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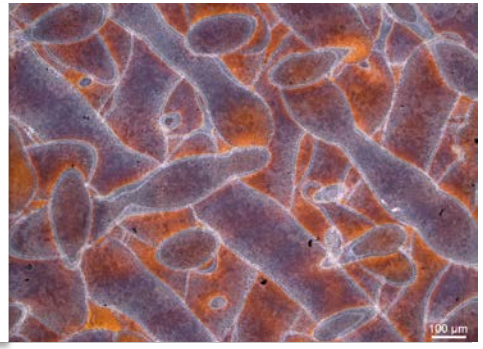

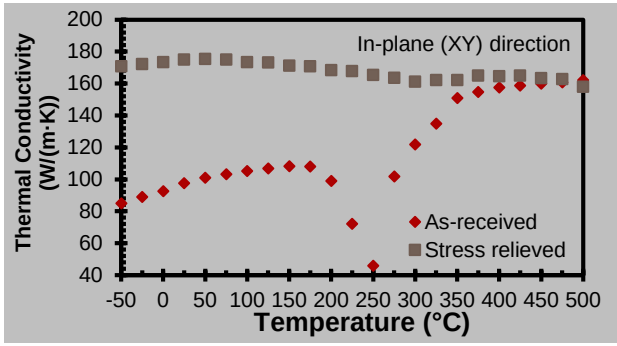

The Change of Thermal Properties and Microstructure of an AM Fabricated AlSi10Mg Alloy During Thermal Annealing

Pin Yang*, Mark A. Rodriguez, Daniel K. Stefan, Amy Allen, Donald Bradley, Lisa Deibler, and H. Jared

U.S. DEPARTMENT OF ENERGY

NNSA National Nuclear Security Administration

AM – Selective laser melting process

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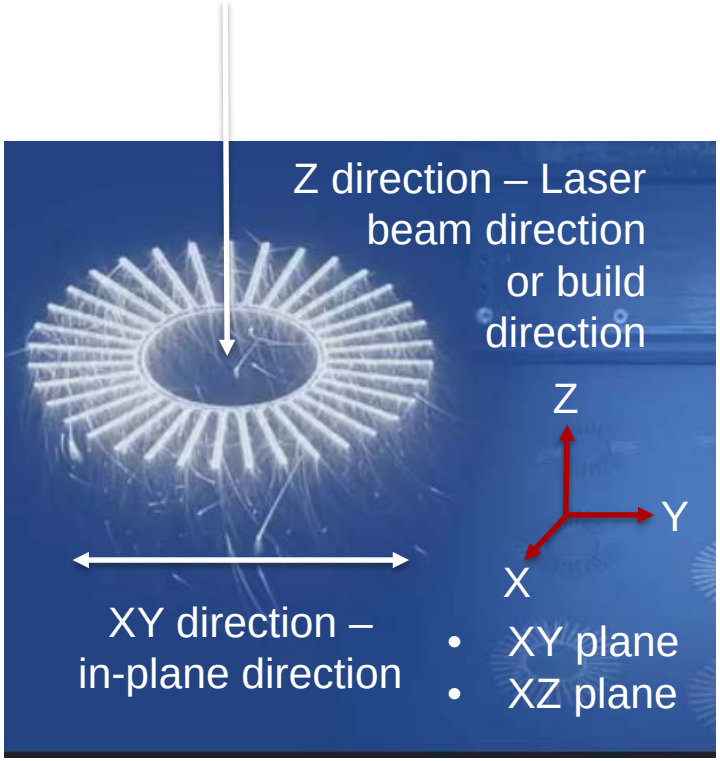
Advantages of Laser-based AM Process:

- Agility and flexibility in design/fabrication of intricate components
- Quick turn-around time for manufacturing and critical in-mission repair
- Conservation of source materials
- Reduction in manufacturing footprint and ancillary tooling requirement
- Unique physical properties: non-equilibrium state
  - Superior high hardness†
  - High strength and cycle fatigue resistance*



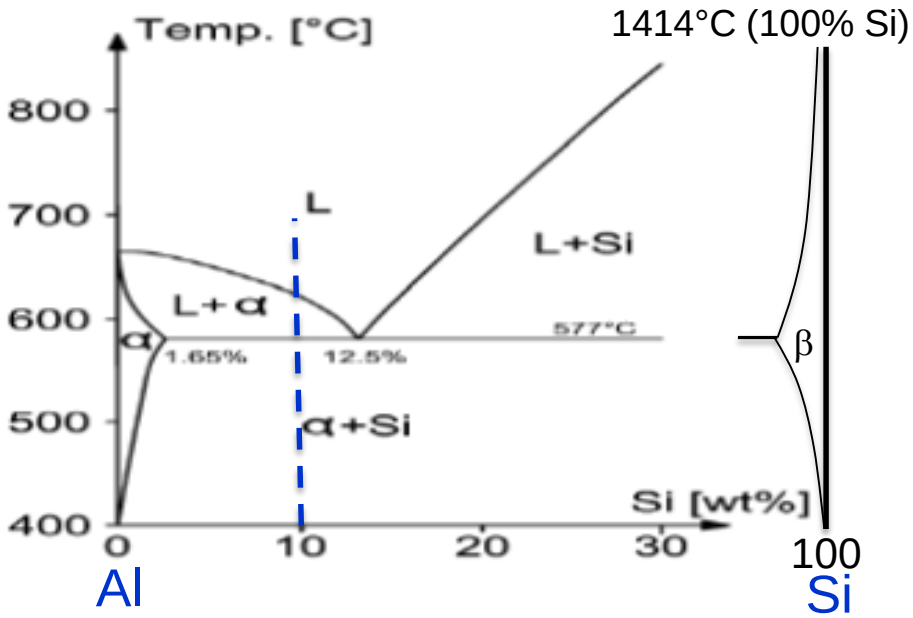
Modified from Edelstahl Rosswag Engineering

† A. Martens et al., 26th SSF symposium , 1007-1016 (2005)
*E. Brandl et al., *Mater Des*, **34** 159-169 (2012) and ….

AlSi10Mg – Light weight, good strength, hardness, as well as dynamic and thermal properties

- **Phase diagram - AlSi10Mg:**
  - Hypoeutectic composition
    - Lower melting point
    - Narrow solidification window

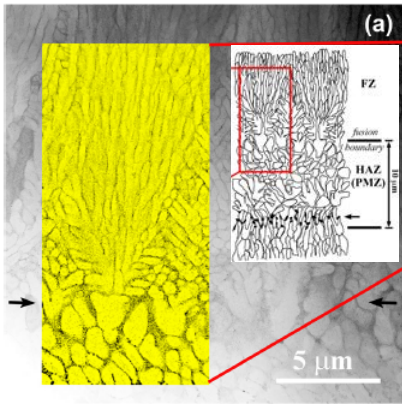
Automobile, aerospace, structural and thermal applications



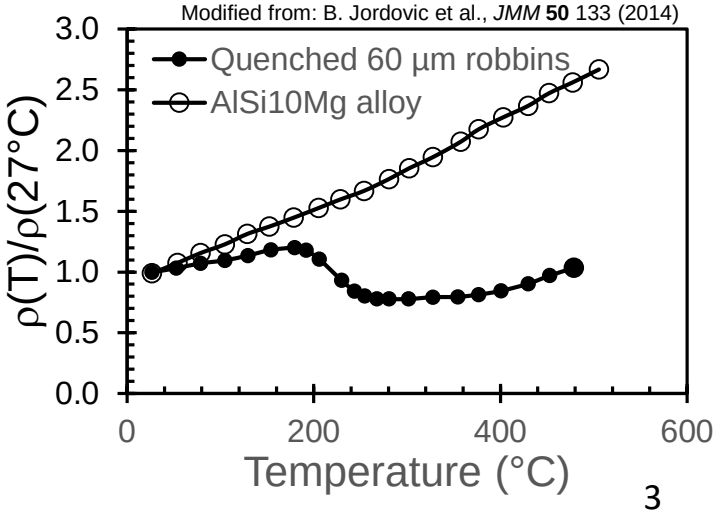
Rapid melting and fast quenching in AM process introduce a *non-equilibrium state*

- Ultrafine, textured, devoiced eutectic cellular microstructure
- Increased Si solubility in Al
- Residual stresses
- High concentration of lattice defects and low thermo-electromotive force

Modified from: Holesinger et al., *JOM* **68** 1000 (2016). Cellular wall has high concentration of Si and Mg.



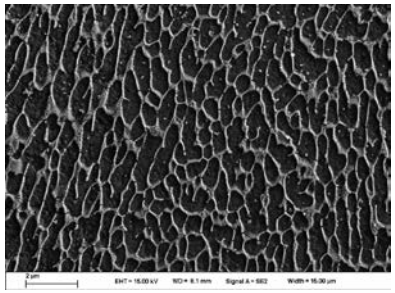
Modified from: B. Jordovic et al., *JMM* **50** 133 (2014)



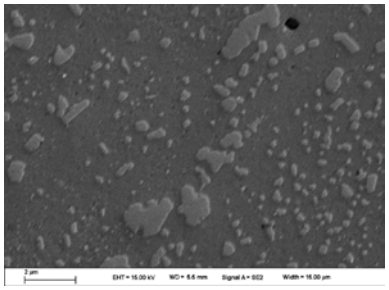
Objectives

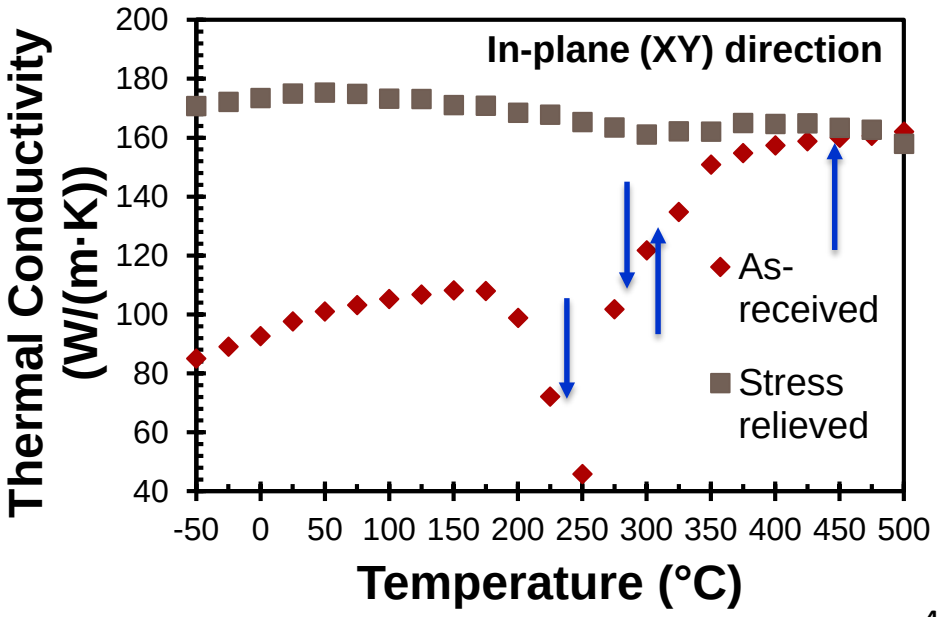
- Compare microstructure and thermal properties of as-built and thermally annealed AM fabricated parts to highlight the differences imparted by a non-equilibrium process
- Correlate the microstructure evolution and thermal properties and compare with a first order calculation to shed light on thermophysical changes in AM fabricated AlSi10Mg parts

As- built



Thermally annealed





Things which affect heat transfer

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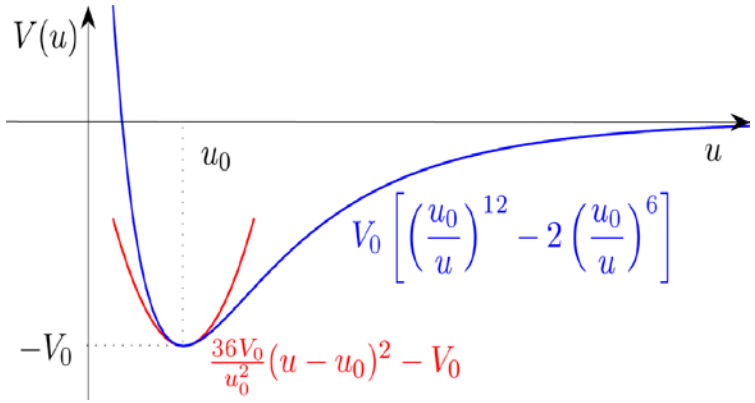
Phonon gas and collisions

Conservation of momentum: $K_1 + K_2 = K_3 + G$

- G = 0: Normal processes – no collision
- G ≠ 0: Umklapp processes – collision and scattering

- Anharmonicity vibration in lattice and scattering



Things can affect electron and phonon scattering:

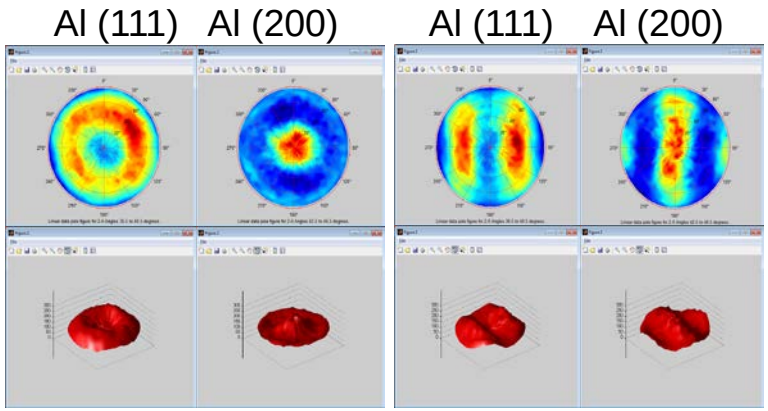
(1) Bulk – contact interfaces, residual stresses

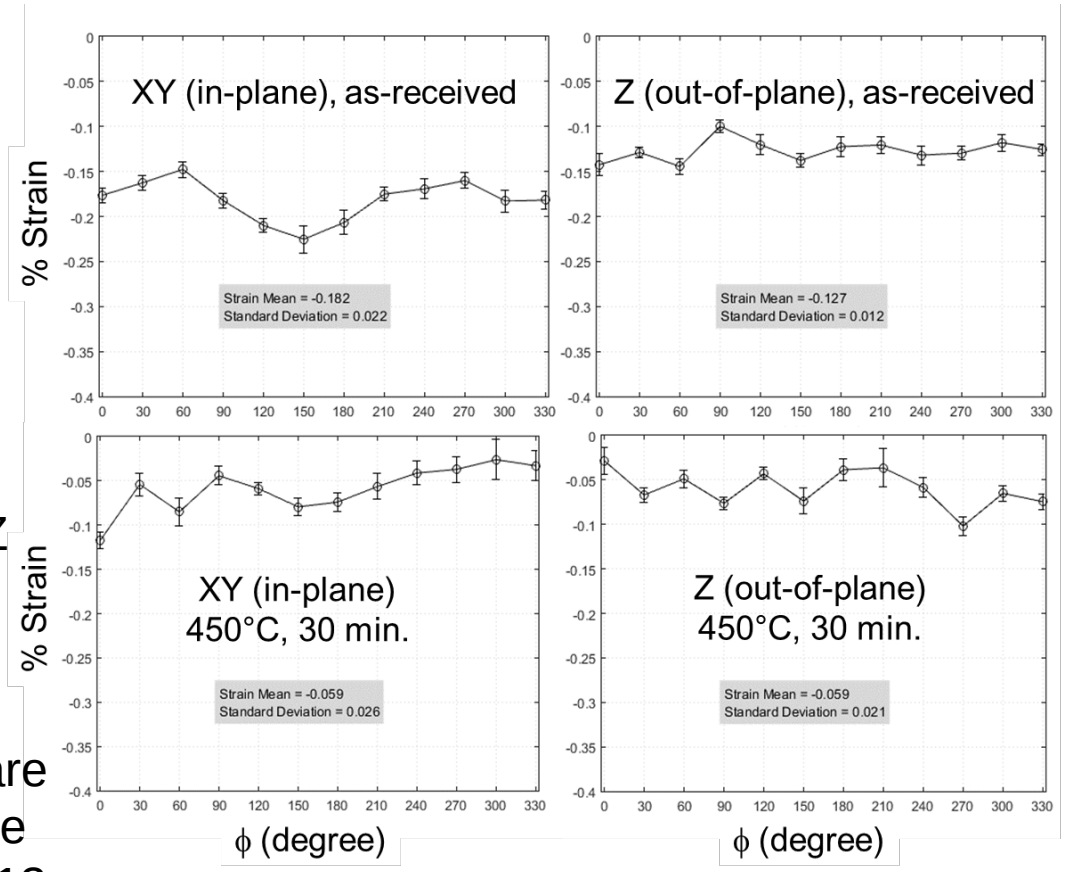
(2) Microstructure – boundaries (FZ, grain, cellular), porosity

(3) Atomic level – lattice defects, foreign atoms (alloying), dislocations, ...

(4) Soft phonon modes, … , etc.

Bulk - Residual stress induced scattering

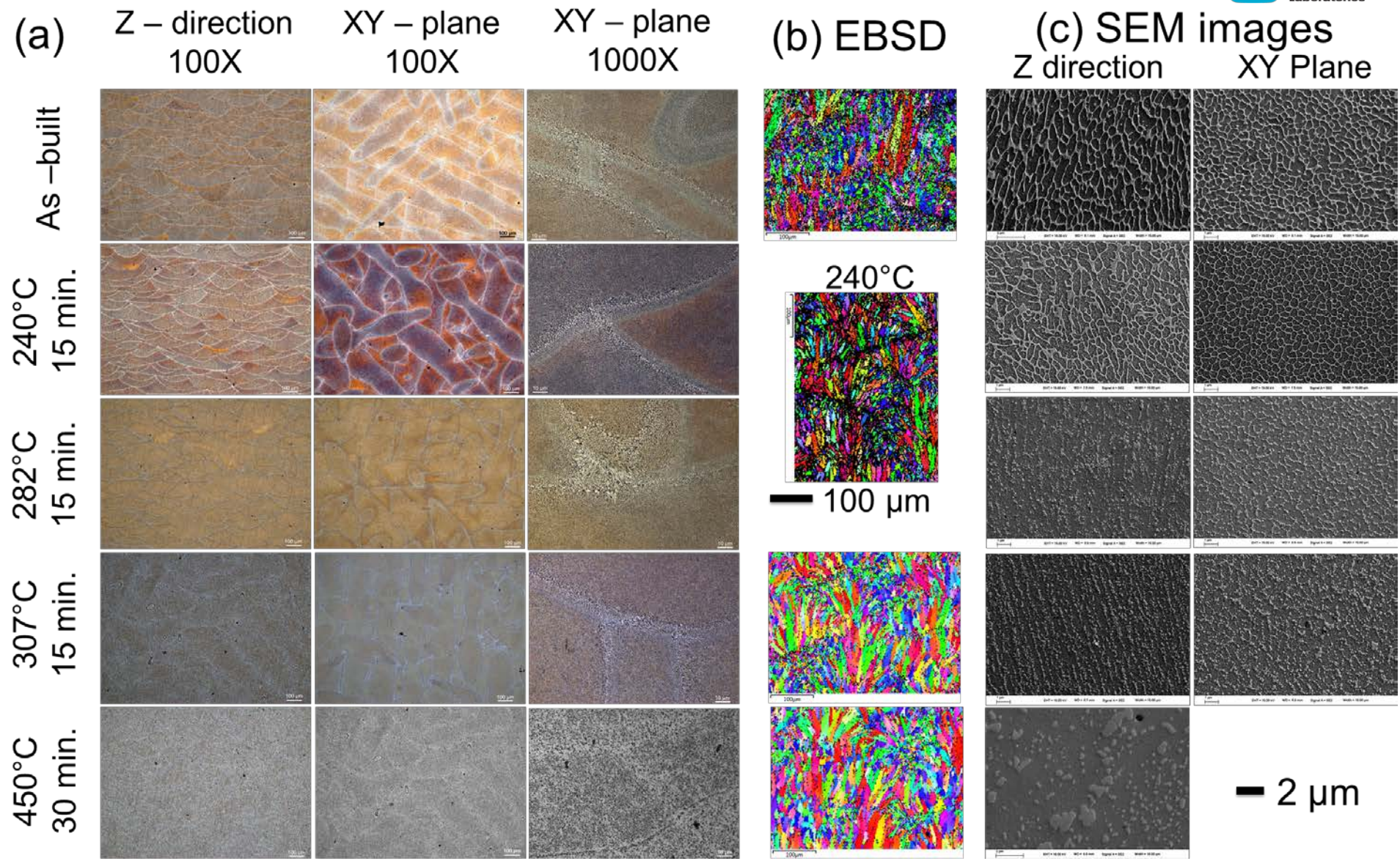




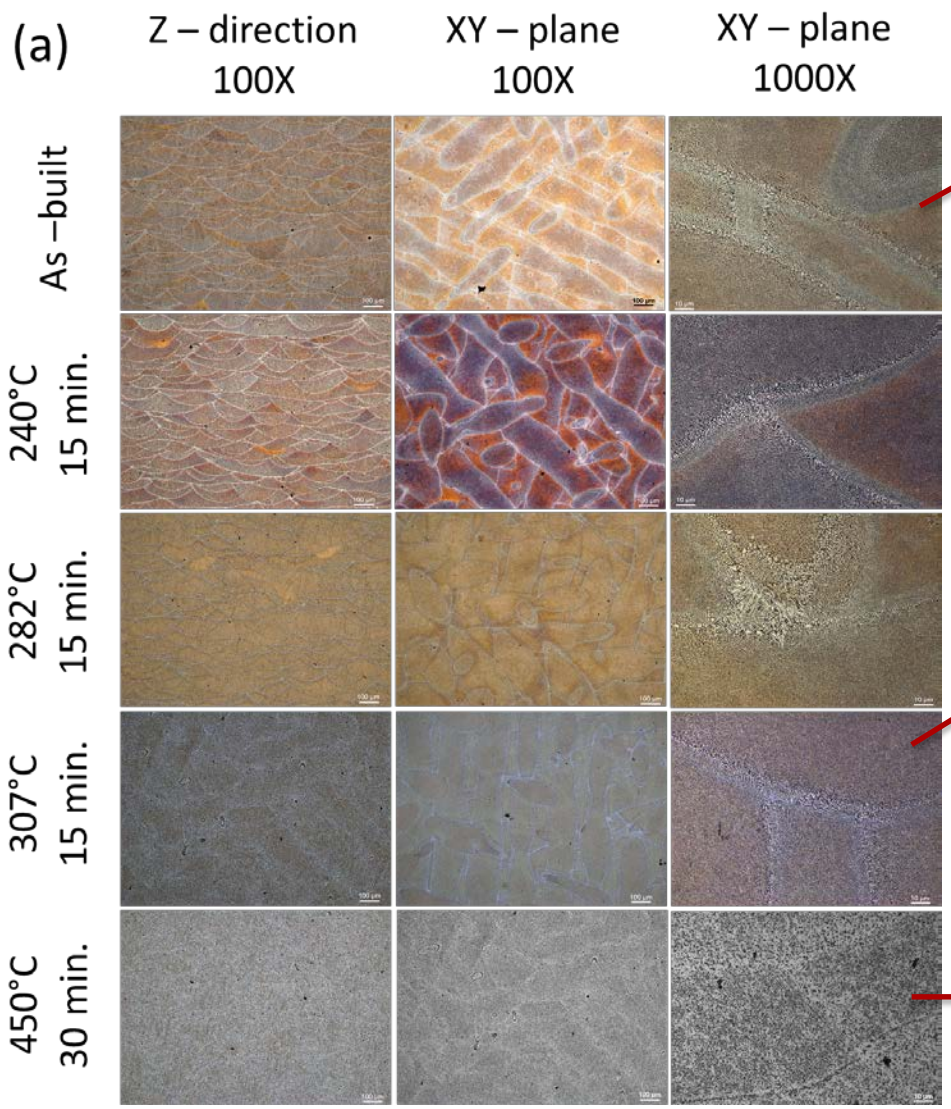
- XY samples have a typical (200) out of plane orientation, while the Z samples show a (200) rolling texture.
- The compressive in-plane strains presented in the as-built samples are initially significant, with values in the -0.18% for the XY samples and -0.13 to -0.17% for the Z samples. Heat treatment significantly decreases residual strain values down to about -0.06% for both the XY and X samples.

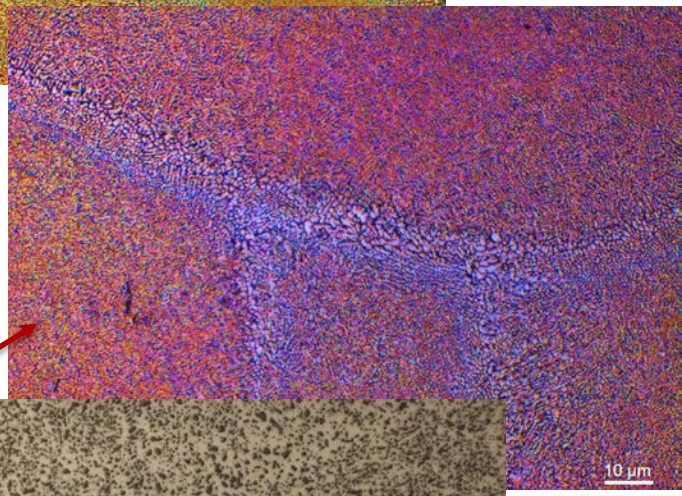
- AM process introduces crystalline texture and an “isotropic” compressive stress in the part during rapid solidification.
- An “isotropic residual stress state” should not significantly affect the heat transfer.

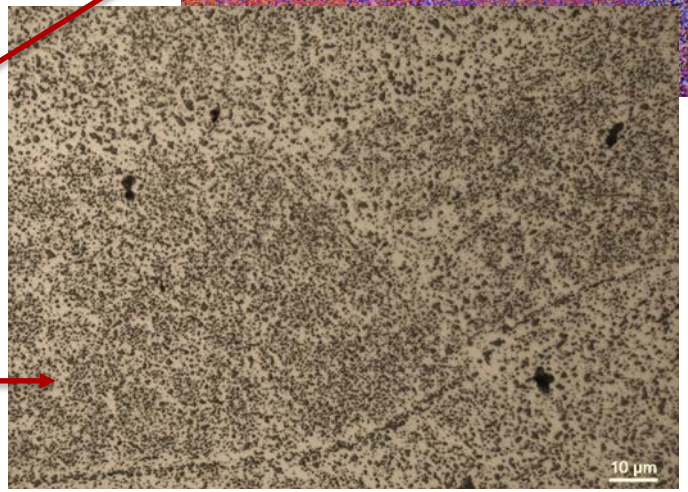
Microstructure and Temperature



Microstructure change of freeze zone boundary







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Change in grain size

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(b) EBSD

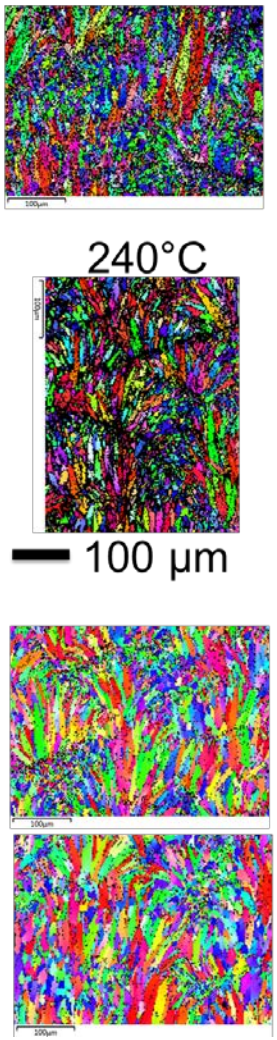
As-built

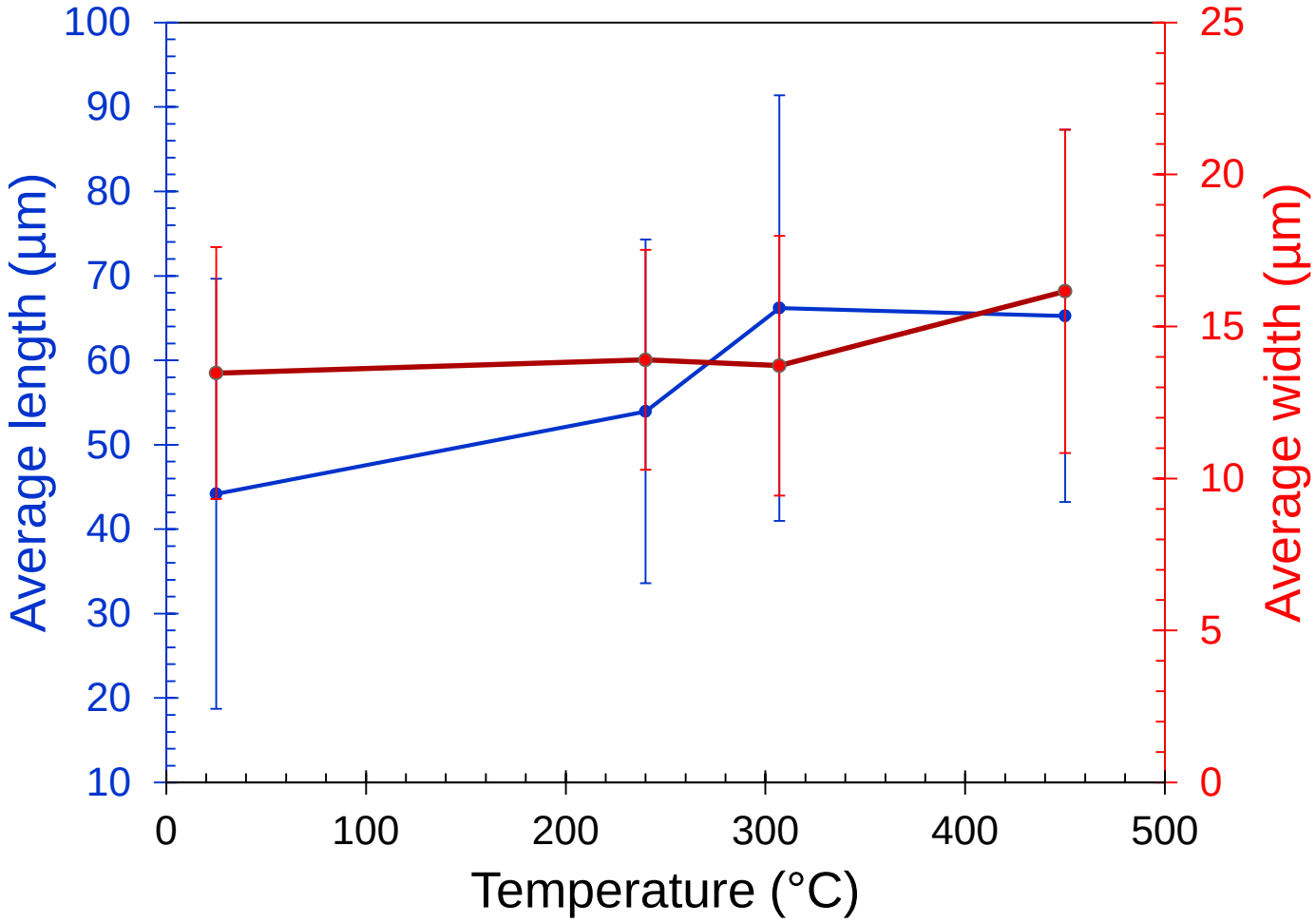
240°C 15 min.

282°C 15 min.

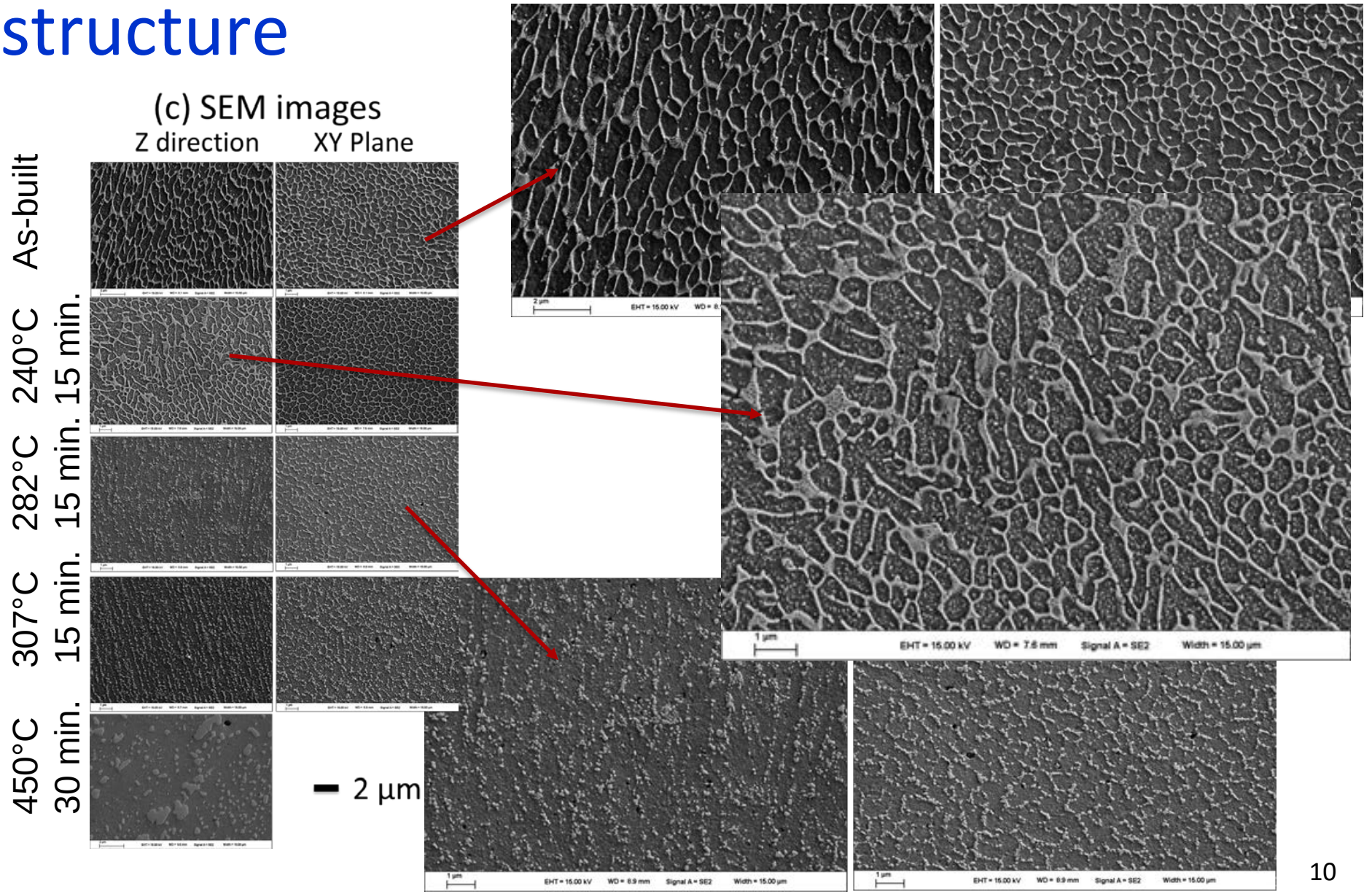
307°C 15 min.

450°C 30 min.

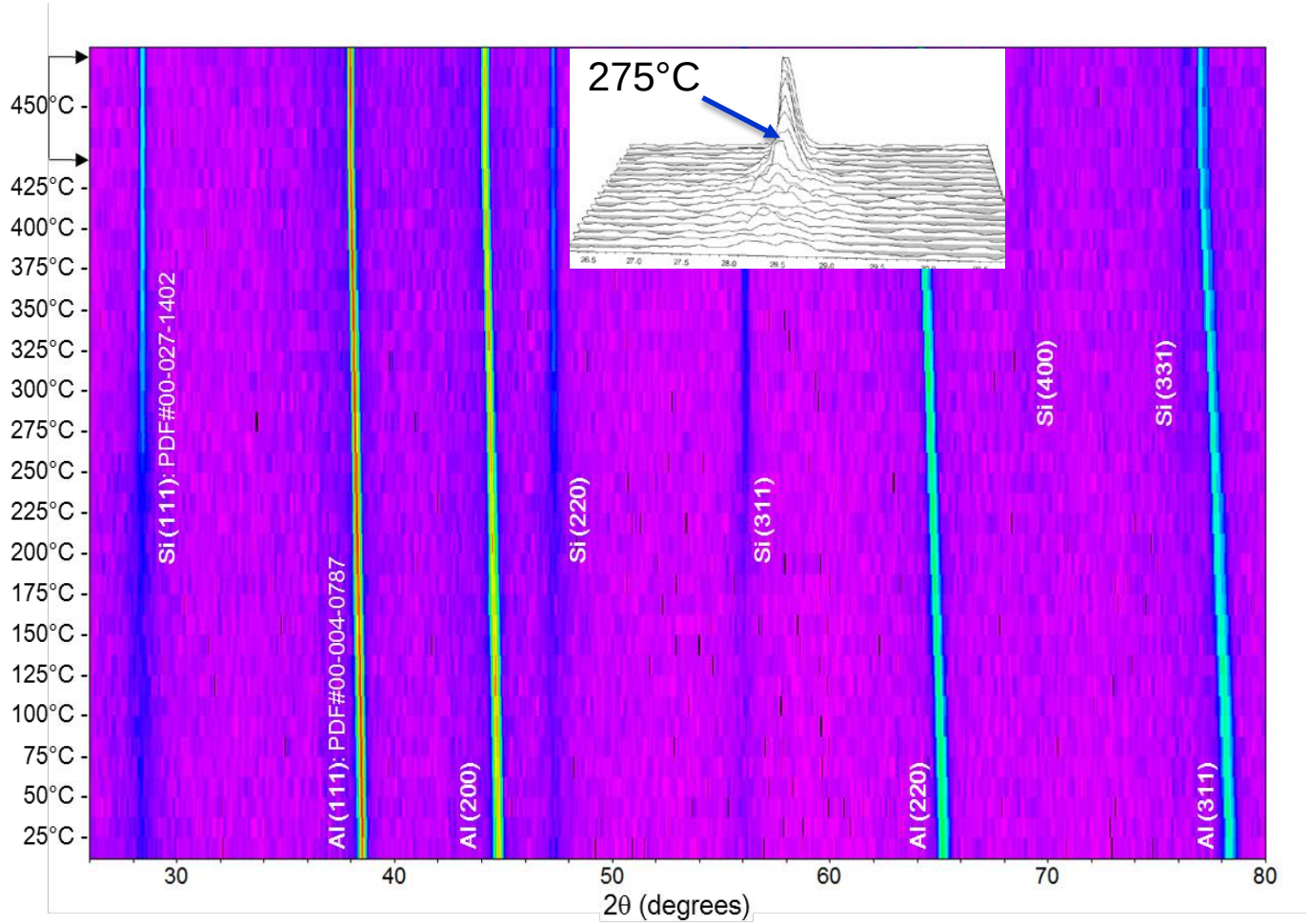




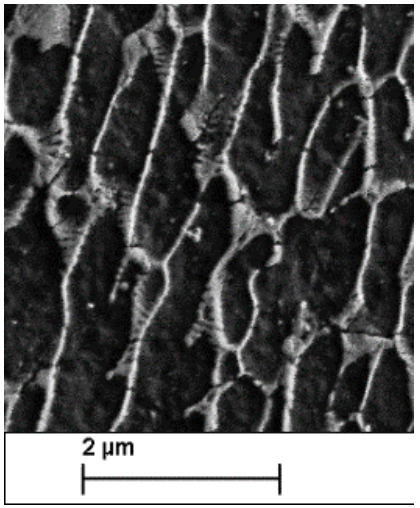
Microstructure evolution of cellular structure

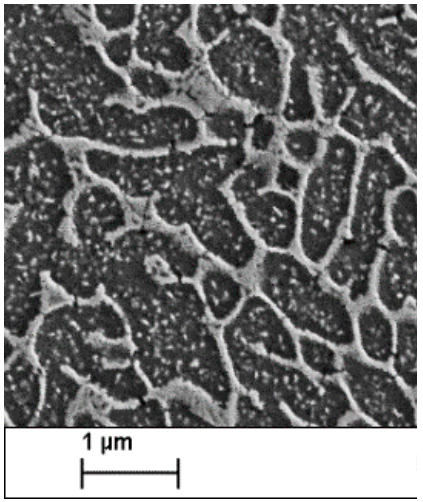


Dissolution of silicon



As-built

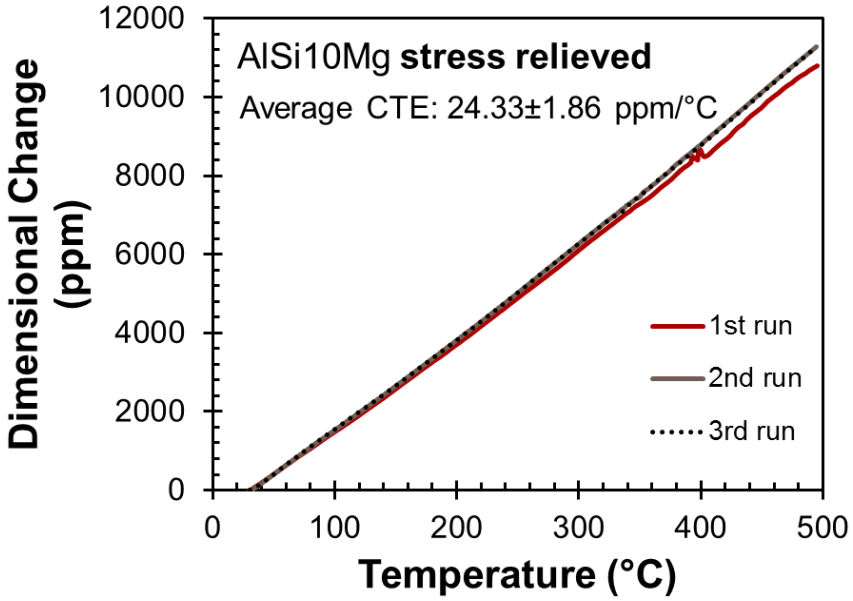


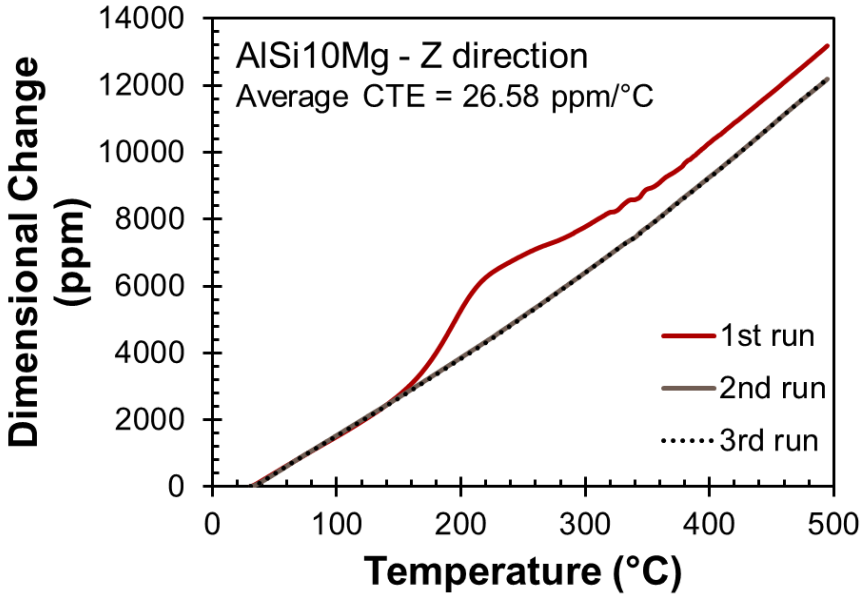


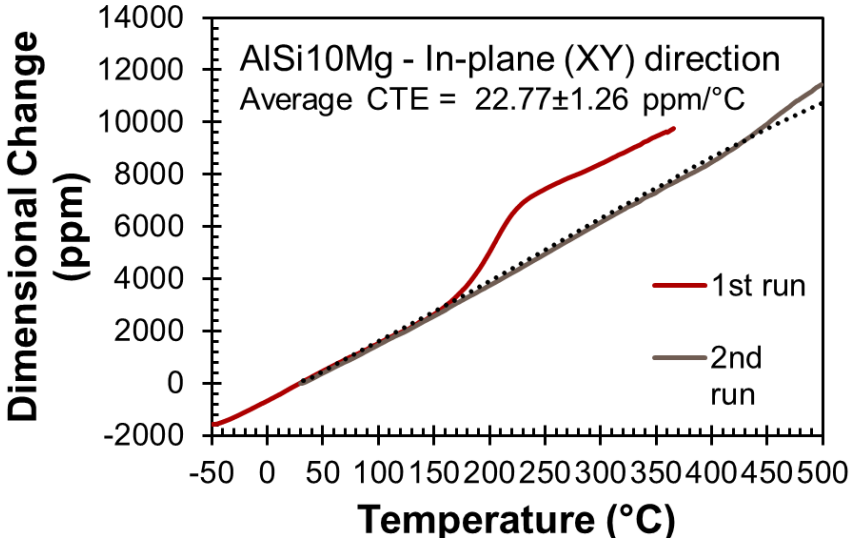
240°C, 15 min.

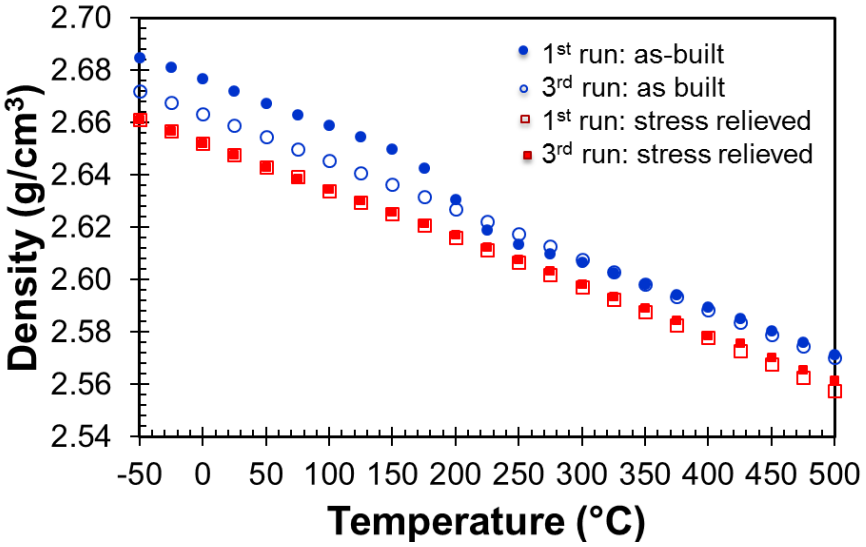
- Below 150°C, excess Si forms nano-clusters in the alloy.
- Coarsening of Si nanoclusters is observed above 240°C.

Thermomechanical response and density (ρ)

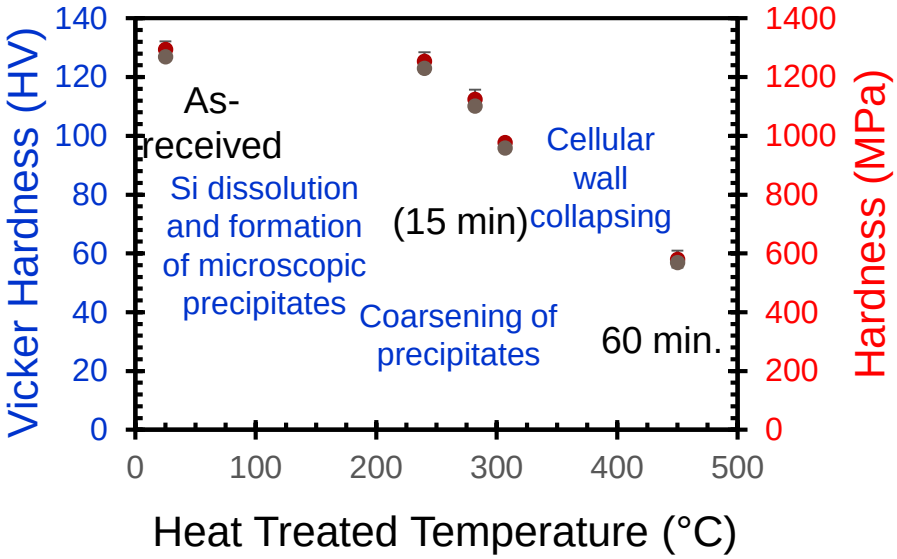


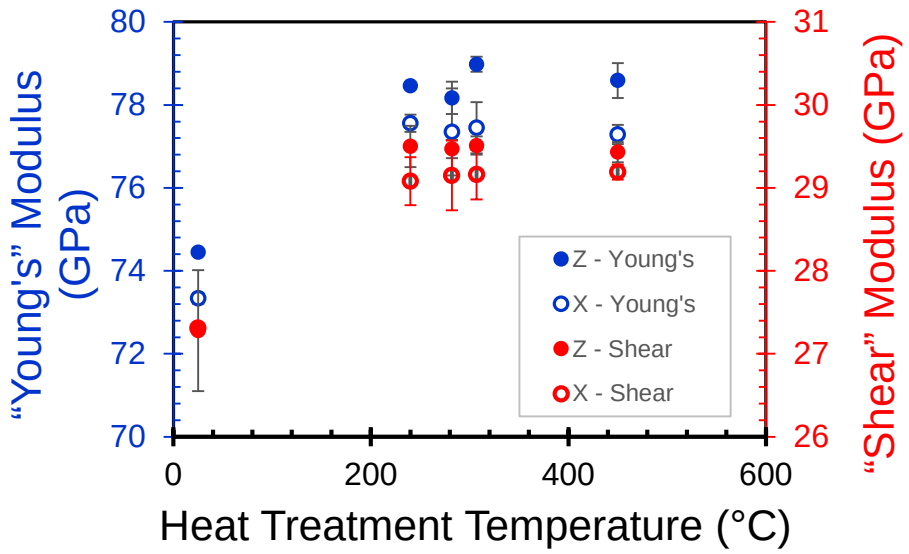


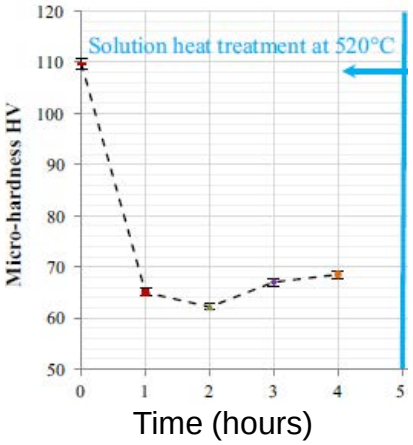




Hardness and Elastic Constants





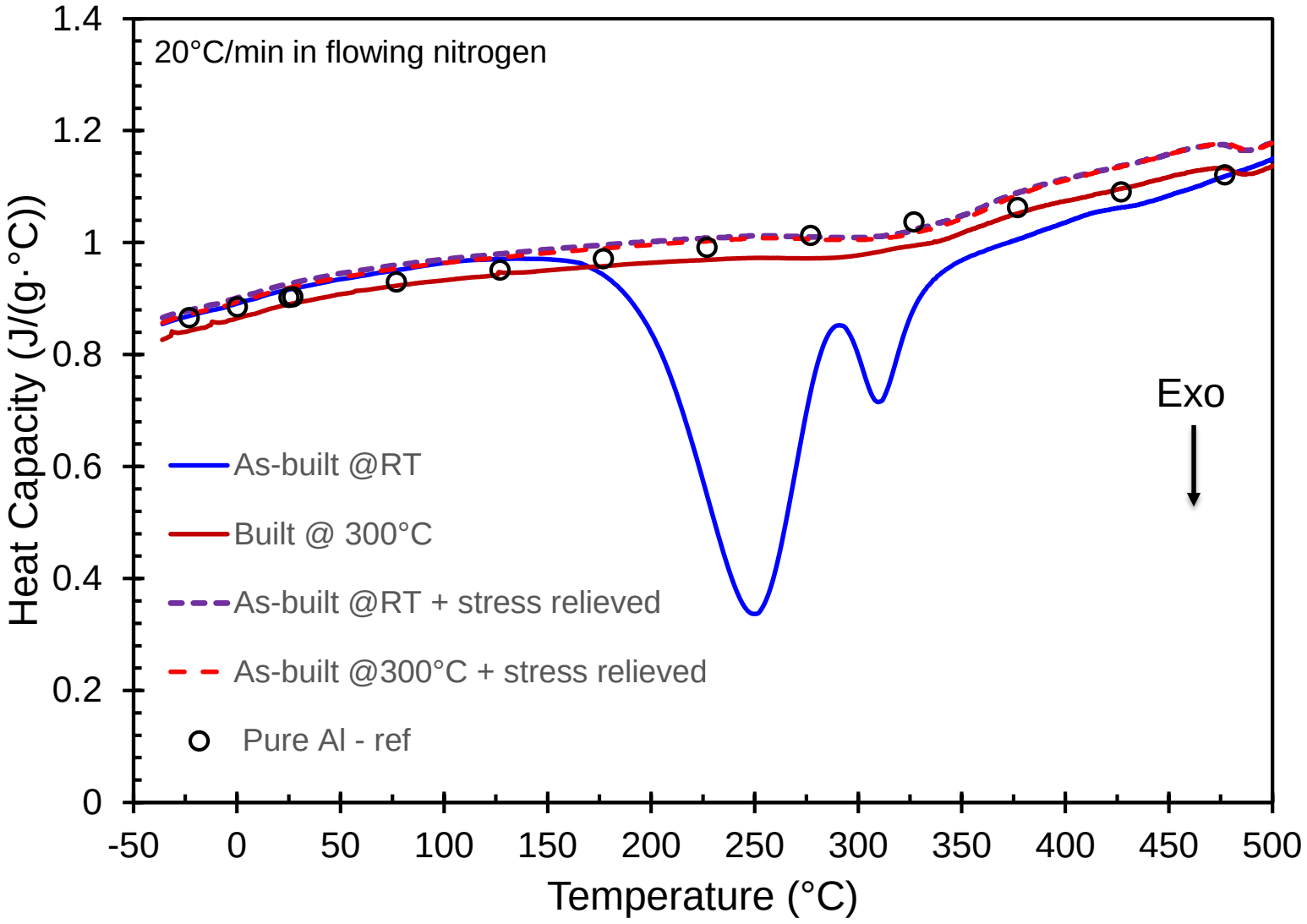


N. T. Aboulkhair et al., "On the Precipitation Hardening of Selective Laser Melted AlSi10Mg," Metall. Mater. Trans. A, 3337 (2015)

cation strengthening.[14] In the as-built samples, the dislocation motion is mainly hindered by the increased volume of grain boundaries, whereas in the hardened material the dislocation motion is obstructed by the dispersoids acting as obstacles. For overaged materials, the strength decreases because the precipitates are bypassed by the dislocation, depressing the effect of Orowan strengthening.[15] This is because the increase in

- Hardness in the as-built part is dominated by the "nano-cluster" hardening and solution hardening.
- Microhardness progressively decreases as the dominant mechanism changes form solution hardening to precipitation hardening, to collapsing of cellular wall, and spheroidizing.

Heat capacity as a function of temperature



Ref: E. H. Buyco and F. E. Davis, "Specific Heat of Aluminum from Zero to Its Melting Temperature and Beyond," J. Chem. Eng. Data, 15 [4] 518-523 (1970)

1st order calculation of thermal properties

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Room Temperature Properties for Aluminum and Al Si10Mg Alloy from Literature* and Calculation.

	Electronic Contribution to Thermal Properties			Reference
Al	Free electronic density – (e/m^3)		1.809 X10^{29}	
	Fermi Level (E_F) at 0 K – (eV)		11.66	
	Electron velocity at Fermi Level (V_F)– (m/s)		2024917	
	Time between collision (τ) – (s)		7.16 X 10^{-15}	
	Electron mean-free-path (l_e) – (Å)		145.1	
	Electrical conductivity* (σ) – (Ohm^{-1} cm^{-1})		365 X10^3	REF
	Calculated thermal conductivity (σ) – (W/m·K)		267.7	
	Thermal conductivity* (λ_e) – (W/m·K)		237	NIST
Al	Phonon Contribution to Thermal Properties			
	Atomic density (atoms/m^3)		6.029 X 10^{28}	
	Mean acoustic velocity* (v) – (m/s)		3666	Kittle
	Debye Temperature* – (K)	155°C	428	Kittle
	Averaged phonon mean-free path ($3\lambda/C_v v$) – (Å)		80.0	
AlSi10Mg	Longitudinal sound velocity (m/s)		6453	
	Shear sound velocity (m/s)		3119	
	Average acoustic velocity (v) (m/s)		3507	
	Debye temperature (K)	136°C	409	
	Thermal diffusivity (α_d) – (m^2/s)		4.648 X 10^{-6}	
	Averaged phonon-mean-free Path from ($3\alpha_d/v$) – (Å)		39.8	

* Depends on XY or Z plane

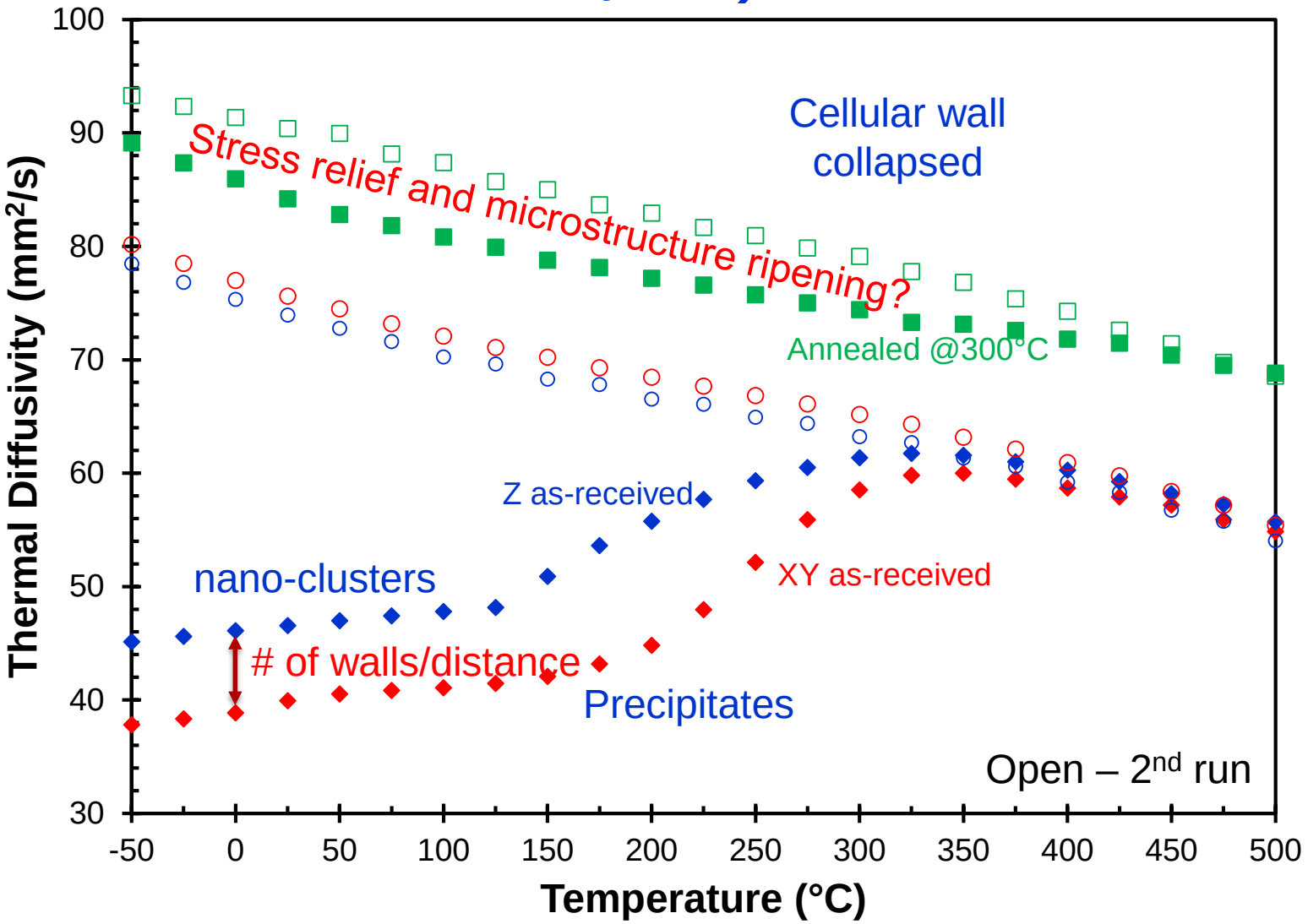
† At 240°C, before wall collapsed

Average size and distance	
FZ boundary	>> or > 100 µm
Grain boundary	15 to 65 µm*
Cellular wall	442-1650 nm*
Thickness of C wall	64.8±21.3 nm
Precipitates†	~ 100 nm
Size of precipitates†	< 50 nm
Nanoclusters	<< 50 nm

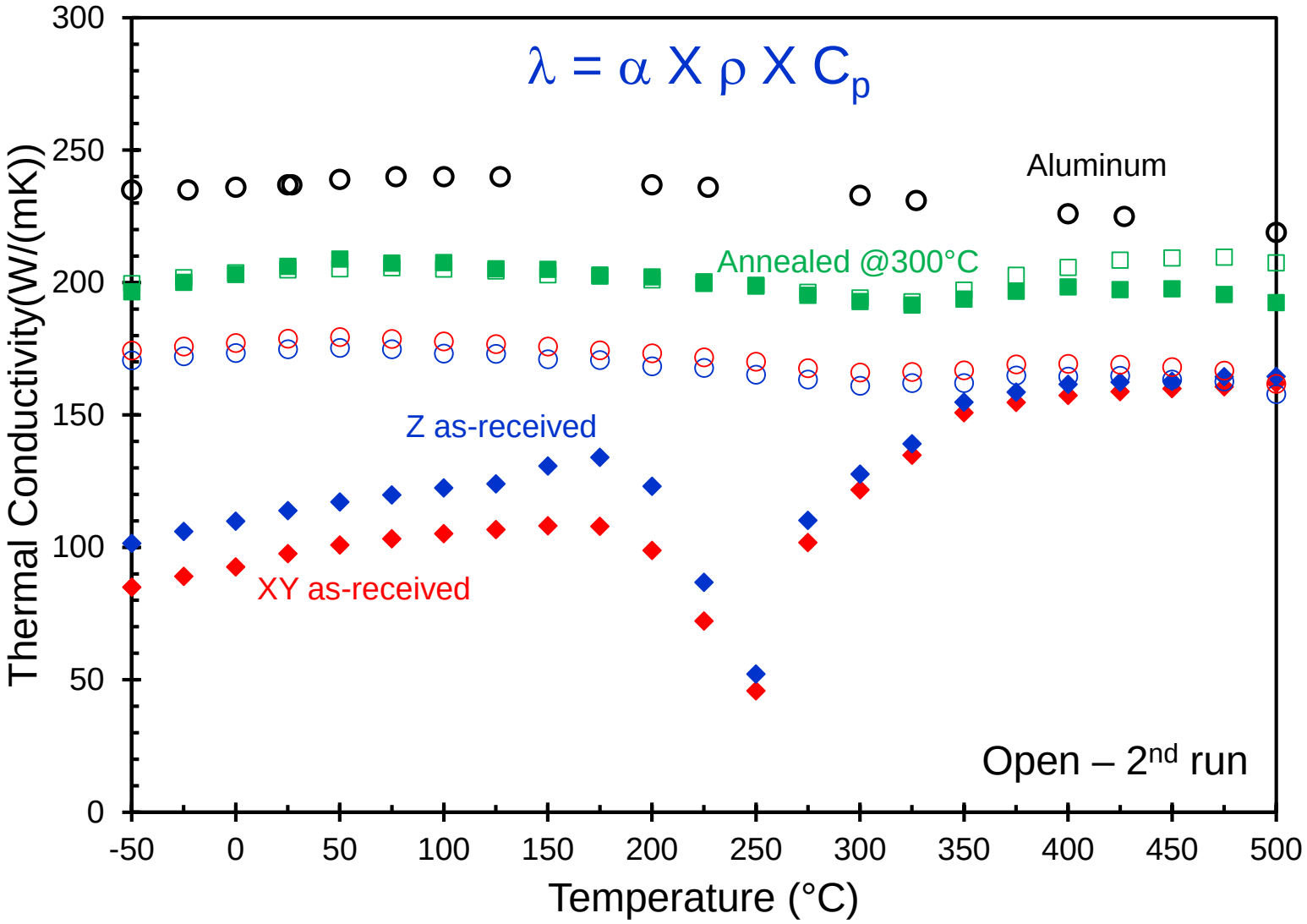
- Nanoclusters, precipitates, and cellular structure significantly effect heat transfer at low temperature before cellular wall collapses.
- After the cellular wall collapses, the heat transfer will be only limited by electron and phonon mean free paths in the alloy.

* C. Kittle, *Introduction to Solid State Physics*, 5th Ed. John Wiley & Sons, Inc. (1976)

Thermal diffusivity (α)



Thermal conductivity (λ)



Ref: C. Y. Ho, R. W. Powell and P. E. Liley, "thermal Conductivity of the Elements, J. Phys. Chem. Ref. Data vil. 1, No. 2, 305 (1972)

Conclusion

- Fast melting and rapid solidification can significantly impact the thermal properties of AM fabricated parts.
- Microstructure evolution, including the dissolution of excess Si, the growth of Si precipitates, and the collapsing of the cellular structure, has a profound effect on the thermal transport in AM fabricated AlSi10Mg alloy.
- Implications based on this study are important to ensure thermal performance of AM fabricated, solution treatable alloys for practical applications.

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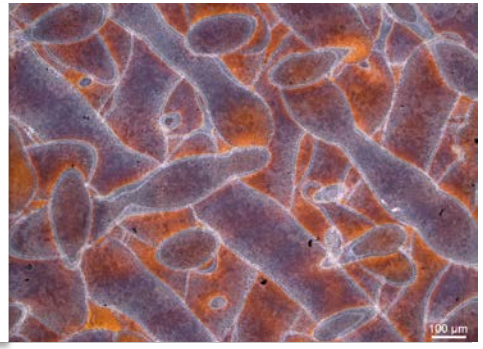
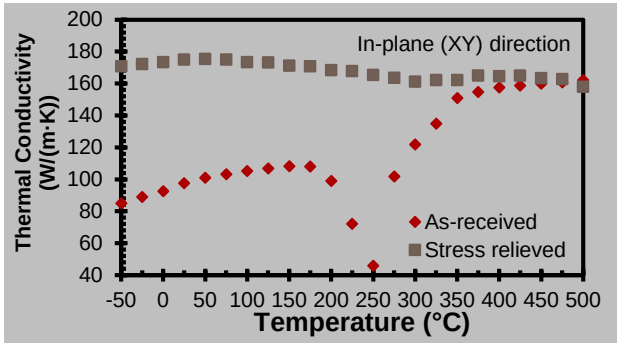
Thank You





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Thermal calculation

(1) The mean free path of electron in pure aluminum can be calculated by

$$I_e = V_F \tau$$

Where l is the man free path, V_F is the velocity of the electron above Fermi level, and τ is the average time between electronic collisions. The Fermi velocity can be calculated by

$$V_F = \sqrt{2E_F / m_e}$$

Where the E_F is the Fermi energy and m_e is the effective mass of electron (9.11 X 10^{-31}). The Fermi energy at zero Kevin is given by

$$E_F = \frac{\hbar}{2m_e}\left(\frac{3N}{8\pi V}\right)$$

Where N/V is the free electron density, and $\hbar$ is the Plank's constant. The average time between collision τ is determined by the mass of the electron, the number of atoms per unit volume, electrical resistivity (ρ), and the electron charge (e)

$$\tau = \frac{m_e}{\rho n e^2}$$

The thermal conductivity K can be estimated by the Wiedemann-Franz law

$$K = \frac{\sigma T}{3}\left(\frac{\pi k}{e}\right)^2$$

Where σ is the electrical conductivity and k is the Boltzmann constant.

(2) Phonon calculation

Phonon mean free path (l_p) above Debye temperature can be estimated by

$$l_p \approx \frac{3\lambda}{C_v v} = \frac{3\alpha}{v}$$

Where, C_v is the volumetric heat capacity, C_v is the volumetic heat capacity, v is the sound velocity in the medium, dmeasured longitudinal (v_L: 6453 m/s) and the shear (v_s: 3119 m/s) sound velocities by the following relationship,

$$v = \left[\frac{1}{3}\left(\frac{2}{v_s^3} + \frac{1}{v_L^3}\right)\right]^{-1/3}$$

(3) Debye temperature (θ_D)

$$\theta_D = \frac{\hbar v}{2k}\sqrt[3]{\frac{6N}{\pi V}}$$

Where k is the Boltzmann constant.

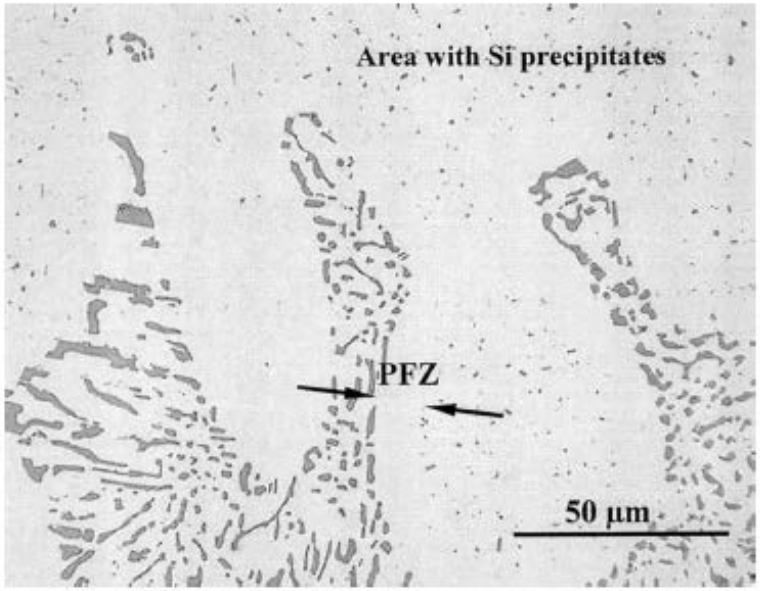

Fig. 9—Silicon precipitates within dendrites in AlSi7Mg0.2 alloy that has been extremely slowly cooled from 813 K.

L. Pedersen and L. Arnberg, “The effect of solution heat treatment and quenching rates on mechanical properties and microstructure in AlSiMg Foundry Alloys,” Metallurgivcal and Materials Transactions A **32A** 525-532 (2001)