European Rotorcraft Forum

ADVANCED HIGH-PERFORMANCE *FERRIUM*® STEELS FOR LIGHTER, MORE ROBUST ROTORCRAFT

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Abstract

QuesTek Innovations LLC (Evanston, IL, USA) has applied its *Materials by Design*® computational design technology to design, develop and insert four new *Ferrium*® high-performance gear and structural steels (*Ferrium* C61™, *Ferrium* C64™, *Ferrium* M54™, and *Ferrium* S53®) that are now commercially available and can significantly reduce rotorcraft weight and manufacturing costs while increasing operational robustness (including oil-out/high temperature survivability). The following paper (and accompanying presentation) will provide a broad overview of the development, materials properties, benefits, and applications (esp. rotorcraft applications) of these four new alloys.

1. INTRODUCTION

QuesTek Innovations LLC (Evanston, IL, USA) has applied its *Materials by Design*® computational design technology to design, develop and insert four new *Ferrium*® high-performance gear and structural steels (*Ferrium* C61™, *Ferrium* C64™, *Ferrium* M54™, and *Ferrium* S53®) that are now commercially available and can significantly reduce rotorcraft weight and manufacturing costs while increasing operational robustness (including oil-out/high temperature survivability). All four of QuesTek's *Ferrium* alloys are currently commercially available from Latrobe Specialty Metals (a Carpenter Company) in a wide range of shapes and sizes from 25 mm (~1") diameter up to 250 mm (~10") diameter. Additional alloy producers are expected to be licensed in the future.

QuesTek uses its proprietary *Materials by Design* technology to computationally design many new materials, including iron-, copper-, aluminium-, nickel-, niobium-, and titanium-based materials. QuesTek was one of only a few commercial firms highlighted in 2008 by the U.S. National Research Council as examples of firms utilizing Integrated Computational Materials Engineering (ICME) for Integrated Manufacturing, Materials, and Component Design [references 1-2].

QuesTek's computational materials design approach considers material design goals and desired performance in the context of a material system. This approach integrates materials process-structure and structure-property models in a systems-based framework in order to meet specific, defined engineering needs, and also address manufacturing processes and material qualification hurdles (including prediction of manufacturing variation). Like any other design effort, judicious decisions regarding key trade-offs among many competing requirements are often needed. Combinations of properties must be considered within specified process, cost, environmental, and life-cycle constraints. Advanced computational modelling tools provide valuable scientific understanding in order to optimize such trade-offs in an efficient and knowledgeable manner, and typically provide enough fidelity to not only determine the favourability of one design solution over another but also to search for design optima in previously-unexplored terrain.

The hierarchical relationships between Processing, Structure, Properties, and Performance are summarized by QuesTek in the form of a "Design Chart," which serves as the template for alloy design (see Figure 1). The performance of the alloy is embodied in the combination of properties outlined in the column on the right. The design process determines suitable microstructural concepts to meet these property goals, as indicated by the middle "Structure" column. Available processing paths to access the microstructural objectives are quantified in the left column. The links between the subsystem blocks in the flow-block diagram represent process-structure and structure-property models required to quantitatively design an alloy to meet the desired material performance objectives.

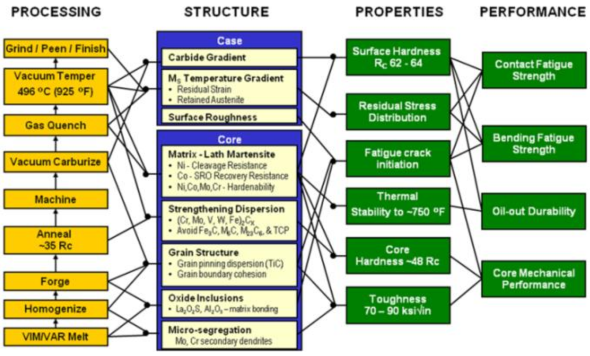


Figure 1. The "Design Chart" used by QuesTek to design the Ferrium C64 alloy. The hierarchical relationships between Processing, Structure, Properties, and Performance are summarized graphically and serve as the template for alloy design.

As it has done in its other development programs, QuesTek and its partners utilized its custom stage-gate process to design and develop the *Ferrium* alloys in a rapid manner, thereby minimizing development costs. The process begins by working with the key stakeholders, such as rotorcraft gear designers and manufacturers, to establish specific system property goals and processing constraints. Within these customer-defined objectives, QuesTek applies its computational models to explore viable microstructural concepts. With the most promising concept selected, the alloy design plan is reviewed for its viability prior to proceeding to the modeling, design, and prototyping phases.

QuesTek's *Materials by Design* process is iterative, with review meetings at critical decision points throughout the modeling, design, and prototyping tasks. After completing the initial modeling and prototype designs, QuesTek procures sub-scale ingots to validate the proof-of-concept with material testing and microstructural characterization. Having achieved the design goals with sub-scale material, QuesTek proceeds to full-scale commercial production. For example, QuesTek prototyped *Ferrium* C64 with one round each of sub-scale and intermediate-scale prototypes prior to the finalized commercial-scale production.

2. *FERRIUM* C61™ AND *FERRIUM* C64™

Ferrium C61 and C64 are new high strength, secondary hardening gear steels that offer different levels of case hardness (see references 3-5). These highly-processable steels exhibit excellent hardenability, and were explicitly designed to leverage the advantages of high-temperature vacuum carburization. *Ferrium* C61 (AMS 6517 / UNS K93061) exhibits both excellent surface fatigue and core properties (see Figure 2 and Figure 3), and is a good candidate for integral gear/shaft applications where maximum torque transfer with minimum weight is tantamount.

Alloy	Yield Strength	Ultimate Tensile Strength	Core Hardness	%El	% RA	K_{IC} Toughness	Achievable Surface Hardness	Tempering Temperature
AISI 9310	1068 MPa (155 ksi)	1206 MPa (175 ksi)	318-412 HV (32-42 HRC)	16	53	93 MPa·√m (85 ksi·√in)	653-746 HV (58-62 HRC)	148°C (300°F)
Pyrowear® Alloy 53	965 MPa (140 ksi)	1172 MPa (170 ksi)	354-434 HV (36-44 HRC)	16	67	126 MPa·√m (115 ksi·√in)	674-772 HV (59-63 HRC)	204°C (400°F)
Ferrium® C61	1551 MPa (225 ksi)	1654 MPa (240 ksi)	484-513 HV (48-50 HRC)	16	70	143 MPa·√m (130 ksi·√in)	697-746 HV (60-62 HRC)	482°C (900°F)
Ferrium® C64	1372 MPa (199 ksi)	1592 MPa (231 ksi)	484-513 HV (48-50 HRC)	18	72	92 MPa·√m (84 ksi·√in)	746-800 HV (62-64 HRC)	496°C (925°F)

Hardness conversions from HRC to HV per ASTM E140

Figure 2. Tabular comparison of gear steel properties (typical).

Ferrium C64 (AMS 6509 / UNS K92731) exhibits excellent surface hardness (62+ HRC after vacuum carburization; see Figure 2 and Figure 3), with the potential for significantly better surface fatigue performance as compared to incumbent gear steels such as AISI 9310 (AMS 6265 / UNS G93106) and *Pyrowear®* Alloy 53 (AMS 6308 / UNS K71040).

The final tempering temperatures of both C61 and C64 (482-510°C) are 200-300°C higher than most incumbent gear steels, providing potential for excellent scoring resistance and superior thermal stability in high-temperature environments and “oil-out” emergency conditions. Figure 4 compares the high temperature strength of C61 with that of X53.

QuesTek’s *Ferrium* C61 and C64 are commercially-available from Latrobe Specialty Steel (Latrobe, PA, USA); additional licenses (including non-US licenses) are anticipated to be awarded as market demand builds for these new alloys.

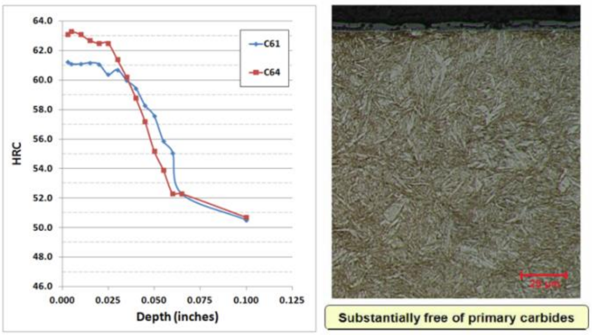


Figure 3. Comparison of *Ferrium* C61 and C64 hardness profiles from typical carburization cycles (left), and photograph of C64 microstructure illustrating absence of primary carbides (right; 25 µm scale bar).

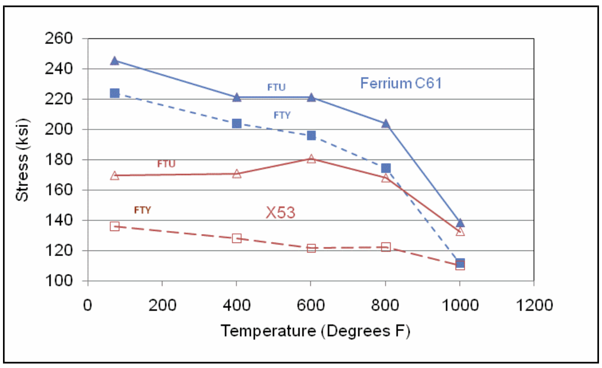


Figure 4. High-temperature strength comparison (*Ferrium* C61 vs. X53).

Benefits of using the *Ferrium* C-series class of steels vs. alloys such as *Pyrowear* 53, 9310, or 8620 can include:

- Smaller, lighter-weight driveshafts or greater throughput. Integral driveshafts (e.g., with integral gears) using C61 and C64 can handle approximately 15-25% higher loads than comparable driveshafts using traditional materials, or be reduced in size and weight by comparable amounts. C61’s core UTS of 1655 MPa is a ~39% increase vs. 9310, for example. C64’s surface hardness of 62-64 HRC and high thermal resistance provide pitting and scoring performance that cannot be achieved in conventional gear steels such as 9310.

- Reduced manufacturing times and costs, yet gain increased flexibility and control. C61 and C64 were specifically designed to take advantage of the benefits offered by vacuum carburizing. Both alloys: 1) were designed to resist grain growth even at high temperatures, thus allowing increased carbon solubility and mobility within the alloy to reduce process times; 2) have high hardenability which allows the use of low pressure gas quench for reduced distortion, while still achieving the minimum properties in large, thick-sectioned components; 3) reduce final machining/finishing costs by eliminating intergranular oxide formation and reducing quench distortion; 4) eliminate the time, expense, equipment and non-uniformity of the traditional after-carburizing oil quench “hardening” step; and 5) permit “dial-in” control of carburized case hardness profile. A paper reviewing the significant manufacturing, processing, and cost benefits associated with the use of C61 and C64 (vs. incumbent steels; see) was presented at the 2011 American Gear Manufacturers Association (AGMA) Fall Technical Meeting (Cincinnati, OH; see reference 6 and Figure 5).

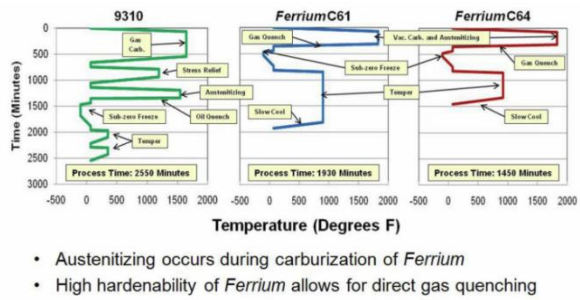
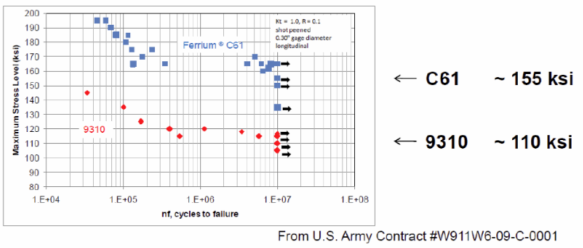


Figure 5. Gear steel processing comparison (typical).

- Superior high temperature operability and survivability such as in oil-out emergency conditions or high-temperature environmments. The 482-510°C tempering temperatures of C61 and C64 are 200-300°C higher than most incumbent alloys, yielding superior thermal stability. This attribute is expected to significantly increase time to reach acceptable landing sites in emergency situations, for example.

- Greater gear durability. Gears and gearboxes using C61 and C64 can handle higher impact loads and internal stresses than comparable designs using traditional materials, or in some cases be reduced in size and weight, due in part to C61's and C64’s very high fracture toughnesses and bending fatigue resistances.
- The combination of excellent gear fatigue properties and high surface hardness in C64 makes it an option for improving durability (and reducing weight) in rotorcraft component designs that incorporate toothed-gears with integral bearing races (e.g., planetary gears in epicyclical rotorcraft transmission designs).
- The combination of high fatigue strength, thermal stability, and high temperature strength translates to excellent potential scuffing and/or scoring fatigue resistance for both C61 and C64.
- The increased alloy content of C61 and C64 provides a reduction in the pitting and general corrosion rate. While the alloys still require sacrificial protection schemes or submersion in oil systems for long-term usage, there is potential for a significant reduction in rework or scrapping of parts due to pitting and corrosion during the manufacturing process.

Ferrium C61 is being examined in a U.S. Army SBIR program as a potential replacement for 9310 in the CH-47 Chinook helicopter forward rotorshaft, yielding a projected potential weight savings of 15–25%. The weight reduction is due to the increase in core properties (strength and fatigue); however, some analysis is being completed for a combination of weight savings and increased power transmission by also taking advantage of the improved surface (gear) properties of C61. See Figure 6 for a comparison of C61 and 9310 core fatigue properties; see Figure 7 for images from C61 prototype CH-47 shaft production. An Aerospace Materials Specification for C61 (AMS 6517 / UNS K92731) was published by SAE in early 2011. *Ferrium* C61’s thermal processing of parts is covered under SAE AMS 2759/7.



From U.S. Army Contract #W911W6-09-C-0001

Material	FTY (ksi)	FTU (ksi)	%elong.	KIC (ksi*in^0.5)
9310	141	185	17	85
Ferrium C61	226	241	15	114

Figure 6. Axial fatigue comparison (C61 vs. 9310).

Figure 7. *Ferrium* C61 prototype CH-47 Chinook helicopter forward rotorshaft production (Army Phase II SBIR contract #W911W6-10-C-0057). A projected potential weight savings of 15–25% is expected over the incumbent shaft material.

Ferrium C64 was developed under a U.S. Navy STTR program (Phase II contract #N68335-06-C-0339) aimed at reducing weight, improving fatigue performance, and improving high temperature operating capability of rotorcraft gear transmission relative to the incumbent alloy *Pyrowear* 53. An Aerospace Materials Specification for C64 (AMS 6509 / UNS K92731) was published by SAE in early 2012. *Ferrium* C64’s thermal processing of parts is covered under SAE AMS 2759/7.

Both *Ferrium* C61 and C64 were evaluated by Boeing in the Enhanced Rotor Drive Systems (ERDS) program (a Technology Investment Agreement between Boeing and the U.S. Army Aviation Applied Technology Directorate). Data for C61 and C64 from the ERDS program (e.g., Figure 8) was presented by Boeing, NASA, and QuesTek at the AHS 2011 Annual Forum (See reference 7). Based on the test data and on Boeing’s analysis, *Ferrium* C61 is planned for further demonstrator gearbox testing under the ERDS program.

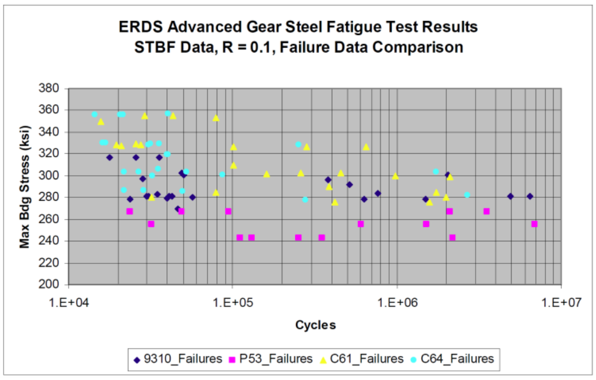


Figure 8. Single tooth bending fatigue data comparisons (*Ferrium* C61, *Ferrium* C64, X53, and 9310; from reference 7).

QuesTek has been awarded a subcontract from Bell Helicopter, a Textron Company, to jointly evaluate the application of *Ferrium* C64 for helicopter gears (see reference 8). This subcontract is part of the $30 million Technology Investment Agreement awarded to Bell by the U.S. Army Aviation Applied Technology Directorate to develop state-of-the-art drive system technology under the Army's Future Advanced Rotorcraft Drive System (FARDS) program. The FARDS program is targeting a 55% improvement in power-to-weight ratio, a 35% reduction in production, operating, and support costs, and other improvements in drive systems for the U.S. Army's Current/Future fleet of rotorcraft and for commercial rotorcraft.

3. *FERRIUM* M54™ AND *FERRIUM* S53®

Ferrium M54 is a new ultra-high-toughness, ultra-high-strength steel that is commercially-available from Latrobe Specialty Steel (Latrobe, PA, USA); additional licenses (including non-US licenses) are anticipated to be awarded as market demand builds for this new alloy., and was designed to be an economical, "drop-in" replacement for *AerMet*®100 (AMS 6532 / UNS K92580) with equal-or-better properties (including significantly better stress-corrosion cracking [SCC] performance). SAE issued an Aerospace Materials Specification for M54 (AMS 6516 / UNS K91973) in early 2011. MMPDS S-basis properties for *Ferrium* M54 were approved and made available in mid-2012; it is anticipated that MMPDS A- and B-basis properties for M54 will be included in 2013. M54 can be used to economically reduce the weight or improve the toughness of key rotorcraft parts such as rotorshafts, drive shafts, landing gear, and actuators in order to improve platform performance and robustness.

General property comparisons for M54 are shown in Figure 9. Another processing constraint in the design of M54 was for a more robust heat treatment window compared to *AerMet*100 (AMS 6532) that avoids precipitation of austenite during tempering. A comparison of M54's tempering response to that of *AerMet*100 (AMS 6532) is shown in Figure 10. The more-robust response to heat treatment exhibited by M54 in Figure 10 (relative to AMS 6532) is expected to result in potential manufacturing savings in terms of a reduction in rejected heat treatment lots, a reduction in waste material, etc. Fatigue data for M54 are shown in Figure 11. Stress corrosion cracking (SCC) test results for M54 are shown in Figure 12 and Figure 13.

A recent aerospace demonstration forging produced from M54 (T-45 Goshawk hookshank; NAVAIR Phase II.5 SBIR contract #N68335-11-C-0369) is shown in Figure 14. First article inspection confirmed that the forging met the requirements of AMS 6516, thus validating the forging process for this material and component.

Alloy	S-basis Minimum Yield Strength	S-basis Minimum Ultimate Tensile Strength	Minimum K_{IC} Fracture Toughness	Reported Minimum KISCC	Corrosion Resistance
4340 (AMS 6414)	**1496 MPa** (217 ksi)	**1792 MPa** (260 ksi)	**~49 MPa·√m*** (~45 ksi·√in)	**~11 MPa·√m** (~10 ksi·√in)	**Poor**
300M (AMS 6419)	**1585 MPa** (230 ksi)	**1930 MPa** (280 ksi)	**~44 MPa·√m*** (~40 ksi·√in)	**~11 MPa·√m** (~10 ksi·√in)	**Poor**
AerMet100 (AMS 6532)	**1620 MPa** (235 ksi)	**1930 MPa** (280 ksi)	**110 MPa·√m** (100 ksi·√in)	**~24 MPa·√m** (~22 ksi·√in)	**Marginal**
Ferrium® M54 (AMS 6516)	**1654 MPa** (240 ksi)	**1965 MPa** (285 ksi)	**110 MPa·√m** (100 ksi·√in)	**~96 MPa·√m** (~88 ksi·√in)	**Marginal**

* No procurement minimum

Figure 9. *Ferrium* M54 property comparisons (vs. 4340, 300M, and *AerMet*100; Aerospace Materials Specification [AMS] minimum value comparisons).

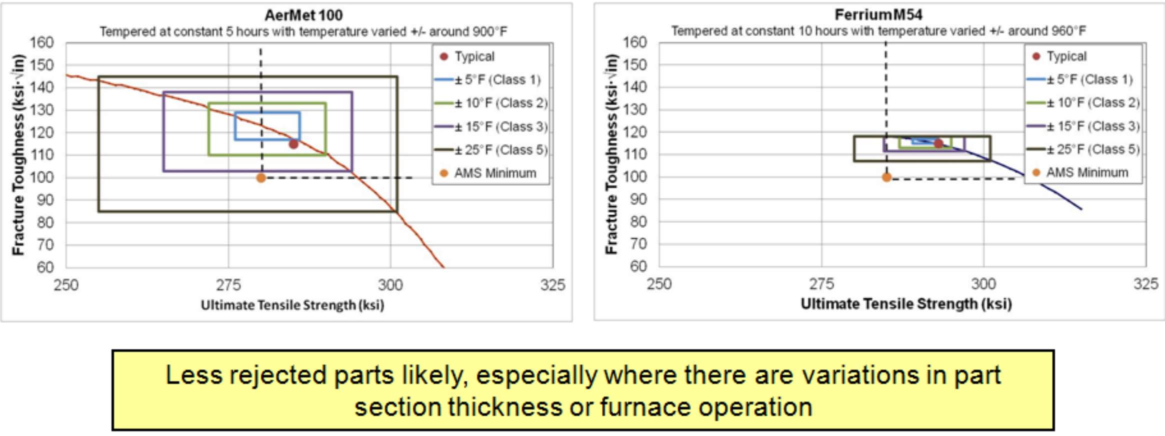


Figure 10. A comparison of *Ferrium* M54's tempering response to that of *AerMet*100 (AMS 6532).

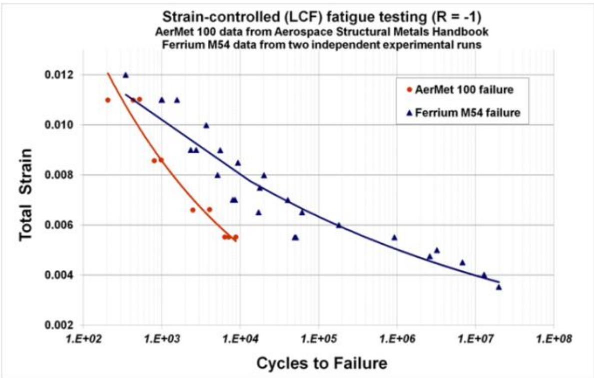


Figure 11. *Ferrium* M54 strain-controlled fatigue data (vs. *AerMet*100 data from Aerospace Structural Metals Handbook).

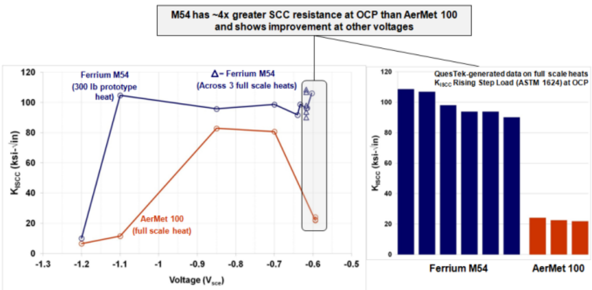


Figure 12. A comparison of *Ferrium* M54's SCC resistance to that of *AerMet*100 (AMS 6532).

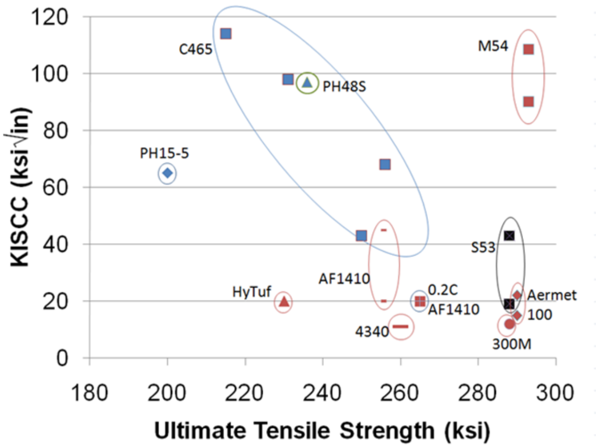


Figure 13. *Ferrium* M54's SCC resistance.

Figure 14. *Ferrium* M54 T-45 Goshawk hookshank forging.

A U.S. Navy supported machinability study of M54 (vs. *AerMet*100) was recently completed (contract #N00421-11-P-0491; public release of final report expected in 2012; see Figure 15). The study demonstrated that M54 machines as-good-or-better than *AerMet*100 in terms of feeds, speeds, etc. across a range of basic machining operations (interrupted and continuous turning, milling, drilling/tapping, grinding, bottle boring, etc.) in both the annealed and hardened (tempered) states. A gear manufacturer has also provided feedback in terms of increased throughput and reduced tooling consumption for spline cutting of M54 (vs. *AerMet*100).

Figure 15. M54 machining study.

Ferrium S53 is a new corrosion-resistant, ultra-high-strength steel that is commercially-available from Latrobe Specialty Steel (Latrobe, PA, USA); additional licenses (including non-US licenses) are anticipated to be awarded as market demand builds for this new alloy. and has received industry certifications, including SAE AMS 5922 (UNS S10500) and inclusion in MMPDS (A- and B-basis) that both occurred in 2008. QuesTek computationally designed S53 to be a drop-in replacement for 300M steel, yet offer significantly more resistance to grinding burn damage, hydrogen embrittlement, SCC and general corrosion. S53 provides excellent resistance to fatigue and corrosion fatigue, and is being evaluated for rotorcraft masts under a U.S. Navy SBIR Phase II project.

General property comparisons for S53 are shown in Figure 16. Notch fatigue data comparisons (S53 vs. 300M) are shown in Figure 17, and general corrosion behaviour comparisons are shown in Figure 18. Corrosion fatigue data (vs. 300M) is shown in Figure 19. There have been several demonstration aerospace components produced on military platforms such as the A-10, C-5, KC-135, T-38, etc. ranging in size from 2 to 2,000 pounds. Images of a recently completed field service evaluation of a prime and paint only protection scheme for a T-38 main landing gear piston is shown in Figure 20.

Alloy	Yield Strength	Ultimate Tensile Strength	Hardness	%El	% RA	K_{IC} Toughness
4340	**1585 MPa** (230 ksi)	**1723 MPa** (250 ksi)	**577-697 HV** (54-60 HRC)	**10**	**40**	**65 MPa·√m** (60 ksi·√in)
9310	**1068 MPa** (155 ksi)	**1206 MPa** (175 ksi)	**653-746 HV** (58-62 HRC)	**16**	**53**	**110 MPa·√m** (100 ksi·√in)
300M	**1730 MPa** (251 ksi)	**2054 MPa** (298 ksi)	**653 HV** (58 HRC)	**11**	**34**	**65-76 MPa·√m** (60-70 ksi·√in)
Ferrium® S53	**1558 MPa** (226 ksi)	**1985 MPa** (288 ksi)	**577 HV** (54 HRC)	**15**	**60-70**	**76 MPa·√m** (70 ksi·√in)

Hardness conversions from HRC to HV per ASTM E140

Figure 16. *Ferrium* S53 typical property comparisons (vs. 4340, 9310, and 300M).

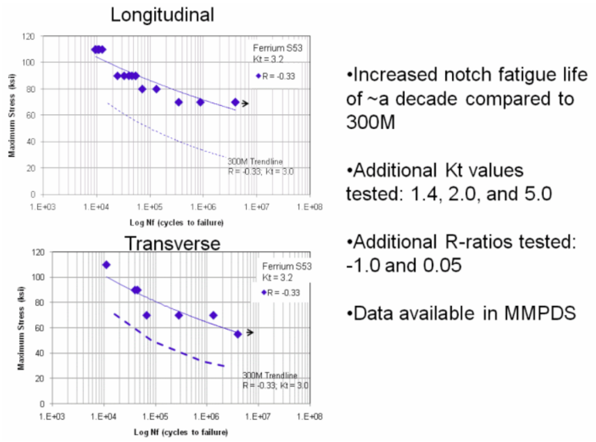


Figure 17. *Ferrium* S53 notch fatigue data (vs. 300M).

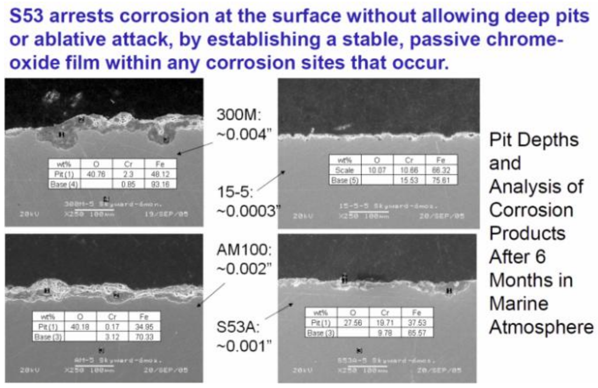


Figure 18. *Ferrium* S53 general corrosion behavior (vs. 300M, 15-5, and *AerMet*100).

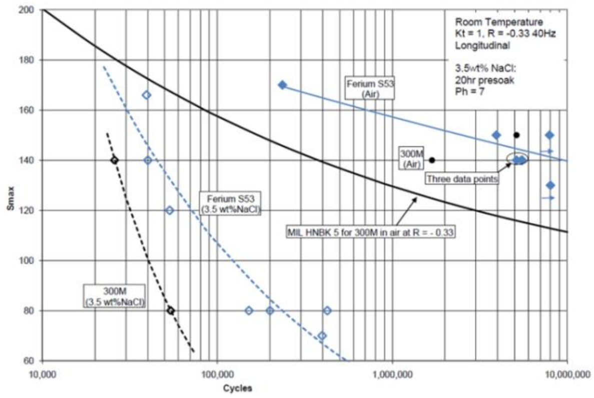


Figure 19. *Ferrium* S53 corrosion fatigue data (vs. 300M).

Figure 20. Production of demonstration aerospace components from *Ferrium* S53—T-38 main landing gear piston.

Details from an ongoing NAVAIR Phase II SBIR on the evaluation of S53 for rotorcraft mast applications are shown in Figure 21. It is expected that S53 can provide performance benefits (strength, fatigue, weight) over existing rotorcraft mast materials while additionally offering significantly better corrosion resistance (including general corrosion and pitting resistance). As an additional part of this program, QuesTek has developed a (preliminary) surface hardening process for S53 to take the case hardness to ~60 HRC (see Figure 22).

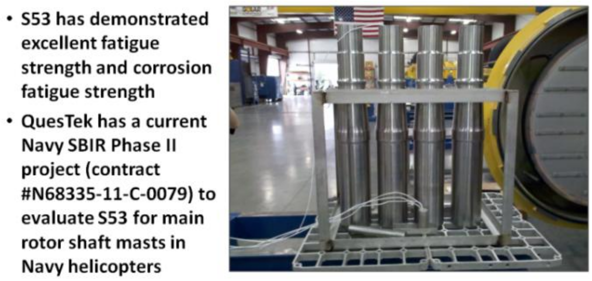


Figure 21. Ongoing NAVAIR Phase II SBIR on the evaluation of *Ferrium* S53 for rotorcraft mast applications.

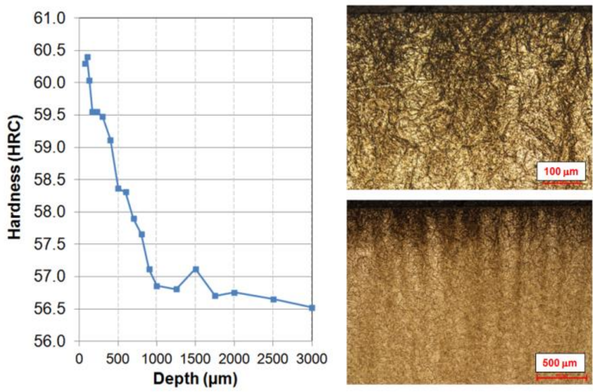


Figure 22. *Ferrium* S53 surface nitriding (average of three separate hardness profiles). Case (and core) microstructure is clean and free of primary inclusions and precipitates.

4. CONCLUSIONS

QuesTek Innovations LLC has applied its M*aterials by Design* computational design technology to design, develop and implement two new high-performance gear steels (*Ferrium* C61 and *Ferrium* C64) and two new high-performance structural steels (*Ferrium* S53 and *Ferrium* M54) that are now commercially available and can significantly reduce rotorcraft weight and manufacturing costs while increasing operational robustness (including gear steel oil-out/high temperature survivability). All four of QuesTek's *Ferrium* alloys are currently commercially available from Latrobe Specialty Metals (a Carpenter Company) in a wide range of shapes and sizes from 25 mm (~1") diameter up to 250 mm (~10") diameter. Additional alloy producers are expected to be licensed in the future.

5. ACKNOWLEDGMENTS

QuesTek acknowledges the support of the Department of Defense via Navy Phase II SBIR contract #N68335-11-C-0079, Navy Phase II.5 SBIR contract #N68335-11-C-0369, Army Phase II SBIR contract #W911W6-10-C-0057, Navy STTR Phase II contract #N68335-06-C-0339, and Navy contract #N00421-11-P-0491.

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