Big and Smart: The Future of Forging for the Construction and Mining Industries

Matthew Kiser
Advanced Materials Technology
Caterpillar Inc.
CATERPILLAR: OUR GLOBAL FOOTPRINT

PRODUCT LINE
- Construction
- Mining Equipment
- Diesel & Natural Gas Engines
- Industrial Gas Turbines
- Diesel-Electric Locomotive

3 Million+ Products at Work Around the World

98,400 Full-time Employment*

We Provide Solutions that Help Our Customers Build a Better World

171 Dealers Serving 192 countries*

500,000+ Connected Assets*

*Based on 2017 year-end data
CONSTRUCTION INDUSTRIES

1.4M active construction machines globally

RESOURCE INDUSTRIES

>500M tons have safely been moved with autonomous trucks

ENERGY & TRANSPORTATION

6M+ tons of scrap metal recycled through remanufacturing and repair processes

CUSTOMER & DEALER SUPPORT

~550K connected assets
Steel Use: Track-Type Tractors

Sheet: Body Panels
- Frame
- ROPS
- Blade, Ripper (Q&T)

Plate
- Frame
- ROPS
- Blade, Ripper (Q&T)

Bar
- Engine Components: Cranks, Rods, Pistons
- Gears
- Shafts and Hubs
- Undercarriage: Links, Bushings, Pins, Rollers, Sprocket Segments
- GET: Ripper Tips, End bits
- Hydraulics: Yokes

Rolled Sections
- Structural members
- Shoes
- Edges

Tube
- ROPS
- Hydraulic Cylinders
- Hydraulic Tubing
Steel Use: Track-Type Tractors

<table>
<thead>
<tr>
<th>D11T</th>
<th>Total Mass: 134,180 kg (148 tons)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Steel: 119,854 kg (132 tons)</td>
</tr>
</tbody>
</table>

- **Steel**, 90%
- **Iron**, 6%
- **Nonferrous**, 1%
- **Fluids**, 2%
- **Other**, 1%
Dumb Iron?

• Mentality leads to
  – Wasted energy
  – Lost opportunity for material and process data
  – Potentially lower performing part
  – Wasted $
Die Forging – Process Flow

1. Shear or Saw Cut
2. Induction Heat
3. Preform Rolls for Cranks and Rods
4. Forge: 2 or 3 Stage Forming
5. Trim Flash
6. Control Cool
Steel Procurement Considerations

• Rolling Reduction
  – Large components present challenge to achieving desired wrought condition
  – Cost savings to use as cast blooms/billets and achieve all work in forging
  – Understanding impact requires forging process models with good map of degree of work, coupled with component stress models and material life models

• Steel Process History
  – Recently have found impact of steel process route on processing performance (eg. heat treat distortion and response)
  – Limits ability to interchange material from different mills
Rolling Reduction Ratio

Assume constant strains through workpiece: \( \varepsilon_Z = \ln \left( \frac{L_f}{L_i} \right) \quad \varepsilon_r = \varepsilon_\theta = -\frac{1}{2} \ln \left( \frac{L_f}{L_i} \right) \)

Total effective strain: \( \varepsilon_i = \sqrt{\frac{2}{3} \left( \varepsilon_Z^2 + \varepsilon_r^2 + \varepsilon_\theta^2 \right)} = \ln \left( \frac{L_f}{L_i} \right) \)

Rolling reduction ratio definition: \( RR = \frac{A_i}{A_f} = \frac{L_f}{L_i} = e^{\varepsilon_i} \)

- This model is usually used only in rolling or extrusion processes.
- This model does not consider the stress status during 3D deformation in forging processes.
Effective Reduction Ratio

Effective Reduction Ratio: \[ ERR = A \int d\varepsilon_{\text{eff}} = A \sum \varepsilon_{\text{eff}} dt \]

\( \overline{\varepsilon}_{\text{eff}} : \) Effective strain rate

\[
A = -1 \quad \text{if} \quad \sigma_m \geq 0 \\
A = 1 \quad \text{if} \quad \sigma_m < 0
\]

Where mean stress: \( \sigma_m = (\sigma_{11} + \sigma_{22} + \sigma_{33})/3 \)

- More appropriate model to quantify the amount of beneficial work during general forging processes
- Model is modified based on Cockroft & Latham damage theory for plasticity
- Model considers the effect of stress status, but does not consider the magnitude of stresses
EDC Model

Effective Deformation Coefficient definition:

$$EDC = Q = \int_{0}^{\varepsilon_f} \left( -\frac{\sigma_m}{\sigma_{eq}} \right) d\varepsilon_{eff} = \sum \left( -\frac{\sigma_m}{\sigma_{eq}} \right) \varepsilon_{eff} \Delta t$$

- Model is modified based on Ayada’s damage model by Kakimoto et al.
- This model does consider both the stress status and the magnitude of stresses.

H. Kakimoto, T. Arikawa, etc, Development of forging process design to close internal voids, Journal of Materials Processing Technology, 210(2010), p415-422.
Case Study: Mining Truck Spindle Forging Analysis

• Bar rolled from ingot had less reduction than required by specification
• Forging simulation conduction to understand state of internal work
• Analysis used Effective Deformation Coefficient (EDC)
EDC Contours
Applied Stress vs. Work

Regions of high stress not necessarily aligning with regions of high forging work.
Region with the highest fatigue strength is at the OD skin
• Highest stressed region
• EDC comparable to core
Simulation was unable to incorporate the work in the rolled bar
• Greatest amount of deformation near the surface
Mult/Billet Heating

• Concerns
  – Induction Heating:
    • Bar temp uniformity
    • Limited data from pyrometer
  – Furnace Heating
    • Furnace temperature monitoring
    • Box furnace heating duration monitoring

• Case study
  – Microalloy components received with low ductility and low hardness resulting from excess grain size
  – Mult surface temps going into forging at 1285 -1340C
  – Root Cause:
    • Induction heating process favorably heating outside of mults, leaving a cool center.
    • Excess temps enabled grain growth.
  – Corrective Action:
    • Replaced induction heating line
    • Heating set point changed to 1230C (1260C max) with no impact on formability
    • Grain size reduced and ductility improved
Mult/Bar Heating Opportunities

- Induction heating modeling to limit through thickness temperature gradient
- Induction heating validation with thermocouples
- Robust temperature measurement & mapping in reheat furnaces
- Computer tracking of material in box furnaces to ensure first-in, first-out
- Enhanced measurement of each mult temperature
- Data logging of each mult temperature (1st key data point)
Preforming

- Perform forming simulation to limit or eliminate flash
- Design preforming operations with consideration of grain flow
Forging

- Increased sophistication of modeling
  - Strain mapping
  - Temperature profile prediction
  - Press loads

- Increased process sensors
  - Surface temperature map of part going into press/hammer
  - Forging load measurement
  - Surface temperature map of part exiting forging
  - New/improved NDT methods?

Data enhances models

- Guide maintenance
- Flag issues
Flow Line and Performance Prediction

- Need to use forging models to predict grain flow directions
- Couple models with performance models to understand impact of resulting grain flow on component performance
Flow Lines – Location of Centerline

- Also a need to couple flow line models with component process models (machining, heat treat)
- Capture impact of flowlines and original bar centerline location
Cooling

- Most forgings just thrown in tub after trimming
- Microalloy steels require controlled cooling to achieve properties

Could more steels benefit from controlled cooling?
Metallurgical Condition Impacts Heat Treat Distortion

What if these parts had been controlled cooled?
Case Study: Low Strength Piston Crowns

- Issue: PPAP evaluation of pistons crowns showed non conforming tensile properties
- Material: C38mod
- Heating and forging practices showed no concerns

- Parts cooled with 3 level, slanted conveyor
- Best theory: Parts piling up in conveyor
Case Study: Low-Strength Piston Crowns

Outcome of improved cooling:
All pieces have acceptable hardness, at middle of spec

Parts moved to horizontal, single layer conveyor
Opportunity

• Add temperature sensors to inlet and outlet of controlled cooling zones
• Develop models of controlled cooling environments and couple with:
  – Heat transfer models of components
  – Feedback controls of conveyor
• Cost savings for forger and customer:
  – Rapid feedback on potential non-conforming parts
  – Reduce need for normalizing
  – Positioned for next generation of steels poised to even further reduce heat treat
## Conventional Microalloy Steels

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Carbon</th>
<th>Manganese</th>
<th>Min Yield (MPa)</th>
<th>Min UTS (MPa)</th>
<th>CVN (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15V16</td>
<td>0.13-0.17</td>
<td>1.75-1.95</td>
<td>440</td>
<td>635</td>
<td></td>
</tr>
<tr>
<td>15V37 / C38 Mod</td>
<td>0.35-0.41</td>
<td>1.1-1.5</td>
<td>530-550</td>
<td>800-850</td>
<td>5-10</td>
</tr>
<tr>
<td>15V45</td>
<td>0.42-0.47</td>
<td>1.3-1.6</td>
<td>650-680</td>
<td>925-950</td>
<td>3-9</td>
</tr>
</tbody>
</table>

Pearlite & Ferrite with V[C,N] Precipitates

Innovation & Technology Development Division
Advanced Materials Technology
Caterpillar: Non-Confidential
Carbide-Free Bainitic Steels

- Microstructure and performance can be tailored by modifying cooling rates
- Offer potential to significant reduce need for heat treat

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Carbon</th>
<th>Manganese</th>
<th>Min Yield (MPa)</th>
<th>Min UTS (MPa)</th>
<th>CVN (J)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15V16</td>
<td>0.13-0.17</td>
<td>1.75-1.95</td>
<td>440</td>
<td>635</td>
<td></td>
</tr>
<tr>
<td>15V37 / C38 Mod</td>
<td>0.35-0.41</td>
<td>1.1-1.5</td>
<td>530-550</td>
<td>800-850</td>
<td>5-10</td>
</tr>
<tr>
<td>15V45</td>
<td>0.42-0.47</td>
<td>1.3-1.6</td>
<td>650-680</td>
<td>925-950</td>
<td>3-9</td>
</tr>
<tr>
<td>CF Bainite</td>
<td>0.35</td>
<td>1.5</td>
<td>1100</td>
<td>&gt;25</td>
<td></td>
</tr>
</tbody>
</table>

Bainite, Martensite, retained Austenite with optional V[C,N] Precipitates

Still Air Cooled
Cooling rate = 0.6C/s

Fan Cooled
Cooling rate = 1.4C/s
Die Forging – Process Flow – Future Vision

- Cut
- Induction Heat
- Pre-form
- Forge
- Trim
- Control Cool
- Load Measurement
- Process Modeling
- Temperature Measurement
- Automation
Materials Genome Initiative (MGI) - 2011

• Goal: Greatly reduce time and cost of developing new materials innovations

• Three main thrusts:
  – Digital data
  – Computation tools
  – Experimental tools

• Orlando Principles (2012) include*:
  – We will actively incorporate integrated computational materials engineering tools and concepts to accelerate commercial product development, design, and manufacturing across all industries.
  – We will create a materials innovation infrastructure with common resources for data and knowledge sharing that can be openly utilized for model development and validation.

* Developed in meeting coordinated by TMS with representatives from industry, universities, and national labs: www.tms.org/orlandoprinicples/pdf/Orlando_Principles2013.pdf
The Materials Data Infrastructure
Managing Big Data

Recognizes the role material data has in accelerating and lowering the cost of materials and technology innovation.

Report looks to “…provide knowledge and guidance, and motivate community action, to help further the development of a robust materials data infrastructure.”

Harnessing Materials Innovations to Support Next-Gen Manufacturing

• Goal: Identify technology and manufacturing breakthrough opportunities that would present high value to US manufacturing

• Four of the top 7 identified opportunities include:
  – Analytics for nondestructive evaluation and sensors
  – Machine learning for accelerated materials discovery and design
  – Qualification for new materials and processes
  – Materials for smart manufacturing and digital thread technologies

Vision

- Predicted and measured process data passed through value stream
- Digital model or twin of material created facilitating
  - Validation (process and component)
  - Conformance
- Process measurement data informs models and enables machine learning

Steel Making
- Centerline Location
- Work Gradients
- Microstructure

Forging
- Grain Flow
- Work Gradients
- Microstructure
- Temperature Gradients

Controlled Cooling
- Cooling Rate
- Microstructure
- Property
- Cooling Out Temp
- Tensile/Hardness

Cast Structure

Measurements

Model + Measurements

Innovation & Technology Development Division
Advanced Materials Technology
Caterpillar: Non-Confidential
Innovation & Technology Development Division
Advanced Materials Technology

Trends

Process Modeling at OEM ➔ Process Modeling at Suppliers
Machining and Heat Treat at OEM ➔ Machining and Heat Treat at Suppliers
Normalize and Harden ➔ Properties Off Forge
Limited Process Data (Temp After Reheat) ➔ Multiple Temp Sensors + Other Sensors
Temp Measurements as Process Check ➔ Temp Measurements Inform Process
Forging Model ➔ Digital Twin
Thank you for the opportunity!