Micromechanics Analysis of Fretting Fatigue

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Leon Keer Symposium, Symi 2010

**Leon: “focus on real problems”**
Fretting Fatigue Experiment

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Oscillating $\sigma_o$ creates an oscillatory tangential force, $\Delta Q$ (fretting contact).

Specimen is cycled to failure.

Nominally flat pads are used to simulate blade/disk fretting contact.

The test is designed so that conditions of partial slip exist at the contact interface.

$\mu$ is measured by increasing $\sigma_0$ until gross sliding occurs at the contact interface.
Mechanics of Fretting

Flat Punch Problem

\[ \frac{dw}{dx} = 0 \text{ at contact surface} \]

infinite peaks in pressure at edges of contact

Fretting Problem

\[ \frac{du}{dx} = 0 \text{ at contact surface for complete stick} \]

infinite shear traction required at edges of contact

\[ |Q| < \mu_{\text{avg}} P \]
For localized **stick**, $|q(x)| < \mu p(x)$

For localized **slip**, $|q(x)| = \mu p(x)$

$\text{sgn}(\delta) = -q(x)/\mu p(x)$

**normal pressure,** $p(x)$

$\text{shear tractions, } q'(x)$ and $q''(x)$

**net normal and shear tractions**
Coupled Thermoelasticity

• Helmholtz free energy

\[ f(\varepsilon_{ij}, T) = u(\varepsilon_{ij}, T) - Ts(\varepsilon_{ij}, T) \]

– strain and temperature are independent variables

– For isotropic body, constitutive relation becomes

\[ \sigma_{ij} = \lambda \delta_{ij} \varepsilon_{kk} + 2 \mu \varepsilon_{ij} - (3\lambda + 2\mu) \alpha \Delta T \]

– where \( \lambda \) and \( \mu \) are isothermal Lamé constants

• Heat conduction in terms of strain

\[ k \nabla^2 T = \rho C_v \dot{T} + T \left[ \left( 3K \alpha - \frac{\partial \lambda}{\partial T} \varepsilon_{kk} \right) \varepsilon_{ll} - 2 \frac{\partial \mu}{\partial T} \varepsilon_i \varepsilon_i \right] \]
Infrared Thermography

• Modular forward looking infrared (FLIR) sensor
• Offers full-field real-time temperature measurement with resolution down to 10 μm
• Relies on an InSb focal plane array to convert thermal radiation to intensity values
• Sensitivity of 0.025 K
• Calibration performed between intensity and temperature
• Uniaxial tension tests used for verification
Fully-Coupled Thermoelasticity

Uniaxial tension

Theoretical temperature = \( T_o - \frac{\alpha T_o}{\rho C_p} \sigma_{kk} \)
Temperature Measurement

- load cell washer
- specimen strain gages
- beam strain gages

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\[ \sigma = \sigma_0 \sin \omega t \]
Partial Slip (Ti-6Al-4V)

\[ P = 1200 \text{N/mm} \]
\[ (Q/P)_{\text{max}} = 0.35 \]
\[ (Q/P)_{\text{min}} = -0.19 \]
\[ \sigma_o = 283 \text{ MPa} \]
\[ \text{R-ratio} = 0.51 \]
\[ \text{radius} = 127 \text{ mm} \]

Harish, et al, 
*ASTM 1367*  
(2000)
Aluminum Temperature

\[ P = 504 \text{ N/mm} \]
\[ (Q/P) = 0.34 \]
\[ \sigma_o = 100 \text{ MPa} \]
\[ R\text{-ratio} = -1 \]
\[ \text{radius} = 178 \text{ mm} \]

IR Temperature Measurements

- A full-field real-time in-situ method of characterizing the near-surface temperatures in fretting contacts has been developed.
- The prominent features of gross sliding and partial slip contact have been identified from the temperature maps.
- A finite element implementation of the coupled thermoelastic effect has been developed (Verification).
- There is a strong correspondence between the applied loads and the peak temperatures.
- Change in friction coefficient is manifested as change in temperature near the center of contact (Validation).
Blade/Disk Contact Model

dovetail joint

contact surface

high-frequency aeroelastic drivers and system vibrations

rotating disk (bulk inertial stress)

equivalent contact problem

\[
g(x) = g_0(x) - u_{y_1}(x,0) + u_{y_2}(x,0) - C_0 - C_1x
\]

Contact Surface Geometry

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Variation of Q and P in Blade-Disk Dovetail

- Blade slides outward (along COF line) into dovetail during disk speed acceleration
- At maximum speed, bulk sliding stops and the ends of the contact are in partial slip
  - At lower speeds and during mission cycling, the shear load can experience both large ranges and changes in direction
- When the speed decreases to the point the shear load to normal load exceeds the COF, the blade will slide inward toward the disk bore (Gean and Farris, JAM, In-Press)
Step 1: governing equation

\[- \frac{dg_o}{dx} + C_1 = \frac{2(\kappa + 1)}{4\pi\mu} \int_a^x p(s)ds\]

Step 2: obtain series representation of contact geometry through discrete Fourier sine transform

\[- \frac{dg_o}{dx} \rightarrow \sum_{n=1}^\infty g_n \sin n\phi\]

Step 3: relate series representation of geometry to pressure distribution

\[\sum_{n=1}^\infty g_n \sin n\phi \propto \sum_{n=1}^\infty p_n \sin n\phi / \sin \phi\]

Step 4: use force and moment balance to obtain \(p_o\) and \(p_1\)

\[p_o = -\frac{P}{\pi a} ; \quad p_1 = -\frac{2Pd}{\pi a^2}\]

Step 5: obtain pressure distribution (FFT)

\[p(\theta) = p_o + \sum_{n=1}^\infty p_n \sin n\theta / \sin \theta\]

\(a\) is contact halfwidth, \(P\) is the applied force, \(d\) is the moment arm

Murthy, Harish, and Farris, JOT (2004), Leon and collaborators have made much progress in application of FFT to contact, including thermal effects

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Flat with Rounded Edges

McVeigh et al., *IJF*, 1999

2b = flat length
2a = contact length

P' = 9000 lbs/in
Q' = 2300 lbs/in

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• Addition of shear load (Q) results in highly localized stress at leading and trailing edges
• When the direction of shear load reverses, the leading edge becomes the trailing edge resulting in a very large fatigue cycle
Analysis of Fretting Experiments

Fretting contact is modeled as 2D, i.e., $u_x$, $u_y$, $u_z$ only depend on $x$ and $y$.

- For anisotropic materials $u_z(x,y)$ is not necessarily zero $\Rightarrow$ out of plane relative slip $\Rightarrow$ out of plane shear traction.

- The specimen is modeled as a half-space subject to remote stress.

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Example Load History Effects

- The final loads are the same for each of these examples
- Integral equations can be used for “Representative” missions can be
- For dissimilar materials, slip zones may be too small to resolve, Rajeev and Farris, JSA (2002)
  
  Goryacheva, Murthy and Farris, IJF, (2002), Sundaram and Farris, IJSS, (2009)

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Surface Observations

- Right pad
- Failure Test
- Fracture surface
- Fretting debris
- Fatigue crack growth
- Fast fracture
- Left pad
- Run-out Test
- Trailing Edges
- Left pad
- Right pad

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## Ti-6Al-4V on Ti-6Al-4V Experiments

<table>
<thead>
<tr>
<th>Exp.</th>
<th>P (lbs/in)</th>
<th>( \sigma_{\text{max}} ) (ksi)</th>
<th>( R_\sigma )</th>
<th>( Q_{\text{max}} ) (lbs/in)</th>
<th>( Q_{\text{min}} ) (lbs/in)</th>
<th>( N_f )</th>
<th>( \sigma_{\text{eq}} ) (ksi)</th>
<th>( N_i )</th>
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Life Prediction

- Alternating Walker equivalent stress, $\Delta \sigma_{\text{equiv}}$ was calculated at each point. The maximum stresses, $\sigma_{\text{max}}$ was capped at 110ksi as a first approximation to account for plasticity

$$\sigma_{\text{equiv}} = 0.5(\Delta \sigma_{psu})^w (\sigma_{\text{max}})^{(1-w)}$$

$w =$ walker equivalent stress component

(w = 0.433 was used for calculations)

- More weightage is given to max. tensile stress
- The stress invariants at a given location are defined as

$$\Delta \sigma_{psu} = \frac{1}{\sqrt{2}} \sqrt{(\Delta \sigma_{xx} - \Delta \sigma_{yy})^2 + (\Delta \sigma_{yy} - \Delta \sigma_{zz})^2 + (\Delta \sigma_{zz} - \Delta \sigma_{xx})^2 + 6(\Delta \sigma_{xy}^2 + \Delta \sigma_{yz}^2 + \Delta \sigma_{zx}^2)}$$

$$\sigma_{\text{mean}} = \frac{\beta}{2\sqrt{2}} \sqrt{(\sum \sigma_{xx} - \sum \sigma_{yy})^2 + (\sum \sigma_{yy} - \sum \sigma_{zz})^2 + (\sum \sigma_{zz} - \sum \sigma_{xx})^2 + 6(\sum \sigma_{xy}^2 + \sum \sigma_{yz}^2 + \sum \sigma_{zx}^2)}$$

$$\sigma_{\text{max}} = \Delta \sigma_{psu} + \sigma_{\text{mean}}$$

Equivalent stress corresponding to the smooth specimen data can be calculated as

\[
\Delta\sigma_{eq,1} = \left( \frac{F_{S_2}}{F_{S_1}} \right)^{\left( \frac{1}{\alpha} \right)} \Delta\sigma_{eq,2}
\]

\[
F_{S_2} = \sum_{i=1}^{n} \left[ -\left( \frac{\sigma_i}{\sigma_{i,max}} \right)^{\alpha} \right] \Delta A_i
\]

\( F_{S_1} = -0.161 \) (smooth spec.)
\( \alpha = 35 \) (from notch data)

Fretting Pad Fractography

- Heat tinting is useful for identifying cracks
- Featureless fracture surface and transition region
- Fretting fatigue cracks nucleate throughout the edge of contact with similar shapes and sizes
- Transgranular growth perpendicular to surface
- Severe wear and debris obscure fretting fatigue cracks on specimens

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• Transgranular Crack Growth
• Crack Growth perpendicular to surface
• Example at a Polished depth of 0.0365 inches

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Life Prediction Comparison

- Ti-6-4 on Ti-6-4
  - Two groups
    - P = 9300 lb/in, R = 0
    - P = 6700 lb/in, R = 0.5
- Life predictions
  - \( N_f = N_i + N_{prop} \)
  - \( N_i \) from \( \sigma_{eq} \)
- Total life prediction
  - 1-2 orders of magnitude above \( N_i \)
  - Good comparison with experiment using conventional life prediction tools

Leon and others applied fracture mechanics to contact fatigue in the 80s
Applied to various surface treatments, Murthy, Msies, and Farris, *Trib Int* (2009)

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Load transfer based on a principle similar to that of room temperature fretting rig
- Igniters used for heating the specimen and the pads, locally, to high temperature
- Temperature controller unit designed using the output of thermocouple as input signal
- Ceramic shields to prevent loss of heat
- Water used to cool the chassis and the wedges that grip the specimen
Coefficient of Friction Results

- Similar evolution in $\mu$ for peened and unpeened Rene’ 88
- More rapid evolution and saturation of $\mu$ for Rene’ 95
  - Higher initial $\mu$ for Rene’ 95
  - Similar $\mu$ for Rene’ 95 after 500-2000 cycles
- Only able to determine $\mu$ after 2,000 cycles because of hardware limitations
  - Continued increase in $\mu$ after 2,000 minimal
  - Near saturation in $\mu$ evolution between 1,000 and 2,000 cycles
Baseline Results

- 8 baseline experiments
  - Rene’ 95 specimen
  - Rene’ 80DS, pads
- Normal load constant at 15,000 lbs/in
- Bulk stress ratio constant at 0.05
- Variable maximum bulk stress
- Determine maximum bulk stress to produce 100,000 cycle life
**Effect of Material and Surface Treatment**

- 2x increase in life between peened/unpeened Rene’ 95
  - Elevated temperature (600 °F) in Ti-17 shows similar improvement in life, Gean, et al. (2006)
- 10% increase in life between peened/unpeened Rene’ 88
- Peened Rene’ 95 longer life than peened Rene’ 88
- Unpeened Rene’ 95 shorter life than unpeened Rene’ 88

<table>
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<tr>
<th>Specimen Material</th>
<th>Shot Peen</th>
<th>Pads Material</th>
<th>Shot Peen</th>
<th># Exps</th>
<th>Average N</th>
<th>Standard Deviation N</th>
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<td>No</td>
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<td>28,156</td>
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</table>

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Block Loading

- Left plot demonstrates simple block loading
  - 1 Major cycles with $\sigma_{\text{max}} \sim 550$ MPa
    - $R_\sigma \sim 0$
  - 30 Minor cycles with $\sigma_{\text{max}} \sim 550$ MPa
    - $R_\sigma \sim .5$

- Right plot demonstrates block loading plus overpeak
  - Similar to simple block loading with 10% overload
Results

Minor cycles in block loading produce significant reduction in life. Occasional overpeak increases block life.

<table>
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<tr>
<th>Material</th>
<th>Shot Peen</th>
<th>Load Type</th>
<th>Material</th>
<th>Shot Peen</th>
<th># Exps</th>
<th>Average N</th>
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<td>3</td>
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<td>28,156</td>
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</table>

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Fretting Fatigue Failure Fracture Surface

- Rene’ 95 fracture surface
- Analyzed with an optical microscope
- 40x-100x magnification
- Observe multiple fretting crack initiation sites
- Maximum crack depth ~25% of the specimen depth away from free surface
5,000 Cycle Interrupted Test

5,000 Cycle Interrupted Test (Unpeened)
Left Edge of Contact Fracture Surface

Largest Crack

Separate Cracks

Right Crack Edge

• Multiple cracks
• ‘Almost’ edge crack
• Shallow depth

Gean, Tate, and Farris, *SDM* 2009

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Conclusions

- Attachment fatigue can be reproduced under controlled laboratory conditions
- Characterization of the contact mechanics through a combination of experiments and analysis allows use of conventional life prediction tools
- Analysis tools have been adopted by OEMs
- Robust characterization of load history effects (Minor cycles are very damaging)
- Many fretting fatigue crack initiation sites
  - Cracks semi-elliptical
  - Link together to form edge crack early in experiment
- Shot peening produces slight life improvement, 2x Rene’ 95, 10% Rene’ 88
Vision of EoC Implementation by OEMs

“Spring” Model

Prediction of contact loads (P,Q,M) through mission history (reduction in FEM analysis)

Integral Equations

Prediction of local stress fields using history dependent integral equations (reduction in analysis time vs. FEM)

Mission 1B

Q vs. P for the Individual Tangs

EoC stress

Including different material combinations

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Some of Leon’s Academic Grandchildren

- M.P. Szolwinski, Ph.D., 1997, Section Mgr, GE, ASME Marshall Peterson Tribology Research Award
- P.A. McVeigh, Ph.D., 1998, Boeing, Mgr ISS Structural Integrity
- G. Harish, Ph.D., 1999, IQCAIS, SDM Best Paper Award
- C.R. Tieche, MS, 1999, Product Specialist, W.L. Gore & Associates
- P.T. Rajeev, Ph.D., 2001, Director, BULK Eng, Soraa, PE Publishing Award
- E. Perez-Ruberte, MS, 2001, Honeywell
- H. Murthy, PhD, 2004, IIT Madras, Associate Professor
- J.F. Matlik, PhD, 2004, Rolls-Royce Corporation, Best Student Paper, SDM
- B. Bartha, PhD, 2005, USA, Best Student Paper ASTM
- G. Gao, PhD, 2005, Cooper Tire and Rubber
- G. Msies, MS, 2006, Livermore
- S. Kumari, PhD 2007, Pratt & Whitney
- M. Gean, PhD 2008, nanoPrecision Products, Inc.
- N.J. Tate, MS 2009, RAAF
- N. Sundaram, PhD 2009, Purdue PostDoc
- Luke Robinson, MS 2010, Air Vehicles, Wright Patterson

Collaborators

- M. Okane, TNCT, T. Sakagami, Kobe University
- I. Goryacheva, Russian Academy of Sciences
- Bob VanStone and others at GEAE

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**Experimental Flowchart**

- **Pad profile**
  - Representation of contact
  - Material properties
  - Friction Coefficient from friction tests

- **Integral Equation solution suite**
  - Experimental loads
  - Stresses/strains for actual pad profile

- **Experiment**
  - Analysis of fracture surface and wear
  - Profile change due to wear
  - Characteristics of contact and fracture surface

- **Life prediction (multiaxial parameter)**
  - Life prediction
  - Estimation of propagation life
  - Comparison with experimental lives
• Surface profiles of the pads were measured before and after the experiment using Talysurf.

• The small deviations from the prescribed profile result in significant deviations in contact tractions.

• Contact analysis of fretting experiments was carried out using smoothed “real” profiles of the pads.
Fretting Contact Stresses

Expt. Fret.02
P = 8160 lb/in
Q_{\text{max}} = 3463 lb/in
Q_{\text{min}} = -2369 lb/in
\sigma_{\text{max}} = 35.6 \text{ ksi}

Prescribed

After, smoothed
Load Selection

- Dovetail loading coupled normal and shear load
- Fretting Fatigue Experiment
  - Constant normal load
  - Alternating shear load

Gean, M. and Farris T., SDM (2005)

\[ P = \text{normal load} \]
\[ Q = \text{shear load} \]
Objective and Approach

• Characterize the high temperature fretting fatigue behavior nickel based alloys typically used in gas turbine engines

• Conduct fretting fatigue experiments of high temperature nickel based alloys
  – Rene’ 88 and Rene’ 95, turbine disk materials, specimen
  – Rene’ N5 and Rene’ 80DS, turbine blade materials, pads

• Tests conducted at 1200 °F to simulate the temperatures experienced in engine hardware
  – Constant experimental conditions to determine the influence of surface treatments on life
  – Block loading experiments to determine effect of loading on fretting fatigue life

• Observations of fretting fatigue crack morphology
Contact pressure and shear traction are related to the slip and gap functions by means of a pair of coupled singular integral equations (SIEs) as,

\[
\frac{\partial}{\partial x} \begin{bmatrix} s(x) \\ H(x) \end{bmatrix} = \begin{bmatrix} \alpha_{11} & \alpha_{12} \\ \alpha_{21} & \alpha_{22} \end{bmatrix} \begin{bmatrix} q(x) \\ p(x) \end{bmatrix} + \begin{bmatrix} \beta_{11} & \beta_{12} \\ \beta_{21} & \beta_{22} \end{bmatrix} \int_{a_1}^{a_2} \begin{bmatrix} q_x(t) \\ p(t) \end{bmatrix} \, dt 
\]

Relative slip at a given loading stage cannot be known beforehand. Hence, Contact problem has to be solved incrementally.

- Incorporating stick/slip behavior in the out-of-plane direction would mean solving three coupled SIEs to obtain \( p(x) \), \( q_x(x) \), \( q_z(x) \).
- Problem can be simplified by assuming that the frictional traction acts only to resist motion in the \( x \)-direction, i.e., \( \mu_x = \mu \) & \( \mu_z = 0 \).
- Since \( q_z(x) \equiv 0 \), the number of coupled SIEs is reduced to two.
- Effect of the remote stress on the relative slip function and hence the contact tractions can be included as,

\[
s(x) = s_c(x) - \frac{(1 - \nu_{xx} \nu_{xz})}{E_x} \sigma_0 x
\]

where \( s_c(x) \) is the relative slip due to the contact tractions alone and \( \sigma_0 \) is the applied remote stress.

Verification of CAFDEM (Dissimilar Anisotropic Materials)

- 2D FEM analysis to validate the SIE model when one of the material principal axes is parallel to the z-axis.
- 16400 elements with 300 elements in contact
- Rigid indentor used to save analysis time
- Infinite elements to simulate elastic half space

$R = 0.120 \text{ in}$

$\mu = 0.2$
$\theta_z = 45^\circ, \theta_x = 0^\circ$
Nominal $p_{\text{ave}} = 100 \text{ ksi}$

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3-D contact tractions

Slip zone in the vicinity of the edge

z=0 corresponds to the edge.

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Thermal Imaging of Contact Surface

Schematic of surface imaging

Specimen

Pad

Sapphire pad on aluminum specimen

Camera

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High P and Overpeak Cyclic Results

- OP cyclic stress level reduces life by a factor of 2
- 10% increase in normal load reduces life by about 10%

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<th>Load Type</th>
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