Simulating Heat Treatment of Steel Parts

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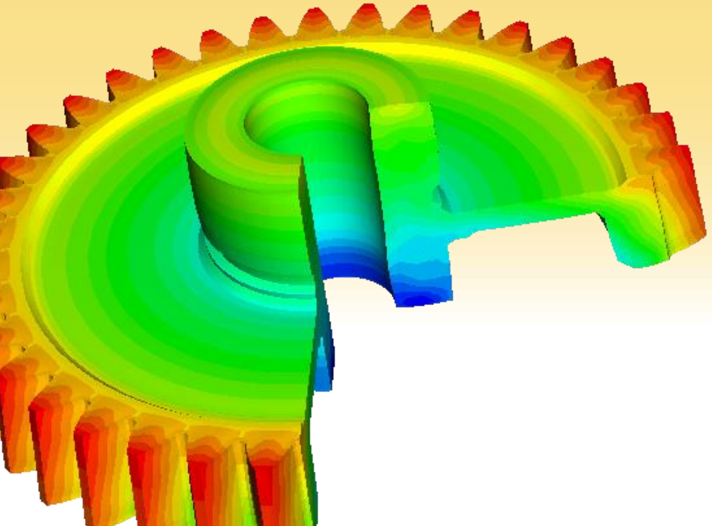
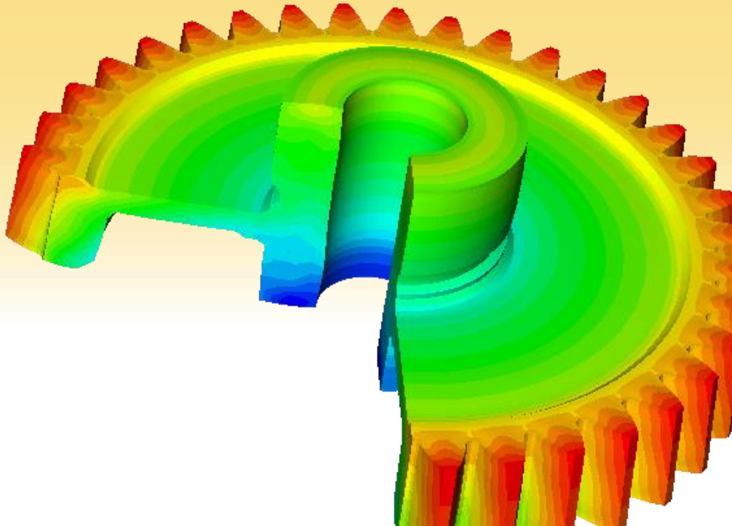




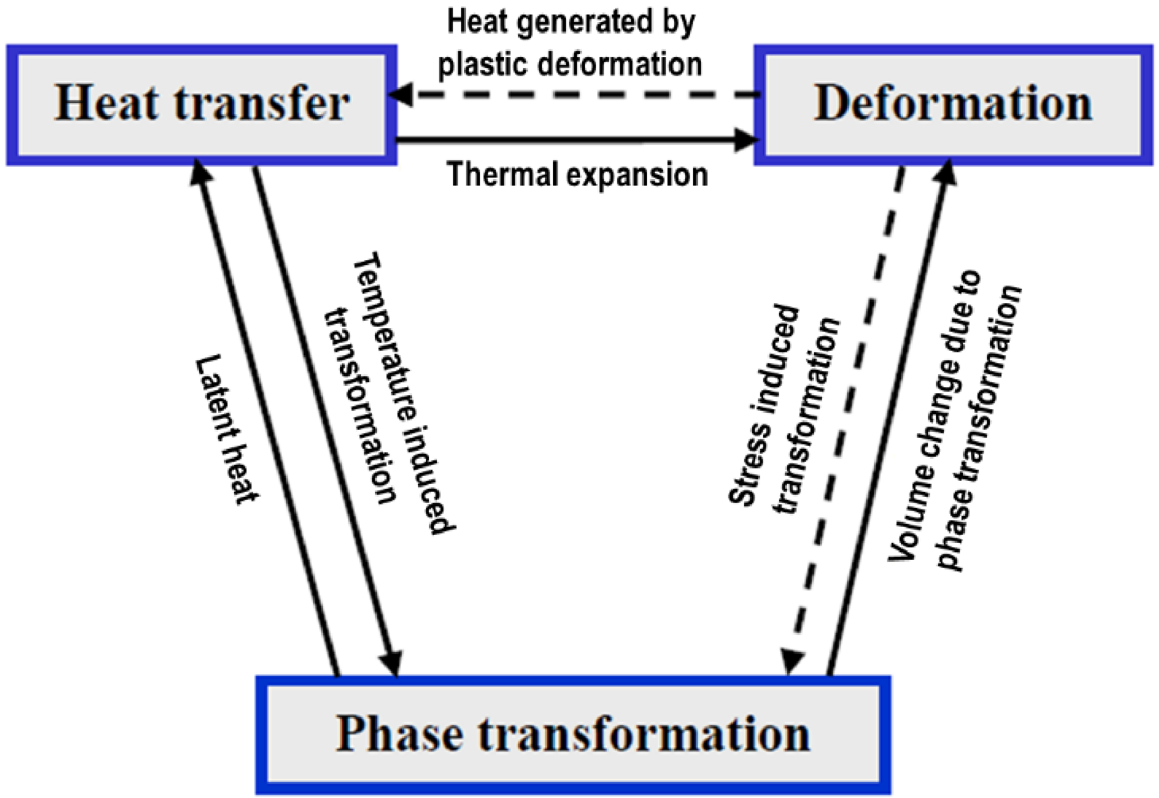
Outline

- Steel heat treatment modeling overview
  - Requirements for a useful heat treatment model
- Diffusion processes:
  - Model data, material data, and process data requirements
  - Case studies
- Hardening processes:
  - Model data, material data, and process data requirements
  - Case studies
- Specialized processes:
  - Induction hardening
  - Press/fixture quenching
  - Model data, material data, and process data requirements
  - Case studies

What is Required for an Accurate and Practically Useful Steel Heat Treatment Model?

<u>Phenomena to consider for steel heat treatment process modeling</u>

- Solid-state phase transformation models
- Multiphase mechanical models
- Transformation induced plasticity (TRIP) models
- Mixture law
- Tempering models
- Diffusivity models



Diffusion Processes

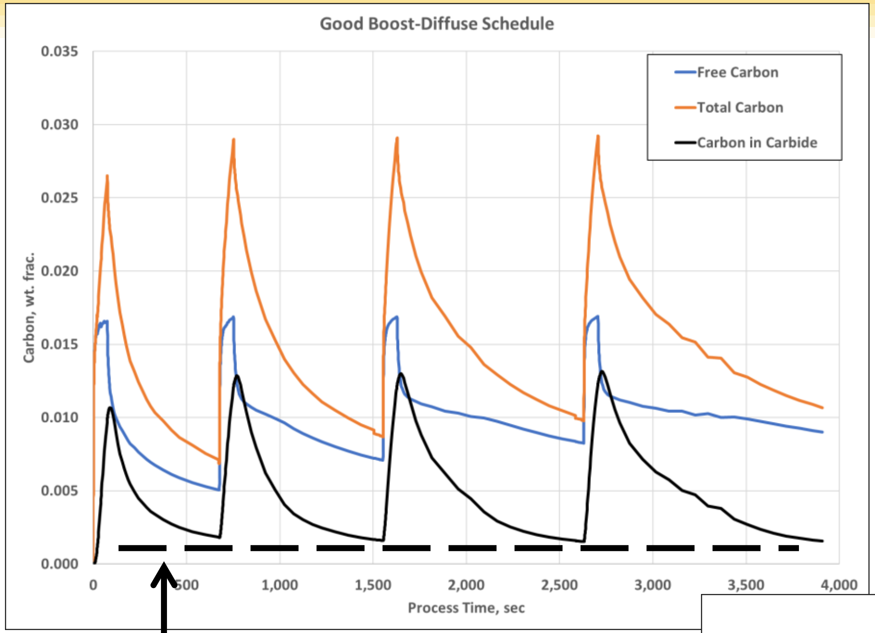
- Carburizing
- Nitriding
- Boronizing

Material Data Needs for Heat Treat Simulation

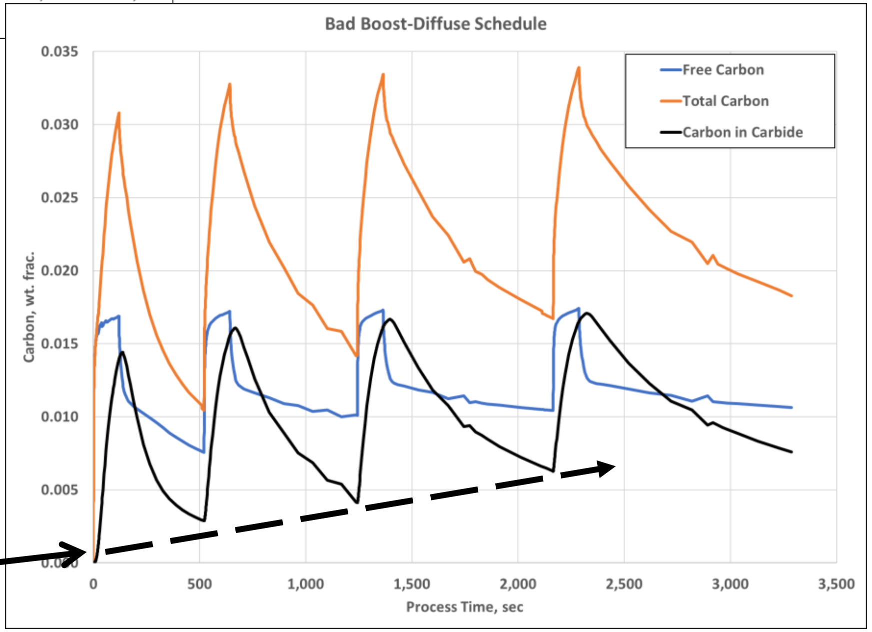
Diffusion Based Processes

<u>Diffusivity Properties</u>

- Diffusivity, as a function of
  - Temperature
  - Species concentration
- Carbide, nitride, and boride formation and dissolution, as a function of
  - Temperature
  - Time
  - Species concentration
  - Size
  - Critical for processes which regularly exceed saturation limits (LPC, nitriding)
- Carbide, nitride, and boride dissolution during heating needed for
  - High carbon alloys
  - Reheat after carburization



Good Process



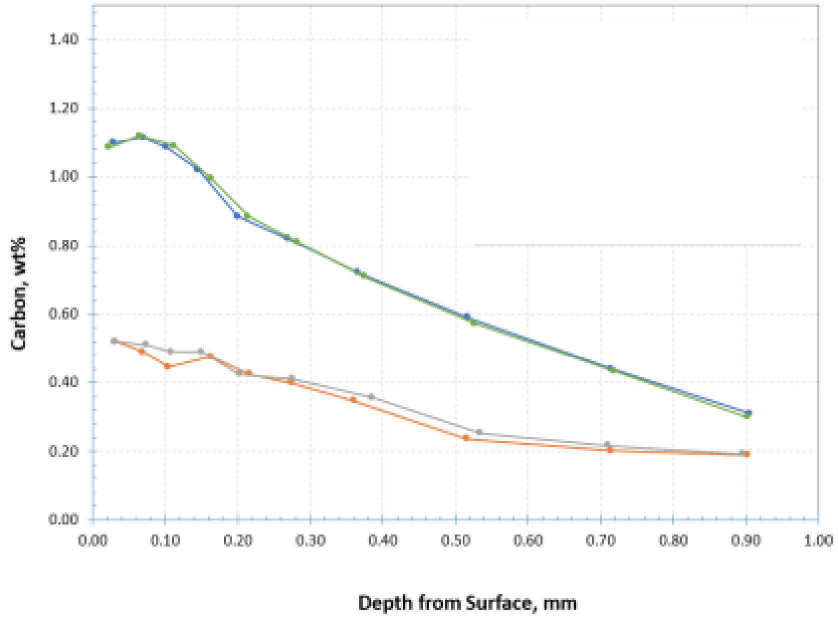
Bad Process

Equipment/Process Data Needs for Heat Treat Simulation

Diffusion Based Processes

Gas Diffusion Processes

- Gas potential
- Temperature
- Total time
- Surface condition
- Process parameters translate well to model



Low Pressure Diffusion Processes

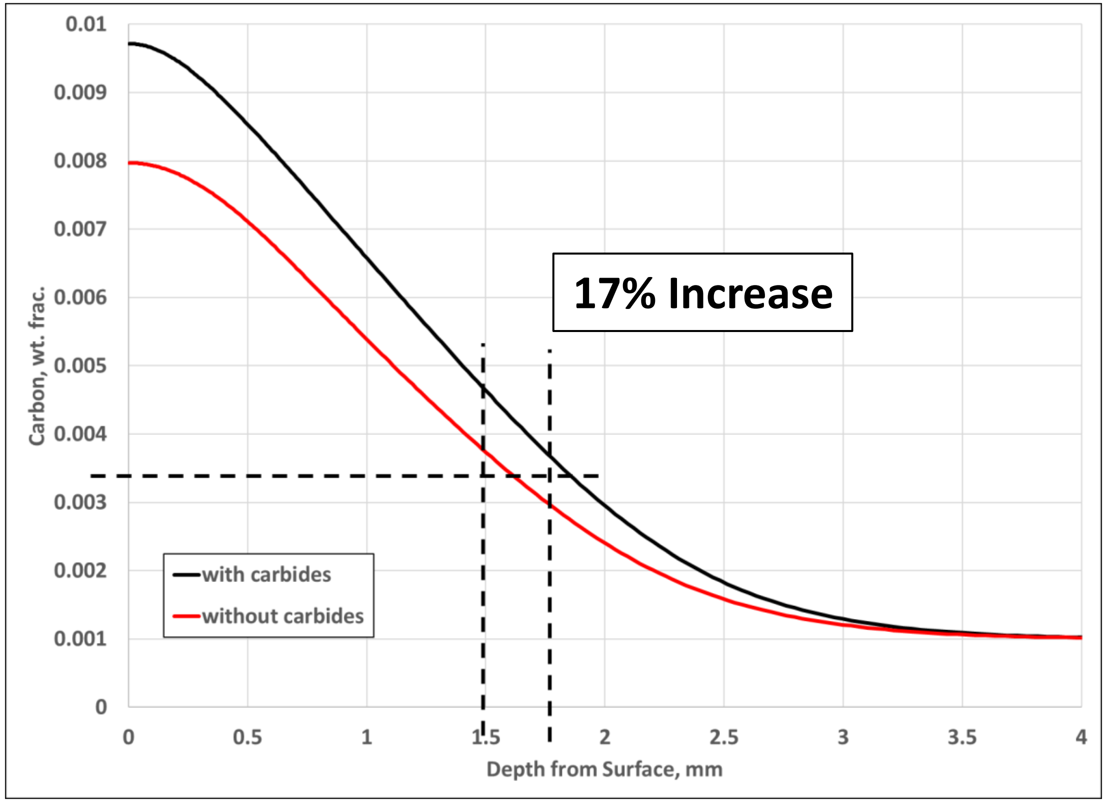
- Boost-Diffuse schedule (what is programmed into the equipment)
  - "Boost" introduces species carrying gas
  - "Diffuse" removes gas to near vacuum condition
- Effective boost-diffuse times (what the part experiences)
- Temperature
- No gas potential control for low pressure diffusion processes
  - Saturation limit in austenite/ferrite is the limiting factor
  - Saturation limit should be included as a function of temperature
- Process parameters more difficult to convert to model parameters
  - Time to reach saturation
  - "Gas potential" and boost-diffuse schedule provided by the equipment may not actually be what the part experiences

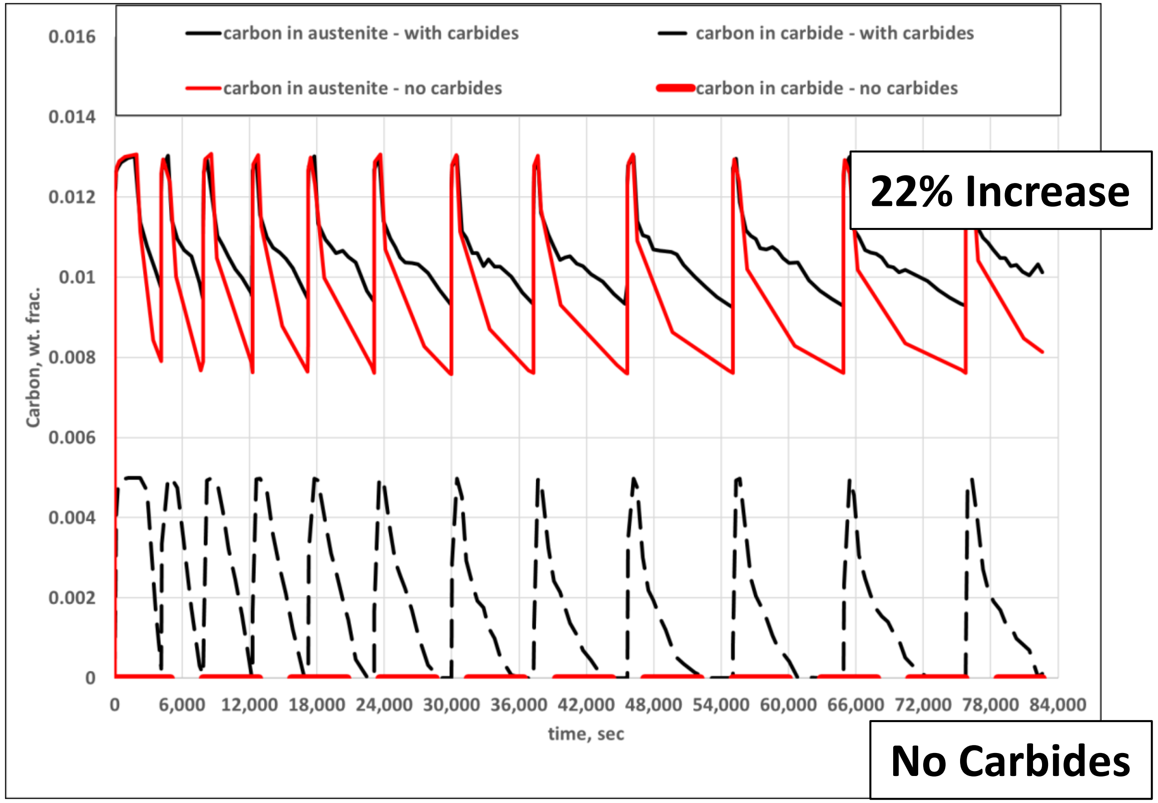
Tale of 2 furnaces: Same boost recipes, different total carbon in case

Example

Considering Carbides for LPC Recipe Design

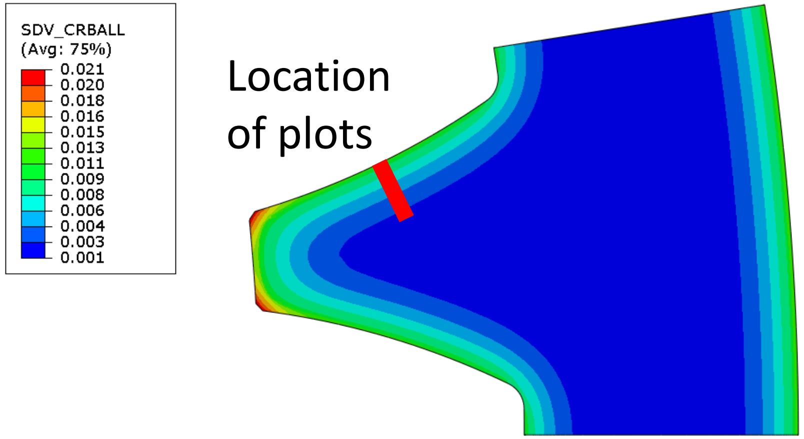
- LPC boost-diffuse schedule determined using DANTE's VCarb for AISI 9310 without considering carbides
  - Surface carbon = 0.8%
  - ECD = 1.5 mm
- Same schedule executed for AISI 9310 considering carbide formation and dissolution

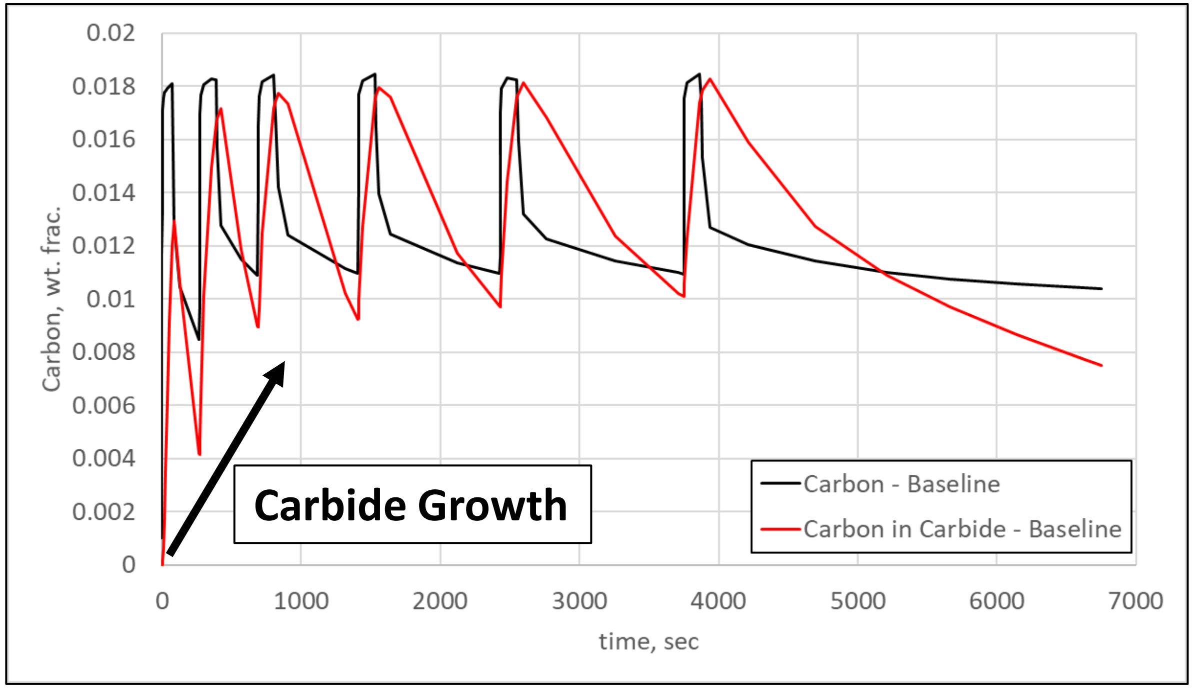


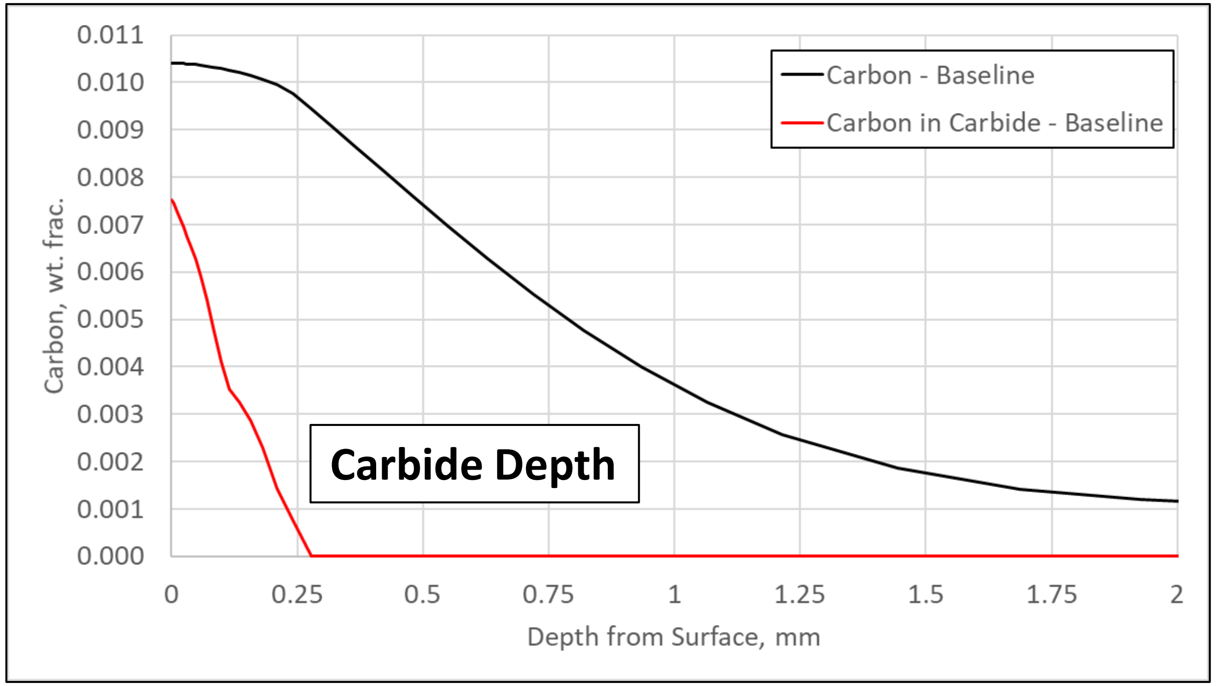


Case Study
LPC Process Modeling: Baseline Process

- Material: Ferrium C64
- ECD originally designed for 0.75 mm
  - ~0.35 mm deeper than required
  - Surface carbon also higher than required to meet hardness
- Carbides to depth of 0.25 mm
  - Carbides formed during the first boost step continue to grow



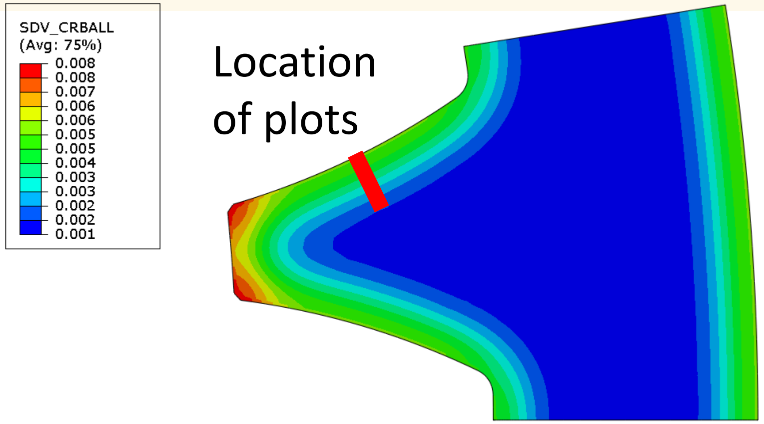


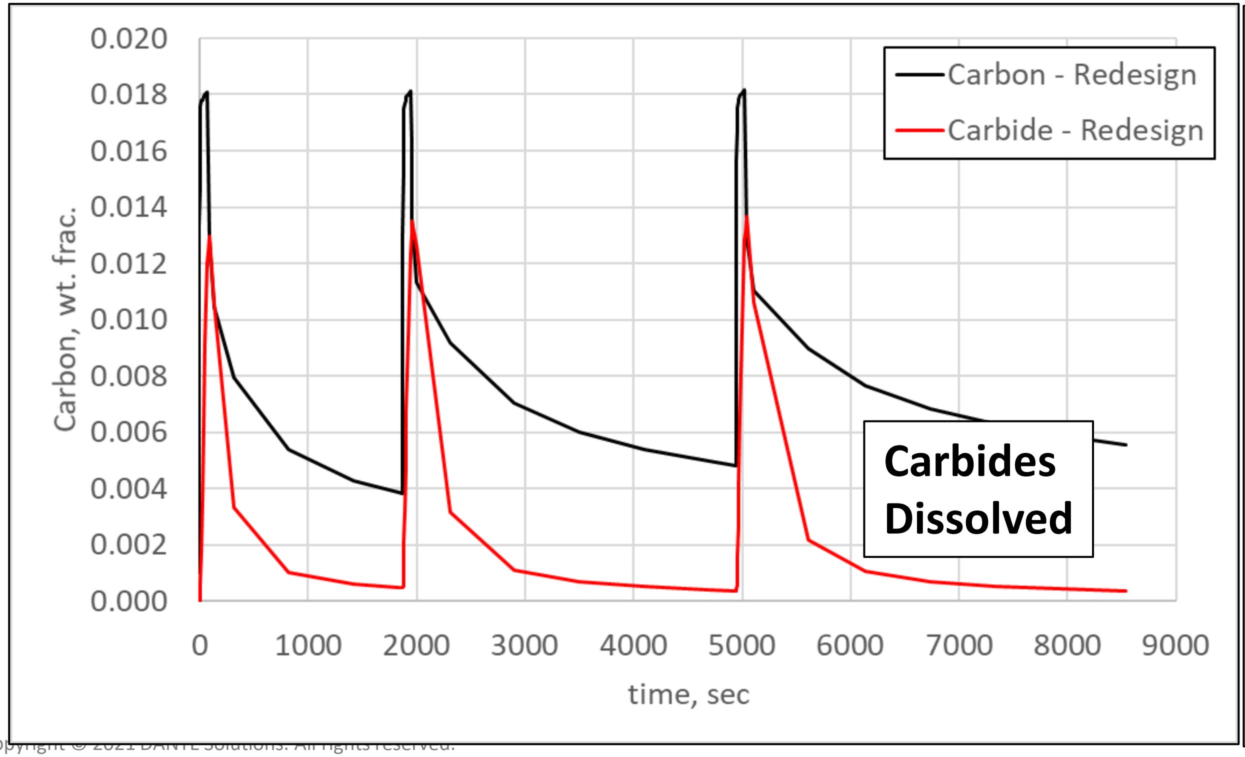


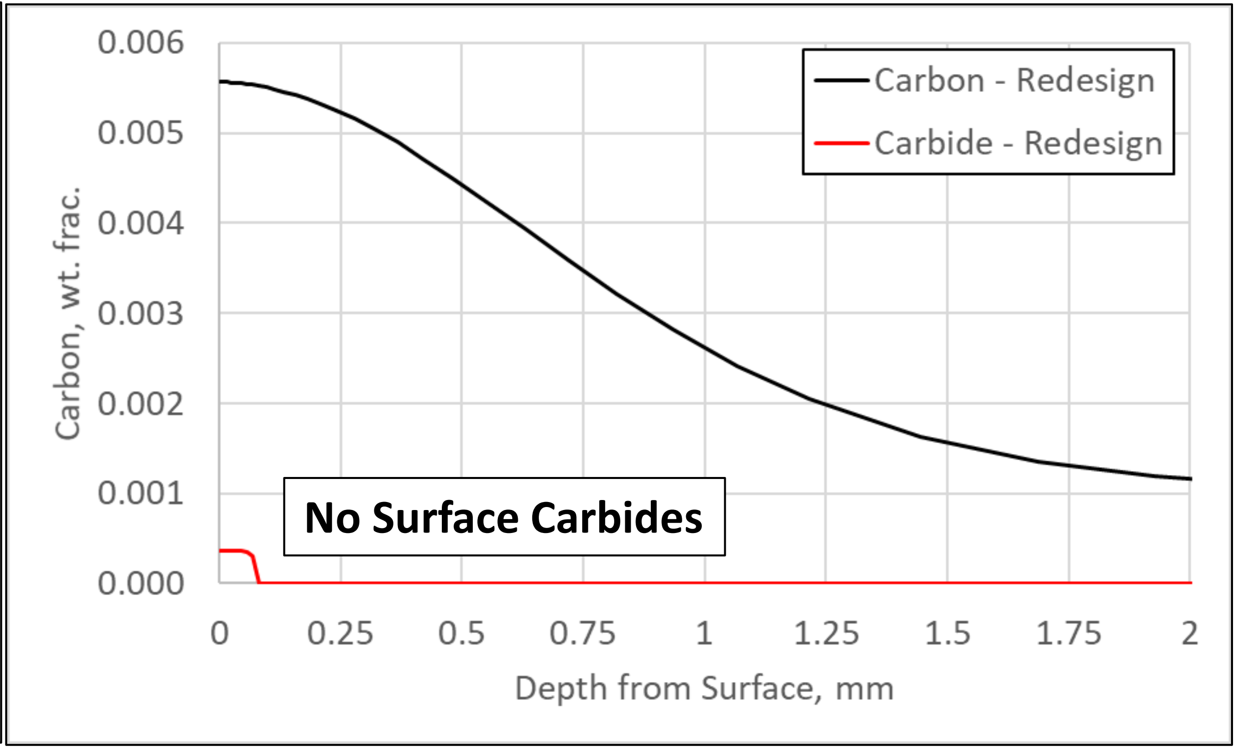
Case Study

LPC Process Modeling: Improved Process

- New schedule developed to reduce carbides and surface carbon
- 3 boost-diffuse steps removed & diffuse times increased







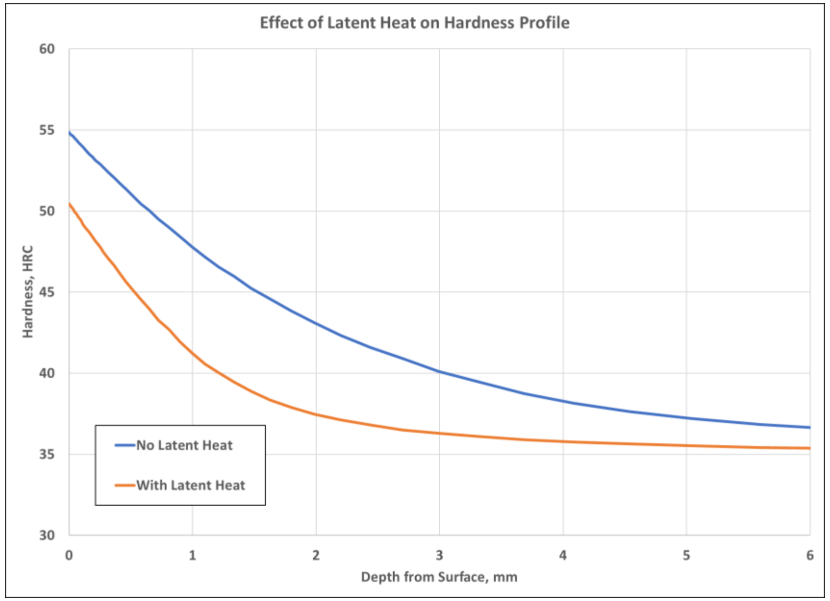
Hardening Processes

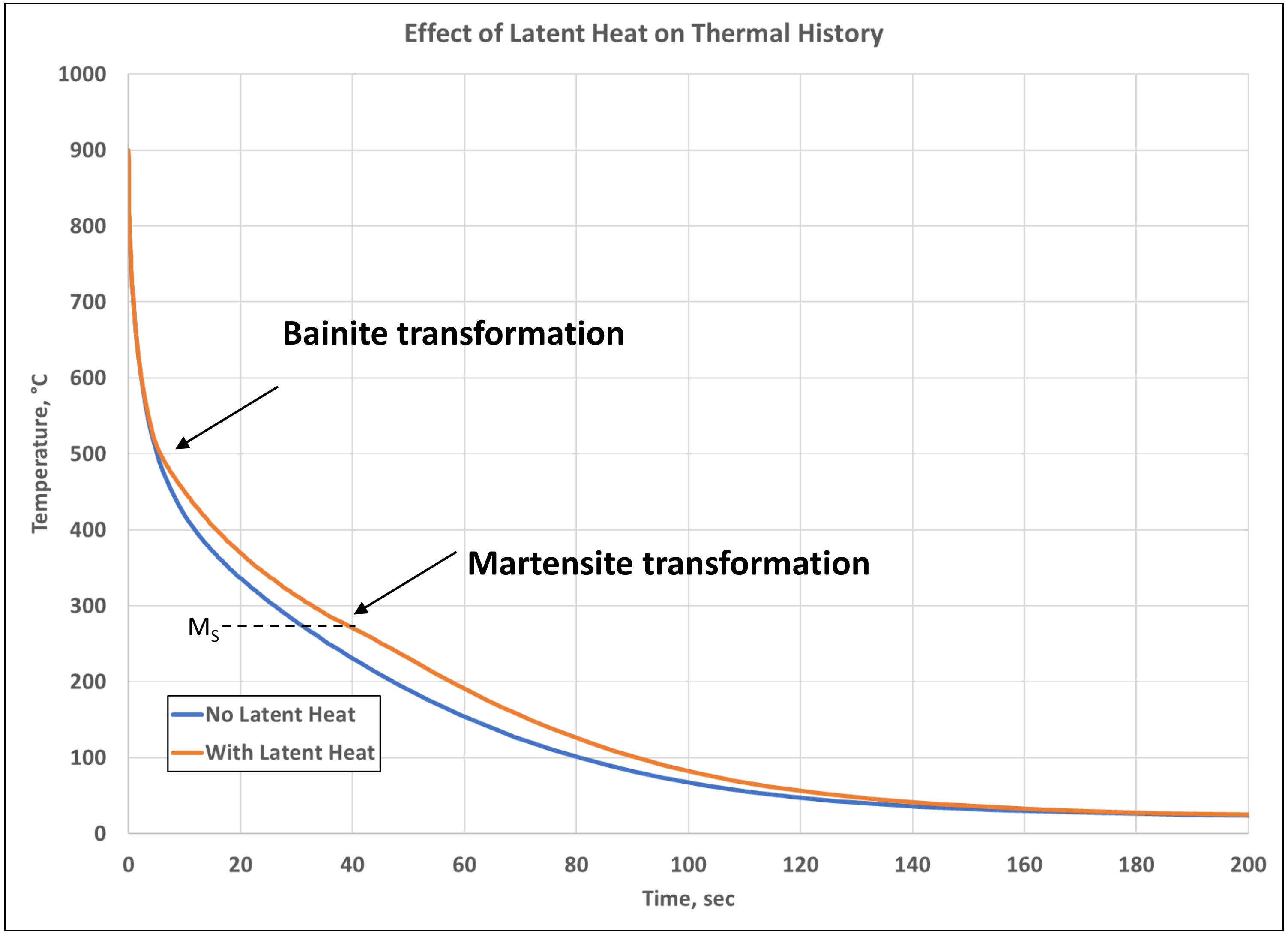
- Liquid quenching
- Gas quenching
- Martempering
- Austempering
- Any thermal process involving phase changes, including tempering

Material Data Needs for Heat Treat Simulation
Quench Hardening Processes

Thermal Material Properties

- Thermal properties should be a function of temperature, phase, and carbon
  - Thermal conductivity
  - Specific heat
  - Latent heat
  - Coefficient of thermal expansion (technical a mechanical property)





Material Data Needs for Heat Treat Simulation, cont'd

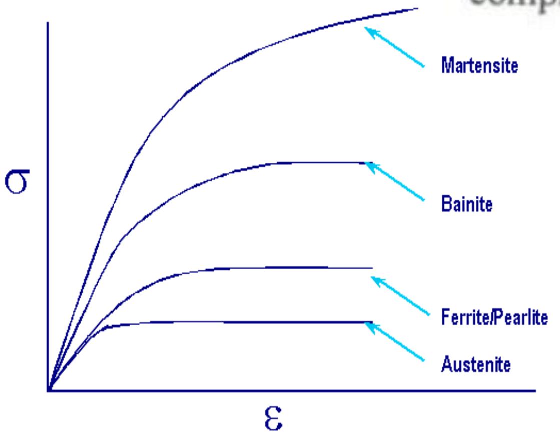
Quench Hardening Processes

Elastic Material Properties

- Elastic properties should be a function of temperature, phase, and carbon
  - Young's modulus
  - Poisson's ratio

Plastic Material Properties

- Plastic properties should be a function of temperature, phase, carbon, strain, and strain rate
- Hardening and softening
- Stress reversals
- Transformation induced plasticity (TRIP)
- Transformation strain



Test of AISI 304L SS

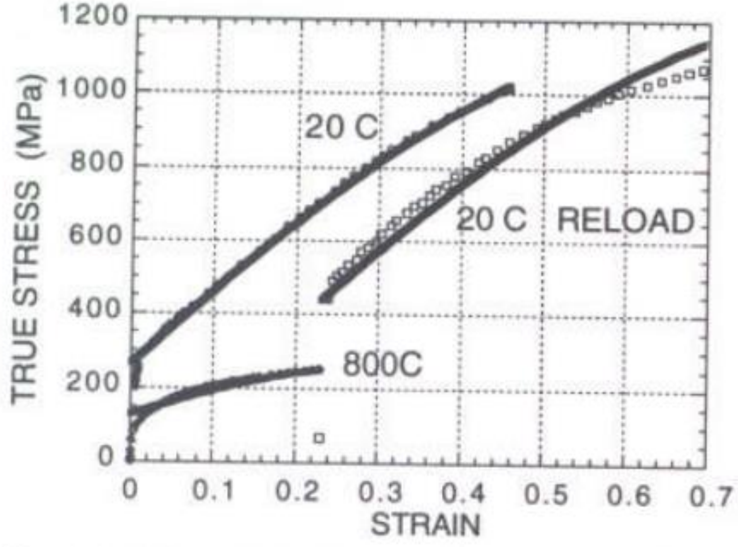


Figure 2. Model prediction of compression tests and compression reload demonstrating temperature history effects

Development of a Carburizing and Quenching Simulation Tool: A Material Model for Carburizing Steels Undergoing Phase Transformations

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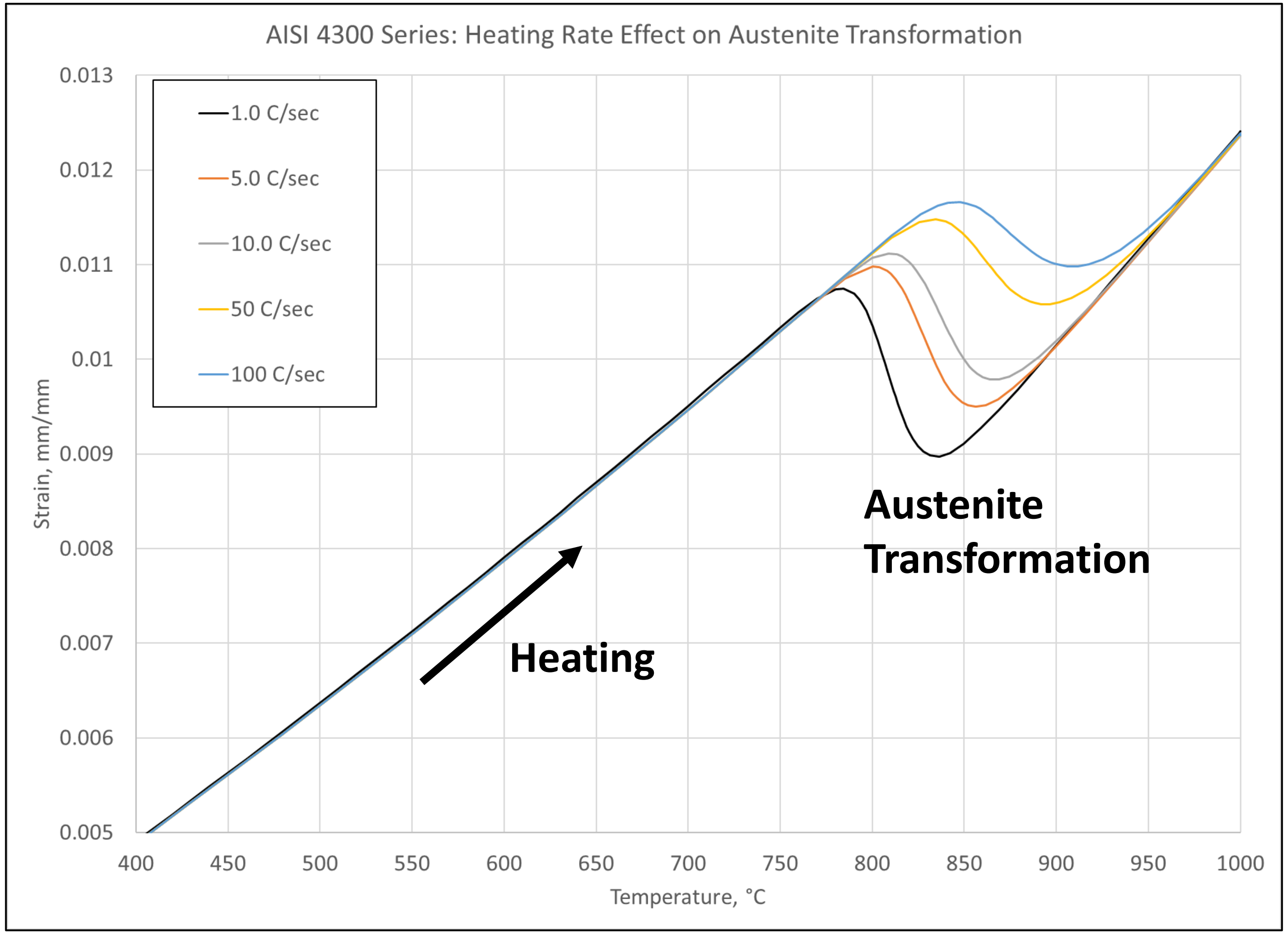
Material Data Needs for Heat Treat Simulation, cont'd

Quench Hardening Processes

Phase Transformation Kinetics

- Ferrite, Pearlite, Bainite, Martensite, Tempered Martensite → Austenite
  - Carbon
  - Heating rate
  - Grain size

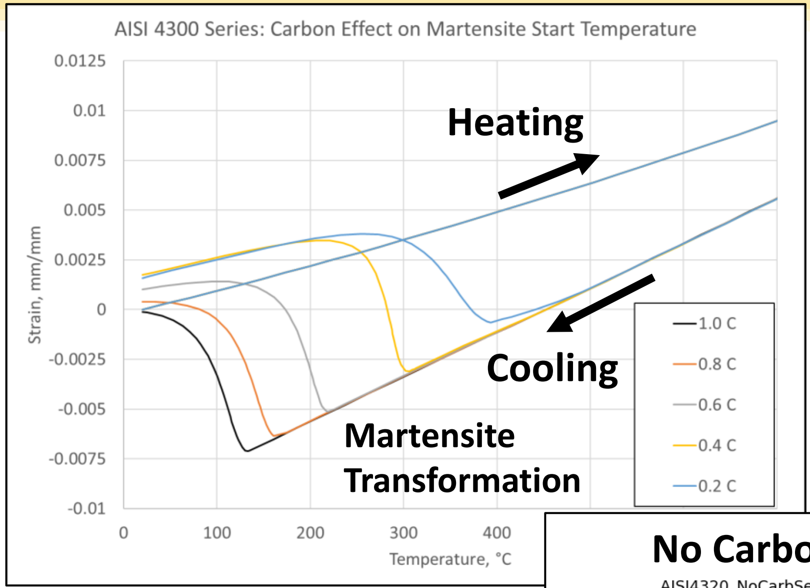


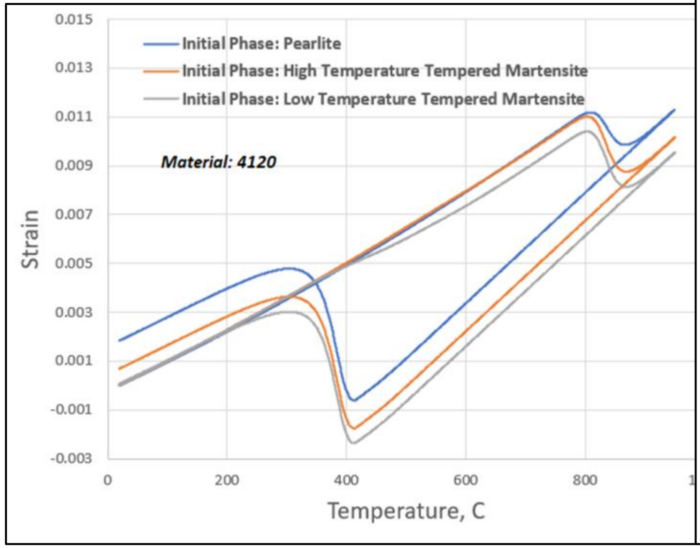
Material Data Needs for Heat Treat Simulation, cont'd

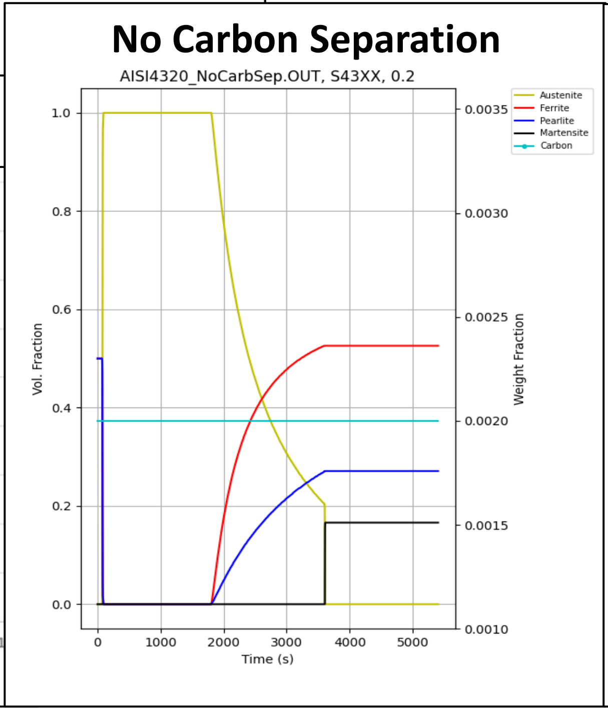
Quench Hardening Processes

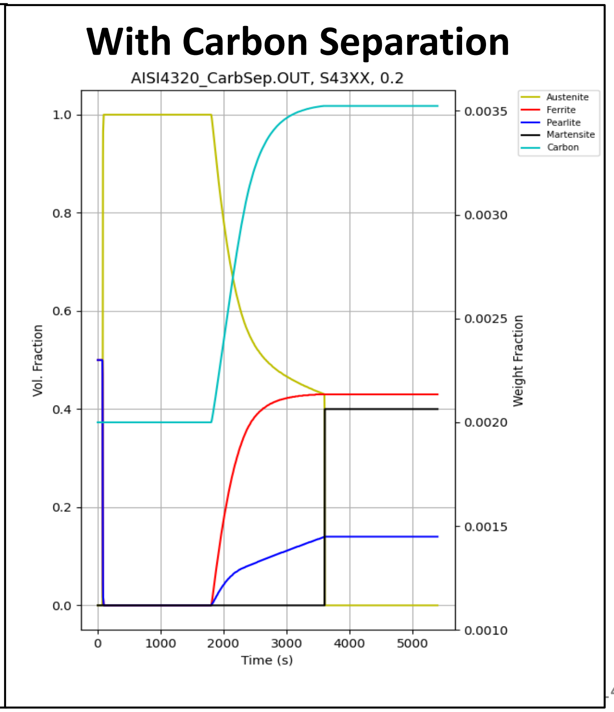
Phase Transformation Kinetics

- Austenite → Martensite, Ferrite, Pearlite, and Bainite
  - Martensitic transformation should be a function of carbon and cooling rate
  - Diffusive phase transformation kinetics should be a function of carbon and time
    - Carbon rejected during ferrite formation
  - Grain size
- Martensite → Tempered Martensite (low and high temperature)
  - Dimensional change
  - Stress relaxation









Equipment Data Needs for Heat Treat Simulation
Quench Hardening Processes

Furnace Heating

- Heat transfer coefficient (HTC) as a function of part surface temperature
  - Influenced by equipment operation and loading configuration
- Ambient temperature (constant)
- Total time

Transfer

- HTC (constant)
- Ambient temperature (constant)
  - Dependent on mass, surface area, and racking orientation of the load
  - Generally, not room temperature
- Total time

Equipment Data Needs for Heat Treat Simulation, cont'd

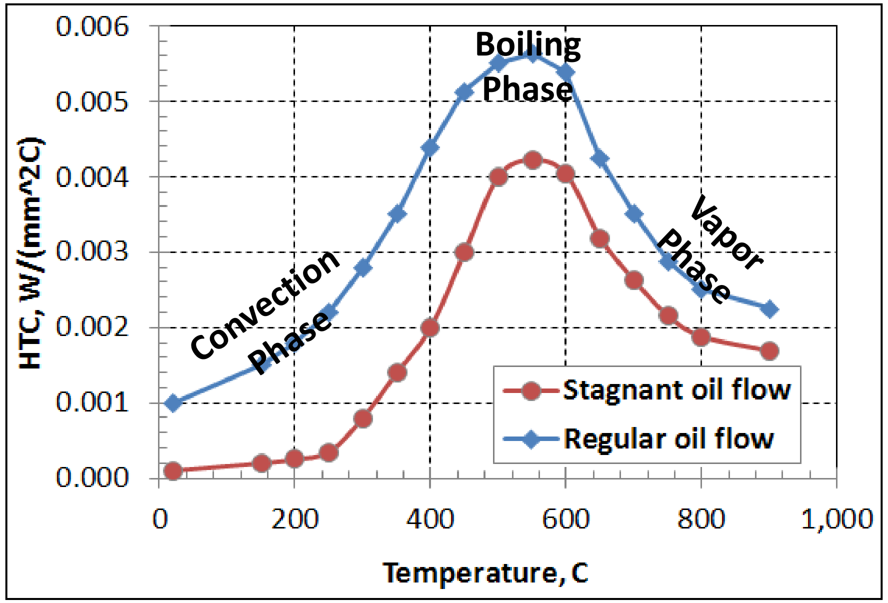
Quench Hardening Processes

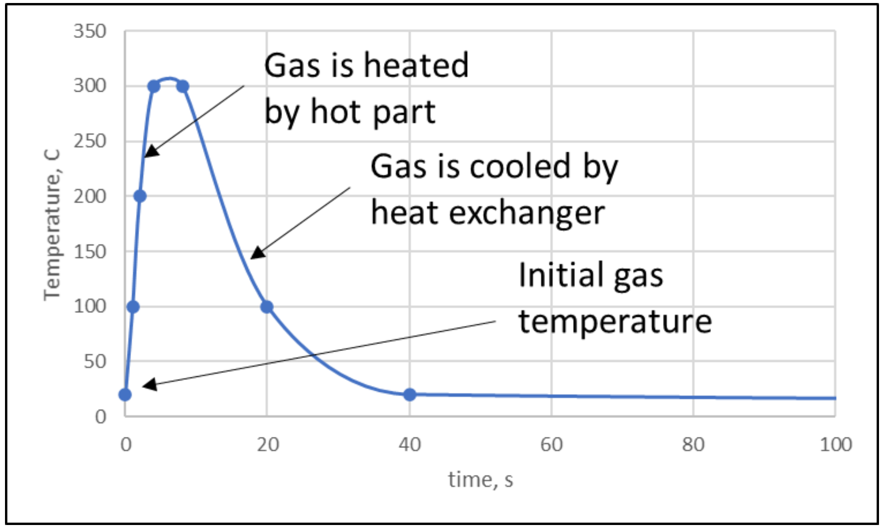
Liquid Quenching

- HTC as a function of part surface temperature
  - 3 stages of liquid quenching
  - Dependent on part geometry, load geometry, and equipment design and operation
- Ambient temperature (constant)
- Total time; immersion should be considered for long parts

Gas Quenching

- Ambient temperature as a function of time
  - Significantly influenced by hot load and dependent on:
    - Equipment type
    - Load mass and surface area
    - Equipment's heat exchanger capabilities
- HTC (constant)
- Total time

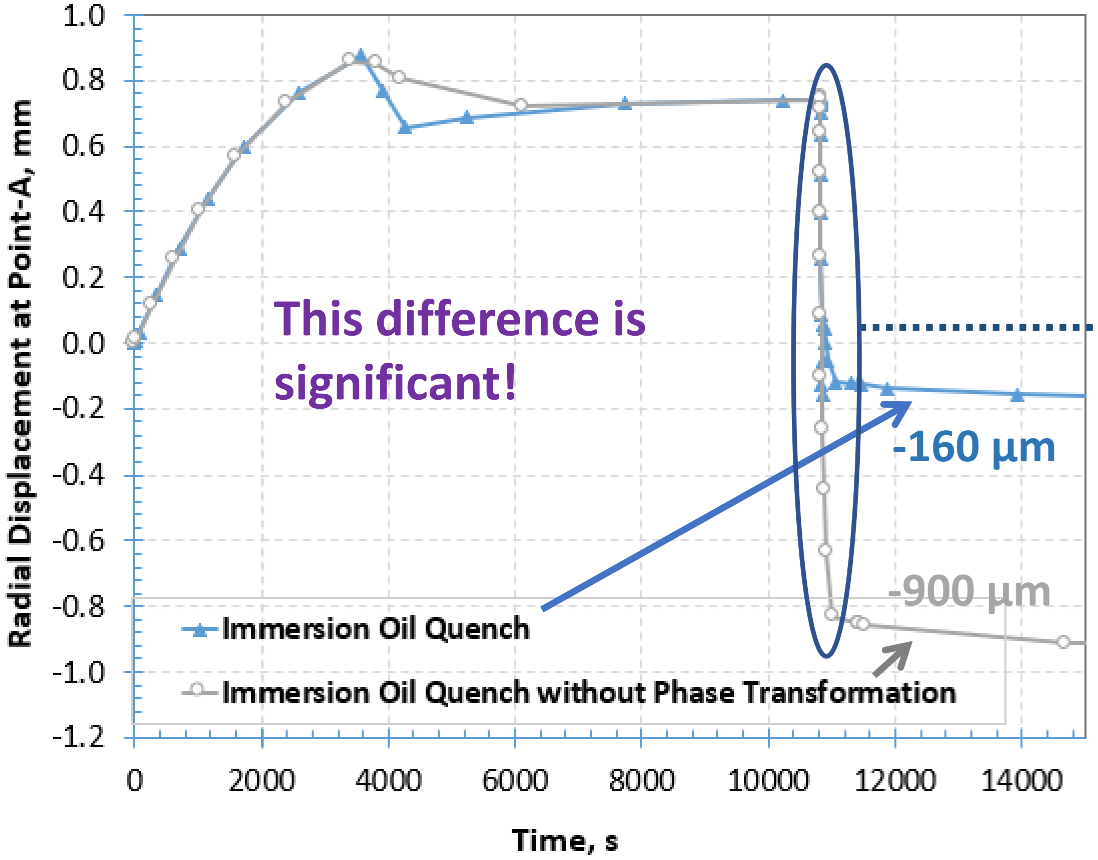


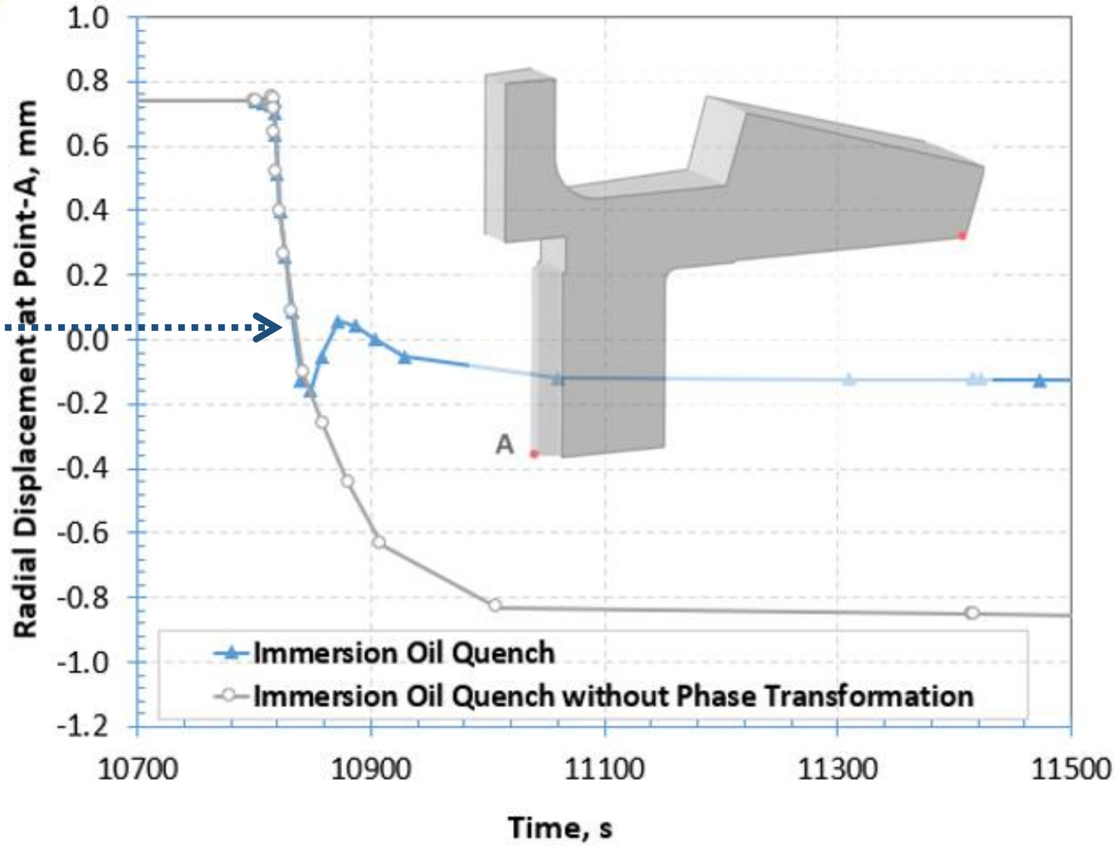


Significance of Phase Transformation on Distortion

Model Comparison with and without Phase Transformations

- Phase transformation has significant effect on final distortion
  - With phase transformations: 160 µm radial shrinkage
  - Without phase transformations: 900 µm radial shrinkage



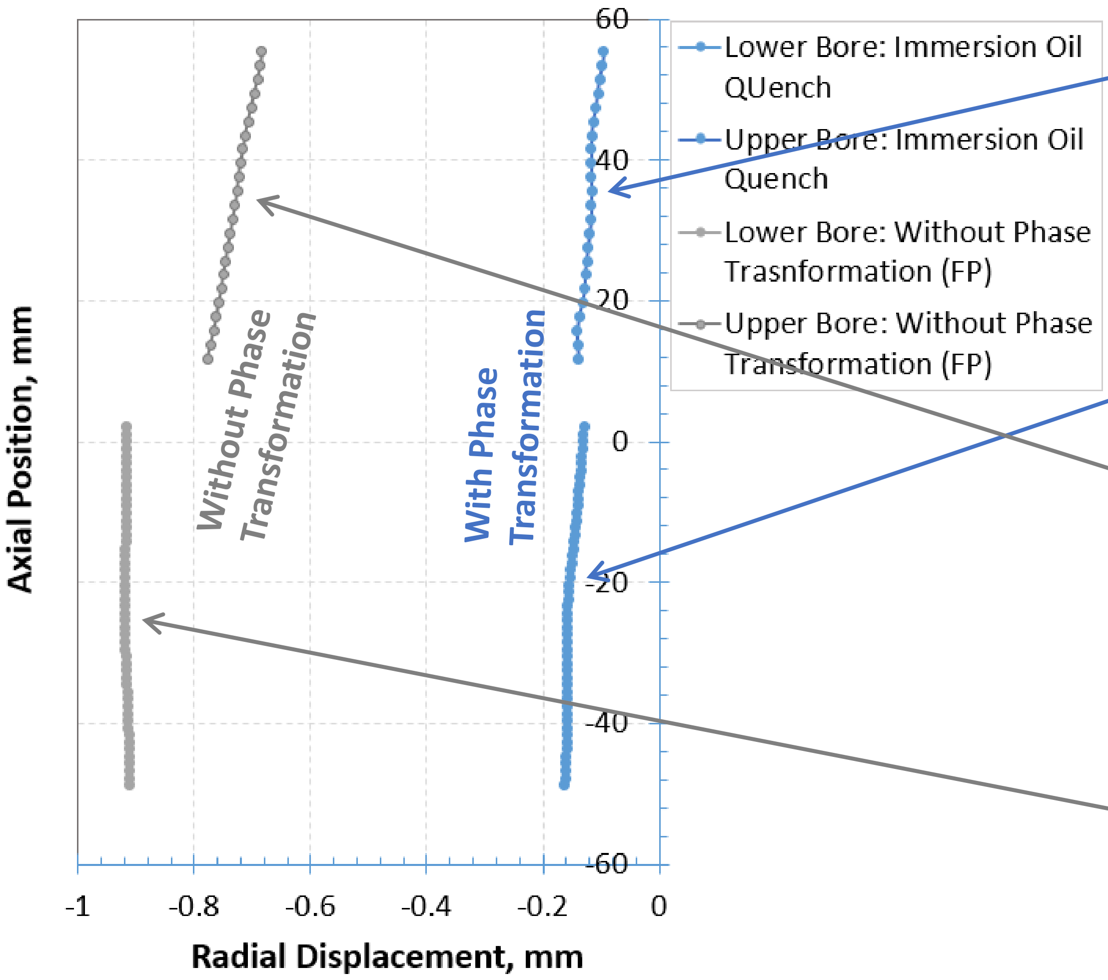


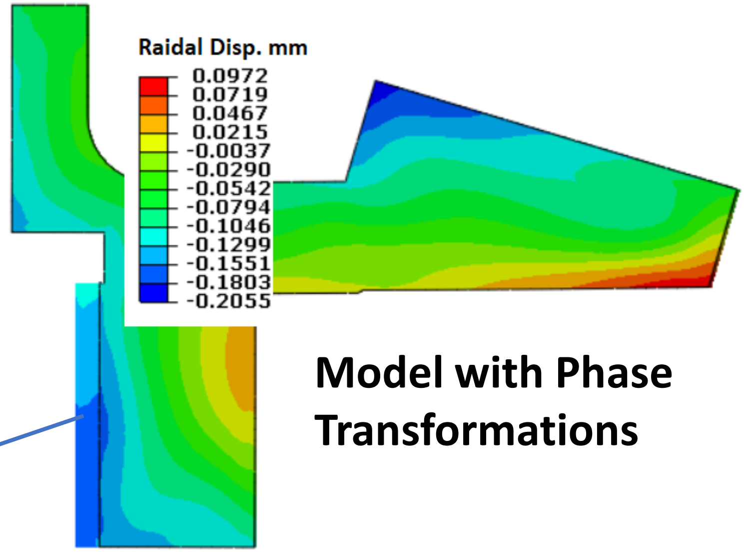
Assuming material is in F/P phase without phase transformation

Significance of Phase Transformation on Distortion, cont'd

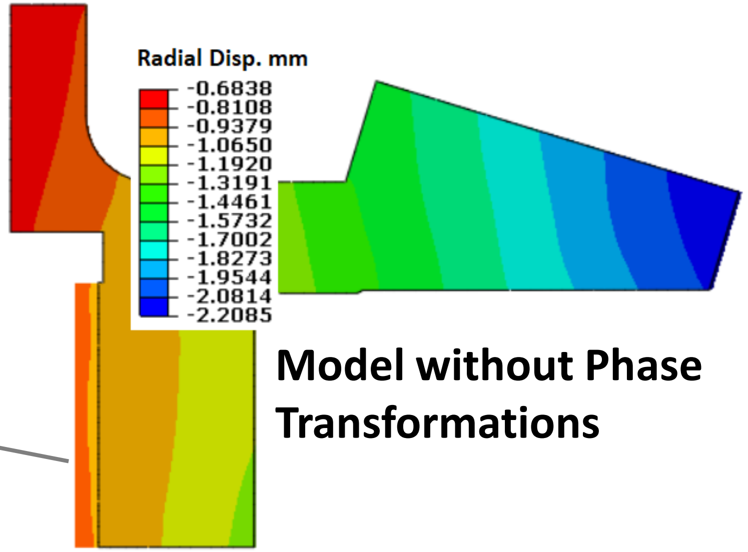
Model Comparison with and without Phase Transformations

Assuming material is in F/P phase without phase transformation





Model with Phase Transformations

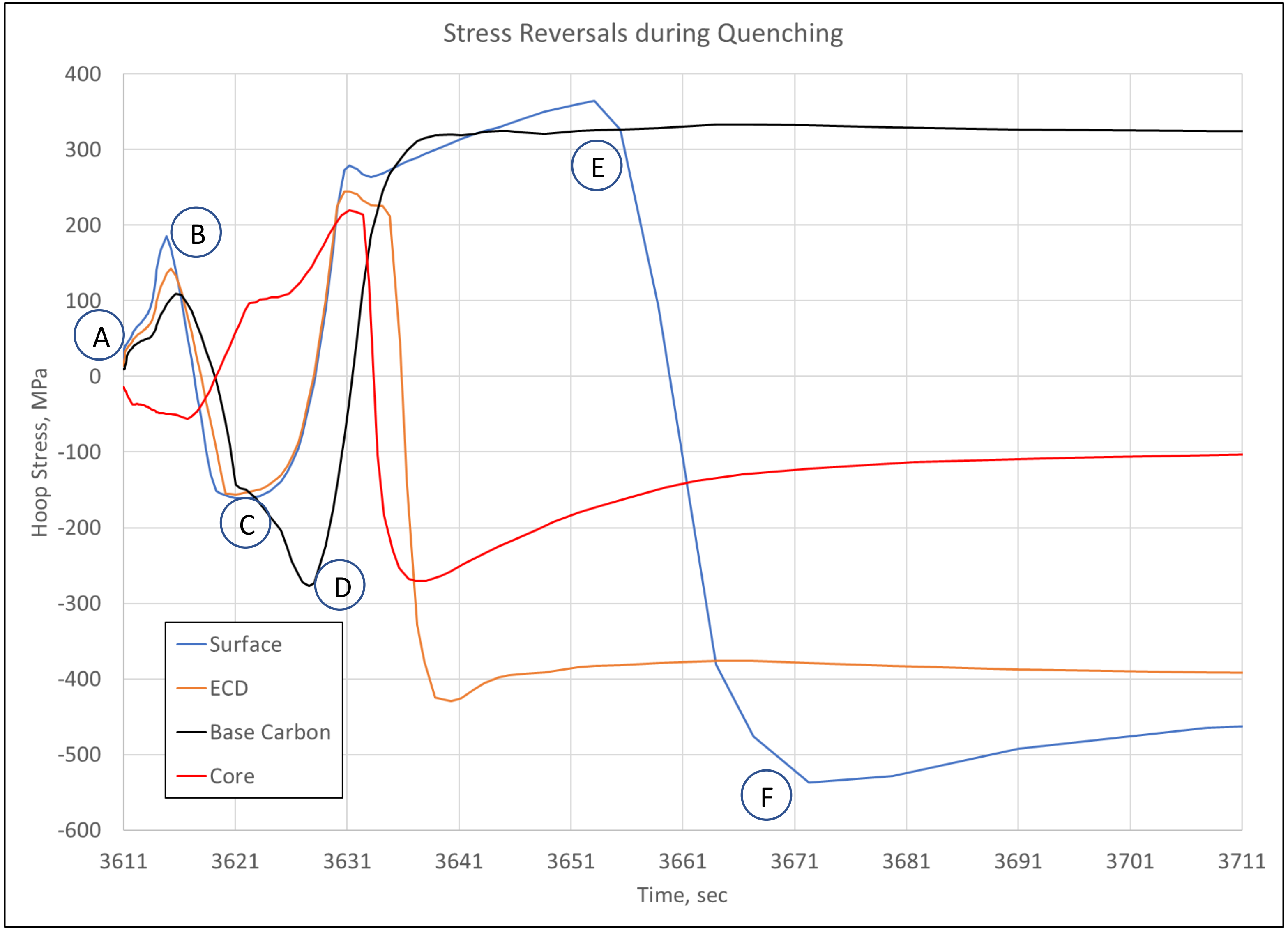


Model without Phase Transformations

Stress Reversals during Quenching of Carburized Part

Location of Points

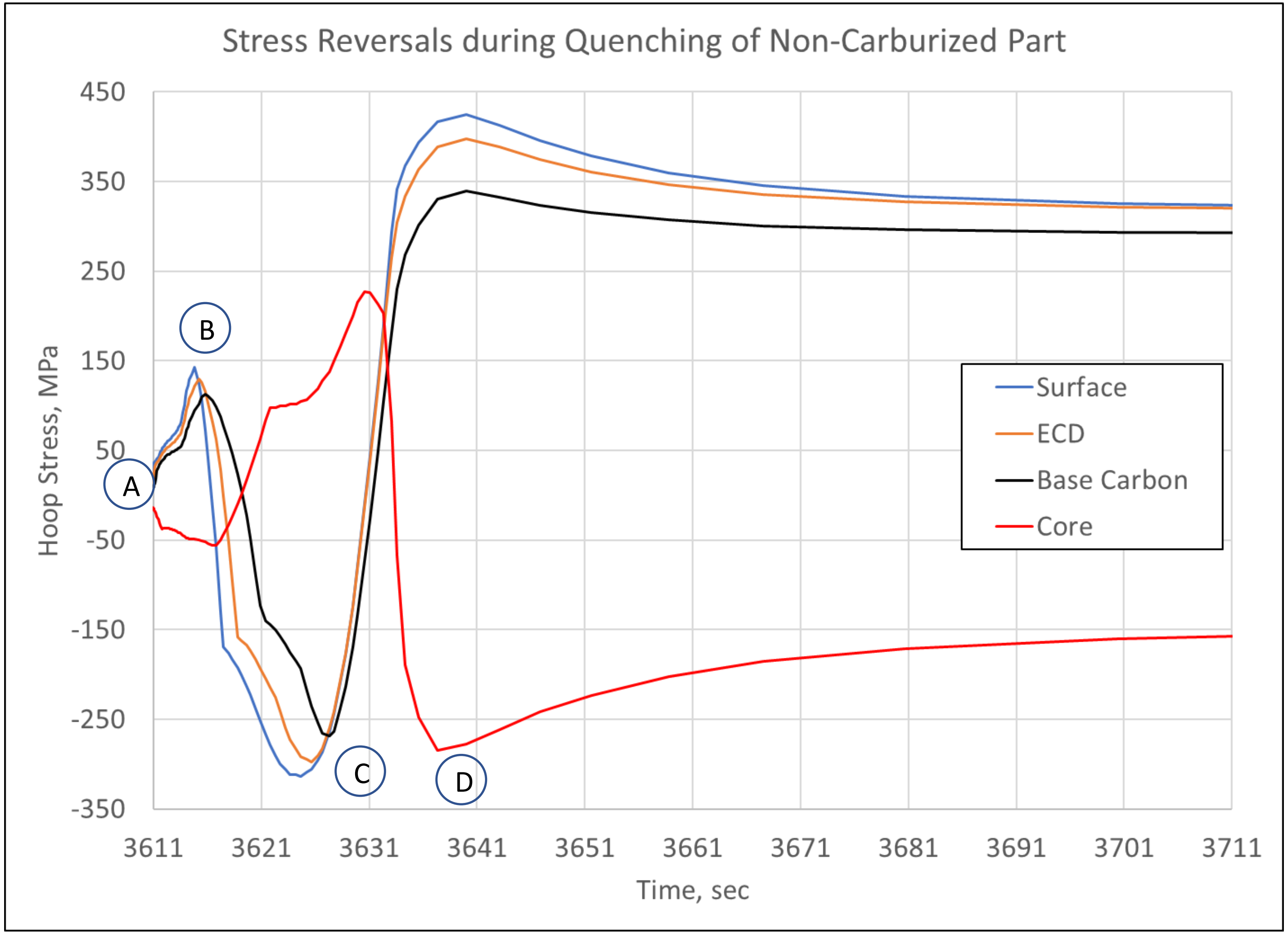
- Surface
- ECD: 0.8 mm
- Base Carbon: 1.5 mm
- Core: 6 mm



Stress Reversals during Quenching of Non-Carburized Part

Location of Points

- Surface
- ECD: 0.8 mm
- Base Carbon: 1.5 mm
- Core: 6 mm



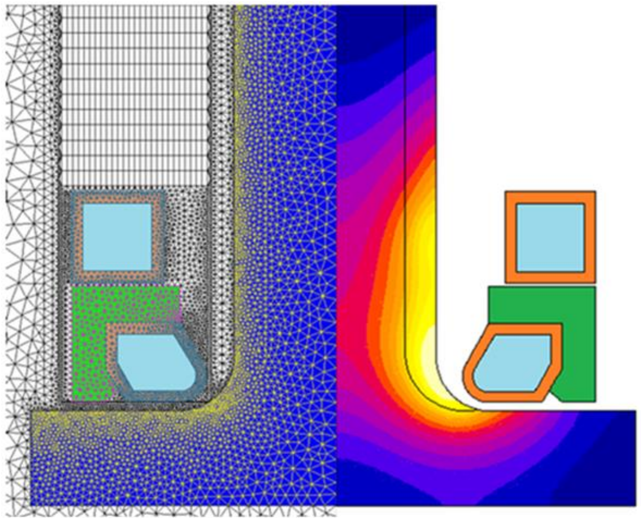
Specialized Processes

- Induction hardening
- Press quenching

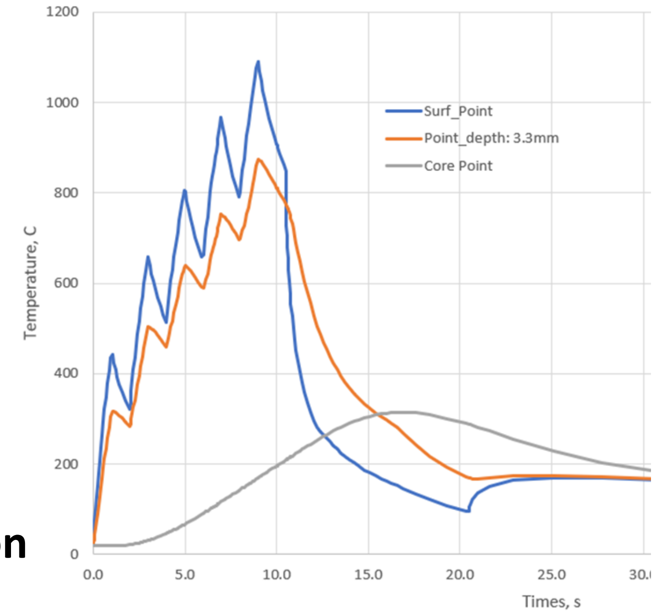
Equipment Data Needs for Heat Treat Simulation
Specialized Hardening Processes

Induction Hardening (Induction Heating + Spray Quenching)

- Joule heating is used as the input to drive the thermal model
  - Electromagnetic (EM) software
  - Based on actual or projected case depth and surface temperature requirements
  - Frequency and power of inductor(s) should be known
- HTC and ambient temperature (constant)
  - Fresh fluid ensures vapor is immediately removed
  - Fluid does not remain in contact with surface long
- Scanning processes, including dwells and scan rate changes

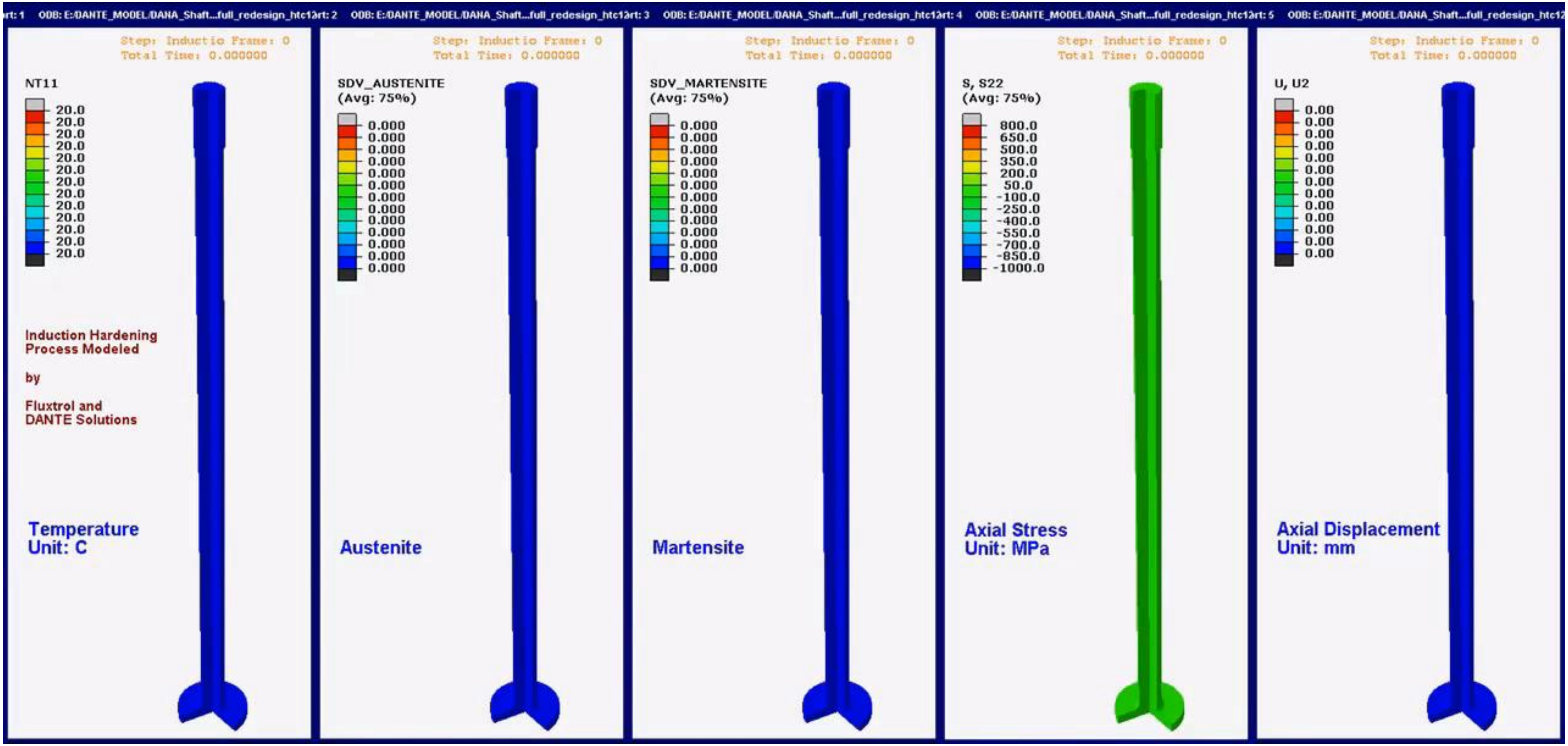


EM Model



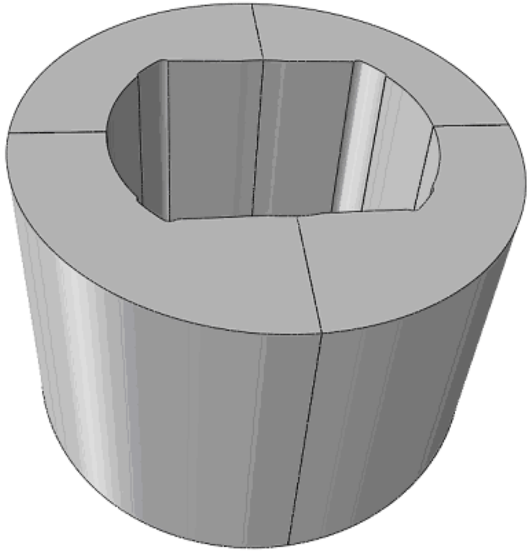
Induction heating with rotation

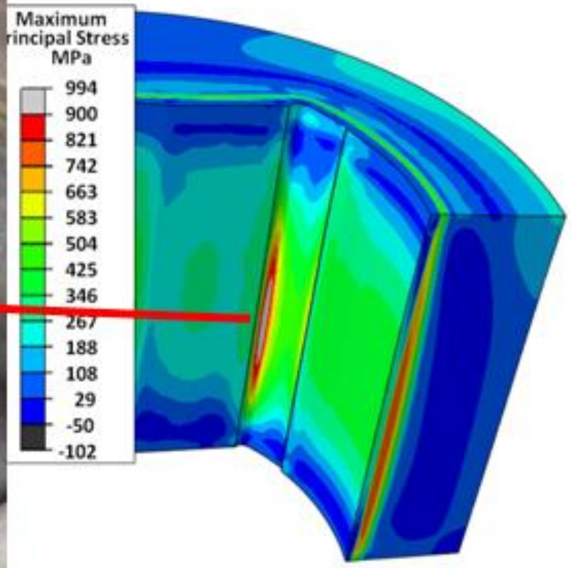
Scanning Induction Hardening of Axle Shaft Animation



Scanning Induction Hardening of Steel Coupler
Model & Process Description

- Material: AISI 4340
- Case depth: 4 mm
- Estimated power distribution
- Width of inductor: 100 mm
- Inductor travel speed: 3 mm/sec
- Dwell between inductor and spray modeled
- Cost to manufacture part: $20,000.00

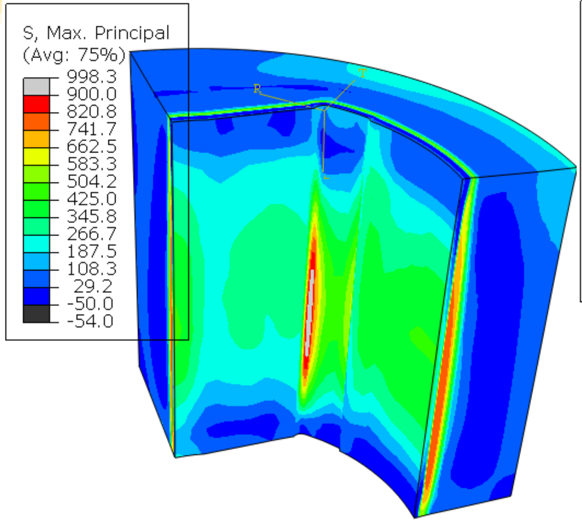


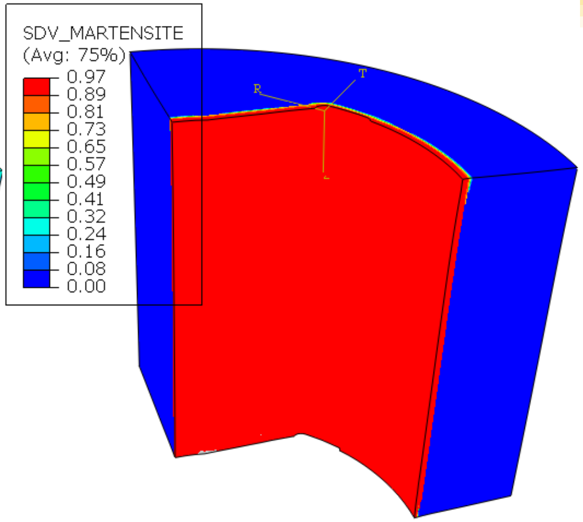


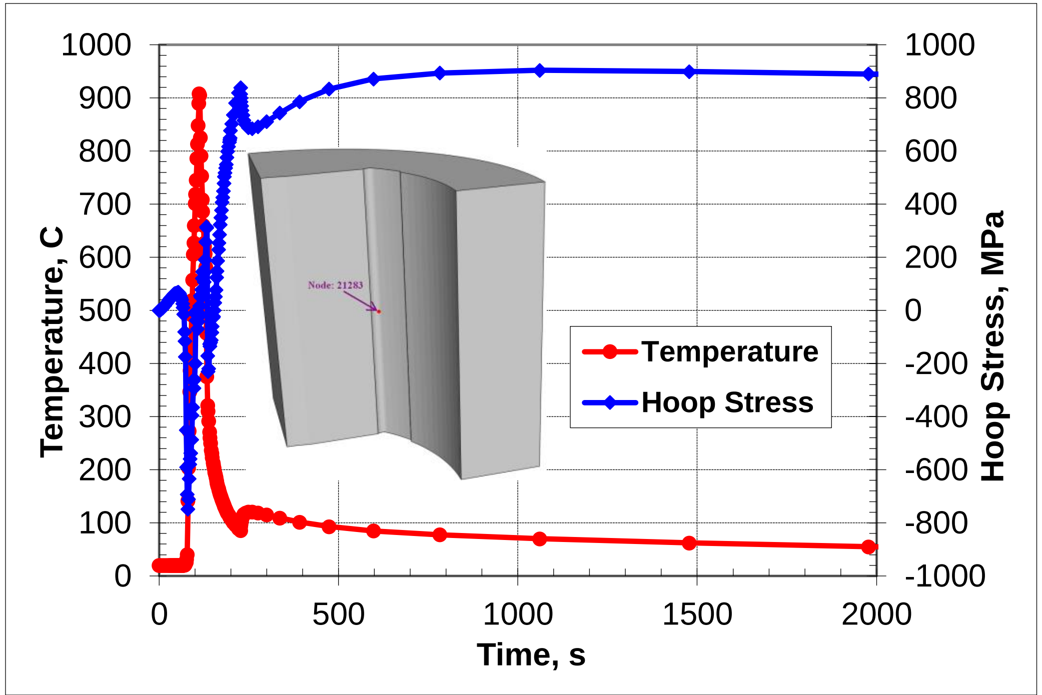
Scanning Induction Hardening of Steel Coupler

Original Process Results

- ➢ Maximum principal stress (top-left) and martensite (top-right) at end of quenching shown
  - High stress at the location of cracking
- ➢ Maximum principal stress is in hoop direction
  - Matches cracking mode observed
- ➢ Strength of martensite with 0.4% carbon is ~1300 MPa
  - Surface may crack below material strength
- ➢ Surface cracking possible if maximum surface stress exceeds 900 MPa
- ➢ Surface cracking not likely at stress levels below 650 MPa







Alternative Processes

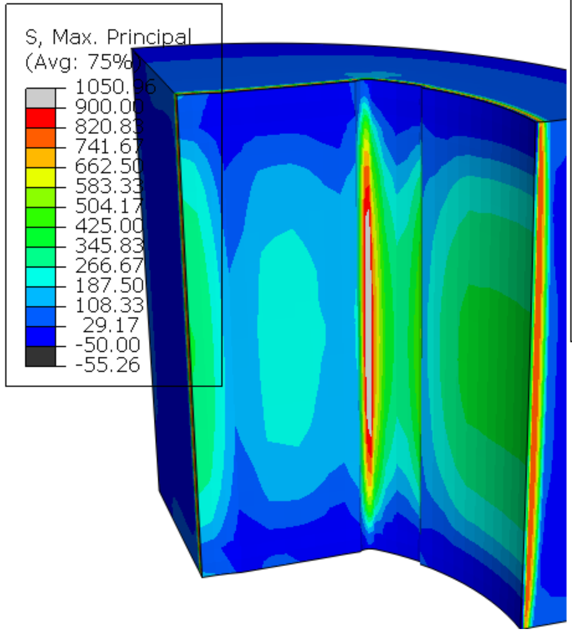
Two alternative processing routes evaluated:

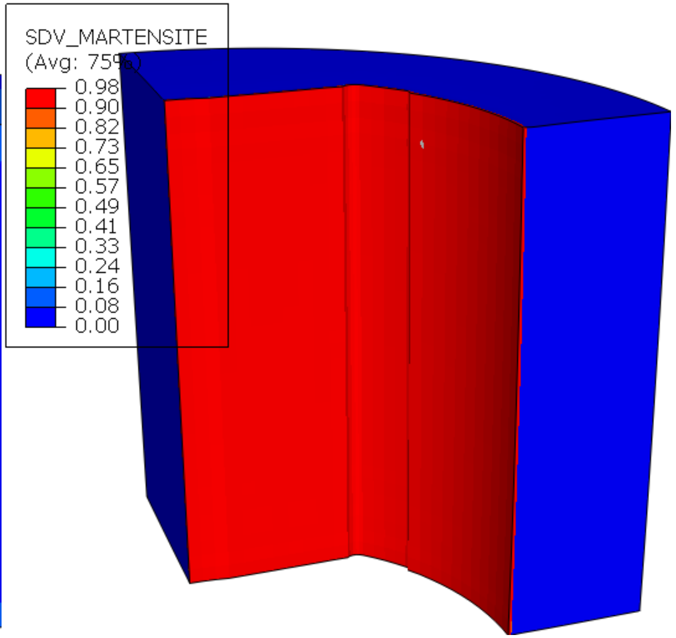
1. Shallower hardened case
    - 0.120 inch (original: 0.160 inch)
    - Reduce bending effect
2. Preheat before hardening
    - Preheat to 500° F
    - Thermal shrinkage helps relieve surface tension
    - Furnace or low frequency/low power induction

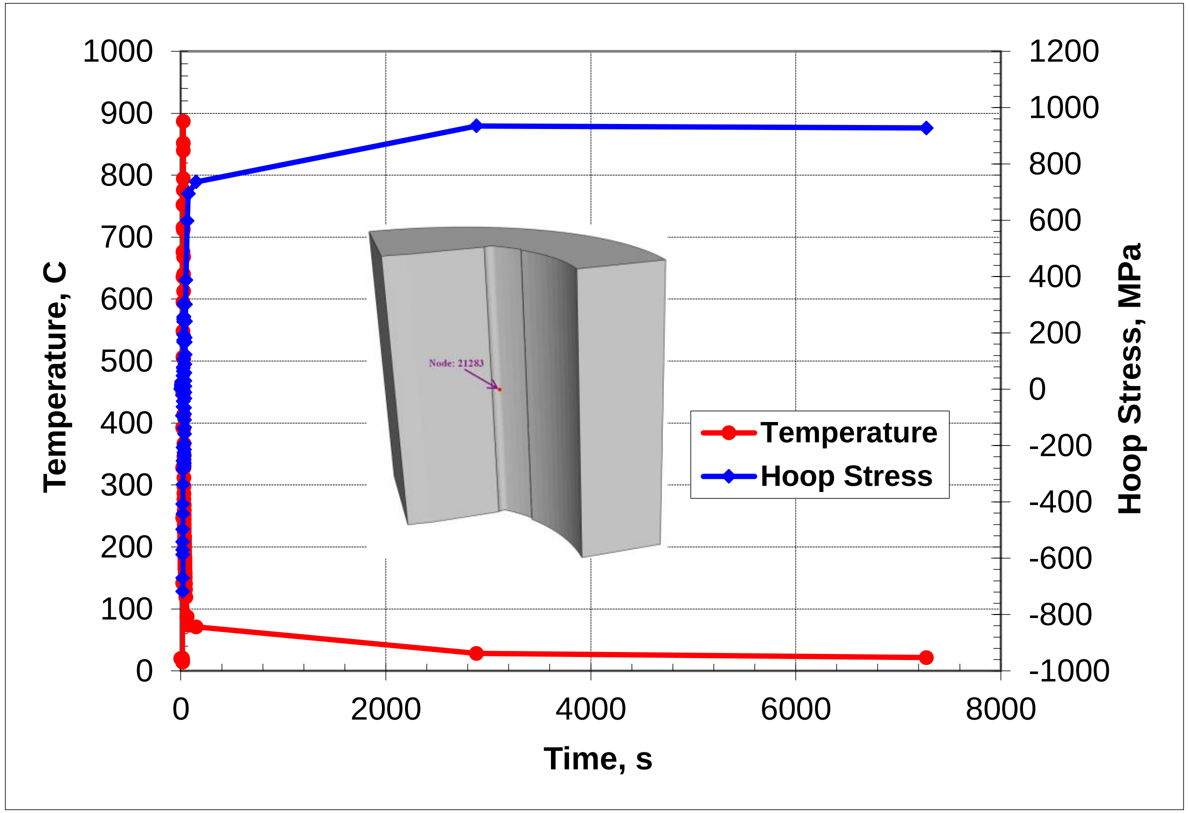
Scanning Induction Hardening of Steel Coupler

Reduced Case Depth Process Results

- Predicted stress is approximately the same as the original process
- Reducing the case depth was not a solution
- Significant finding, saving time and money

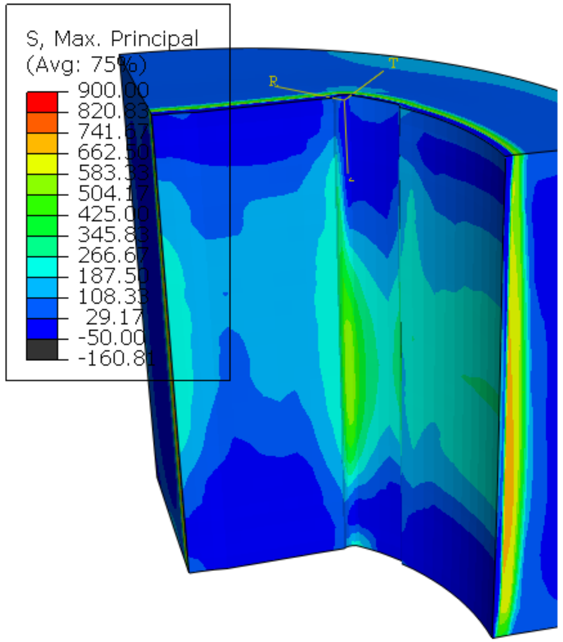


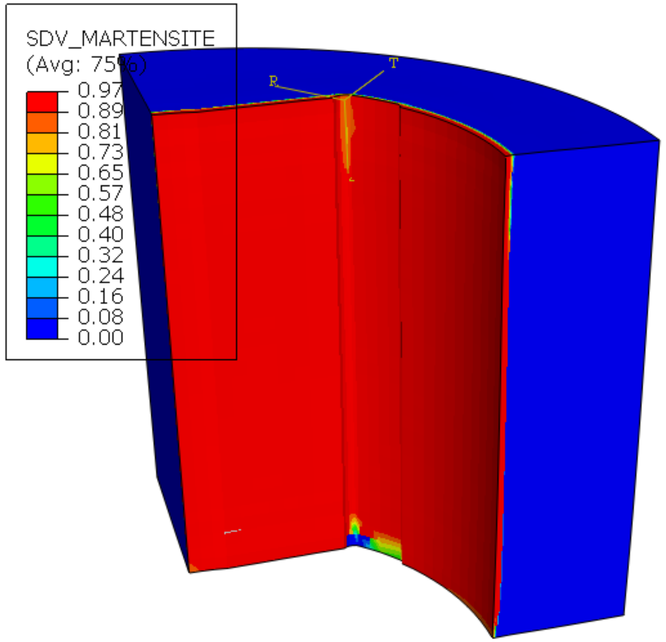


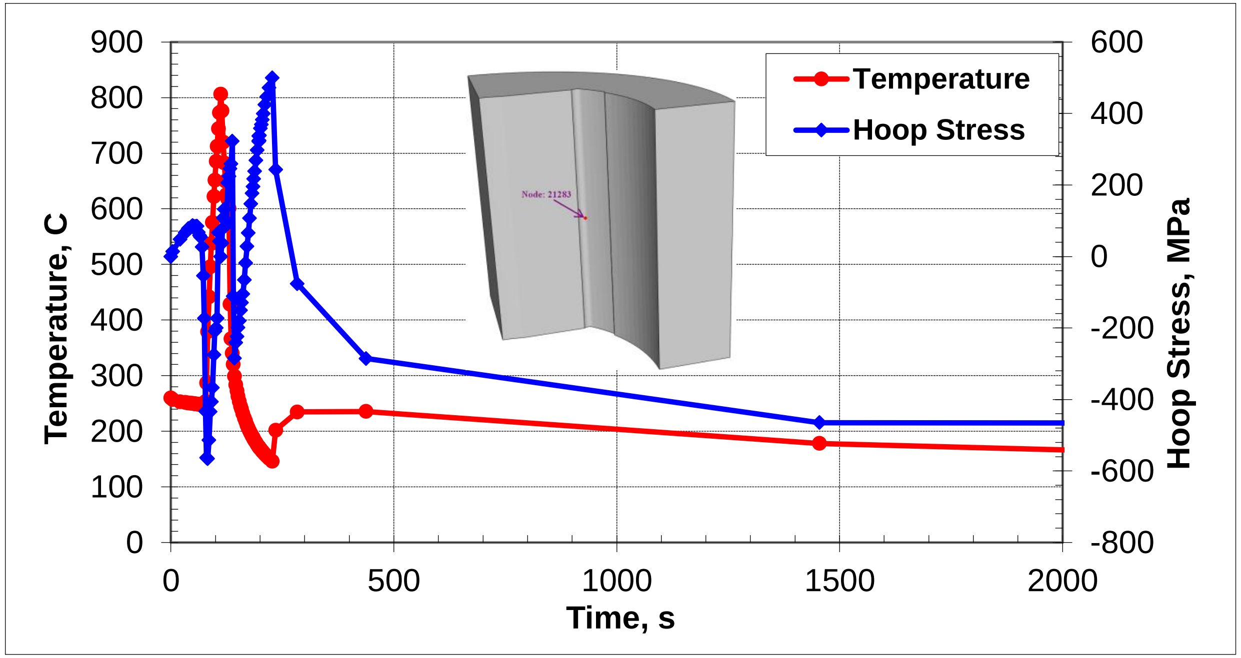


Scanning Induction Hardening of Steel Coupler
Preheat Process Results

- ➢ Preheat temperature: 500° F
  - Can be optimized using simulation
- ➢ Highest in-process stress: 550 MPa
  - Residual surface compressive stress
- ➢ Estimated that cracking should not occur







Equipment Data Needs for Heat Treat Simulation
Specialized Hardening Processes, cont’d

<u>Press/Fixture Quenching</u>

- HTC as a function of part surface temperature
  - Depending on oil flow around the part, can behave more like spray quench than liquid (immersion) quench (constant HTC and ambient temperature)
  - Dependent on part geometry, equipment design, and equipment operation
- Loads exerted on part from tooling
  - Force exerted on the part is required, not the load applied to the press ram
  - Simulation of the press equipment can be helpful
  - Press equipment design, operation, and loading scheme should be well understood
- Thermal effects between the part and the tooling can be considered
  - For high hardenable steels, this is insignificant
  - For lower hardenable steels, this can be significant
    - Can act as a thermal sink, allowing diffusive transformations under the tooling and martensitic transformations elsewhere

Material Data Needs for Heat Treat Simulation
Challenges

<u>Challenges in Collecting Heat Treatment Simulation Data</u>

- Range of temperatures (all properties)
  - 20 ° C to 1100° C; this is in contrast to other industrial processes using simulation, which all have mature simulation tools
    - structural loading (~ room temperature or working temperature)
    - casting (~ solidification temperature)
    - forging (~650 - 1000° C)
  - Temperature range may need to be higher for welding and AM simulation and lower if cryogenic treatments are used
- Isolating single phases for mechanical and thermal testing
  - Ferrite and pearlite can be difficult to separate from each other for certain alloys and carbon levels
  - Austenite between A_{C1} and A_{C3}
  - Different bainite morphologies

Material Data Needs for Heat Treat Simulation, cont'd

Challenges

Challenges in Collecting Heat Treatment Simulation Data

- Ensuring uniform carbon in dilatometry specimen used for transformation kinetics
  - Lab melts with higher carbon may not be representative of carburized, base carbon production melts
  - Through carburization may be problematic given the alloy; long furnace times and/or significant carbide formation and/or grain growth
- Ensuring uniform temperature in dilatometry specimen used for transformation kinetics
  - Critical for accurate strain information; thermal and transformation strain must be separated during data analysis
- Process/Equipment data accuracy and consistency
  - Many variables affect HTC and ambient temperature
    - Vary day-to-day and batch-to-batch
  - Sensitivity analysis is a powerful simulation tool
    - Determine important process parameters

THANK YOU!

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