Air Force A-10 main landing gear. Efforts to qualify Ferrium S53 for this component are currently underway.

Computational Design for

Ultra High-Strength Alloy

QuesTek Innovations designed Ferrium S53 to serve as an ultra high-strength corrosion-resistant drop-in replacement in landing gear and other aerospace components.

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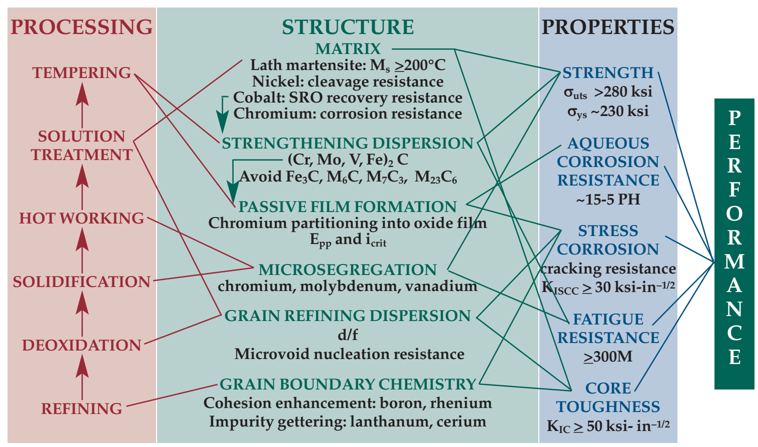

Fig. 1— Flow block diagram for design of Ferrium S53.

Performance requirements for commercial and defense aircraft have always required high specific-strength materials for critical landing gear components. Until recently, designers had to compromise between strength and corrosion resistance: They had to choose between steels such as 300M, 4340, and AerMet 100 for ultra-high strength but relatively low corrosion resistance; or stainless steels such as 17-4 and 15-5, which provide higher corrosion resistance but less strength.

To solve this dilemma, QuesTek Innovations designed Ferrium S53 to serve as an ultra high-strength corrosion-resistant drop-in replacement for 300M. Department of Defense funding with Air Force leadership enabled the design, development, and major demonstrations of S53. This article outlines the design, processing, and resulting properties of S53, and concludes with a roadmap toward implementation in landing gear and other aerospace components.

Computational materials design

The application of systems engineering principles, utilizing computational materials science, has enabled the rapid and efficient design of corrosion resistant ultra high-strength steels. The system flow-block diagram shown in Figure 1 resulted from evaluation of several potential systems.

As the diagram shows, S53 is a secondary hardening steel strengthened by efficient M_2C carbide precipitates. It also contains sufficient chromium to provide passivation against general corrosion. Grain boundary chemistry is controlled to maximize cohesion, leading to excellent SCC resistance.

The sequential processing steps shown on the left-most column of the flow-block diagram are similar to existing processes. The subcomponents of this system are connected by the process-structure and structure-property relationships essential for quantitative computational design.

Design goals

Key to achieving the stated design goals is the development of an efficient strengthening dispersion. M_2C carbide is an efficient strengthener in steels due to its high modulus misfit with BCC iron, and its ability to precipitate coherently at the nanoscale.

It is important to note that the coherency leads

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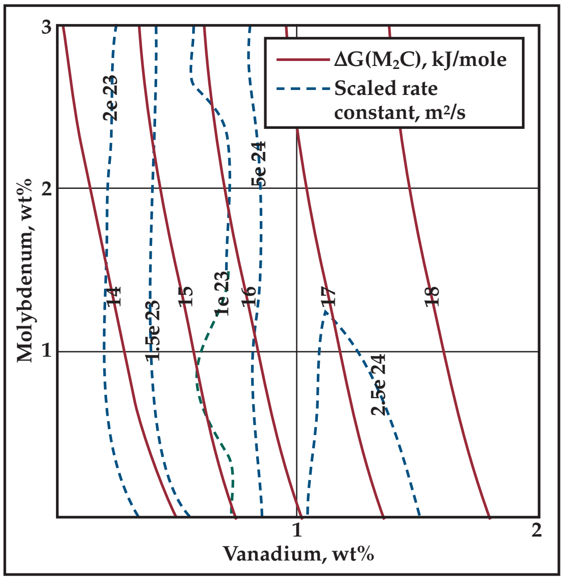


Fig. 2— Calculated overall precipitation driving force and coarsening rate constant.

to significant complications in predicting the precipitation kinetics, because the coherency strain energy must be accommodated in the precipitation model. This has been well studied and reported in the literature, and such models were utilized in Fig. 2, where the overall precipitation driving force and the normalized coarsening rate constant are reported as a function of molybdenum and vanadium content in the S53 alloy.

This design calculation maximizes the resulting strength through the precipitation driving force, while assuring that this strength can be achieved with reasonable tempering parameters.

Another key design tradeoff is to achieve high strength while maintaining adequate martensite kinetics to ensure a martensitic alloy. Quantitative martensite kinetic models can predict the martensite start temperature along with the M_2C precipitation driving force as a function of cobalt and nickel. These designs maximize strengthening while requiring a sufficiently high Ms temperature to maintain a predominantly martensitic alloy.

Design for corrosion resistance utilized the results of prior efforts studying the stability of passivating films in secondary hardening alloys. Multicomponent thermodynamic effects are analyzed to maximize chromium partitioning in the spinel oxide, primarily driven by cobalt content. In addition, the nanoscale M_2C carbides are designed to be sufficiently smaller than the oxide scale to enable their oxidation during passivation. This frees the chromium to be incorporated into the passive film.

Additional constraints on ductile fracture, grain-boundary chemistry, and grain-pinning dispersions complete the design optimization, and uniquely identify the alloy composition that represents the best compromise of the diverse design goals and constraints.

Design for production

Full-scale processing concerns were also integrated into the design. Solidification of candidate compositions were simulated via 1-D multicomponent diffusion simulations in DICTRA. The results of these simulations show the segregation profiles across secondary dendrite arms expected during large-scale production of ingots during typical VAR processing. These findings were later validated from actual production ingots.

Of greater importance is the ability to homogenize expected solidification segregation with commercially acceptable thermal treatments. DICTRA calculations predicted required homogenization treatments for S53, which were later proven in both prototype and production ingots, demonstrating scalability.

Chemical composition of Ferrium S53, in weight percent

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

In summary, computational materials design enabled the development of a complex multicomponent alloy that targeted properties enabling a drop-in replacement for cadmium-plated ultra high-strength steels by a corrosion-resistant alternative (see table above).

- The S53 design features efficient M_2C strengthening in a fine ductile lath martensite matrix.
- The matrix contains sufficient chromium for passivation and sufficient cobalt to increase chromium activity to levels greater than would be typical for 12 wt% Cr steels.
- Grain boundary chemistry is controlled to maximize grain boundary cohesion and improve resistance to SCC and hydrogen embrittlement.
- Additionally, grain-pinning particles were designed to be an effective pinning dispersion, while minimizing the impact on microvoid formation during ductile fracture.

Computational techniques thus achieved the ambitious S53 design in three design-prototype-test iterations, representing a significant cost and time savings over traditional empirical development techniques.

Process optimization

After designing the chemical composition, process evaluation and optimization were initiated for bar product. Specifically, forging, machining, and heat treatment were evaluated with respect to landing gear manufacture.

Forgeability: Ferrium S53 is forged with practices similar to those for conventional alloy steels. GFM and standard open-die processing initially reduce the alloy from ingot form at the production mill. Closed die forgings are very common in landing gear manufacture; hence, S53 was evaluated for performance in closed die operations.

Forging capability has been demonstrated by studies that examined tensile (L, T-L orientations), fatigue (L and T smooth, and L-T notched bar), fracture toughness (L-T and T-L), and Charpy Impact (L-T,T-L) in production forgings. No deficits

Environmental properties

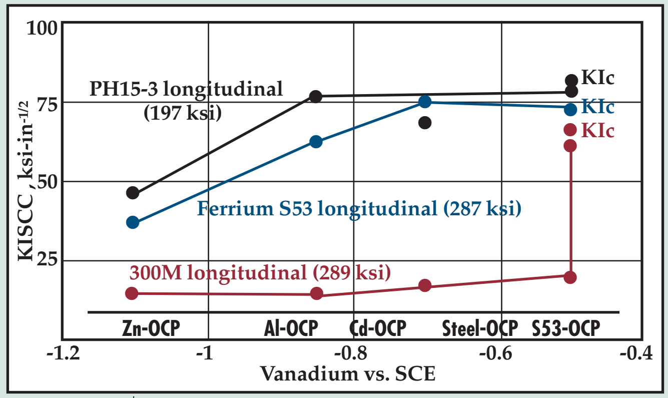
Corrosion resistance: Inherently corrosion resistant steels achieve two important characteristics: 1) passivate by forming a protective chrome-oxide layer on its surface, and 2) arrest any corrosion product at the surface without allowing deep pits or ablative attack.

In seawater, salt-spray oceanfront marine atmosphere exposure, Ferrium S53 (both shot-peened and grit-blasted ground surfaces, with passivation) demonstrated both of these abilities. After one year of exposure, S53 showed shallow surface oxidation and scattered pits with depths of 0.001 to 0.002 inches. EDX analysis showed strong partitioning of chromium to the surface to retard iron-oxide formation. The table shows point scans taken from matrix material in S53 as compared to a pit formed on the surface during corrosion testing.

Element	Fe	O	Cr	Co	Ni	Mo	W
Matrix chemistry	65.57	0.00	9.78	14.38	7.24	1.86	1.47
Pit chemistry	23.10	24.80	28.75	5.99	4.16	8.03	3.58

Testing to date indicates S53 should allow for the elimination of cadmium coating prior to paint protection on landing gear components; however, additional testing is planned to further address this key implementation consideration.

SCC resistance: Ferrium S53 provides good protection against stress corrosion cracking. A preferred test for evaluating SCC resistance is ASTM F1624, a rising step load test of a precracked specimen in 3.5% salt water and applied potentials of contact with a surface of Cd, Al, or Zn. The figure shows the results of SCC testing on 300M, S53, and 15-5PH steels. The corrosion resistant materials 15-5 and S53 maintain resistance to crack propagation in the presence of a corrosive environment, whereas 300M drops to 20 ksi√in or less in a corrosive environment. The S53 tested in the figure is 90 ksi higher in ultimate strength than the 15-5PH tested.



in properties were found over baseline wrought bar stock.

Machinability: In machinability evaluations of mill-annealed S53, over 20 different machining operations were evaluated, including drilling, tapping, boring, threading, milling, and turning. Final machining and grinding steps typical for after hardening were also investigated. Recommended feeds and speeds were identified for each operation, as well as optimal inserts and cutting tools. Certain operations (boring, milling, and turning) required slower feeds and speeds than typically used on 300M, while other operations (drilling, tapping, and threading) were identical to 300M. In summary, no limitations were identified and the study provided a set of recommended parameters for machining S53.

Heat treatment: Heat treatment was optimized via test coupons from prototype and initial production-scale material of Ferrium S53. (See Ferrium S53 datasheet on www.questek.com for detailed heat-treatment instructions). Production-scale parts have been successfully heat treated by common commercial practices. Figure 3 shows two rough-machined pistons in a vacuum furnace for heat treatment. S53 experiences 0.003 inch/inch growth from the annealed state to the hardened state. This growth is isotropic and has been shown to be consistent when heat-treating parts as small as one inch to parts as large as 37 inches. In addition, conventional processes for electroplating chromium and nickel, necessary by design in specified regions of landing gear, were demonstrated. The 375°F bake-out removes absorbed hydrogen satisfactorily to meet ASTM F519 criteria.

Fig. 3 — A-10 MLG pistons in heat-treatment. Image courtesy Solar Atmospheres.

Combination of properties: Ferrium S53 is by no means the first secondary hardened nickel-cobalt steel. AF1410 (14%Cobalt, 10%Nickel) is a classic example of the superior combination of strength and toughness achievable in secondary-hardened alloys. Ferrium S53 extends the performance of previous alloys by optimizing the M_2C precipitate strengthening dispersion. The efficiency of this strengthening dispersion, coupled with QuesTek's optimization thereof, results in a superior combination of properties.

Strength: Strength is a key design factor for landing gear components, as ultimate tensile strength is generally the weight-limiting design factor. Higher UTS means lighter landing gear. The UTS minimum of 300M is 280 ksi, and a drop-in replacement must at least meet this requirement. This specific UTS requirement eliminates the available corrosion-resistant materials. Alloys 17-4, 15-5, and more recently developed stainless

COMMERCIAL AVAILABILITY

QuesTek has licensed two manufacturers, Carpenter Technology Corporation and Latrobe Specialty Steel, to produce and distribute Ferrium S53. Carpenter licensed S53 in early 2007 and produced material for Air Force specification and implementation efforts. Commercial and test quantities of S53 are available from Carpenter today. Latrobe, a recent licensee, anticipates commercial availability in 2008.

Typical properties of Ferrium S53

UTS, ksi	288
YS, ksi	227
El., %	14-16
RA, %	55-65
Fcy, ksi	255
Fsu, ksi	181
Hardness, Rc	54
CVN, ft-lb	18
Kic, ksi√in	70

steels such as Custom 465, do not approach the 280 ksi UTS minimum.

Furthermore, S53 is the first corrosion-resistant steel to achieve good fracture toughness at this strength level, enabling a weight-neutral replacement for 300M-class alloys. The graphic at left highlights the typical properties of Ferrium S53. The alloy exhibits substantial uniform plasticity like 300M prior to the onset of instability. Deep hardening capability is another similarity.

Fracture toughness: K_{IC} fracture toughness is an important consideration for ultra high-strength steels. 300M has typical fracture toughness values in the 50 to 60 ksi√in range, compared with 65 to 75ksi√in for Ferrium S53. The AMS specification for S53 denotes a 50 ksi√in minimum requirement. The AMS specification for 300M has no fracture toughness minimum.

Fatigue: Landing gear parts are often limited by fatigue life. In the design of Ferrium S53, the U.S. Air Force requested fatigue life "as good as or better than" 300M.

- Axial fatigue testing at various stress levels, (ranging from 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 to 300M.
- Notched axial-fatigue test results show that Ferrium S53 displays superior lifetime to 300M trendcurves in MMPDS. (K_t=3.2 tested at R= -1,-0.33,0.05, for L-T and T-L). Figure 4 is one example of the numerous fatigue studies of S53.

Specification development

Working closely with the Air Force throughout the design and development of Ferrium S53 has sped the implementation process. Traditionally, structural design engineers do not consider a material until the following two criteria are met: the Aerospace Material Specification (AMS) has issued, and the Metallic Materials Properties Development and Standardization (MMPDS) minimums are published.

Through Accelerated Insertion of Materials (or AIM) methodologies, QuesTek has used computational design models to predict MMPDS minimum properties from the AMS dataset. This has allowed design engineers to consider S53 before MMPDS minimums are complete, and has paved the way for more rapid implementation. The Aerospace Material Specification for S53 (tentatively AMS 5922) is expected to issue in January 2008, and S53 approval for MMPDS publication is expected in mid-2008. The *projected* MMPDS minimums for S53 are compared to 300M in the table below. (Note that the final minimums are subject to change based on the remaining tests currently being conducted.)

S53 projected MMPDS minimums vs. 300M

Property	UTS, ksi	YS, ksi	El., %	RA, %	Fcy, ksi	Fsu, ksi	Kic, ksi√in
300M	280	230	8	30	247	162	
S53	280	213	11	44	244	175	50

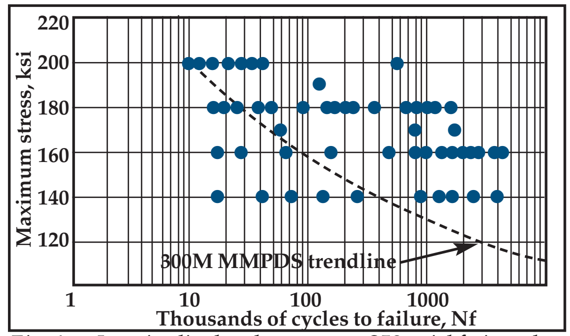


Fig. 4 — Longitudinal and transverse S53 axial fatigue data vs. 300M, R = -0.33.

Yield strength

As shown in the table below, the predicted A-basis yield strength minimum of S53, 213 ksi, is 17 ksi lower than the 300M minimum. The Air Force typically designs landing gear components using an ultimate load analysis that results in designs that are rarely yield strength limited. The 227 ksi typical yield strength of S53 exhibits a slightly skewed distribution on the low side due to austenite effects. It should be noted that the measured strain is not "slip" in the traditional sense, rather a measure of phase transformation for austentite that has some distribution in stability. The phase transformation is accompanied by volume change due to austentite transformation. This volume change appears like typical "yield" strain, in that the stress strain curve departs more than 0.2% from linear behavior. However at 0.4% offset, even low-yielding S53 curves equal typical 300M stress levels.

The stress state dependence of this transformation plasticity makes the effects most pronounced in uniaxial tension. Compressive yield strength minimums for S53 and 300M are nearly identical. Good fatigue performance, specifically in axial fatigue at R=0.05 stress ratio and over 200 ksi stress level, is compelling evidence that the deficit in 0.2% yield strength minimum should not affect mechanical performance of parts designed using limit load analysis based on ultimate strength.

Component qualification

The Air Force is considering a number of components on various platforms that would benefit from the added corrosion resistance of Ferrium S53. Resistance against microstructural changes from abusive machining is another positive attribute. The main landing gear piston on the Air Force A-10 is to undergo component level fatigue tests. QuesTek is also working with an Air Force team and ESTCP funding to explore S53 applicability on rotary gear actuation systems. In addition, a transition candidate list developed by the Air Force identifies components that are most often condemned due to corrosion and may be good choices for transition from 300M to S53. Consideration for implementation of S53 is proceeding on a component-by-component basis.

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