# Physics of Ultrasonic Treatment of Metals & Applications


**Raquel Fierro Jaime**

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*Advisor: Prof. Diran Apelian, UC Irvine*

*Focus Group: Martijn Vos, Mark Henson, James Herbert, Brian Began, Stuart Weisner, Ravi Tilak, Mick Nallen*


December 11th, 2024

ADVANCED CASTING RESEARCH CENTER





UCI Samueli School of Engineering | Department of Materials Science and Engineering

# Outline

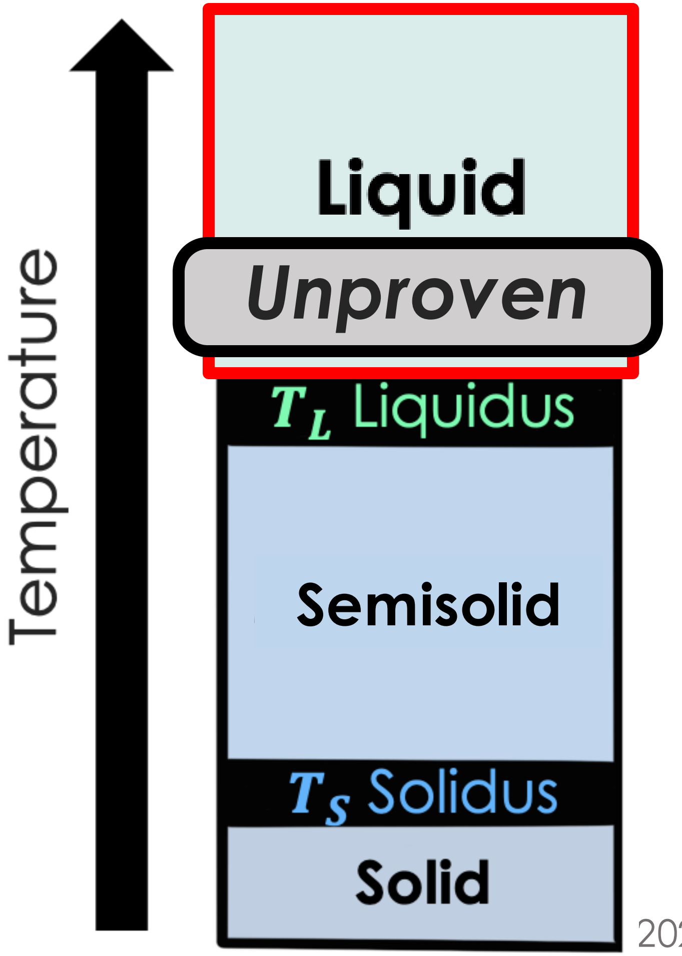
| | |
|---|---|
| *(5 min.)* | 1. **Liquid-State Multifrequency UST Applications** |
| *(5 min.)* | 2. **Hypothesis & Approach** |
| *(16 min.)* | 3. **Results of Intermetallic Mod. & Grain Ref.** |
| *(2 min.)* | 4. **Next Steps** |
| *Total: 28 min.* | |

# Outline

1. **Liquid-State Multifrequency UST Applications**
2. Hypothesis & Approach
3. Results of Intermetallic Mod. & Grain Ref.
4. Next Steps

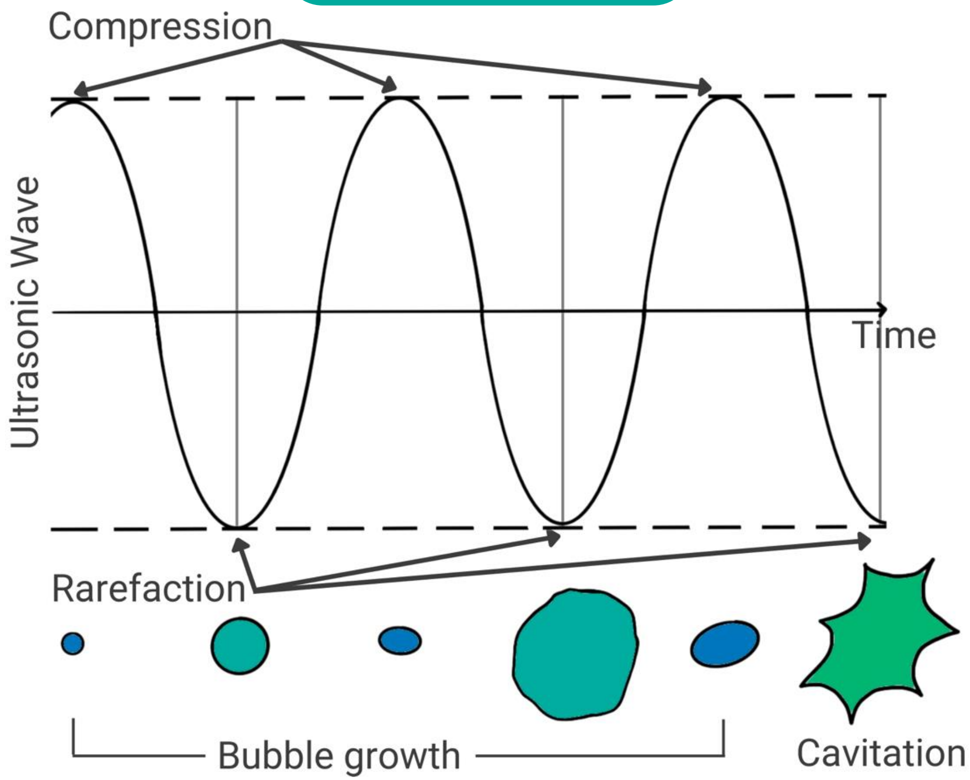
# Ultrasonic Treatment (UST) of Aluminum

*Applying ultrasonic waves to the molten state metal for microstructural modification*

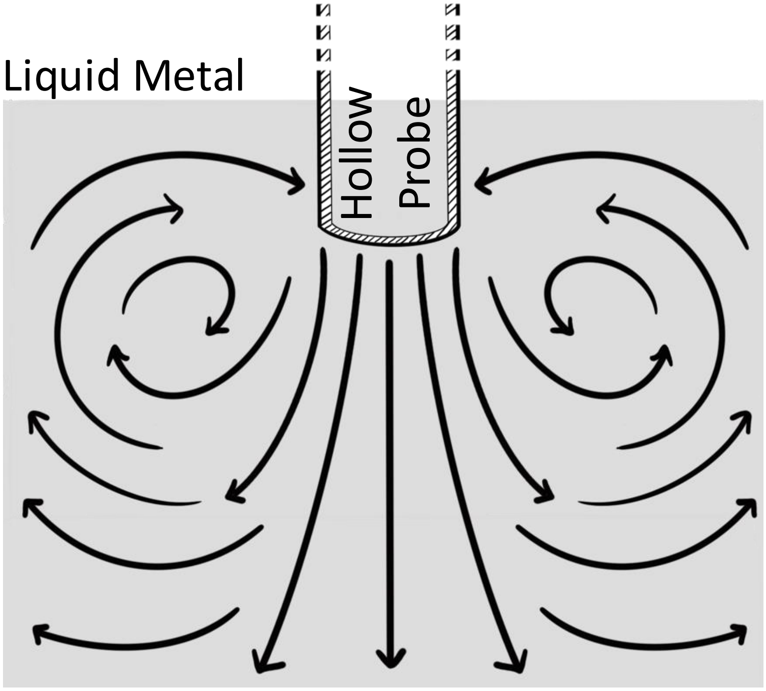



2024

**Cavitation**




**Streaming**



# Liquid-State UST Applications & Goals

*Jan-Mar 2024*

**Degassing** *(recap)*
*Hydrogen/Inclusion Removal*

*Mar-Present 2024*

**Intermetallic Morphology Modification**
*Modify phases without chemical additions*

**Grain Refinement**
*Reduce grain size without chemical refiners*

*O. Fishman, Inductotherm*

# Liquid-State UST Applications & Goals

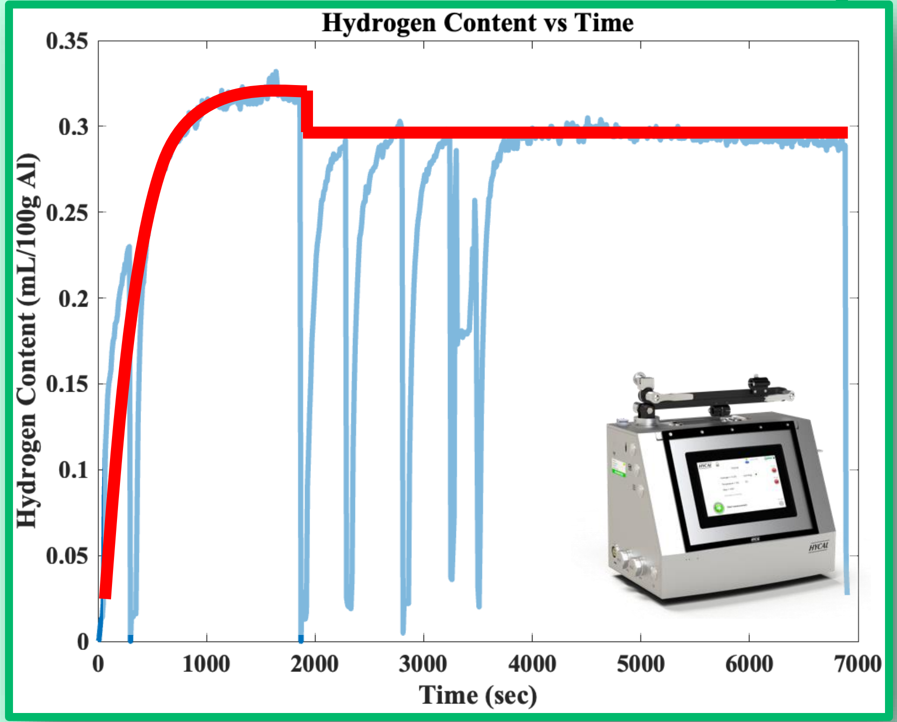
*Jan-Mar 2024* | *Mar-Present 2024*

**Degassing** *(recap)* | Intermetallic | Grain Refinement

## *Results*

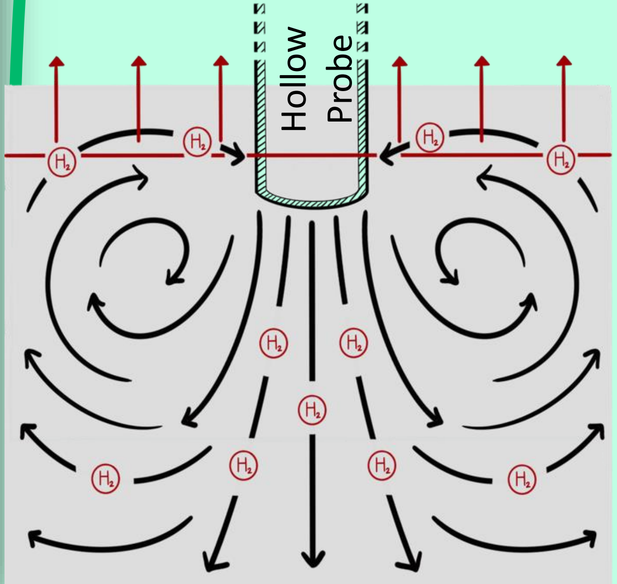
*As Cast A356*

*UST A356*

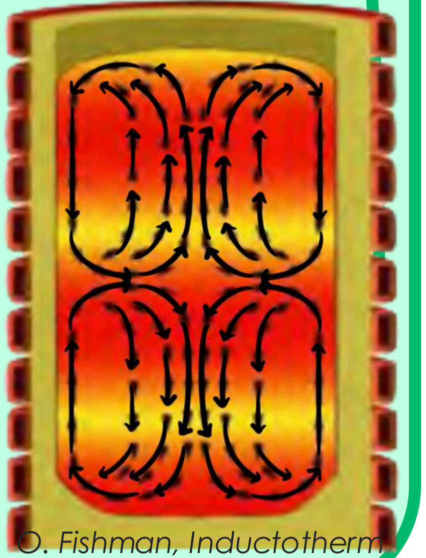



## *Reasoning*

*UST Degassing*
*5 secs on, **2 secs off***




*Inductive Convection*



*O. Fishman, Inductotherm*

# Liquid-State UST Applications & Goals

Jan-Mar 2024

Mar-Present 2024

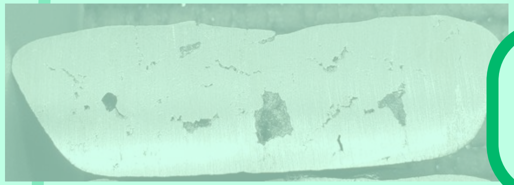
**Degassing** *(recap)*

Intermetallic

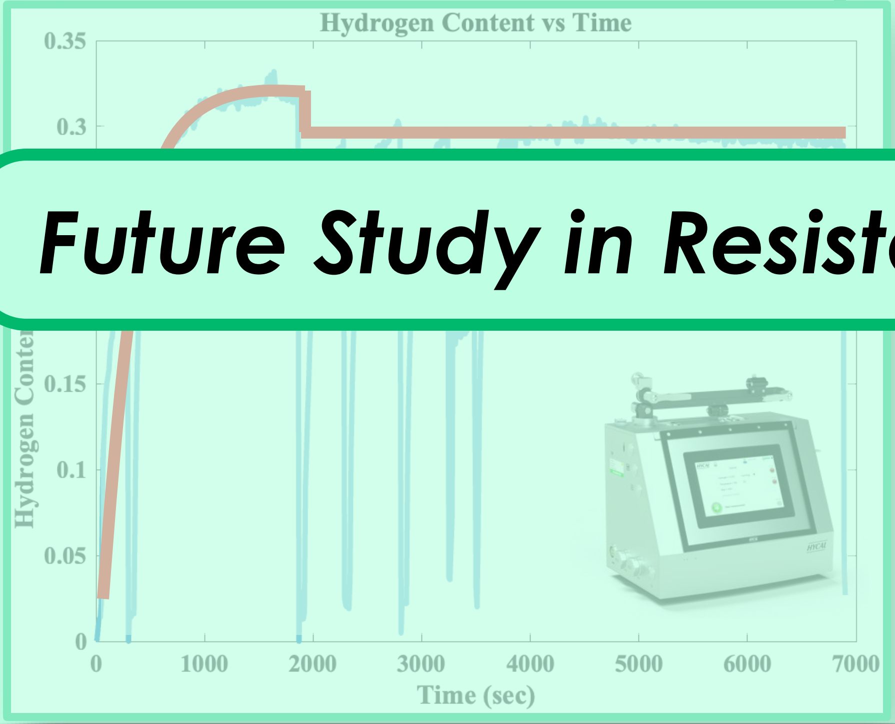
Grain Refinement

Results

As Cast A356

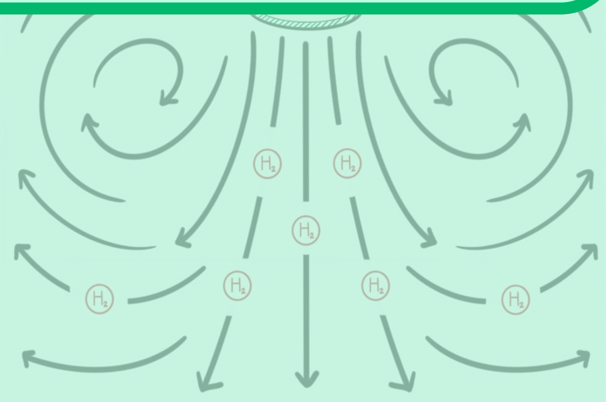


UST A356

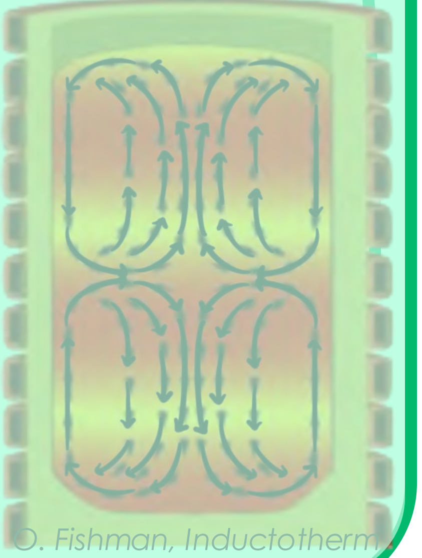



Reasoning

UST Degassing
5 secs on, **2 secs off**



Inductive Convection




***Future Study in Resistance Furnace***

# Liquid-State UST Applications & Goals

*Jan-Mar 2024*

**Degassing** *(recap)*
*Hydrogen/Inclusion Removal*

*Mar-Present 2024*

**Intermetallic Morphology Modification**
*Modify phases without chemical additions*

**Grain Refinement**
*Reduce grain size without chemical refiners*

**Goal:**
*Explain underlying mechanisms of Intermetallic Modification & Grain Refinement*

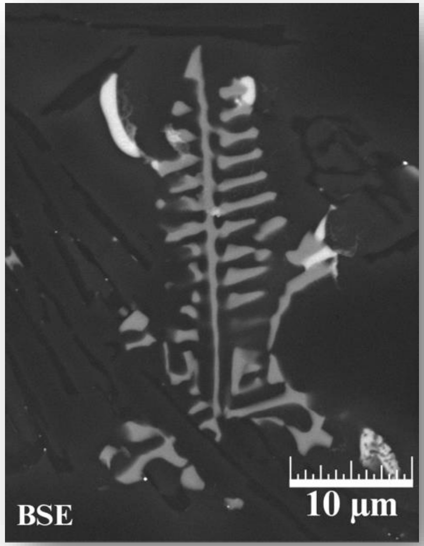
# Outline

1. Liquid-State Multifrequency UST Applications
2. **Hypothesis & Approach**
3. Results of Intermetallic Mod. & Grain Ref.
4. Next Steps

# UST for Intermetallic Mod. & Grain Ref.

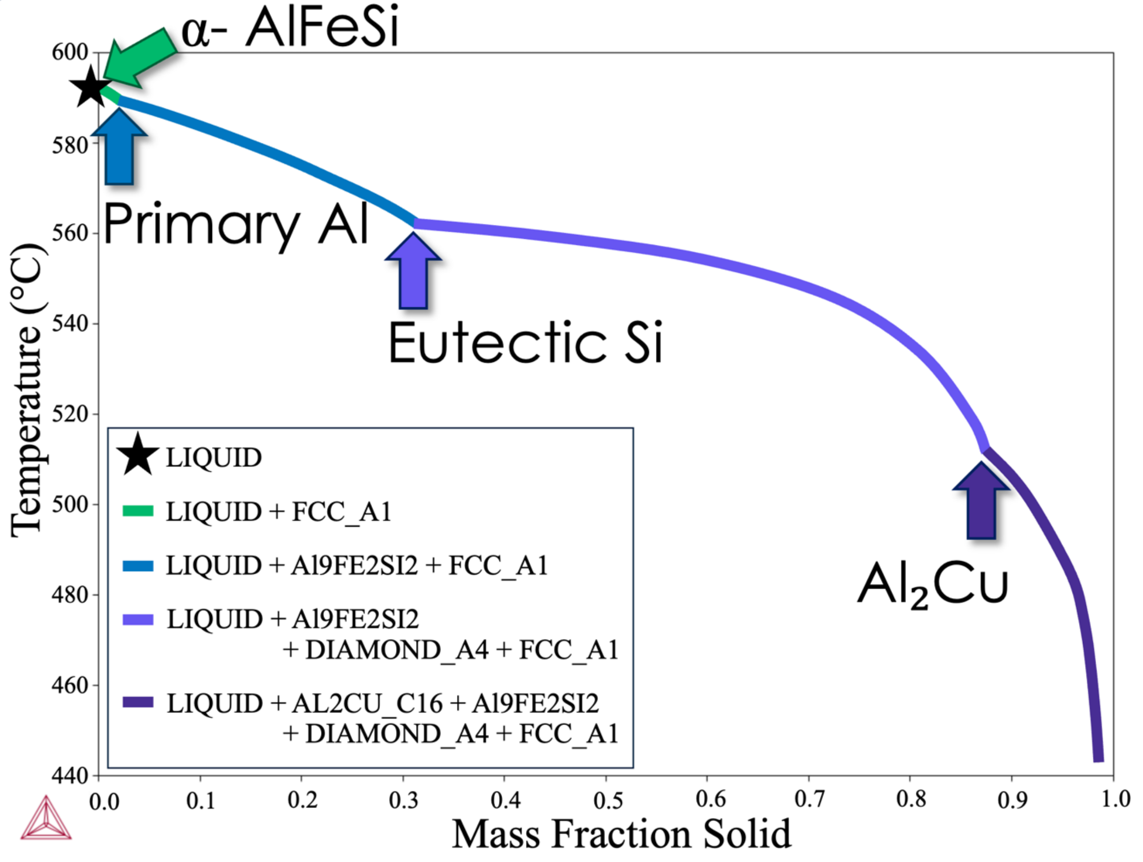
*Target:* **Treat recycled Al compositions with detrimental phases**

α-AlFeSi




Si Eutectic

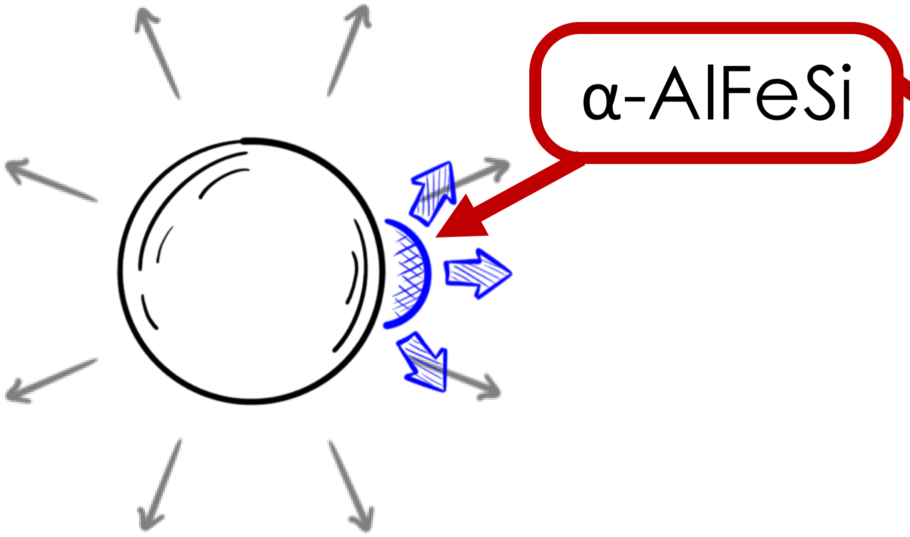

## Aluminum A380




| | wt % |
|---|---|
| Si | 8.25 |
| Cu | 3.53 |
| Fe | 0.845 |
| Mn | 0.200 |
| Cr | 0.0698 |
| Zn | 2.27 |
| Mg | 0.0808 |

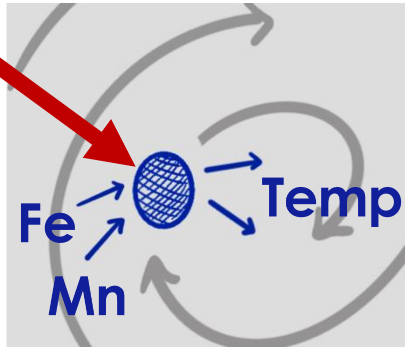
# Hypothesis for Liquid State Treatment

## Cavitation Undercooling

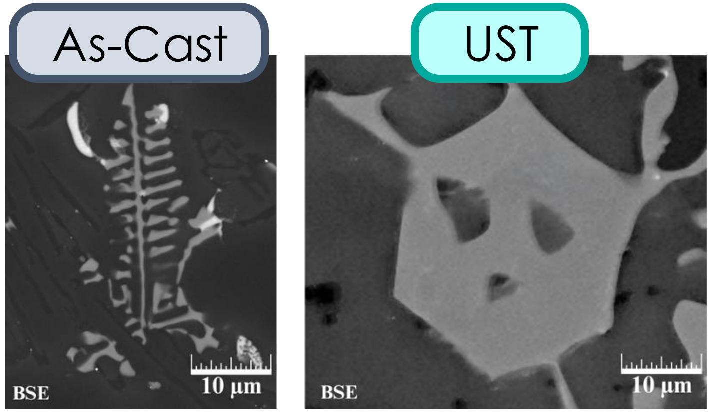


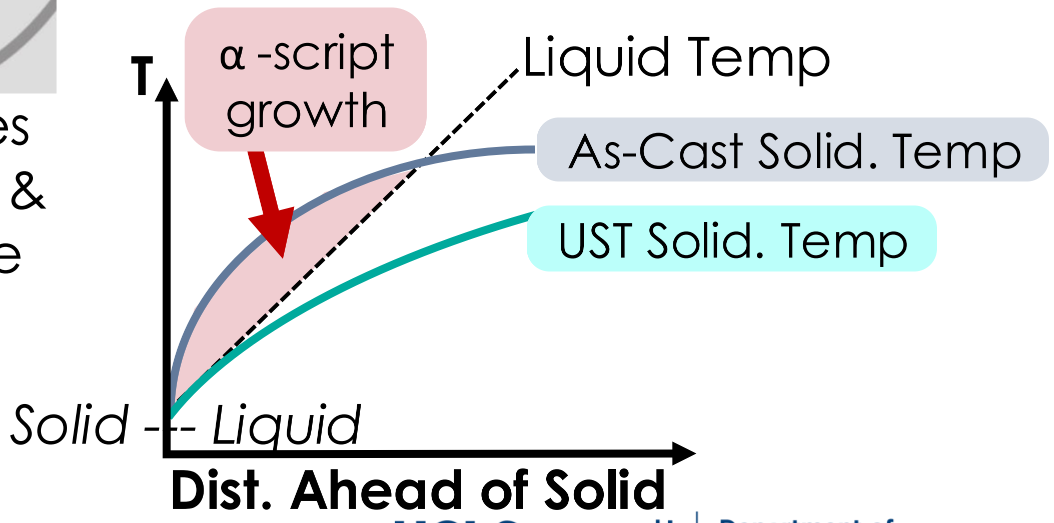

Cavitation bubble expansion results in local undercooling & nucleation

## UST-Enhanced Diffusion




Homogenizes Composition & Temperature



# Liquid State Multifrequency UST Trials

*Investigate limiting factors as functions of*
***Intermetallic Modification & Grain Refinement***

| Treatment Temperature | Treatment Time | Volume Treated | Decay with Time |
|---|---|---|---|
| $T > T_{Liquidus}$<br>Phase mod. varies<br><br>Grain refinement at all temps | > 5 minutes forms β-AlFeSi | Effects minimized with greater volume | Refinement remains 20 minutes after UST |

# Outline

1. Liquid-State Multifrequency UST Applications
2. Hypothesis & Approach
3. **Results of Intermetallic Mod. & Grain Ref.**
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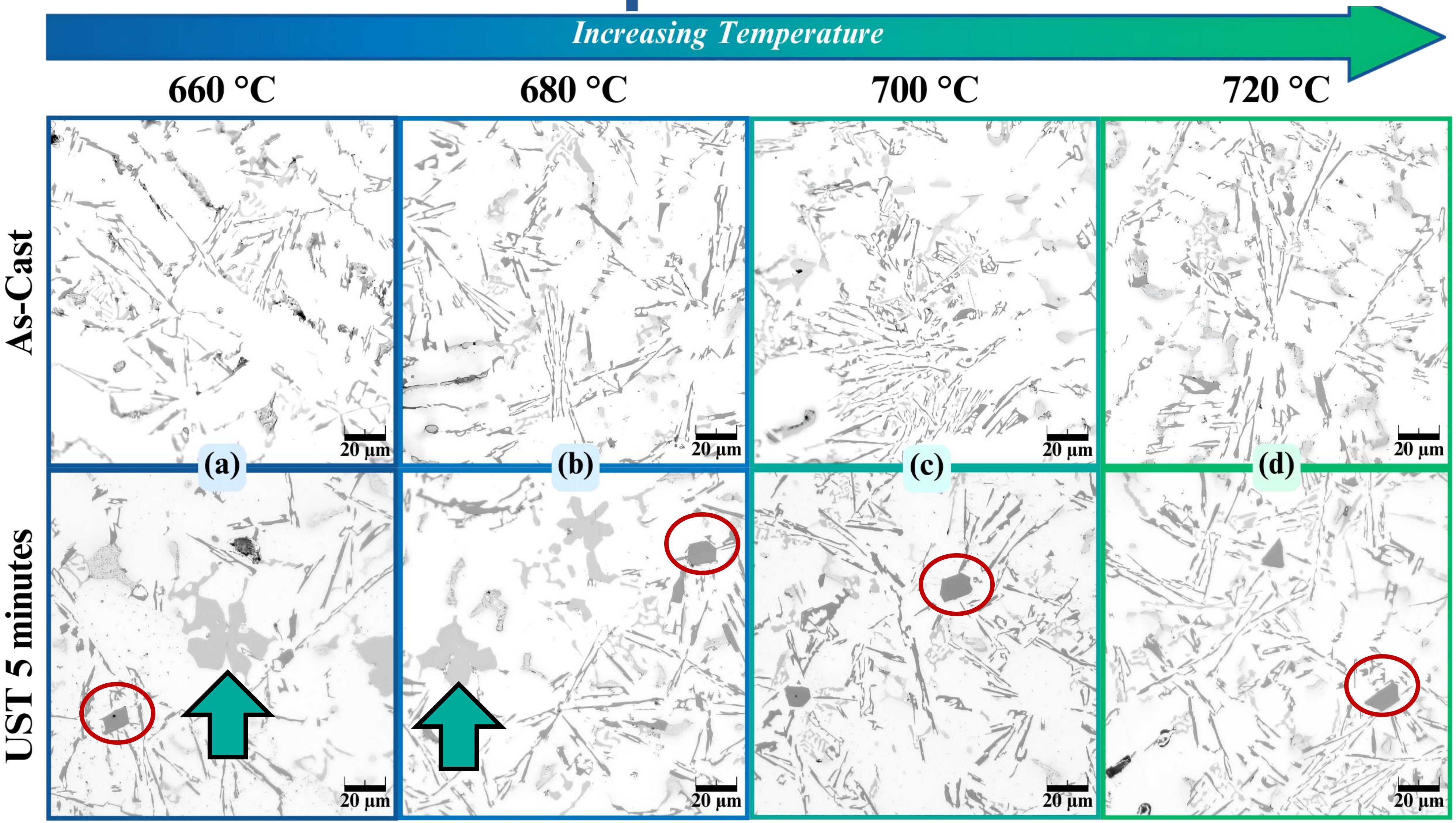
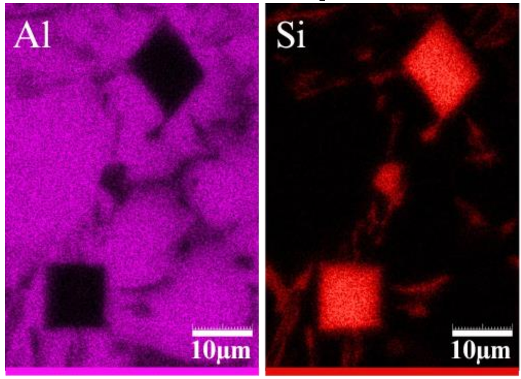
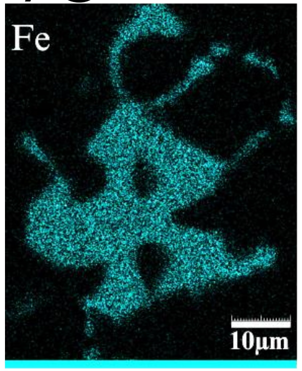
# Treatment Temperature



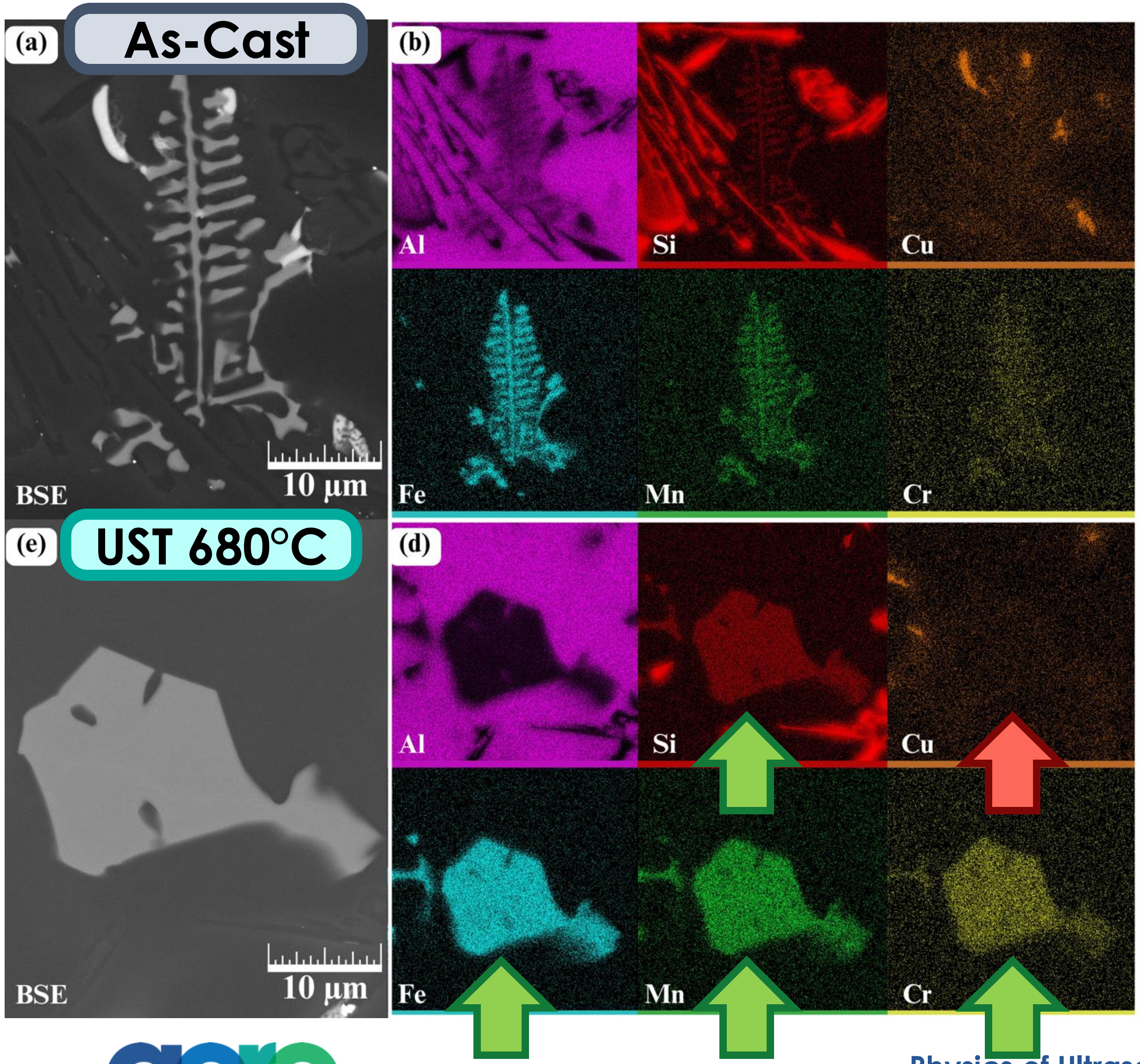

Primary Si

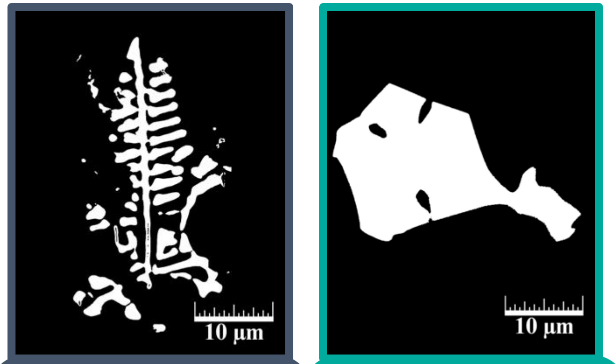



Polygonal-Fe



# α-AlFeSi Phase Relative Composition




| wt% | As-Cast | UST 680°C |
|---|---|---|
| Al | 70.79 | 61.71 |
| Si | **8.82** | **10.25** |
| Cr | **0.94** | **2.97** |
| Fe | **11.53** | **16.03** |
| Mn | **2.91** | **6.15** |
| Cu | 3.78 | 1.16 |
| Zn | 1.23 | 1.73 |

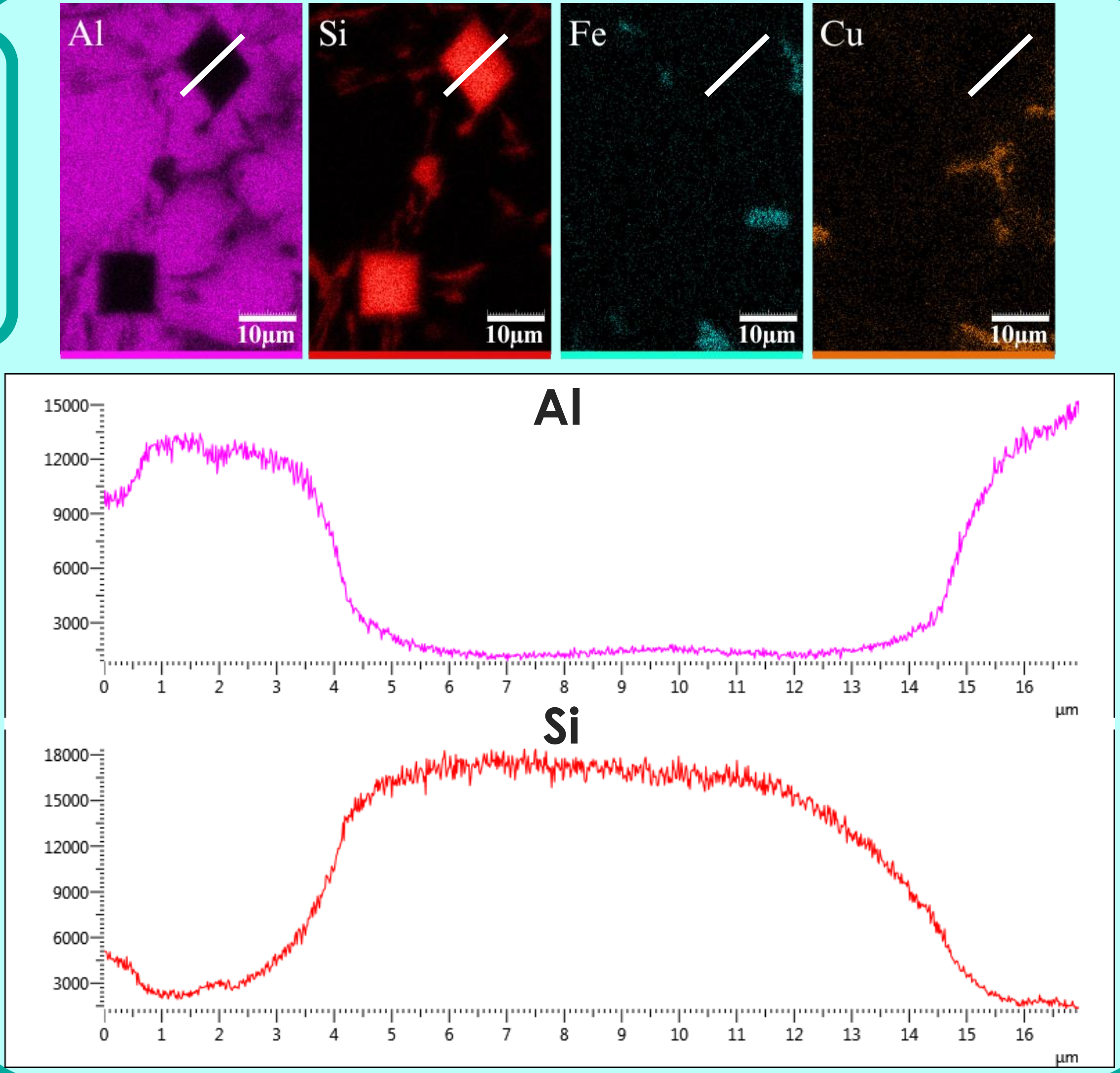
*Attributed to UST-enhanced diffusion…*

**Increases**

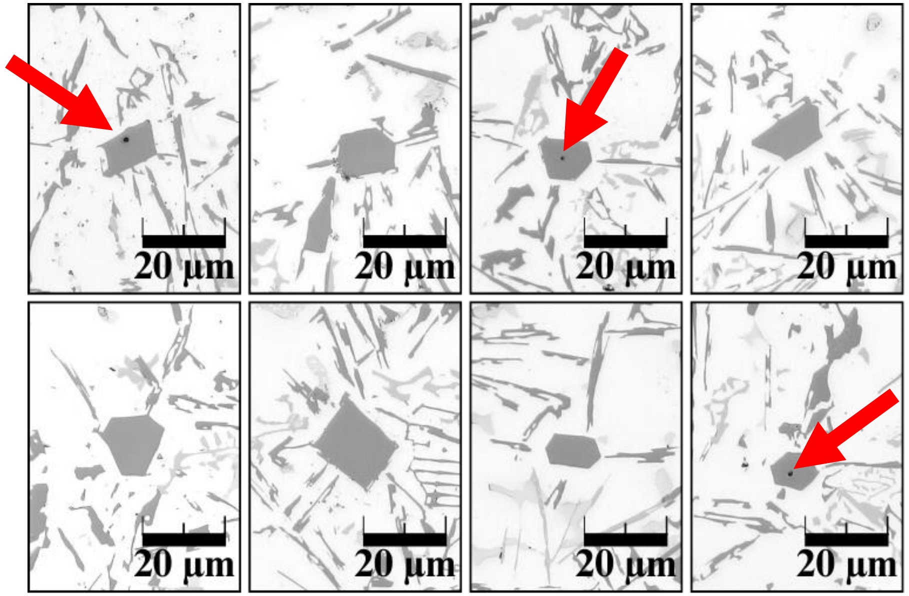
**Decrease**

# Primary Si

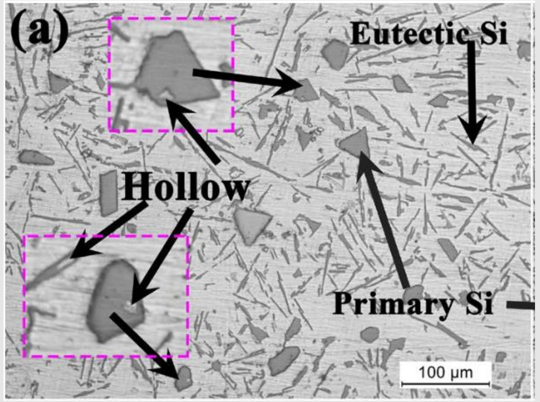
UST 700°C




*UST Hypoeutectic A380*

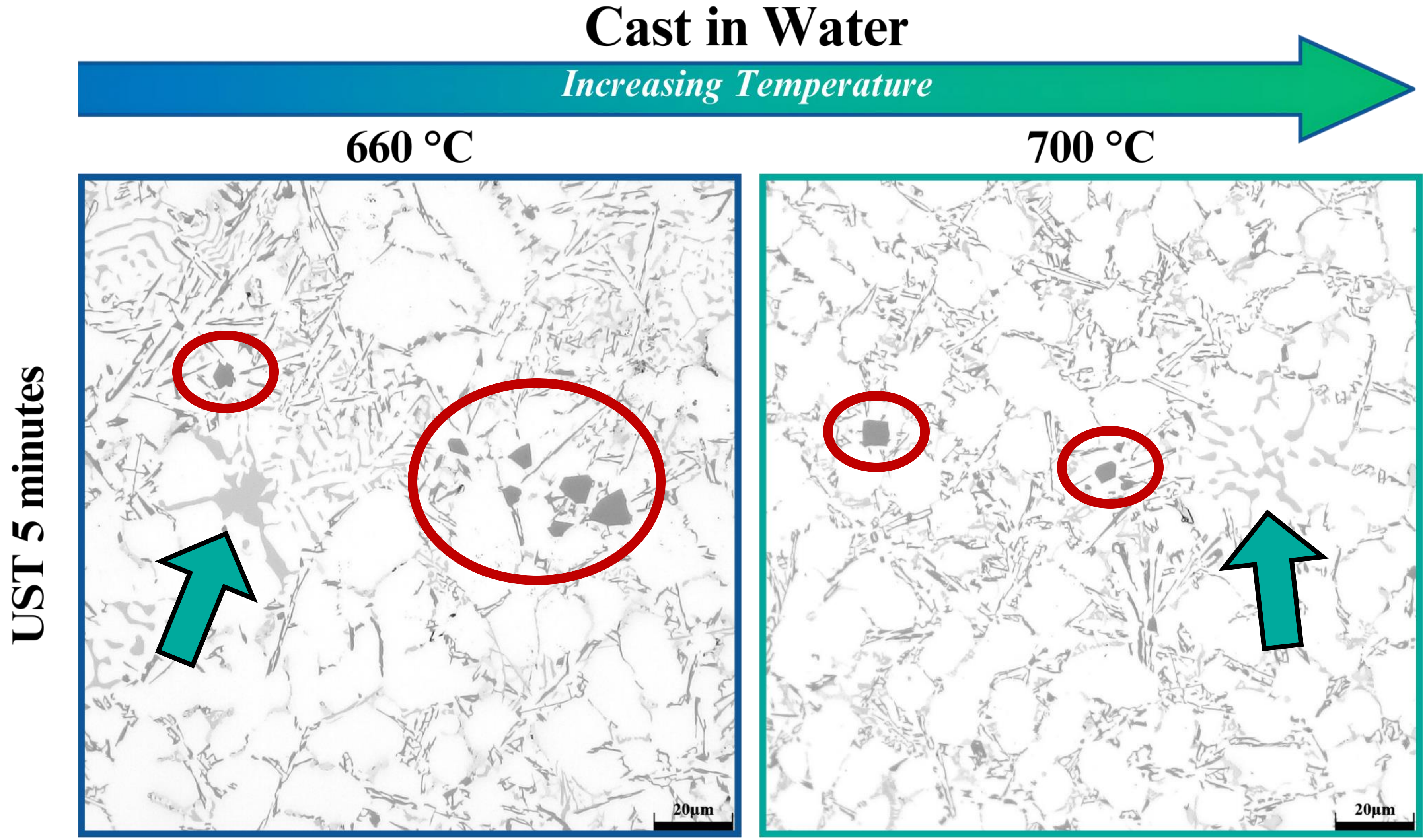



*Hypereutectic Al-Si Alloy*




P. Biswas, *et al* Metals & Materials International, 2019

# High Temperature Existence

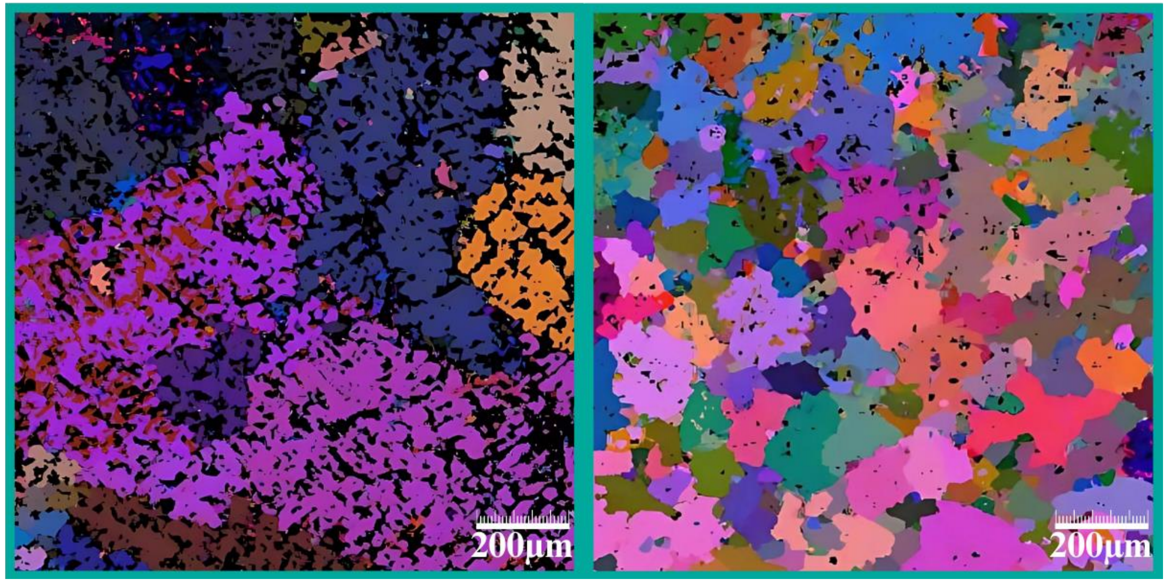


# Grain Refinement

*Connection between Intermetallic Modification & Grain Refinement*

700 °C

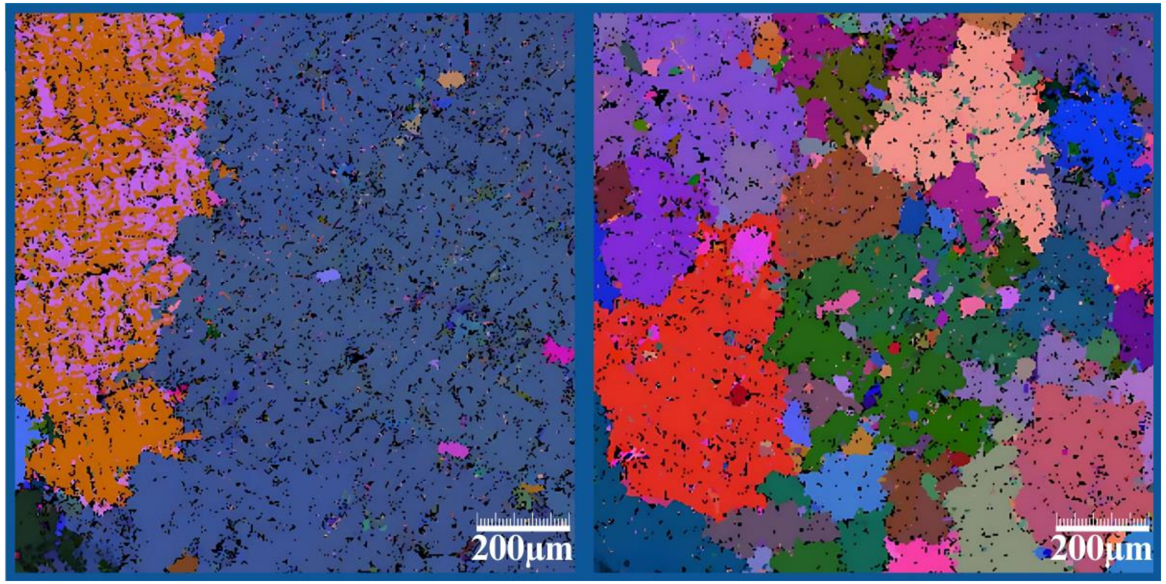
As-Cast | UST 5 minutes




Avg. 452.9 µm | Avg. 110.5 µm

660 °C

As-Cast | UST 5 minutes



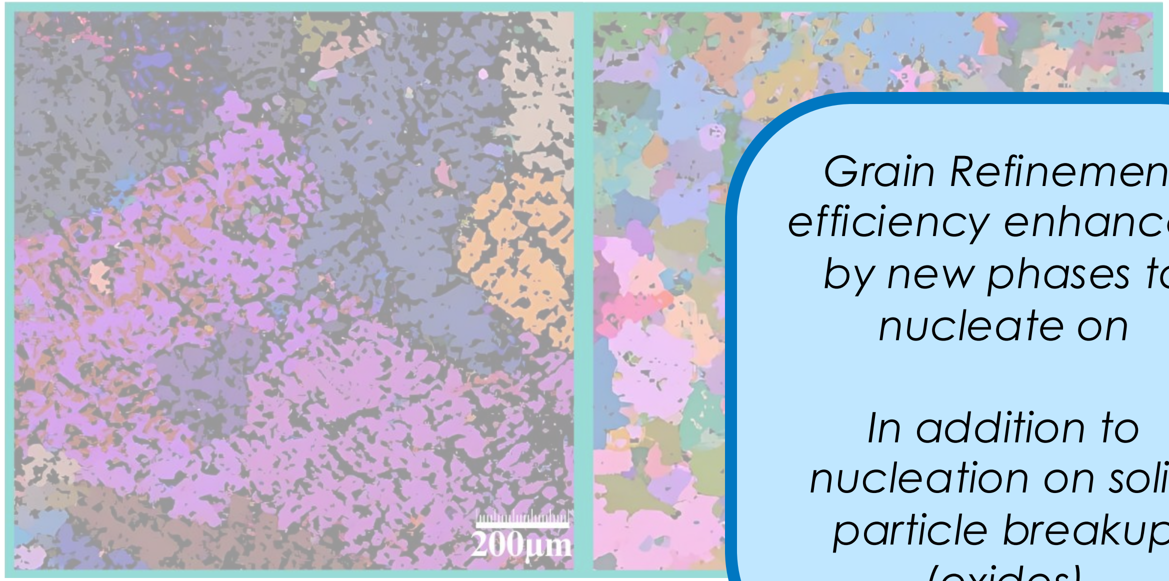

Avg. >1301.6 µm | Avg. 192.9 µm

**700°C: 75% decrease**

**660°C: 85% decrease**

# Grain Refinement

*Connection between Intermetallic Modification & Grain Refinement*

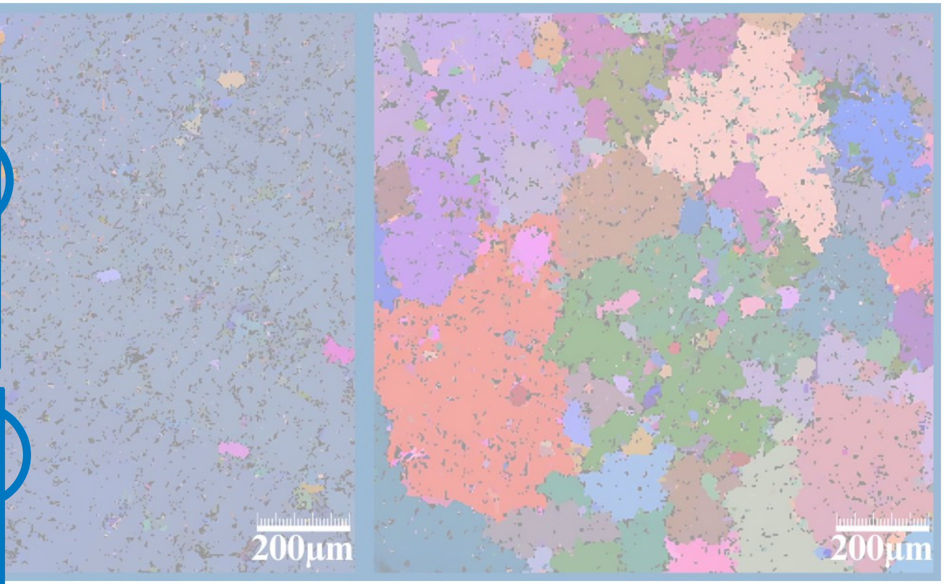



Avg. 452.9 µm

Av

*Grain Refinement efficiency enhanced by new phases to nucleate on*

*In addition to nucleation on solid particle breakup (oxides)*

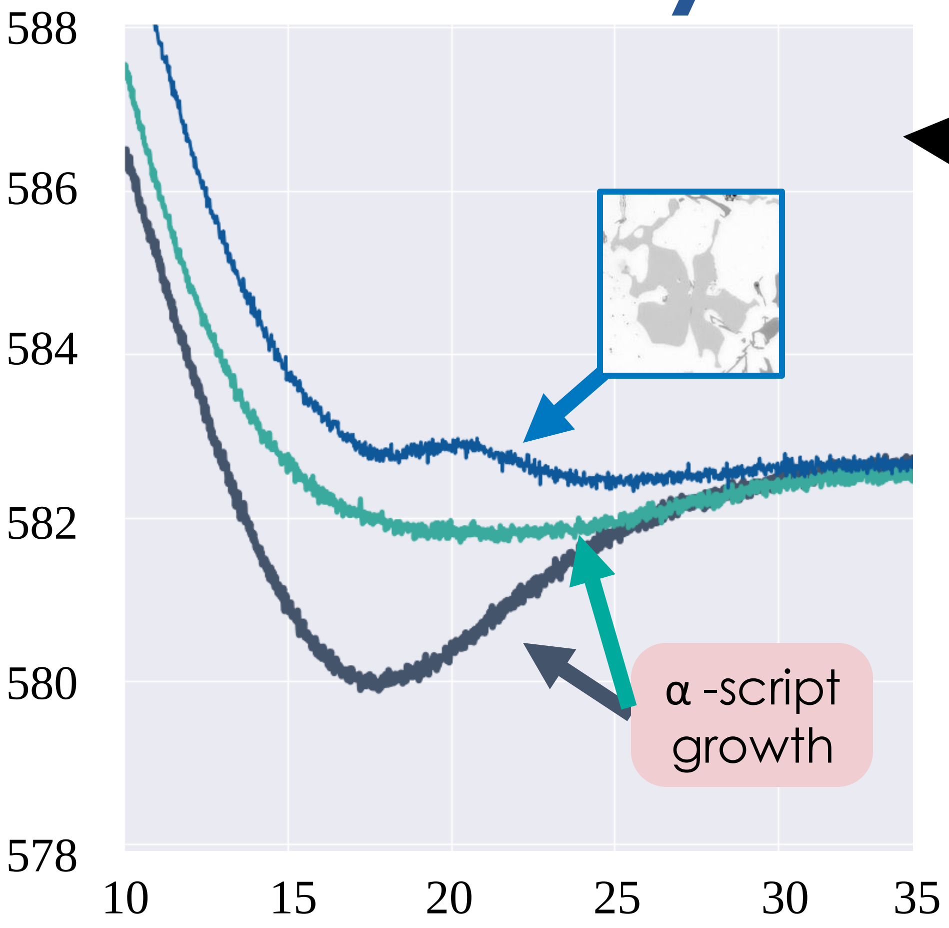

>1301.6 µm

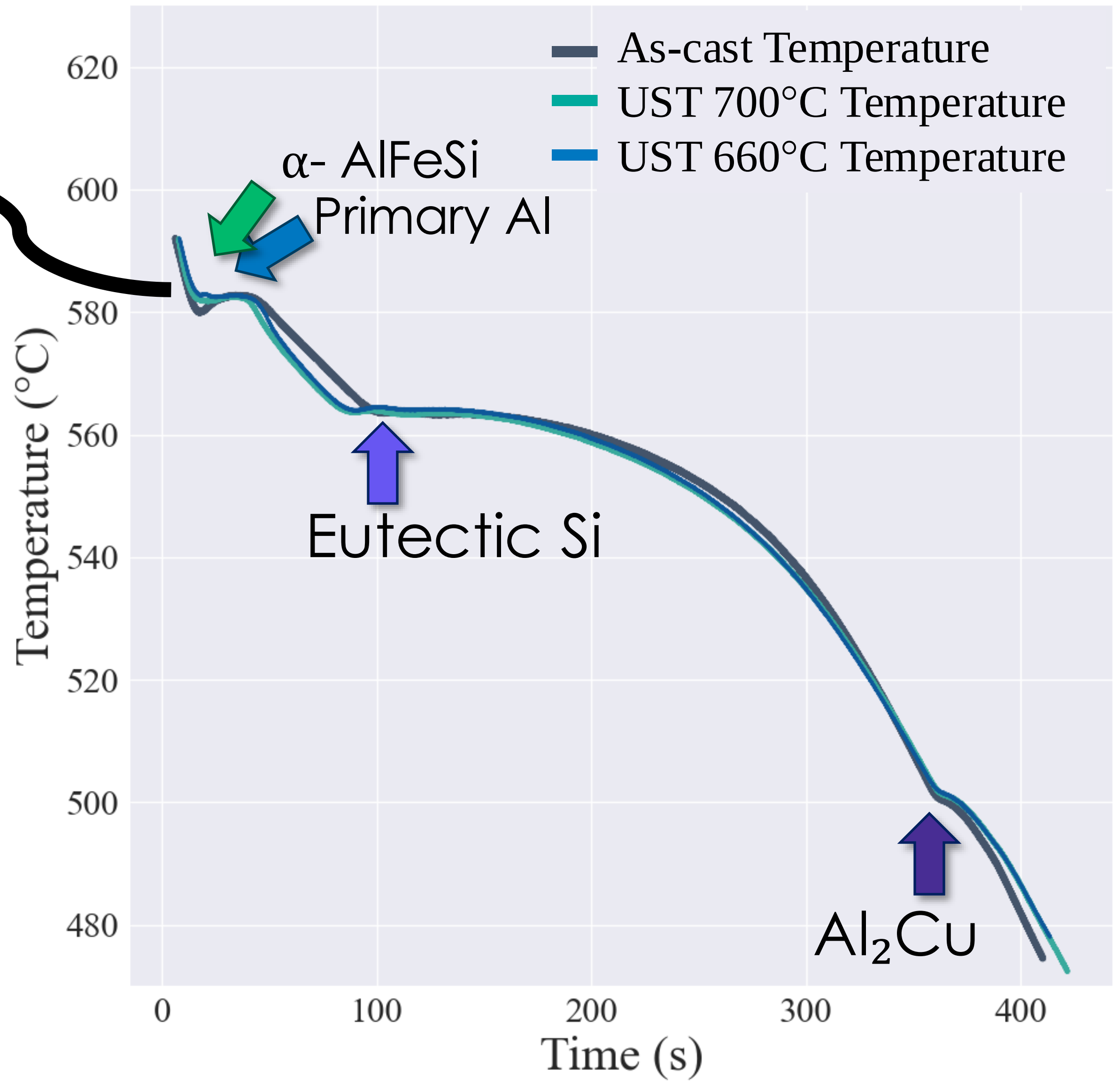
Avg. 192.9 µm

**700°C: 75% decrease**

**660°C: 85% decrease**

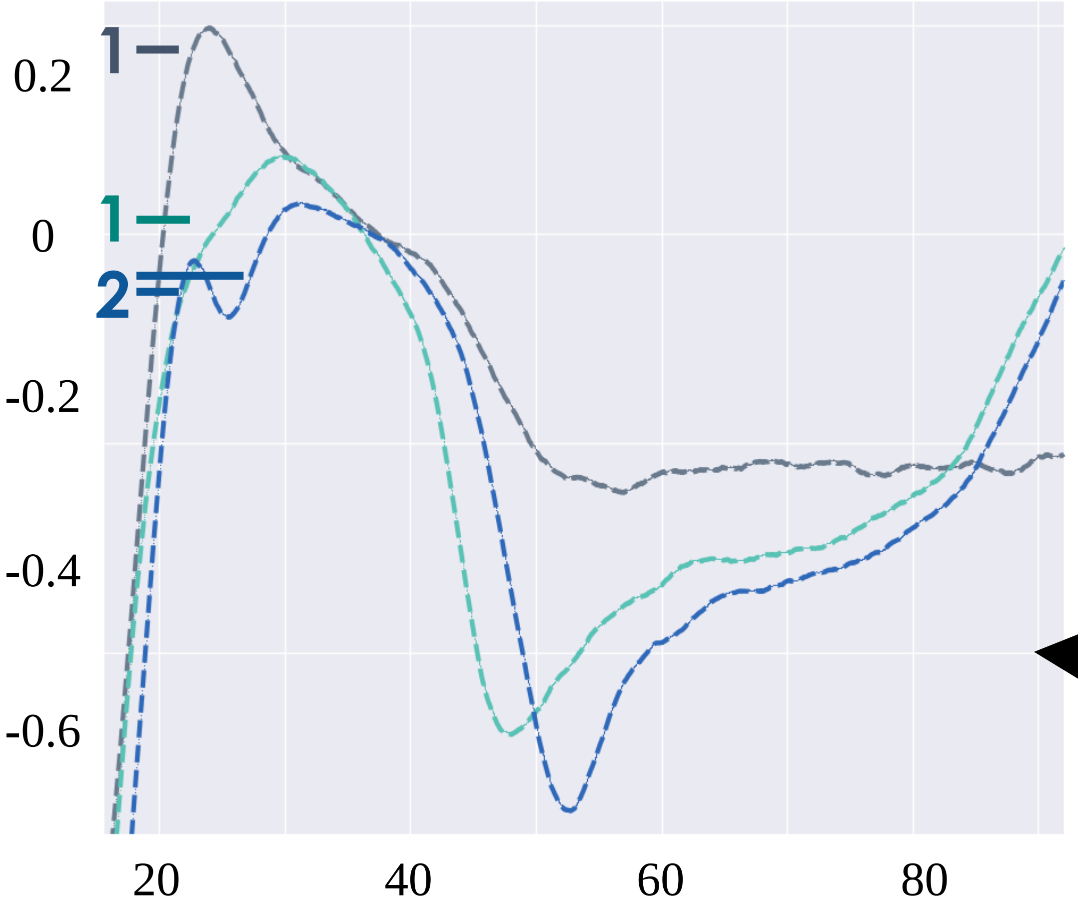
# Thermal Analysis

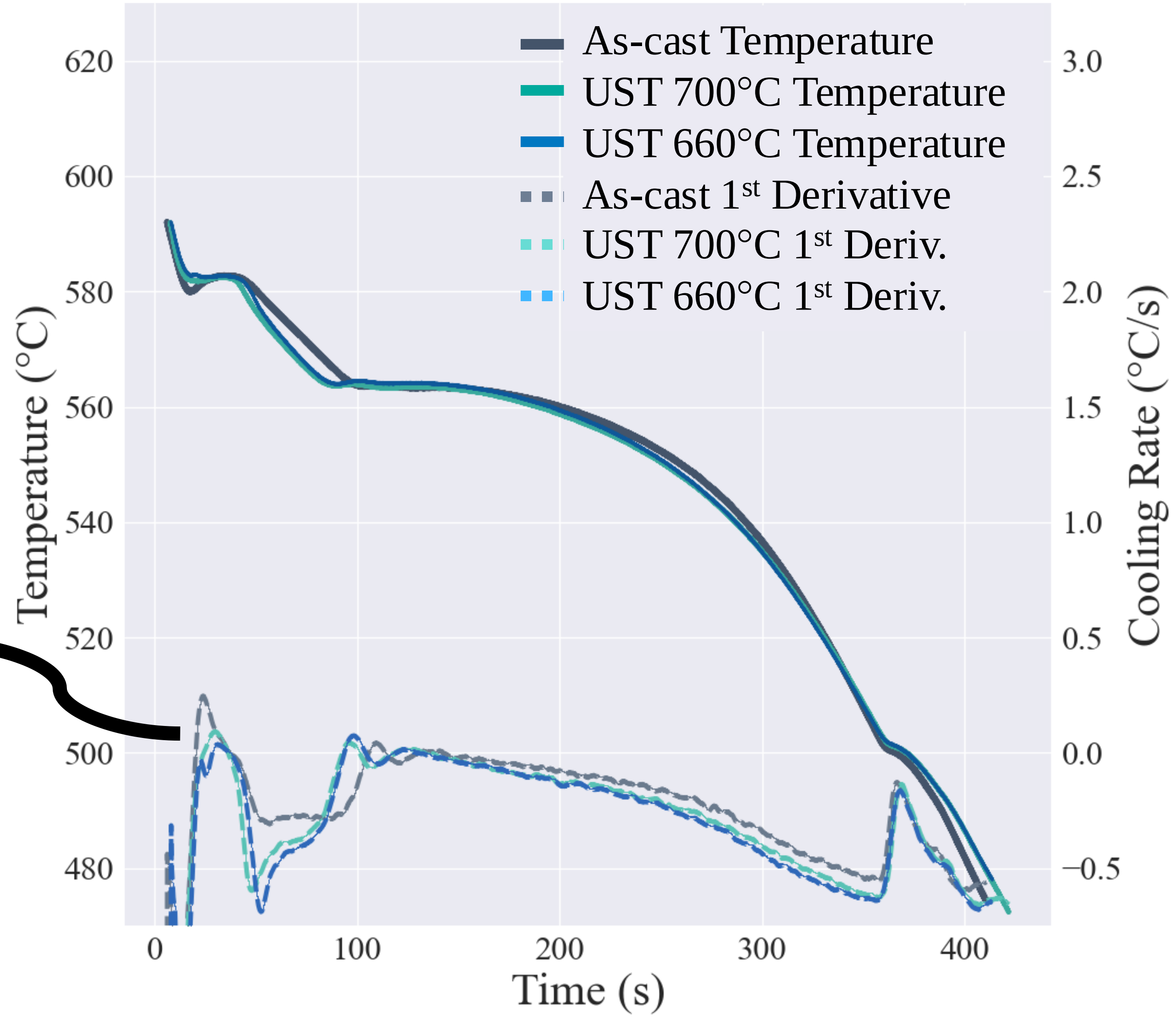



*Limited undercooling in both 660°C & 700°C indicate sufficient nuclei*

# Cooling Rate

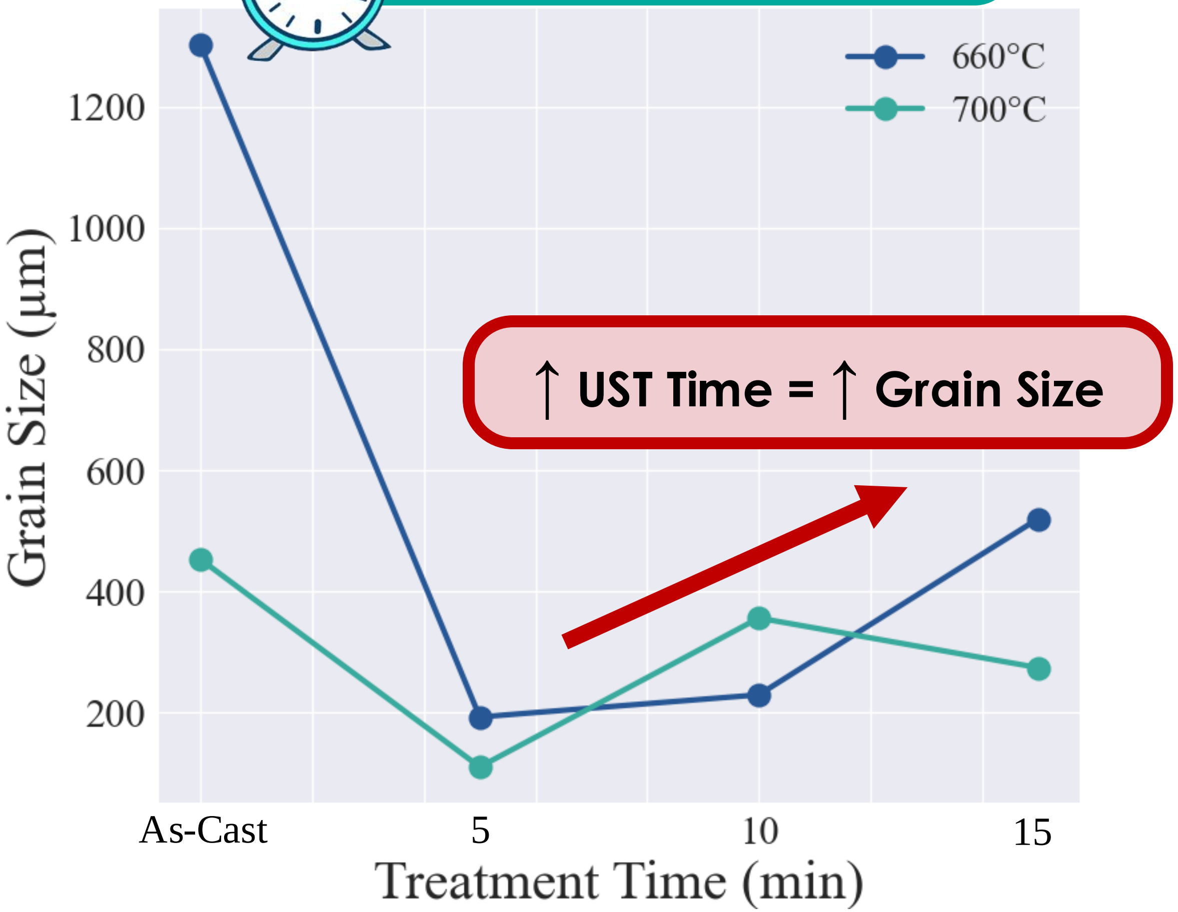


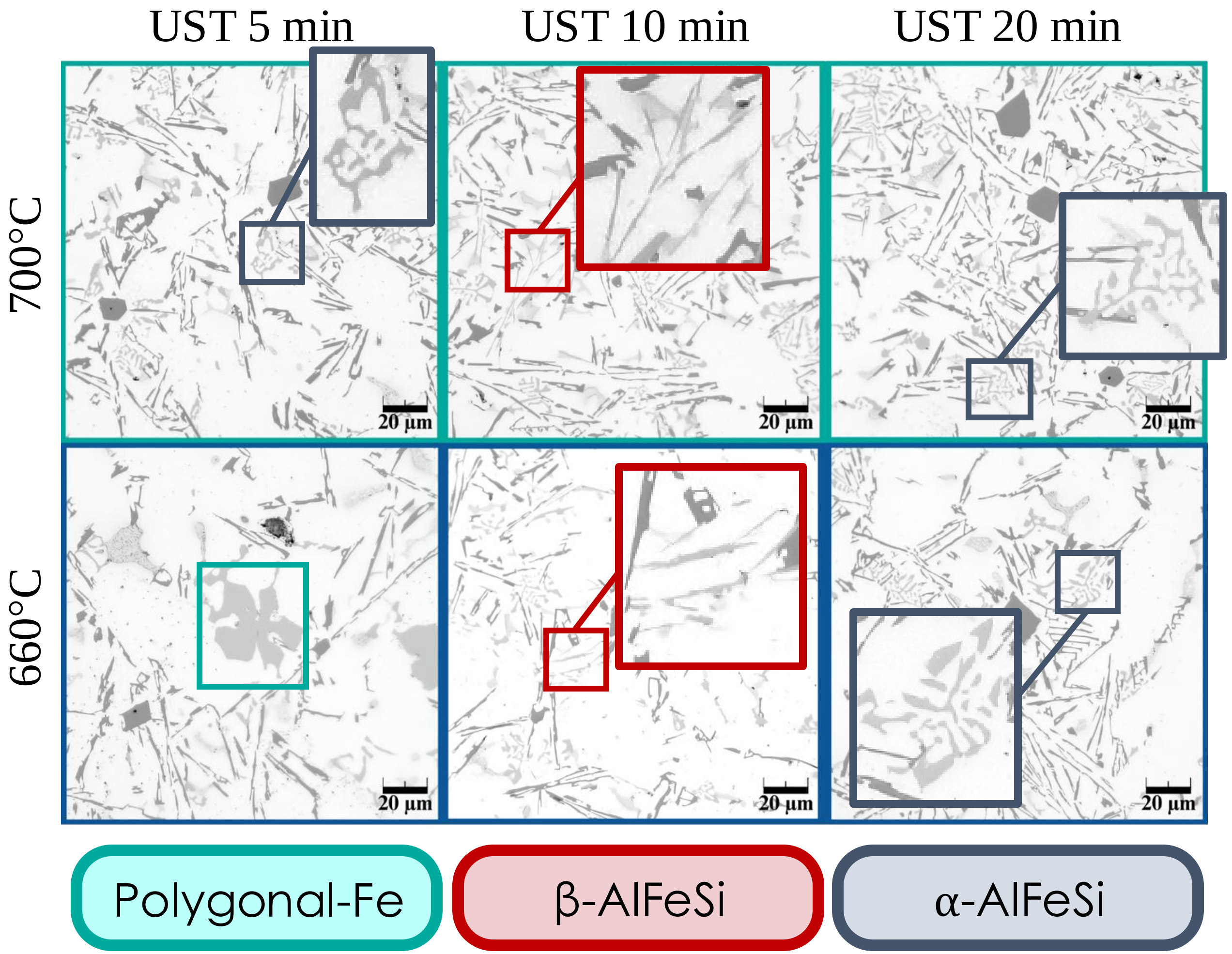




*Confirms new Polygonal-Fe in 660°C*

# Grain Size: Treatment Time

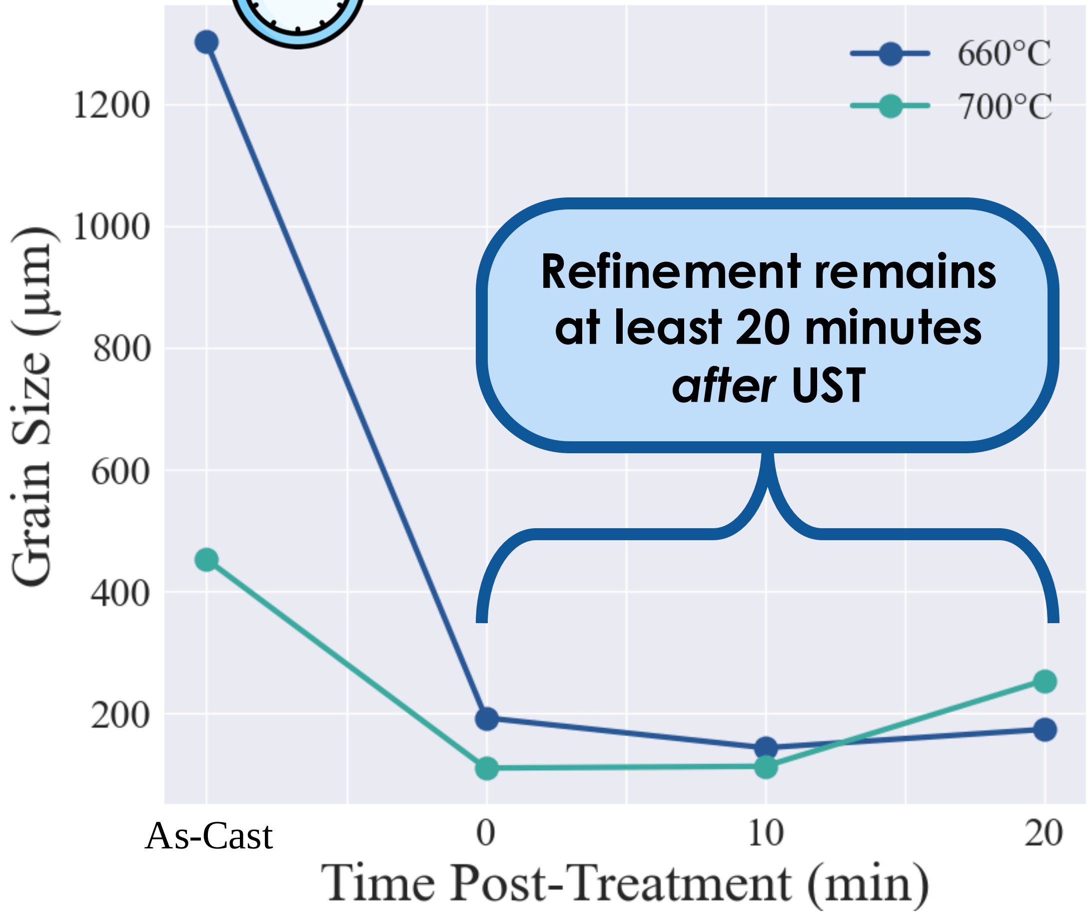
## Treatment Time



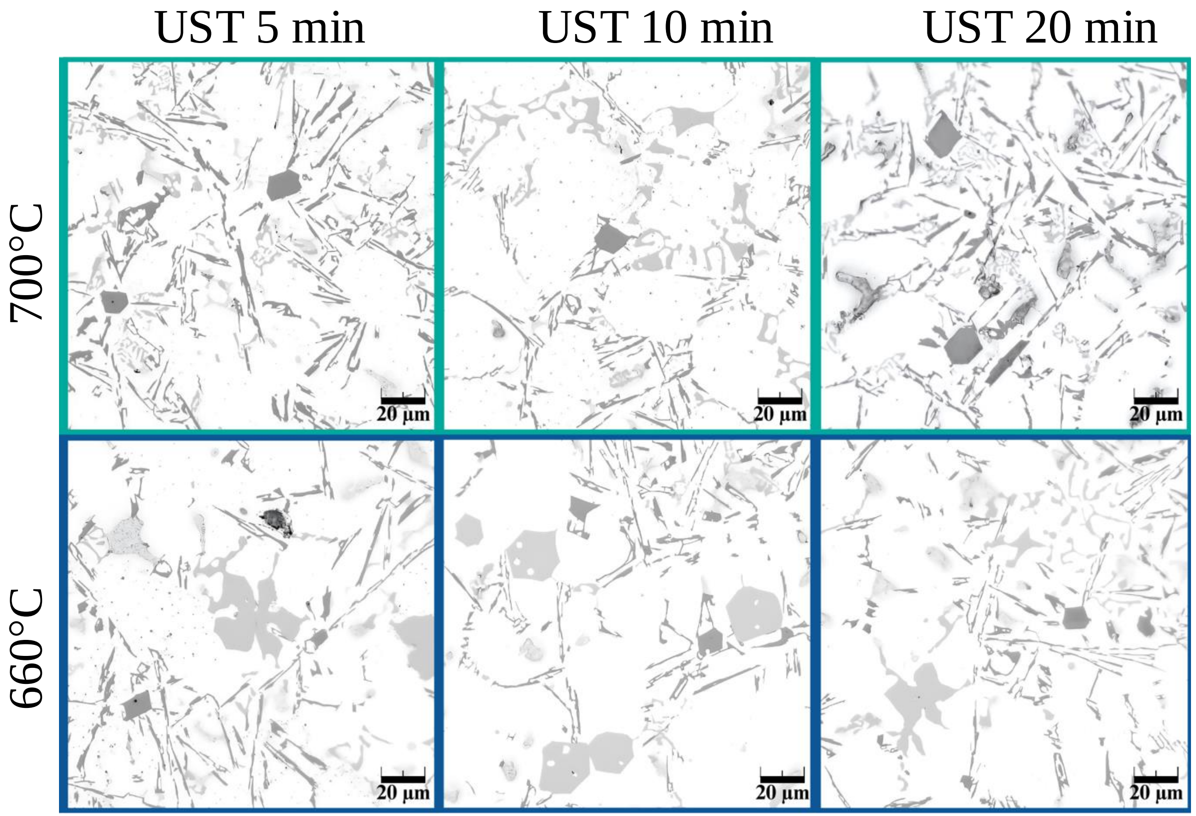



# Grain Size: UST Effect Decay with Time

**Decay with Time**




**Refinement remains at least 20 minutes *after* UST**




Primary Si & Polygonal-Fe exist up to 20 min after UST

# Conclusions

**Liquid-State Multifrequency UST is capable of intermetallic modification & grain refinement in adequate size melt above the liquidus**

**Early intermetallic modification adds pathway aside from oxide breakup for grain nucleation & refinement**

**UST provides sufficient energy for production of stable phases above the liquidus temperature**

- *Primary Si in hypoeutectic Al-Si alloy*

**Multifrequency UST produces uniform fields of cavitation bubbles for early phase nucleation**

- *Primary Si & Polygonal-Fe phase*

**UST provides an alternate route to modifying β-Fe without chemical modifiers**

- *UST-enhanced diffusion shows potential to form α-Fe in systems with insufficient Mn addition*

# Outline

1. Liquid-State Multifrequency UST Applications
2. Hypothesis & Approach
3. Results of Intermetallic Mod. & Grain Ref.
4. **Next Steps**

# Publications

On ACRC Website: https://acrc.manufacturing.uci.edu/

## FUNDAMENTALS OF ULTRASONIC TREATMENT OF ALUMINUM ALLOYS

**Raquel F. Jaime, Carl Söderhjelm and Diran Apelian**
Advanced Casting Research Center (ACRC), University of California, Irvine, California 92697, USA

**Hélder Puga**
CMEMS, University of Minho, Guimarães, Portugal

**Miodrag Prokic**
MPI Interconsulting, Le Locle, Switzerland


https://doi.org/10.1007/s40962-023-01253-w

### Abstract

*High integrity cast aluminum components require the use of molten metal processing technologies prior to casting. These include processes such as degassing to reduce porosity, filtration to reduce inclusion content, addition of grain refiners to refine the grain structure, and the addition of chemical modifiers to alter the morphology of eutectic phases. Ultrasonic treatment (UST) is a novel processing method through which ultrasonic energy is introduced into molten metal for the purpose of degassing as well as modifying the cast microstructure. To optimize the use and applications of UST, it is necessary to examine the fundamental mechanisms and the limiting values of controlling parameters. The effectiveness of UST to perform a desired application within a molten metal is highly dependent on temperature, volume of liquid metal, and the state of the frequency in use. The mechanisms of ultrasonic energy imparted within molten metal will be discussed as well as the benefits of UST during molten metal processing.*

***Keywords:*** *ultrasonic treatment, degassing, grain refinement, intermetallic morphology modification, aluminum, ultrasonic equipment, Multi-Frequency Mode Modulated (MMM) technology*

TMS
The Minerals, Metals & Materials Society

## Multifrequency Ultrasonic Treatment of Aluminum Alloys for Microstructural Modification

*Raquel Fierro Jaime[1], Hélder Puga[2], Miodrag Prokic[3], Martijn Vos[4], Diran Apelian[1]*

*[1]University of California, Irvine – Department of Materials Science & Engineering, Irvine, CA 92697*
*[2]University of Minho – CMEMS, Guimarães, Portugal*
*[3]MPI Interconsulting, Le Locle, Switzerland*
*[4]Aluminium Rheinfelden, Rheinfelden, Germany*

### ABSTRACT

Ultrasonic Treatment (UST) is a novel and nascent liquid processing method with potential as a sustainable casting technology for use in the treatment and refinement of scrap and downcycled aluminum alloy systems. UST is the application of ultrasonic energy into a liquid metal which induces modification and refinement in the solidified microstructure. The two frequency modalities through which UST is imparted into the liquid metal, i.e.- fixed frequency and multifrequency, dictate the effectiveness of treatment. Applying a multifrequency ultrasonic wave increases the efficiency, intensity, and depth of treatment. Downcycled and scrap aluminum alloys contain an increased presence of detrimental intermetallic phases whose morphologies have a negative impact on mechanical performance, making them unfit for cast products. Multifrequency UST demonstrates the ability to modify the intermetallic phases and grain size through liquid-state application. Changes to the microstructure in an Al-7.8 %Si-1.27 %Fe will be discussed and briefly compared with changes seen in a complimentary study of A380. Multifrequency UST exhibits a time-dependent behavior. UST produced a 51.5 % decrease in the grain size of Al-7.8 %Si-1.27 %Fe and primary Si formed in a hypoeutectic system.

### KEYWORDS

*Ultrasound, aluminum, processing, grain refinement, intermetallic, multifrequency*

# Next Steps

**Liquid-State Multifrequency UST for Intermetallic Modification & Grain Refinement of A380**

- *Publication in progress*
- *Translate findings to mechanical properties in future work*

**TMS 2025 REWAS Sustainability Session**

**Industry trials in Portugal (March 2025)**

- *A356 Gravity Castings + UST Degassing*
- *Collaboration with Prof. Hélder Puga*

**New UST equipment arrival in Irvine**

- *~April 2025*
- *UST in A380 with minimal Mn*
- *UST in A356 with increased Fe*
- *UST in A356 with TiB2*

# Acknowledgements

mpi ultrasonics
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EMC

AFS AND THE INSTITUTE
ADVOCATE. EDUCATE. INNOVATE.

INDUCTOTHERM GROUP

RHEINFELDEN

SF

ALMEX

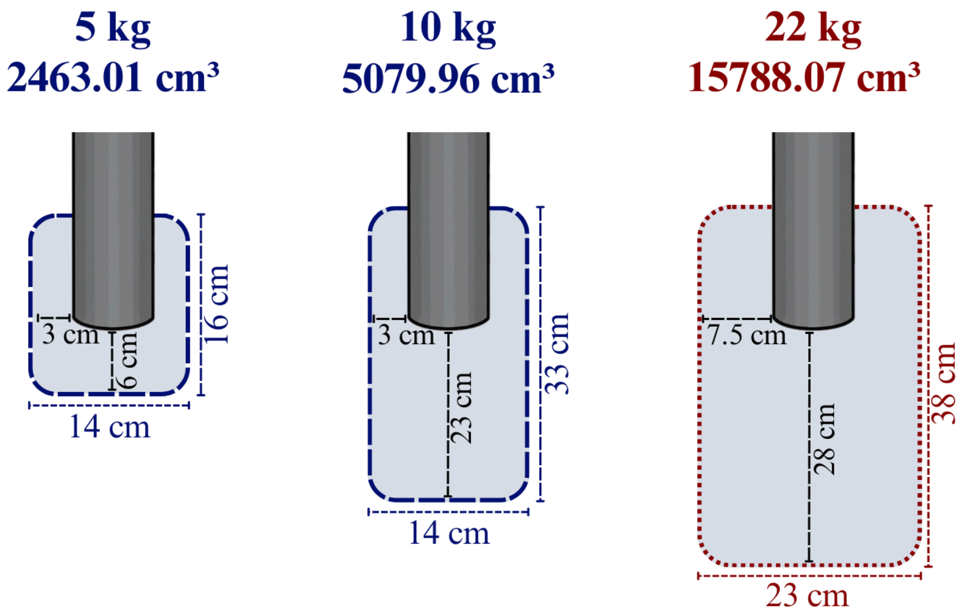
EVIDENT

BUEHLER

**Thank you!**

*Special Thanks to* ***Prof. Hélder Puga***

# Focus Group Discussion Points




**'Volume' Treated**

- How to describe this?

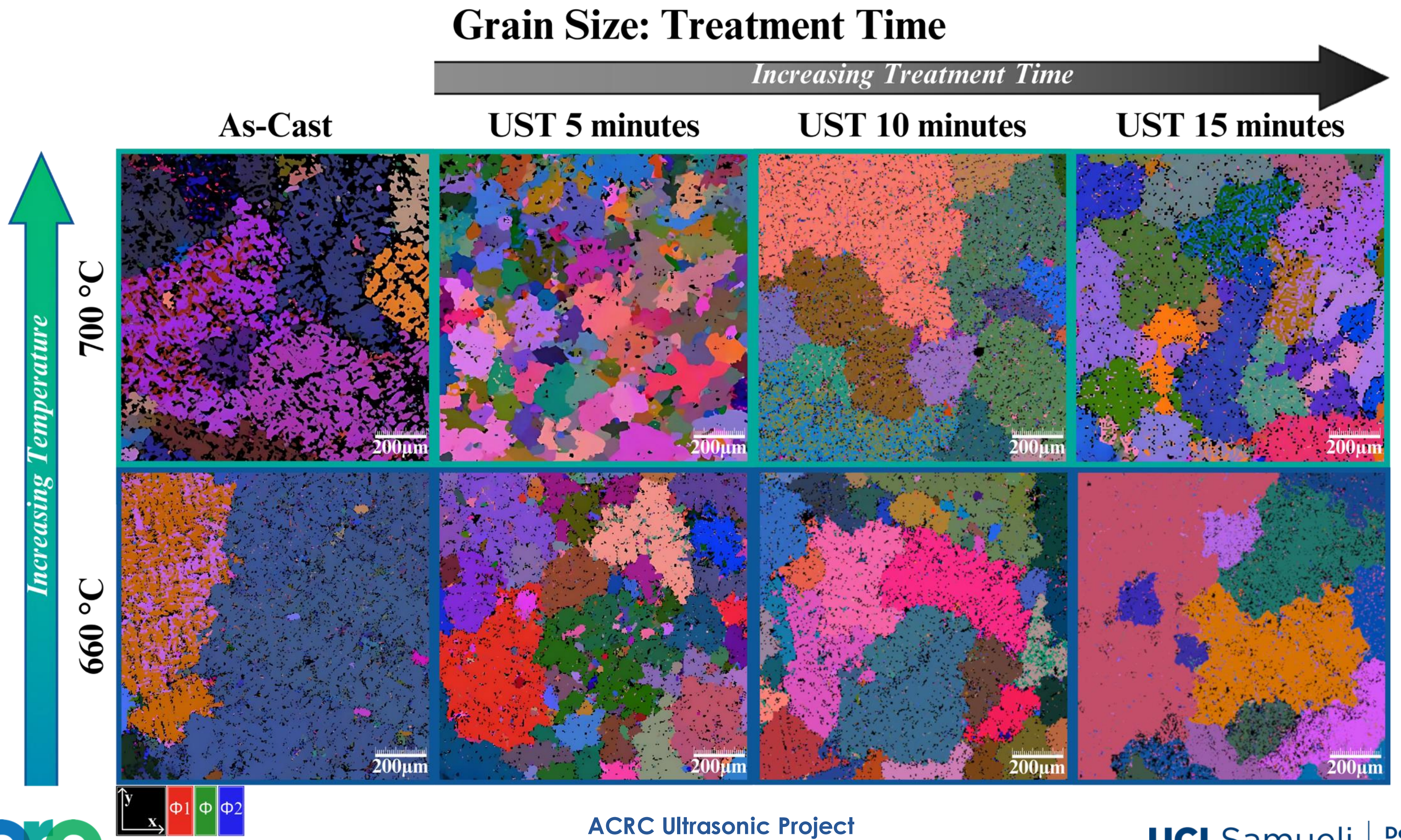
**Mechanical Properties**

- Not practical to interpret tensile data due to treatment temperature restriction
- 3 point bending?

**Future Studies**

- A356 with high Fe content
- Unrefined A356 with/without TiB2 grain refiner & UST

# EBSD: Treatment Time




ACRC Ultrasonic Project



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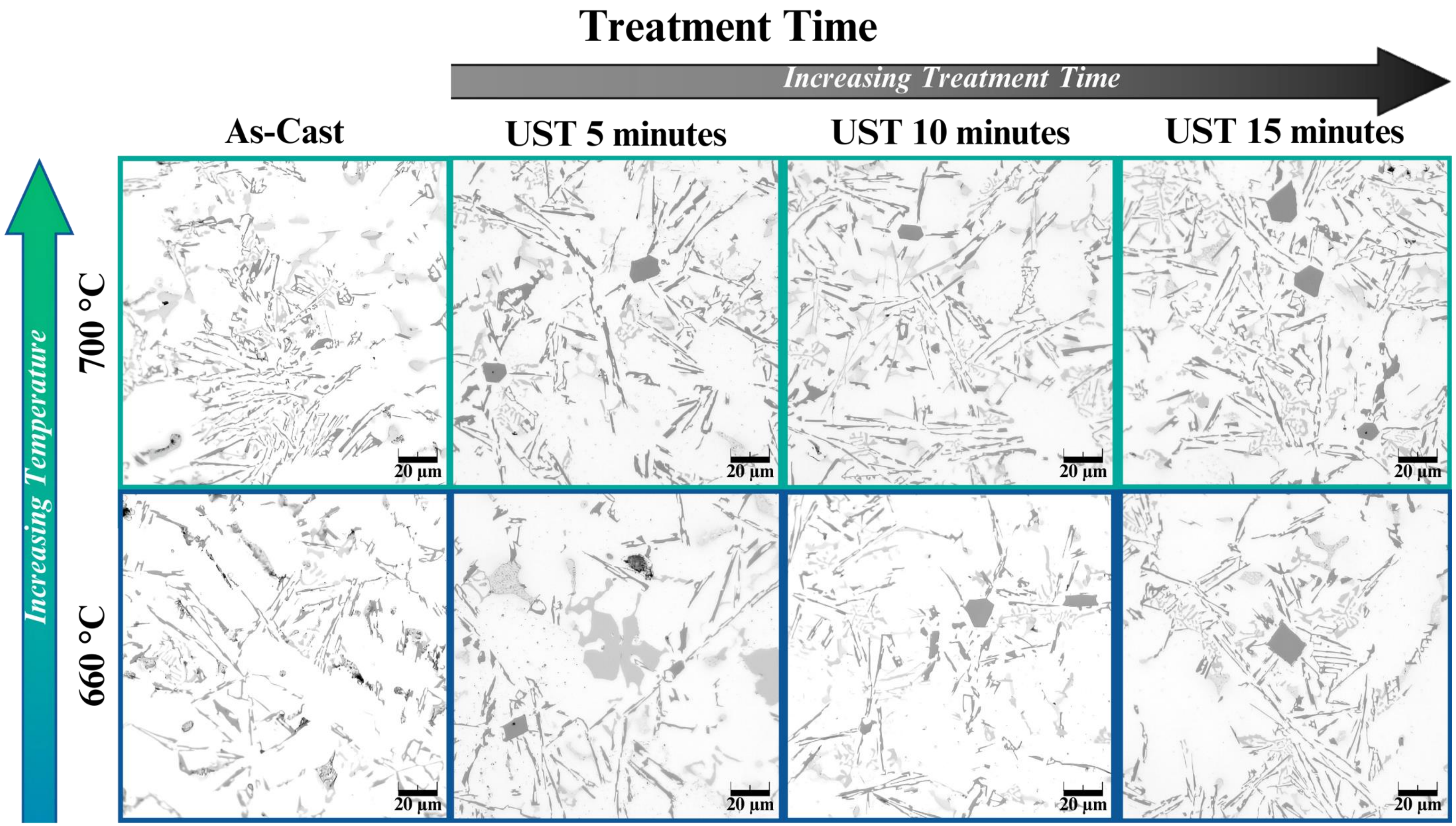
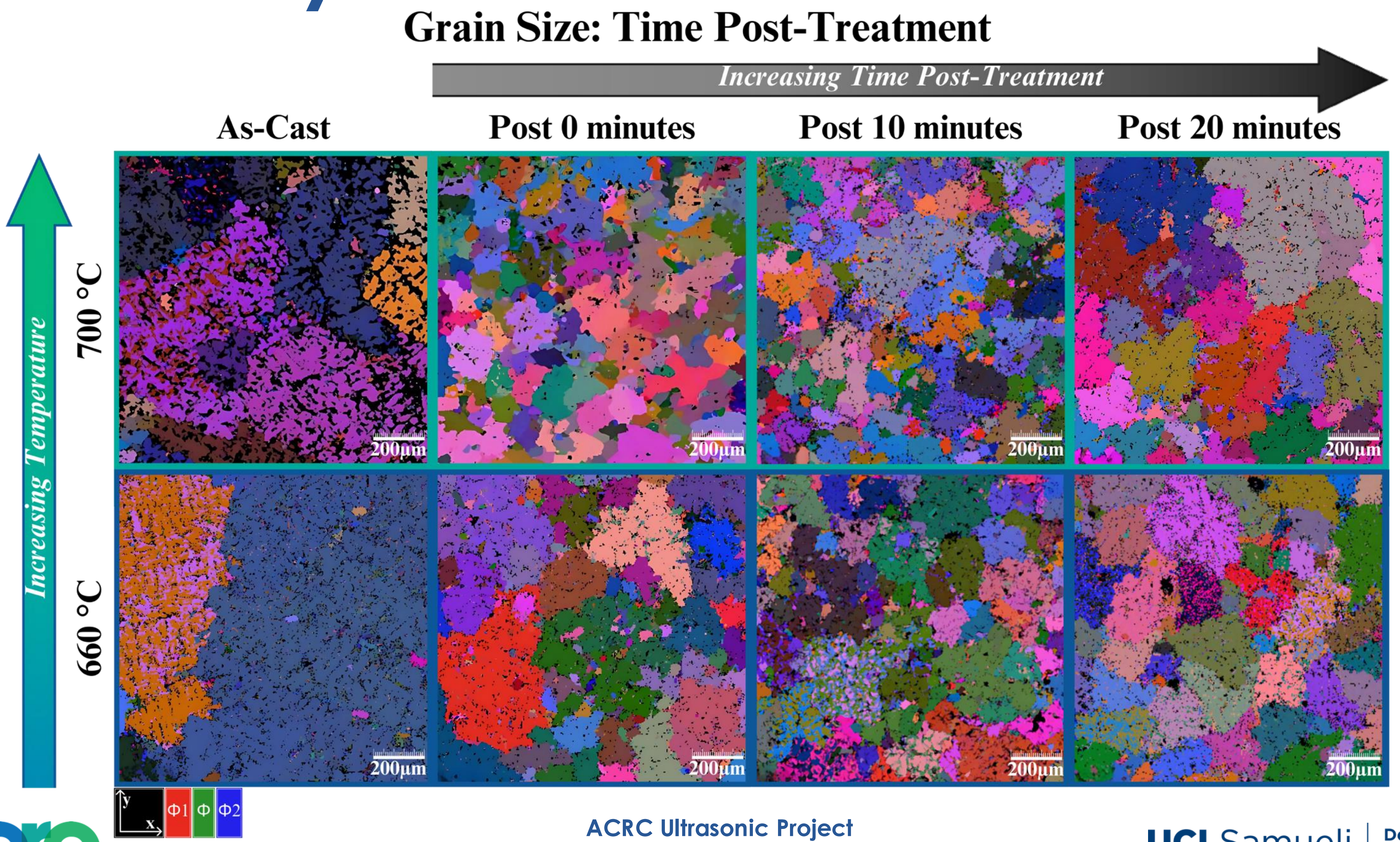
# Microstructure: Treatment Time



# EBSD: Decay with Time





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# Microstructure: Decay with Time