Project 22: Development of Novel High Temperature Aluminum Alloys

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Student: Joe Jankowski (Mines)

Faculty: Michael Kaufman, Amy Clarke, Robert Field, Steve Midson (Mines)

Industrial Mentors: Krish Krishnamurthy (Honeywell), Paul Wilson (Boeing)

Project 22: Development of Novel High Temperature Aluminum Alloys

CANFSA
CENTER FOR ADVANCED NON-FERROUS STRUCTURAL ALLOYS

- Student: Joe Jankowski (Mines)
- Advisors: Michael Kaufman, Amy Clarke (Mines)

Project Duration

PhD: June 2015 to August 2019

- Problem: Aluminum alloys with acceptable high temperature structural properties are expensive and difficult to produce.
- Objective: Develop high-temperature, high-strength Al alloys without use of rapid solidification by forming stable microeutectic.
- Benefit: Reduce production cost and increase selection of high performance high-temperature Al alloys.

Recent Progress

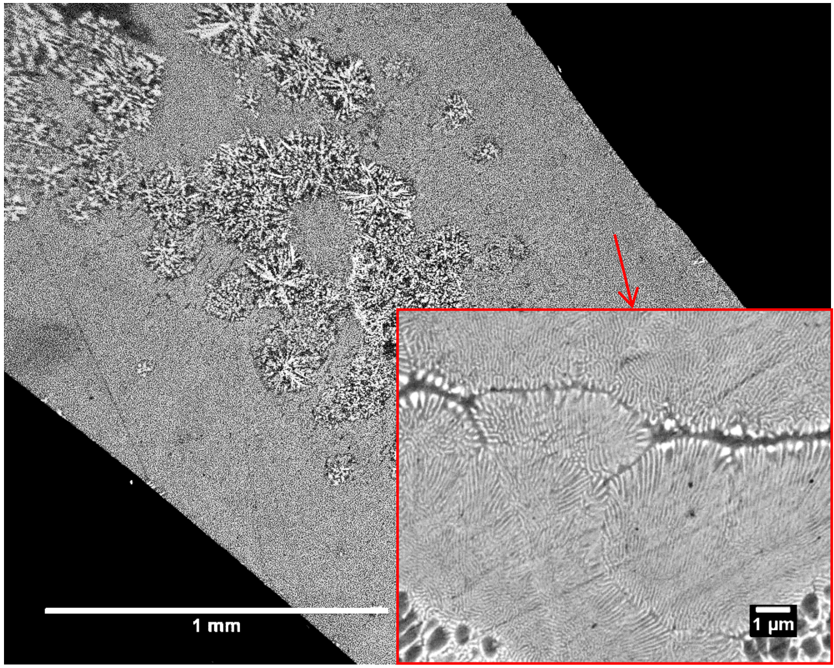
- Processing-microstructure study
- Gas tungsten arc welding (GTAW) autogenous welding study feasibility demonstration
- Compression testing of J35 alloy
- SEM characterization of J35 microstructure
- High accuracy density functional theory (DFT) modeling of α-phase

Metrics

Description	% Complete	Status
1. Develop experimental protocols for reproducible castings	100%	●
2. Mechanical testing and characterization of microeutectic-containing microstructures	90%	●
3. Develop crystallography / phase stability knowledge of α-phase	100%	●
4. Assess ability to produce microeutectic in chill castings	100%	●
5. Determine how fundamental solidification parameters affect microeutectic formation	50%	●

Project Motivation

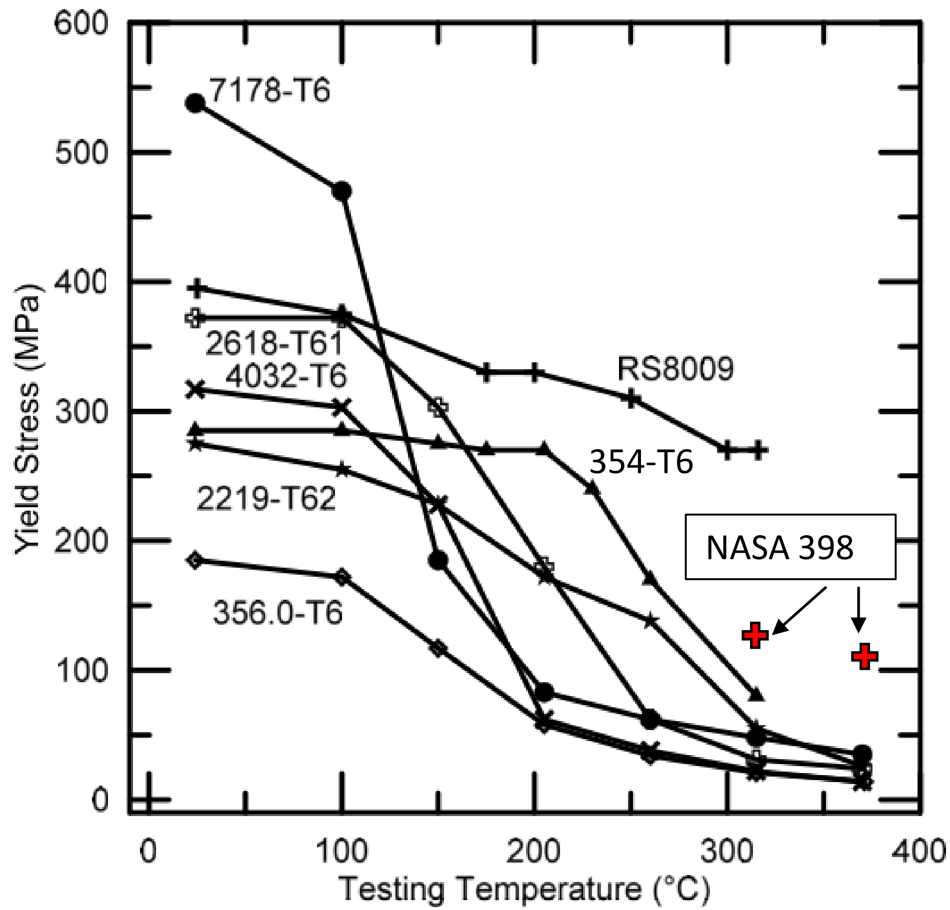
- Microeutectic between Al and α-$Al_{13}(Fe,V)_3Si$ in chill castings
- Hardness of microeutectic similar to RS8009
- Lower cooling rate than rapidly solidified alloys
  - 10^2-10^3 K/s vs. 10^4-10^6 K/s
- Potential high-temperature Al structural alloy



Alloy	Al (at%)	Fe (at%)	V (at%)	Si (at%)
RS8009	Bal.	4.3	0.7	1.7

Industrial Relevance

- Development of a lower cost high-temperature Al structural alloy
- Identify alternative processing routes for high-temperature Al alloys
- Rapid screening of composition space for nonequilibrium systems



Mechanical properties of selected Al alloys (RS8009 is high-temperature alloy)*

*R. Marshall. Master's Thesis. (2016).

Presentation Overview

- Prior Work
- Recent Progress
- Project Timeline

Prior Work

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Goal: Develop alloy with high volume fraction of microeutectic constituent, improve understanding of system

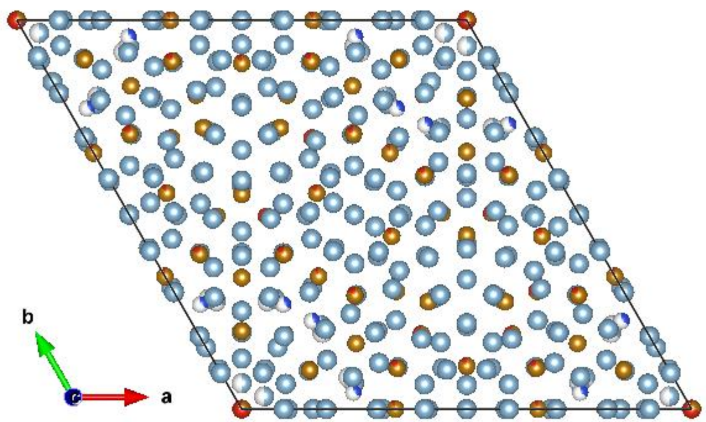
Completed work

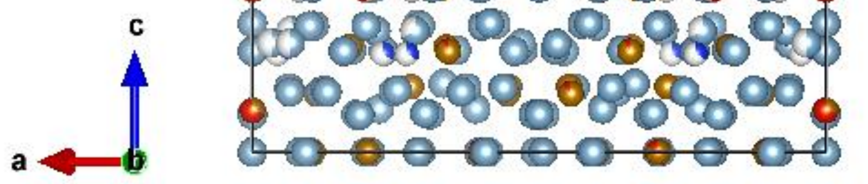
- Structure determination of deleterious h-phase using powder diffraction
- Develop method of using density functional theory (DFT) to screen compositions
- Experimental validation of DFT
- Determination of cooling rates in Cu chill mold
- Selection of final alloys

h-Phase Crystal Structure

- Most complex intermetallic crystal structure solved by powder diffraction, ~472 atoms per unit cell, 4 different elements present

- Used synchrotron x-ray and neutron powder diffraction

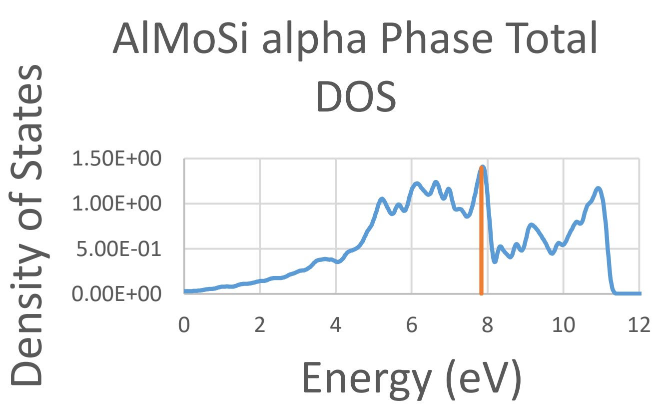


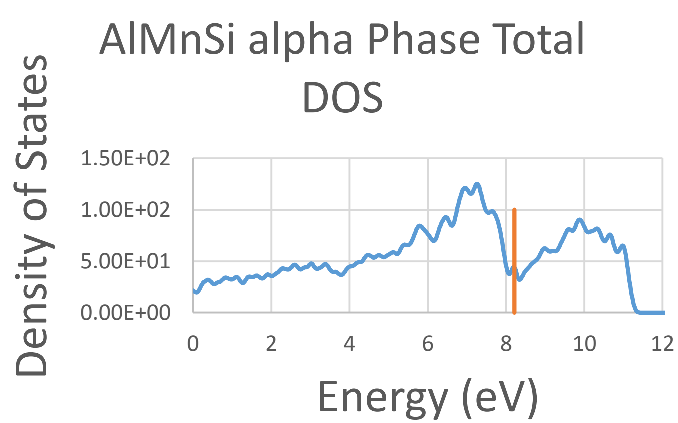


DFT Composition Screening

- Density of states (DOS)
  - Relatively inexpensive calculation
  - Large unit cells for α and h-phase
  - Easier to get useful DOS vs. enthalpy/charge density
- Based on actual physics of system
- Intuitive visual representation of bonding interactions in 2D

α-AlXSi ternary phase	Area under curve from "stable" to calculated Fermi level	Deep pseudogap
Ti	-245	Yes
V	-117	Yes
Cr	-49	Yes
Mn	0 (reference)	Yes
Fe	22	Yes
Co	120	Borderline
Ni	145	No
Cu	130	No





DFT Validation

- Method assesses possibility, does not determine if something will actually form
- Best for extrapolation from known system, for example Al-Fe-V-Si
- Results for α-phase are promising
- Potential to accelerate alloy design in **all metallic systems**

Alloy System	Expected to form α-phase from theory?	Is α-phase experimentally observed?
Al-Fe-V-Si	Yes	Yes
Al-Fe-Cr-Si	Yes	Yes
Al-Co-Ti-Si	No	No
Al-Co-Cr-Si	No	No
Al-Fe-Mn-Cr-Si	Yes	Yes

Final Alloy Selection

- Chosen with processability in mind
  - Equilibrium liquidus
- Cr vs. V
- V-containing alloys may contain h-phase or low-Si α-phase
  - From WDS/XRD analysis

Alloy	Liquidus (°C, approx.)	Total TM (at%)
J35	730	3.4
J40	760	4.1
J45	780	4.6
J50	800	5.1
RS8009	850	5.0

Composition (at%)

Alloy	Al	Fe	Mn	Cr	Si
J35	Bal.	1.5	1.5	0.4	1.6
J40	Bal.	1.8	1.8	0.5	1.8
J45	Bal.	2.0	2.0	0.6	2.1
J50	Bal.	2.2	2.2	0.7	2.3

Recent Progress

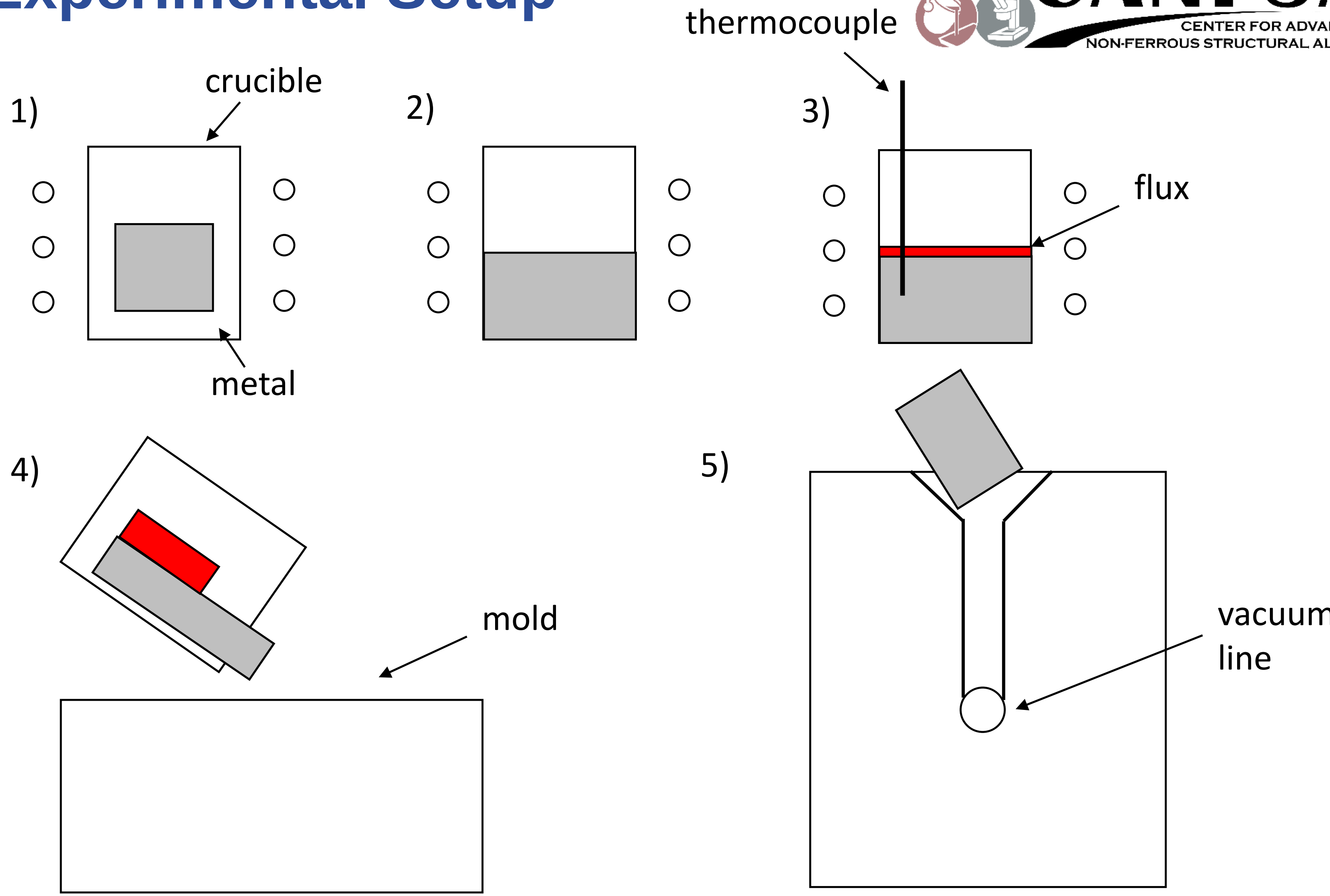
- Processing-microstructure study
- Compression testing
- GTAW autogenous welding solidification experiment

Processing-Microstructure Study

Goal: Develop links between processing conditions and microstructure in chill mold castings

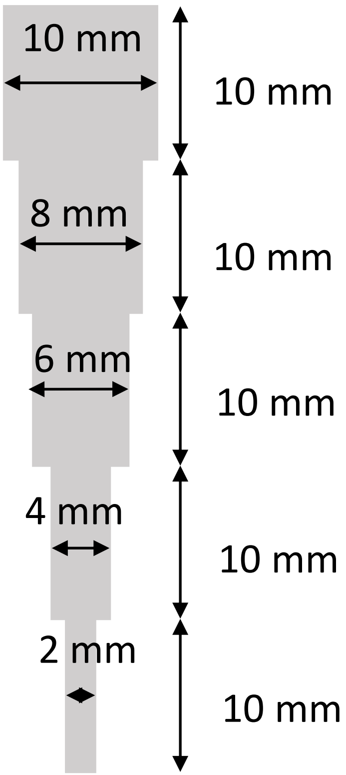
- Alloys being studied are highly processing sensitive
- Need to identify robust processing conditions
- Evaluate ability to produce microeutectic microstructure consistently

Experimental Setup



Variables in Study

- Melt superheat
  - Shown to be critical to microstructure formed
- Mold geometry / cooling rate
  - Stepped cylindrical mold shape
  - Variable solidification conditions in mold
- Alloy composition
  - Transition metal level has strong effect on microstructure



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Results of Study

- Difficult to find conditions that produce consistent microstructures through thickness
  - Found one particularly promising condition—J35 w/ 200 C superheat (6mm)

<u>Additional results</u>

- Higher transition metal content enhances α-phase nucleation
  - Narrows processing window for coupled growth
- Lower transition metal content promotes primary Al growth
  - Al dendrites with interdendritic Al-α microeutectic

Mechanical Testing

Goal: Determine if microeutectic-containing alloys have high strength and microstructural stability at elevated temperatures

- Room + elevated temperature compression
  - Room temperature tests performed with 20 kip hydraulic MTS frame
  - Elevated temperature tests performed with Gleeble thermomechanical simulator
  - 10^{-3} s^{-1} strain rate

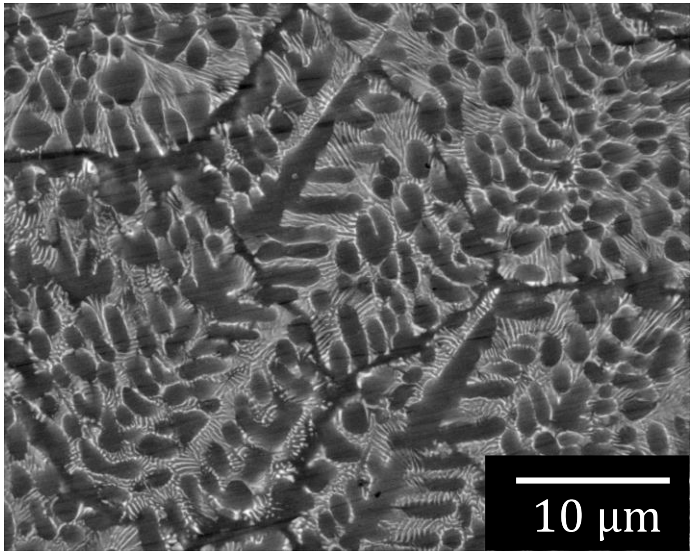
- Evaluate degradation of strength at temperature over time

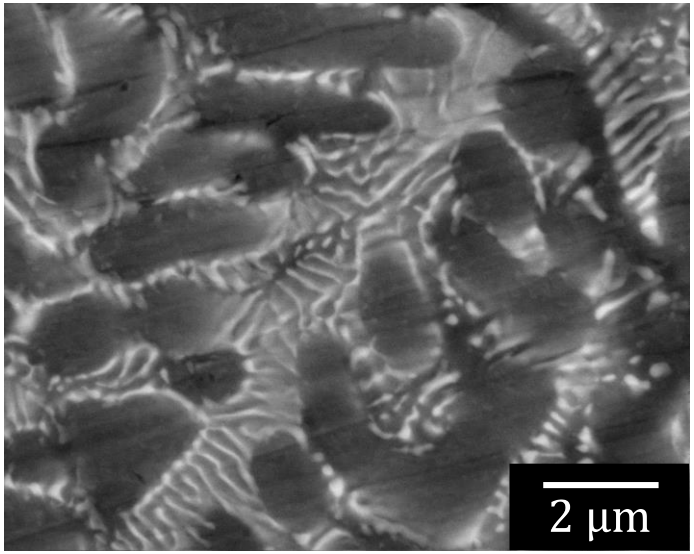
- Link performance to microstructures through characterization

J35 Microstructure Overview

- Previous mechanical testing identified "primary Al" as most desirable solidification morphology in alloys J35 and J40
  - Microhardness
  - Compression testing
- J35 cast at 200 °C superheat w.r.t. equilibrium liquidus (6 mm diameter)
- Cooling rates <1,000 K/s
  - Thin-walled die casting
  - Twin roll strip casting*
- "primary Al"
  - Al dendrites (appear to be primary)
  - Solute-enriched lamellar microeutectic

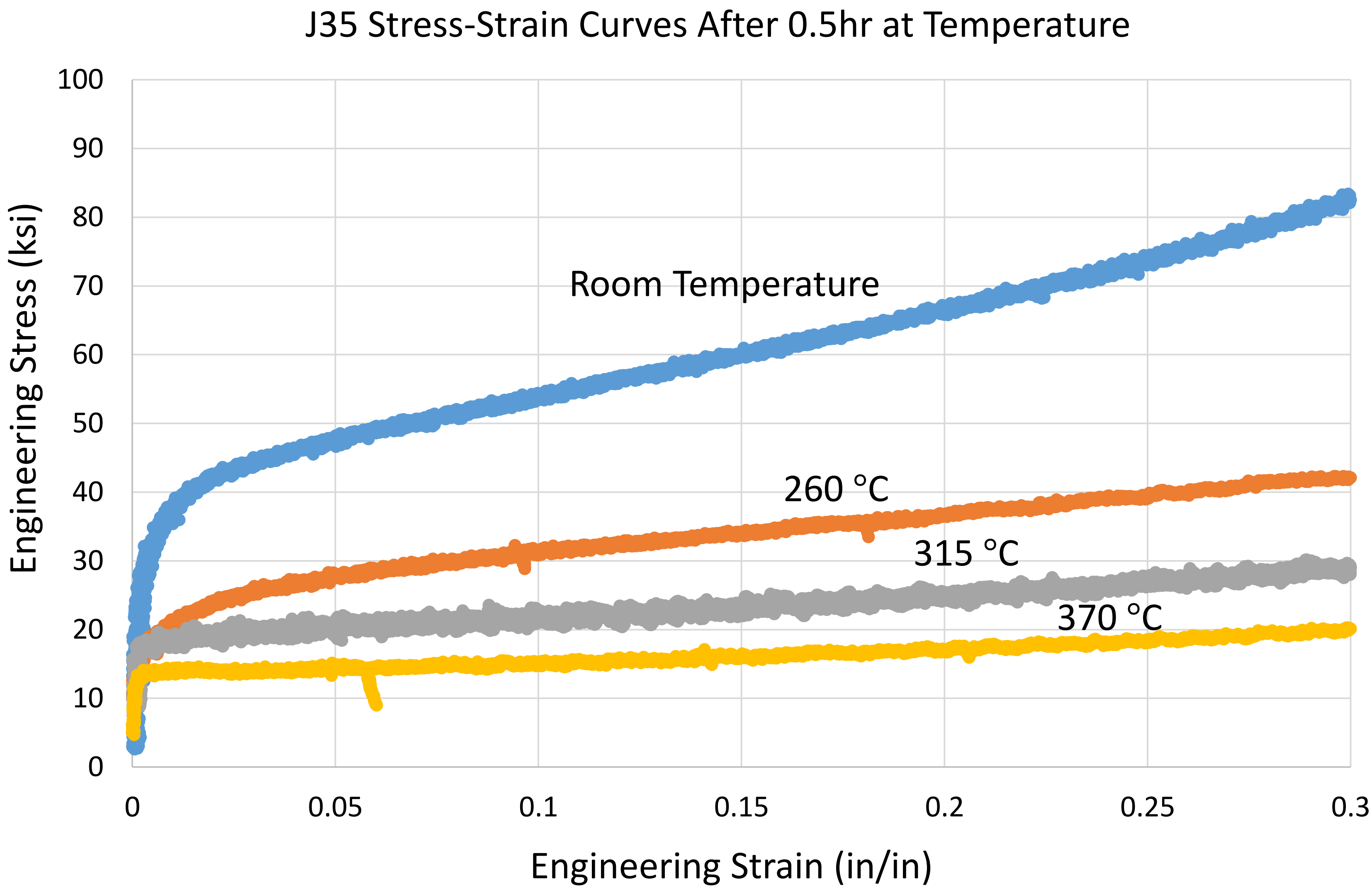
BSE images





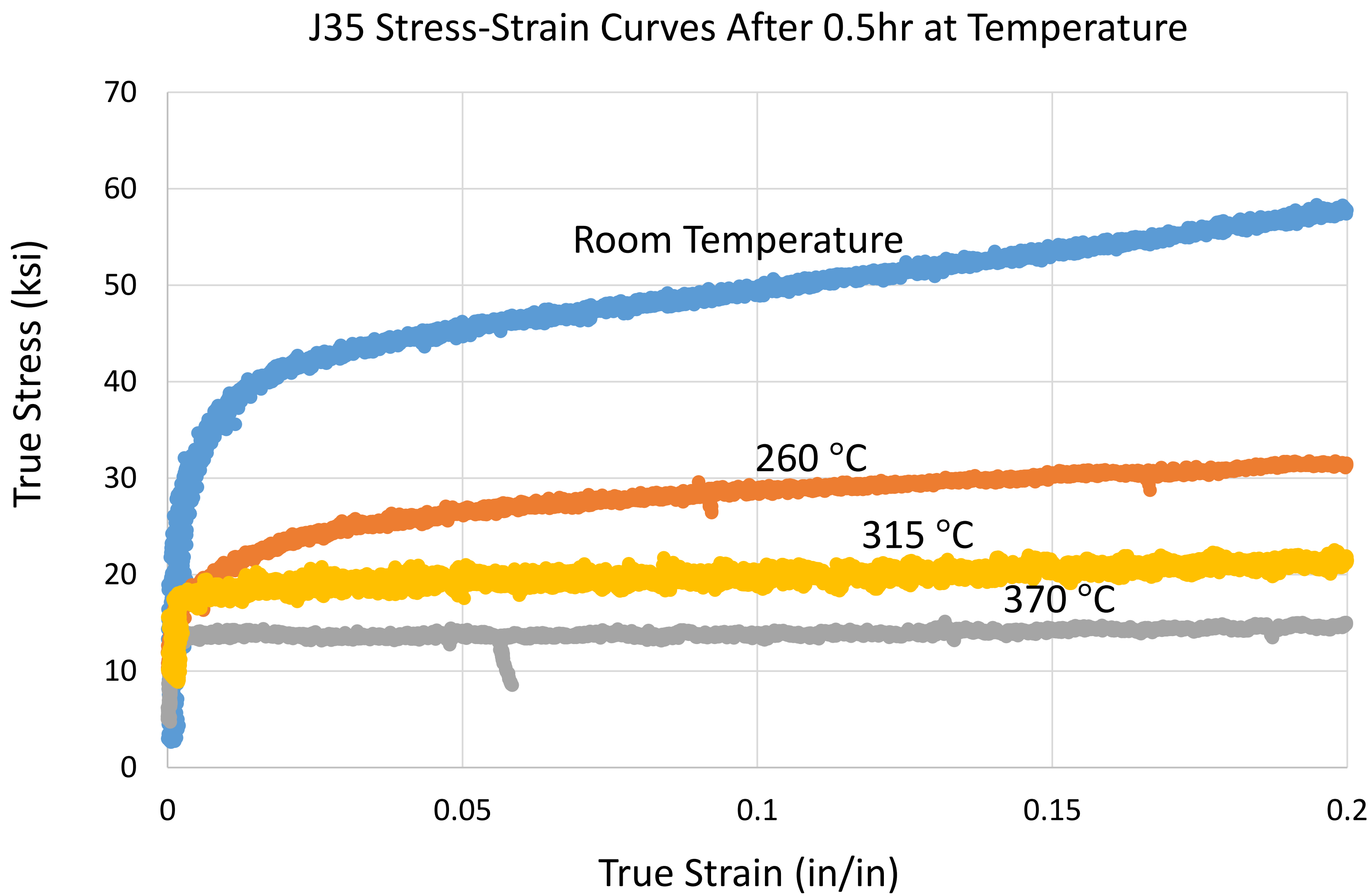
*P.N. Anyalabechi. EPD Congress. (2004).

J35 Mechanical Properties



J35 Mechanical Properties

estimate



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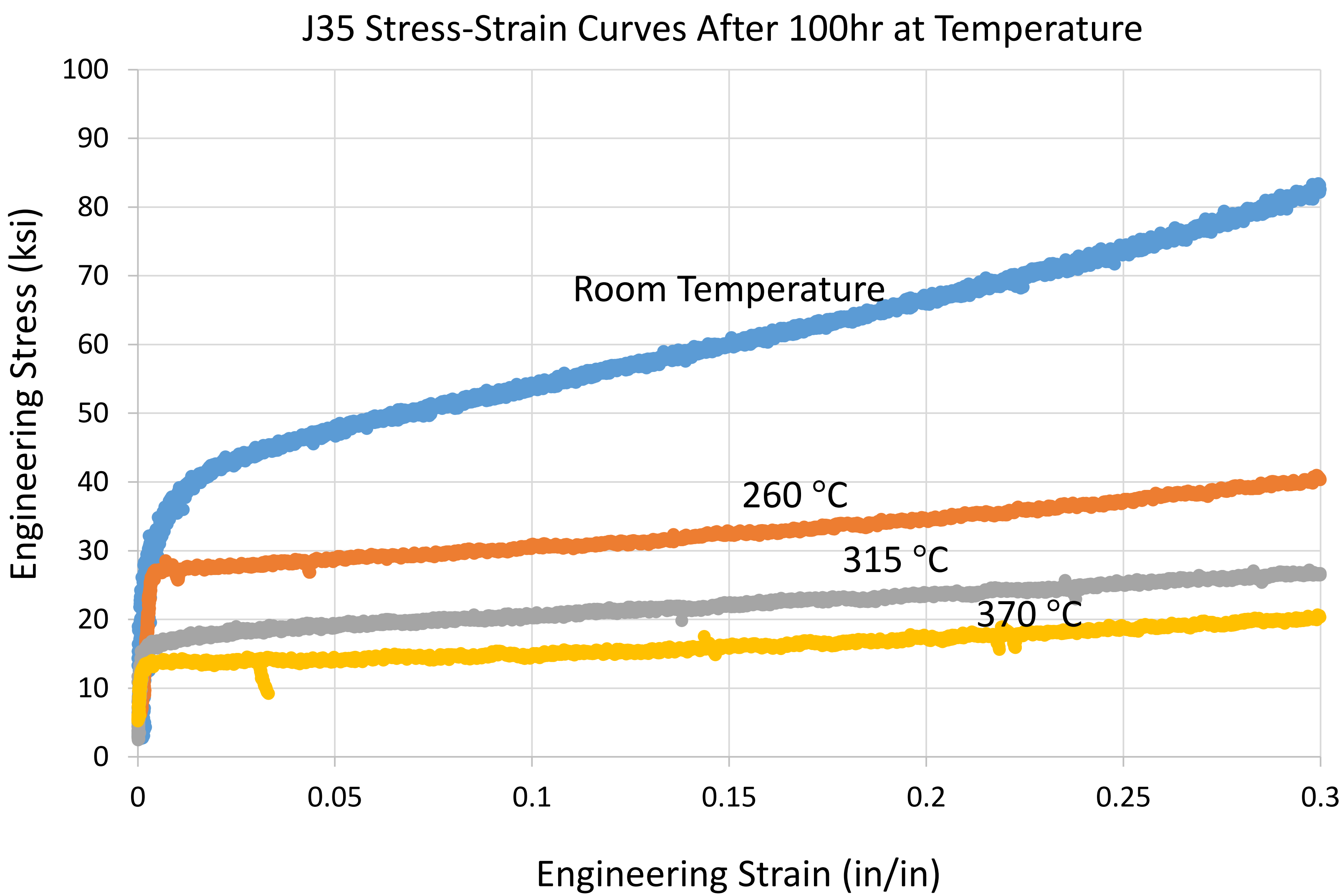
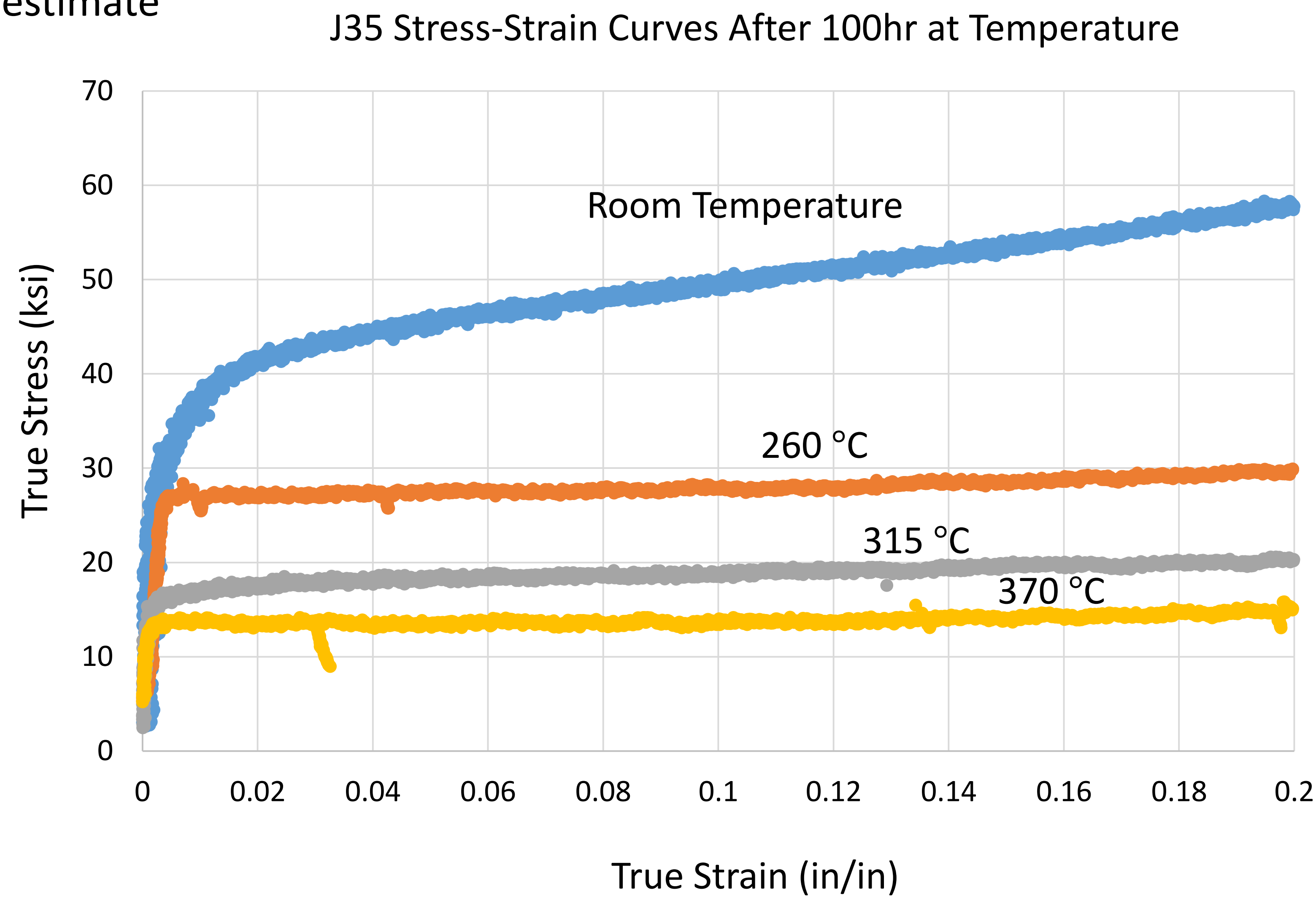


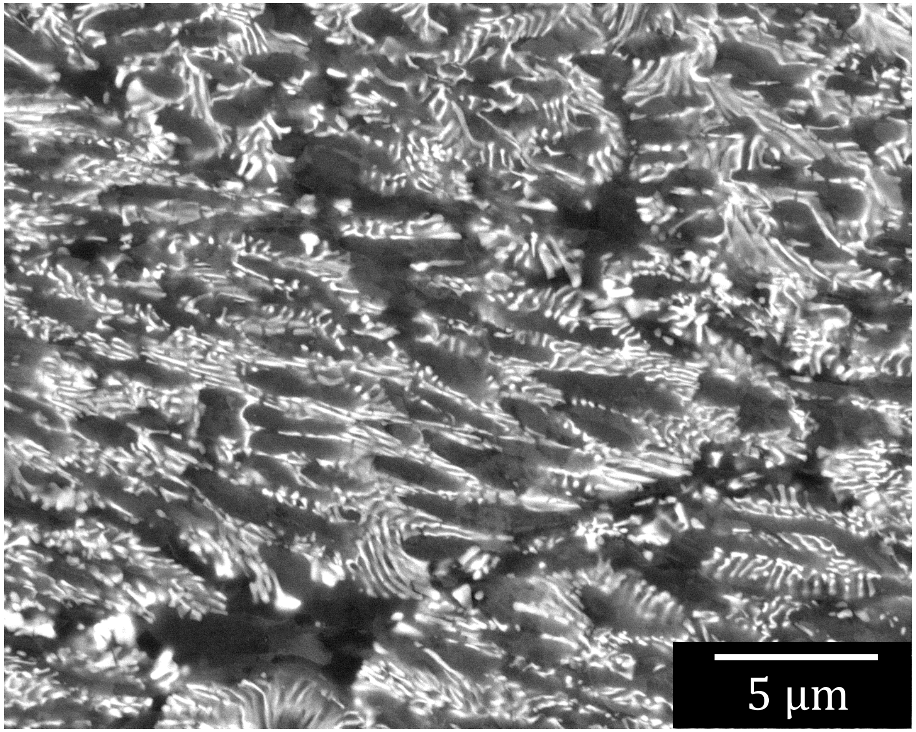
J35 Mechanical Properties

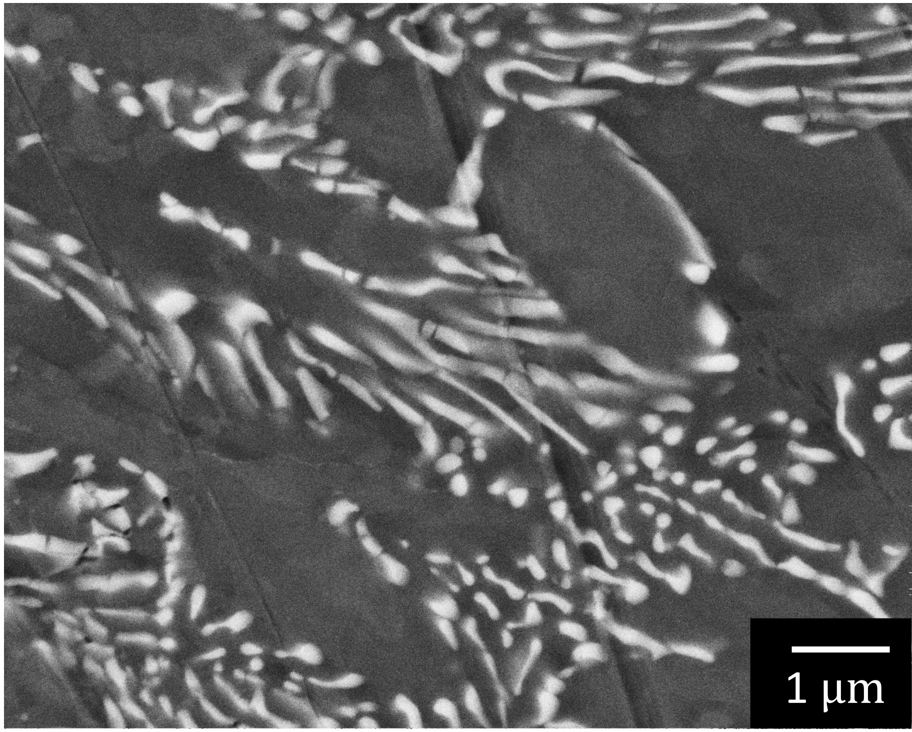
estimate



Deformed Microstructure

- J35, 100 hr at 260 °C
- Deformation breaks up dendritic as-cast microstructure
- Possibility for refinement of structure through deformation





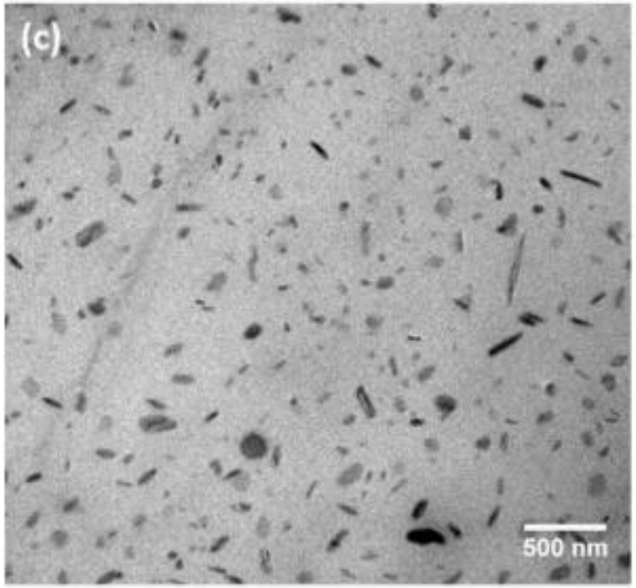
Potential Aging in J35

- 0.2% YS in J35 changed:
  - 20 ksi, 0.5 hr at 260 C
  - 27 ksi, 100 hr at 260 C

- Increase in strength consistent with aging

- α-phase known to precipitate out in solute-rich Al dendrites*

- Needs further investigation

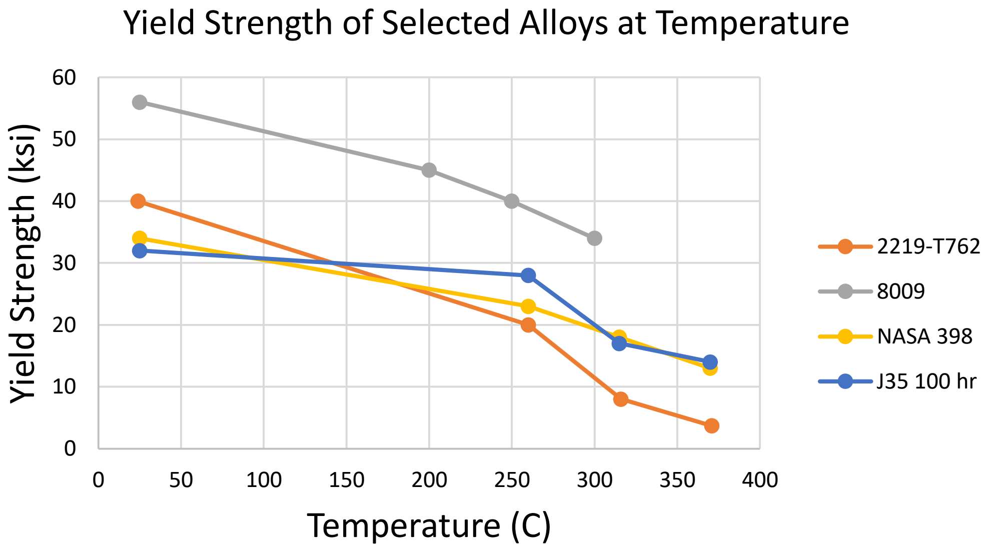


α-Al(Fe,Mn,Mo)Si dispersoids precipitated in an Al dendrite during an aging heat treatment for Al-7Si-0.5Cu-0.3Mg-0.1Fe-0.3Mo-0.5Mn*

*A.R. Farkoosh *et al*. (2015)

Summary of Mechanical Testing

- Possible aging response at 260 °C
  - Further investigation needed
  - Potential to create hierarchical, thermally stable microstructure
- Measured yield strengths comparable to or exceed existing conventionally processed Al alloys
- Negligible degradation of mechanical properties with time
- Samples produced at cooling rates lower than 1000 K/s
  - Thin-walled die casting
  - Twin roll strip casting



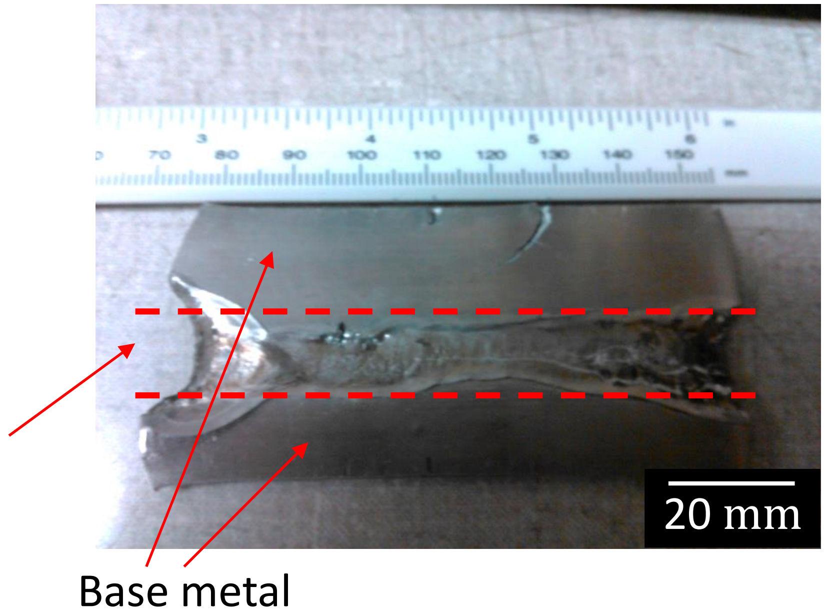
GTAW Solidification Study

<u>Goal:</u> Link as-cast microstructures to fundamental solidification parameters

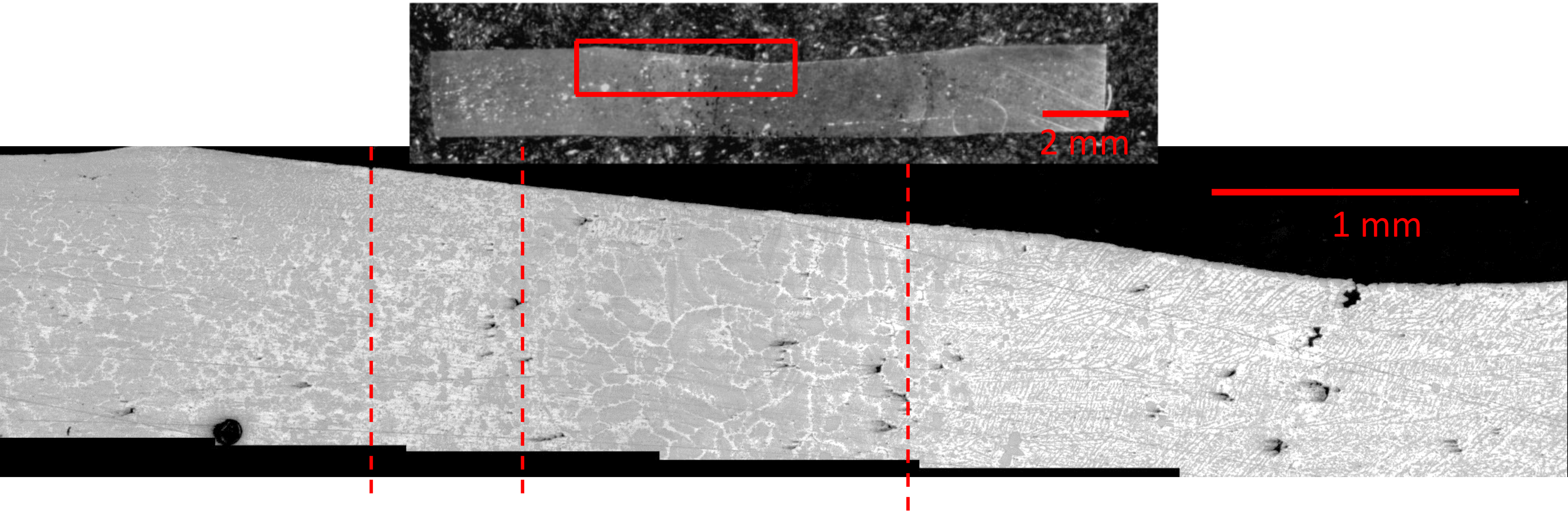
- Controlled solidification velocity
- Can estimate thermal gradients from cooling rates
- More generally applicable than processing-microstructure study

Demonstration Weld

- Cast J35 plate with dimensions of 40x40x4 mm
- Rolled plate to approximately 80x40x2 mm
- Used GTAW with 110 A AC current, ~4 mm/s travel speed
- Able to achieve a melt pool in the plate



Weld Microstructure



Base metal

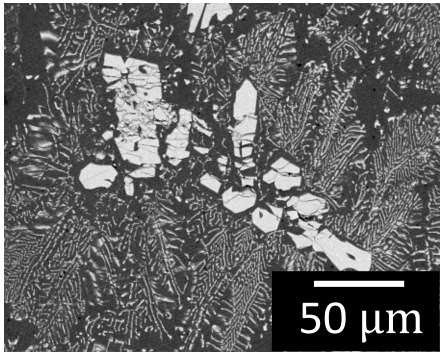
HAZ

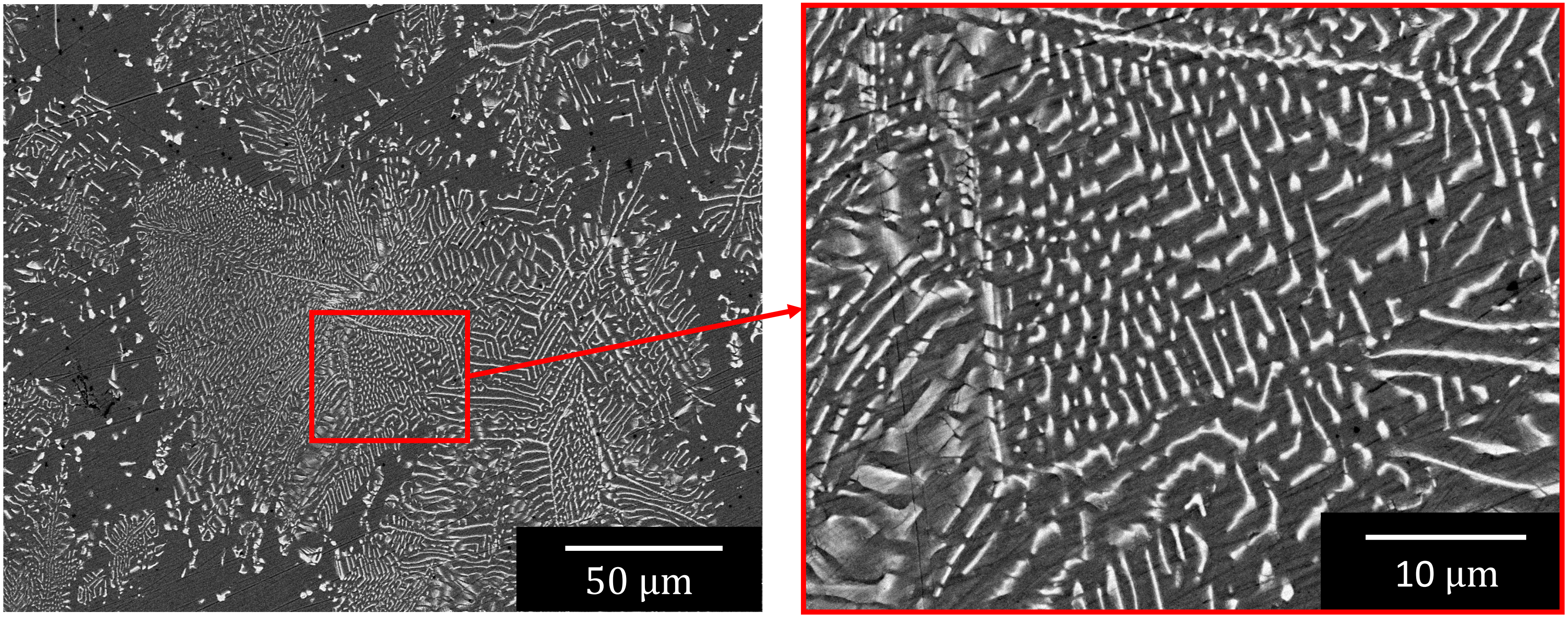
Fusion zone
(coupled growth)

Fusion zone
(primary intermetallic)

Base Metal

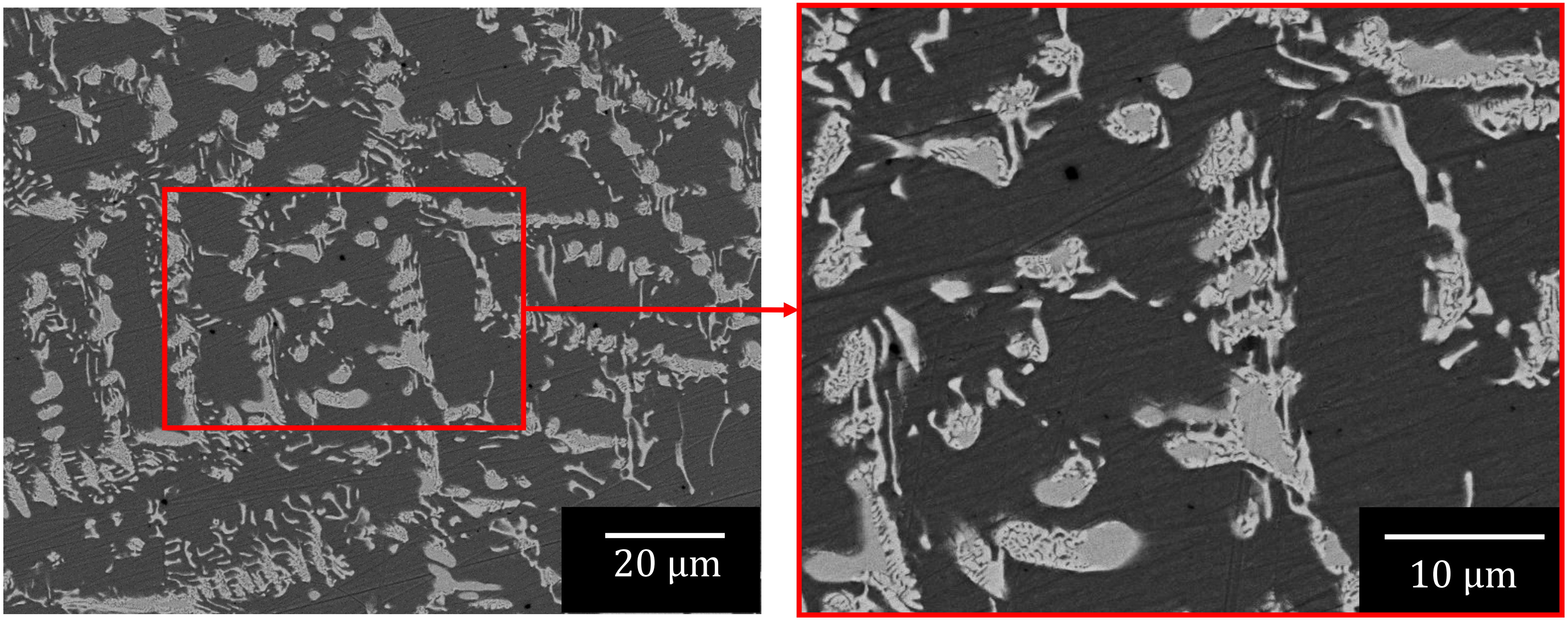
- Consists of coarse primary particles and coarse eutectic
- Fine scale relative to size of melt pool





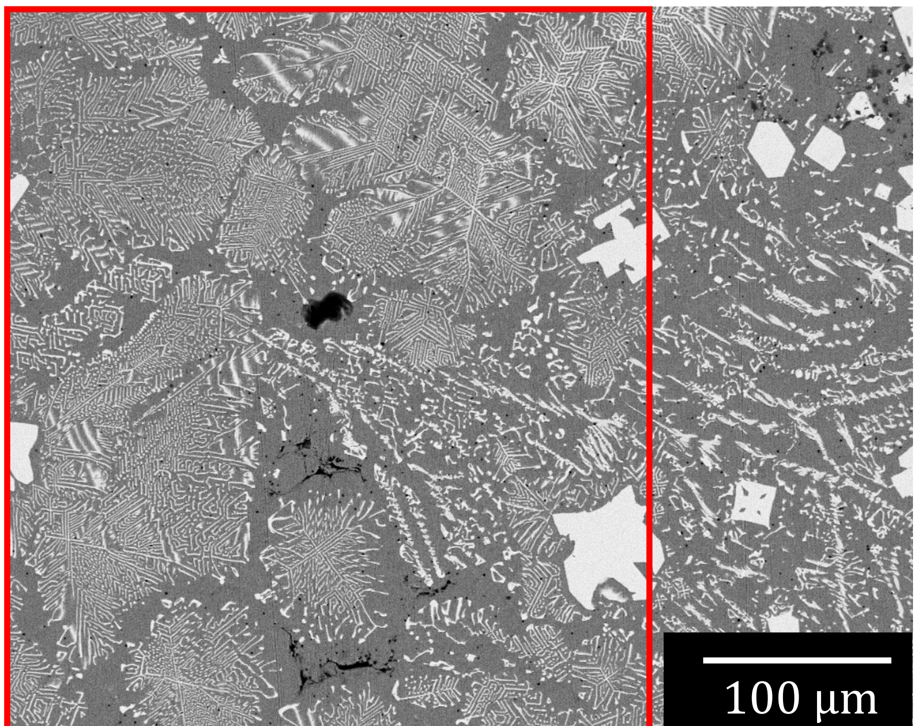
Fusion Zone (Center)

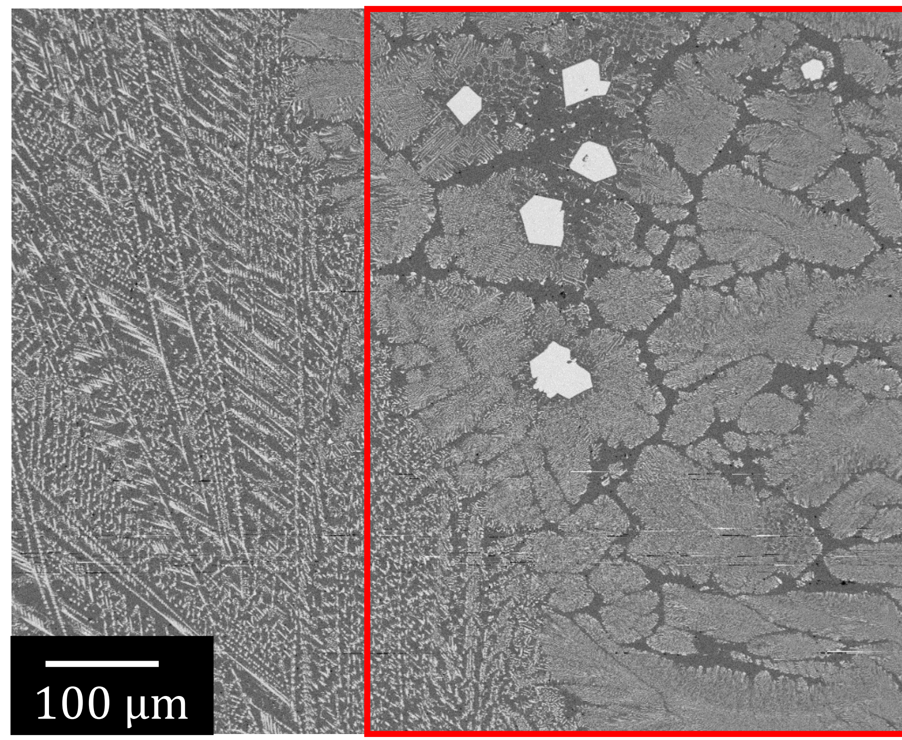
- Expected to have highest solidification velocity
- Microstructure looks like primary intermetallic formation



Fusion Zone (Edge)

- Expected to have lowest solidification velocity
- “Eutectic islands” at edge of fusion zone
- Appears to contain partially re-melted α particles





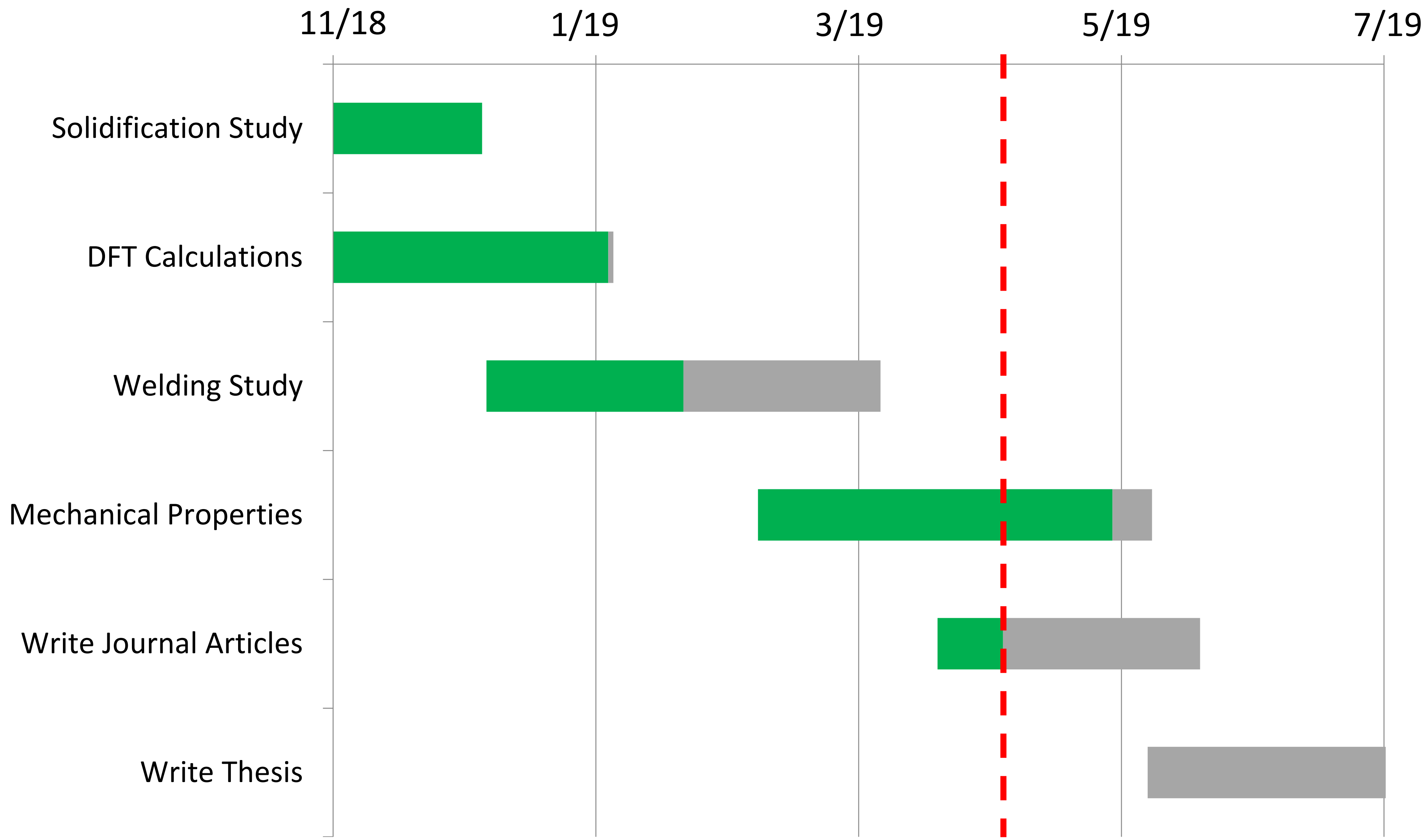
GTAW Summary

- Have already made welding plates and developed welding experiment for study—largest bottleneck
- Still need to perform autogenous welds at various travel speeds using automated GTAW setup
- Characterize microstructures using SEM
- Use results to link microstructures to solidification velocities, and potentially thermal gradients

Future Work

- Investigate aging in J35
  - TEM characterization of 100 hr at 260 °C condition
  - Verify results with a second heat treatment
  - Try two-step heat treatment: 100 hr at 260 °C, 100 hr at 315 °C
- Complete autogenous GTAW solidification study
  - Complete welds
  - Characterize welds using SEM
- Write journal articles on completed research
- Write thesis

Progress



11/18
1/19
3/19
5/19
7/19
Solidification Study
DFT Calculations
Welding Study
Mechanical Properties
Write Journal Articles
Write Thesis

Thank you!

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Project Duration: *June 2015 - August 2019*

Achievement

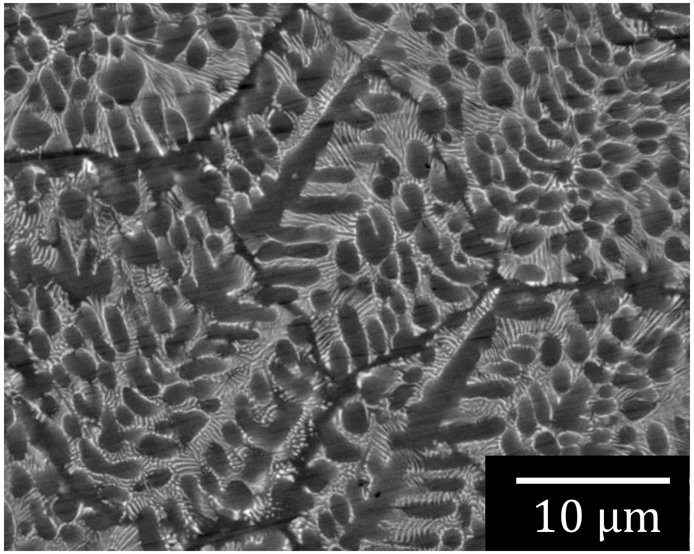
- Production of aluminum alloys with high strength at high homologous temperatures utilizing conventional processing routes, identified using *ab initio* DFT calculations

Significance and Impact

- Reduced cost of high performance Al structural alloys, improved methods for metastable alloy design.

Research Details

- Performed DFT calculations to determine promising alloy compositions and identified required solidification conditions to form lamellar microeutectic constituent.



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Program Goal

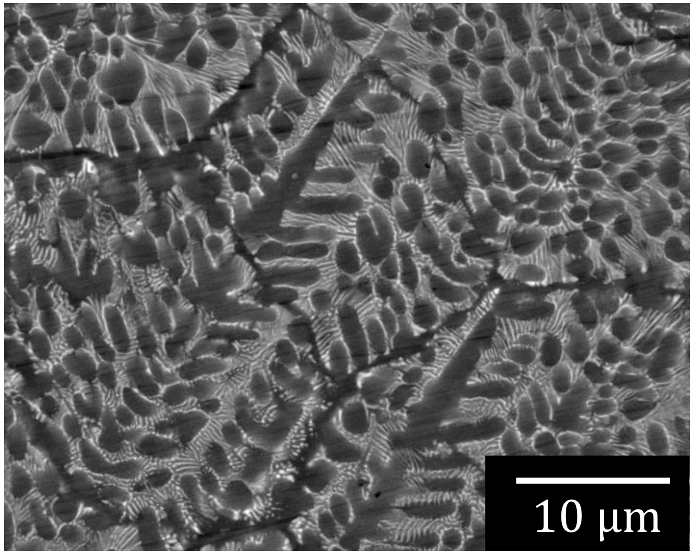
- Develop Al alloys with high volume fraction of microeutectic between Al and α-phase intermetallic.

Approach

- Utilize DFT calculations and characterization techniques to develop a new class of Al alloys based on the eutectic between Al and α-phase.

Benefits

- Improved scientific understanding of microeutectic, new high performance Al alloys, new method of metastable alloy design.



Cu Chill Mold Cooling Rates

- Measure of repeatability
- Indicative of solidification conditions
- Evidence cooling rates are between 10^2 and 10^3 K/s