Mechanistic-based Ductility Prediction for Complex Mg Castings

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Pacific Northwest National Laboratory

Richland, WA, USA

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Project ID#: LM057

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Overview

- Timeline
  - Start: Oct. 2010
  - End: Sep. 2013
  - 25% Complete
- Budget
  - Total funding:
    - DOE - $1,800K
    - Industries (in-kind) - $900K
  - Funding in FY11:
    - DOE - $600k
    - Industry - $300k
  - Funding in FY12:
    - DOE - $600k
    - Industry - $300k

- Barriers
  - Limited ductility of Mg castings hindering its wider applications as vehicle components
  - Lack of capability of conventional computational software/models in predicting ductility of Mg castings, resulting from various types of defects
- Partners
  - University of Michigan
  - Ford Motor Company
  - Mag-Tec Casting Corporation
  - CANMET Materials Technology Laboratory

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
- Provide a modeling framework that can be used in future Mg alloy design and casting process optimization
  - Develop an empirical casting process simulation tool that can estimate the variation in ductility and be used by the casting industry in the near future
  - Develop a mechanistic-based predictive capability 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 for estimating the spatial variation of ductility and the influence of casting process variables (on-going; due 6/30/2012)
- Modeling and experimental methods in quantifying location-dependent intrinsic and extrinsic ductility limiting factors for complex Mg castings (on-going; due 9/30/2012)
- Experimentally validated predictive models for stress versus strain curves, including ductility, for Mg castings considering both intrinsic and extrinsic ductility limiting factors (on-going)

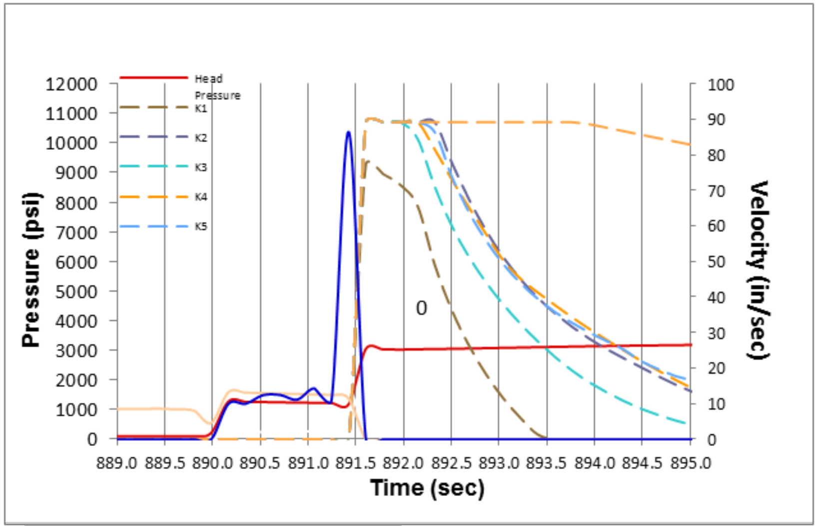
Technical Approaches

- Cast a number of AM50/AM60 castings of complex geometries under a variety of conditions (i.e., melt temperature, shot speed, die temperature, gating geometry)
- Perform alloying and casting process simulation to predict spatial variations in casting defects and other microstructural features under different conditions
- Characterize microstructure and defect features at various locations of the castings and perform tensile tests with samples machined from various locations
- 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

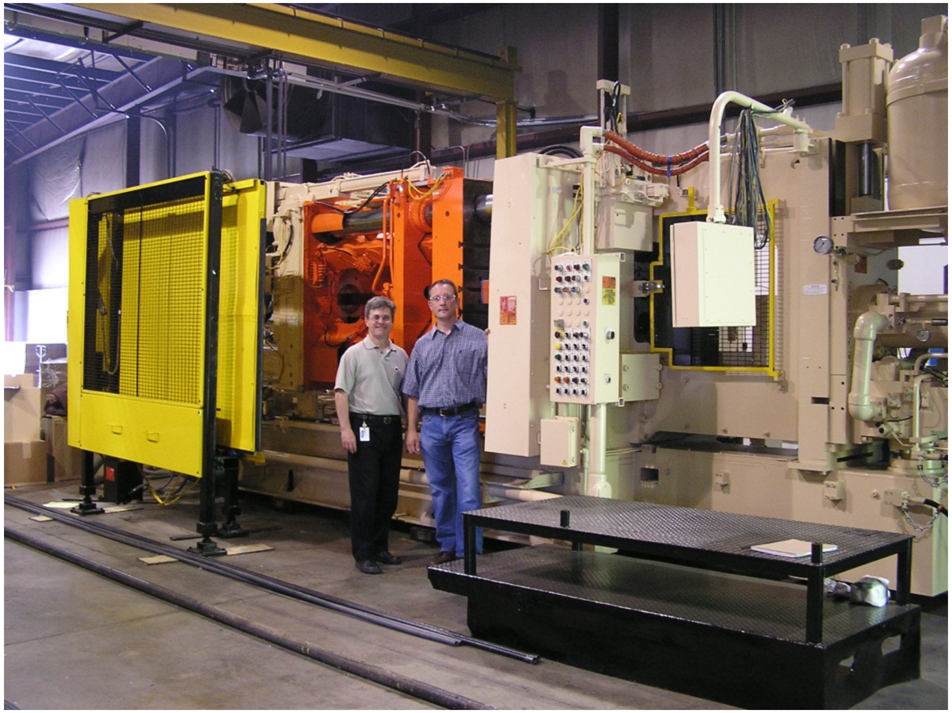
Ford High Pressure Die Casting Research Facility

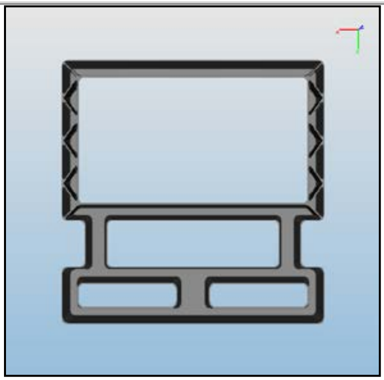
Description: State of the art high pressure die casting facility for conducting research on Mg casting. 900 T press, Mg pump & vacuum capability.

Fully Instrumented Castings



900 T HPDC Machine

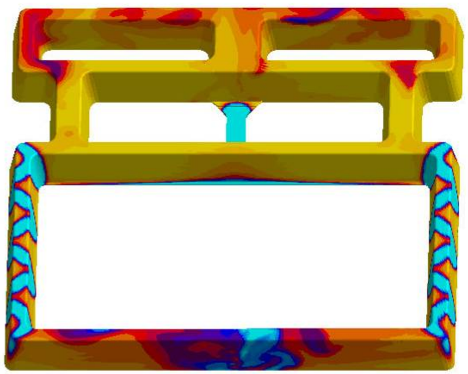




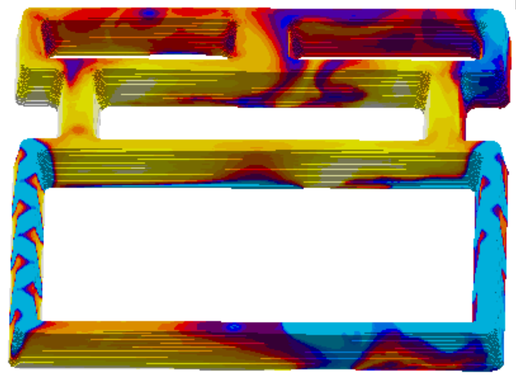
Simulated Mg Lift Gate
(Generic Closure Inner Panel - GCIP)
Cast over 250 Castings (Mg Alloys AM50 and AM 60) & 40 Plate Castings

Impact of Local Properties and Process Scatters on Mg HPDC (AM60) Performance

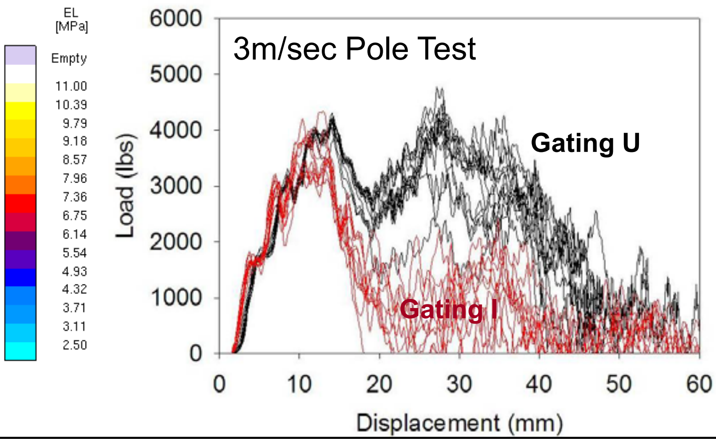
Issue A - "Local Properties"



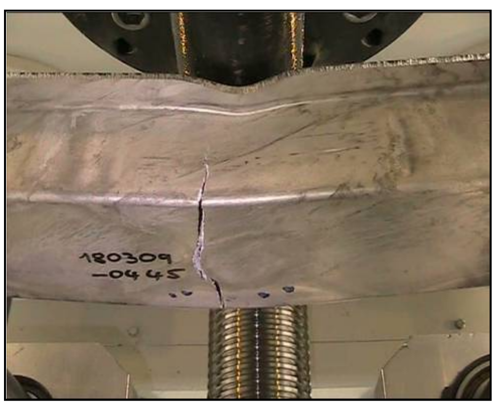
Symmetrical Gating (I)



Asymmetrical Gating (U)

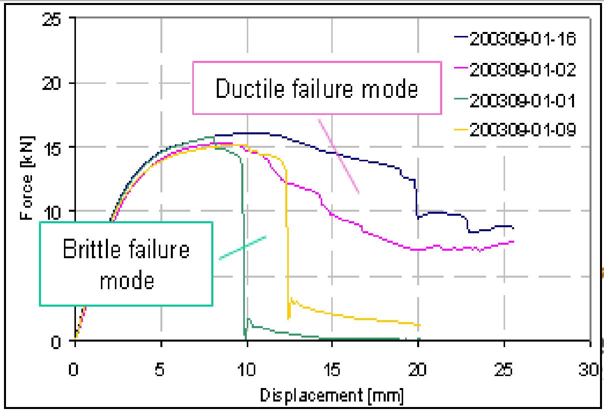


Issue B - "Process Scatter"

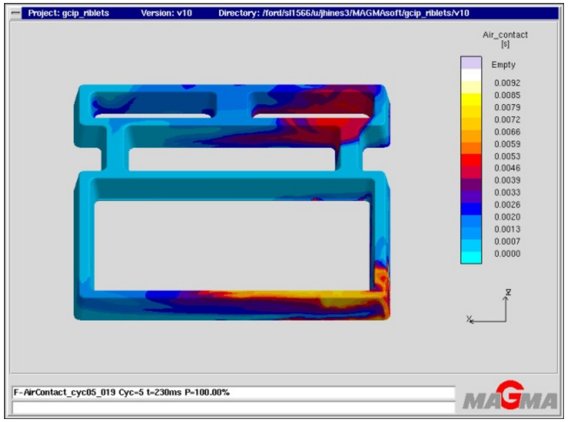


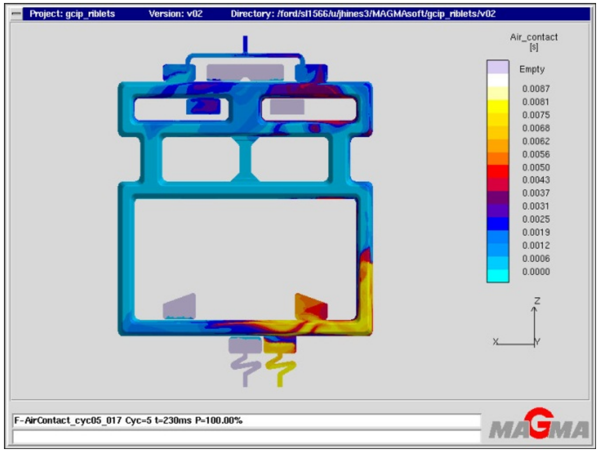
"Brittle" failure mode

"Ductile" failure mode



Technical Accomplishments
-- Quality Mapping of Local Ductility





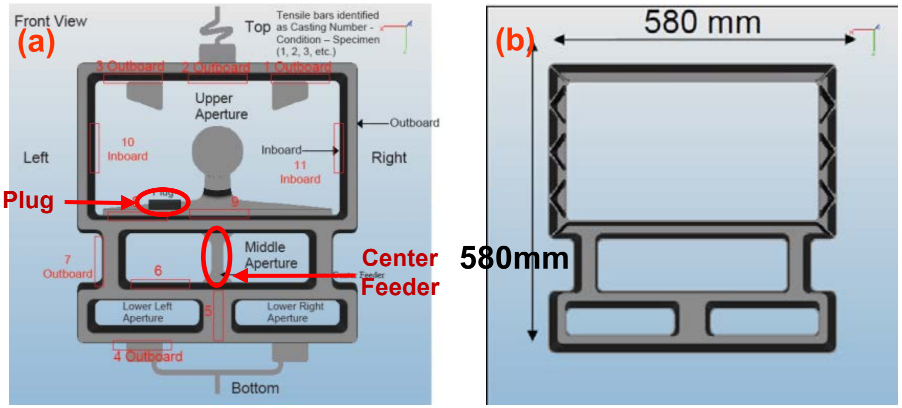
Different Processing Conditions:
- Melt Temp
- Die Temp
- Flow Pattern
- Shot Speed
- …

Different Criteria Functions:
- Flow Length
- Air Entrapment
- Air Contact
- Solidification Time
- …

Optimization of criteria functions and constants to give local index map for <u>Mechanical Properties (i.e. ductility).</u>

*Quality Index = c1*FL^c2+c3*Ma^c4+c5*AP^c6+c7*ST^c8*

Technical Accomplishments --MAGMAsoft Simulations (1)

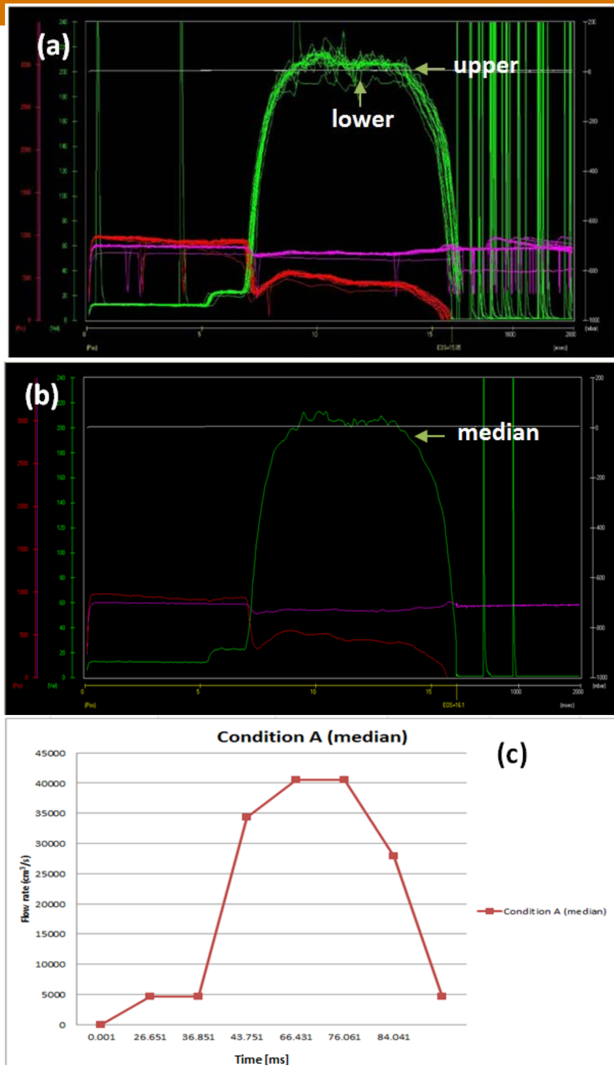


Generic Closure Inner Panel (GCIP) (a) Front View (b) Back View

- Used **GCIP** as a case to generalize the correlation between **criteria function** and **elongation** of Mg high pressure die casting.

Designation	Alloy	Fast Shot m/sec	Melt Temp. Degree ℃	Gating Configuration	Center Feeder
A	AM60	5.2	675	No plug	No
J	AM60	6.47	691	No plug	Yes
K	AM60	5.3	711	No plug	Yes
D	AM60	6.6	738	No plug	No
M	AM60	5.2	677	plug	Yes
G	AM60	5.08	731	plug	No
Q	AM60	6.09	727	plug	Yes
U	AM60	5.84	720	plug	Yes

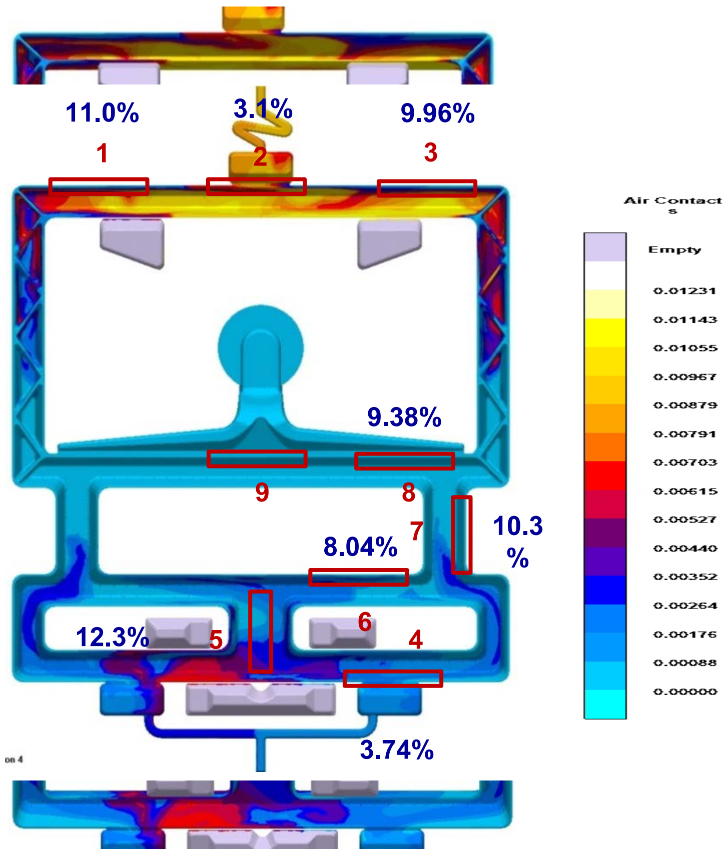
Table 1. Actual values used in MAGMA soft simulation, representing processing conditions



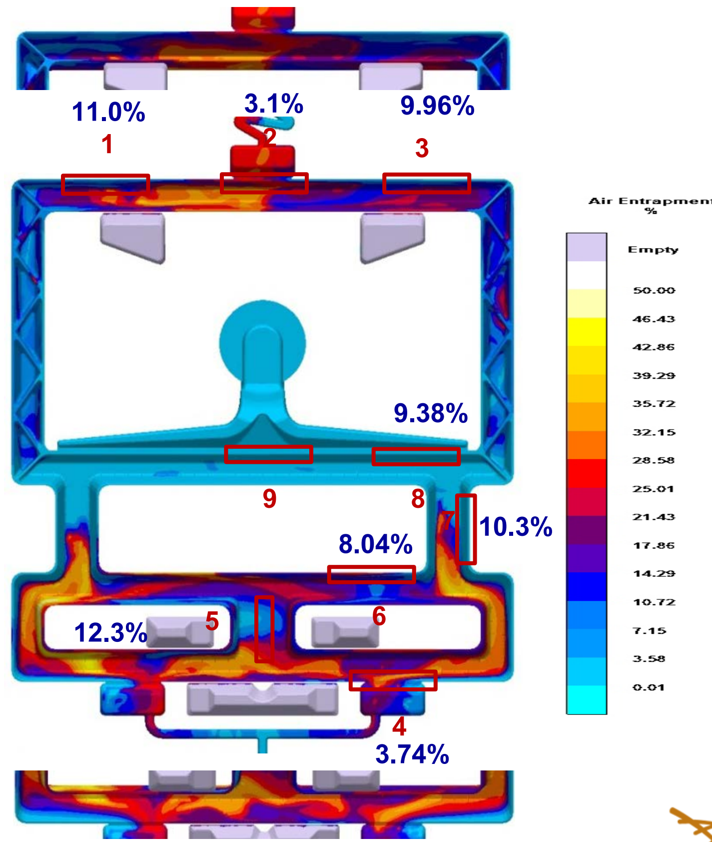
Filling profile of A condition (a) actual filling profiles for the set of castings(b) actual median filling profile (c) filling profile used in MAGMAsoft simulation

Technical Accomplishments --MAGMAsoft Simulations (2)

- Criteria Function



Air contact

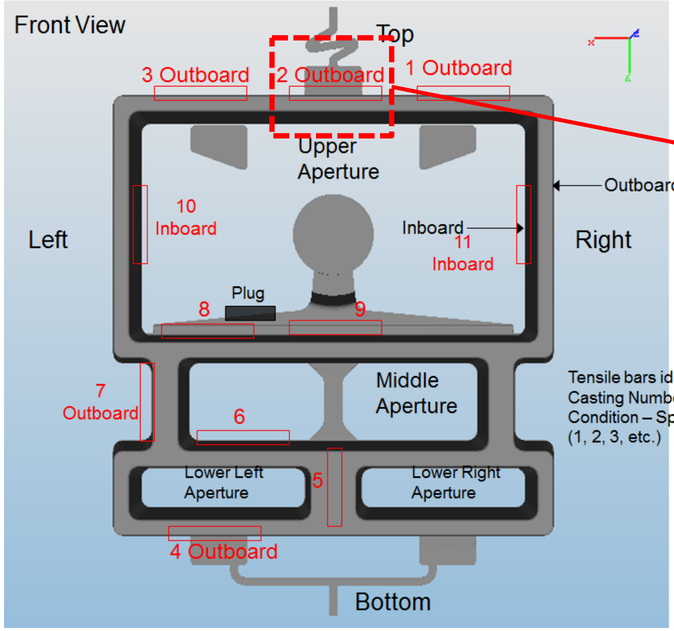


Air entrapment

Condition A

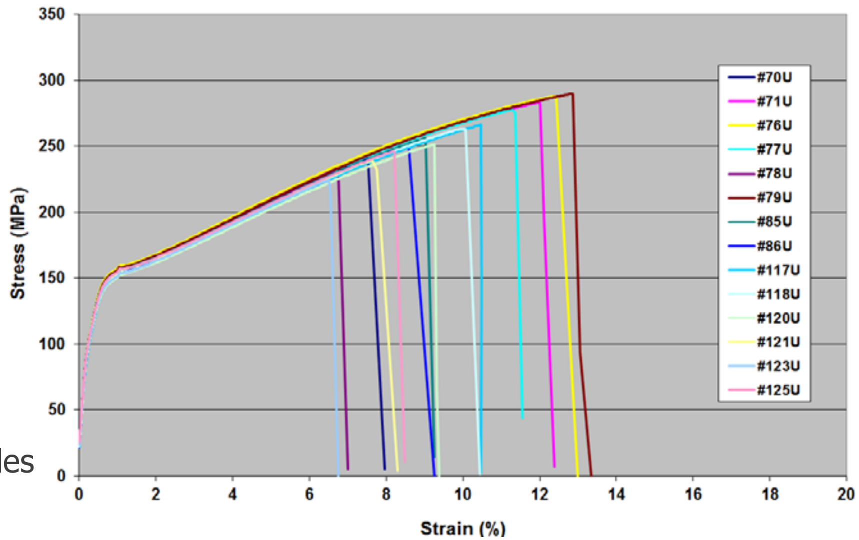
Technical Accomplishments
-- Stress-Strain Curves (AM60, Condition U)

Designation	Alloy	Fast Shot m/sec	Melt Temp Degree C	Gating Configuration	Center Feeder
A	AM60	5.2	675	No plug	No
G	AM60	5.08	731	plug	No
U	AM60	5.84	720	plug	Yes
Q	AM60	6.09	727	plug	Yes



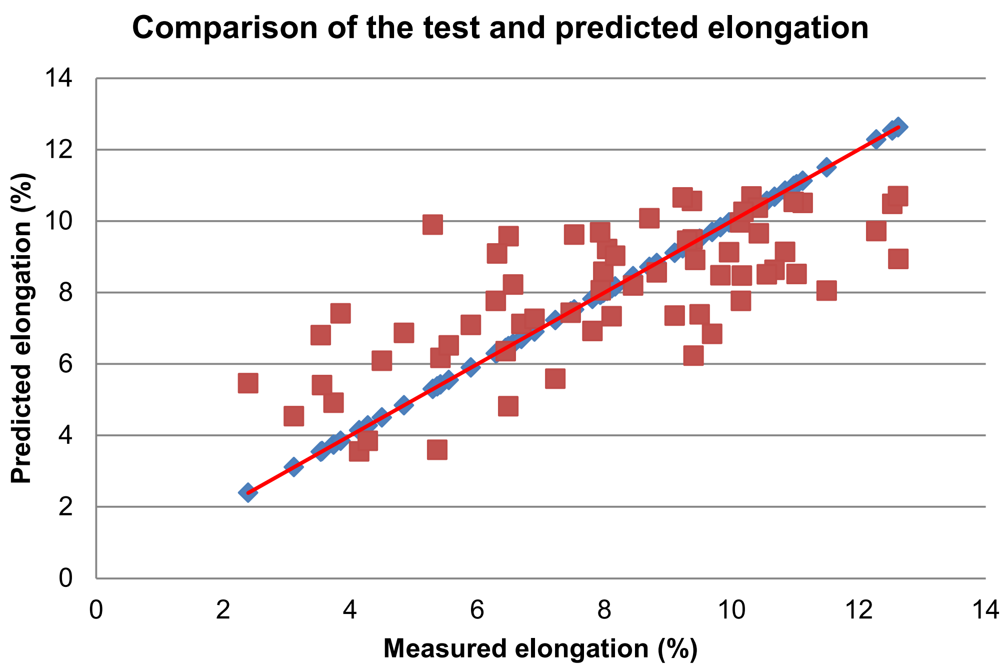
Samples were cut from the same location (#2)

Failed tensile samples



Stress-strain curves

Technical Accomplishments --Preliminary Quality Map Relationship for Ductility

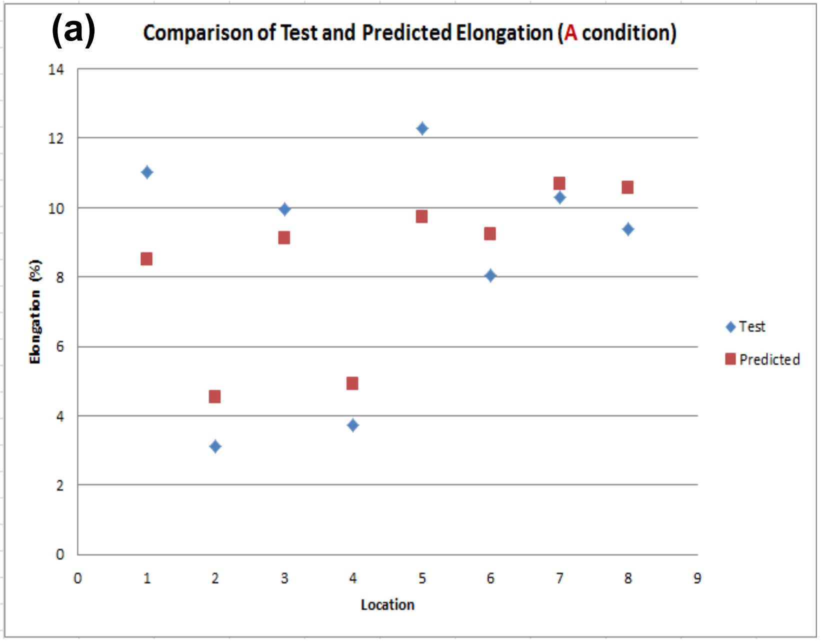


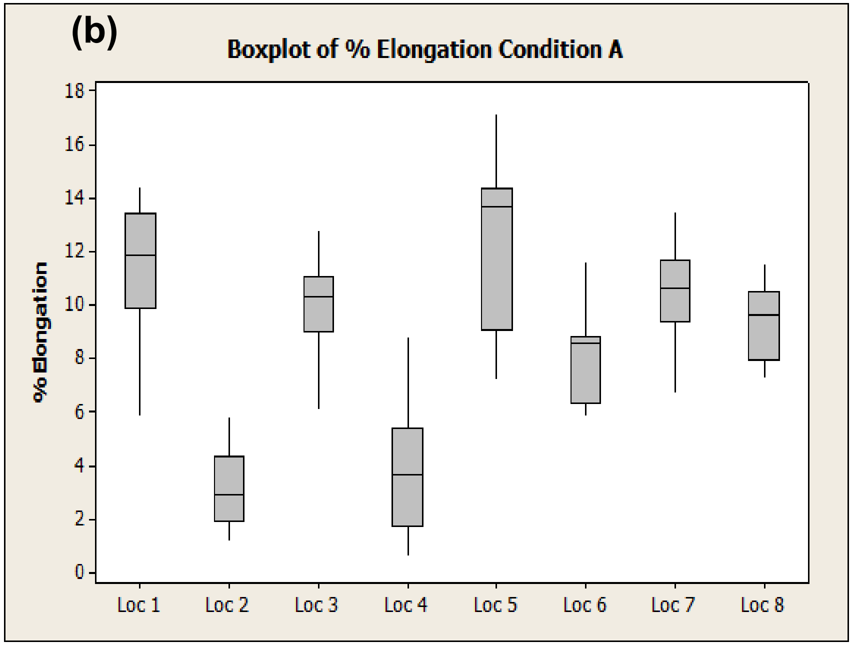
Elongation $= 26.291 - 18.96 * STnorm^{0.19934} - 1.8144 * FLnorm^{0.91472} - 5.8475 * AEnorm^{4} - 7.0759 * ACnorm^{0.92389} + 27.613 * Tnorm^{4}$

The criteria functions were normalized as follows:
STnorm = Liq to Sol/4; AEnorm = AE/35; FLnorm = FL/1500; ACnorm = AC/0.015;
Tnorm = (T100%-620)/620

R^2 = 0.51

Technical Accomplishments
--Prediction of Mean Value of Ductility from Preliminary Relationship





Comparison of the test and predicted elongation
(a) comparison of the test and predicted elongation (b) box plot of elongation

- The box plots show the statistical variation in the data collected. The boxes consist of the first and third quartiles with the center line in the box showing the location of the median. The whiskers show the standard deviation.

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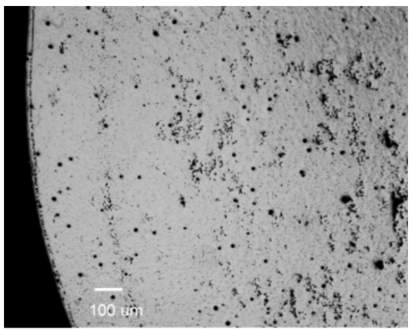
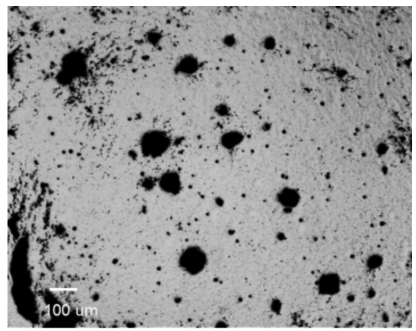
Technical Accomplishments --Development of Synthetic Microstructure of Mg Castings

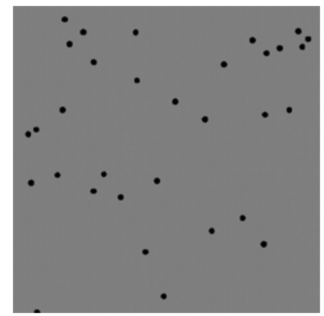
- Obtained cross-section micrographs of AM50 casting samples (Dog-bone shaped)
- Performed porosity analysis
  - Pore volume fraction: 0.5%~1.5% near skin, 2~6% at the center area
  - Pore size : 4~80um
- Generated synthetic microstructure of the Mg castings based on porosity analysis



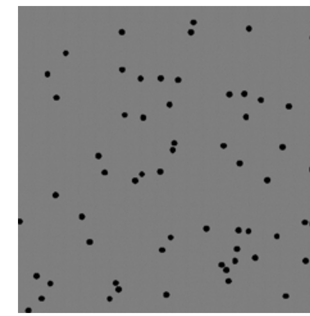
Skin region of sample #3



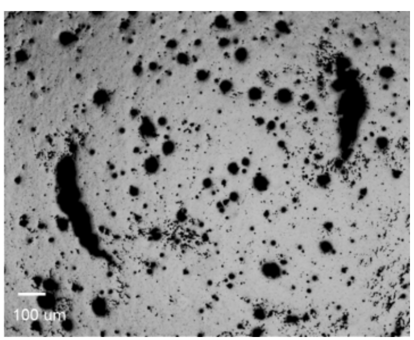
Center region of sample #3



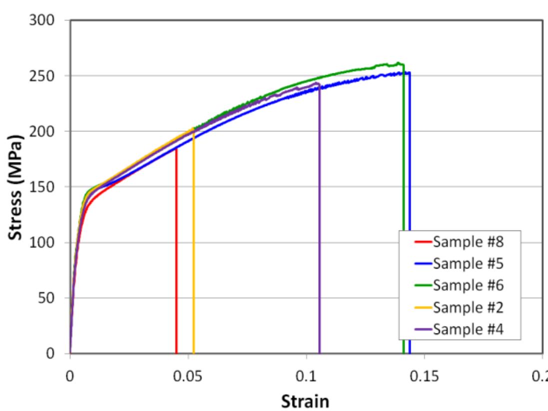
VF: 1%
PS: 20um

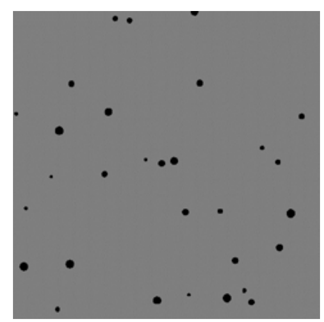


VF: 2%
PS: 20um

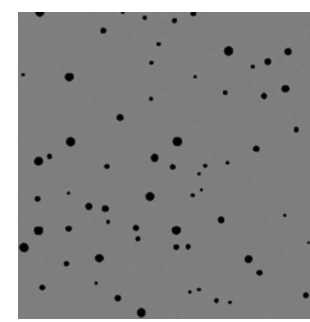


Center region of sample #5





VF: 1%
PS: avg 20um
(10~30um)



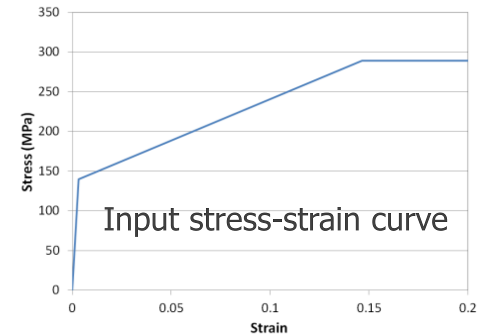
VF: 2%
PS: avg 20um
(10~30um)

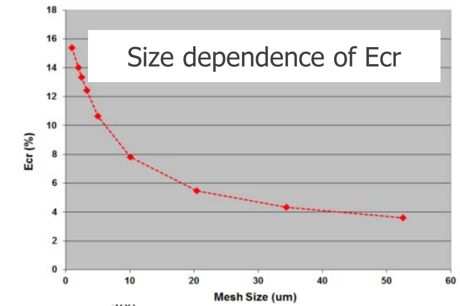
Micrographs of AM50 castings and their stress-strain curves

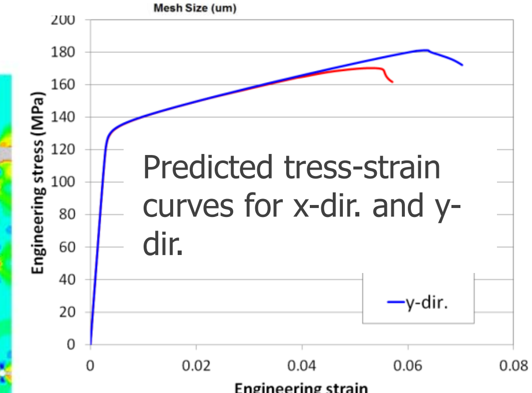
Examples of synthetic microstructure

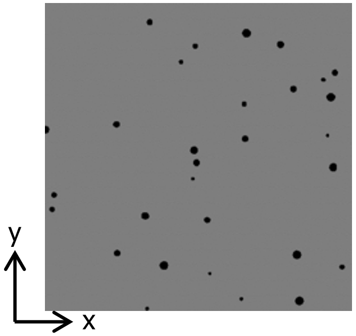
Technical Accomplishments
-- Developed Finite Element-based Ductility Prediction Technique for Mg Castings

- Generated finite element models based on synthetic microstructures
  - 2-Dimensional plane-stress model
  - Model size: 1mm X 1mm, Mesh size: 2um
  - Elastic modulus : 45GPa, Yield strength: 140MPa
  - Constant plastic hardening rate (1,065MPa) is assumed
  - Intrinsic critical strain (Ecr) : ε_p=14% (No hardening is present beyond this)
  - Failure : based on plastic strain localization induced by pores
- Simulation cases
  - 3 different pore volume fractions : 1, 2, 4%
  - 5 different pore sizes : 4, 12, 20, 28, 40 um in diameter
  - 2 different pore size distributions : constant/distributed pore size
  - Ran 6 different simulations for each case to obtain statistics

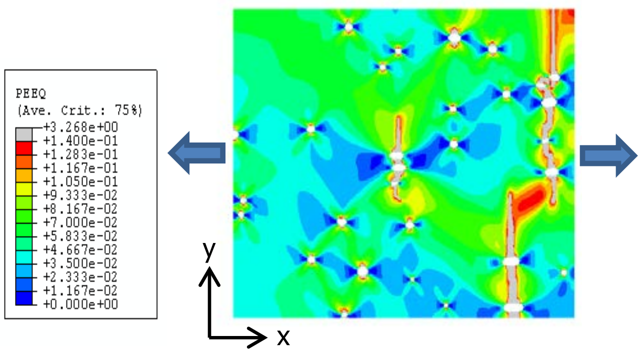




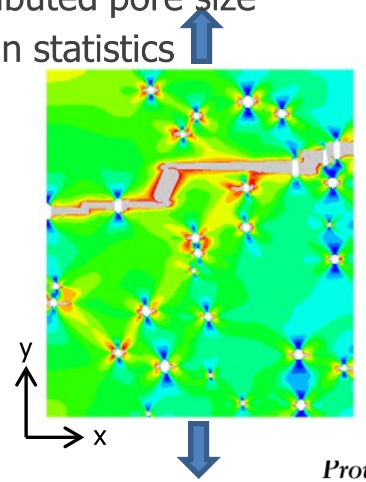




VF: 1%
PS: avg 20um (10~30um)



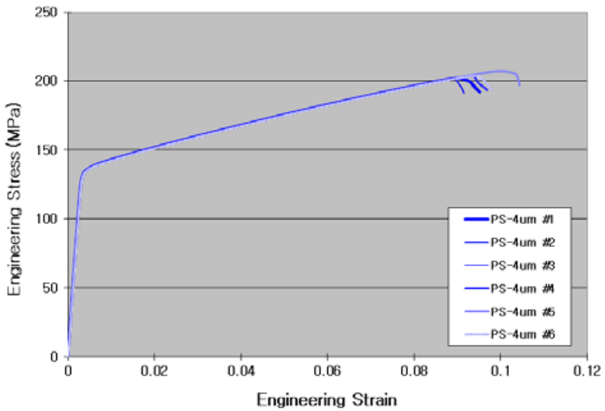
x-dir. tension



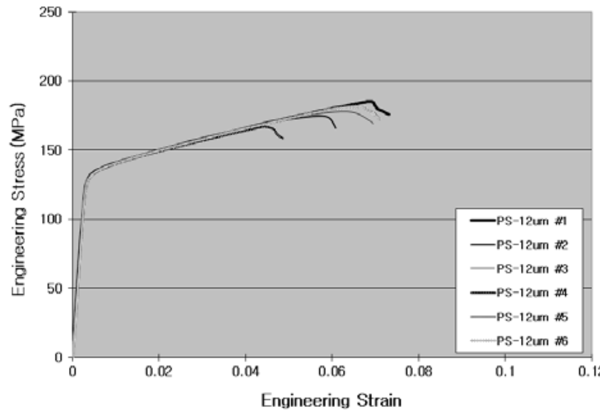
y-dir. tension

Technical Accomplishments
--Predicted S-E Curves for Various Pore Sizes
(VF=1%, Constant Pore Size Distribution)

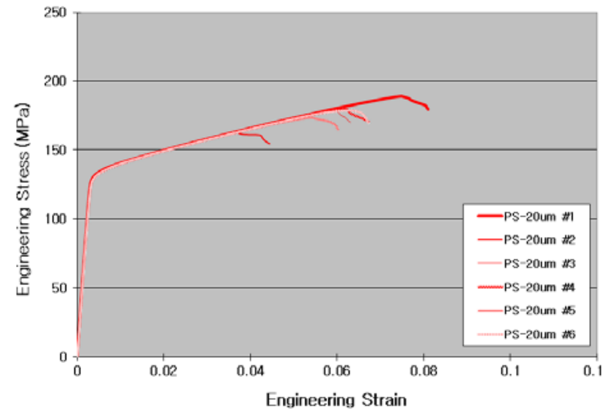
- 6 stress-strain curves predicted for 6 microstructures under each condition
  - Ductility depends on pore distributions in the model
  - In general, ductility decreases as pore size increases



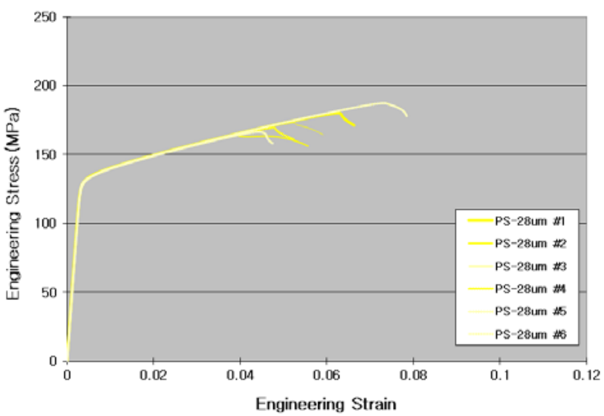
PS: 4um



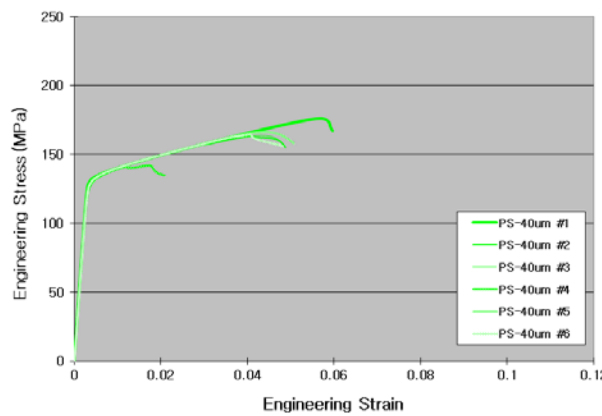
PS: 12um



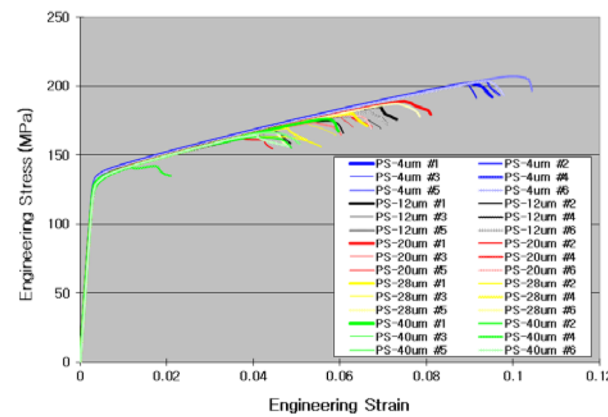
PS: 20um



PS: 28um



PS: 40um

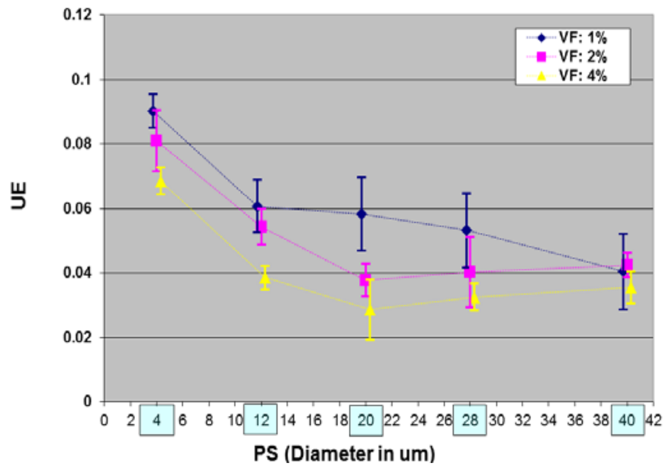


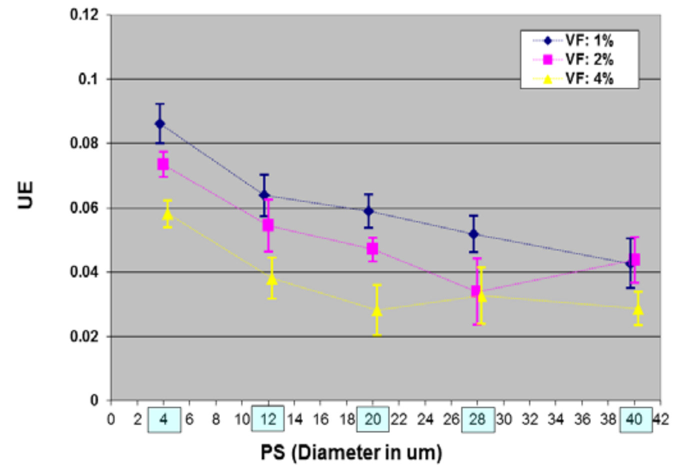
PS: 4~40um

Technical Accomplishments
--Effects of Pore Size, Volume Fraction and Distribution on Uniform Elongation

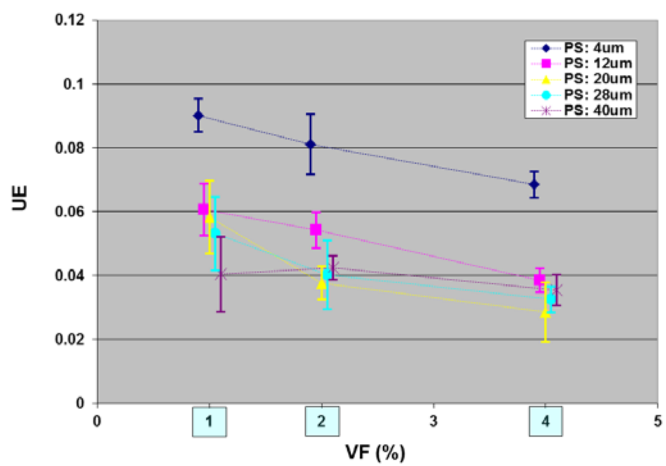
- In general, uniform elongation decreases as pore size and/or volume fraction increases
- This may not always be the case in some range of pore size and volume fraction since the mean distance between the pores seems to have substantial influence on ductility → Needs further study
- Considered pore size distributions (i.e., constant/distributed) do not show significant difference

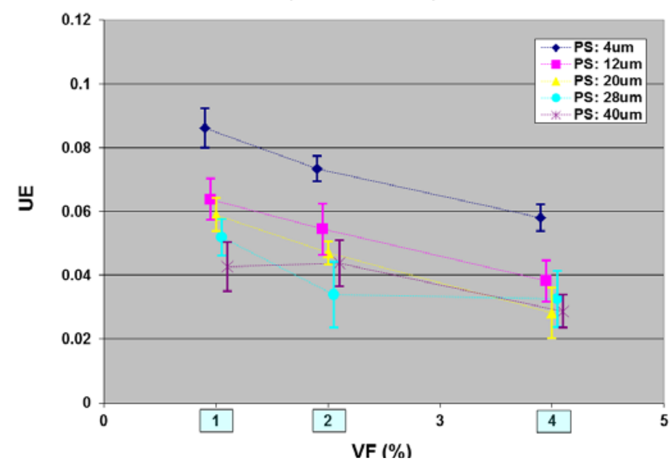
Effect of pore size





Effect of pore volume fraction

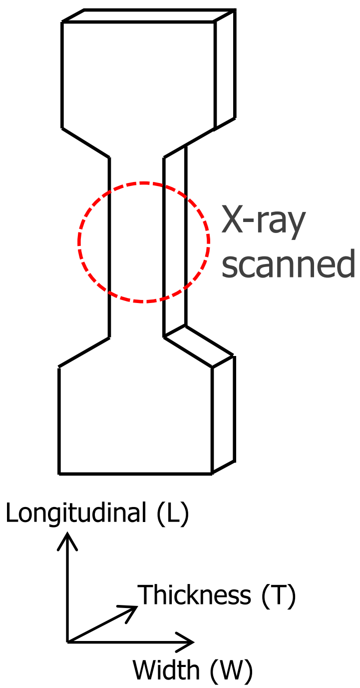


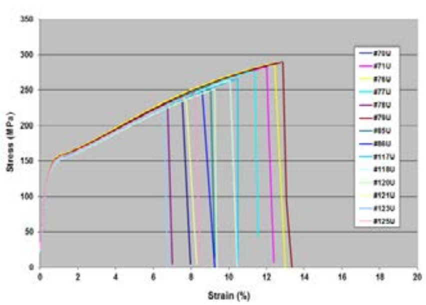


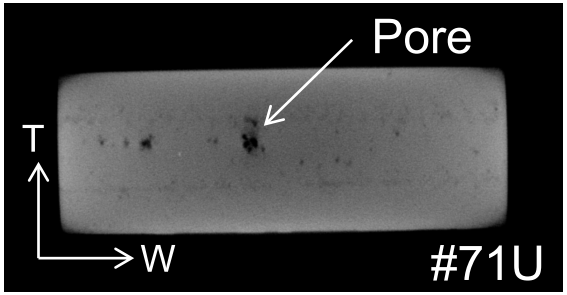
Constant pore size

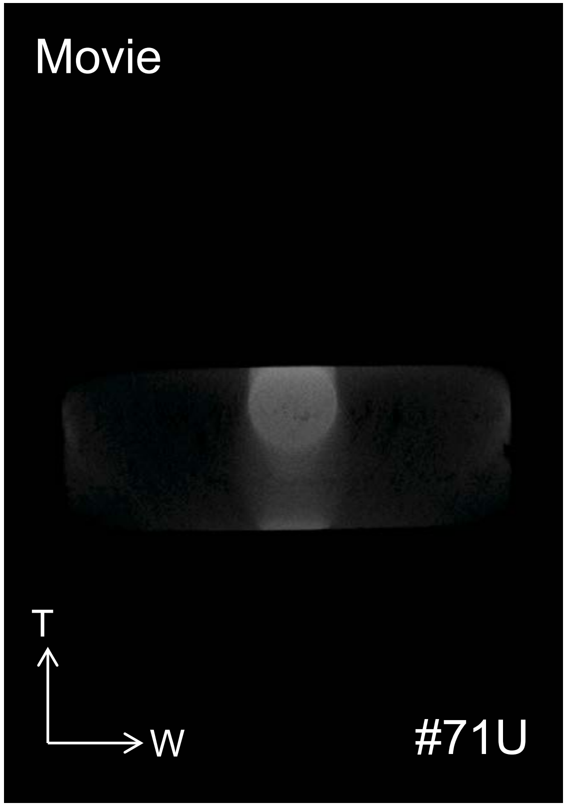
Distributed pore size

Technical Accomplishments -- Preliminary Results of 3-D X-ray Tomography

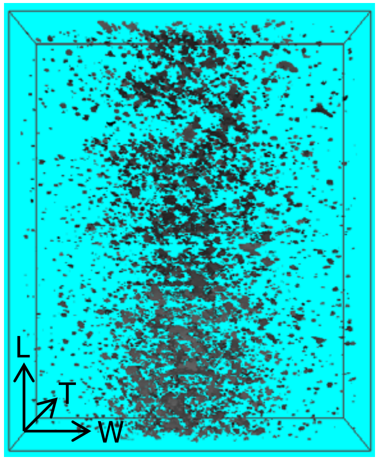




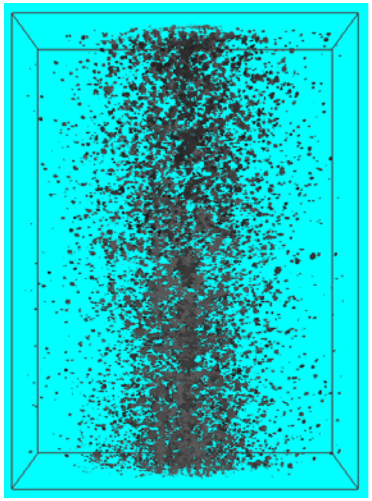




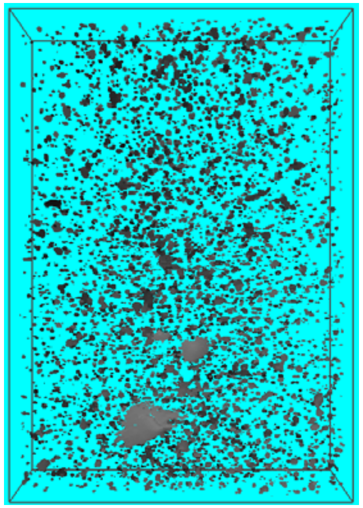
Visual representation of pores in samples



#71U (VF: 0.64%)



#76U (VF: 0.62%)



#123U (VF: 1.04%)

- Image analysis is underway based on X-ray tomography
- The result will be used for actual microstructure-based finite element modeling

Summary

- Over 250 castings of AM50/AM60 were cast under variety of conditions
- Preliminary quality map for predicting average local values of ductility was developed and it predicts similar trends to those of experimental measurements
- Approaches for predicting knit lines and ductility variability are under evaluation
- Fractographic analysis for development of empirical micromechanical ductility model has been initiated
- X-ray tomography has been used to generate three-dimensional images of tensile samples with porosity in it
- Two-dimensional finite element analysis has been conducted based on synthetic microstructures with different pore size, volume fraction and distributions
- Mesh size effect and scalability regarding FEA have been studied

Collaborations

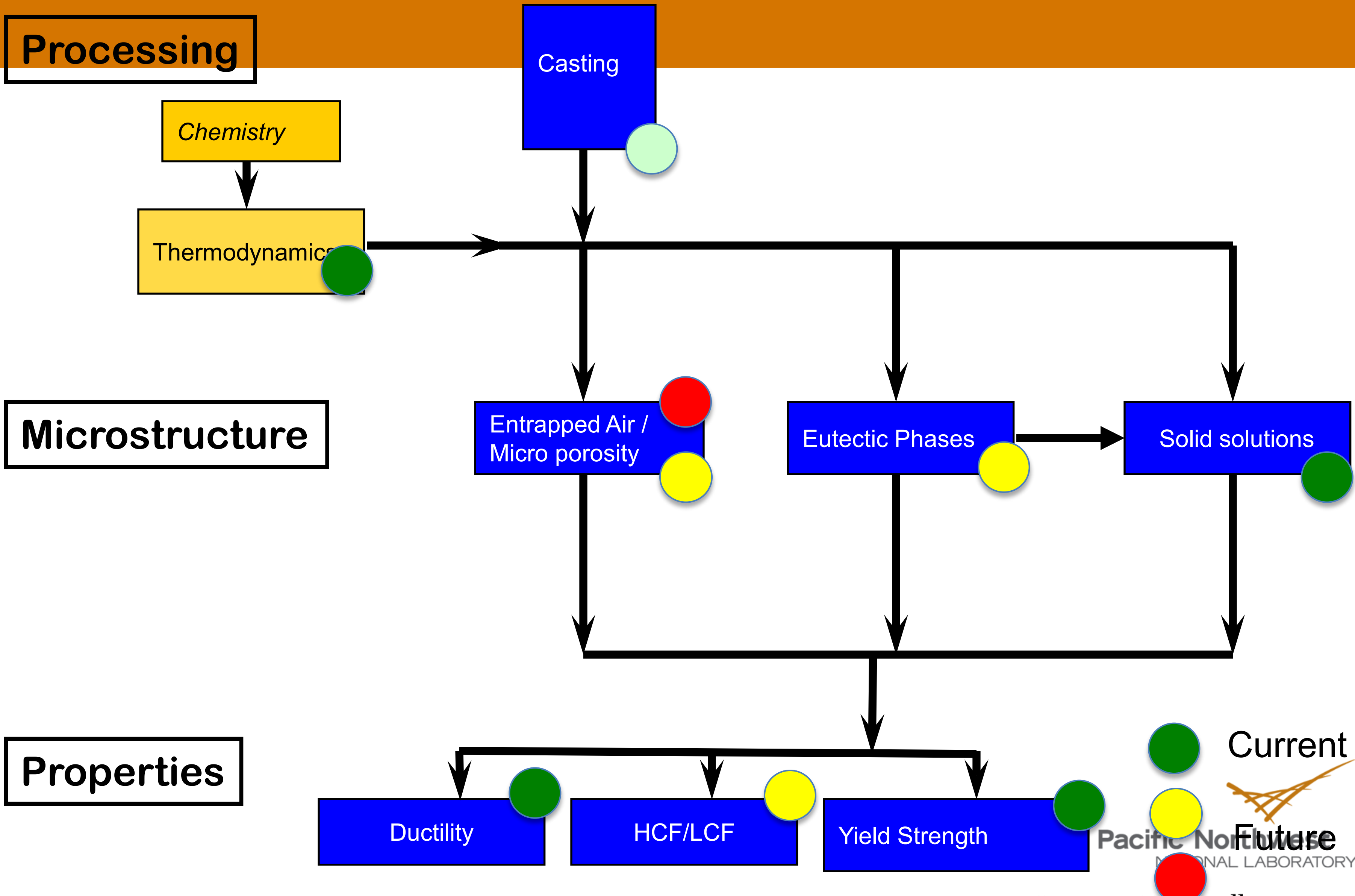
- Ford, Mag-Tec Casting Corporation, CANMET Materials Technology Laboratory (Industry)
  - Provided/operated high pressure casting equipment
  - Characterized component level impact behaviors and coupon level stress versus strain curves for different conditions and locations
  - Performed alloying and casting process simulations
  - Collaborated on characterization of microstructure and defect features at various locations on castings
  - Developing Mg casting quality map
- University of Michigan (Academic)
  - Developing empirical micromechanical ductility modeling
  - Collaborating on characterization of microstructure and defect feature
  - Collaborating on development of Mg casting quality map

Proposed Future Work

- Evaluate approaches for predicting knit lines and ductility variability
- Improve quality mapping capability
- Complete fractographic analysis for empirical micromechanical model
- For synthetic microstructures, extend the modeling regime to include other porosities up to 10% and maximum pore size up to 500μm
- Perform actual microstructure-based finite element models based on X-ray tomography to validate the modeling method
- Experimentally quantify size-dependent critical strain/strength
- Perform actual microstructure-based finite element analysis to examine the interactions and competitions between the pores and the brittle eutectic β phase
- Quantify the skin effects on the predicted ductility with various thicknesses of pore-free zone

Technical Back-up Slides

HPDC Mg Processing-Structure-Property ICME Foundational Engineering Problem Linkages



Alloy compositions

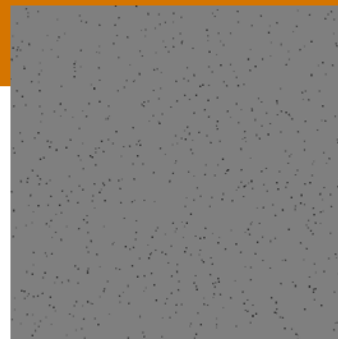
Table 1. Chemical Composition of Alloys

Alloy	Al wt.%	Zn wt.%	Mn wt.%	Si wt.%	Fe wt.%	Cu wt.%
AM50	5.69	0.057	0.37	0.006	0.0053	0.0034
AM60	4.56	0.052	0.37	0.006	0.0060	0.0041

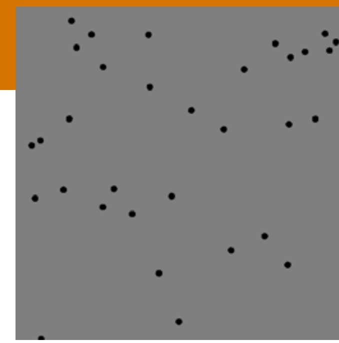
Examples of Synthetic Microstructures

Pore Volf. 1%

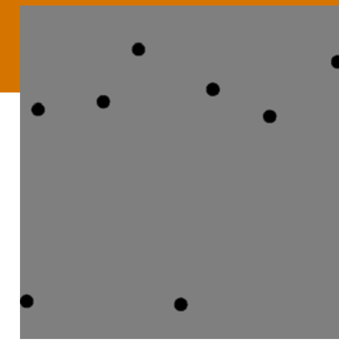
Const. pore size



PS 4um



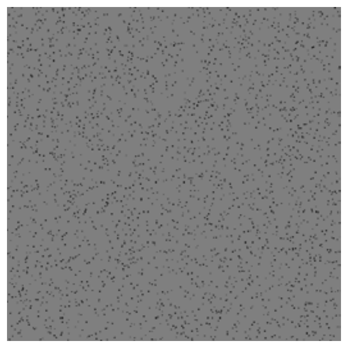
PS 20um



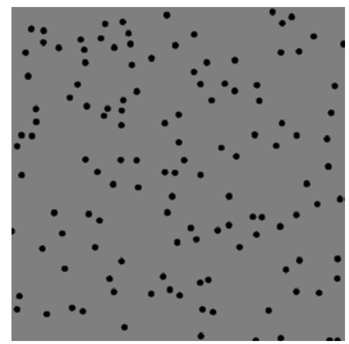
PS 40um

Pore Volf. 4%

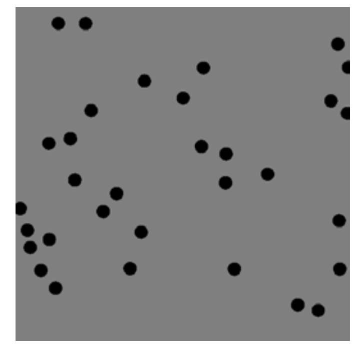
Const. pore size



PS 4um



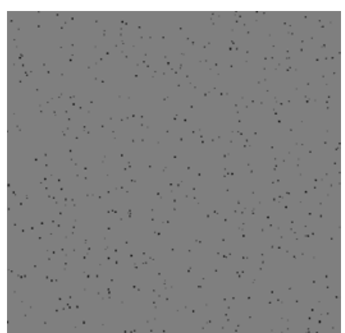
PS 20um



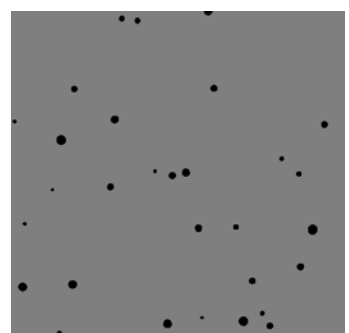
PS 40um

Pore Volf. 1%

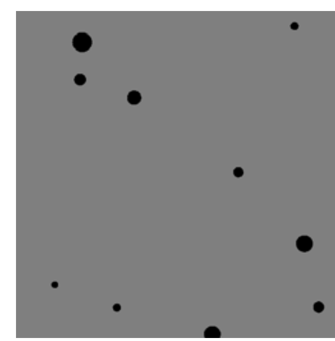
Distri. pore size



AVG. PS 4um

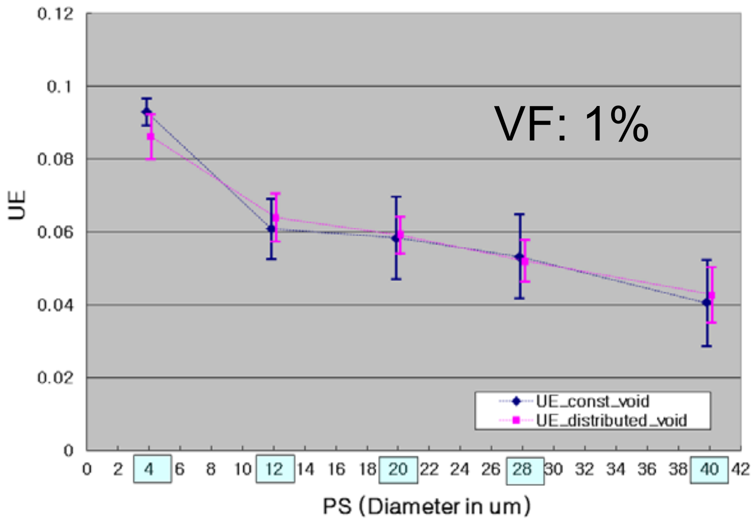


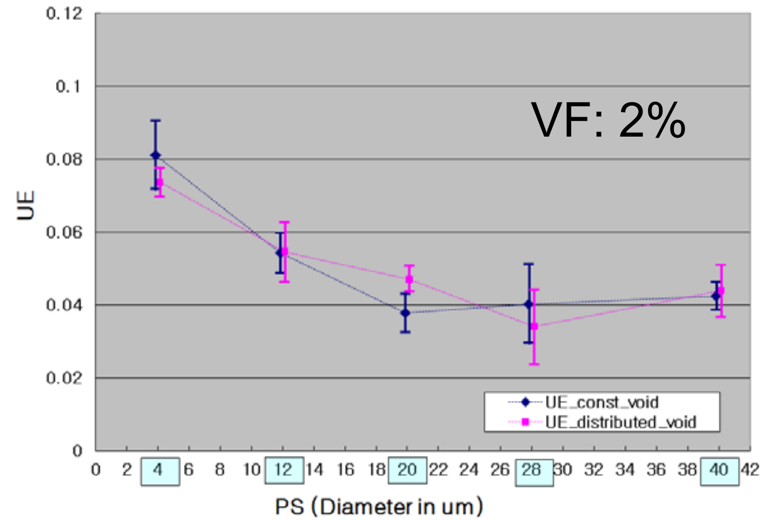
AVG. PS 20um

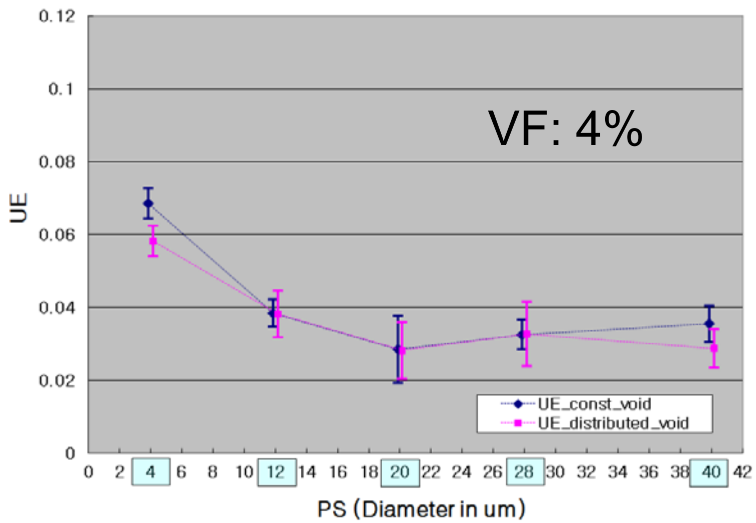


AVG. PS 40um

Effects of Pore Size Distribution







- The two pore size distributions considered here do not have significant difference in the ductility

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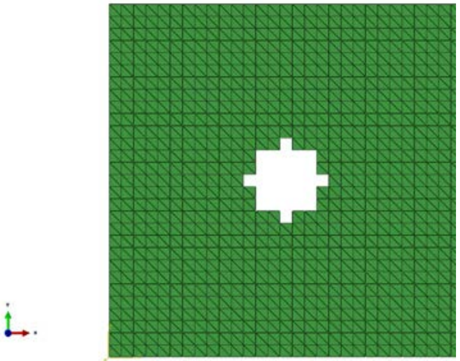
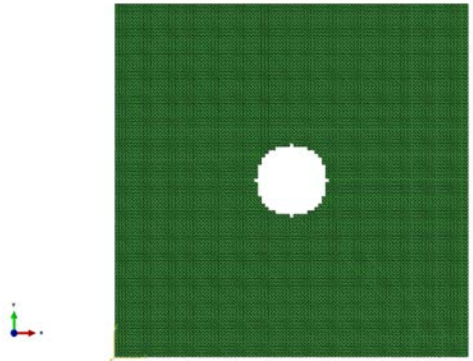
Technical Accomplishments
--Mesh Size Effects Study

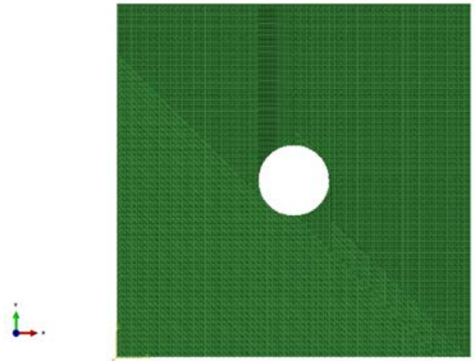
- Used hole models (1mmx1mm) with mesh size ranging from 1um to 50um
- Critical strain was correspondingly determined for each mesh size by adjusting critical strains to have the same uniform elongation as that of base model



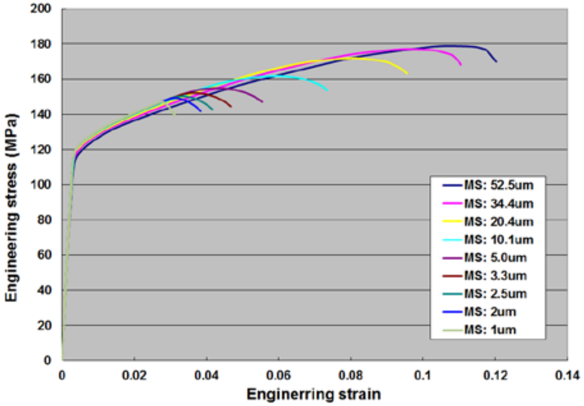
MS: 34.4um



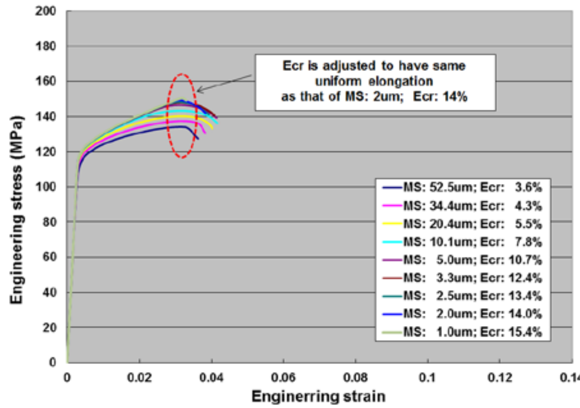
MS: 10.1um



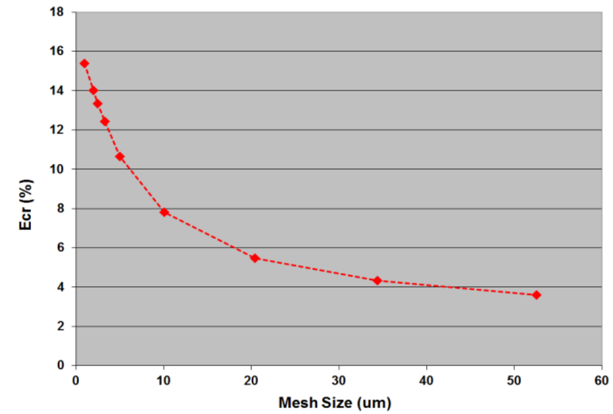
MS: 2.5um



S-E curves for different mesh size models (based on same Ecr=14%)

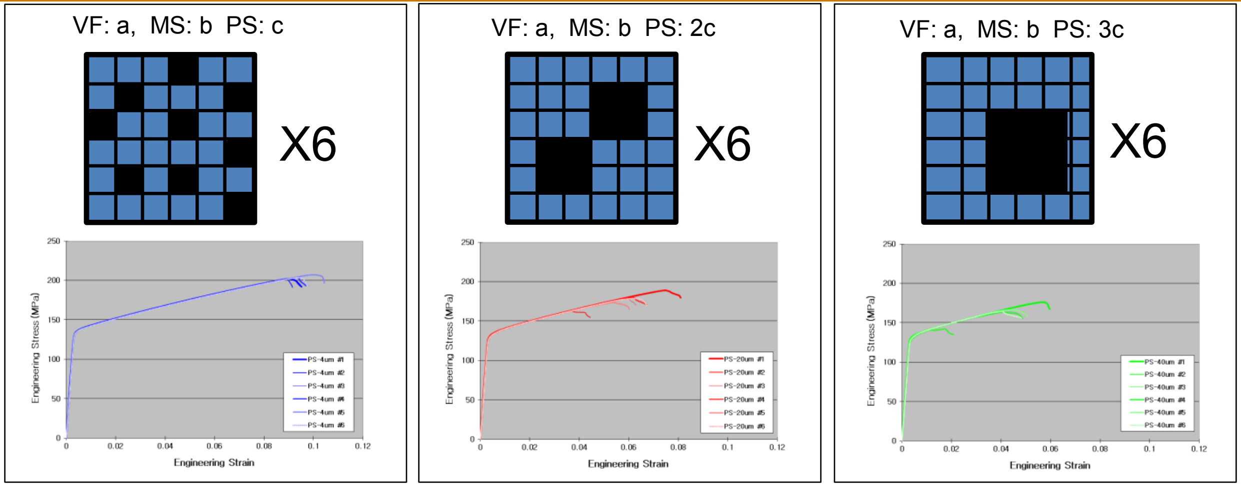


S-E curves with same UE (based on adjusted Ecr)

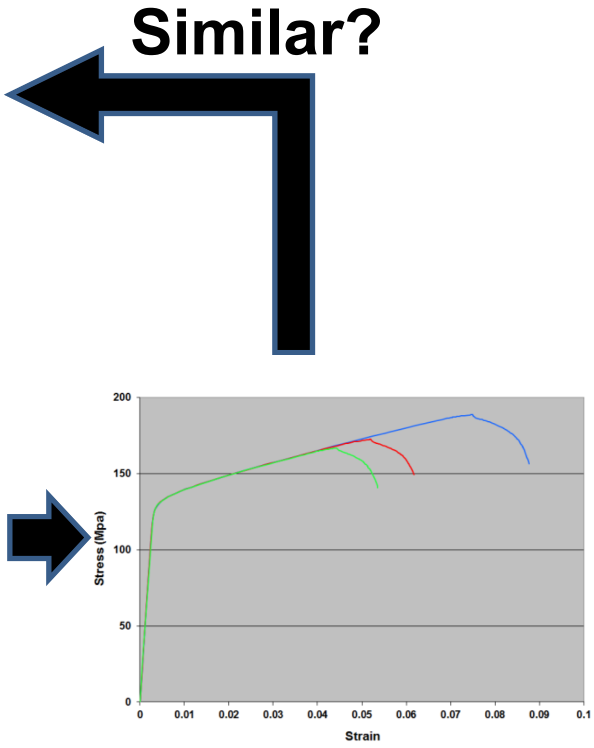


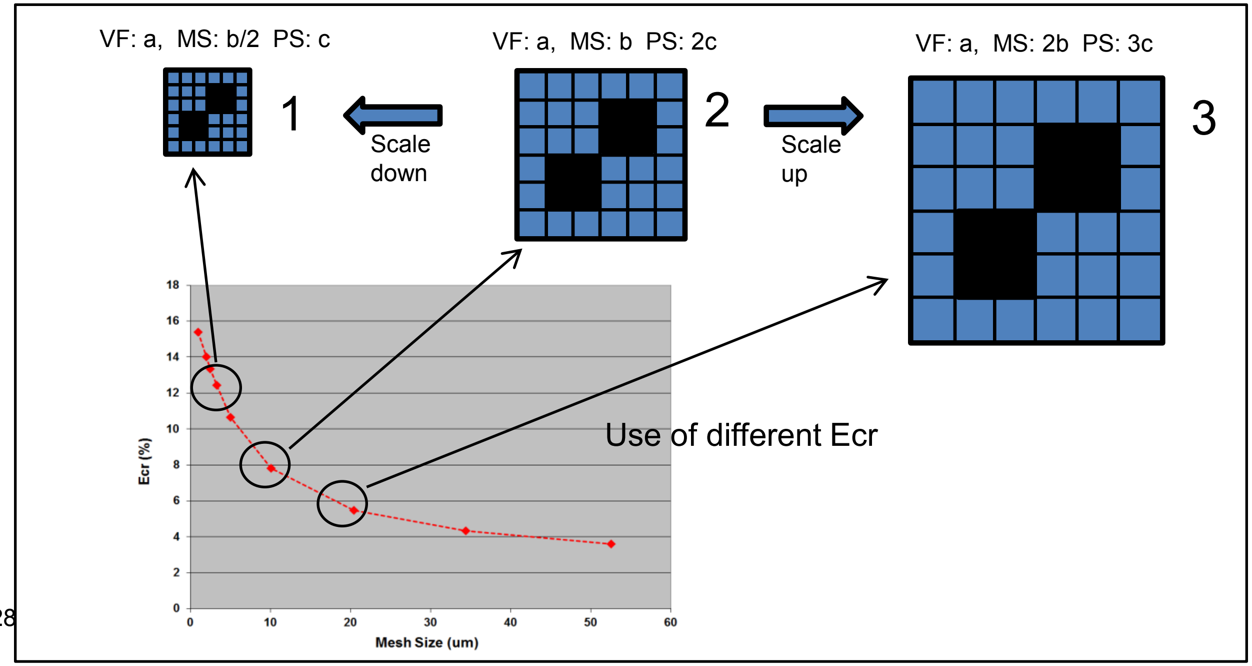
Mesh size effect on Ecr

Technical Accomplishments --Scalability Study (Concept)



- Can the S-E curves from scaled models be similar to the avg. S-E curves on the left-side?

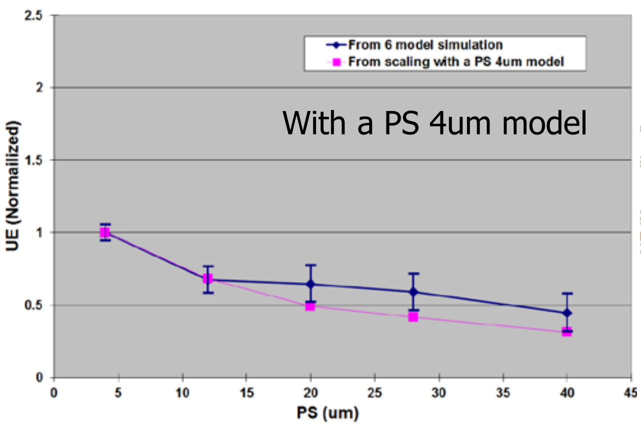


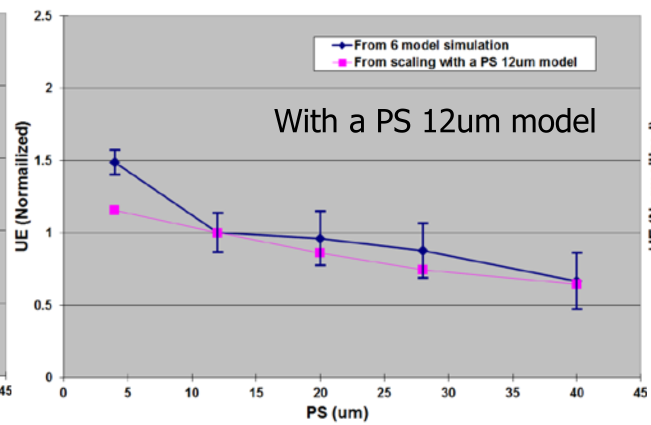


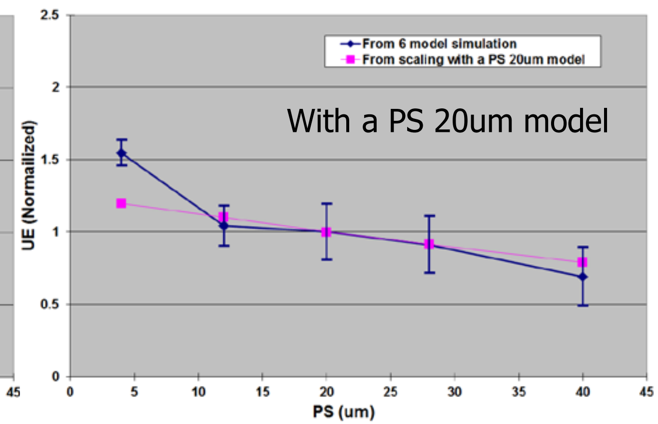
S-E curves from scaled models

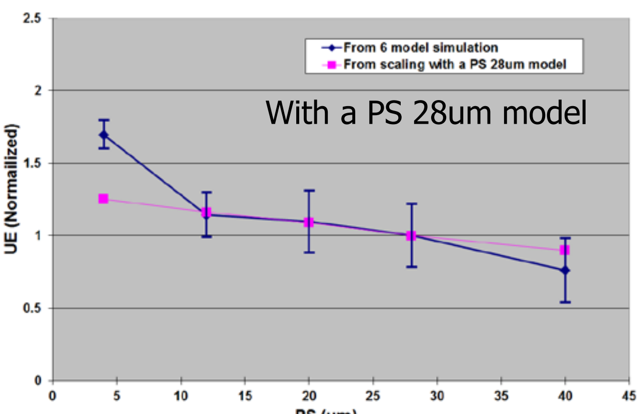
Technical Accomplishments --Scalability Study (Application)

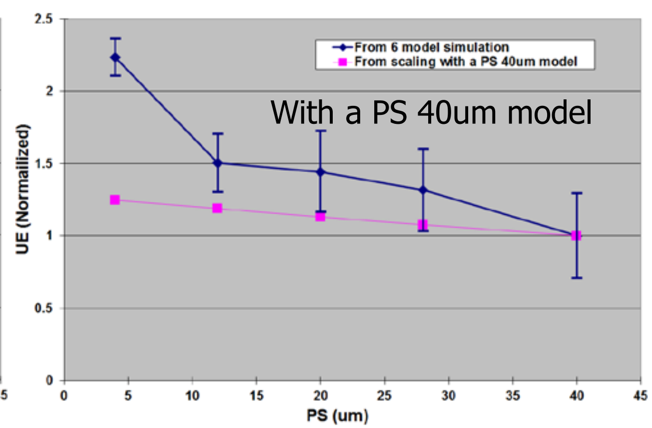
- Uniform elongations (normalized) based on scaling method are compared with those predicted from 6 model simulations
- Scaling with PS 4um/40um models do not seem to match well with prediction from 6 model simulations
  - Different pore shape (for PS 4um models) and pore distribution (relatively uneven distribution for PS 40um models) are suspected to be the sources for the discrepancy











- Within the ranges considered in this study, scalability appears to be applied to the models with reasonable pore shapes/distributions