

Physics of Ultrasonic Treatment of Metals & Applications

Raquel Fierro Jaime

Supervising Professor: Diran Apelian

Academic Collaborator: Hélder Puga

Focus Group Chair: Martijn Vos

June 20th, 2024

Outline

(3 min.)

1. UST Applications in Liquid Metallurgy

(5 min.)

2. Multifrequency Degassing under Induction

(17 min.)

3. Multifrequency Liquid State Trials

(2 min.)

4. Next Steps

Total: 27 min.

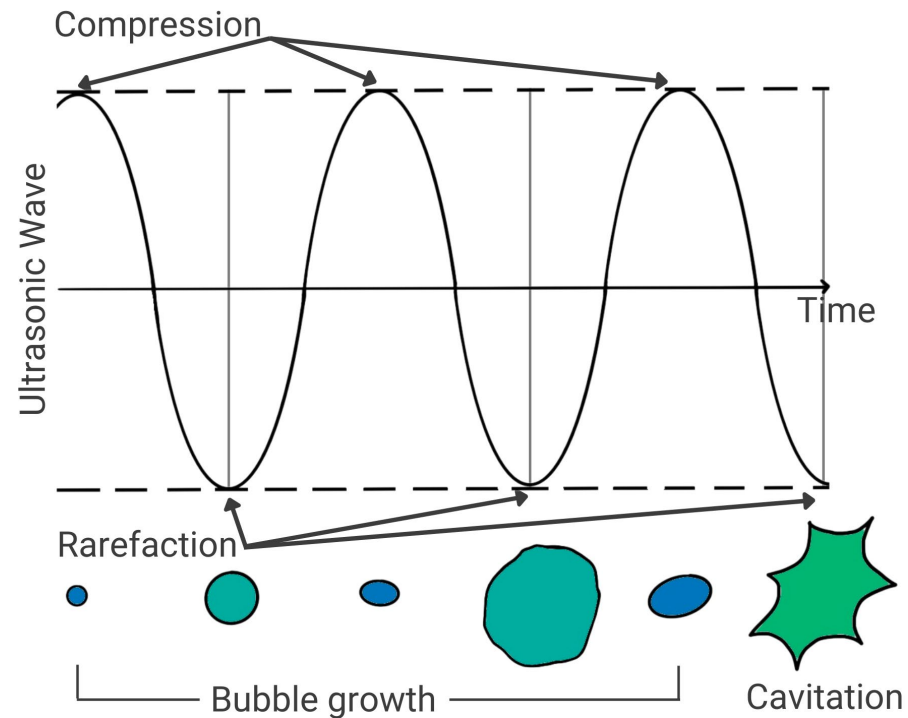
Outline

- 1. UST Applications in Liquid Metallurgy**
2. Multifrequency Degassing under Induction
3. Multifrequency Liquid State Trials
4. Next Steps

Ultrasonic Treatment (UST)

Applying ultrasonic waves to the molten state metal for microstructural modification

Acoustic Cavitation



Acoustic Streaming

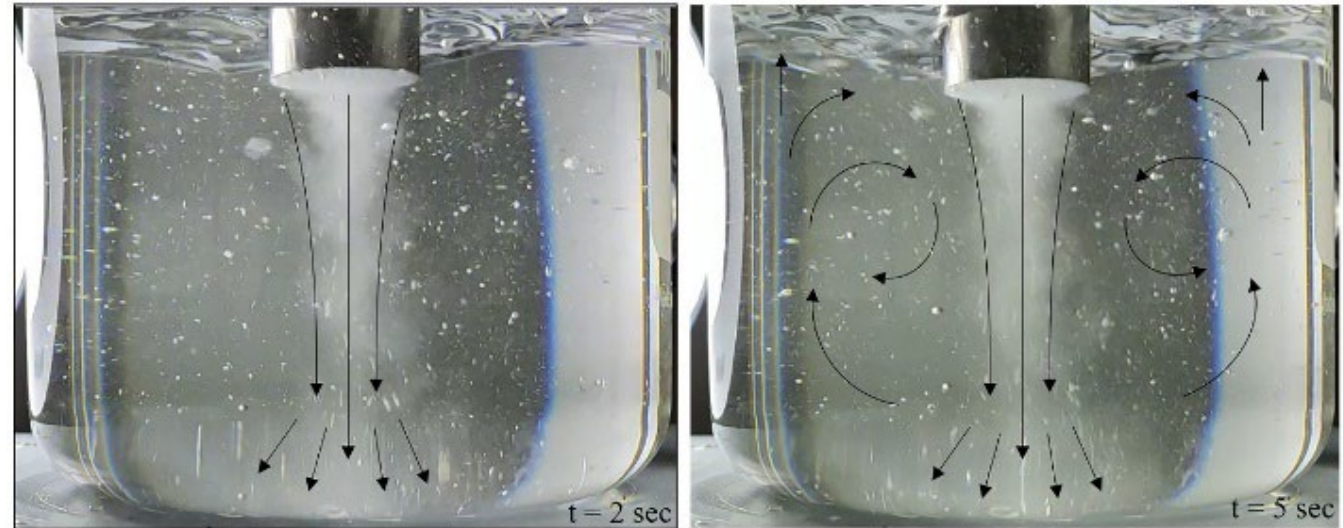
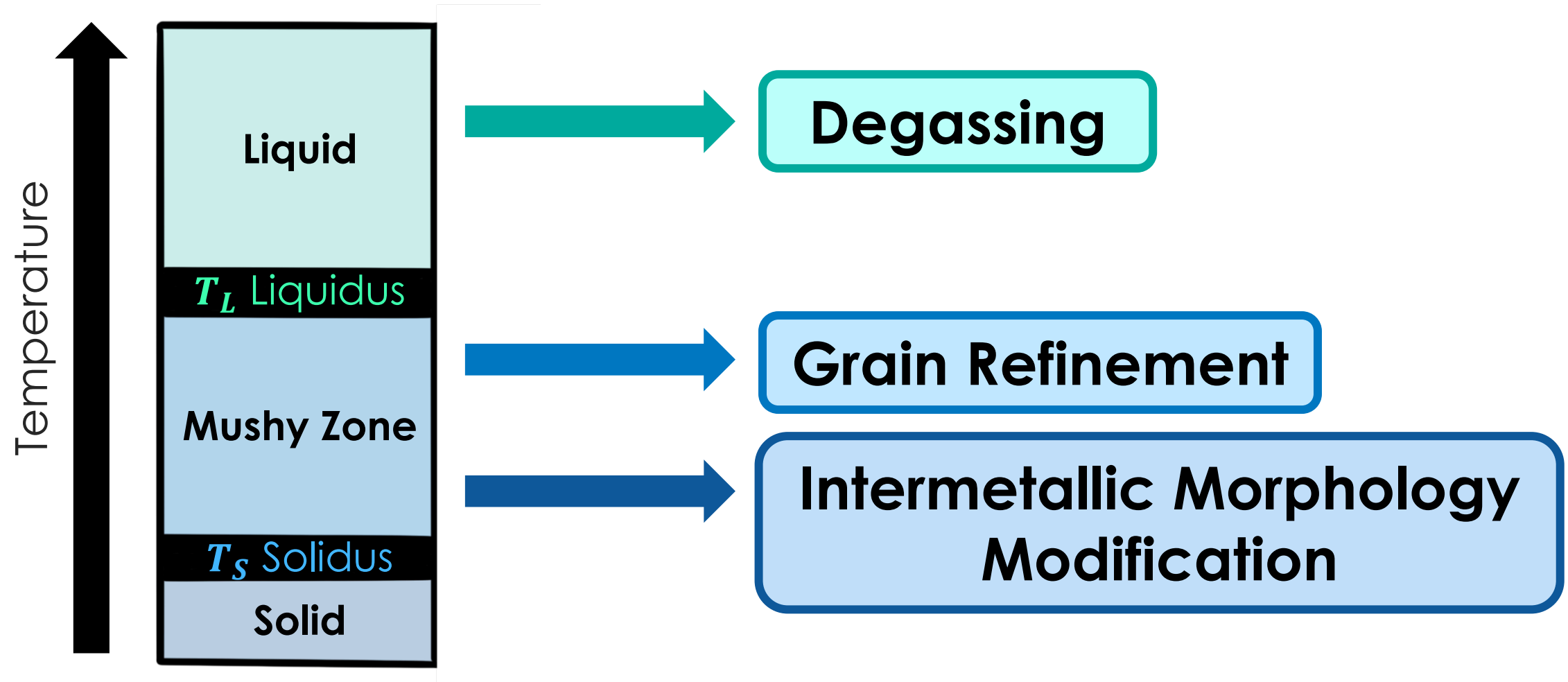
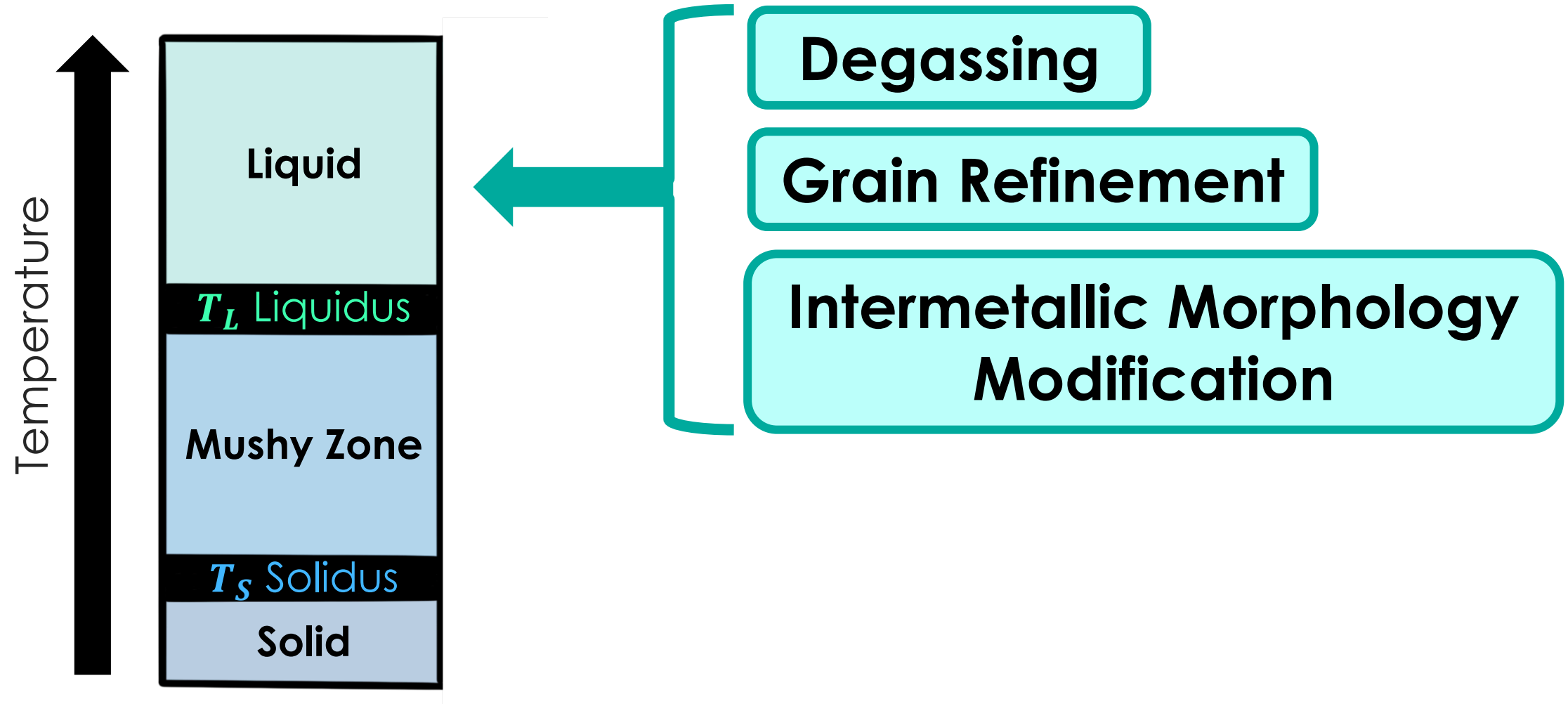


Photo Courtesy H. Puga

UST Applications



Goal for UST in Liquid Metallurgy



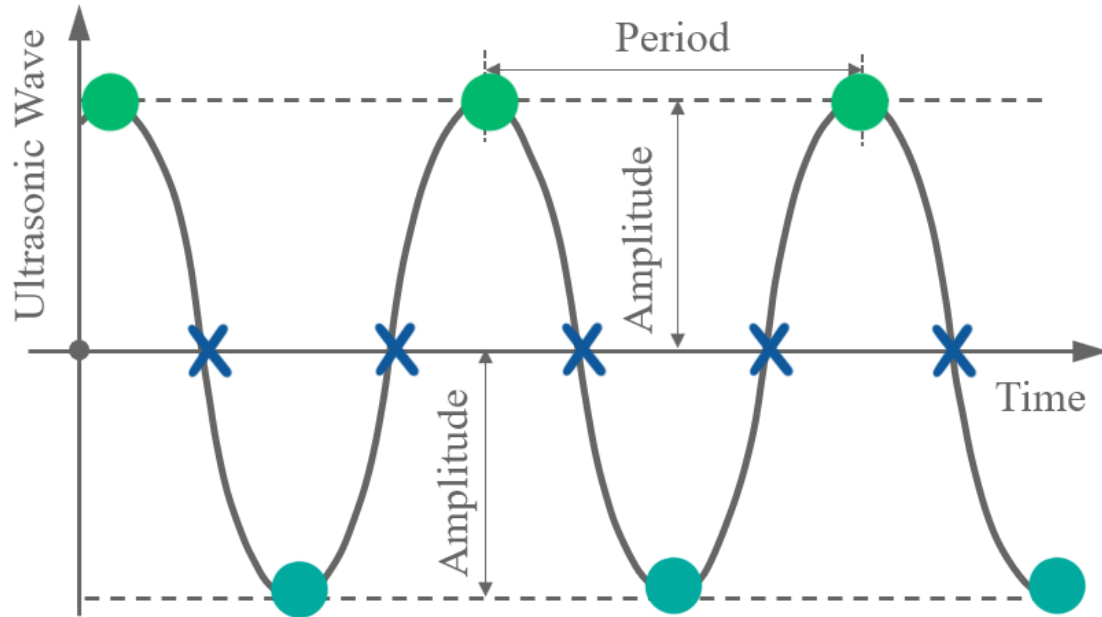
Ultrasonic Systems & Modalities

Mechanism & efficiency dependent on equipment parameters

Ultrasonic output method influences:

- Amplitude/intensity
- Depth of treatment
- Optimization

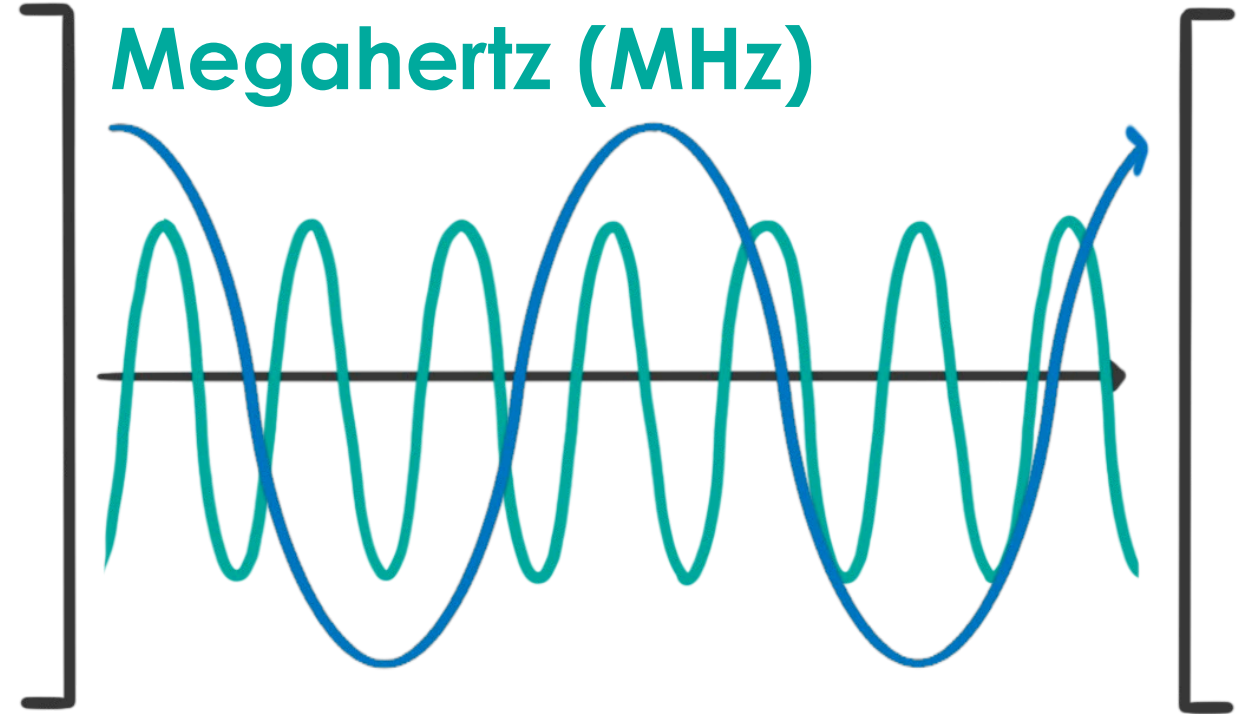
Frequency Modalities



- Fixed $f = 19\text{-}22\text{kHz}$
- Most commonly used

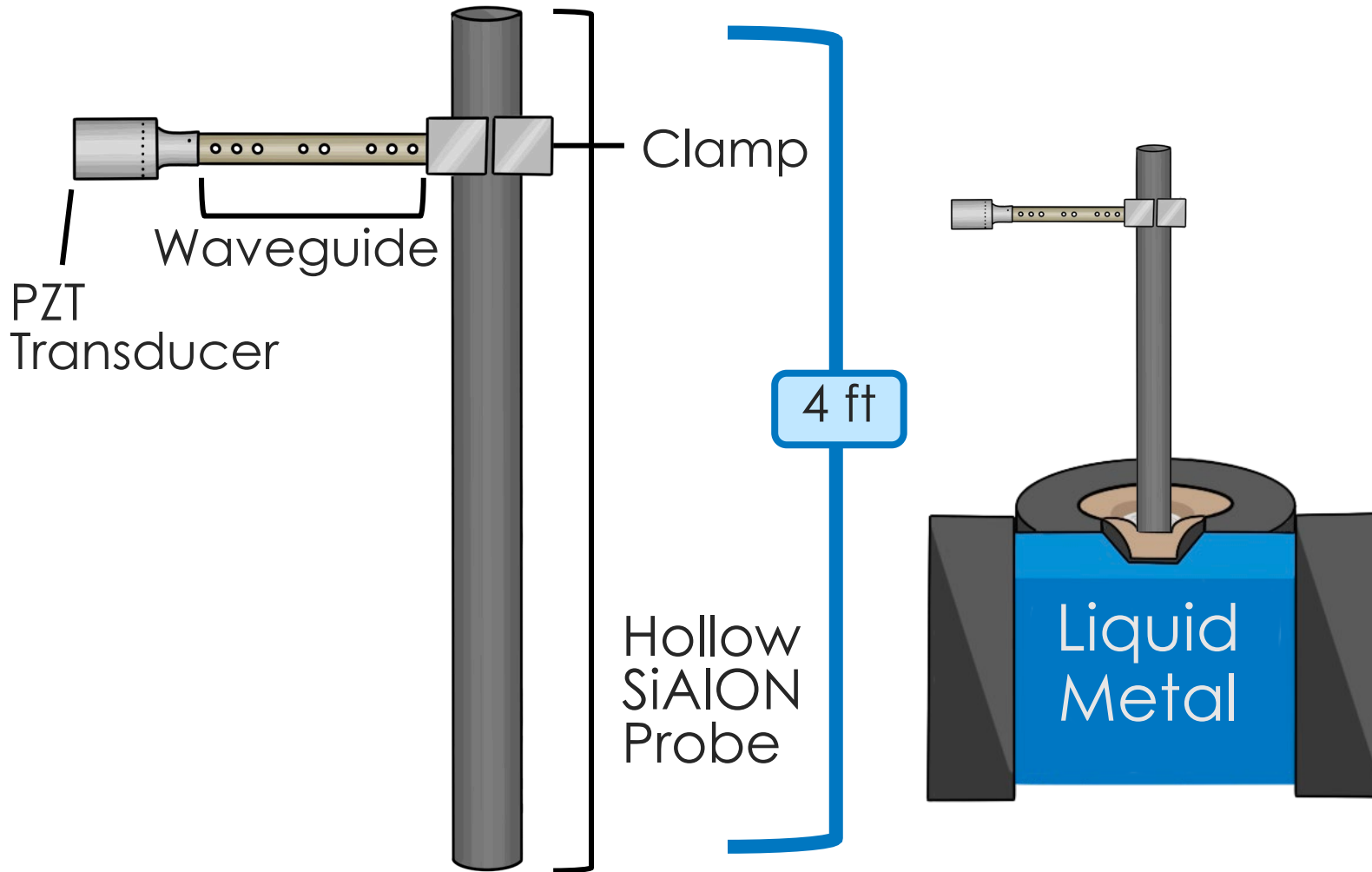
Kilohertz (kHz)

Megahertz (MHz)



- Variable f superposition

Multifrequency Ultrasonic Equipment



Radial Expansion

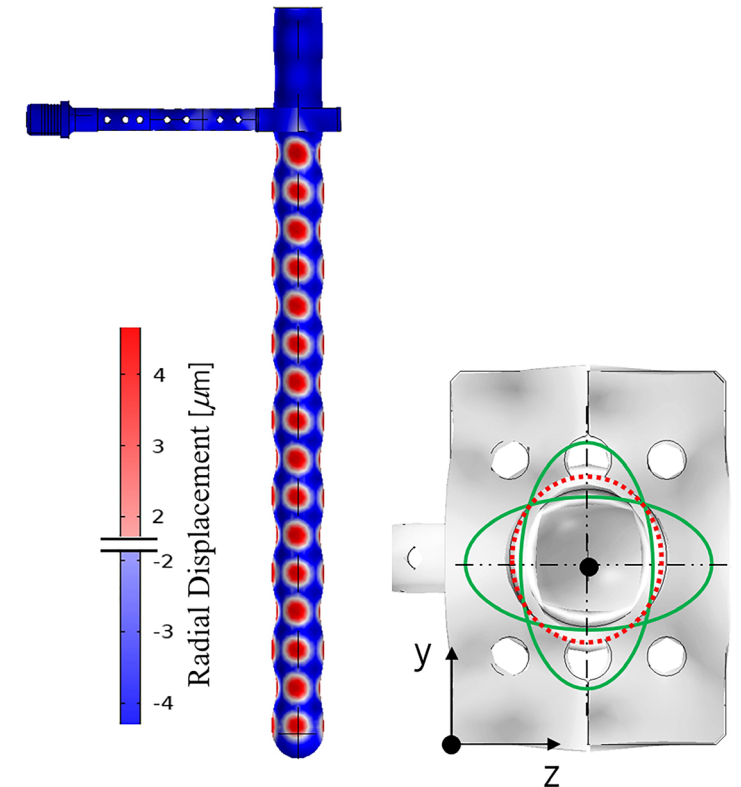


Photo Courtesy H. Puga

Outline

1. UST Applications in Liquid Metallurgy
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3. Multifrequency Liquid State Trials
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Goals for Multifrequency UST Degassing

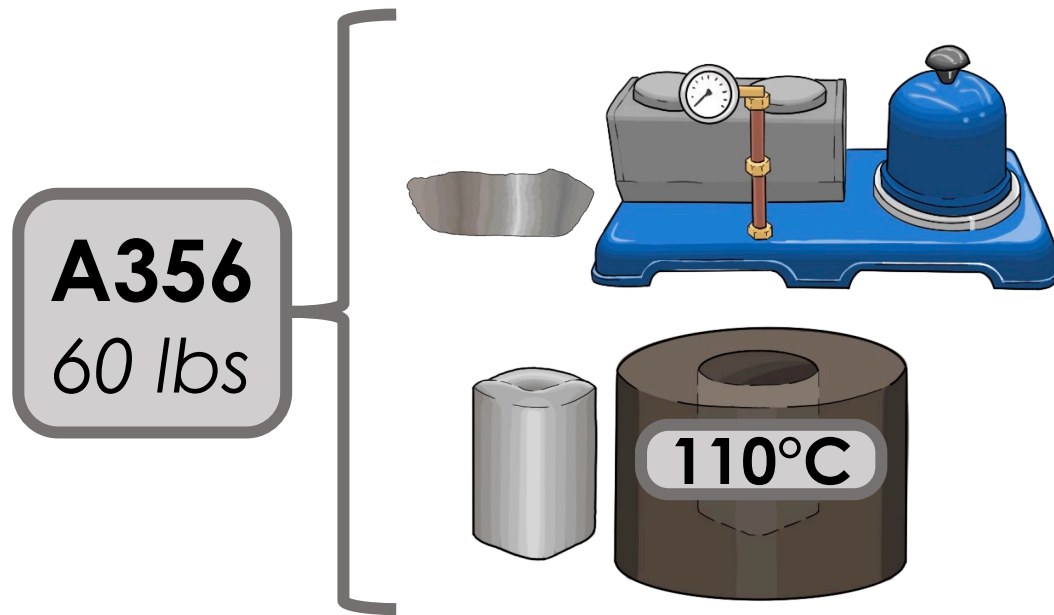
1. Assessment of Multifrequency Degassing

- a) *Rate of hydrogen release*
- b) *Turbulence: Introduction of oxide bifilms*
- c) *Energy density: UST scale to volume of melt*

2. Comparative Study

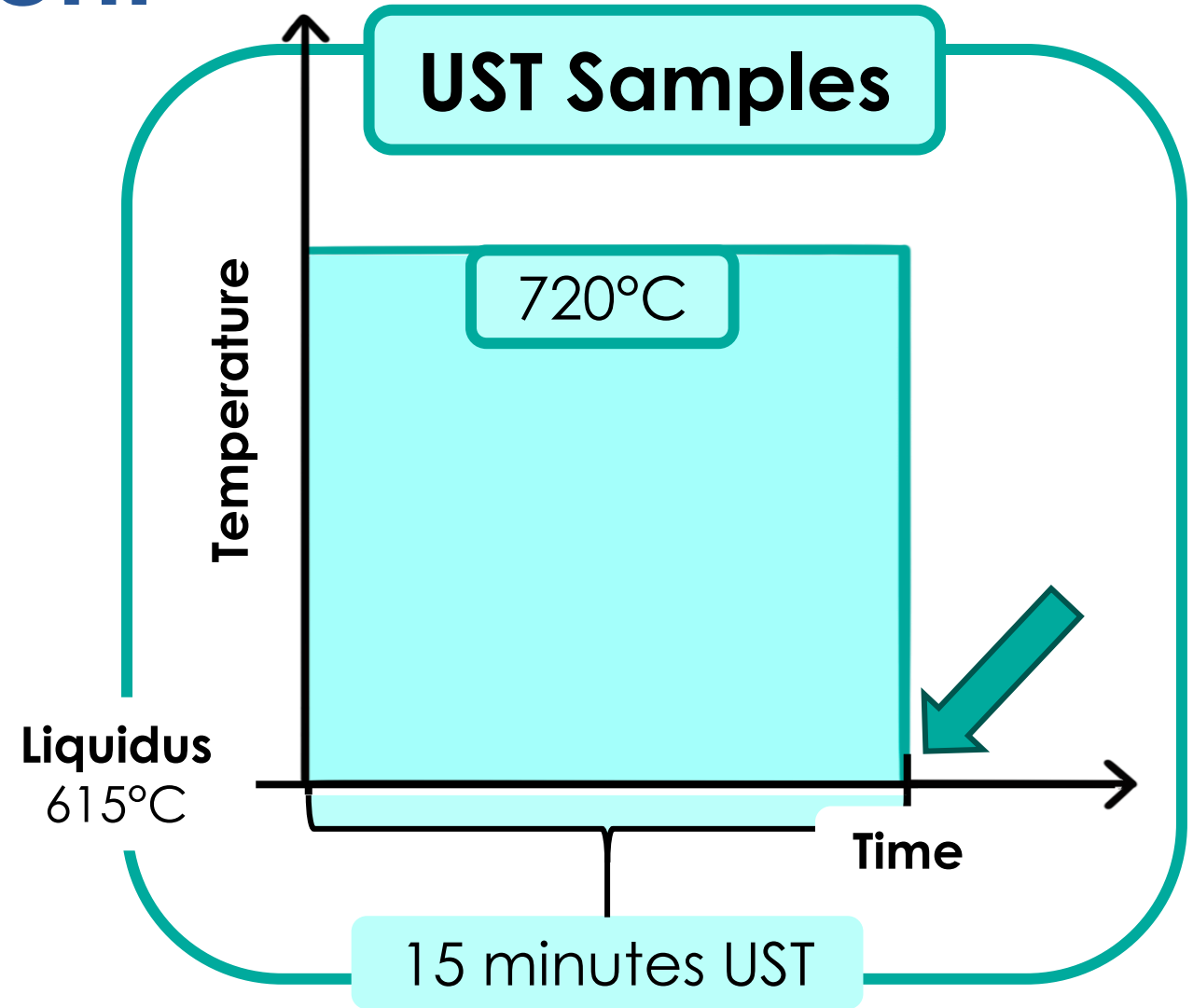
- a) *Rotary Degassing, Fixed Frequency, Multifrequency*
- b) *Dross Comparison*

Degassing Experiment

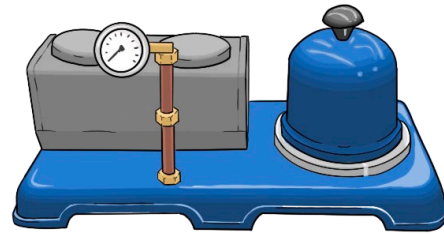


As-Cast
720°C

vs.



Reduced Pressure Test & CT Scan



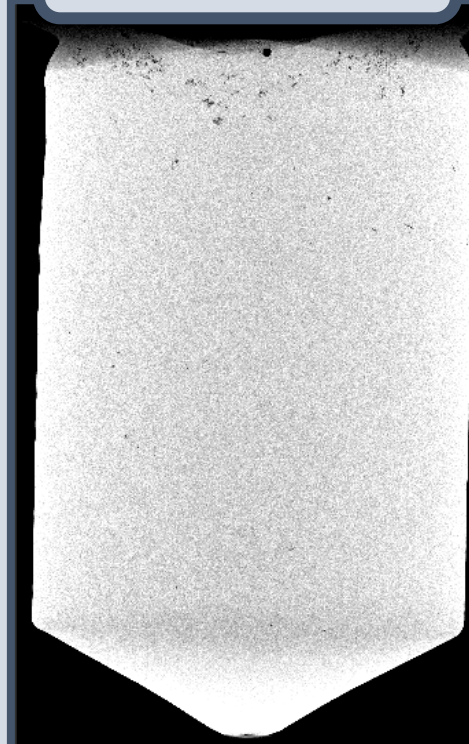
As Cast



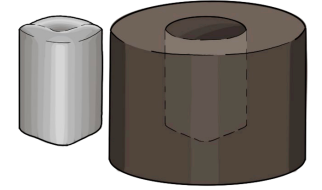
UST



As Cast

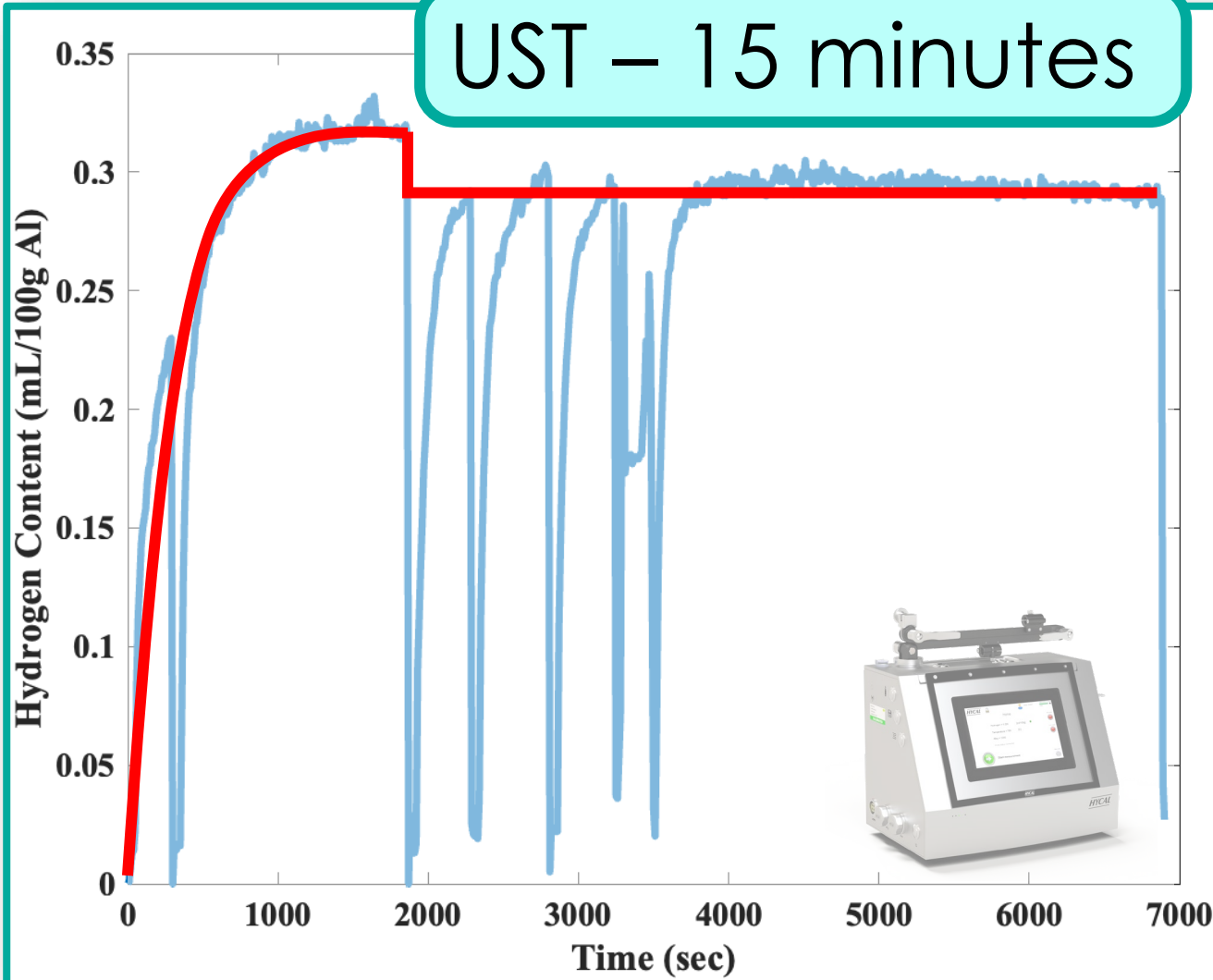


UST

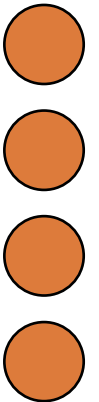


Hydrogen Content vs. Time

UST – 15 minutes



Ultrasound: 5 seconds on
3 seconds off



Next Steps for UST Degassing

Collaboration with Dr. Hélder Puga

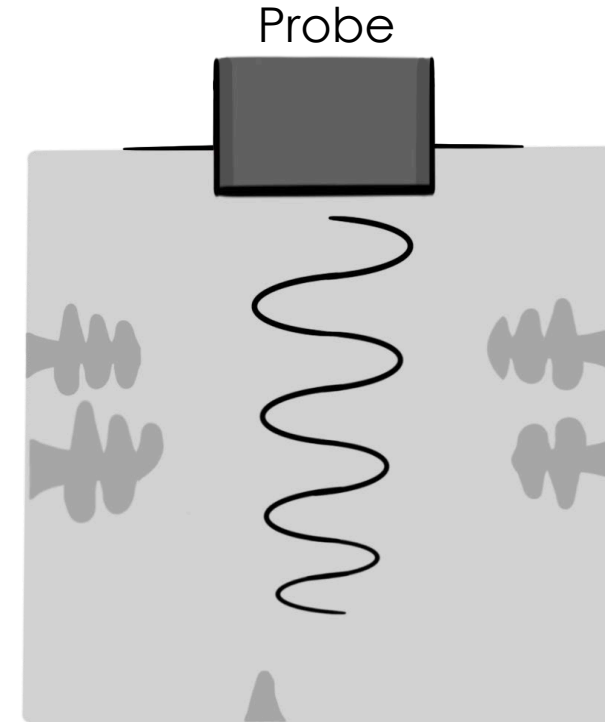
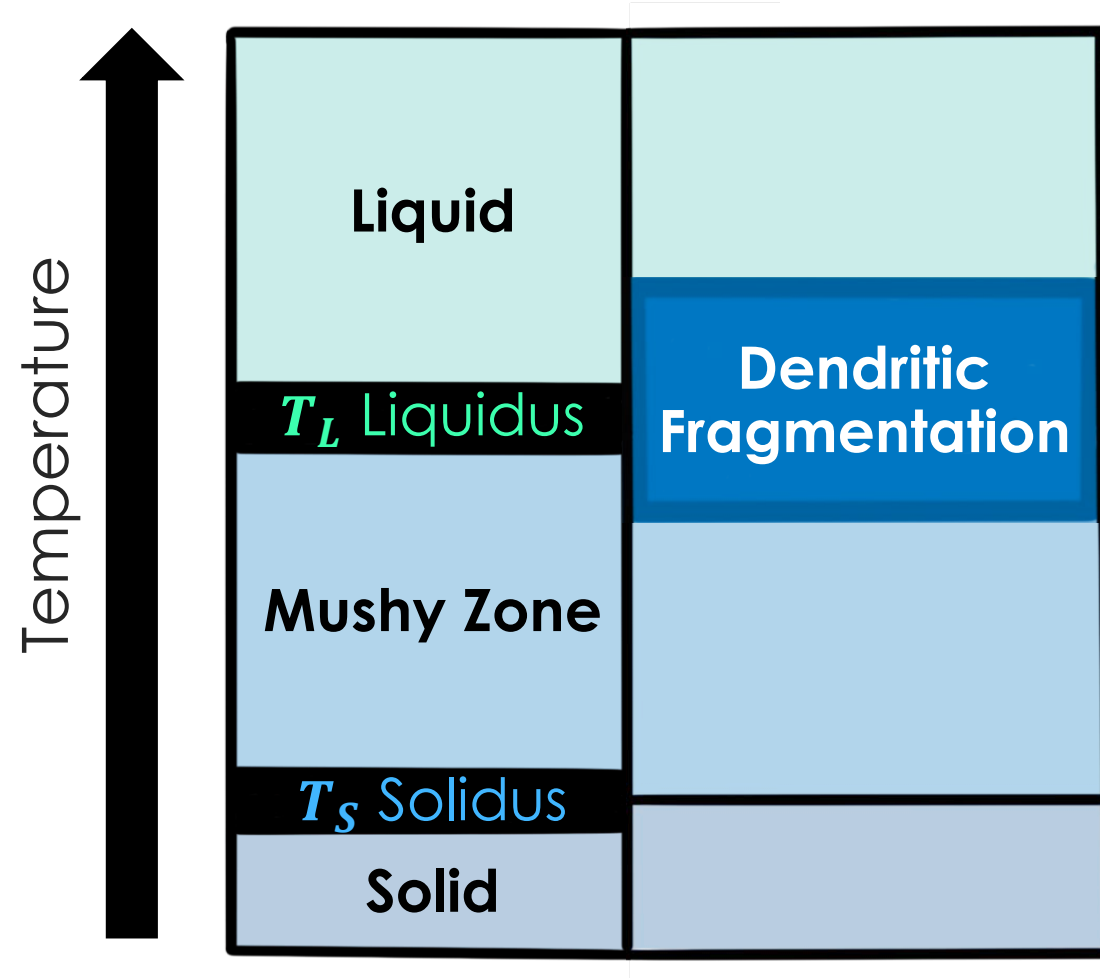
- a) *Validation of Induction-UST Degassing Interference*
- b) *Comparison with Resistive Furnace*
- c) *Continuation of UST Degassing Goals*

Pursue Work with Grain/Phase Modification

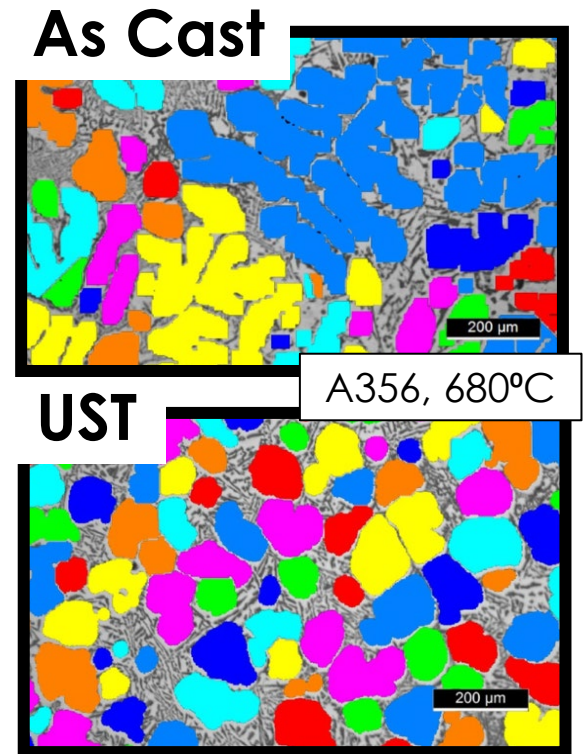
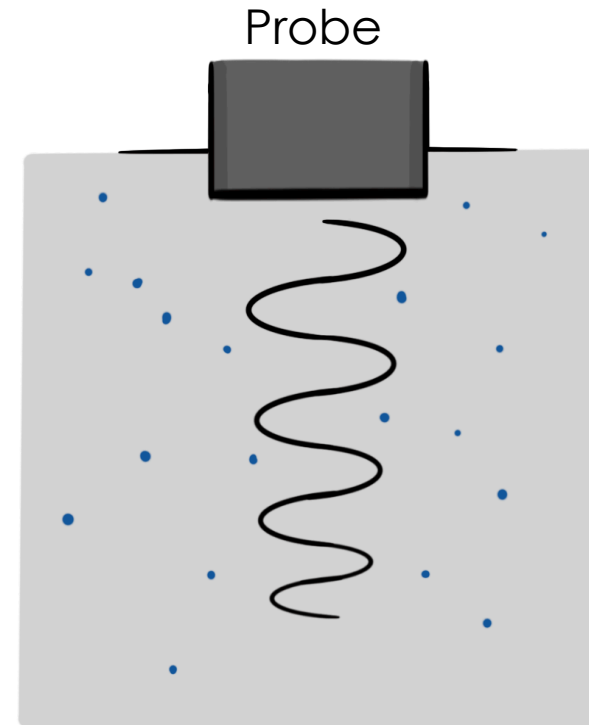
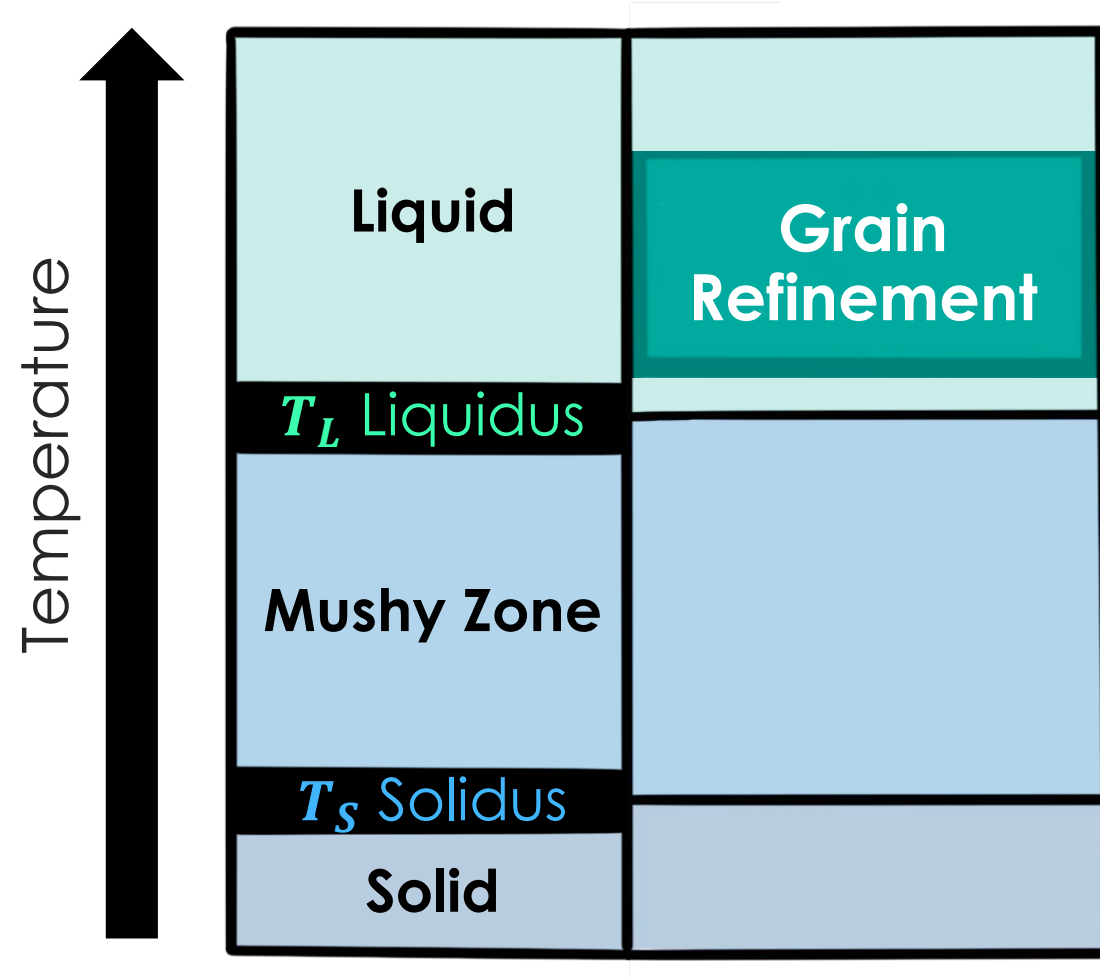
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Mechanisms of UST Grain Refinement



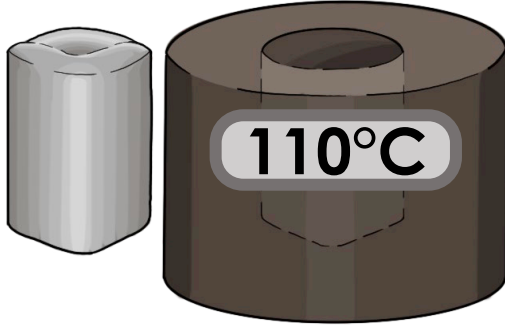
Mechanisms of Liquid State UST



H. Puga et al. AFS, 2020

Effect of UST Treatment Temperature

A380



110°C

As-Cast

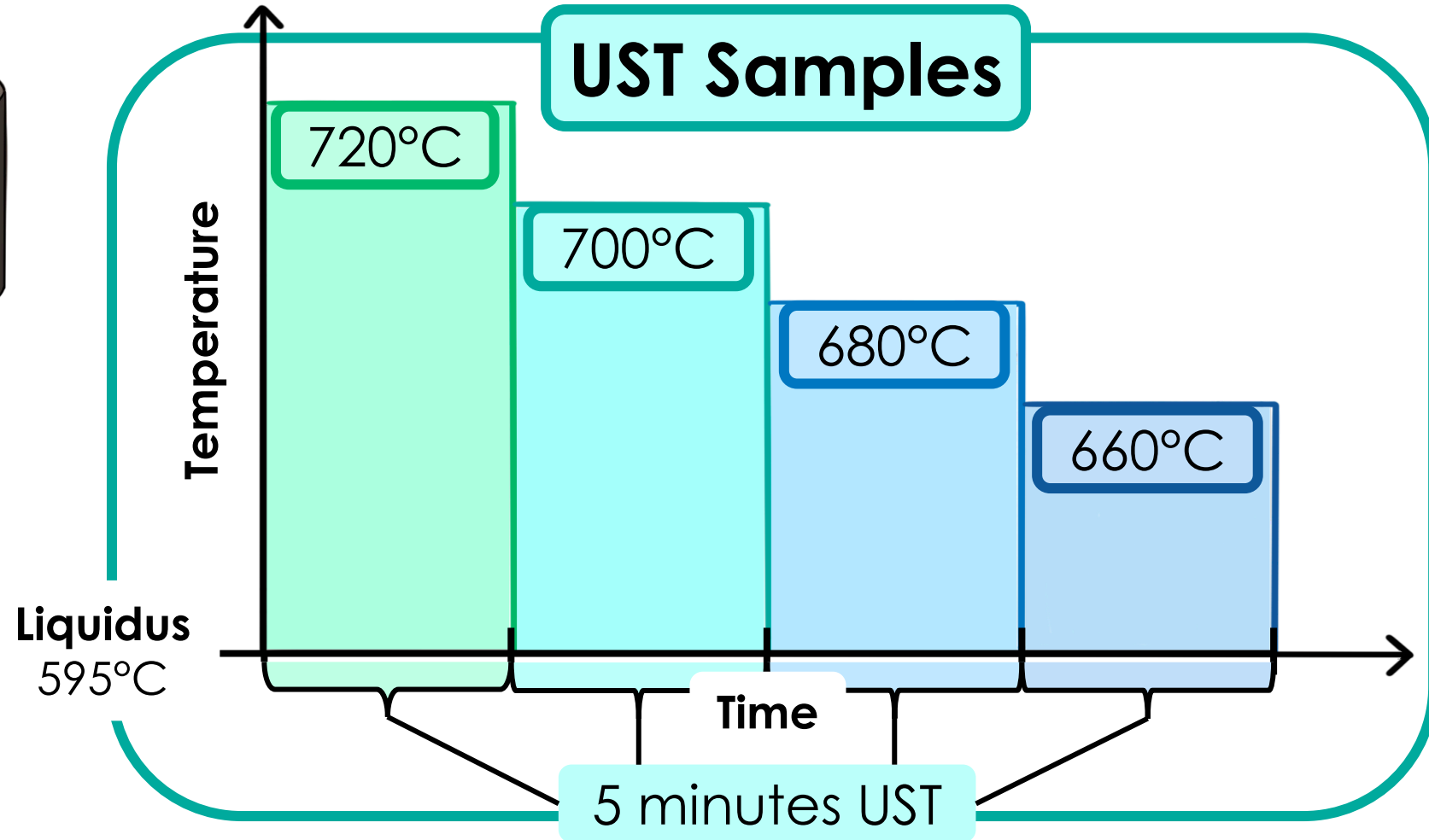
720°C

700°C

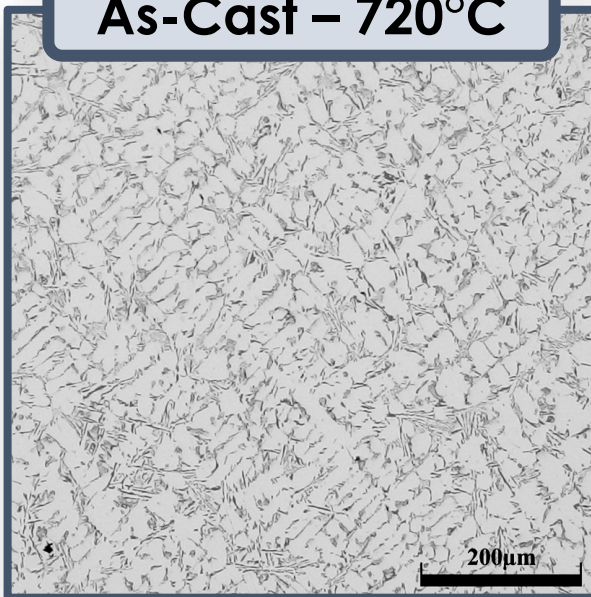
680°C

660°C

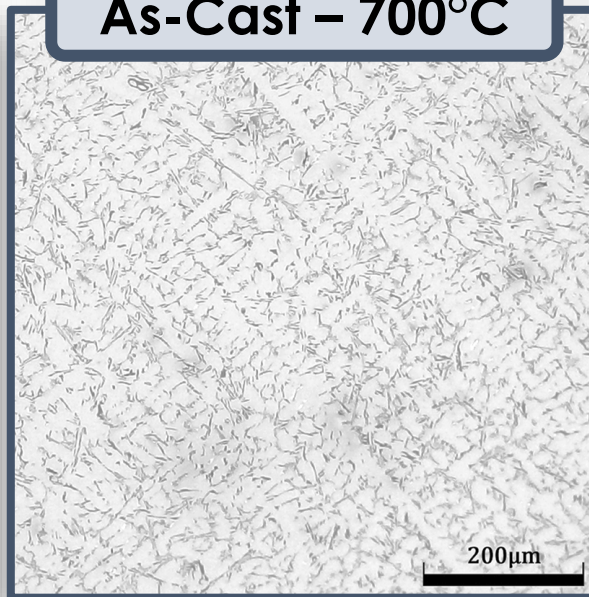
vs.



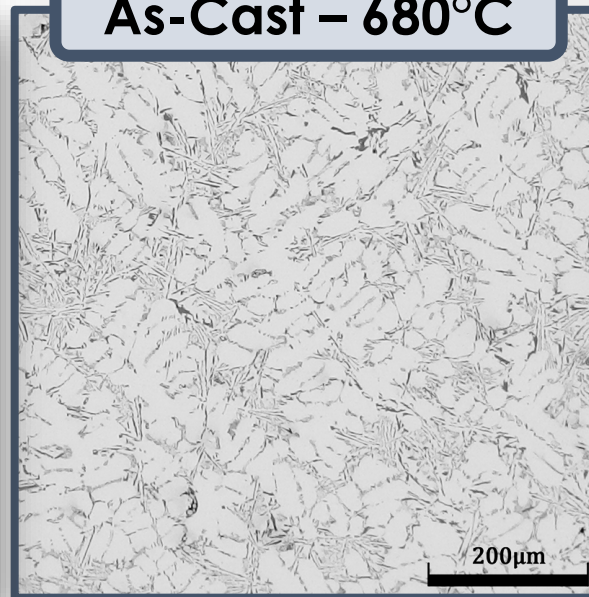
As-Cast – 720°C



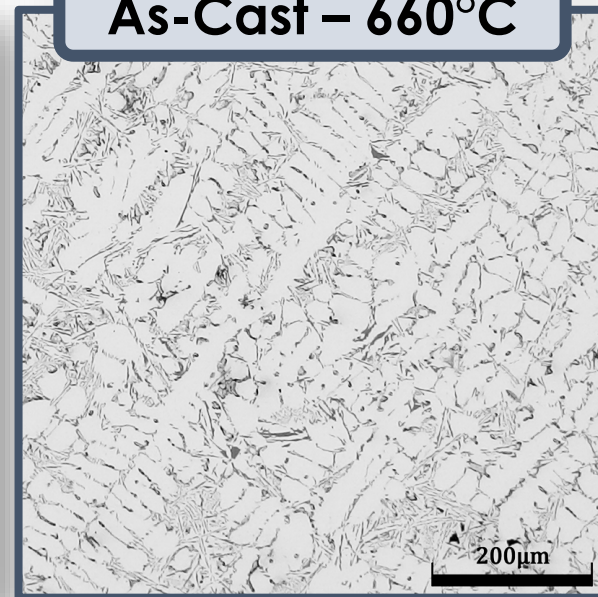
As-Cast – 700°C



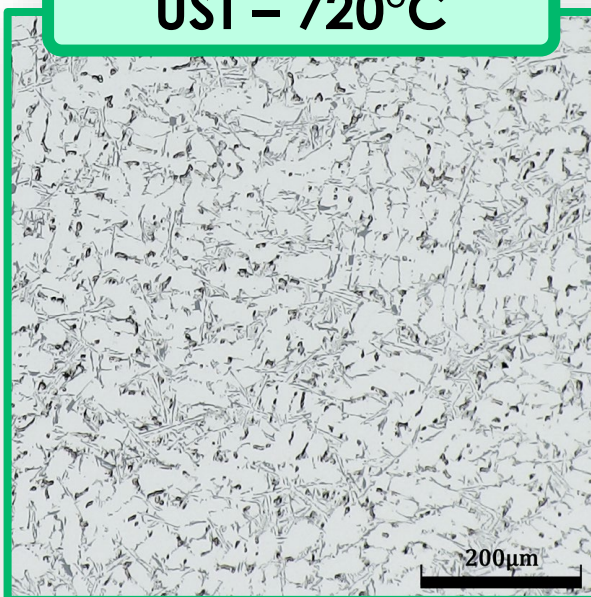
As-Cast – 680°C



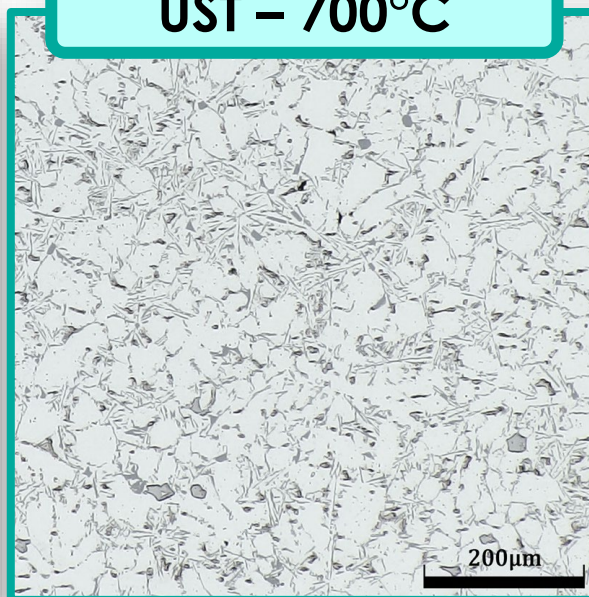
As-Cast – 660°C



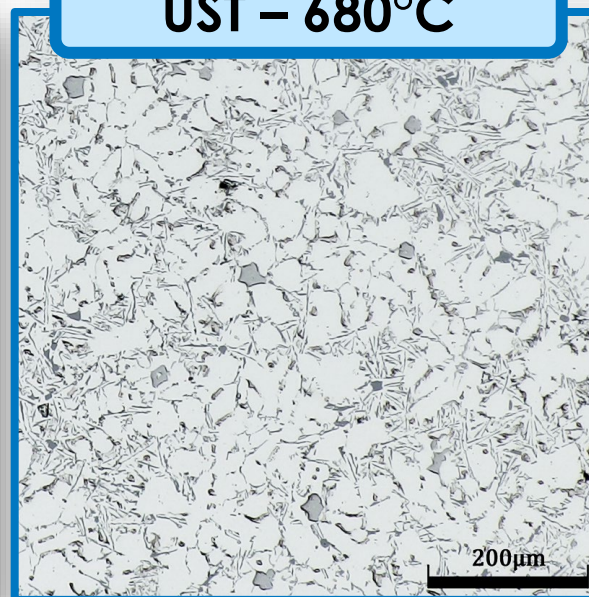
UST – 720°C



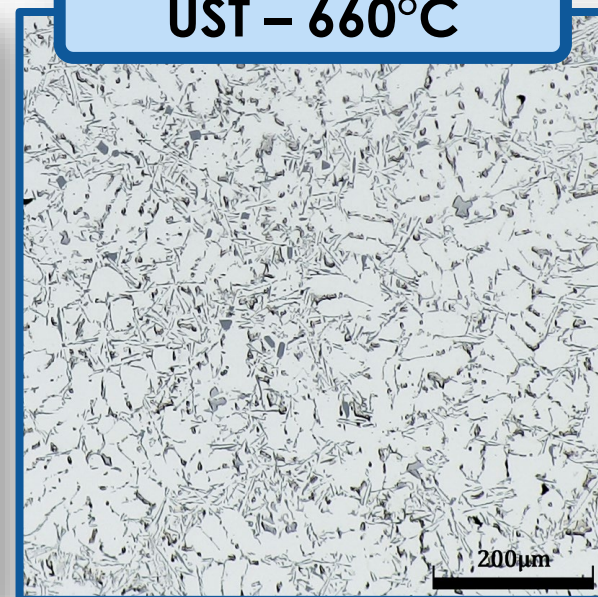
UST – 700°C



UST – 680°C

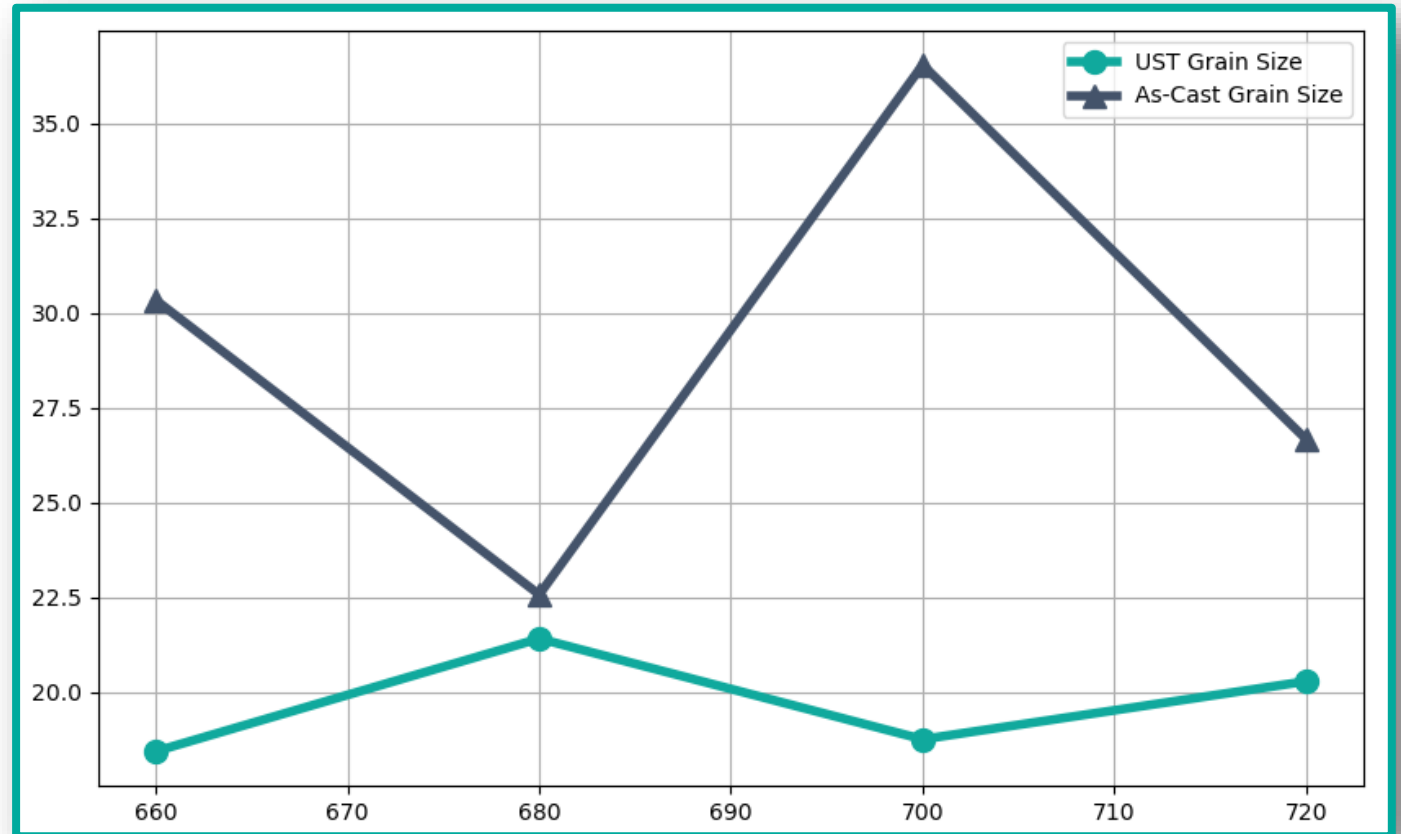


UST – 660°C



Grain Size Correlation with Treatment Temperature

Average Grain Size (μm)



Treatment Temperature ($^{\circ}\text{C}$)

As-Cast – 720 $^{\circ}\text{C}$

As-Cast – 700 $^{\circ}\text{C}$

UST – 720 $^{\circ}\text{C}$

UST – 700 $^{\circ}\text{C}$

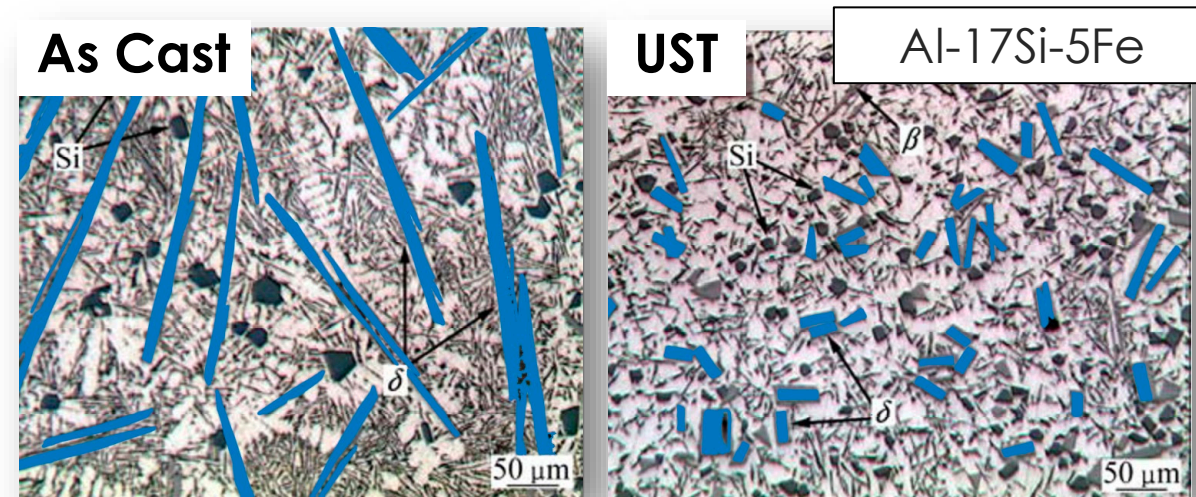
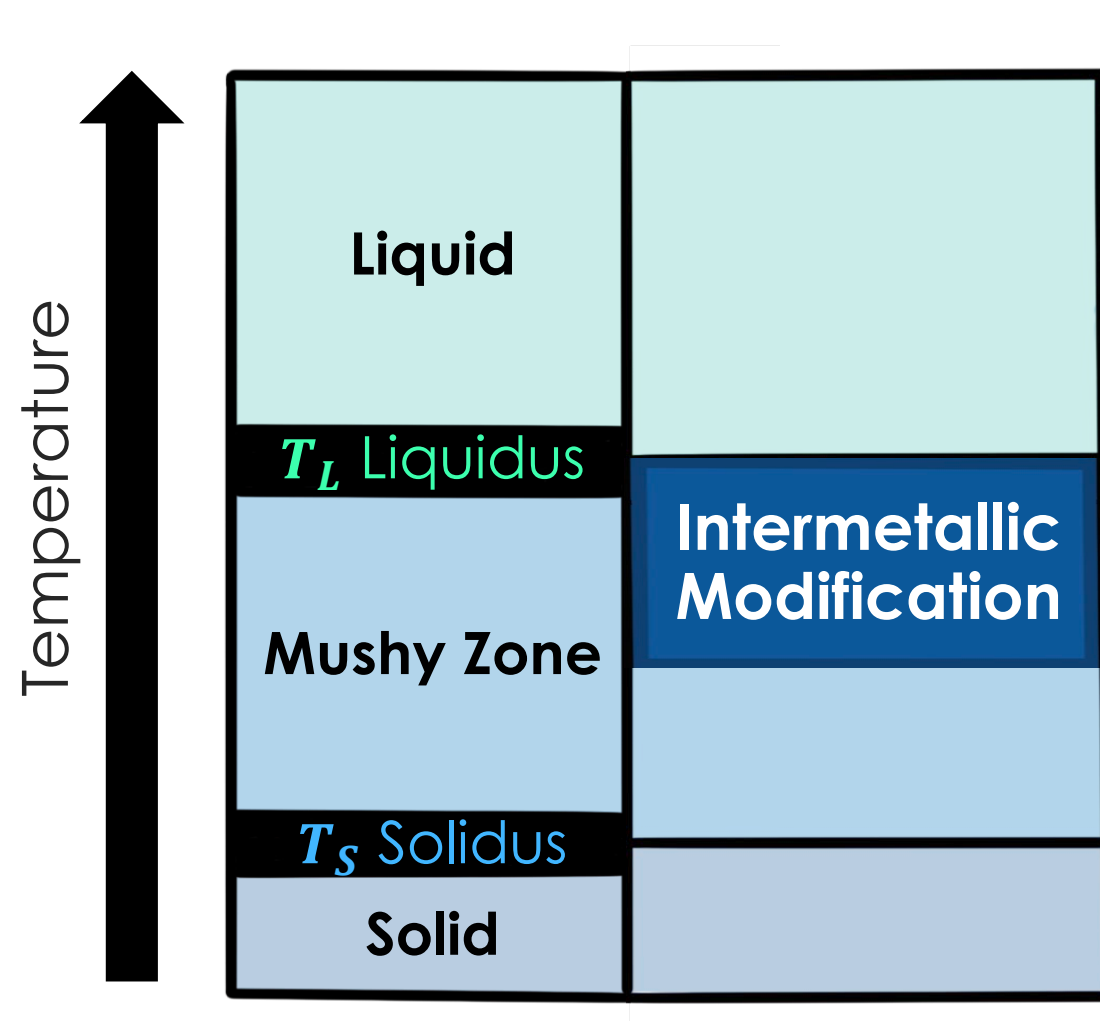
As-Cast – 680 $^{\circ}\text{C}$

As-Cast – 660 $^{\circ}\text{C}$

UST – 680 $^{\circ}\text{C}$

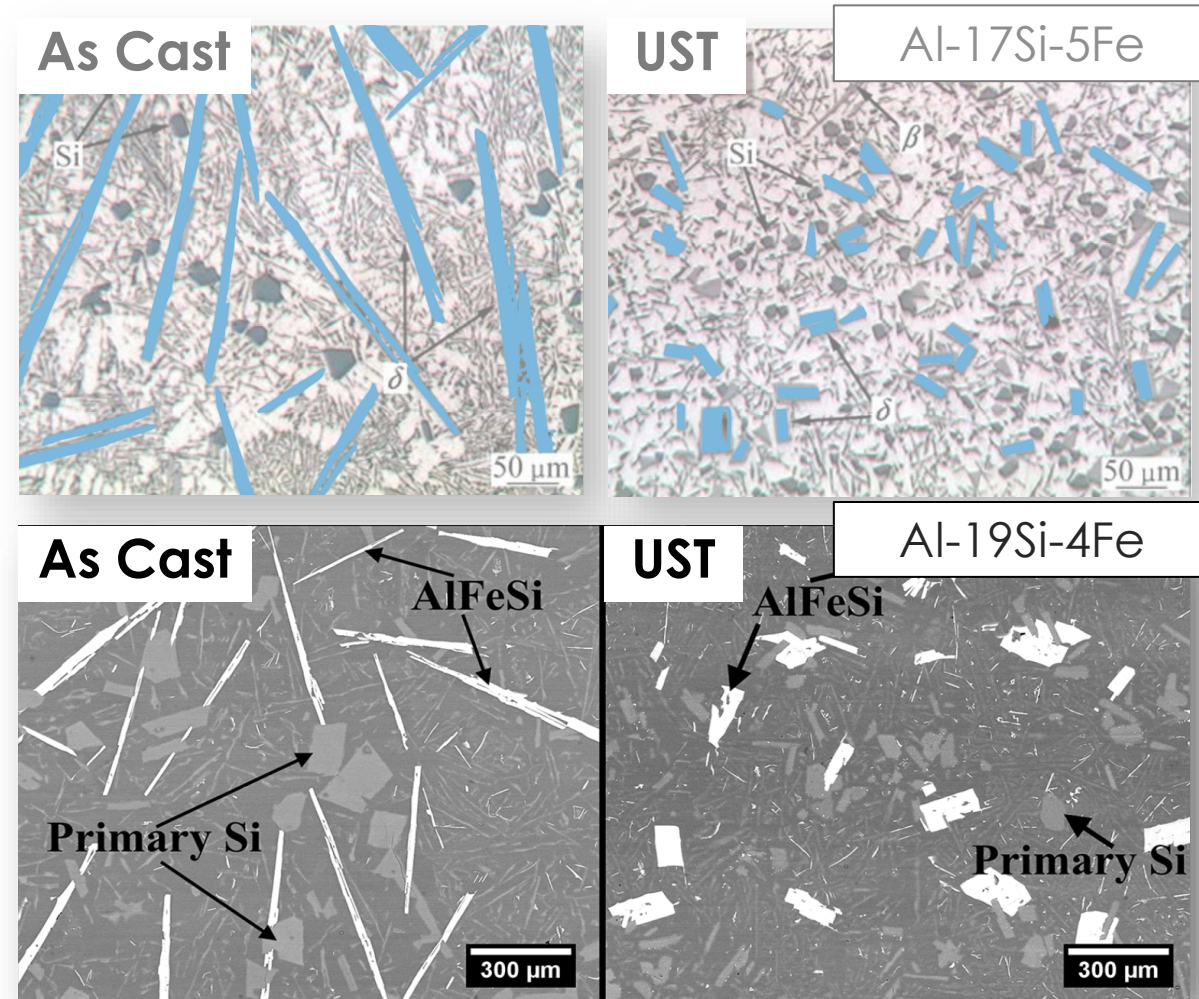
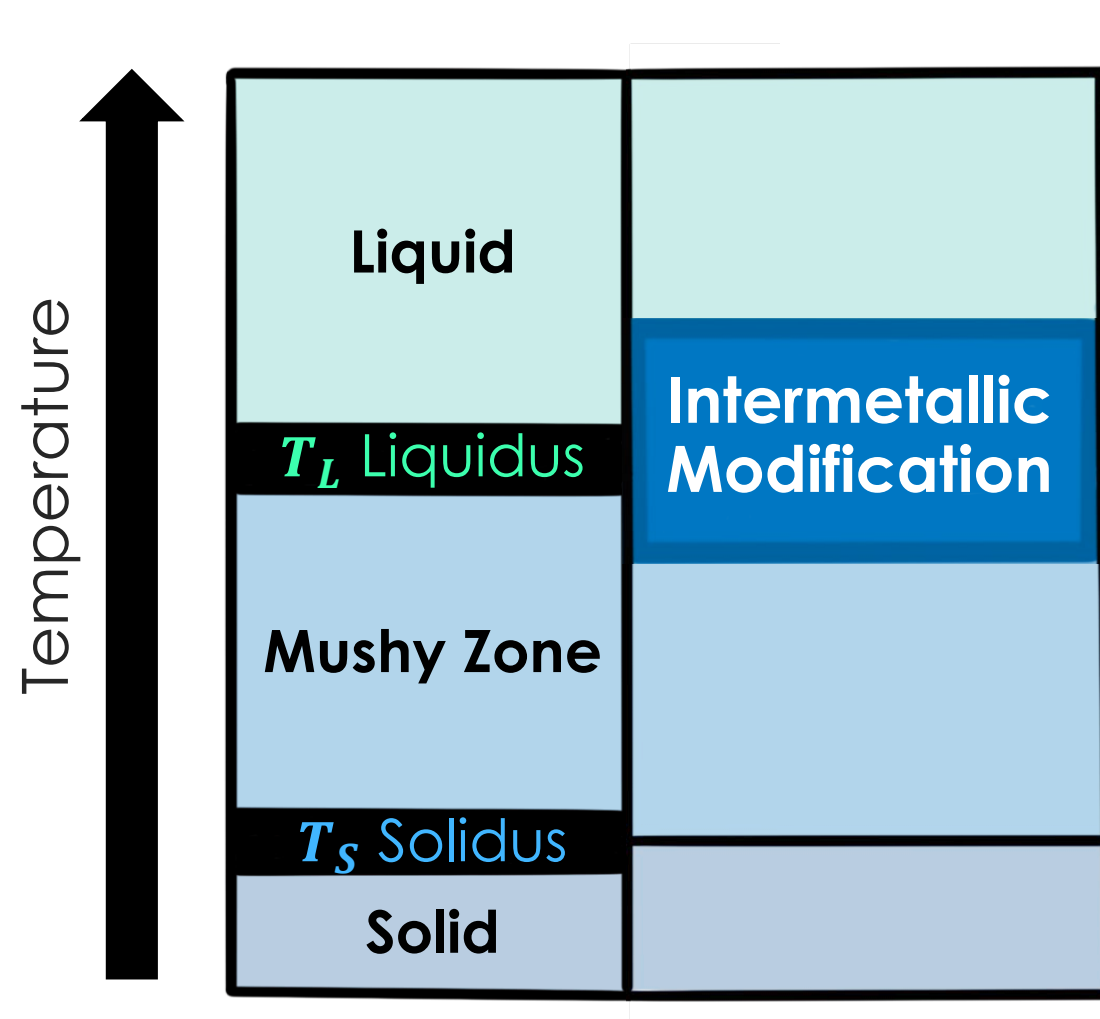
UST – 660 $^{\circ}\text{C}$

Mechanisms of UST Intermetallic Mod.



C. Lin *et al* Trans. Nonferrous Met. Soc. China , 2013

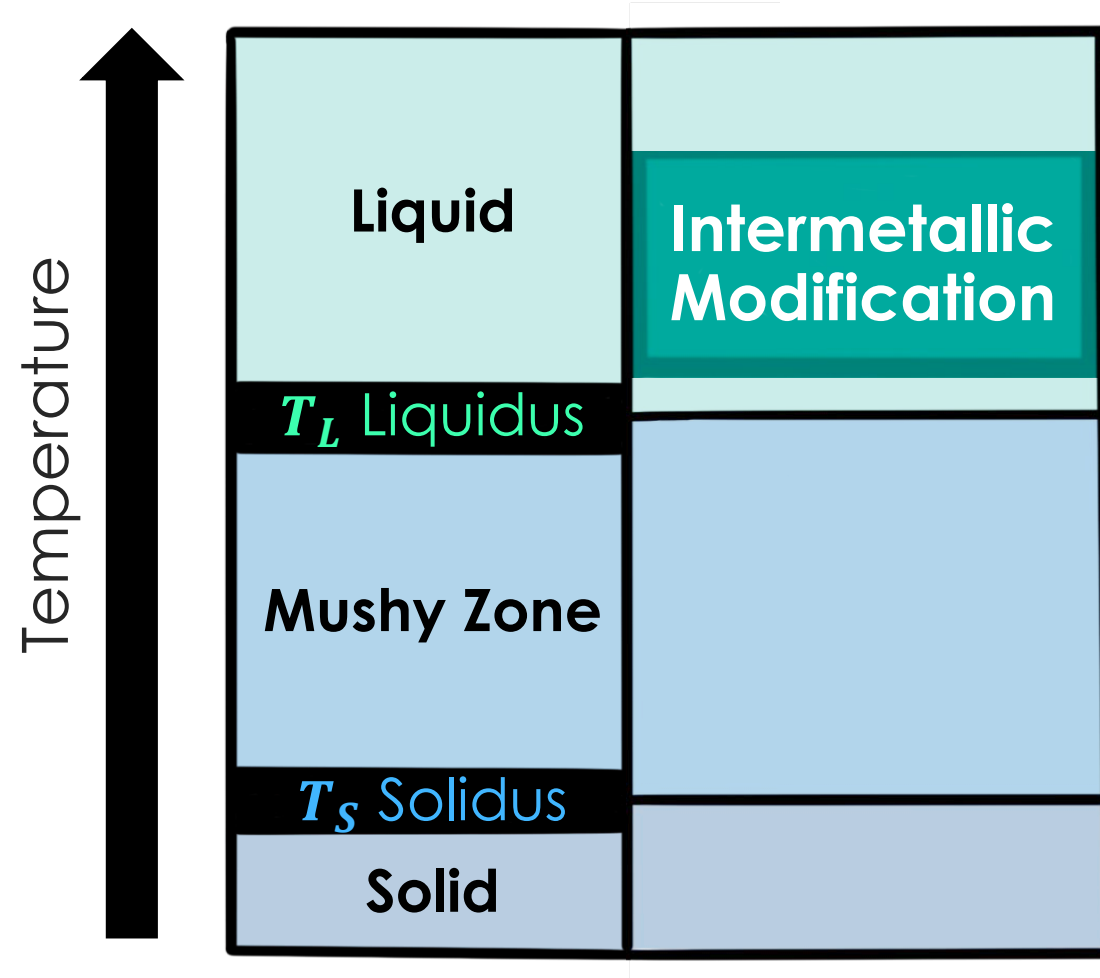
Mechanisms of UST Intermetallic Mod.



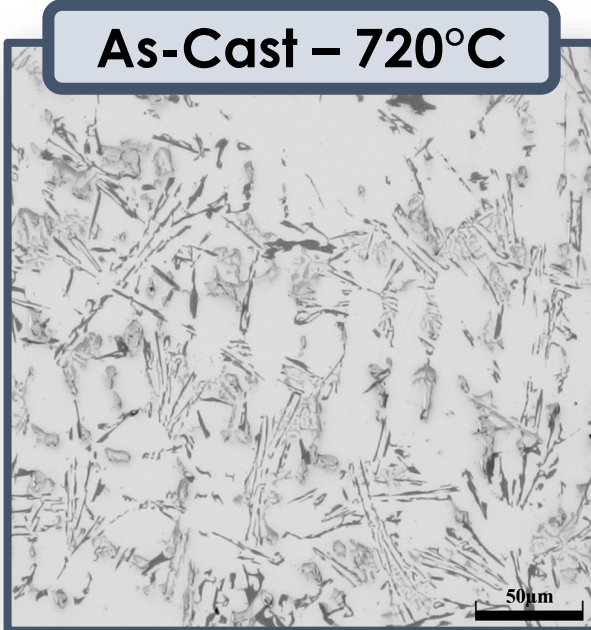
C. Lin *et al* Trans. Nonferrous Met. Soc. China , 2013

C.J. Todaro *et al* TMS, 2017

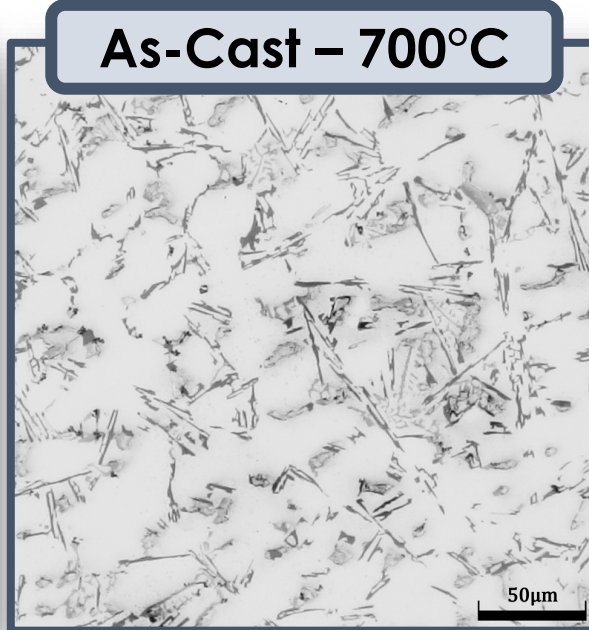
Mechanisms of Liquid State UST



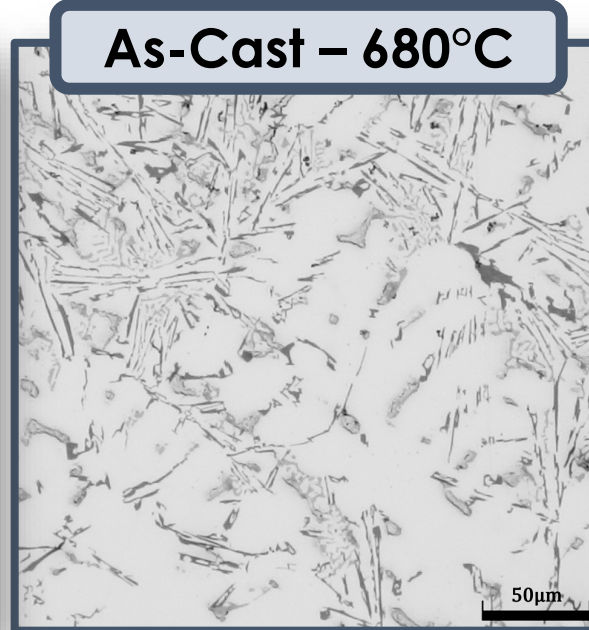
As-Cast – 720°C



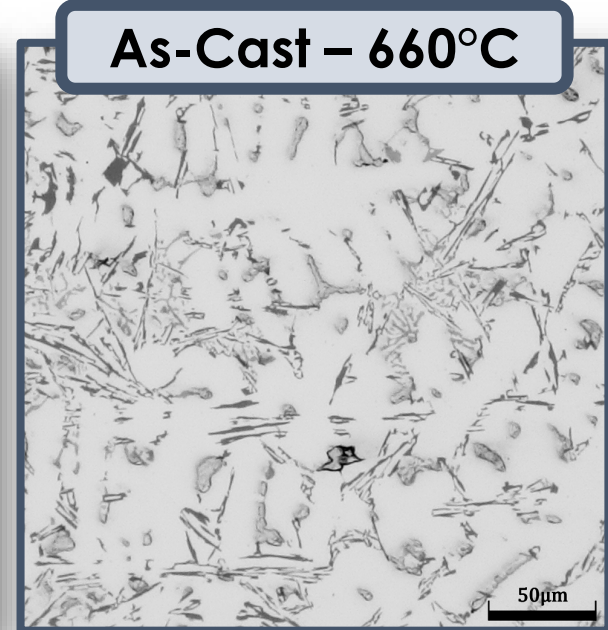
As-Cast – 700°C



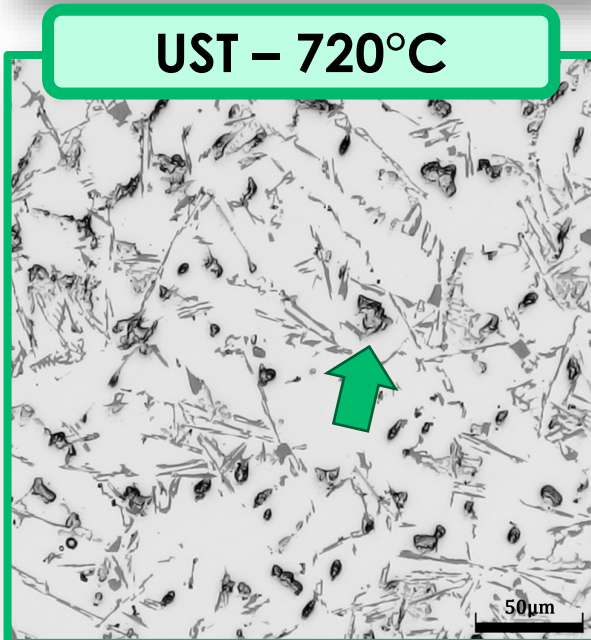
As-Cast – 680°C



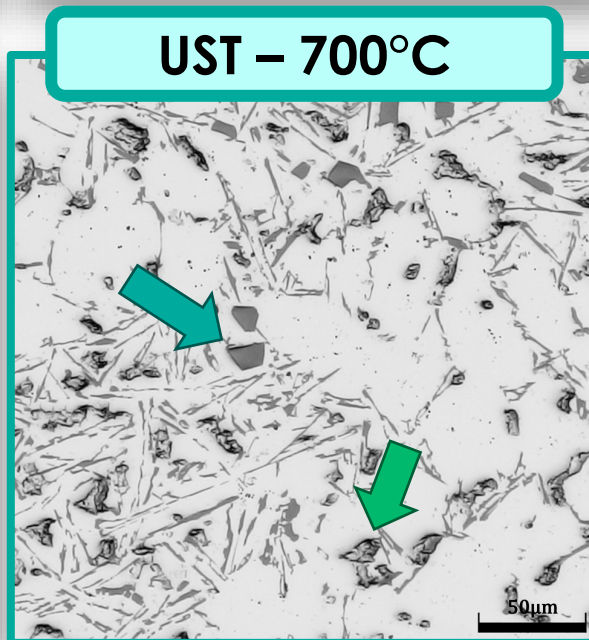
As-Cast – 660°C



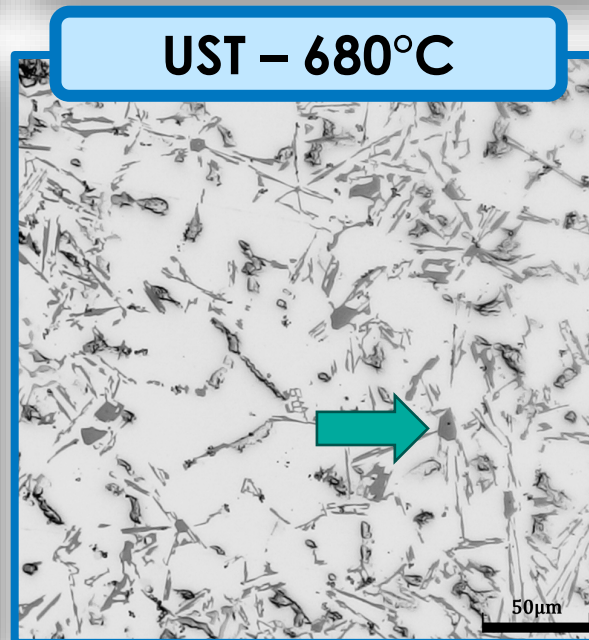
UST – 720°C



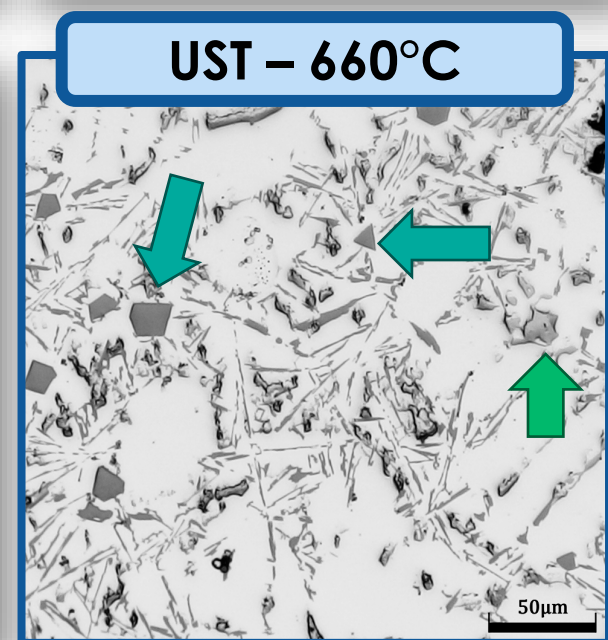
UST – 700°C

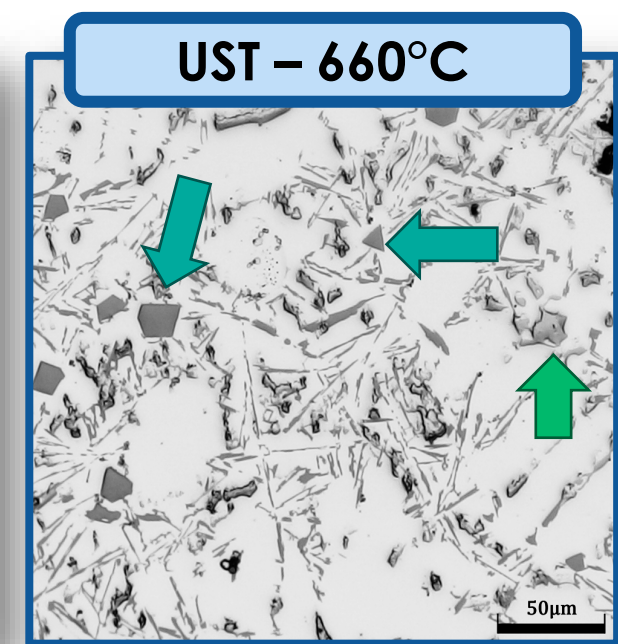
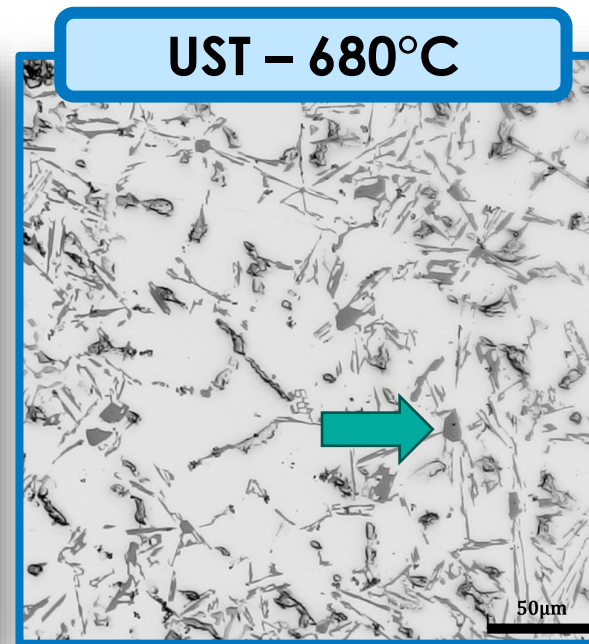
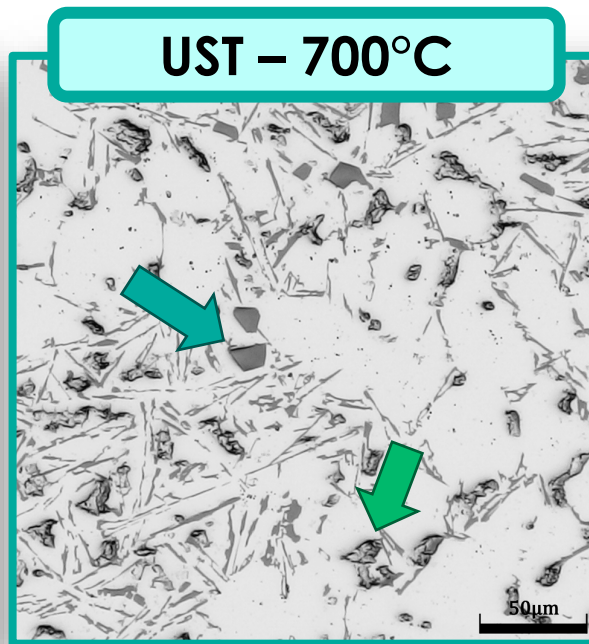
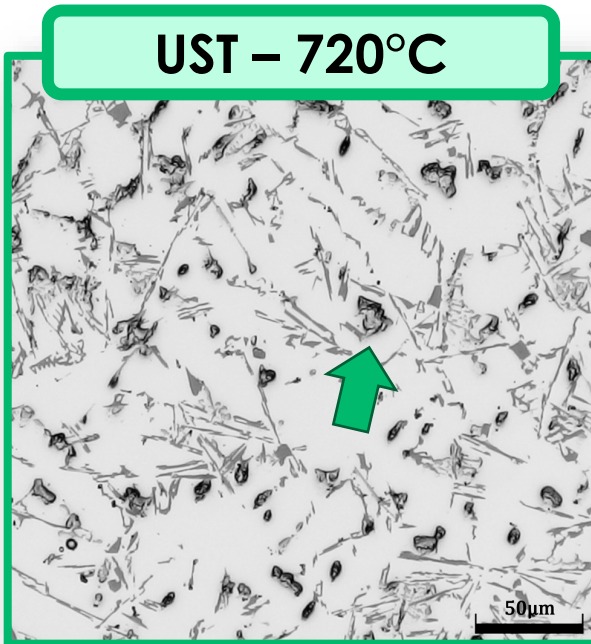


UST – 680°C



UST – 660°C

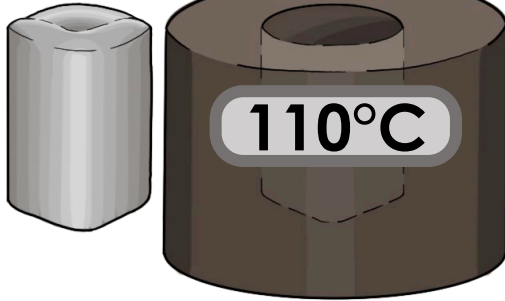




	Al	Si	Fe	Mn	Cu	Zn	Cr
	40.87%	56.13%	0.01	--	1.62	--	1.36
	61.53%	8.796	17.25%	6.558%	1.518%	0.708%	3.28%
	71.00%	2.11%	0.92%	0.14%	21.73%	3.75%	--

Time Decay of Treatment

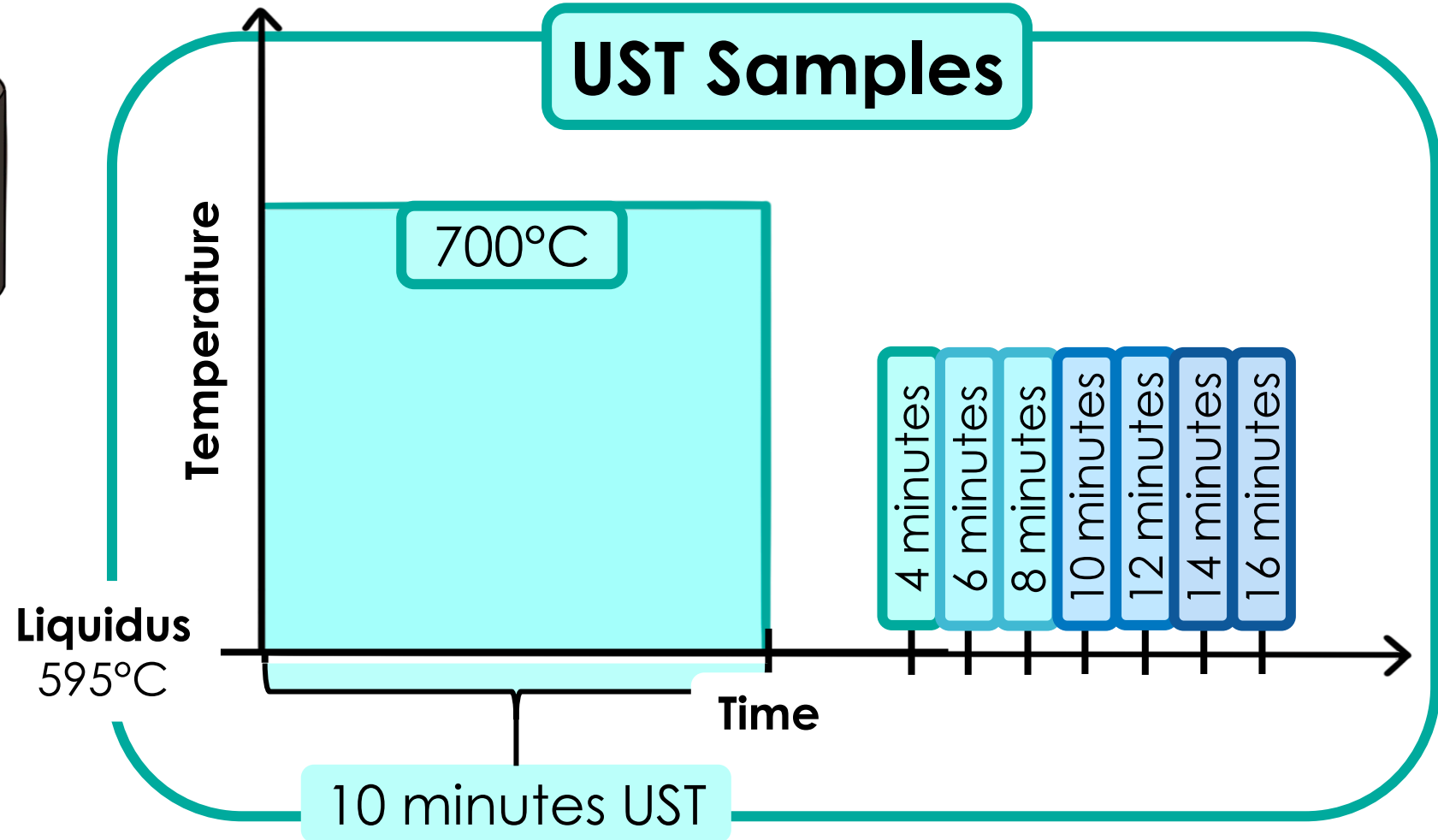
A380



As-Cast
700°C

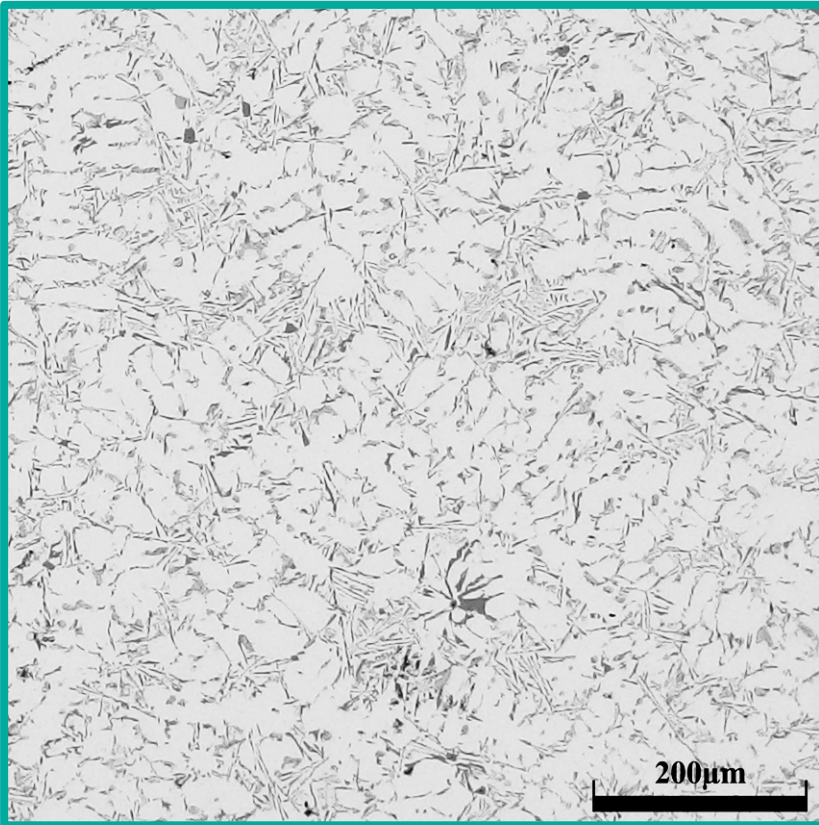
vs.

Liquidus
595°C

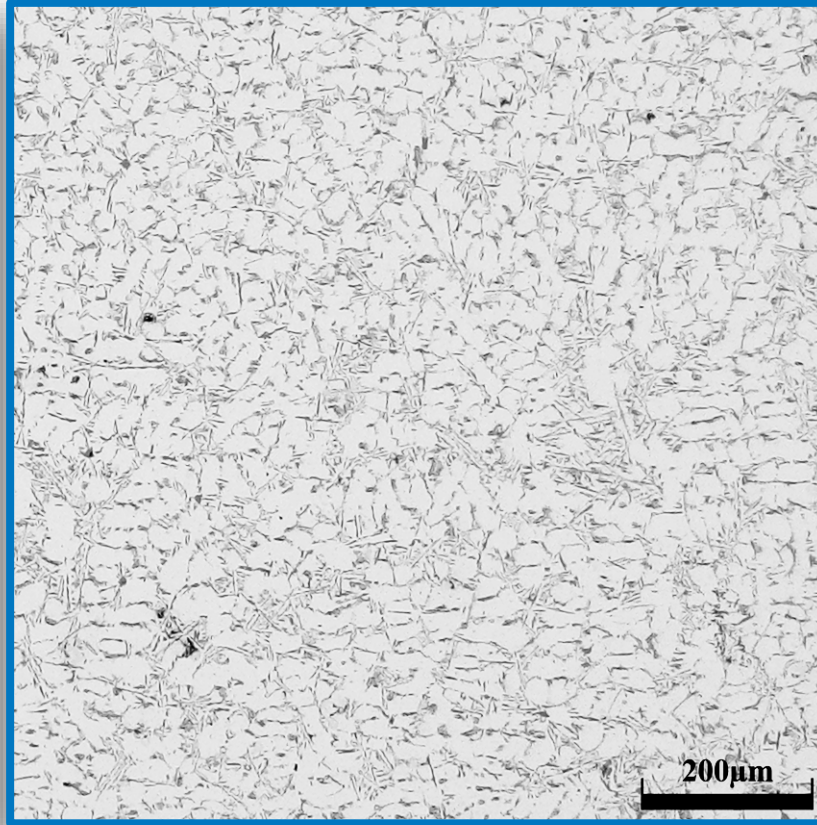


Multifrequency Time Decay: Grain Ref.

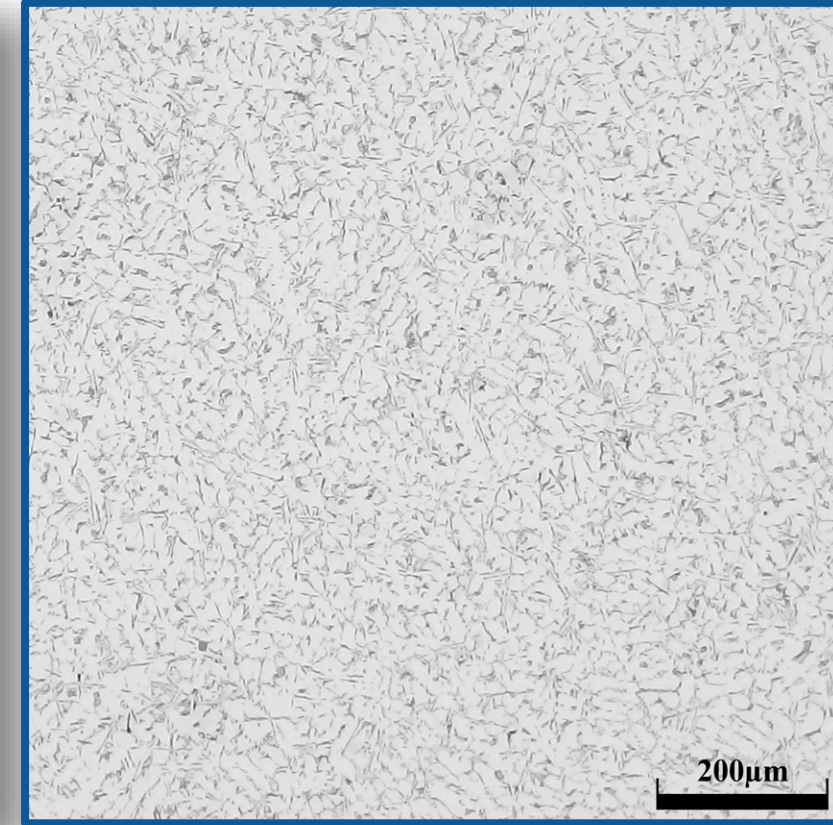
Post-UST 6 minutes



Post-UST 12 minutes

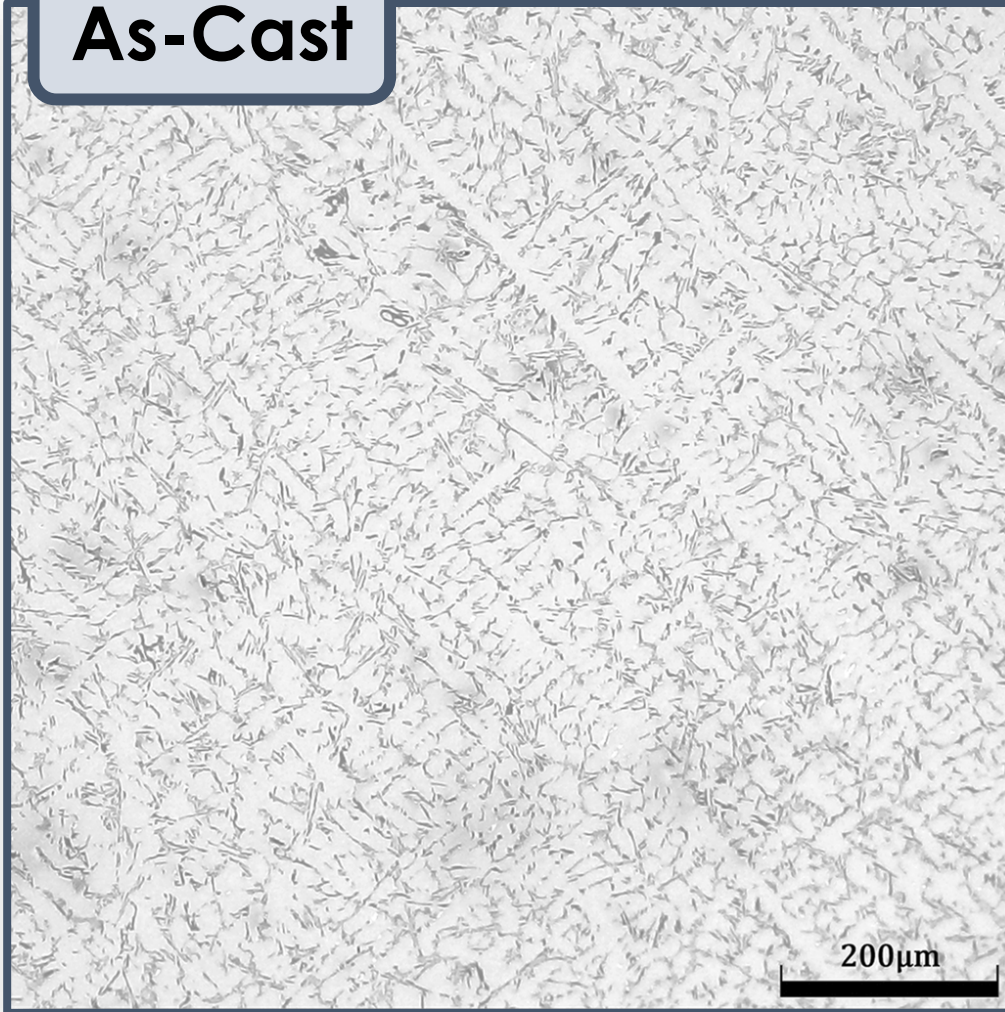


Post-UST 16 minutes

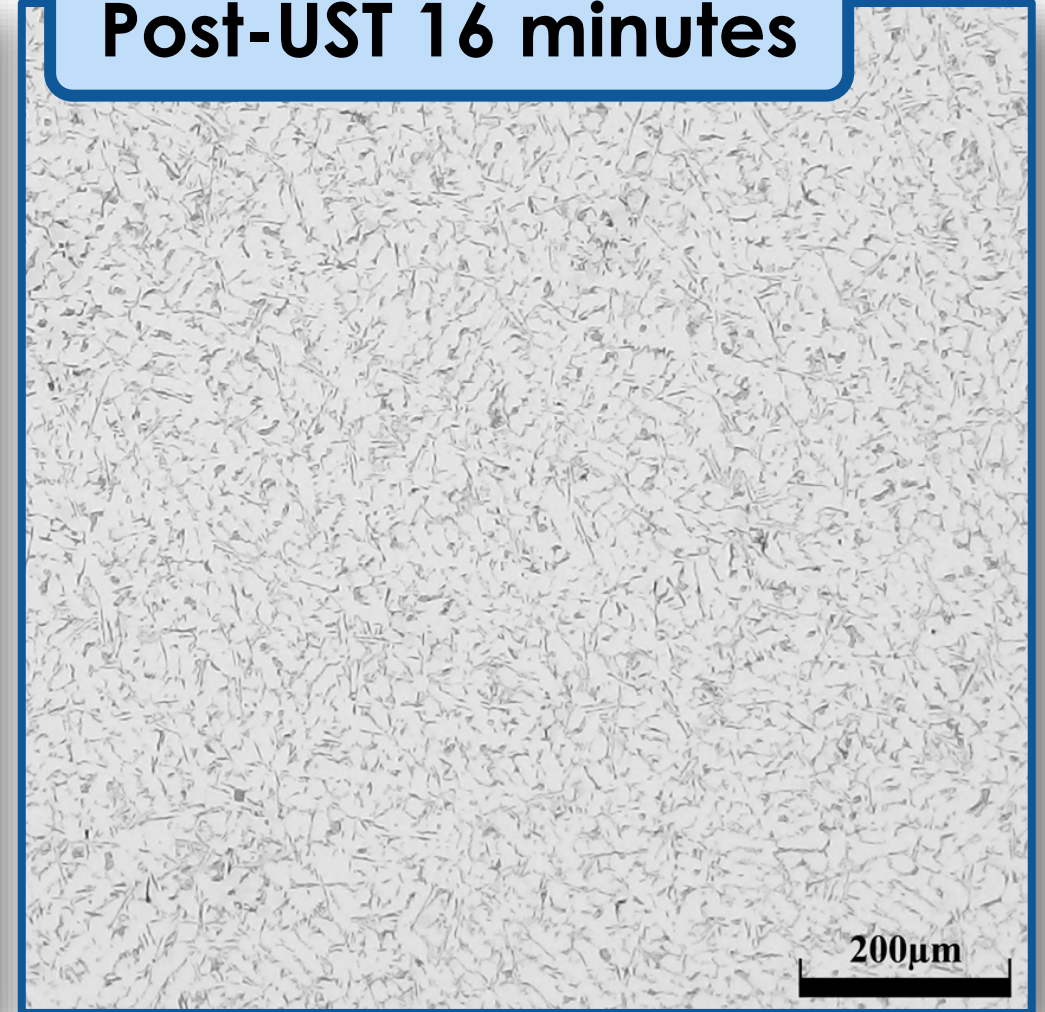


Multifrequency Time Decay: Grain Ref.

As-Cast



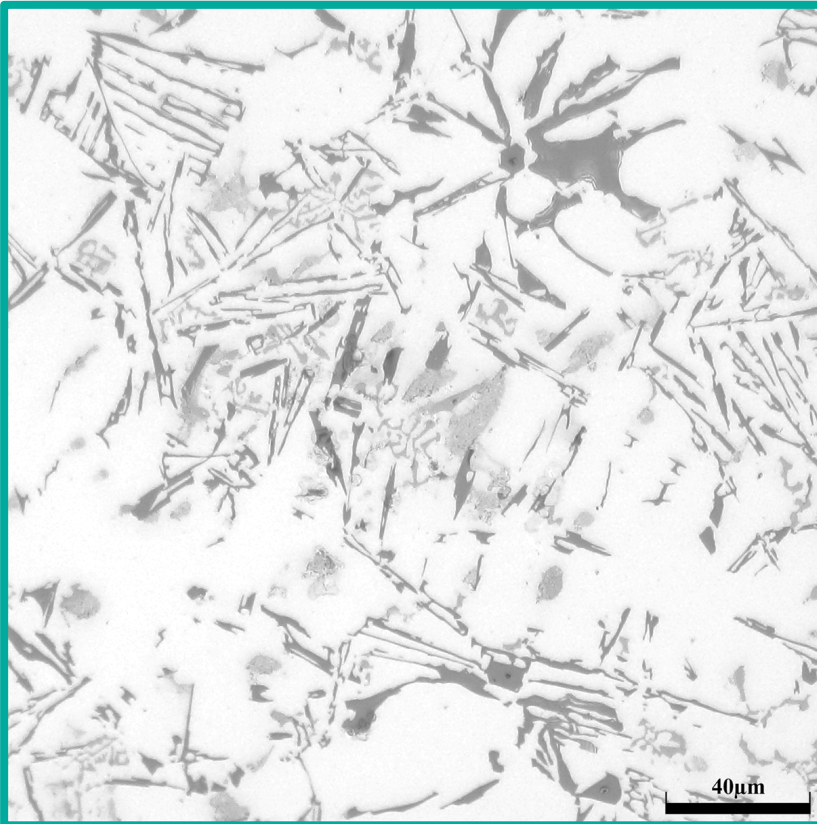
Post-UST 16 minutes



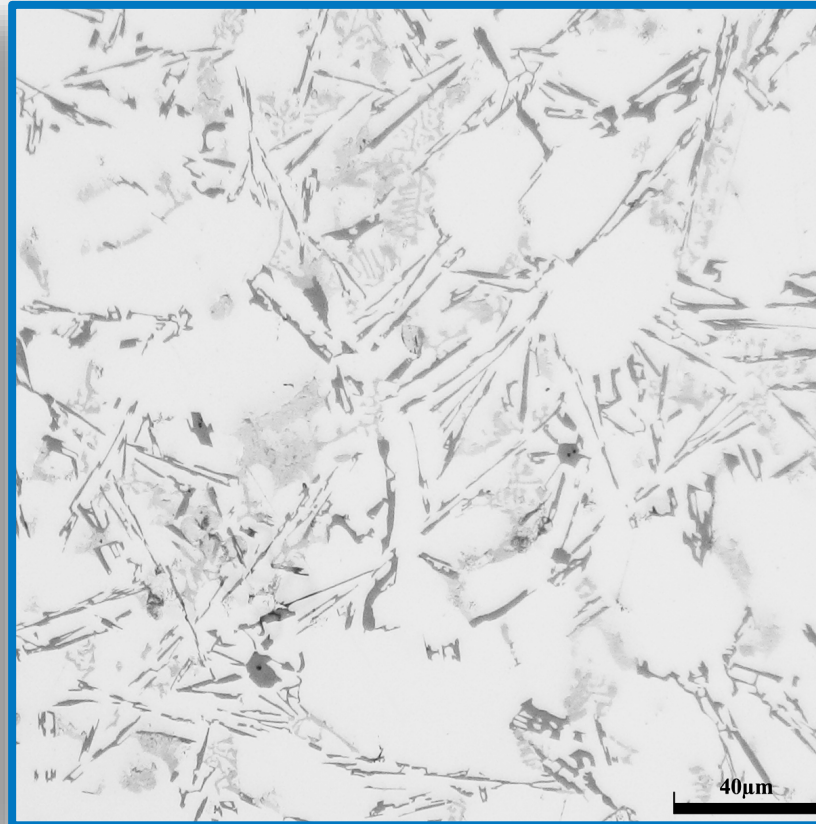
A380
700°C

Multifrequency Time Decay: Phase Mod.

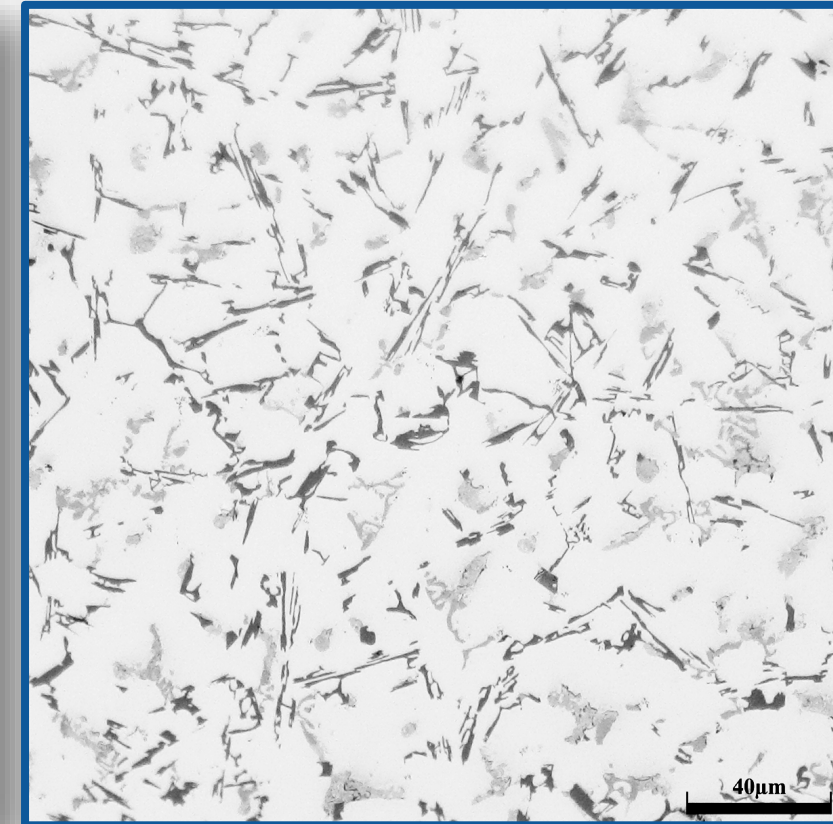
Post-UST 6 minutes



Post-UST 12 minutes

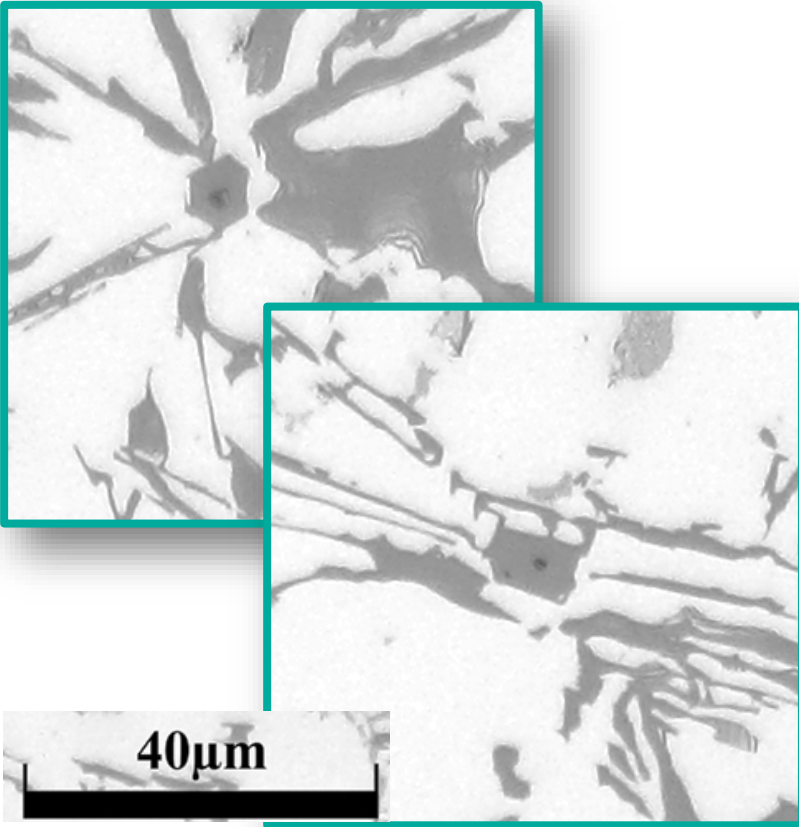


Post-UST 16 minutes

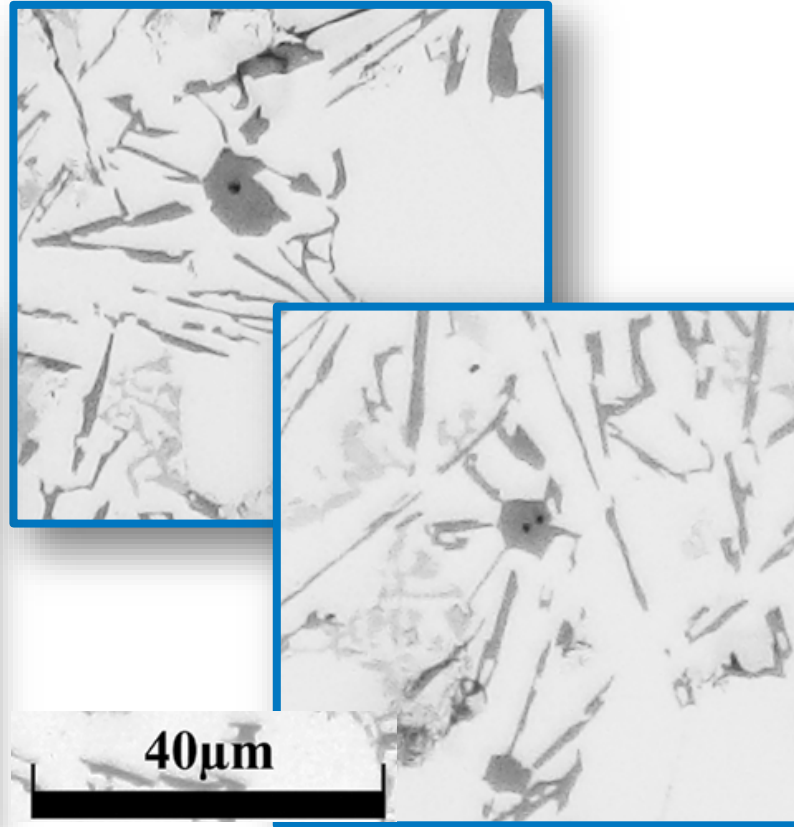


Multifrequency Time Decay: Phase Mod.

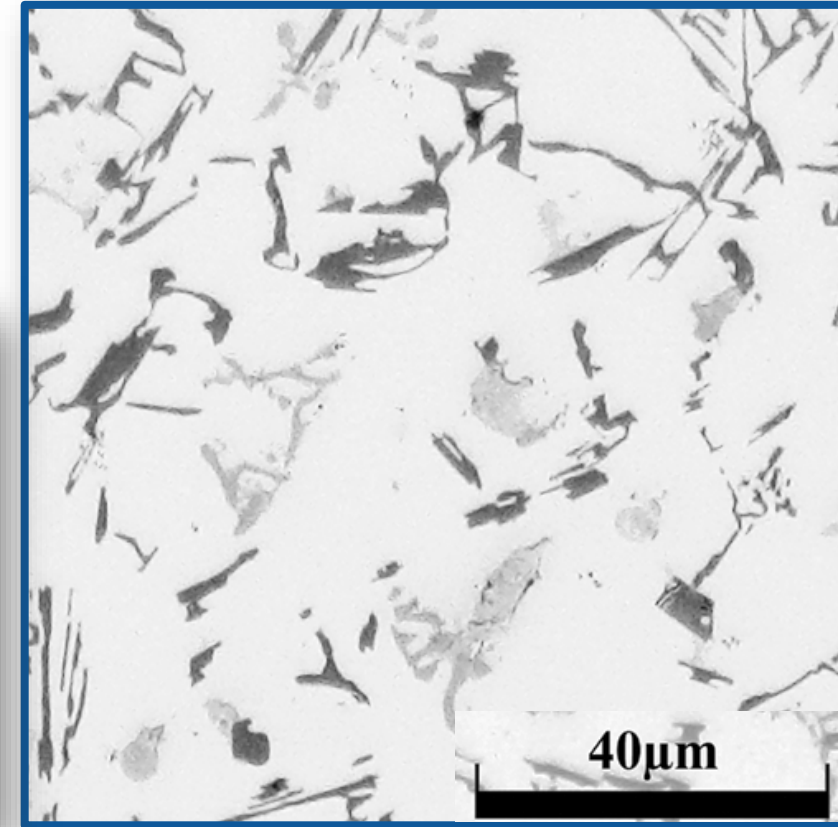
Post-UST 6 minutes



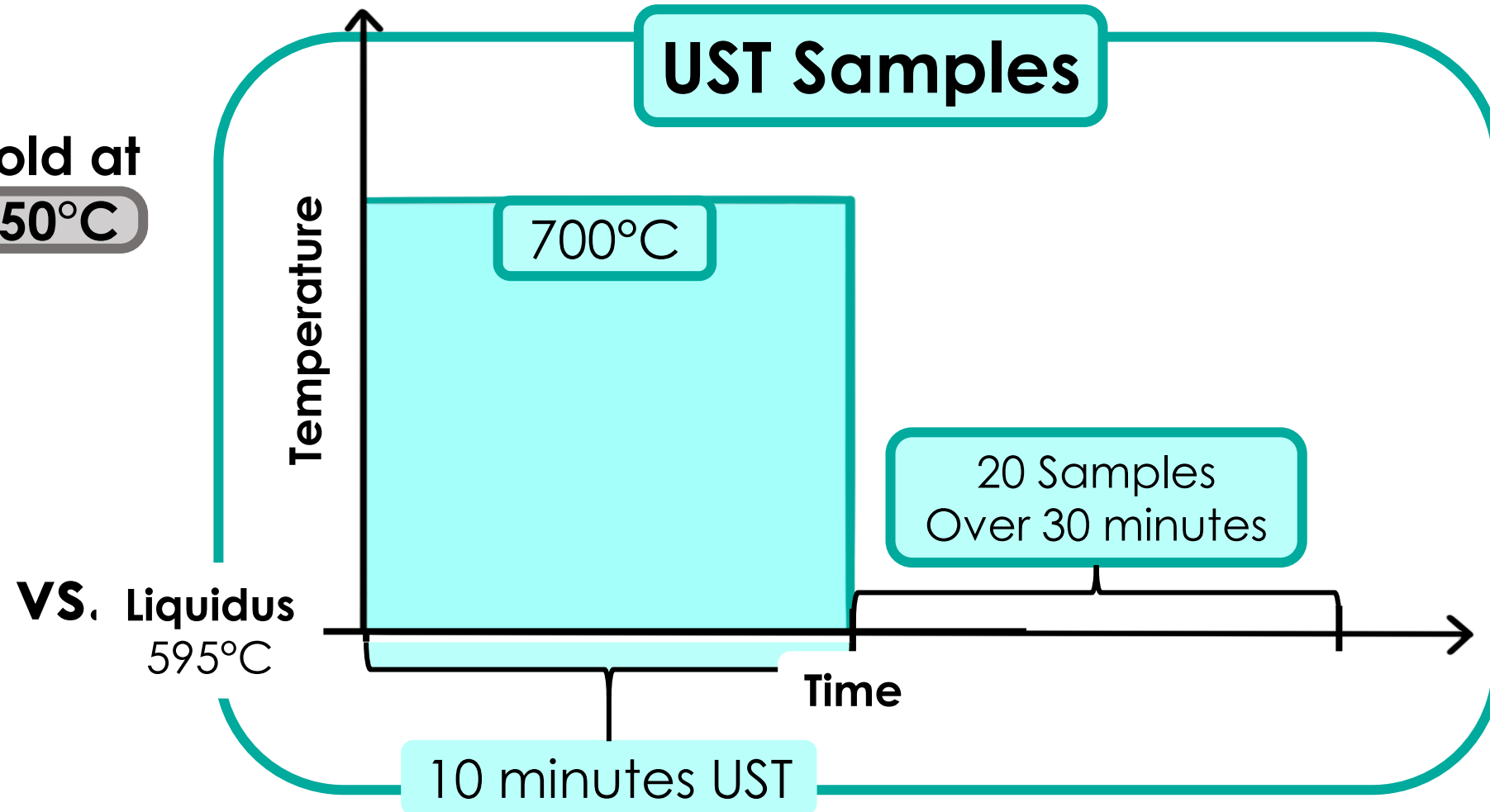
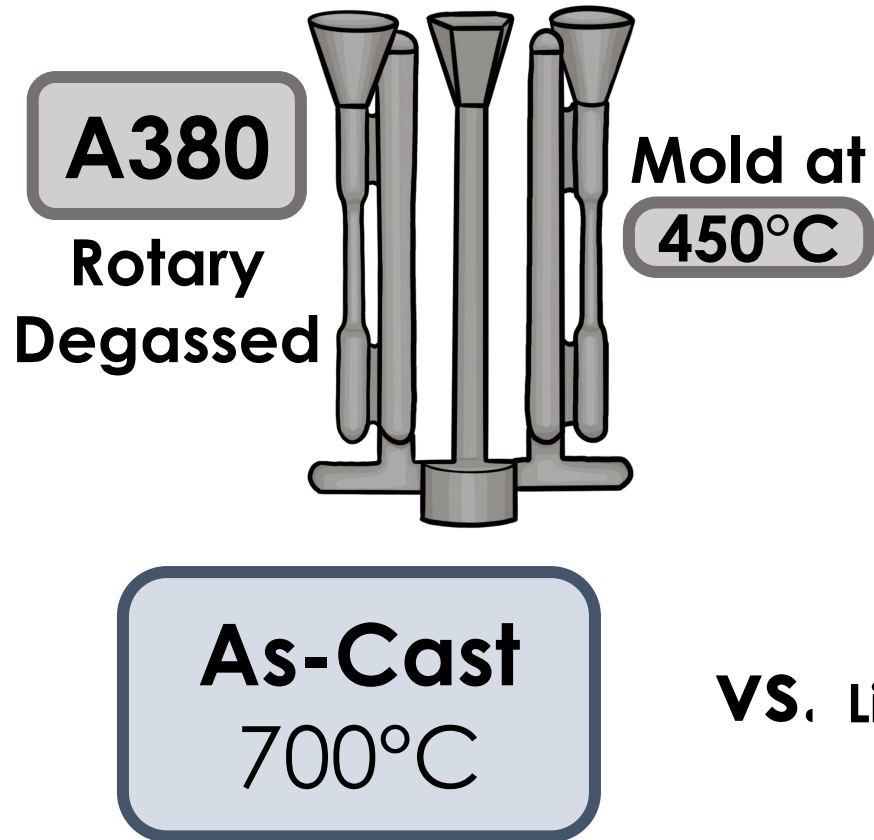
Post-UST 12 minutes



Post-UST 16 minutes

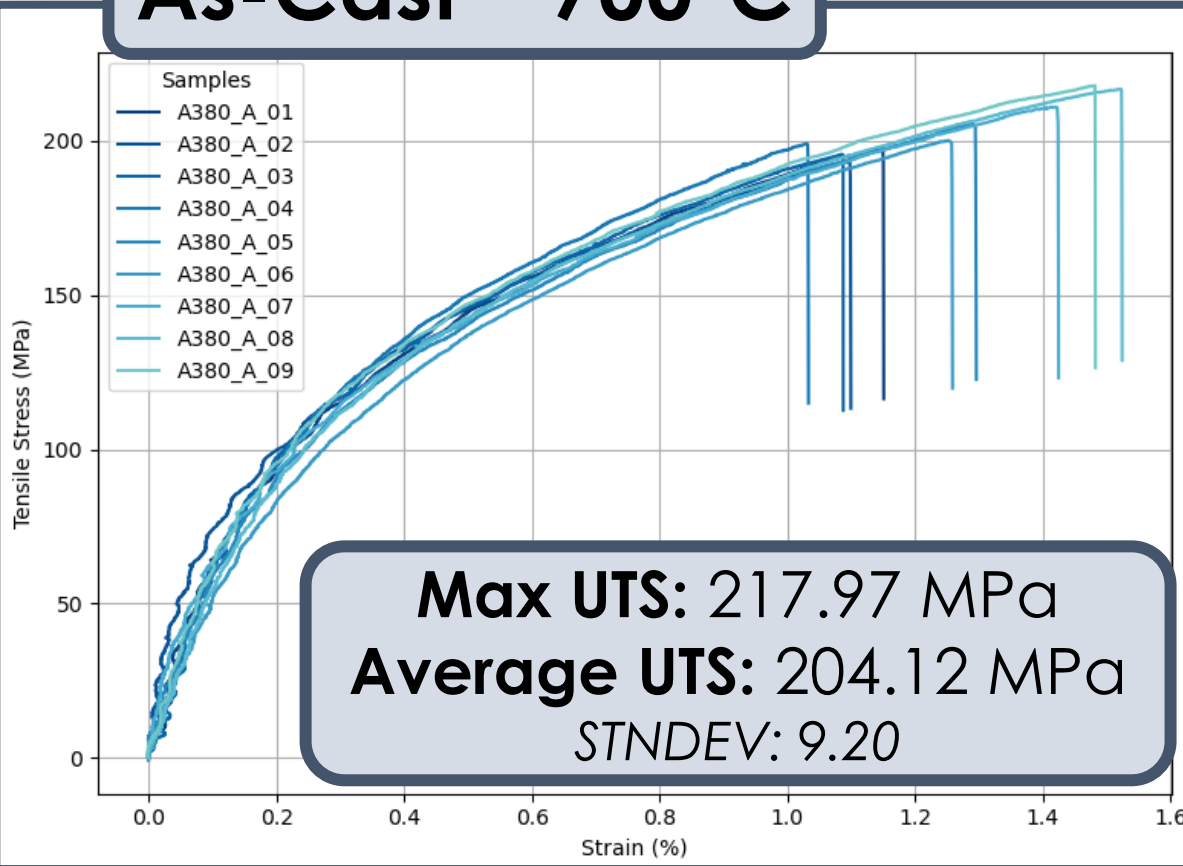


Effect of 700°C UST & Time on Tensile Properties

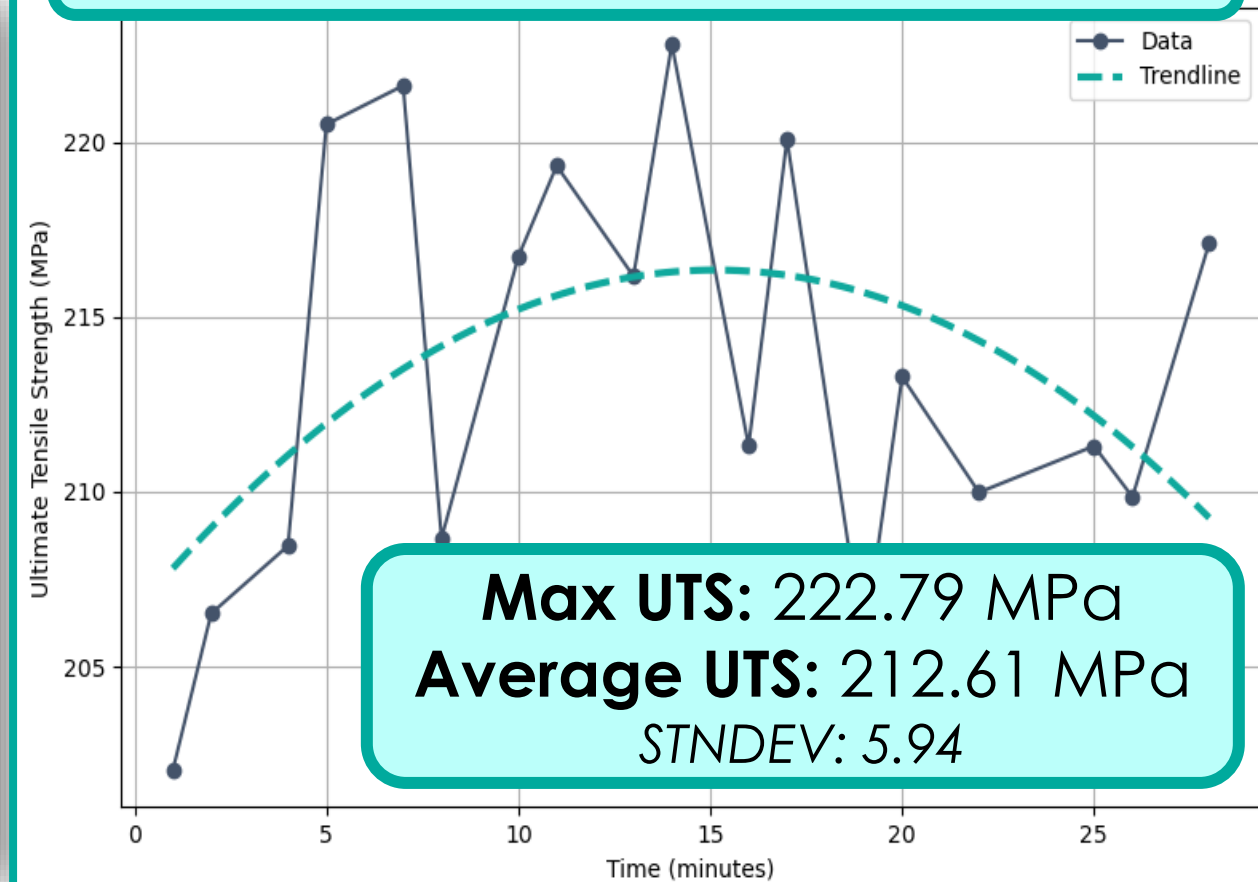


UST Influence on Material Properties

As-Cast – 700°C

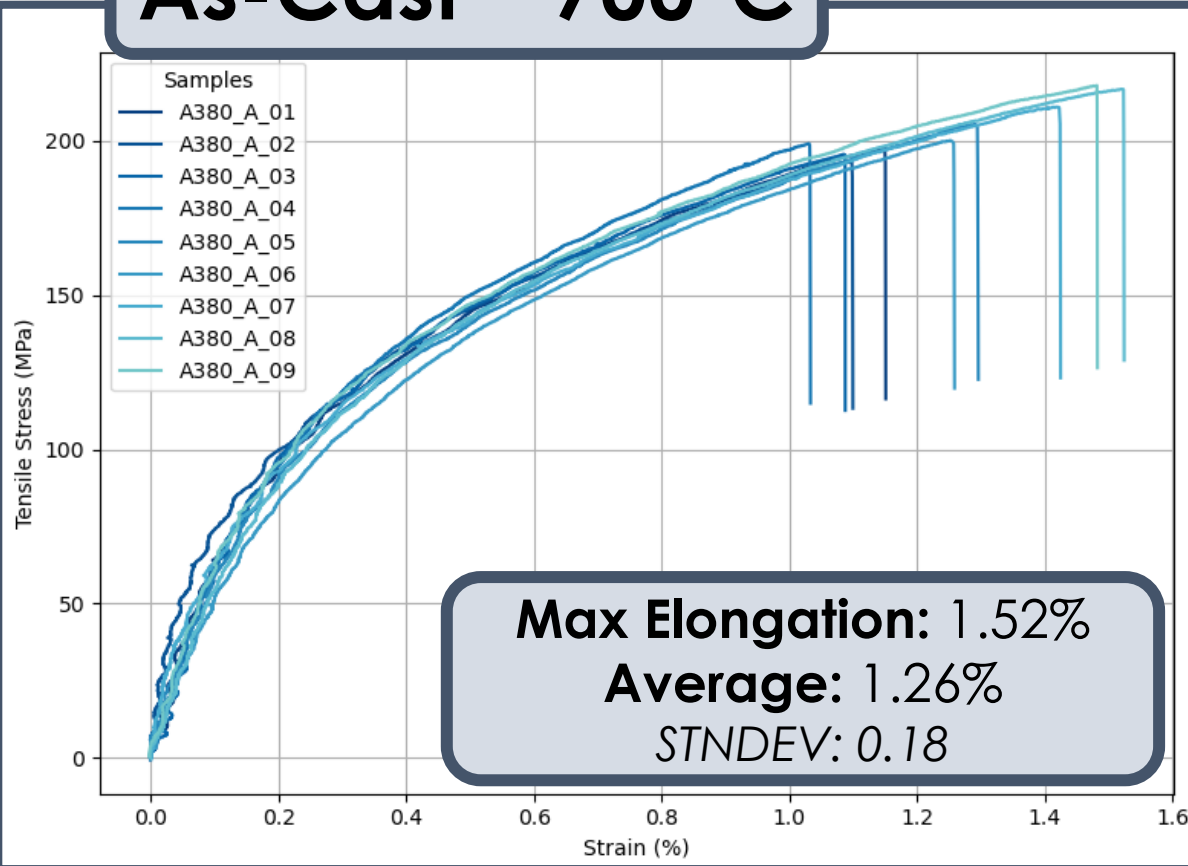


UST - 700°C; 0 to 30 Minutes

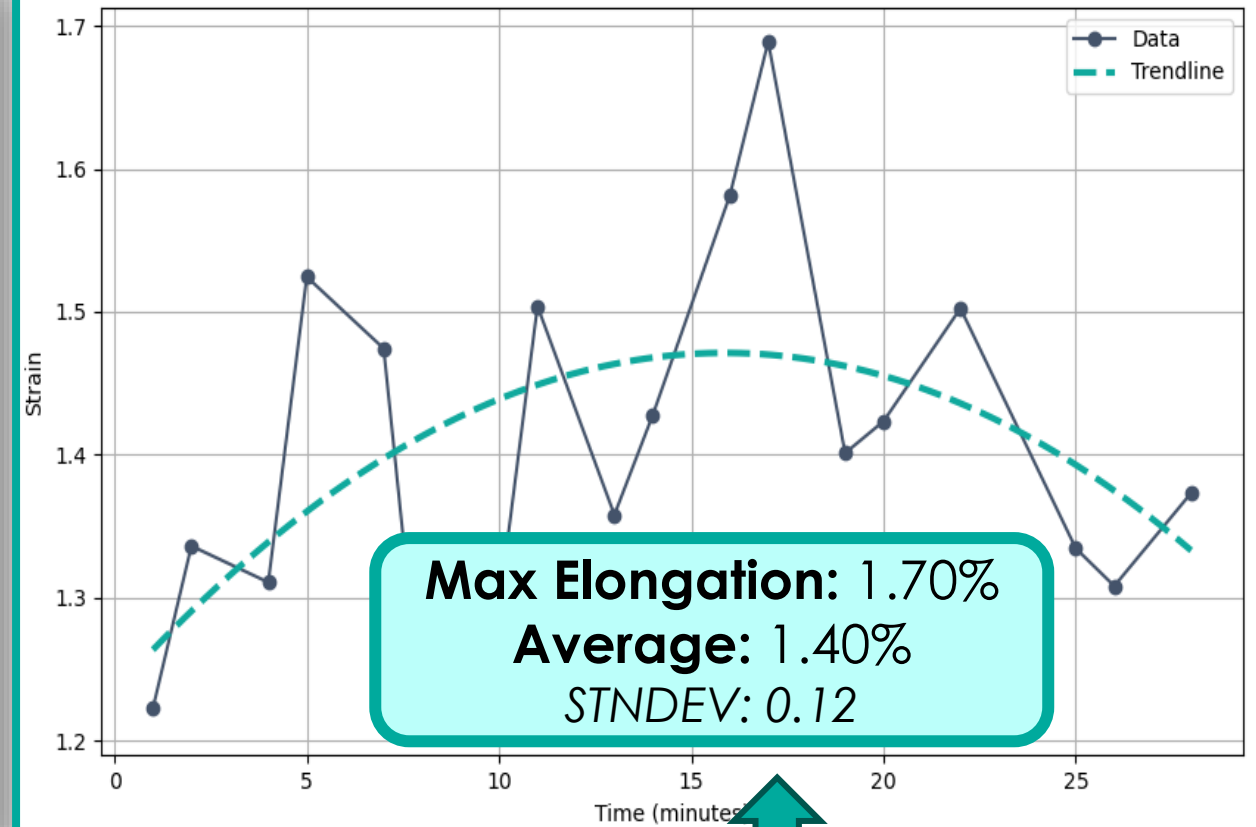


UST Influence on Material Properties

As-Cast – 700°C



UST - 700°C; 0 to 30 Minutes



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1. UST Applications in Liquid Metallurgy
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3. Multifrequency Liquid State Trials
- 4. Next Steps**

Next Steps

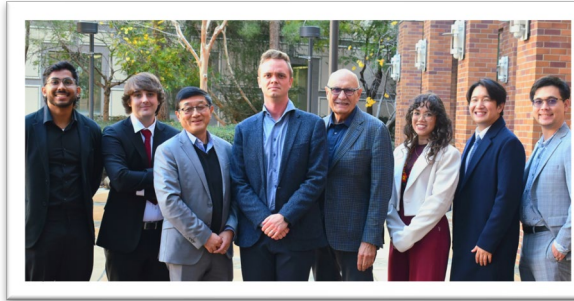
Degassing

1. *Validate interference of induction with UST degas*
2. *Collaboration with Professor Puga*

Grain Refinement & Intermetallic Modification

1. *Minimum oxide content: Oxide Refiners*
2. *Identifying mechanism for visible change & time decay*
3. *Energy Density*
4. *Compositional Analysis of Phases*

Acknowledgements



ACRC Ultrasonic Project

Proprietary Information: dissemination and use restricted to members of the ACRC

Thank you! 

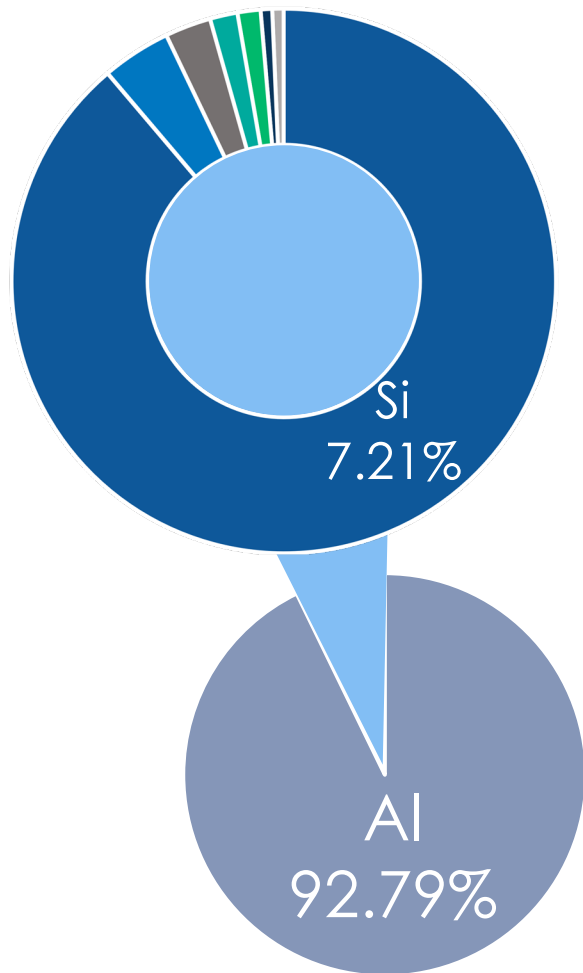
Discussion

- <https://uci.zoom.us/j/97926336058>

Additional Slides for Questions

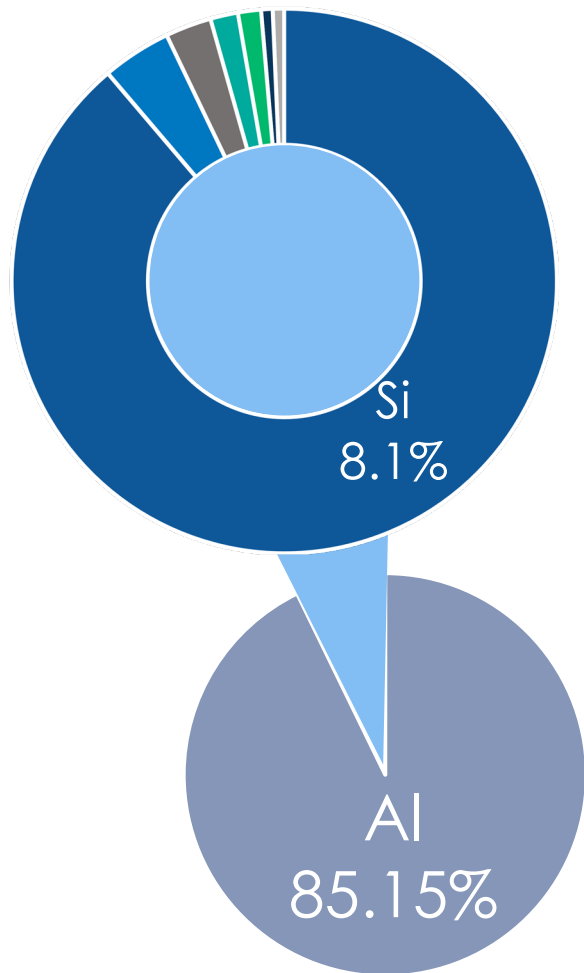
Multifrequency Ultrasonics Procedure

A356 Composition



	wt %
Si	7.210
Mg	0.297
Ti	0.112
Fe	0.112
Cu	0.003
Zn	0.010
Mn	0.007

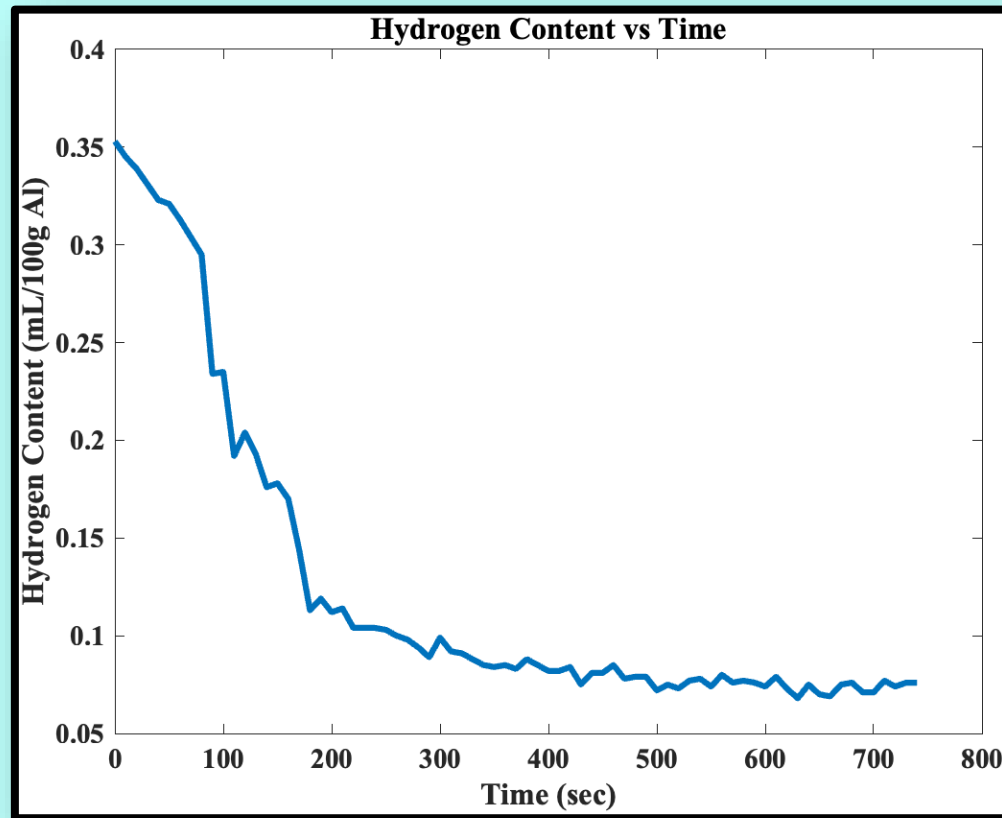
A380 Composition



	wt. %
Si	8.1
Cu	3.406
Zn	2.177
Fe	0.811
Mn	0.201
Mg	0.0784
Cr	0.067

Traditional Rotary Degassing

HYCAL Plot



RPT

0 minutes

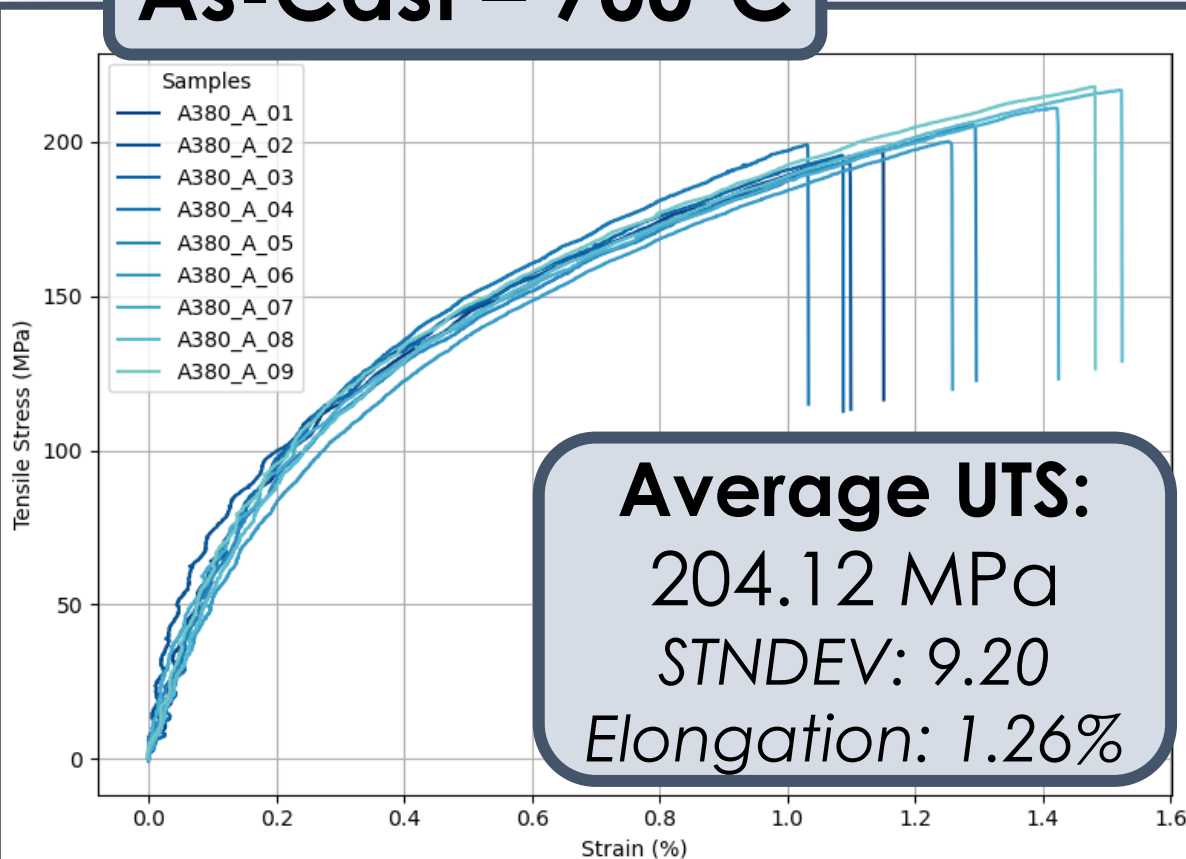
15 minutes



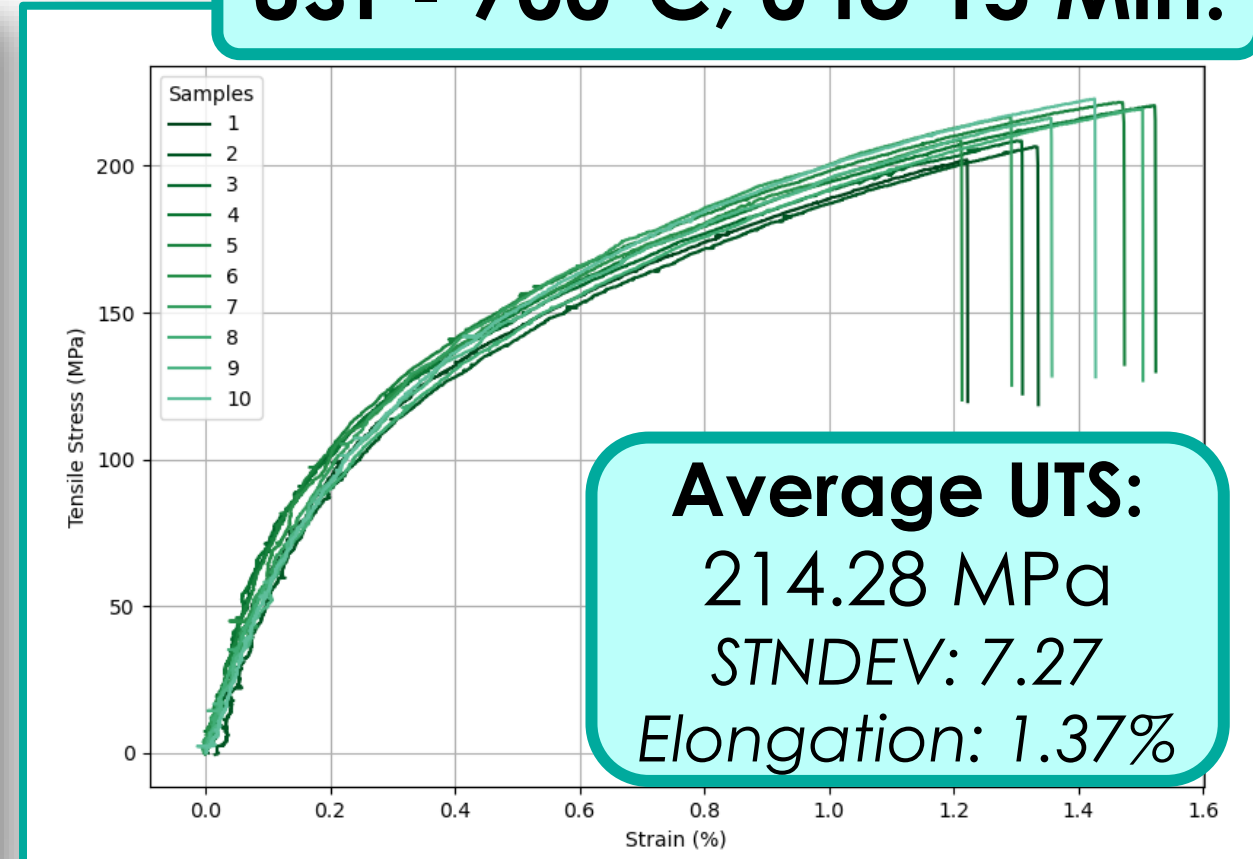
UST Influence on Material Properties

Tensile Data

As-Cast – 700°C



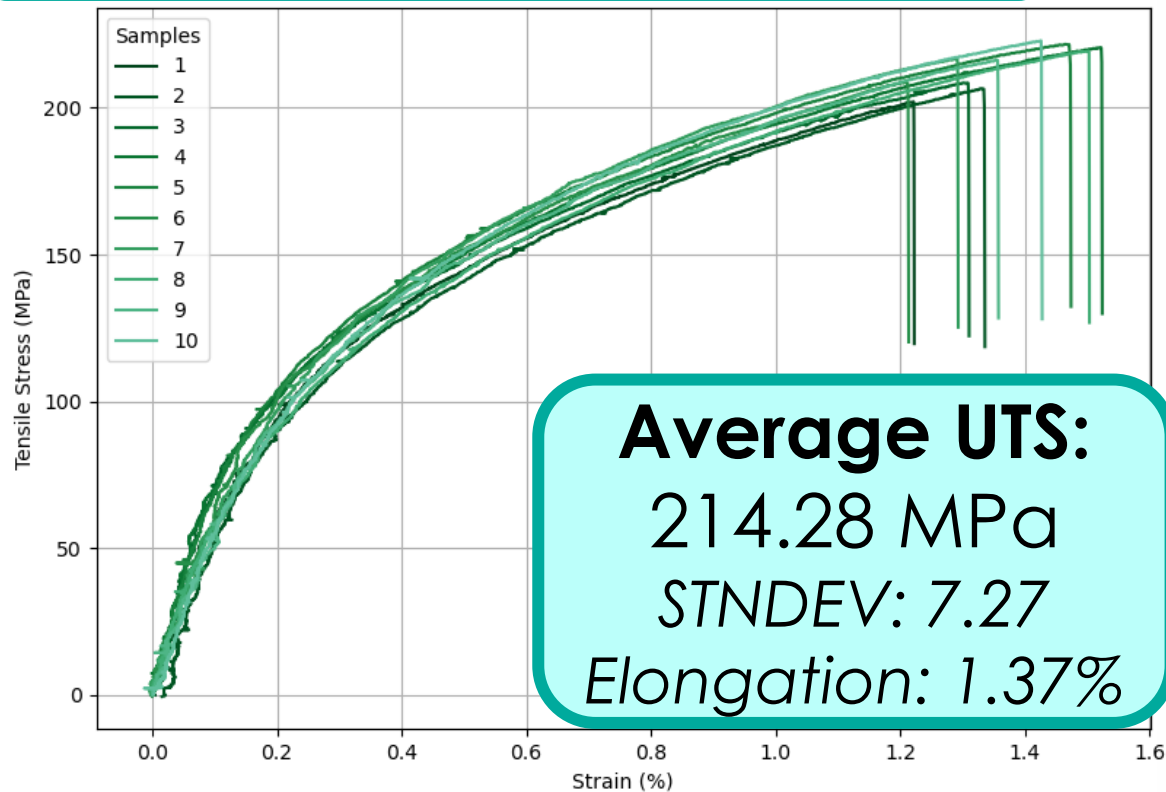
UST - 700°C, 0 to 15 Min.



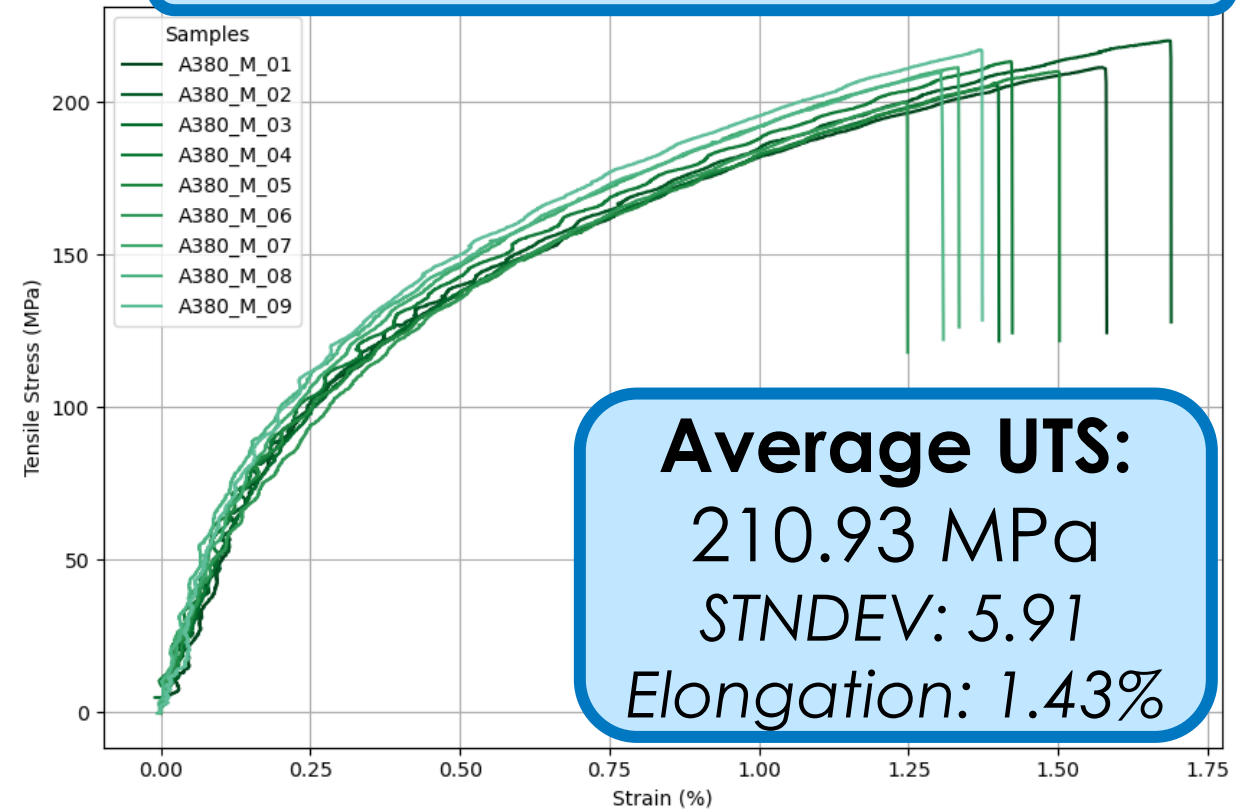
UST Influence on Material Properties

Tensile Data

UST – 700°C, 0 to 15 Min.

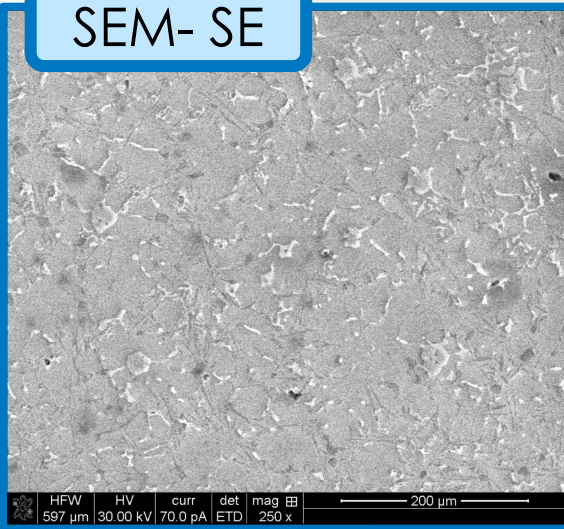


UST - 700°C, 15 to 30 Min.

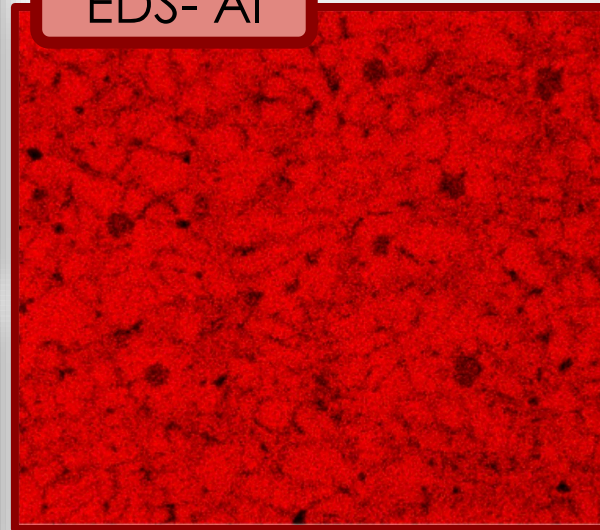


SEM-EDS Results: UST Phase Modification

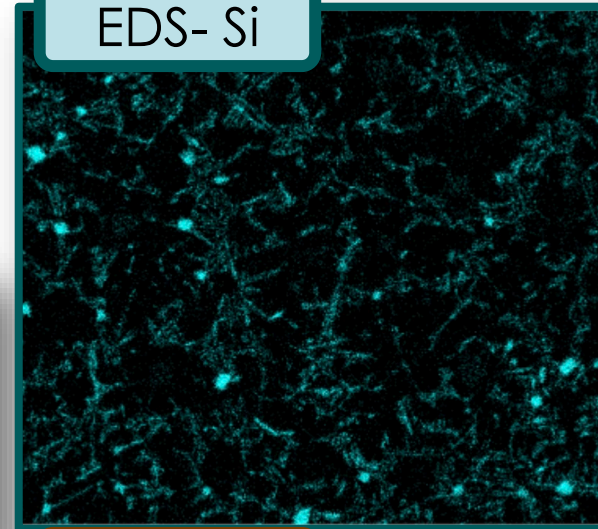
SEM- SE



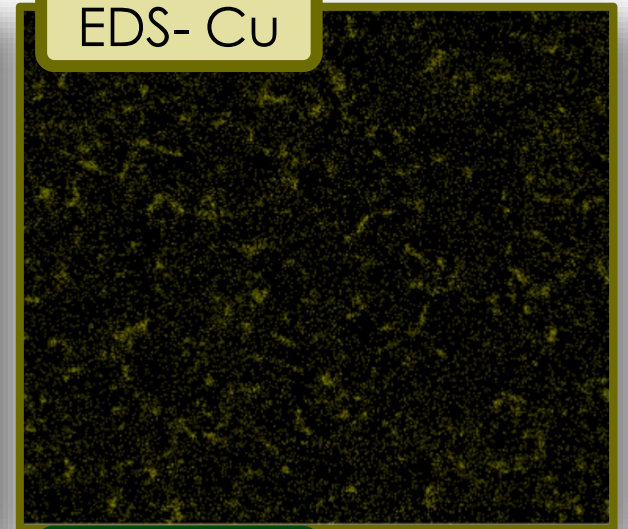
EDS- Al



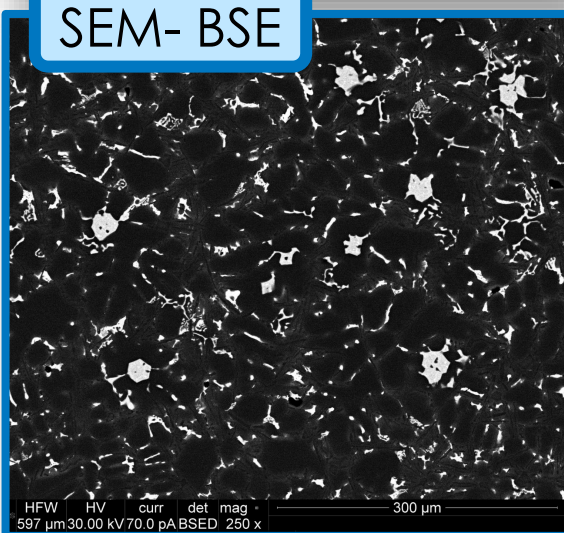
EDS- Si



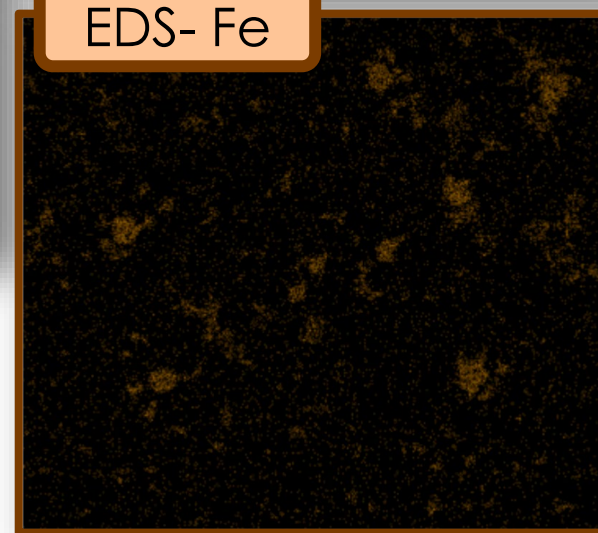
EDS- Cu



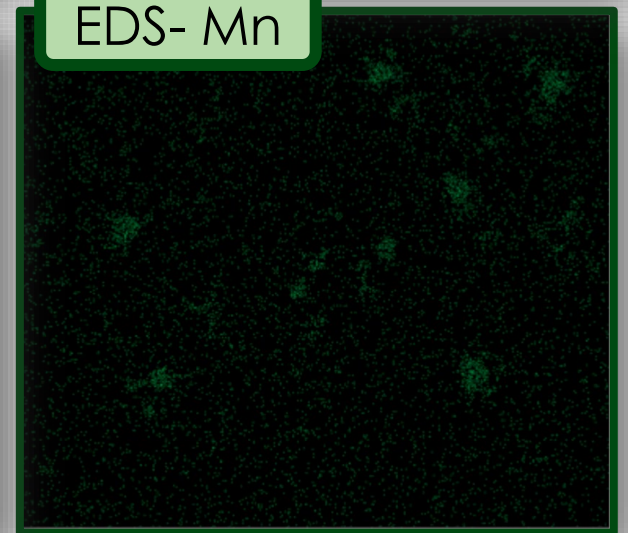
SEM- BSE



EDS- Fe



EDS- Mn

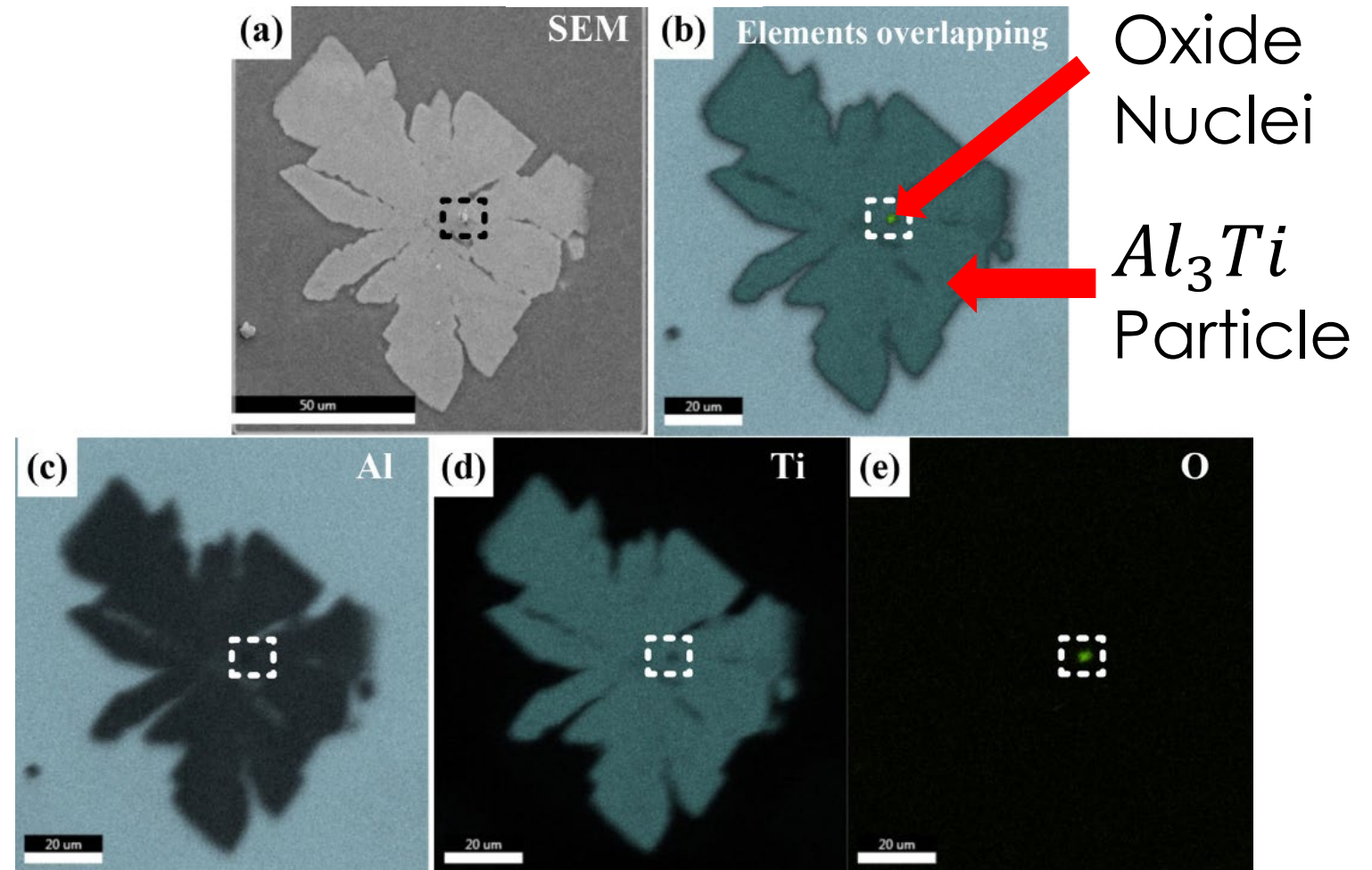


Theory: Oxide Break-up

**Al-0.4 wt% Ti
without UST**

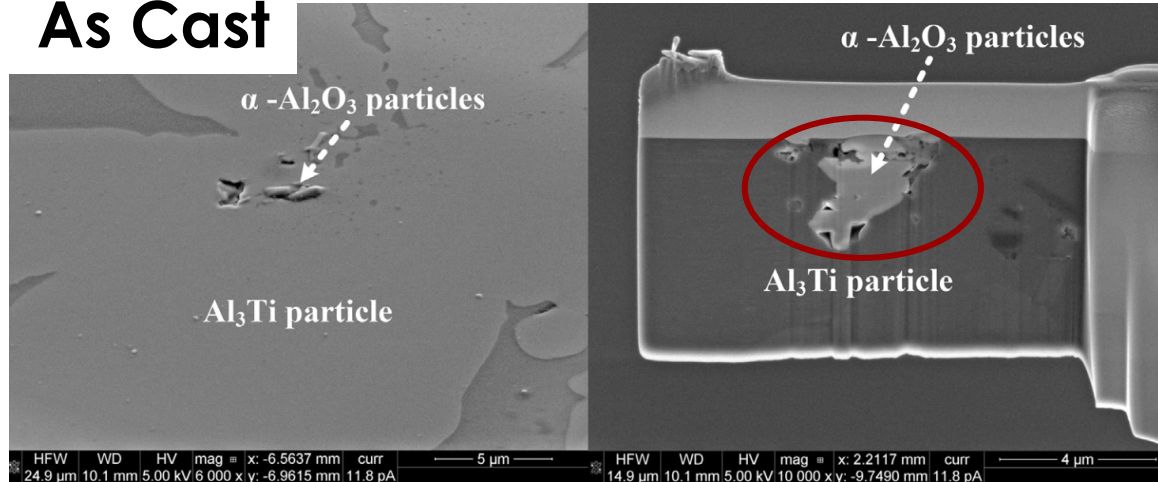
- Evidence of Al_2O_3 nuclei at center of Al_3Ti particle

As Cast

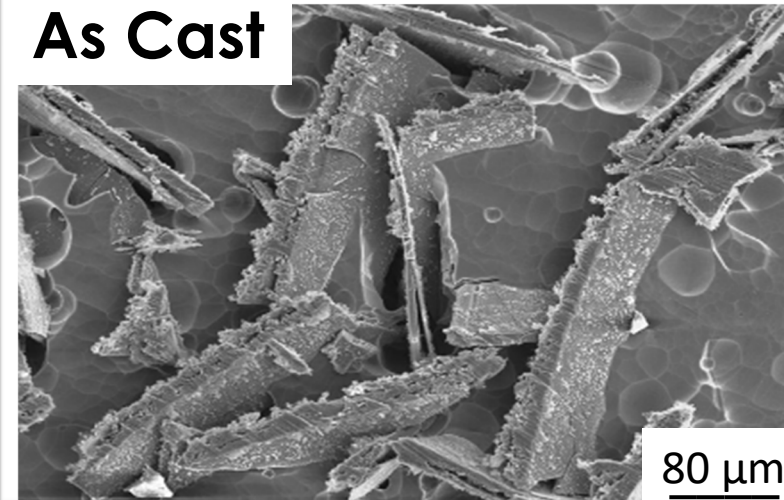


Theory: Oxide Break-up

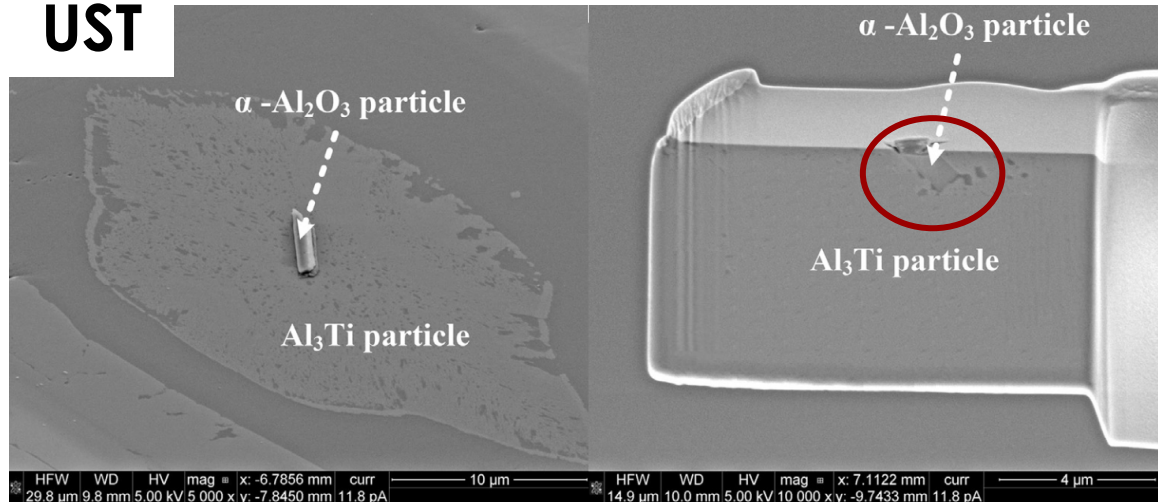
As Cast



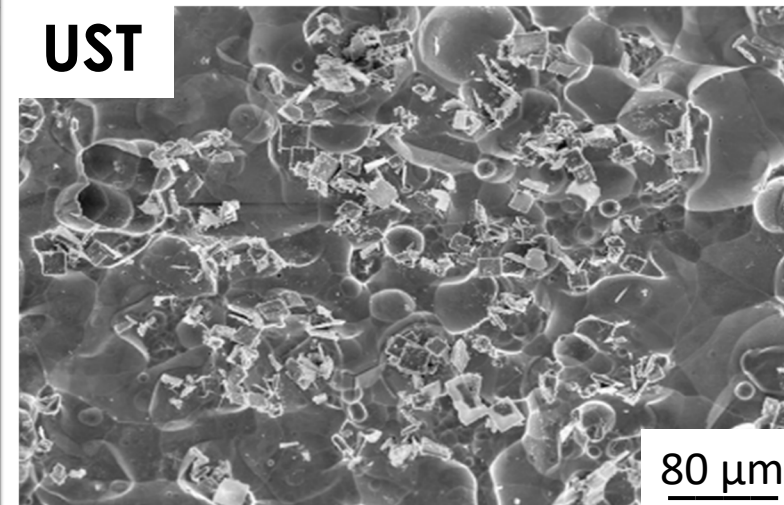
As Cast



UST



UST



UST breaks
oxides into
smaller
particles

$\therefore$

Refined
 Al_3Ti
particles

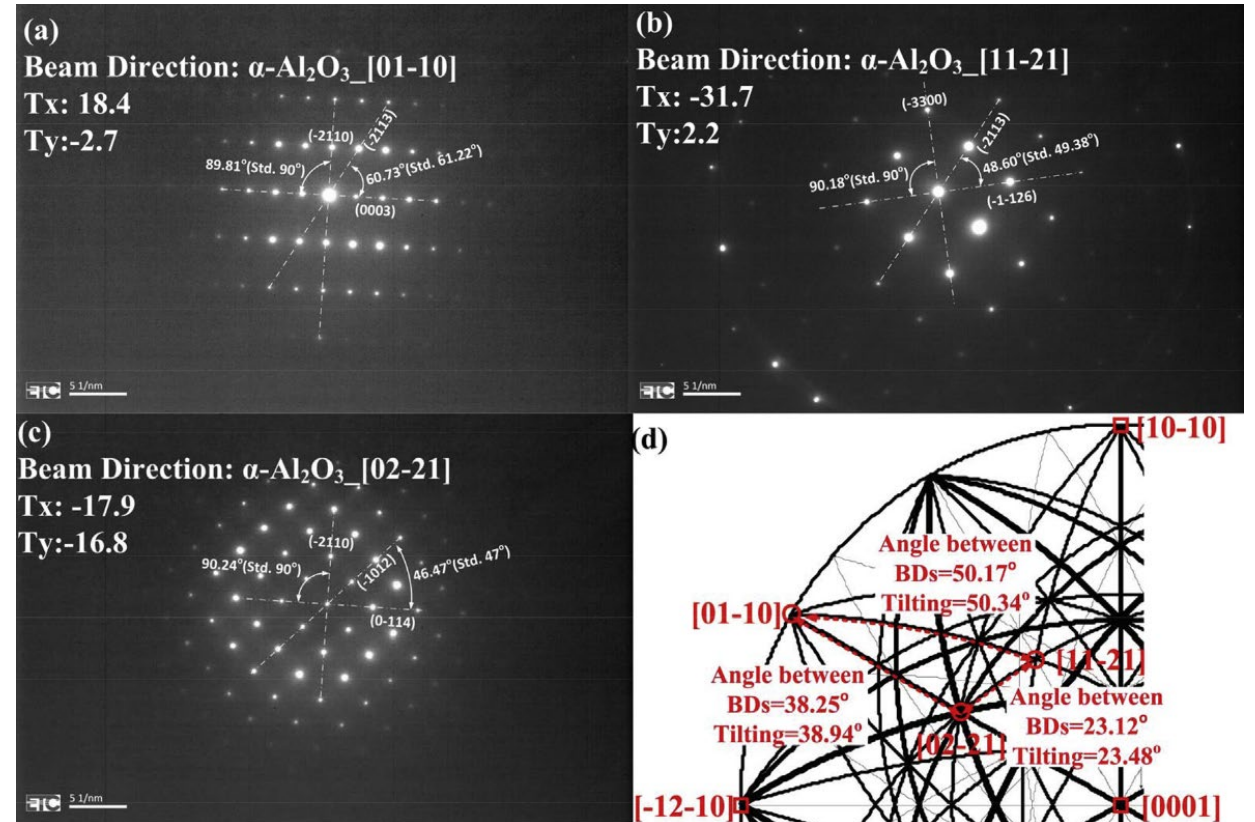
Theory: Oxide Break-up

TEM Diffraction Patterns

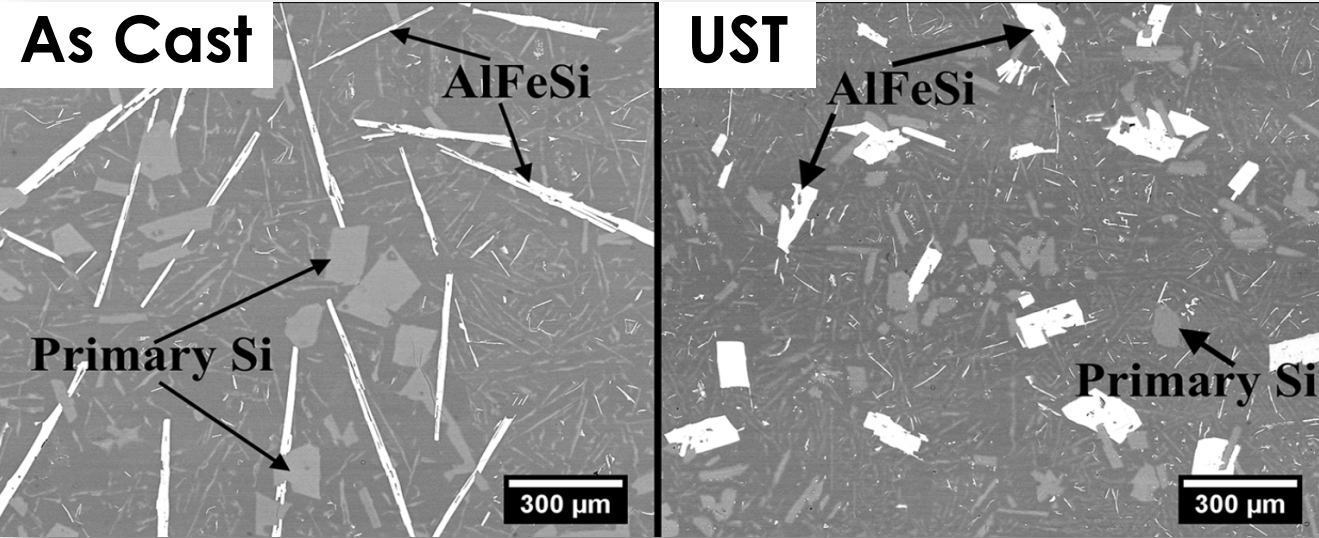
- Prove α -Al₂O₃ via crystallographic pattern

Plane	<i>d</i> -spacing, nm measured	<i>d</i> -spacing, nm calculated [30,31]
($\bar{2}$ 110)	0.2400	0.2375
(0003)	0.4316	0.4323
($\bar{2}$ 113)	0.2097	0.2082
($\bar{3}$ 300)	0.1395	0.1371
($\bar{1}$ 126)	0.1595	0.1599
($\bar{1}$ 012)	0.3468	0.3474
(0 $\bar{1}$ 14)	0.2527	0.2547

F. Wang et al. Acta Materialia, 2016

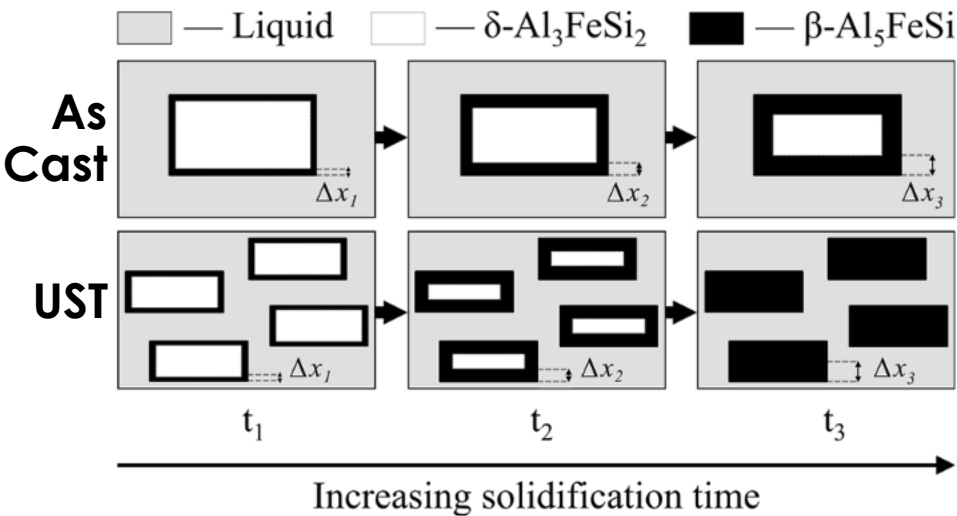
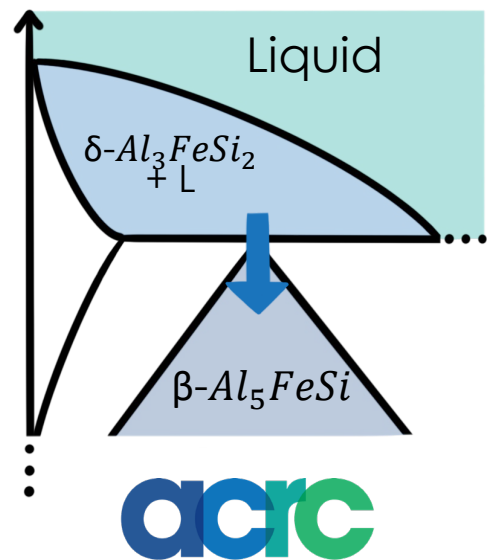


Intermetallic Modification at Higher Temp



Al-19Si-4Fe

C.J. Todaro et al TMS, 2017



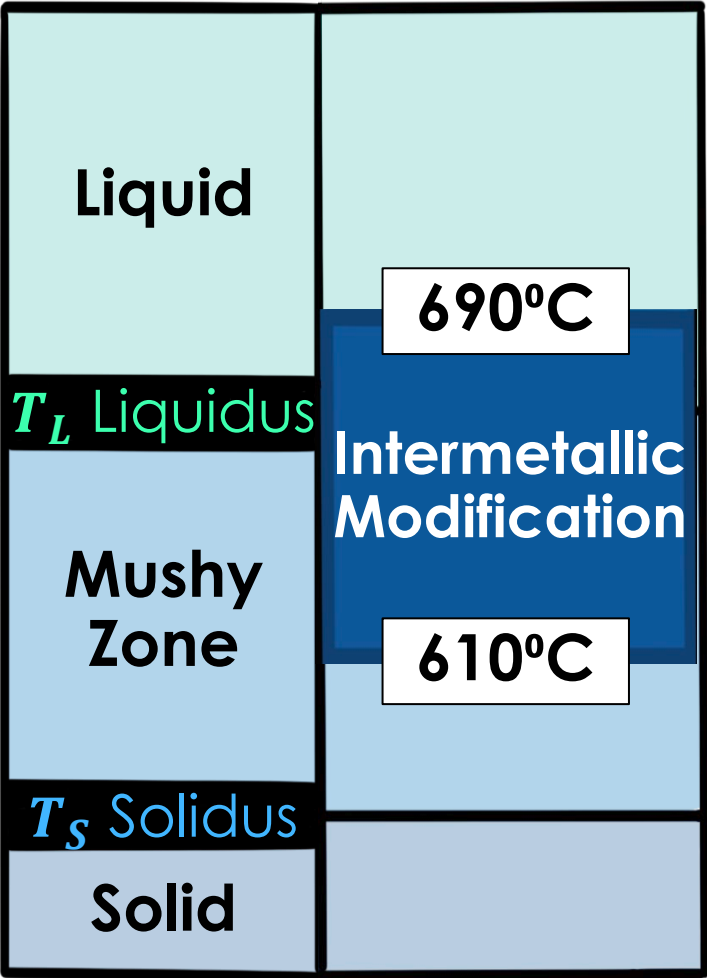
665°C T_L Liquidus

690°C

Intermetallic Modification

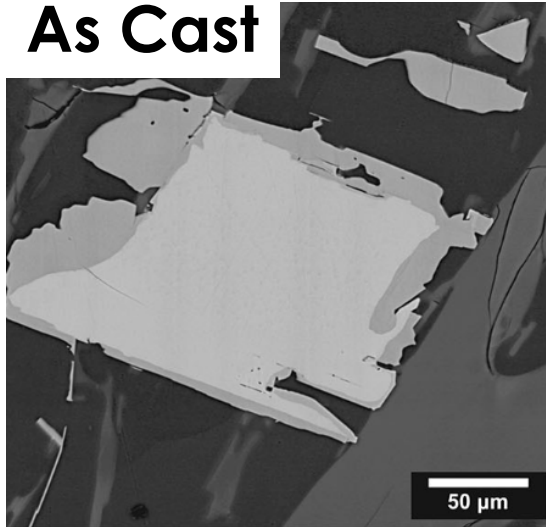
610°C

575°C T_S Solidus

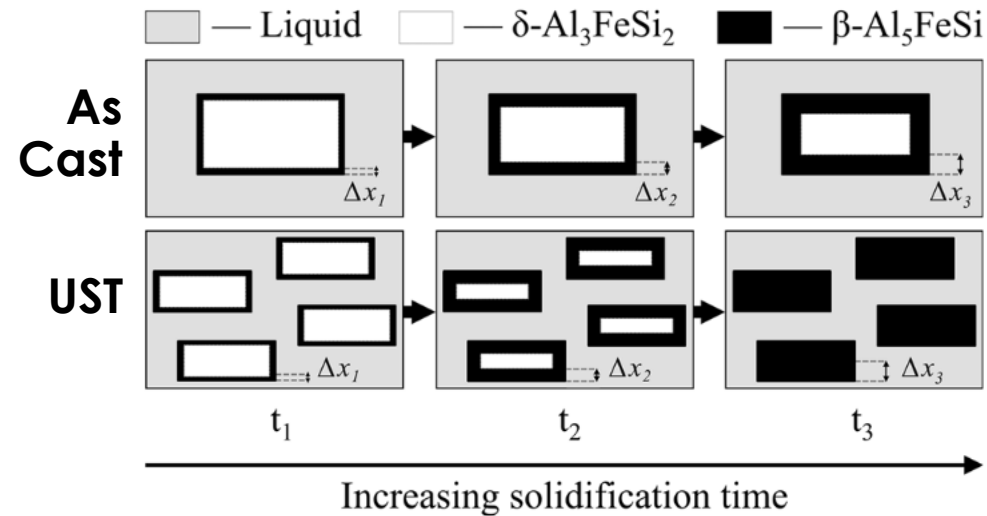
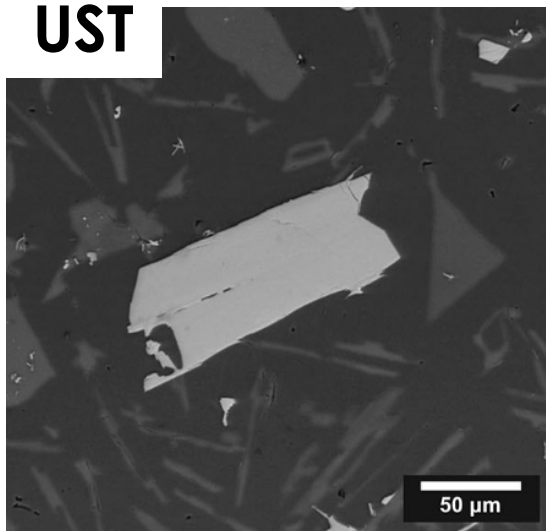


Intermetallic Modification at Higher Temp

As Cast



UST



Cavitation & streaming promote diffusion to form $\beta\text{-Al}_5\text{FeSi}$

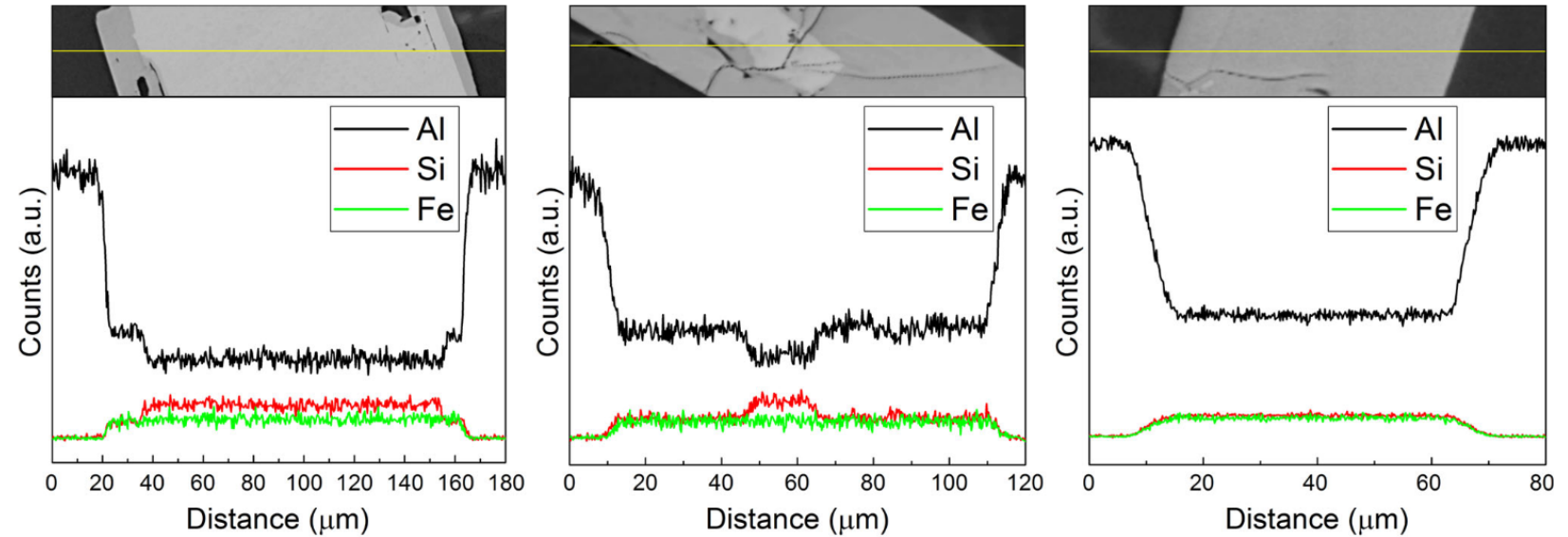
$\therefore$

Less δ , more β ,
less platelets, more blocks

Intermetallic Modification at Higher Temp

As Cast:

- More “Complex” particles
- Platelets larger in size
- Higher δ -Al₃FeSi₂ content



UST:

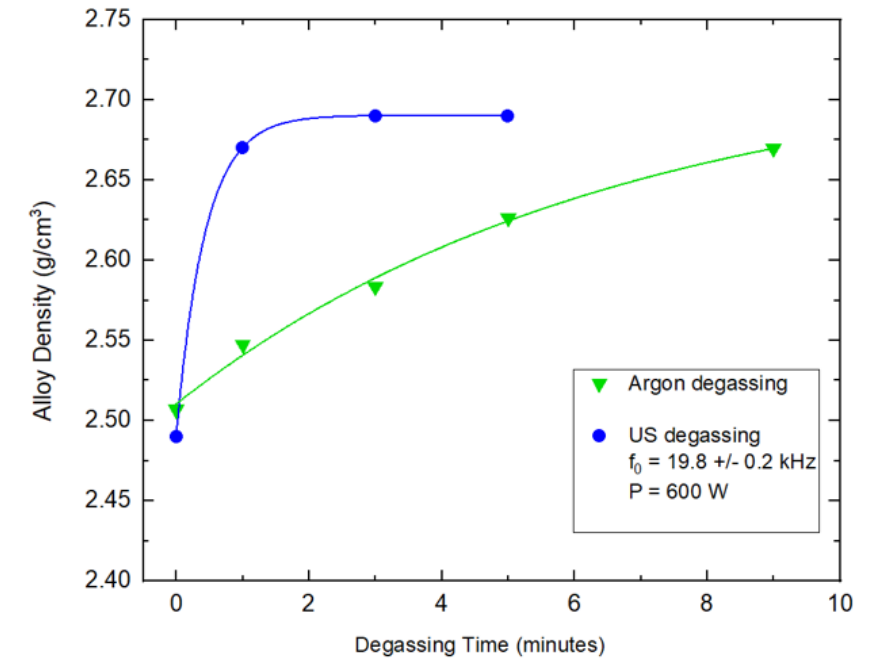
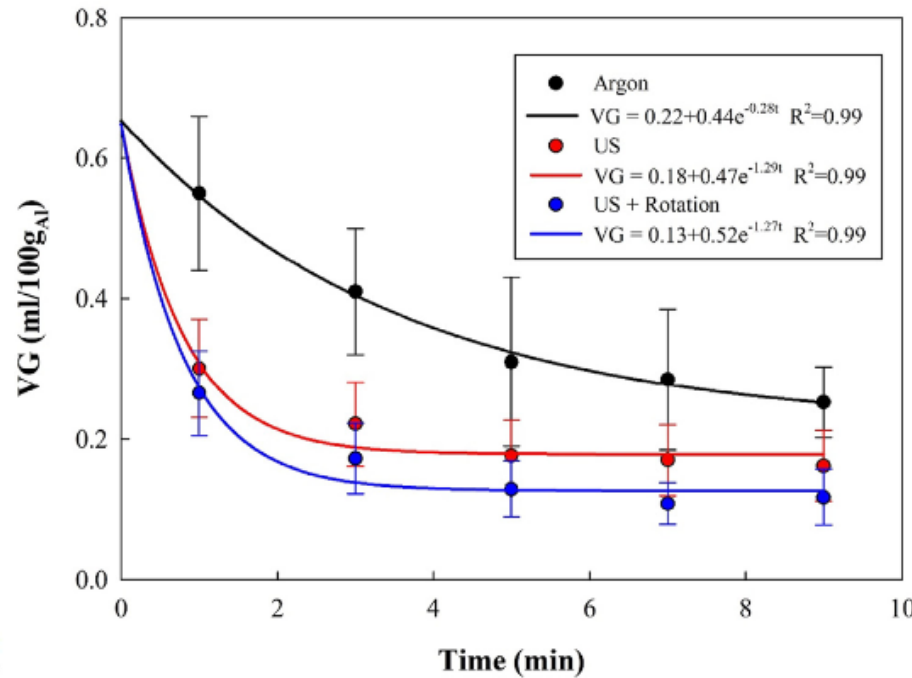
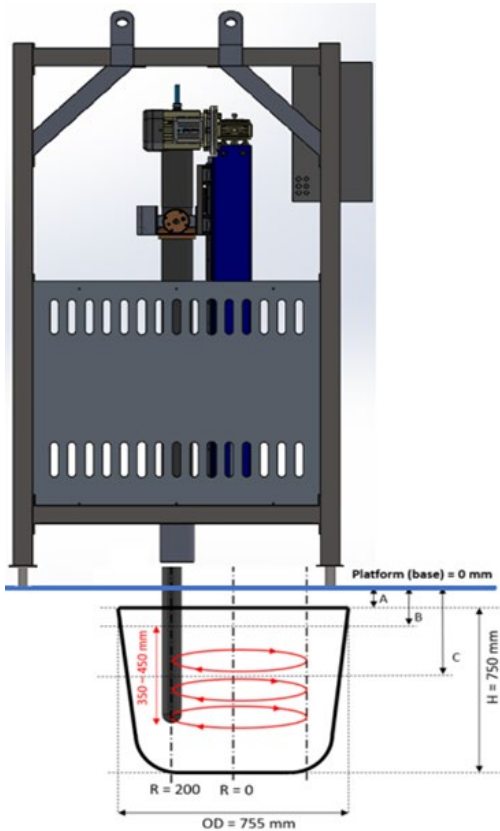
- More “single-phase” particles
- Blocky shape
- Higher β -Al₅FeSi content

Table III. EDS Point Analysis Results of Primary Fe-Containing Intermetallic Particles

Alloy	Structure		Composition (At. Pct)				Probable Phase
			Al	Fe	Si	Fe:Si	
Without USMT	complex particles	central	50.92 ± 3.28	18.03 ± 3.11	31.05 ± 0.84	0.58 ± 0.07	δ -Al ₃ FeSi ₂
		outer	65.89 ± 0.77	16.47 ± 0.88	17.64 ± 0.93	0.92 ± 0.10	β -Al ₅ FeSi
With USMT	single-phase particles	—	65.94 ± 0.77	16.30 ± 0.67	17.76 ± 0.57	0.92 ± 0.05	β -Al ₅ FeSi
	complex particles	central	50.97 ± 4.62	18.19 ± 4.06	30.85 ± 0.83	0.59 ± 0.09	δ -Al ₃ FeSi ₂
		outer	65.96 ± 1.17	16.53 ± 0.92	17.51 ± 0.87	0.94 ± 0.10	β -Al ₅ FeSi

C.J. Todaro *et al* TMS, 2017

Existing Data on UST Degassing

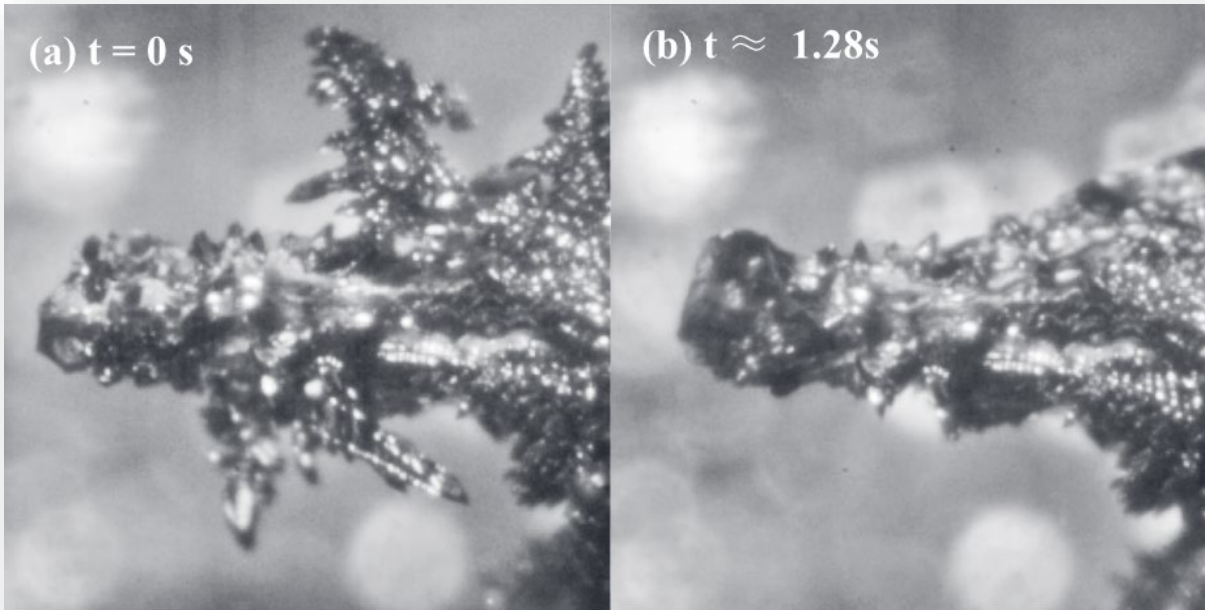


- Achieves lower hydrogen content
- Reaches steady state hydrogen removal
- Eliminates purge gas

Grain Refinement Mechanism

Treatment Mechanism:

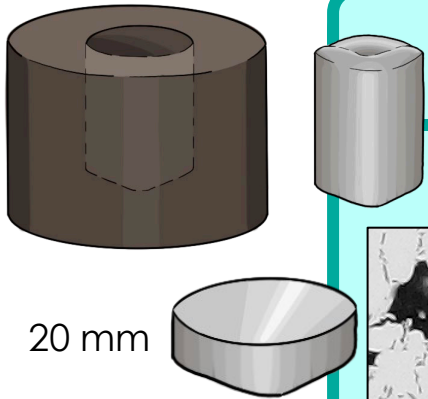
Dendritic Fragmentation



F. Wang et al Ultrasonics- Sonochemistry, 2017

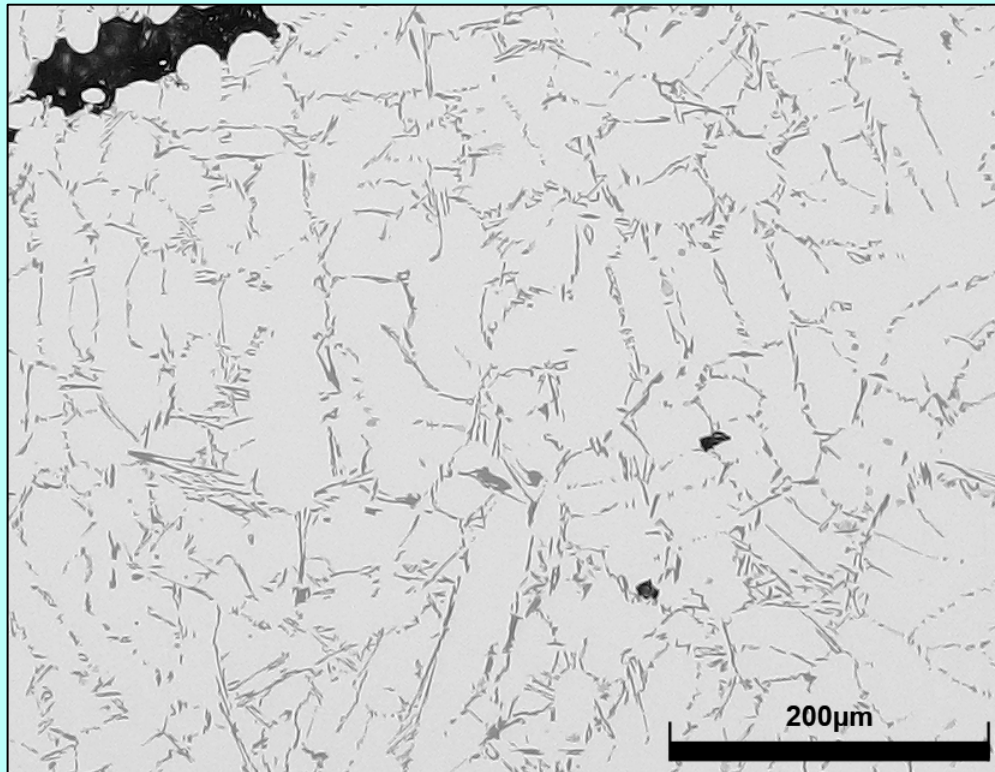
- Cavitation & streaming fragment dendrites
- Dendrite arms act as in-situ nucleation sites

Grain Refinement Preliminary Data



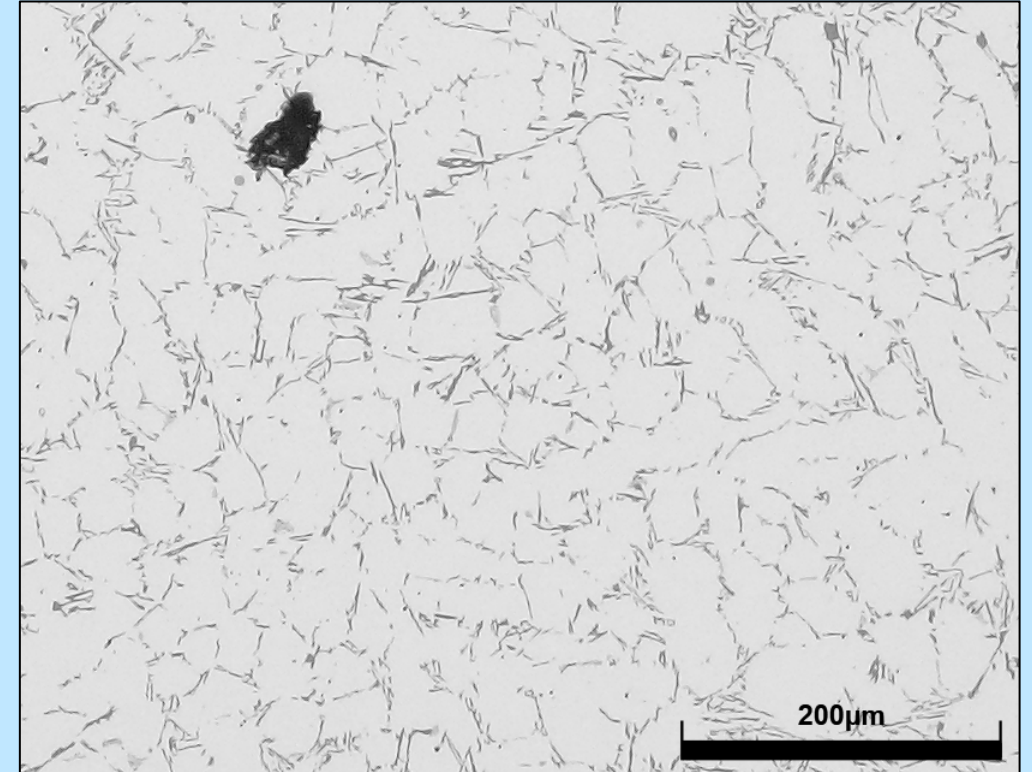
No Treatment

(0 min)

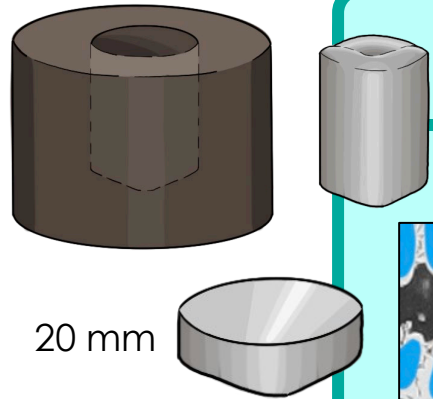


Variable f

Treatment: (10 min)



Grain Refinement Preliminary Data



No Treatment

(0 min)



Variable f

Treatment: (10 min)

