# The Effects of Copper on Wear and Rolling Contact Fatigue of Hypereutectoid Rail Steels

Jarred Froman

# ASPPRC

**A**dvanced **S**teel **P**rocessing and **P**roducts **R**esearch **C**enter.

Industry/University Cooperative Research

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Glenn Eavenson

# Project Funded by EVRAZ, Pueblo and COEDIT

- Evraz
  - Largest Supplier of Rail in North America
  - Dr. Mark Richards
  - Joe Kristan
  - Dr. Greg Lehnhoff
- Colorado Office of Economic Development and International Trade
  - Looking to advance the state's economy through financial and technical assistance

# Industrial Relevance - Copper

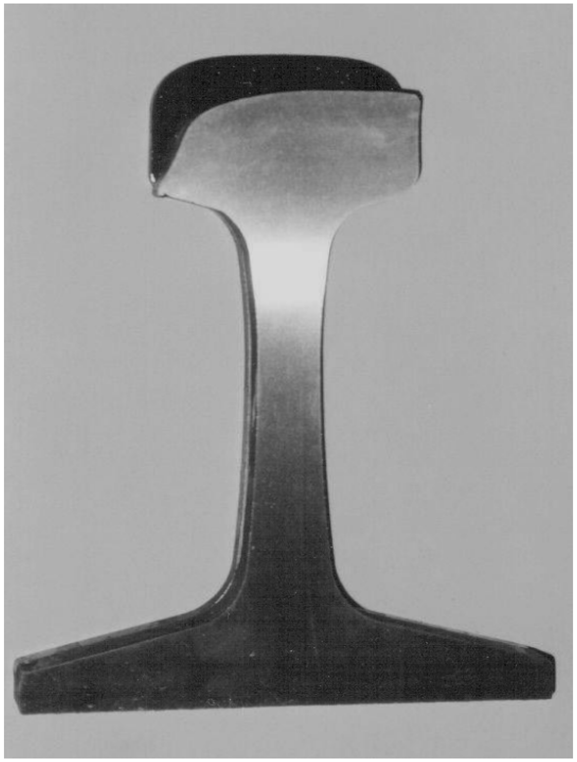
- Each rail supplier in North America produces rail through EAF steelmaking.
- Increase electrical equipment in scrap sources have caused residual copper levels to rise.
- There is not a practical and economical method for the removal of copper.
- Increased production from electric arc furnaces have led to greater demand for low residual scrap.

Yellishetty et al., 2011
Noro et al., 1997

# Industrial Relevance – Wear

- Wear is the progressive loss of material from the surface as a result of relative motion
- Wear is the main cause of rail replacement in rail lines.

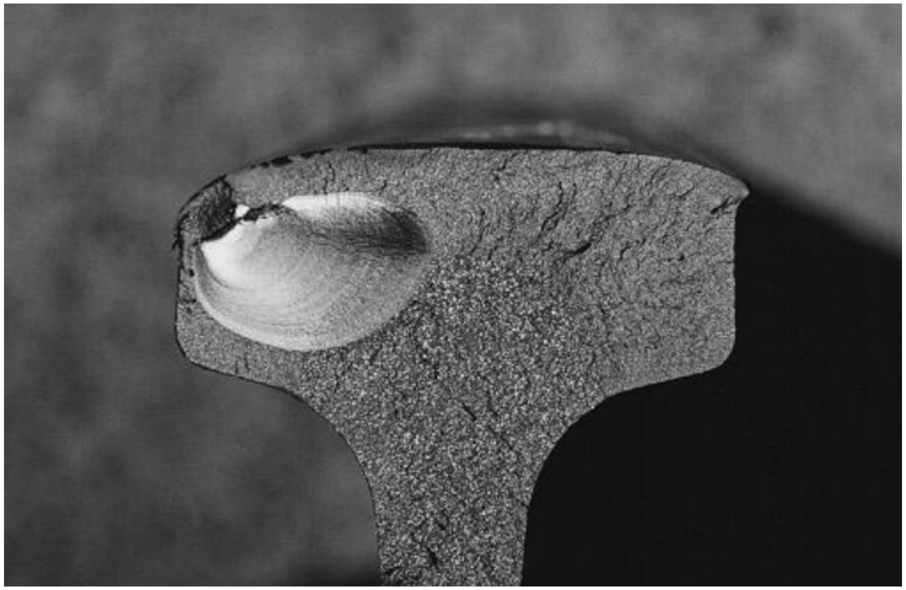
Cannon et al., 2003



S. Marich., 2009

# Industrial Relevance – Rolling Contact Fatigue

- Rolling Contact Fatigue (RCF) is the initiation and propagation of cracks as material is subjected to repeated cyclic stresses as wheels roll along the rail.



S. Marich., 2009

# Materials

| Alloy | C | Mn | Si | Ni | Cr | Mo | Cu |
|---|---|---|---|---|---|---|---|
| 0.07 Cu | 0.93 | 1.02 | 0.38 | 0.04 | 0.23 | 0.01 | 0.07 |
| 0.38 Cu | 0.93 | 1.01 | 0.33 | 0.08 | 0.22 | 0.02 | 0.38 |
| 0.85 Cu | 0.93 | 1.05 | 0.32 | 0.07 | 0.21 | 0.02 | 0.85 |
| IH | 0.76 | 0.81 | 0.24 | 0.08 | 0.24 | 0.02 | 0.22 |

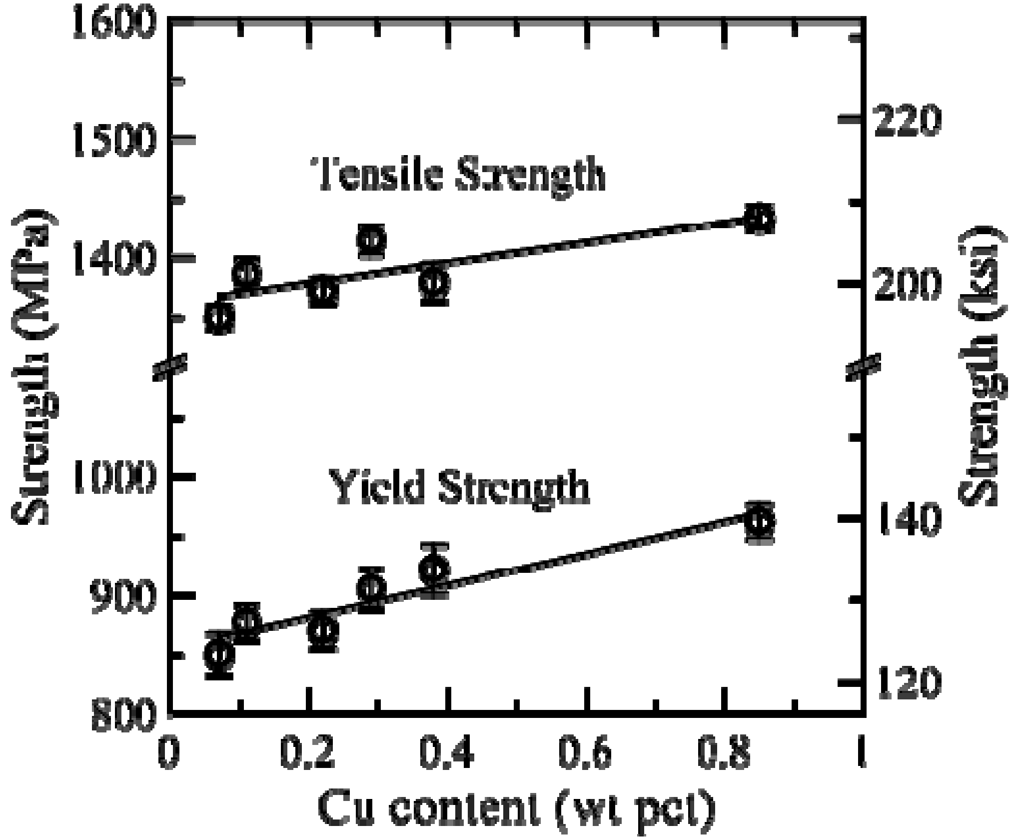
- 3 Heats of Hypereutectoid rail
- 1 Heat of Intermediate Hardness as a frame of reference

# Material Processing

- All of the material was industrially produced
  - EAF Steelmaking
  - Continuously Cast
  - Reheated
  - Hot Rolled
  - Head Hardened
  - Cold Straightened

# Mechanical Properties

- An increase in yield and tensile strength were observed with increasing Cu content.



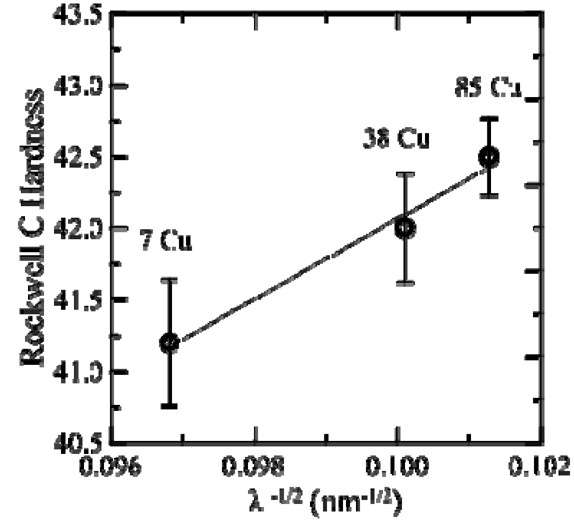

G.E. Eavenson, 2015

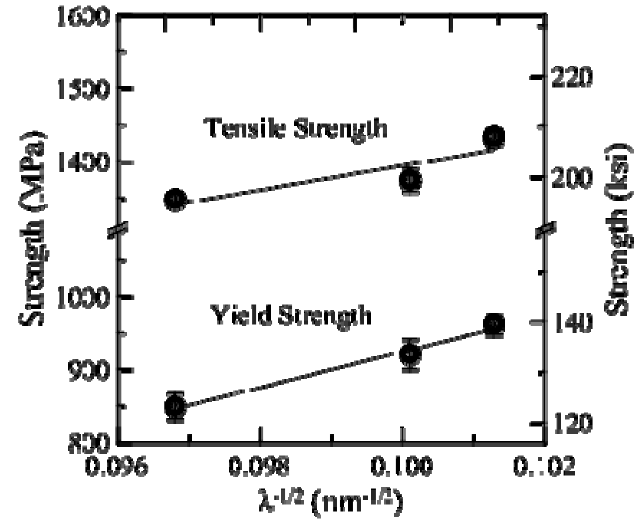
# Strengthening Mechanisms

- Cu content increases retards pearlite transformation
  - Refines Interlamellar Spacing, λ
- Hall-Petch Relationship

$$\sigma = \sigma_0 + k\lambda^{-\frac{1}{2}}$$

  - Interlameller spacing decreases, strength increases.

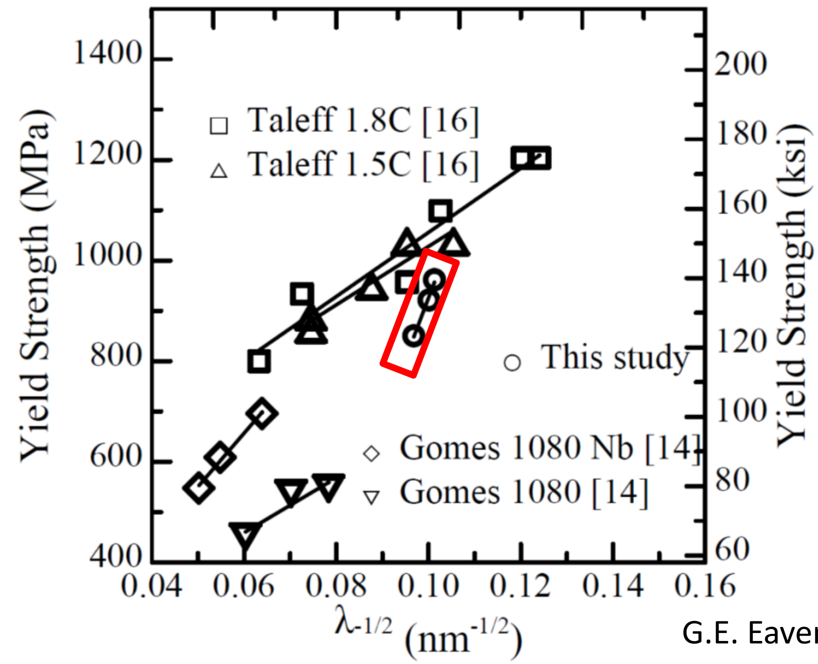


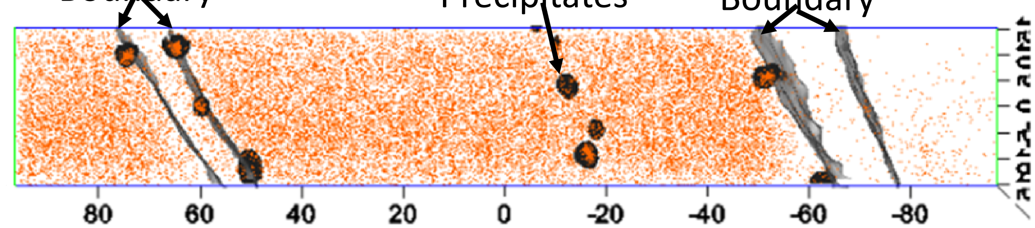

G.E. Eavenson, 2015

# Strengthening Mechanisms

- Strength increases more than expected for simply decreasing λ.
- Presence of another strengthening mechanism.
- Copper Precipitates inhibit dislocation motion.



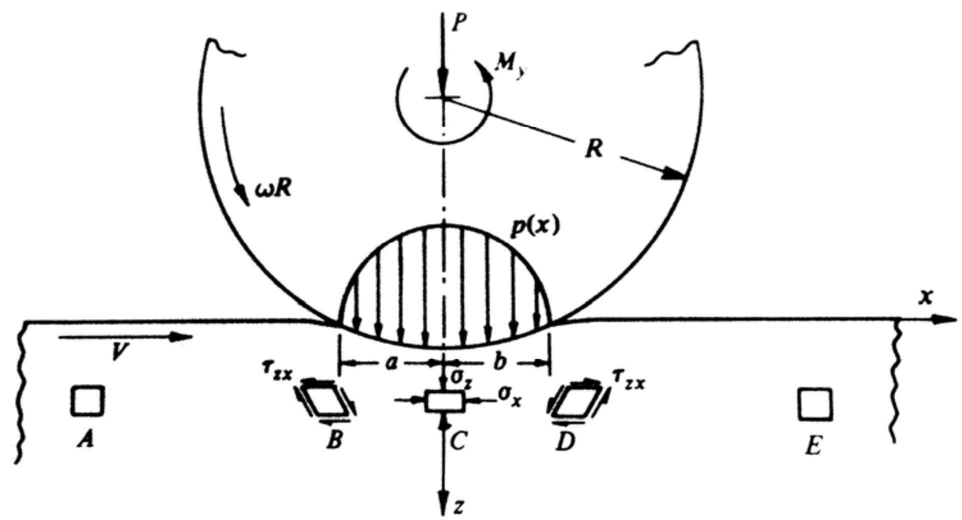

G.E. Eavenson, 2015




Courtesy of Dr. Stephanie Kaster

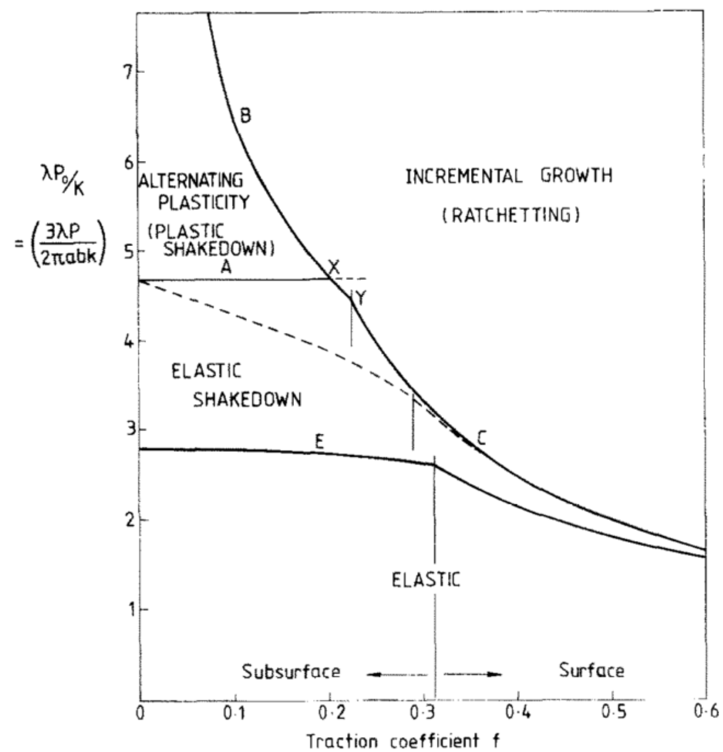
# Rail/Wheel Contact

During pure rolling, material in the rail undergoes a pattern of reversed shear and compression.



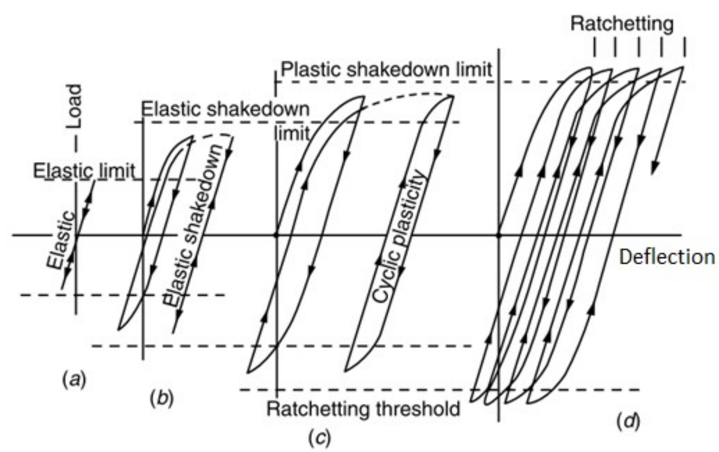

K.L. Johnson, 1985

# Shakedown Diagram



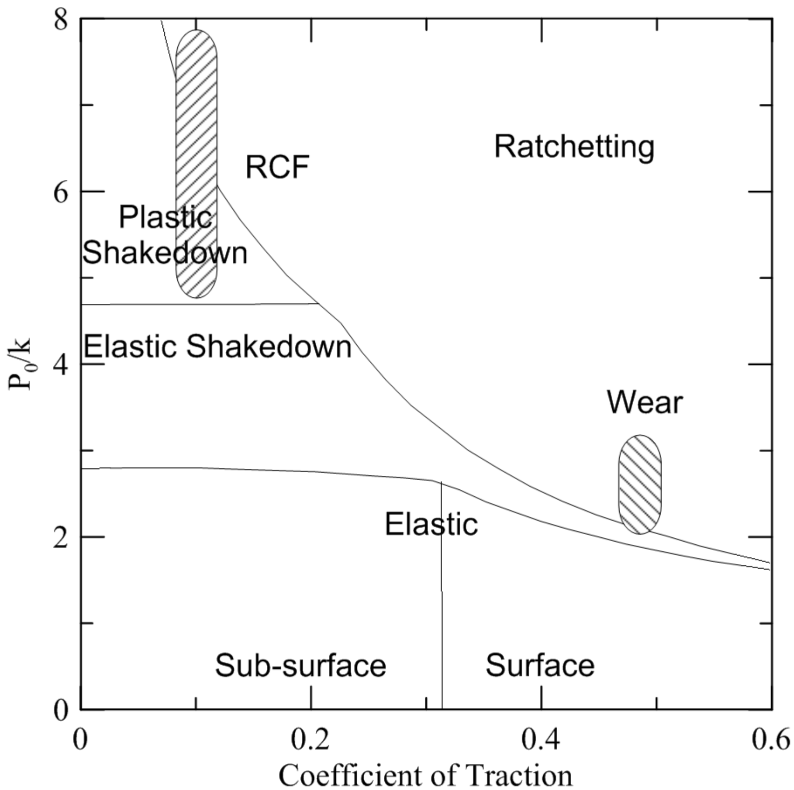

Bower and Johnson, 1991

- The accumulation of residual stresses may limit cyclic deformation.
- Assumes Perfectly Elastic Perfectly Plastic Material.
- This shakedown diagram is for a circular contact patch.




Kapoor et al., 2001

# Shakedown Diagram



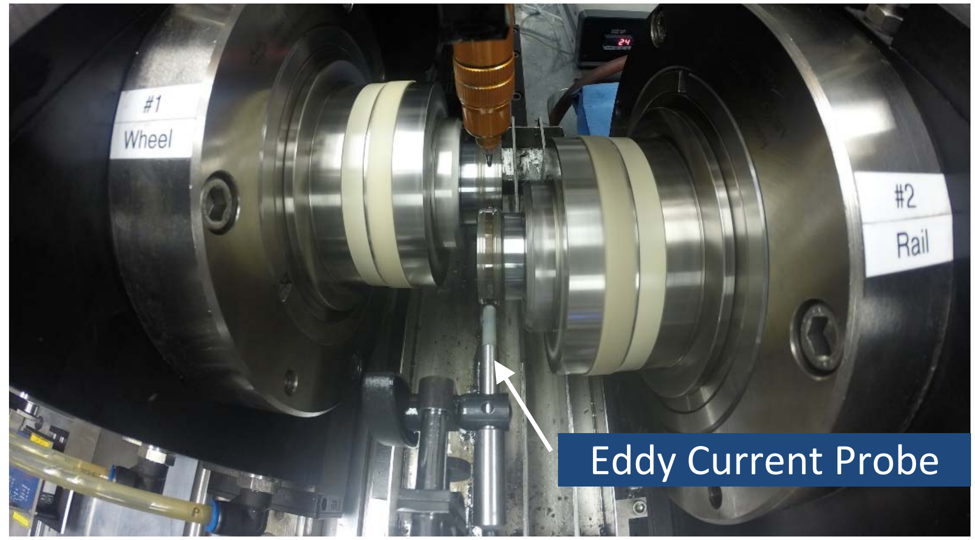

Modified from Bower and Johnson, 1991

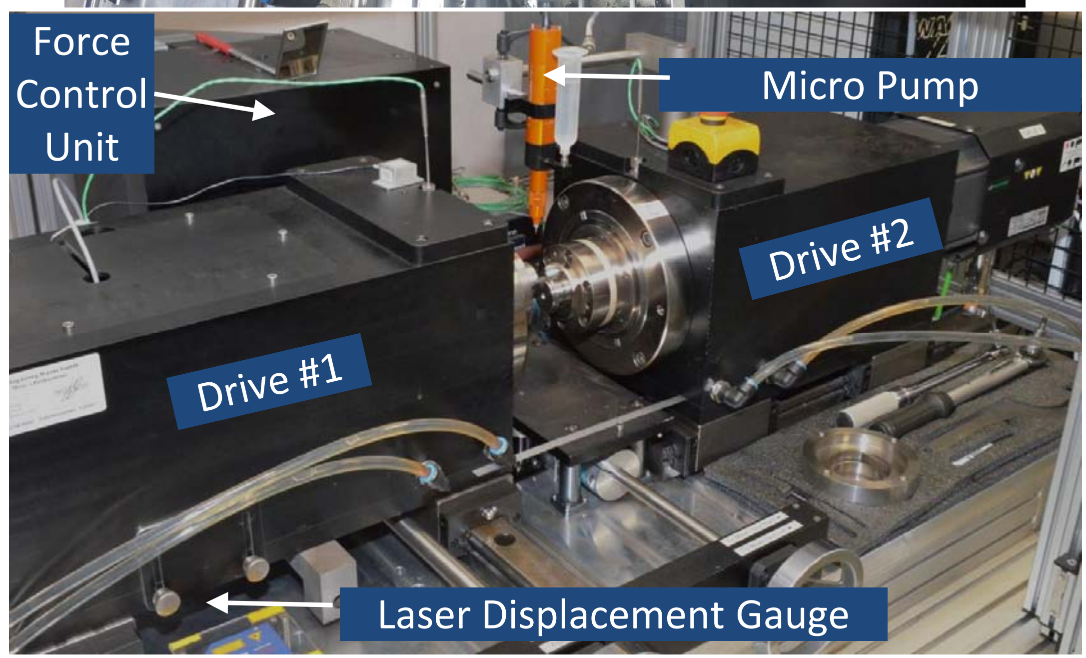
- Wear Testing
  - High T/N (~0.5)
    - Unlubricated
  - Low Hertzian Contact Stresses

- RCF Testing
  - Low T/N (~0.1)
    - Fully Lubricated.
  - High Hertzian Contact Stress

# Wazau UTM 5000

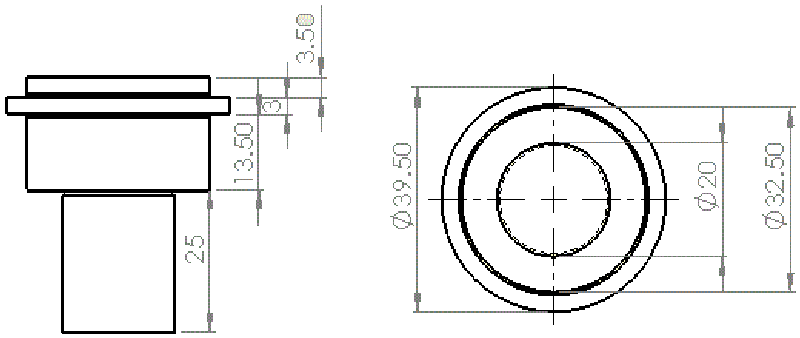
- 5000 N Force Capacity
- 50 N*m Torque Capacity
- Independent drive spindles
- In-situ eddy Current
- Micro pump lubrication system



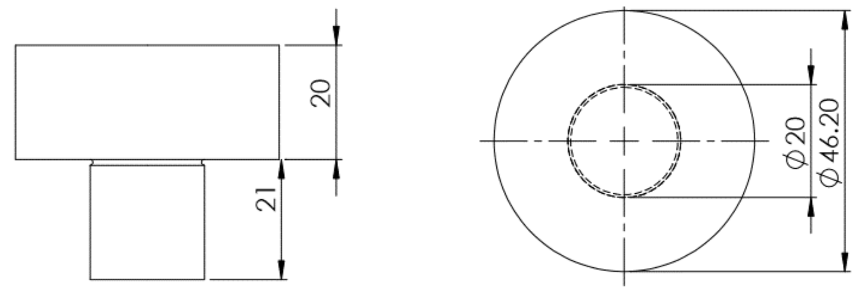



# Wear Testing - Samples

**Rail Wear Sample**




**Wheel Surrogate Sample – IH Material**



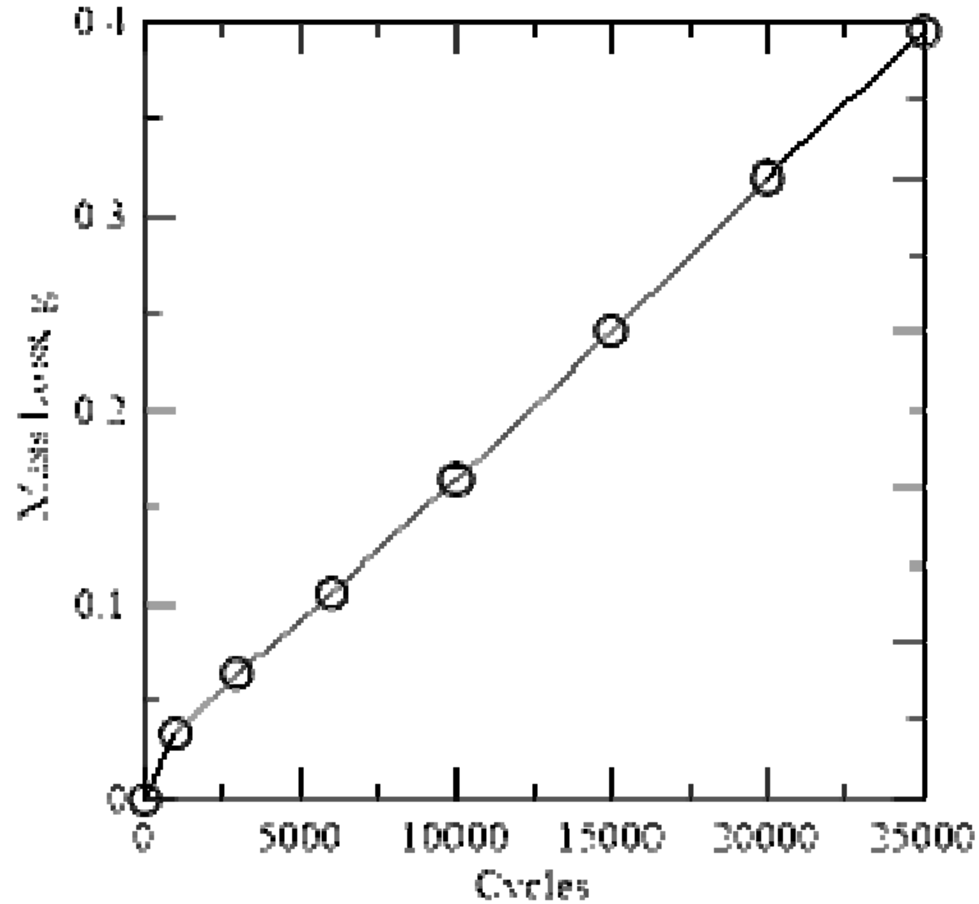

Courtesy of Dr. Mark Richards

# Wear Testing – Testing Conditions

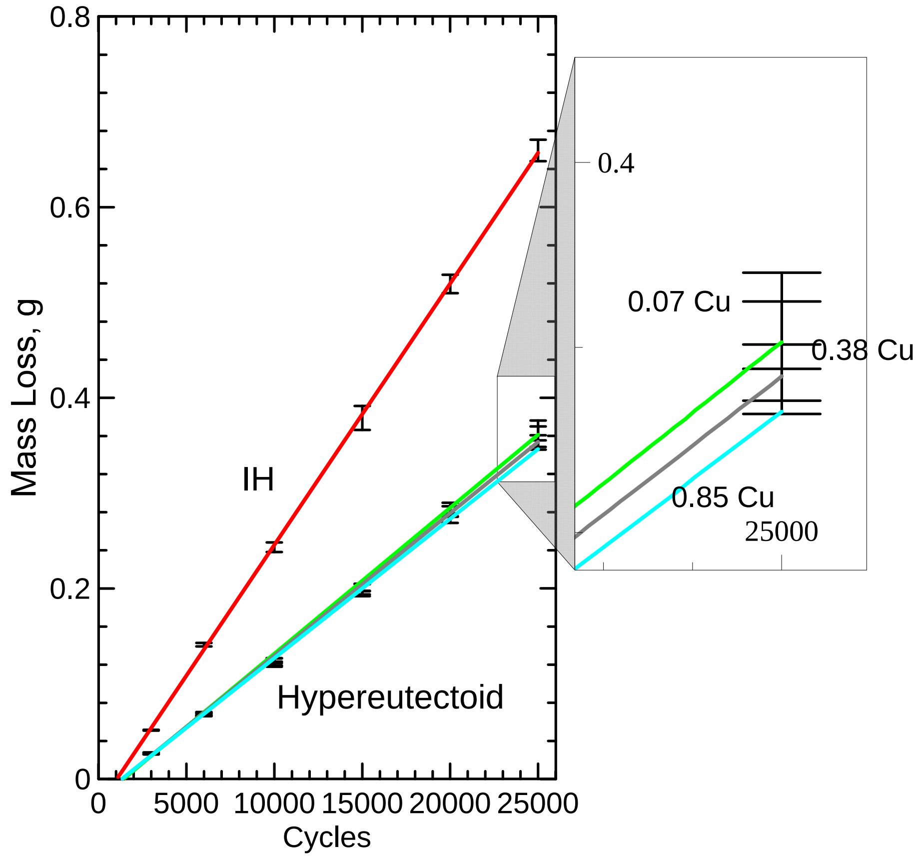
- Contact Pressure, $P_0 = 1300\ MPa$
- Slip Ratio = 10 % where the $V_{wheel} > V_{Rail}$
  - $Slip\ Ratio = \frac{V_{Wheel} - V_{Rail}}{0.5\ (V_{Wheel} + V_{Rail})} * 100\%$
- Unlubricated
- Rail samples cleaned and weighed at 1,000, 3,000, 6,000, 10,000, 15,000, 20,000, and 25,000 cycles.
- Contact Patch was switched at 10,000 cycles to prevent spalling of the surrogate wheel.

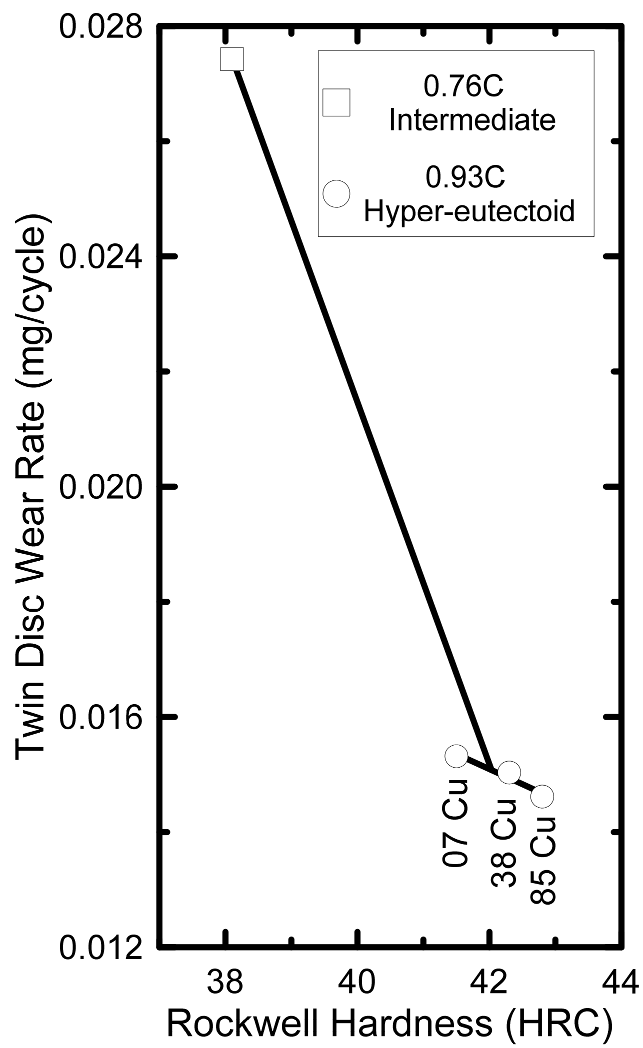
# Wear Testing - Results

- Initial high wear rate
  - Run – in period
- Subsequent linear wear rate
- Materials compared after first 1000 cycles.

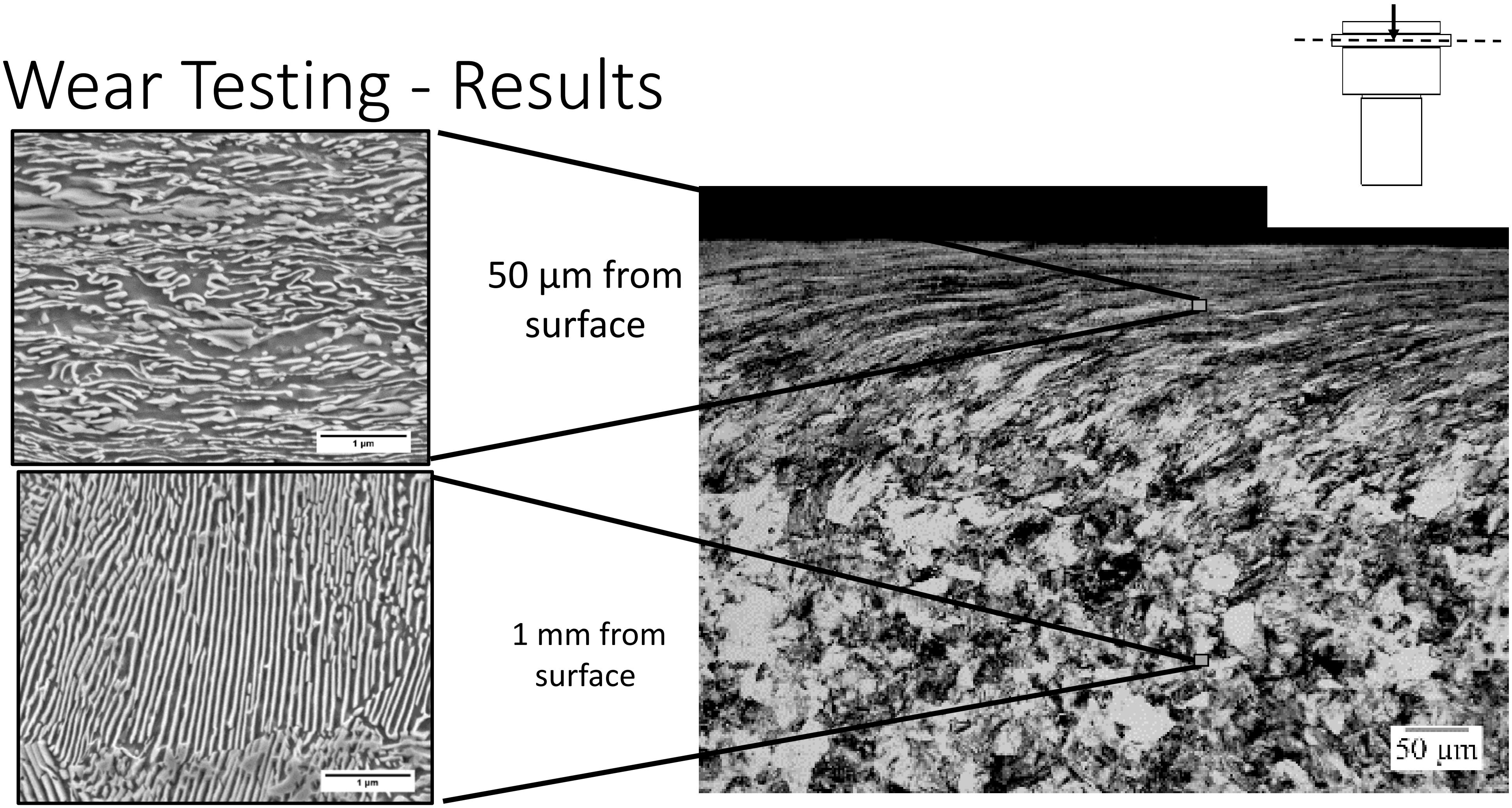


# Wear Testing - Results



# Wear Testing - Results



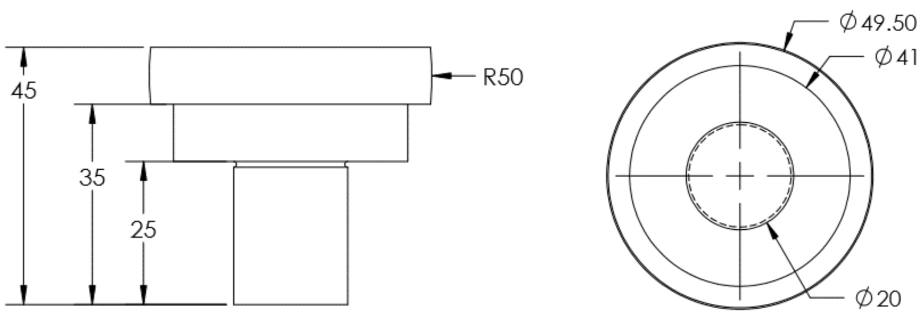
# Wear Testing - Results

- Unlubricated, twin-disc wear testing shows an approximately 4% decrease in the wear rate from the 0.07 wt % Cu rail to the 0.85 wt % Cu steel

- The increase in hardness and tensile strength with increasing copper does not have as much of an impact on the wear resistance as expected from increasing the hardness and tensile strength with increased C content.

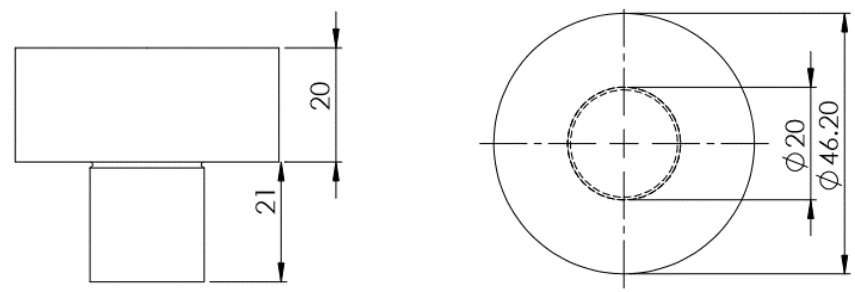
# RCF Testing - Samples

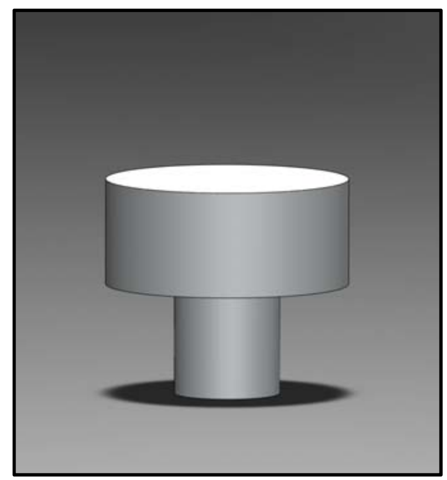
## Rail RCF Sample




Courtesy of Dr. Mark Richards

## Wheel Surrogate Sample – Q&T 4140 Material



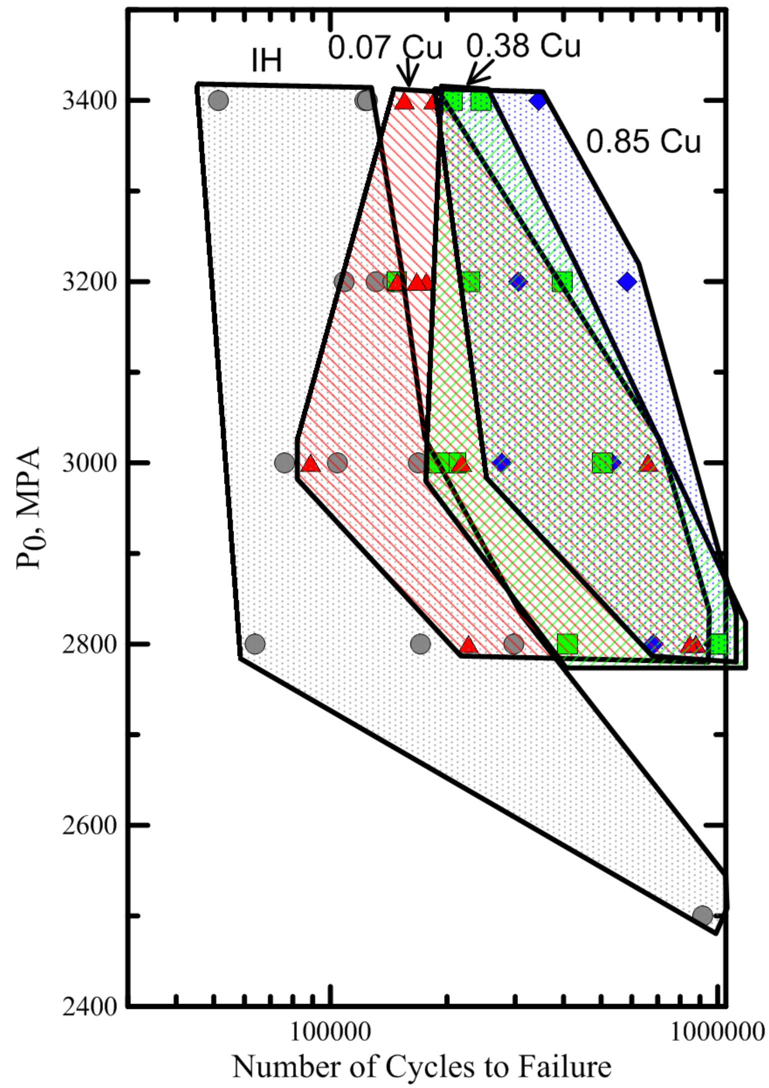



# RCF Testing – Testing Conditions

- Fully Lubricated
  - Commercially Available Top-of-Rail Friction Modifier
- Contact Pressures of 2800, 3000, 3200, 3400 MPa
  - IH material also tested at 2500 MPa
- 1,000,000 cycle runout
- Eddy Current Arrest Criteria
  - Calibrated off of 1.0 mm EDM flaw in a reference sample
  - Secondary Failure Criterion of accelerometer, force limit and torque limit for machine safety.

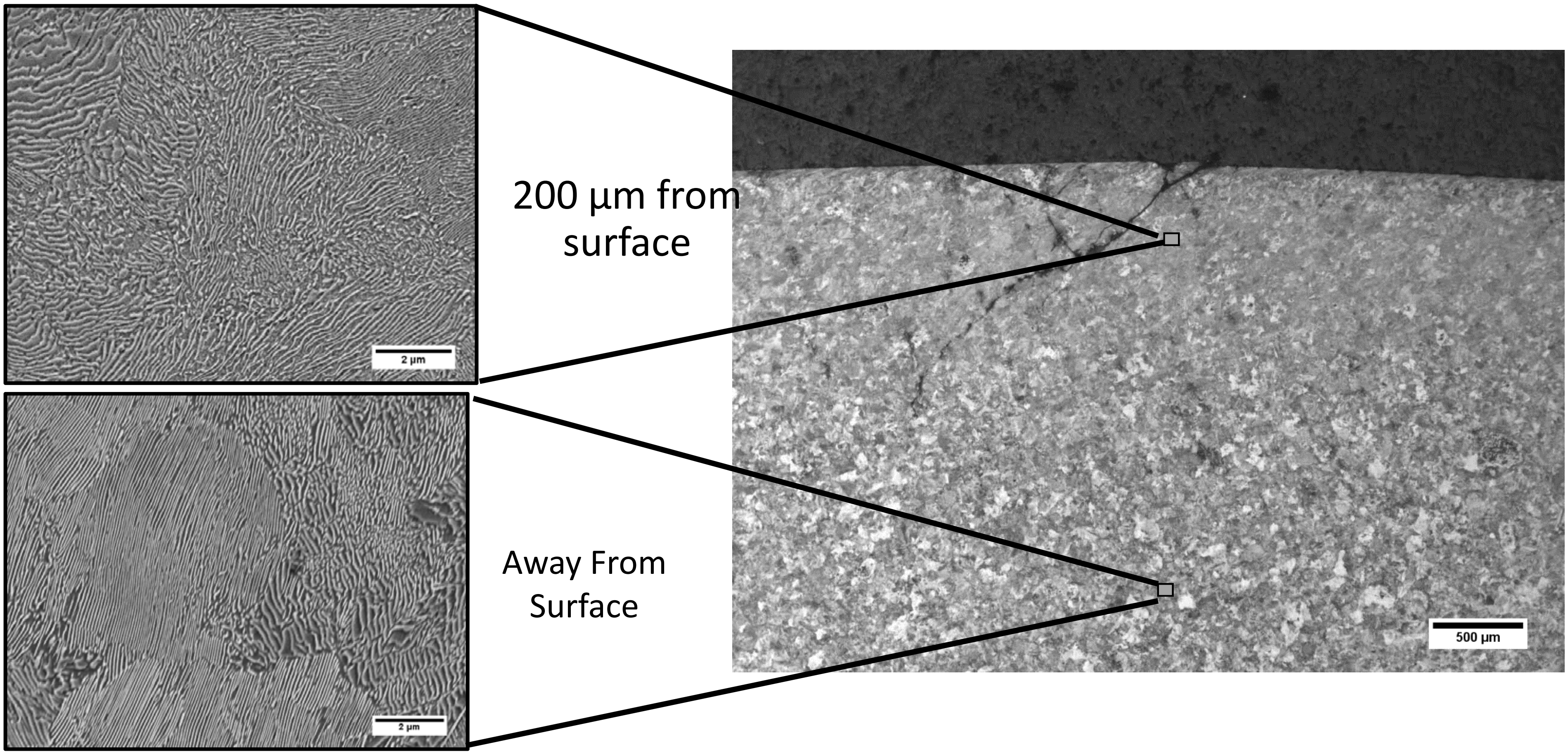
# RCF Testing - Results

- Initial Maximum Contact Pressure, $P_0$, vs. RCF Cycles to Failure
    - Based Upon Initial Geometry
    - Hypereutectoid rail had a longer RCF life than the IH rail
    - RCF life increased with increasing Cu content in the hypereutectoid rail.
    - Slight increase in RCF life with decreasing contact pressure



# RCF Testing - Results

0.85-Cu

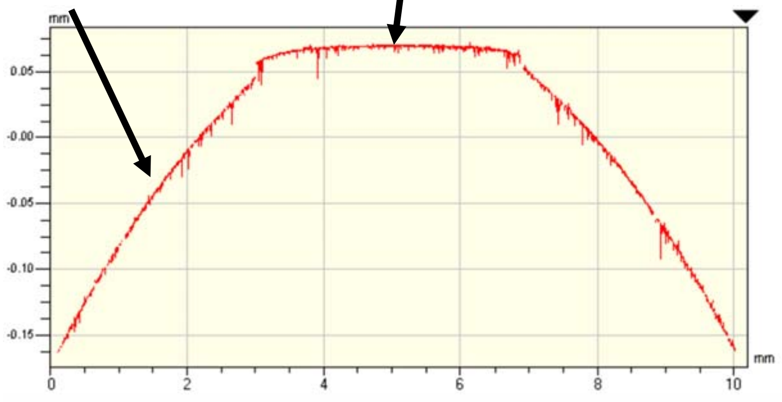


# RCF Testing - Results

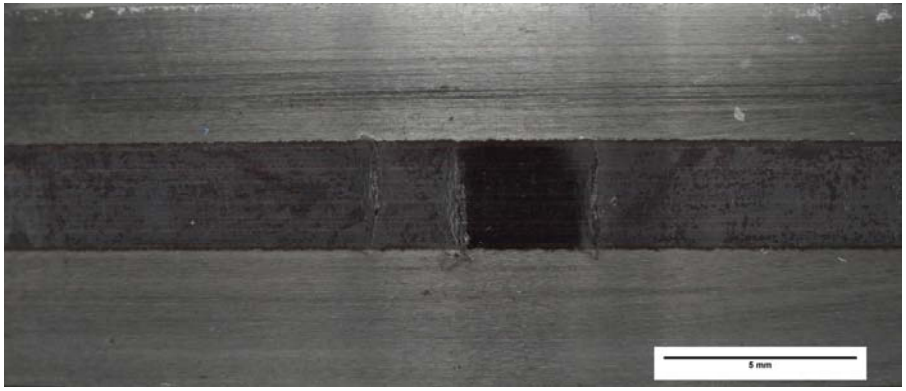
- Material plastically deformed and conformed to the harder wheel

Machined Crown

Contact Area

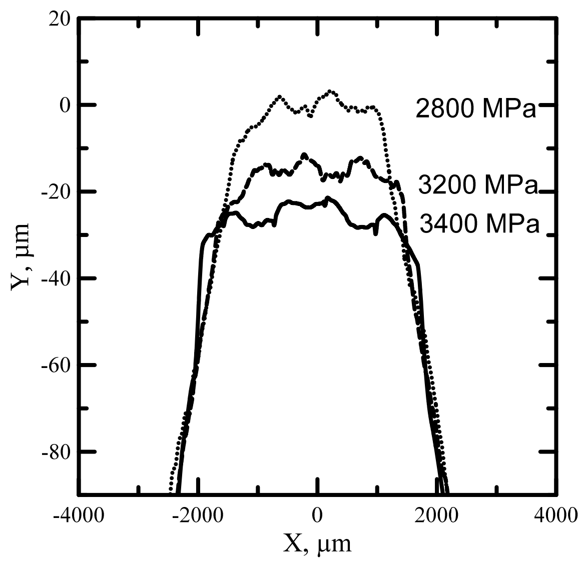


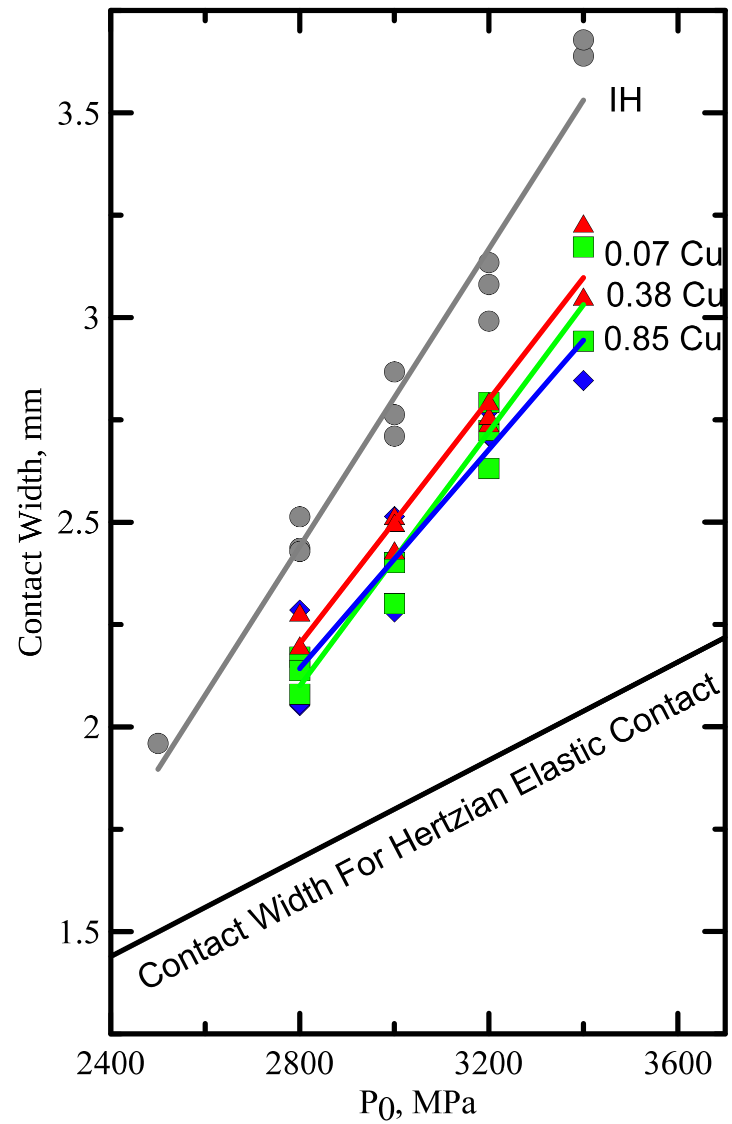

- The samples developed a dark band at the contact patch
  - Heat generation from plastic deformation



# RCF Testing - Results

- Conformal Deformation at the Contact Patch
  - Larger at higher contact pressure
  - Larger with lower strength material

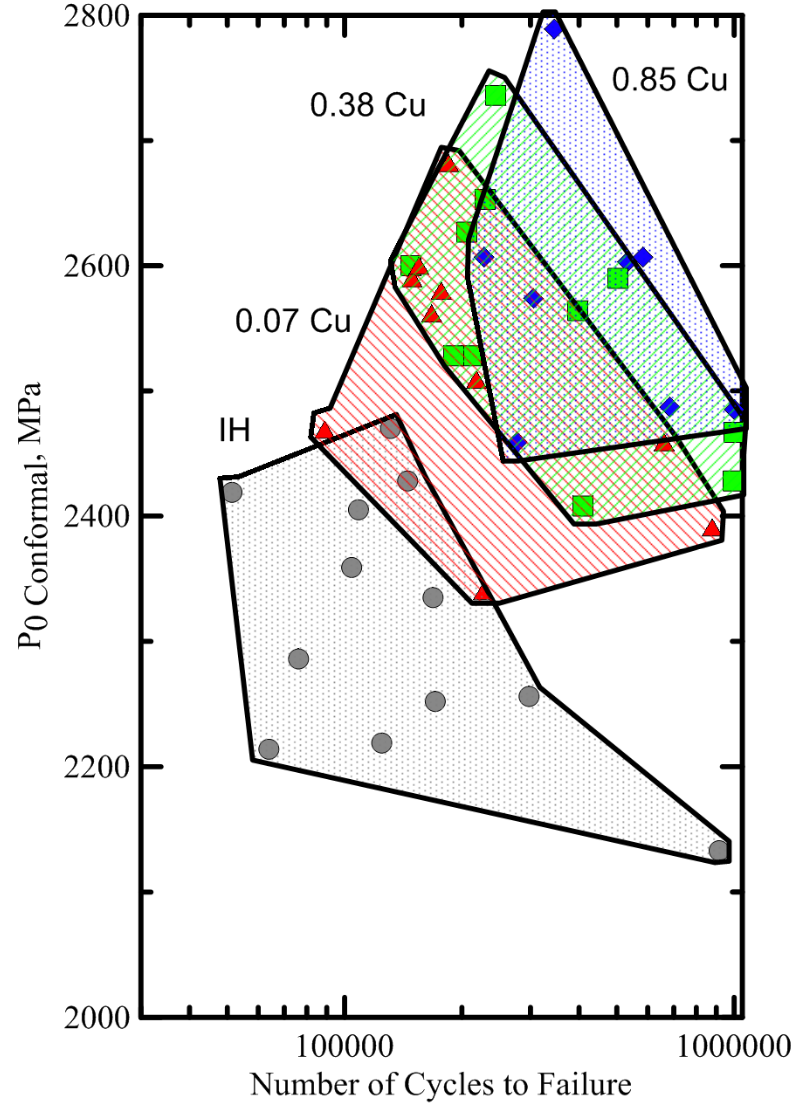


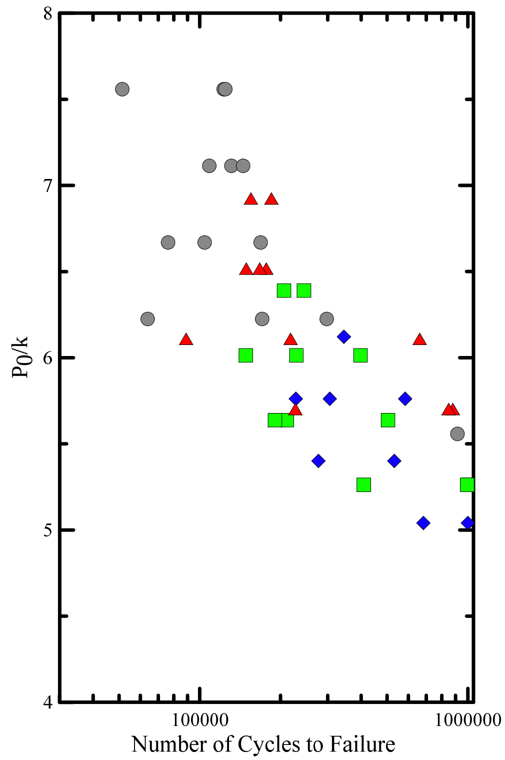
# RCF Testing – Conformal S-N

- Lower strength material is subjected to lower contact pressures for a given initial contact pressure
- We need a way to calculate the sustained contact pressure
- Calculated conformal contact pressure from load, and measured contact width, using the crown radius as a degree of freedom.

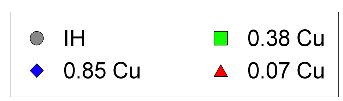
- **IH < 0.07Cu < 0.38Cu < 0.85Cu**

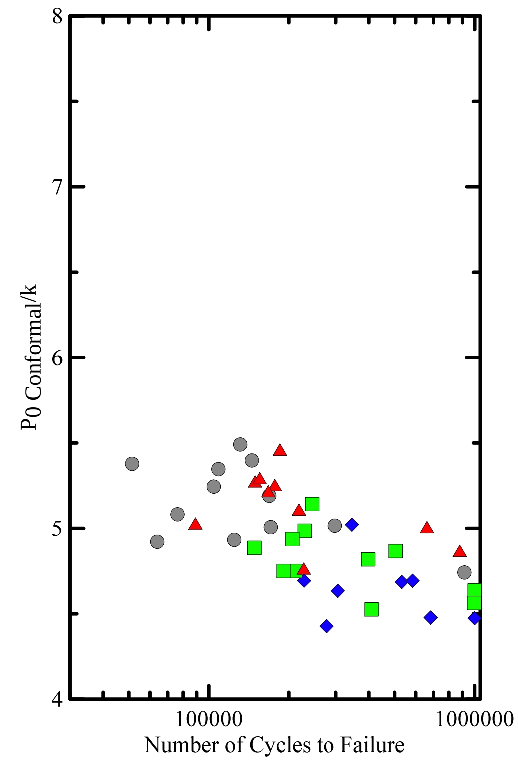


# RCF Testing – Normalized S-N




- RCF life of all of the materials forms a narrow band when normalizing the initial contact pressure and the conformal contact pressure by the shear yield strength of the material.



# Conclusions

- Increased copper content of the material increased the yield strength and the tensile strength of the material.
- Increasing the Cu content of the material slightly increased wear resistance, however it appeared to have a much smaller impact than increasing C content
- Increasing the Cu content of the material increased the RCF life of the material.

- If processing is controlled well enough, Cu can be used as a beneficial alloying element.

# References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