# *Ferrium* S53® Corrosion-Resistant, Ultra High Strength Steel - - One of Many New Computationally-Designed Alloys

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Jim Wright, Ph.D. is a specialist in the field of computational materials design. As Director of Product Development, he heads a team of material design engineers and also manages QuesTek's stage-gate process for material design and development. Since joining QuesTek in 2002, he has led teams to design new materials such as: high-performance gear and bearing alloys; a new class of investment cast, high-strength stainless steel; non-toxic Cu-based alloys to replace Be- and Pb-containing bronzes; a low-cost, castable titanium alloy; a highly-processable Ni-based superalloy; aluminum alloys for aerospace and defense applications; and a Fe-based amorphous alloy. He has also developed a grain pinning model that has been integrated into QuesTek's *PrecipiCalc*® software under the DARPA Accelerated Insertion of Materials (AIM) initiative. Earlier in his career he worked as an intern at the Pratt & Whitney Bearing Business Center and also at Pratt & Whitney's Materials Research Center.

# *Ferrium* S53® Corrosion-Resistant, Ultra High Strength Steel - - One of Many New Computationally-Designed Alloys

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**Abstract:** *Ferrium* S53® is a new corrosion resistant, ultra high strength steel that was computationally designed, invented and developed by QuesTek Innovations LLC of Evanston, IL, USA. A global leader in computational materials design, QuesTek is currently designing, inventing and developing more than 10 new high-performance alloys, and bringing them to market through licensees. QuesTek has licensed both Carpenter Technology Corp. and Latrobe Specialty Steel Co. to produce, market and sell S53. This paper reviews the computational design and development of S53 and summarizes current corrosion testing activity and results. QuesTek's design and development of S53 won a Pollution Prevention "Project of the Year" award from the Strategic Environmental Research and Development Program (SERDP), a U.S. Department of Defense program. Current applications and uses of S53 are outlined (including in the aerospace and defense sector), as well as potential applications in the chemical, petrochemical and power generation industry. Property data available in SAE AMS 5922, MMPDS, and the Aerospace Structural Materials Database is summarized. A brief overview of other alloys in development by QuesTek is also provided.

# 1 Need for Improved Corrosion Resistance

The cost of corrosion to the U.S. Department of Defense is approximately $22.5 billion/year[1]. The Department has been a leader in many areas of research (ranging from understanding the fundamentals of corrosion to applying advanced materials, coatings, inhibitors, and cathodic protection for corrosion control) and has established an Office of Corrosion Policy and Oversight to focus on corrosion[2]. As one example of need, the U.S. Air Force (as well as the commercial aviation industry and other industries) uses alloy 300M fairly extensively in applications such as aircraft landing gear. Unfortunately ultra high strength steels such as 300M and 4340 provide limited corrosion resistance. When 300M is used in aircraft landing gear service, it is often plated with toxic cadmium in order to improve resistance to general corrosion. Alternate alloys with greater corrosion resistance such as 17-4PH and 15-5PH stainless steels provide greater corrosion resistance but substantially less strength.

In addition to the direct impacts to worker health, safety and environment that arise from using plating materials such as cadmium, the overall costs of repair, maintenance and condemnation due to general corrosion remains quite significant despite the use of cadmium plating. Also, failures due to Stress Corrosion Cracking (SCC) can often be of greater concern than those due to general corrosion; SCC-driven failures are often unpredictable, difficult to diagnose, and reduce equipment availability and reliability. Thus the susceptibility of ultra high strength steels such as 4340 or 300M to stress corrosion cracking (SCC) or hydrogen embrittlement can hinder their application. Cyclic fatigue enhanced by hydrogen embrittlement and stress corrosion cracking can result in unpredictable and unacceptable failures.

# 2 *Ferrium* S53®

## 2.1 S53 is a Computationally-Designed Alloy

Historically most new engineered materials have been discovered by laborious, inefficient, expensive and time-consuming trial-and-error experimental efforts, or sometimes by random chance. During the last several decades, powerful physics-based, mechanistic, computational tools have been developed which when integrated with detailed physical databases of fundamental material parameters allow materials to actually be designed to deliver specific properties and performance. For example, materials can be specifically designed to deliver properties such as: general corrosion resistance; SCC resistance; tensile strength; fatigue strength; fracture toughness\creep; ductile-to-brittle transition temperature (DBTT); coefficient of thermal expansion (CTE); electrical conductivity; martensite start (Ms) temperature; thermal stability; thermal conductivity; and solidification segregation.

With support from U.S. governmental agencies and others, QuesTek Innovations LLC computationally designed, invented, developed, and qualified *Ferrium* S53[3] to replace cadmium-plated 300M used by the U.S. Air Force in aircraft landing gear, in order to reduce the expense and downtime associated with equipment corrosion, condemnation, repair and maintenance, and reduce the use of cadmium and its EHS impact. S53 is a new 280 ksi A-basis UTS steel that offers significantly greater corrosion resistance over other ultra high strength steels such as 4340 and 300M, and substantially greater strength than stainless steels such as 17-4PH and 15-5PH. For its design and development of S53, QuesTek won a Pollution Prevention "Project of the Year" award from the Strategic Environmental Research and Development Program (SERDP), a program of the Department of Defense in full partnership with the Environmental Protection Agency and the Department of Energy.

QuesTek used its *Materials by Design*® approach to computationally design S53. This approach integrates targeted materials process-structure-property models within a systems framework to meet specific engineering needs. Using a proprietary software platform, QuesTek couples design models that integrate fundamental physical parameters of materials and fundamental thermodynamic and mobility material databases with higher-level, physics-based modeling tools; these tools include *DICTRA*, *Thermo-Calc* and QuesTek's *PrecipiCalc*® (a multi-component, multi-particle precipitation code) as well as strength, solidification, intergranular cohesion, toughness, and martensite/bainite transformation kinetic modeling tools. In addition, QuesTek applies its expertise in Accelerated Insertion of Materials (AIM) and its stage-gate Design and Development process to yield integrated computational materials design (iCMD™). For additional information about the field of integrated computational materials engineering and QuesTek's methodology, see for example the cited references[4,5] as well as www.questek.com. QuesTek was one of only a few commercial firms cited in 2009 by the U.S. National Research Council for utilizing Integrated Computational Materials Engineering for Integrated Manufacturing, Materials and Component Design[6].

Materials are mechanistically described as a system of inter-connected subsystems which address user-defined performance objectives, and which are mapped to specific property targets (determined by the alloy microstructure), which are in turn defined by material chemistry and processing paths. When illustrated in the form of a "System Design Chart" or "Olson Chart", flow-block diagrams are used to outline the major processing – microstructure – properties – performance relationships for a given material system. Figure 1 illustrates the system design chart for S53.

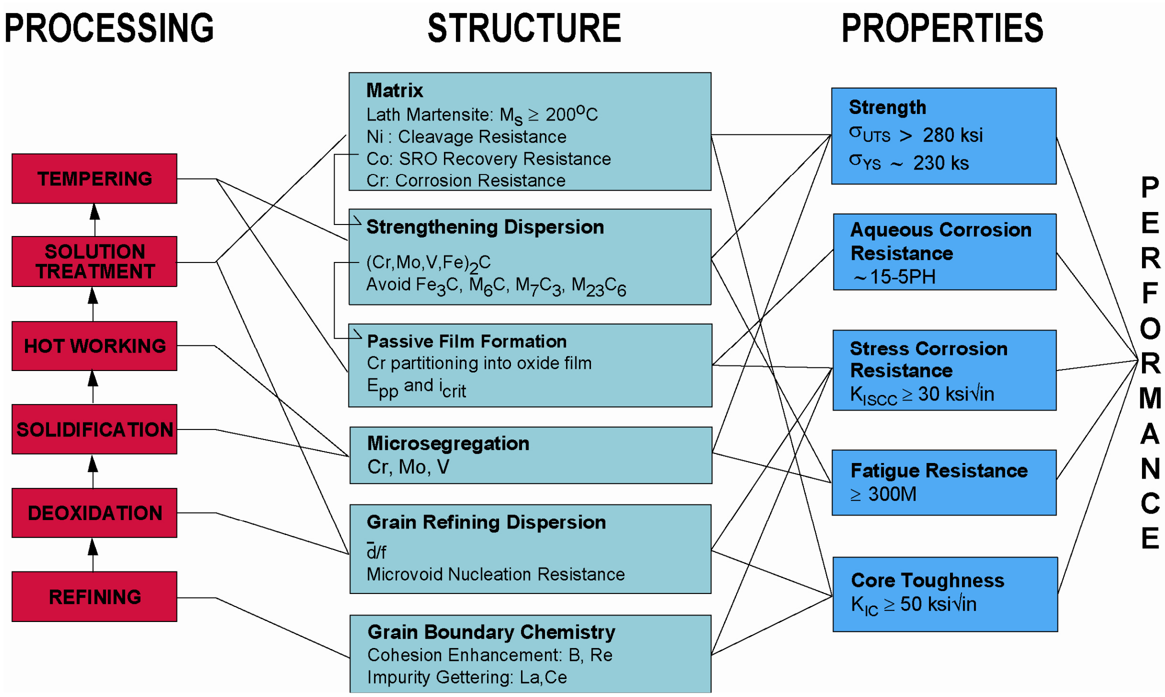



*Figure 1: System Design Chart for Ferrium S53*

The composition of S53 is shown in Table 1. S53 is a secondary hardening steel with a fine ductile lath martensite matrix that incorporates $M_2C$ carbides (which provide efficient strengthening due to their high modulus misfit with BCC iron and ability to precipitate coherently at the nanoscale). Grain-pinning particles are incorporated to minimize grain growth, and grain boundary chemistry is controlled in order to maximize grain boundary cohesion and to substantially improve resistance to SCC and resistance to hydrogen embrittlement. S53 is produced using vacuum induction melting (VIM) followed by vacuum arc remelting (VAR), to yield optimum metallurgical quality and repeatability.

| Fe | C | Co | Cr | Ni | Mo | W | V |
|---|---|---|---|---|---|---|---|
| Balance | 0.21 | 14 | 10 | 5.5 | 2 | 1 | 0.3 |

*Table 1 — Chemical composition of Ferrium S53, in weight percent*

QuesTek's business model is to license its invented alloys and associated intellectual property to others for production, sale or use. S53 was commercially introduced in 2008-2009 when QuesTek licensed both Latrobe Specialty Steel Company and Carpenter Technology Corporation to produce, distribute and sell S53. Extensive mechanical and physical property technical design data for S53 is available in: the Metallic Materials Properties Development and Standardization (MMPDS) handbook; the SAE Aerospace Material Specification (AMS) 5922; the CINDAS Aerospace Structural Metals Database (ASMD); and QuesTek's, Latrobe's and Carpenter's websites.

## 2.2 Strength, Toughness and Fatigue Resistance of S53

Table 2 summarizes key mechanical property data of S53. S53 has a 280 ksi UTS A-basis minimum (matching that of 300M). S53 offers significantly greater UTS when compared to other corrosion-resistant alloys such as 17-4PH, 15-5PH, 440C and Custom 465®. S53 is also the first corrosion-resistant steel to achieve good fracture toughness at this strength level. S53 exhibits typical fracture toughness values of 65 ksi√in, and the AMS specification for S53 denotes a 50 ksi√in minimum requirement. The AMS specification for 300M has no fracture toughness minimum.

| Orientation | U.T.S. | | 0.2% Yield | | %El | %RA | Impact energy | | Fracture Toughness | | HRC |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | ksi | MPa | ksi | MPa | in 4D | | ft-lbs | J | ksi√in | MPa√M | |
| Long. | 288 | 1986 | 225 | 1551 | 15 | 57 | 18 | 24 | 65 | 71 | 54 |
| Trans. | 288 | 1986 | 225 | 1551 | 15 | 55 | 18 | 24 | 65 | 71 | 54 |

*Table 2 — Typical mechanical property data of Ferrium S53*

S53 has an A-basis yield strength minimum of 213 ksi, which is 17 ksi lower than the 300M minimum. While S53 exhibits lower yield strength than 300M, its overall plastic deformation is similar to 300M. For instance, if yield strength was evaluated at a 0.4% strain offset rather than a 0.2% offset, then S53 would be equivalent to 300M. The earlier onset of yielding in S53 vs. 300M is driven by transformation plasticity, in which a small amount of austenite remaining in S53 after heat treatment transforms to martensite on the application of stress and produces yielding. Because this yielding is not slip (in the traditional sense), S53 is still stable against plastic flow to higher stresses. Compressive yield strength minimums for S53 and 300M are nearly identical.

## 2.3 Resistance of S53 to General Corrosion and to Stress Corrosion Cracking (SCC)

S53 provides very good SCC resistance, as demonstrated in ASTM F1624 and ASTM G49 tests. The ASTM F1624 test applies a rising step load to pre-cracked specimens in 3.5% salt water, and allows testing to be completed at Open Circuit Potential (OCP) as well as at applied potentials that represent contact with materials such as Al, Cd, Zn, etc. Figure 2 shows the results of SCC testing on 300M, S53 and 15-5PH steels.

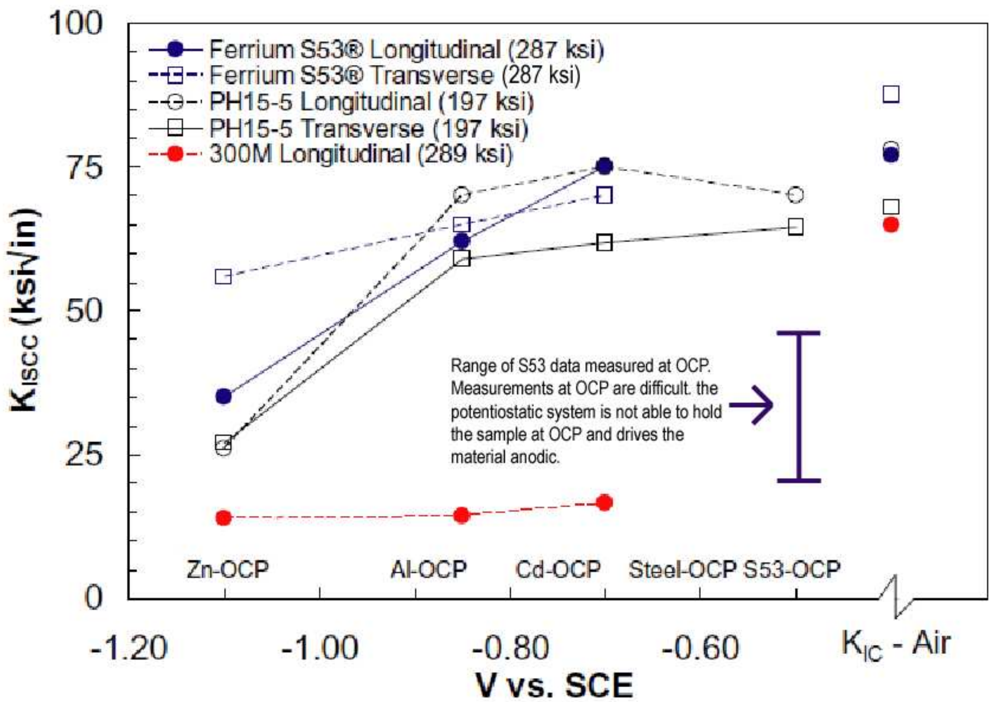
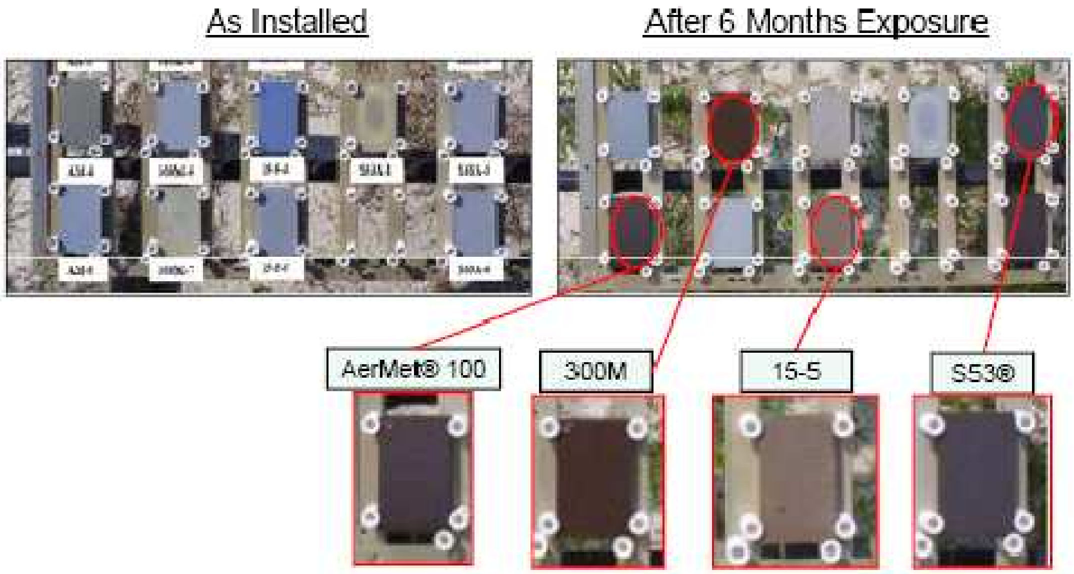



*Figure 2 — ASTM F1624 test results for 300M, Ferrium S53 and PH15-5*

Corrosion-resistant materials 15-5PH and S53 maintain resistance to crack propagation in the presence of a corrosive environment, whereas 300M drops to less than 20 ksi√in in a corrosive environment. Yet S53 offers approximately a 90 ksi increase in UTS over 15-5PH.

The resistance of S53 to general corrosion is comparable to that of 440C stainless steel. In both shot-peened and grit-blasted ground conditions (with passivation), S53 demonstrates a stable passive chrome-oxide film and arrests corrosion products at the surface without allowing deep pits or ablative attack. For example S53 test panels showed shallow surface oxidation and scattered pits with depths of 0.001 - 0.002 inches after one year of exposure when placed 100 yards from mean tide in a seawater, salt-spray oceanfront marine atmosphere (Kure Beach, NC); EDX analysis showed strong partitioning of chromium to the surface oxide scale retarding pit formation (see Figure 3).

## General Corrosion on Bare Metal Samples in Marine Environment (Kure Beach, NC)




## Corrosion Pit Depths after Six Months in Marine Environment (Kure Beach, NC)

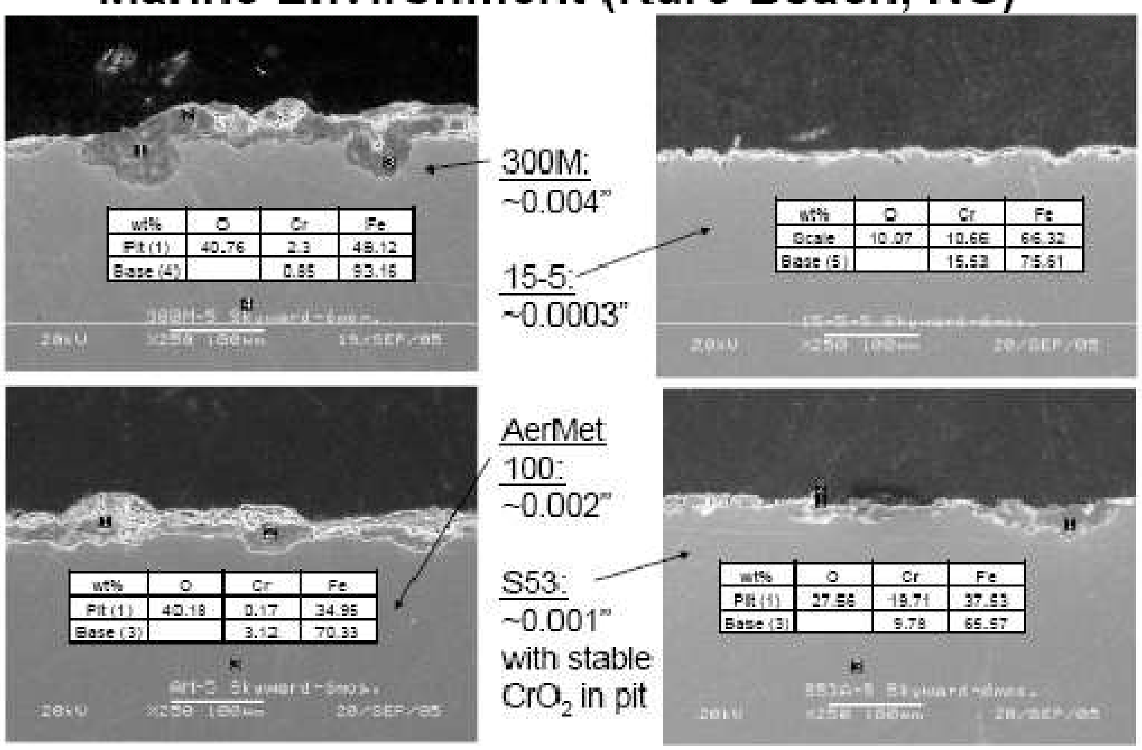



*Figure 3: Results of general corrosion tests in marine environment (Kure Beach, NC) demonstrates that S53 forms a stable passive chrome-oxide film and arrests corrosion products at the surface without allowing deep pits or ablative attack.*

Results of a ASTM G49 test (in which a uni-axial tension-loaded test specimen is alternately submerged in 3.5% NaCl solution and air) indicate no failure at 1,000 hours of S53 at 220 ksi vs. 300M at only 130 ksi; S53 exhibits substantially less corrosion, as illustrated in Figure 4.

*Figure 4  Final results of Ferrium S53 at 220 ksi (left) vs. 300M at 130 ksi (right) tension-loaded specimens in ASTM G49 test, alternately submerged in 3.5% NaCl solution and air for 1,000 hours.*

S53 has demonstrated excellent corrosion fatigue resistance, as illustrated in Figure 5. Axial fatigue testing at various stress levels (120-220 ksi) at a number of R-ratios (-1, -0.33, 0.05) and in both longitudinal and transverse orientations, has shown superior behavior of S53 to 300M.  Notched axial-fatigue test results (trendcurves are available in the MMPDS handbook and elsewhere) show that S53 displays superior lifetime to 300M ($K_t$=3.2 tested at R=-1, -0.33, 0.05 for L-R and R-L).

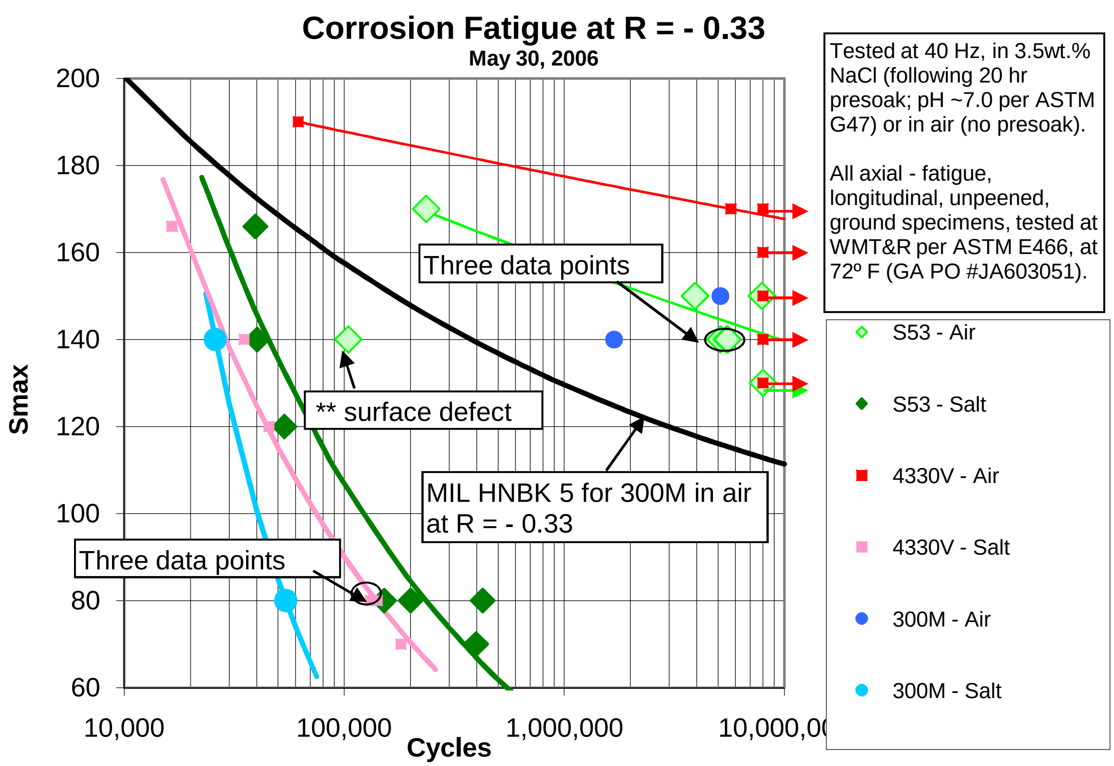



*Figure 5  Representative corrosion fatigue performance for S53. See the Metallic Materials Properties Development and Standardization (MMPDS) handbook and CINDAS LLC Aerospace Structural Materials Database (ASMD) for additional data.*

## 2.4 Plating and Hydrogen Embrittlement of S53

S53 is compatible with numerous conventional plating technologies (including chromium, ZnNi, cadmium, etc.), if additional surface corrosion resistance is desired for specific applications. Conventional processes for electroplating chromium and nickel have been demonstrated. If a prime and paint protection scheme is desired, then a film (spray) application of "*Boegel*" or equivalent is recommended (as is often used with other corrosion-resistant steels).

The sensitivity of S53 to hydrogen embrittlement has been and continues to be investigated. Hydrogen embrittlement failures are caused by the presence of atomic hydrogen that segregates to lath or grain boundaries, reducing ductility and resulting in brittle fast-growing cracks that are usually transgranular or intergranular in nature. The atomic size of hydrogen is small enough that it can readily diffuse within a BCC or FCC lattice. The hydrogen can then be "trapped" within the lattice at dislocations, grain boundaries, or phase interfaces. Hydrogen that is induced by processing can also be readily reversed by completing a baking cycle, a method to increase hydrogen mobility and allow it to detach and escape from within the BCC or FCC lattice and evolve from the material. Typical plating operations will deposit 0.002 to 0.008" thickness, and for low-alloy steels will be followed by a bake-out of 375°F for 23 hours.

S53 uses a fine distribution of $M_2C$ particles for strengthening and for hydrogen trapping. These $M_2C$ particles serve as good hydrogen traps, however the action is reversible.[7] Because of their very small size (and thus large surface-area-to-volume ratio) they can trap a very large amount of hydrogen before they become saturated. To evaluate the effects of various plating operations that have the capability to cause hydrogen embrittlement, testing of S53 per ASTM F519 in various conditions has been completed; further testing is also in progress by QuesTek and others under DoD-sponsored programs. Using standard chromium plating processes during manufacturing and/or overhaul should not have an adverse affect on the hydrogen embrittlement resistance of S53. However to ensure complete removal of hydrogen from an S53 component, it may be conservative to specify a longer time or higher temperature for the post plating bake out of S53. As with low alloy steels, a hydrogen embrittlement test should be completed to ensure that the hydrogen has been successfully removed from the components during the bake-out via ASTM F519. The standard criteria for pass/fail is 200 hours without cracking at 75% of fracture strength. Additional S53-related test data will be forthcoming, and QuesTek can be contacted for additional information.

## 2.5 Applications of S53

To date S53 has principally been applied in the aerospace industry, where applications can include landing gear, axles, actuators, flap tracks and other structural applications. QuesTek is currently working with the U.S. Air Force to identify specific parts on USAF aircraft platforms to use S53. Potential applications in chemical, petrochemical, energy and other industries are being evaluated, and in general can include current applications of 4340 where increased resistance to general corrosion and to SCC is desirable.

Power transmission drive shafts in corrosive, weight-sensitive environments are a particularly interesting application for S53, due in part to the excellent corrosion fatigue performance and ultra-high-strength of S53. For example, S53 is being considered as a material to replace 4340 for the main rotor shafts of U.S. Navy helicopters. Under a recent SBIR Phase I program, QuesTek demonstrated a process to harden the surface of S53 in its tempered condition from 54 Rockwell C Hardness to approximately 57 HRC, in order to provide increased hardness at contact points such as shaft splines.

# 3 Additional Corrosion-Resistant and High-Strength Alloys in Design and Development

QuesTek is a leading recipient of Small Business Innovation Research (SBIR) and other governmental contracts to design, invent, develop and insert new alloys. Four QuesTek-designed materials are now commercially available (*Ferrium*® S53, M54™, C61™ and C64™), and QuesTek has more than 10 other major new alloys in its development pipeline. All of these alloys are expected to be commercialized through licensees such as alloy producers and processors. QuesTek also designs new materials directly for Original Equipment Manufacturers (OEMs), to provide them a competitive advantage with exclusive use in their industry. A few examples of other material design programs follow.

## 3.1 *Ferrium* PH48S™: Ultra High-Strength, High-Toughness, Castable Stainless Steel Alloy

QuesTek completed a 2-year-long, U.S. Marine Corps-funded Phase II SBIR project to design and develop *Ferrium* PH48S, a castable and forgeable corrosion-resistant high-strength steel designed to offer increased toughness and stress corrosion cracking (SCC) resistance as compared to commercially available stainless steel alloys. One project goal was to replace cast titanium components with cast stainless steel components for section thicknesses up to 3” and reduce dissimilar metal connections, with the benefit of lower costs at equivalent specific strength compared to titanium.

## 3.2 Low-Cost, Castable Titanium Alloy

QuesTek is in the first year of a 2-year-long, U.S. Army-funded, Phase II SBIR project to design and develop a new castable titanium alloy composition, by exploring designs that incorporate lower cost alloying components and processing steps. Alloy design activities include minimizing sensitivity to elevated impurity levels (e.g. oxygen and iron) encountered in non-aerospace-grade stock materials.

## 3.3 High-Strength, High-Toughness Aluminum Alloy

QuesTek is in the first year of a 2-year-long, U.S. Air Force-funded SBIR Phase II program to develop a high-strength 2xxx-type aluminum alloy that retains mechanical strength after prolonged exposure to high temperatures.

## 3.4 Tuned Sacrificial Anode

In 2010 QuesTek completed a NAVSEA-funded SBIR Phase I program to develop a new sacrificial anode alloy with a corrosion potential tuned to about -0.8V, with maximum current carrying capacity, that can eliminate or reduce the risk of hydrogen embrittlement of high strength steels.

## 3.5 *Ferrium* M54™: Ultra-High-Strength, High-Toughness Steel

QuesTek is in the second year of a 2-year-long SBIR program to design and develop *Ferrium* M54 as a lower-cost, drop-in replacement for *AerMet*® 100. While not a corrosion-resistant alloy, M54 does offer a unique combination of very high toughness and ultra-high-strength for industrial applications such as where 4340 is currently used. M54 is commercially produced and sold by Latrobe Specialty Steel Co.

## 3.6 *Ferrium* C61™ and C64™: High-Temperature, High-Power-Density Gear Steels

QuesTek completed a 2-year-long, NAVAIR-funded STTR program to develop *Ferrium* C64. While not corrosion-resistant alloys, C64 and its sister alloy C61 offer very high temperature resistance, fatigue resistance, hardenability, toughness and strength for industrial power transmission applications, as improvements over AISI 9310, *Pyrowear*® 53 and other alloys. Potential applications may include for example down-hole drives where compactness and high-temperature capability is valued. C61 and C64 are commercially produced and sold by Latrobe Specialty Steel Co.

# 4 Conclusions

*Ferrium* S53 is a new computationally-designed, ultra high strength steel that provides significantly greater strength, corrosion resistance, SCC resistance, and corrosion fatigue resistance than existing alternative steels such as 4340 and 300M. S53 can be competitively purchased from two leading specialty steel producers, and processed using conventional procedures. Extensive mechanical and physical property data is available for designers, allowing them to create significantly smaller, lighter, tougher or more durable products to be used in more corrosive, fatigue-sensitive environments and with greater predictive confidence in product performance. QuesTek is designing a number of new corrosion-resistant and high-performance alloys of interest to the industrial community, which have been or will be commercialized through various production and sales licensees.

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[3] *Ferrium*, S53 and *Materials by Design* are all registered U.S. trademarks assigned to QuesTek Innovations LLC

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