**Ferrium® M54™**: A New Fatigue-Resistant, Lower Cost, Ultra-High Strength Steel for Landing Gear and Arrestment Applications

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April 3, 2012
Agenda

- QuesTek Introduction
- *Ferrium®* M54™ Overview
- Properties vs. Baseline Alloys
- AMS and MMPDS Updates
- Application Engineering Considerations
- Application Examples
- Alternate Temper Investigation for UTS >305 ksi
- Q&A
Background - QuesTek Innovations LLC

- Founded 1997
- 17 engineers (10 with PhDs)
- A global leader in computational materials design:
  - Our Materials by Design® technology and expertise applies Integrated Computational Materials Engineering (ICME) tools and methods to design new alloys 50% faster and at 70% less cost than traditional empirical methods
  - Aligned with President Obama’s Materials Genome Initiative
- Creates IP and licenses it to alloy producers, processors or OEMs
- 30+ patents awarded or pending worldwide
- 4 computationally-designed, commercially-sold alloys
- Designing 10+ new Fe, Al, Cu, Ni, Co, Nb, Ti, Mo and W based alloys for government and industry
Commercializing New Alloys Through Licensees

All four are **double-vacuum-melted VIM/VAR steels:**

**Ferrium S53®**
- Licensee #1 - Feb. 2007:
- Licensee #2 - Dec. 2007:

**Ferrium C61™ and C64™**
- Licensee #1 - Nov. 2009:

**Ferrium M54**
- Licensee #1 - April 2010:

**More Licensees are Anticipated**
QuesTek is creating robust, competitive supply chains
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Aircraft Airworthiness & Sustainment Conference, April 3, 2012

NAVAIR: N88355-07-C-0021

ONR: N00014-05-M-0250

NAVAIR: N88355-06-C-0339

ONR: N00014-05-M-0250

NAVAIR: N88355-06-C-0339

DOED/AFSC: Air Force, Ogden UT; General Atomics

Ferrium® 553 Corrosion Resistant Landing Gear Steel

Innovations LLC

Materials By Design
New Alloys Nearing Commercialization

- Ferrium PH48S™ stainless steel (castable or wrought) with >210 ksi YS and high fracture toughness
- Low-cost castable Ti alloy, with properties equivalent to wrought Ti 6-4
- Aluminum alloy stronger than 7050-T74 with equivalent SCC resistance
- Aluminum alloy with greater strength retention than 2014 after high temperature exposure
Ferrium M54
Superior Properties, Lower Risk, Lower Cost

- VIM / VAR steel, commercially available
- Numerous benefits of using M54 vs. AerMet® 100:
  - Lower procurement cost
  - ~4x greater resistance to Stress Corrosion Cracking (SCC)
  - Exceeds or meets all S-basis procurement minima of AerMet 100
  - Superior low and high cycle fatigue life
  - More robust thermal processing
  - Lower machining costs
- Upgrade from 4340, 300M, Maraging 250/300, etc.
- AMS 6516 for M54 issued in 2011
- Anticipated MMPDS data development completion by 2013
- Significant DoD support for M54

Note: AerMet is a registered trademark of CRS Holdings, Inc., a subsidiary of Carpenter Technology Corp.
# M54 Design and Development Timeline

<table>
<thead>
<tr>
<th>Milestone</th>
<th>Date</th>
</tr>
</thead>
<tbody>
<tr>
<td>Created System Design Chart (Design Goals)</td>
<td>Aug. 2007</td>
</tr>
<tr>
<td>300 lb prototype proof-of-concept production</td>
<td>Jun. 2008</td>
</tr>
<tr>
<td>Feasibility to meet static property requirements</td>
<td>Sep. 2008</td>
</tr>
<tr>
<td>Multi-ton full-scale ingot production</td>
<td>Jul. 2009</td>
</tr>
<tr>
<td>Static property data development</td>
<td>Jan. 2011</td>
</tr>
<tr>
<td>Metallic Materials Development and Standardization (MMPDS)</td>
<td>~ 2013</td>
</tr>
</tbody>
</table>

![M54 Design and Development Timeline](image_url)

Less than 2 years from definition of design goals to full-scale ingot production
# M54: Improved Minimum Properties vs. Other VIM/VAR Steels

<table>
<thead>
<tr>
<th>Property</th>
<th>4340 (AMS 6414)</th>
<th>300M (AMS 6419)</th>
<th>AerMet100 (AMS 6532)</th>
<th>Ferrium M54 (AMS 6516)</th>
</tr>
</thead>
<tbody>
<tr>
<td>S-basis Minimum Ultimate Tensile Strength</td>
<td>260</td>
<td>280</td>
<td>280</td>
<td>285</td>
</tr>
<tr>
<td>Minimum Yield Strength</td>
<td>217</td>
<td>230</td>
<td>235</td>
<td>240</td>
</tr>
<tr>
<td>Minimum $K_{IC}$ Fracture Toughness</td>
<td>~45*</td>
<td>~40*</td>
<td>100</td>
<td>100</td>
</tr>
<tr>
<td>Reported Minimum $K_{ISCC}$</td>
<td>~10</td>
<td>~10</td>
<td>~22</td>
<td>~88</td>
</tr>
<tr>
<td>Corrosion Resistance</td>
<td>Poor</td>
<td>Poor</td>
<td>Marginal</td>
<td>Marginal</td>
</tr>
</tbody>
</table>

* No procurement minimum

M54 has higher S-basis minimums, 4x the SCC resistance, and a lower raw material cost than AerMet 100
M54: Superior $K_{ISCC}$ and UTS Combination
M54: Higher Strain-Controlled Fatigue Resistance vs. AerMet 100

Strain-controlled (LCF) fatigue testing (R = -1)

- AerMet 100 data from Aerospace Structural Metals Handbook
- Ferrium M54 data from two independent experimental runs

![Graph showing strain-controlled (LCF) fatigue testing for M54 vs. AerMet 100](image)

- **AerMet 100 failure**
- **Ferrium M54 failure**

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NAVAIR Public Release
Approved for public release; distribution is unlimited
M54: Higher Stress-Controlled Fatigue Resistance vs. AerMet 100

Non shot-peened M54 has a substantial increase in fatigue life vs. non shot-peened AerMet 100.
Non shot-peened M54 has equivalent or better fatigue life than shot-peened AerMet 100.
M54: Far Superior $K_{\text{ISCC}}$ Performance vs. AerMet 100

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M54 has ~4x greater SCC resistance at OCP than AerMet 100 and shows improvement at other voltages

M54 has lower susceptibility to unexpected SCC-induced failures

**Ferrium M54**
(300 lb prototype heat)

**AerMet 100**
(full scale heat)

**$\Delta = \text{Ferrium M54}$**
(Across 3 full scale heats)

**QuesTek-generated data on full scale heats $K_{\text{ISCC}}$ Rising Step Load (ASTM 1624) at OCP**
MMPDS Update

- MMPDS S-Basis data package has been submitted to MMPDS; anticipate approval for inclusion in June 2012
- Anticipate A-Basis and B-Basis data package to be submitted to MMPDS in late 2013
M54 Less Susceptible to Cobalt Price Fluctuations than AerMet 100

- M54 has ~50% less cobalt than AerMet 100, reducing exposure to:
  - Co pricing fluctuations
  - Strategic sourcing issues from Asia/Africa
- Current $16/lb for Co is near historic low, but it has been as high as $50/lb
- Since AerMet 100 is 13.4% Co, its alloy price will increase > $2.50/lb if the price of Co increases by $20/lb

M54 is Commercially Available
In a Range of Sizes

- 10 full scale heats produced to date
- Latrobe’s current inventory includes:
  - 1.25” round
  - 4” round
  - 7.625” round
- New inventory being continually added
- Latrobe can produce custom sizes from ~0.875” to 13.5” round and up to 15.5” octagon
- Latrobe is first licensee; other alloy producers expected to be added in time
Robust M54 Thermal Processing

M54 provides more robust tempering kinetics and wider thermal processing windows → Can increase manufacturing yield, and reduce waste/re-work

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M54 Less Costly to Machine vs. AerMet 100

- Initial machining study completed
- Initial feedback: M54 machines at faster speeds than AerMet 100
- Full report with speeds, feeds and inserts will be available later in 2012; contact QuesTek for details

<table>
<thead>
<tr>
<th>Small Test Coupons (3.75&quot; RD x 6&quot; length)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machining Operation</td>
</tr>
<tr>
<td>Mill Annealed</td>
</tr>
<tr>
<td>Interrupted OD Turn</td>
</tr>
<tr>
<td>Continuous OD Turn</td>
</tr>
<tr>
<td>Face Mill</td>
</tr>
<tr>
<td>Gundrill</td>
</tr>
<tr>
<td>Hole Drilling</td>
</tr>
<tr>
<td>Tapping</td>
</tr>
<tr>
<td>OD Thread Turning</td>
</tr>
<tr>
<td>OD Grind</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Large Test Coupons (4&quot; RCS x 40&quot; Length)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Machining Operation</td>
</tr>
<tr>
<td>Mill Annealed</td>
</tr>
<tr>
<td>Interrupted OD Turn</td>
</tr>
<tr>
<td>Deep Bottle Boring</td>
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Significant DoD Support For M54

M54 was designed and developed by QuesTek under NAVY SBIR funding, in response to Navy SBIR N07-032

N07-032  TITLE: Innovative Material for Enhancing Landing Gear Life
TECHNOLOGY AREAS: Materials/Processes
ACQUISITION PROGRAM: PMA 274; Presidential Helicopters Program

OBJECTIVE: Develop and demonstrate innovative low-cost, high-strength, high-fracture-tough, corrosion-resistant metal alloys.

Navy SBIR N07-032 currently evaluating M54 for production of T-45 hook shanks

Navy SBIR N093-175 currently evaluating M54 for production of F-18 hookpoints
M54 T-45 Hook Shank Forgings

- First article cut up to validate forging process underway (tensile, $K_{IC}$, etc.)
- Once component manufacturing completed, will be rig tested by Navy
Other Applications For M54

• Components made from AerMet 100 for lower cost and higher performance
• Components made from 4340, Maraging 250/300, 300M, Hy-Tuf, etc. for a weight savings / performance upgrade
• Where ultra high strength is needed in combination with high SCC resistance
• Some Examples
  – Landing gear (e.g. JSF, F-18E/F)
  – Lighter, smaller driveshafts / rotorshafts
  – Penetrating ordnance shells, gun barrels, plate armor
  – Blast-resistant components and containers
  – Structural members, tubing, rotary gear actuators
  – Jet engine blade lock rings
  – Reciprocating engine parts
Alternate Temper Investigation ("M54 HS")
To Achieve >305 ksi UTS Minimum

- Temper development to address Navy need for higher strength (and thus lower fracture toughness) variant of M54
- Property target mins of M54 HS: 305 ksi UTS, 70 ksi-$\sqrt{\text{in}}$ $K_{IC}$
- Preliminary typical properties of M54 HS: 313 ksi UTS, 94 ksi-$\sqrt{\text{in}}$ $K_{IC}$

<table>
<thead>
<tr>
<th></th>
<th>M54 (960°F, 10 hr Temper)</th>
<th>M54 HS (Alternate Temper)</th>
<th>AerMet 310</th>
<th>AerMet 340</th>
<th>Maraging 300</th>
</tr>
</thead>
<tbody>
<tr>
<td>Typical YS (ksi)</td>
<td>251</td>
<td>269</td>
<td>275</td>
<td>314</td>
<td>282</td>
</tr>
<tr>
<td>Typical UTS (ksi)</td>
<td>293</td>
<td>313</td>
<td>315</td>
<td>352</td>
<td>291</td>
</tr>
<tr>
<td>Typical $K_{IC}$ (ksi-$\sqrt{\text{in}}$)</td>
<td>115</td>
<td>94</td>
<td>65</td>
<td>32</td>
<td>68</td>
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<tr>
<td>Min YS (ksi)</td>
<td>240</td>
<td>TBD</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>Min UTS (ksi)</td>
<td>285</td>
<td>305 (target)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>Min $K_{IC}$ (ksi-$\sqrt{\text{in}}$)</td>
<td>100</td>
<td>70 (target)</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
Contact Information

For technical information, contact:
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To purchase Ferrium M54, contact:
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www.latrobesteel.com