



Modeling Spin Testing Using Location Specific Material Properties

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Scientific Forming Technologies Corporation

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Participants

- Funding Agency
 - U. S. Air Force STTR Program
- Research partners
 - Scientific Forming Technologies Corporation
 - Northwestern University
 - ATI Ladish
- Industrial observers
 - GE, Honeywell, Pratt and Whitney, Rolls Royce

Project Objectives

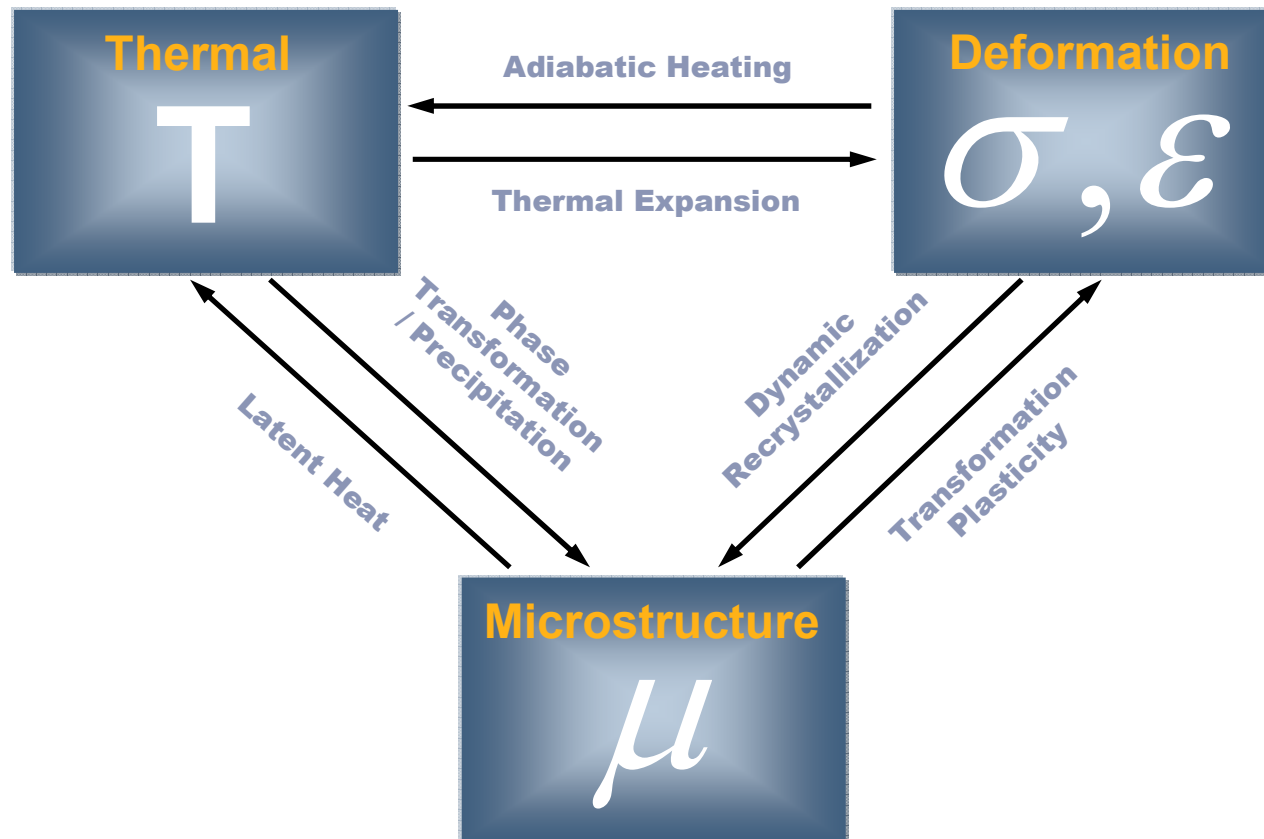
- Establish an infrastructure in DEFORM for location specific microstructure features such as grain size, precipitate size / shape
- Develop and implement grain evolution models as a function of grain curvature, Zener pinning (precipitates)
- Develop and implement fast acting precipitation models
- Implement Langdon and Dorn Creep Models as a function of grain size, precipitate size and volume fraction in addition to temperature, strain and stress
- Develop flow stress models as a function of grain size and precipitate size in addition to temperature, strain and strain rate
- Demonstrate spin pit test / service models using location specific material properties

Challenges

- **Prior to this project, there was no modeling system** available to the industry which would take location specific material properties including microstructural features and prior residual stresses into account in predicting the disk behavior during spin test
- Representation and evolution of location-specific material properties (microstructure) during thermomechanical processing and under service conditions is critical
- There is a need for a modeling system that is capable of linking microstructure evolution and property response (strength, creep, flow stress) for performance evaluation

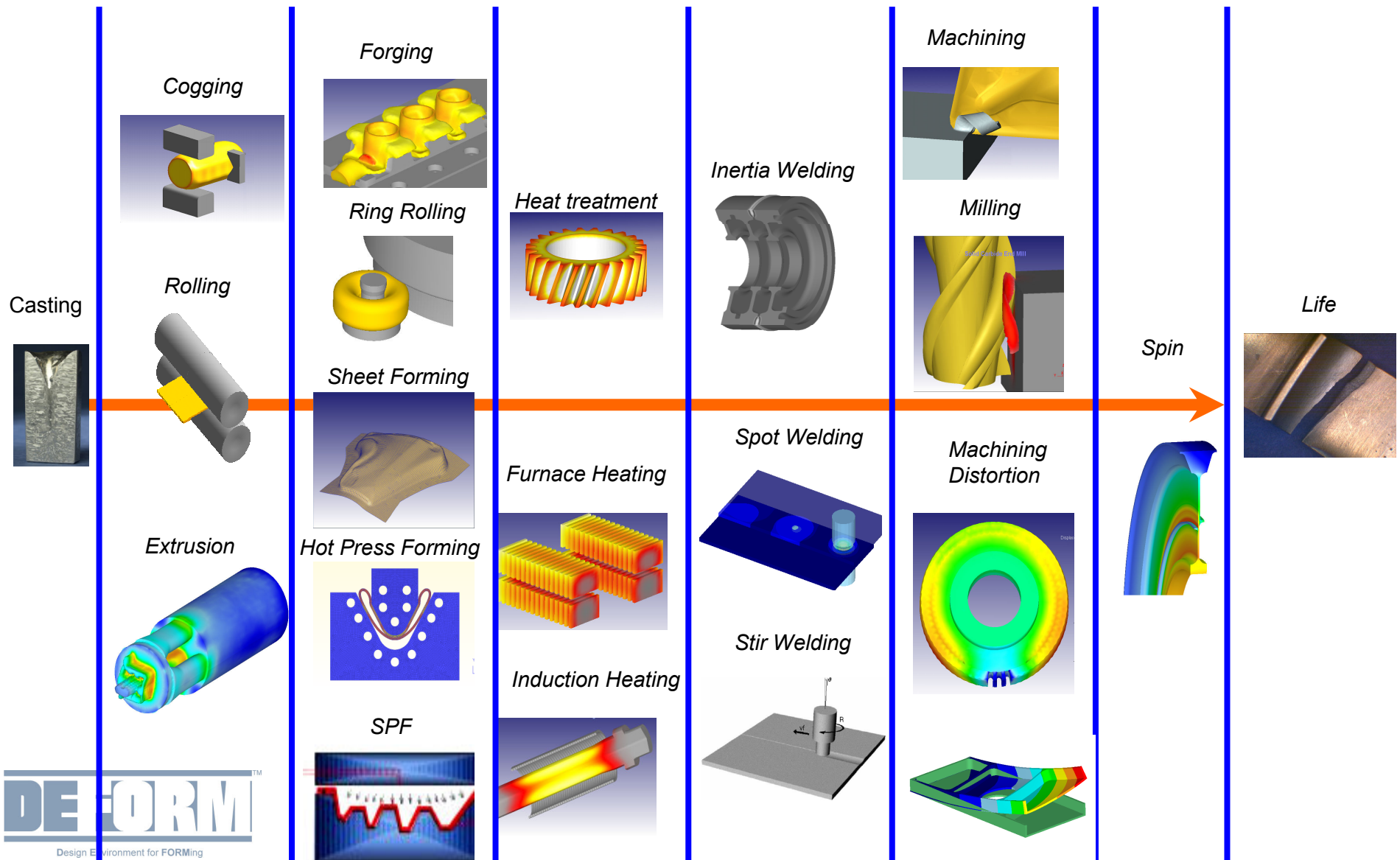
Current DEFORM Integrated Process Simulation Architecture

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Integrated Process Modeling

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Corporation



Empirical – JMAK Method

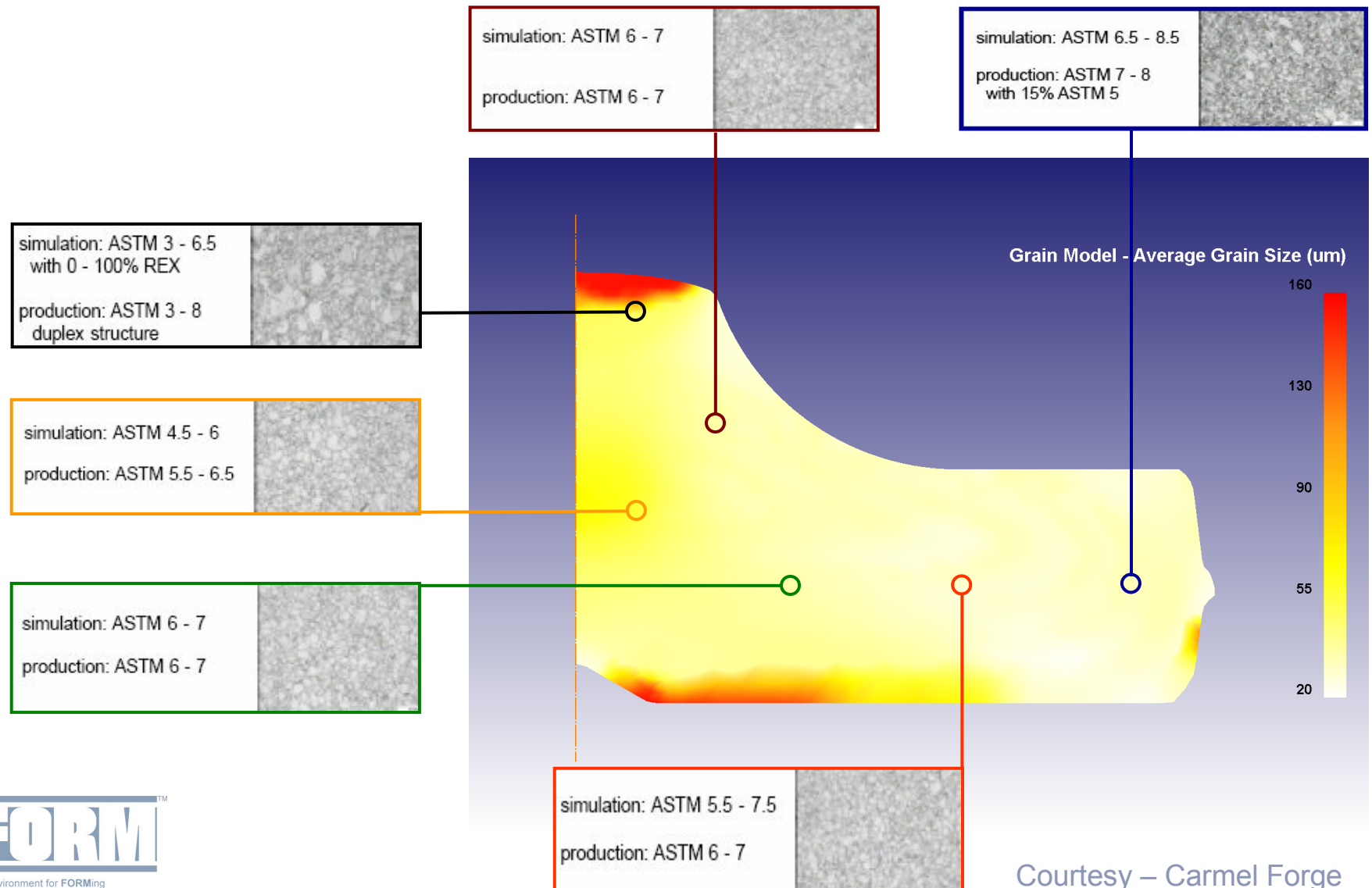
Input:

- initial average grain size distribution
- strain, temperature, strain rate history
- grain growth equations
- recrystallization kinetics
 - dynamic
 - metadynamic
 - static

Output:

- grain size contours
- percentage recrystallization

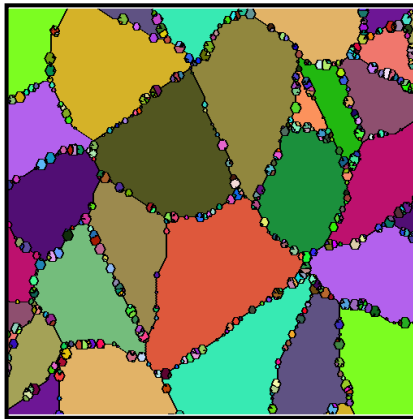
Location Specific Grain Size (Component Level Prediction)



Location Specific Microstructure Evolution (at a select point)

- Developed a proven phase transformation capability (*TTT, Magee function, others*)
- Recently developed high-fidelity 2D “Cellular Automata” model (*virtual microstructure*)
- Currently developing a fast-acting “Statistical” model (*integrated with FEM*)

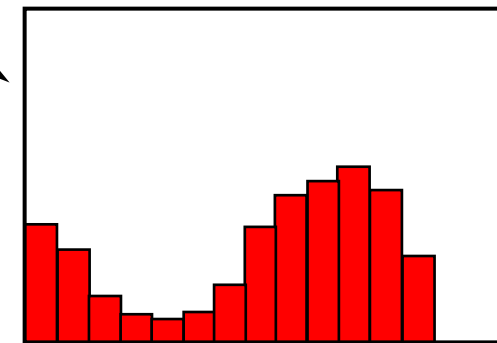
2D Spatially Representative Model



Statistically
equivalent

Grain
boundary
surface
area

Statistically Representative Model



Misorientation angle θ

Microstructure Features

Values are computed from
2D map, which evolves as
a function of state
variables and neighbor-
to-neighbor reactions

Grain size
Dislocation density
Fraction recrystallized
Rex/Unrex surface area
etc.

Values stored explicitly,
and calculated via
statistical equations
which are solely
functions of state
variables

Project Significance to Industry

- Capability to include location specific material properties and microstructure in spin test modeling
- Improved understanding of interaction of microstructural features on mechanical property response under service conditions
- Ability to predict disk component performance during spin testing and service
- Ability to understand and optimize the processing window during the manufacture of jet engine components to maximize its performance in service

SFTC Tasks

Task 3.1.1. Material Representation

Task 3.1.2 Model representation

Task 3.1.3. System Integration

Task 3.1.4. Demonstration / Validation of models

SFTC Accomplishments

- Implemented grain growth as $f(\text{grain curvature})$
- Implemented Zener pinning as $f(\text{ppt size})$
- Implemented new tabular creep model and flow stress model in DEFORM
 - Tabular creep strain rate is $f(\epsilon, \sigma, T, D, \text{ppt})$
 - Tabular flow stress is $f(\epsilon, \dot{\epsilon}, T, D, \text{ppt})$
- Infrastructure to account for location-specific particle size and shape is available in DEFORM
- Demonstrated virtual spin-pit test model

Modeling Approach

Model the DMHT process in a
nickel-base superalloy turbine disk



Model local microstructural evolution as a
function of TMP



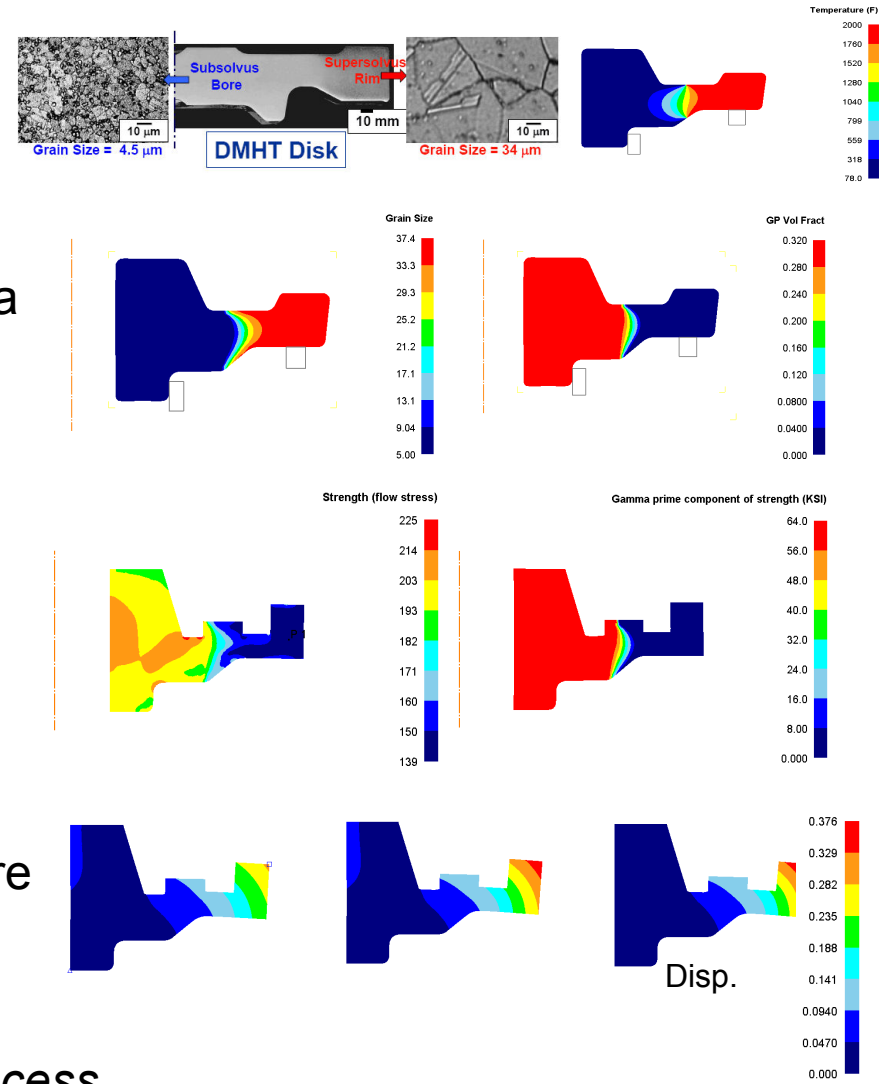
Machine to final disk shape (carry over
microstructure features, predict
distortion due to residual stress)



Predict performance of the disk during
service as a function of material
properties resulting from microstructure
features and processing-induced
residual stresses



Iterate to improve design of disk, DMHT process



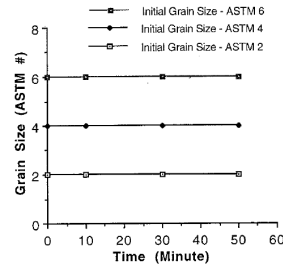
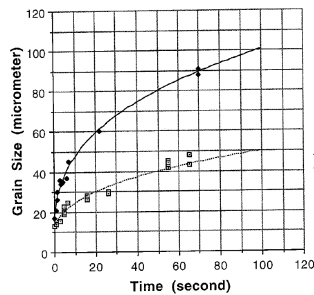
Grain Growth, Gamma Prime Precipitation Models

- Hybrid model for short term and long term grain growth

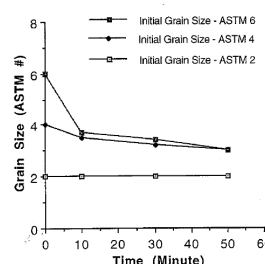
$$d^m = d_0^m + A \exp\left(-\frac{Q}{RT}\right)t$$

$$d = BT^n$$

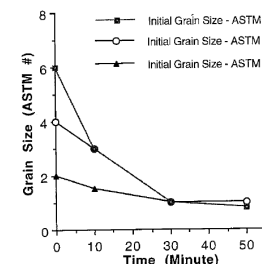
$$d_{\text{hybrid}} \text{ (DEFORM)}$$



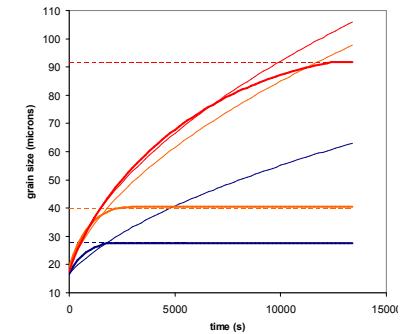
1010C
(1850°F)



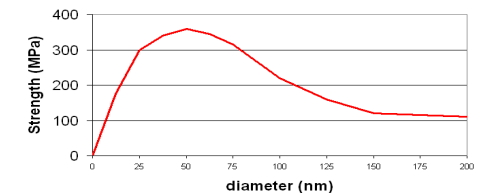
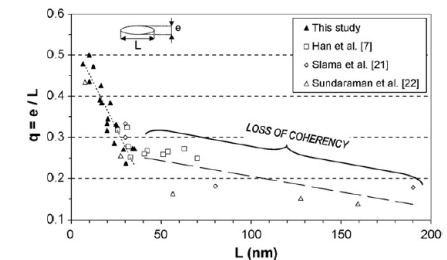
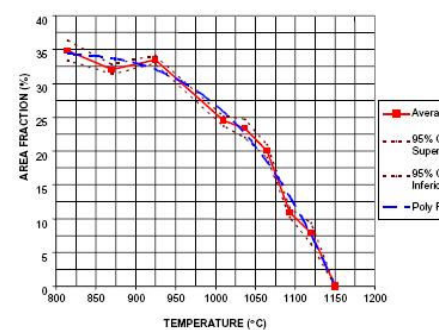
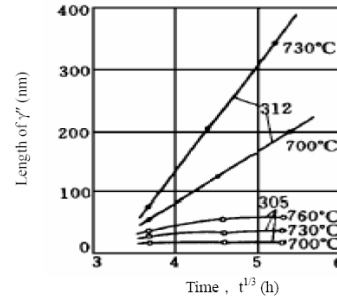
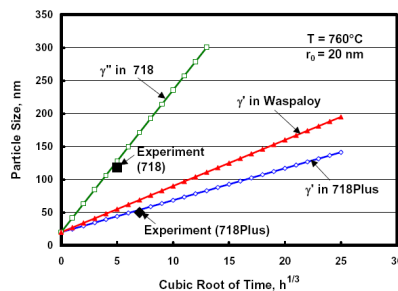
1066C
(1950°F)



1121C
(2050°F)



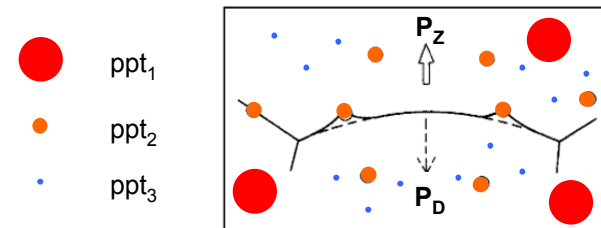
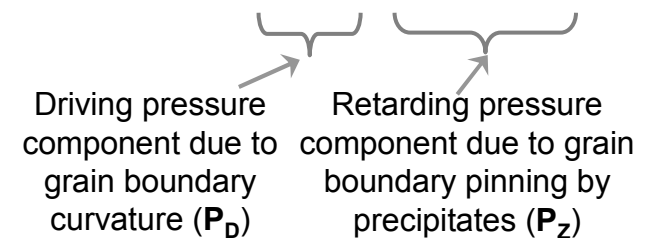
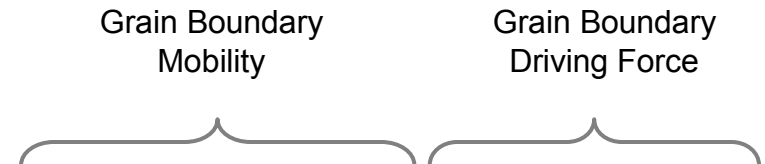
- Model for gamma prime volume fraction prediction



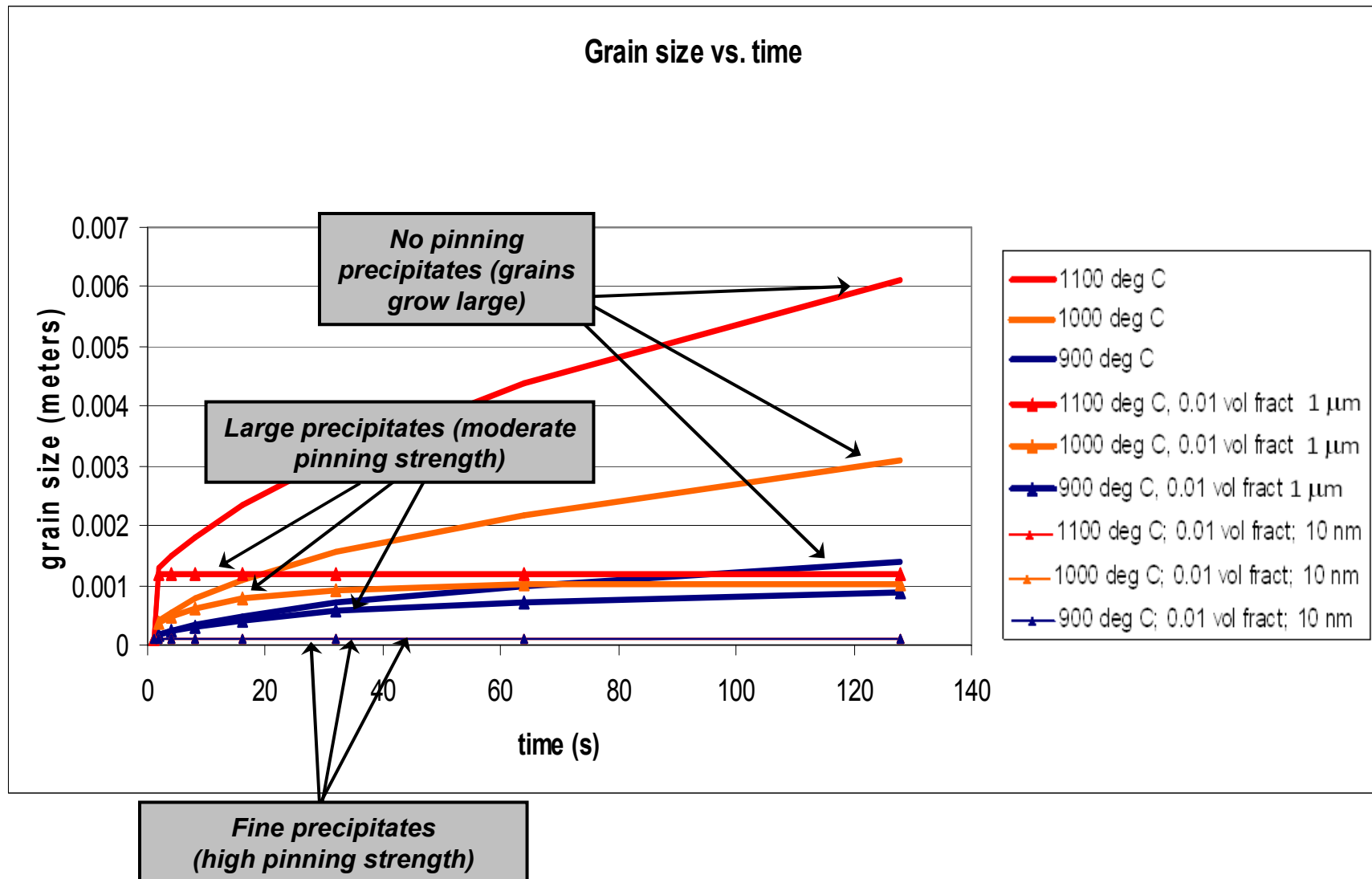
New Mechanism-Based Grain Growth model

- **Classic DEFORM model: empirical**
 - Fits exponential grain growth equation to observed grain size measurements, as $f(t, T, d_0, Q, \text{constant})$
- **New Mobility-based grain growth model**
 - Driving force is reduction of free surface energy
 - Computes velocity of grain boundary as $f(T, Q, \text{mobility constant, and } D \text{ (grain size) and } d \text{ (ppt size)})$
 - Grain Boundary Velocity = (Mobility) * (Driving Force)
 - M_0 = mobility constant
 - Q = activation energy
 - R = gas constant
 - T = temperature
 - γ_s = grain boundary surface energy
 - D = grain diameter
 - F_v = volume fraction of precipitates
 - γ_b = surface energy of precipitate/matrix interface
 - d = precipitate diameter

$$d_g = \left[d_0^m + a_9 t \exp\left(\frac{-Q_9}{RT}\right) \right]$$

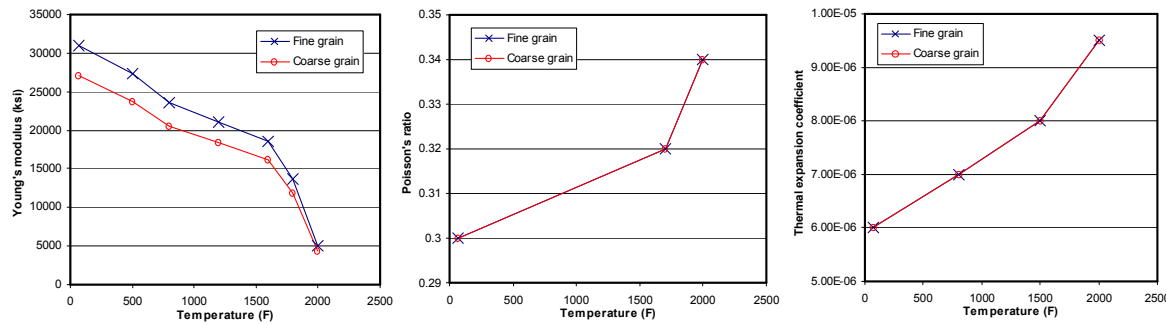


Results of new grain growth model

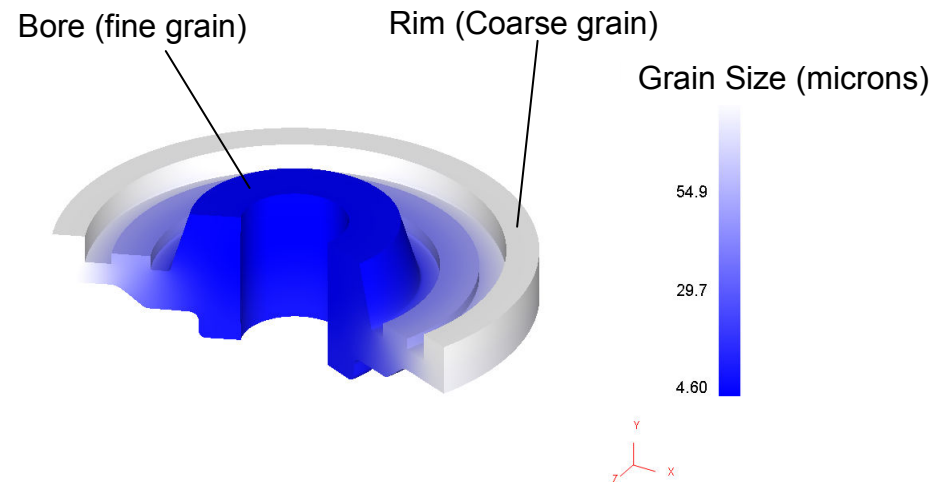
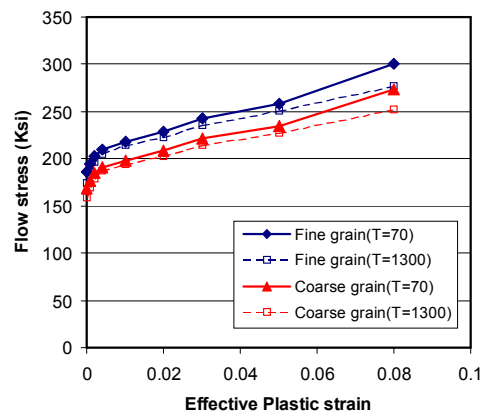


Physical Properties of coarse, fine grained regions (LSHR)

- Elastic properties

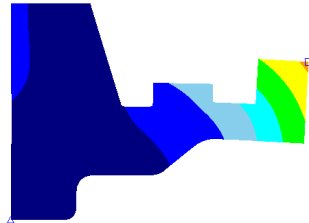


- Flow stress

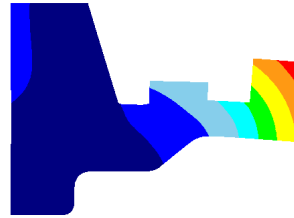


Service Condition Analysis

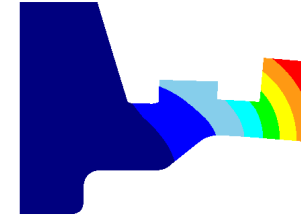
Centrifugal Loading



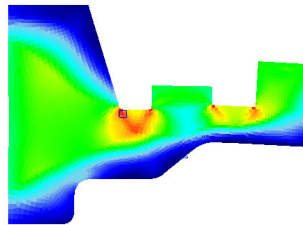
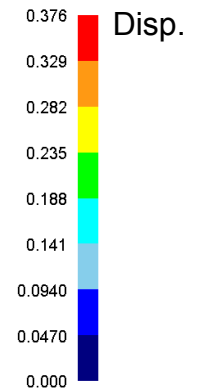
Uniform grain size, non-uniform initial residual stress distribution



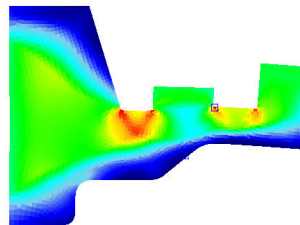
Non-uniform grain size, non-uniform initial residual stress distribution



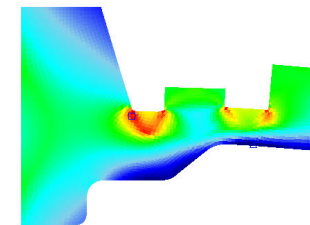
Non-uniform grain size, zero initial residual stress distribution



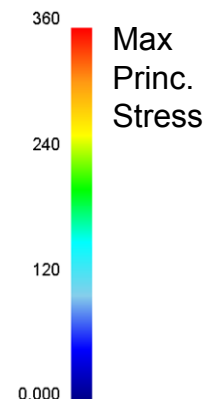
Uniform grain size, non-uniform initial residual stress distribution



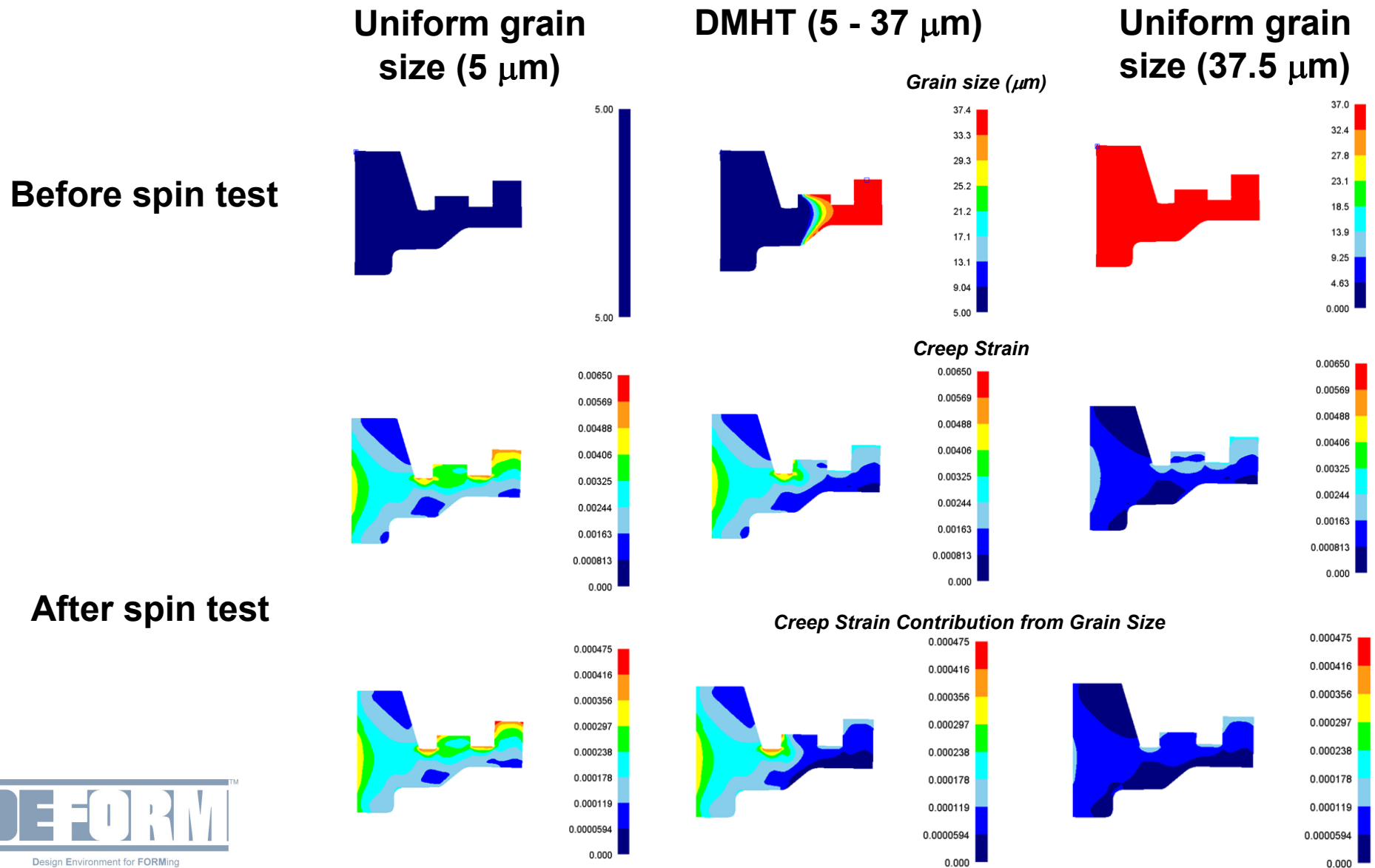
Non-uniform grain size, non-uniform initial residual stress distribution



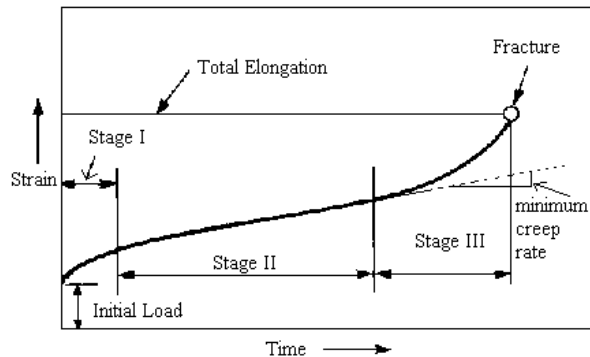
Non-uniform grain size, zero initial residual stress distribution



Permanent strain after spin test as a function of grain size



Creep Models as f(microstructure)



Creep strain rate **tabulated**
as function of state
variables (T , σ , ε) and
microstructure (**grain size**,
precipitate size)

	T_1	ε_1	D_1	ppt_1
$\dot{\varepsilon}$	1e-4	1e-4	1e-4	1e-4

	T_2	ε_1	D_1	ppt_1
$\dot{\varepsilon}$	1e-3	1e-3	1e-3	1e-3

Constitutive Models

Dorn Model

(function of 2nd phase pinning)

$$\dot{\varepsilon} = A \left(\frac{\sigma_a - \sigma_b}{E} \right)^n \exp \left[-\frac{Q_{real}}{RT} \right]$$

A	constant
E	elastic modulus
σ_a	applied stress
σ_b	back-stress
n	stress exponent
Q_{real}	activation energy for creep (defined later)
R	gas constant
T	temperature

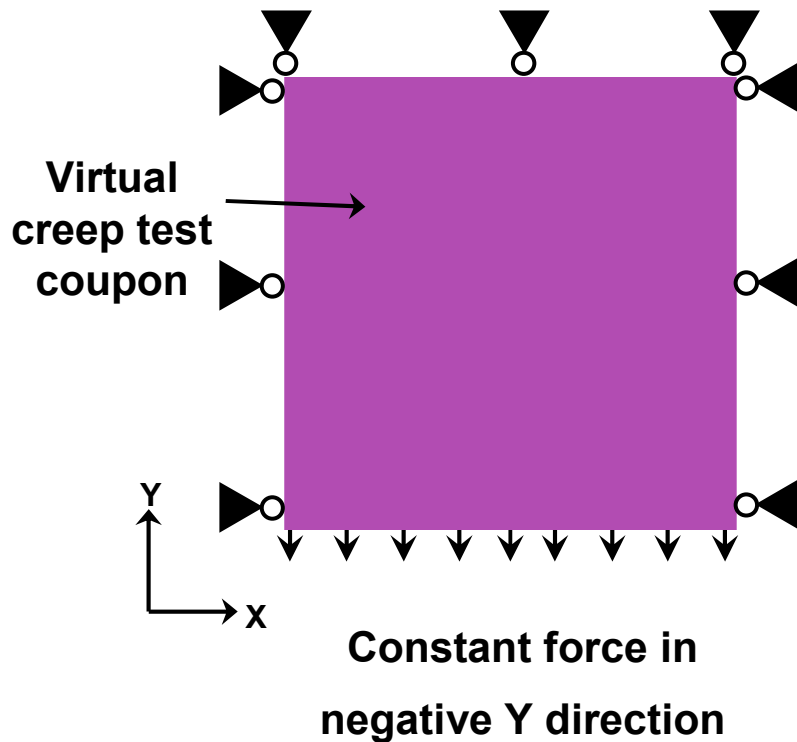
Langdon Model

(function of matrix grain size)

$$\dot{\varepsilon} = \frac{ADGb}{kT} \left(\frac{b}{d} \right)^p \left(\frac{\sigma}{G} \right)^n$$

D	appropriate diffusion coefficient $D = D_0 \exp \left(-\frac{Q}{RT} \right)$
G	shear modulus
b	Burgers vector
k	Boltzmann's constant
p	inverse grain size exponent
n	stress exponent
A	dimensionless constant

Constant Load Creep Test Simulation (Tabular Data)



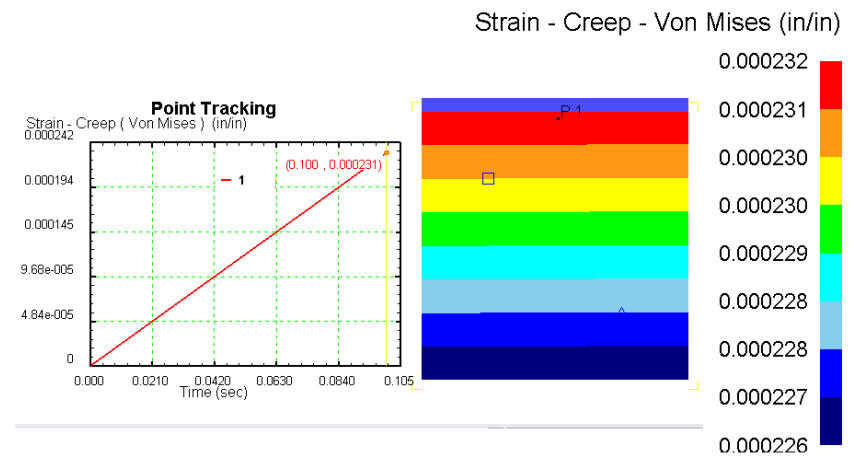
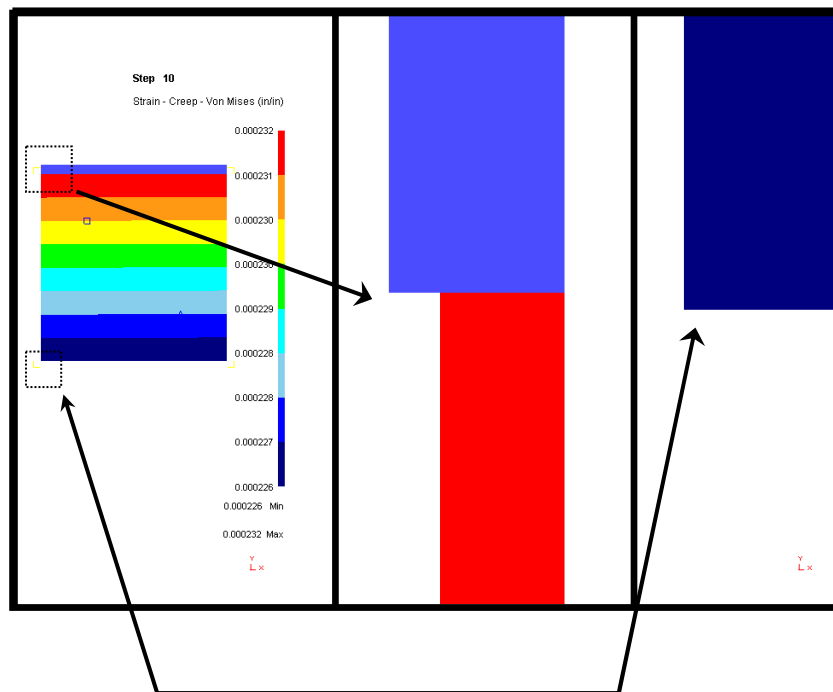
Fixed velocity boundary conditions in Y direction

Sliding permitted in X direction

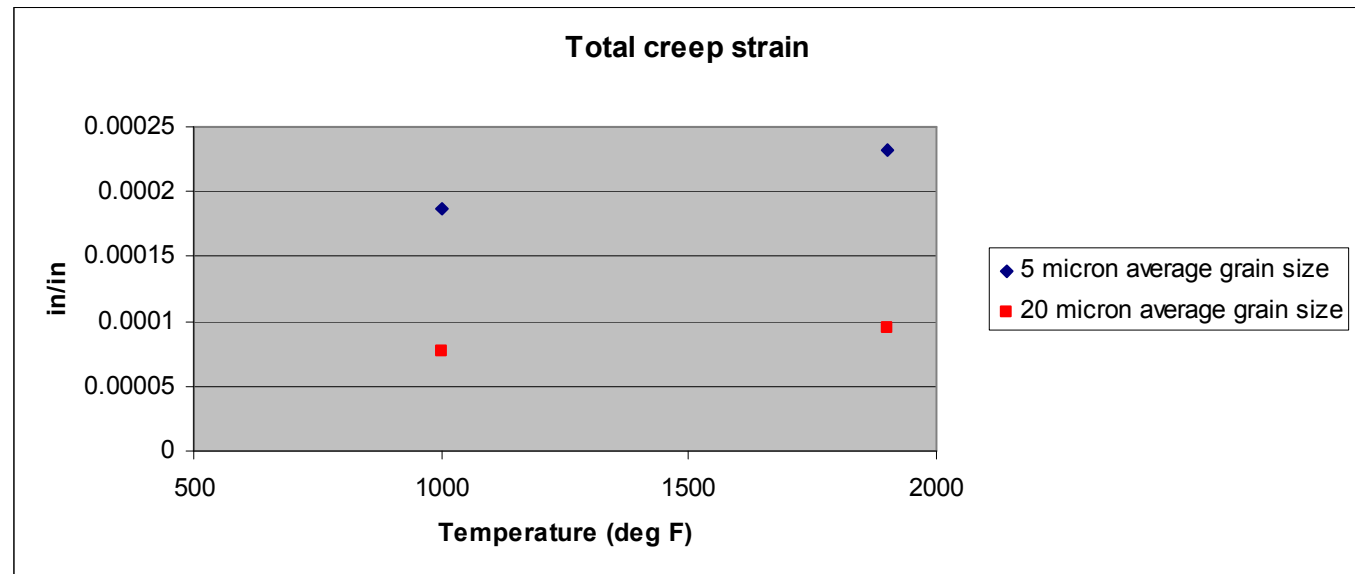
Creep strain rate for $T_1, \sigma_1, GS_1, ppt_1$
 Creep strain rate for $T_1, \sigma_1, GS_1, ppt_2$
 Creep strain rate for $T_1, \sigma_1, GS_2, ppt_1$
 Creep strain rate for $T_1, \sigma_1, GS_2, ppt_2$
 Creep strain rate for $T_1, \sigma_2, GS_1, ppt_1$
 Creep strain rate for $T_1, \sigma_2, GS_1, ppt_2$
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 Creep strain rate for $T_2, \sigma_1, GS_2, ppt_1$
 Creep strain rate for $T_2, \sigma_1, GS_2, ppt_2$
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 Creep strain rate for $T_2, \sigma_2, GS_1, ppt_2$
 Creep strain rate for $T_2, \sigma_2, GS_2, ppt_1$
 Creep strain rate for $T_2, \sigma_2, GS_2, ppt_2$

T1	1000			t2	2000		
s1	100			s1	100		
g1	10			g1	10		
p1	0.1	1.00E-05		p1	0.1	1.00E-04	
T1	1000			t2	2000		
s1	100			s1	100		
g1	10			g1	10		
p2	0.5	1.00E-04		p2	0.5	1.00E-03	
T1	1000			t2	2000		
s1	100			s1	100		
g2	50			g2	50		
p1	0.1	2.00E-05		p1	0.1	2.00E-04	
T1	1000			t2	2000		
s1	100			s1	100		
g2	50	2.00E-04		g2	50	2.00E-03	
p2	0.5			p2	0.5		
t1	1000			t2	2000		
s2	250	5.00E-05		s2	250	5.00E-04	
g1	10			g1	10		
p1	0.1			p1	0.1		
t1	1000			t2	2000		
s2	250	5.00E-04		s2	250	5.00E-03	
g1	10			g1	10		
p2	0.5			p2	0.5		
t1	1000			t2	2000		
s2	250	1.00E-04		s2	250	1.00E-03	
g2	50			g2	50		
p1	0.1			p1	0.1		
t1	1000			t2	2000		
s2	250	1.00E-03		s2	250	1.00E-02	
g2	150			g2	150		
p2	0.5			p2	0.5		

Creep Coupon Animation



Example Creep Coupon Results (function of grain size, temperature)

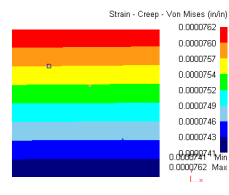
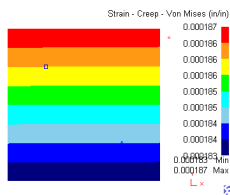


5 microns

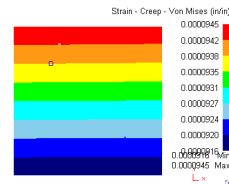
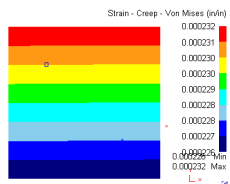
20 microns

Creep Strain

1000 deg F



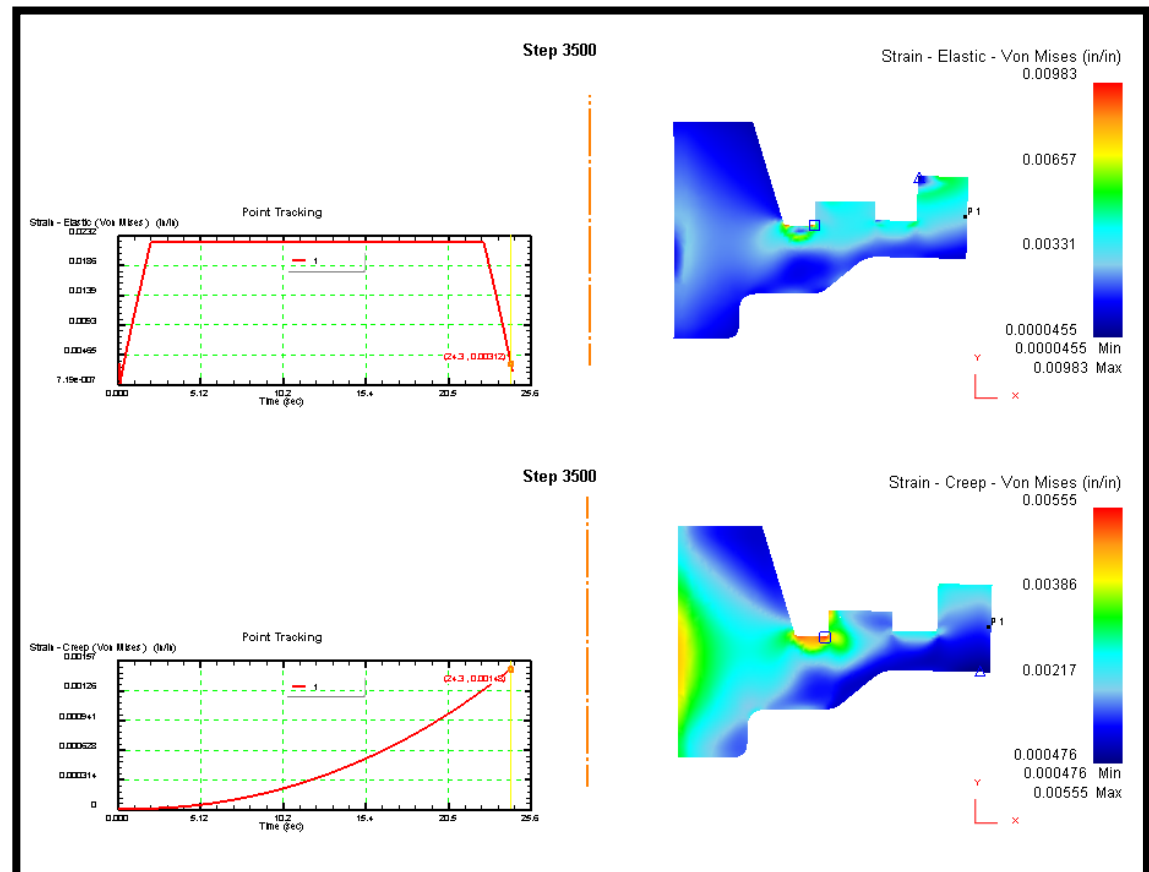
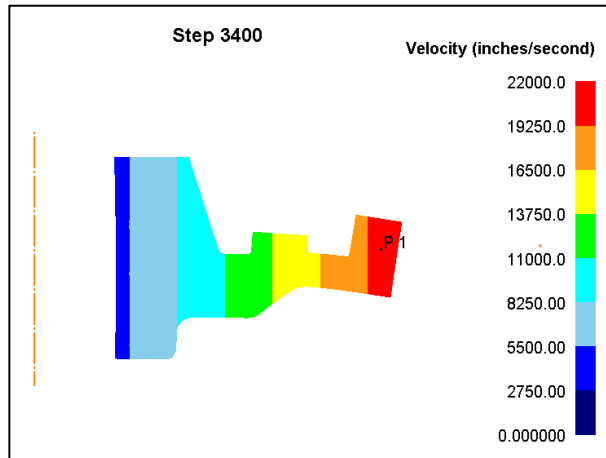
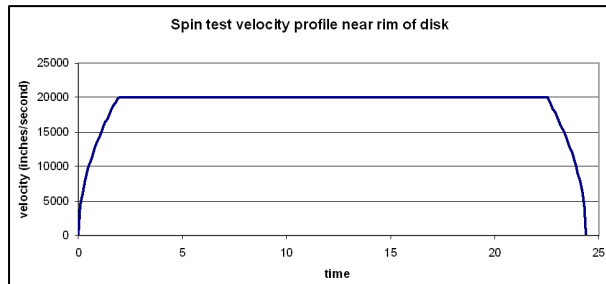
1900 deg F



	Grain Size = 5 microns	Grain Size = 20 microns
T = 1000 deg F	0.000187	0.0000762
T = 1900 deg F	0.000232	0.0000945

Simulated spin test results (Uniform Grain Size)

- Elastic and creep related distortion during simulated spin test

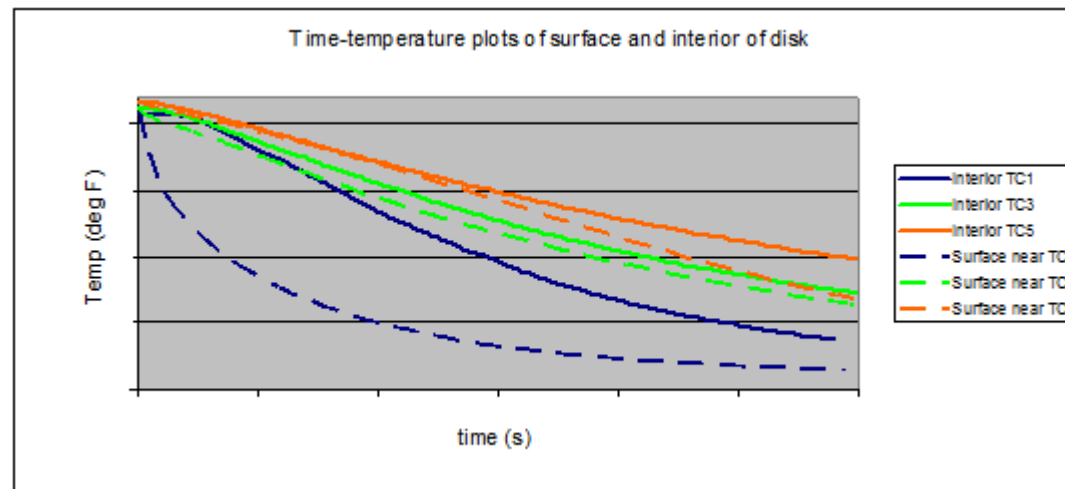


Ladish Tasks in Phase II

- Ladish provided time vs. temperature data for 5 critical locations in a DMHT LSHR disk
- This data was used by Northwestern University to establish/validate a fast acting precipitation model
- Ladish ran PrecipiCalc simulations of LSHR DMHT process and reported gamma prime precipitate volume fraction and size distribution

Time-temperature plots of disk cooling

- A DMHT LSHR heat treatment process simulation was performed by Ladish
- The DMHT process simulation was experimentally validated by Ladish
- Point tracked time-temperature histories of surface and interior points were exported
- The time-temperature histories were provided to NU for input to their PrecipiCalc simulations
- A fast acting precipitation model was derived

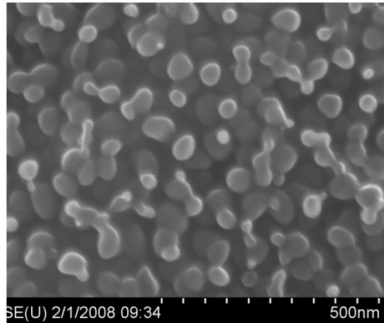


Northwestern University Task List

3.2. Northwestern University Tasks in Phase II

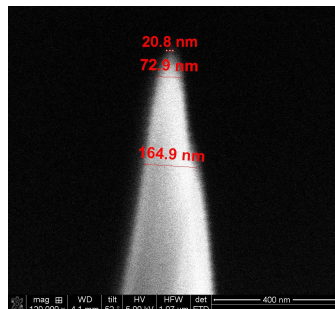
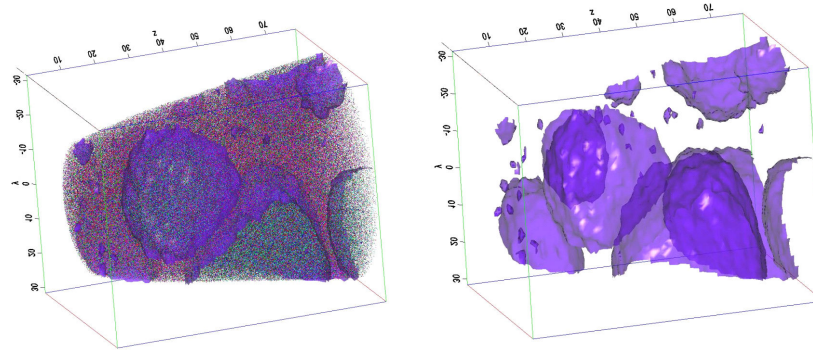
- Task 3.2.1. Fast acting Precipitation evolution models for DMHT processing of LSHR Disk
- Task 3.2.2. Constitutive models for strength, Zener pinning, LSHR
- Task 3.2.3. Microanalysis (FEG-SEM, atom probe, TEM) of LSHR

Material Characterization by Northwestern University



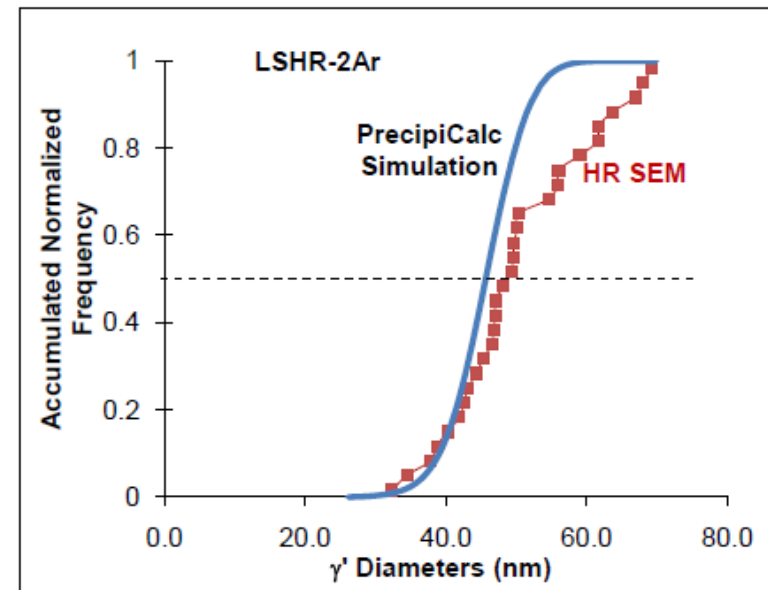
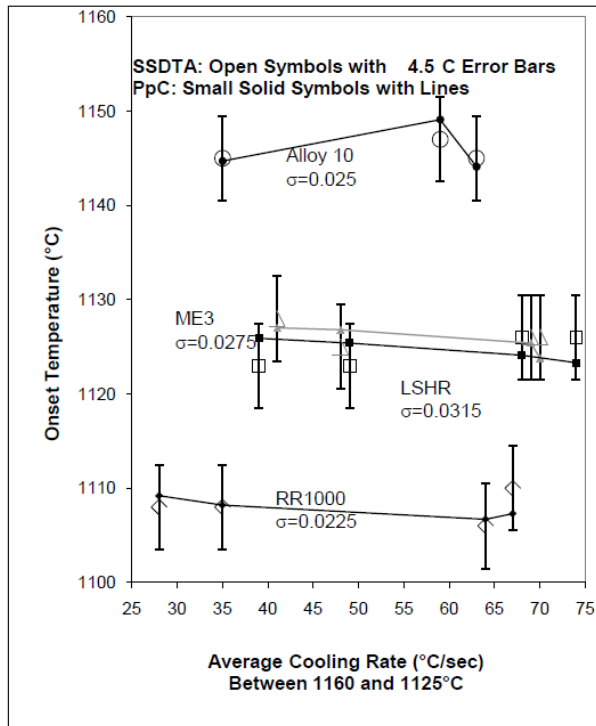
High-resolution SEM image of the secondary
gamma' distribution in LSHR

Characterization of size and
shape of secondary gamma
prime precipitates in LSHR via
LEAP study



Typical
LEAP specimen

Precipitate Nucleation Kinetics Characterization



Determination of nucleation kinetics for LSHR.
A coherent interfacial energy of 0.0315 J/m²
gives a best fit to the measured nucleation
undercooling in simulations employing the
PrecipiCalc simulation code

Gamma prime precipitate
diameter predicted by
PrecipiCalc simulation code vs.
experimentally observed data

PrecipiCalc Simulation Matrix

- A set of *PrecipiCalc* calculations with linear cooling at various solution treatment temperatures was conducted to form a set of calibration data.
- A series of PrecipiCalc simulations was performed, where solution temperatures varied from 1130 to 1190°C at every 5°C, and cooling rates vary from 0.7 to 12°C/s, with equal spacing in log scale.
- Parameters for the fast acting equations were determined with this calibration data set. γ' primary particles are presented below, although secondary and tertiary were also parameterized.

Primary γ' Microstructure at end of quenching:

Volume fraction (note, if result becomes negative, set it to zero):

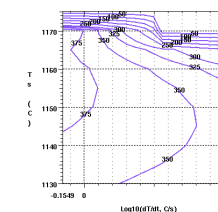
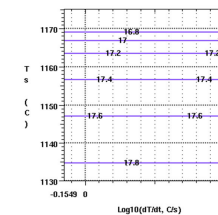
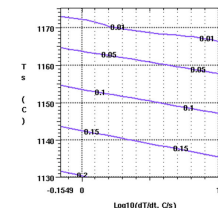
$$f_1(T_s, \dot{T}) = f_{\gamma'}^{eq}(T_s) + 0.85276 - 0.02967 \log_{10}(\dot{T}) - 0.00071497 T_s$$

Number density $N_1(T_s)$ (1/m³):

$$\log_{10}(N_1(T_s)) = 16.7 + 0.20673(1170 - T_s)^{0.46827}$$

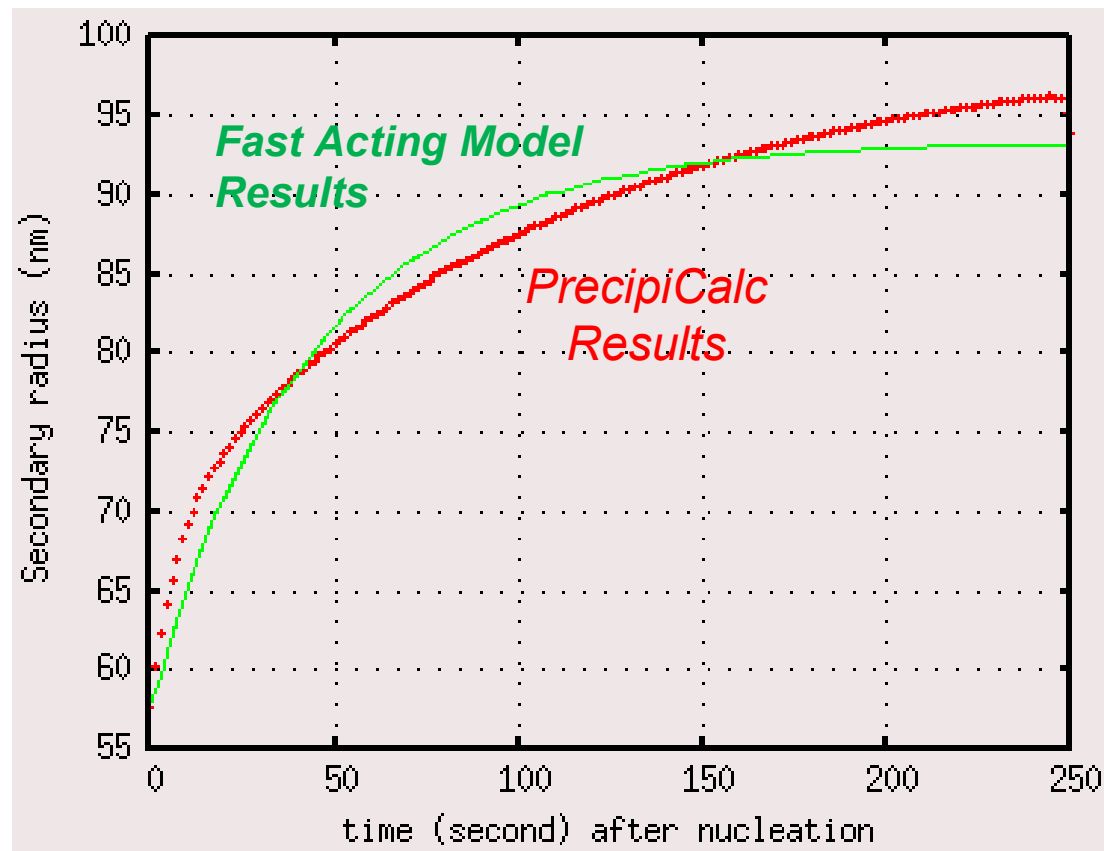
Mean particle radius R_1 (in meters):

$$R_1 = 0.877 \left[\frac{f_1}{N_1 \frac{4\pi}{3}} \right]^{\frac{1}{3}}$$

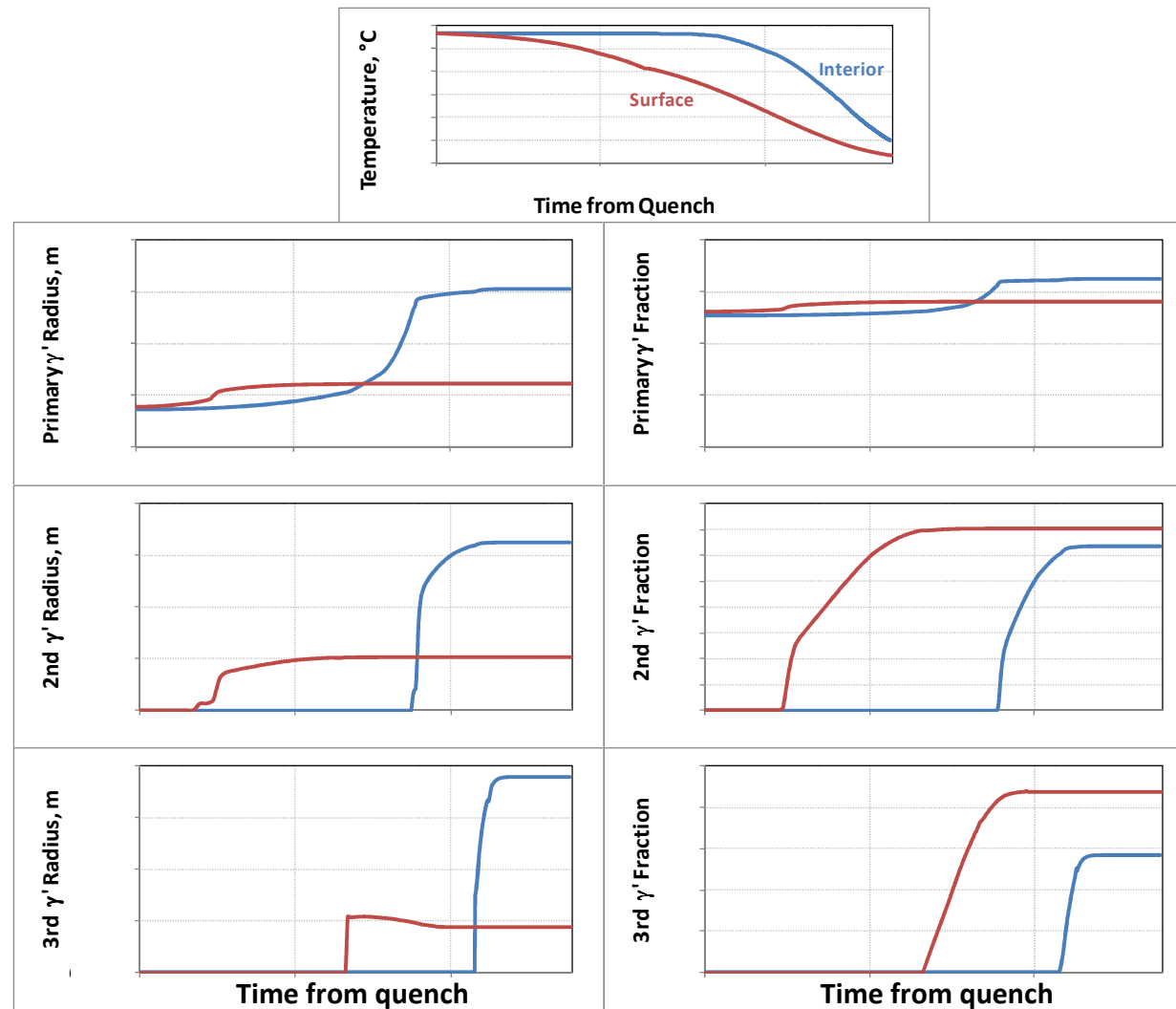


Comparison between PrecipiCalc and Fast Acting Model

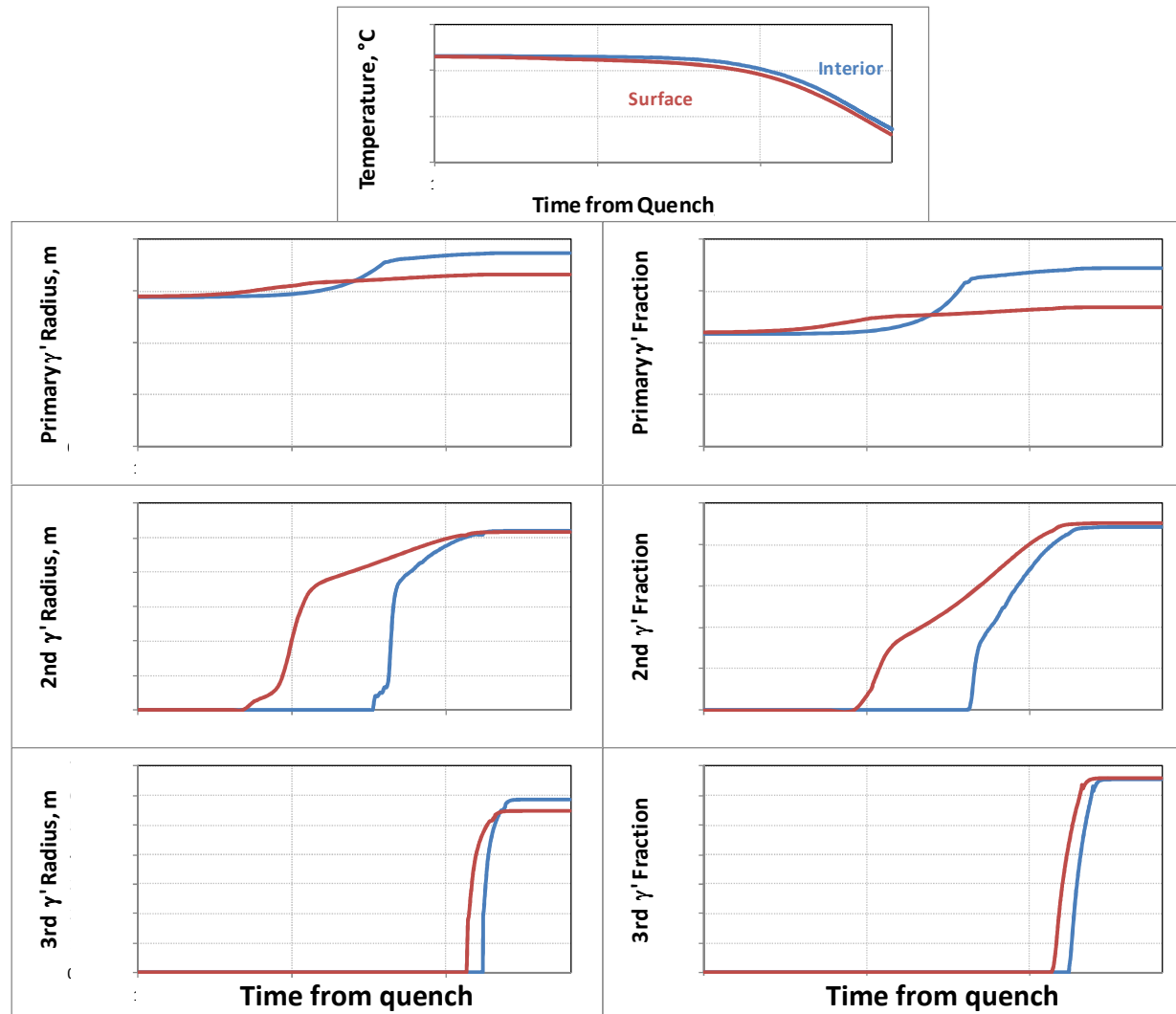
Radius of secondary γ' particles



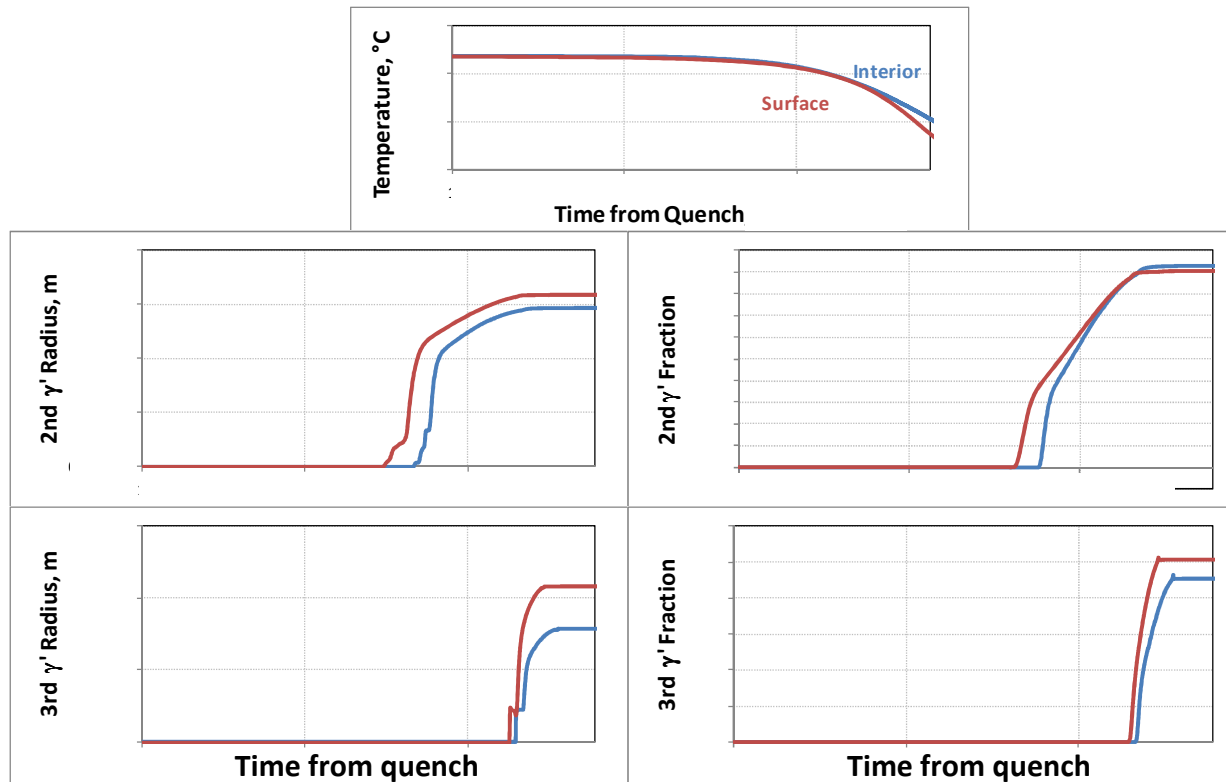
1°, 2°, 3° γ' features predicted by fast acting model at TC1



1°, 2°, 3° γ' features predicted by fast acting model at TC3



2° , 3° , γ' features predicted by fast acting model at TC3





Thank You