High-Intensity Thermomechanical Processes for Enhanced Strength, Fatigue Resistance and Ductility in Aluminum (Al) Castings

Project ID: MAT248

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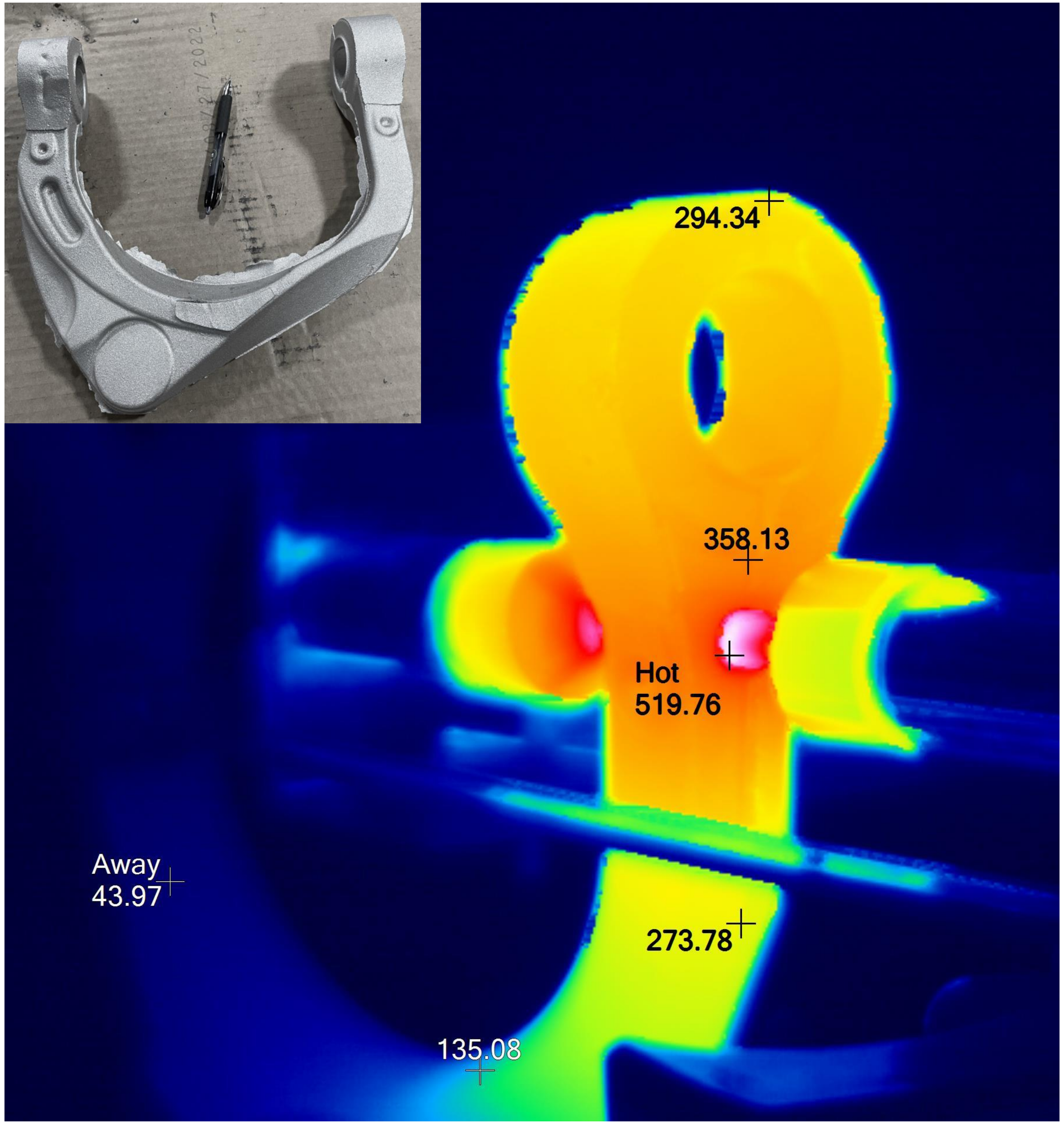
Pacific Northwest National Laboratory

June 15, 2023

DOE Vehicle Technologies Office
Annual Merit Review



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Overview

Timeline

Project start date	Nov 2020
Project end date	Sept 2023
Percent complete	75%

Budget

Total project funding	$1,200,000
Funding for FY2022	$ 400,000
Funding for FY2023	$ 400,000

Thrust 2. Localized Property Enhancements for Cast Structural Aluminum Applications

Project	Title	FY23
2A1	Local Thermomechanical Processing of Die-Cast Aluminum Alloys for Improved Fatigue and Fracture Toughness Behavior (PNNL)	$400k
2A2	Power Ultrasonic Surface Processing of Die-Cast Al Alloys (ORNL)	$200k
2B	High-Intensity Thermomechanical Processes for Enhanced Strength, Fatigue Resistance and Ductility in Al Castings (PNNL)	$400k
2C	Cast and Print (ORNL)	$450k
	Thrust Totals	$1.45m

Barriers and Technical Targets

Recycling

- Enable increased use of secondary aluminum

Low-Cost Manufacturing Processes

- Reduced energy use associated with heat treatment

Interactions

Lead Laboratory

- Pacific Northwest National Laboratory

Partner Laboratories

- Argonne National Laboratory (Argonne)
  - Advanced Photon Source (APS)
- Oak Ridge National Laboratory (ORNL)

Industry Engagement

- Eck Industries
- Sugino Corp.
- LSP Technologies

Relevance and Objectives

- Relevance
  - Most aluminum (Al) used in automotive industry is in the form of castings
    - ✓ Benefits: Lower manufacturing costs, parts consolidation, and lower assembly costs
    - ✓ Issues: Lower strength and ductility than wrought products limit the number of casting applications and lightweighting potential
  - Casting is a mature technology; new techniques are needed that can reduce manufacturing costs and improve casting performance to enable greater use of Al castings for lightweighting
- Objectives
  - Improve the local cast microstructure during casting and enhance local mechanical properties of castings
  - Develop new process technologies that are cost effective and compatible with existing casting practices and processes
    - ✓ Three independent techniques that address the casting, heat-treatment, and surface-treatment processes

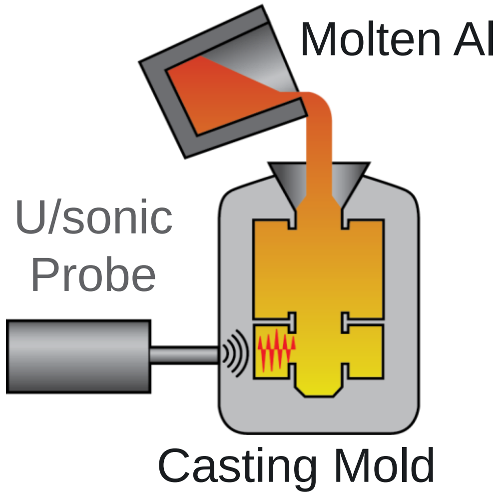
Project Milestones (FY23)

Milestone	Criteria	Due Date
Apply high-frequency ultrasound during aluminum solidification in a permanent steel mold.	Grain size in the casting produced by ultrasonication is smaller than in a non-sonicated casting by 50% or more.	12/31/2022 Completed
Down-select a peening process and perform peening experiments on the surface of cast aluminum.	Subsurface hardness is greater by 15% or more relative to unpeened material.	3/31/2023 Completed
Perform heat treatment of a prototype aluminum casting using Joule heating.	Maintain target heat-treatment temperature to within ± 5°C in the selected location of the casting.	6/30/2023 On-Track
Perform fatigue testing of peened cast aluminum.	Fatigue life of peened cast Al is higher than that of the unpeened material by 2x or more.	9/30/2023 On-Track

Approach
Processing at Different Stages of Casting Development

During Solidification

Local Ultrasonic (u/s) Intensification During Casting Solidification

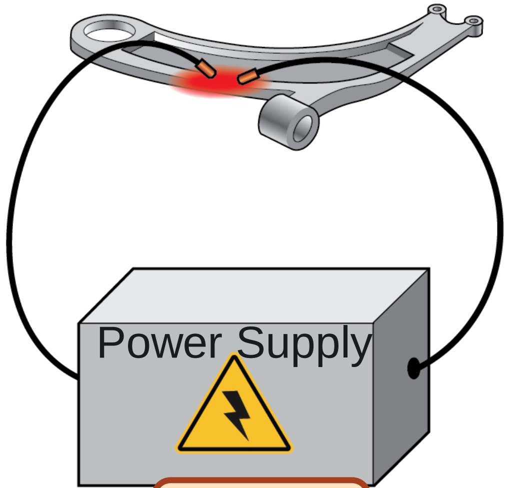


Task 1

A356 Al (with added Fe) is used to mimic a recycle grade cast Al

Post-Solidification

Local Heat-Treatment Intensification Through Joule Heating

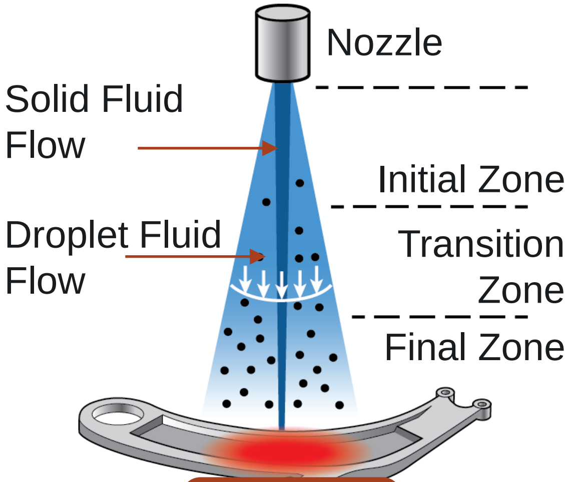


Task 2

HPDC A380 plates are used to demonstrate local heat-treatment

Post-Heat-treatment

Local Surface-Treatment Intensification by Waterjet Peening (WJP)



Task 3

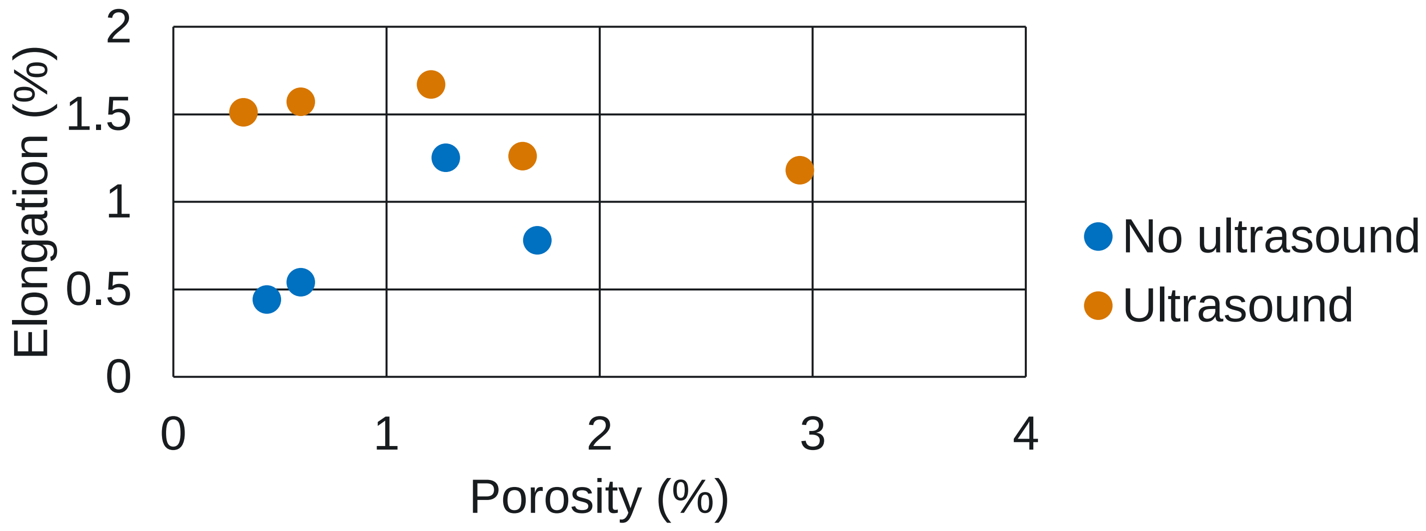
HPDC A380 plates are used to evaluate peening processes

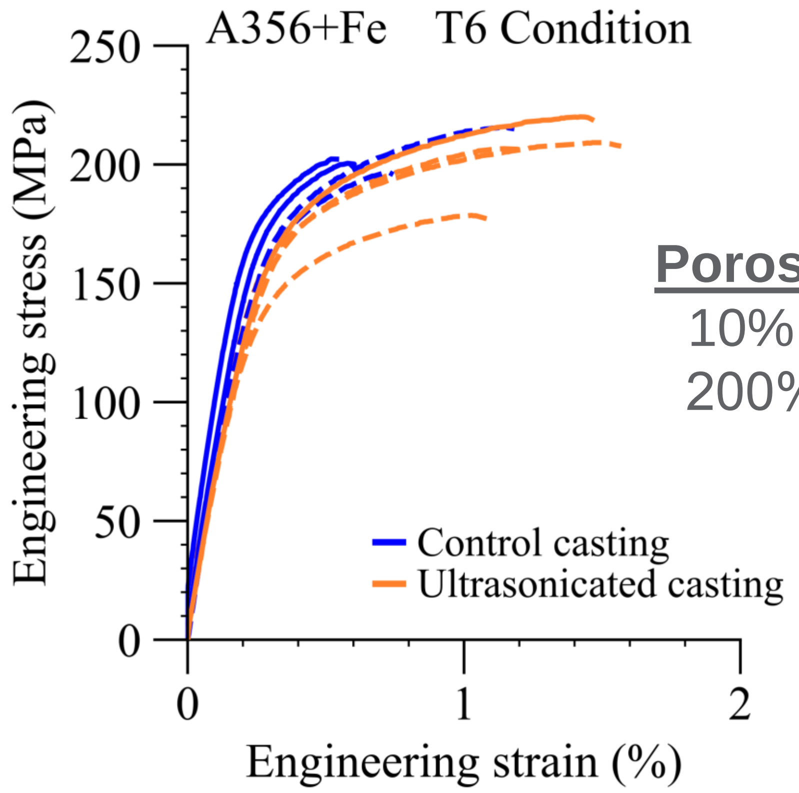
Task 1 Accomplishment

Ultrasound-Induced Improvement in Mechanical Properties

- A356 (+Fe) Al; tensile specimens extracted from castings and heat treated to a T6 condition

Microstructure	Grain Size (µm)	YS (MPa)	UTS (MPa)	e_{rup} (%)
Dendritic (no ultrasound)	140	191 ± 6	204 ± 8	0.75 ± 0.36
Globular (with ultrasound)	36	177 ± 13	203 ± 18	1.41 ± 0.23





Porosity <1%

10% ↑ UTS

200% ↑ e_{rup}

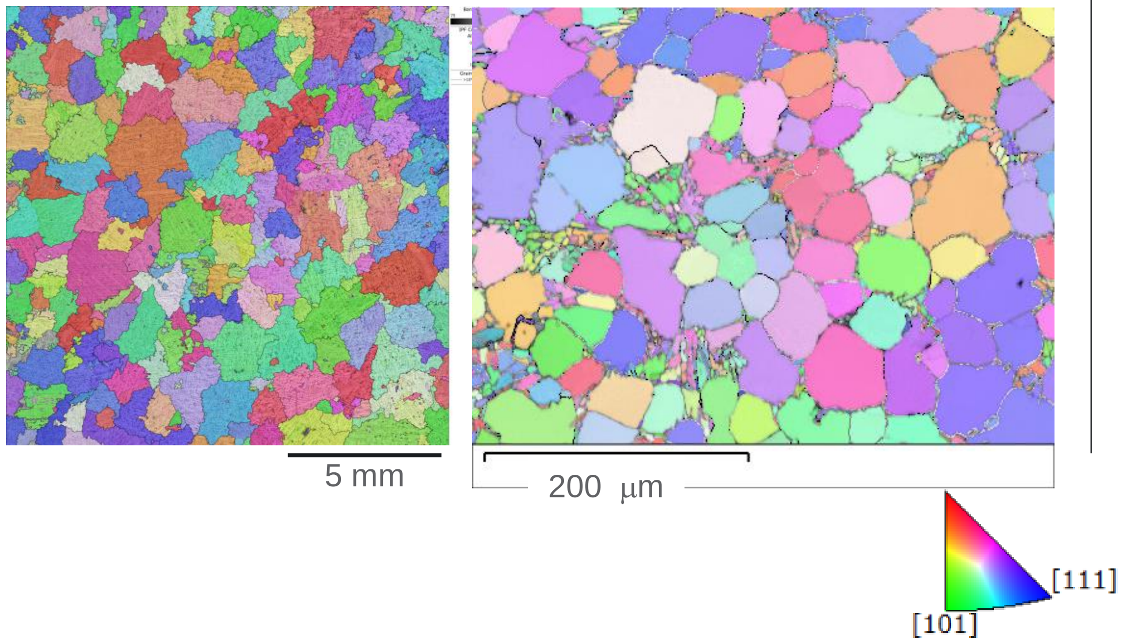
- Ductility ↑ by 88% on average
- Globular microstructure can accommodate more plastic deformation → greater ductility → greater UTS

Task 1 Accomplishment
Ultrasonic Processing During Casting in Pre-heated Steel Mold

Steel Mold

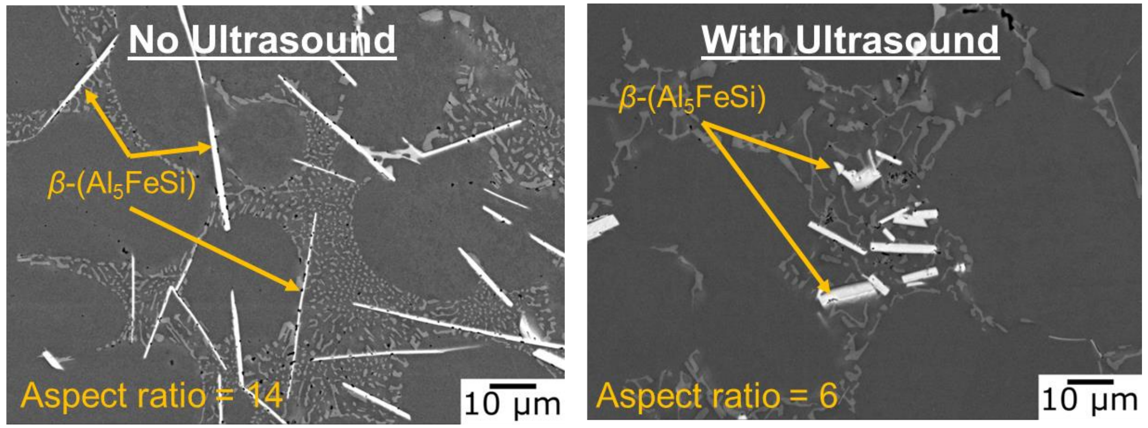
No Ultrasound
Grain Size = 1820 µm

Ultrasound
Grain Size = 56 µm



>30X reduction in grain size, as well as non-dendritic globular microstructure

Recycle-grade
A356 Al (0.9% Fe)



>2X reduction in aspect ratio of brittle Fe-intermetallics

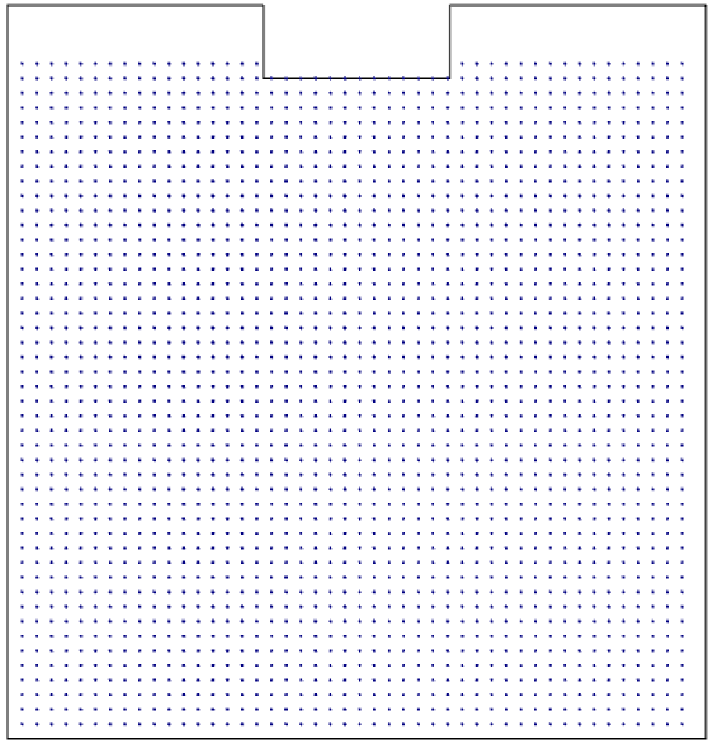
- Non-dendritic microstructure using low-cost hardware → Cost-effective lighweighting
- Reduced aspect ratio of intermetallic needles → Enable recycle-grade cast Al
- Microstructural refinement over ~2000 mm^2 area (tailorable over small/large area)

Task 1 Accomplishment

CFD Simulation of U/S Stirring in Solidifying Al

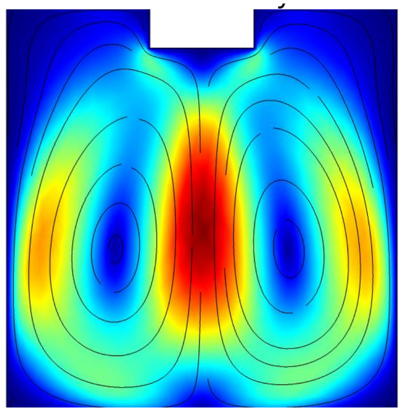
- Simulate effect of viscosity and dendrites on acoustic streaming and dendrite size on particle velocity

d = 1 to 200 µm, 0 to 300 s

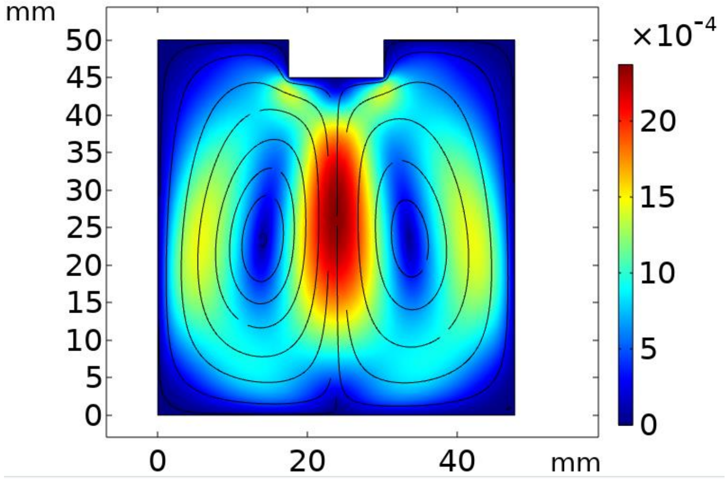


For the grain sizes that we observe (< 100 um), dendrite size should not affect the distribution pattern.

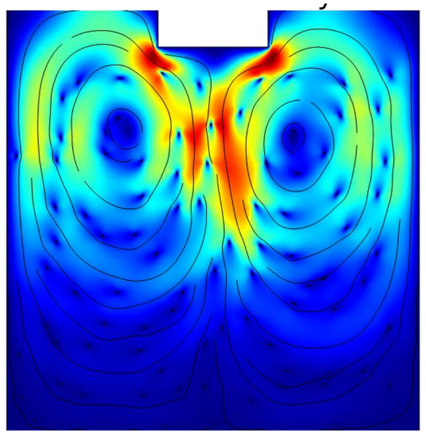
No Dendrites



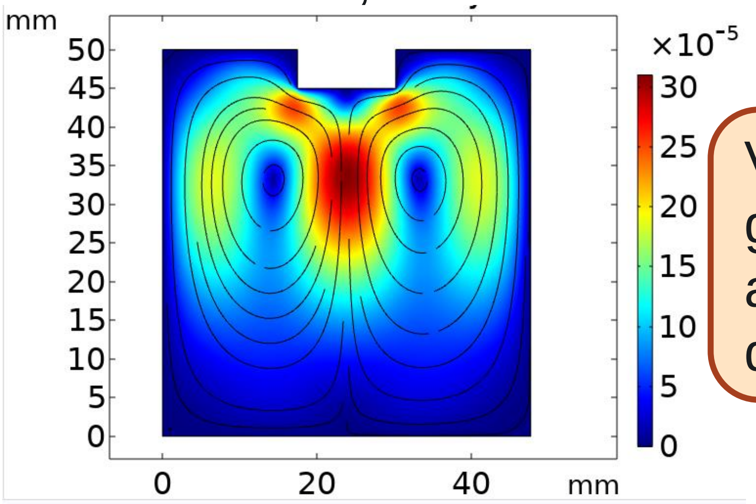
Viscosity = 1.47cP
Attenuation, $\alpha = 1E-3$



With Dendrites (Fixed)



Viscosity = 1.47cP
Attenuation, α = 1E-4



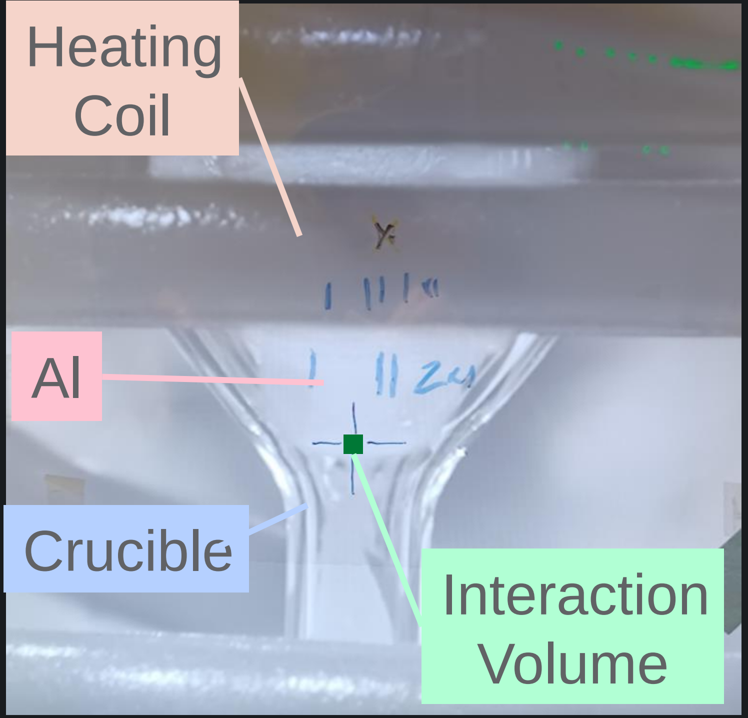
Formation of dendrites affects the liquid flow patterns.

Velocity field gets smaller as attenuation decreases.

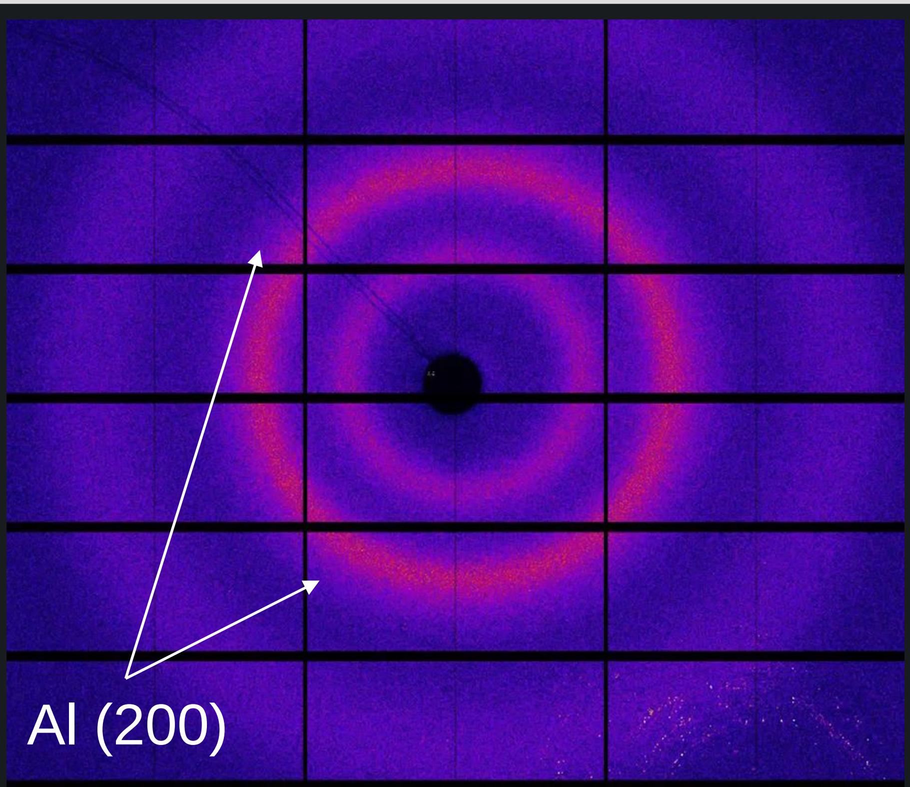
Task 1 Accomplishment

In Situ Diffraction Patterns During Solidification

Solidification Sequence: Liquid → α-Al → Eutectic Al + Si → Solid

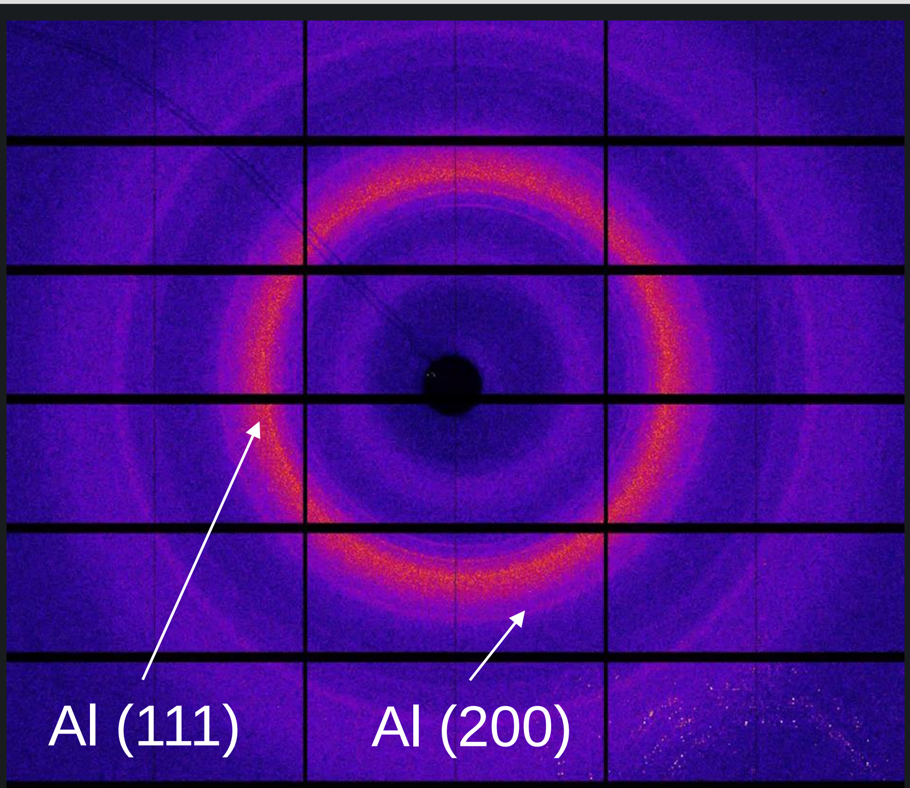


Solidification without Ultrasound



Large α-Al diffraction spots = Large α-Al grains

Solidification with Ultrasound



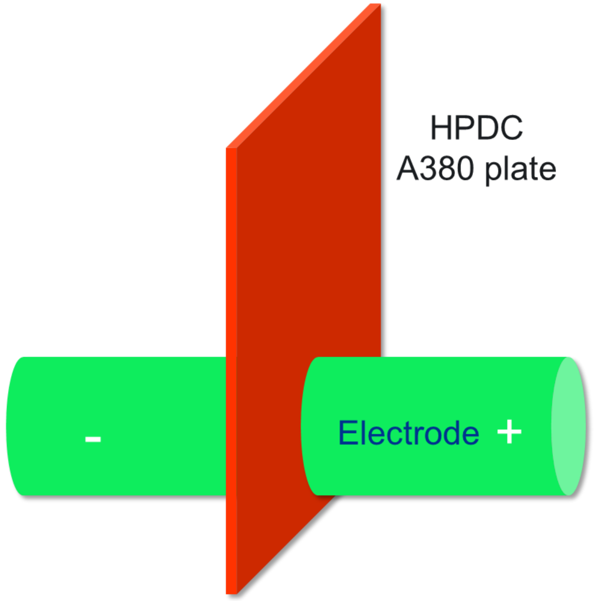
Small α-Al diffraction spots = Small α-Al grains

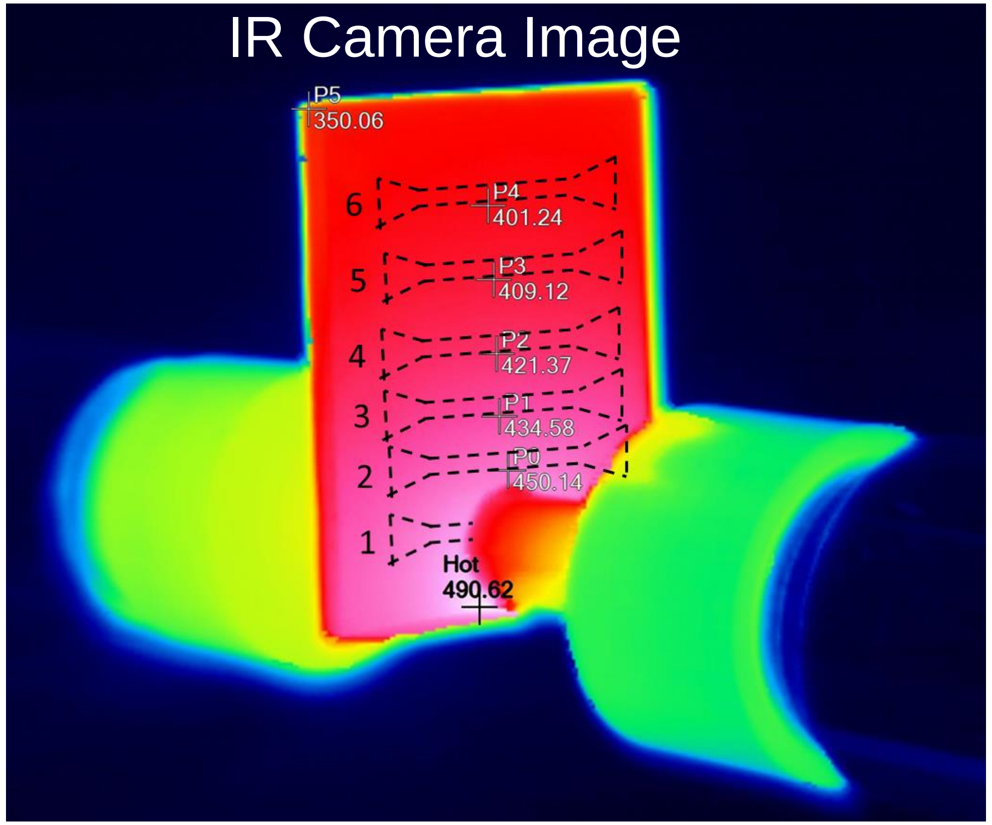
First reported (to our knowledge) in situ diffraction experiments to study ultrasonic refinement

Note: Innermost diffraction ring is from the fused quartz crucible.

Task 2 Accomplishment

Improvement in Mechanical Properties through Local HT





Two-minute heat treatment:

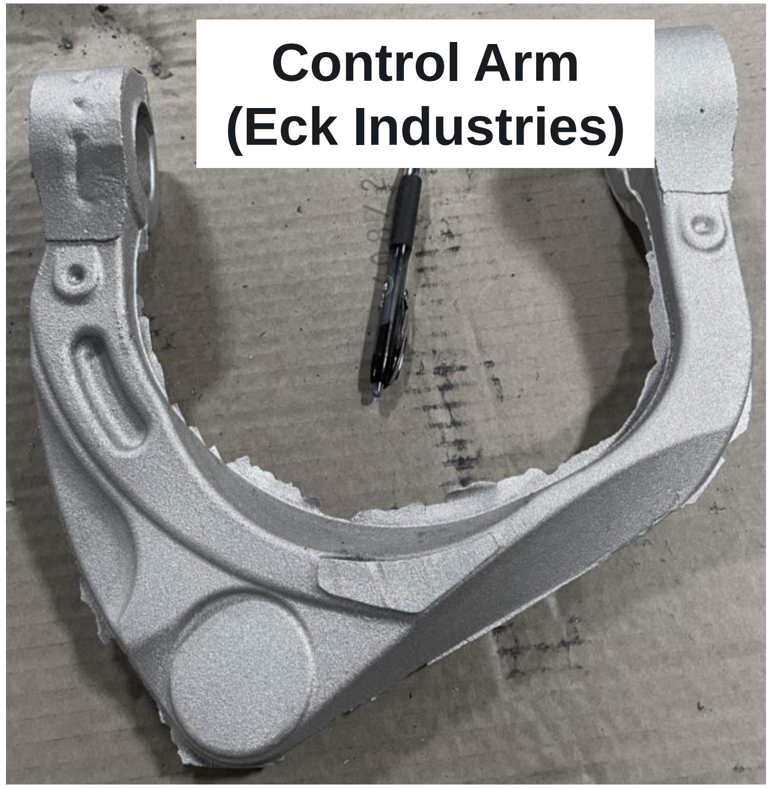
- 13% increase in strength
- Strengthening limited by blisters
- No significant ductility loss

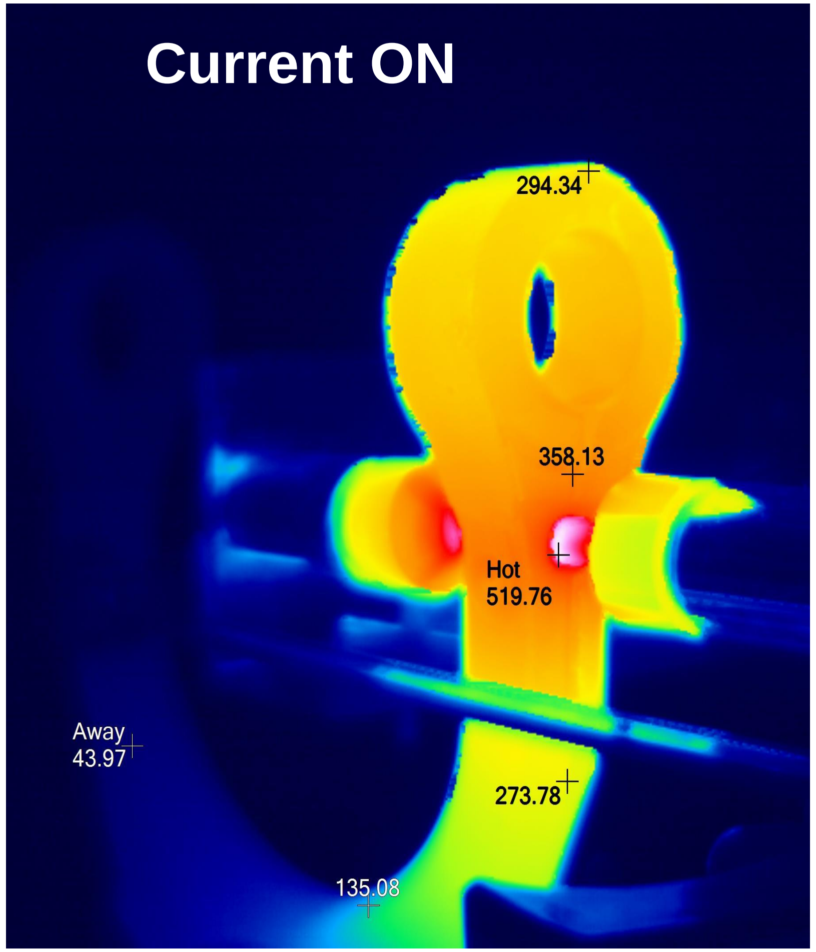
Hardness:

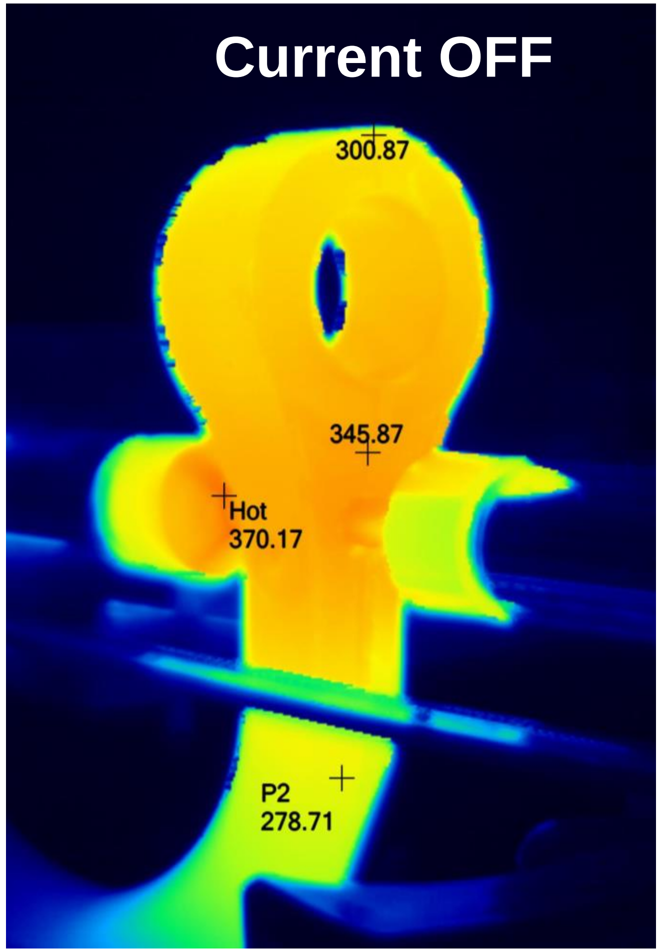
- 15% increase in hardness
- Joule heating > Furnace

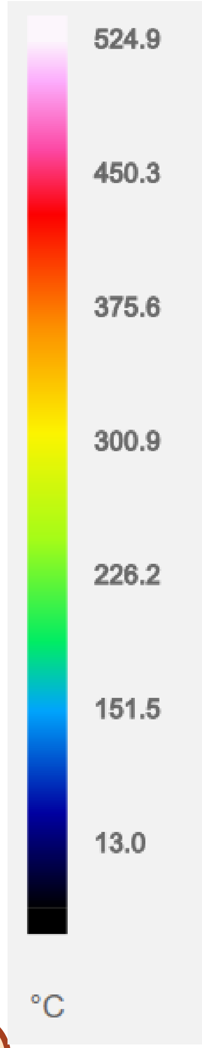
Task 2 Accomplishment

Demonstration of Local HT on a Large Casting







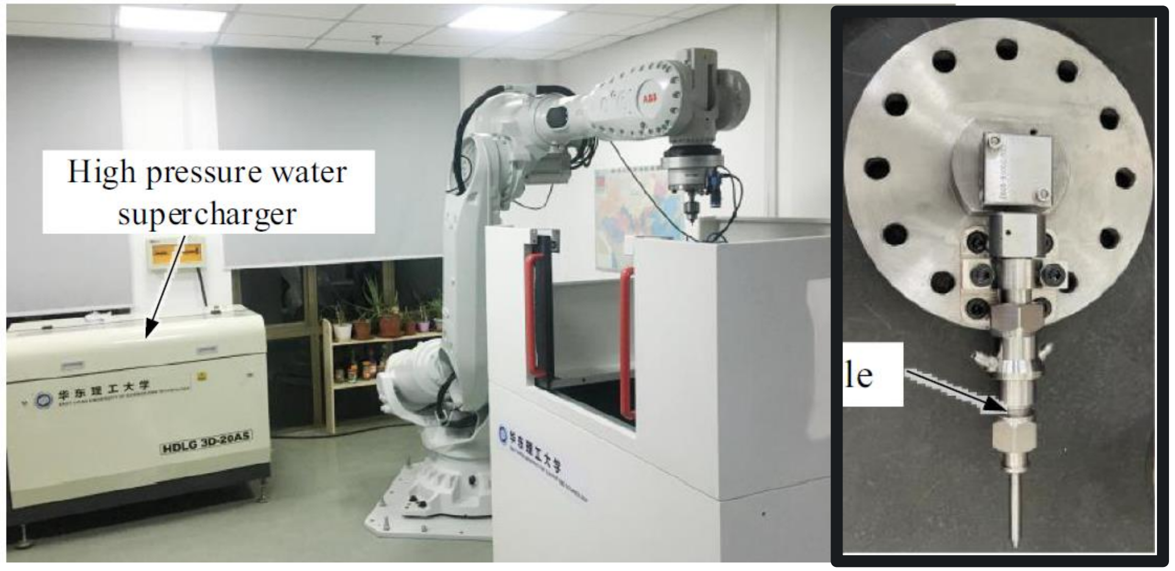


- Joule heating can be adapted for local solutionization (e.g., 520 °C in current work)
- Potentially applicable to “large” castings where bulk heat treatment is impractical

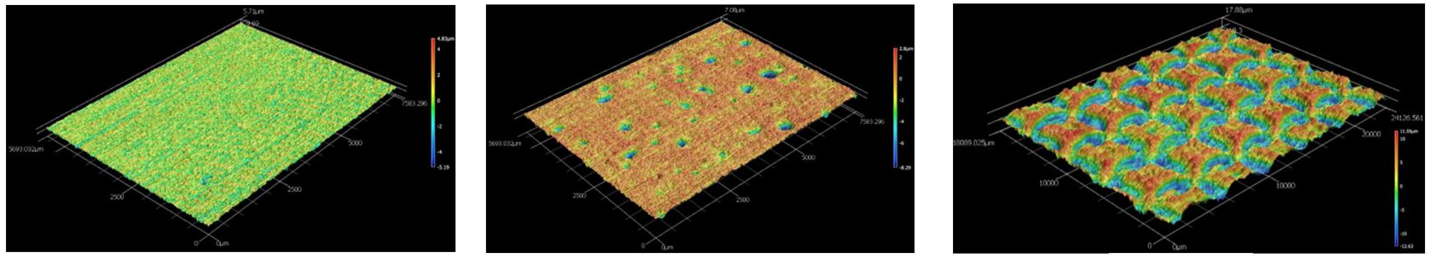
Task 3 Accomplishment

Local Surface Treatment (HPDC A380)

Sugino Corp. (WJP)

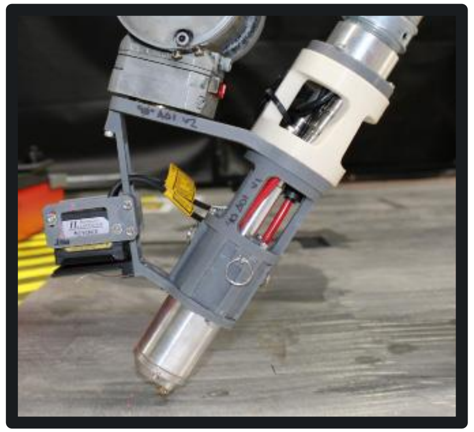


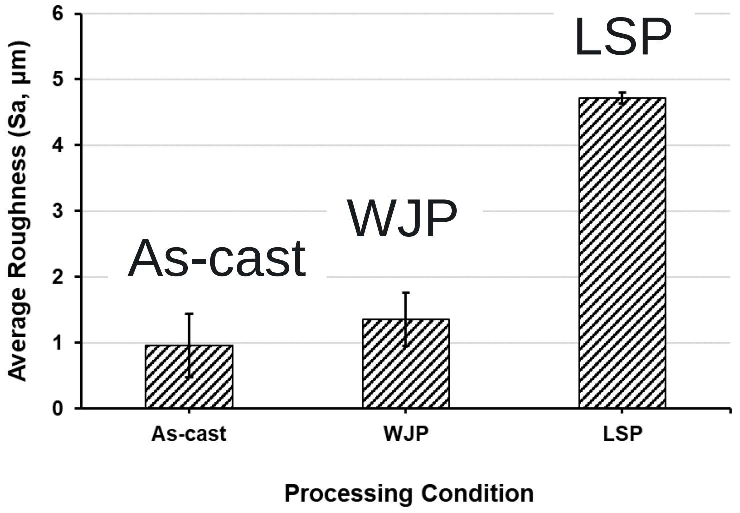
- WJP and laser shock peening (LSP)
- 3.5 mm thick HPDC A380 Al plate



As-cast **WJP** **LSP**

LSP Technologies (LSP)





Surface Roughness

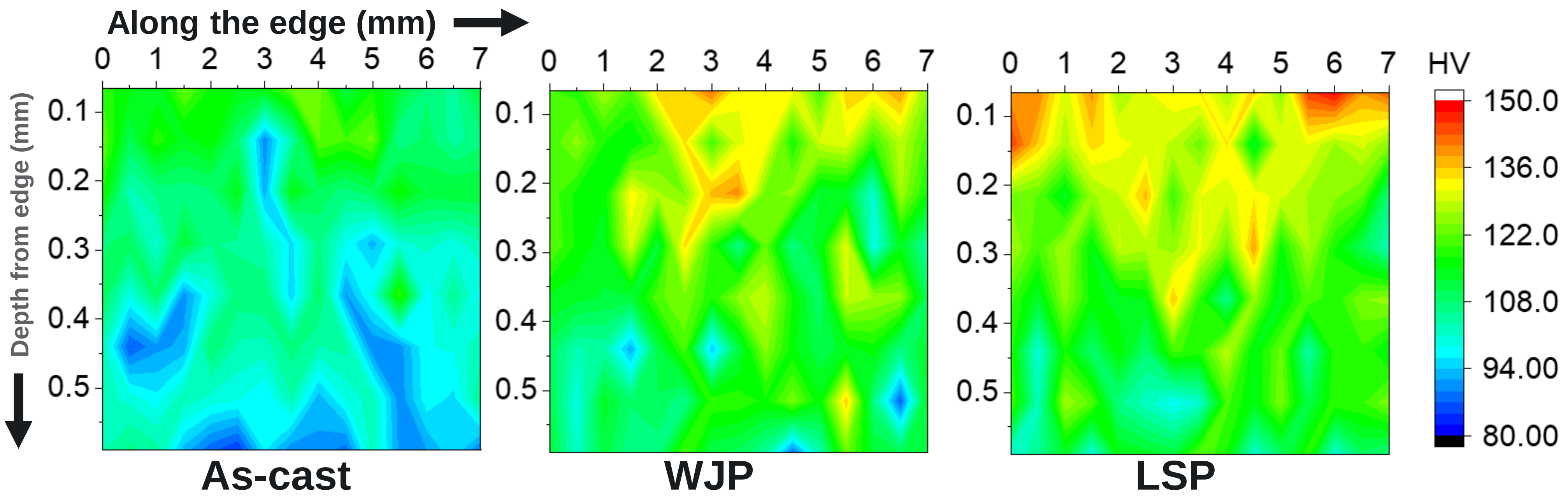
LSP > WJP > As-cast

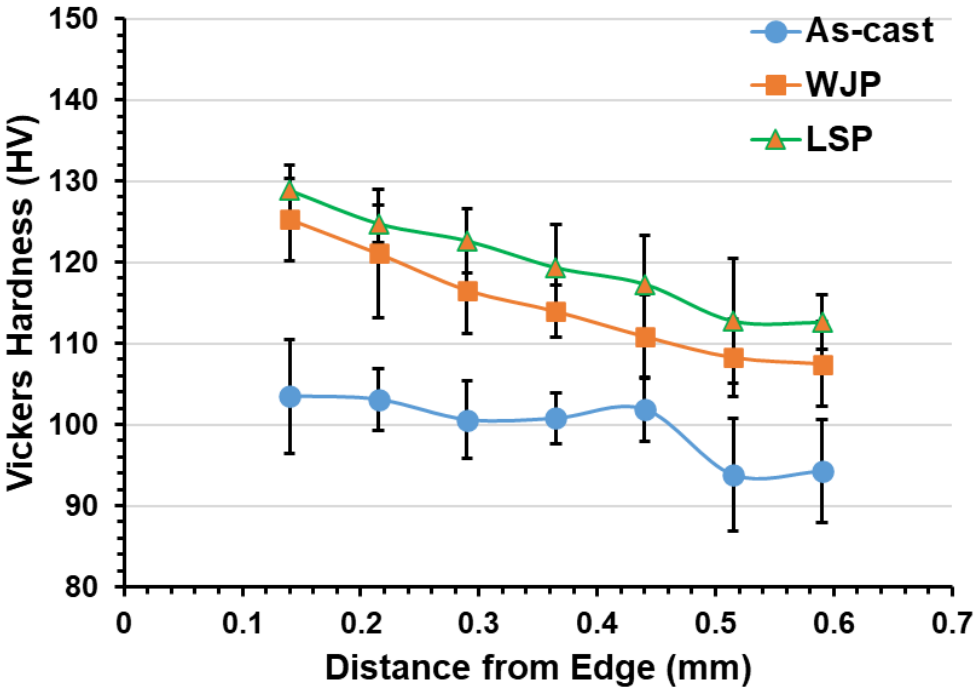
- Can fatigue life improvement due to peening overcome roughness-induced crack nucleation?

Task 3 Accomplishment

Local Surface Treatment (HPDC A380)

Sample	Average Vickers Microhardness (± Std. Deviation)
	Edge
As-cast	103.5 ± 7.0
WJP	125.3 ± 5.1
LSP	128.8 ± 3.2





- Distortion-free peening, even in “thin” HPDC plate
- Significant depth of hardness (residual stresses) increase → >0.6 mm from each side (~30% of plate thickness)
- Subsurface hardness increase by ~20% for WJP and ~25% for LSP

Response to Previous-Year Reviewers' Comments

Accomplishments and progress

- "…results so far are impressive and…shown a significant change in the microstructure due to ultrasonic processing during casting."
- "…impressive progress in use of ultrasound to achieve microstructural refinement in cast alloys, as well as…brittle Fe-containing phases that could enable greater use of recycled materials."

Response: Thank you! We've further extended our work and demonstrated microstructural refinement in preheated steel mold

Collaboration and coordination

- "…strong collaborations with ORNL and ANL….and APS…as well as PNNL for modeling and ultrasonics and microstructure analysis…collaborations with Eck Industries are viewed as important…."
- "…well informed by industry perspective"

Response: Thank you! Project was designed to address lightweighting challenges, guided by industry and leveraging expertise in experimental and modeling techniques that are unique to the national labs

Relevance

- "…well-aligned…unique.."; "..aspect of secondary alloys shows great promise.."

Response: Align research with VTO's and industry's desire for greater sustainability

Collaboration and Coordination

Sugino Corp. and LSP Technologies

- TASK 3: Collaboration on developing peening (WJP and LSP) for Al alloy (HPDC A380)

Eck Industries (Integration within Existing Casting Practice)

- TASKS 1 and 2: Discussions on mold design, casting practice, and challenges and opportunities of ultrasonication processing

ORNL (Solidification Modeling)

- TASK 1: Collaborating with Adrian Sabau (ORNL) to model volume fraction of phases and progress of solidification during pour casting of the A356 alloys

Argonne National Lab (Advanced Photon Source (APS) Beamline at Argonne)

- TASK 1: Collaborating with APS/Argonne staff (Andrew Chuang, Jonova Thomas, Dileep Singh, and Peter Kenesei) and performed in situ diffraction (beamline 1-ID-E) and imaging (beamline 32-ID-B) experiments

PNNL

- TASK 1: Yucheng Fu and Naveen Karri (ultrasonics modeling)
- TASK 1: Kranthi Balasu and Ayoub Soulami (thermal modeling)
- TASK 3: Saumyadeep Jana and Avik Samanta (fatigue testing)

Remaining Challenges and Barriers

1. Solidification Casting

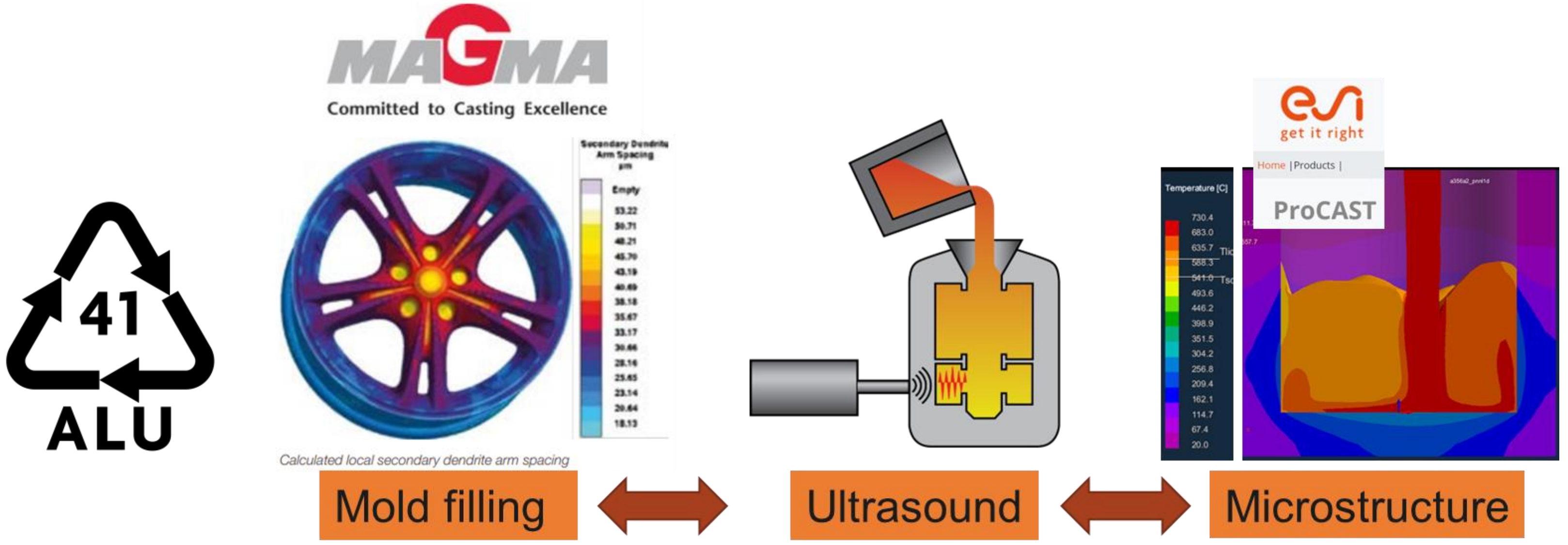
- Low x-ray absorption contrast between the liquid and the solid Al phases → Difficult to visualize ultrasonic effects during solidification in in situ imaging experiments

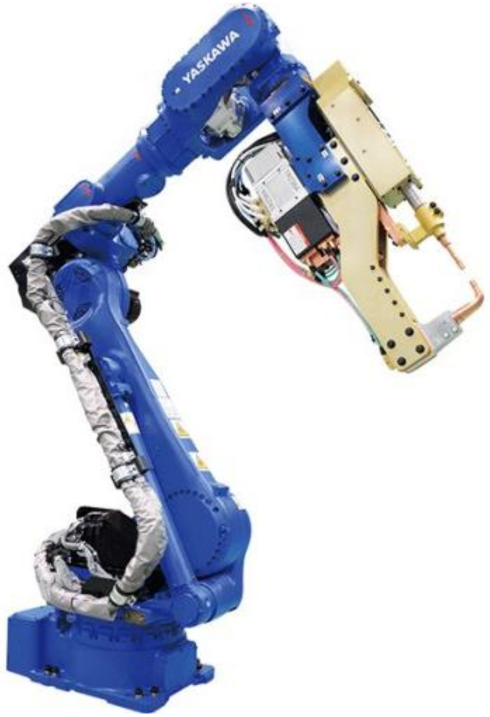
2. Heat Treatment of HPDC Alloy

- Coupled electrical-thermal modeling is needed to predict thermal profile during Joule heating of arbitrary geometrical shapes of automotive components

3. Peening

- Peening processes need to be developed for thin-walled and 3-D-shaped castings → Avoid distortion





FUTURE

1. Develop u/s for recycle-grade Al and integrate fluid dynamics with casting software
2. Robotic heat treatment; coupled electrical-thermal modeling
3. Robotic 3-D peening

Proposed Future Research

Task 1: Local ultrasonic intensification during casting solidification

- Data analysis of in situ diffraction experiments
- Data analysis of in situ imaging experiments
- Model effect of u/s in liquid + solid state

Task 3: Local surface-treatment intensification by WJP and LSP

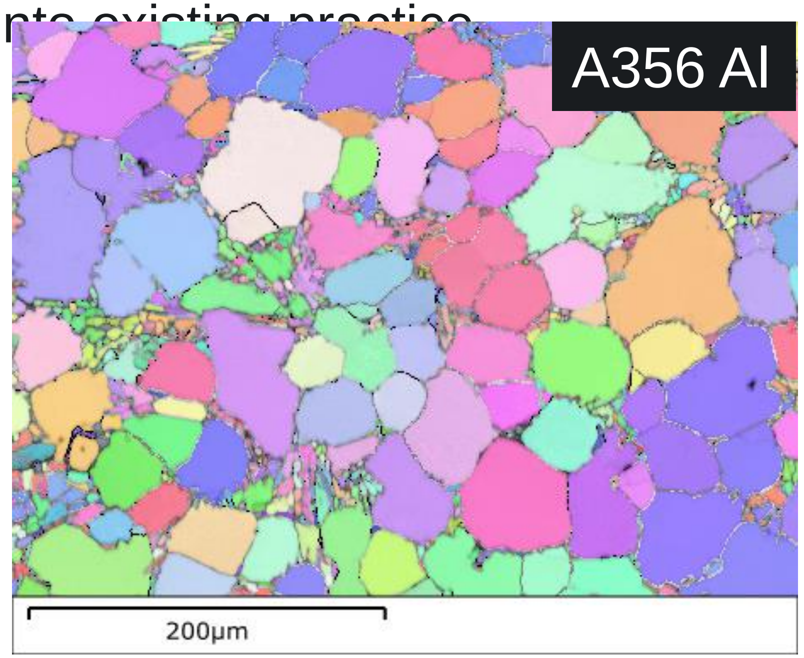
- Fatigue testing of peened cast Al (Target 2x improvement relative to unpeened Al)

Any proposed future work is subject to change based on funding levels

Summary

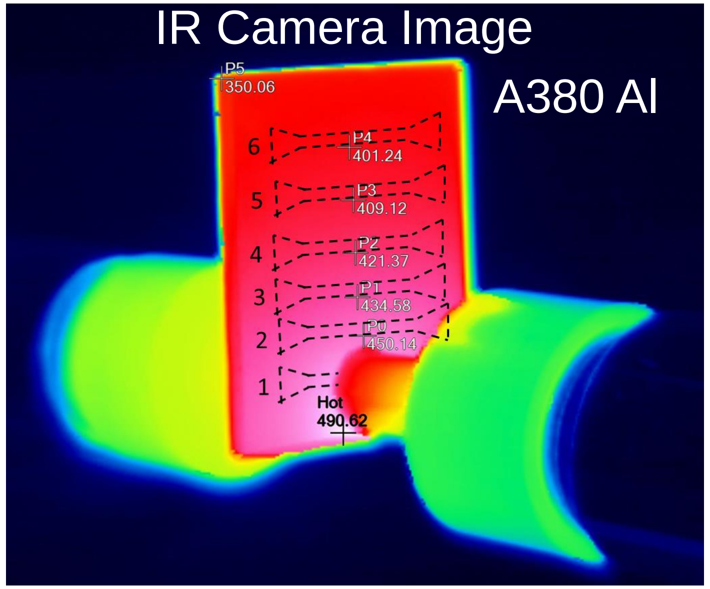
Sustainable and cost-effective Al castings through U/S processing

- Refined as-cast microstructure can enable greater use of recycled Al and produce high-strength and ductility
- Refinement ability is equivalent or better relative to chills, HPDC, grain refiners, and mechanical processing, enabling cost-effective integration into existing practice



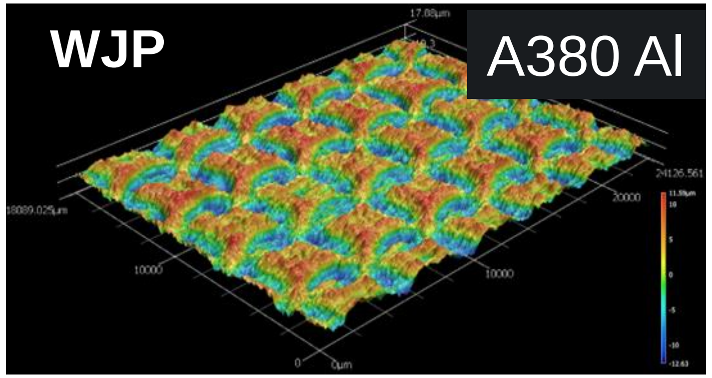
Heat treatment of large Al castings using Joule heating

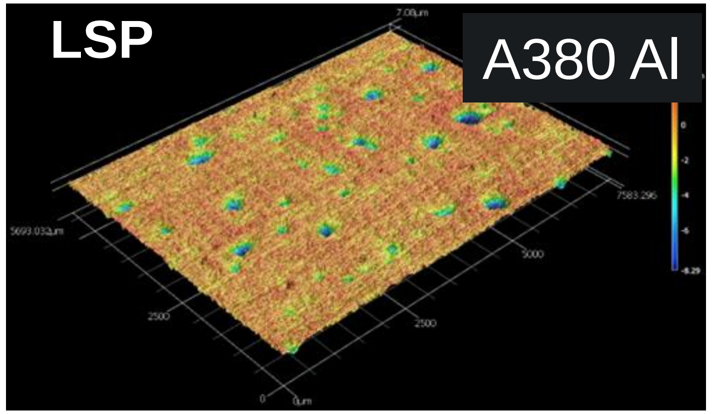
- Local strengthening is achievable without significant ductility loss or blistering



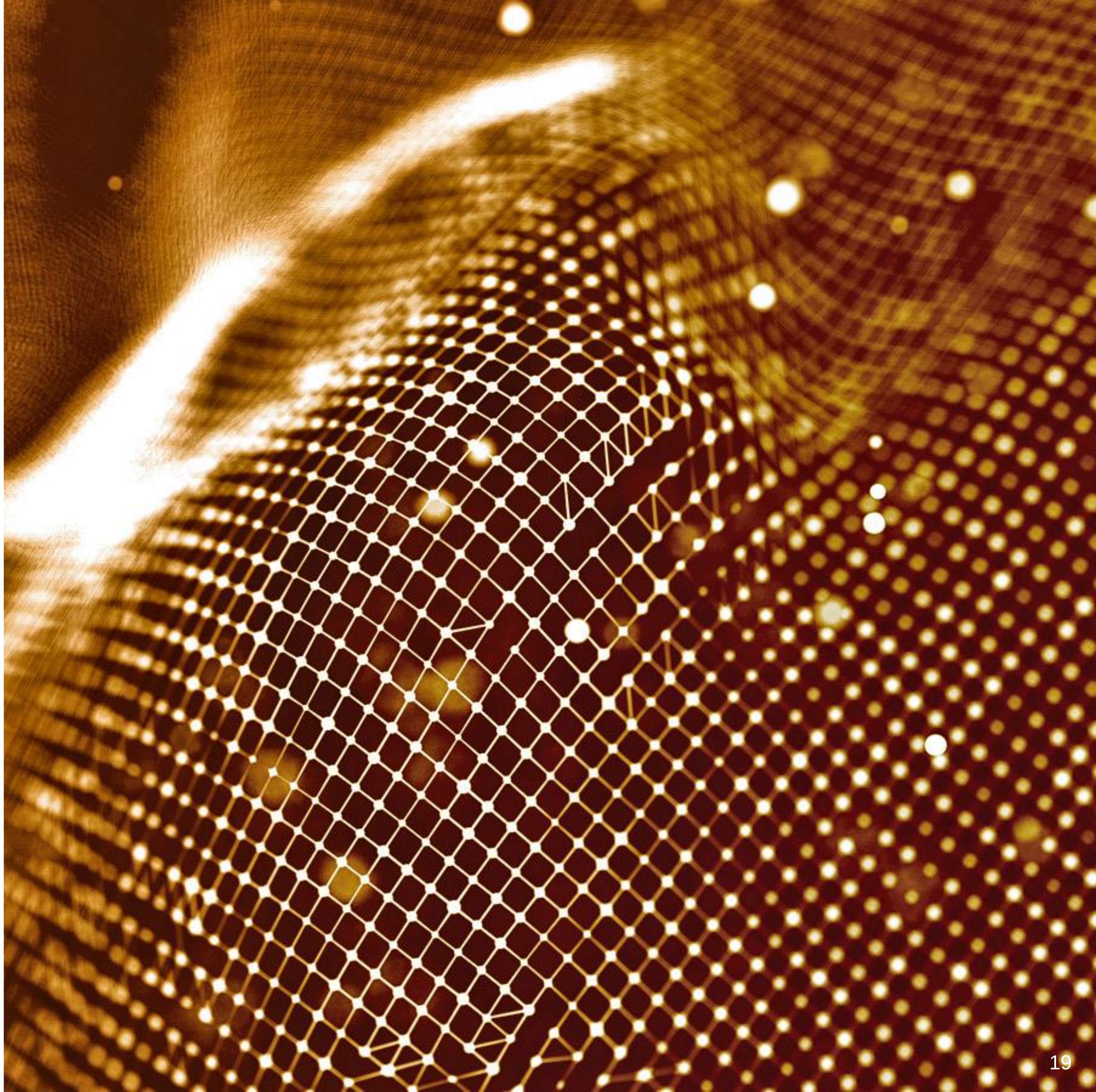
Distortion-free peening of thin Al castings

- 20 to 25% increase in sub-surface hardness (≈ residual stresses) → Increased fatigue life





Thank you



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Technical Backup Slides

U.S. DEPARTMENT OF ENERGY BATTELLE

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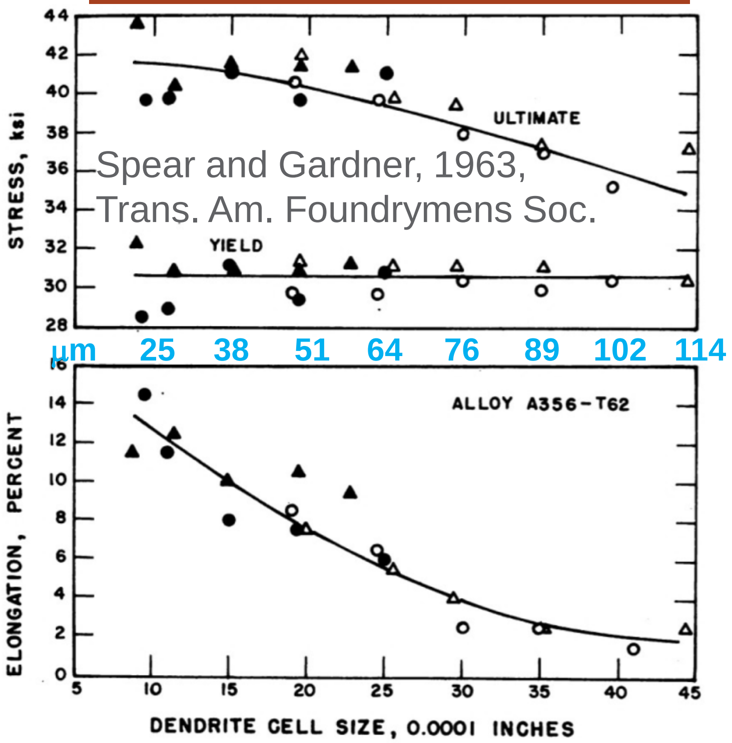
Background/Problem Statement

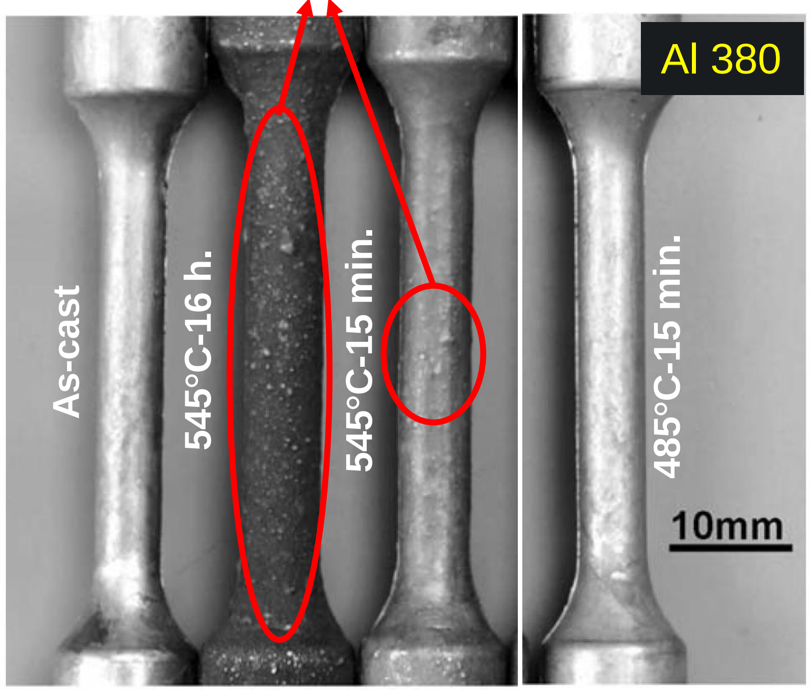
- Castings → Coarse microstructure, porosity, intermetallics → Poorer mechanical properties vs. wrought

PERF.

σ, Ductility. α 1/Dendrite Size

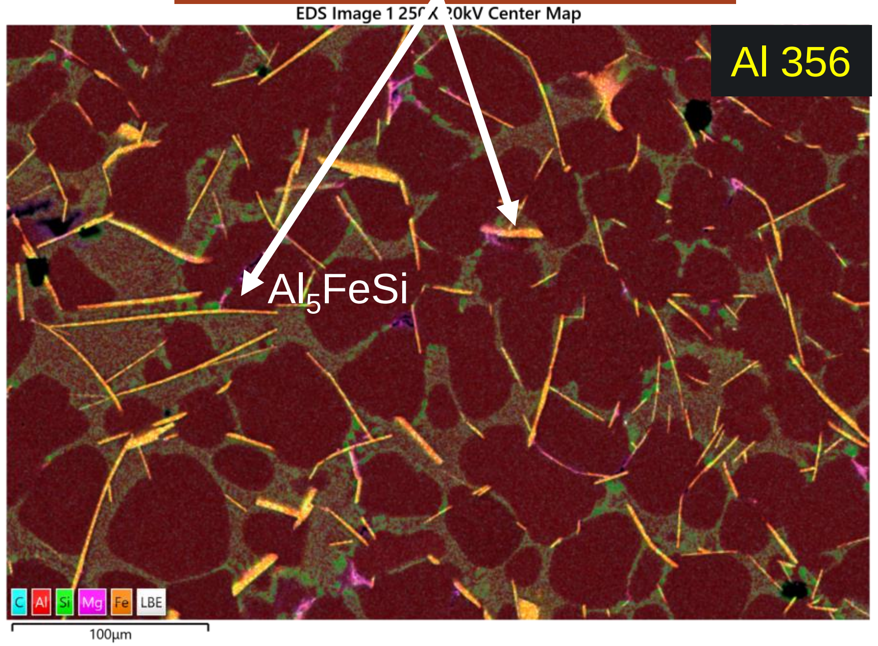


Blistering α (Temp., time)



Lumley et al., Met. Trans. A, 2007

Fatigue life 1/α Aspect ratio



PNNL (2020)

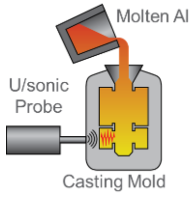
CURRENT PRACTICE

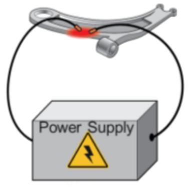
-Grain refiners (Al-Ti-B): ~100's µm
-Chills (↑ cooling rate): Practicality
-U/sonic in melt: Dendrites not broken

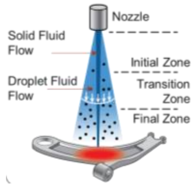
-Not heat treated → Lower strength (F or T5)
-Vacuum die-casting to reduce entrapped air (Expensive) → Furnace-heat treatable

-Shot peening: Access vs. casting geometry
-Primary alloys with low Fe%: Expensive
-Modifiers (Na, Sr): H_2 pickup, porosity, lower fluidity

Project Tasks



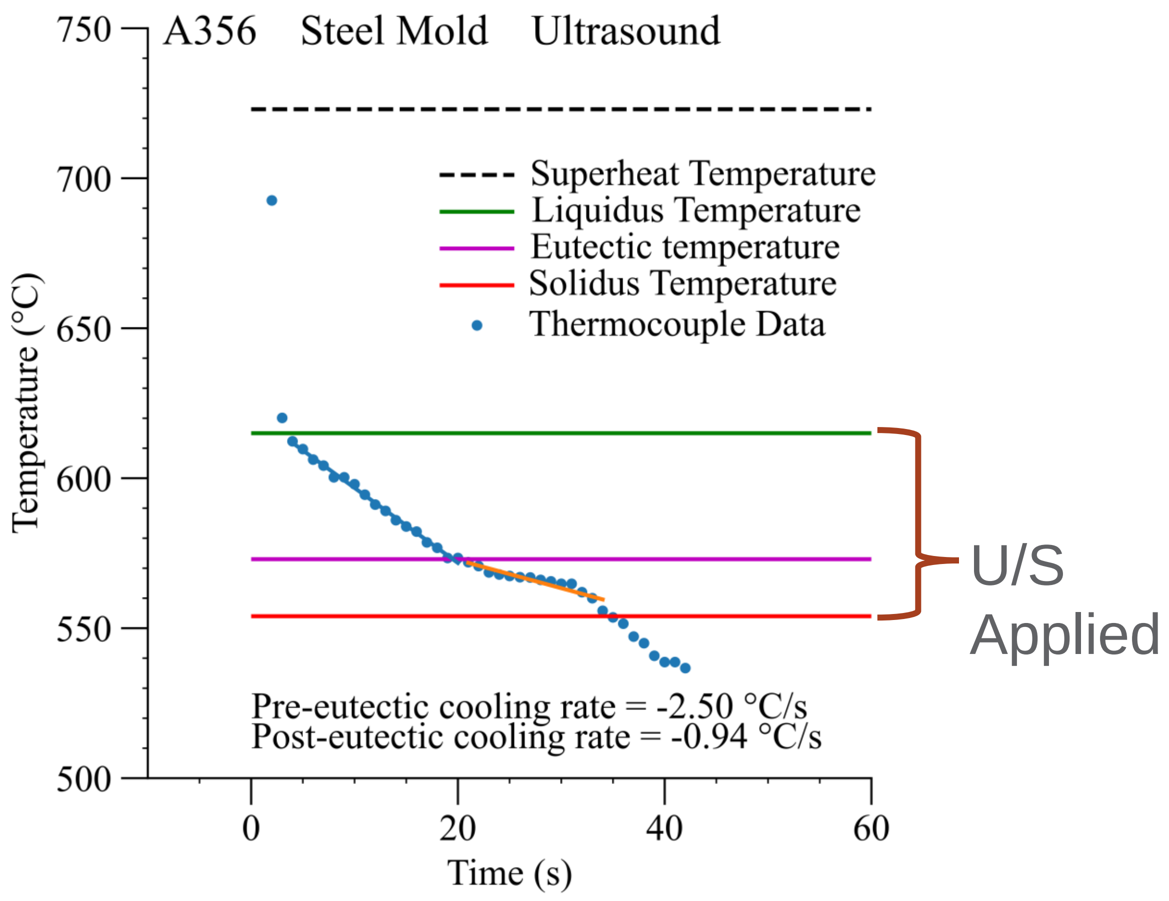


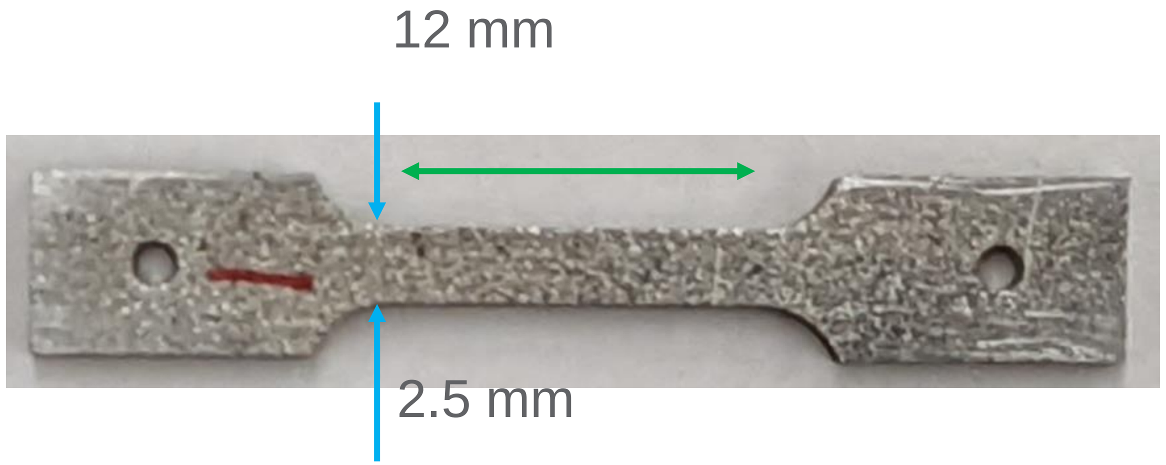


Task #	Task Name	FY21				FY22				FY23			
		Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4	Q1	Q2	Q3	Q4
Task A1	Alloy Selection												
Task A2	Mold Design												
Task A3	Integrate Ultrasonic Probe in the Mold												
Task A4	Solidification With and Without Ultrasonication												
Task A5	Characterization (Microstructure and Mechanical Properties)												
Task B1	Alloy Selection												
Task B2	Casting Design												
Task B3	Joule Heating Setup Design												
Task B4	Joule Heating and Furnace Heating Runs												
Task B5	Characterization (Microstructure and Mechanical Properties)												
Task C1	Alloy Selection												
Task C2	Casting Design												
Task C3	Water Jet Peening Equipment/Process												
Task C4	Characterization (Microstructure and Mechanical Properties)												

Task 1 Accomplishment

Ultrasonic Vibrations During Casting in Preheated Steel Mold





Tensile specimen geometry extracted from the casting

Solidification path, phases, and their amounts were calculated using the CompuTherm and Pandat database

Composition of each alloy in wt. %:

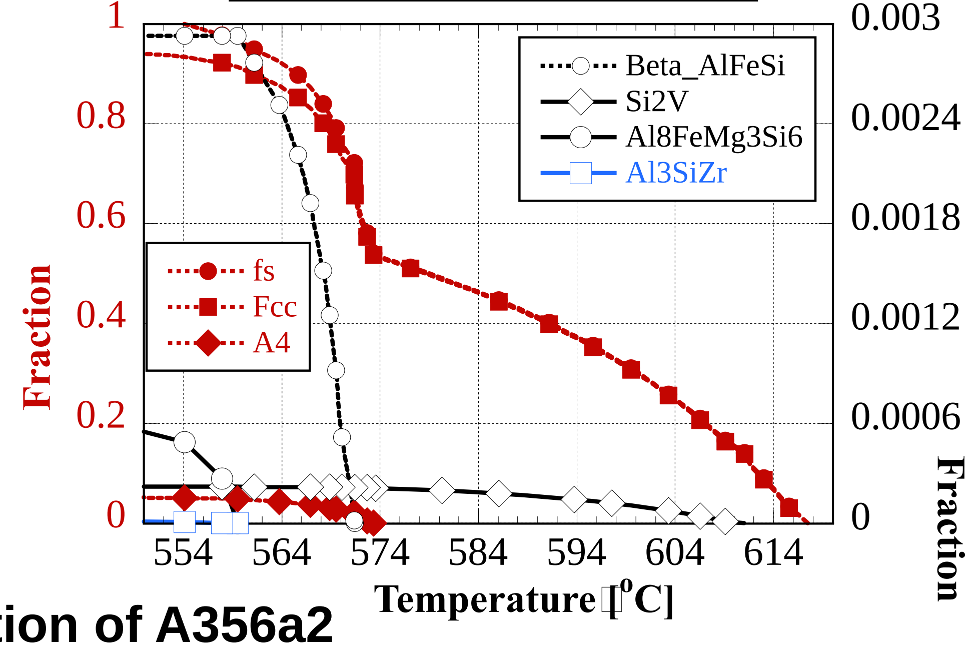
	Si	Cu	Fe	Mn	Mg	Ni	Ti	V	Zr
A356a1	6.72	0.0021	0.0867	0.002	0.418	0.0053	0.106	0.0169	0.0022
A356a2	6.78	0.0094	0.914	0.0092	0.354	-	0.112	0.0152	0.0013

Fraction of each phase expected in fully solid state:

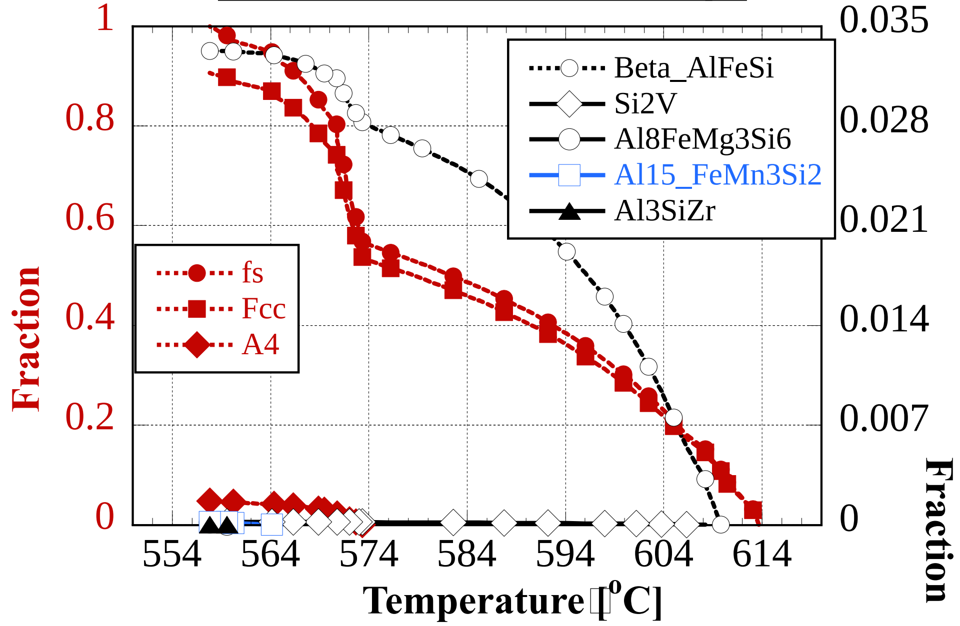
	Model	α-Al	Si (Diamond A4)	β-(Al_5FeSi)	$Al_8FeMg_3Si_6$	Mg_2Si
A356a1	**BD	94.16	5.195	0.293	0.056	-
	Scheil	93.78	5.233	0.269	0.112	0.322
A356a2	**BD	91.44	4.824	3.326	0.034	-
	Scheil	91.11	4.88	3.31	0.078	0.266

- Increasing Fe content from 0.09 wt.% (alloy A356a1) to 0.9 wt.% (alloy A356a2) increases fraction of β phase from 0.3% to 3%
- In alloy A356a2, the β phase begins to form at a higher temperature than in alloy A356a1 (~610 °C vs. ~571 °C)

Phase fraction of A356a1 as a function of temp.



Phase fraction of A356a2 as a function of temp.

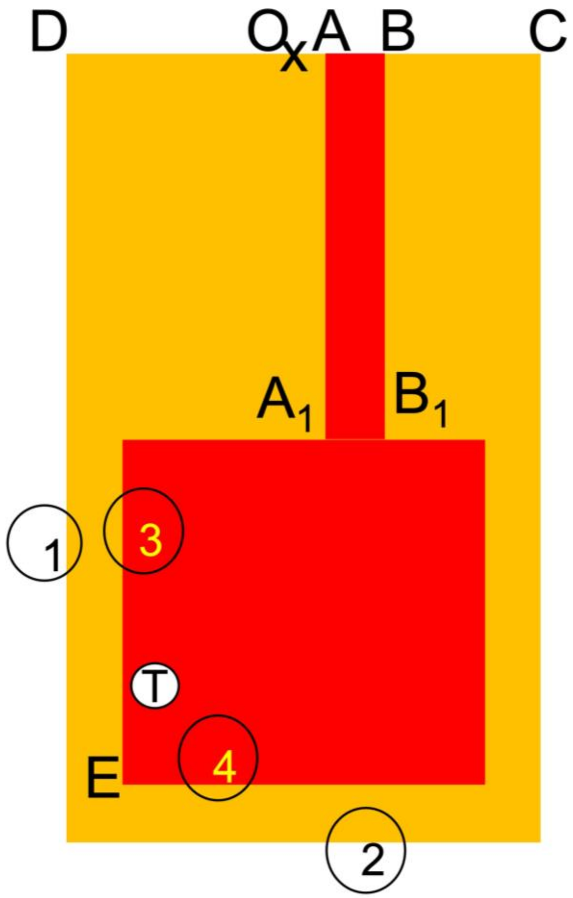


All casting conditions were identified from data provided by PNNL and ORNL based on prior experience

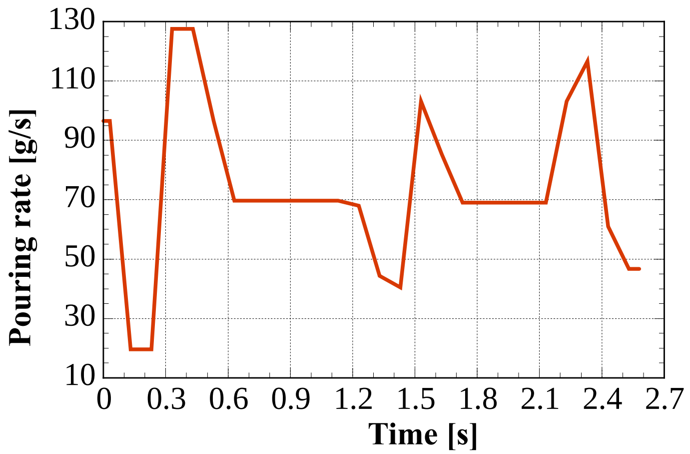
Mold-filling data (i.e., pouring area and flow rate) were obtained from experiments conducted at PNNL

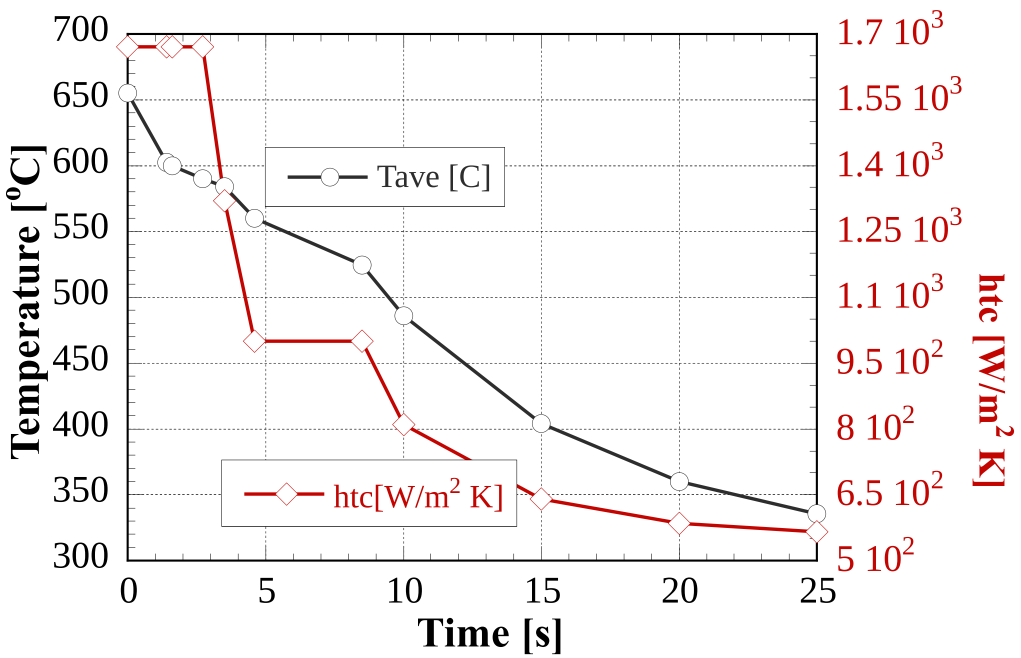
Schematic of mold (yellow), casting and pouring stream (red) indicating different boundary conditions needed for process simulations →

- Boundary condition 1 – heat-transfer coefficient around the mold circumference
- Boundary condition 2 – heat-transfer coefficient between the mold and support (contact pressure)
- Boundary conditions 3 & 4 – heat-transfer coefficient between the metal and mold



Pouring rate [g/s] obtained from experimental data:



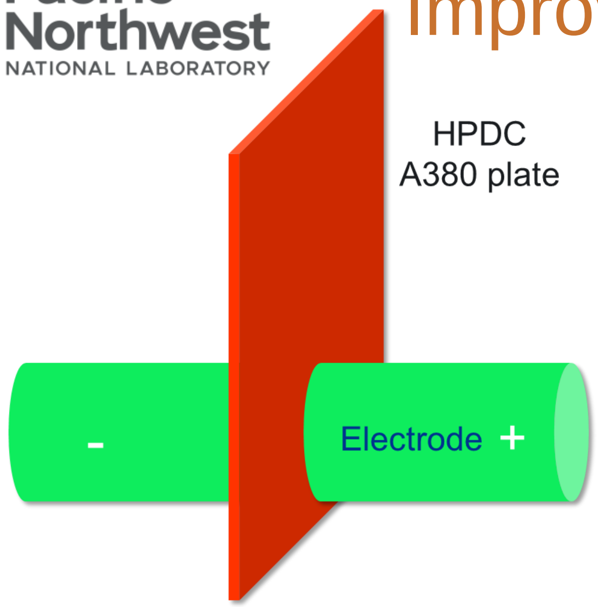


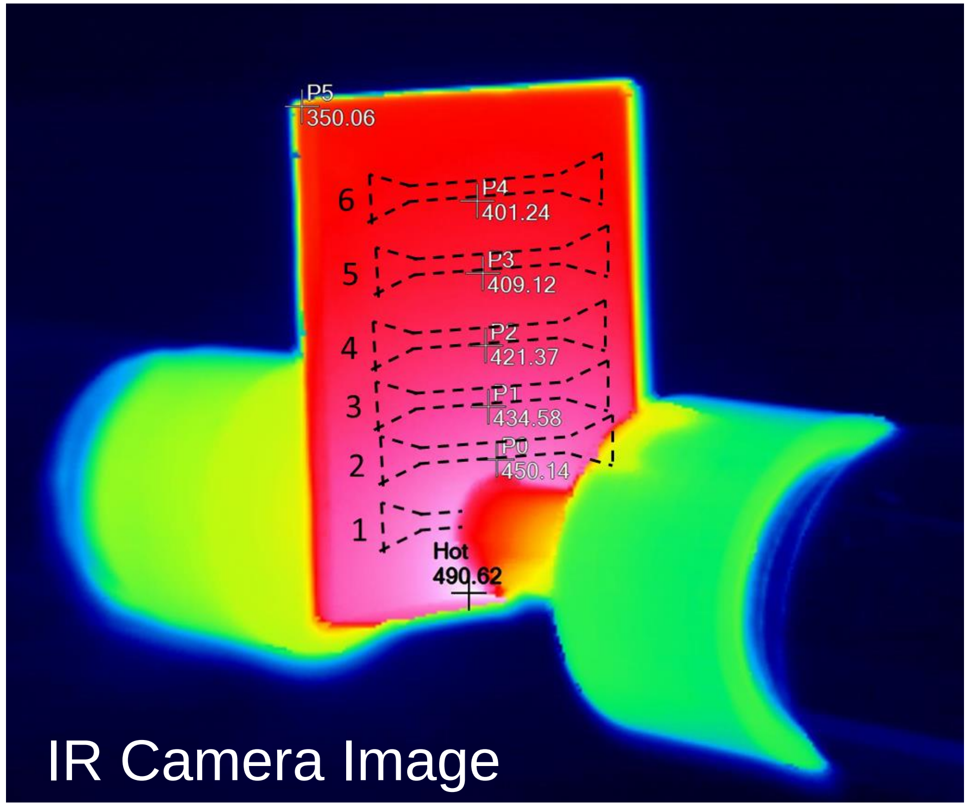
Data on HTC at metal-mold interface, as estimated from experimental measurements Sabau (2006)

←

Task 2 Accomplishment

Improvement in Mechanical Properties through Local HT



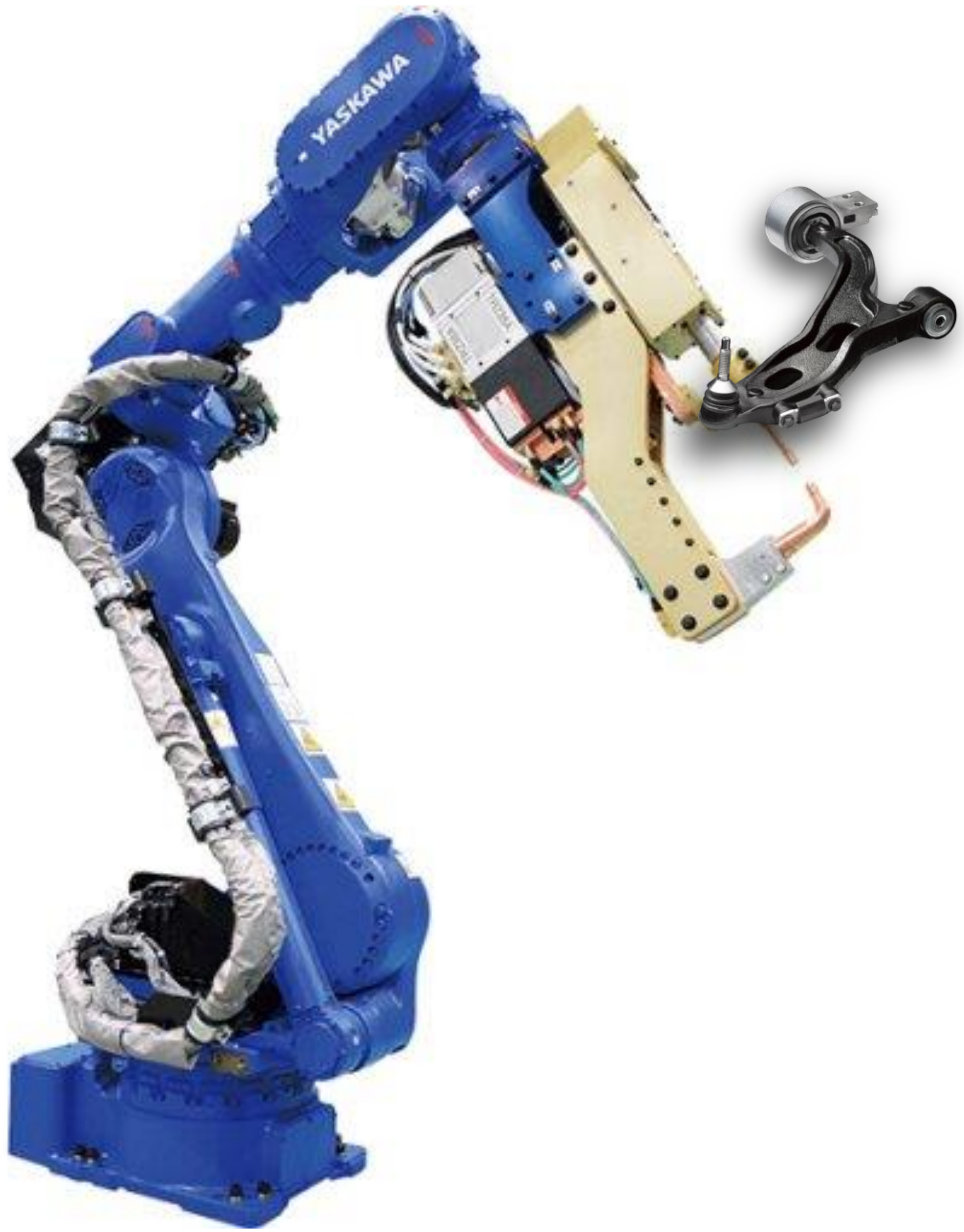


IR Camera Image

#Sample Location	*490 °C – 2 minutes Joule Heating			490 °C – 2 minutes Furnace Heating	As-Cast
	UTS	%el	Hardness		
1	308.0	1.76	68.5	Hardness: 62.3 ± 1.8	273.1 ± 16.9 MPa 2.7 ± 1.2 % (avg. of 10 samples) Hardness: 59.5 ± 1.7 HRB
2	260.8	1.01	67		
3	297.4	2.05	61		
4	269.1	1.83	55		
5			51		
6	260.2	2.01	48		

*maximum temperature adjacent to the electrode. Samples aged at 155 °C for 18 hrs.

Task 2
Implementation of Local Joule Heating

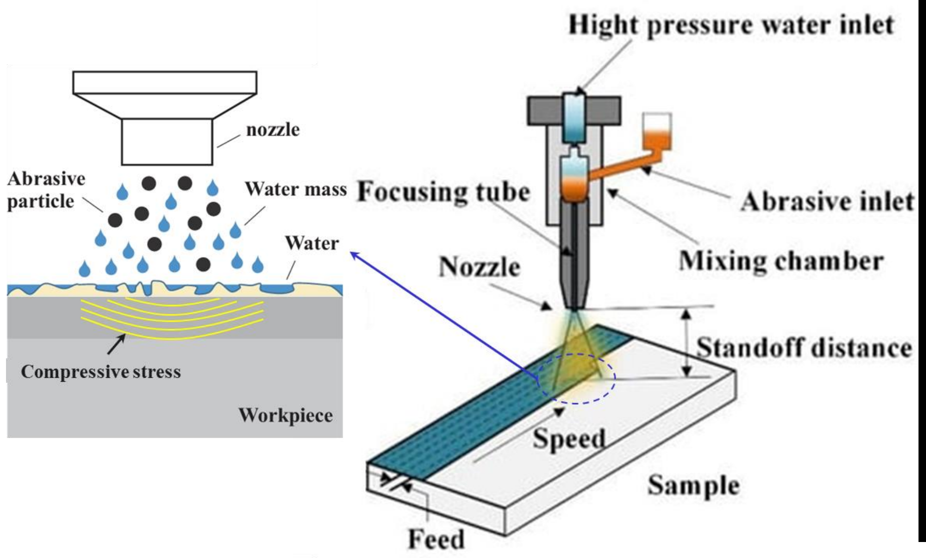


- Robotic aluminum spot welding is a commercial process in assembly lines
- Currents ~ 25 kA can be regularly achieved in robotic spot welding by drawing 150 A per phase in 440 V line
- Much less current is needed for local heating, ~ 100 A/mm^2
- Robot can perform the heat treatment on parts while moving them from one location to another
- Possible heat treatments are: solutionizing, rapid-aging, or just softening

Source: Yaskawa America, Inc.

Task 3 Accomplishment
Local Surface Treatment (HPDC A380 Plate)

WJP(Sugino Corporation)



LSP (LSP Technologies)