Fatigue Crack Initiation Mechanisms in Case Hardened Steel Alloys

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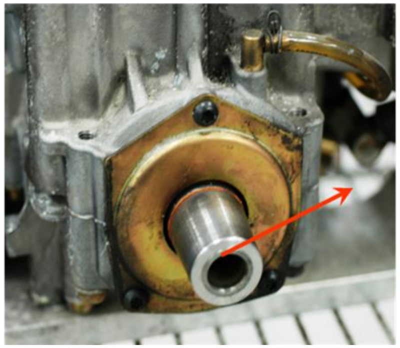
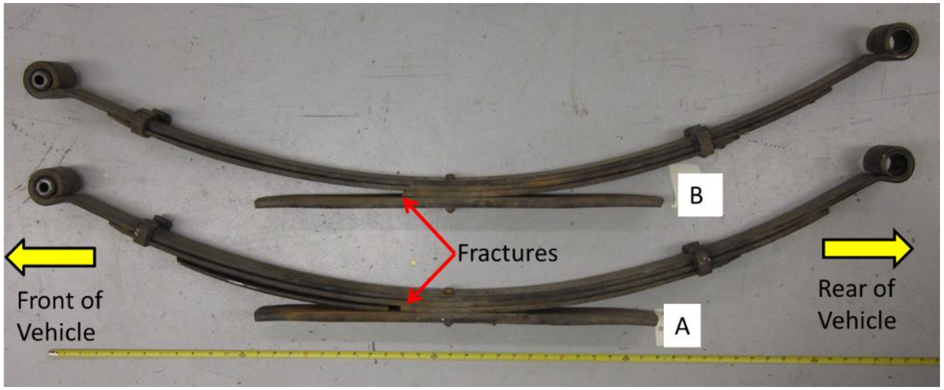
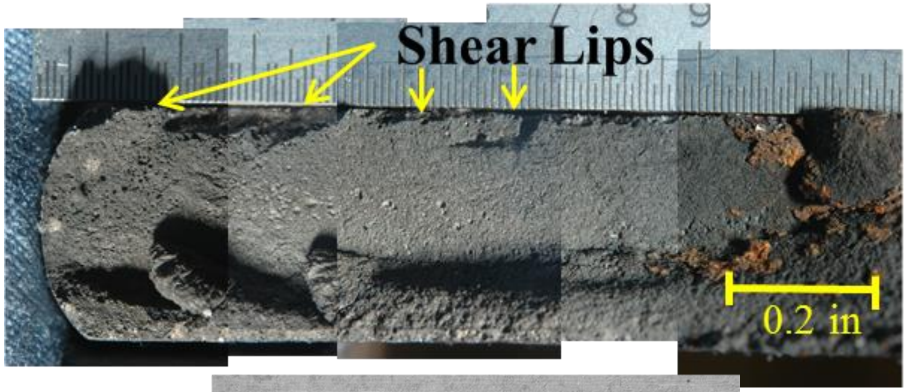
Example Failures in Case Hardened Components

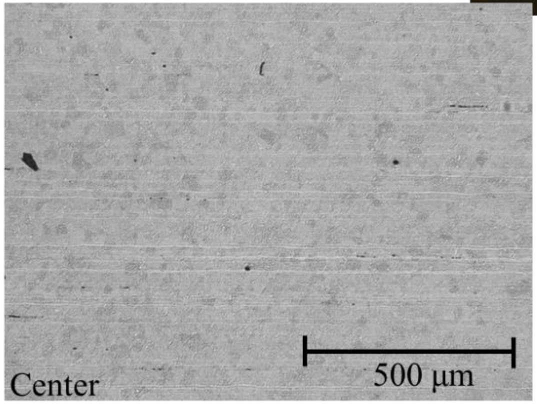
Fatigue Failure of Nitrided Snowmobile Crankshaft



Fatigue Failure of Shot-Peened SUV Leaf Springs





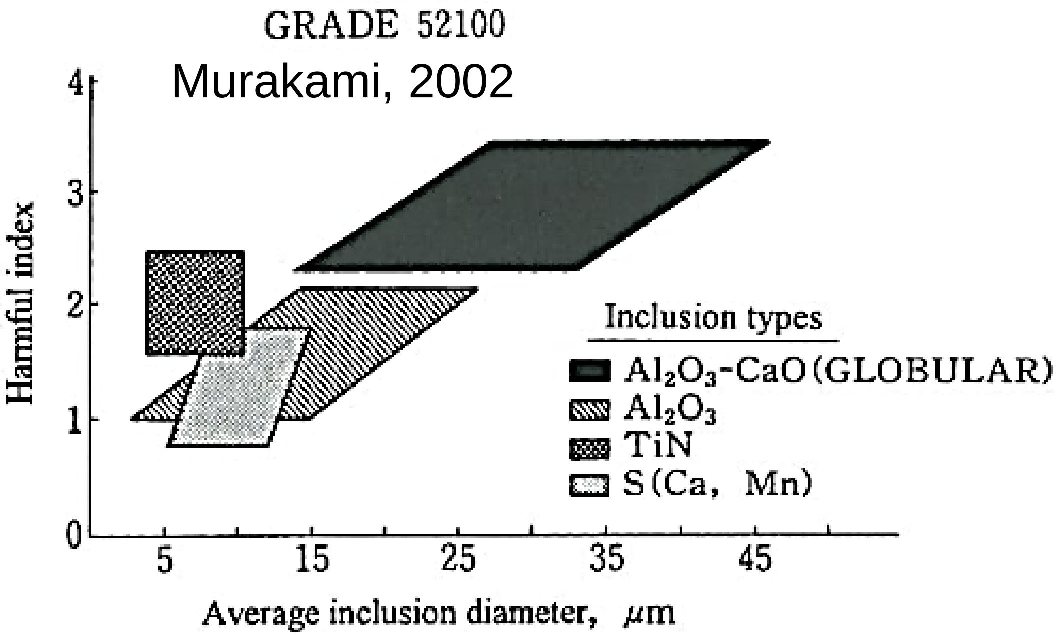


Presentation Overview

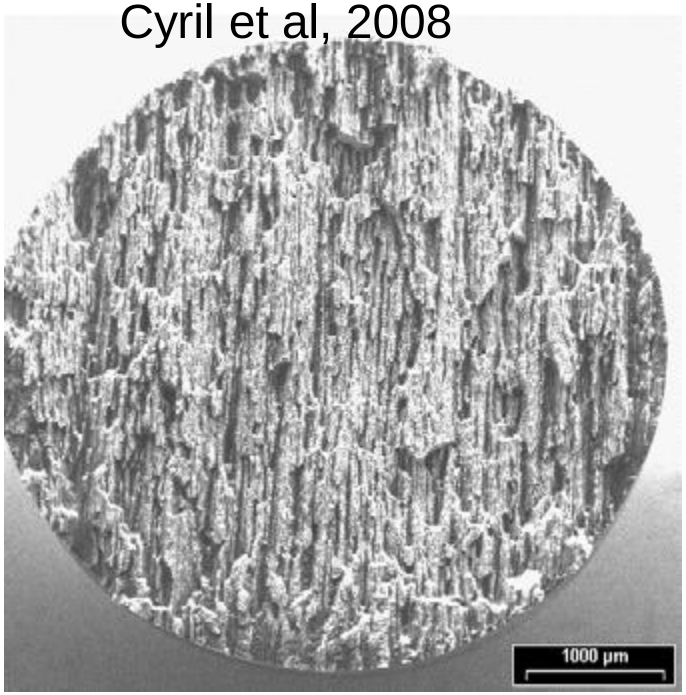
Premise: Fatigue crack initiation and thus life prediction in surface hardened components is a complicated function of microstructure, residual stress, and stress state

- Role of Inclusions, Processing, and Microstructure in Crack Nucleation
- Residual Stresses Effects on Crack Nucleation
- Crack Initiation Resistance in Surface Hardened Parts: Carburized, Induction Hardened, and Deep Rolled Steels

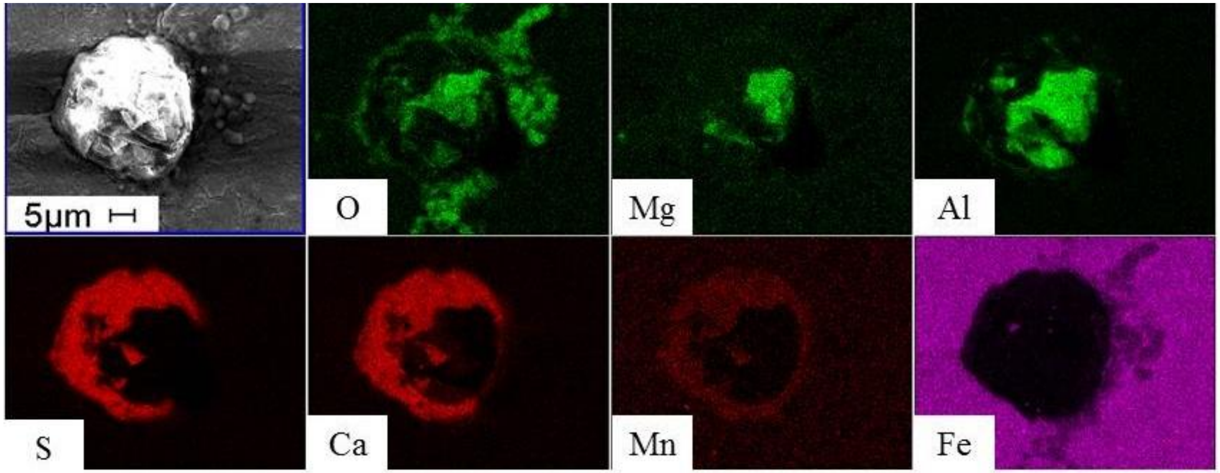
Inclusions and Fatigue Properties



High Sulfur 4140
Cyril et al, 2008



Induction hardened 1045
Nissan, 2012

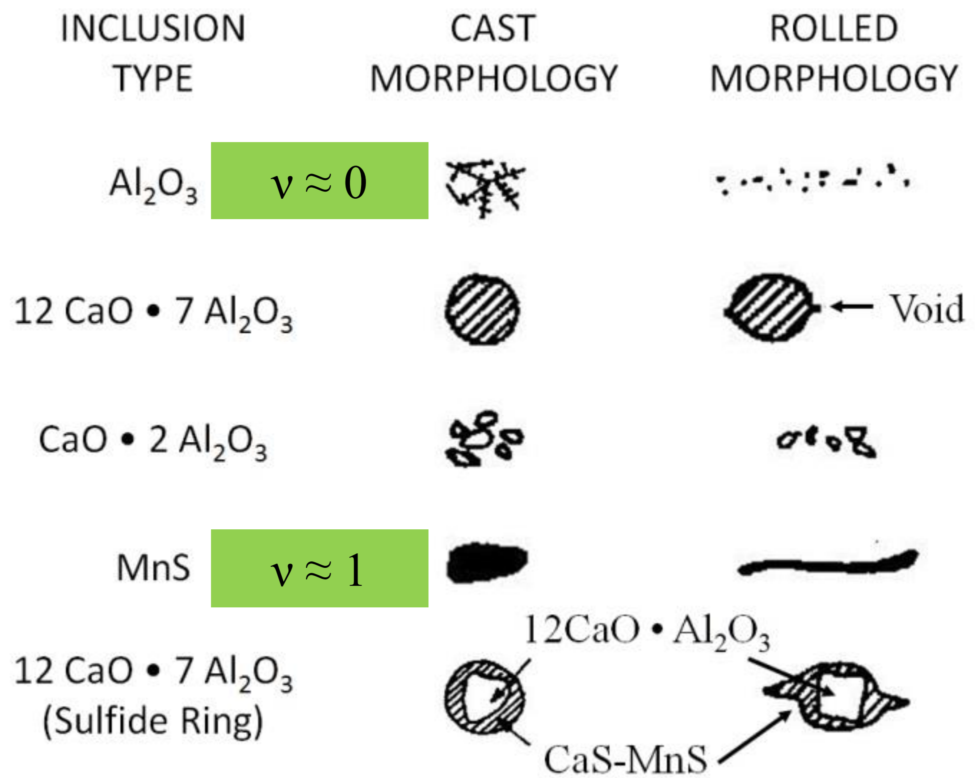


Relevant Inclusion Characteristics

- Deformability

$$\nu = \frac{2}{3}\frac{\log \lambda}{\log h}$$

- Orientation/Morphology
- Volume Fraction
- Size



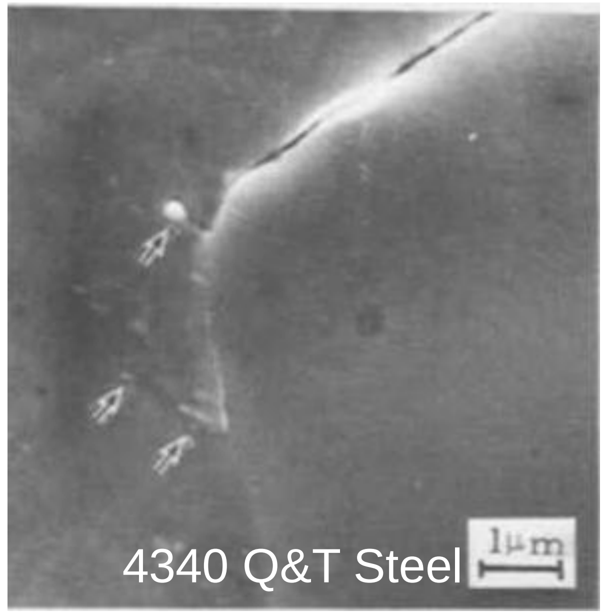
Ghosh, 2001

Area fraction of sulfide and oxide inclusions in a typical vacuum degassed carburizing bar steel.

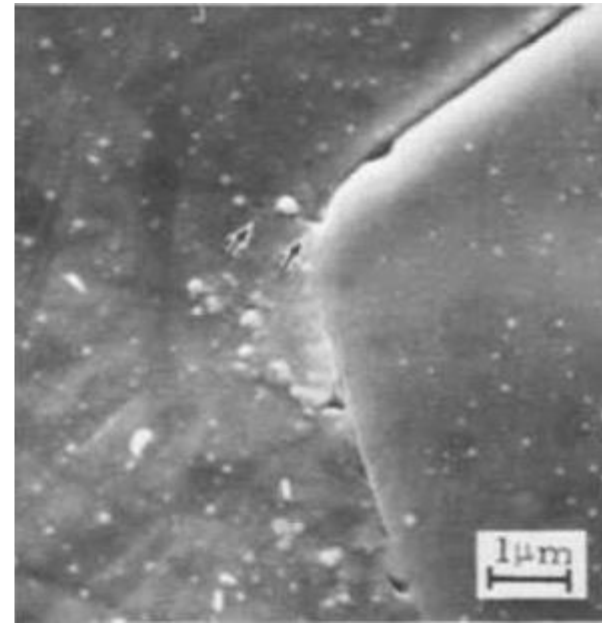
Inclusion Type	Manganese Sulfide	Alumina	Globular Oxides
Area Fraction	0.0257	0.0004	0.0035

Fatigue Crack Nucleation Mechanisms Around Inclusions

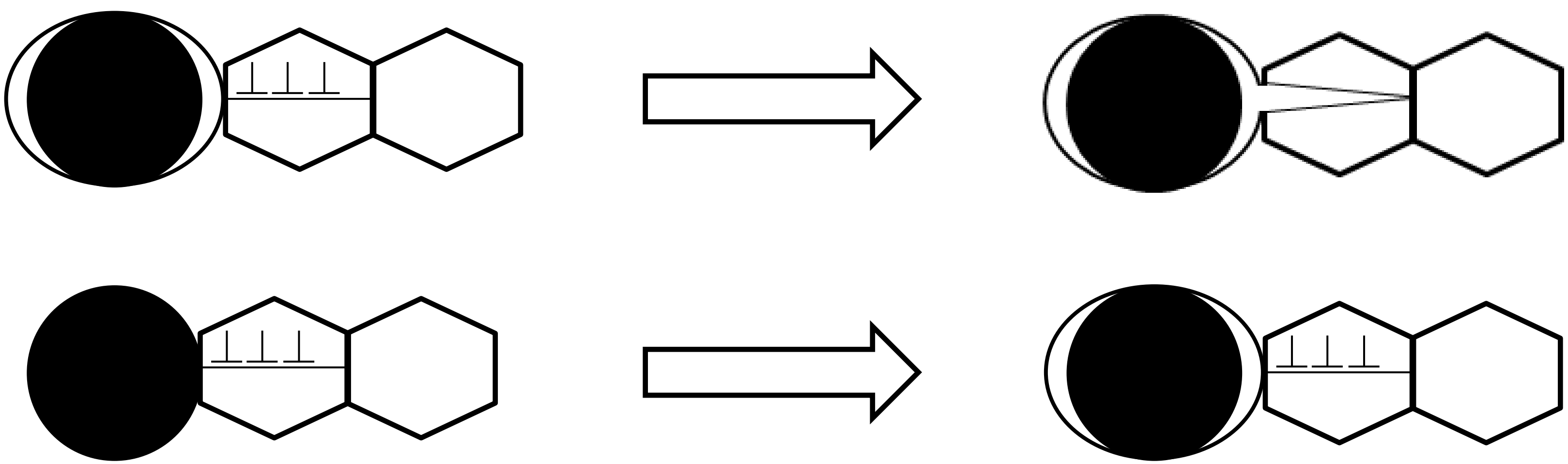
1 Cycle (matrix debonds from inclusion)



2000 Cycles



5000 Cycles



Tanaka and Mura Crack Nucleation Models

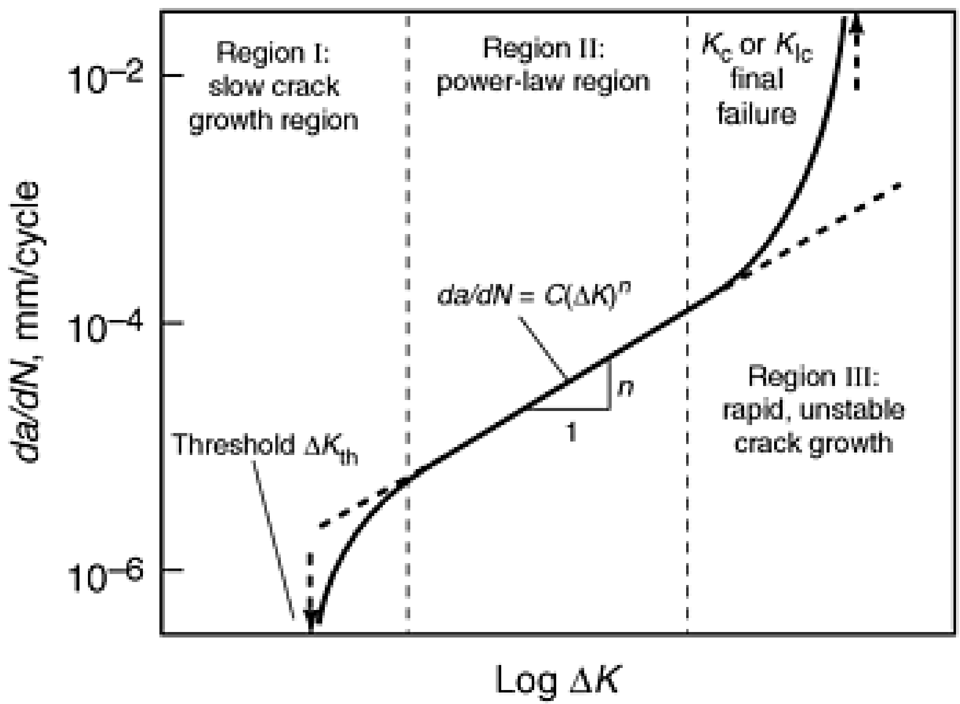
Competition in crack nucleation mechanisms

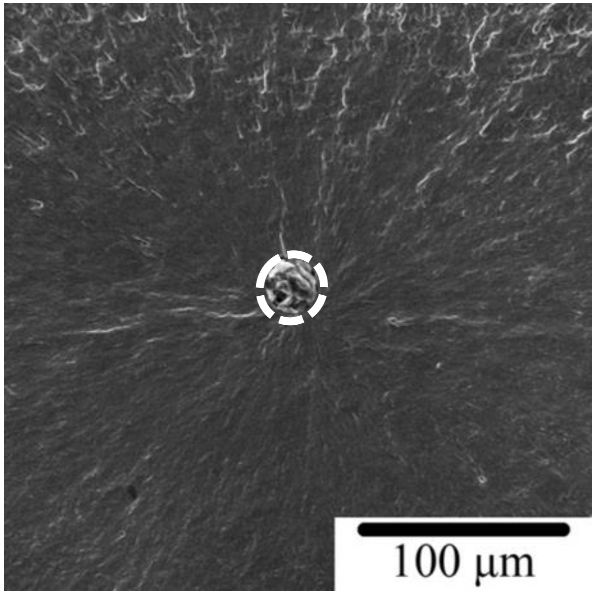
Plastic Damage in the Microstructure

Onset of plastic damage related to:
σ_{ys} or τ_{ys}

Crack Nucleation from Inclusions

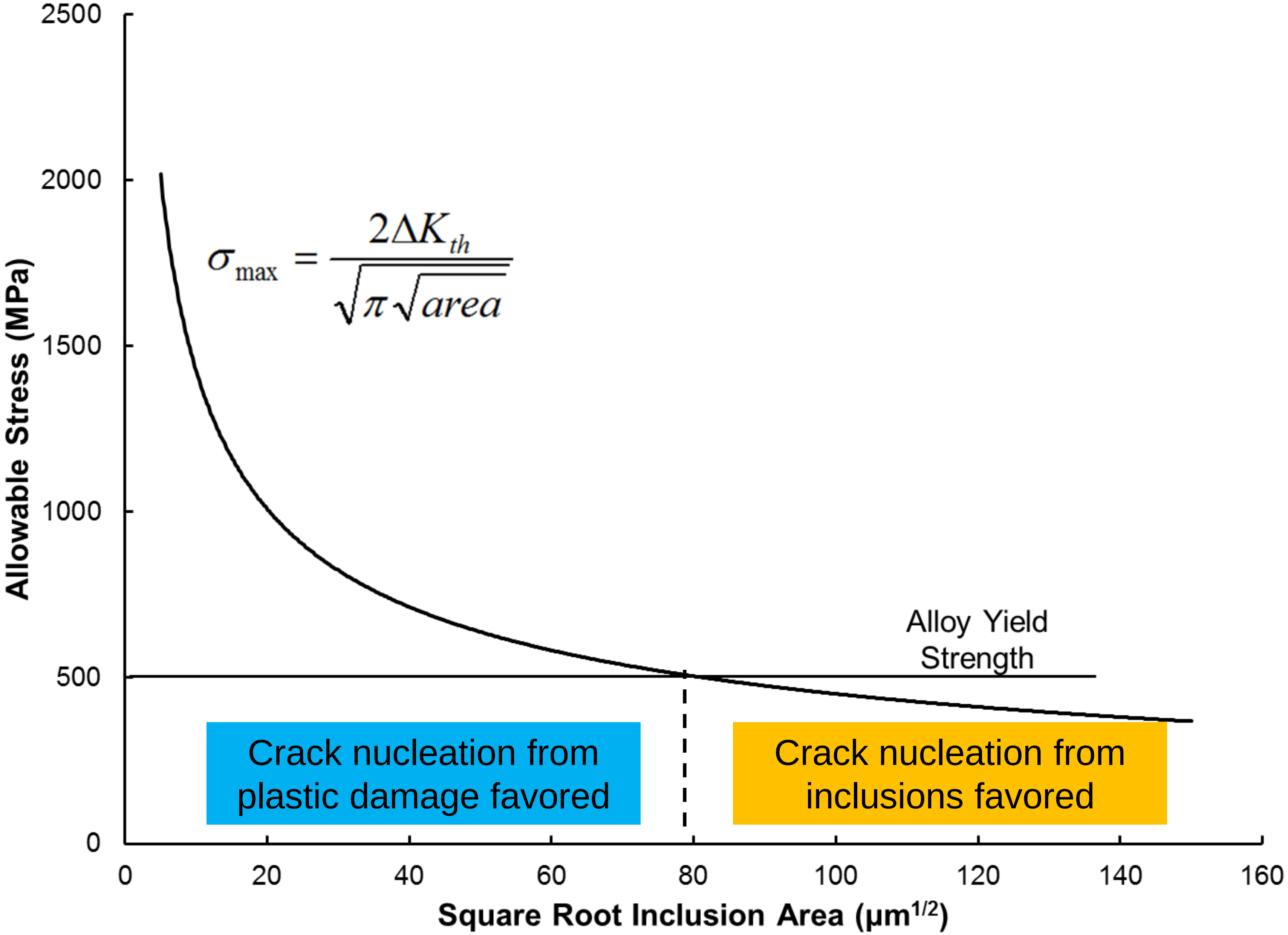
Onset of crack growth related to:
ΔK_{th}



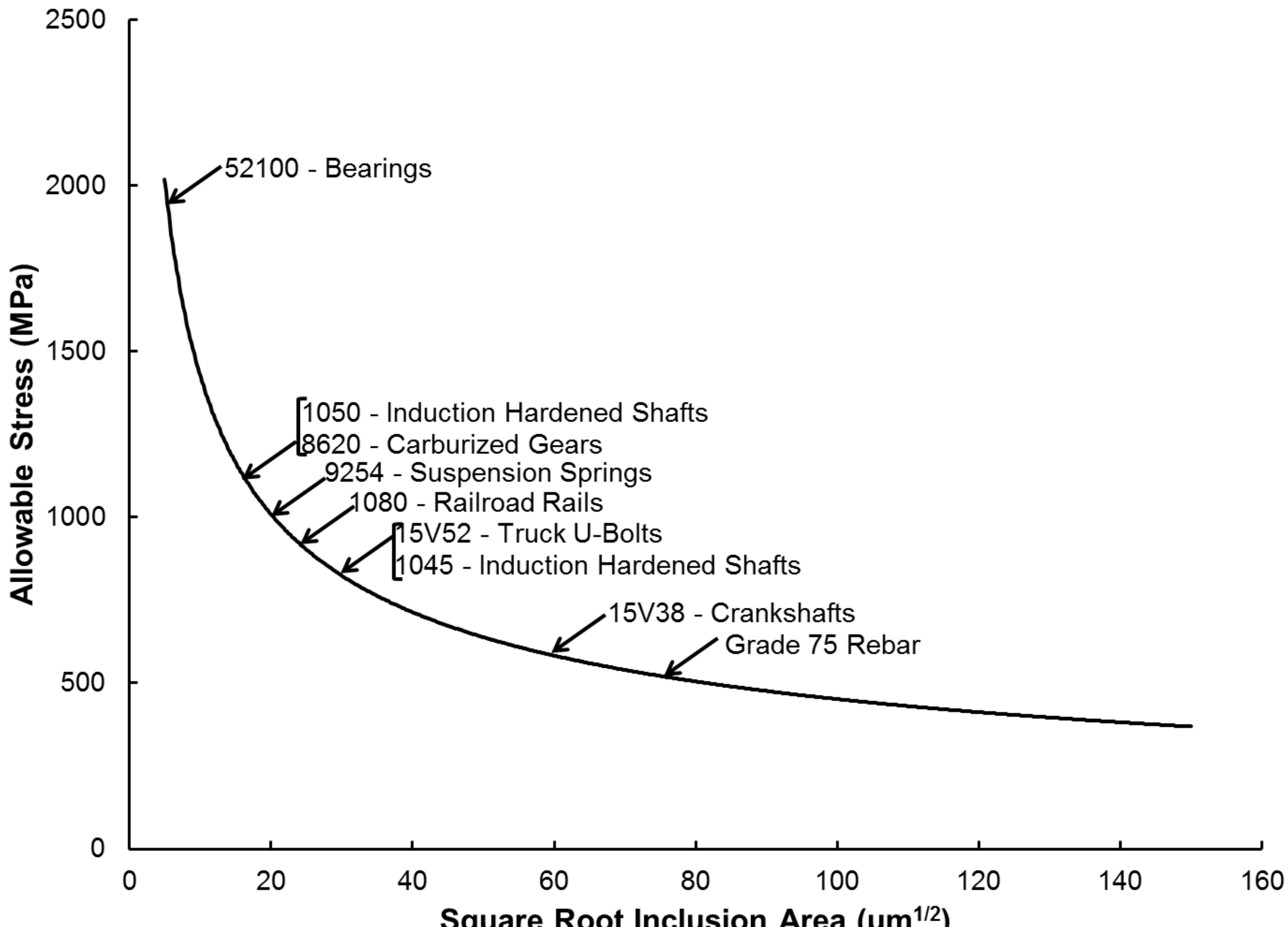


Crack growth when: $$\Delta K_{I,\max} = 0.5 \cdot \sigma_{\max} \sqrt{\pi \sqrt{area}} \geq \Delta K_{th}$$

Graphical Comparison of Crack Nucleation Competition

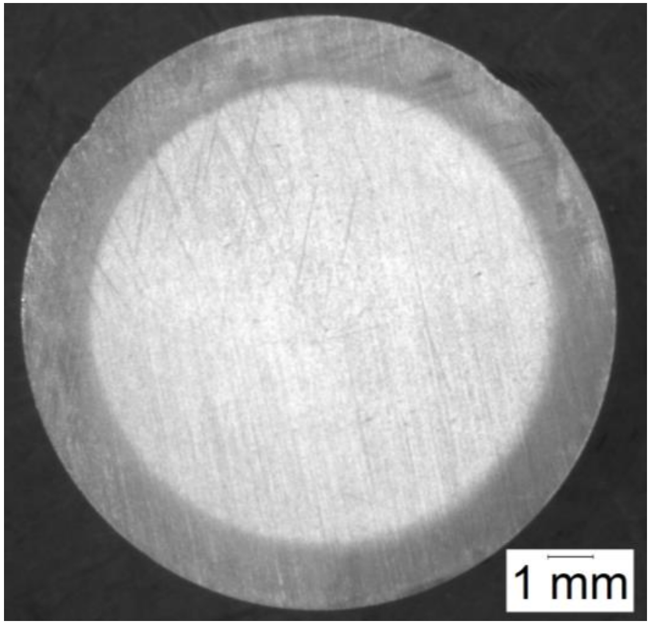


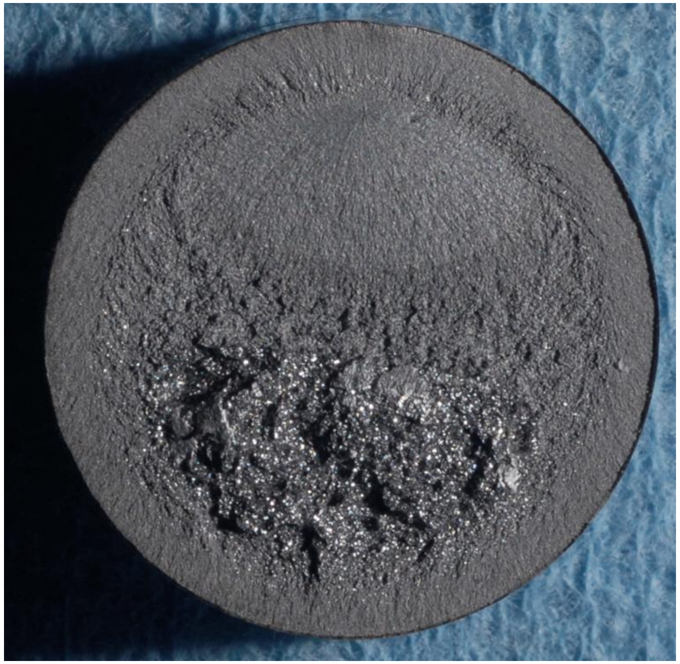
Alloy Dependent Threshold Inclusion Sizes



Model Applied to Induction Hardened Steel

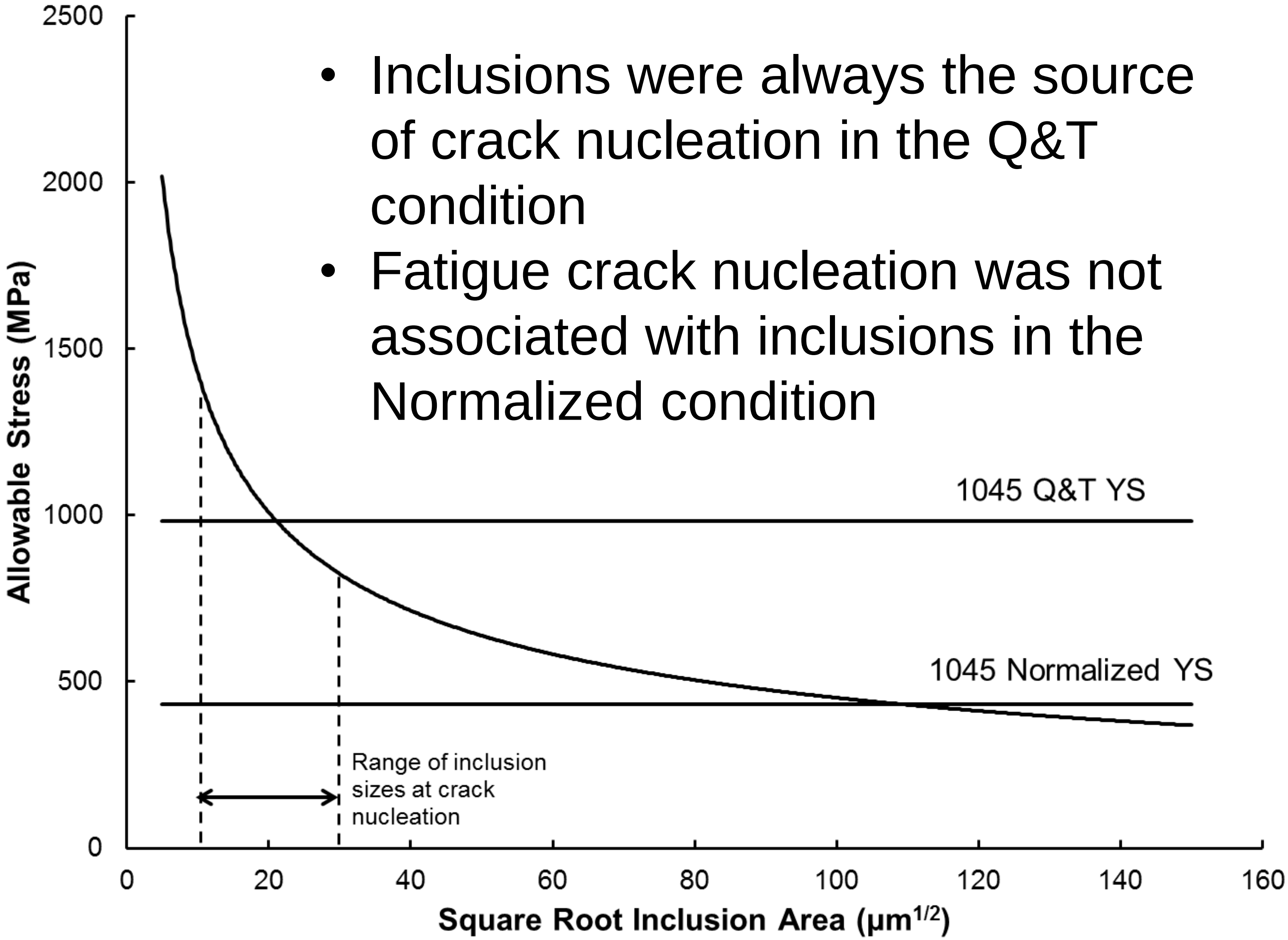
- 1045 steel – Q&T or Normalized (Ferrite-Pearlite)
- Induction hardened to achieve similar case depths
- Cantilever bending fatigue tests
- Crack nucleation always occurred at the case-core interface



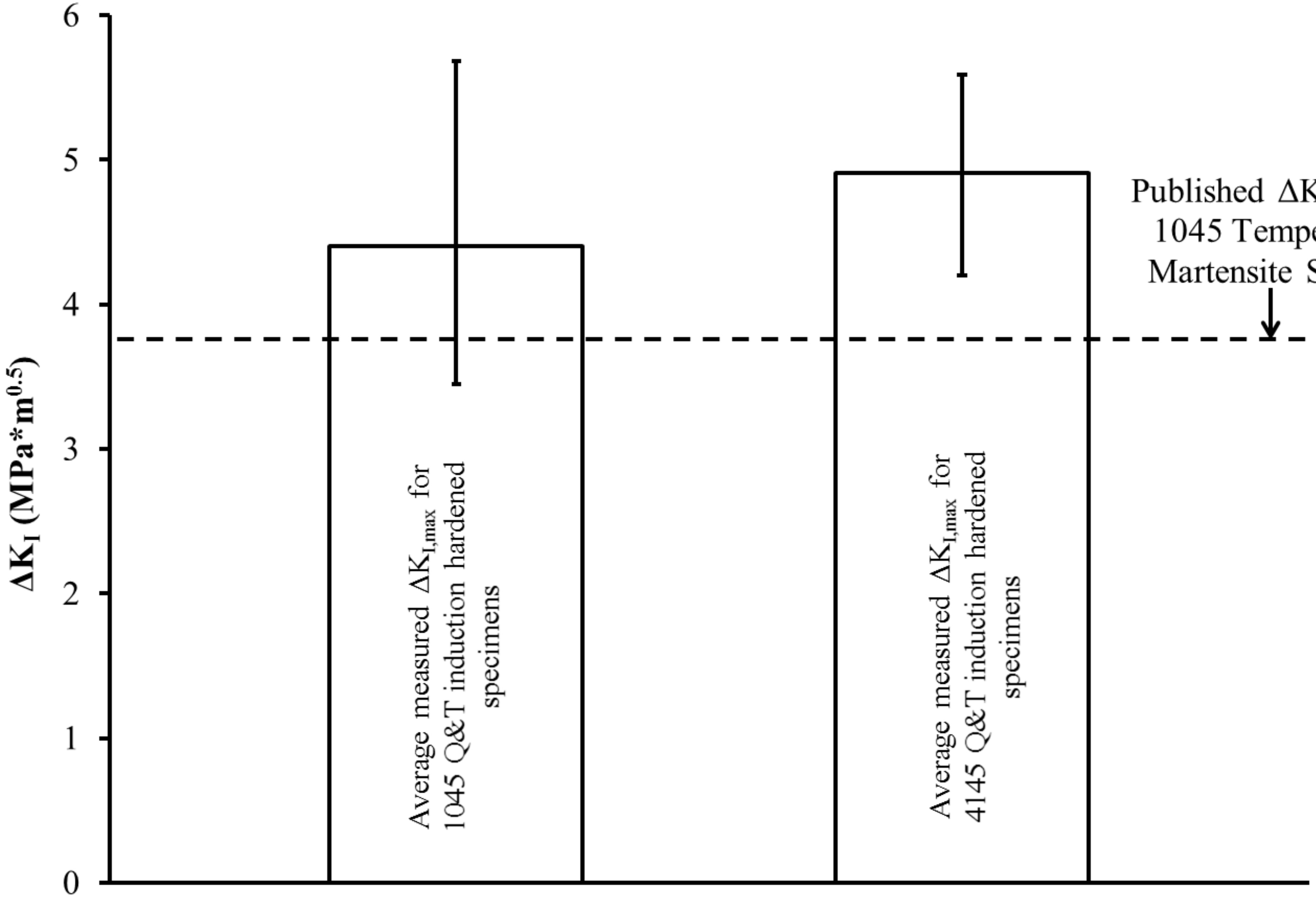


Crack Nucleation Observations

- Inclusions were always the source of crack nucleation in the Q&T condition
- Fatigue crack nucleation was not associated with inclusions in the Normalized condition



ΔK_{th} Comparison – 1045 and 4145 Q&T Steel



Role of Inclusions and Surface Microstructure in Rolling/Sliding Contact Fatigue

- Pitting/spalling
  - Common form of gear tooth failure
  - Result of rolling-sliding contact fatigue
- Applications:

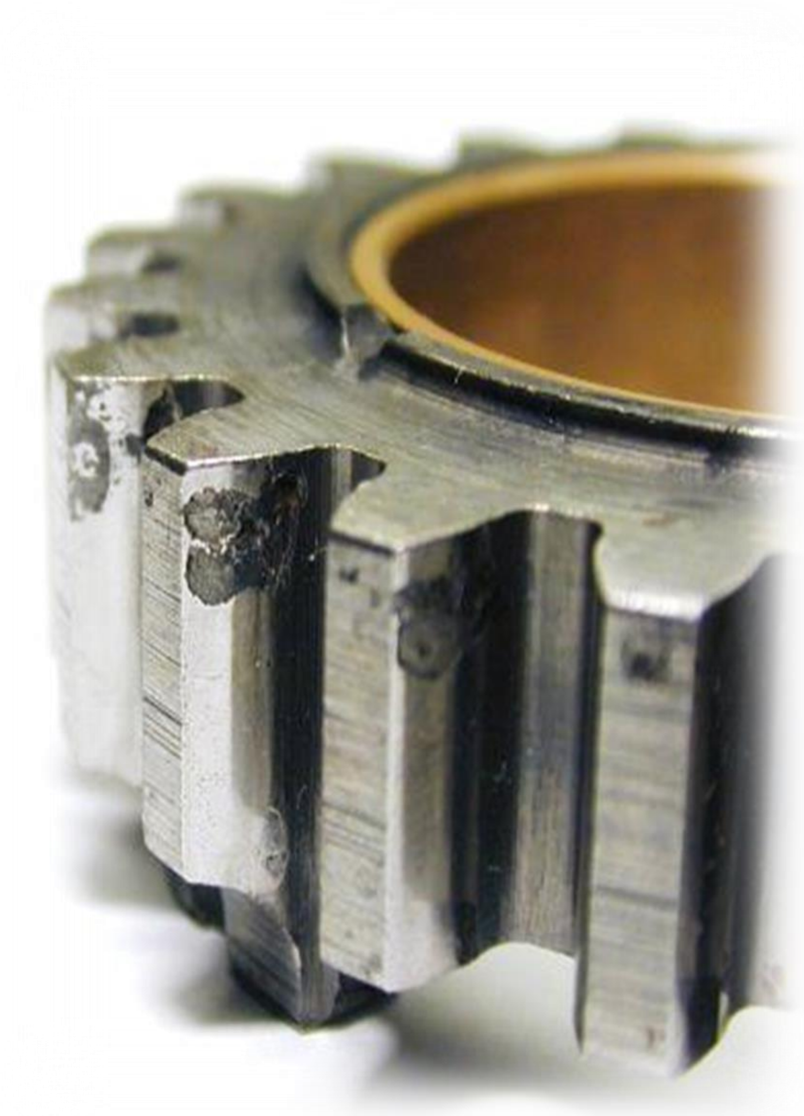
Automotive

Agriculture

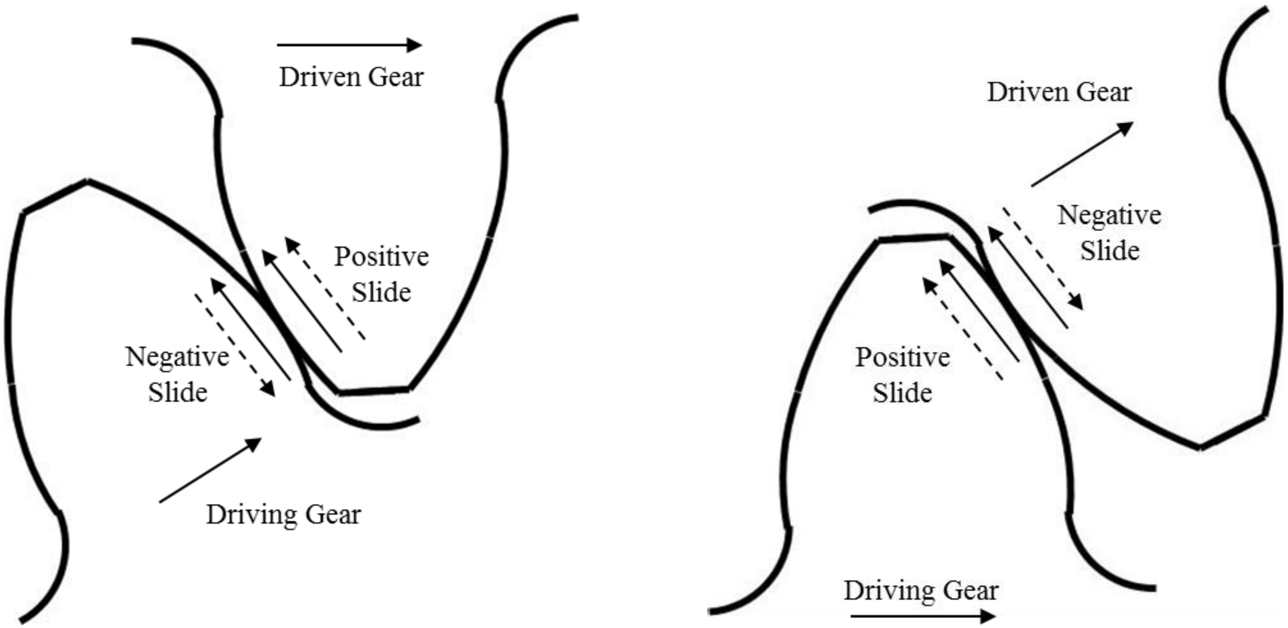
Construction

Wind Energy

Trains

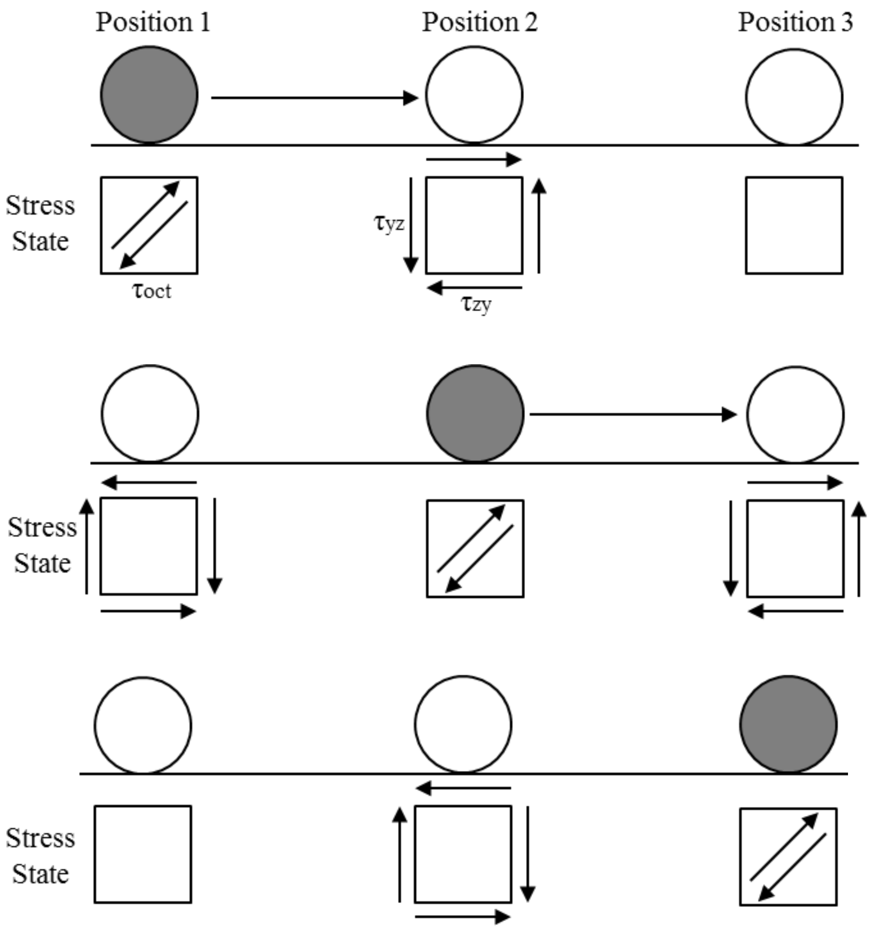


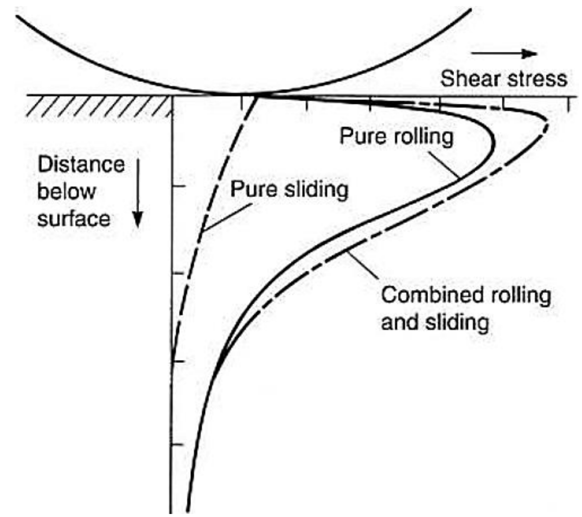
Gear Contact and Sliding

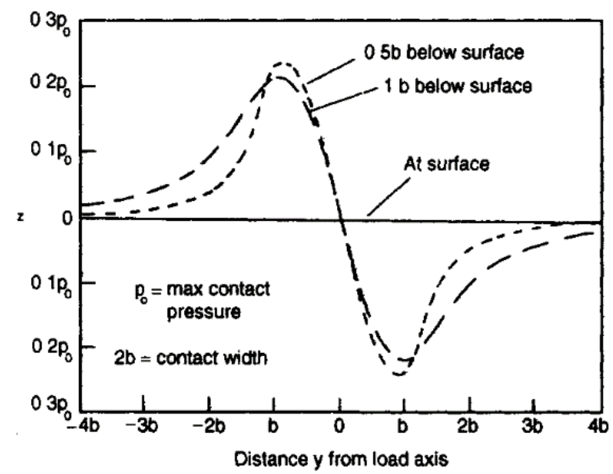


Stresses induced from rolling, bending, and sliding

Stress State During RSCF (Hertzian Contact)







Orthogonal stress as a function of position

RSCF in Carburized Microstructures

- Base alloy contains <0.2 wt.% C
- Carburized layer contains >0.8 wt.% C
- Gradient of compositions and microstructures
  – Plate martensite and retained austenite in case transitioning to lath martensite in core

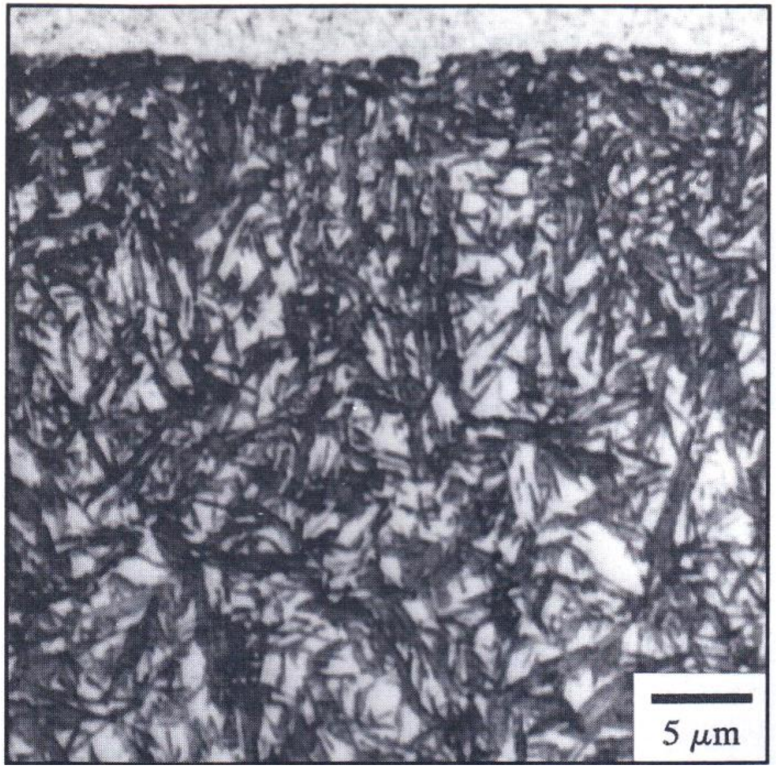


Plate martensite and retained austenite microstructure in carburized layer (Pacheco and Krauss, 1990)

An Investigation of Rolling-Sliding Contact Fatigue Damage of Carburized Gear Steels (Kramer - 2013)

Steel	C	Mn	Si	Ni	Cr	Mo	Ti	Nb
4320	0.20	**0.58**	0.28	**1.72**	0.52	0.22	0.003	0.001
4120	0.20	**1.09**	0.26	**0.13**	0.50	0.15	0.002	0.002

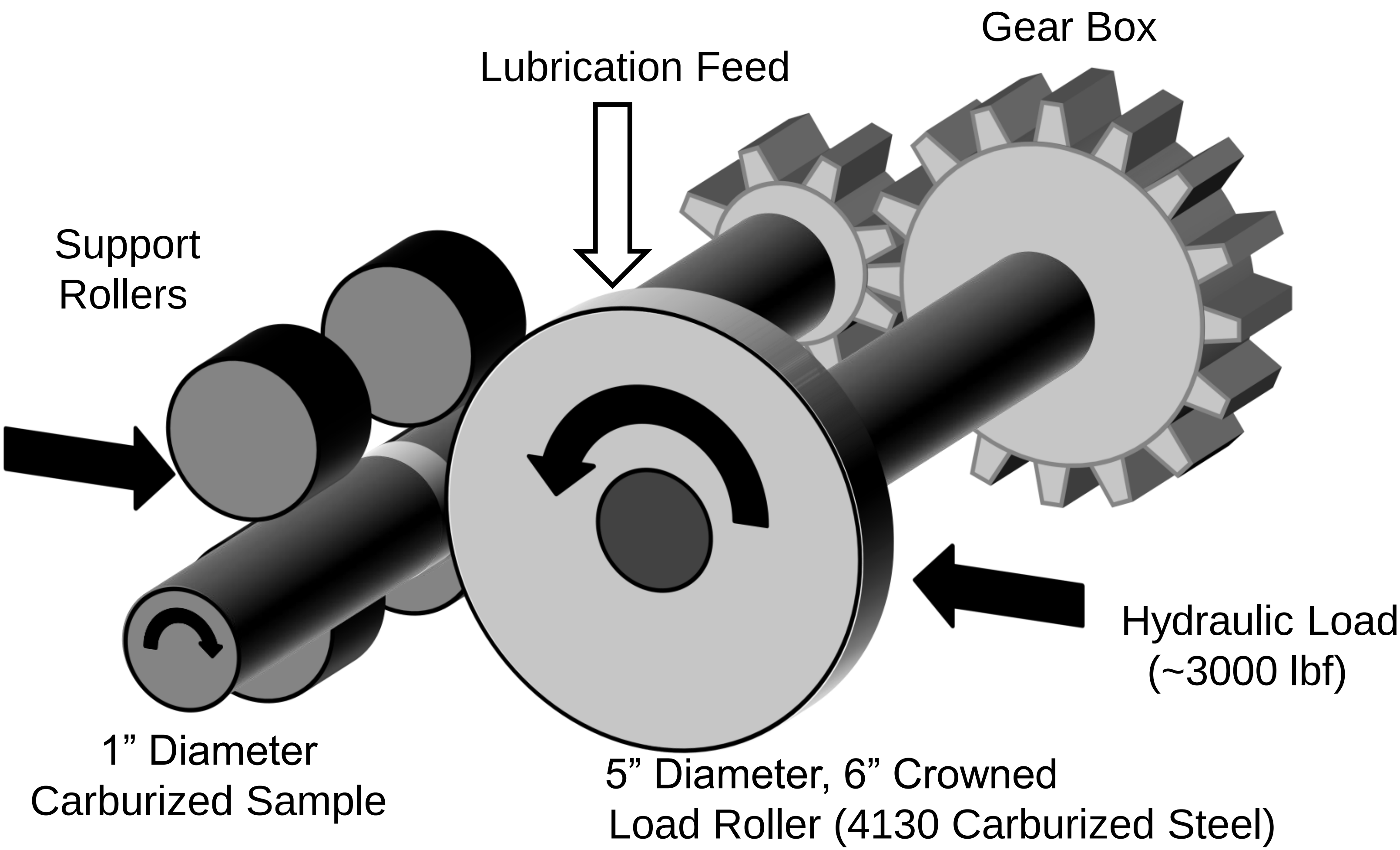
Steel	V	Al	N	S	P	Cu	B
4320	0.005	0.028	0.0100	0.021	0.009	0.21	0.0002
4120	0.004	0.026	0.0082	0.023	0.007	0.18	0.0002

Manganese – Attempt to influence the amount/extent of IGO

Nickel – Offset decrease in hardenability with lower Mn in 4320

Alloys were gas or vacuum carburized

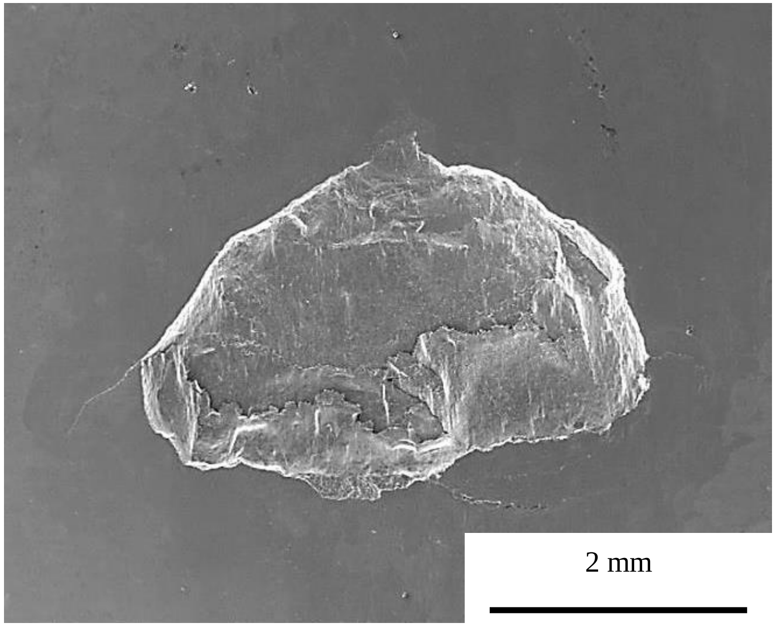
RSCF Testing Apparatus



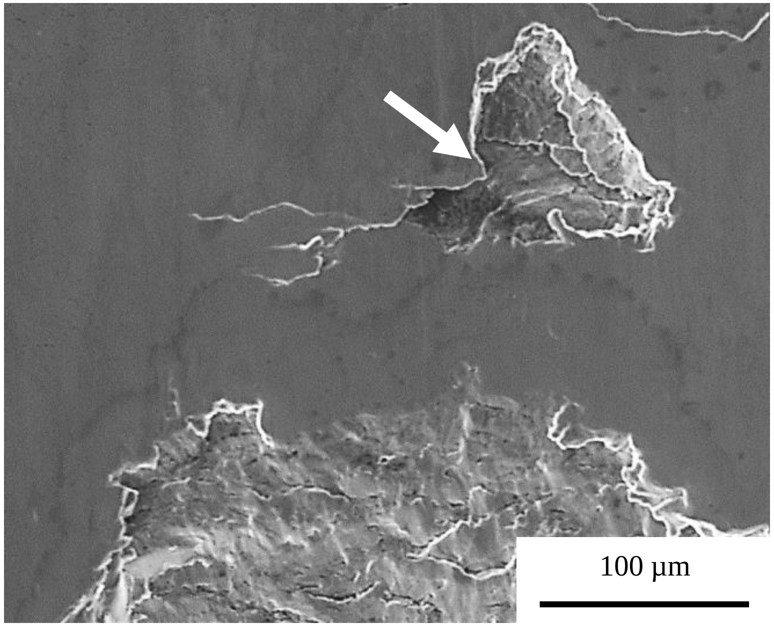
RSCF Testing Conditions

- 3.2 GPa contact stress
  - Based on pure rolling conditions
- -20% slide on RSCF bar sample
- Lubricant heated to 100°C
- 1000 RPM (1000 cycles per minute)
- Test ended after formation of macropit
  - Vibration spike detected by accelerometer

Pitting and Initiation

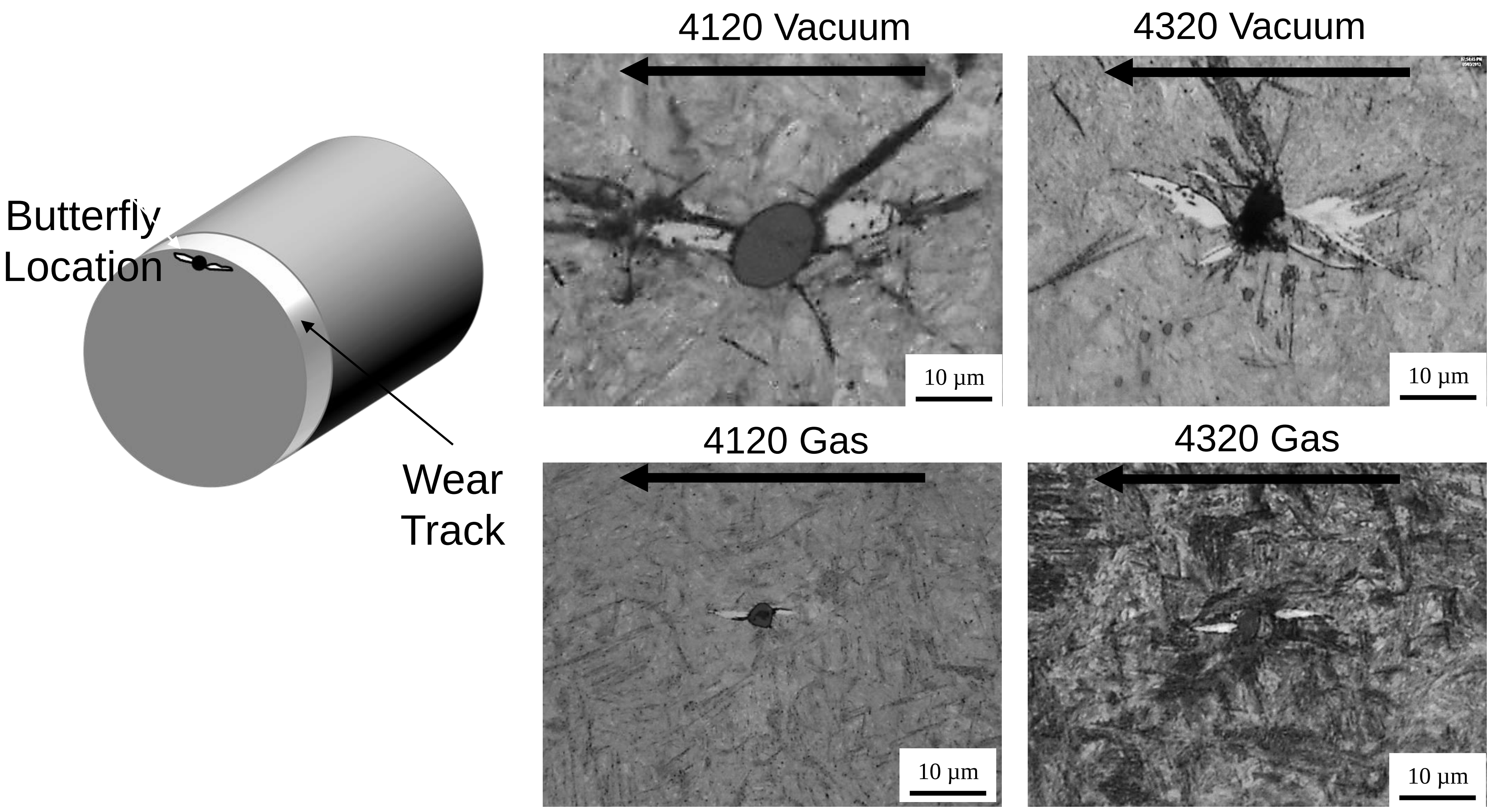


4320 Gas Carburized
Macro Pit



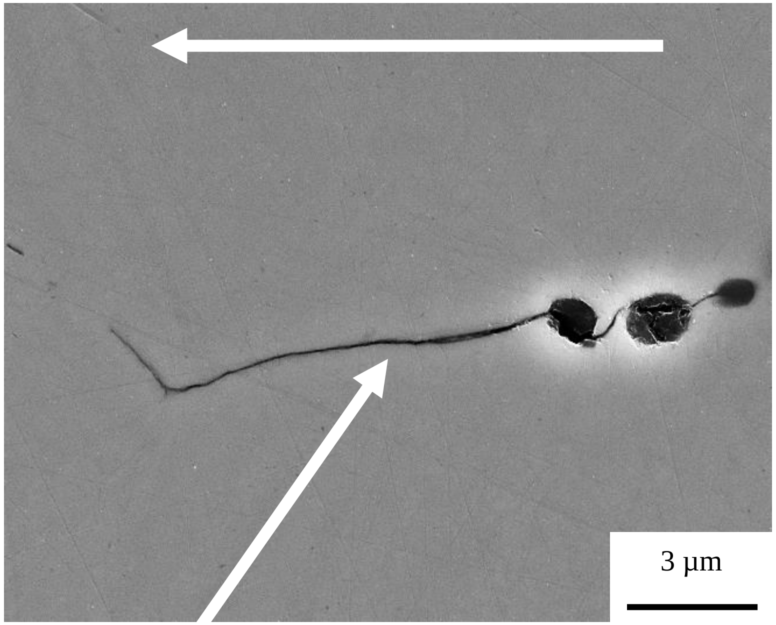
Micropitting at pit tip

Crack Nucleation



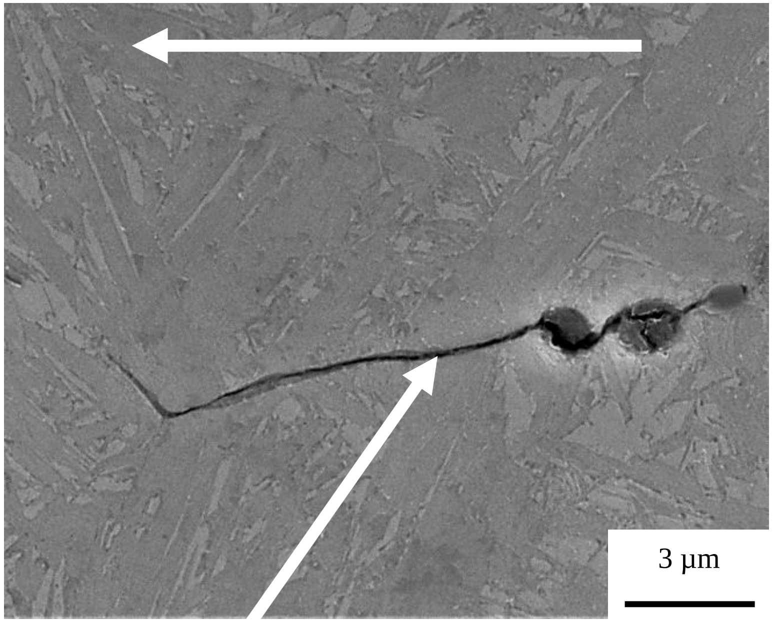
Incremental Testing
10,000 Cycles - Microcracking

As-polished



Microcrack

Picral etch

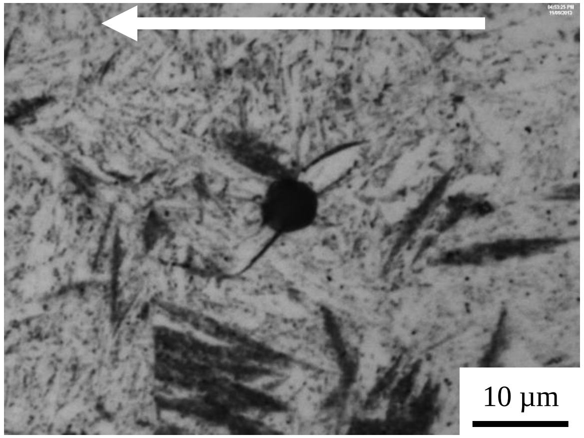


No wing

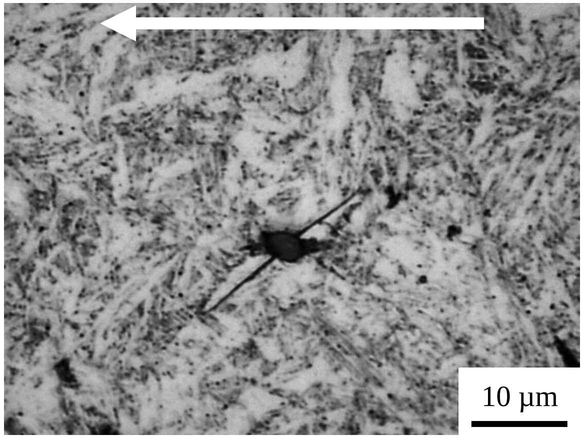
4320 Vacuum Carburized Condition

RCF vs. RSCF - Butterflies

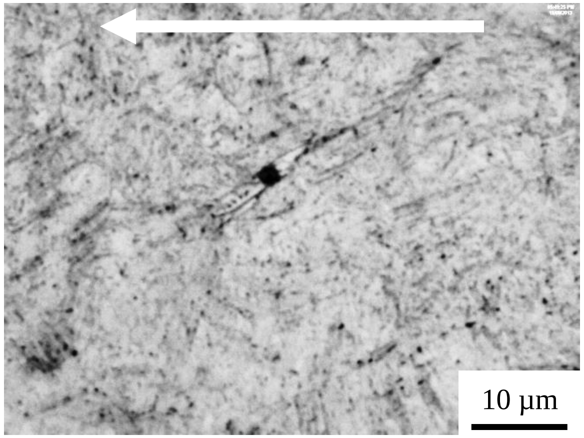
4120V



4320V



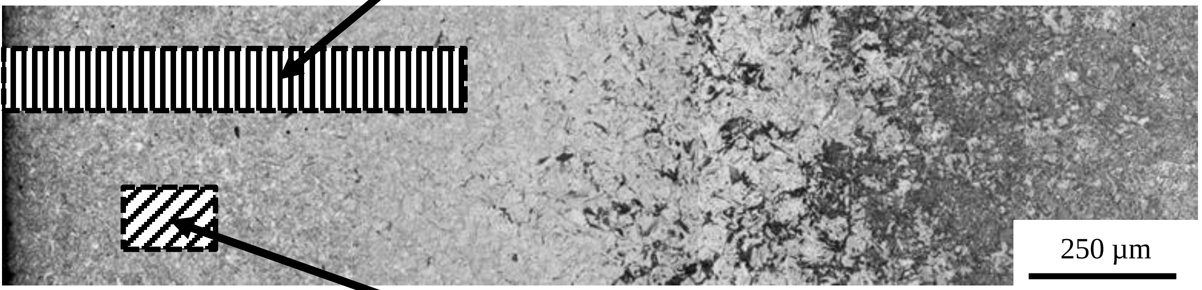
4120G



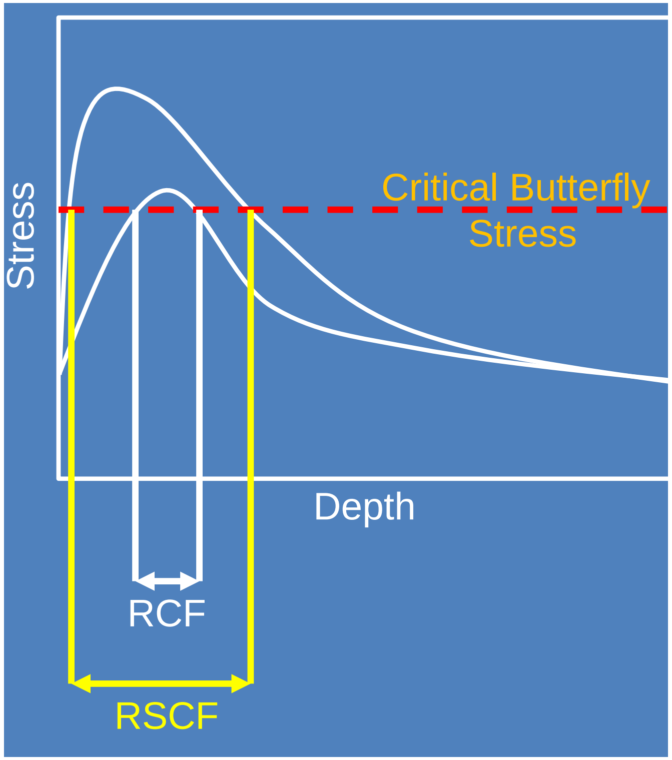
- Less numerous in RCF than RSCF
- ~45° to rolling direction (~parallel in RSCF)
- No butterflies observed in 4320G RCF sample

RCF vs. RSCF – Butterfly Depth

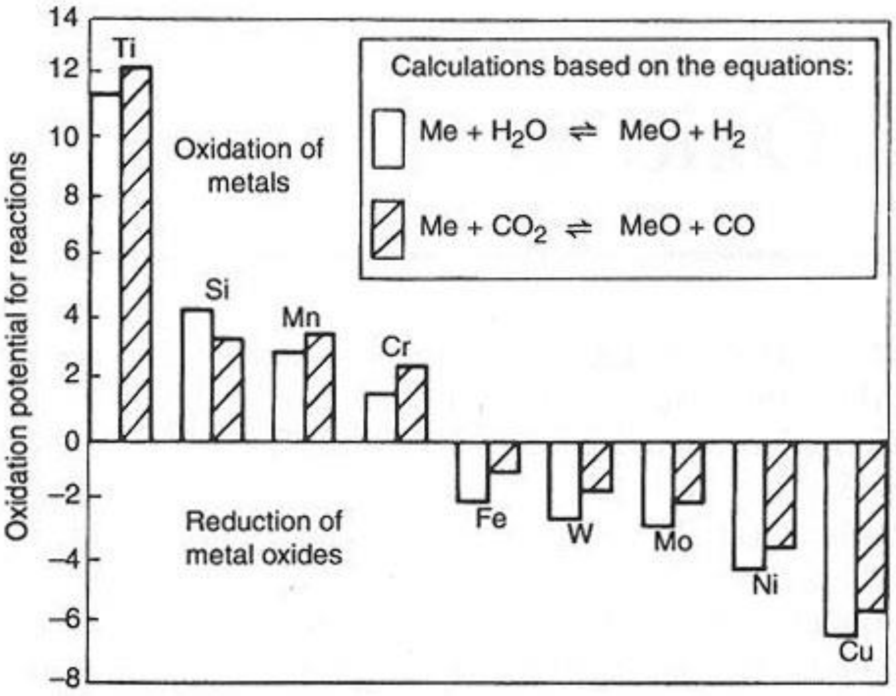
RSCF butterfly depth range



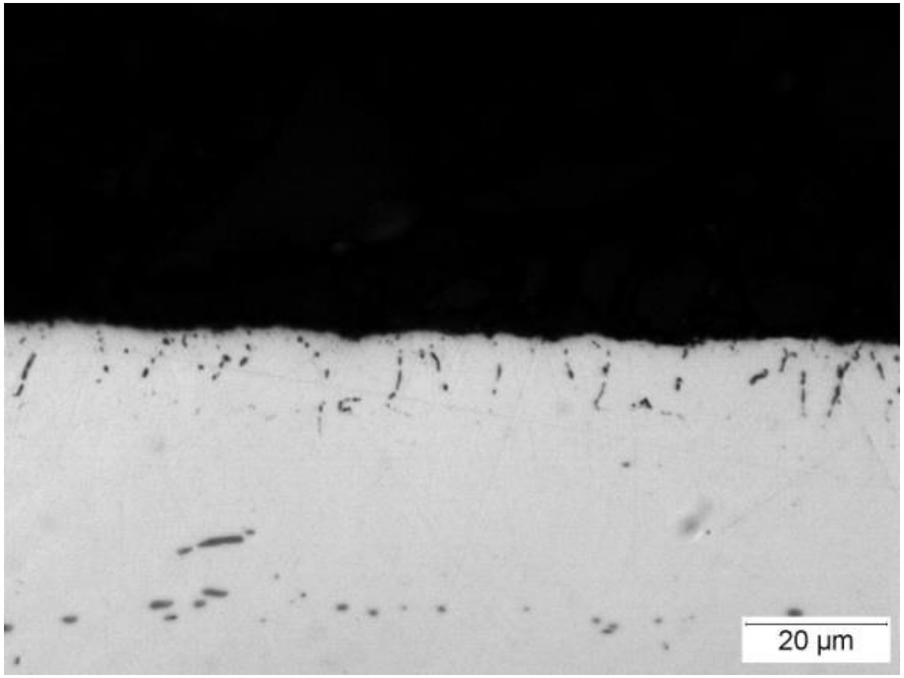
RCF butterfly depth range



Intergranular Oxidation

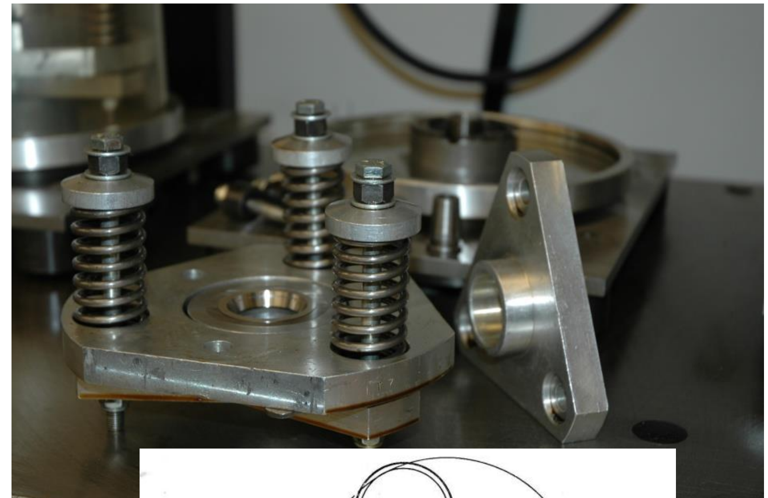


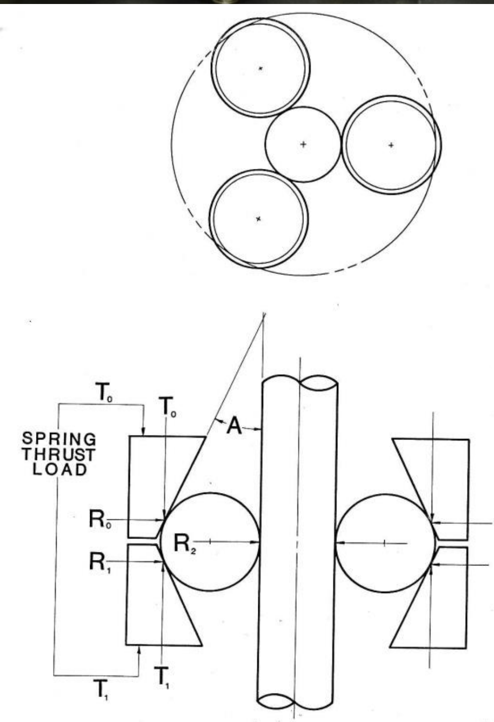
Oxidation potentials of common elements during gas carburizing at a temperature of 930˚C (Kozlovskii *et al.*, 1967)



Cross-section of 4120 specimen showing IGO after gas carburizing with a peak temperature of 954 °C (Bykowski, 2008)

Effects of High Temperature Gas Carburizing on Metallurgical Variables that Influence Rolling Contact Fatigue Performance – Bykowski, 2008

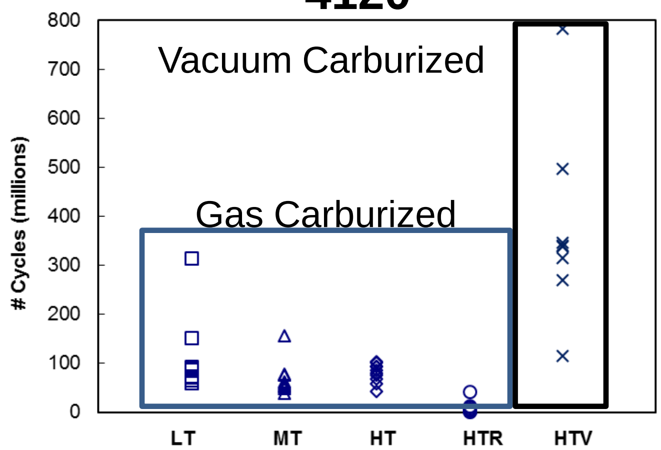




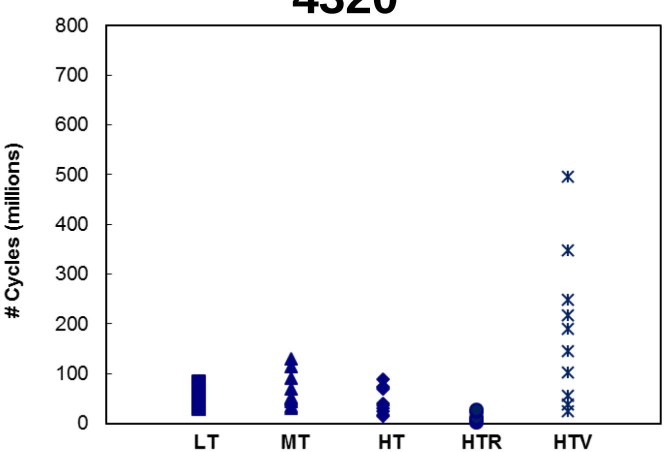
- Ball-rod type tester donated to CSM by The Timken Company
- 5.4 GPa contact stress level
- Same alloys as Kramer
- Gas and vacuum carburization

Effects of IGO on Crack Nucleation and Fatigue Life

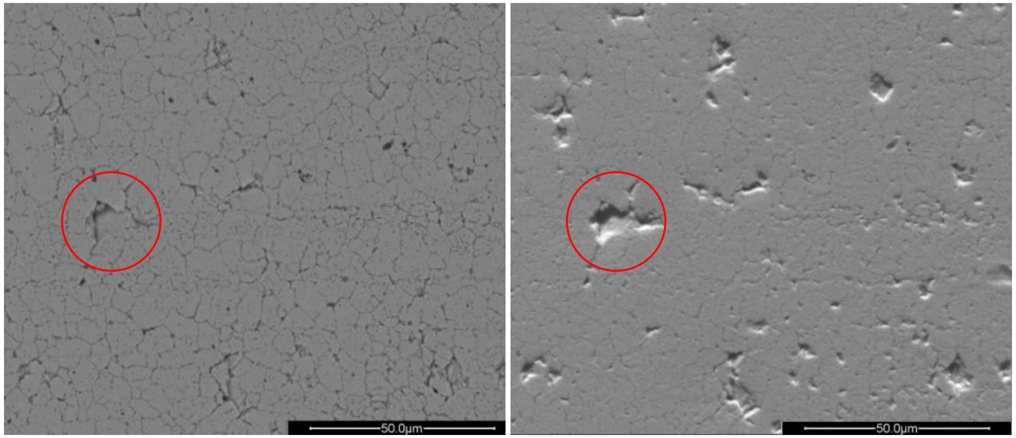
4120



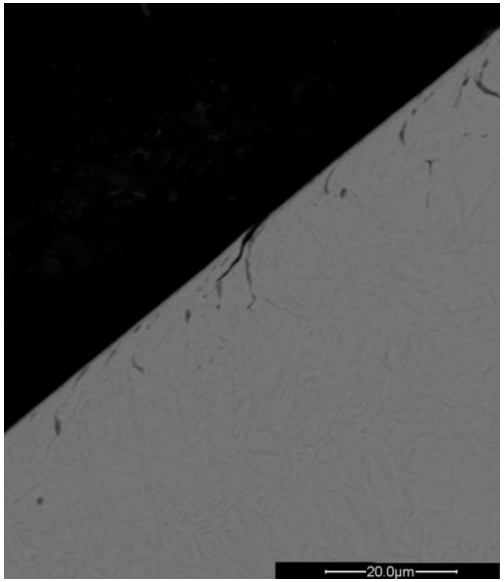
4320



Rolling contact fatigue lives of carburized 4120 and 4320 specimens



Intergranular pitting initiation at prior austenite grain boundaries for a 4320 specimen gas carburized at 954 °C



Crack nucleation along grain boundary oxides in a 4120 specimen gas carburized at 1010 °C

Bykowski, M.S. Thesis, 2008

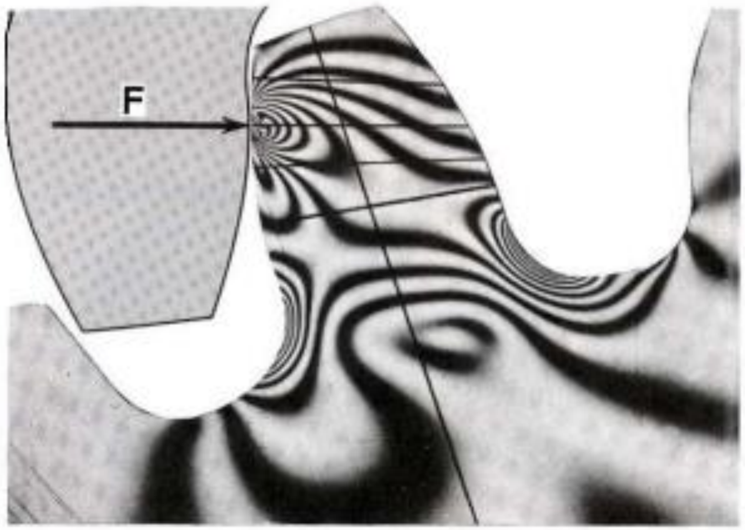
Other Aspects of RSCF Fracture…

- Likely interaction between subsurface inclusion cracks and surface oxide/intergranular cracks in pit formation

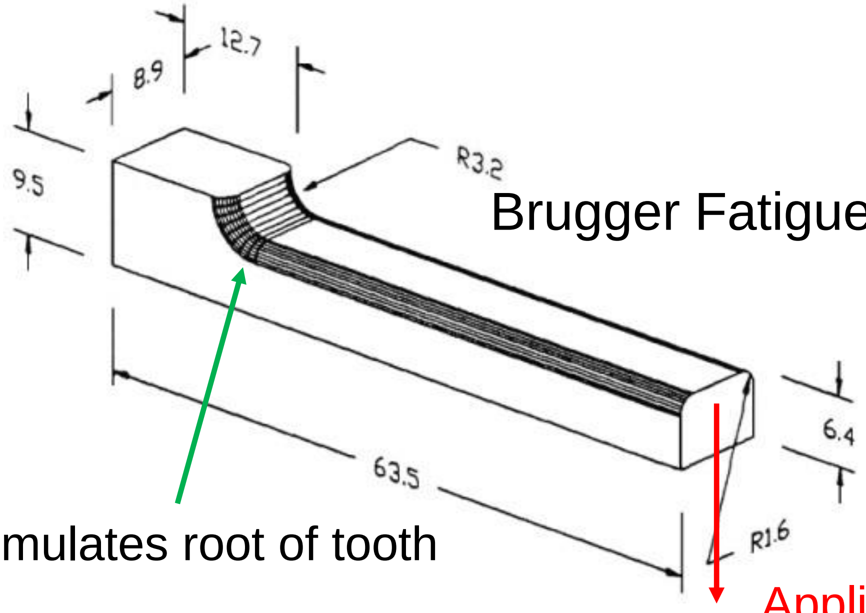
- Role of inclusions on fatigue crack nucleation related to increased concentration of plasticity (due to shear stresses) around inclusion during compressive loading

Bending Fatigue of Carburized Steels

Bending stresses in root of notch



Fixed End



Brugger Fatigue Specimen

Simulates root of tooth

Applied Load

Stages of Fatigue in Carburized Steels

Zone I – Intergranular crack initiation

- 1 cycle at stresses above the endurance limit

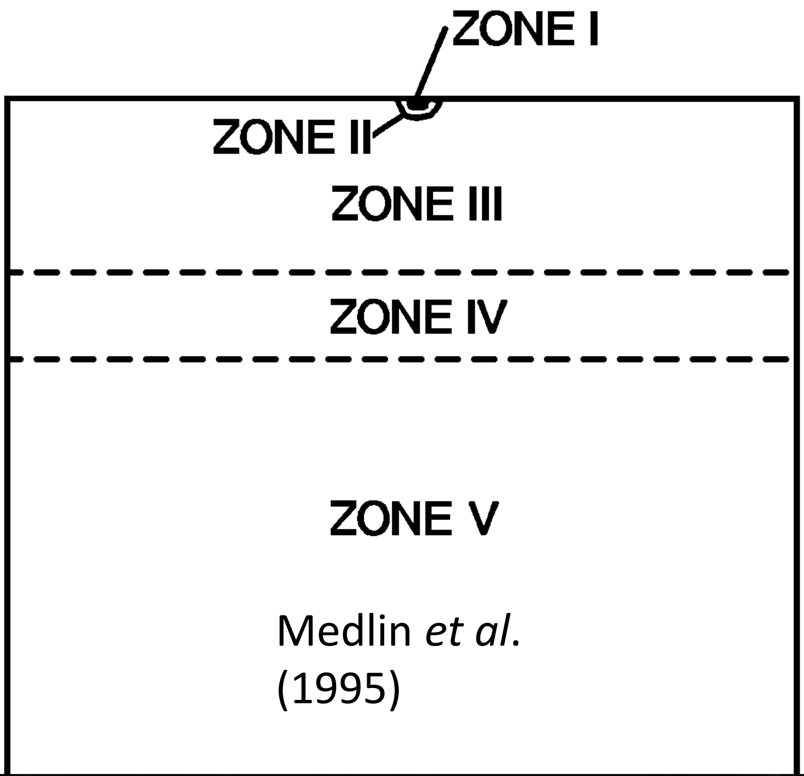
Zone II – Transgranular Stable Crack Growth

- Semi-elliptical shape, possibly bulk of fatigue life

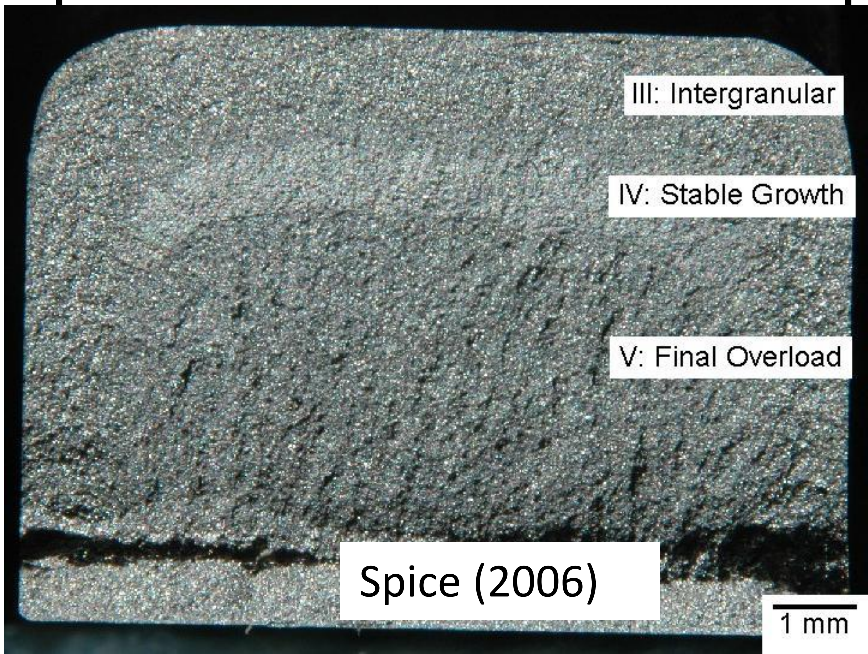
Zone III – Intergranular unstable crack growth

Zone IV – Transgranular stable crack growth (small # of cycles)

Zone V – Ductile Overload

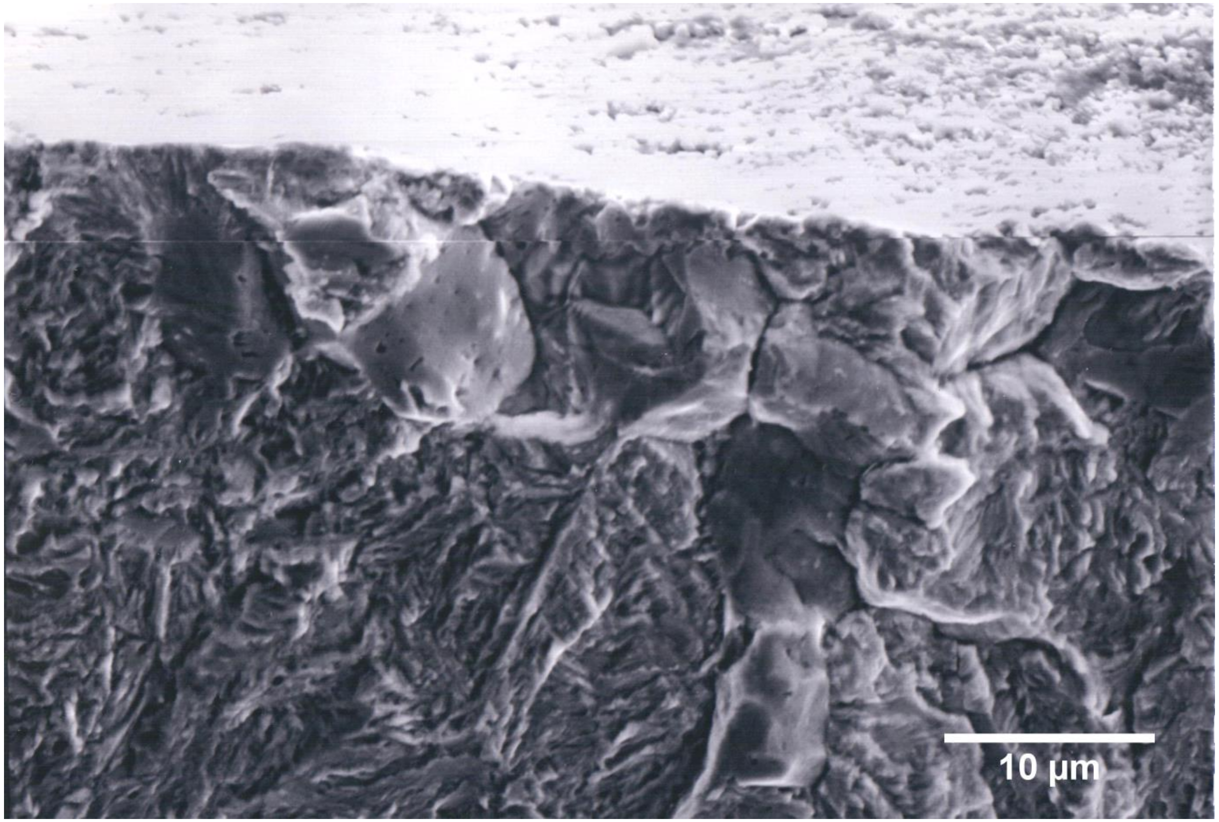


Medlin *et al.* (1995)



Spice (2006)

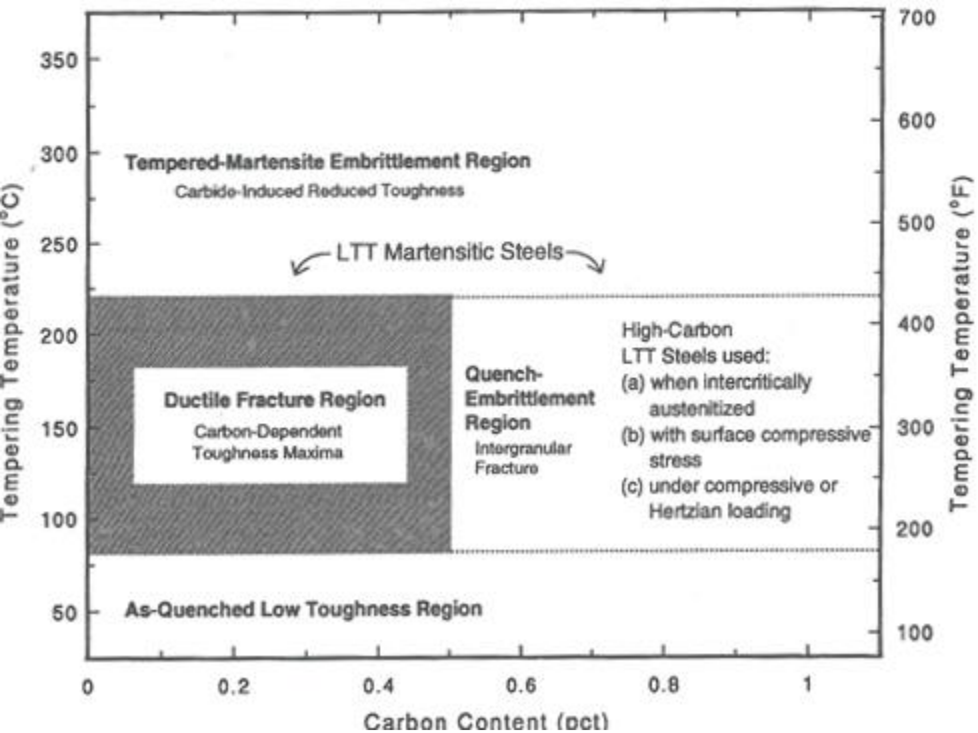
Zones I and II



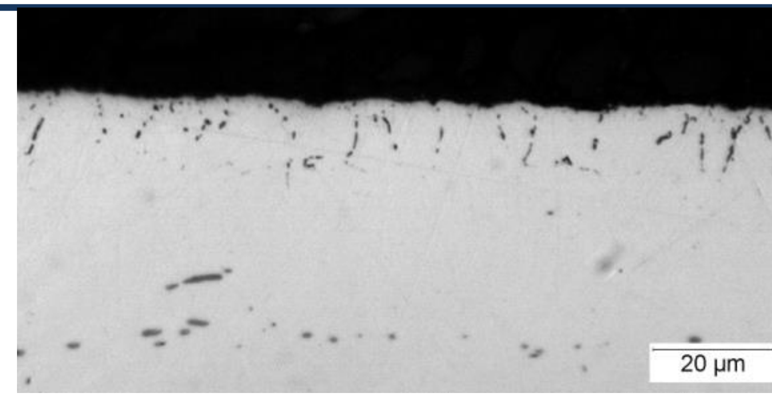
Sanders (1995)

- Intergranular crack initiation (1-2 grains deep)
- Transgranular fracture, stable crack growth immediately behind

Intergranular Crack Nucleation



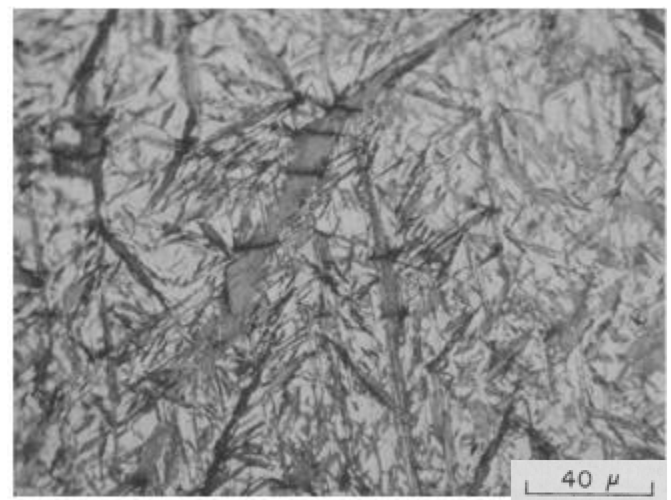
G. Krauss, *Steels*, Materials Park, Ohio. ASM International, 2005. pp. 395.



Intergranular oxide formation

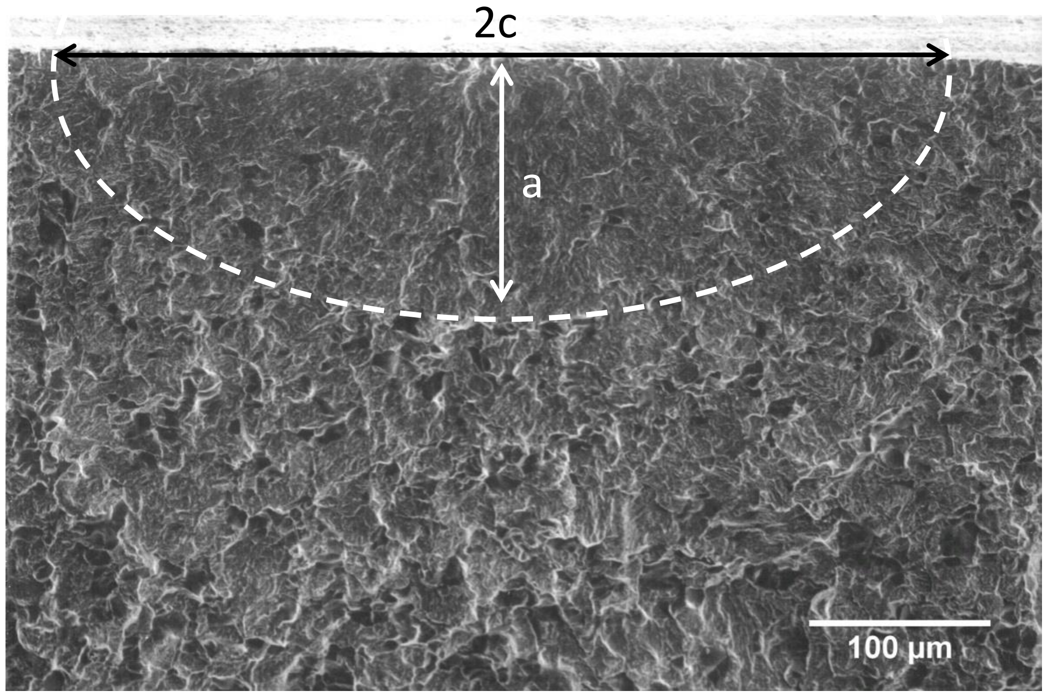
Phosphorous segregation to austenite grain boundaries during austenitizing.

Cementite formation at austenite grain boundaries during cooling.



Microcracking due to martensite plate impingement – scales with austenite grain size (Apple and Krauss, 1973)

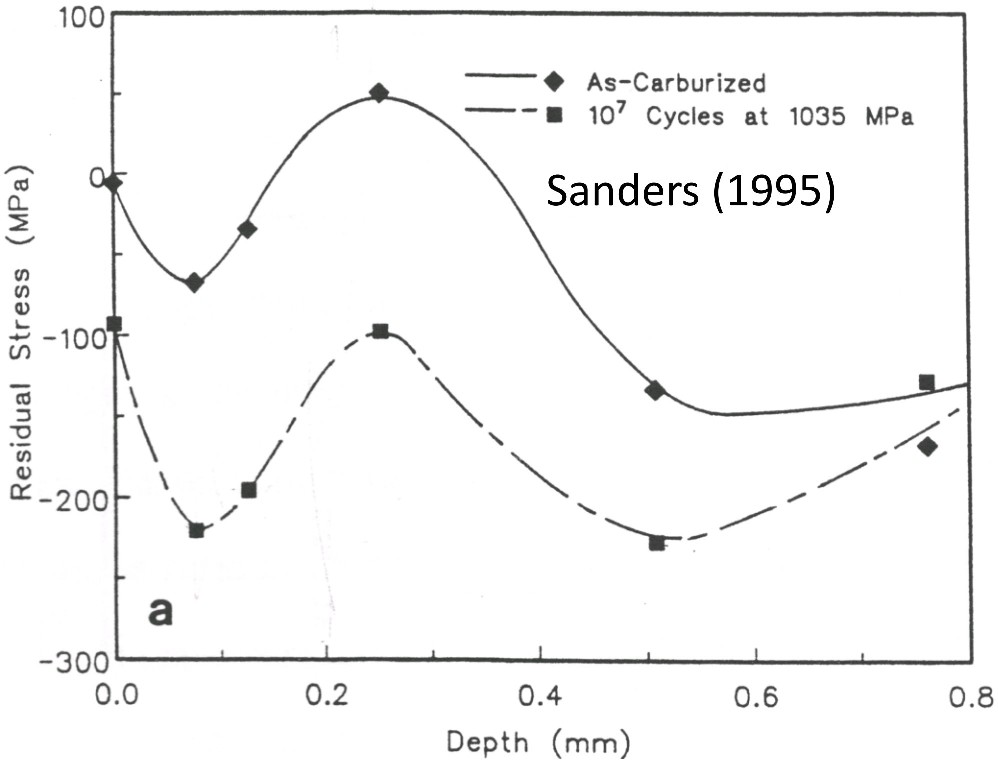
Zone II



Sanders (1995)

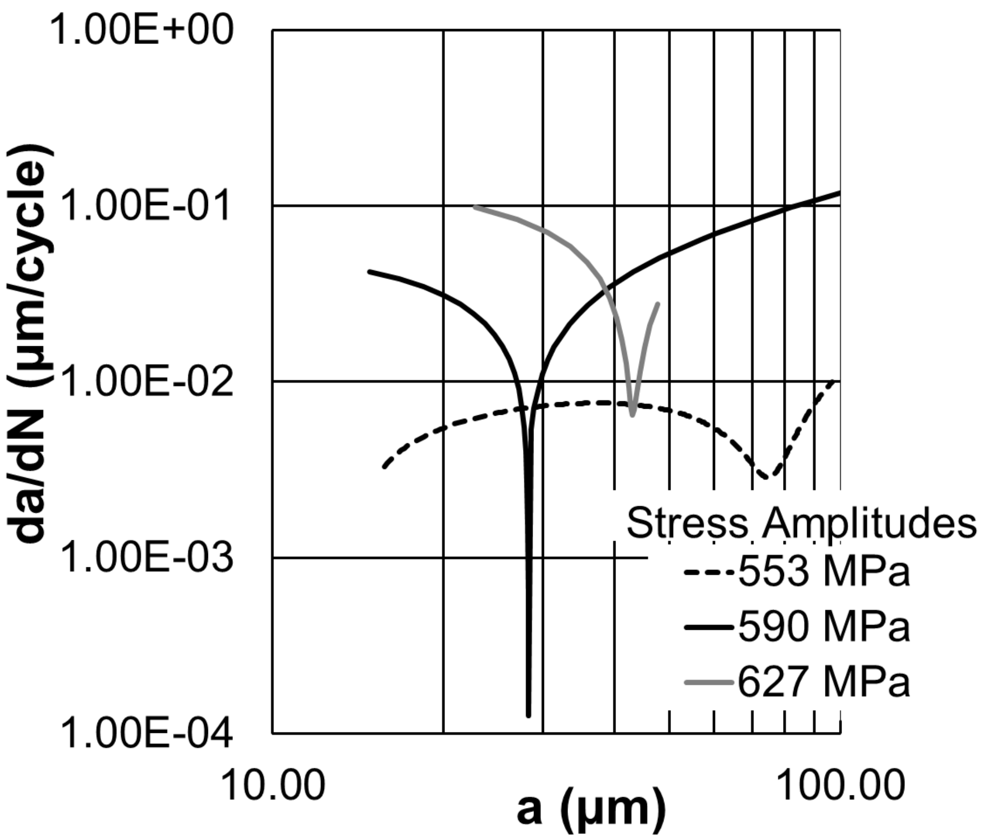
- Semi-elliptical crack growth from initiation
- Transgranular/stable crack growth
- Complex interaction between applied stress, residual stresses, and retained austenite to martensite transformation
- At critical crack length, K_{Ic} of case material is exceeded
  - Unstable, intergranular crack growth follows

Residual Stresses



- Initial residual stress due to cooling and transformation stresses
- Retained austenite to martensite transformation contributes to the final residual stress profile

Carburized Steel Crack Growth Data



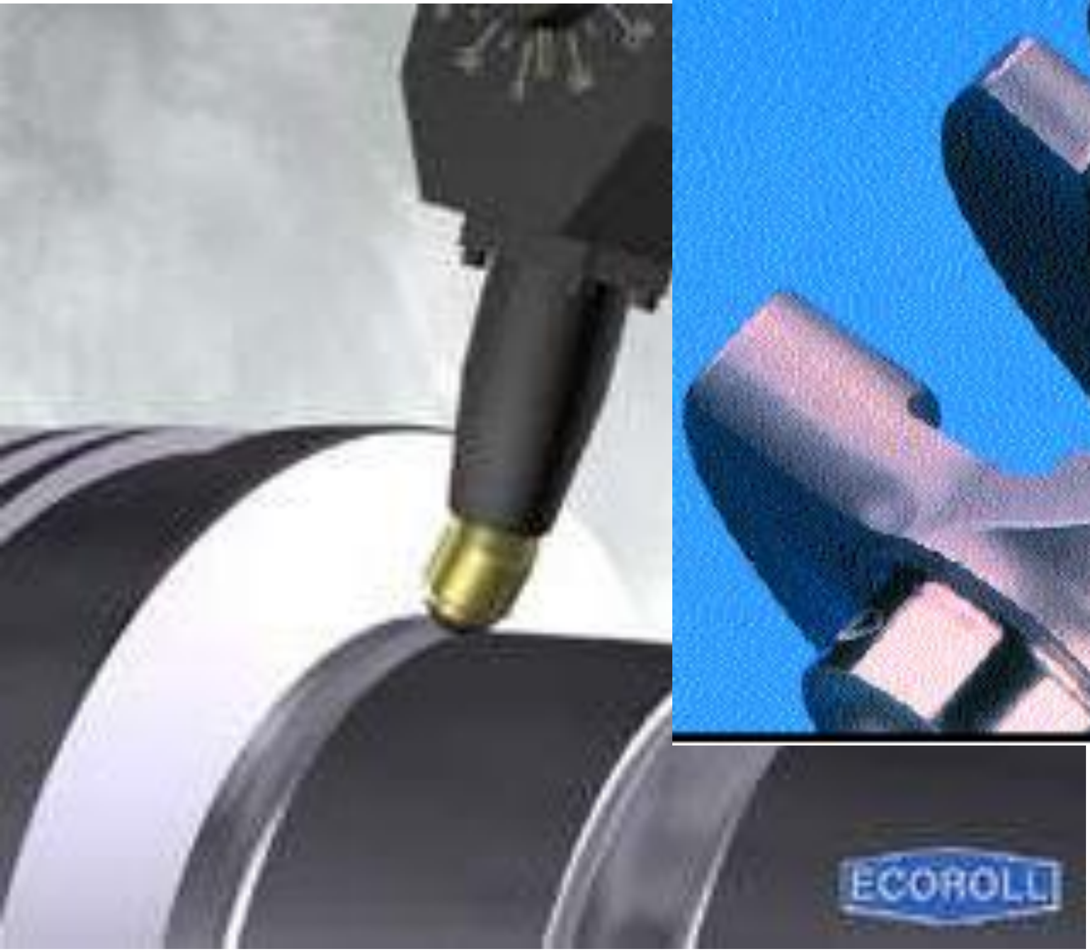
Residual stresses from heat treatment and RA transformation impede crack growth

Fatigue strength in carburized steels may be related to crack arrest

Crack growth rate vs. crack length data for a carburized 8620 steel (da Silva *et al.*, 1999)

Fatigue of Deep Rolled Parts (also related to crack arrest)

Photo courtesy of Ecoroll



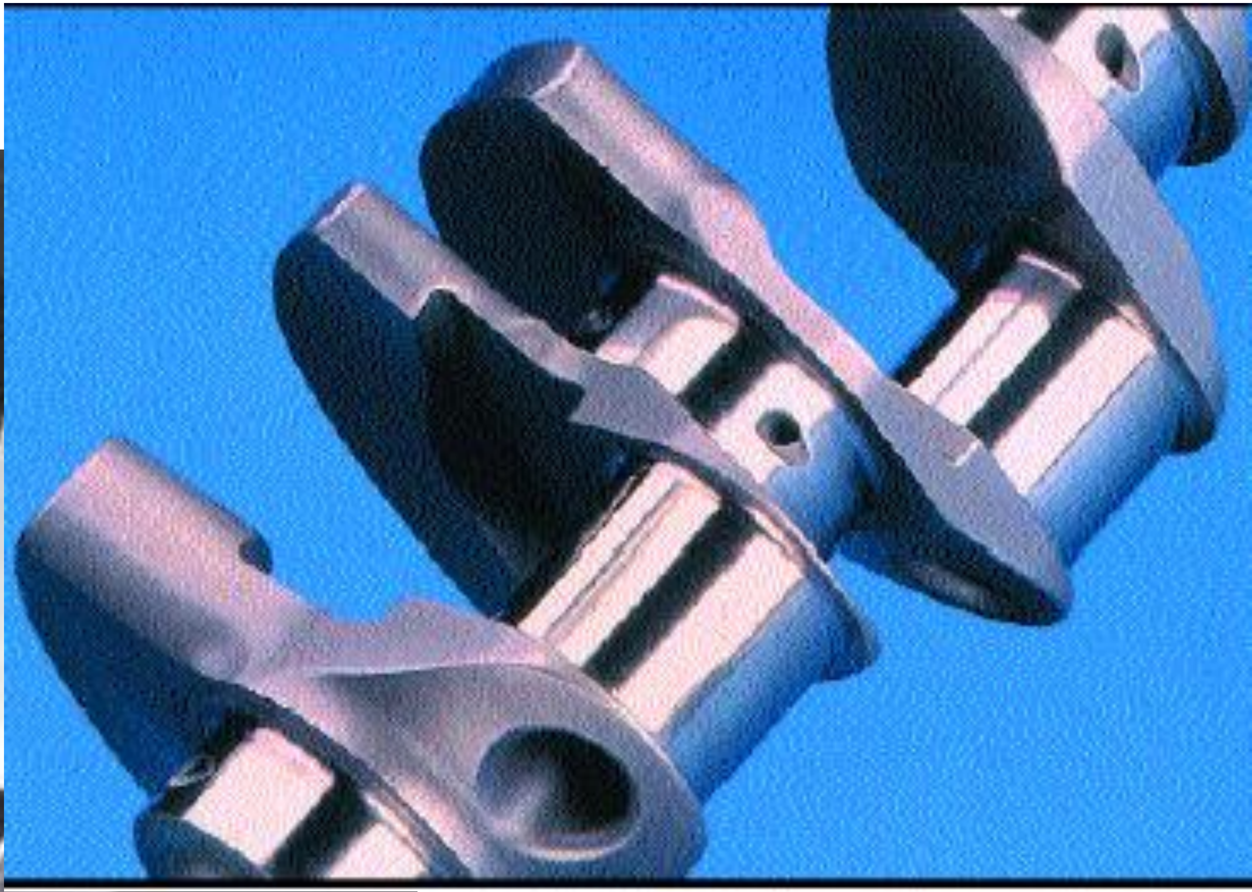
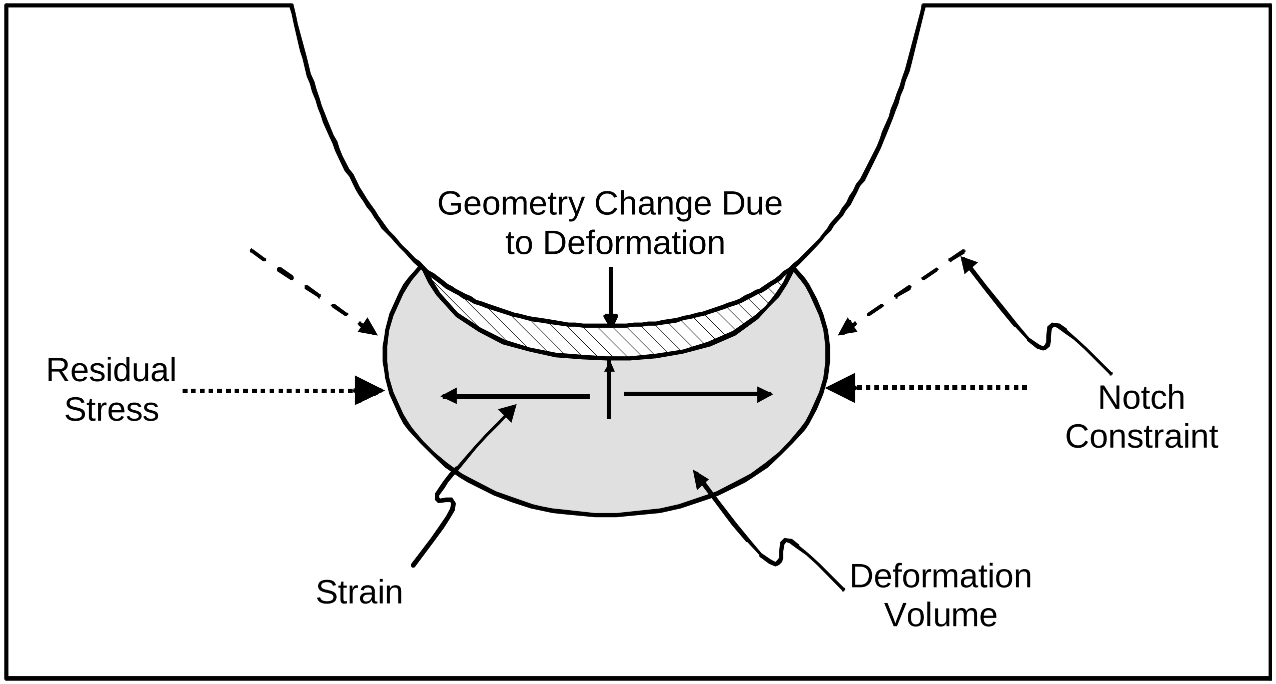


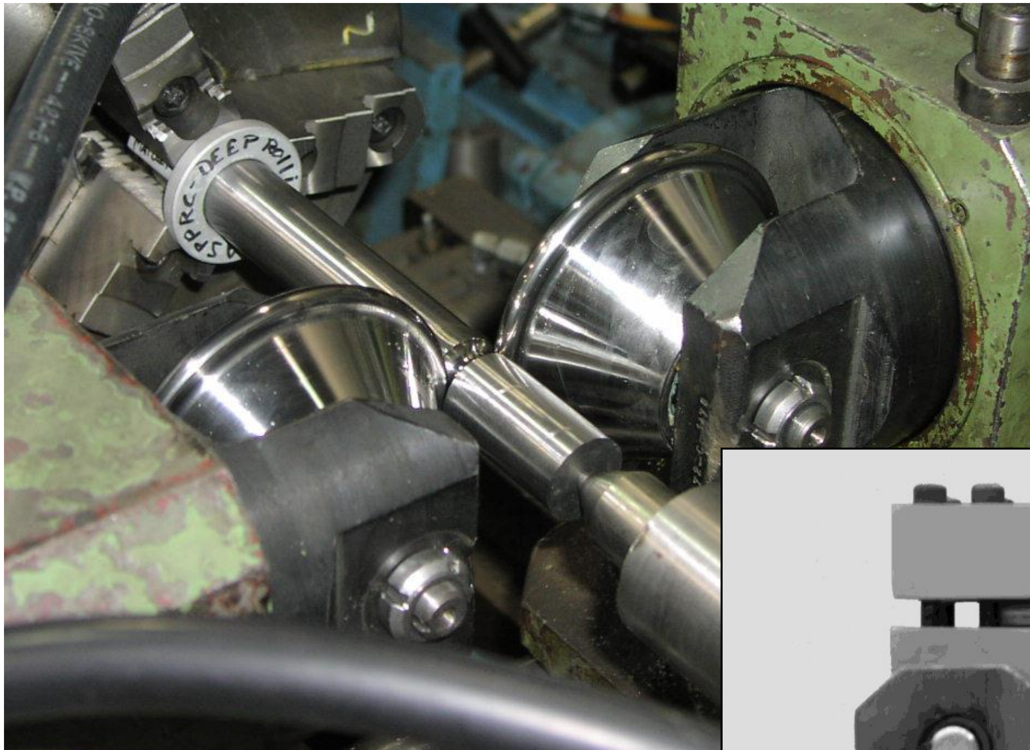
Photo courtesy of Scot Crankshafts

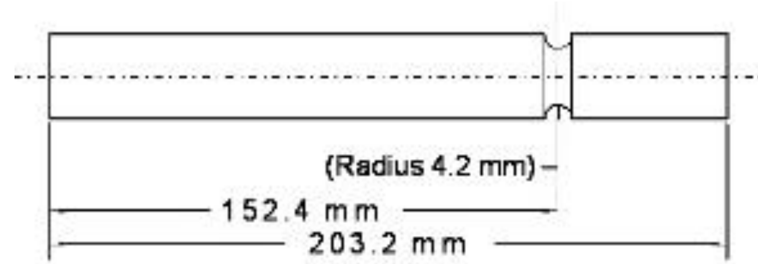
Deep Rolling Process



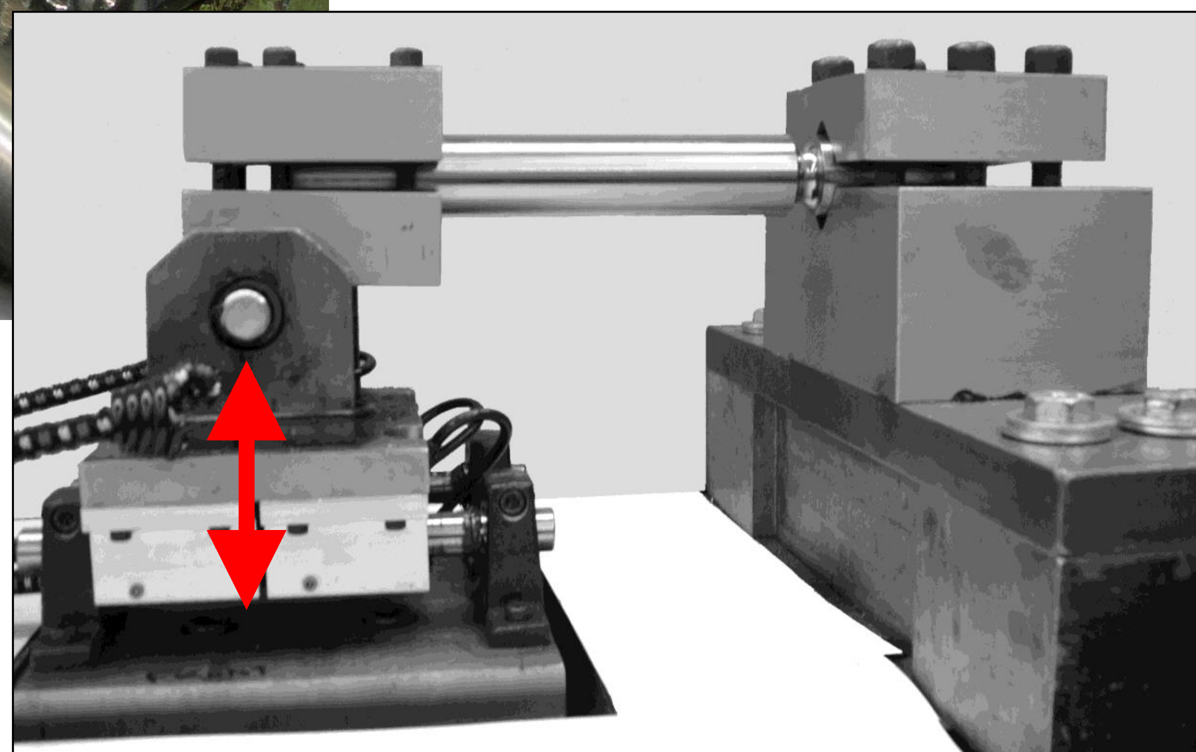
- **Deep Rolling is used primarily for surface finish, hardness, and residual stress control.**
- **Non-uniform strain**
    - **Local strength increases**
    - **Residual stress develops**
- **Cyclic application of strain**
    - **Strain reversal imposed = Bauschinger effect**

Deep Rolling and Fatigue Testing at CSM

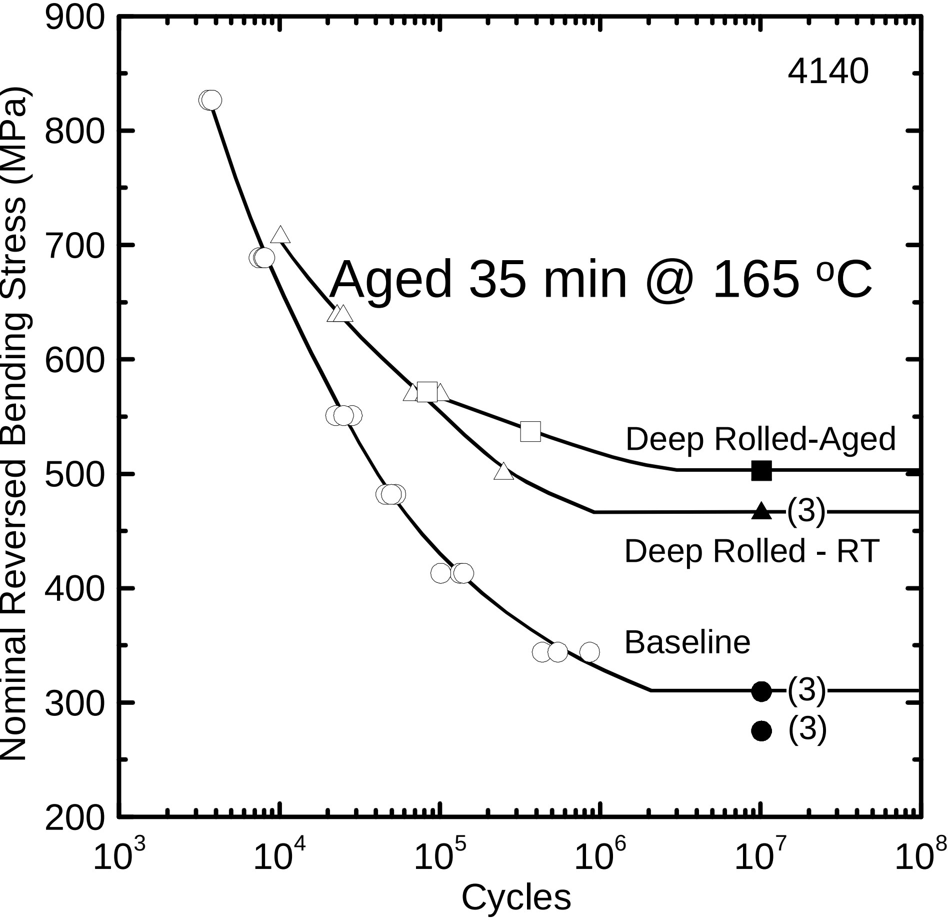




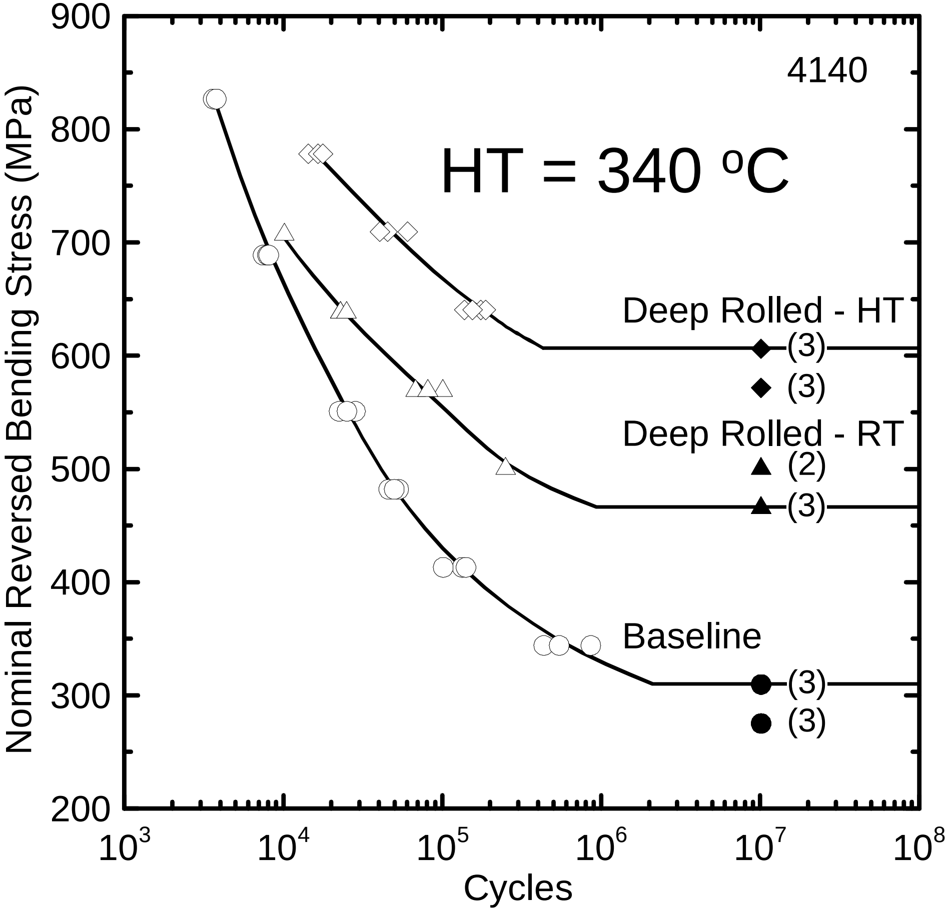
Sample d = 25 mm



Bending Fatigue Results – Strain Aging Effects (M. Richards, D.K. Matlock)



Moderate increase in endurance limit

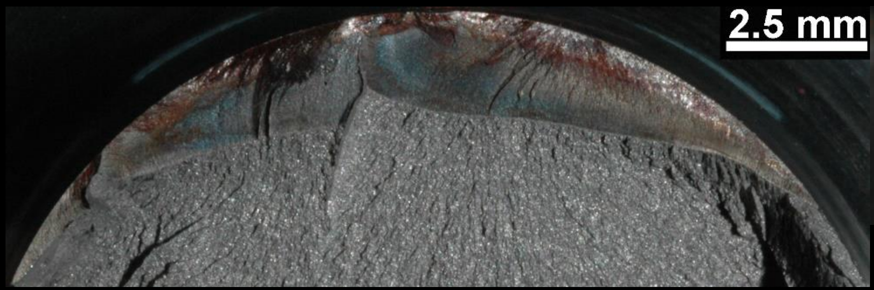


Deep rolling at elevated temperatures increases EL by approximately 100%

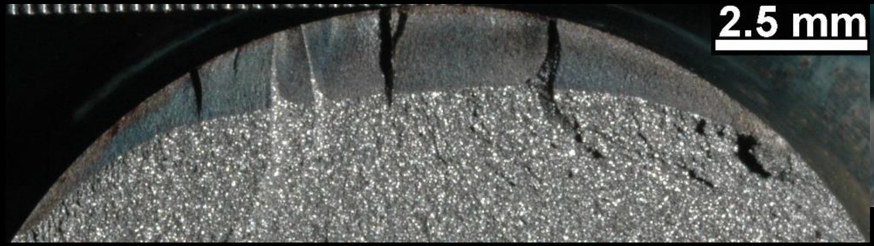
Non-Propagating Fatigue Cracks

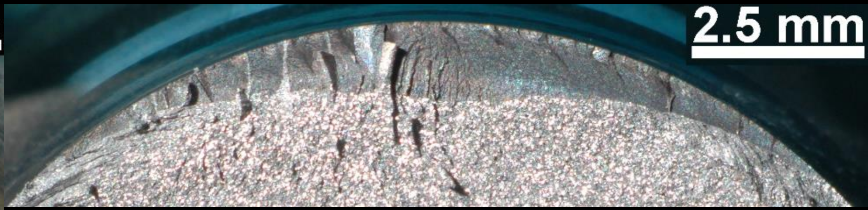
	RT Deep Rolled	HT Deep Rolled

4140

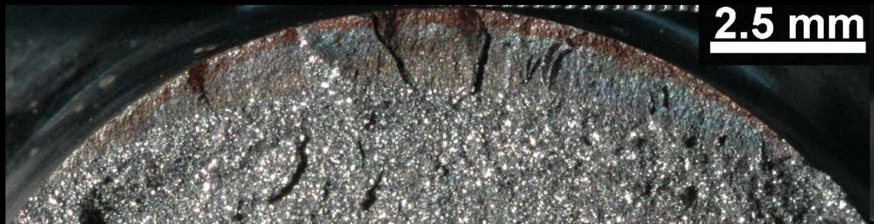


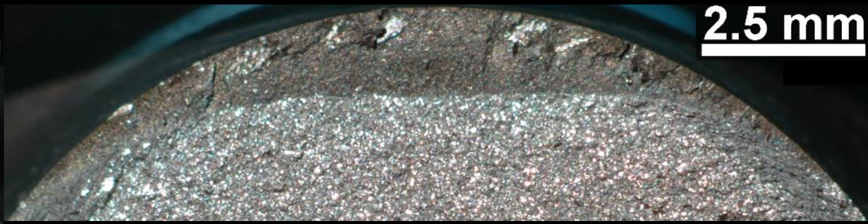
NTB



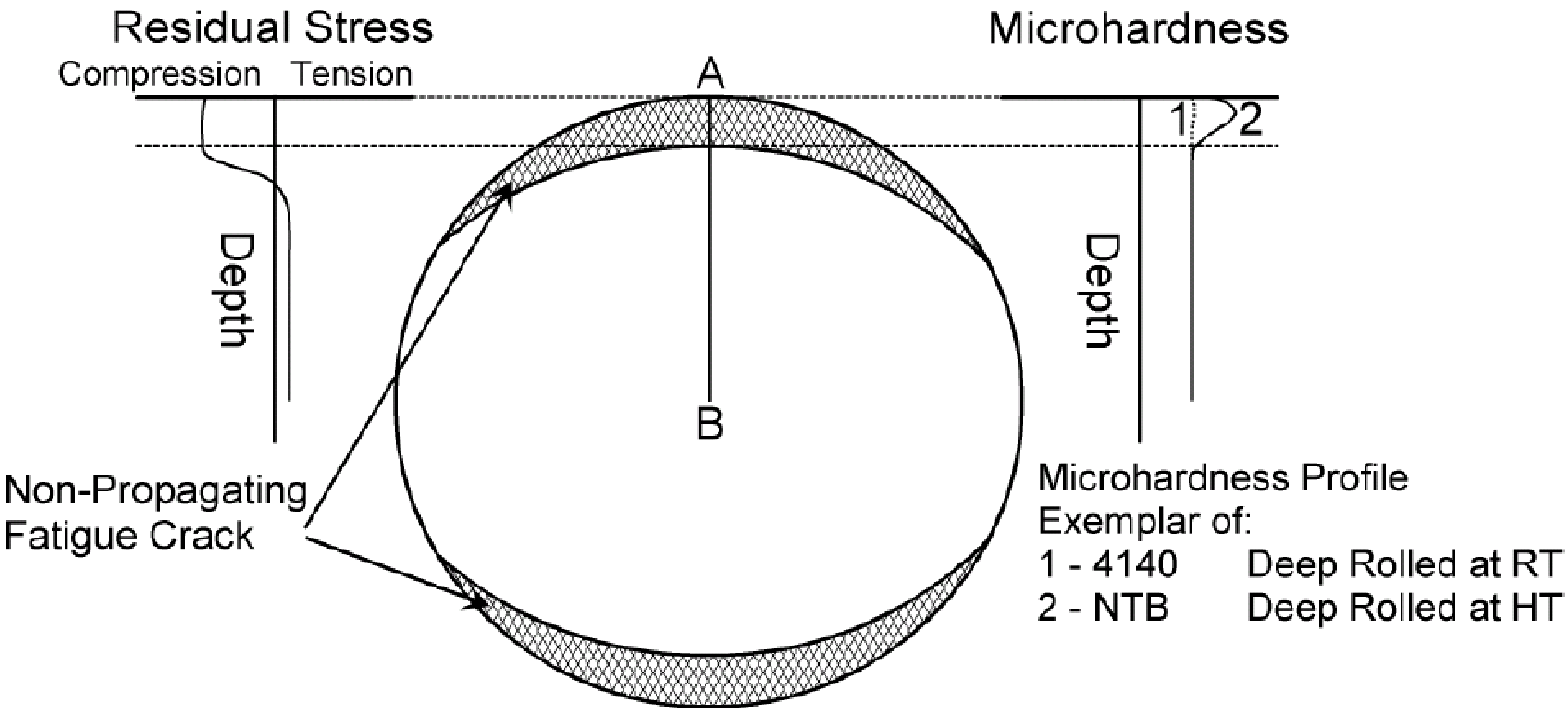


C38M





Schematic of Crack Arrest

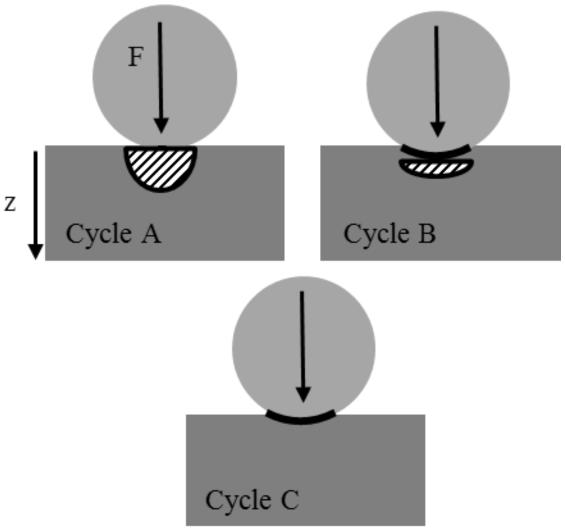


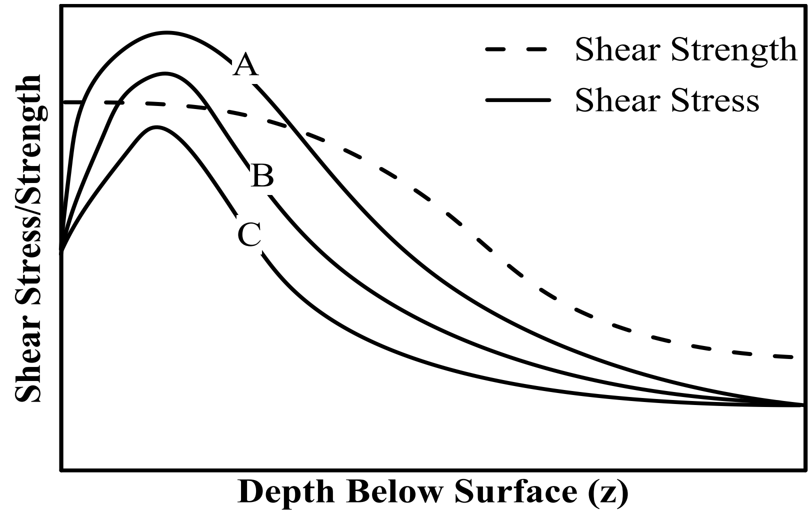
Summary

- There is a competition between crack nucleation due to inclusions or microstructural damage in case-hardened alloys
  - Controlled by the local strength, fatigue crack growth resistance, and inclusion population of the alloy
- Fatigue resistance of case-hardened alloys is controlled by microstructural features and residual stresses that are dependent on prior processing and loading conditions

Evolution of Stress and Alloy Strength

Strain Hardening/Ratchetting





Geometrically Induced Stress Changes