QuesTek's *Ferrium* C64 carburizable gear steel

Themomechanical Process Optimization and High-Cycle Fatigue Resistance

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SRG Meeting, Evanston, IL
25 March 2014

Agenda

- SBIR program overview
- QuesTek background
- *Ferrium* C64
- Fatigue initiation and microstructural fatigue modeling
- Impact of HIP on fatigue
- C64 results
  - Axial fatigue
  - Single tooth bending fatigue
- Conclusions

“Fatigue Resistant Martensitic Steel for Rotorcraft Drive Train Components”

- Army-funded SBIR program - Topic No. A10-035
- Phase I project - Contract No. W911W6-11-C-0007
- Phase II project - Contract No. W911W6-11-C-0053
- Program Officer - Matthew Spies & Clay Ames

- Phase I
  - *Ferrium* C64 steel was developed to improve bending and contact fatigue resistance
  - Developed novel hot isostatic pressing (HIP) technique to improve interfacial cohesion between nonmetallic inclusions and steel matrix
  - ~40% improvement in mean fatigue life behavior
- Phase II
  - Optimize HIPping process
  - Manufactured *Ferrium* C64 specimens (axial and single tooth bending fatigue) that were testing against incumbents (*Pyrowear* X53)
  - Statistical analysis shows HIPping significantly improves C64 fatigue (axial) performance

Background - QuesTek Innovations LLC

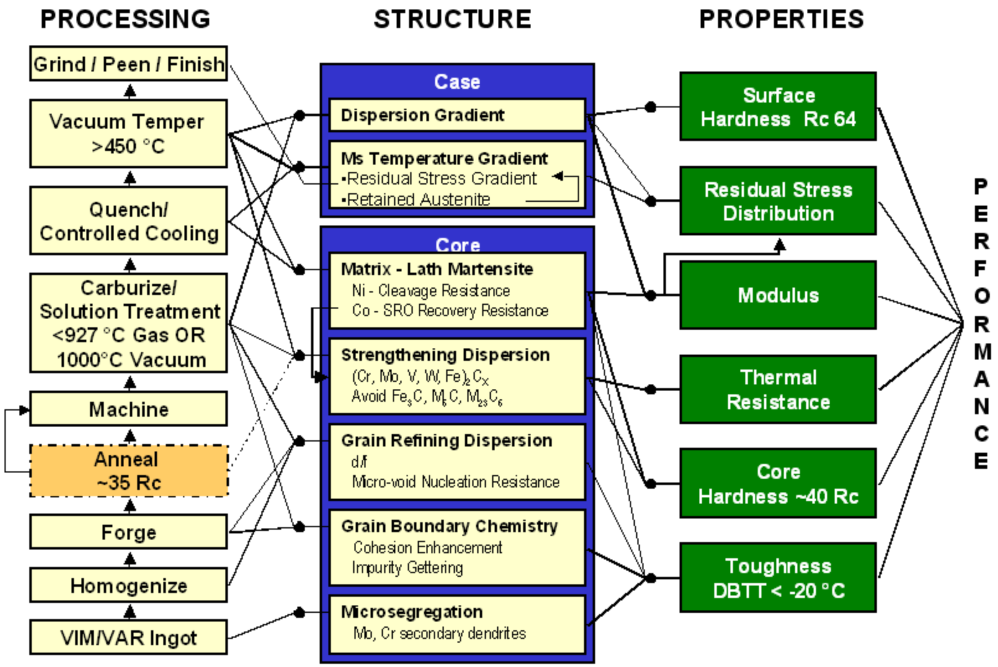
- Founded 1997
- 15 employees (7 with PhDs)
- A global leader in computational materials design:
  - Our ***Materials by Design***® technology and expertise applies Integrated Computational Materials Engineering (ICME) tools and methods to design new alloys 50% faster and at 70% less cost than traditional empirical methods
  - Aligned with President Obama's Materials Genome Initiative
- Creates IP and licenses it to alloy producers, processors or OEMs
- 30+ patents awarded or pending worldwide
- 4 computationally-designed, commercially-sold alloys
- Designing 10+ new Fe, Al, Cu, Ni, Co, Nb, Ti, Mo and W based alloys for government and industry

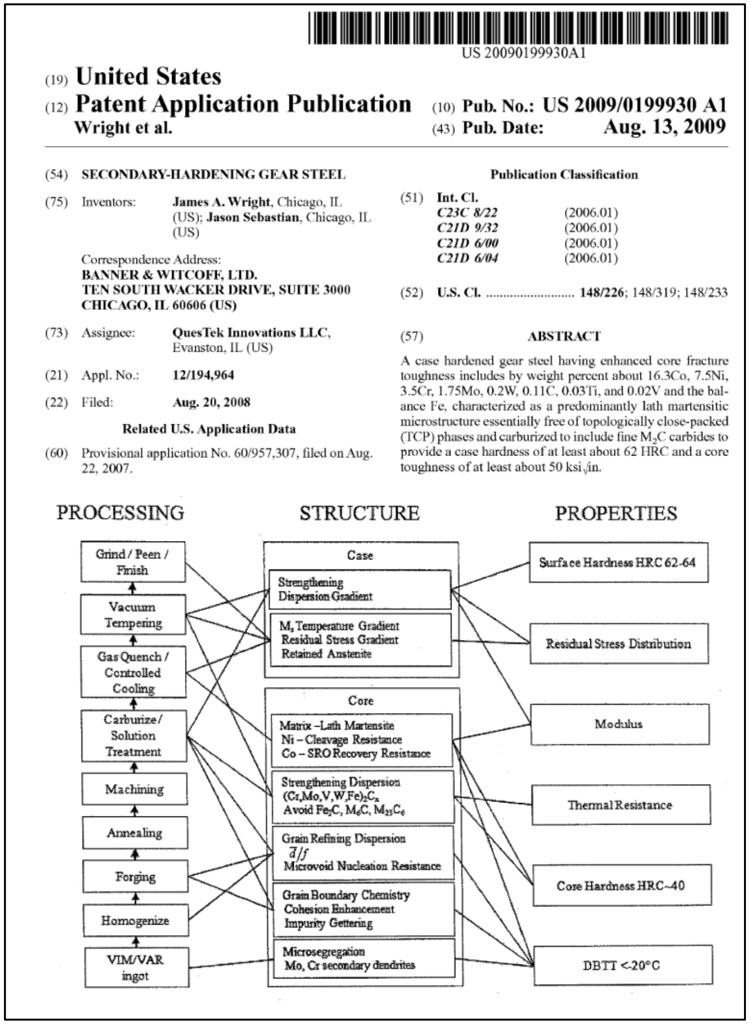
aluminium	titanium	iron	cobalt	nickel	copper	niobium	molybdenum
13	22	26	27	28	29	41	42
Al	Ti	Fe	Co	Ni	Cu	Nb	Mo
26.982	47.867	55.845	58.933	58.693	63.546	92.906	95.94

Computational Materials Design Overview

Design material as a system to meet customer-defined performance goals

e.g. this “Design Chart” for *Ferrium* C64 was developed under a contract resulting from U.S. Navy Solicitation Topic #N05-T006.





US 20090199930A1

(19) **United States**

(12) **Patent Application Publication** (10) **Pub. No.: US 2009/0199930 A1**

Wright et al. (43) **Pub. Date: Aug. 13, 2009**

(54) **SECONDARY-HARDENING GEAR STEEL**

(75) Inventors: **James A. Wright**, Chicago, IL (US); **Jason Sebastian**, Chicago, IL (US)

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(73) Assignee: **QuesTek Innovations LLC**, Evanston, IL (US)

(21) Appl. No.: **12/194,964**

(22) Filed: **Aug. 20, 2008**

Related U.S. Application Data

(60) Provisional application No. 60/957,307, filed on Aug. 22, 2007.

Publication Classification

(51) **Int. Cl.**

C23C 8/22	(2006.01)
C21D 9/32	(2006.01)
C21D 6/00	(2006.01)
C21D 6/04	(2006.01)

(52) **U.S. Cl.** **148/226**; 148/319; 148/233

(57) **ABSTRACT**

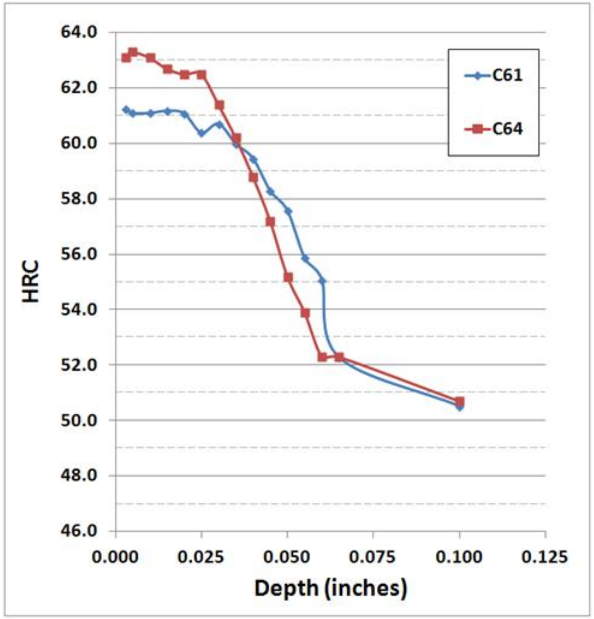
A case hardened gear steel having enhanced core fracture toughness includes by weight percent about 16.3Co, 7.5Ni, 3.5Cr, 1.75Mo, 0.2W, 0.11C, 0.03Ti, and 0.02V and the balance Fe, characterized as a predominantly lath martensitic microstructure essentially free of topologically close-packed (TCP) phases and carburized to include fine M_2C carbides to provide a case hardness of at least about 62 HRC and a core toughness of at least about 50 ksi$\sqrt{\text{in}}$.

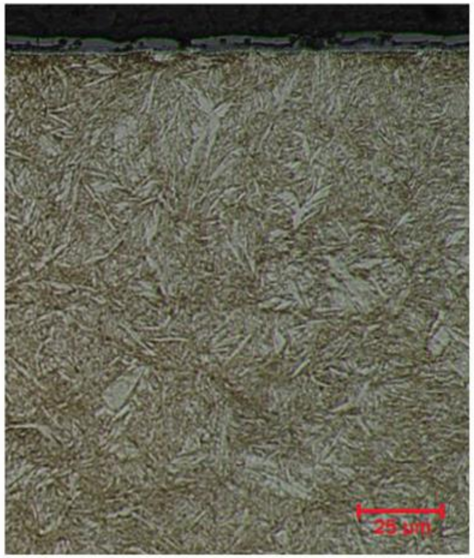
Ferrium® C61® and C64® property comparisons

C61 = AMS 6517

C64 = AMS 6509

Alloy	YS (ksi)	UTS (ksi)	Core hardness (HRC)	El (%)	RA (%)	K_{IC} 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





Substantially free of primary carbides

Potential platform applications for C64—examples

- **Rotorcraft**
  - **Upgrades e.g. V-22**
  - **New platforms e.g. CH-53K**
  - **Evaluation in new U.S. Army-funded Future Advanced Rotorcraft Drive Systems (FARDS) program**
- **Weight/size-sensitive or high-temperature ground vehicle drive assemblies**
- **Bearings**
- **Vehicle plate armor**
- **Other TBD**


V-22 Future Upgrade


CH-53K

Commercializing new alloys through licensees

All four are double-vacuum-melted VIM/VAR steels:

***Ferrium* S53®**

Licensee #1 - Feb. 2007: CARPENTER

Licensee #2 - Dec. 2007: LATROBE SPECIALTY METALS A Carpenter Company

***Ferrium* C61™ and C64™**

Licensee #1 - Nov. 2009: LATROBE SPECIALTY METALS A Carpenter Company

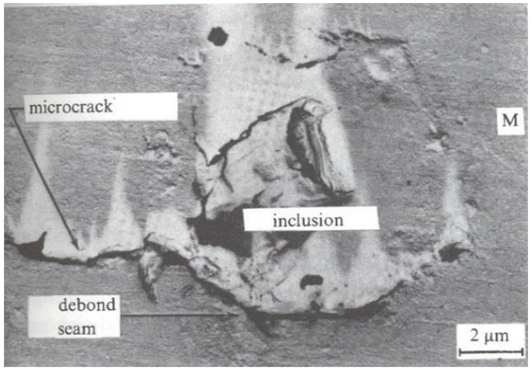
***Ferrium* M54**

Licensee #1 - April 2010: LATROBE SPECIALTY METALS A Carpenter Company

More Licensees are Anticipated

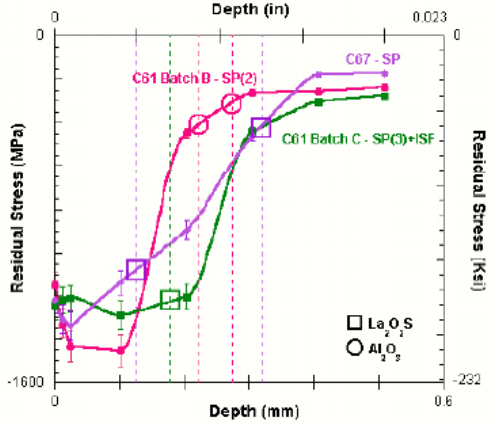
QuesTek is creating robust, competitive supply chains

Introduction: Fatigue crack nucleation at inclusions

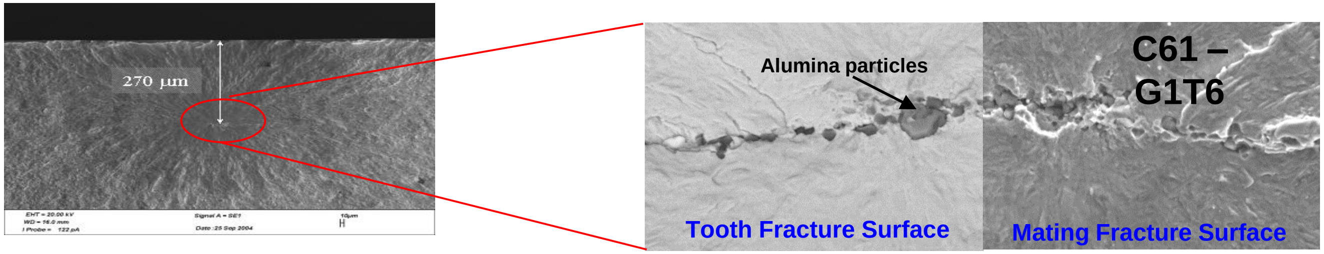


Crack formation at inclusions
(4340 steel with $MnO\text{-}SiO_2\text{-}Al_2O_3$ inclusions)
(Figueroa, *et. al.*, 1983)

Extensive experimental evidence is available on fatigue crack initiation at non-metallic primary inclusions in processed high strength steels



Influence of residual stress and inclusion type on crack nucleation site



Ben Tiemens, PhD Thesis, NWU, 2006

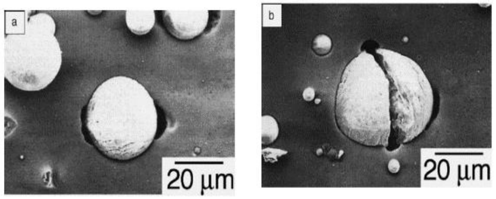
Clusters of debonded particles on fracture surface

Fatigue crack nucleation and small crack growth at primary inclusions consumes a significant portion of service life (~70-90%) under high cycle fatigue (HCF)

(Lankford and Kusenberger , Met. Trans A, 1973)

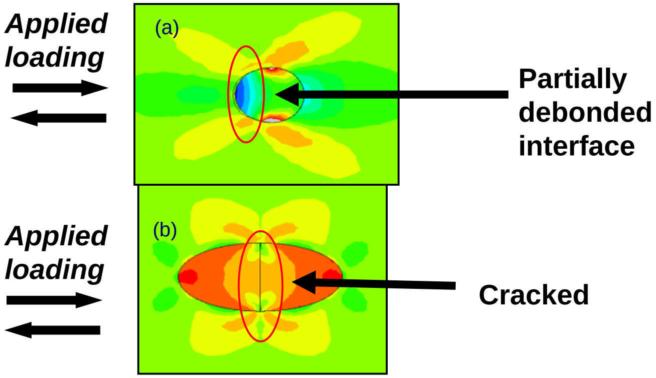
Introduction: Fatigue crack nucleation at inclusions

- Intact
- Debonded
- Fractured particles



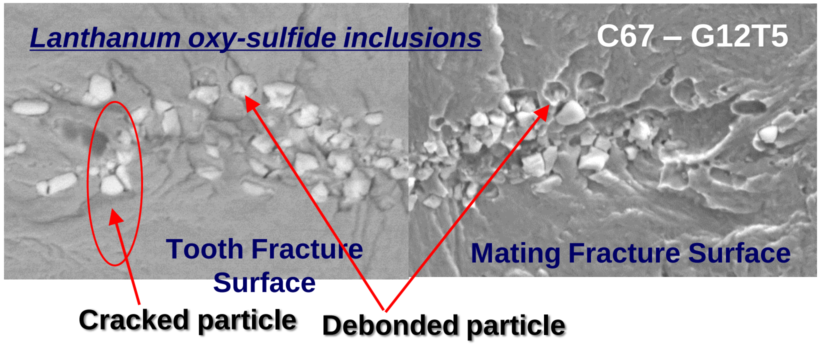
Alumina particles in Al 6061 matrix: (a) debonding, (b) particle fracturing*

Segurado and Llorca, IJSS, 41, 2004, 2977-2993.

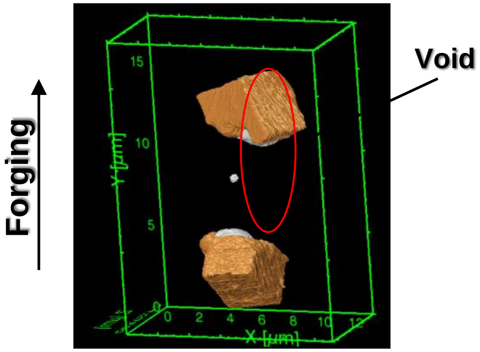


FE simulation of stress localization around damaged particles

Ben Tiemens, PhD Thesis, NWU, 2006



FE simulations reveal debonded inclusions to be the worst case scenario for fatigue crack nucleation

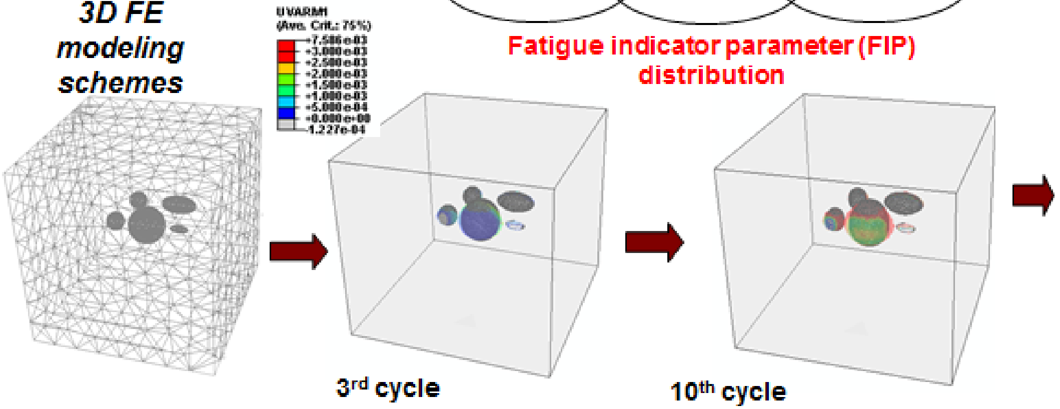


Void formation at primary inclusions in mod4330 steel

Modeling process-structure-property relations to support *Materials by Design*®

Process | Structure | Property

3D FE modeling schemes



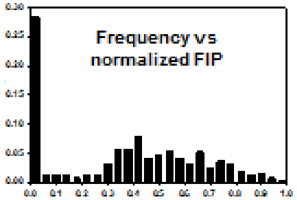
Fatigue indicator parameter (FIP) distribution

3rd cycle

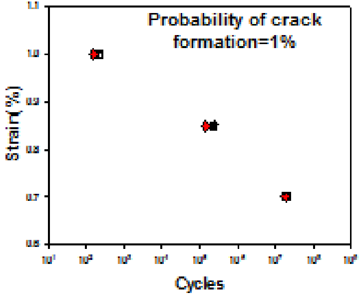
10th cycle

Quantify fatigue potency at primary inclusions

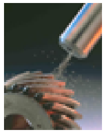
Characterize variability of fatigue response



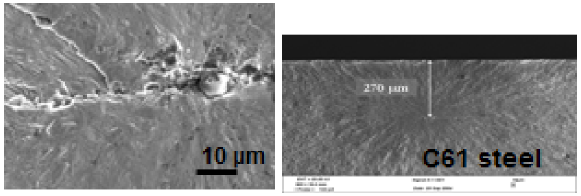
Minimum-life design



DARPA-ONR D3D Program (D. McDowell, GaTech)



Process history



Primary inclusions -critical life-limiting features

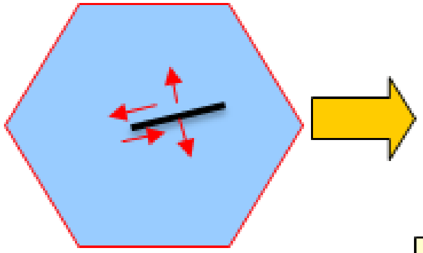
Ben Tiemens, PhD Thesis, NWU, 2006

Lend support to designing fatigue-resistant materials

Modeling: fatigue indicator parameters (FIPs)

Fatigue indicator parameters (FIPs) applied at the grain scale can reflect local driving forces for fatigue damage formation

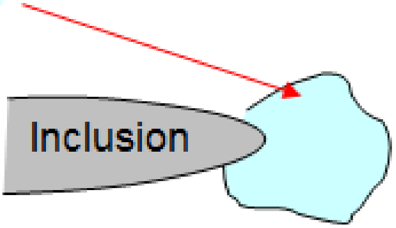
e.g. Fatemi-Socie Parameter (1988) → Accounts for max shear plus effect of crack opening force



$$P_{FS} = \frac{\Delta\gamma^{p*}_{\max}}{2}\left(1+K'\frac{\sigma_n^{\max*}}{\sigma_y}\right)$$

$P_{FS} \Longleftrightarrow \Delta CTD$ (cf. McDowell & Berard, FFEMS, 1992)

(cf. Findley and Saxena, 2006, Dunne, 2006, Papadopoulos, 1995, Dang Van, 1993, and others for similar multiaxial parameters applied at grain scale)

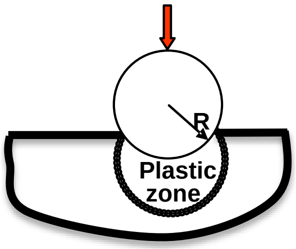


Nonlocal averaging Region

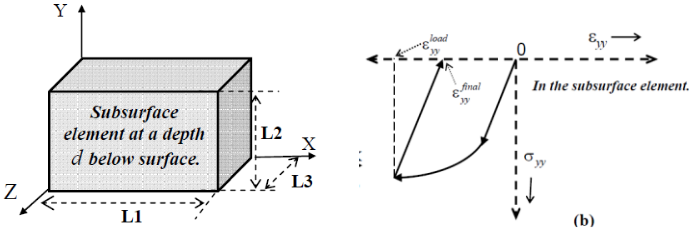
$$\Longleftrightarrow \quad \varepsilon^{p*}_{ij} = \frac{1}{V}\int_V \varepsilon^{p}_{ij}\,dV$$

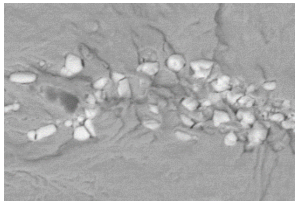
Modeling: process route effects—shot peening

A hierarchical modeling approach followed to couple process route effects with microstructure attributes that influence fatigue crack nucleation and growth in HCF



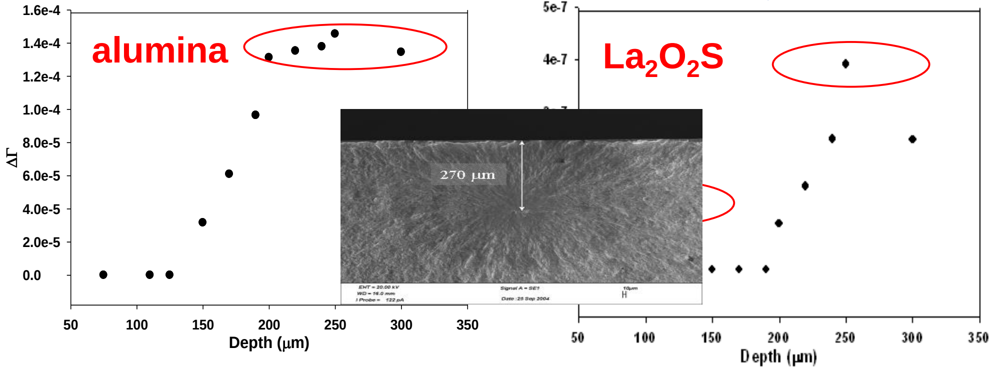
Process history



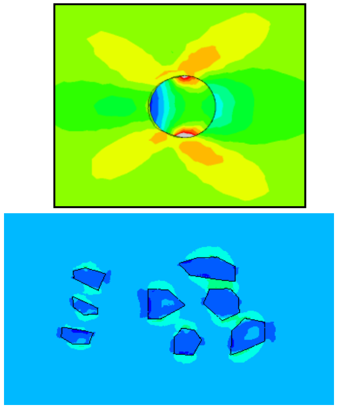


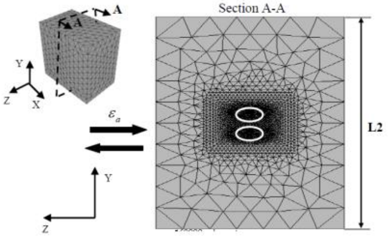
Higher length scale where process parameters are framed

grain scale or size of primary inclusion



ΔΓ vs. depth

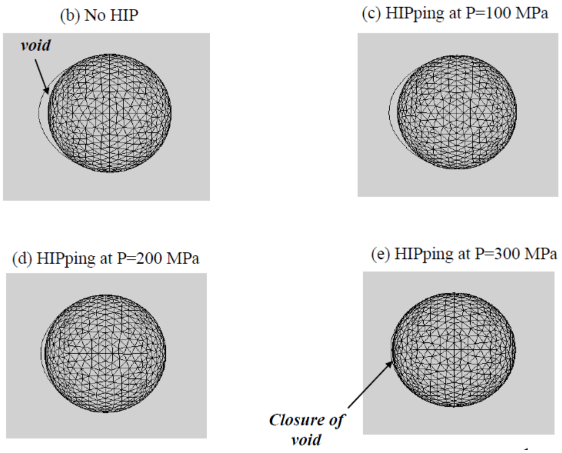




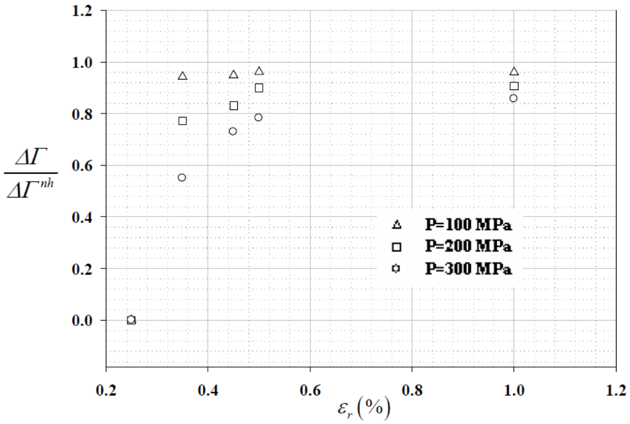
Prasannavenkatesan R, PhD Thesis, GaTech, 2009

Modeling: process route effects – HIPing

FE HIPing process model using compression creep data



Effect of HIPing pressure on void closure

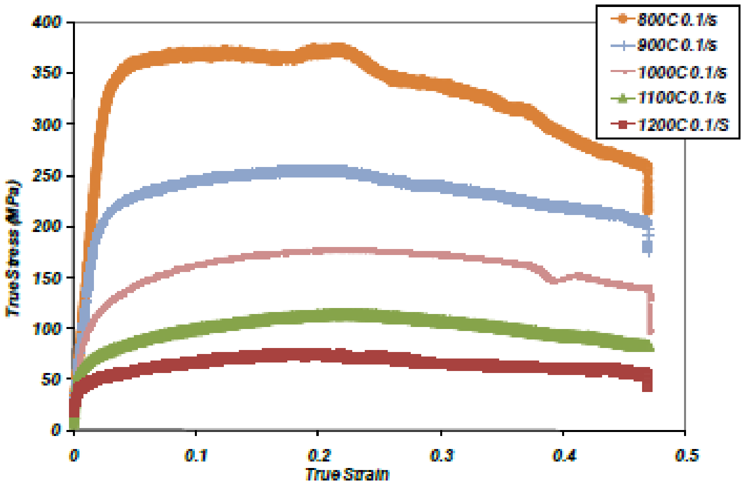


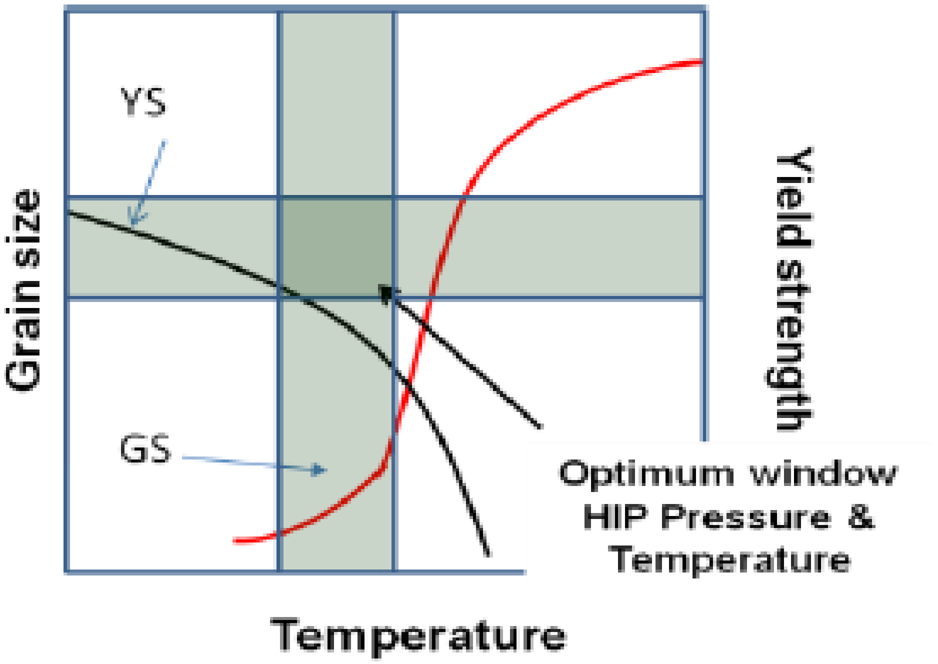
Effect of HIPing pressure on void closure and fatigue potency

Prasannavenkatesan R, PhD Thesis, GaTech, 2009

HIPing significantly improves fatigue life for inclusion initiated failures

Optimization of C64 HIP parameters



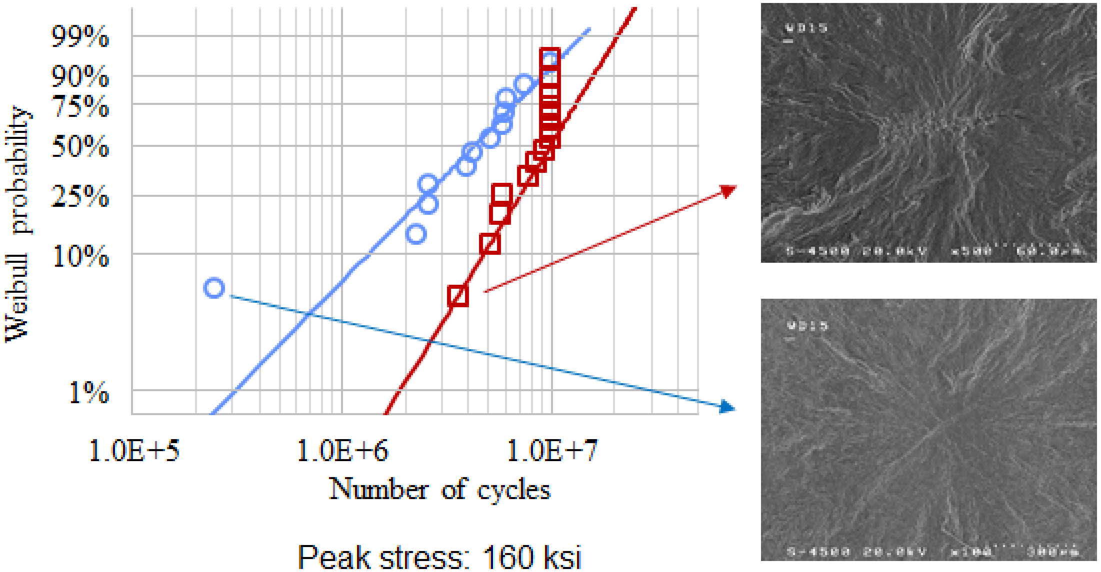


Variation in strength with strain (left); variation grain size and yield strength with temperature (right)

Results – HIPing is very beneficial to axial fatigue life

HIPing significantly improves fatigue life for inclusion initiated failures

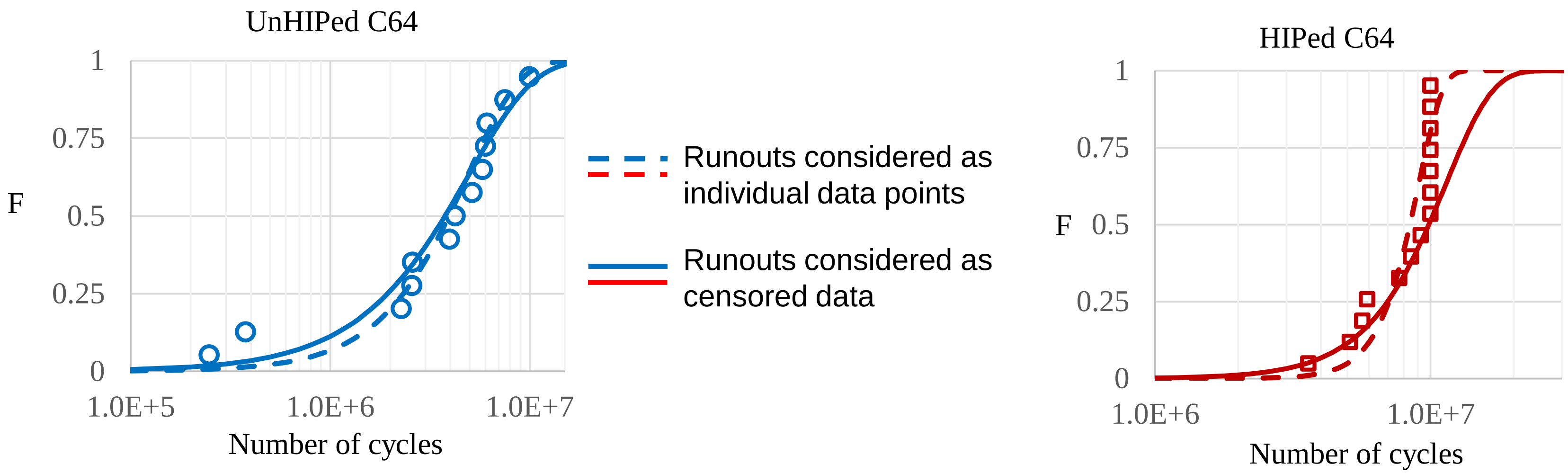
- All samples loaded at a peak load of 160 ksi and load ratio 0.1
- Samples considered runouts at 10^7 cycles
- 13 UnHIPed samples with 1 runout
- 14 HIPed samples were tested with 7 runouts



Peak stress: 160 ksi
R = 0.1. 20 Hz.

- Weibull survival probability plots indicate benefit of HIPing
- Significant increase in fatigue life for a 1% failure probability

Results – effect of number of runouts

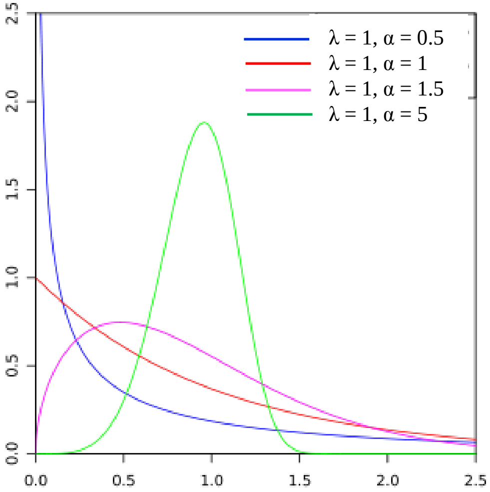


- Number of runouts greatly influences the 'shift' of the Weibull distribution describing the scatter

MLE approach

The pdf of a 2 parameter Weibull distribution is given by

$$f(x;\ \lambda,\alpha) = \begin{cases} \frac{\alpha}{\lambda}\left(\frac{x}{\lambda}\right)^{\alpha-1} e^{-(x/\lambda)^{\alpha}} & x \geq 0 \\ 0 & x < 0 \end{cases}$$



For a discrete sample of size n, optimum parameters are estimated by maximizing the likelihood

$$L = \prod_{i=1}^{n} f\left(x_i;\ \hat{\lambda},\hat{\alpha}\right)$$

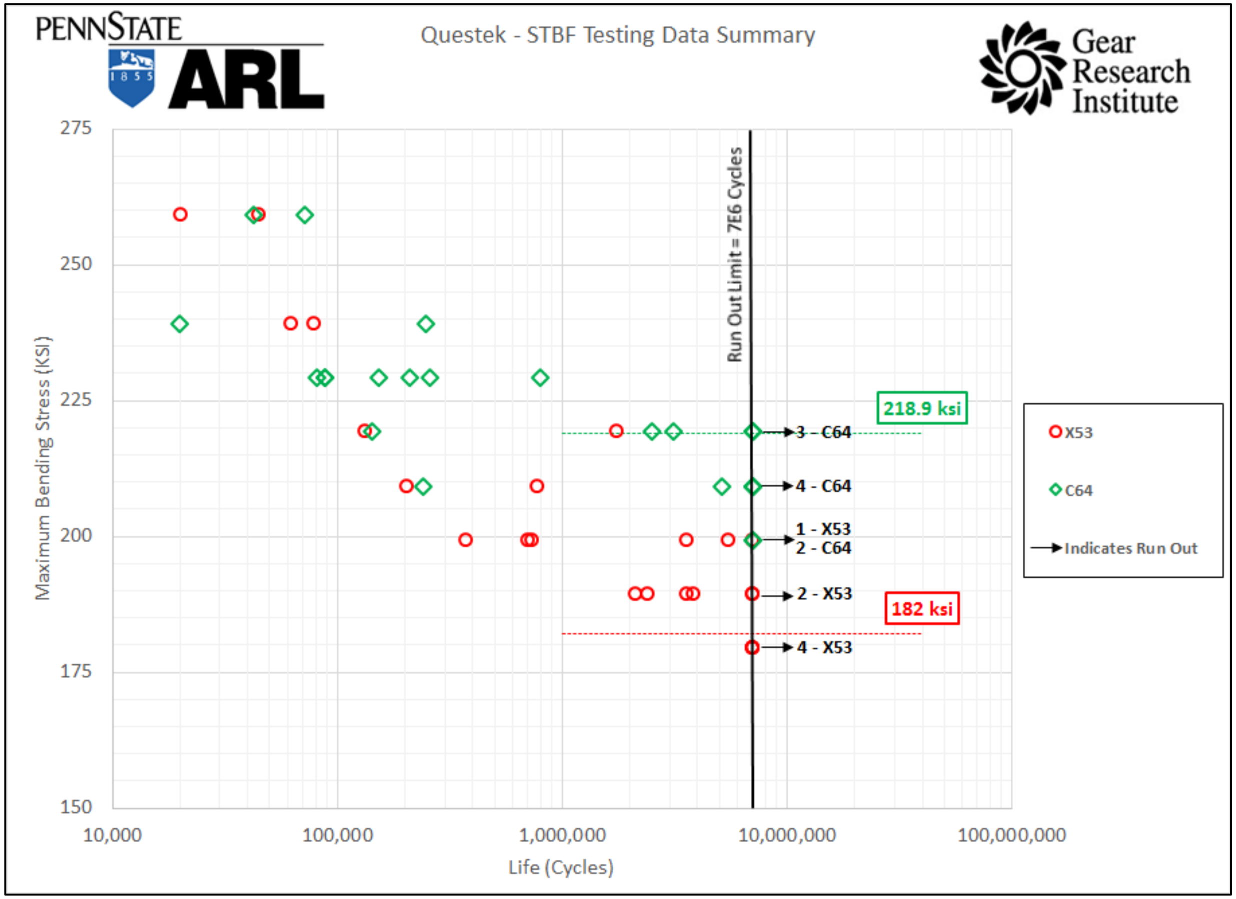
For a discrete sample of size N, with n failures (Type I censoring)

$$L = \frac{N!}{(N-n)!}\left[\prod_{i=1}^{n} f\left(x_i;\ \hat{\lambda},\hat{\alpha}\right)\right]\left[1 - F\left(x_i;\ \hat{\lambda},\hat{\alpha}\right)\right]^{N-n}$$

Approach directly extendable to 3 parameter Weibull distribution.

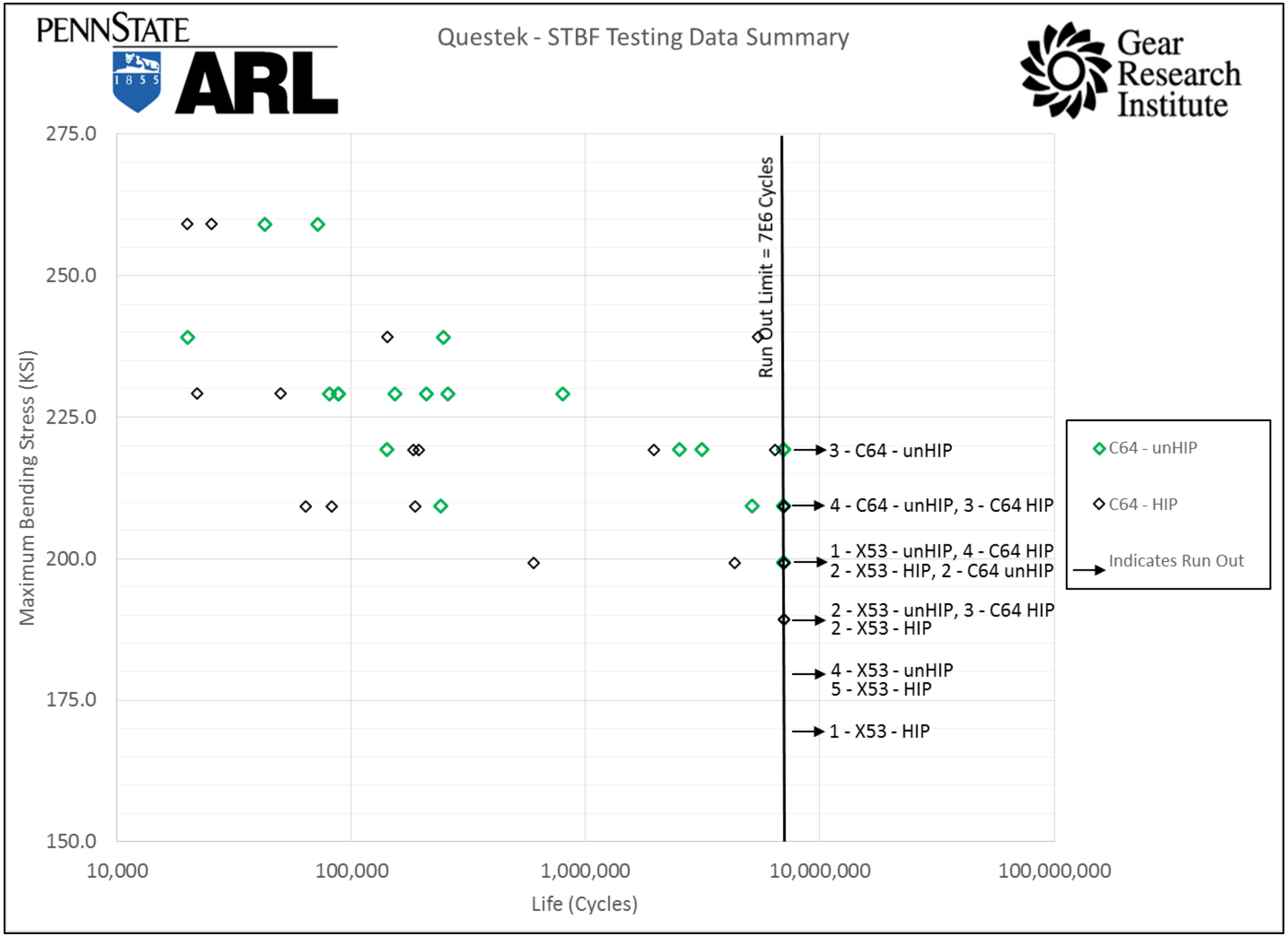
Single tooth bending fatigue comparison—*Ferrium* C64 vs. X53

- Testing performed under Army SBIR contract
- Test gears manufactured and processed via typical aerospace gear processing methods
  - Vacuum carburization and heat treatment
  - Shot peening
  - Ground surfaces (low surface roughness)
- “50% failure stress” (analysis by PSU-GRI)
  - 182.0 KSI for X53
  - 218.9 KSI for C64
  - **C64 exhibits ~20% higher performance over X53**

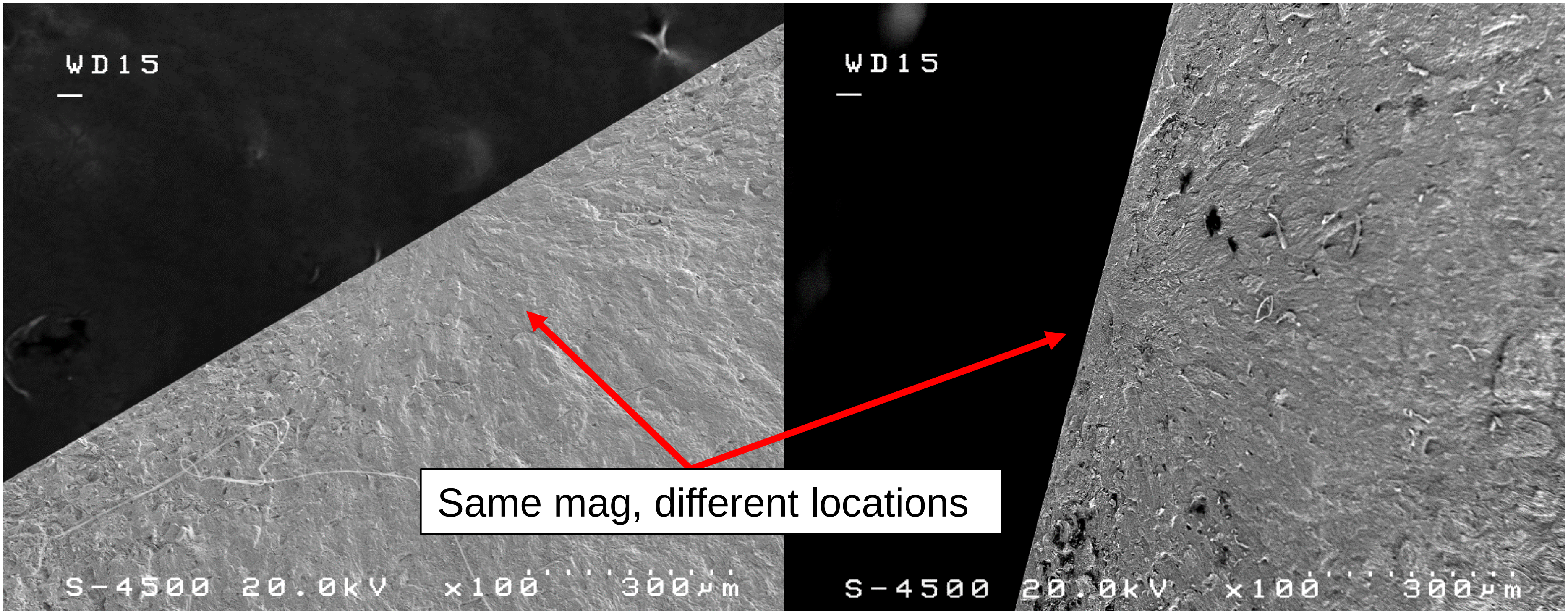


C64’s superior single tooth bending fatigue performance enables higher gearbox power density and better durability

Single tooth bending fatigue comparison—*Ferrium* C64—HIP vs. un-HIP



SN021-T2: C64 HIPped

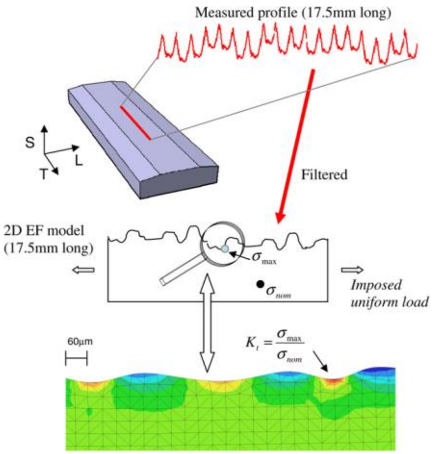


Same mag, different locations

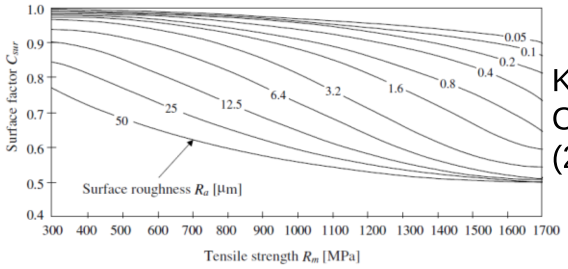
- Bending stress—209.3 ksi
- Cycles to failure—82,214
- Initiation site—surface

Extensions and next steps

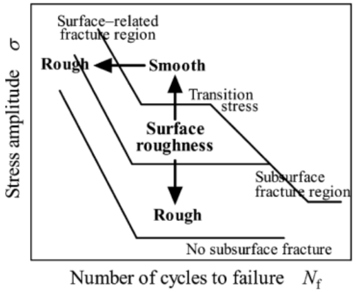
Better address the effect of surface roughness through equivalent fatigue life reduction factors.



Suraratchai et al. Int. J. Fat. 30 (2008)

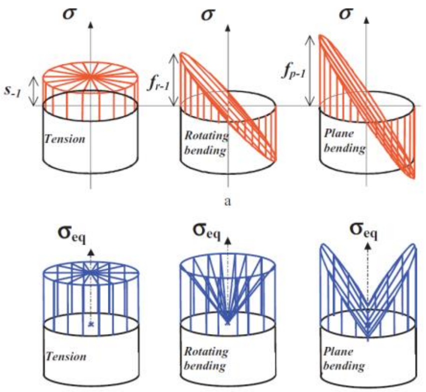


Kramberger et al. Comp. Struc. 82 (2004)



Itoga et al. Int. J. Fat. 25 (2003)

Flaceliere and Morel, Fat. Frac. Engg. Mat. Struc. 27



Account for loading conditions and surface-volume effects through a weakest link approach. The probability of finding a life limiting defect scales with volume subject to maximum stress.

$$P_F[\sigma_{eq}, V] = 1 - \exp\left[-\frac{V}{V_0 \sigma_u^m} \sigma_{max}^m H_m\right]$$

Conclusions

- *Ferrium* C64 (and C61) are *the* next-generation gear steels
- Fatigue nucleation consumes the majority of fatigue life
- Ability to model statistical microstructures and their impact on fatigue life
- Ability to model and optimize specialized processing steps, and predict their quantitative impact on fatigue life
- HIP has a significant impact on improving minimum fatigue life