Flying Cybersteels

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Product Commercialization
March 25, 2014

Agenda

- Introduction to QuesTek
- *Ferrium*® steels
  - Benefits over incumbent alloys
  - Accelerating the qualification
  - Leading and future applications
- Other breakthrough alloys nearing commercialization
  - Steel (castable stainless; nitridable stainless)
  - Aluminum 7XXX
  - Castable Ti-6Al-4V
  - Be-free copper
- Additive manufacturing

Background - QuesTek Innovations LLC

- Founded 1997; 12 employees
- A global leader in computational materials design:
  - Our ***Materials by Design***® technology and expertise applies Integrated Computational Materials Engineering (ICME) tools and methods to design new alloys 50% faster and at 70% less cost than traditional empirical methods
  - 4 computationally-designed, commercially-sold high-performance steels (*Ferrium*® steels licensed to Carpenter)
    - 2 AIM and flight qualified landing gear steels
- Specialty alloys for government and industry

aluminium	titanium	iron	cobalt	nickel	copper	niobium	molybdenum
13	22	26	27	28	29	41	42
Al	Ti	Fe	Co	Ni	Cu	Nb	Mo
26.982	47.867	55.845	58.933	58.693	63.546	92.906	95.94

- Technology transfer to a major Silicon Valley consumer electronics corporation in 2012
- QuesTek to serve as research partner of the American Lightweight Materials Manufacturing Innovation Institute, a $148 million public-private partnership to develop and deploy advanced lightweight materials manufacturing technologies
- QuesTek is a partner in the Northwestern University-led consortium for the $30 million, National Institute of Standards and Technology (NIST)-sponsored Center of Excellence for Advanced Materials (Focused on AIM: Ni-Ti and Co alloys)

Four steels commercially available (Carpenter Technology)

Double-vacuum-melted VIM/VAR steels:

- ***Ferrium*® S53®** (AMS 5922; MMPDS-05)
- ***Ferrium*® C61™** (AMS 6517) and **C64®** (AMS 6509)
- ***Ferrium*® M54®** (AMS 6516; MMPDS-09)

More Licensees are Anticipated

QuesTek is creating robust, competitive supply chains

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Ferrium S53 steel
Ultra high-strength, corrosion resistant

- Replace 300M/4340 where corrosion is an issue; reduce/eliminate cadmium
- Replace 440C where greater toughness/ductility is required
- Corrosion rate of 0.33 mpy, vs. 0.26 for 15-5 PH and 7.0 for 300M
- In flight service today without cadmium plating
- AMS 5922; MMPDS-05

Typical Alloy Properties	YS (ksi)	UTS (ksi)	El (%)	RA %	Fracture Toughness (ksi-√in)	Corrosion Resistance
300M	245	288	9	31	65	Poor
AerMet® 100	250	285	14	65	115	Marginal
***Ferrium* M54**	250	293	15	61	115	Marginal
***Ferrium* S53**	225	288	15	57	65	Good

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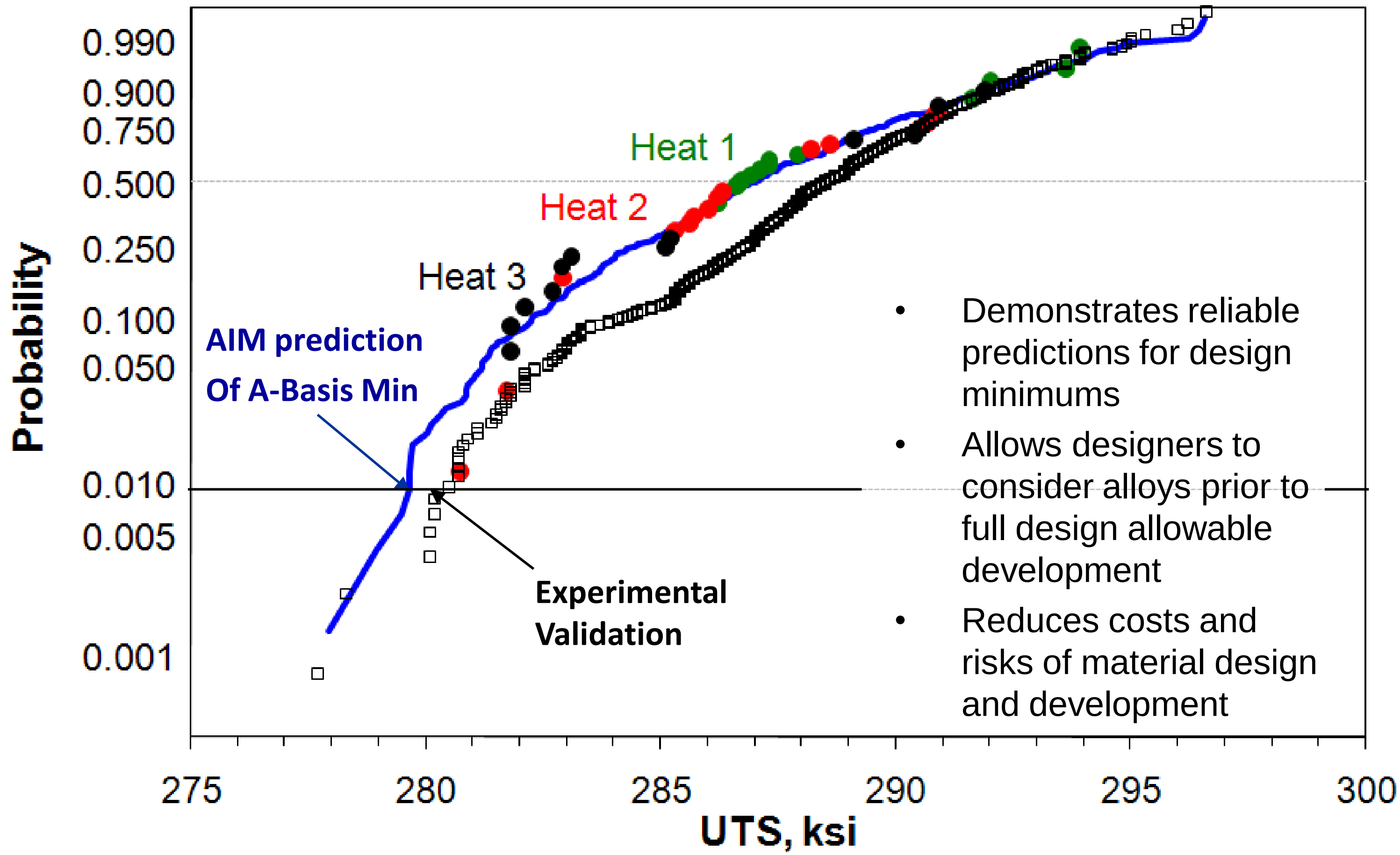
Accelerated Insertion of Materials (AIM) predicted A-Basis UTS for S53 using 3 Heats



- Demonstrates reliable predictions for design minimums
- Allows designers to consider alloys prior to full design allowable development
- Reduces costs and risks of material design and development

First flight: QuesTek's *Ferrium* S53
T-38 main landing gear piston (No cadmium plating)

December 17, 2010

Material approval:	**November 2009**
Component approval:	**August 2010**
Component installation:	**November 2010**
First flight:	**December 2010**

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Flying S53 (No Cadmium Plating) landing gear components to replace 300M

A-10 Main Landing Gear (MLG) piston, NLG drag brace/strut & NLG axle

- First flight began in August 2012
- Second aircraft identified, flight in 2014
- Initial filed components inspected in Feb. 2014

A-10

C-5 roll-pin

- First flight began in January 2014
- Corrosion limited on internal splines
- High condemnation rate during overhaul

C-5

A-10 Nose Landing Gear (NLG) piston

- Grinding burn issues
- Final production completed and components delivered to Hill Air Force Base in early 2014

KC-135 truck beam & forward/aft axles

- Fatigue, limit and ultimate load rig test completed in Nov 2013 at WPAFB
- Field service awaiting aircraft in 2014

KC-135

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Ferrium M54 steel
Superior properties, lower risk, lower cost

- Navy-funded alloy design project for a lower-cost, drop-in replacement for *AerMet*® 100 steel
- Within 2 years, demonstrated full scale production of alloy with:
  - Improved resistance to Stress Corrosion Cracking (SCC)
  - Improved or equivalent all S-basis procurement minima
  - Superior low and high cycle fatigue life
  - More robust thermal processing and lower machining/procurement costs
- Upgrade from 4340, 300M, Maraging 250/300, etc.
- AMS 6516; MMPDS-09

	4340 (AMS 6414)	300M (AMS 6419)	*AerMet*100 (AMS 6532)	*Ferrium* M54 (AMS 6516)
S-basis Minimum Ultimate Tensile Strength (ksi)	260	280	280	285
S-basis Minimum 0.2% Yield Strength (ksi)	217	230	235	240
Minimum K_{IC} Fracture Toughness (ksi-√in)	~45*	~40*	100	100
Reported Minimum K_{ISCC} (ksi-√in)	~10	~10	~22	~88
Corrosion Resistance	Poor	Poor	Marginal	Marginal

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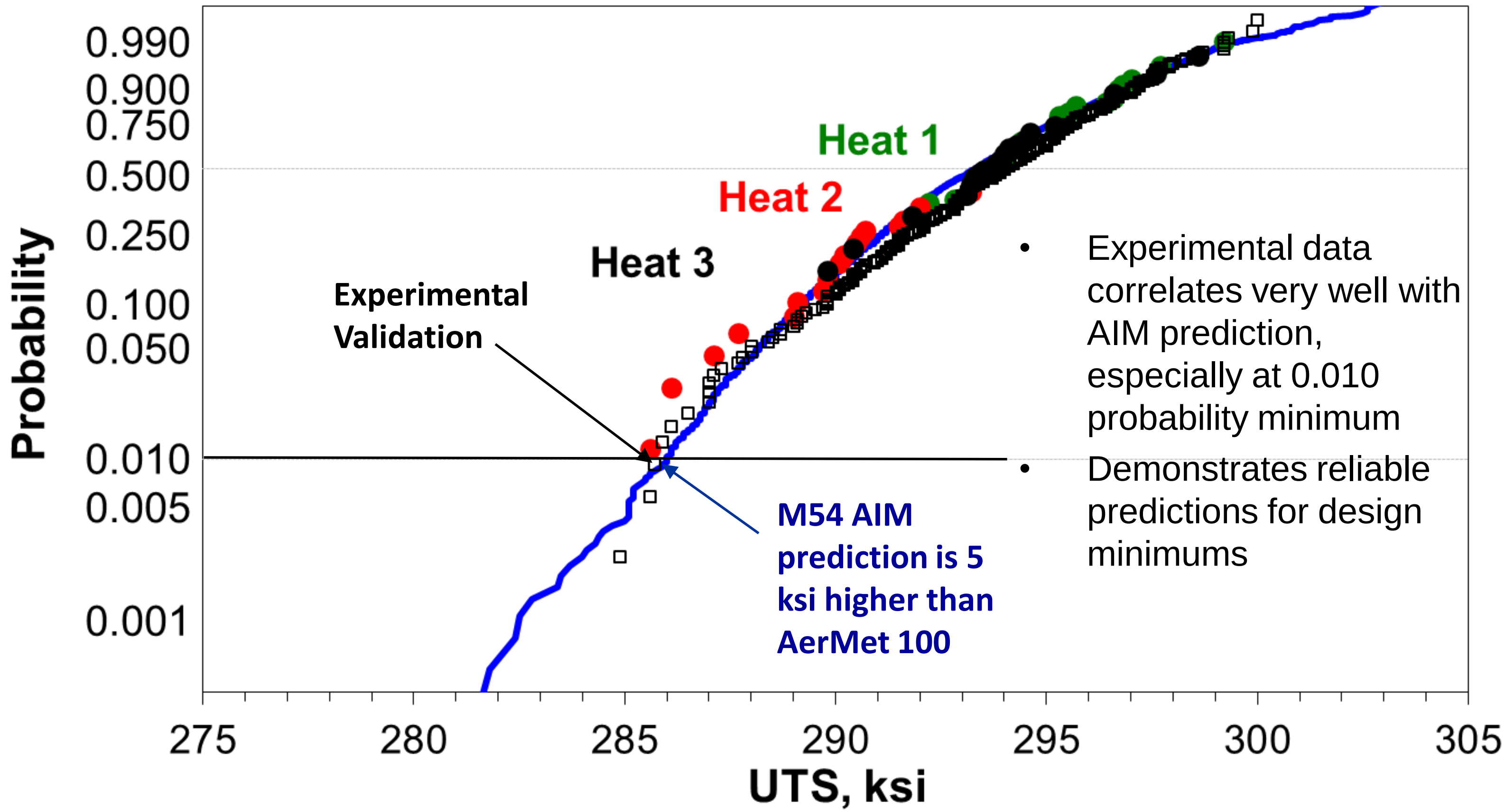
AIM analysis of M54 steel predicted A-Basis Minima



- Experimental data correlates very well with AIM prediction, especially at 0.010 probability minimum
- Demonstrates reliable predictions for design minimums

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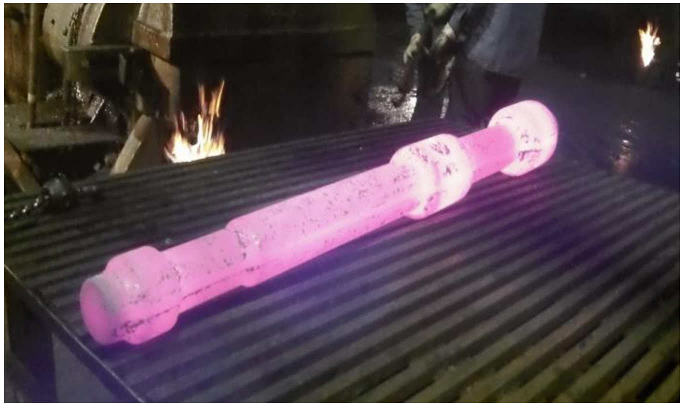
Accelerated M54 component qualification for demanding aerospace applications

- Navy-funded SBIR project to replace **T-45 hook shank** landing gear
  - Rig testing of prototype components completed in 2013 with success
  - Production of 60 hook shanks starting in 2014



- M54 steel for production of **F-18 hook points**
  - Prototype hook point fabrication completed
  - Rig testing in 2014

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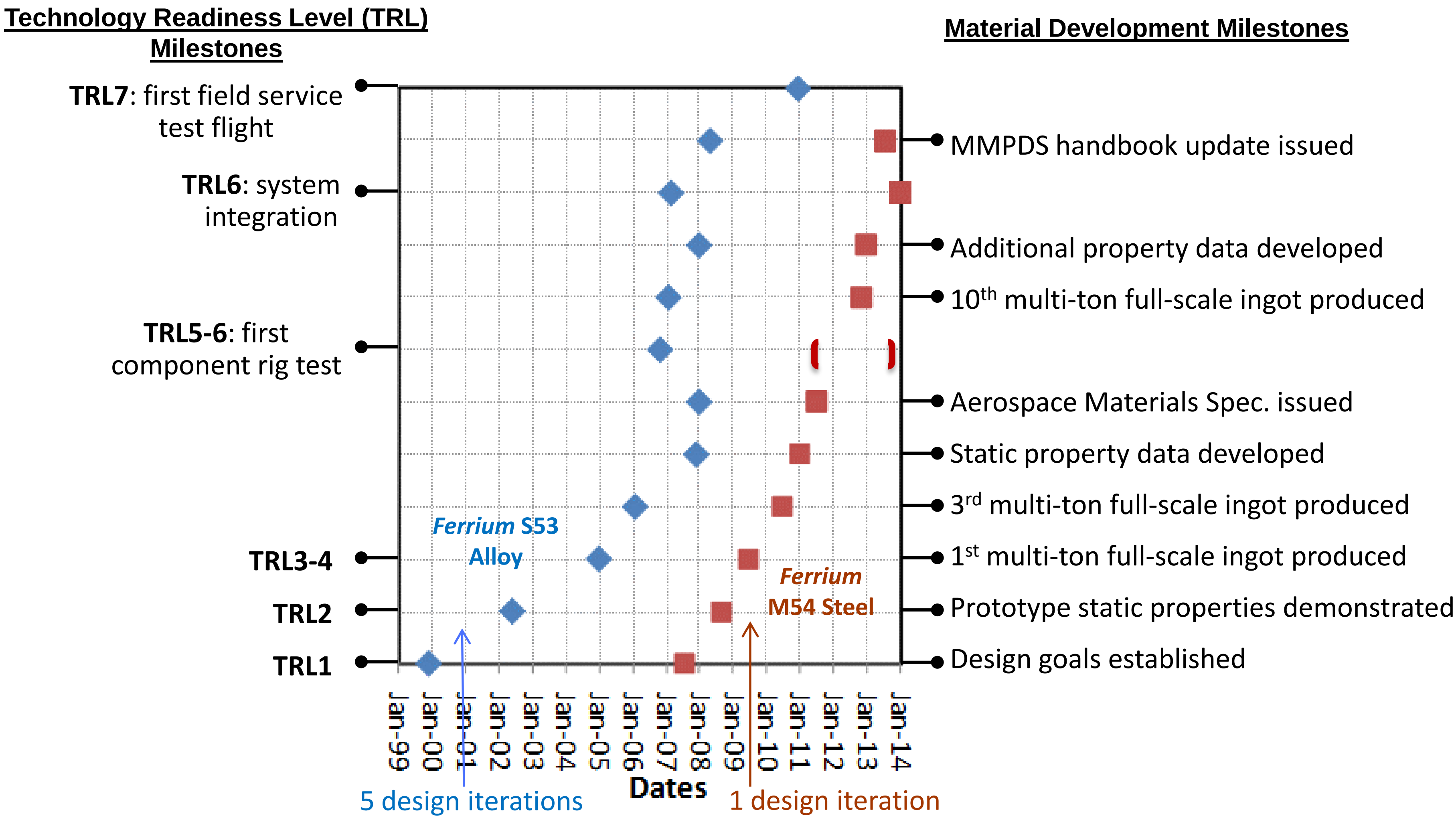
Computational materials qualification acceleration of QuesTek's *Ferrium* S53 and M54 steels



Ferrium C61 & C64 High Performance Carburizing Steels

C61 steel (AMS 6517): 60-62 HRC case, high-strength & high-toughness core

C64 steel (AMS 6509): 62-64 HRC case, high-strength core

- For gears, shafts, integrally-geared shafts, pins, ball screws, etc.
- Upgrade from AISI 9310 or Pyrowear® Alloy 53
- Designed for vacuum carburization
- Greater temperature resistance → superior oil-out capabilities
- Greater corrosion resistance than incumbent alloys

Typical Alloy Properties	YS (ksi)	UTS (ksi)	Core Hardness (HRC)	El (%)	RA %	Fracture Toughness (ksi√in)	Achievable Surface Hardness (HRC)	Tempering Temperature (°F)
AISI 9310	155	175	34-42	16	53	85	58-62	300
Pyrowear® Alloy 53	140	170	36-44	16	67	115	59-63	400
***Ferrium®* C61**	225	240	48-50	16	70	130	60-62	900
***Ferrium®* C64**	199	229	48-50	18	75	85	62-64	925

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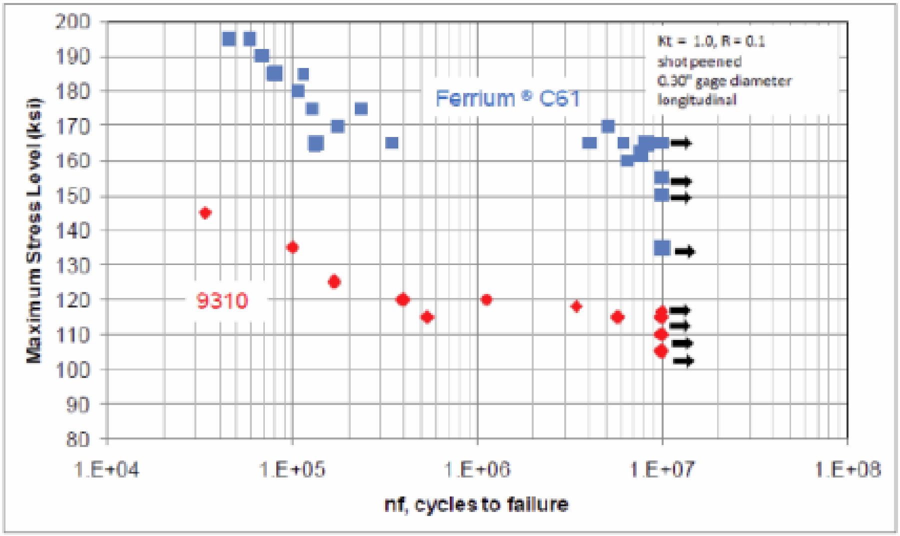
C61 and C64 steels - Superior Fatigue Performance

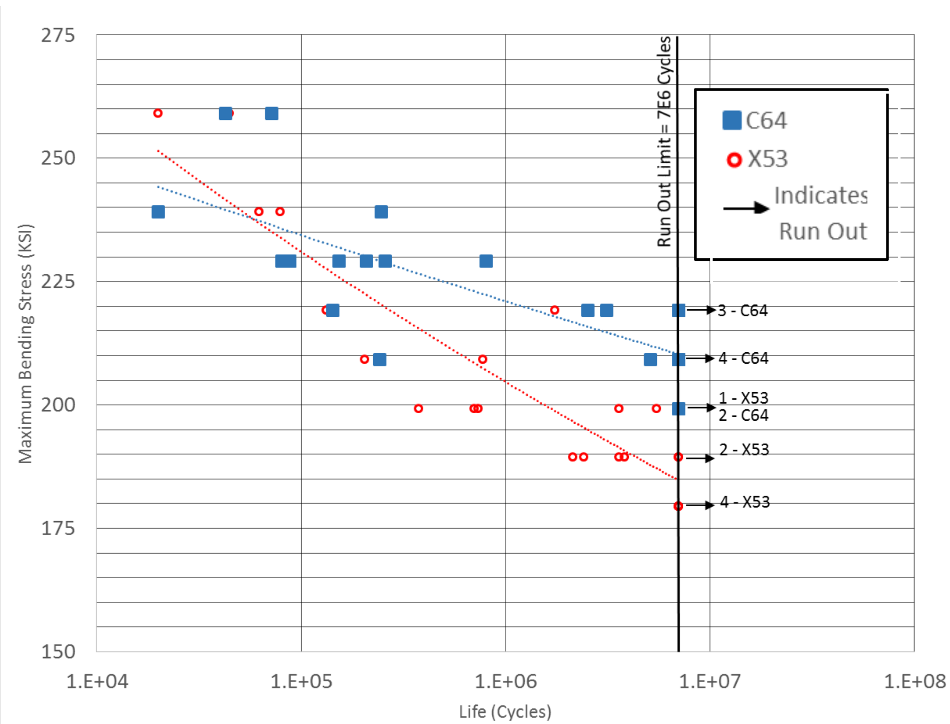
Axial Fatigue



From U.S. Army Contract #W911W6-09-C-0001

9310	~ 110 ksi
C61	~ 155 ksi

Single Tooth Bending Fatigue



Greater core strength of C61 steel leads to significant improvement in axial fatigue performance

Single tooth bending fatigue: ~20% higher performance of C64 steel over Pyrowear 53

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Demanding applications for C61 and C64 steels

Notable C61 Applications

- CH-47 Chinook helicopter forward rotor shaft application under SBIR Phase II
  - Prototypes completed in 2013, rig testing to begin in 2014
  - Boeing/Army intend to replace 9310 in Chinook upgrade
- Evaluated by Boeing in U.S. Army-funded Enhanced Rotor Drive Systems (ERDS) program
  - C61 chosen as material of choice for demonstrator gear boxes
  - Demonstrator gear boxes for Apache helicopter assembled and testing in 2014
- Oil & gas; commercial aerospace

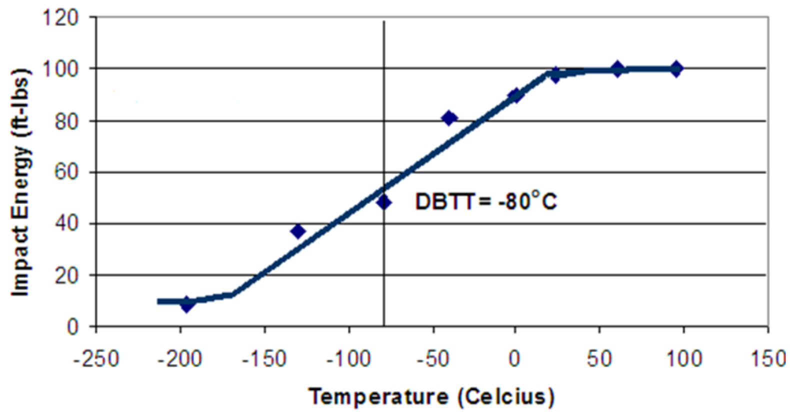
Notable C64 Applications

- Evaluation with Bell Helicopter in U.S. Army-funded Future Advanced Rotorcraft Drive System (FARDS) program for next generation transmission gears
- Several other major aerospace OEMs producing demonstrator gearboxes for evaluation
- Racing components where 9310 fails

New alloys developed and in process of commercialization

Ferrium PH48S™ Castable Stainless Steel

- Martensitic, maraging, precipitation-hardening, casting stainless steel designed and developed under USMC SBIR
- Exceeds strength to weight ratio of Ti6-4 but at lower cost
- Equivalent strength of conventional high strength steels, with greater corrosion resistance
- High Charpy impact toughness at low temperatures and good ductility through low DBTT of -80°C
- Substantially higher resistance to SCC and hydrogen environment assisted cracking (HEAC) over Custom® 465



Material	Processing	Yield Strength (ksi)	Ultimate Tensile (ksi)	K_{IC} (ksi √inch)	K_{ISCC} (ksi √inch)	Density (lb/in^3)	Specific YS (in * 10^5)	Specific UTS (in * 10^5)
PH48S	Cast	220	230	90	>75	0.288	764	799
TI6-4	Cast (1550F)	112	124	95	>58	0.161	696	770
13-8	Wrought (H1000)	205	215	98	>90	0.279	735	771
13-8	Cast	195				0.279	699	

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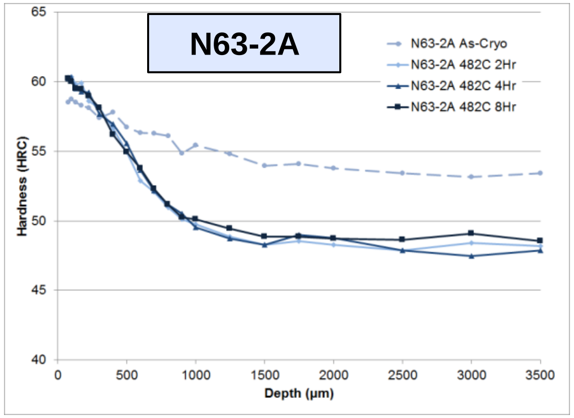
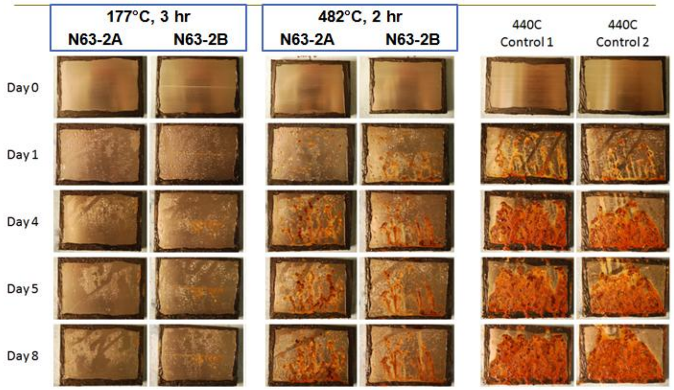
Ferrium N63 solution-nitridable stainless steel

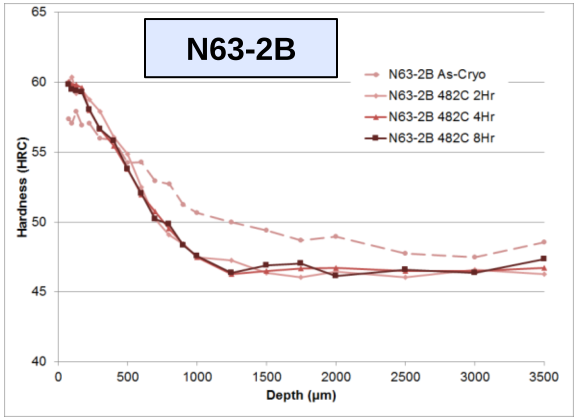
- U.S. Navy-funded SBIR Phase I and II program funding
- Goal: design a material with improved strength and corrosion resistance over Pyrowear 675
- Alloy design refinements promise further improvement of corrosion resistance and potential for fully-stainless behavior

Alloy	0.2% YS (ksi)	UTS(ksi)	%elong	%RA
N63-2A	171	222	23	71
N63-2B	162	207	24	74
Pyrowear 675	154	185	20	73
440C	275	285	2	10



B117 Salt Fog Testing results show significantly improved corrosion resistance over 440C





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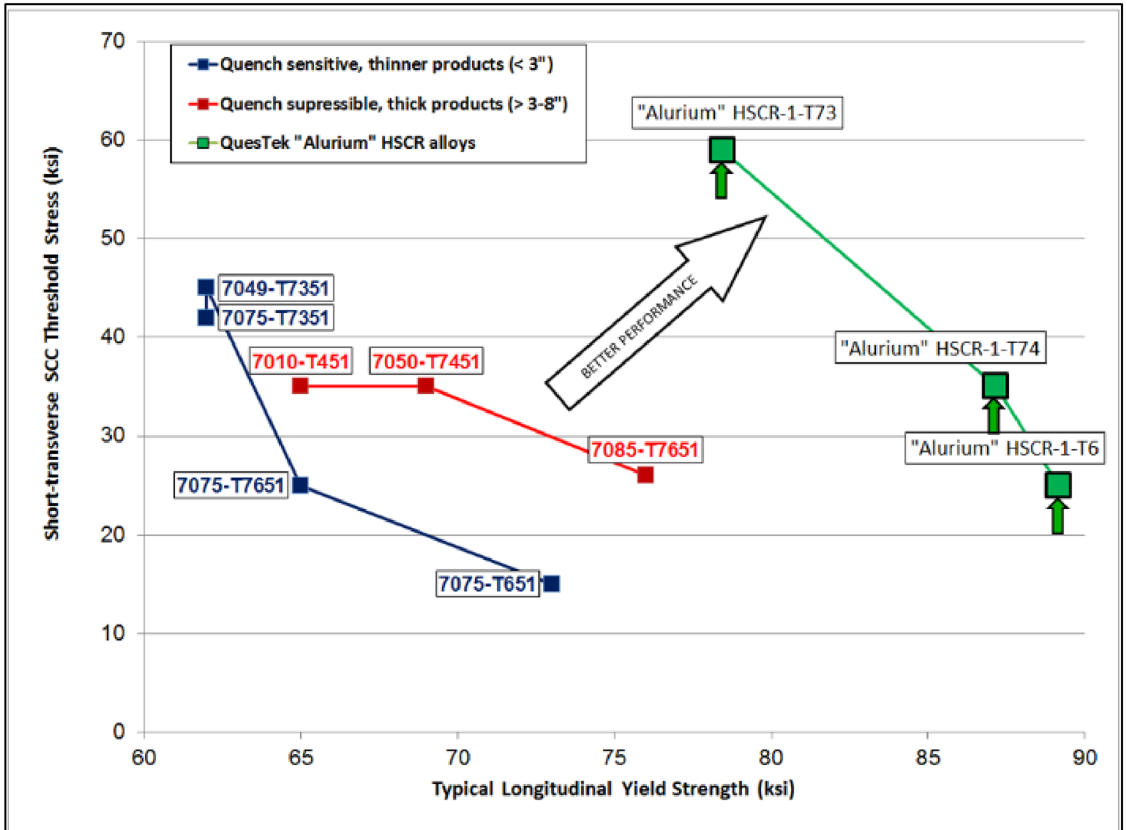
Alurium™ HSCR alloy

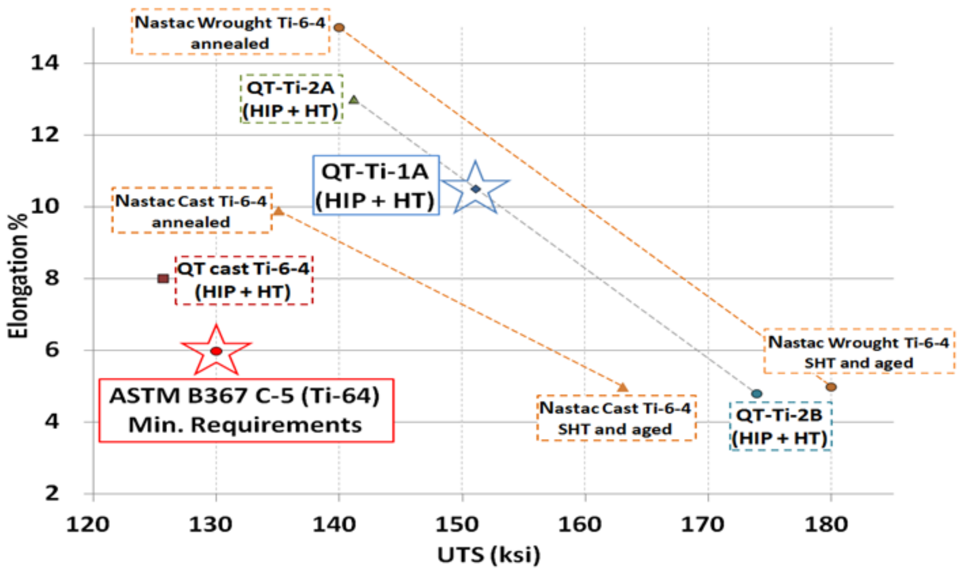
- Excellent strength and SCC resistance; upgrade from 7000 series aluminum
- Applications: aircraft structural frame components (e.g., wing spars) and internal components (e.g., seating)



QuesTek "*Alurium*" alloys achieve a combination of strength and transverse SCC resistance significantly better than any incumbent aerospace aluminum alloy (including 7050-T74)

Three new low-cost castable titanium alloys

- QT-Ti-1A can be considered for example to:
  - replace cast Ti-6-4 to increase a part's durability or reduce its weight;
  - replace wrought Ti-6-4 ro reduce costs; or
  - replace Ti-6242 in high-temperature applications to reduce costs
- Lower cost
  - Reduced vanadium (relative to Ti-6-4)
  - Tolerance to oxygen
  - Can incorporate up to 75% Ti-6-4 scrap into melting stock
- This titanium alloy to be evaluated by major aerospace OEM for additive manufacturing processes



QuesTek Be-free high strength alternative alloys

Computationally-designed high-strength, low-friction, environmentally benign BeCu replacement alloys that eliminate health concerns:

***QuesTek*-Co alloy**: Precipitation hardening Co-Cr alloy

- Comparable yield strength; superior tensile strength, ductility and frictional behavior vs. commercially-available BeCu alloys
- Demonstrator project for scale-up and accelerated qualification under NIST Center of Excellence

***Cuprium*® alloy**: Cu alloy

- Comparable yield and tensile strength, ductility and frictional behavior vs. commercially-available BeCu alloys
- QuesTek patent pending

Property	Cu-Be (Cu-1.9 Be)	QuesTek Cuprium™	QuesTek-Co (Co-Cr)	ToughMet® 3 (Cu-15Ni-8Sn)	BioDur® CCM (Co-Cr-Mo)
0.2 % Yield Strength	140 ksi (minimum) (non-CW)	142 ksi (non-CW)	126 ksi demonstrated (non-CW)	107ksi (minimum) (non-CW)	85 ksi (non-CW) (typical)
Elongation	3 - 8%	15%	33%	3 – 10%	26%
Wear Ranking	3 (worst)	2	1 (Best)	2	1

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Alloys for additive manufacturing

There is increasing interest in the development of new alloys specifically designed for additive manufacturing (AM)

- Adaptation of traditional wrought/cast alloys to AM processing presents limitations

Additive manufacturing alloy design considerations:

- Rapid heating / cooling / solidification
- Oxygen tolerance ("gettering")
- Novel precipitation strengthening concepts (e.g., elements with limited solid-state solubility)

Currently

- QuesTek subcontract under Honeywell DARPA "Open Manufacturing" project (Ni superalloys)
- QuesTek computational models:
  - Process-structure-property of the Additive Manufacturing process
  - Rapid solidification
  - Multiple heating/cooling cycles
  - Innovative new compositions (powders) specifically for Additive Manufacturing to enhance materials performance

QuesTek sees tremendous opportunity (and interest) in the design and development of new alloys for additive manufacturing

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Conclusions

- QuesTek remains a global leader in Integrated Computational Materials Engineering (ICME)
- Four ICME-designed steels were rapidly developed, qualified, and are being adopted in demanding applications in aerospace, oil & gas, energy and other industries
- A number of breakthrough alloys are in the process of being scaled up and licensed and should be commercially available soon
- Demonstrating accelerated component qualification
- Aligned with the national Materials Genome Initiative
- QuesTek continues to seek out new alloy design and modeling opportunities with private industry and government

Contact information

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