Artificial Neural Networks to Predict Tensile Properties in Titanium Forgings

Vikas Saraf

October 7-10, 2012 • Atlanta, Georgia

An ICME Approach: Integrated Computational Materials Engineering
Overview

Predicting Tensile Properties in Titanium Forgings

- ICME in action
- Ti6-4 processing
- Models developed
- Integration and results
- Summary

ICME: Integrated Computational Materials Engineering
ICME in Supply chain

Engine design requirement

OEM shape design

In-engine

Machined

Forging/HT/Machining requirement

Billet Requirement

© ATI 2012. All Rights Reserved.
Advanced Material Usage- Titanium in Boeing 777

Titanium in Boeing 777: 10% of the structural weight (Source: ITA).
Ti6-4 Processing

Primary processing

Secondary processing

Evolving microstructure
Ti6-4 Processing

- Alpha-Beta structure refined through conversion and forging process.
- Reduced Cross-Section thicknesses Cooling rates better for high strength.
- Heavy Cross-Section thicknesses Cooling rate is too slow...

Alpha Prime phase basketweave structure within prior beta grains.

This structure results from fast cooling from Heat Treating in the Beta phase field.
Predictability

- Phase Equilibrium/ Beta approach curve
- Phase Field/ Alpha and beta volume fraction
- Crystal Plasticity
  - Yield surface
  - Strain partitioning
  - Texture
- Primary alpha growth/ volume fraction
- Prior beta grain size
- Secondary alpha growth (lath width)
- Variant selection ($\alpha_s$ transformation)
- Texture formulation (Kearns number)

- **RT Tensile properties**
## Predictability

Neural Network model, Ti6-4

<table>
<thead>
<tr>
<th>Input</th>
<th>Output</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Input</strong></td>
<td><strong>Output</strong></td>
</tr>
<tr>
<td>AI</td>
<td>Yield Strength</td>
</tr>
<tr>
<td>V</td>
<td>UTS</td>
</tr>
<tr>
<td>Fe</td>
<td>Elongation</td>
</tr>
<tr>
<td>O</td>
<td>Reduction in Area</td>
</tr>
<tr>
<td>Avg. Fv glob α</td>
<td>ksi</td>
</tr>
<tr>
<td>Avg. glob α size</td>
<td>ksi</td>
</tr>
<tr>
<td>Median sec. α-lath width</td>
<td>%</td>
</tr>
<tr>
<td>α-Texture</td>
<td>Kearns #</td>
</tr>
</tbody>
</table>

Fv- volume Fraction

Artificial Neural Network Training using PatternMaster® Program
Predictability

Neural Network model, Ti6-4

Validation

UTS; ±5%

Predicted vs Measured

- Trained
- Untrained
Production results

Ti 6-4 pancake forged in production environment
α-β forged; α-β heat treated; aged

Process Simulation
- Billet conversion
- Secondary near-net forging
- Heat Treatment

Data Generation
- Beta approach curve
- Flow stress generation
- Strain partitioning
- Initial Texture

Prediction
- α, β growth
- α Fv
- α-lath
- ND α-texture

Post-Processing
- RT Tensile properties
Production results

Volume fraction of primary alpha

<table>
<thead>
<tr>
<th>Location</th>
<th>$\alpha_p$-size ($\mu$m)</th>
<th>$\alpha_p$-Fv</th>
<th>$\alpha_s$-width ($\mu$m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BC</td>
<td>0.26</td>
<td>0.07</td>
<td>0.07</td>
</tr>
<tr>
<td>MC</td>
<td>2.50</td>
<td>0.07</td>
<td>0.02</td>
</tr>
<tr>
<td>RC</td>
<td>0.37</td>
<td>0.00</td>
<td>0.21</td>
</tr>
<tr>
<td>BT</td>
<td>0.98</td>
<td>0.22</td>
<td>0.01</td>
</tr>
<tr>
<td>MT</td>
<td>0.69</td>
<td>0.00</td>
<td>0.09</td>
</tr>
</tbody>
</table>

Grain size (radius) of primary alpha

Thickness of secondary alpha lath
Production results

UTS

% Diff (Predicted - Measured)

Location #

With Texture
Without Texture
Production results

Yield Strength

<table>
<thead>
<tr>
<th>Location #</th>
<th>BT</th>
<th>MT</th>
<th>RT</th>
<th>BC</th>
<th>MC</th>
<th>RC</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

% Diff (Predicted - Measured)

-40.00 -30.00 -20.00 -10.00 0.00 10.00 20.00

Location #

With Texture
Without Texture
Production results

Elongation
Reduction in Area

With texture

Without texture
Neural Network model, Ti6-4

ANN Prediction

Upper bound

YS (ksi)

(-) Nominal (+)

O % comp.

Lower bound

Glob.-α Size 4.0μm
Glob.-α Size 8.0μm

UTS (ksi)

(-) Nominal (+)

O % comp.
Neural Network model, Ti6-4

Figure: ANN Prediction

- Upper bound
  - YS (ksi)
  - Lower bound
  - $\alpha_s$-lath width (\(\mu m\))

- UTS (ksi)
- Elongation (%)

Lines:
- Glob.-\(\alpha\) Size 4.0\(\mu m\)
- Glob.-\(\alpha\) Size 8.0\(\mu m\)
- %El. Glob.-\(\alpha\) Size 4.0\(\mu m\)
- %El. Glob.-\(\alpha\) Size 8.0\(\mu m\)
Tensile strength prediction; Shaft forging
\(\alpha-\beta\) forged; \(\alpha-\beta\) heat treated; aged

\[\text{UTS} \quad \text{YS}\]

\[
\begin{align*}
\text{Radial} & : 148.5/3 & 150/0 & 156/0 \\
\text{Axial} & : 147.5/1 \\
\text{Hoop} & : 135.5/1 & 136/0 & 133.5/1
\end{align*}
\]
Tensile strength prediction; Complex forging
α-β forged; Mill annealed

Shen, Saraf, Furrer; TMS 2006
Summary

Infrastructure to predict complex microstructural evolution and, subsequently, its effect on tensile properties, has been developed.

Simple geometrical shapes produced in an industrial environment confirm the predictability and application of the developed infrastructure.

Complex, near-net-shape aerospace components have shown good correlation between prediction and measurements.
Acknowledgement

Development and integration of models was funded by the USAF under the auspices of Materials Affordability Initiatives.

Michael Glavicic, Tom Broderick, Vasisht Venkatesh, Todd Morton, Yoji Kosaka, Ron Wallis, Vikas Saraf
(AIPT Team members from Rolls-Royce, GE, Pratt & Whitney, Boeing, Timet, Wyman Gordon and ATI Ladish respectively)

And

Fan Zhang, Wei-Tsu Wu, Ravi Shankar, Ayman Salem, Yunzhi Wang, Donald Boyce
(Sub-contractors from CompuTherm, Scientific Forming Technologies Corp., Materials Resources, The Ohio State University and Cornell University, respectively)