Design, Development and Application of New High-Performance Gear Steels

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Topics Covered

• Acknowledgements and Background
• The Need for Better Gear Steels
• Computational Material Design Overview
• Ferrium® C61™, C64™ and C69™ Design Principles
• Property Comparison Overview
• Property Details (by alloy)
• Manufacturing and Processing Issues
• Summary
• Q&A
Acknowledgements

QuesTek gratefully acknowledges the support, cooperation and assistance provided by our partners in developing *Ferrium* C61, C64 and C69, including:

- The U.S. Army and the U.S. Navy
- The U.S. Department of Energy
- Battelle/NASA
- Bell Helicopter, A Textron Company
- The Boeing Company
- Northwestern University and its Steel Research Group
- Pennsylvania State University’s Gear Research Institute
- Sikorsky, A United Technologies Company
Background - QuesTek Innovations LLC

- 16 employees (10 PhDs); founded 1997
- Designs materials to meet specific performance needs, using sophisticated software, modeling and analysis
- Creates and licenses IP to alloy producers or processors
- Currently designing new aluminum-, copper-, iron-, nickel-, niobium-, and titanium-based alloys
- Uses a *Materials by Design®* approach that can design new materials ~70% faster and at ~10-20% of the cost of traditional empirical methods
- Recipient of many business and technology awards
The Need for Better Gear Steels

Goals of the *Gear Industry Vision* for 2025 by AGMA & others include:

- “Increase power density by 25% every 5 years”
- “Reduce costs of manufacturing and operations by 5% per year”
- “Optimize high quality, low deviation, stable production process, including heat treatment…”
- “Explore steels that treat to RC70+”
Example of a Specific Need for the U.S. Navy

• “The new thrust is to significantly enhance the performance of gears and provide increased power density and operational life…

• A 20% improvement in gear endurance…would result in a cost avoidance of about $17 million/year to the DLA alone…

• To achieve the required bending strength and surface durability, power transmission gears are needed
  – high surface hardness of >HRC 61-63…
  – and with a strength gradient specified by a case depth (to HRC 50…) of 0.030” - 0.040” on tooth flanks and about 0.020” in the root fillet region.”

U.S. Navy 2005 STTR Solicitation Topic # N05-T006
Design material as a system to meet customer-defined performance goals e.g. this “Design Chart” for *Ferrium* C64 was developed under a contract resulting from U.S. Navy Solicitation Topic #N05-T006.

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**PROCESSING**
- Grind / Peen / Finish
- Vacuum Temper >450 °C
- Quench / Controlled Cooling
- Carburize / Solution Treatment <927 °C Gas OR 1000°C Vacuum
- Machine
- Anneal ~35 Rc
- Forge
- Homogenize
- VIM/VAR Ingot

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**STRUCTURE**
- Case
  - Dispersion Gradient
  - Ms Temperature Gradient
    - Residual Stress Gradient
    - Retained Austenite
  - Core
    - Matrix - Lath Martensite
      - Ni - Cleavage Resistance
      - Co - GRO Recovery Resistance
    - Strengthening Dispersion
      - (Cr, Mo, V, W, Fe), C
    - Grain Refining Dispersion
      - M micro-void Nucleation Resistance
    - Grain Boundary Chemistry
      - Cohesion Enhancement
      - Impurity Gettering
    - Microsegregation
      - Nb, Cr secondary dendrite

**PROPERTIES**
- Surface Hardness Rc 64
- Residual Stress Distribution
- Modulus
- Thermal Resistance
- Core Hardness ~40 Rc
- Toughness DBTT < -20 °C

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Fall Technical Meeting 2009

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Computational Materials Design Overview (cont.)

Use advanced materials characterization techniques to validate material designs...

LM, SEM/EDS
LM, TEM
MQD
DSC

Solidification Design
DICTRA
TC/Δρ

Transformation Design
TC/MART
CASIS, MAP

Micromechanics Design
ABAQUS/SPO
TC, ΔV

Nano Design
TC(Coh)/DICTRA - Kc
ABAQUS/EFG

Quantum Design
SAM
Kgb(Δγ)

FLAPW
DVM
RW-S

...that are developed using sophisticated computational models and evaluated at various length scales,...
Computational Materials Design Overview (cont.)

... and combine this with Accelerated Insertion of Materials (AIM) to rapidly and economically design, develop and qualify new materials.
Ferrium C61, C64 and C69 Design Principles

- High hardenability Ni-Co lath martensitic matrix
- Nano-scale $M_2C$ secondary-hardening
- Minimal fraction of primary carbides for grain pinning
- Optimized for high temperature vacuum carburizing
- Designed to offer a variety of case and core properties:
  - **C61** High-performance core properties (60-62 HRC case)
  - **C64** Balance of case and core properties (62-64 HRC case)
  - **C69** High-performance case properties (65-67 HRC case)
## Comparison of Typical Properties

<table>
<thead>
<tr>
<th>Alloy</th>
<th>YS (ksi)</th>
<th>UTS (ksi)</th>
<th>Core Hardness (HRC)</th>
<th>EI (%)</th>
<th>RA %</th>
<th>Fracture Toughness (ksi/in)</th>
<th>Achievable Surface Hardness (HRC)</th>
<th>Tempering Temperature (°F)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>AISI 9310</strong></td>
<td>155</td>
<td>175</td>
<td>34-42</td>
<td>16</td>
<td>53</td>
<td>85</td>
<td>58-62</td>
<td>300</td>
</tr>
<tr>
<td><strong>Pyrowear&lt;sup&gt;®&lt;/sup&gt; Alloy 53</strong></td>
<td>140</td>
<td>170</td>
<td>36-44</td>
<td>16</td>
<td>67</td>
<td>115</td>
<td>59-63</td>
<td>400</td>
</tr>
<tr>
<td><strong>Ferrium&lt;sup&gt;®&lt;/sup&gt; C61</strong></td>
<td>225</td>
<td>240</td>
<td>48-50</td>
<td>16</td>
<td>70</td>
<td>130</td>
<td>60-62</td>
<td>900</td>
</tr>
<tr>
<td><strong>Ferrium&lt;sup&gt;®&lt;/sup&gt; C64</strong></td>
<td>199</td>
<td>229</td>
<td>48-50</td>
<td>18</td>
<td>75</td>
<td>85</td>
<td>62-64</td>
<td>925</td>
</tr>
<tr>
<td><strong>Ferrium&lt;sup&gt;®&lt;/sup&gt; C69</strong></td>
<td>195</td>
<td>235</td>
<td>48-50</td>
<td>19</td>
<td>65</td>
<td>40</td>
<td>65-67</td>
<td>925</td>
</tr>
</tbody>
</table>
Graphical Comparison of $K_{IC}$ vs. UTS

$K_{IC} = 0.05C_V^2 + 5.484C_V$

$K_{IC}^2 = 740(C_V)$
C61 Properties (High Performance Core Properties)

- UTS = 240 ksi
- Fracture toughness = 130 ksi√in
- Surface hardness = 60-62 HRC
- AMS specification process anticipated to begin in 2009
- Commercial availability anticipated in 2009
- Superior axial fatigue strength vs. 9310 (~39% increase!)

\[
\begin{align*}
\text{Maximum Stress Level (ksi)} & \\
\text{nf, cycles to failure} & \\
\end{align*}
\]
Some C61 Applications To Date or In Evaluation

- Off-road racing (e.g. SCORE 1600)
  - Ring and Pinion class 1/2-1600 (4.57 ratio) used 8620 or 9310
  - 3-4x life improvement vs. 9310
  - C61 introduced Jan. 2005; now ~80% of SCORE 1600 market and >100 installations

- Process machinery in commercial use

- CH-47 helicopter main rotor shaft
  - Potential 15-25% weight reduction
  - Evaluation underway in U.S. Army Contract #W911W6-09-C-0001
**C64 Properties** (Balanced Core and Case Properties)

- UTS = 229 ksi
- Fracture toughness = 85 ksi√in
- Surface hardness = 62-64 HRC
- Additional gear testing underway
- U.S. Navy Contract N68335-06-C-0339 and related contracts
- Commercial availability anticipated in 2009
C64 Single Tooth Bending Fatigue Results

C64 shows improvement in STBF test over X53
C64 Design and Development Timeline

Select Development Program Milestones

- Created System Design Chart (Design Goals)  
  Completed  
  Sept. 2005
- 30 lb proof-of-concept production  
  Jan. 2006
- 300 lb prototype ingot production  
  Oct. 2006
- Carburization process optimization  
  June 2007
- Static property data  
  Jan. 2007
- Gear profile engineering  
  Mar. 2007
- 10,000 lb full-scale ingot production  
  July 2007
- Full scale carburization process optimization  
  Nov. 2008
- Single tooth bending fatigue testing  
  Apr. 2009

Less than 2 years from definition of material needs (i.e. design goals) to full-scale ingot production
C69 Properties (High Performance Case Properties)

- UTS = 230 ksi
- Fracture toughness = 40 ksi√in
- Surface hardness = 65-67 HRC
- As-ground C69 rotating gears demonstrated 3x L50 life vs. X53 at NASA
- Application for camshafts, bearings, etc.
Manufacturing and Processing Issues

These alloys were designed for low-pressure (vacuum) carburization to **reduce manufacturing costs**

- Higher temperatures → shorter process times
- Higher hardenability → slower cooling rate → less distortion
- Direct gas quench → eliminate hardening & oil quench processes
- Less distortion and no intergranular oxides → less grinding stock removal
Austenitizing occurs during carburization of *Ferrium*.
High hardenability of *Ferrium* allows for direct gas quenching.

9310 processing from: “Effect of Shot Peening on Surface Fatigue Life of Carburized and Hardened AISI 9310 Spur Gears”, The Shot Peener, Fall 2002
Manufacturing and Processing Issues (cont.)

The design of these alloys for low-pressure (vacuum) carburization also permits increased manufacturing flexibility and control.

- Able to “dial in” the hardness depth and profile using different carburization and heat treatments
  - Control lapping or grinding removal
Summary

Computational design methods have rapidly created new gear steels that have attractive properties and processing routes:

- **High hardenability (enabling less severe gas quench)**
  - Less quench distortion
  - Eliminate hardening and oil quench manufacturing steps
- **Core steel tensile strengths > 225 ksi**
  - Enhanced options for integral shaft and gear designs
  - Enhanced options for compact, lightweight designs
- **Increased surface fatigue resistance**
  - Contact fatigue
  - Bending fatigue
  
  \[\text{Alloy specific - dependent upon case hardness}\]
- **Higher temperature resistance (500°F increase in tempering temperature vs. X53 or 9310)**
  - Superior loss-of-lube and high temperature operability
Thank You

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