FERRIUM® STEELS AND OTHER HIGH PERFORMANCE MATERIALS FOR NEXT GENERATION ROTORCRAFT TRANSMISSIONS AND APPLICATIONS

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Abstract

Integrated Computational Materials Engineering (ICME) technologies are effective tools to accelerate implementation of new higher performance alloys, shortening design time and reducing cost compared to empirical methods. Using these technologies and their *Materials by Design*® approach, QuesTek Innovations LLC has designed, commercialized and deployed a class of high-performance Ferrium steels specifically addressing demanding and critical transmission applications for the global rotorcraft industry. Furthermore, these ICME technologies have been expanded to the field of Additive Manufacturing (AM) to adapt the Ferrium steels and design new alloys specifically tailored to the unique processing conditions to bring advanced capability to the rotorcraft and aerospace industries.

1. INTRODUCTION

1.1. Integrated Computational Materials Engineering Overview

Integrated Computational Materials Engineering (ICME) technologies combine physics-based mechanistic models and extensive material property databases in a computational framework to describe a material's processing-structure and structure-property interactions. Coupled with advanced experimental characterization techniques, the modelling of these interactions is used to design specifically tailored microstructures to achieve targeted end-use properties, providing a more rapid and cost-effective approach to new alloy development compared to empirical trial-and-error methods. In order to achieve the targeted engineering needs specified for a novel material design, the computational models must be incorporated into a systems framework to integrate the process-structure and structure-property relationships within an alloy design space.[1]

1.2. Ferrium Steel Development

The Ferrium steels were designed and developed to achieve targeted properties for high performance through a uniquely tailored microstructure. Specifically, the Ferrium steels are martensitic secondary-hardening steels that utilize an efficient nano-scale M_2C precipitate strengthening dispersion to provide a combination of high surface hardness and high core properties (strength and toughness). Further attributes of the microstructure, as illustrated in Figure 1, lead to benefits including thermal stability, robust processability, refined and stable grain size, and ease of machinability.

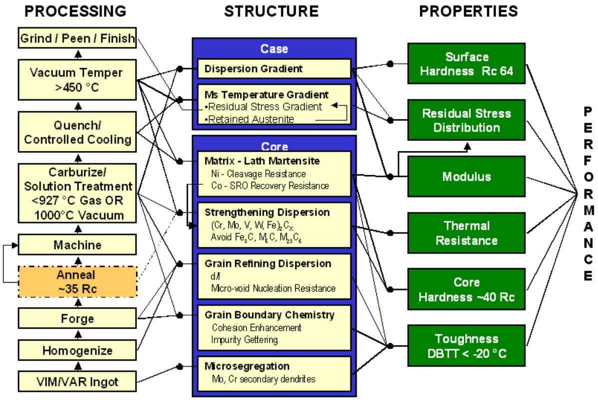

Figure 1. The "System Design Chart" for Ferrium C64 steel, used to formulate the microstructural concepts and processing parameters and design a novel alloy that achieves the targeted properties. The chart details the hierarchical relationships between processing, structure, property and performance.[2]

1.2.1. Carburizable Ferrium Gear Steels

In the Ferrium class of steels, Ferrium C64® steel is a next generation, carburizable gear steel for advanced aerospace applications. C64 steel provides enhancements over incumbent gear steels such as 20NiCrMo13-4, 15NiMoCr10, 16NCD13 and Alloy 53, by providing a combination of high core strength, toughness, surface hardenability and thermal stability, allowing for lightweighting, increased power density, and drastically extended loss-of-lubrication performance on the component and system levels. Ferrium C-series steels have shown these advantages in applications, such as adoption of Ferrium C61™ steel in the forward rotorshaft on Boeing's Chinook CH-47 Block II upgrade, and next-generation helicopter transmission gearbox components.

Under the US Army funded Future Advanced

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Rotorcraft Drive Systems (FARDS) program, Bell evaluated Ferrium C64 steel for next generation helicopter transmission components. The demonstration main rotor gearbox under evaluation employed a range of novel technologies including Ferrium C64 steel in several components, such as a friction welded gearshaft and input pinion. The demonstration gearbox was tested in loss-of-lubrication testing, during which over 80 minutes of operation with no lubrication yielded no failures in the C64 components. This result is illustrated by the post-test images of the gearshaft and input pinion in Figure 2, showing only minor scuffing on the gear teeth and no failures.[3]

Figure 2. Ferrium C64 input shaft (top) and gearshaft (bottom) imaged after 85 minutes of loss-of-lubrication testing in the Bell FARDS program loss-of-lubrication testing, showing minor scuffing on the gear teeth but no signs of surface damage or failure.[3]

Due to the findings of the above research and test programs, Ferrium C64 steel provides a unique combination of properties that have enabled critical advancements in the rotorcraft industry, including:

- Reduction of system weight through lightweighting of components
- Increased power density at equivalent geometry for legacy systems
- Improved component and system durability due to enhanced fatigue life
- Enhanced platform safety through greater high temperature survivability and expanded safety margins
- Enablement of novel designs that combine the above benefits

1.2.2. Structural Ferrium Steels

Beyond carburizable gear steels in the Ferrium class are the Ferrium M54®, S53® and N63™ steels. M54 steel is an ultra-high strength, high toughness monolithic structural steel that was designed and developed for landing gear applications. The U.S. Navy estimates $3 million USD saved by implementing M54 steel in the production and use of safety-critical hook shank landing gear components on the T-45 platform.[4] Through a unique combination of ultra-high core mechanical properties and enhanced stress corrosion cracking (SCC) resistance through grain boundary cohesion mechanisms, Ferrium M54 steel has been adopted in a wide range of aerospace applications, and has recently shown promise in rotorcraft applications. M54 is currently being evaluated by commercial entities for shafting applications to provide lightweighting, enhanced durability, and greater power-to-weight ratios.

The properties of Ferrium M54 are presented in Table 1.

Table 1. Mechanical property comparison of Ferrium M54 steel to high strength aerospace grade steels.

Alloy	Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	K_{IC} Fracture Toughness (MPa·√m)	Reported Minimum K_{ISCC} *[1] (MPa·√m)
***Ferrium* M54 (AMS 6516)**	1731	2020	126	99
4340 (AMS 6414)	1531	1903	55	11
300M (AMS 6419)	1667	1979	55	13

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[1] Testing per ASTM F1624, lowest recorded value

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Ferrium S53 steel was designed with the goal of eliminating the use of toxic cadmium plating on landing gear applications. Providing a combination of high strength, high toughness, corrosion resistance, and high fatigue and corrosion fatigue life, S53 steel is flying on several Air Force platforms as landing gear without the use of cadmium plating. For rotorcraft applications, S53 steel was evaluated for the main rotorshaft component of the US Navy MH60S SeaHawk, and is being considered for rotorshaft applications in Europe that require improved corrosion performance.

Ferrium N63 steel was designed and developed to address corrosion issues for key transmission ball and roller bearings that suffer from standstill corrosion in aerospace systems. Corrosion pitting can accelerate fatigue failures by acting as initiation sites at carburized surfaces, and available aerospace alloys such as 52100, M50, and M50NiL are not corrosion resistant. Other options may also provide some level of corrosion resistance, such as in 440C and *Pyrowear®* 675, but, ultimately, corrosion resistance is compromised on the bearing races due to suboptimal case carburized microstructure and low matrix chromium content. N63 steel was designed as a solution-nitrided, high-Cr martensitic steel to combine fully stainless properties and high surface hardness, while providing the mechanical performance necessary for the application of interest.

Table 2. Mechanical properties for N63 steel.

0.2% Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	% El	%RA	K_{IC} Fracture Toughness (MPa·√m)
1082	1386	21.3	73.0	61.9

Properties for N63 have been validated on a production scale heat of material. Table *2.* Mechanical properties for N63 steel. shows mechanical properties and Figure 3 presents corrosion testing results for Ferrium N63 steel, both for surface hardened and non-surface hardened samples. Heat treatment for the surface hardened samples was conducted by solution nitriding at 1100°C for 12 hours, quenching, -73°C for 1 hour, and 482°C for 2 hours, achieving a case depth profile with 61 HRC surface hardness and 58 HRC at 0.38 mm. Heat treatment for the core material includes the same heat treatment process, with a 1 hour solution treatment at 1100°C in place of solution nitriding. Based on the results, the N63 case material displays stainless properties after 200 hours of testing, and minor pitting in the core material after 200 hours.

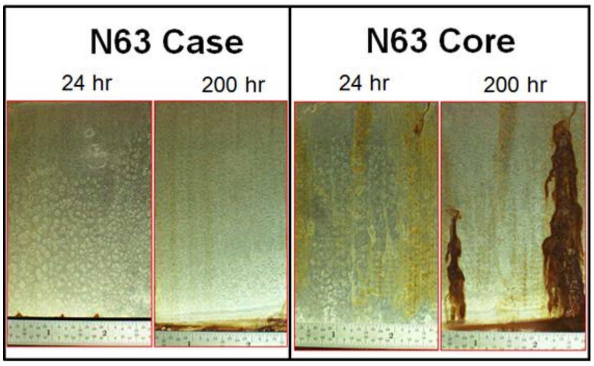

Figure 3. Images of Ferrium N63 case and core samples after 24 and 200 hours of ASTM B117 salt spray testing.

2. ALLOY DEVELOPMENT FOR ADDITIVE MANUFACTURING IN THE ROTORCRAFT INDUSTRY

Additive manufacturing (AM) is a novel process of fabricating components in a layer-by-layer method under the control of computer-aided design (CAD) information, rather than by the traditional use of casting molds and forming dies. By allowing for net-shape fabrication of highly complex geometries without molds or machining, this process offers the potential to reduce material usage, energy consumption, component cost, and fabrication time. While AM presents the unique opportunity to manufacture single components quickly, it also provides the potential to examine the effects of individual design alterations on overall system performance.

Having demonstrated the success of an ICME approach to design, develop and deploy high performance wrought alloys to solve in-service issues and enhance system performance, QuesTek applied its Materials by Design methodology and ICME technologies to design novel and adapt existing alloys, including Ferrium C64 steel, to additive manufacturing processes.

2.1. Rapid Prototyping of Advanced Gear Steel Components

Under a US Army funded Small Business Innovation Research (SBIR) program, QuesTek is addressing the pressing need for reduced lead time in rapid prototyping of novel rotorcraft designs. Due to the long lead times in current manufacturing pathways for novel rotorcraft components, which includes primary melting of material, forging, rough machining, heat treatment, final machining and relevant finishing processes, a new production solution is critical for advancing next generation designs and technologies.

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Through applying ICME technologies, QuesTek has adapted Ferrium C64 steel to AM processes. The program is currently in the final year of a three year research and development timeline.

To demonstrate the viability of Ferrium C64 for direct metal laser sintering (DMLS) additive manufacturing, QuesTek began the program with evaluation and optimization of material procurement and deposition process parameters. The evaluations consisted of procurement of Ferrium C64 powder in the 15-53 µm diameter powder size range for printing on an EOS M280 system. The powder was inert gas atomized, and characterization of the powder, including spheroidicity and approximate particle size distribution, confirmed consistency between the procured powder lots for DMLS size range requirements.

Mechanical property testing on AM-built coupons was performed for heat treated samples, and the results are shown in Table 3 Samples were fabricated in the XY, Z and XY-45° Z orientations to account for potential anisotropy. In the preliminary results, the additively-manufactured C64 material achieved properties comparable to wrought C64 steel. Furthermore, no anisotropy was observed in the fully heat treated condition.

Table 3. Summary of mechanical properties for additively manufactured C64 steel compared to wrought material.

Property	**DMLS C64**	**Typical C64**
0.2% Yield Stress σ_y	1394.1 MPa (XY) 1413.4 MPa (Z) 1387.9 MPa (XY 45°-Z)	1372 MPa
Ultimate Tensile Stress (UTS)	1587.9 MPa (XY) 1614.8 MPa (Z) 1609.9 MPa (XY 45°-Z)	1579 MPa
% Elongation	16.5 (XY) 16.5 (Z) 16.3 (XY 45°-Z)	18
%RA	70.5 (XY) 69 (Z) 68.5 (XY 45°-Z)	75

The current status of the program includes ongoing single tooth bending fatigue (STBF) testing with printed test gears and additional mechanical property data collection including axial fatigue. The STBF test gears have been additively manufactured, heat treated, final machined, shot peened and super finished. Test results are expected in late 2019. Test gears are shown below in Figure *4*.

Figure 4. Fully processed STBF test gears built from Ferrium C64 steel powder, processed by DMLS deposition on an EOS M280, hot isostatic pressing, machining, carburization and heat treatment, final machining, shot peening and superfinishing.

All processing steps, apart from hot isostatic pressing, were conducted using the same parameters as for wrought C64 steel, including machining, carburization, heat treatment, shot peening and superfinishing.

Furthermore, fracture toughness and fatigue crack growth rate testing are underway. These results will inform further considerations for mechanical design and potentially enable additively manufactured complex geometries for evaluation and demonstration. [5]

2.2. Aluminum for AM

Beyond application of carburizable gear steels to AM, QuesTek is using their ICME modeling technologies to both design new materials specifically for AM, and adapt alloys originally developed for wrought and casting applications. These efforts include the design and development of novel, high strength aluminum alloys.

With the intention of addressing lead time concerns, but also providing alternate manufacturing solutions that enable design freedom and cost-effective solutions, QuesTek is designing unique aluminum alloy compositions specifically tailored for additive manufacturing under funding from the Office of Naval Research and NAVAIR. The designs focus on two novel compositions targeting (1) elevated temperature (200°C - 250°C) applications, and (2) replacement of wrought 7000 series aluminum components.

Traditional high strength aluminum alloys that are applied to additive manufacturing are highly susceptible to hot tearing upon deposition due to

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their solidification characteristics and the intense residual stresses formed during rapid solidification. This phenomenon has limited the application of aluminium alloys to AM, where AlSi10Mg is the most common printable alloy but is limited in mechanical properties for more demanding applications.

Through utilization of QuesTek's existing ICME modelling tools and technologies, new designs were explored that addressed a combination of printability (crack-free, low porosity builds) through hot cracking resistance and high strength through microstructural strengthening mechanisms, as illustrated in Figure 5.

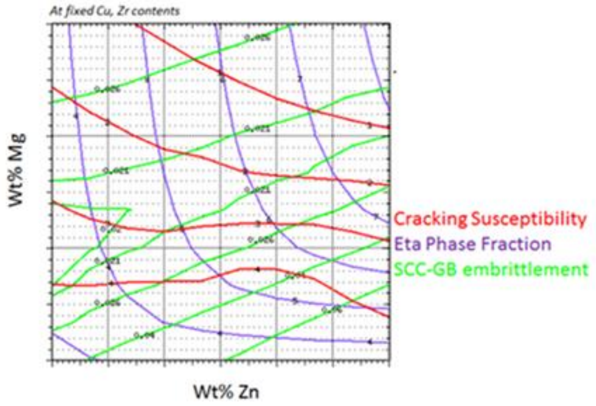

Figure 5. Integration of model outputs, represented as contours in a defined composition space, which represents key design metrics for an Al-Mg-Zn system.

QuesTek built upon modeling iterations to refine the formulation of a novel 7000-series aluminum optimized for AM, QT-7X, that incorporated mechanisms for enhanced printability (e.g., crack-free depositions), efficient precipitation strengthening to achieve targeted mechanical properties (e.g., strength and ductility), and robust processing windows for ease of post-build processing (optimized through heat treatment studies).

The selected composition was optimized for subsequent characterization. Powder was sourced at intermediate scale (~100kg) at DMLS particle size (20 - 63 µm diameter) in multiple lots, test samples were printed on EOS M280 and M290 machines, processed using optimized, robust post-build heat treatment processing parameters, and mechanical properties were tested, as presented in Figure 6. These preliminary results show comparable to better mechanical properties compared to wrought 7050-T74 alloy, with nearly isotropic properties paralle and perpendicular to the build direction.

Preliminary corrosion testing show promising results. QT-7X demonstrates better pitting and exfoliation resistance than 7050-T74. Regarding stress corrosion cracking (SCC) susceptibility, heat-treated QT-7X has a greater than 30-day life held at 241 MPa (SCC threshold for 7050-T74).

Additional work under this program is focusing on further refining the alloy design to enhance stress corrosion cracking resistance and fatigue properties. Furthermore, developments are underway to complete a comprehensive property and processing dataset, including component-level evaluations with OEM partners, assessments across different machines and powder lots, and prediction of design allowables.

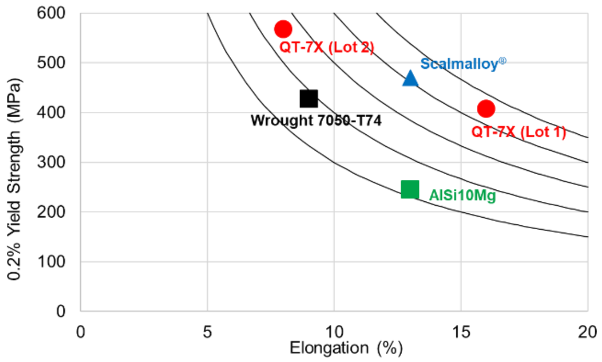

Figure 6. Tensile properties of novel aluminum design QT-7X (heat-treated, XY-direction) compared to high strength wrought 7050-T74 (longitudinal) and additive alloys.[6]

Under separate funding, QuesTek has designed novel compositions for printable aluminum alloys with the goal of achieving superior mechanical properties at elevated temperatures (200°C – 250°C). The alloy concepts target improved temperature strength and ductility by enhancing the stability and coherency of strengthening precipitates.

Elevated temperature strength and ductility data is presented in Figure *7*, showing high strength and ductility in the 200°C – 250°C range.

Ongoing work for the development of these alloy designs includes procuring an additional lot of powder to further develop a mechanical property data set, optimize post processing parameters, evaluate and optimize complex build geometries, and conduct a chemistry and property variability analysis.

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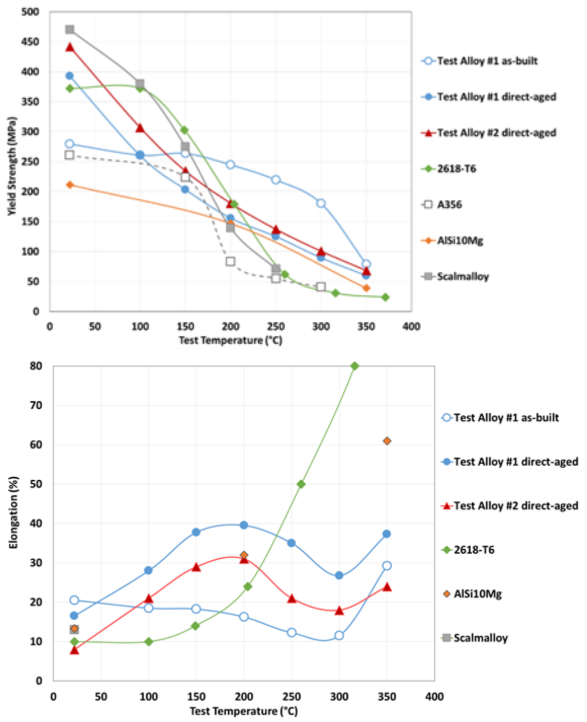

Figure 7. Yield strength (top) and elongation (bottom) as a function of test temperature for two QuesTek compared to incumbent alloy data.

3. CONCLUSION

QuesTek Innovations has applied their ICME technologies to successfully introduce high performance wrought steels to the rotorcraft market, pushing the boundaries of performance through allowing for lightweighting, increased system power, enhanced oil out survivability, and other benefits. Furthermore, these tools have been utilized in additive manufacturing to both adapt existing materials and design new alloys. These efforts have led to unique microstructures tailored specifically for printability in AM systems and to achieve high properties including strength, toughness and thermal stability. Following initial property validation on production lots of powder, next steps for all alloy systems include further material procurement, data development, and demonstration of scalability to complex build geometries.

4. REFERENCES

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