Design, Development, Qualification and Insertion of Corrosion-Resistant, Ultra-High Strength Ferrium S53® Steel for Aircraft Sustainment and Airworthiness

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Jim Wright, Ph.D.

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Topics Covered

• QuesTek Innovations LLC - Background
• S53 Overview, Production and Qualification
• S53 Design and Development
• S53 Performance, including Corrosion Resistance
• S53 Qualification and Testing - Landing Gear
• S53 Insertion in Defense Platforms - Landing Gear
• S53 Insertion in Defense Platforms - Driveshafts
• Q&A
Background - QuesTek Innovations LLC

- 16 engineers, 9 with PhDs; founded 1997
- Designs materials to meet specific performance needs, using sophisticated software, modeling and analysis
- Creates IP and licenses it to alloy producers or processors
- Currently designing new iron-, aluminum-, copper-, nickel-, niobium-, cobalt-, molybdenum, and titanium-based alloys
- Uses a *Materials by Design®* approach to design new materials 50+% faster and 70+% less costly than traditional empirical methods
- 30+ patents pending or awarded worldwide
- *Ferrium® M54™, S53®, C61™ & C64™* commercially available
Serving DoD and Others to Significantly Improve Equipment Performance, Affordability and EHS

- Marine Corps: M67854-05-C-0025
  - EFV
  - Cost-Stainless Suspension Components
- Army: W15QKN-03-C-0025
  - Howitzer Spade
  - Low-cost Titanium Castings
- Navy: N65538-05-M-0088
  - Virginia Class
  - Sacrificial Anode
- Navy: N65535-07-C-0202 and N65535-08-C-0289
  - V22
  - Ferrum C61™ Gear Steel
- ONR: N00014-05-M-0250
  - VH71
  - Ferrum™ M54™ Low-Cost High Performance Landing Gear Steel
- NAVAIR: N88325-07-C-0339
  - V22
  - Ferrum C61™ Gear Steel
- DoD/ESTCP: Air Force, Ogden UT; General Atomics
  - Ferrum™ 553 Corrosion Resistant Landing Gear Steel
- Army/Picatinny: DAAE30-04-S-0080
  - Naval EM Railgun
  - C530 Deck Steel
- Army/Picatinny: W15QKN-03-P-0181
  - M253 Mortar
  - High Temperature High Strength Alloy
- ONR: N00014-07-M-0446 STRT-I
  - Seahawk
  - Prognosis Smart Steel
- Army/W9111W-06-9-C-0001
  - CH-47
  - Ferrum C61™ Gear Steel Rotor Shaft Weight Reduction
- Navy/M67854-10-C-6592
  - Future Lightweight Medium Machine Gun
  - Cobalt-based gun barrel alloy
- Marine Corps: M67854-10-C-6592
  - Armature Alloy
  - Future Lightweight Medium Machine Gun
  - Cobalt-based gun barrel alloy
- AFRL/Pittsburgh, PA 4410000226
  - Rocket Engine Turbopump
  - Gas Turbine Engine
- AFRL/Pittsburgh, PA 4410000226
  - Gas Turbine Engine
  - Gas Turbine Engine
  - Microstructure Modeling in Ni-Superalloys
  - Burn Resistant Ni-Alloys
- AFRL/Pittsburgh, PA 4410000226
  - Gas Turbine Engine
  - Gas Turbine Engine
  - Gas Turbine Engine
  - Fatigue Life Prediction
- AFRL/PA9850-09-M-0216
  - DOE: DE-SC0002224
  - Boiler Components in Coal Fired Power Plants
  - Creep-Resistant Alloys
- NSF-IIP-0839678
  - DOE: DE-SC0002475
  - Oxidation and Creep-Resistant Superalloys
  - Processable Ni-Alloys

AA&S 2011

INNOVATIONS LLC
Materials By Design®
Computational Materials Design Overview

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.
Integrated Computational Materials Design™ Approach
**Ferrium S53® - Summary**

- Ultra High-Strength, Corrosion Resistant Steel
- Designed and developed to replace 300M (/4340) in landing gear/other parts and reduce cadmium plating

<table>
<thead>
<tr>
<th>Alloy</th>
<th>YS (ksi)</th>
<th>UTS (ksi)</th>
<th>EI (%)</th>
<th>RA %</th>
<th>Fracture Toughness (ksi√in)</th>
<th>Corrosion Resistance</th>
</tr>
</thead>
<tbody>
<tr>
<td>300M</td>
<td>245</td>
<td>288</td>
<td>9</td>
<td>31</td>
<td>65</td>
<td>Poor</td>
</tr>
<tr>
<td>AerMet® 100</td>
<td>250</td>
<td>285</td>
<td>14</td>
<td>65</td>
<td>115</td>
<td>Marginal</td>
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<tr>
<td>Ferrium® M54</td>
<td>251</td>
<td>293</td>
<td>15</td>
<td>64</td>
<td>118</td>
<td>Marginal</td>
</tr>
<tr>
<td><strong>Ferrium S53®</strong></td>
<td>225</td>
<td>288</td>
<td>15</td>
<td>57</td>
<td>65</td>
<td>Good</td>
</tr>
</tbody>
</table>
Ferrium S53® – Qualification and Production

- Vacuum Induction Melted, Vacuum Arc Remelted, Normalized, and Annealed
- Extensive Qualifications:
  - MMPDS-05
  - AMS 5922
  - CINDAS ASMD/ASMH
  - AMS 2759/3 for processing (work in process)
- Commercially Available:

<table>
<thead>
<tr>
<th>Element</th>
<th>Min</th>
<th>Max</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carbon</td>
<td>0.19</td>
<td>0.23</td>
</tr>
<tr>
<td>Manganese</td>
<td>--</td>
<td>0.10</td>
</tr>
<tr>
<td>Silicon</td>
<td>--</td>
<td>0.10</td>
</tr>
<tr>
<td>Phosphorus</td>
<td>--</td>
<td>0.008</td>
</tr>
<tr>
<td>Sulfur</td>
<td>--</td>
<td>0.006</td>
</tr>
<tr>
<td>Chromium</td>
<td>9.50</td>
<td>10.50</td>
</tr>
<tr>
<td>Nickel</td>
<td>5.20</td>
<td>5.80</td>
</tr>
<tr>
<td>Cobalt</td>
<td>13.50</td>
<td>14.50</td>
</tr>
<tr>
<td>Molybdenum</td>
<td>1.80</td>
<td>2.20</td>
</tr>
<tr>
<td>Tungsten</td>
<td>0.80</td>
<td>1.20</td>
</tr>
<tr>
<td>Titanium</td>
<td>--</td>
<td>0.015</td>
</tr>
<tr>
<td>Aluminum</td>
<td>--</td>
<td>0.01</td>
</tr>
<tr>
<td>Vanadium</td>
<td>0.25</td>
<td>0.35</td>
</tr>
<tr>
<td>Oxygen</td>
<td>--</td>
<td>0.0020 (20 ppm)</td>
</tr>
<tr>
<td>Nitrogen</td>
<td>--</td>
<td>0.0015 (15 ppm)</td>
</tr>
</tbody>
</table>
## Computational Design Accelerates Development

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Ferrium S53</th>
<th>Ferrium M54</th>
</tr>
</thead>
<tbody>
<tr>
<td>System Design Chart (Design Goals) Established</td>
<td>DEC 1999</td>
<td>AUG 2007</td>
</tr>
<tr>
<td>Number of design iteration(s)</td>
<td>5</td>
<td>1</td>
</tr>
<tr>
<td>Static properties demonstrated at prototype</td>
<td>JUN 2002</td>
<td>SEP 2008</td>
</tr>
<tr>
<td>1st multi-ton full-scale ingot produced</td>
<td>JAN 2005</td>
<td>JUL 2009</td>
</tr>
<tr>
<td>3rd multi-ton full-scale ingot produced</td>
<td>FEB 2006</td>
<td>JUL 2010</td>
</tr>
<tr>
<td>Static property data developed</td>
<td>DEC 2007</td>
<td>JAN 2011</td>
</tr>
<tr>
<td>Aerospace Materials Specification issued</td>
<td>JAN 2008</td>
<td>AUG 2011*</td>
</tr>
<tr>
<td>10th multi-ton full-scale ingot produced</td>
<td>FEB 2007</td>
<td>NOV 2012*</td>
</tr>
<tr>
<td>Additional derived and static property data developed</td>
<td>JAN 2008</td>
<td>JAN 2013*</td>
</tr>
<tr>
<td>MMPDS Handbook update issued</td>
<td>MAY 2008</td>
<td>AUG 2013*</td>
</tr>
</tbody>
</table>

**Material Qualification Time**  
8.5 Years  
~6 Years  

*Estimate

**Ferrium S53**  
**Ferrium M54**
Accelerated Insertion of Materials (AIM)
Application Example: *Ferrium S53®*

**Customer Requirement:** AMS and MMPDS; 280 ksi UTS A-basis minimum

**Initial Data Development**
- Heat Treatment Optimized for 1 Melt
- Applied Heat Treatment to 3 Melts
- Predicted Minimum ~277 ksi UTS

**Modified Data Development**
- Heat Treatment Optimized for 3 Melts
- Strength-Toughness Tradeoff
- Predicted Minimum = 280 ksi UTS
Accelerated Insertion of Materials (AIM) Application Example: *Ferrium S53®*

- Predicted A-basis minimum = 280 ksi UTS
- A-basis minimum: 280 ksi UTS

- AIM methodology has demonstrated reliable predictions for design minimums
- Allows designers to apply design models to estimate property variation prior to full design allowable development
- Reduces costs and risks of material design and development
Ferrium S53® Provides Excellent Resistance Stress Corrosion Cracking (SCC)

Range of S53 data measured at OCP. Measurements at OCP are difficult. The potentiostatic system is not able to hold the sample at OCP and drives the material anodic.

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Ferrium S53® Provides Excellent Resistance to Stress Corrosion Cracking (SCC)

Reduce unpredictable SCC failures and corresponding risk to crew and equipment.

Accidents by Aircraft System
Commercial Jet Transport Aircraft 1958-1993

SCC Failure

Source: FLIGHT SAFETY FOUNDATION-FLIGHT SAFETY DIGEST-DECEMBER 1994
Further ASTM G49 Tests Underway to Determine Stress Threshold of Stress Corrosion Cracking

- Initial testing for 1,000 hours
  - 0.25” gage diameter
  - Bare material
  - Longitudinal polish

S53 passed at 220 ksi

300M passed at 130 ksi

- Up to 12 samples at each condition
- Scribe width of 0.02”
- Gage diameter of 0.25”
Ferrium S53® Provides Good Resistance to General Corrosion

All circled specimens are bare metal

Marine Environment Tests

Highlights of 6-month (bare metal) specimens
Ferrium S53® Provides Good Resistance to General Corrosion

S53 arrests corrosion at the surface without allowing deep pits or ablative attack, by establishing a stable, passive chrome-oxide film within any corrosion sites that occur.

<table>
<thead>
<tr>
<th>Sample</th>
<th>O</th>
<th>Cr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pit (1)</td>
<td>40.76</td>
<td>2.8</td>
<td>48.12</td>
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<tr>
<td>Base (4)</td>
<td>0.65</td>
<td>93.15</td>
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</table>

300M: ~0.004”

<table>
<thead>
<tr>
<th>Sample</th>
<th>O</th>
<th>Cr</th>
<th>Fe</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pit (1)</td>
<td>40.18</td>
<td>0.17</td>
<td>34.95</td>
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<tr>
<td>Base (3)</td>
<td>8.12</td>
<td>70.33</td>
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15-5: ~0.0003”

<table>
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<th>Sample</th>
<th>O</th>
<th>Cr</th>
<th>Fe</th>
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<tr>
<td>Pit (1)</td>
<td>27.56</td>
<td>19.71</td>
<td>37.53</td>
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<tr>
<td>Base (3)</td>
<td>9.78</td>
<td>86.67</td>
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</table>

AM100: ~0.002”

<table>
<thead>
<tr>
<th>Sample</th>
<th>O</th>
<th>Cr</th>
<th>Fe</th>
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<tbody>
<tr>
<td>Pit (1)</td>
<td>10.07</td>
<td>10.08</td>
<td>88.82</td>
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<tr>
<td>Base (5)</td>
<td>15.53</td>
<td>75.61</td>
<td></td>
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</tbody>
</table>

Pit Depths and Analysis of Corrosion Products After 6 Months in Marine Atmosphere
Ferrium S53® Provides Good Resistance to General Corrosion

B117 Painted & Scribed Panel Tests
5wt% NaCl – 500hrs

300M (AMS 6257) Cd + Chromate + Prime & Paint: Presents with a small number of localized corrosion sites, indicating the cathodic protection offered by the Cd layer adjacent to a scribed bare zone of 300M appears to be limited to less than 500hrs in a salt fog cabinet test environment.

Ferrium S53 (AMS 5922) AC-131 + Prime & Paint: Presents with a larger number of localized corrosion sites with some localized regions of no corrosion attack. The paint protection system is effective, i.e. no undercutting of the primer and paint system was observed and the extent of corrosion was consistent with previous marine exposure studies (i.e. limited attack with small pits and some areas displaying resilient passive film protection).

PH15-5 (AMS 5659) AC-131 + Prime & Paint: The paint protection system is effective. No corrosion product observed.
Additional Surface Protection – Can I?

**Answer:** Yes, S53® is compatible with conventional additional surface protection options, including:

- Prime and paint
- Zn-Ni, prime, and paint
- IVD Aluminum, prime, and paint
- AlumiPlate, prime, and paint
- Cd, prime, and paint

All of the above systems have been successfully applied to S53 parts.
Additional Surface Protection – Should I?

Answer: An engineering selection, based in part on:

- Frequency of inspection/overhaul cycles
- Amount of impact expected (gravel, contact points, etc.)
- Operating environment (e.g. ocean vs. other)
- Visual acceptance of some potential surface rust

Field Service Evaluations will also help assess the value of additional surface protection for specific parts.

Additional tests comparing prime-and-paint to Cd-plating are in progress (5wt% NaCl for 500–1,000 hours; 2 different scribe thicknesses); estimated completion is June 2011.
Significant Corrosion Fatigue Benefit for S53®

Room Temperature
Kt = 1, R = -0.33 40Hz
Longitudinal

3.5wt% NaCl:
20hr presoak
Pn = 7

Ferium S53
(Air)

300M
(Air)

Three data points

MIL-HDBK 5 for 300M in air at R = -0.33
Significant Axial Fatigue Benefit for S53®

- Increased fatigue life of ~a decade compared to 300M in longitudinal orientation

- Comparable fatigue life to 300M in transverse orientation

- Additional R-ratios tested: -1.0 and 0.05

- Data available in MMPDS
Significant Axial Fatigue Benefit for S53® (cont.)

Longitudinal

- Increased notch fatigue life of ~a decade compared to 300M

- Additional $K_t$ values tested: 1.4, 2.0, and 5.0

Transverse

- Additional $R$-ratios tested: -1.0 and 0.05

- Data available in MMPDS
Ferrium S53® - Qualifying Main Landing Gear Pistons

- Sub-scale piston fatigue testing
  - Compared S53 to 4340M and 4330V
  - Tests were run at 3 different loads
  - S53 demonstrated longer life in all load cases

- Average of 3 samples, except 4330V at 21,800lbs is average of 2 samples
Ferrium S53® - Qualifying Main Landing Gear Pistons

Component Fatigue and Yield/Limit-Load Rig-Tests

• Simulated component in service by applying loading spectrum with actuators (e.g. spring-back on take-off, and turning during taxi)
• S53 A-10 MLG Piston: Successfully completed required 4 life-cycles
• S53 T-38 MLG Piston: Successfully completed required 4 life-cycles, then increased stress 15% and successfully completed 10 life-cycles; also successfully completed yield and limit load testing
Producing a *Ferrium S53®* T-38 MLG Piston
Typical S53® Component Production Sequence

1. Material – AMS 5922
2. Heat Treatment – AMS 5922 Section 3.5.3 (future – AMS 2759/3)
3. Final Machine Cut Threads – SAE AS-8879
4. Stress Relieve – min. 4 hours at 525°F ±25°F
5. Fluorescent Magnetic Particle Inspection – ASTM E1444
6. Fluorescent Dye Penetrant Inspection – ASTM E1417
7. Shot Peen – SAE AMS 2430 or 2432
8. Passivate – AMS 2700, Method 1, Type 6 or 8, with post treatment bake within 4 hours after passivation at 375°F ±25°F for 4 hours ±0.25 hours, air cool
10. Chrome Plate – MIL-STD-1501, Type II Class 2, using the HF+H2SO4 pre-plating surface preparation procedure
12. Pre Prime – AMS 3175 using AC-131BB
13. Prime – MIL-PRF-85582, Type I Class C2 or N within 8 hours of primer application
14. Paint – MIL-PRF-85285, Type I, Class W within 4 hours of primer application
Ferrium S53® - Field Service Evaluation

T-38 MLG Piston

17 DECEMBER 2010 – First S53 Landing Gear in Service

T-38 main landing gear piston (4340 – 260 ksi)
More complex loading
Forged component
Currently in production for spares
Potential S53® Landing Gear Demonstration Parts

A-10

A-10 drag brace (300M - 270 ksi)
Simple tension loading
No forging required
Corrosion related failures

A-10 main landing gear piston (4330V – 240 ksi)
More complex loading
Forged component
Currently in production for spares

A-10 nose landing gear axle
Potential S53® Landing Gear Demonstration Parts

C-5 roll-pin (300M – 280 ksi)
- Corrosion limited on internal splines
- Forged component
- Currently in production for spares

A-10 NLG piston tube (300M – 280 ksi)
- Grinding burn issues
- Machined component
- Currently in production for spares

KC-135 truck beam (300M – 280 ksi)
- SCC vulnerable in current design
- Forged component
- Currently in redesign for production of spares

KC-135 forward/aft axles (300M – 280 ksi)
- Corrosion limited in current design (threads)
- Machined component
- Currently in redesign for production of spares
S53® Driveshaft Applications – e.g. Helicopter Mast

- S53 has demonstrated excellent fatigue strength and corrosion fatigue strength
- QuesTek recently completed a Navy SBIR Phase I project to evaluate S53 for main rotor shaft masts in Navy helicopters such as the Sikorsky MH60S
Summary - *Ferrium S53*®

- **In flight service today** for landing gear/other components
- Substantially increases resistance to SCC failures
- Eliminates or reduces use of cadmium on landing gear
- Compatible with numerous surface protection schemes; allows engineering-application options for specific parts
- Attractive properties for driveshafts/pins/other applications
- Extensive data available: MMPDS-05; AMS 5922; CINDAS ASMD/ASMH; AMS 2759/3 for processing
- Commercially Available:

![Latrobe Specialty Steel Company](image1.png)
![Carpenter](image2.png)
Thank You

www.questek.com/ferrium-s53.html

Booth #714