Modeling the Heat Treatment Response of P/M Components

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Objectives

Develop and verify a computer simulation software and strategy that enables the prediction of the effect of heat treatment on P/M components

Simulation predictions will include:

- Dimensional changes and distortion
- Residual stresses
- Type and quantity of metallurgical phases
- Hardness
Background

Need

- Model provides insight and control of processing conditions to meet
  - Dimensional tolerances.
  - Mechanical properties.

- Model can be used to design a process.
- Model can be used to optimize an existing process.
Methodology

- **Task-1**: Assessment of Dante’s ability to predict heat treatment response of wrought components.
- **Task-2**: Adapting Dante to modeling the heat treatment response of fully dense P/M components.
- **Task-3**: Adapting Dante to modeling the heat treatment response of porous P/M components.
- **Task-4**: Computer experimentation to characterize the effect of various processing parameters on the heat treatment response of P/M components.
Task 1- Assessment of Dante’s ability to predict heat treatment response of wrought components.

Summary of accomplishments during this reporting quarter

**Task1.1:**
- ✓ The measured heat transfer coefficients were adjusted using inverse calculations

**Task1.2:**
- ✓ Samples prepared from 5160 steel were quenched in Hougton-G oil
- ✓ Hardness measurements were performed on these samples and were compared with the model predictions.
- ✓ Distortion measurements were performed on these samples using a CMM machine and were compared with model predictions.
- ✓ Residual stresses at specific locations on the part were measured using the X-Ray diffraction technique and the measurements were compared with model predictions.
- ✓ Amount of retained austenite after quenching was measured using XRD along the cross section of each sample and compared with model predictions.
**Measurement of the surface heat transfer coefficient**

Using the Lumped parameter analysis:

Probe dimensions: D= 9.5 mm , L= 38 mm

For smaller Biot number (Bi=hL/k)<0.1

Heat Balance can be applied at the surface to compute the heat transfer coefficient

\[-hA_s(T_s - T_f) dt = \rho V C_p dT\]

\[h = -\frac{\rho V C_p}{A_s(T_s - T_f)} \frac{dT}{dt}\]

Where,

- \(h\) Heat transfer coefficient at the surface of the probe
- \(T_s\) Temperature at the surface of the probe
- \(T_f\) Temperature of the quenching oil
- \(A_s\) Surface area of the probe
- \(V\) Volume of the probe
- \(\rho\) Density of the steel
- \(C_p\) Specific heat of the steel
Using Inverse calculations:

- Direct problem $T(x,t)$
- Stopping criteria
- Adjoint problem $\lambda(x,t)$
- Search direction
- Sensitivity problem $\Delta T(x,t)$
- Search step size $\beta$
- The new estimation for $h^{n+1}$
Measurement of the surface heat transfer coefficient (contd.)

![Graph showing Biot number vs. Temperature, °C]
Comparison of heat transfer coefficient

Inverse calculations

Lumped parameter analysis

Temperature, °C

Heat transfer coefficient, W/mm²K
Residual stress measurement using X-Ray Diffraction

Courtesy: PANalytical Inc., Natick, MA
Residual stress measurement using X-Ray Diffraction (contd.)

\[
\frac{d - d_0}{d_0} = \left(\frac{1 + \nu}{E}\right)\sigma_{\phi} \sin^2 \psi - \frac{\nu}{E} (\sigma_{11} + \sigma_{22})
\]

\[
\sigma_{\phi} = \sigma_{11} \cos^2 \phi + \sigma_{22} \sin^2 \phi
\]

- \(E\) Modulus of elasticity
- \(\nu\) Poisson’s ratio
- \(\sigma_{ii}\) Principle stresses
- \(d_0\) Strain free d-spacing
- \(d\) d-spacing calculated from the pattern
Residual stress measurement using the crack compliance method

- Stain gauges are mounted on the part’s surface.
- A Slot is progressively machined into the part using wire EDM, and stain is noted for every incremental slot depth.
- Slot releases the residual stress normal to its face.
- Strain is plotted as a function of depth
- The stain vs. depth data is converted into stress as a function of depth
### Comparison chart for various residual stress measurement techniques

<table>
<thead>
<tr>
<th>Depth (mm)</th>
<th>0.001</th>
<th>0.01</th>
<th>0.1</th>
<th>1</th>
<th>10</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>Measurement techniques</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Non-Destructive</td>
<td>X-ray</td>
<td>Magnetic</td>
<td>Ultrasonic</td>
<td>Neutrons</td>
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<td>Semi-Destructive</td>
<td>Hole drilling</td>
<td>Ring core</td>
<td>Crack compliance</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Destructive</td>
<td>Layer removal</td>
<td>Sectioning</td>
<td></td>
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<td></td>
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</tr>
</tbody>
</table>

#### Stresses produced by common processes
- Thin films
- Machining, penning
- Welding, case hardening
- Cladding, heat treating, quenching
- Forming, casting and extrusion

Measurement of the amount of retained austenite by X-ray diffraction

- Selecting proper radiation.
- Running diffraction experiment on required location on the sample.
- Selecting appropriate peaks of martensite and austenite for comparison.
- Measuring the diffracted intensity after removing the background from the pattern.
- Comparing two or more lines if texture is present in the samples.
- Applying the appropriate equation to calculate fractions of the phases.

\[
\frac{I_\gamma}{I_\alpha} = \frac{R_\gamma c_\gamma}{R_\alpha c_\alpha}
\]

\[c_\alpha + c_\gamma = 1\]

Peak positions for Cr-k\(_a\) radiation

<table>
<thead>
<tr>
<th>Peak</th>
<th>Range for 2(\theta)</th>
<th>Peak width</th>
</tr>
</thead>
<tbody>
<tr>
<td>200A</td>
<td>76°-82°</td>
<td>6°</td>
</tr>
<tr>
<td>200M</td>
<td>97°-113°</td>
<td>16°</td>
</tr>
<tr>
<td>220A</td>
<td>123°-135°</td>
<td>12°</td>
</tr>
</tbody>
</table>
DANTE/ABAQUS model setup

- 3-D geometry
  - 5118 hexahedral elements
  - 6685 nodes

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Magnitude</th>
</tr>
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<tbody>
<tr>
<td>Length</td>
<td>76.33 mm</td>
</tr>
<tr>
<td>Height</td>
<td>9.525 mm</td>
</tr>
<tr>
<td>Width</td>
<td>39.624 mm</td>
</tr>
<tr>
<td>Diameter of center hole</td>
<td>31.75 mm</td>
</tr>
</tbody>
</table>
DANTE/ABAQUS model setup (contd.)

- Process steps
- Initial conditions
- Boundary conditions

Geometry and mesh
(ABAQUS-CAE)

Thermal analysis
(ABAQUS solver + DANTE subroutine)

Stress analysis
(ABAQUS solver + DANTE subroutine)

Post processing
(ABAQUS visualization module)
Process steps and initial conditions used in the model

- Process steps:
  1) Furnace heating up to 850°C
  2) Immersion in quenching tank
  3) Quenching in oil down to room temperature

- Initial conditions:
  - For thermal analysis
    1) nodal carbon content (0.59 wt. % C )
    2) temperature (20°C)
    3) heat treatment modes: a) Heating, b) Cooling
  - For stress analysis
    1) initial stress level (set to zero in our case)
    2) heat treatment modes: a) Heating, b) Cooling

Note: The stress model must be similar to the thermal model in its number of process steps, process time for each step, and the number of elements and nodes.
**Boundary conditions**

- **For thermal analysis:**
  1) Furnace heating:
     - Heat transfer coefficient data used from DANTE example problems.
  2) Immersion in quench tank:
     - Immersion velocity = 100 mm/s
     - Immersion direction = along the length of the part
  3) Quenching in oil:
     - Heat transfer coefficients from inverse calculation for samples quenched in Houghton-G oil

- **For stress analysis:**
  - Nodal constraint to prevent rigid body translation and rotation.
Comparison of measured vs. predicted hardness

- Distance from one end to the center (mm)
- Hardness (HRC)

Measured

Predicted
Comparison of measured vs. predicted retained austenite

Volume fraction of retained austenite

Distance along the cross section of the part (mm)
Comparison of measured vs. predicted residual stresses

The graph compares measured and predicted residual stresses. It shows the stress values in MPa for different points, with measured values represented by black bars and predicted values by grey bars. The stress values range from -300 MPa to 0 MPa, and the x-axis represents different points or conditions.
Comparison of measured vs. predicted coordinates of circular hole before and after quenching (distortion)

Measured by CMM

Predicted by model
Evolution of martensite during quenching
Work planned for next reporting period

Task-1:
- Thoroughly investigate the x-ray diffraction method and the crack compliance method for measuring residual stresses in metallic components, compare the two techniques, and adopt the technique that is more reliable and produces repeatable measurements.
- Fixturing and programming the CMM machine to enable direct comparison of the measured part distortions to the model predicted part distortions.
- Fine-tune the model in order to improve its predicting ability.

Task-2:
- Produce samples from fully dense, powder-forged 46XX series alloy steel for Task-2. These include samples for dilatometry and mechanical property measurements (to generate parameters used internally by the software to make the predictions), as well as samples to be used in verifying the model predictions.
- Perform dilatometric measurements to generate the kinetics parameters as well as transformation plasticity data required by the model.
- Perform mechanical property measurements to generate the temperature-dependant, phase specific data required by the model.
## Schedule

### TASK 1: Assessment of Dante’s ability to predict heat treatment response of wrought components. (7/1/2003 to 12/31/2003)

<table>
<thead>
<tr>
<th>Subtask 1.1: Computer simulations</th>
<th>Start</th>
<th>End</th>
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<table>
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<tr>
<th>Subtask 1.2: Experiments and measurements</th>
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<tbody>
<tr>
<td>➢ Measurement of dimensional changes and distortion</td>
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<tr>
<td>➢ Measurement of hardness</td>
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<tr>
<td>➢ Measurement of volume fraction of phases</td>
</tr>
<tr>
<td>➢ Measurement of residual stresses</td>
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</table>

### TASK 2: Adapting Dante to modeling the heat treatment response of fully dense P/M component (1/1/2004 to 12/31/2004)

<table>
<thead>
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<table>
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<tbody>
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<td>➢ Measurement of dimensional changes and distortion</td>
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**TASK 3:** Adapting Dante to modeling the heat treatment response on porous P/M components (1/1/2005 to 12/31/2005)

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<tr>
<td>Measurement of volume fraction of phases</td>
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<tr>
<td>Measurement of residual stresses</td>
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<td>12/31/2005</td>
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**TASK 4:** Computer experimentation to characterize the effect of various processing parameters on the heat treatment response of P/M parts (1/1/2006 to 6/30/2006)

<table>
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</table>
Material properties required in DANTE/ABAQUS simulations

1. Elastic properties as a function of temperature.
   - Modulus of elasticity (E)
   - Poisson’s ratio (\( \nu \) )

2. Coefficient of thermal expansion as a function of temperature for Austenite, Martensite, Ferrite + Pearlite, and Bainite.

3. Latent heat for Austenite, Martensite, Ferrite + Pearlite, and Bainite.

4. Specific heat for Austenite, Martensite, Ferrite + Pearlite, and Bainite.

5. Thermal conductivity as a function of temperature for Austenite, Martensite, Ferrite + Pearlite, and Bainite.

6. Hardness of the material as a function of temperature.

7. Hardness of Martensite.