Integrated Computational Materials Engineering (ICME) Development of *Ferrium*® N63™ Stainless Gear and Bearing Steel

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Leading applications of QuesTek commercially-available Ferrium® alloys

**Ferrium® S53® steel**
In flight service on U.S. Air Force platforms A-10, C-5, KC-135, and T-38 to replace existing corrosion-prone steels.
*From materials design to flight in 10 years*

Being used for numerous flight-critical components on SpaceX’s successful Falcon rocket program

**Ferrium M54® steel**
Navy qualified landing gear hook shank with >2x life vs. incumbent alloy; cost savings of $3 Million to fleet.
*From materials design to flight in 7 years*

**Ferrium C61™ and C64® steel**
Being qualified for next generation helicopter transmission shaft and gears for U.S. Navy and U.S. Army, replacing existing steels used for 50 years

Falcon 9 Launch And Landing Streak, courtesy of SpaceX

NAVAIR Public Release #2014-712
Distribution Statement A: "Approved for public release; distribution is unlimited”
Motivation - improved high-hardness corrosion resistant materials

• Navy aircraft has gears and bearings that are subjected to moist air
  – Bearing not in service long enough to drive off moisture during operation
  – Condensation results in corrosion, especially on carburized surfaces

• Motivation and objectives of the SBIR program are:
  – Develop a fully stainless, surface hardenable bearing steel
    • Dimensional stability
    • High surface hardness (~62HRC)
    • Fully stainless
Limitations of stainless bearing steels

- Best-in-class stainless bearing steels (e.g., Pyrowear® 675) do not maintain stainless properties after carburization
  - The alloy cannot be carburized in single phase field
    - Corrosion pitting is due to large (micron-scale) Cr-rich carbides interacting with surrounding, Cr-depleted matrix
  - Grain growth limits processing temperature (no grain pinning) – forging & heat treatment
    - Elaborate thermal processing needed to mitigate grain growth and primary carbide formation

Calculated equilibrium step diagram for Pyrowear 675 with 0.35 wt%C and 0.4wt%N from U.S. patent 7,186,304 B2

Example Pyrowear 675 case microstructure, showing presence of large Cr-rich carbides
## Ferrium N63 Steel Design Goals

<table>
<thead>
<tr>
<th><strong>Core</strong></th>
<th><strong>Case</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>The target properties for the core material are:</td>
<td>The target properties for the case material are:</td>
</tr>
<tr>
<td>– Fracture toughness:</td>
<td>– <strong>Surface hardness</strong></td>
</tr>
<tr>
<td>• &gt;50 ksi (\sqrt{\text{in}})</td>
<td>• 60-62 HRC</td>
</tr>
<tr>
<td>– Corrosion resistance:</td>
<td>– <strong>Corrosion resistance:</strong></td>
</tr>
<tr>
<td>• stainless</td>
<td>• stainless</td>
</tr>
<tr>
<td>– Ultimate tensile strength:</td>
<td>– Contact fatigue strength:</td>
</tr>
<tr>
<td>• &gt;175 ksi</td>
<td>• similar to carburized M50NiL or Pyrowear 675</td>
</tr>
<tr>
<td>– Fatigue resistance:</td>
<td>– Thermal capability</td>
</tr>
<tr>
<td>• similar to M50NiL or Pyrowear 675</td>
<td>• similar to M50NiL</td>
</tr>
<tr>
<td>– Ease of manufacture</td>
<td>– Dimensional stability</td>
</tr>
<tr>
<td>• (minimize processing cost)</td>
<td>• Minimized retained austenite</td>
</tr>
</tbody>
</table>
SBIR program overview

“Design and develop a stainless, solution-nitrided, bearing alloy”

Phase I:
• 30-lb prototype-scale feasibility demonstration, targeting improved corrosion resistance with optimized surface hardness, core properties

Phase II:
• Finalize target composition at prototype-scale
• 300-lb intermediate scale-up and optimization of processing
• 10T VIM/VAR full-scale commercial production and initial data development

Project partners:
• Rolls Royce – OEM
• Solar Atmospheres – Heat treatment vendor
• Carpenter Technology – full-scale producer
QuesTek’s strategy: case/core approach

• Case: solution nitriding
  – Nitrogen is dissolved into austenite ~1100°C without the formation of primary nitrides
  – Case hardened by $M_2X$ (C+N >0.4 wt%)
    • Avoids debit in corrosion related to carburizing (no primary carbides)
  – Alloy specifically optimized for low pressure nitrogen, process in many existing vacuum furnaces

• Core: 13Cr Martensitic stainless steel
  – Secondary hardened by $M_2C$
    • High-temperature capability (tempered ~482°C)
  – High-hardenability: low-pressure gas quench capable
  – Cu-assisted nucleation – low Co
  – Optimized grain pinning dispersion particle to mitigate grain growth
Key design factors for Ferrium N63 steel

**PROCESSING**
- Grind / Peen / Finish
- Temper 4XX °C or 2XX °C
- Gas Quench
- Solution Nitride
- Machine
- Anneal
- Forge
- Homogenize
- VIM/VAR Melt

**STRUCTURE**

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**Case**
- Nitride Gradient (~0.45 wt%)
  - Depth ~1 mm M₇N
  - Avoid Cr primary particles
- Mₜ Temperature Gradient
  - Residual Strain
  - Retained Austenite

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**Core**
- Matrix – Lath Martensite
  - Ni – Cleavage Resistance
  - Cr, Mn – N Solubility
  - Ni, Mo, Cr - Hardenability
- Strengthening Dispersion
  - (Cr, Mo, Fe)₃(N,C)_x
  - Avoid Fe₃C, M₇C₃, M₂₃C₆, & TCP
- Grain Structure
  - Grain Pinning Dispersion (Nb/TiC)
  - Grain Boundary Cohesion
- Oxide Inclusions
  - La₂O₃, Al₂O₃ – matrix bonding
- Micro-segregation
  - Mo, Cr Secondary Dendrites
  - FCC/BCC solidification/stability

**PROPERTIES**
- Corrosion Resistant (case)
- Surface Hardness R_c 61-63
- Residual Stress Distribution
- Fatigue Initiation
- Thermal Stability to ~400°F
- Core Strength ≥ 180 ksi
- Toughness ≥ 50 ksi·in

**PERFORMANCE**
- Corrosion Resistant (case)
- Contact Fatigue Strength
- Dimensional Stability
- Oil-out Durability
- Core Mechanical Performance
Prototype scale concept validation

- Excellent solution nitridability
  - Achieved case nitrogen of >0.3 wt%, Case HRC ≥60
- Good microstructure
  - Free of primary carbonitrides
  - ASTM GS of 7 in case
- Good core mechanical properties
- Corrosion resistance > 440°C and P675, fully stainless in Case N63-3B
- High case retained austenite (>8%) in 1st designs, <5% in 3B concept alloy

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Core HRC</th>
<th>Case HRC</th>
<th>TYS (ksi)</th>
<th>UTS (ksi)</th>
<th>% Elong</th>
<th>% RA</th>
<th>KIC (ksi√in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>N63-2A (482°C)</td>
<td>48</td>
<td>60</td>
<td>172</td>
<td>223</td>
<td>23</td>
<td>71</td>
<td>60</td>
</tr>
<tr>
<td>N63-3B (482°C)</td>
<td>44</td>
<td>60</td>
<td>156</td>
<td>196</td>
<td>20</td>
<td>70</td>
<td>78</td>
</tr>
<tr>
<td>P675 (315°C)</td>
<td>39</td>
<td>60-62</td>
<td>143</td>
<td>185</td>
<td>20</td>
<td>73</td>
<td>150</td>
</tr>
</tbody>
</table>

Core Mechanical Properties

Solution Nitriding

![Hardness vs. Depth Graph](image)

ASTM B117 Salt Fog testing

1.25-2.25” plates
Prototype scale thermal process optimization

**Temper Evaluations**

**Solution Nitriding Optimization**

![Graph showing temper evaluations and solution nitriding optimization](image)

ICME Development of Ferrium N63 Gear and Bearing Steel
AeroMat Presentation, 12 April 2017
Rev. 1. August 2017
Full scale production validation

• 10T VIM/VAR melt, homogenized, forged to four product sizes (1”, 3”, 5”, and 7” RD), normalized, and annealed
• Scale-up validation
  – Uniform UTS, YS, elongation, %RA, and KIC across all four product sizes
Full scale case hardness profile validation

- Hardness profile determined based on requirements for rolling contact fatigue testing
- Targeted 61HRC on surface and 58HRC at 0.015” case depth achieved in N63 with 12 hour solution nitriding duration
- Peak case hardness (61 HRC) achieved with 482°C/2h temper

<table>
<thead>
<tr>
<th>Temper Condition</th>
<th>Surface HRC</th>
<th>TYS (ksi)</th>
<th>UTS (ksi)</th>
<th>% Elong</th>
<th>% RA</th>
<th>KIC (ksi√in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>482°C / 2hr</td>
<td>61</td>
<td>201</td>
<td>157</td>
<td>21</td>
<td>73</td>
<td>56</td>
</tr>
<tr>
<td>482°C / 8hr</td>
<td>59.5</td>
<td>203</td>
<td>159</td>
<td>24</td>
<td>73</td>
<td>59</td>
</tr>
</tbody>
</table>

Full heat treatment: $1100^\circ C/12hr + 6\text{bar GQ} + -73^\circ C/1hr + 482^\circ C/2hr$ temper
Full scale case/core microstructure

Nitrided Case

Core

Clean microstructure, fine grain size after nitriding
Full scale corrosion resistance (ASTM B117)

Case N63 significantly outperforms case P675 baseline

<table>
<thead>
<tr>
<th></th>
<th>N63 Case</th>
<th>N63 Core</th>
<th>P675 Case</th>
</tr>
</thead>
<tbody>
<tr>
<td>24 hr</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>200 hr</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

N63 1100° C/12hr + 6bar GQ + -73° C/1hr + 482° C/2hr temper
Fatigue testing – core material

**Low Cycle Fatigue**
- Ferrium N63: 1100°C/1hr + OQ + -73°C/1hr + 482°C/2h
- Testing conditions:
  - ASTM E606
  - Room temperature
  - R=0, Kt=1
  - 1M cycle runout

**RR Moore High Cycle Fatigue**
- Ferrium N63: 1100°C/1hr + OQ + -73°C/1hr + 482°C/2h
- Testing conditions:
  - ISO 1143
  - Room temperature
  - R=-1, Kt=1
  - 10M cycle runout

![Graphs showing strain amplitude and stress](image)
Rolling contact fatigue testing – case hardened

- 3 ball on rod RCF testing:
  - MIL-PRF-23699 (~10 drip/min)
  - Room temperature
  - 5.42 GPa (786 ksi) peak contact stress
  - 3600 rpm
  - 15 wear tracks spread across 6-7 samples, ran to fatigue spallation failure

- P675 baseline: Carburized + 315°C temper
- Ferrium N63: Solution nitrided + 482°C temper
- Surfaces ground to 3-4µin Ra
- Weibull analysis of the probability of cycles to failure under fixed contact stress

**Reduced variance and improved L_{10} minimum life compared to baseline Pyrowear 675**
### Alloy Comparison Summary

<table>
<thead>
<tr>
<th>Alloy</th>
<th>Salt Spray Corrosion Resistance (Case)</th>
<th>Surface Hardness (HRC)</th>
<th>Core Hardness (HRC)</th>
<th>TUS (ksi)</th>
<th>TYS (ksi)</th>
<th>EI (%)</th>
<th>Reduction in Area (%)</th>
<th>KIC (ksi√in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferrium N63 (900F/2h)</td>
<td>Stainless</td>
<td>61</td>
<td>44</td>
<td>201</td>
<td>157</td>
<td>21</td>
<td>73</td>
<td>56</td>
</tr>
<tr>
<td>P675 (600F)</td>
<td>Marginal</td>
<td>60-62</td>
<td>39</td>
<td>185</td>
<td>154</td>
<td>20</td>
<td>75</td>
<td>150</td>
</tr>
<tr>
<td>M50Nil (450F)</td>
<td>Poor</td>
<td>60-64</td>
<td>46</td>
<td>200</td>
<td>175</td>
<td>18</td>
<td>75</td>
<td>50</td>
</tr>
<tr>
<td>X53 (450F)</td>
<td>Poor</td>
<td>61-62</td>
<td>35</td>
<td>175</td>
<td>140</td>
<td>16</td>
<td>65</td>
<td>110</td>
</tr>
<tr>
<td>440C (300F)</td>
<td>Marginal</td>
<td>-</td>
<td>60</td>
<td>285</td>
<td>275</td>
<td>2</td>
<td>10</td>
<td>30</td>
</tr>
<tr>
<td>M50</td>
<td>Poor</td>
<td>-</td>
<td>60-64</td>
<td>380</td>
<td>320</td>
<td>4</td>
<td>6</td>
<td>16</td>
</tr>
</tbody>
</table>

*All properties are presented as typicals*
Target Applications

• Primary application
  – Corrosion prone components for Navy aircraft

• Alternate applications
  – Aerospace applications requiring increased resistance to general corrosion including:
    • Bearings
    • Gears in corrosive environments
  – Pitch bearings for offshore wind turbines
  – Offshore oil & gas bearing applications
  – Bearings for the food processing industry
Conclusion

Summary
• Ferrium N63 successfully produced at full commercial scale
• Full scale material meets primary performance criteria necessary to be considered for target application
• Full scale material demonstrates case corrosion improvements over current best-in-class alloys (e.g., Pyrowear 675)

Next Steps:
• Pursue qualification for primary and alternate market opportunities
• Seeking partnerships in target application industries