DEVELOPMENT OF A NEW HIGH-PERFORMANCE GAS CARBURIZABLE GEAR STEEL

Jason Sebastian, Ph.D.
Jim Wright, Ph.D.
QuesTek Innovations LLC

Problem: Higher performance rotorcraft

Improved gear steel for the V-22 tiltrotor

Navy requirements for:

- Higher survivability
- Smaller package sizes
- Longer maintenance intervals

Driving the need for rotorcraft transmission with:

- High power densities
- Higher operating temperatures

A new gear steel with:

- High-strength
- High-toughness
- Highly fatigue-resistant
- Better temperature resistance

"Significantly enhance the performance of gears and provide increased power density and operational life"

- STTR Topic #: N05-T006 Solicitation

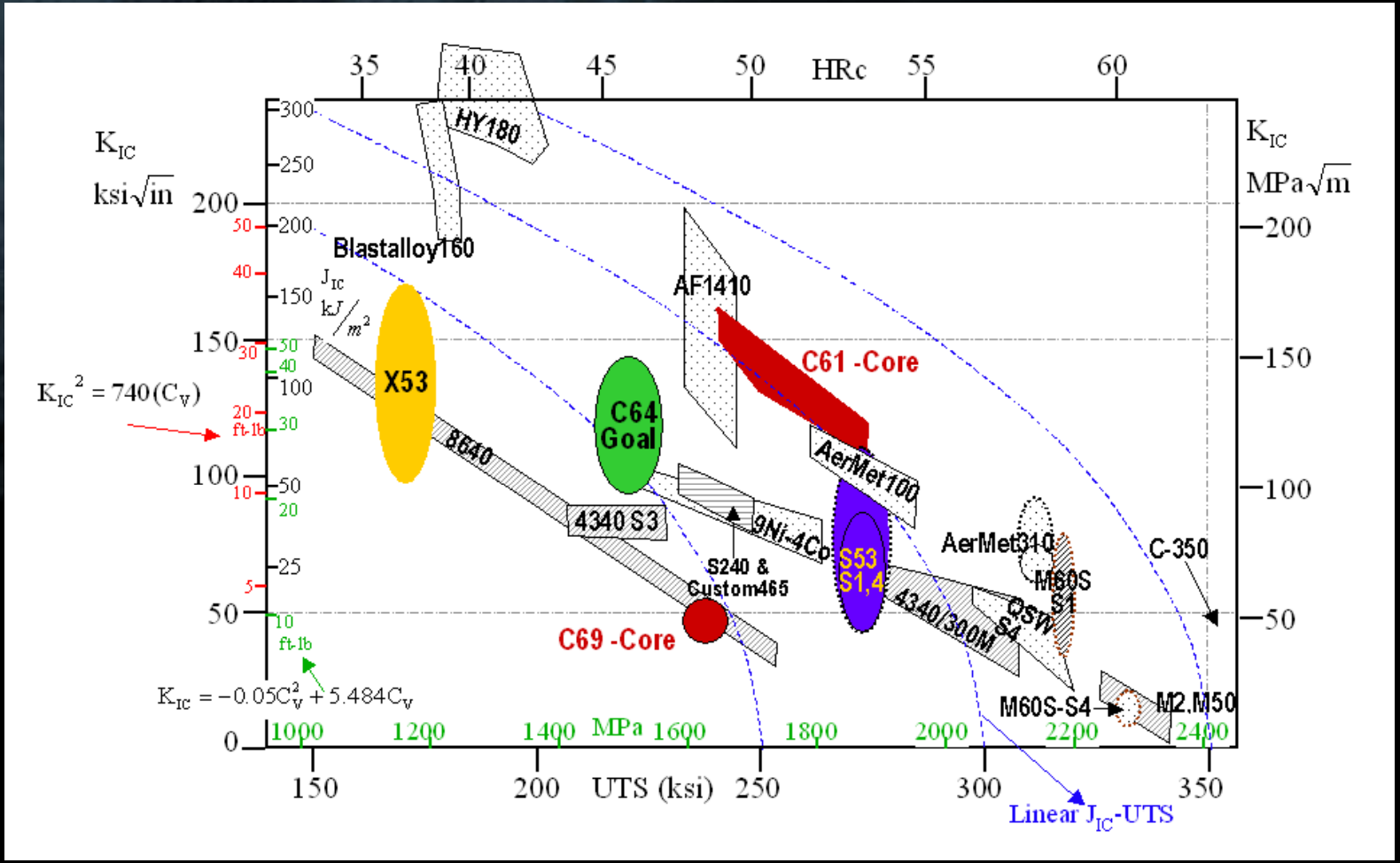
Organizations with Materials Needs

NAVAIR

Bell Helicopter
A Textron Company

Bell Boeing
THE TILTROTOR TEAM

Current Technology: Pyrowear X53



Comparison of core properties

Pyrowear X53 vs. *Ferrium C64*

Background: QuesTek C61 and C69 Alloy Design History

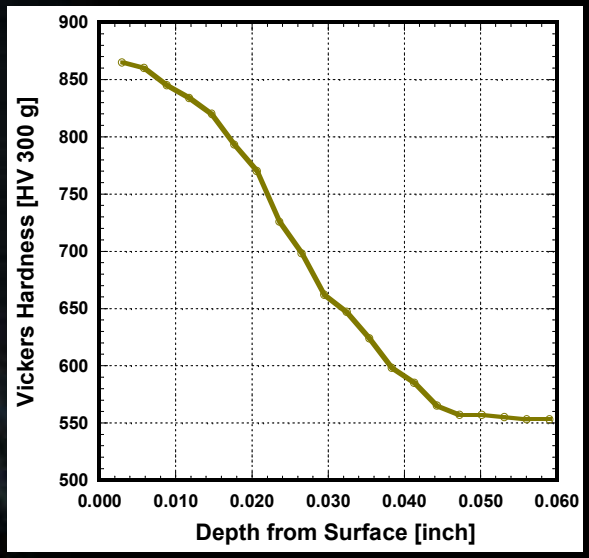
- Developed at Northwestern University by Greg Olson, Charles Kuehmann, and John Wise
- Optimal Microstructure
  - Fe-Ni-Co lath martensite
  - Efficient nano-scale M_2C carbide strengthening
  - Primary carbide-free
- High temperature (vacuum) carburized
- Secondary-hardened
- Exclusively licensed by QuesTek Innovations LLC
  - U.S. Patent 6,176,946B1
- Commercial production and heat treatment

QuesTek C61 and C69 Gear Steel Properties

C69

- Excellent surface HRC & fatigue resistance
- High Temperature Resistance

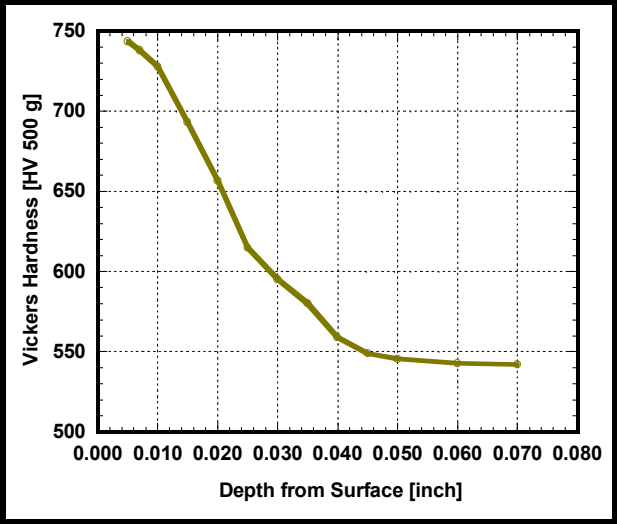
Temper	YS (ksi)	UTS (ksi)	El (%)	Core (HRC)	Case (HRC)
Overage	*180*	*230*	*17*	*48-50*	*65-67*



C61

- High strength / toughness core
- High Temperature Resistance

Temper	YS (ksi)	UTS (ksi)	El (%)	Core (HRC)	CVN (ft-lb)	K_{IC}
Peak	*230*	*250*	*16*	*50-52*	*40*	*>105*
Overage	*225*	*240*	*16*	*48-50*	*50*	*>105*

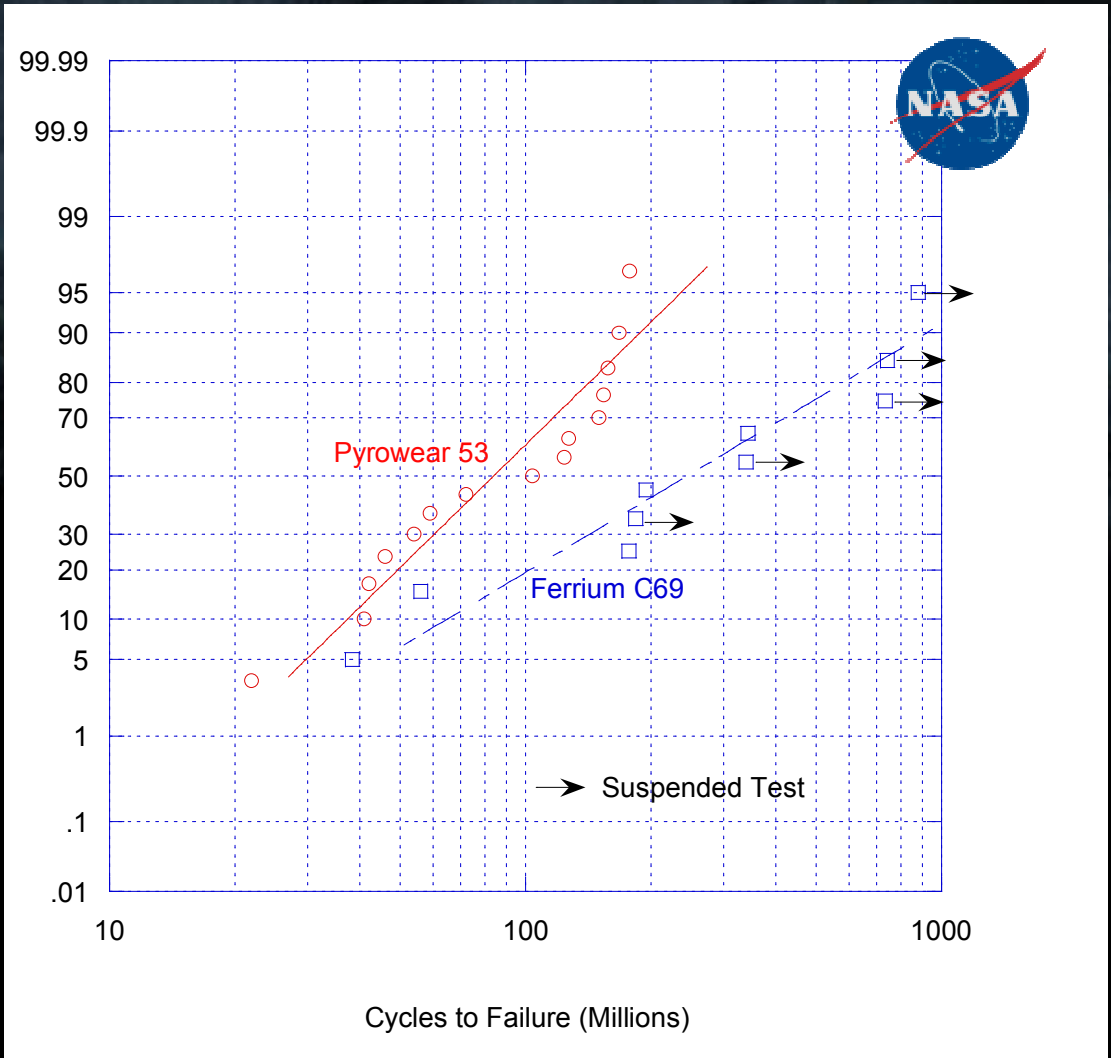


Ferrium C61 - Off-Road Performance

- Off-road series
  - SCORE, SNORE, CORR
- Ring and pinion
  - Class 1/2-1600 (4.57 ratio)
- Baseline-8620 and 9310
  - Typically fail in two races or less
  - Failures by notch root fatigue
- C61 Introduced Jan. 2005
  - 50% market share and growing

4-6x improvement in life

NASA – C69 Surface Fatigue Tests

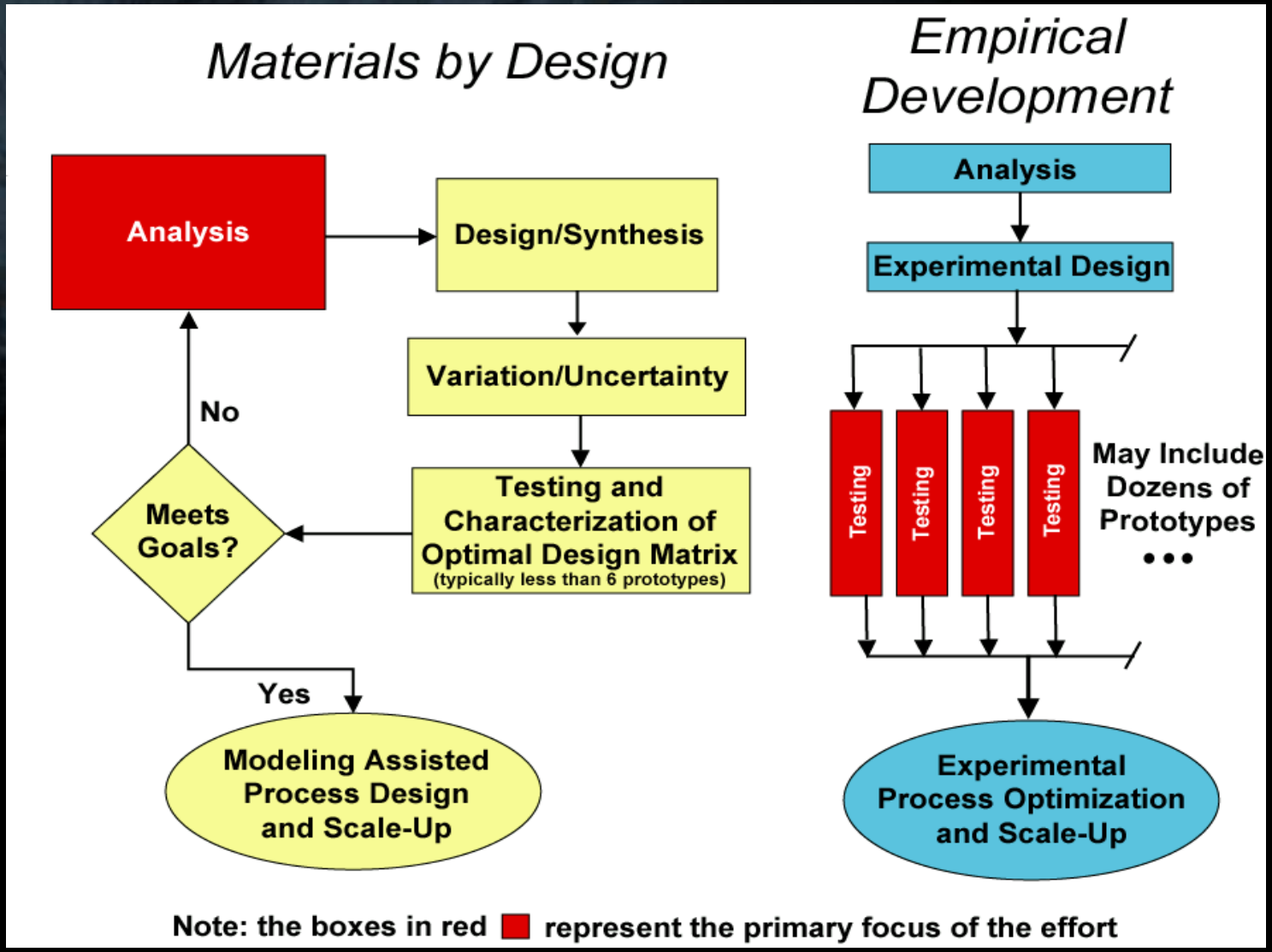


- NASA Glenn Research Center
- Supported by Battelle
- Recirculating Spur Gear Fatigue Rig
- *Ferrium*® C69, Case carburized & ground
- Measure surface fatigue, benchmark against Pyrowear53
- 24 gears yield 12 data points
- Set to test surface fatigue, pitting tendency

QuesTek *Ferrium C64* Alloy Goals

- Fatigue strength increase of 25%
- Gas and vacuum carburizable
- Core strength ~220 ksi UTS
- Core fracture toughness ~90 ksi√in
- Suitable for super-finishing
- Stable microstructure/hardness up to 400°C
- Machinability
- Minimal heat treat distortion

Traditional Approach: Empirical Alloy Discovery

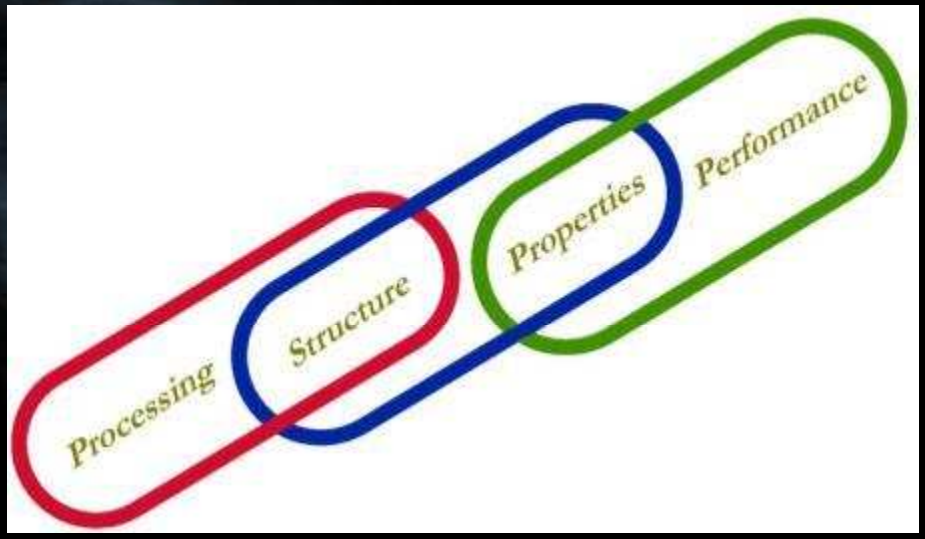


QuesTek Approach: Computational Materials Design

Materials by Design®

- Proven alternative to "Trial and Error" Methods
- Better Materials
  - Faster
  - Cheaper
- Designed Properties
  - Accelerated Insertion
  - Stronger patents
- Niche applications

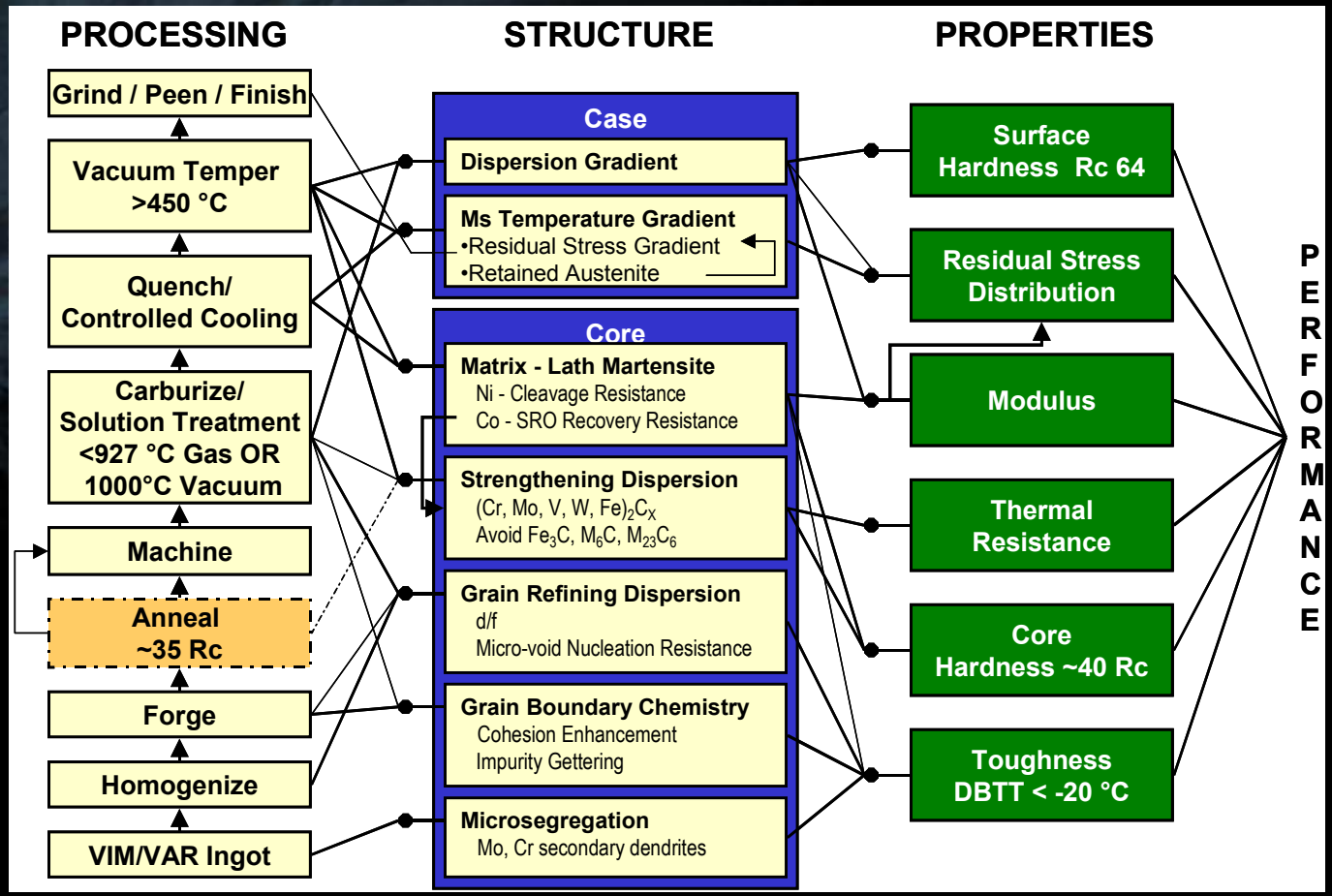
- **Accelerates the creation, development, and insertion of new and enabling materials for defense-based systems**



Ferrium C64 alloy design

- Optimal Microstructure
  - Fe-Ni-Co lath martensite
  - Efficient nano-scale M2C carbide strengthening
  - Primary carbide-free
- High temperature (vacuum) carburized
- Secondary-hardened
- Initial prototype production
  - Validate predicted properties

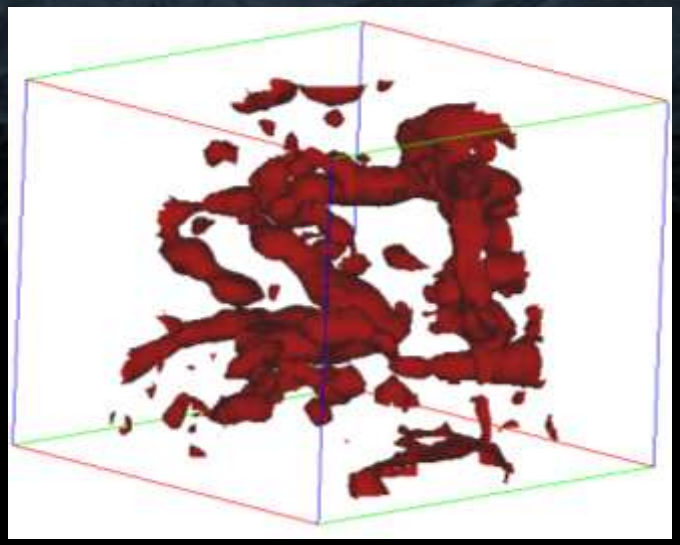
Alloy Design Chart



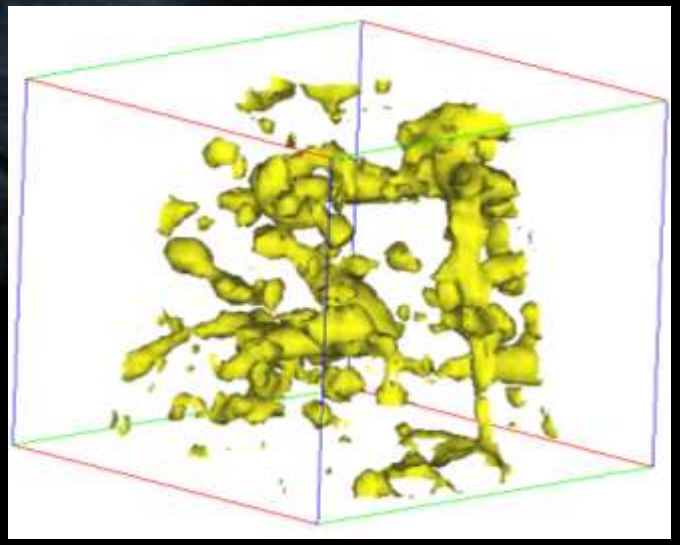
Validate Critical Design Factors (Core)

- Validate core nano-scale carbide dispersion: Local Electron Atom Probe analysis
  - High tensile elongation for all tested alloys and conditions

65 x 65 x 35 nm^3 dimensions



C surfaces



Cr surfaces

- Reasonably low core annealed hardness for machinability: C64 ~33 R_C vs. C61: ~36 R_C

Current Technology: Pyrowear X53

Relative comparison of X53 and C64 properties

Fatigue Strength (ksi)	25% increase
Yield Strength (ksi)	40% increase
Ultimate Tensile Strength (ksi)	36% increase
Increased Case Hardness	R_c62-64 vs. R_c60-62
Fracture Toughness (ksi$\sqrt{in}$)	Same
Tempering Temperature (ºF)	500ºF higher
Processing (heat treat, machining)	Same - adaptable

Increased power density

Better dry run performance and efficiency

QuesTek *C64* Alloy State of Development

- Alloy produced at full scale (10,000 lb.) at Carpenter Technologies
  - Tensile: 202 ksi 0.2% YS, 228 ksi UTS (typical)
  - Toughness: 85 ksi√in
- Preliminary carburization (gas, vacuum) and heat treatment optimization is complete
- Fatigue data development is underway
  - Rolling-sliding contact fatigue
  - Single-tooth bending fatigue
  - Rotating spur gear fatigue data
    - Scoring
    - Pitting
    - Bending

QuesTek *C64* Alloy State of Development

- Current development
  - Initial production and coupon testing

STTR	Milestone	TRL	Measure of success	TRL date
Phase 1-Yr 1	Sample testing and process optimization	2-3	Laboratory data	June 2007
Phase 2-Yr 1	Full scale alloy production	4	Steel mill certification	July 2007
Phase 2-Yr 2	Coupon fatigue testing	4	Fatigue test data	January 2008
Phase 2-Option 1	Rotating spur gear fatigue testing	5	Fatigue test data	January 2009
Phase 2-Option 2	Full-rig testing	6	Material fatigue allowances	January 2010

C64 Transition to the Fleet

V-22 tiltrotor transmission

- Full-rig (component-level) fatigue testing
- V-22 upgrade targeted as initial Navy application

Other rotorcraft (and other) applications

- Increase volume
- Generate data for AMS specification

C64 Transition to the Fleet

- Future development
  - Ingot production, full-rig testing, and specification development

TRL	Required tests, demos, next steps	Target date	Organizations to be involved
7	Production of two further heats, with testing and initial aerospace qualification	~2011	• Navy / DoD (rotorcraft platform system managers) • Steel producers (e.g., Carpenter, Latrobe) • Rotorcraft manufacturers (Bell, Boeing, Sikorsky, Augusta-Wentland) • Drive system engineers
7-8	Production of seven further heats, with testing and full aerospace qualification	~2014	"
7-8	System (flight) testing of full scale heat components	~2014	"
9	Mission (flight) testing of full scale heat components	~2016	"

Strategic Partners Sought

- Currently working with Bell Helicopter (V-22)
  - Qualification testing
- Boeing / Army interest for Apache (AH-64)
  - Enhanced Rotorcraft Drive System (ERDS) program
  - Also CH-47
- Other strategic partners related to:
  - Aerospace gearing applications
  - Oil / gas / energy gearing applications
  - Racing
  - Industrial gears
- Typical Partners
  - Component OEMs
    - Rotorcraft manufacturers (military and commercial)
  - Alloy producers
  - End users

QuesTek's Role

- Materials design and processing lead
- File utility patents
  - Maintain and defend
- Define manufacturing specifications
  - Qualify multiple alloy manufacturers
    - Material procurement
    - Secure AMS / MMPDS specifications as needed
  - Qualify secondary processors
    - Forging
    - Machining
    - Heat-Treatment
    - Carburization
    - Peening / superfinishing

About QuesTek Innovations

- Leader in emerging field of Computational Materials Design
- Solving complex material issues for
  - DoD, NASA, DOE, NSF, Industry
- Carburized Steel, Stainless Steel, High-strength Steel, Wrought and Cast Aluminum, Nickel, Copper
- Technology of the Year - IndustryWeek
- DoD/SERDP Project of the Year - *Ferrium® S53*
- Fortune 500 Breakout Company
- Patents: 13 Issued, 33 Pending

Contact Information

www.questek.com

Jason Sebastian, Ph.D.

Booth #760

Office Phone (847) 328-5800 Ext. 227

jsebastian@questek.com

Jim Wright, Ph.D.

Office Phone (847) 328-5800 Ext. 225

jwright@questek.com