Phase Transformation Kinetics and Alloy Microsegregation in High Pressure Die Cast Magnesium Alloys

PI: John E. Allison
University of Michigan
4/10/2015

Project ID #LM091

Overview

Timeline

- Start: October 2013
- End: October 2017
- 35% Complete

Budget

- Total project funding
  - DOE share: $600K
  - Contractor share: na
- Funding received in FY14: $175K
- Funding for FY15: $148K

Barriers

- Lack of understanding and predictive models for HPDC/SVDC Mg processes:
  - Limits ability to quickly optimize Mg components and reduce costs.
  - Limits ability to rapidly develop new alloys & processes for challenging applications and increases risk.

Partners

- Ford Motor Company (Dr. Mei Li)
- Tsinghua University (Prof. S. Xiong)

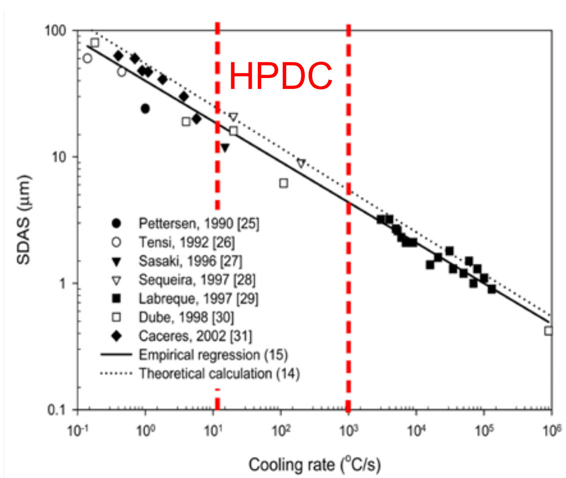
Relevance

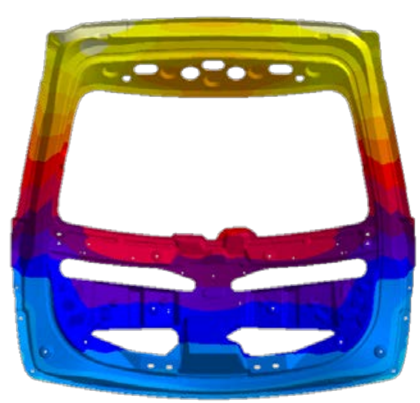
- Mg components represent a major opportunity for reducing vehicle weight (35-50%), energy consumption and greenhouse gas emissions.

- High Pressure Die Casting (HPDC) is used for over 90% commercial Mg products because it is fast, economical, and yields complex thin-wall Mg components

- High solidification rates, from 10 to 1000ºC/s – far from equilibrium

- No systematic, quantitative knowledge of microsegregation or phase transformation kinetics –> limits ICME predictive capabilities & thus increase risks, time and cost for use of Mg in new and challenging applications.





Relevance – Project Objectives

- Quantify & understand phase transformation & microsegregation during HPDC/SVDC
- Quantify & understand phase transformation & changes in microsegregation during solution treatment & ageing
- Develop physics-based transformation kinetics micro-models
- Transfer knowledge through NIST D-Space Repository & UM Materials Commons

Approach / Tasks

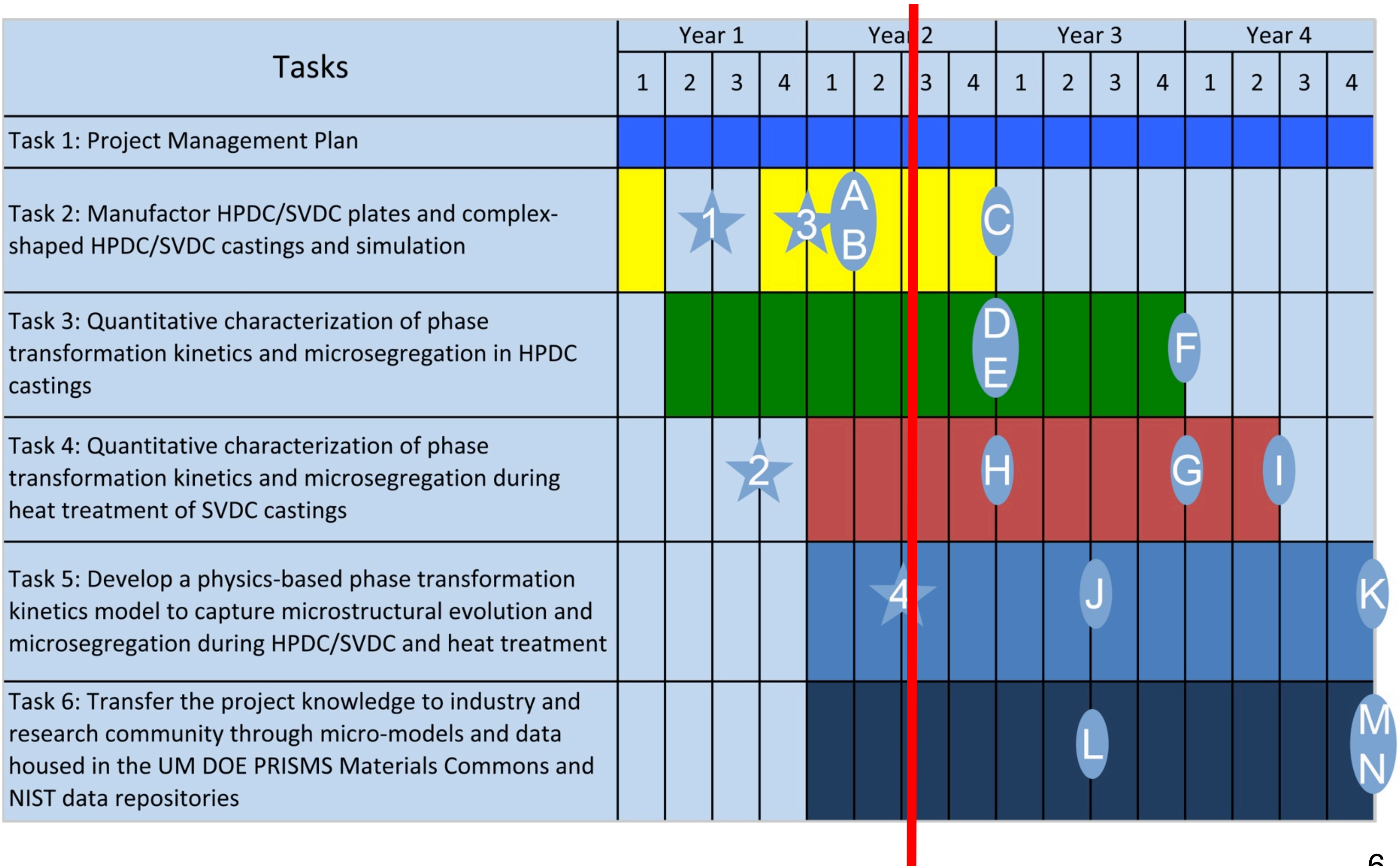
1. Simulate & manufacture high quality HPDC/SVDC plates & complex shapes of binary and ternary alloys
   - Mg-Al & Mg-Al-X; X=Mn, Zr, Ca, Sr (AM, AZ, AX, AK alloys)
   - Precision MagmaSoft simulation

2. Systematic study of phase transformation & microsegregation during HPDC/SVDC
   - Advanced EPMA & analysis
   - Quantitative Optical and SEM analysis

3. Systematic study of phase transformation & changes in microsegregation during solution treatment & ageing
   - Selected alloys
   - Advanced EPMA & analysis
   - Quantitative Optical, SEM & TEM analysis

4. Develop physics-based transformation kinetics micro-models
   - Analytical model coupled with precision MagmaSoft results
   - Validate ThermoCalc model for precipitate evolution
5. Transfer knowledge through NIST D-Space Repository & UM Materials Commons

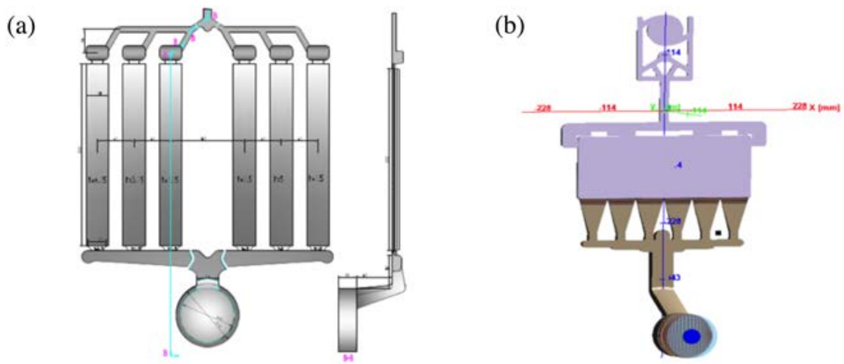
Milestones

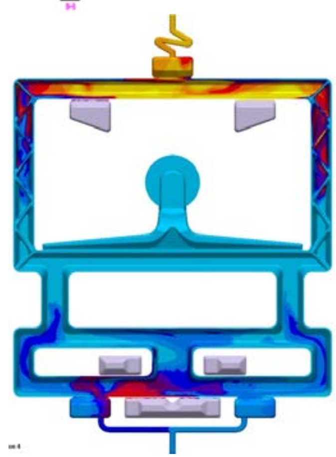


Tasks
Year 1
Year 2
Year 3
Year 4
1 2 3 4 1 2 3 4 1 2 3 4 1 2 3 4
Task 1: Project Management Plan
Task 2: Manufactor HPDC/SVDC plates and complex-shaped HPDC/SVDC castings and simulation
1
3
A
B
C
Task 3: Quantitative characterization of phase transformation kinetics and microsegregation in HPDC castings
D
E
F
Task 4: Quantitative characterization of phase transformation kinetics and microsegregation during heat treatment of SVDC castings
2
H
G
I
Task 5: Develop a physics-based phase transformation kinetics model to capture microstructural evolution and microsegregation during HPDC/SVDC and heat treatment
4
J
K
Task 6: Transfer the project knowledge to industry and research community through micro-models and data housed in the UM DOE PRISMS Materials Commons and NIST data repositories
L
M
N

High Pressure Die Casting & Alloys

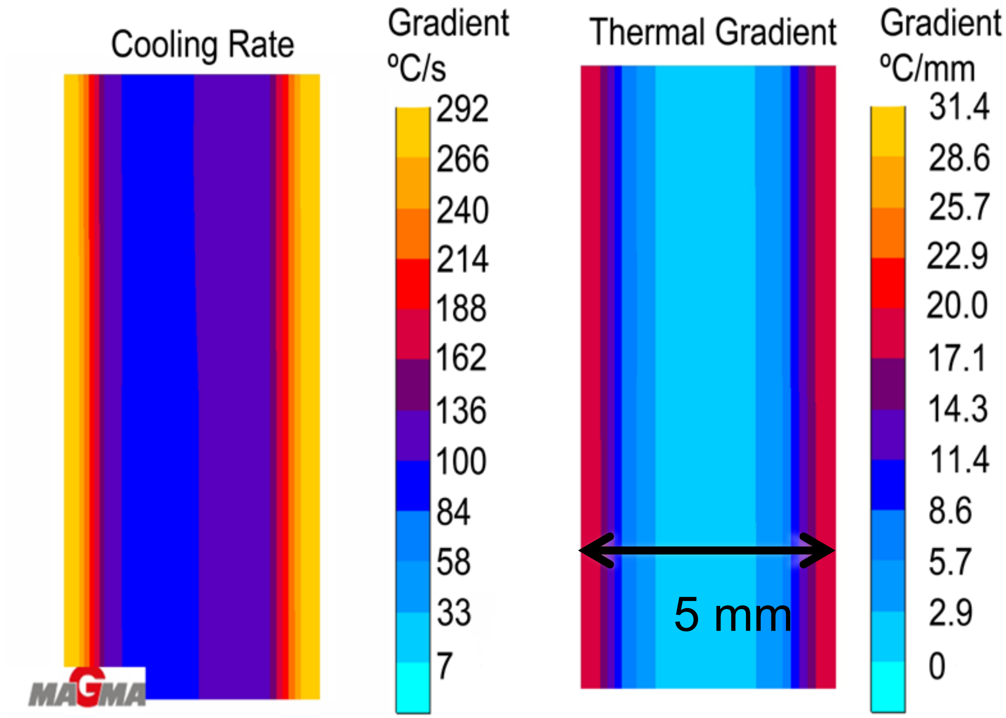
- Plate castings being provided by Tsinghua University & Ford (Mag-tec)
- AM60 & AZ91 complex castings provided by Ford

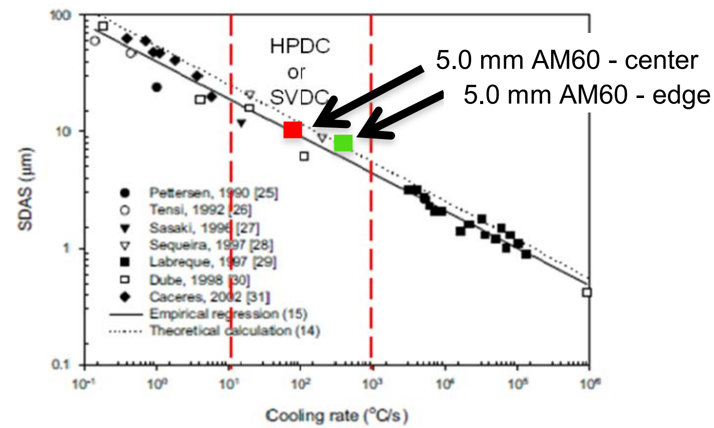




Alloy Compositions (wt%)					
Mg	Al	Zn	Mn	Ca	Sr
Bal	3				
Bal	5				
Bal	9				
Bal	12				
Bal	9	0.5			
Bal	9	1			
Bal	9	2			
Bal	5		0.5		
Bal	5		1		
Bal	5		2		
Bal	5			3	
Bal	5				3

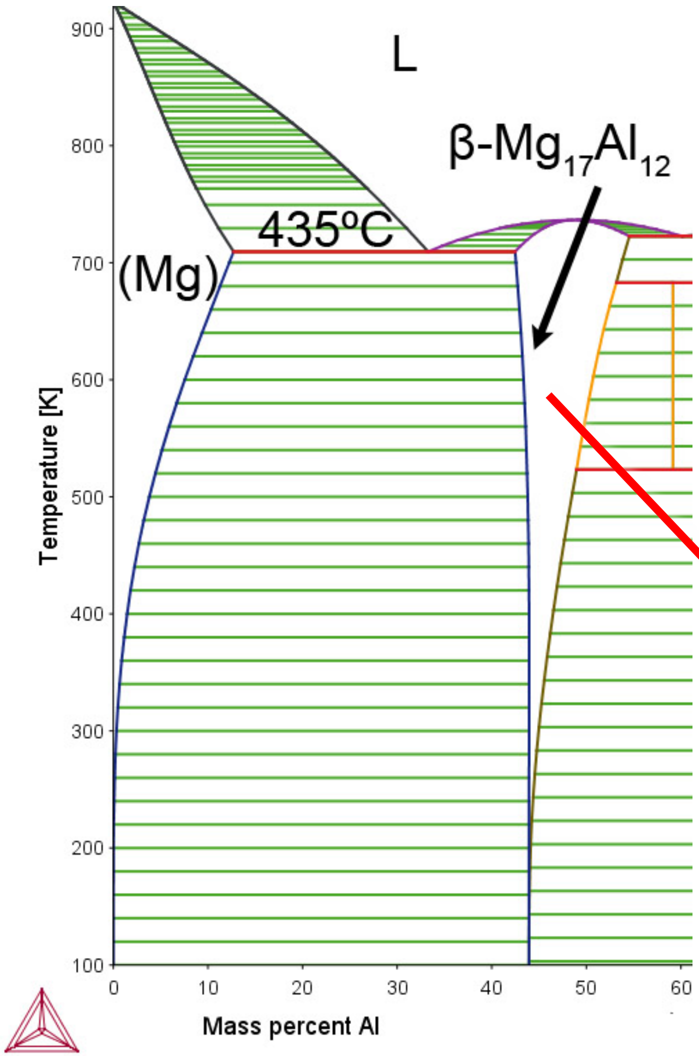
Technical Progress: Precision HPDC Simulation

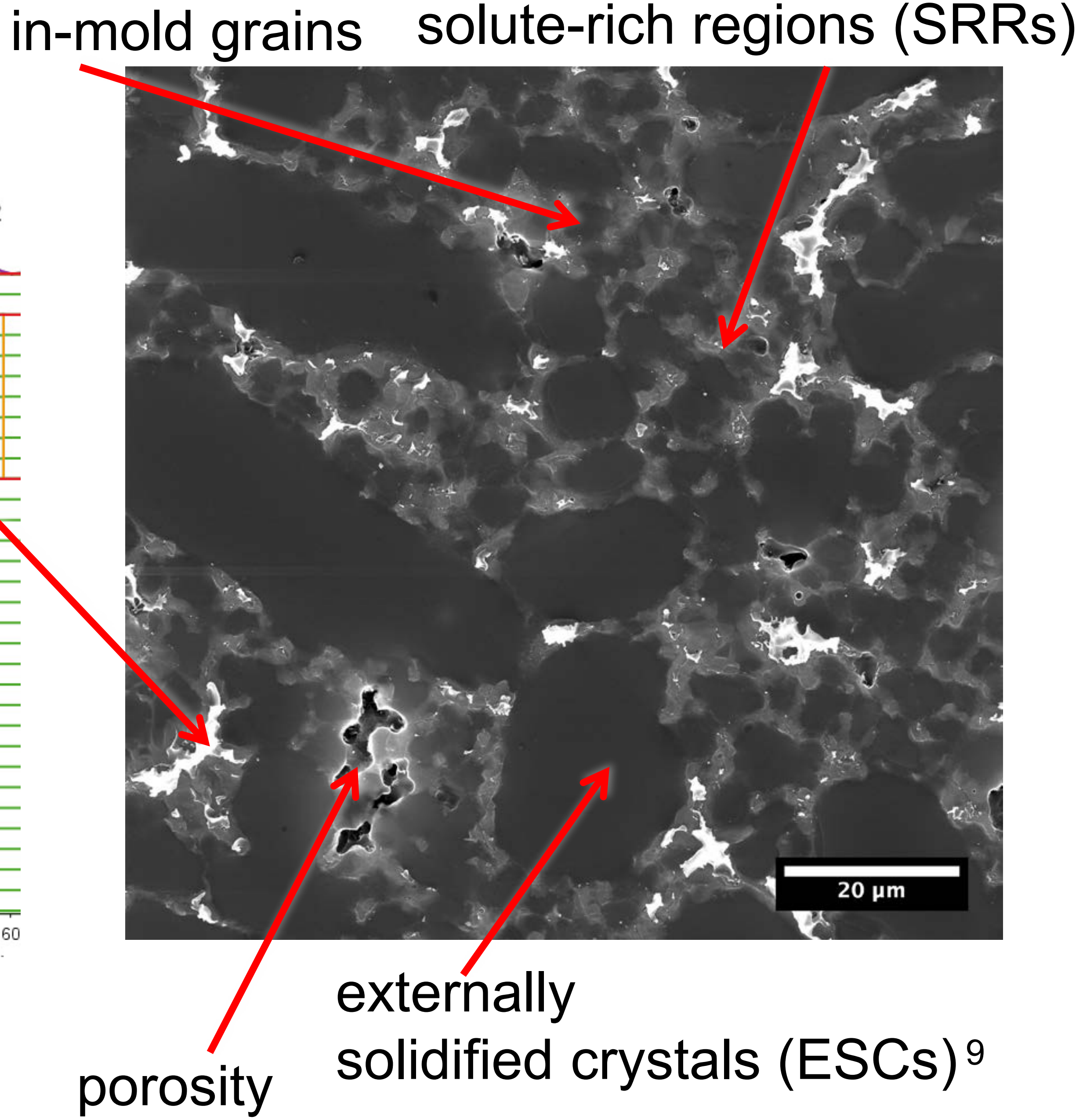




- Precision simulation achieved using advanced IHTC (from Ford/Tsinghua: 3-countries Mg Front End program) and very fine mesh
- Solidification front velocity, cooling rate (°C/s), and thermal gradient (°C/mm) determined as a function of location through plate
- Cooling rates ranging from 100-300°C/s are predicted

Technical Progress: Phase Quantification





Technical Progress: Location Dependent Phase Distribution*

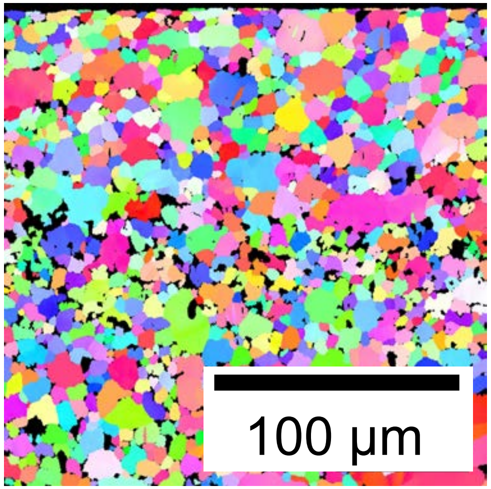
Constituent	Center	Edge
Al- Mn intermetallics	0.1	0.2
pores	1.6	0.3
β-phase	2.0	1.9
solute-rich regions (SRRs)	24.0	38.7

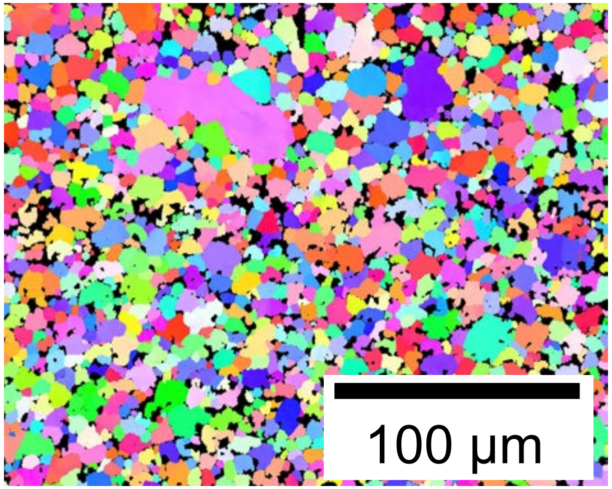
* Example: AM60 2.5mm SVDC Plate

- β-phase volume fraction much lower than predicted by Scheil solidification model (2% vs 9.1%) and not location dependent
- Higher fraction of SSRs observed at edge of castings

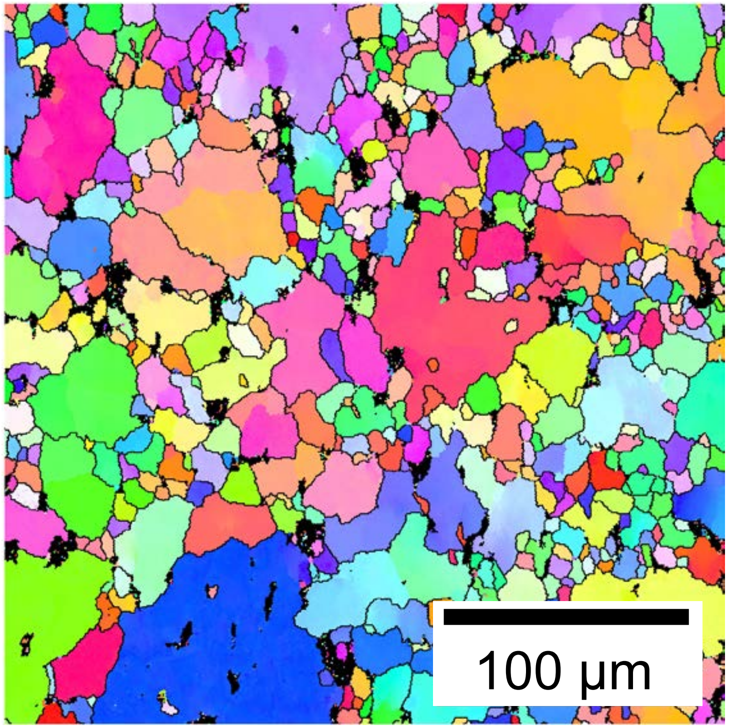
Technical Progress: Characterization of Grain Size Distributions*

Edge





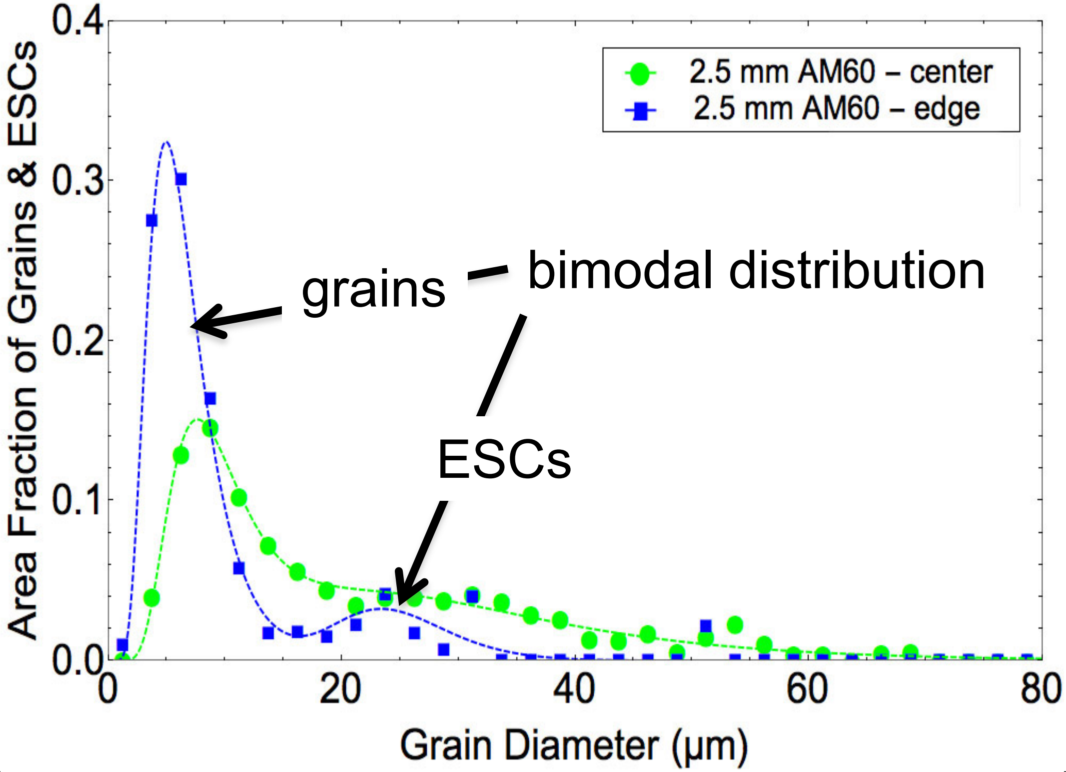
Center



- Effect of:
  - Alloying
  - Plate Thickness
  - Location
- Electron back-scatter diffraction (EBSD)

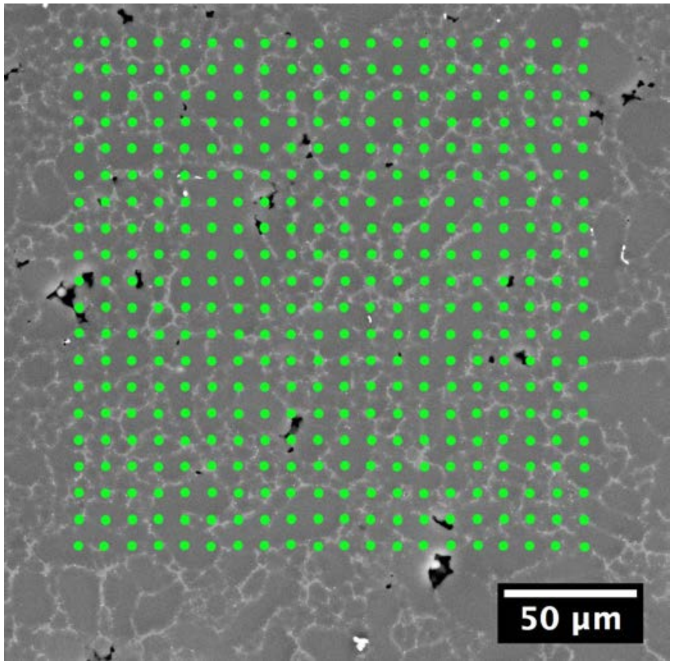
* Example: AM60 5mm thick plate

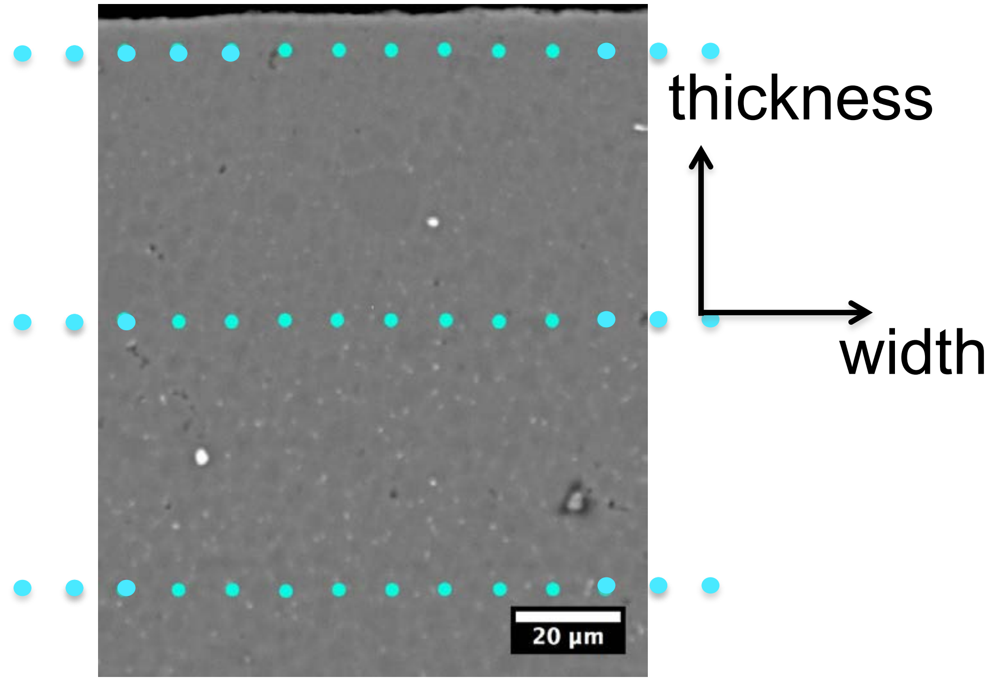
Technical Progress: Grain Size Distributions



- Bimodal distribution represents in-mold grains and Externally Solidified Crystals (ESCs)
- Lower number of ESCs at edge of castings
- Peak grain size slightly larger at center (8 μm vs. 5 μm)
- Grain size and number of ESCs increase with increasing plate thickness
- Grain size was not influenced by alloy content

Technical Progress: Advanced EPMA Analysis of Microsegregation





To construct segregation profile (WIRS):

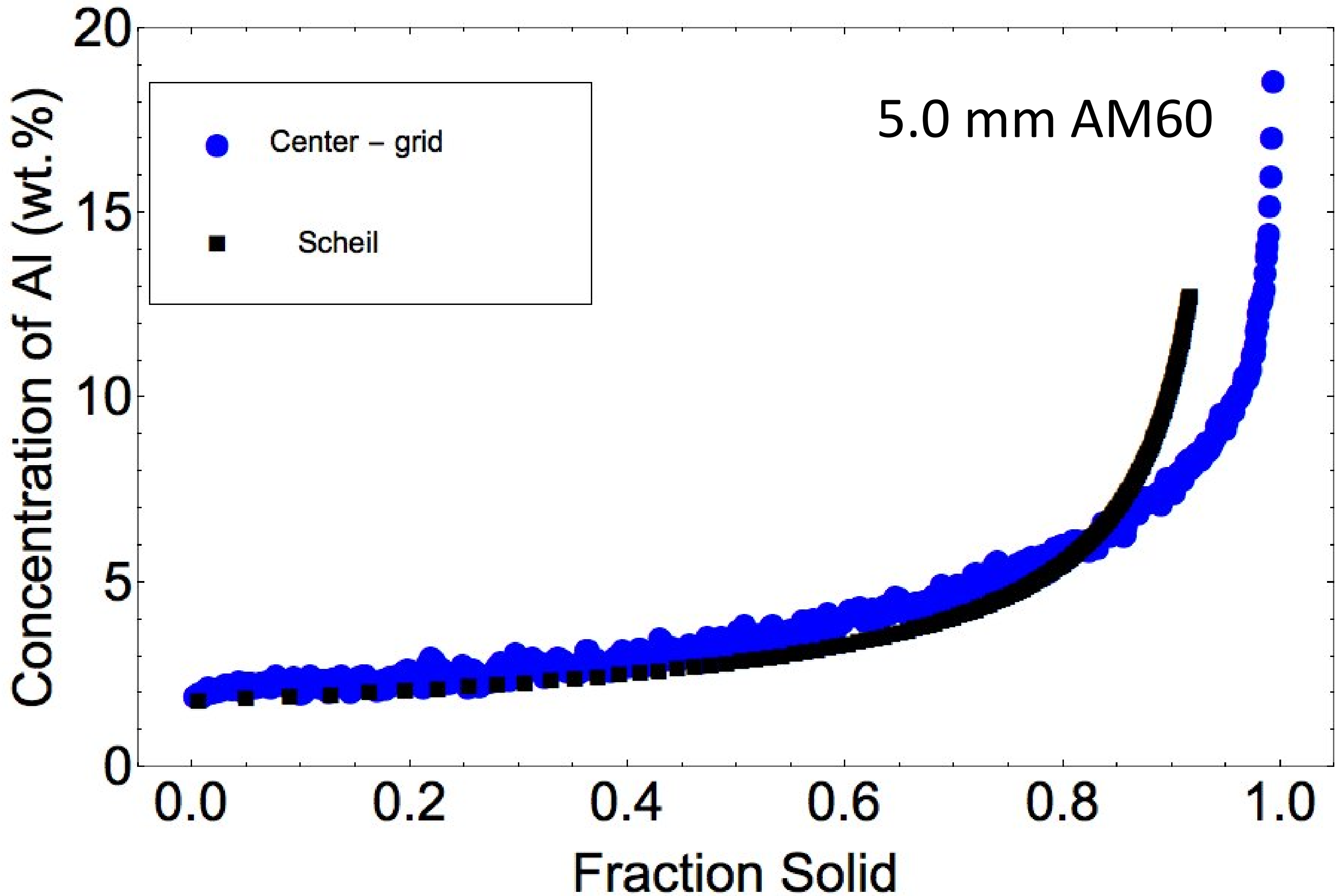
1. determine partitioning direction
2. order and rank data (Al solute)
3. assignment of fraction solid

$$\bar{C}_i^j = \frac{C_i^j - C_{min}^j}{\sigma^j}$$

$$\bar{\bar{C}}_i = \frac{\sum_{j=1}^{n} \bar{C}_i^j}{n}$$

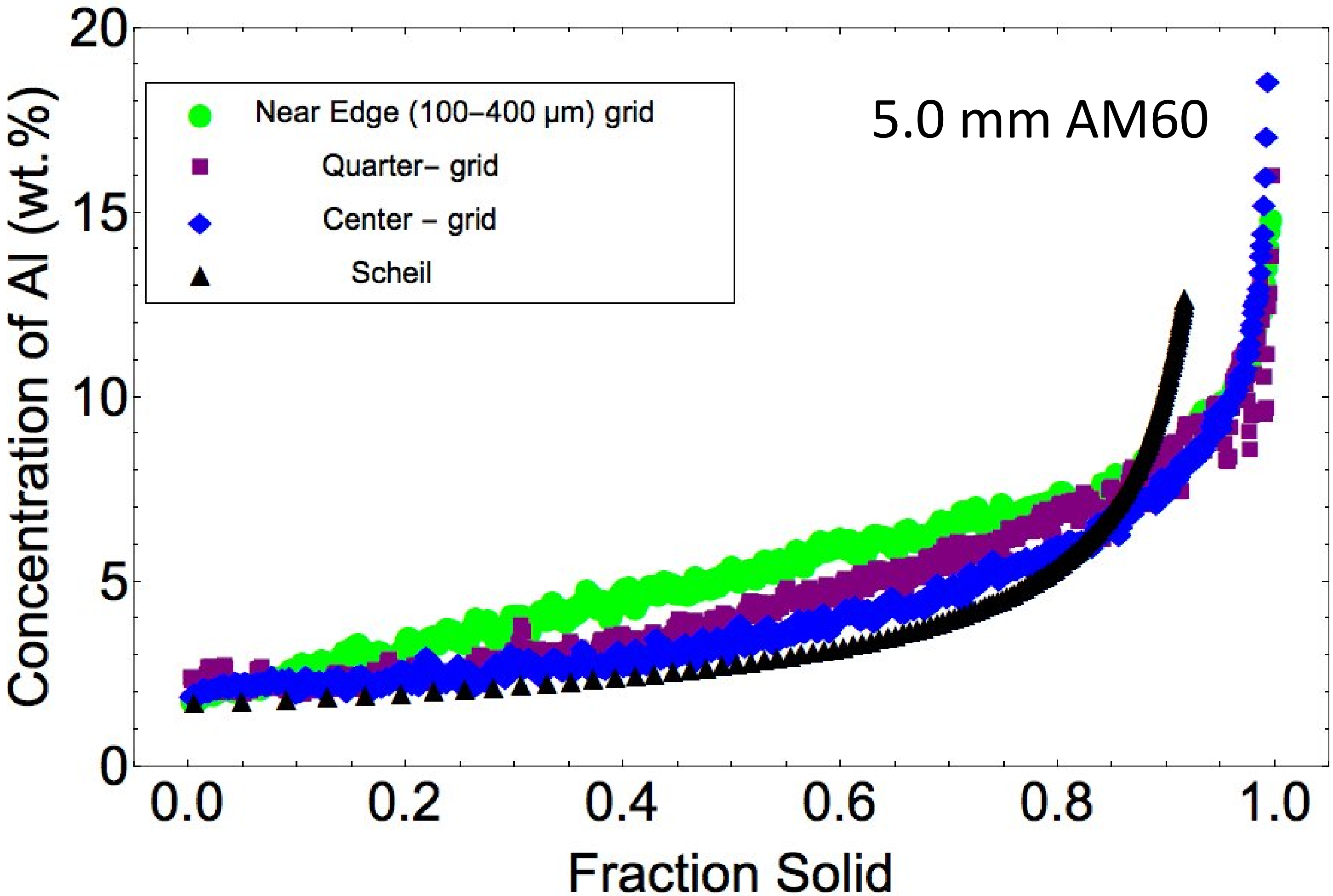
$$f_s = (R_i - 0.5)/N$$

Technical Progress: Characterizing the Microsegregation Profile



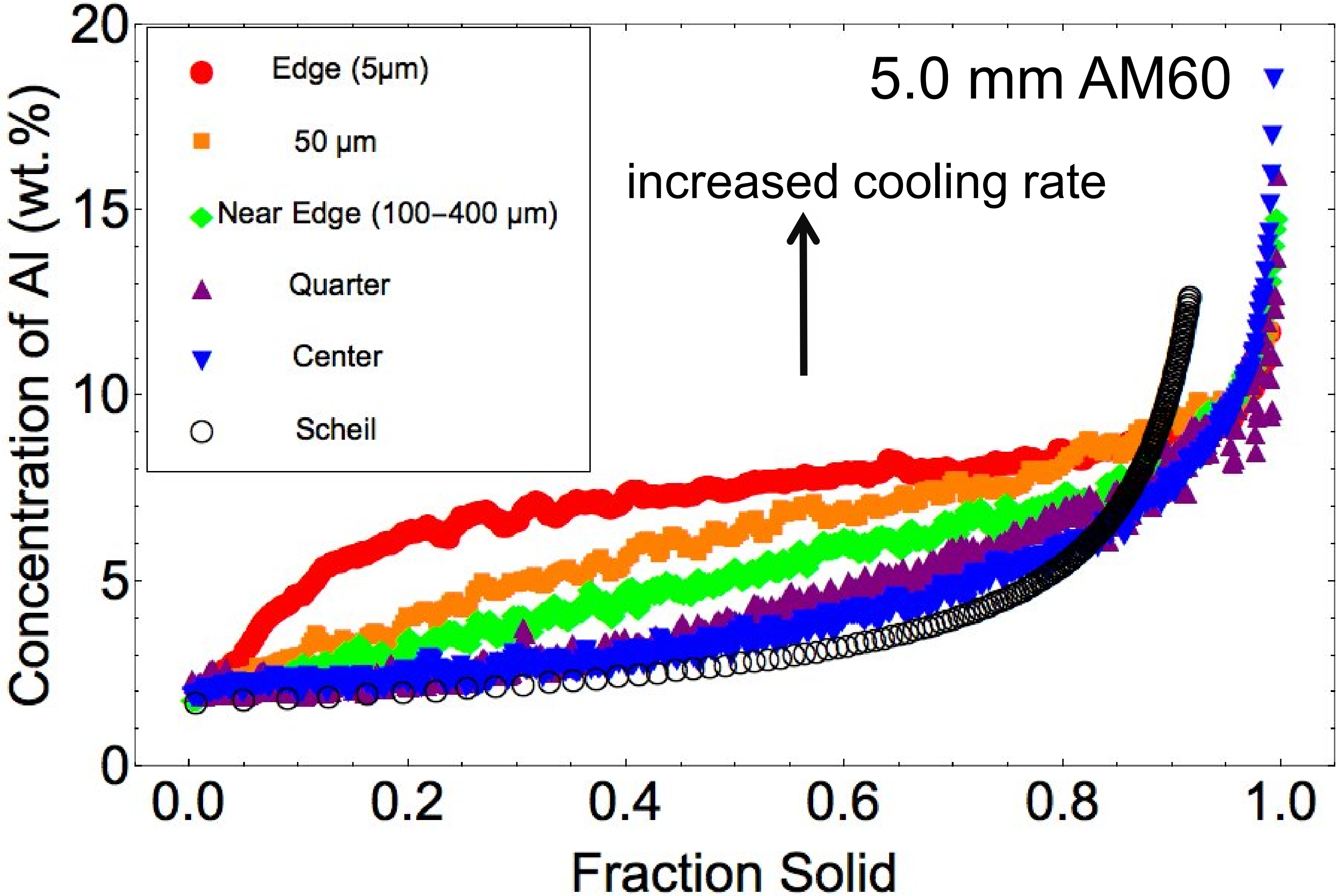
- EPMA microsegregation profile at the center of the castings is close to Scheil up to a high solid fraction

Reconstructing the Microsegregation Profile



- Microsegregation deviates from Scheil as you move towards the edge of the casting

Technical Progress: Reconstructing the Microsegregation Profile

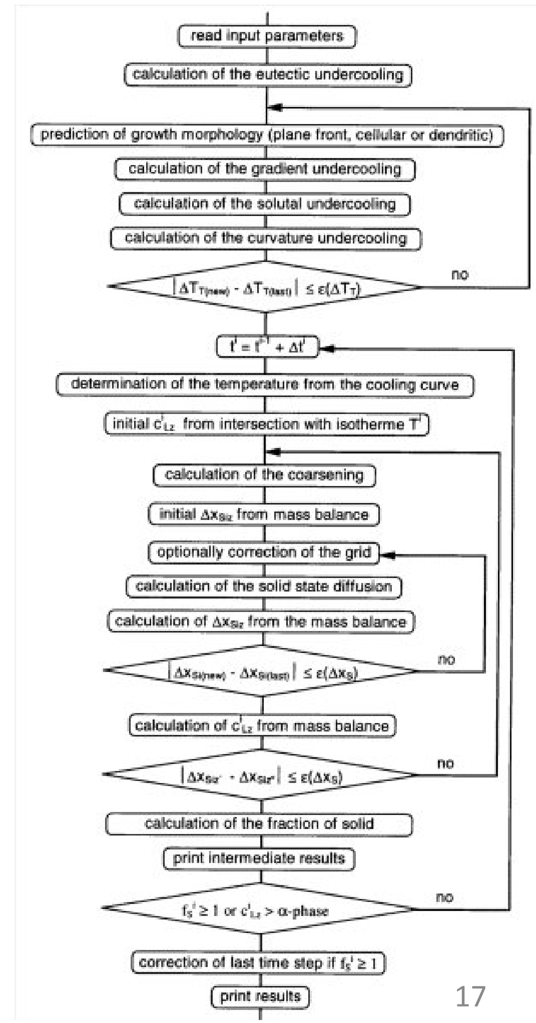


- Solute trapping increases near the edge of the plate where cooling rate is the highest

Technical Progress: Micro-Model
As-cast Microstructure Prediction

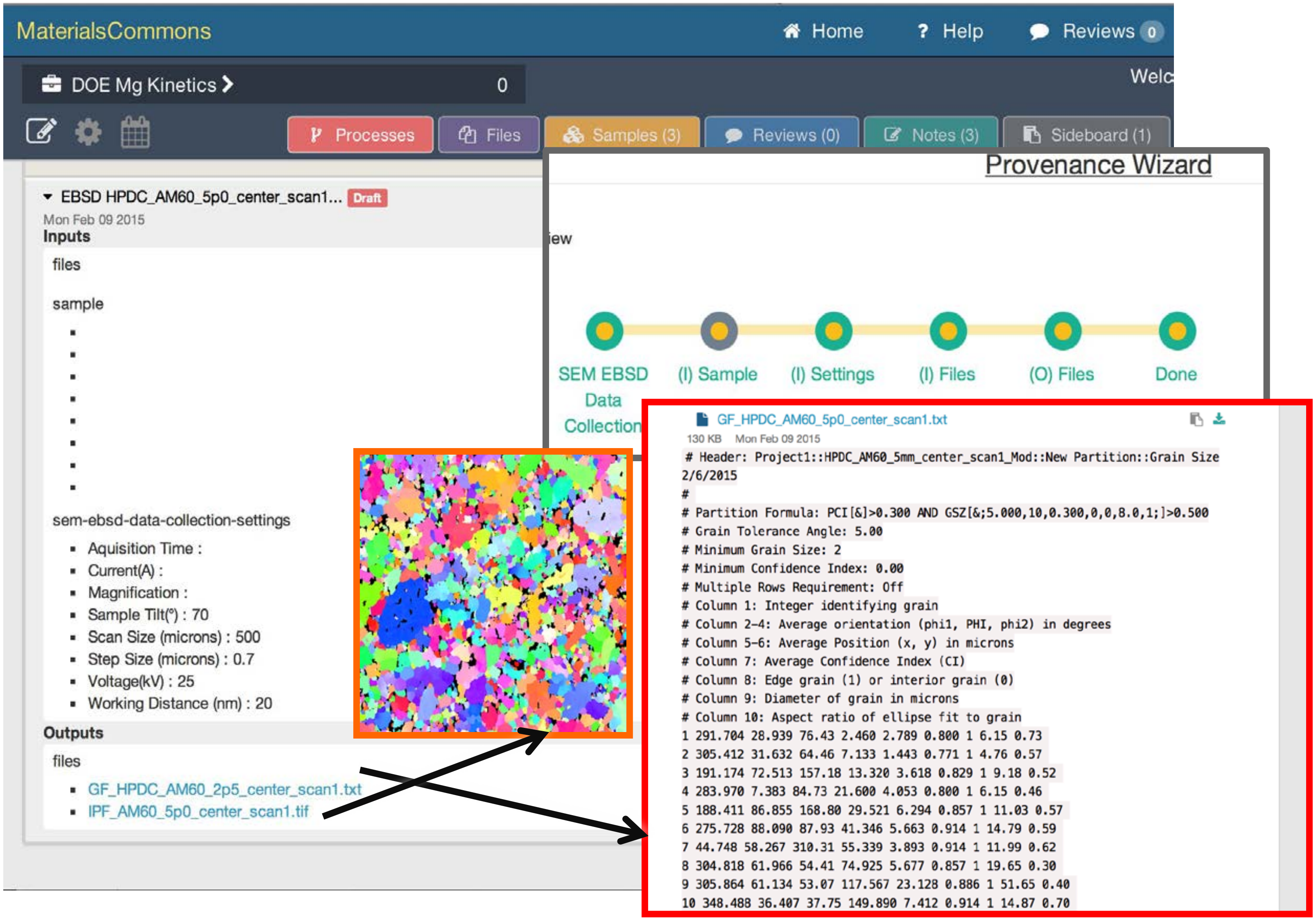
- Solidification rate and composition dependent partition coefficients can be expressed as [Aziz & Kaplan 88']:

$$K_v = \frac{\frac{a_0 v}{D_i} + K_e}{\frac{a_0 v}{D_i} + 1 - (1 - K_e) C_{lv}}$$



- v: solidification front velocity (MagmaSoft)
- D_i: interface diffusion coefficient
- k_e : equilibrium partition coefficients (ThermoCalc/PANDAT)
- C_{lv}: the solidification rate dependent liquidus concentration
- a_0: solute trapping parameter <- experimentally calibrated

Technical Progress: Materials Commons & NIST D-Space



Responses Reviewers' Comments

- NA - This project has not yet been reviewed

Partnerships/Collaborations

- Ford Motor Company: Mei Li, Jake Zindel and Larry Godlewski
  - Provided super vacuum die cast samples and components
  - Provided HPDC MagmaSoft casting simulations
  - Collaborating on development of kinetics micro-model

- Tsinghua University: S. Xiong (under contract to Ford Motor Co.)
  - Provided super vacuum die cast samples

- OSU: J. C. Zhao and Alan Luo
  - Informal collaboration on precipitation evolution and diffusion

Remaining Challenges and Barriers

- Microstructural scale (cell size) and EPMA beam size are similar which makes direct characterization of microsegregation a challenge.
- Our approach is a “forward” model which will be used to extract the actual (true) microsegregation behavior from the experimentally measured EPMA microsegregation profile.

Proposed Future Work

- Continuing systematic characterization of microsegregation & phase transformation kinetics in as-cast AM alloys, Mg-Al binaries and ternaries
- Begin systematic characterization of microsegregation & phase transformation kinetics following solution treatment and aging of selected SVDC alloys
- Continue developing electron probe micro-analyzer “forward model” and use to extract the true microsegregation behavior
- Develop micro-models to predict microstructure & microsegregation evolution during HPDC and after heat treatment
- Transfer knowledge to industry and the research community through micro-models and data housed in UM DOE PRISMS Materials Commons and the NIST DSpace Repository

Summary

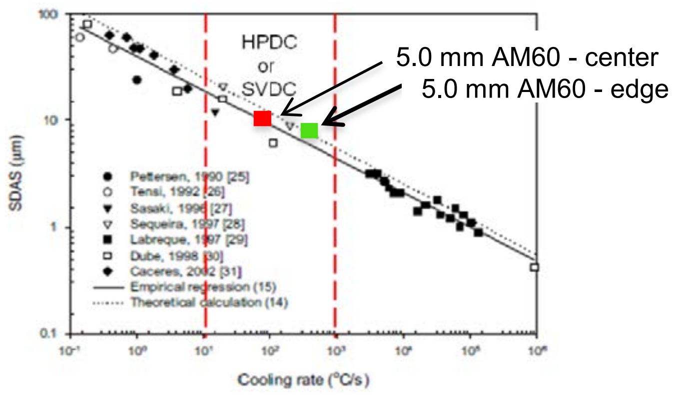
- Objective: Combining advanced experimental techniques, analytical models & simulation tools to develop a systematic understanding of phase transformation kinetics in HPDC Mg-Al-X alloys

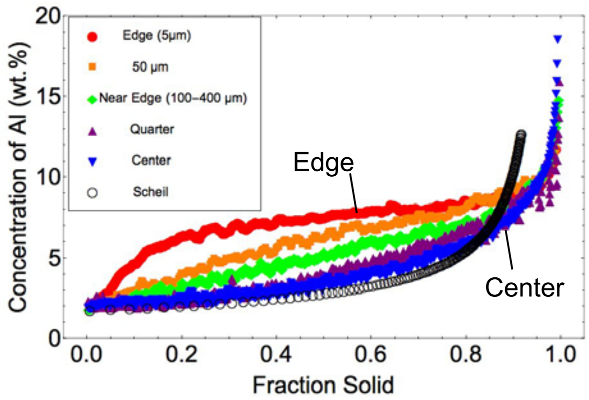
- Robust characterization & simulation methods are being developed for
  - phase quantification via SEM
  - grain size via EBSD
  - microsegregation via EPMA
  - simulating solidification velocities & phase transformation kinetics

- Templates have been developed for uploading our data & metadata to Material Commons

Summary - Findings

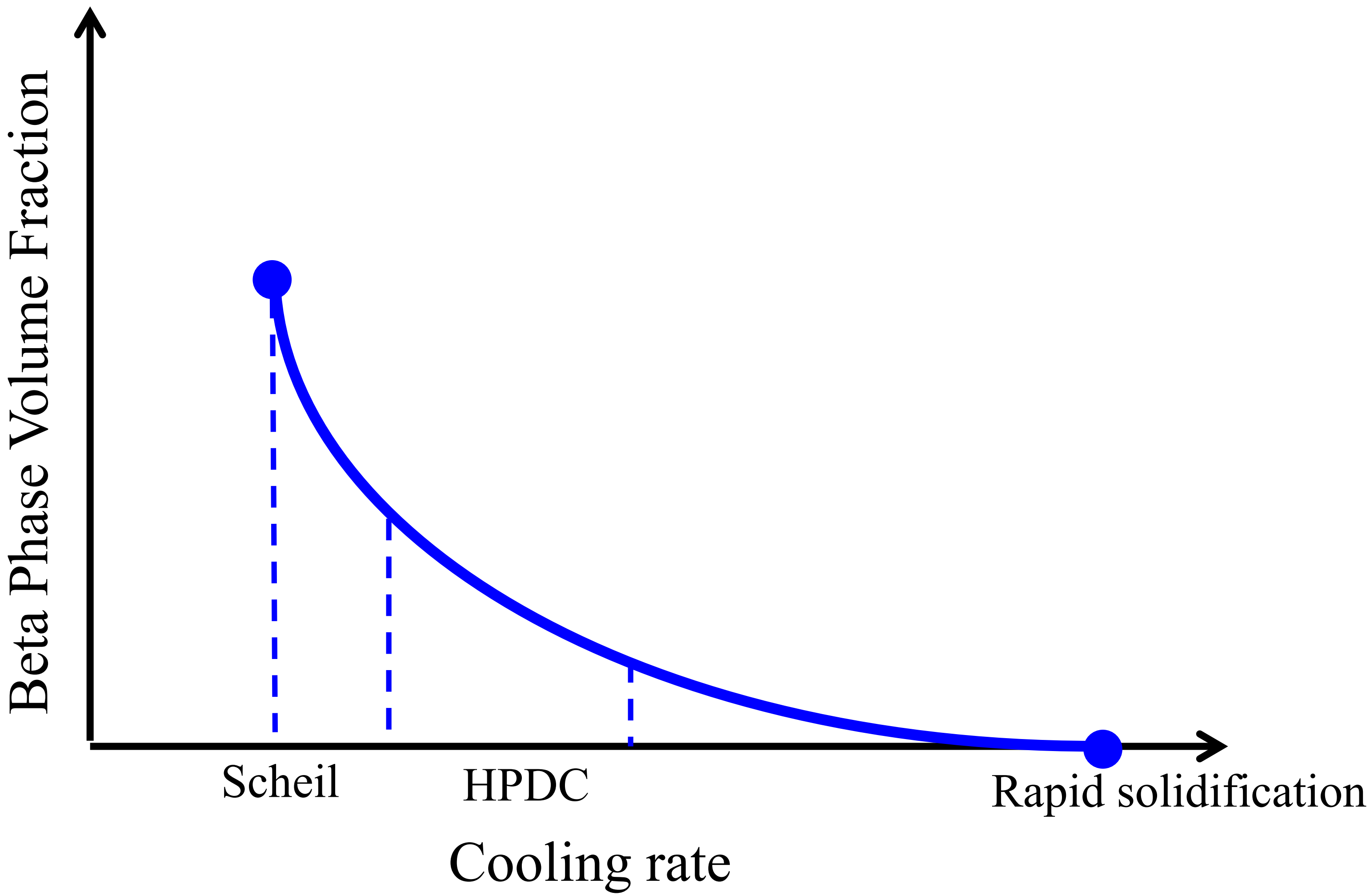
- HPDC alloys have a bimodal distribution with contributions from in-mold grains and externally solidified crystals
- HPDC plates undergo cooling rates from 100 to 300 ºC/s
- β-phase volume fraction is much lower than predicted by Scheil solidification models (2% vs ~9% for AM60) and more Al is partitioned to the α-Mg
- Microsegregation profiles are casting location dependent and current models must be modified to account for this





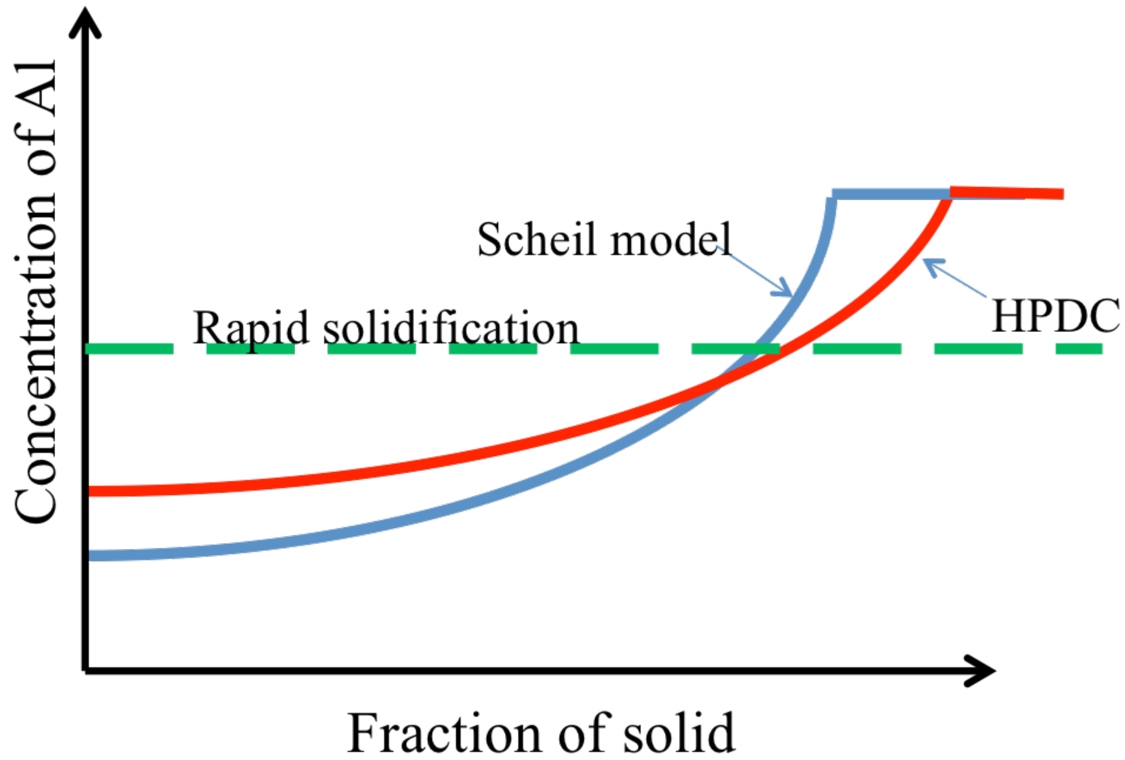
Technical Back-Up Slides

Effect of Cooling Rate on β-phase Fraction



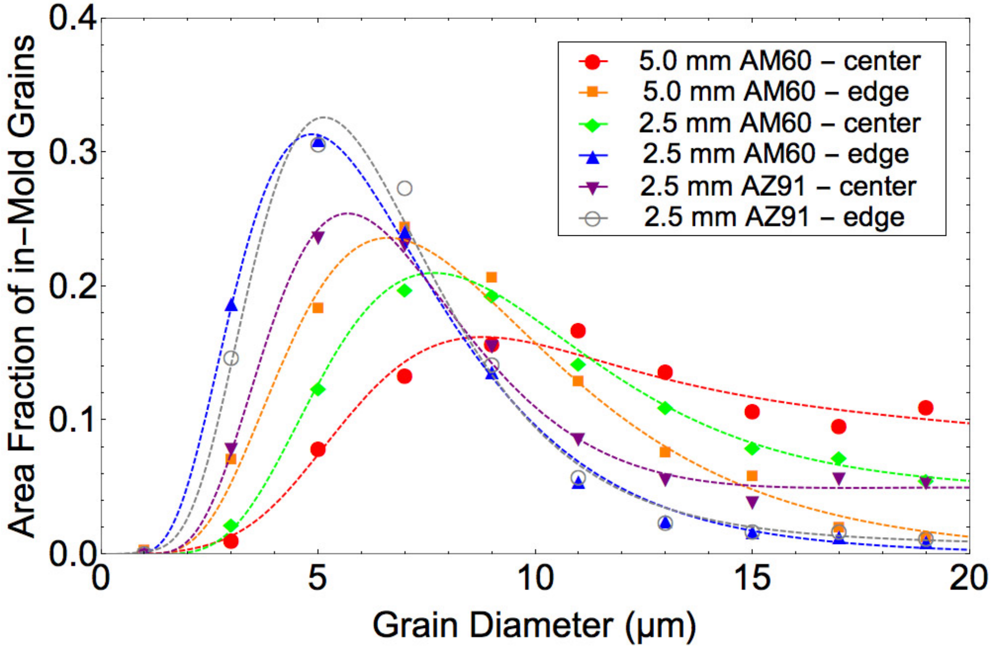
- As cooling rate increases we expect:
  - β-phase fraction to decrease
  - More Al will be trapped in α-Mg (increased fraction of SRRs)

Developing a HPDC Solidification Model



- Scheil solidification model over predicts the amount of as-cast eutectic phases, and especially will for fast solidification condition (HPDC)
- Is not solidification rate dependent
- Can be improved with solidification rate and composition dependent partition coefficients

Technical Progress: Grain Size Distributions - Summary



- Lower number of ESCs at edge
- Peak grain size slightly larger at center
- As plate thickness increases the grain size increases slightly and a higher fraction of ESCs are observed
- Grain size was not affected by alloy

Milestones (Details)

Milestones	Duration (months)	Tasks
A	0-15	Complete casting SVDC Mg-Al binaries
B	0-15	Complete casting SVDC Mg-Al binaries with a range of processing conditions
C	12-24	Complete casting SVDC Mg-Al-Mn, Mg-Al-Zn, Mg-Al-Ca, and Mg-Al-Sr ternary alloys
D	2 -24	Complete phase transformation kinetic study of binaries and Mn and Zn ternaries
E	2-24	Complete microsegregation characterization of binaries and Mn and Zn ternaries
F	18-36	Complete phase transformation and microsegregation characterization of Ca and Sr ternaries and in complex casting of AM50 and AZ91
G	12-36	Complete eutectic dissolution phase transformation and precipitate kinetic study of selected Mg-Al binaries and Mg-Al-Zn ternary
H	6-24	Complete microsegregation characterization of dissolution phase transformation in binaries and Mn and Zn ternaries
I	18-42	Complete eutectic phase dissolution, phase transformation, precipitation kinetics, and microsegregation characterization of Ca and Sr ternaries
J	12-30	Complete micro-model of Mg-Al binaries and Mg-Al-Mn and Mg-Al-Zn ternaries for HPDC conditions
K	24-48	Complete micro-model for Mg-Al-Ca and Mg-Al-Sr ternaries for HPDC and heat treatment conditions
L	12-30	Incorporate experimental data on Mg-Al binaries and Mg-Al-Mn and Mg-Al-Zn ternaries into Materials Commons and release to public
M	24-48	Incorporate experimental data on Mg-Al-Ca and Mg-Al-Sr ternaries into Materials Commons and release to public
N	36-48	Incorporate micro-model into Materials Commons and release to public