FE MODELING OF CARBIDE ASSISTED CYCLIC HARDENING IN BEARING STEELS DURING ROLLING CONTACT FATIGUE

Anup S. Pandkar
Nagaraj Arakere
Ghatu Subhash

Mechanical & Aerospace Engineering Department
University of Florida, Gainesville

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Outline

• Introduction to Rolling Contact Fatigue
• Experimental findings and interpretations (3 ball-on-rod tests)
• Research objective
• FEA modeling technique
• Comparison of results (experimental vs. simulation)
• Conclusions
Rolling Contact Fatigue (RCF)

Ref: images.yourdictionary.com


Ref: Lundberg & Palmgren (1947)

Ref: Branch N. (2010)
Accelerated Ball-on-Rod RCF Test

**M50-NiL bearing steel**
- Case hardened steel
- Graded material properties
- Vanadium carbides
- Spherical, uniformly distributed and ~1 μm

Max. Hertz stress can be controlled

8600 RCF cycles/min

Ref: Klecka M. (2011)

Experimental Results

**M50-NiL rod**

**Si₃N₄ balls**

**Rod surface**

**RCF affected region**

**Vickers indents**

**Tabor’s rule**

\[ \sigma_y = \frac{H}{CF} \]

**For M50-NiL**

\[ CF = 2.5 \]

**Ref: Bhattacharyya et al. (2014)**

![Graph showing centerline depth vs hardness](image)

**Hardness (Hv)**

**Centerline depth (µm)**

**After 246x10⁶ cycles**

![Graph showing stress vs centerline depth](image)

**Centerline depth (µm)**

**Ref: Bhattacharyya et al. (2014)**
Research Goals

The primary objective of this research is to understand the cause of such increase in hardness over millions of RCF cycles i.e. cyclic hardening.

In doing so we would also learn,
- The response of bearing steels to the RCF loads
- Role of microstructure towards RCF failures
- Account for material plasticity
- Determination of cyclically evolving stress-strain fields
Finite Element Model of RCF Test

Model accounts for:
• Continuously changing contact
• Cyclic plasticity
• Graded material properties
• Localized & Multiaxial stresses

Computationally expensive

40 hrs./rev of rod

2 revolutions are simulated i.e. 6 RCF cycles
Finite Element Model of RCF Test

Radial load

Si$_3$N$_4$ ball

M50-NiL rod

Global model

Contact region

Region of interest

Submodel

Ball

Rod

σ$_y$

τ$_{xy}$

σ$_x$

σ$_y$

Carbide

Matrix

S$_1$, Mises (Avg: 75%)

- 3.343e+03
- 3.064e+03
- 2.786e+03
- 2.507e+03
- 2.229e+03
- 1.950e+03
- 1.672e+03
- 1.393e+03
- 1.115e+03
- 8.364e+02
- 5.579e+02
- 2.794e+02
- 8.898e-01
Orthogonal Shear Stress Cycle

Carbides (or any other form of heterogeneity)

Alter shear stress cycle

Non-zero mean shear stress

Global model (without carbides)

Submodel (with Carbides)

Shear stress (MPa)

Rolling direction

Rolling direction

$\tau_{min} \approx -1420 \text{ MPa}$

$\tau_{min} \approx -1580 \text{ MPa}$

$\tau_{max} \approx 1428 \text{ MPa}$

$\tau_{max} \approx 1800 \text{ MPa}$

$\tau_m \approx 0 \text{ MPa}$

$\tau_m \approx 110 \text{ MPa}$
Ratcheting Near Carbide Particle

Global model (without carbide)

Submodel (with carbide)

Global model does not cyclically accumulate plastic strain
Elastic shakedown

The stress concentration and non-zero mean stress promote continuous plastic strain accumulation
Ratcheting mechanism

Ratcheting ⇔ Cyclic hardening

Monotonic loading

Plastic strain accumulation ⇔ Material hardening (Increase in yield stress)

Cyclic loading

Continuous Plastic strain accumulation (Ratcheting) ⇔ Continuous Yield stress increase (Cyclic hardening)

localized ratcheting ⇔ cyclic hardening

Ref: Stephens et al. (2000)
Vickers indents on the surface of a test rod after 246x10^6 cycles. The centerline depth of indents is measured. The graph shows the relationship between the number of RCF cycles and the von-Mises stress. The peak stress remains constant throughout the cycles. The submodel represents the representative indent based on the volume fraction (Vf) of carbides. Upper stress limit controls the extent of cyclic hardening.
Variation of Cyclic Hardening Near Carbide

\( (\sigma_{VM})_{max} = 3231 \text{ MPa} \)

\( (\sigma_{VM})_{max} = 3071 \text{ MPa} \)

\( (\sigma_{VM})_{max} = 3181 \text{ MPa} \)

\( (\sigma_{VM})_{max} = 2876 \text{ MPa} \)

\( (\sigma_{VM})_{max} = 2990 \text{ MPa} \)

\( (\sigma_{VM})_{max} = 3170 \text{ MPa} \)

\( (\sigma_{VM})_{max} = 3273 \text{ MPa} \)

\( (\sigma_{VM})_{max} = 3238 \text{ MPa} \)

\( (\sigma_{VM})_{max} = 3181 \text{ MPa} \)
Average Cyclic Hardening over an indent

\[
(\sigma_y)_{FEA} = \frac{\sum_{n=1}^{N} [V_n \times ((\sigma_{VM})_{\text{max}})_n]}{\sum_{n=1}^{N} V_n}
\]

- \((\sigma_y)_{FEA}\) – volume averaged yield strength
- \(V_n\) – volume of a FE 'n'
- \(((\sigma_{VM})_{\text{max}})_n\) – peak von-Mises stress in FE 'n'
- \(N\) – number of FE in the submodel

Discrepancy at 75 μm depth can be attributed to:
- Edge effects (indent is closest to the surface)
- Cyclic hardening is governed by max. VM stress that occurs at 150 μm
- 2D plain strain model instead of 3D model
Conclusions

1. Carbide particles $\rightarrow$ Shear stress cycle with non-zero mean stress
2. Stress-controlled loading + Non-zero mean stress $\rightarrow$ Ratchetting
3. Ratcheting $\rightarrow$ Cyclic hardening during RCF

Publications


Author Contact

Dr. Anup Pandkar
Email: apandkar@ufl.edu
LinkedIn: https://www.linkedin.com/in/anuppandkar