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Design, Development and Application of New High-Performance Gear Steels

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Design, Development and Application of New High-Performance Gear Steels

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[The statements and opinions contained herein are those of the author and should not be construed as an official action or opinion of the American Gear Manufacturers Association.]

Abstract

QuesTek Innovations LLC is applying its *Materials by Design*® computational design technology to develop a new class of high strength, secondary hardening gear steels that are optimized for high-temperature, low-pressure (i.e., vacuum) carburization. The alloys offer three different levels of case hardness (with the ability to “dial-in” hardness profiles, including exceptionally high case hardness), and their high core strength, toughness and other properties offer the potential to reduce drivetrain weight or increase power density relative to incumbent alloys such as AISI 9310 or Pyrowear® Alloy 53. This new class of alloys utilizes an efficient nanoscale M₂C carbide strengthening dispersion, and their key benefits include: high fatigue resistance (in contact, bending, scoring); high hardenability achieved via low-pressure carburization (thus reducing quench distortion and associated manufacturing steps); a tempering temperature of 900°F or higher (providing up to a 500°F increase in thermal stability relative to incumbent alloys); and core tensile strengths in excess of 225 ksi. *Ferrium*® C61™ is one alloy in this family and is currently used in transaxle ring and pinions for SCORE® 1600 class off-road racing cars as well as process equipment applications; C61 is also being examined in a Army SBIR program as a potential replacement for 9310 in CH-47 Chinook helicopter main rotor mast applications, yielding a projected potential weight savings of 15–25%. Secondly, *Ferrium* C64™ is being developed under a Navy STTR program aimed at rotorcraft gear transmission applications in order to reduce weight, improve fatigue performance, and improve high temperature operating capability relative to the incumbent alloy Pyrowear® Alloy 53. Lastly, *Ferrium* C69™ can achieve a carburized surface hardness of HRC 67 (with a microstructural substantially free of primary carbides) and has exceptionally-high contact fatigue resistance, which makes it a candidate for applications such as camshafts and bearings as well as gear sets.

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Introduction

Carburized steel gears are widely used for power transmission in rotorcraft, transportation vehicles, agricultural and off-road equipment, industrial rotating equipment, and thousands of other applications. Commonly-used alloys such as AISI 9310 (AMS 6265) and Pyrowear® Alloy 53 ("X53") (AMS 6308; UNS K71040) have functional limitations which may not meet all of the performance requirements arising in next-generation equipment. Increasing demands to reduce energy consumption, material use, and environmental impact are driving the need for dramatic performance improvements in gear steel manufacturing and performance. For example, the *Gear Industry Vision* for 2025 (published in 2004 by AGMA, ASME and other leading governmental, professional and commercial interests) identified strategic goals such as "Increase power density by 25% every 5 years".[1] Or as another example, the U.S. Navy estimates that a 20% increase in gear endurance could provide \$17 million/year in cost savings to the Defense Logistics Agency alone.[2]

Past efforts to increase the power density, reliability, or endurance performance of gears have included studies of hard tribological coatings; however, many potential coatings do not work well due to processing constraints or poor adhesion to the underlying alloy.[3, 4, 5] Powder alloy approaches have also been studied, but are often inadequate for fatigue-limited applications due to the higher fraction of oxide inclusions and porosity, which can act as fatigue initiation sites. Many improvements in the fatigue performance of commonly-used alloys have been made using surface processing technology advancements such as superfinishing, shot peening, laser shock peening, or cavitation peening, but these do not improve the intrinsic characteristics of the base alloys. This paper summarizes a first-principles-based, integrated computational materials design approach that is being used to create next-generation, high-

performance base alloys with improved performance and reduced manufacturing complexity and variability.

Overview of computational materials design technology

New materials have historically been discovered either by chance or by intricate and costly cycles of trial and error, yielding a limited understanding of optimization and design. The limitations of the past approach are widely known, and numerous national studies over the past decade have consistently emphasized that traditional empirical material development methods have not kept pace with modern design-based product development efforts. One result is that a number of renowned materials companies have all but dropped their labor-intensive internal research and development programs due to their prohibitive cost, and have instead refocused their efforts on reducing costs to manufacture and process generic materials.

The use of powerful computational tools, property databases and intellectual expertise to computationally design and create new materials is a rapidly-emerging alternative approach. These techniques can be used to quickly and economically design and develop unique materials as integrated systems, in order to deliver optimal performance requirements for a given application. The Steel Research Group (SRG) at Northwestern University of Evanston, IL pioneered this technology beginning in the mid-1980s. The strategic importance of computational materials design to the national mission was set forth in 2000 when the U.S. President's Office of Science and Technology identified computational design of materials as one of five critical technologies for the coming decade.[6]

QuesTek Innovations LLC (QuesTek) of Evanston, IL was founded in 1997 and is building on the SRG's initial efforts by using QuesTek's proprietary *Materials by Design*® technology to computationally design many new materials, include iron-, copper-, aluminum-, nickel-, niobium- and

titanium-based materials. Dr. Gregory B. Olson, the Wilson–Cook Chaired Professor in Engineering Design at Northwestern University’s Department of Materials Science and Engineering, is QuesTek’s Chief Science Officer and a founder of the company. 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.[7]

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 modeling 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 favorability of one design solution over another but also to search for design optima in previously-unexplored terrain.

Some of the SRG’s and QuesTek’s work has focused on computationally designing next-generation, high-performance gear steels, in order to significantly improve performance properties such as strength, corrosion resistance, wear resistance and fatigue resistance while designing for robust, efficient and flexible processing paths. The new resulting alloys are in a class of QuesTek alloys termed *Ferrium*® alloys.

Design and overview of *Ferrium* gear steel alloys

Ferrium C61™, C64™ and C69™ are three new alloys being used or considered for power transmission applications. All of these alloys utilize an efficient nanoscale M₂C carbide strengthening dispersion within a Ni–Co lath martensitic matrix.

Utilizing their suite of computational models, QuesTek designed these alloys considering the complex interplay of critical design factors including: martensitic matrix stability (M_s temperature); M₂C carbide thermodynamic stability and formation kinetics; matrix cleavage resistance; and embrittling phase thermodynamic stability.

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 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.

As it has done in its other development programs[8], QuesTek and its partners utilized its custom stage-gate process, as graphically illustrated in Figure 2, to design and develop the *Ferrium* alloys in a rapid manner while minimizing development costs. The process begins by working with the key stakeholders, such as gear designers and manufacturers, to establish specific system property goals and processing constraints. Within these customer-defined objectives, QuesTek applied 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 design phase.

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 complete, 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.