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Mechanistic-based Ductility Prediction for Complex Mg Castings

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2015 DOE VEHICLE TECHNOLOGY PROGRAM REVIEW
JUNE 8-12, 2015

Project ID#: LM057

Overview

- Relevance of Mg castings
  - Potential 60-75% weight savings
- Barriers
  - Performance: Limited ductility and high ductility variations of Mg castings; Lack of sufficient characterization of various Mg alloys
  - Predictive Modeling Tools: Lack of adequate predictive tools in predicting ductility of Mg castings, resulting from various types of defects
- Partners
  - Ford Motor Company
  - University of Michigan
  - CANMET Materials Technology Laboratory

- Timeline
  - Start: Oct. 2010
  - End: Sep. 2015
  - 90% Complete
- Budget
  - DOE - $2,100K
    - FY11 - $600k
    - FY12 - $600k
    - FY13 - $500k
    - FY14 - $100k
    - FY15 - $300k
  - Industries (in-kind) - $1,150K
    - Industry - $300k/Yr FY11-13
    - Industry - $250k FY15

Project Objectives

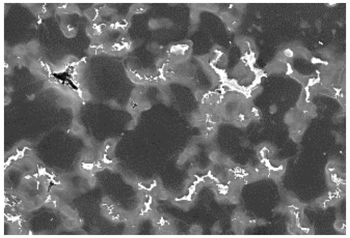
- Background and motivation
  - Conventional computational technique (i.e., homogenization, continuum damage mechanics, crystal plasticity) and some phenomenological approaches have no or very limited ductility predictive capability for Mg castings
- Objectives: To provide a modeling framework that can be used in future Mg alloy design and casting process optimization by
  - Developing an empirical casting process simulation tool that can *estimate the variation in ductility* and be used by the casting industry in the near future
  - Developing a *mechanistic-based predictive capability* on key factors controlling Mg ductility that can be coupled with future advances in casting process simulation and will lead to further casting process optimization and alloy design

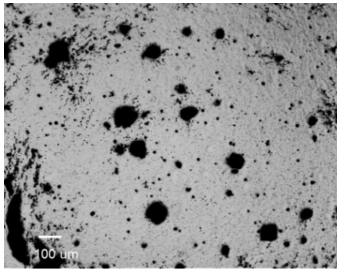
Deliverables

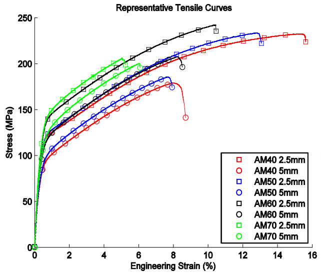
- A validated simulation tool (quality map approach) for estimating the spatial variation of ductility and the influence of casting process variables (completed)
- Modeling and experimental methods in quantifying location-dependent intrinsic and extrinsic ductility limiting factors for complex Mg castings (completed 9/30/2013)
- Experimentally validated predictive models for stress versus strain curves, including ductility, for Mg castings considering both intrinsic and extrinsic ductility limiting factors (on-going; due 9/30/2015)

Technical Approaches

Cast and quality mapping (Ford)

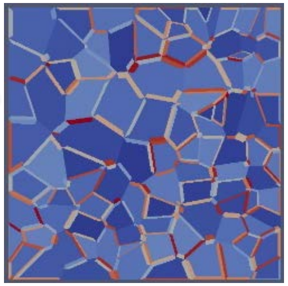


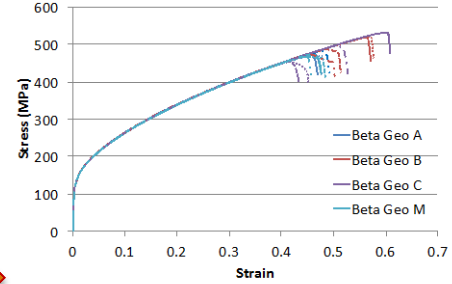


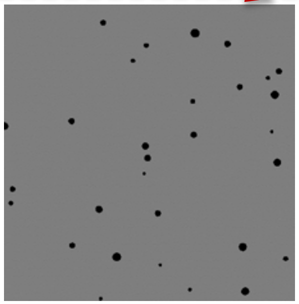


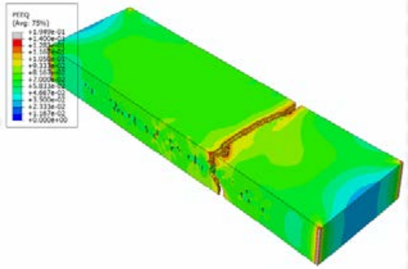
Quantitative Characterization of Alloy-Microstructure-Property Relationships (UM, Ford)

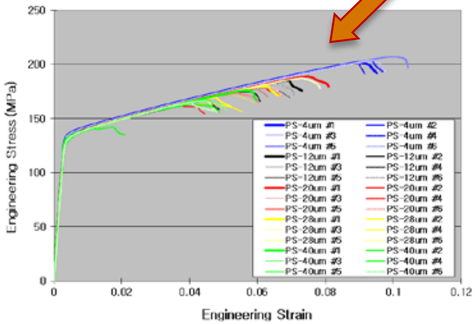
Intrinsic modeling for matrix property prediction (PNNL)







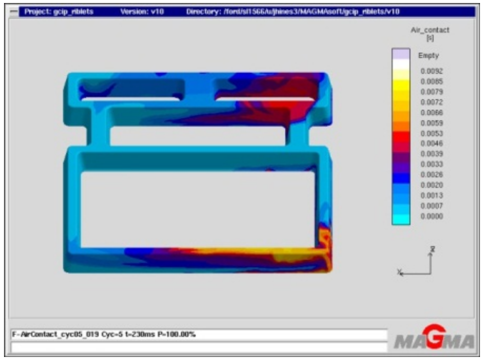




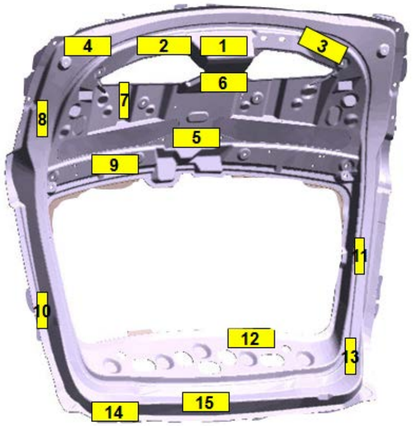
Extrinsic modeling for prediction of ductility of Mg castings (PNNL)

Previous Ford Accomplishment

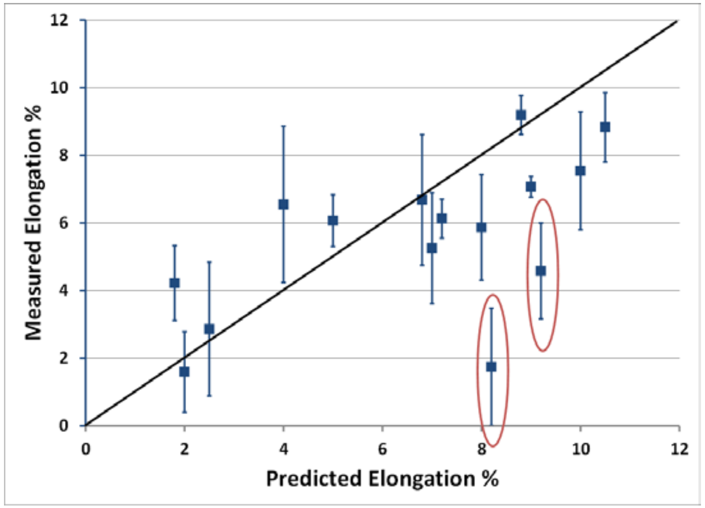
- Compared quality mapping model obtained using an idealized component to a real prototype component
- Achieved reasonable correlation, except at 2 locations
- Results showed need for further understanding of the impact of local variations on elongation
  - thickness variation
  - alloy variation
  - statistical defect variation



GFC



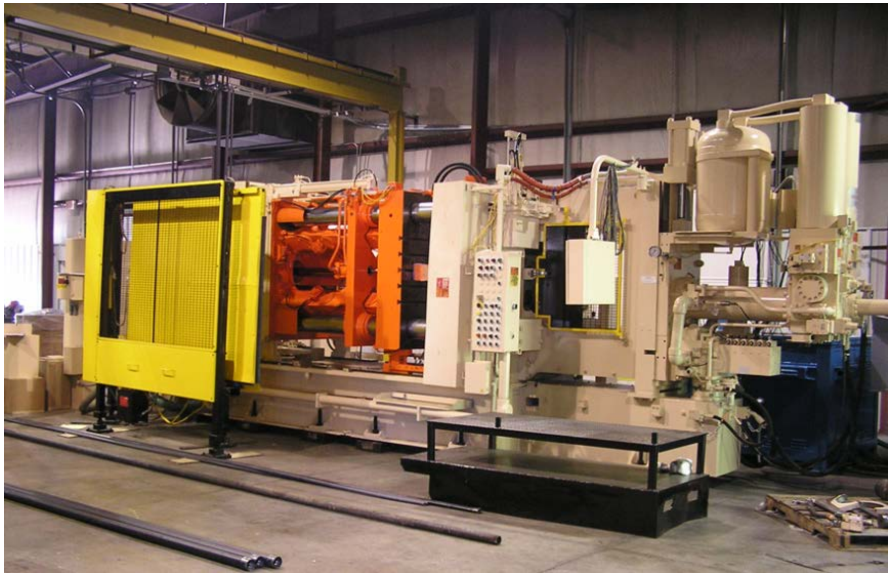
Sample locations



JH Forsmark, JW Zindel, L Godlewski, J Zheng, JE Allison, M Li;
Integrating Materials and Manufacturing Innovation 4 (1), 6 2015

Previous Ford Accomplishment

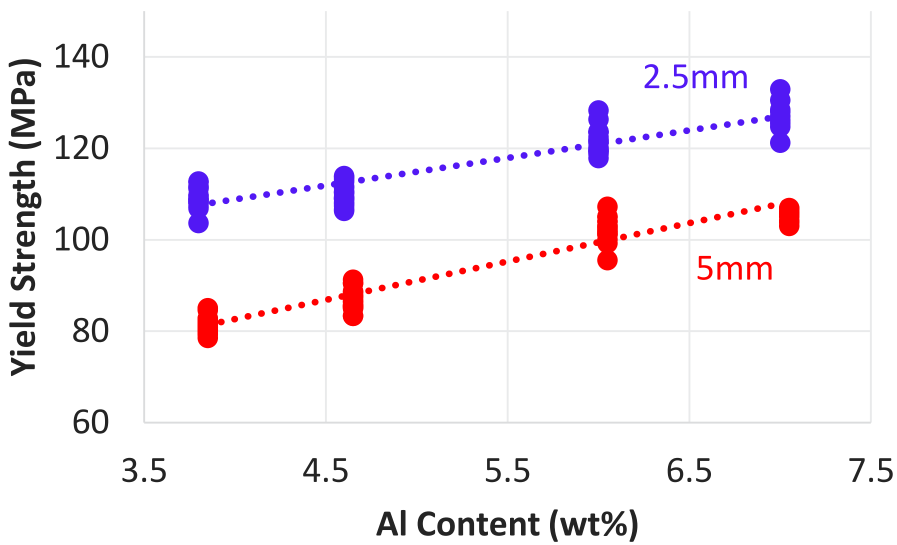
- Produced a series of plate castings for
  - Characterization and testing by UM to quantify the impact of local variation on the elongation and variability of the elongation
  - Varying thicknesses: 2.5 and 5 mm
  - Varying alloys: AM40, AM50, AM60, AM70

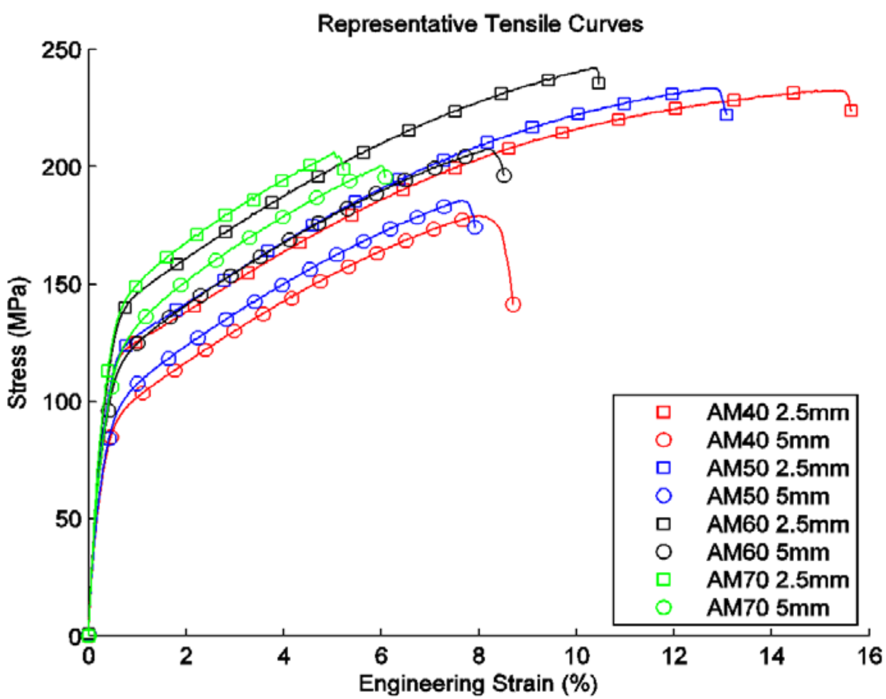


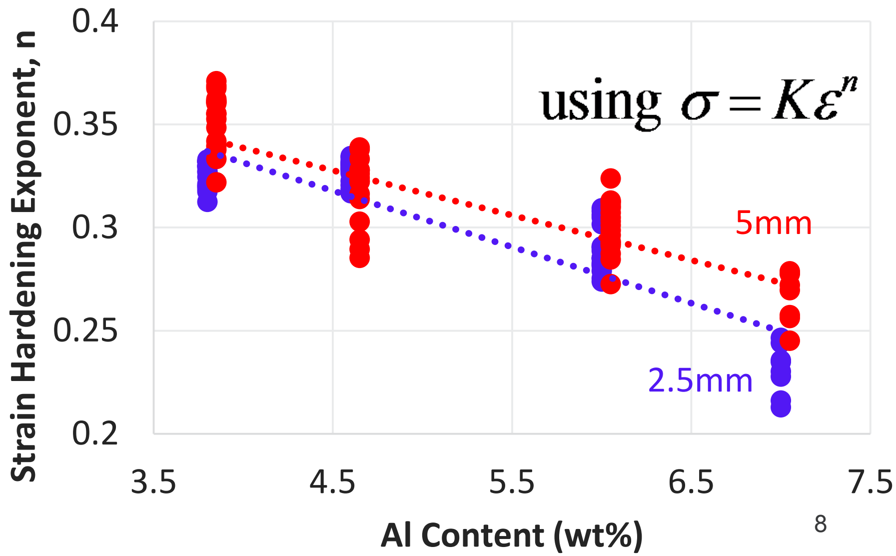
Ford Motor Co. High Pressure Die Casting Machine

Previous UM Accomplishment

- Characterization and testing of plate castings to quantify impact of aluminum content and plate thickness
- Observed increase in yield strength with decreases in ductility and strain hardening exponent with increasing aluminum







UM – Characterize Thru-Thickness Microstructure Variation by Aluminum Content and Plate Thickness

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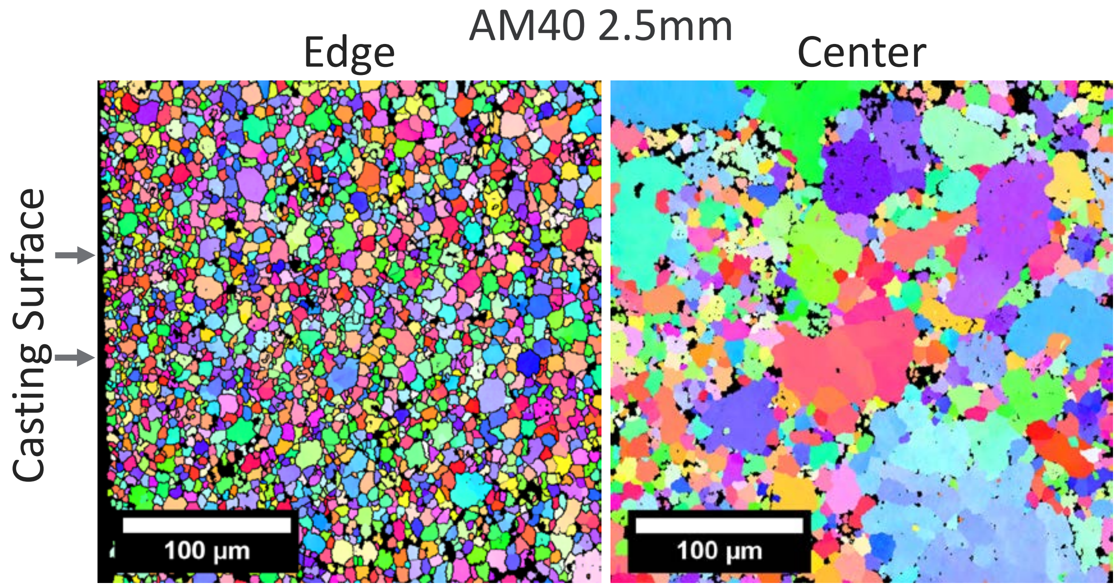
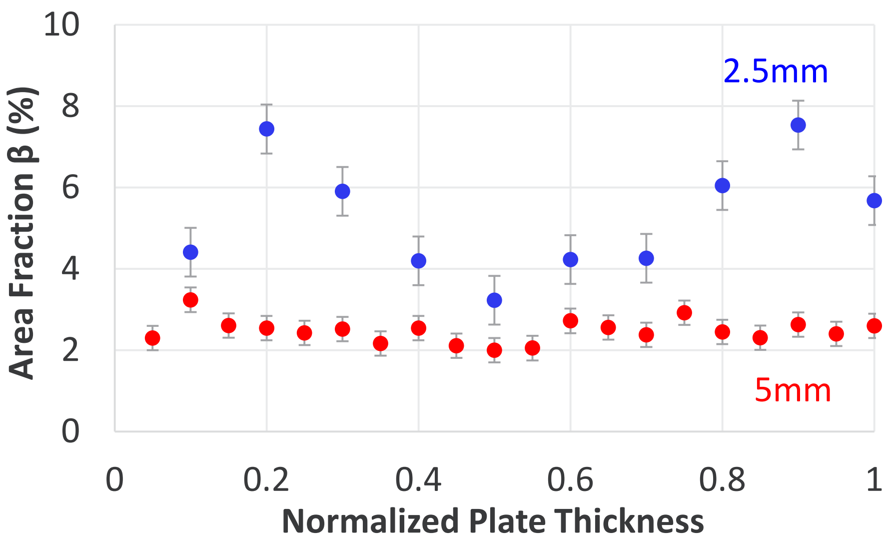
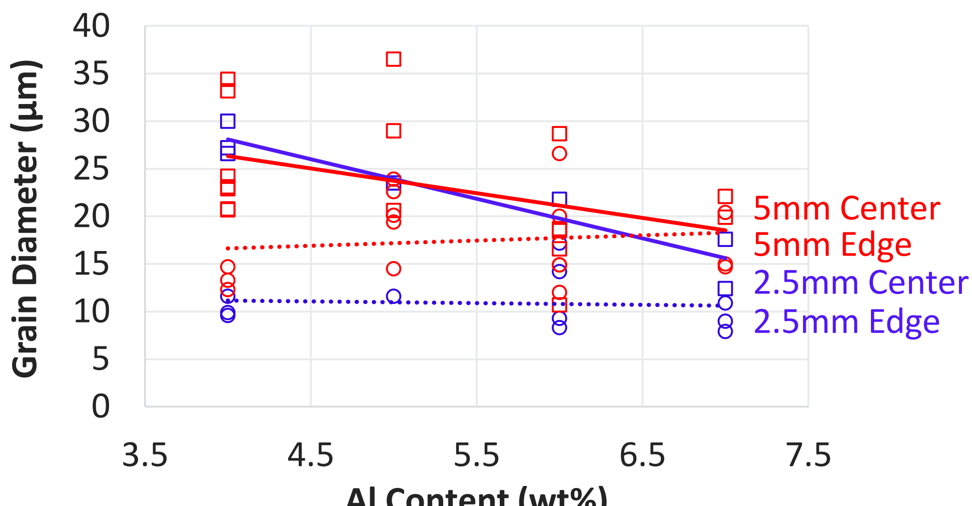
- Quantified thru-thickness variation in grain size and β volume fraction
- Observed skin thickness of approximately 300 μm
- Observed externally solidified cells (ESCs) in the core region
- Quantified variation due to plate thickness and Al content







UM – Experimentally Separate Intrinsic Microstructural Features From Extrinsic Features

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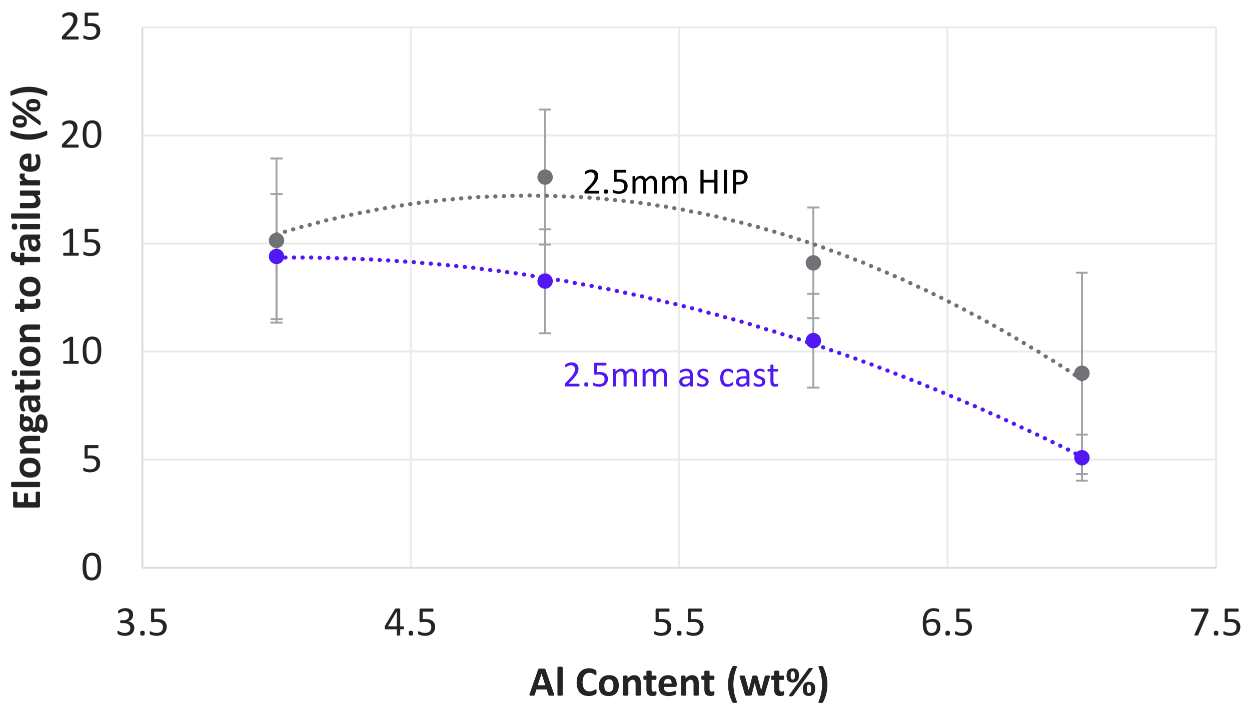
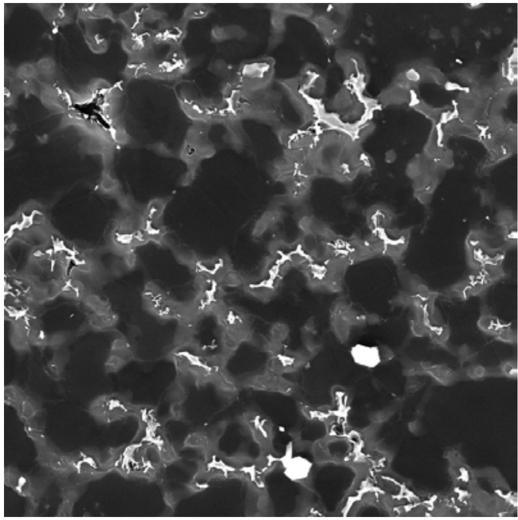
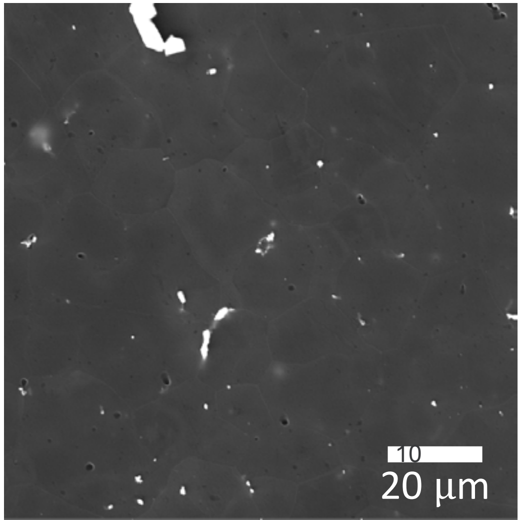
- Utilized hot isostatic pressing (HIP) to dissolve β into α cells and remove shrinkage pores
- Observed increase in upper bound of ductility (i.e. increase in variability)
- Characterization and testing identifies the frequency and impact of large defects



As Cast



HIP



Previous PNNL Accomplishment: Intrinsic Modeling

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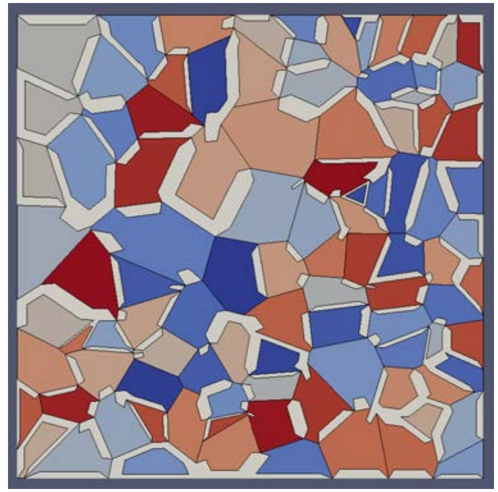
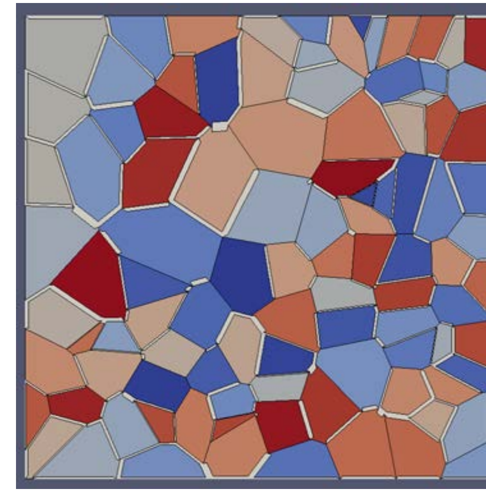
- α phase properties from literature[1,2]
- β phase properties calculated from first-principles[3]
- Synthetic geometries generated to represent UM/Ford observations

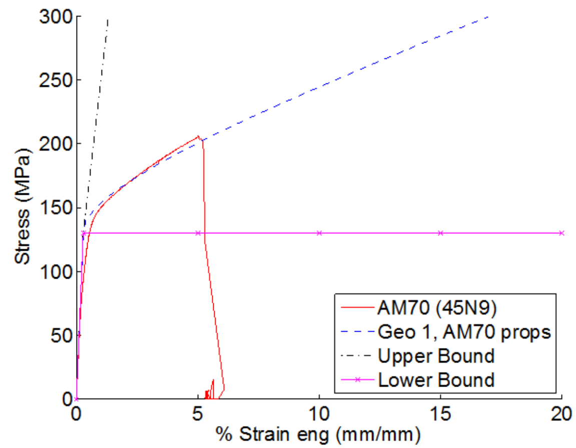
- AM70
  - E = 38 GPa ±5%
  - σ_y = 130 MPa ±5%
  - h' = 0.1 MPa ±10%
  - ν = 0.35
- AM40
  - E = 35 GPa ±5%
  - σ_y = 120 MPa ±5%
  - h' = 0.1 MPa ±10%
  - ν = 0.35
- β
  - AM70: 21% VF (*t*=10%)
  - AM40: 8% VF (*t*=5%)
  - E = 77.7 GPa
  - ν = 0.35

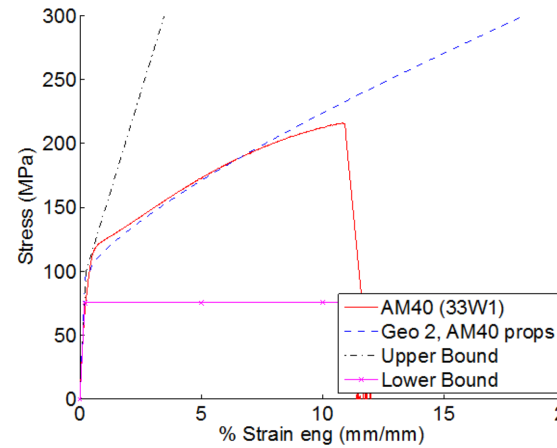


AM70



AM40





Barker, et al., *Comp. Mat. Sci.*, 2014

1 Han et al., MSE A, 473 (2008) 16-27
2 Shan, Gokhale, MSEA, 361 (2003) 267-274
3 J. Wang, et al., Calphad, 35 (2011) 562-573

PNNL – Extracting α Properties using Nanoindentation

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- Extract plastic material parameters along with elastic parameters from nanoindentation
- Sample individual grain parameters from captured distribution of parameters

Conduct nanoindentation experiment:
E and Hv determined by instrument

↓

Scale Hv (due to indentation size effect):
strain gradient approach

$$H = H_0\sqrt{1+\frac{h^*}{h}}$$

↓

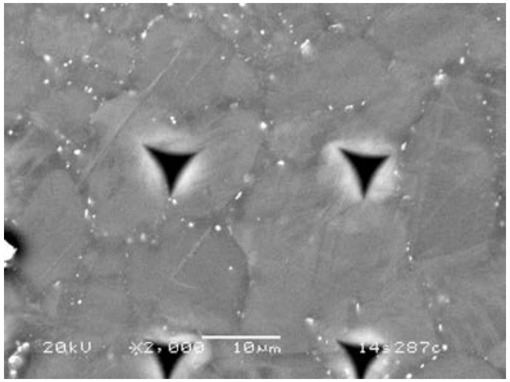
Calculate σ_y from empirical equation

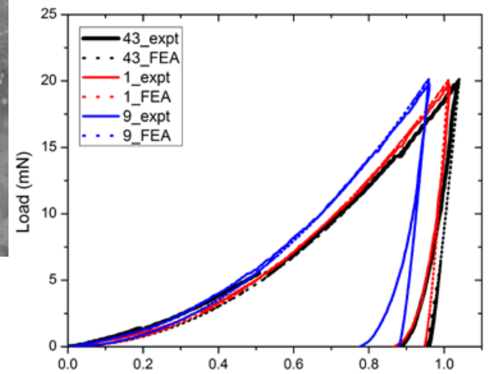
$$\sigma_y = 0.2836 * (0.98H_r - 375)$$

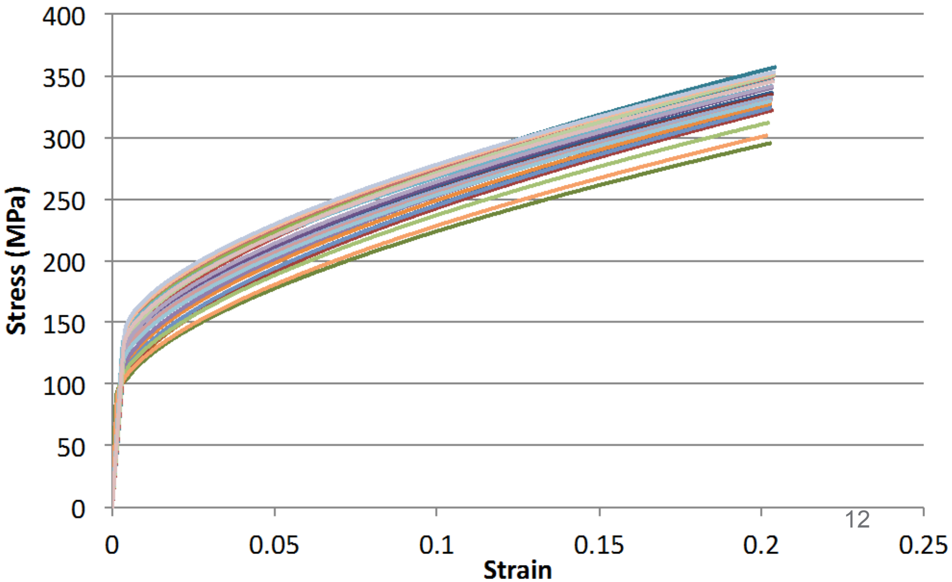
↓

Determine remaining parameters from FEA:
Calculate k for a fixed n (0.8, 0.6, …)

$$\sigma = \sigma_y + k\epsilon_p^n$$







PNNL – Intrinsic Modeling to Capture Hardening Limit and Parameter Study

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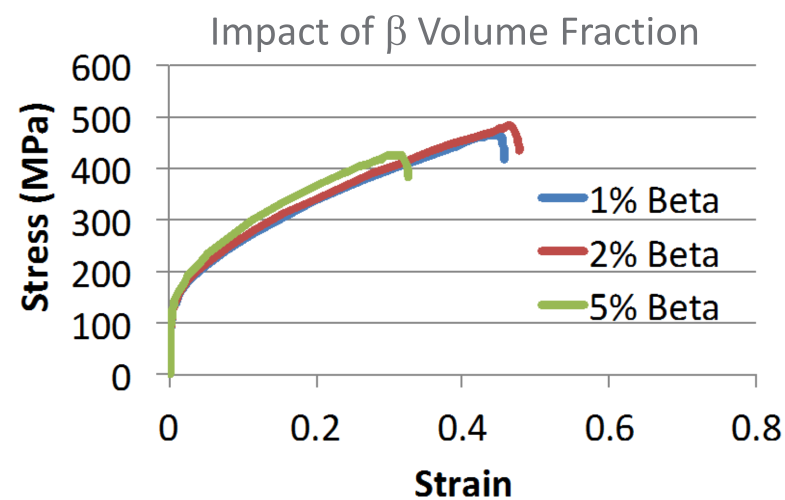
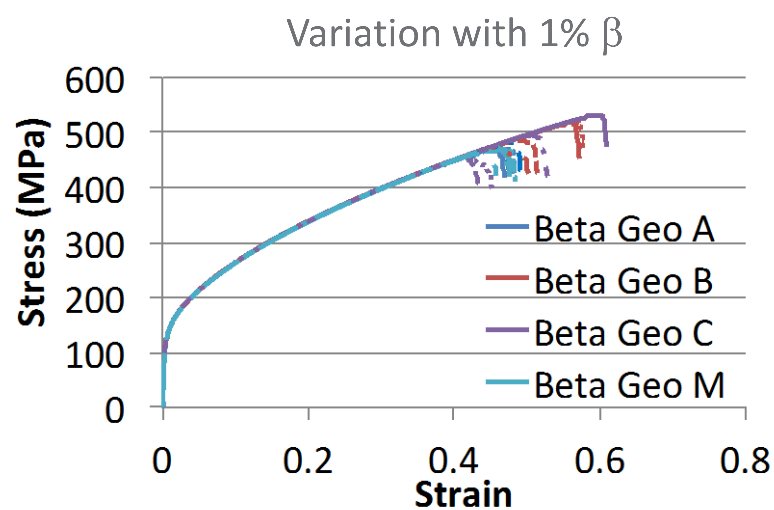
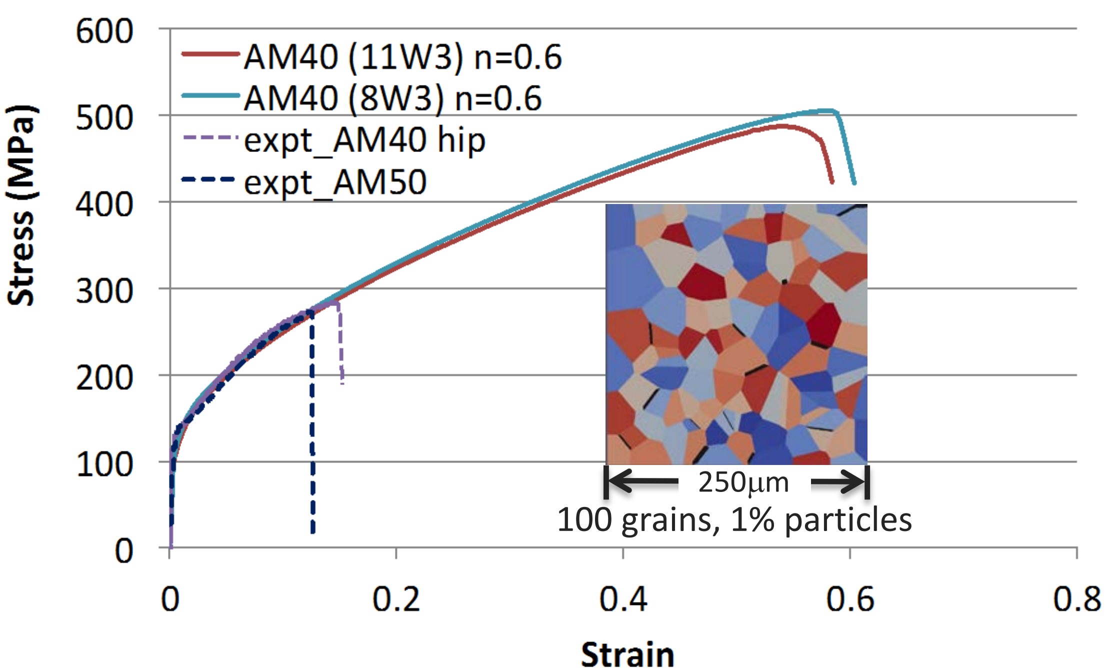
- Utilize α material parameters extracted from nanoindentation, and grain size and β volume fraction from characterization (UM)
- Conducting α parameter sensitivity study to capture impact of values and ranges on response
- Producing input matrix properties for extrinsic modeling







PNNL - Incorporating Intrinsic Microstructure-based Results into Extrinsic Models to Consider Pores

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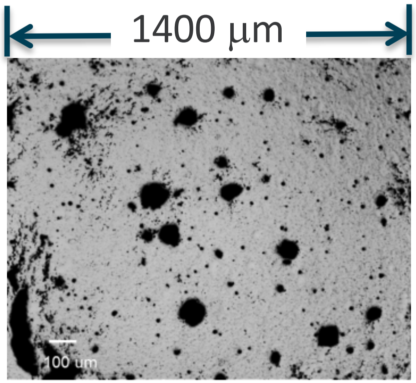
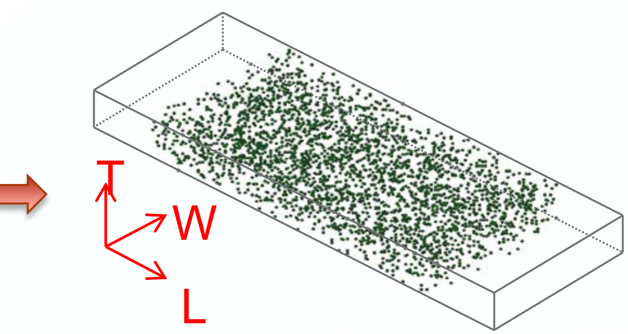
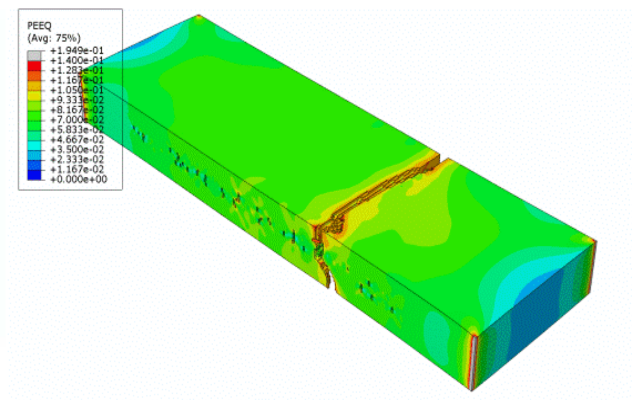
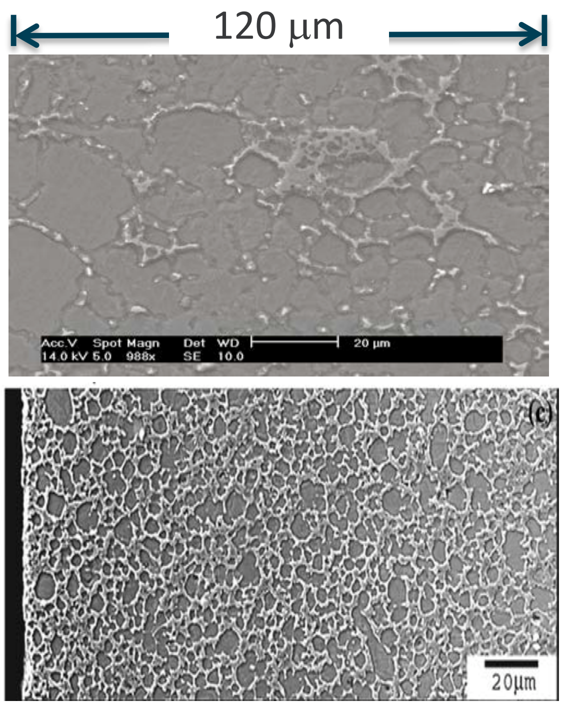


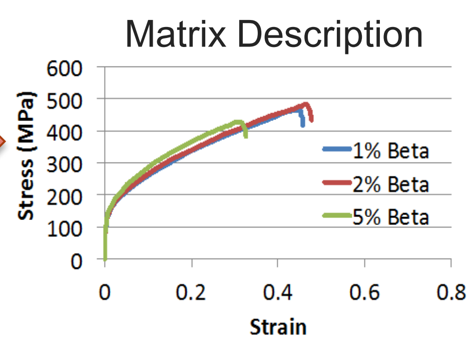


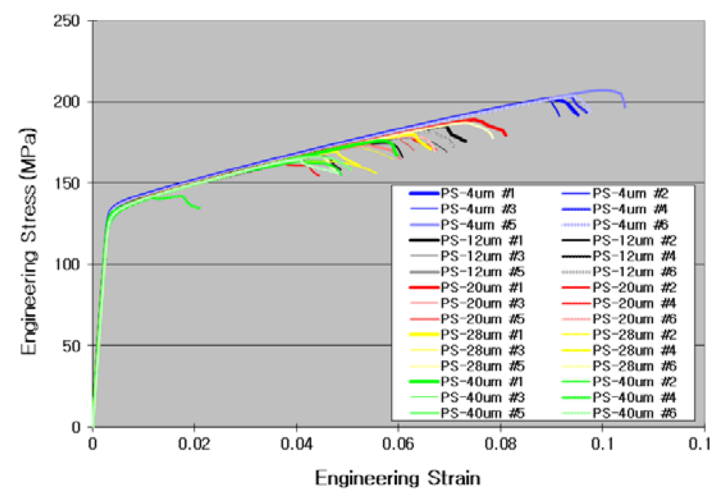
Pore distribution in 3D view





AM50 sample; Chadha, et al., *Metal Mat Trans A*, 2007

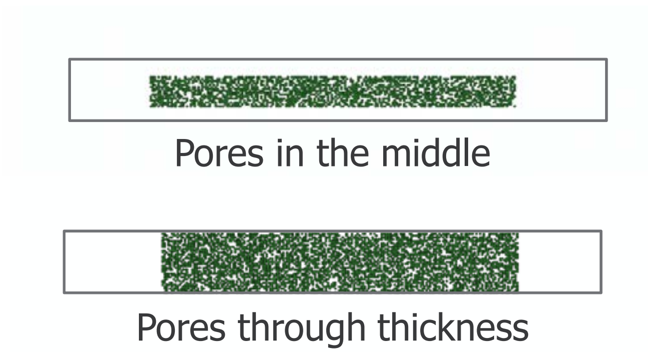


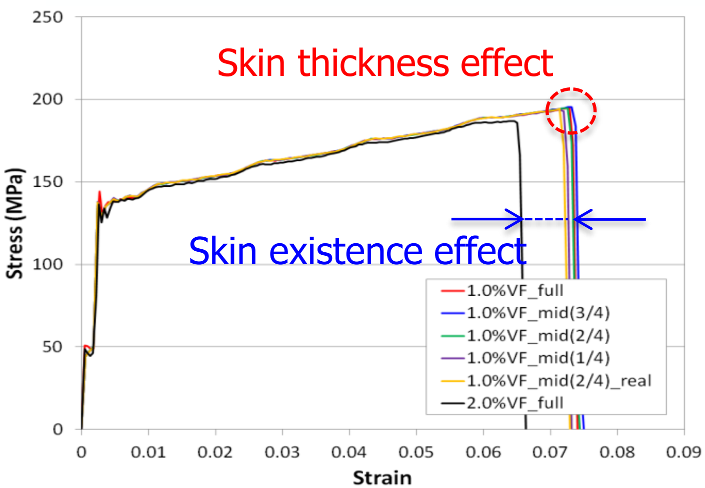


Sun, et al., *Mat. Sci. Eng. A*, 2013.

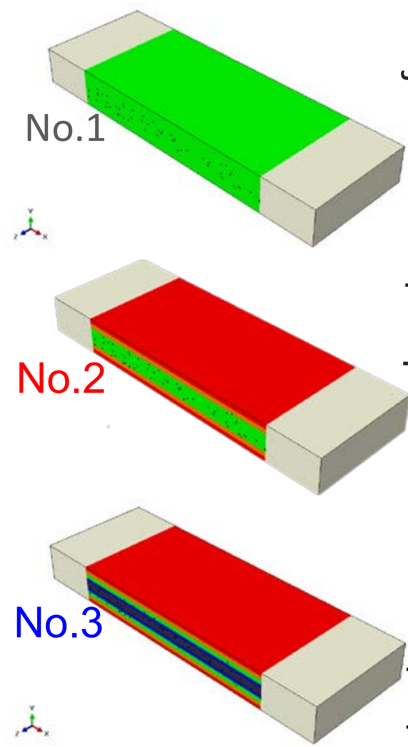
Previous PNNL Accomplishment: Extrinsic Modeling

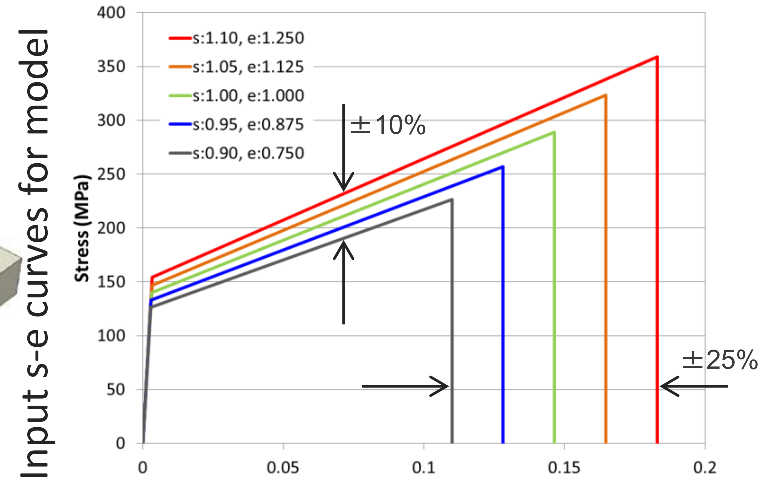
- Demonstrated the impact of having a pore free skin layer
- Determined intrinsic properties of the core region dominate the ductility limit

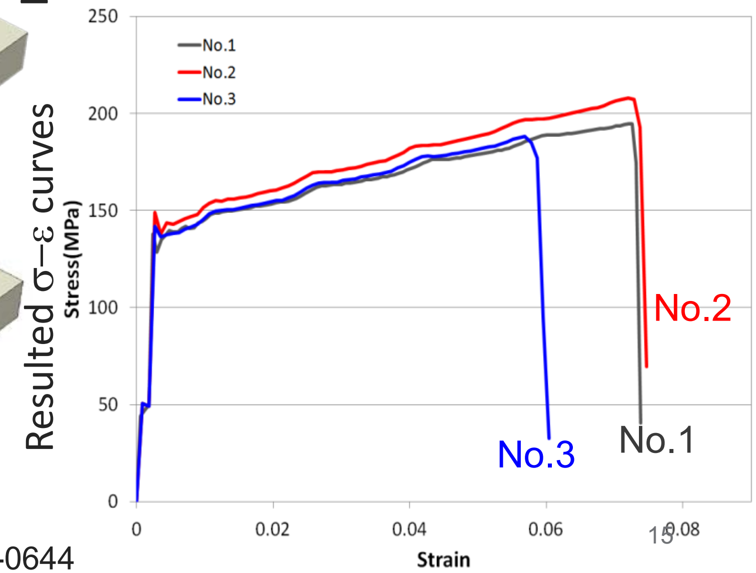




1.0% VF models



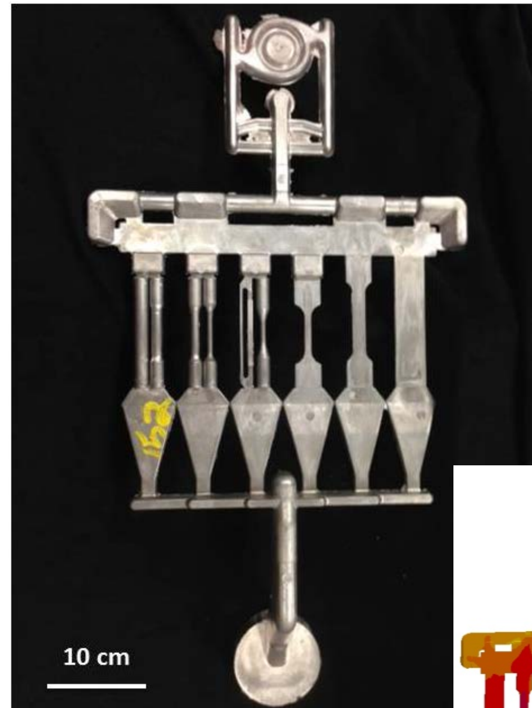


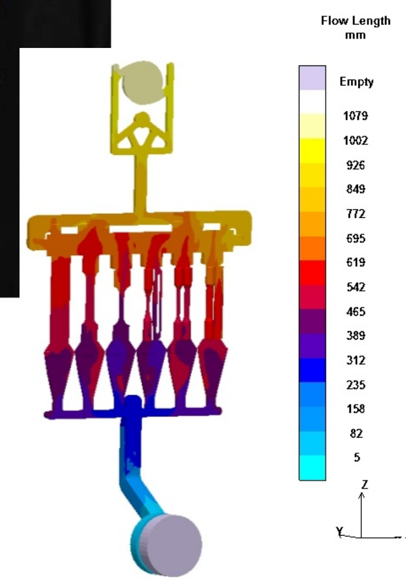


Choi et al. (2013) SAE Technical Paper #2013-01-0644

Ford – Specimen Castings

- Developed a die for directly casting tensile test specimen including
  - Flat and round dog bones
  - Flat plates
  - Round bars
- Test specimens to be used for
  - Capturing full range of microstructure within a test specimen
  - Examining skin effects
    - Comparing machined vs as-cast
    - Examining impact on statistical variation of elongation
    - Determine impact of excising test specimen vs as-cast
  - Providing controlled samples for extrinsic model validation





MAGMA

JH Forsmark, Z Dowling, K Gibson, C Mueller, L Godlewski, J Zindel, and J. Boileau
SAE Technical Paper 2015-01-0510

PNNL - Extrinsic Modeling based on Actual Microstructure from CT Scan

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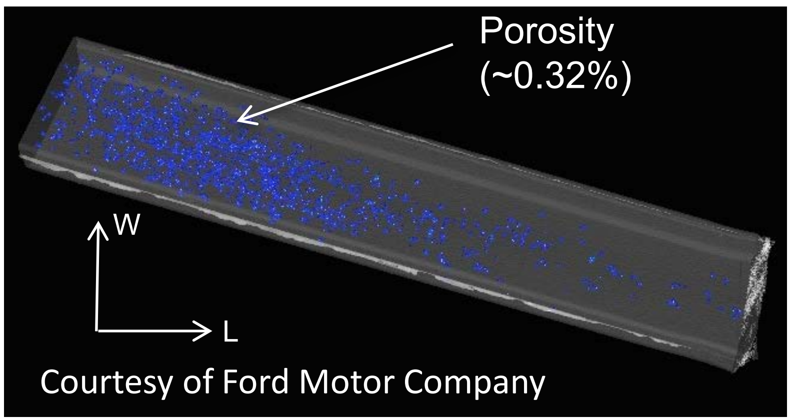
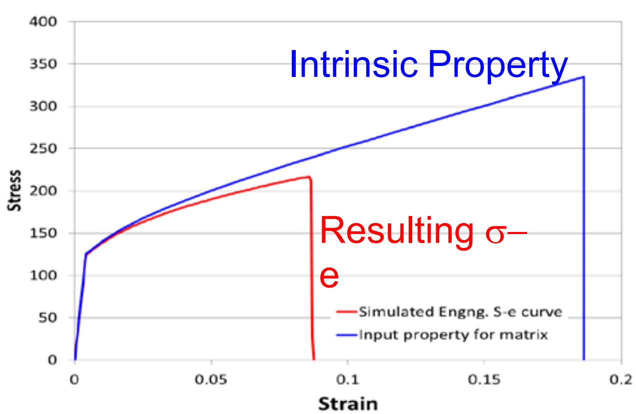
- 3D CT scans of porosity provided by Ford Motor Company
- Developed methodology for generating FE extrinsic models from CT data
- Conducted analyses using real porosity with intrinsic matrix parameters
- Obtaining correct intrinsic properties and pore distributions is crucial for ductility prediction





Collaborations

- Ford Motor Company (Industry)
  - Provided/operated high pressure casting and super vacuum die cast equipment
  - Characterized coupon level stress versus strain curves for different conditions and locations
  - Produced casting samples with varying aluminum content and performed casting process simulations
  - Collaborated on characterization of microstructure and defect features at various locations on castings
  - Developed and validated Mg casting quality map with statistical variation
- University of Michigan (Academic)
  - Developed characterization techniques to quantify grain size and β volume fraction and morphology
  - Established effects of plate thickness and aluminum content on microstructure, yield strength, ductility, UTS, and strain hardening exponent
  - Quantified effects of solution treatment and hot isostatic pressing on hardening parameters and ductility
  - Collaborated with Ford on development of Mg HPDC quality map
- CANMET Materials Technology Laboratory
  - Performed non-equilibrium kinetics simulations to capture solidification

Responses to Previous Year Reviewers' Comments

- Technical Accomplishments:
  - This reviewer commented that the team has made good progress on the variety of investigations as presented. It would be good to get an overview slide that shows the relationships between the various tasks (perhaps a fishbone diagram or other conceptual based diagram that relates the variables and their investigation to the goal of ductility prediction). The reviewer added that the project is still very difficult to understand.

  Response: This is a very good suggestion. The team followed this suggestion and presented our technical flow chart this year. We also took this suggestion and presented a 4-talk session on the project at TMS 2015.

  - The reviewer indicated that predictive results and measurement do not correlate, thus they are not applicable to commercial use. Local material property prediction and correlation with actual test samples is an objective of ICME and in fairness to the researchers will require significant research effort over the next 10 years to achieve.

  Response: We truly agree the need for an ICME approach, and this project represents a portion of the ICME spectrum.

- Collaboration and coordination with other institutions
  - The reviewer stated that the role of CANMET and UM appear to be window dressing for the application. The reviewer recommended that future projects include magnitude of inking from each collaborator.

  Response: We emphasize UM's role in characterization this year and specifically list CANMET's complimentary activity.

- Proposed future research
  - The reviewer remarked that the project team did excellent work but the project is on its last trimester and it is more a question of finishing what has been commenced than starting new ideas. The reviewer added that even though the dimensions of cast samples match thicknesses of larger cast parts, the thermodynamic effect on large casting can have drastic effects on the microstructure and yield different results than from small samples.

  Response: Good suggestion. Ford casted plate castings of different thickness as well as round and flat dog bone samples to quantify the effects of thermodynamic and kinetics on the microstructures and subsequent ductilities.

  - The reviewer recommended to "put a bow on it."

  Response: We followed this good suggestion in the final validation.

Summary

- Relevance
  - Limited ductility and high ductility variations hinder the wider applications of Mg casting in vehicle structures for lightweighting
- Approach
  - Develop a quality-mapping capability for estimating/controlling ductility of Mg castings based on tensile test results and various casting parameters
  - Develop a mechanistic-based ductility prediction capability with separate consideration of intrinsic factors and extrinsic factors
- Technical Accomplishments
  - Validated quality mapping approach in predicting ductility and ductility variations (Ford Motor Co.)
  - Designed and manufactured tensile test castings to investigate variation in skin effect on mechanical properties and provide validation for extrinsic modeling (Ford Motor Co.)
  - Use quantitative fractography and microstructural analysis to establish relationships between properties, microstructure and alloying/processing variables (UM+PNNL)
  - Performing nano-indentation tests to evaluate α cell elasto-plastic properties and variations (PNNL/UM)
  - Predicting intrinsic ductility for Mg with different aluminum content by considering eutectic β phase and α phase variation (PNNL)
- Final Deliverable
  - Validate prediction framework by comparing measured ductility with predicted ductility utilizing reconstructed pore distributions from physical specimen (PNNL)