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Intensive Quenching to Produce High Performance Cast Parts

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Innovative Casting Technologies (ICT)

AMC Technology Review

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MISSOURI S&T University of Science & Technology

SFSA

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Overview

Duration

1	2	3	4	5

Needs and Benefits

- **Reduced operation and sustainment costs** of weapon systems through better reliability of replacement parts
- **Minimized casting weight** by improving steel performance
- **Enhanced design and manufacturing technology** to meet aggressive requirements for legacy and future combat systems

Progress

- Intensive spray quench system at Missouri S&T fully operational
- Demonstration of IQ technology for complex castings
- Improvement in mechanical properties reduced distortion
- Evaluation of cast surface

Transition to Industry

- *Develop Smart IQ Spray facility*
- *Industry standard for evaluating quench performance*

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Objectives

Problems

- *DLA needs cost-effective cast spare parts and rapid transition to supply chain*
- Traditional quenching technologies - produce non-uniform cooling and result in distortion, cracking, and tensile residual stress on the surface
- Complex castings and higher alloy steels are difficult to quench without cracking
- Oversized quench tanks are needed at high maintenance cost and extra expense
- Results in scrapping of otherwise good castings

Project Goals

Evaluate the use of IQ technology to increase performance and reliability

- Complex geometry cast parts
- Hard-to-quench steel chemistries prone to distortion and cracking
- Castings with different surface conditions: scale, surface roughness, and surface defects

Technology Development

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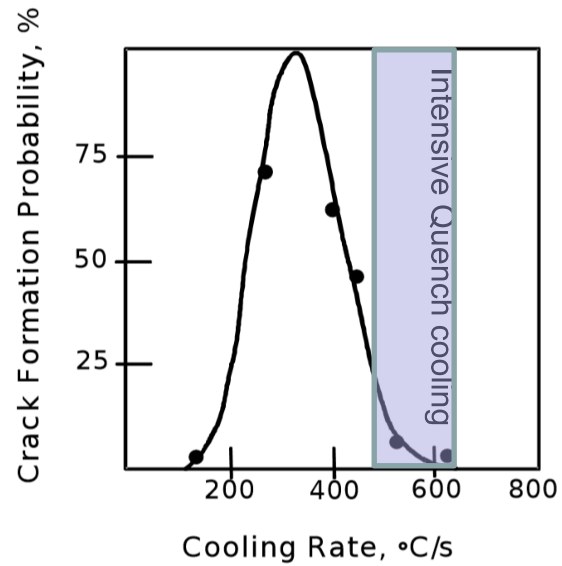
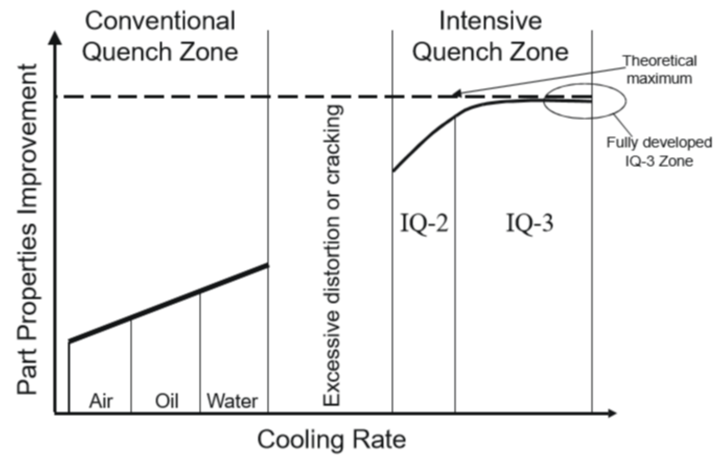
<u>Intensive Quenching Benefits</u>

- Uniform and immediate fast cooling of steel surface – compressive stress that resists quench and fatigue cracking
- Less distortion and resistance to quench cracking
- Reduction of quench tank size

<u>Application to Castings</u>:

- Goal: More dimensional stability, less cracking during quenching of castings
- Can it be used for complex geometry castings? – thick and thin section sizes
- What is the effect of surface roughness, scale formation, porosity, and inclusions on quench performance?
- Sensitivity of different chemistries





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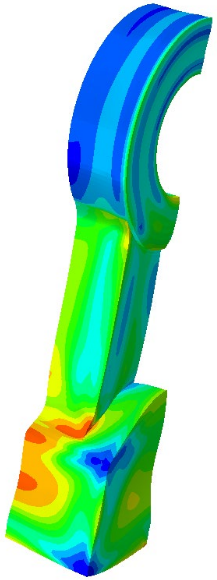
https://www.youtube.com/watch?v=KmrWN-o4QTw

https://www.researchgate.net/publication/278675658_Summary_of_Intensive_Quenching_Process_Theory_and_Applications

Needs and Benefits

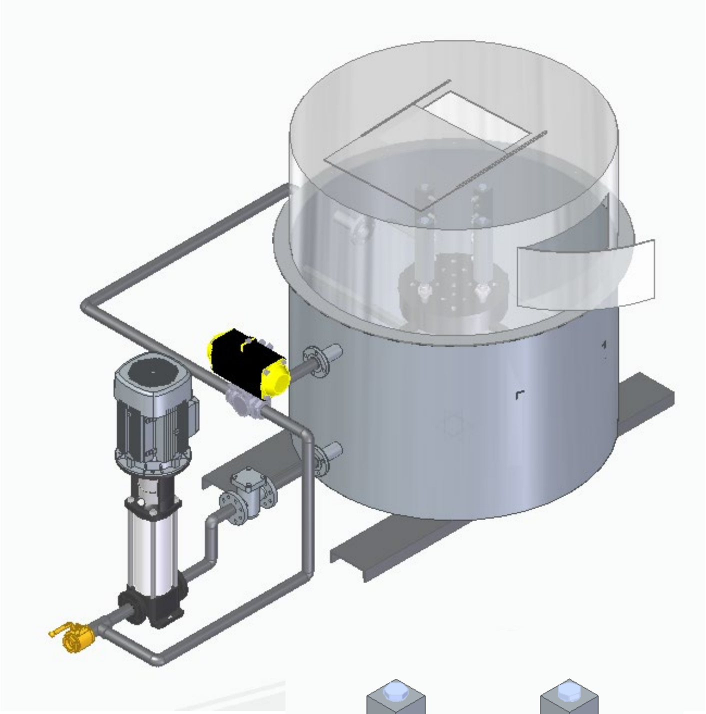
Benefits to the DLA/DoD:

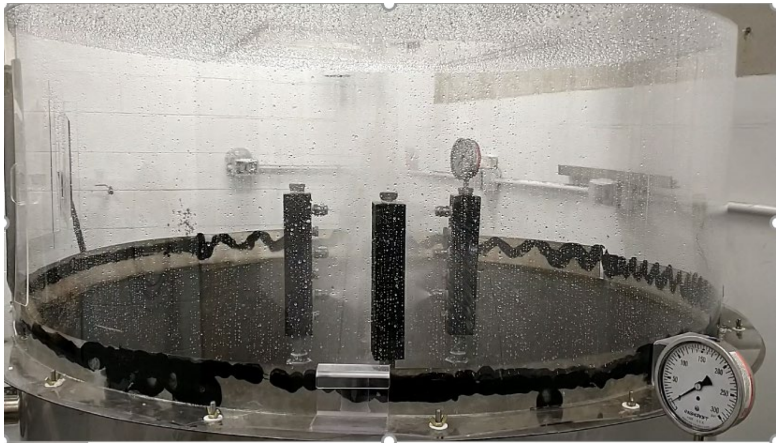
- **<u>Reduced operation and sustainment costs</u>** of weapon systems through better reliability of replacement parts
- Cost savings - reduction of quench tank size and operation costs
    - Improved casting quality / performance
    - Reduction in weight
    - Higher sustainability
    - Faster procurement
- Example part: hammer casting
    - Need high hardness and good toughness
    - Complex geometry
    - Difficult to water quench without cracking

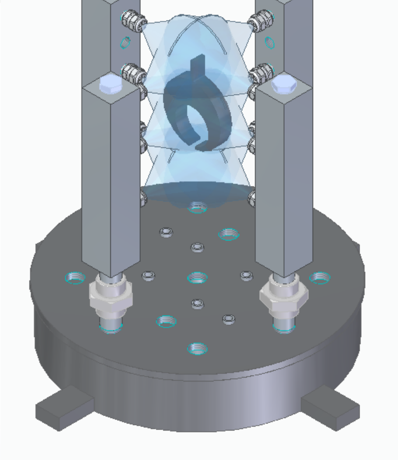


Spray Quench Tank Design

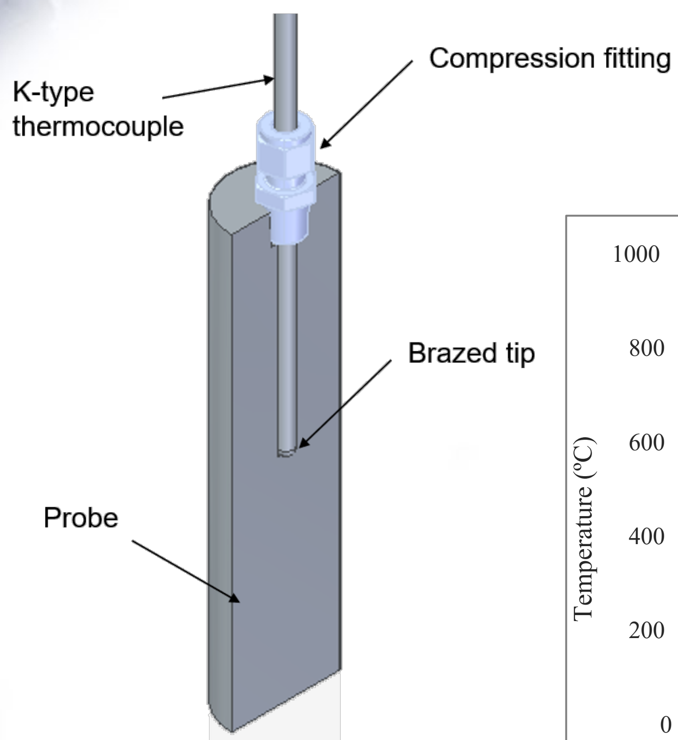
- Intensive spray quench at Missouri S&T
- Nozzles provide proper water jet impingement on the entire surface
- Articulated array of nozzles – quenching of different geometry castings
- 200 psi with 300gal/min multistage pump
- 500 gal tank capacity
- Comparison to immersion quench – different partner foundries and heat treaters



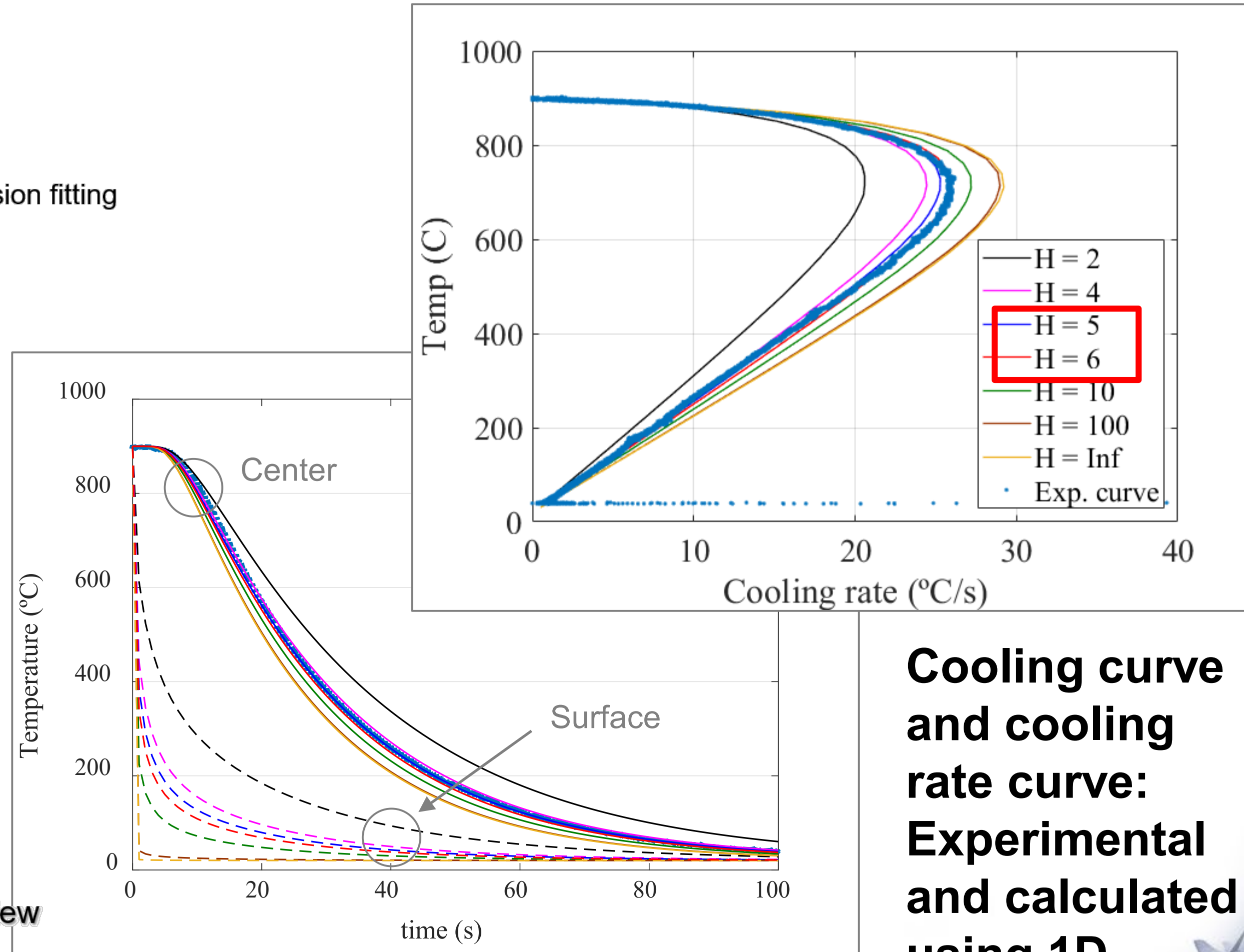




Determination of IQ Quench Severity



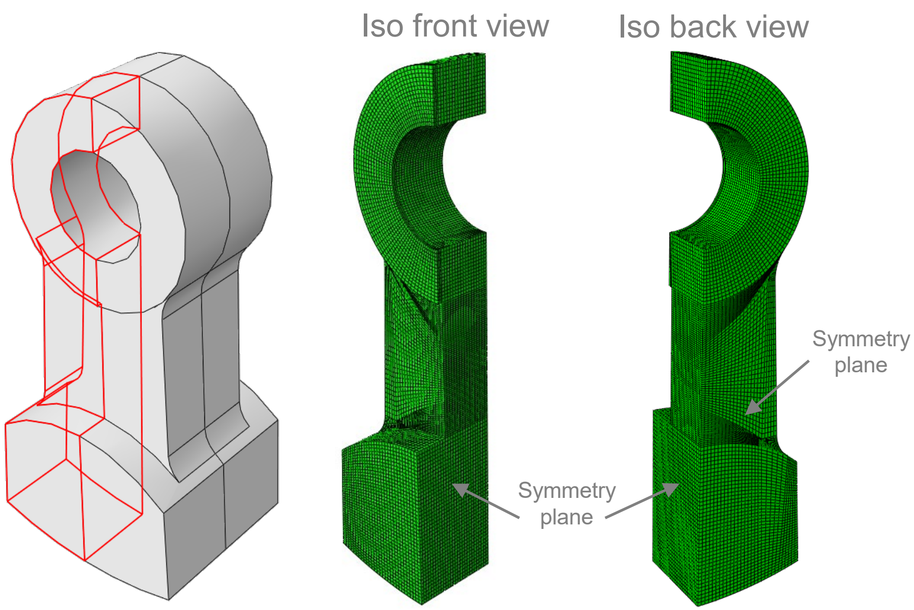
Schematic of temp. probe in sectional view



Cooling curve and cooling rate curve: Experimental and calculated using 1D model

Industrial Casting IQ Trials – Hammer Casting

- Finite Element model: Abaqus-Dante
  - One quarter of the geometry was modeled
  - Material similar to 4340
- Heating
  - From 20ºC to 1000ºC
  - 3600s
- Air-transfer
  - 150s
- Hard quench *or*
  - 600s
  - Water temp. 20ºC
- Interrupted quench
  - 30 sec
  - air cool
  - Water temp. 20°C



FE model of the Hammer: Only a quarter of the pieced was modeled

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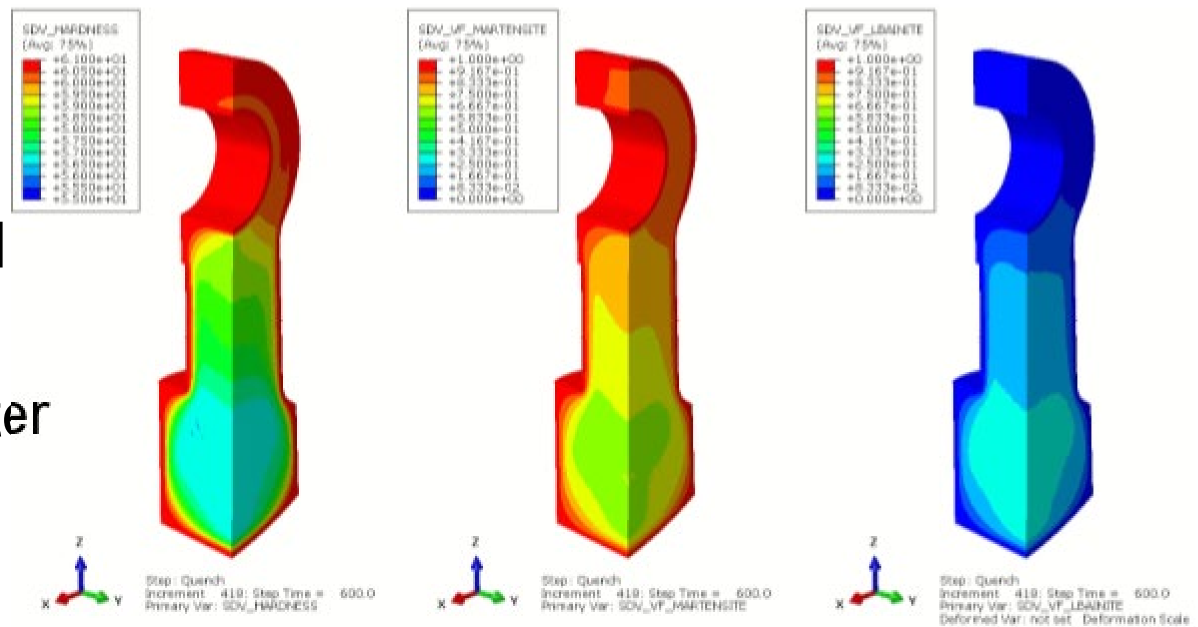
FE model: Hard Intensive Quench Hardness and Microstructure Results

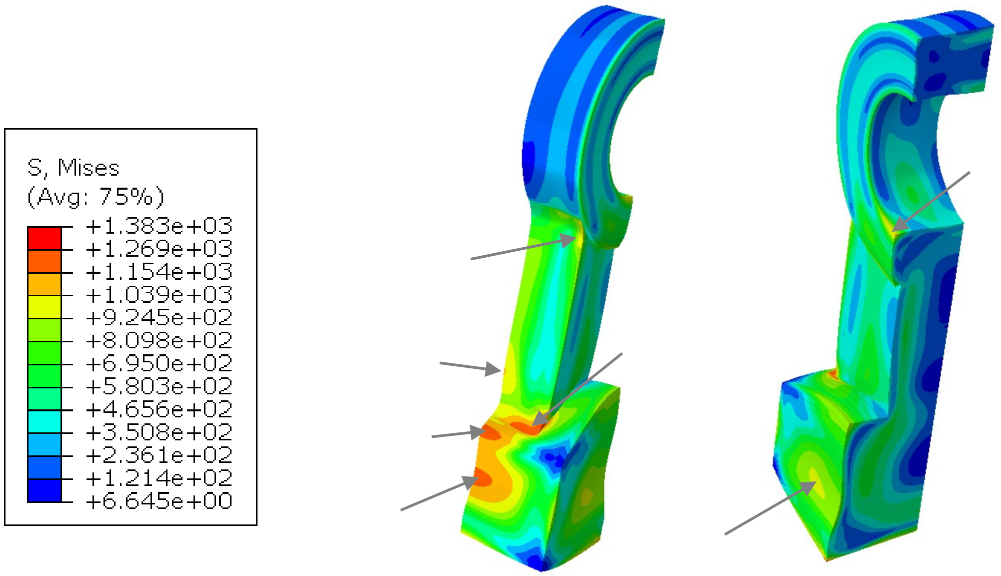
- Hardness
  - 61-57 HRC
- Martensite
  - 100% around surface
  - ~60% at center of the core
- Lower Bainite
  - ~35% at the center of the core



Hardness   Martensite   Lower Bainite

FE model: Hard Intensive Quench Hardness Residual Stress Results

- Residual stress after quenching
  - Max. ~1390MPa (red areas)
  - ~1000 MPa (yellow areas



Results of residual stresses after quenching: von Mises stresses are shown. Arrows are pointing regions of high tensile residual stress (>1000MPa)

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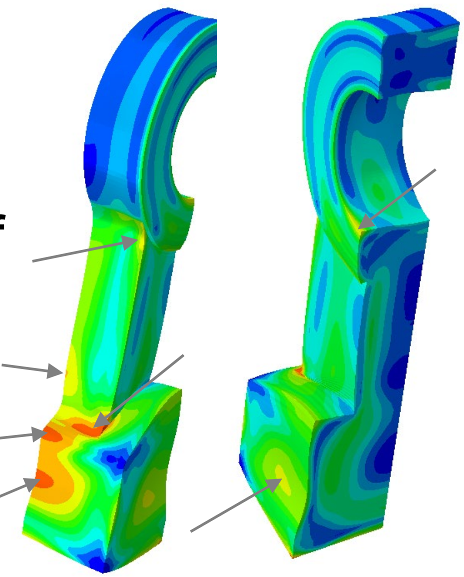
Comparison of FE Quench Simulation to Quenched part

- **High values of tensile stress in FE simulation show agreement with quench crack locations**



Interrupted Intensive Quenching

- Hammer casting austenitized at 1000ºC for 2hrs in protective stainless steel foil.
- Removed from furnace and foil removed – back in furnace for 10min
- Quench in IQ tank – Interrupted quench – 20ºC water max water pressure (180psi) for 30 sec – air cool
- Then tempered at 235C for 7hrs
- Air cool
- Inspect for cracks
- Section for hardness and microstructure
- Compare to Dante modeling

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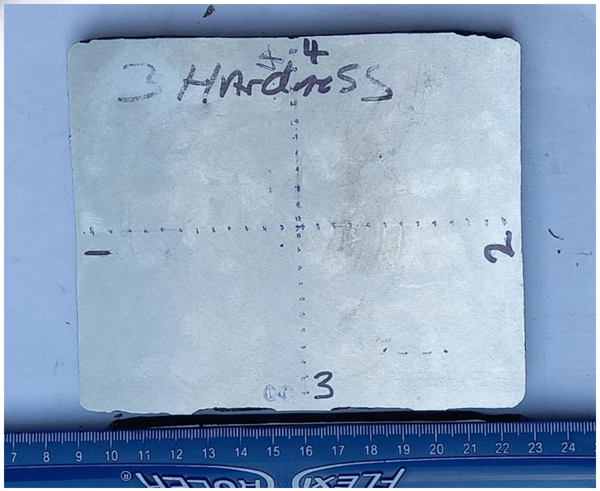
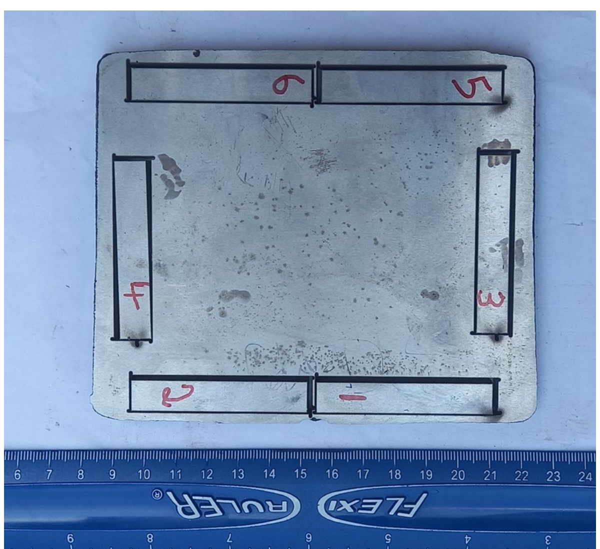
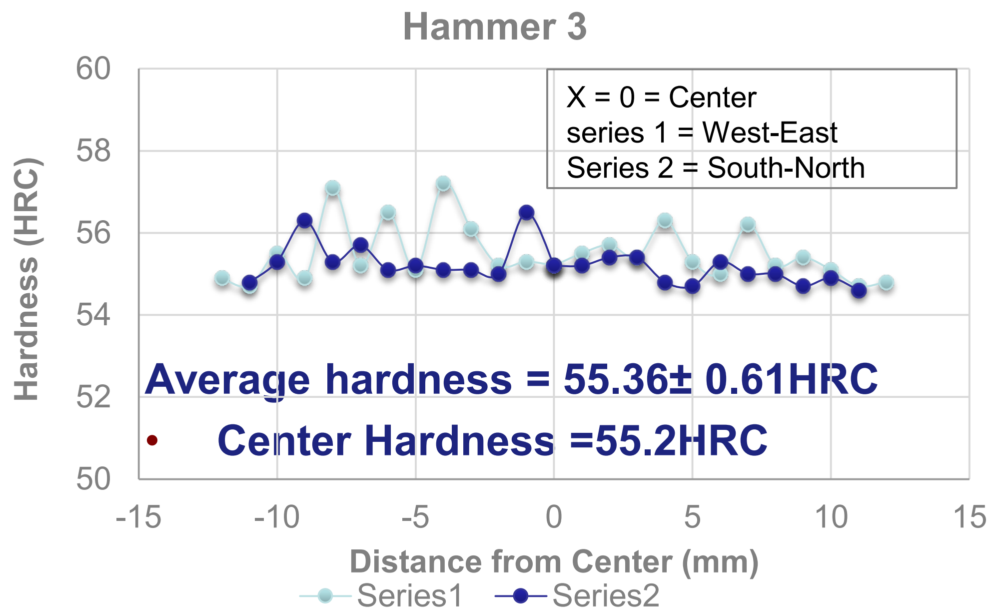
Hardness Profiles After Tempering







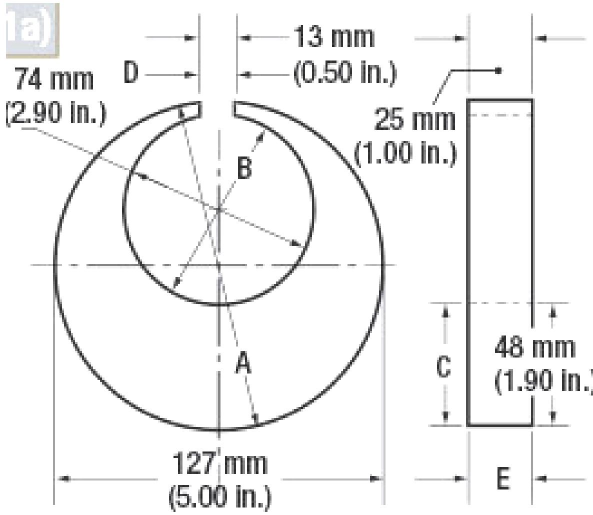
The Charpy samples 2,3 and 6 were be broken (at room temperature) to determine notch toughness

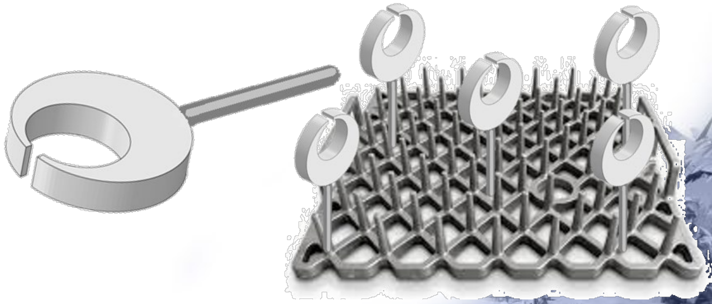
Samples	2	3	6
Toughness (Joules)	**9.56**	**6.09**	**7.78**

Evaluation of Distortion and Cracking

Navy C-Ring Castings – 4340 steel billet

- Comparison of different chemistries
- Modeling of quenching process – distortion, microstructure and residual stress development
- Intensive quenching trials at Missouri S&T
- Immersion tank quenching at 8 different foundries and heat treaters
  - Develop baseline for expected distortion levels
  - Develop a standard practice for foundries to evaluate their quench practice





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Abaqus / Dante Modeling

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1. Heat Up
   - From 20ºC to 900ºC per 3600s
   - HTC1 coefficient was used (see figure 1)
2. Air-Transfer
   - Surrounding air at 200ºC per 15s
   - HTC2 coefficient was used (see figure 1)
3. Quenching
   - Contact with water at 25ºC per 600s
   - HTC3 coefficient was used (see figure 2)
4. Air-Cooling
   - All body to 25ºC
   - HTC2 coefficient was used (see figure 1)

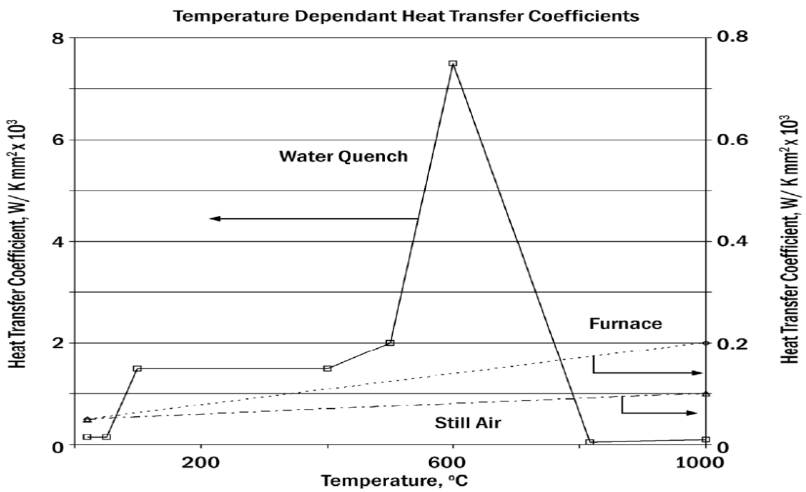


Figure 1. Heat transfer coefficients HTC1 for Carburization (Furnace curve), and HTC2 for Air-transfer and Air-cooling (Still Air curve)[1]

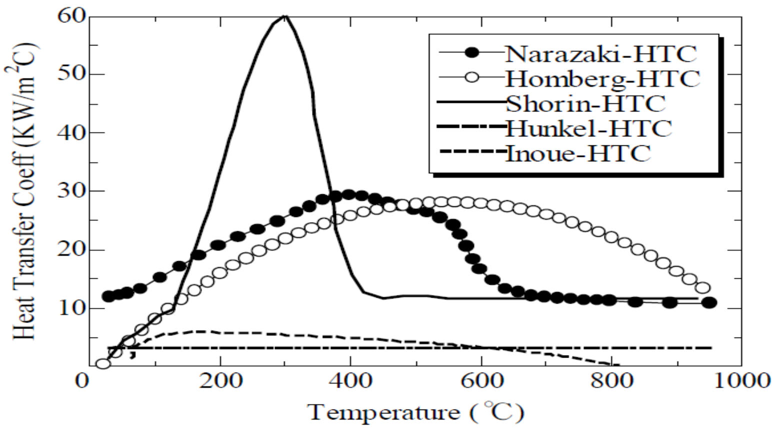
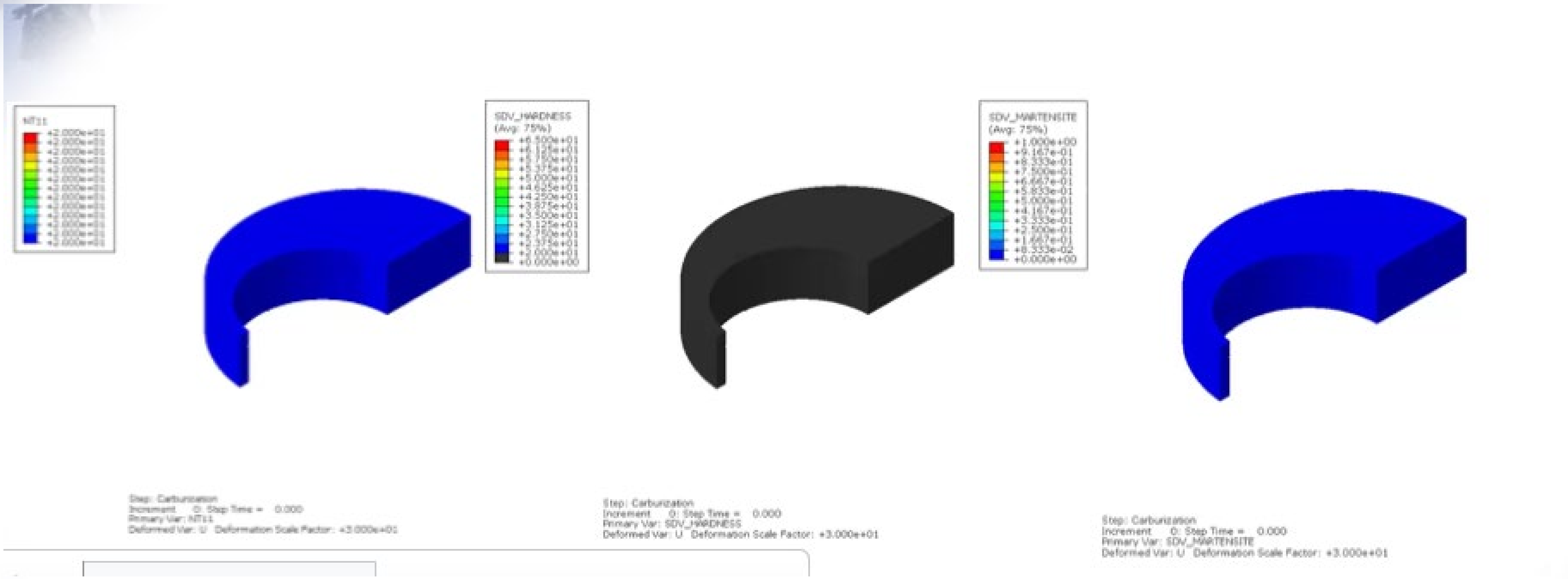


Figure 2. Heat transfer coefficients (HTC3) for quenching (Narazaki-HTC curve)[2]

[1] Brooks, B.E., and Beckermann, C., "Prediction of Heat Treatment Distortion of Cast Steel C-Rings," in Proceedings of the 61st SFSA Technical and Operating Conference, Paper No. 4.5, Steel Founders' Society of America, 2007.

[2] Sugianto, A., et al. "Validity of Heat Transfer Coefficient based on Cooling Time, Cooling Rate, and Heat Flux on Jominy End Quench Test." *Materials Science And Technology-Association for Iron and Steel Technology-* 6 (2007).

Modeling of Temperature, Hardness, and Microstructure



Temperature and Hardness predictions by Abaqus/Dante FEA model for 1045 steel

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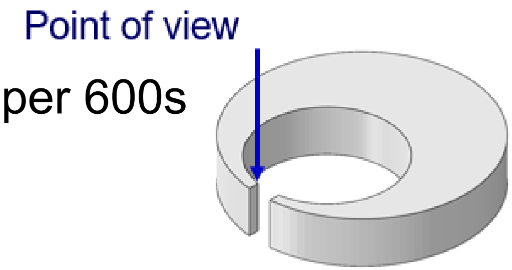
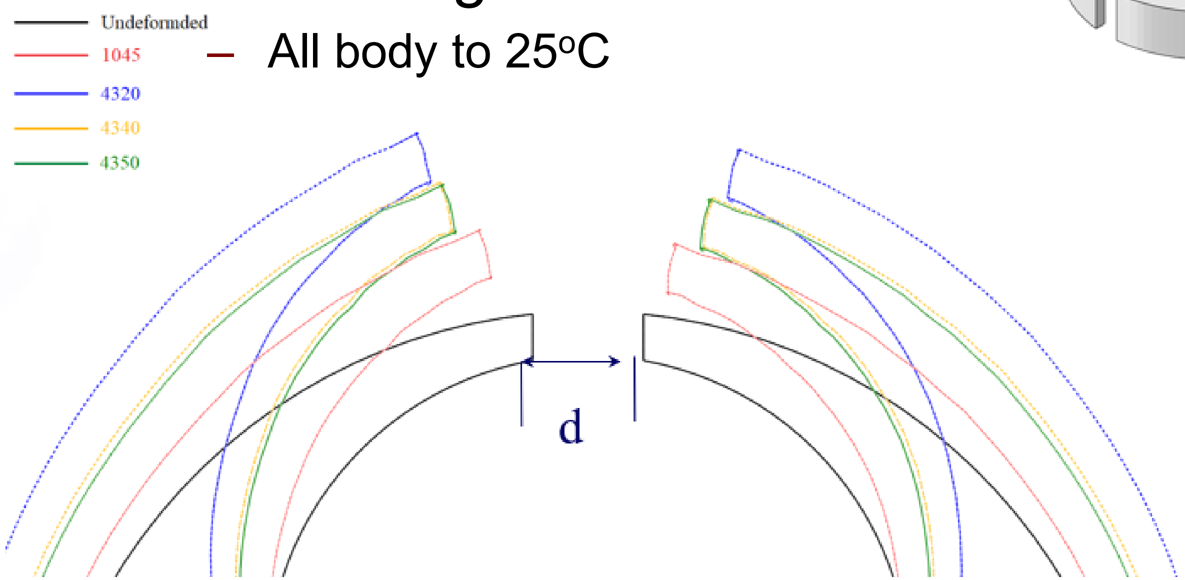
Abaqus / Dante FE Modeling

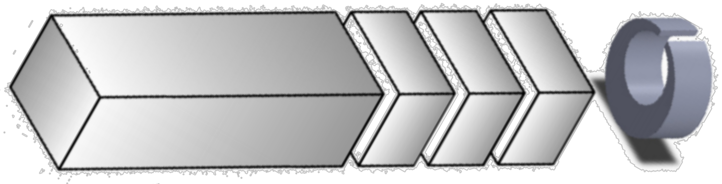
1. Heat Up
   - From 20°C to 900°C per 3600s
2. Air-Transfer
   - Surrounding air at 200°C per 15s
3. Quenching
   - Contact with water at 25°C per 600s
4. Air-Cooling
   - All body to 25°C





FE Model	d [mm]	% Change
Initial	12.7	
Final 1045	12.95	1.97
Final 4320	13.41	5.59
Final 4340	13.24	4.25
Final 4350	13.21	4.02

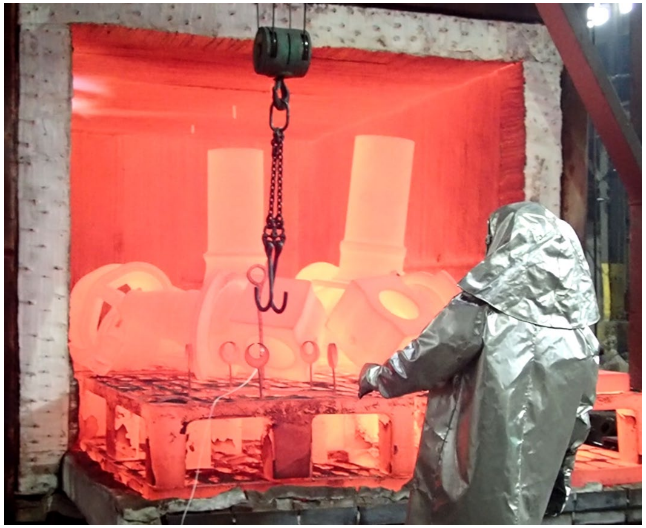
C-Ring Testing Plan



- 100 Navy C-Ring castings sectioned from 4340 billet
- Water-jet cut (at outside machine shop)
- Laser scanned – Iowa State University
- 10 each sent to different 8 different foundries and heat treaters
- 10 quenched in Missouri S&T draft tube quench tank
- 10 quenched using IQ process

- Billet material provided by Nucor Memphis
- Estimated value $4,000

SOW for Partner Foundries



- Self study of quench tank parameters (volume, size, Temp. range, quenchant type, flow rate, transfer type and time, etc)
- Coat C-rings with anti-scale coating
- Fixture 5 C-rings at a time to Quench basket or rack
- Quench with normal production part loading
- Austenitize for 1hr at 900ºC
- Quench into water – record water temperature

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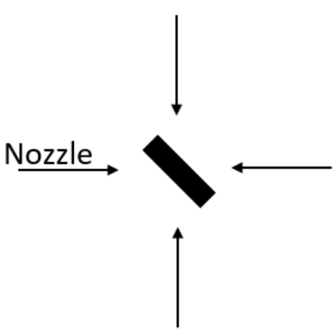
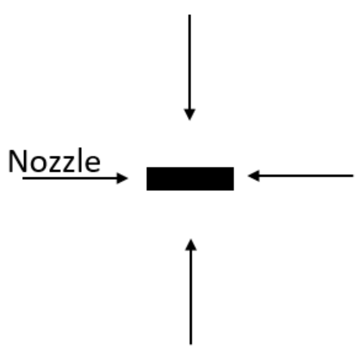
Intensive Quenching of C-Rings

- Fixture designed for uniform quenching of C-rings
- Full pressure – 180 psi
- Hard quench for 8min
- Spray pattern important

- Spray IQ

- Industrial quenching in a forced convection quench tank





Evaluation of Defects on Quench Performance

- Determination effect of controlled "defects" on IQ performance
  - 10 additional C-rings machined
  - Holes of different sizes and different locations drilled to simulate inclusions and porosity
  - Measure response – distortion, cracking, residual stress.

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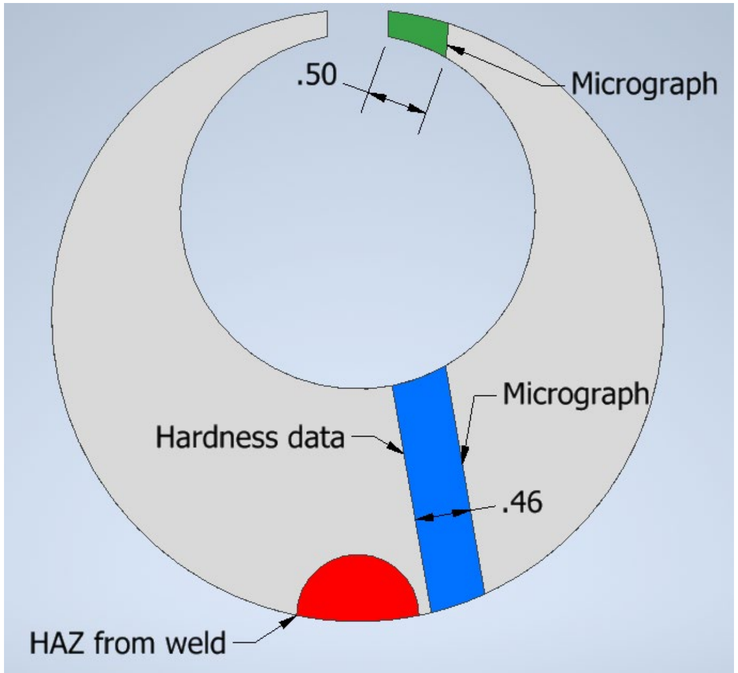
Microstructure and Hardness

- Rings 01, 11, 21, 31, etc. retained for sectioning
- Hardness profile – function of depth from surface
- Hardness varied from 58-59 HRC
- Slight variation in hardness between different industrially quenched castings



Sectioning diagram for hardness and micrograph samples

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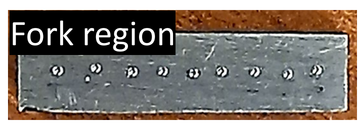
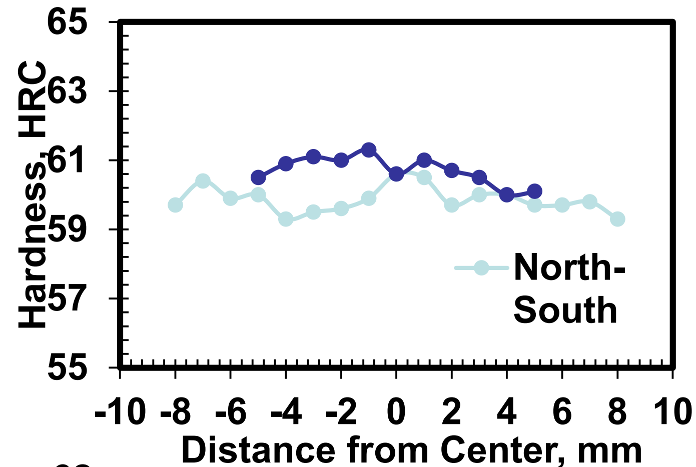
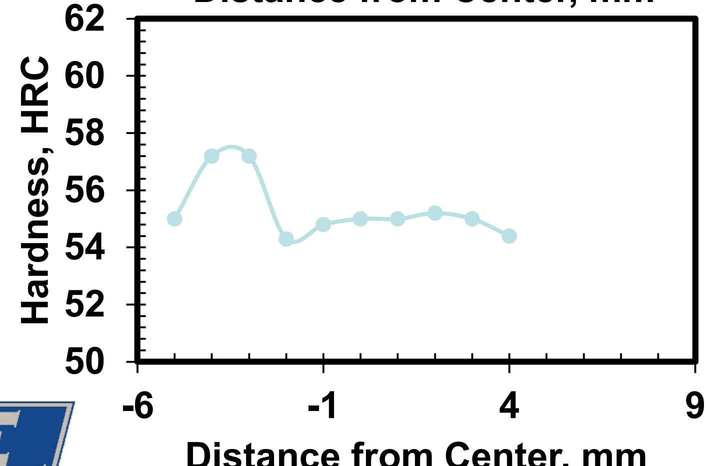
As-Quenched Hardness

Rings	Quenched	Base, HRC
1	Foundry 1	59.1 ±0.78
11	Foundry 2	59.5 ± 0.16
51	S&T Intensive Spray Quench	58.3 ± 0.17
62	Foundry 3	56.9 ±1.13
31	Foundry 4	56.2±0.38
22	Foundry 5	59.1 ±0.92
42	Foundry 6	60.2± 0.57

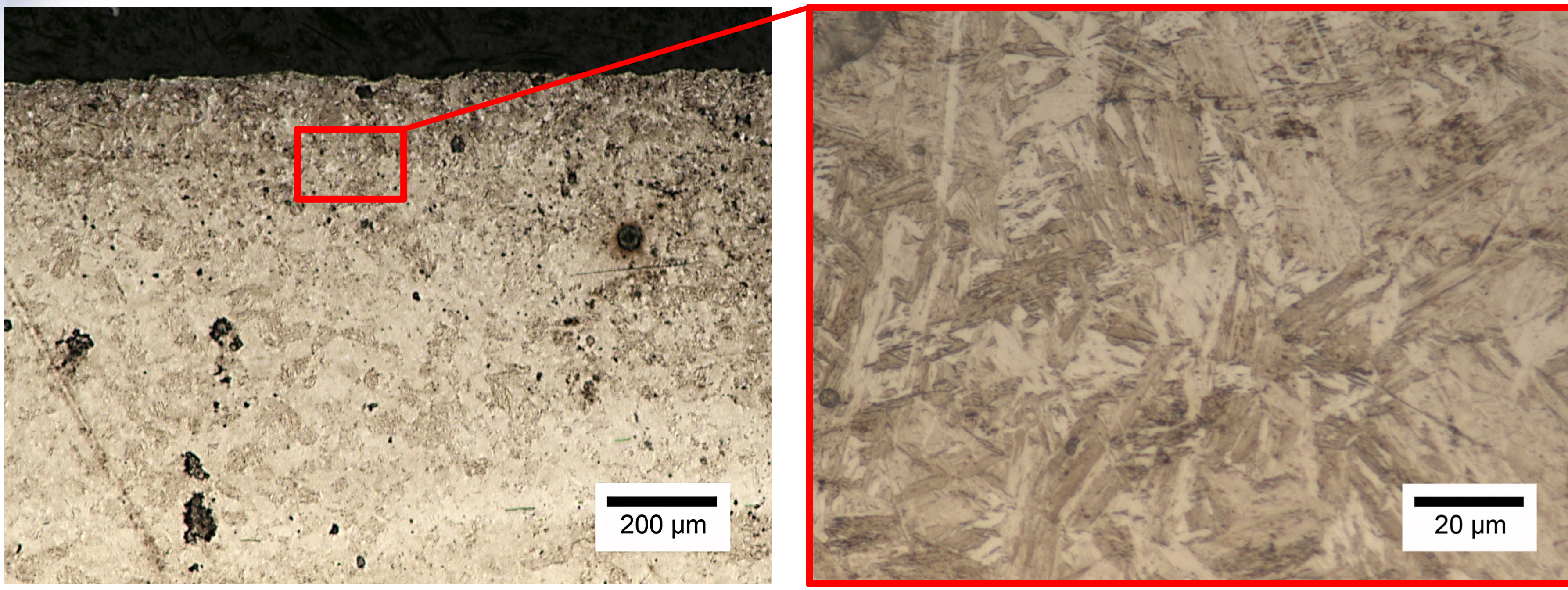






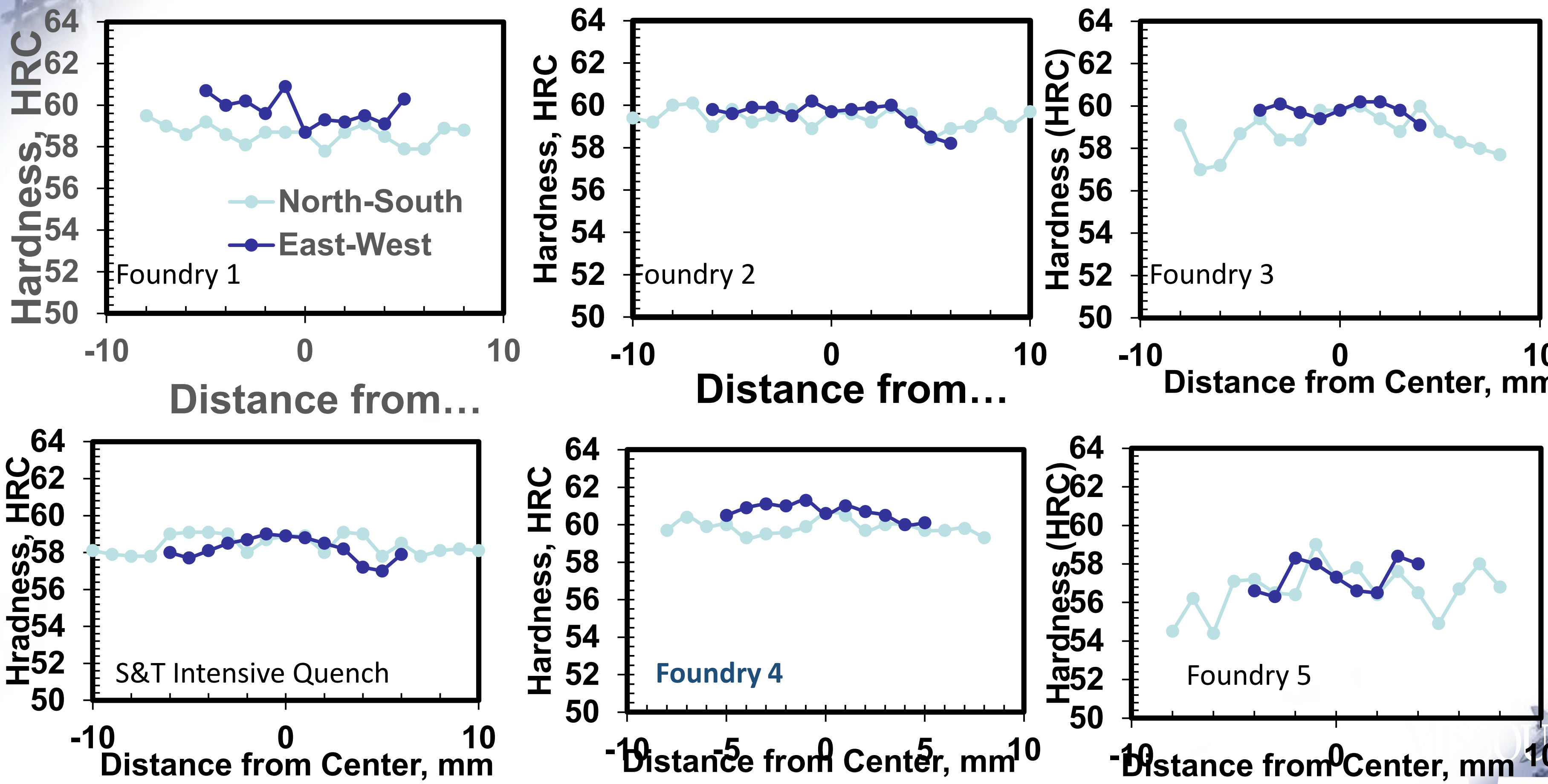
MAGOTTEAUX
MONETT METALS INC.
EFFORT FOUNDRY
HARRISON STEEL CASTINGS COMPANY
EAGLE Alloy, Inc.
SPOKANE INDUSTRIES
PINSON VALLEY HEAT TREATING
MetalTek INTERNATIONAL Making a Lasting Difference

Metallography of Base Section : Ring 42

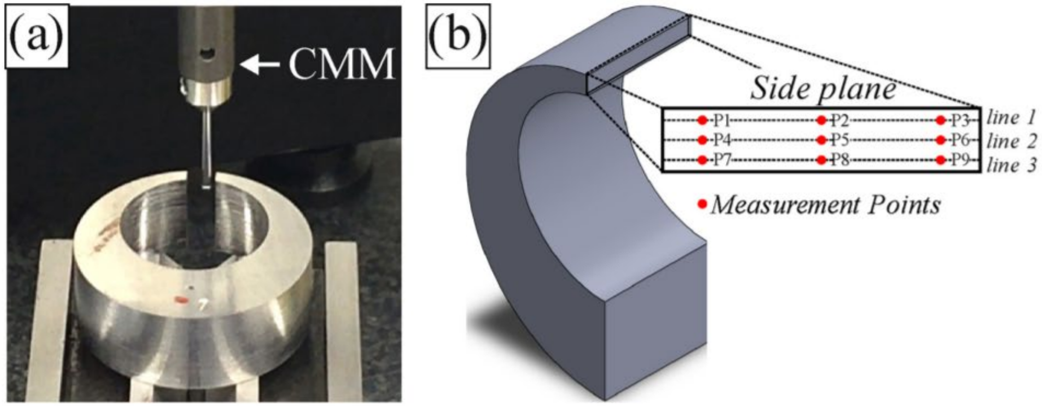


- Microstructure at the casting surface is lath martensite
- No evidence of decarburization

Comparison of Hardness Results



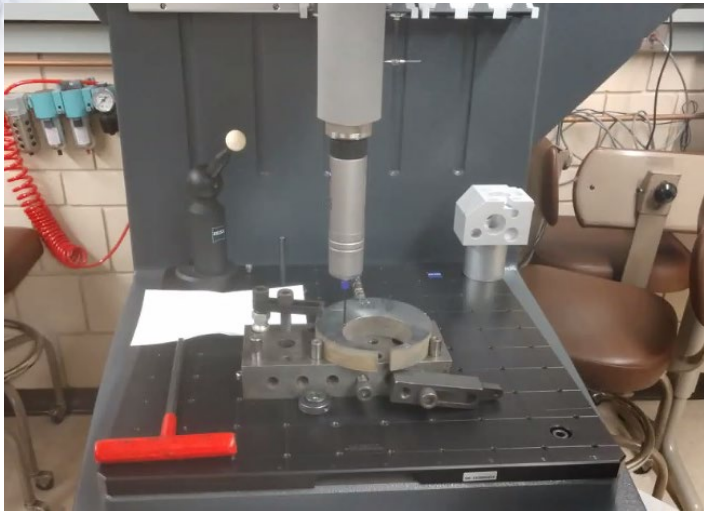
Measuring Quench Performance

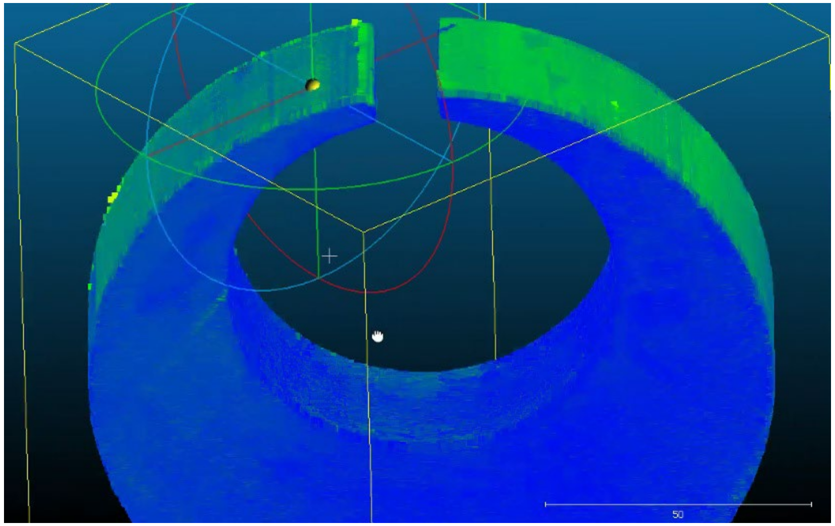


- Dimensions measured before and after heat treatment using CMM and Laser scan

Journal of Materials Processing Tech. 264 (2019) 313–327

CMM and Laser Scanning of Part Surface





- Performed in partnership with ISU – Thank you!
- Preliminary scans of industrially quenched castings show gap opening of 2.9 ± 1.2%
- Consistent with FE models

C-Ring Casting Trials at Missouri S&T

- **Goals**: Evaluate the effect of casting surface on IQ performance
- **Experimental Procedure:**
- Remelt 4340 billet in a 187 lb heat
- Cast 12 4340 and 4350 Navy C-rings
- As-cast C-rings:
- Stress relief annealed
- Section 13 mm fork gap
- Surface scan and IQ trials at Missouri S&T
- Compare with traditional immersion quench

- 4340 billet from Nucor

Fe	C	Si	Mn	Al	Mo	P	S	Cr	Ni
Bal.	0.425	0.248	0.814	0.03	0.268	0.01	0.012	1.046	1.652

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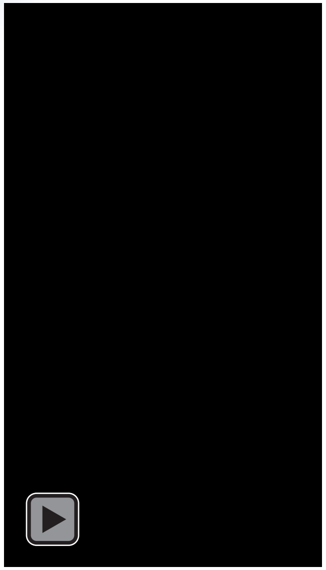
C-Ring Casting Trials at Missouri S&T



- **Procedure:**
- 200lb induction furnace – Ar cover
- ~187lb of 4340 steel billet charge
- 0.02wt.% Al deox in ladle
- Chemistry samples and temperatures taken as a function of time after fully liquid

- Special thanks to our melt crew!
- Castings poured: Navy C-ring castings and SFSA Cast in Steel Competition sword

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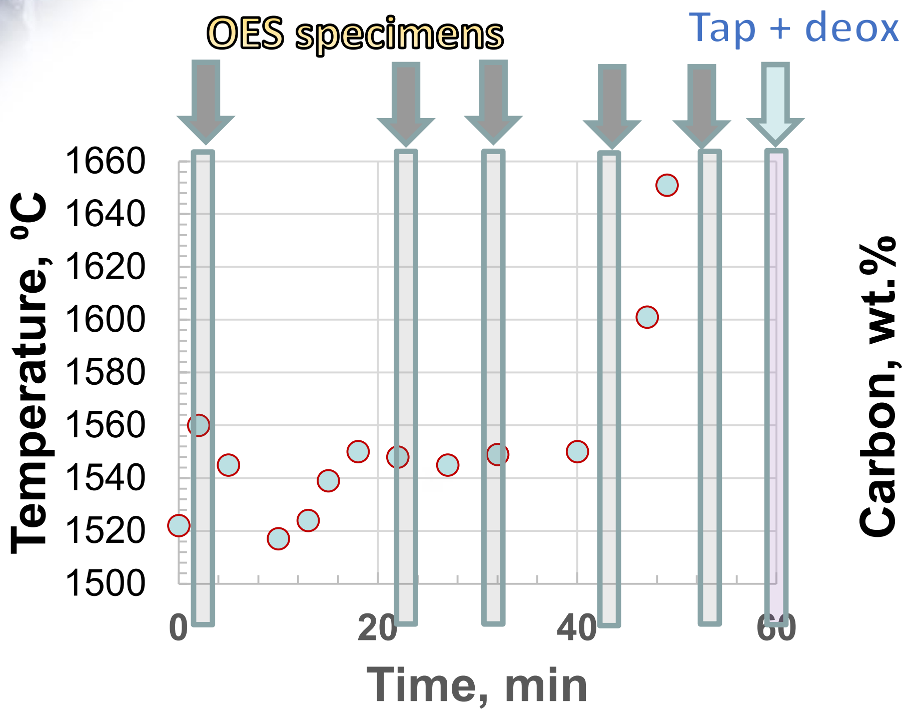
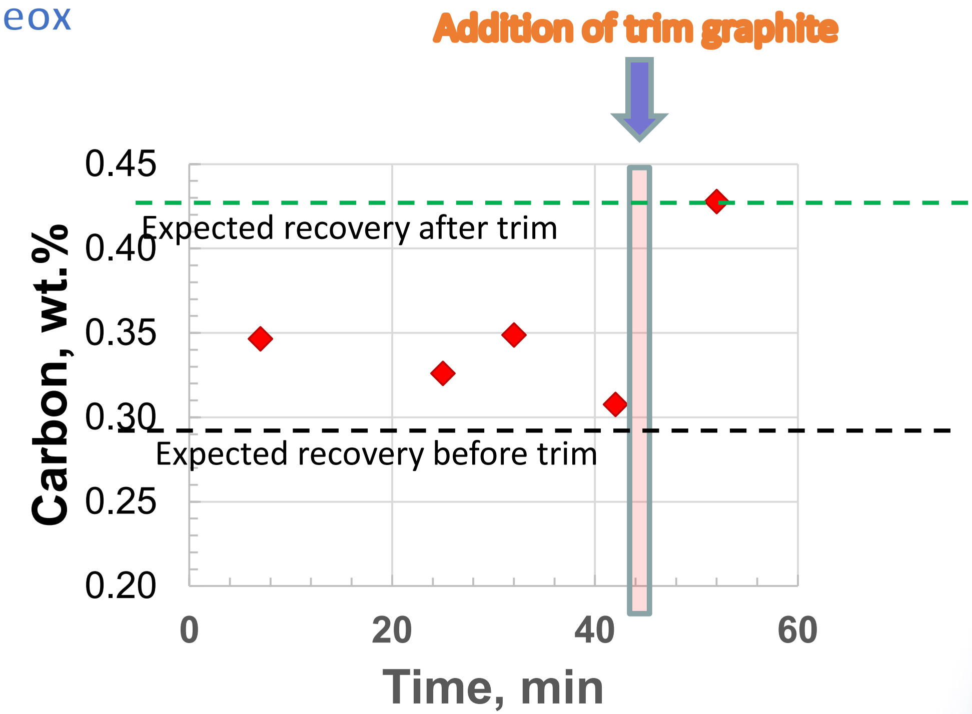
C-Ring Casting Trial Heat Results





- Good control of temperature → holding at 1550ºC
- Charge calculator correctly predicts carbon recovery

Casting Results

Fe	93.7
C	0.573
Si	0.242
Mn	0.754
P	0.0236
S	0.0331
Cr	1.03
Mo	0.267
Ni	1.68
Al	0.032
Co	0.0429
Cu	0.206

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Completion Plans

- Intensive quenching can be used to quench difficult and complex castings without cracking
- Fully hardened part with good mechanical properties
  - Next two months
  - Finish quenching experiments
  - C-ring industry work instruction – in progress
  - Industry Heat Treatment Guidelines for Improved Quenching
- A draft final report will be submitted to ATI by 10/29/22

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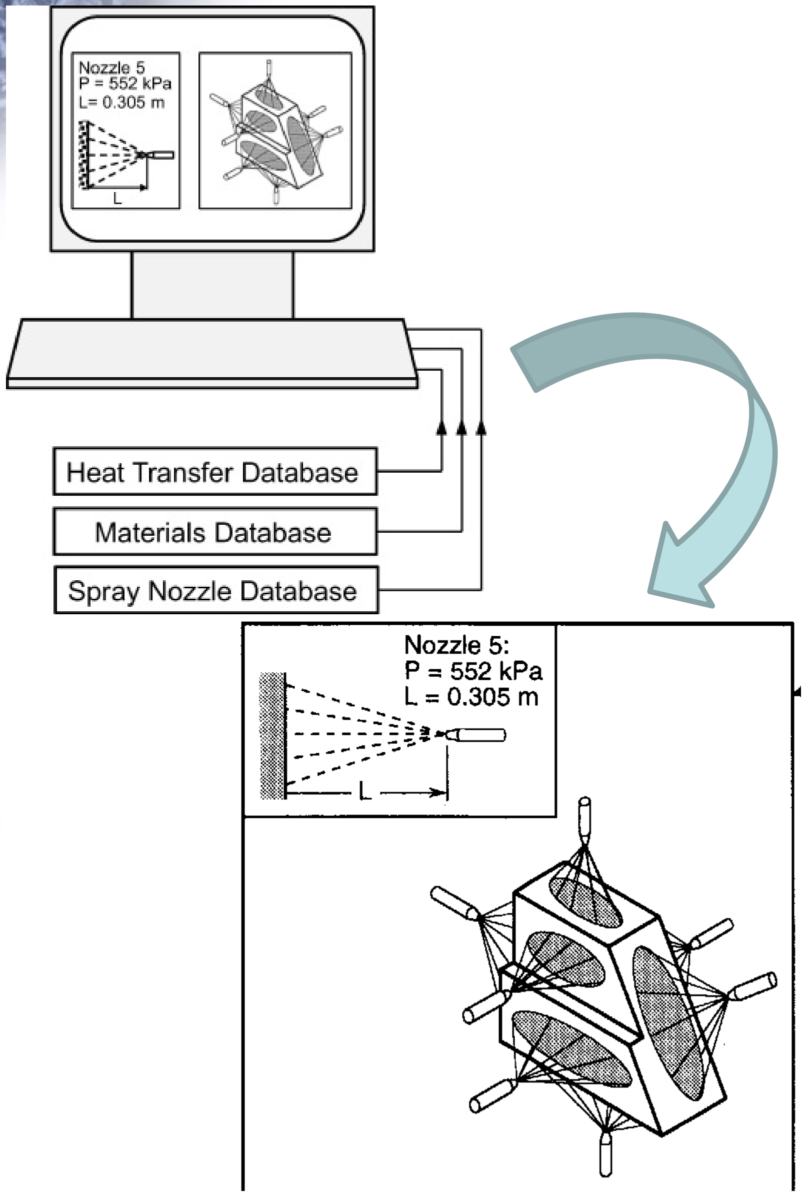
Transition to Industry



- Presentation at SFSA Research Reviews
- Publication in IJMC
- Industry Heat Treatment Guidelines for evaluating distortion and cracking for improved quench performance

- Implement a “Smart” IQ Spray Facility at partner foundry
  - Computer controlled and programable for each casting
  - Robot spray nozzles with vision system

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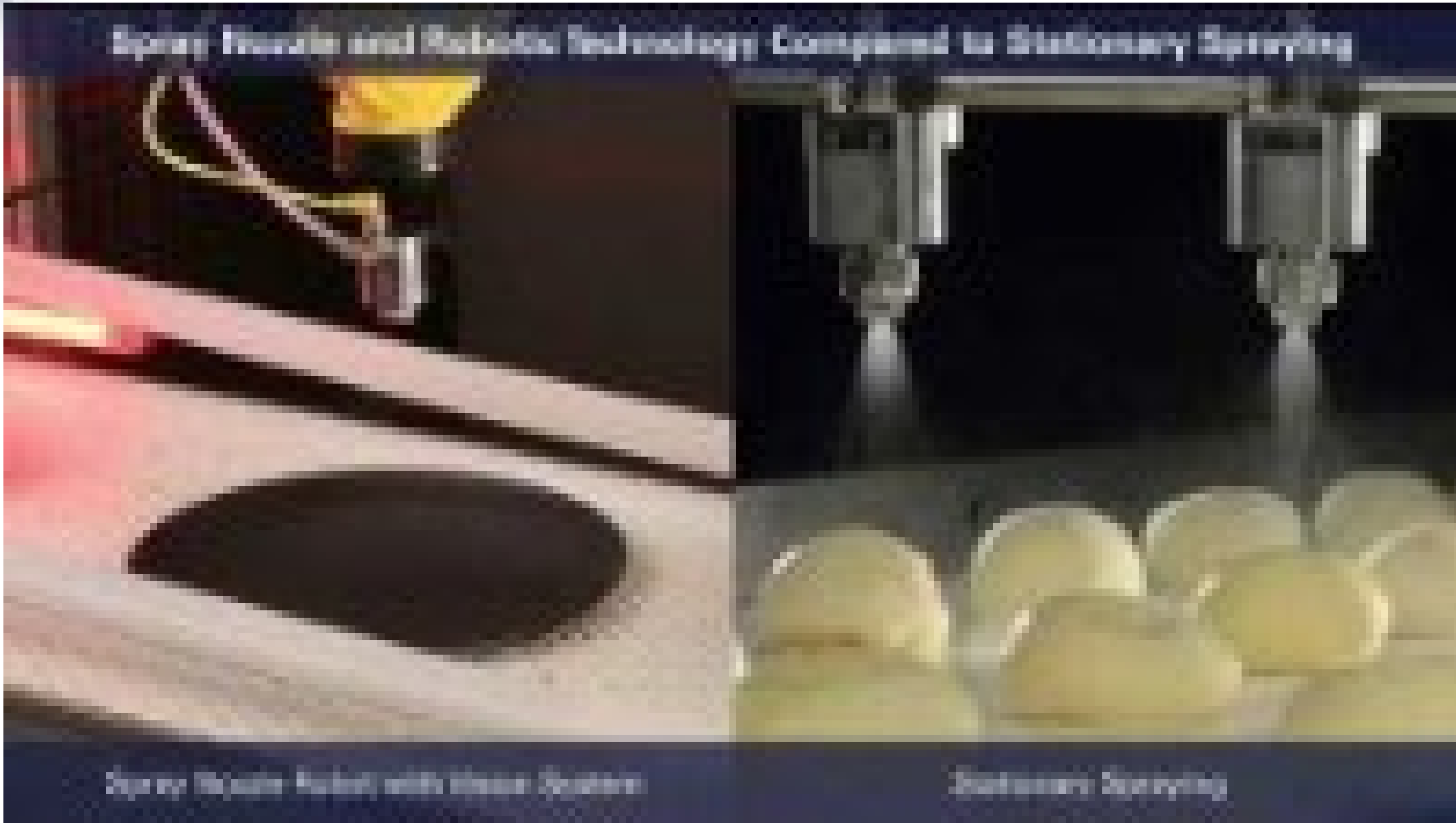
Transition to Industry: Spray Nozzle Robotic Technology



Spraying Systems Inc.

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Leveraging

- DoE project and several PSMRC industrial projects involving high temperature sensor development – create a real-time temperature-strain map of the IQ process using optical fiber sensors
- Intensive quenching of AF9628 - Cooperative Agreement W911NF-19-2-044 with CCDC Army Research Laboratory
- Intensive quenching of FeMnAl steels - SFSA DID Contract# SP4701-17-D-1161

Leveraging

Monitoring Temperature and Strain with Optical Fibers

At 0 min: Plate in the furnace, 117 min: water spray at ~50 psi, 289 min: no water and heat, 302 min: spray at 65 psi

Heating the plate in a box furnace at 200 °C for ~2 hours and then spraying water in a quench tank at 50-65 psi for ~4.5 hours

Leveraging

1. A thin-core high-NA optical fiber in a SS tube (SS 304 tubing: 1.2mm x 0.9mm), adhesive A

- Adhesives applied in a vertical configuration
- Cured at room temperature

	Adhesive A	Adhesive B
Working Temperature	**500°F (260°C)**	500°F (260°C)
Thermal conductivity (BTU-in/Hr. °F Ft^2)	**35**	40
Tensile Strength (psi)	**10,000**	6,550
Curing	**24 hrs @ Room Temp.,**	24 hrs @ Room Temp.,
Viscosity (cps)	**100,000**	43,000

Adhesive A: 132PIP-1 – 16oz - 130.50$
Adhesive B: RK454 – 16oz – 217.6$

~50psi
Video

Lightwave Technology Lab

PSMRC KENT D. PEASLEE STEEL MANUFACTURING RESEARCH CENTER

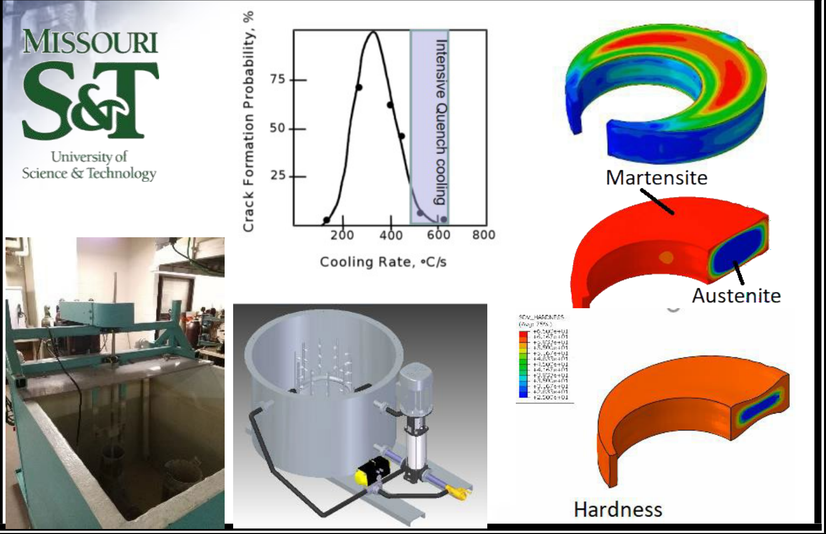
AMC
AMERICAN METALCASTING CONSORTIUM

Project Metrics

Description	Baseline	Threshold	Goal	How Measure d	Target Date	Progress	How Demonstrated
Development of IQ spray quench system (Measured as Quench Severity, H)	Draft tube Quench capacity H = 1.5	Intensive quench with H = 3	Intensive quench with H > 4	Hardnes s microsco py	**August 20 2020**	100%	Laboratory Experiment
Evaluation of IQ technology vs immersion quench to reduce distortion and cracking	Traditional Draft tube Quenched C-Ring Castings	Intensively quenched C-Ring Castings 30% reduction in distortion and cracking	Intensively quenched C-Ring Castings 50% reduction in distortion and cracking	Laser scan Optical metallogra phy	**November 2022**	90%	Laboratory Experiment
Evaluation of IQ technology on quench performance of industrial castings	Production of residual compressive stress on as-cast surface	20% Reduction in cracking	40% reduction in cracking	Optical metallography and inspection Mechanic al test specimen s	**November 2022**	80%	Laboratory Experiment
Implementation of IQ technology at Industrial Foundry	Traditional immersion quench	20% decrease in distortion and cracking	40% decrease in distortion and cracking	Laser scan Mag Particle Inspection Optical metallograp hy	**Jan 2023**		Industrial Trials

Intensive Quenching to Produce High Performance Cast Parts

DLA - POC: DLAR.DPR@dla.mil



Problem

- Traditional quenching technologies - produce non-uniform cooling and result in distortion, cracking, and tensile residual stress on the surface

Objectives

- Evaluate the use of IQ technology to decrease distortion and quench cracking in:
- Complex geometry cast parts
- Hard to quench steel chemistries prone to distortion and cracking
- Castings with different surface conditions: scale, surface roughness and surface defects
- Produce compressive residual stress for better fatigue performance

Benefits to Warfighter

- Reduce operation and sustainment costs of weapon systems through better reliability of replacement part

Description of Project:

This project will evaluate the use of intensive quenching technologies to produce beneficial compressive residual stress and reduce distortion and cracking in difficult to quench steel chemistries

Team:

Missouri University of Science & Technology, Steel Founders' Society of America, ATI

Milestones / Deliverables

- Missouri S&T intensive quench facility operational
- Casting of Navy C-Ring castings – 43XX steels with different levels of inclusions and surface roughness
- Evaluation of intensive quenching in comparison to immersion quenching
- Low temperature stage one temper to preserve residual compressive stress
- Determination of improvement in fatigue properties
- In-plant (foundry) trial of intensive quench on actual casting