New Corrosion-Resistant, Ultra-High-Strength Steel

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The selection of alloys used for demanding applications has often required a compromise between strength and corrosion resistance. Ultra-high-strength steels such as 4340, 300M and AerMet® 100 provide limited corrosion resistance while stainless steels such as 17-4PH and 15-5PH provide greater corrosion resistance, but substantially less strength. The susceptibility of ultra-high-strength steels such as 4340, 300M or AerMet 100 to hydrogen embrittlement or stress corrosion cracking (SCC) can hinder their application for fastener applications. For example, Automotive Racing Products (ARP) concludes in its 2009 catalog that alloys such as 300M and AerMet 100 “are particularly susceptible to stress corrosion and must be kept well oiled and never exposed to moisture including sweat.”

Cyclic fatigue enhanced by hydrogen embrittlement and stress corrosion cracking can result in unpredictable and unacceptable failures.

New Steel Design & Background

Ferrium S53® is a new 280 ksi UTS steel available for fastener and other product applications that offers significantly greater corrosion resistance and other benefits over other ultra high strength steels. QuesTek Innovations LLC used its proprietary Materials by Design® technology to computationally design, invent, develop, qualify and insert S53.

S53 was designed and developed to replace cadmium-plated 300M used by the US Air Force in aircraft landing gear, in order to reduce the expense and downtime associated with corrosion, condemnation, repair and maintenance. The composition of S53 is shown in Table 1.

S53 is a secondary hardening steel with a fine ductile lath martensite matrix that incorporates M2C carbides that provide efficient strengthening due to their high modulus misfit with BCC iron and ability to precipitate coherently at the nanoscale. The matrix also contains sufficient chromium to provide passivation against general corrosion and sufficient cobalt to increase chromium activity to levels greater than would be typical for 12 wt% chromium steels. Grain-pinning particles are incorporated and grain boundary chemistry is controlled to maximize grain boundary cohesion and to substantially improve resistance to SCC and hydrogen embrittlement.

S53 is produced using vacuum induction melting followed by vacuum arc remelting, to yield optimum metallurgical quality and repeatability.

Table 1. Chemical Composition of Ferrium S53®, in Weight Percent.

<table>
<thead>
<tr>
<th></th>
<th>Fe</th>
<th>C</th>
<th>Co</th>
<th>Cr</th>
<th>Ni</th>
<th>Mo</th>
<th>W</th>
<th>V</th>
</tr>
</thead>
<tbody>
<tr>
<td>Balance</td>
<td>0.21</td>
<td>14</td>
<td>10</td>
<td>5.5</td>
<td>2</td>
<td>1</td>
<td>0.3</td>
<td></td>
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</table>

Commercial Availability

S53 was commercially introduced in 2008 to 2009, when QuesTek licensed two premier USA-based manufacturers, Carpenter Technology Corporation and Latrobe Specialty Steel Company, to produce, distribute and sell S53. Exclusive production by these two firms offers fastener designers and users confidence in material quality, sourcing and traceability. Both firms can be directly contacted in order to obtain S53 material and additional technical information.

Technical Data & Specifications

In addition to data available on the producer’s and QuesTek’s websites, extensive mechanical and physical property technical design data for S53 is available in SAE Aerospace Material Specification (AMS) 5922; the Metallic Materials Properties Development and Standardization (MMPDS) handbook; and the CINDAS Aerospace Structural Metals Database.

Table 2 summarizes key performance properties of S53 steel that can benefit fastener applications, as further described below.

Southwest Corrosion Resistance. 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 as well as at applied potentials that represent contact with materials such as Al, Cd, Zn, etc. Figure 1 shows the results of SCC testing on 300M, S53 and 15-5PH steels. 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 a corrosive environment; yet S53 offers approximately a 90 ksi increase in UTS over 15-5PH. Results of an 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 1000 hours of 300M at 130 ksi and S53 at 220 ksi, but S53 exhibits substantially less corrosion as illustrated in Figure 2.

Corrosion Resistance. S53 provides general corrosion resistance comparable to 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 as well as scattered pits with depths of 0.001” to 0.002” after one year of exposure when placed 100 yards from mean tide in a seawater, salt-spray oceanfront marine atmosphere (Kure Beach, NC, USA). EDX analysis showed strong partitioning of chromium to the surface oxide scale retarding pit formation.

Fatigue Resistance. S53 has demonstrated excellent fatigue resistance. Axial fatigue testing at various stress levels (120 to 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 (Kt=3.2 tested at R=−1, -0.33, 0.05 for L-R and R-L).

Fracture Toughness. S53 is the first corrosion-resistant...
steel to achieve good fracture toughness at this strength level. S53 exhibits typical fracture toughness values of 65 ksi/\text{in}, and the AMS specification for S53 denotes a 50 ksi/\text{in} minimum requirement. The AMS specification for 300M has no fracture toughness minimum.

**Ultimate Tensile Strength and Yield Strength.** S53 has an A-basis 280 ksi UTS minimum (matching that of 300M) and thus offers significantly greater UTS than other corrosion-resistant alloys such as 17-4PH, 15-5PH and Custom 465. 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. For instance, if yield strength was evaluated at a 0.4% strain offset rather than a 0.2% offset, S53 would be equivalent to 300M. The earlier onset of yielding in S53 versus 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.

**Processability**

**Machinability.** Machinability assessments of mill-annealed S53 have included evaluations of over 20 different machining operations including drilling, tapping, boring, threading, milling and turning. Final machining and grinding steps typical for after-hardening have also been investigated. While certain operations (e.g., boring, milling and turning) require slower feeds and speeds than those typically used on 300M, other operations (e.g., drilling, tapping, and threading) are identical to 300M. In summary no machining limitations have been identified for S53. Recommended parameters for machining S53 are available including recommended feeds and speeds and optimal inserts and cutting tools. The high temperature stability of S53 reduces its susceptibility to induced microstructure change from abusive grinding (i.e., “burn” damage) during manufacturing that is common in low alloy steels.

**Heat Treatment.** Heat treatment processes have been optimized for S53, and production-scale parts have been successfully heat treated by common commercial practices. S53 experiences a 0.003"/inch isotropic growth from the annealed state to the fully hardened and tempered state.

**Surface Treatment.** 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, and a 375°F bake-out removes absorbed hydrogen satisfactorily to meet ASTM F519 criteria. As with other corrosion-resistant steels, if a prime and paint protection scheme is desired, a film (spray) application of “Boegel” or equivalent is recommended.

**Conclusions**

Ferrium S53 is a new corrosion-resistant, ultra-high-strength steel available for fastener and other product applications that provides significantly greater strength, fatigue resistance, corrosion resistance and SCC resistance than existing alternative steels.

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 fasteners and products to be used in more corrosive, fatigue-sensitive environments and with greater predictive confidence in product performance.

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**Company Profile:**

**QuesTek Innovations LLC** computationally designs, develops, qualifies and inserts new materials in less than 50% of the time and at less than 30% of the cost of traditional empirical methods. The firm achieves reduced design and development times and cost through its proprietary Materials by Design® technology. Ques-Tek's current focus is in high-performance steels and other alloys, but Materials by Design can be used to develop a wide range of materials beyond these. QuesTek has more than 30 patents issued or pending, worldwide. [www.questek.com](http://www.questek.com)

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**Table 2. Typical Mechanical Property Data of Ferrium S53®.**

<table>
<thead>
<tr>
<th>Orientation</th>
<th>U.T.S.</th>
<th>0.2% Yield</th>
<th>%EI</th>
<th>%RA</th>
<th>Impact energy</th>
<th>Fracture Toughness</th>
<th>HRC</th>
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<tbody>
<tr>
<td></td>
<td>ksi</td>
<td>ksi</td>
<td>ksi</td>
<td>ksi</td>
<td>ft-lbs</td>
<td>ksi/\text{in}</td>
<td>MPa/\text{M}</td>
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<tr>
<td>Long.</td>
<td>288</td>
<td>1986</td>
<td>225</td>
<td>1551</td>
<td>15 57</td>
<td>65</td>
<td>71              54</td>
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<tr>
<td>Trans.</td>
<td>288</td>
<td>1986</td>
<td>225</td>
<td>1551</td>
<td>15 55</td>
<td>65</td>
<td>71              54</td>
</tr>
</tbody>
</table>

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**Fig. 1 — ASTM F1624 test results for 300M, Ferrium S53® and 15-5 PH.**

**Fig. 2 — 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 1000 hours.**