Ultrapremium^{TM} and Endurance Steels

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TimkenSteel Corporation

Outline

- TimkenSteel at a glance
- Ultrapremium™ certified air-melt clean steel technology
  - What is clean steel? / Why is clean steel important?
  - Measuring and characterizing clean steel
  - Link between steel cleanness and component fatigue performance
- Endurance Steels
  - Three new, patent-pending steels combining ultra high-strength with high toughness
  - Power densification analysis

TimkenSteel: At a Glance

Overview

- Headquartered in Canton, Ohio
- Annual melt capacity of ~2 million tons
- Only focused North American SBQ producer
- Supplies more than 30% of seamless mechanical tube demand in North America

Alloy steel bars (SBQ)

TimkenSteel Applications

- Bearings
- Fuel injectors
- Gun barrels
- Crankshafts
- Tri-cone bits
- Percussion bits
- Energy CRA production
- CV joints
- Gears

TIMKENSTEEL

Value-added solutions

Machining, honing and drilling

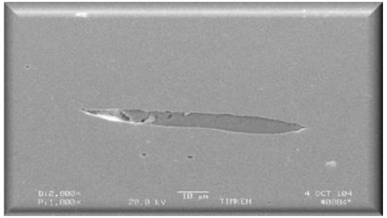
Supply chain

Components

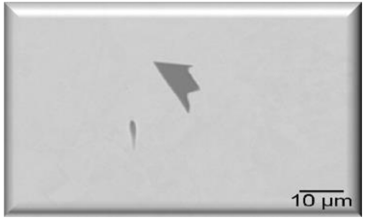
Seamless mechanical tubing

What is Clean Steel?

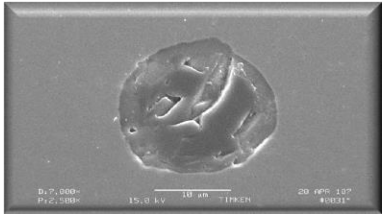
- Various definitions of steel cleanness
  - Non-metallic inclusions
    - Type: oxides, sulfides, nitrides
    - Size range: critical size, macro vs. micro
  - Residual Solutes (Cu, Sn, Sb, As)
- All steels contain some concentration of non-metallic impurities
- Inclusions are of various types (compositions), sizes and shapes



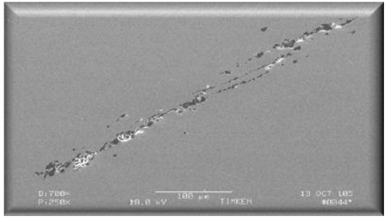
Sulfide



Nitride



Oxide

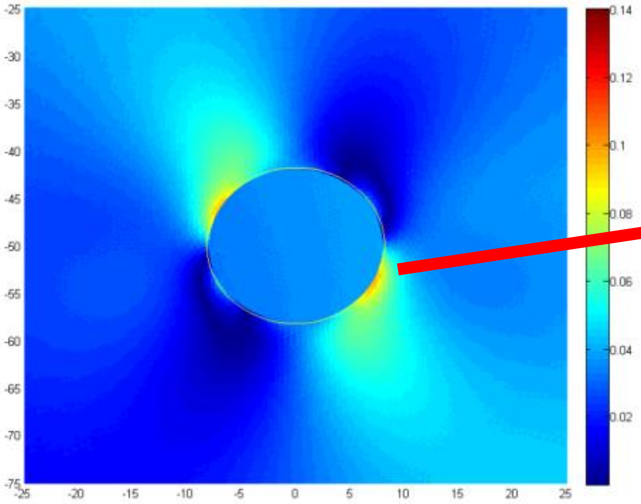


Oxide Stringer

Clean steel contains a minimal number of harmful inclusions

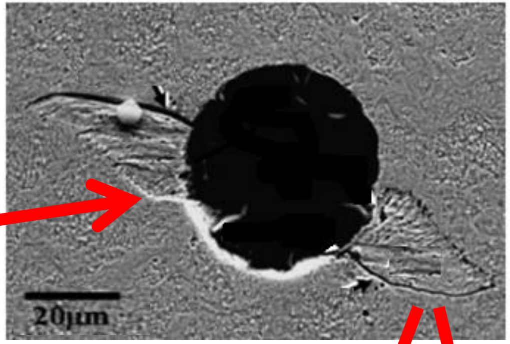
Why is Clean Steel Important?

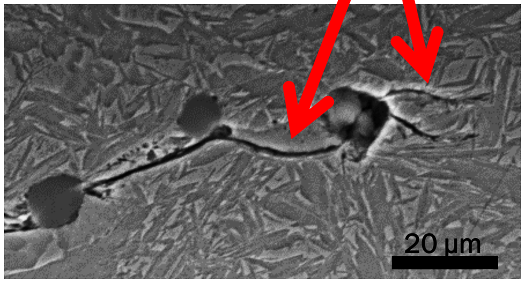
- Inclusions can increase local stresses and initiate fatigue failure



Stress Riser

Crack Initiation





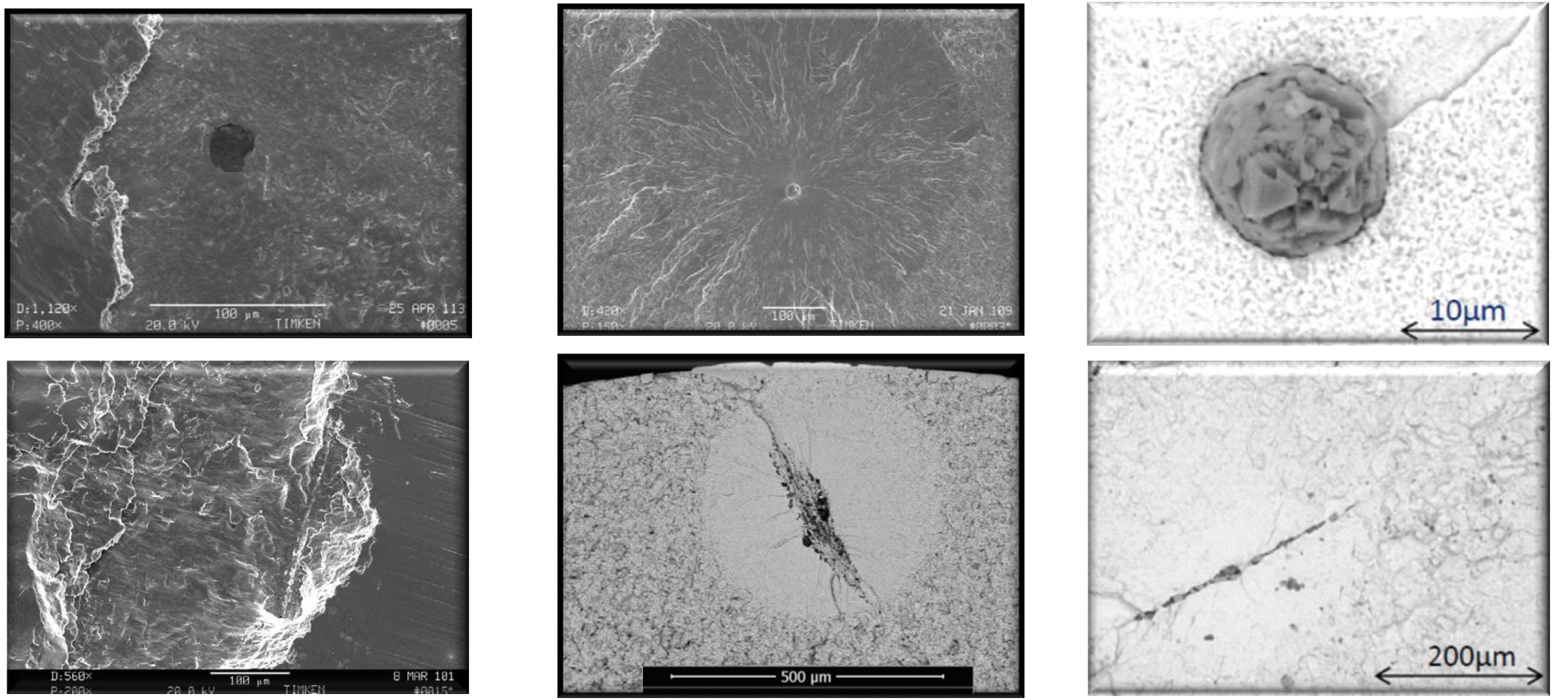
Crack Propagation

Why is Clean Steel Important?

- Inclusion-initiated fatigue failures

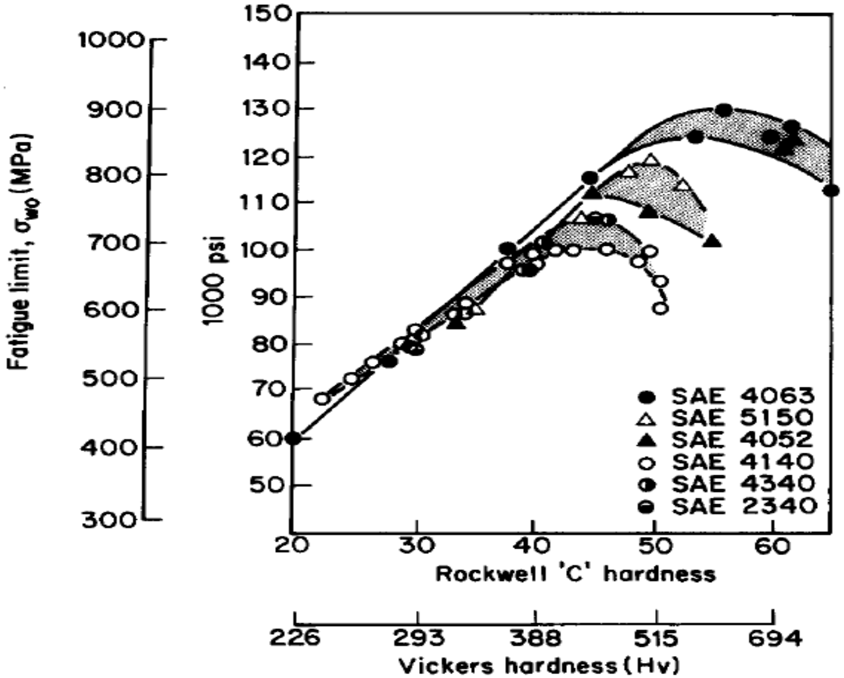
Rolling/Sliding | Bending | Axial

Micro-inclusion / Macro-inclusion



Why is Clean Steel Important?

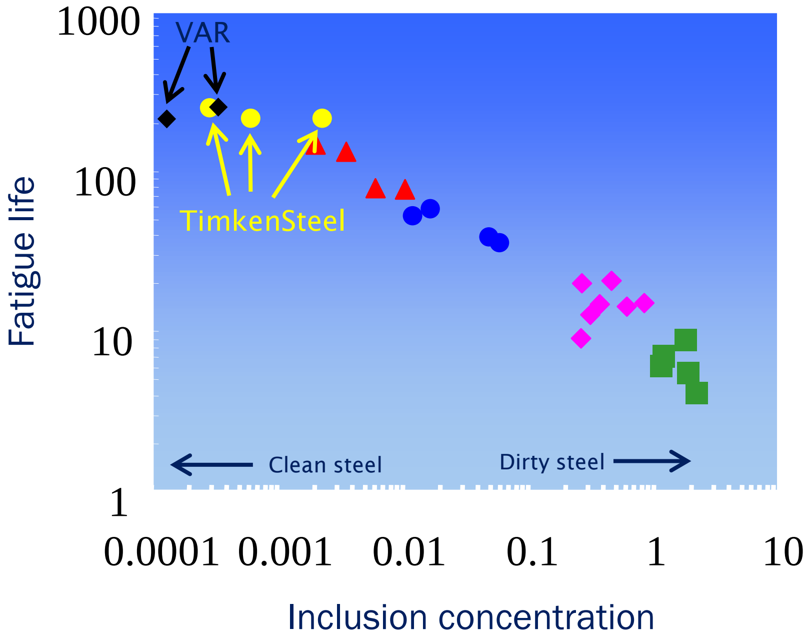
- Effect of non-metallic inclusions on fatigue performance
  - Strong correlation between fatigue limit and hardness
    - Hardness is a proxy for strength (YS & UTS)
  - Fatigue limit data more scattered with high strength steels
  - Scatter in data attributed to variation in non-metallic inclusion populations



M. F. Garwood, H. H. Zurburg and J. F. Millan, "Correlation of Laboratory Tests and Service Performance, Interpretation of Tests and Correlation with Service", ASM, Philadelphia, PA, 1951, pp. 1-77.

Why is Clean Steel Important?

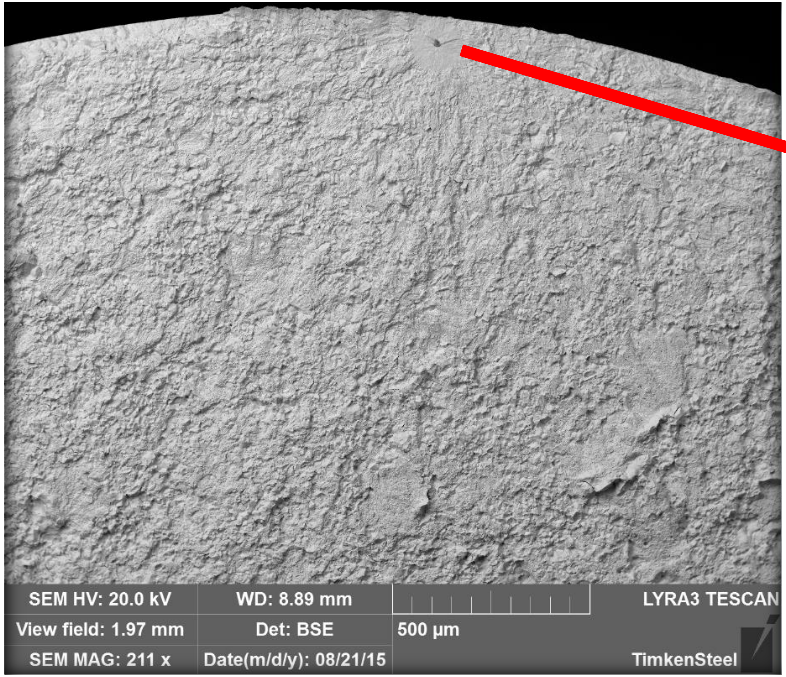
- Improving fatigue life and power density

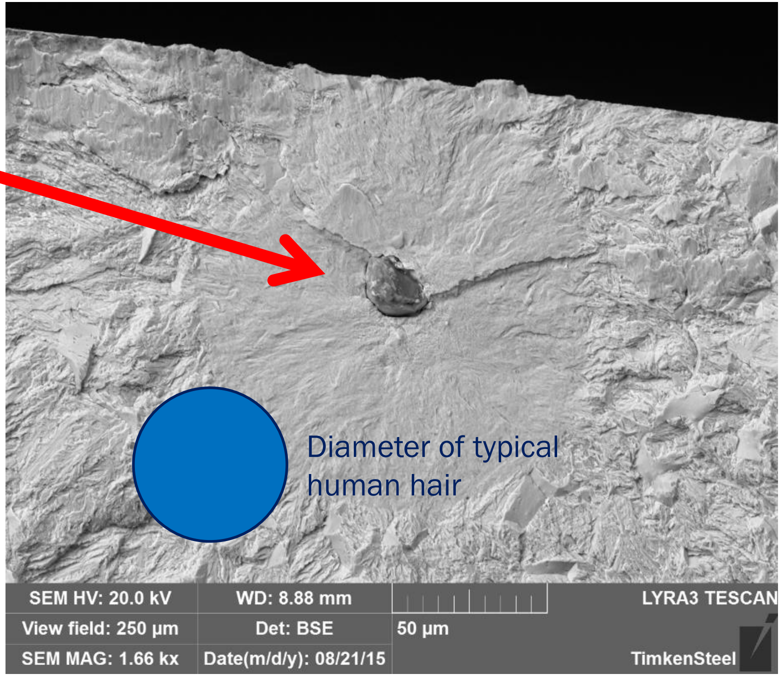


Steel cleanness affects component performance

Clean steels provide power density opportunities

What Size Inclusion can cause a Fatigue Failure?

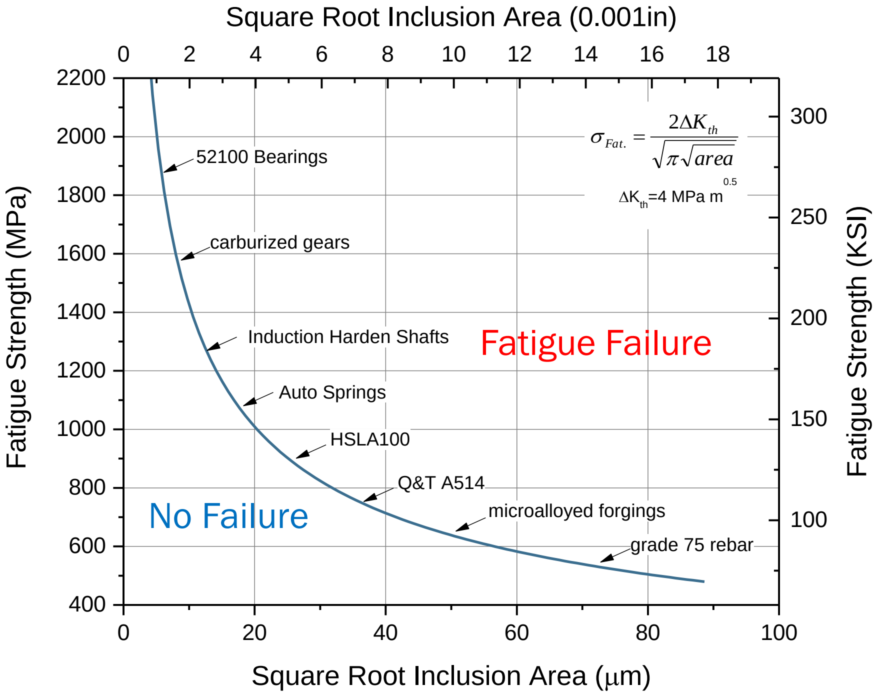




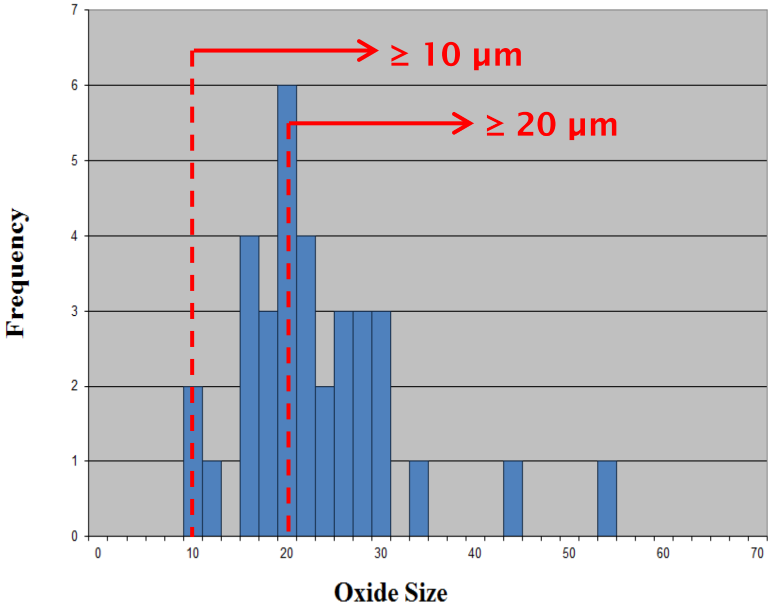
It depends…

What Size Inclusion can cause a Fatigue Failure?

- Highly dependent on loading of the component
  - Estimation based on fracture mechanics:



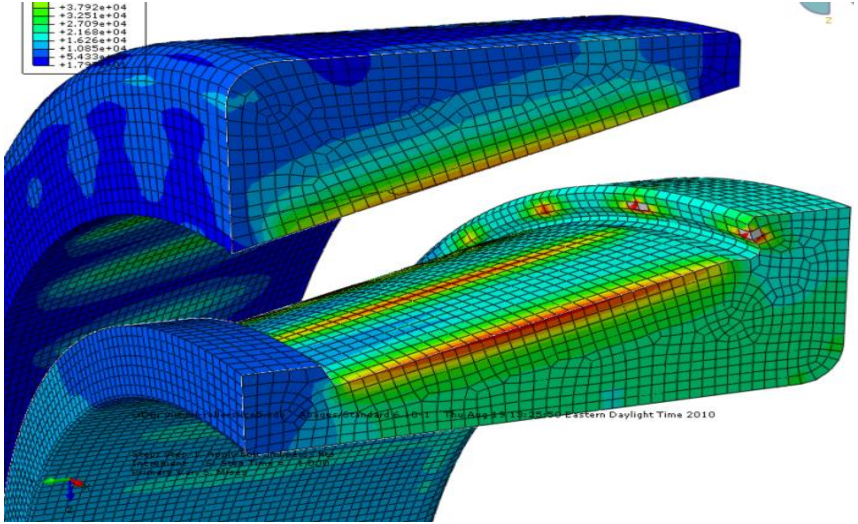
- Actual data from fatigue studies
  - General observation: fatigue failures can initiate at micro-oxides as small as 10 μm



Stressed Volume Concept

Determining the Probability of an Inclusion Initiated Fatigue Failure

- Largest oxide is seldom the one that initiates the failure
- Proportional to probability of having a critical size inclusion in the stressed volume of a loaded component
- Dependent on the population of critical size inclusions in steel



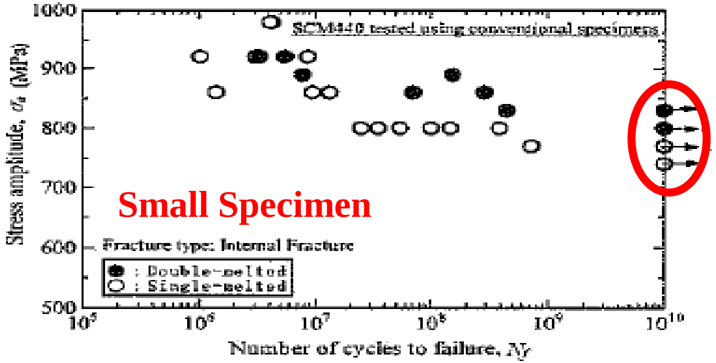
Clean steel has smaller and fewer critical sized oxide inclusions

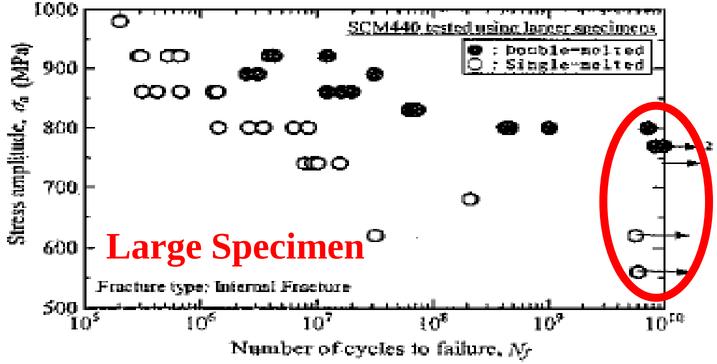
Lower probability of having a critical oxide in the stressed volume

Stressed Volume Concept

High-cycle axial fatigue study*

- Melt process/steel cleanness
  - Clean ●
  - Dirty ○
- Specimen size (stressed volume)
  - Small specimen: 33 mm^3
  - Large specimen: 781 mm^3
- Study results
  - Small specimen ΔFS: ~ 5%
  - Large specimen ΔFS: ~ 25%



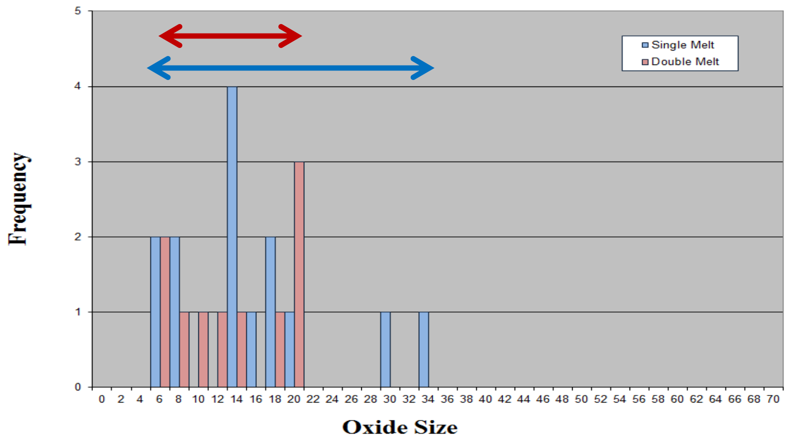


Furuya, Y., "Gigacycle Fatigue Properties of Double Melted SCM440 and Size Effects", ISIJ International, Vol. 54, (2014), No. 6, pp. 1436-1442.

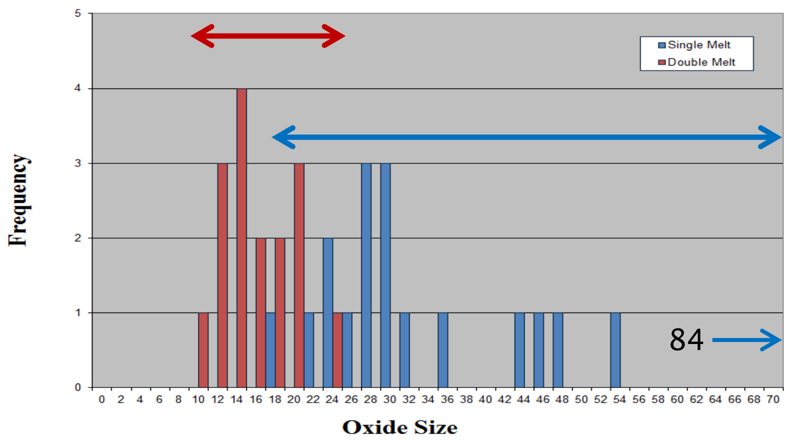
What Size Inclusion can cause a Fatigue Failure?

- Oxide sizes observed at initiation sites of axial fatigue failures*

Small Specimen (33 mm^3)



Large Specimen (781 mm^3)



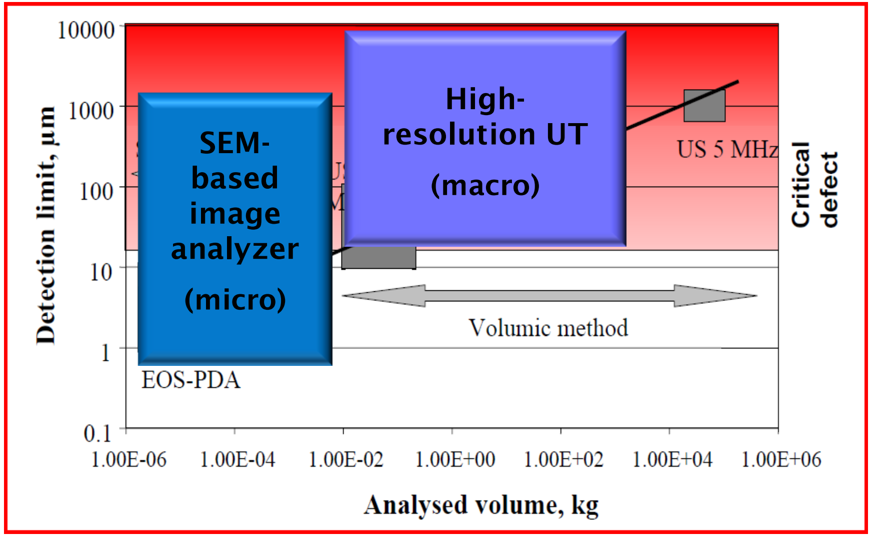
Increased probability of finding a larger oxide inclusion in the larger stress volume

*Furuya, Y., "Gigacycle Fatigue Properties of Double Melted SCM440 and Size Effects", ISIJ International, Vol. 54, (2014), No. 6, pp. 1436-1442.

Steel Cleanness Measurement

- Proper measurement of steel cleanness is important
  - The manufacture of clean steel begins with the ability to accurately measure/characterize the inclusion population

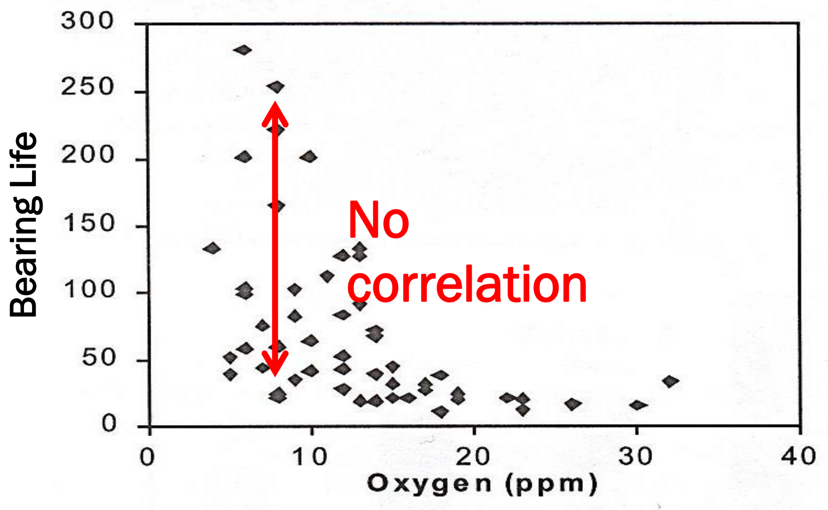
- Two of the key steel cleanness measurement tools employed at TimkenSteel are:
  - Scanning electron microscope (SEM) image analyzers
  - High-resolution ultrasonic scanner



Steel Cleanness Measurement

Deficiencies of Traditional Methods

- Most of the industry steel cleanness standards developed many years ago (outdated)
- Insufficient inspection volume to detect statistically significant number of critically sized inclusions
- Focus on qualitative (or semi-quantitative) metrics with little correlation to application performance



Total oxygen content versus component life

Steel Cleanness Measurement

Meeting industry standards does not provide entire picture

ASTM Specification / Sample	# Samples Insp Area (mm^2)	B Thin	B Heavy	D Thin	D Heavy
A534 (Carburizing Bearing Steels)	6 / 960	2.0	1.0	1.0	1.0
A1089 (Highly Loaded Bearing Steels)	6 / 960	1.5	1.0	1.0	1.0
SBQ A Sample	6 / 1200	0.5	0.0	0.5	0.5
TimkenSteel Sample	6 / 1200	1.0	0.0	0.5	0.5
VAR Sample	6 / 1200	0.5	0.0	0.5	0.5

SEM Image Analysis ----- No. of Samples Insp Area (mm^2)	Conc of Oxides > 10 µm ($\#/10^3$ mm^2)	Conc of Oxides > 20 µm ($\#/10^3$ mm^2)	Oxide Area Total ($\mu m^2/mm^2$)	Oxide Area > 100 μm^2 ($\mu m^2/mm^2$)	Maximum Inclusion $(Area^{1/2})_{max}$ (µm)	SEV Least Squares Max Likelihood $(Area^{1/2})_{30k}$ (µm)
SBQ A 32 / 7324	47.65	3.41	47.94	8.90	31.563	35.13 / 33.54
TMST 32 / 7079	3.15	0.0	11.72	0.43	14.106	19.89 / 19.34
VAR 32 / 6682	1.20	0.0	2.34	0.21	18.06	20.60 / 14.98

Conclusion: Very different cleanness levels with materials rated for the same spec!

Fatigue Performance vs. Steel Cleanness

Rotating Bending Fatigue (RBF) of High Strength 4140 Steel

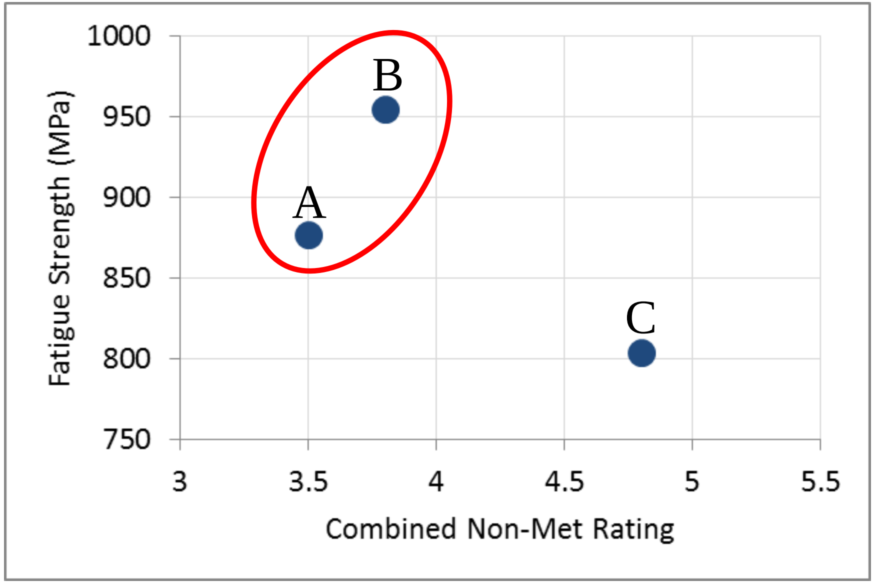
Sample	B Thin	B Heavy	D Thin	D Heavy	Combined Non-Met Rating*	O Total	Conc. of Critical Oxides (> 10 μm)	RBF Fatigue Strength (MPa)
A866	2.0	1.0	1.0	1.0	6.0	---	---	
Group A	1.5	0.5	0.5	0.5	3.5	7	21.7	877
Group B	1.0	1.0	0.5	0.5	3.8	7	8.1	955
Group C	1.5	1.0	1.0	0.5	4.8	15	74.5	804

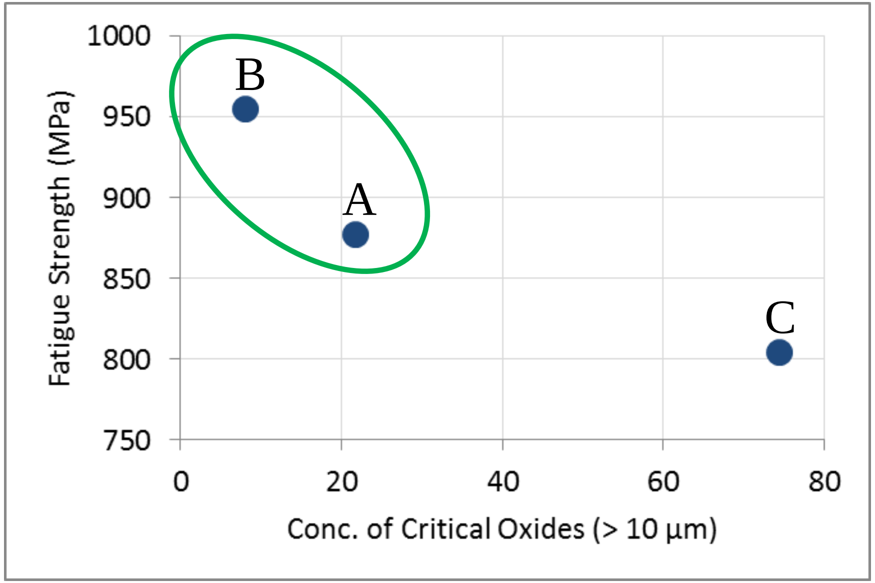
*Combined Non-Met Rating = $(B_T + D_T) + 1.5(B_H + D_H)$

Selection of proper cleanness metrics is critical

Fatigue Performance vs. Steel Cleanness

Rotating Bending Fatigue (RBF) of High Strength 4140 Steel





Which metric is better for predicting fatigue performance of cleaner steels?

Can you Reduce the #/Size of Critical Inclusions?

- Yes! There are multiple ways to achieve this
- TimkenSteel Ultrapremium™ certified air-melt technology reduces the size and concentration of harmful oxide inclusions
- Our most advanced clean steel technology is defined by:
  - A carefully designed steelmaking practice
  - Advanced steel cleanness characterization metrics (SEM Image Analysis)
  - Applicable to most steel grades
- It is our highest quality level
  - A level of cleanness approaching VAR
  - Complements our suite of other clean steels including Parapremium, VacTec, MicroTec and more

Ultrapremium Technology Certification

2.3. Steel Certificate of Test Limits Values

2.3.1. For Micro Inclusions:

Measurement	Provisional Limits*
The average concentration of inclusions ≥ 10 μm in $\sqrt{Area}$ per unit inspected area	≤ 0.02 #/mm^2
The average concentration of inclusions ≥ 20 μm in $\sqrt{Area}$ per unit inspected area	≤ 0.003 #/mm^2

2.3.2. For Macro Inclusions (Stringers):

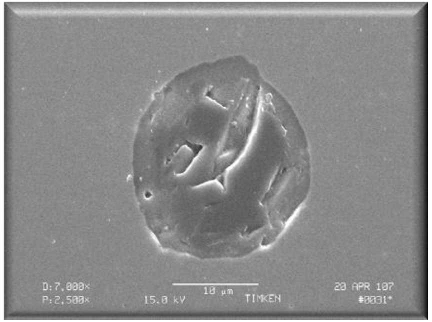
Measurement	Provisional Limits*
The average concentration of stringers ≥ 100 μm in length in the order or heat.	≤ 0.02 #/mm^2
The average concentration of stringers ≥ 200 μm in length in the order or heat.	≤ 0.005 #/mm^2

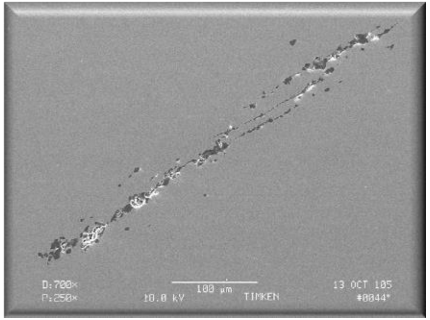
2.3.3. For Statistics of Extreme Values:

Measurement	Provisional Limits*
Maximum sized inclusion likely ($\sqrt{Area}$) – Max Likelihood	≤ 35 μm

*Provisional limits are conservative

Micro inclusion : oxide

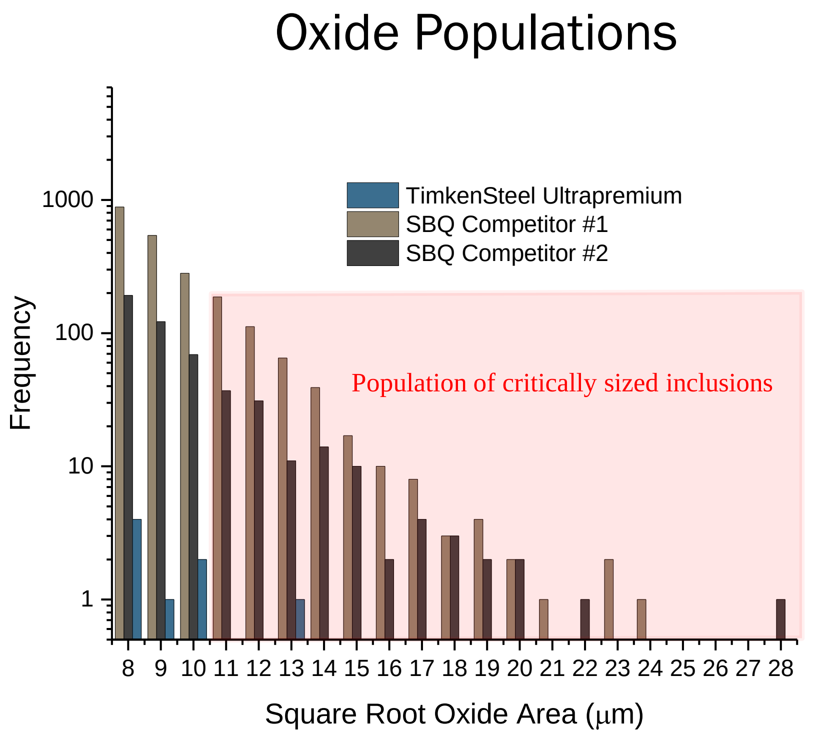




Macro inclusion: oxide stringer

Case Study: Gear Performance Improvement

- Gear set transmitting up to 400 horsepower in a volume about the size of your fist
- Manufacturing / heat treat optimizations improved performance, but still needed more
- Multiple steel suppliers were being used
- Ultrapremium steel was offered as a solution to test for improved fatigue life
  - 10 gear sets reached 100 hours with no signs of fatigue under harshest test conditions (historically multiple failures occurred prior to 100 hours)
- Gear customer now uses Ultrapremium steel in multiple applications
  - Has reported increase in power throughput and decrease in gear-related claims



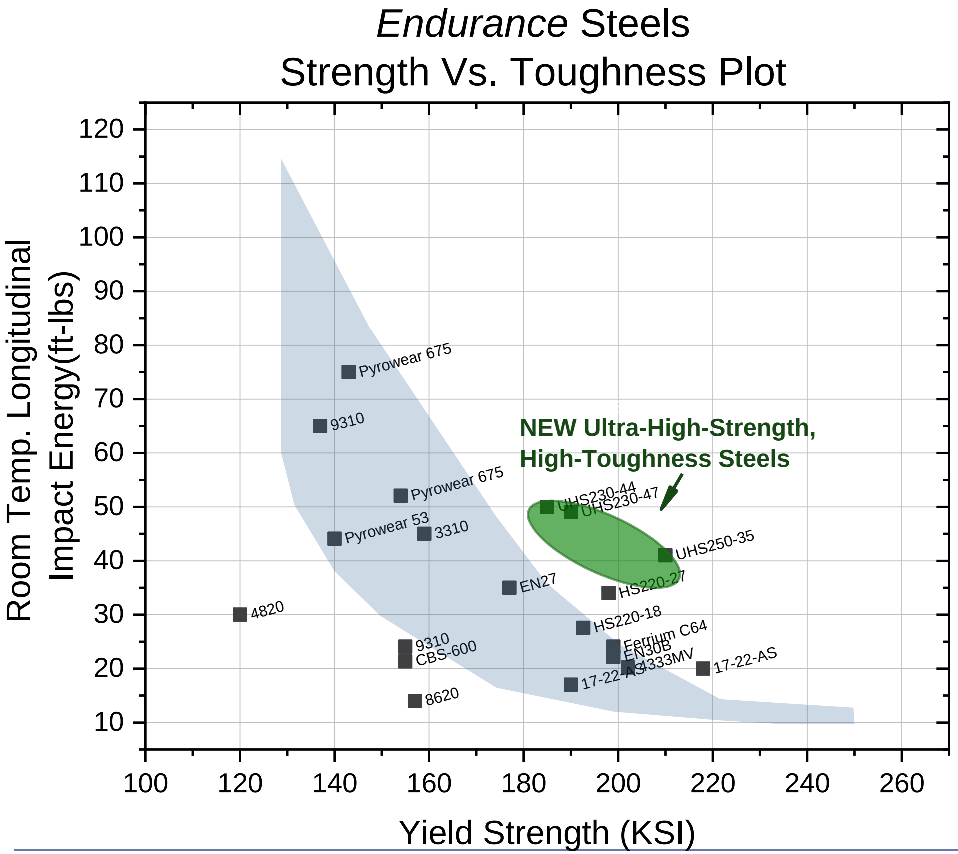
Summary – Clean Steel

- What is clean steel?
  - Clean steel has the least probability of having a critical inclusion in the stressed volume
- Why is clean steel important?
  - Non-metallic inclusions (especially oxides) have a detrimental impact on fatigue performance
- Steel cleanness measurement
  - Industry standards do not provide entire picture
- Fatigue performance vs. steel cleanness metrics
  - Good correlation between concentration of critical size oxide inclusions and fatigue performance
- TimkenSteel Ultrapremium™ certified air-melt technology reduces the size and concentration of harmful oxide inclusions

TimkenSteel Endurance Steels

- Improvements in component performance and power density can also be achieved by using higher strength, higher toughness steels
- TimkenSteel endurance steels are three new, patent pending steels with ultra-high strength and high toughness
  - High strength provides greater load bearing capacity and fatigue strength
    - Requires clean steel to take full advantage
  - High toughness provides greater resistance to fracture
- Affordable solution for power densification
- Broad range of applications
  - Shafts, gears

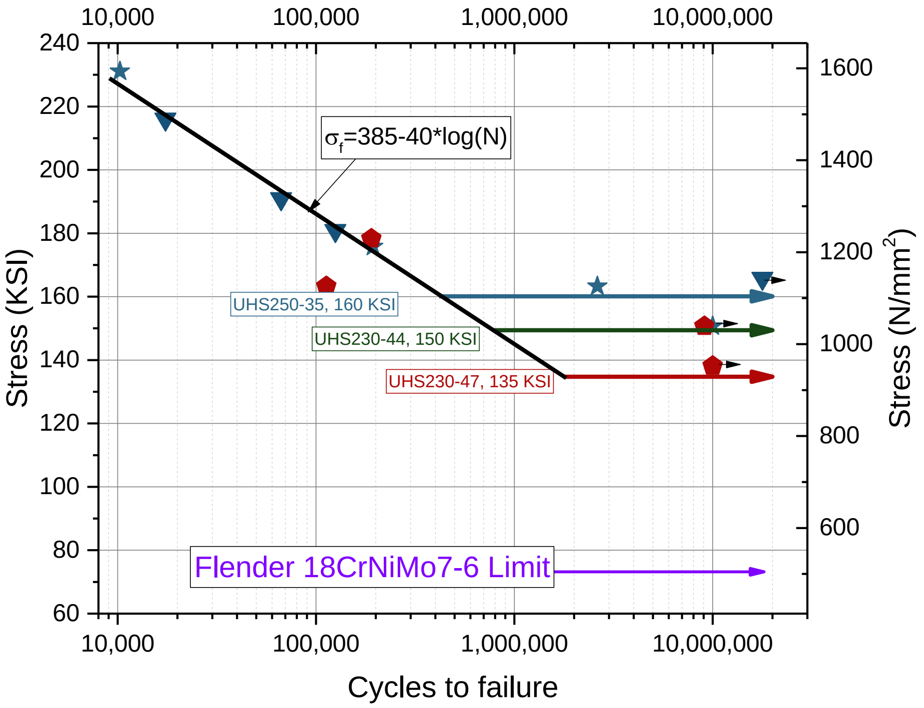
Ultra-High Strength and High Toughness



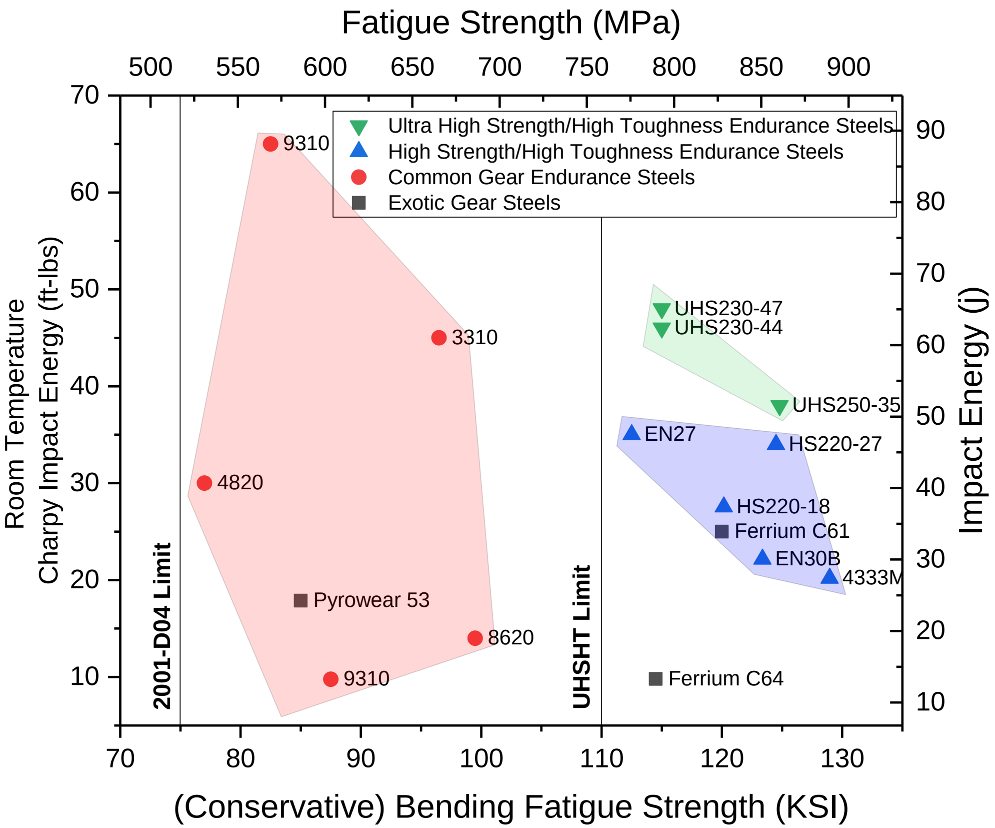
Patent pending endurance steels fill the green NEW oval (UHS230-47, UHS230-44 and UHS250-35)

High Fatigue Strength

- Rotating bending fatigue (RBF) results
- Limited number of samples from small scale laboratory heats
- Recently produced 120 tons of UHS250-35 and UHS230-47 and will complete a full test schedule
- Plan to produce and test UHS230-44 as well



High Fracture and Fatigue Resistance

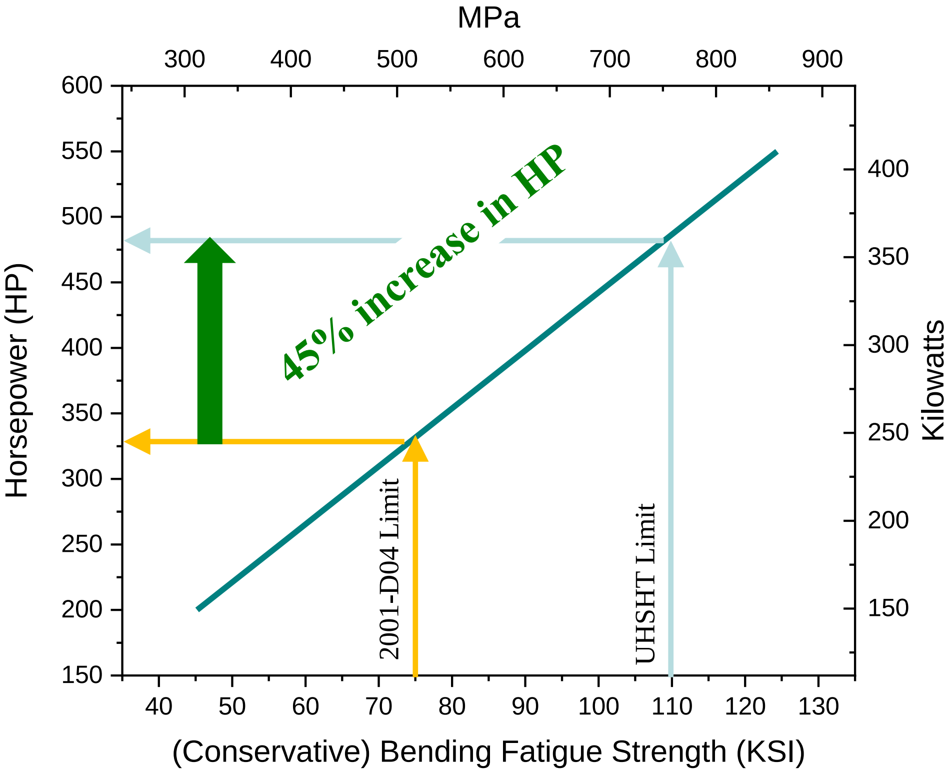


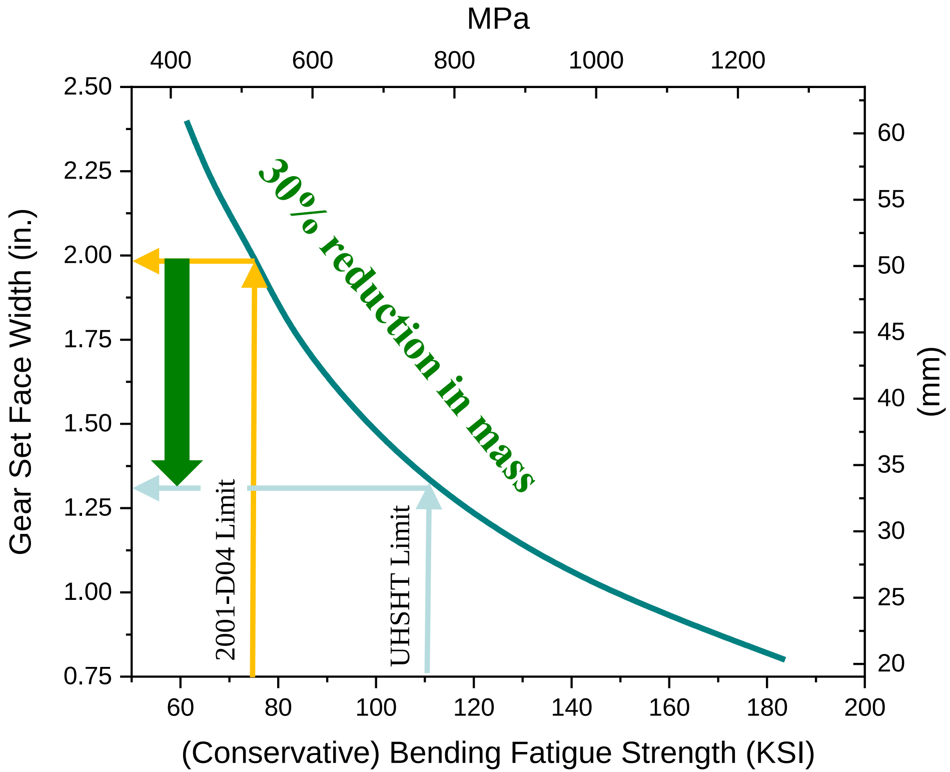
- Fatigue limits shown are calculated as 0.5 x UTS
- Measured fatigue limits
  - UHS230-44: 150 ksi
  - UHS230-47: 135 ksi
  - UHS250-35: 160 ksi

Power Densification Analysis

- Analysis framework: *ANSI/AGMA 2001-D04*
  - *"Fundamental Rating Factors and Calculation Methods for Involute Spur and Helical Gear Teeth"*
  - *Calculation of bending and contact stresses based on gear set and operating parameters*
  - *Comparison to AGMA grade 3 allowable values and to values for TimkenSteel Endurance steels*
- *Gear set*
  - *Gear 1: 2" pitch diameter, 35 tooth gear, 2" face width*
  - *Gear 2: 4" pitch diameter, 55 tooth gear, 2" face width*
- *Baseline calculations*
  - *@ 330 hp, reached bending stress limit of 75 ksi (AGMA grade 3)*
    - *Contact stress below allowable limit*
- *Power densification calculations based on Endurance Steel bending stress limit of 110 ksi*
  - *Increase horsepower or decrease gear face width until 110 ksi limit is reached*

Power Densification Analysis





Contact stress increases from 195 to 230 ksi (Below the 275 ksi limit)

Summary – Endurance Steels

- Three new, patent pending steels with ultra high-strength and high toughness
- Affordable solution for power densification
  - Potential to reduce gear set mass by as much as 30% or increase power throughput by as much as 45%
- Clean steel technology enables full achievement of performance improvements

For More Information

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