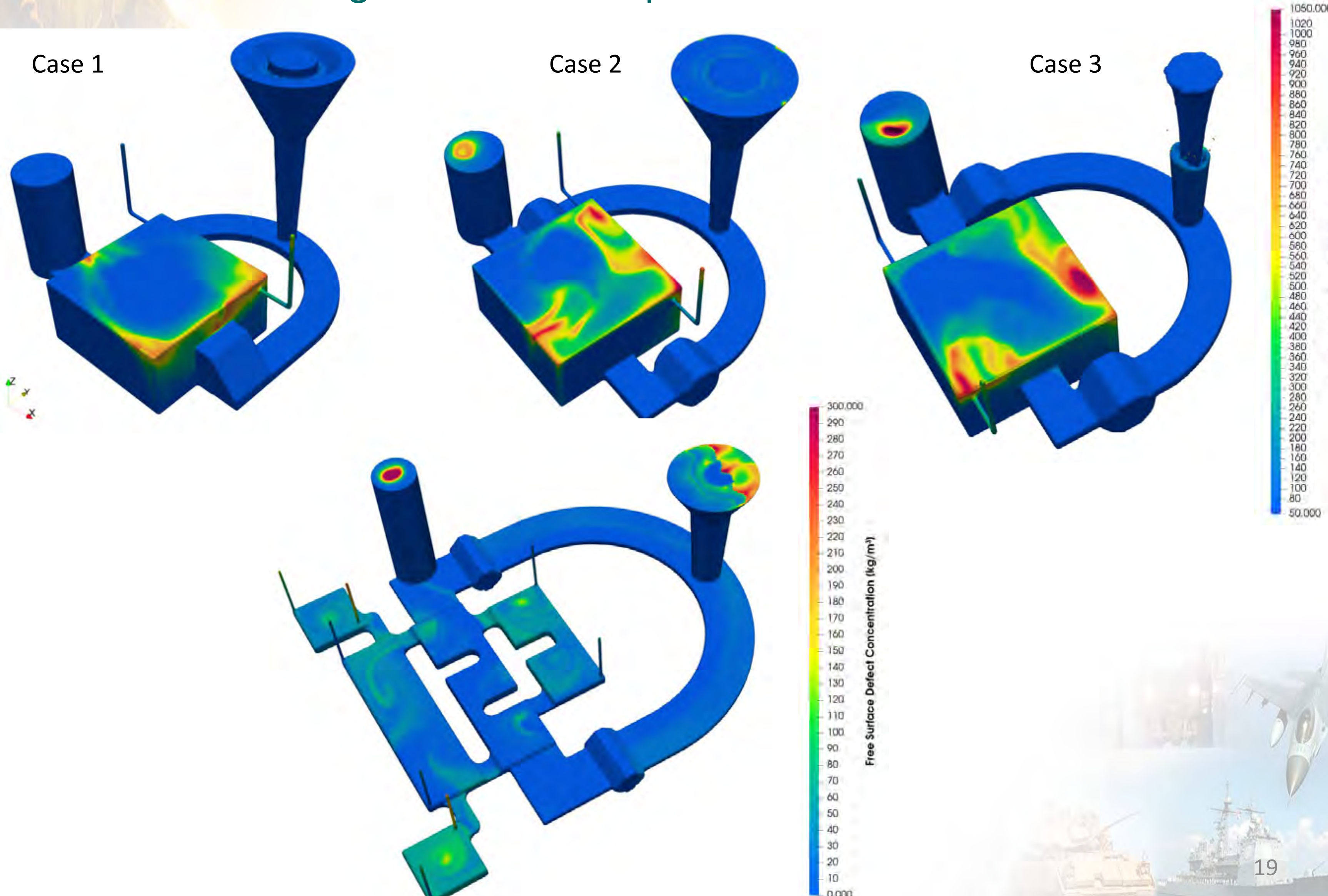
$$FSDC = CO\,A_{FS}\,t$$

where A_{FS} is the metal surface area in contact with the atmosphere, t is the exposure time, C_O is a calibration coefficient accounting for the chemical composition of the alloy and the specific weight of the oxide.

- ***MAGMAsoft*** has *oxide area fraction result* is determined on the casting surface from the total cross-sectional area of oxides in a model cell divided by the casting cell surface area.
- Goals: improve prediction methods and develop new methods for oxide film defect predictions. Determine model parameters giving best correspondence between simulation and experiments

Technical Progress

Task 2 Modeling of Oxide Film Experiments – ***Flow-3D Cast* Results**

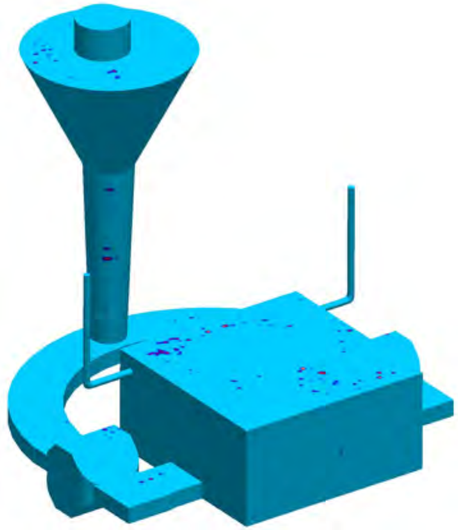


Technical Progress

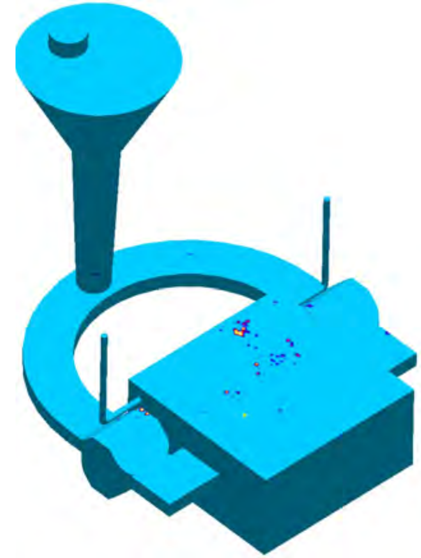
Task 2 Modeling of Oxide Film Experiments – ***MAGMAsoft* Results**

Case 1

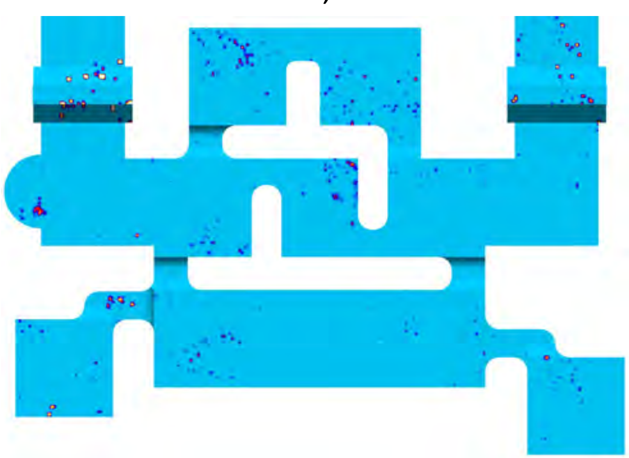
Case 2



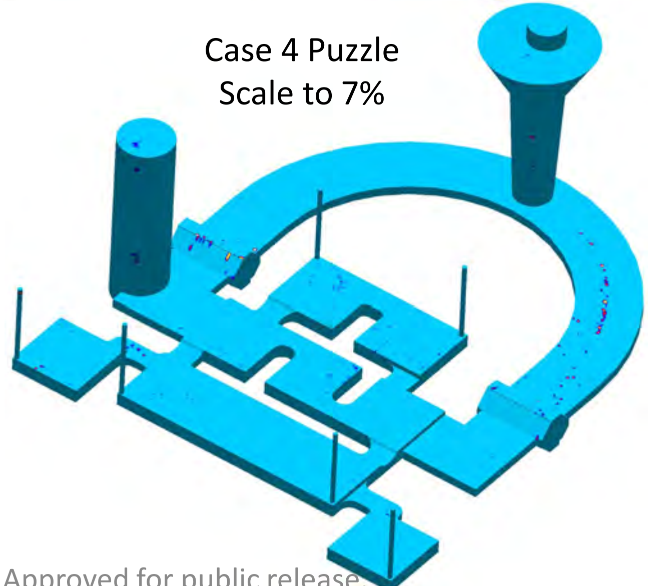
Case 3



Case 4 Puzzle, Scale to 3.5%



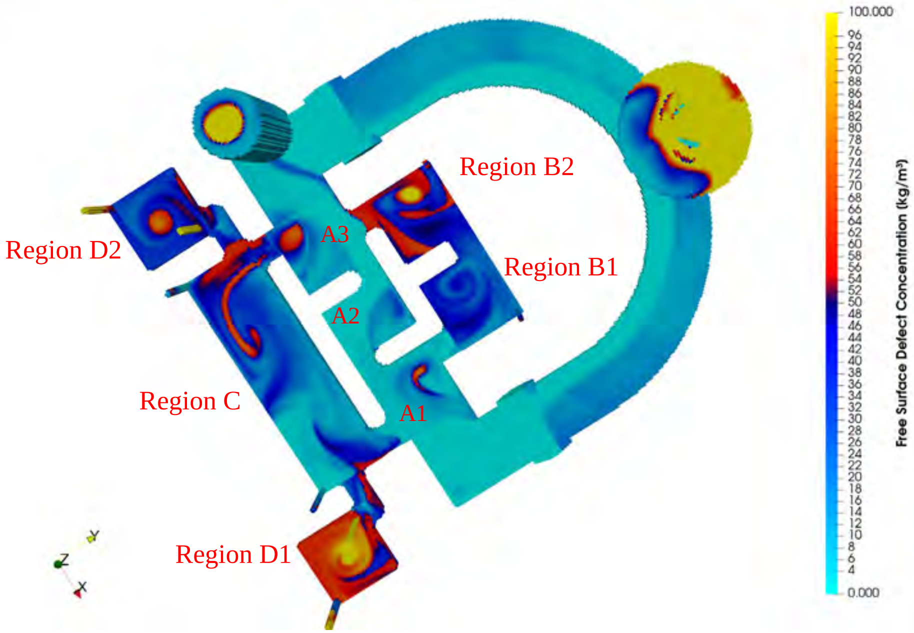
Case 4 Puzzle
Scale to 7%



Task 2 Modeling of Experiments – **Initial Qualitative *Flow-3D Cast* Results**

Case 4 Puzzle Casting

- Free surface defect concentration results from simulation of puzzle casting oxide film experiment. Simulation result for modeling oxide surface defects from *Flow3D*.



- Results 3D scan measurements for the puzzle casting experiments compared to simulations. Film fold **severity level ranked into three groups by: most, medium and least surface defects.**

	Measurement Analysis Results			
Film Fold Level	Roughness	Maximum Depth	Surface Area Ratio	Simulation Result
Most Indications	A2, A3, B2	A2,A3	A2,A3	B2,D1
Medium indications	C,A1	A1,B2,C	A1,B1,B2,C	A3,C,D2
Least Indications	B1,D1,D2	B1,D1,D2	D1,D2	A1,A2,B1

- *Flow3D* model results need improvement

Technical Progress

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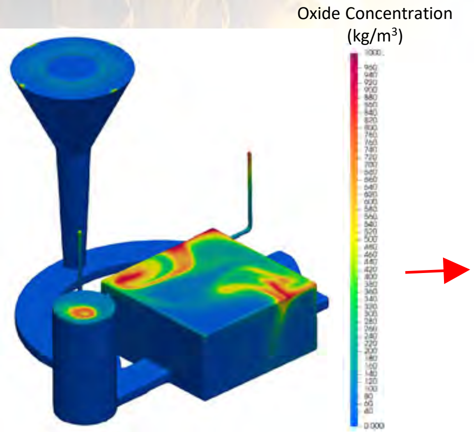
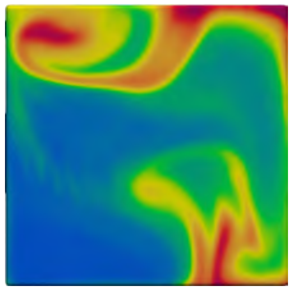
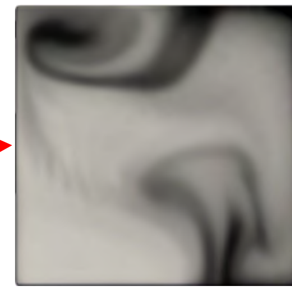
Task 2 Modeling of Oxide Film Experiments – ***Flow-3D CAST*** **Case 1, 2, 3 Results**



Flow-3D CAST Postprocessing Steps

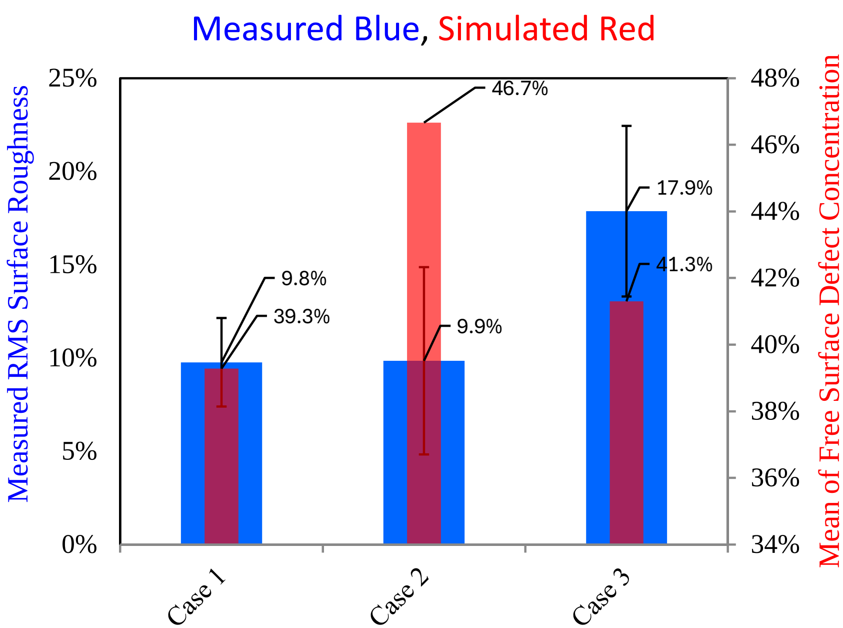


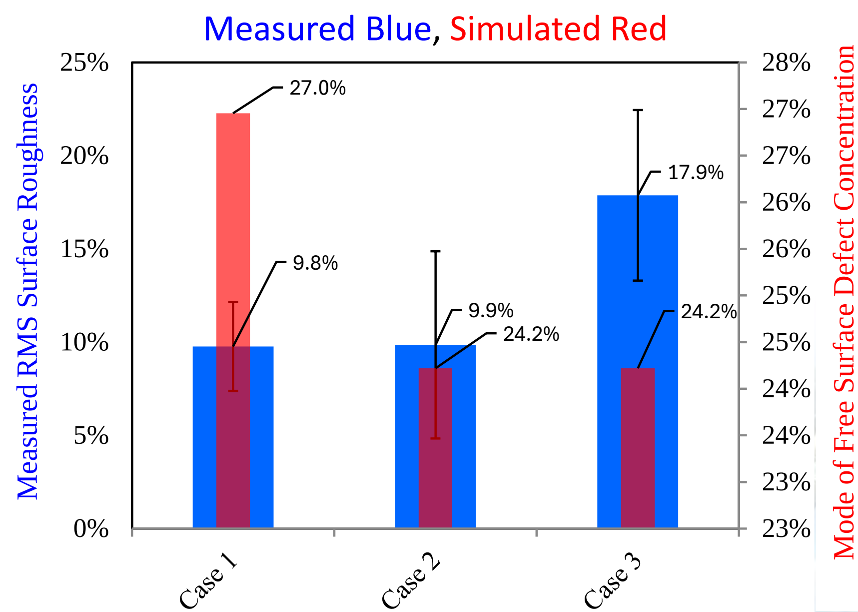


- **Concentration calculated based on percent of 8-bit level, mean and mode**

Image Analysis Results

Area	Mean	StdDev	Mode	Min	Max
1742399	134.6422	46.6452	194	0	255

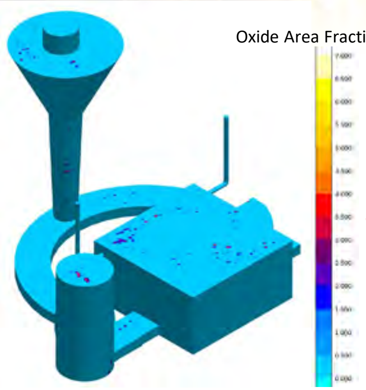




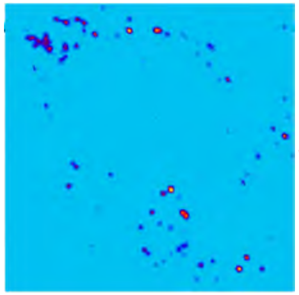
Technical Progress

Task 2 Modeling of Oxide Film Experiments – ***MAGMAsoft* Case 1, 2, 3 Results**

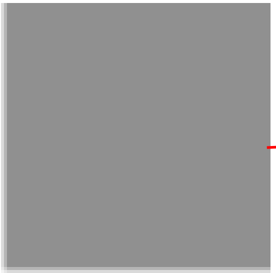
MAGMAsoft Postprocessing Steps



Color Map



Gray Scale Map



Threshold Binary

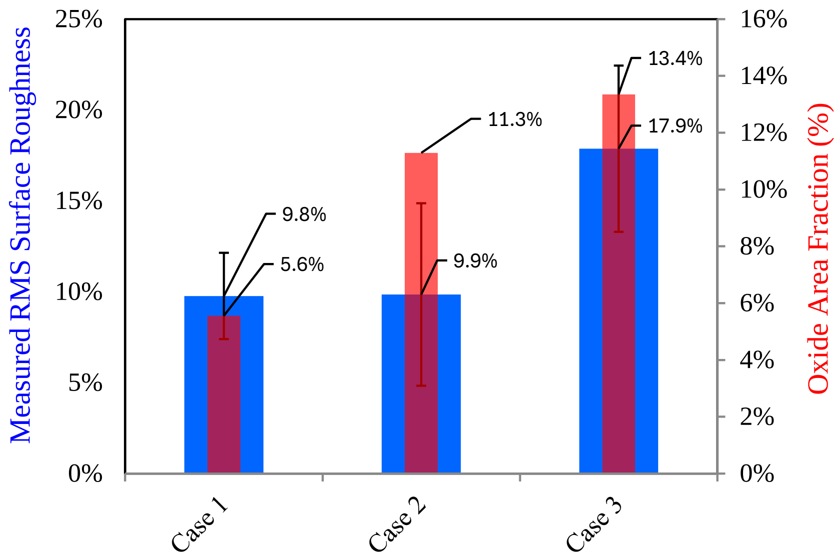
Simulation Oxide Area

Count	Total Area	Average Size	%Area
44	29185	663.2955	1.2758

- **Area percentage of oxides calculated**

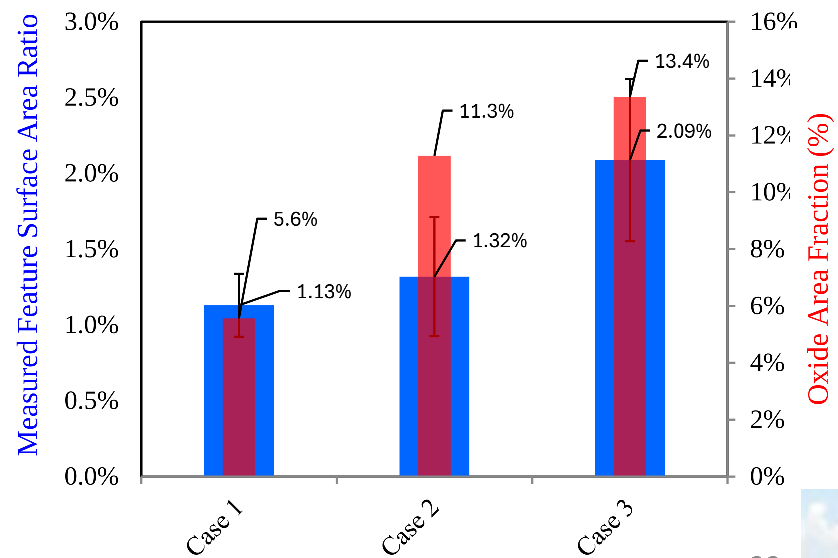
Advanced Model In *MAGMAsoft*

Measured Blue, Simulated Red



Advanced Model In *MAGMAsoft*

Measured Blue, Simulated Red

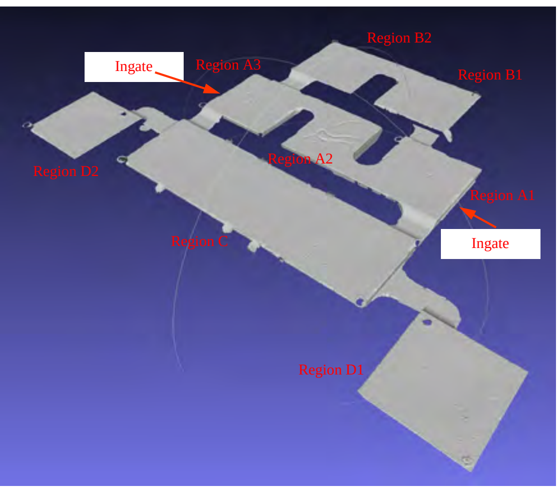


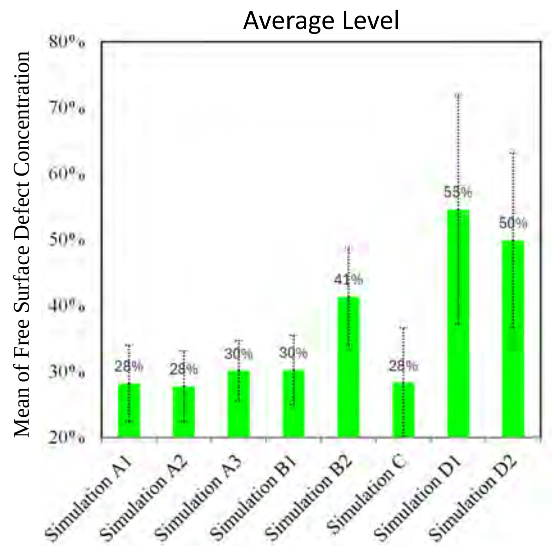
Technical Progress

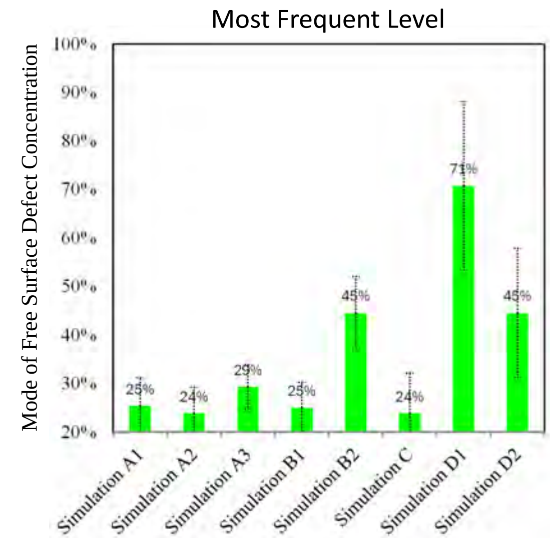
Task 2 Modeling Experiments – **Puzzle Casting Simulations**

***Flow-3D CAST* Results** →

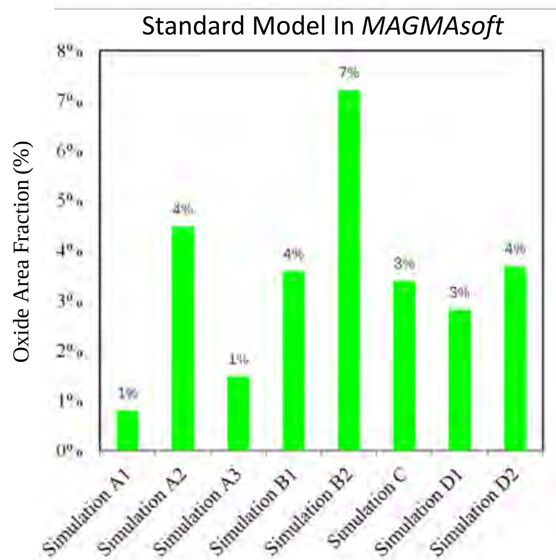
Puzzle Casting Regions

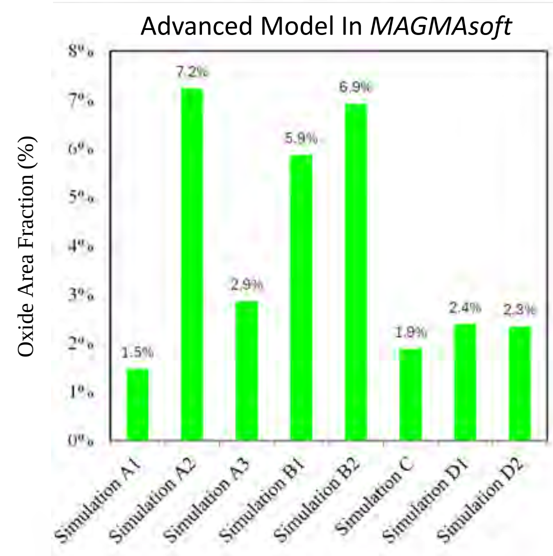






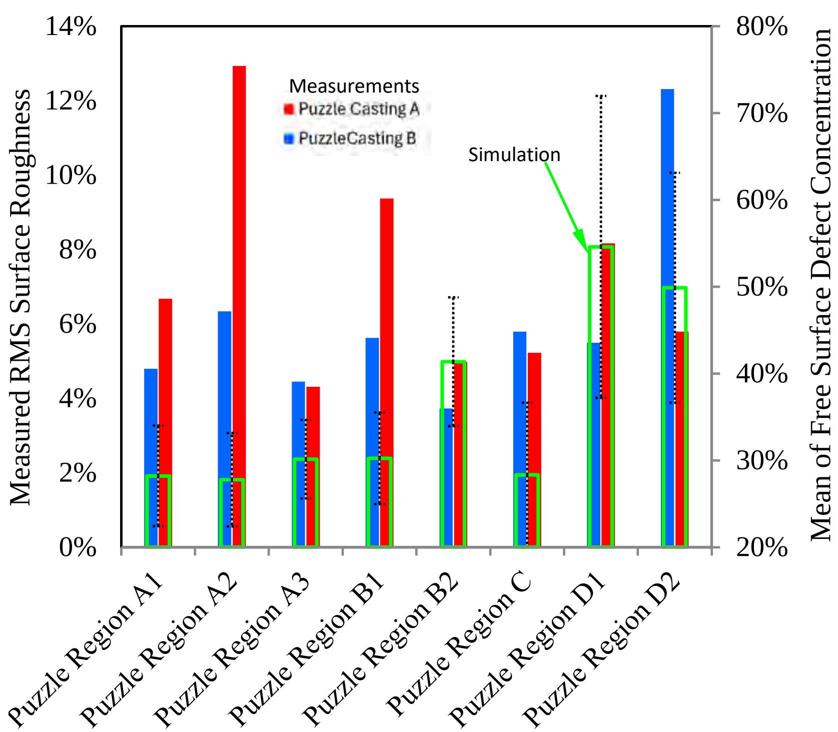
***MAGMAsoft* Results** →

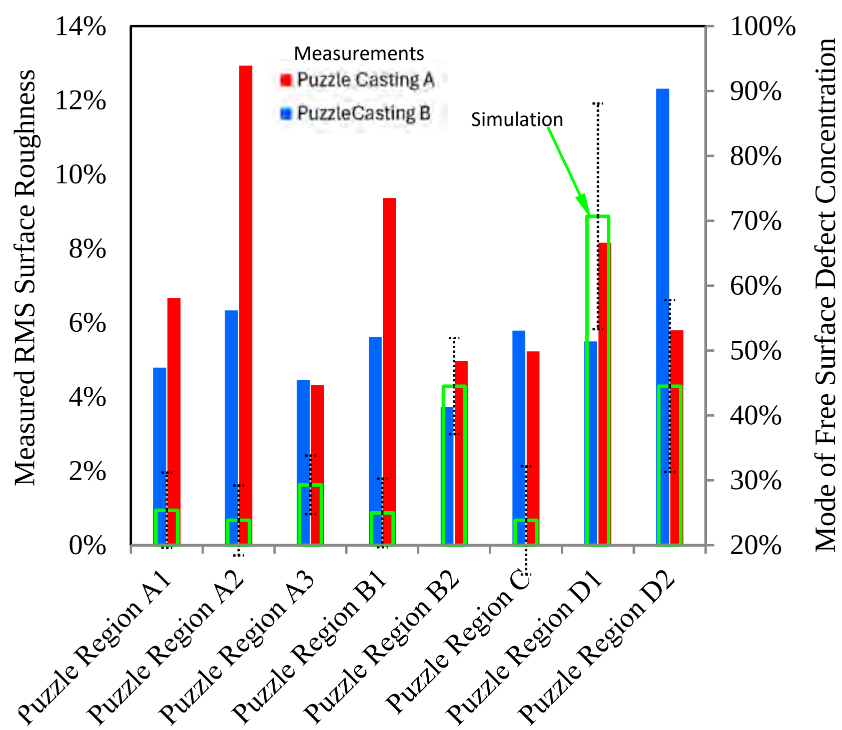




Technical Progress

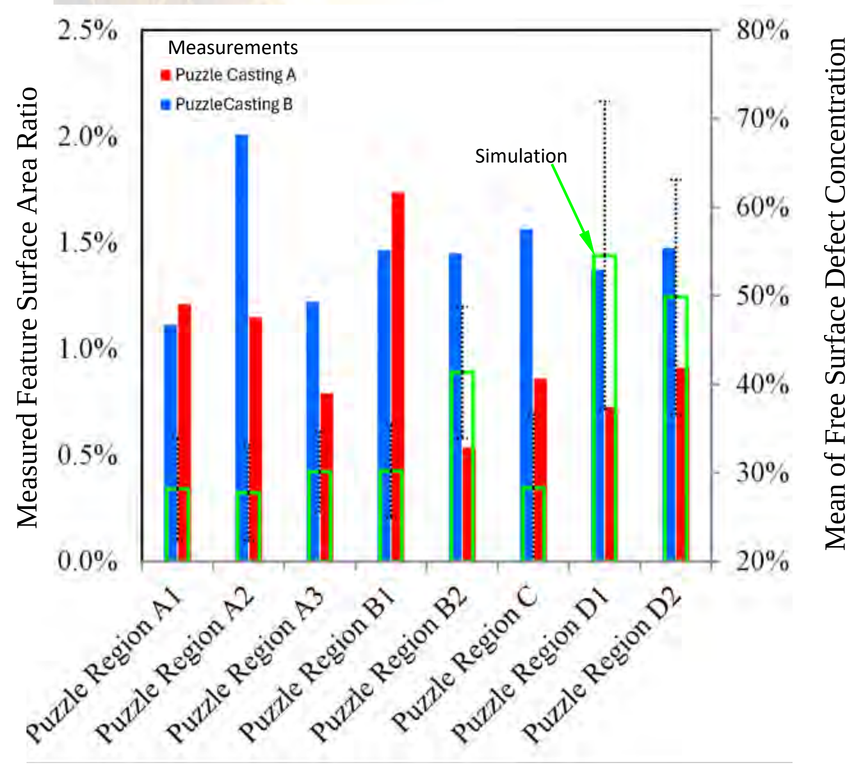
Task 2 Modeling Experiments – **Puzzle RMS Measurements and *Flow-3D Cast* Results**

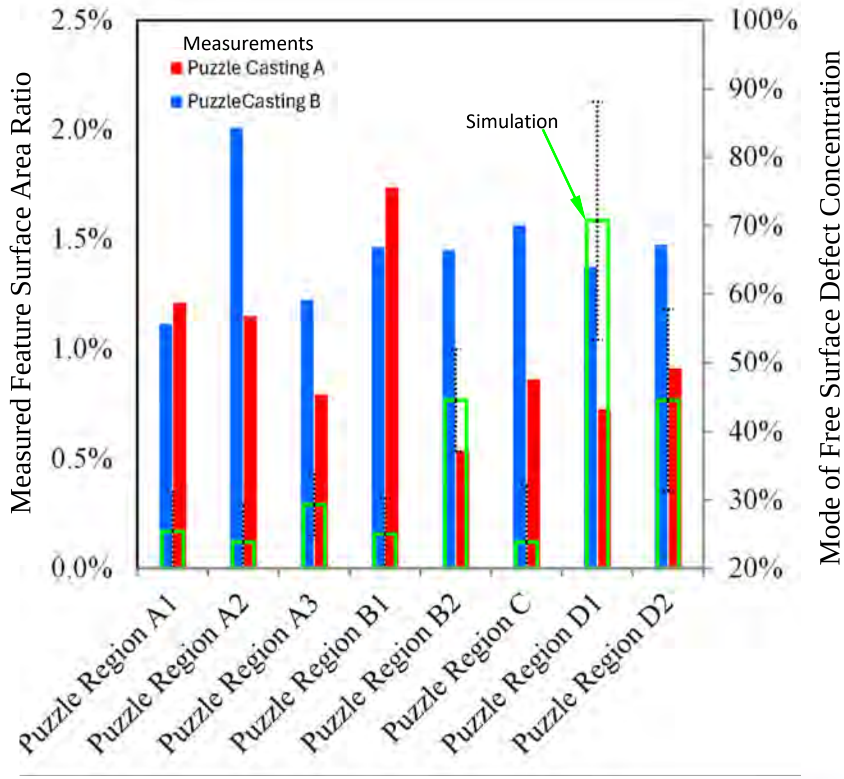




Technical Progress

Task 2 Modeling of Experiments – **Puzzle Area Ratio Measurements & *Flow-3D Cast***

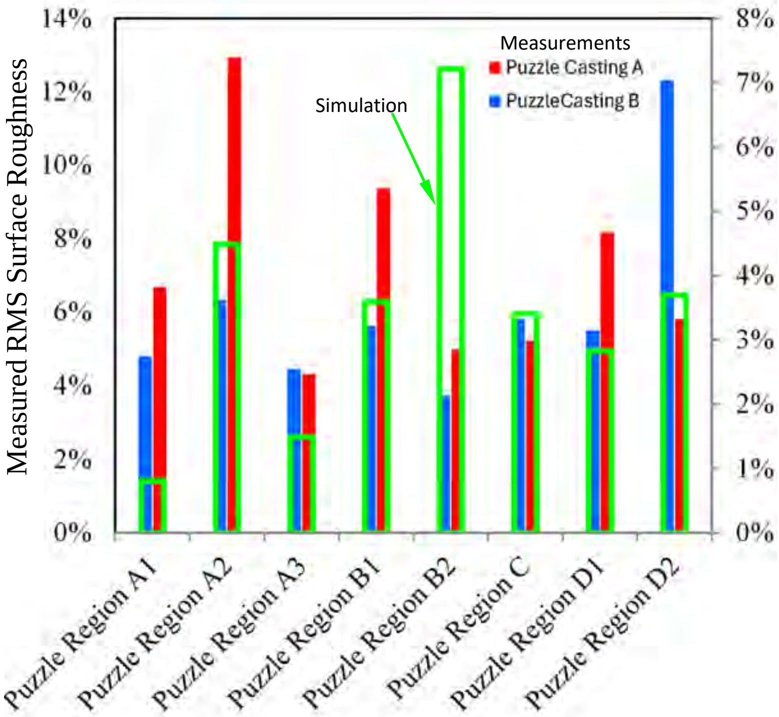




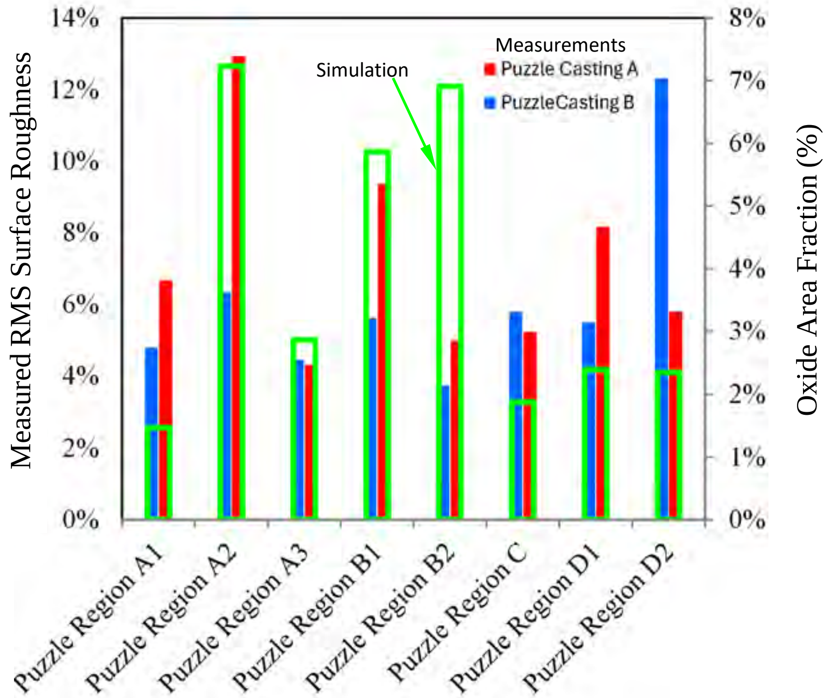
Technical Progress

Task 2 Modeling Experiments – **Puzzle RMS Measurements and *MAGMAsoft* Results**

Standard Model In *MAGMAsoft*



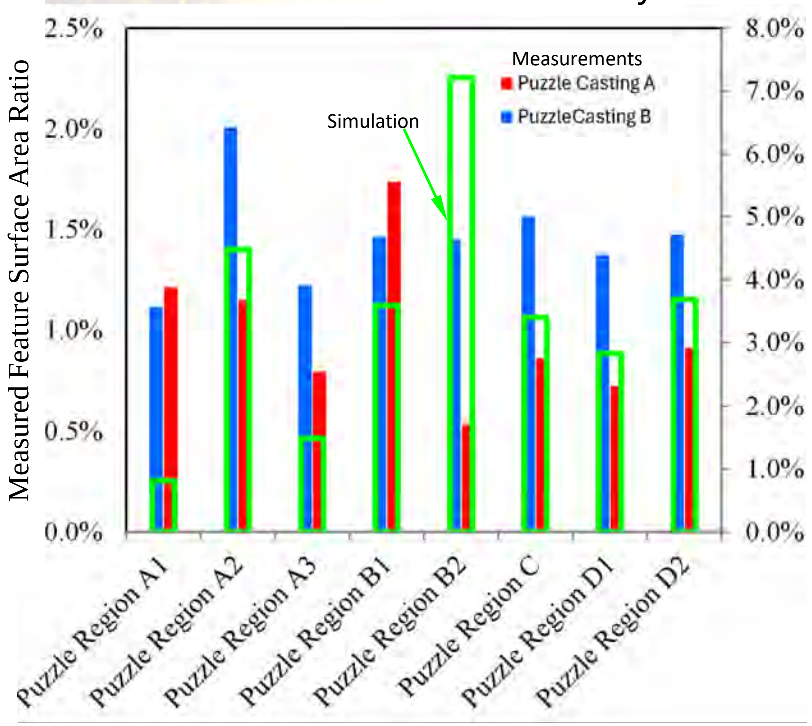
Advanced Model In *MAGMAsoft*



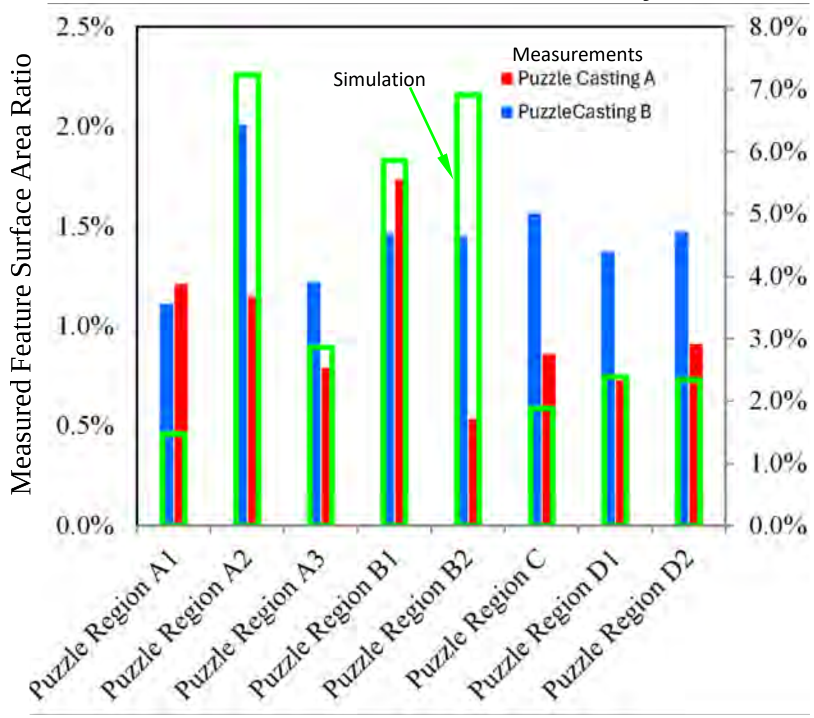
Technical Progress

Task 2 Modeling of Experiments – **Puzzle Area Ratio Measurements & *MAGMAsoft***

Standard Model In *MAGMAsoft*



Advanced Model In *MAGMAsoft*



Technical Progress

Microscopy of Oxide Film Experiment Surface

SEM/EDS Inspection of CY40 (IN600) Puzzle Casting Polished Section

Technical Progress

Microscopy of Oxide Films

Example of Oxides Near Cope Surface (Location 1)

SEM Image

Top Surface

Technical Progress

Microscopy of Oxide Films

Oxides Near Cope Surface (Location 1)

Technical Progress

Microscopy and EDS of Oxide Films

Oxides Near Cope Surface (Location 1a)

SEM Image

1300x

- Oxide has higher levels of Cr and Si, lower Mn level. Cr and Si vary inversely across zones.
- Roach and Hall (1973) reported oxide films with chromium–manganese oxides and SiO_2.
- Mg in EDS data about 3 wt%, no Mg in poured chemistry.

Technical Progress

Task 5 Case Studies Starting Earlier than Planned

- The SFSA identified a case study casting made from IN100 Ni-based alloy from one of their members. Work was performed on this case study ahead of planned project schedule.

- The SFSA member found oxide film defects using the “before” production gating system, which have not been found in a “modified” gating and rigging system. Both were simulated using *FLOW-3D CAST* and *MAGMAsoft.*

Comments on This Result[1]

- The free surface defect concentration is a scalar quantity accumulating at free surfaces at a constant rate.

- This result is interpreted as proportional to the mass of oxide per unit volume.

- No buoyancy, oxide film strength effects or phenomena as oxide film sticking to mold walls are included in the model .

- Distribution of the result indicates locations where oxides are likely to be. Majority of scalar tracked oxides are found at the last place to fill, as would be expected. Oxides accumulate at the metal front and are pushed along until there is no where else for them to go.

1. M. R. Barkhudarov and C. W. Hirt, “Tracking defects,” First International Aluminum Casting Technology Symposium, 1998.

Oxide Film Case Study: Defect Concentration Results from *Flow3D Cast* Software

Technical Progress

Task 5 Case Studies Starting Earlier than Planned

- SFSA member case study of IN100 Ni-based alloy casting.
- Oxide film defects were a problem in the “before” production gating system.

Comments on This Result

- Oxide area fraction result is determined on the casting surface from the total cross-sectional area of the inclusions in a model cell divided by the casting surface area.
- Parameter settings of the oxide generation models and thresholding will be studied and applied to the oxide area fraction result to model the observed films on casting surfaces.
- Oxide generation model used is the advanced air entrainment inclusion model developed as part of an earlier AMC project.

- Case study simulation results to guide, improve and demonstrate modeling capabilities.

Oxide Film Case Study: Defect Concentration Results from *MAGMAsoft* Software

Technical Progress

Ongoing Work Tasks 3 and 4 Modeling and Experiments to Calibrate Models

Technical Progress

Ongoing Work Tasks 3 and 4 Modeling and Experiments to Calibrate Models

- *Flow3D CAST* surface area defect concentration simulation results at six 0.3 s time intervals until the casting is filled at 1.8 seconds, using default oxide defect prediction settings.
-

Development of Experiments: Simulations of Puzzle Casting

Technical Progress

Ongoing Work Tasks 3 and 4 Modeling and Experiments to Calibrate Models

- *Flow3D CAST* surface area defect concentration simulation results using default settings.

Technical Progress

Ongoing Work: Simulations of Oxide Film Experiments

- *Flow3D CAST* free surface oxide concentration and *MAGMAsoft* oxide area fraction results.

Technical Progress

Ongoing Work: Oxide Film Experiments

- Inclusion area fraction results from *MAGMAsoft* software on the cope surface of the angled surface casting experiment.

Project Plans

AMERICAN METALCASTING CONSORTIUM

- Next 12 months
  - Modeling oxide defects using *FLOW-3D CAST* and *MAGMAsoft*.
  - Simulation results will be compared to experimental results, improve oxide film models.
  - Oxide film experimental configurations developed and simulated, compare with experiments.
  - Inspect the experiment castings for oxide films using microscopy, 3D scanning for folds and other means.
- Longer term
  - Implement oxide film model in casting simulation software – Finish 06/30/28
  - Complete casting experiments to test and calibrate model – Finish 12/31/27
  - Complete case studies for production high alloy steel castings – Finish 12/29/28

Transition Plan

AMERICAN METALCASTING CONSORTIUM

- Model for oxide film formation and transport will be implemented in commercial casting simulation software for use by foundries, experiment results and algorithm developed published
  - Partnering with MAGMA, implemented in *MAGMAsoft*
  - Using Flow-3D Cast to develop user particles and customized results.
  - Publish algorithm/ methodology in the open literature, software vendors can implement
  - Model will be calibrated and validated by comparison with measurements.
- Perform case study to demonstrate technology with SFSA members and industry partners
  - Present research program results at SFSA meetings and research reviews.

Leveraging

- Air entrainment and oxide inclusion model developed in a preceding AMC project, models the metal free surface where oxide films form.
- 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
- Cost Share will be provided through software donation and development costs incurred by MAGMA a foundry technologies company.
- Project uses expertise, methods and experiments developed through Iowa Energy Center funded work

Project Metrics

AMC AMERICAN METALCASTING CONSORTIUM

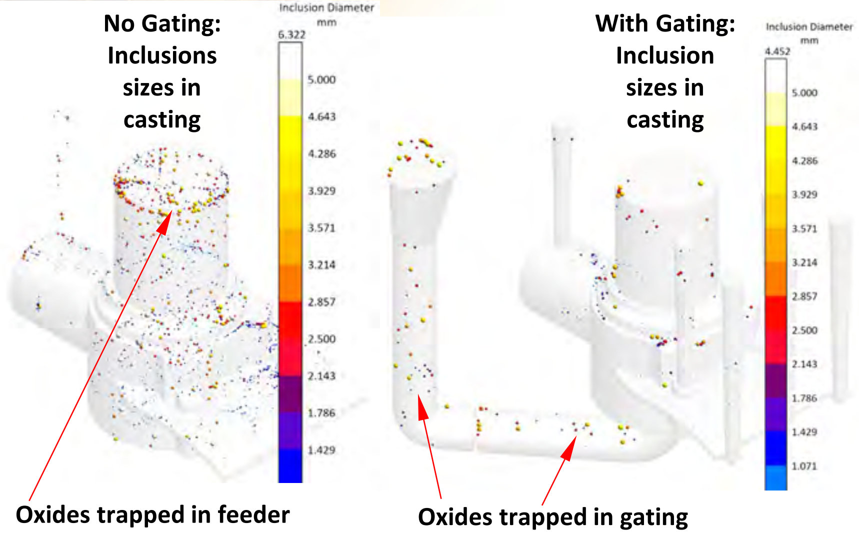
Description	Baseline	Threshold	Goal	How Measured	Target Date	Progress	How Demonstrated
Agreement Between Measured and Simulated Oxide Films in Casting Experiments	Agreement with Current Inclusion Modeling Simulation Results	40% Agreement in Amount of Oxide Films	80% Agreement in Amount of Oxide Film Defects	Quantitative Measurement of Oxide Film Amount on Casting Experiments	April 2026	100% Developed and applied oxide defect modeling methods to casting experiments.	Quantitative Comparison of Measured and Simulated Oxide Area
Agreement Between and Observed and Simulated Oxide Films Size and Area in Production Case Study Casting	Inclusion Simulation Results Using Current Modeling Capabilities	40% Improved Agreement in Comparison of Size and Area of Oxide Films	80% Improved Agreement in Comparison of Size and Area of Oxide Films	Casting Inspection, Markup, Image Analysis Compared to Simulation Results	June 2028	25%, First Case Study Showing Agreement with Process Changes	Quantitative Comparison of Oxide Area, Count and Diameter of Inclusions
Reduction in Oxide Films in High Alloy Casting Experiments and Case Study	Reduction in Surface Film Defects Using Current Modeling Capabilities	Reduce Oxide Film Defects by 40% Using New Model	Reduce Oxide Film Defects by 80% Using New Model	Casting Surfaces Will be Cleaned, Inspected and Marked-up And Analyzed Using Image Analysis	Nov 2028	10%, First Case Study Process Changes Result in Oxide Film Reduction	Degree of Reduction in Area, Count and Size Oxide Films on Casting Surface

Acknowledgements

This research is sponsored by the Defense Logistics Agency Information Operations, J68, Research & Development, Ft. Belvoir, VA and DLA Troop Support, Philadelphia, PA.

Modeling of Oxide Films in High Alloy Steel Castings

DLA - POC: DLAR.DPR@dla.mil



Use the gating system to filter and remove oxide films, distribute them to feeders and less harmful locations in the casting.

Problem

- Inclusions most often result from oxidation of steel during pouring. Leads to the need for rework or scrapping of the casting. Removal and repair of non-metallic inclusions in steel castings can account for up to 25% of the production costs.

Objectives

- Reduce costs associated with casting rework/repair by 50%, reduce costs of casting rejections by 50%, reduce leadtimes by 30%, and enhance service performance from improvements in ductility and fatigue life by 20%.

Benefits to Warfighter

- Use of this model and developed pouring and gating strategies will reduce scrap and production lead times while achieving higher quality high alloy steel castings for DoW/DLA.

Description of Project

Develop a simulation tool for predicting oxide films in high alloy steel castings and pouring and gating design strategies to filter and remove oxides from castings.

Team: Steel Founders' Society of America, University of Iowa, ATI

Milestones / Deliverables

- Conduct fundamental oxide film experiments
- Develop model for predicting oxide films
- Implement oxide film model in casting simulation software
- Conduct casting experiments to test and calibrate model
- Conduct case studies involving production high alloy steel castings