Micromechanics Analysis of Fretting Fatigue

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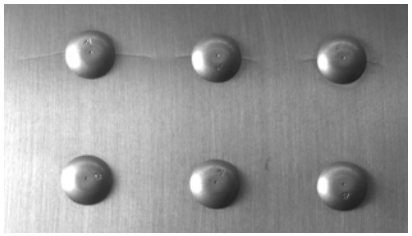
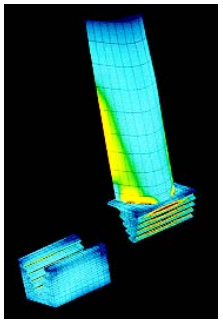
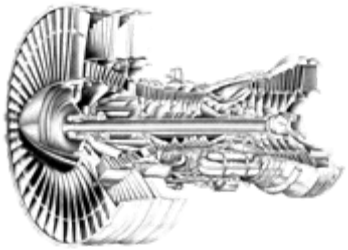
Fretting Fatigue of Aerospace Structures

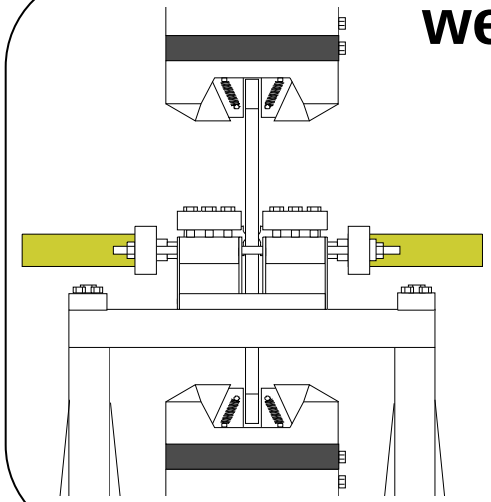




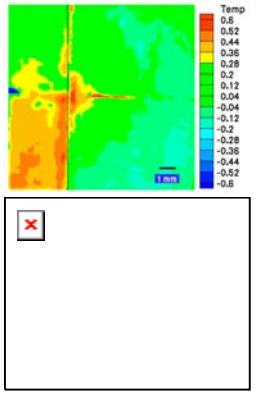
HKS *ABAQUS Brief*

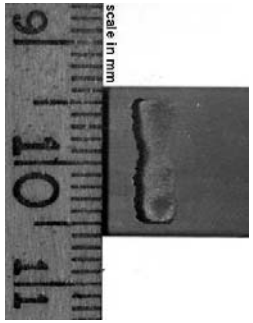


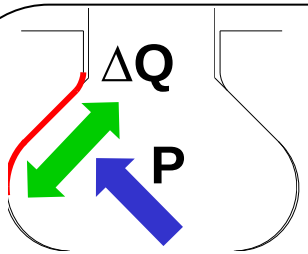
in-service issues



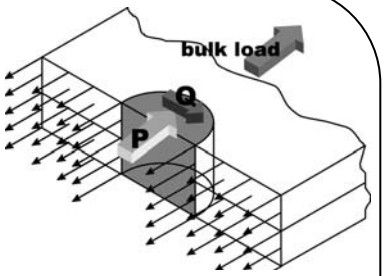
well-characterized experiments

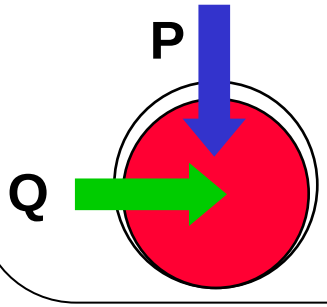


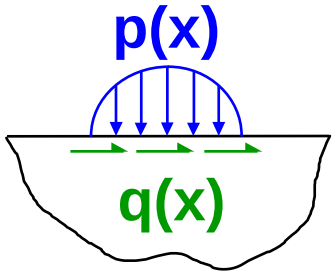


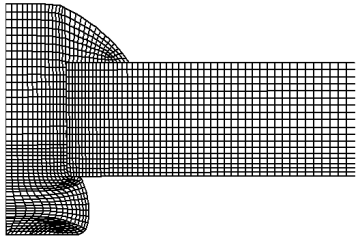


local model of contact

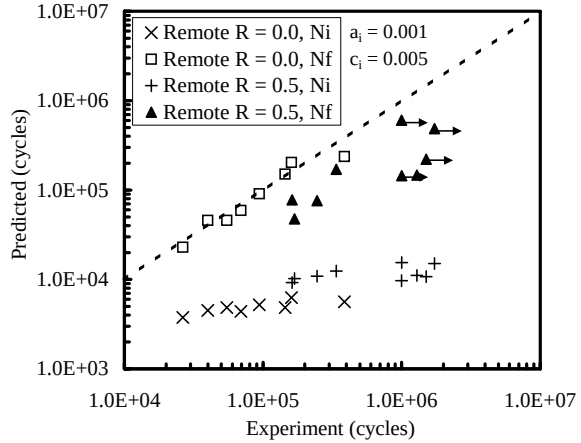






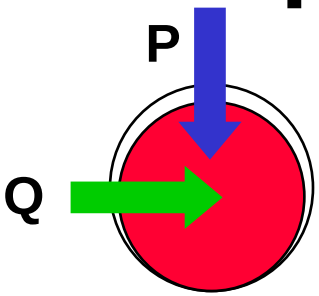


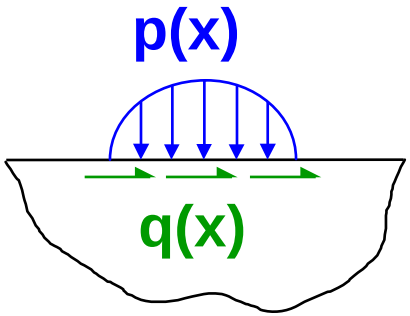
life prediction

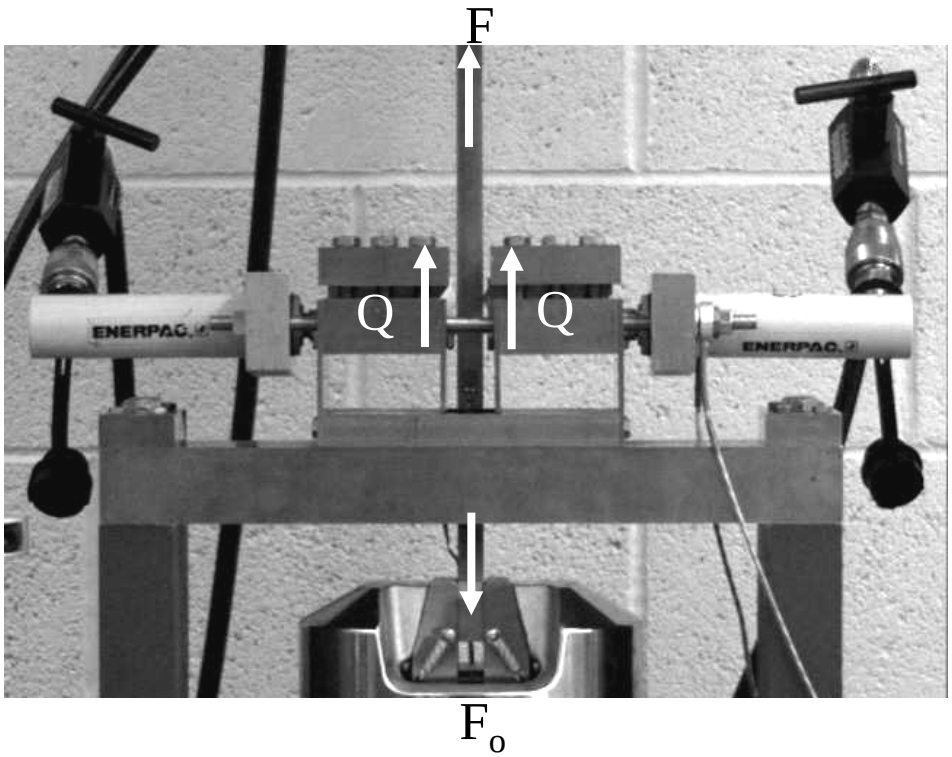


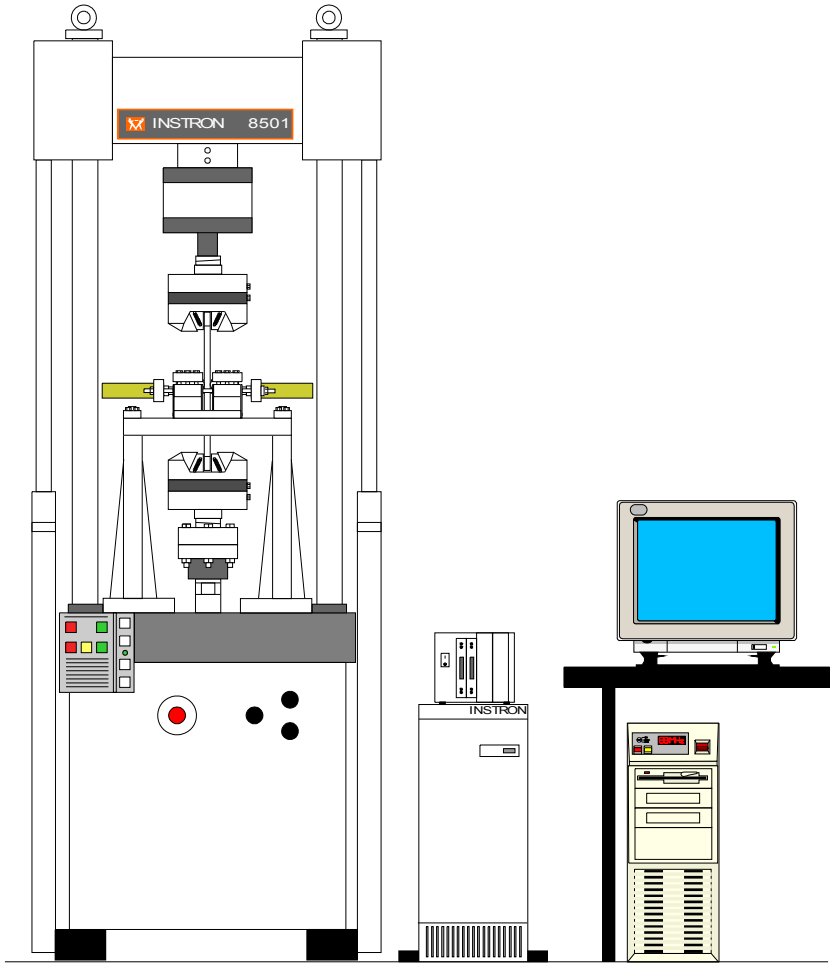
Leon: "focus on real problems"

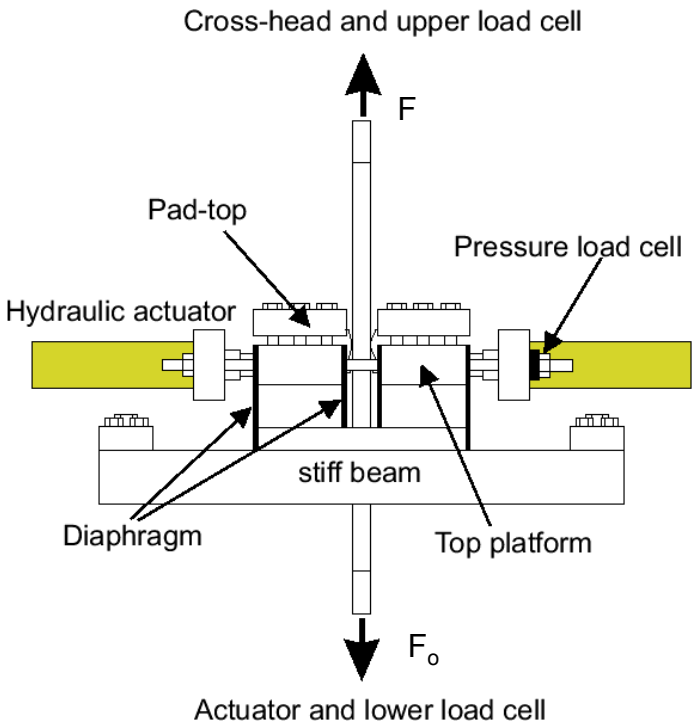
Fretting Fatigue Experiment



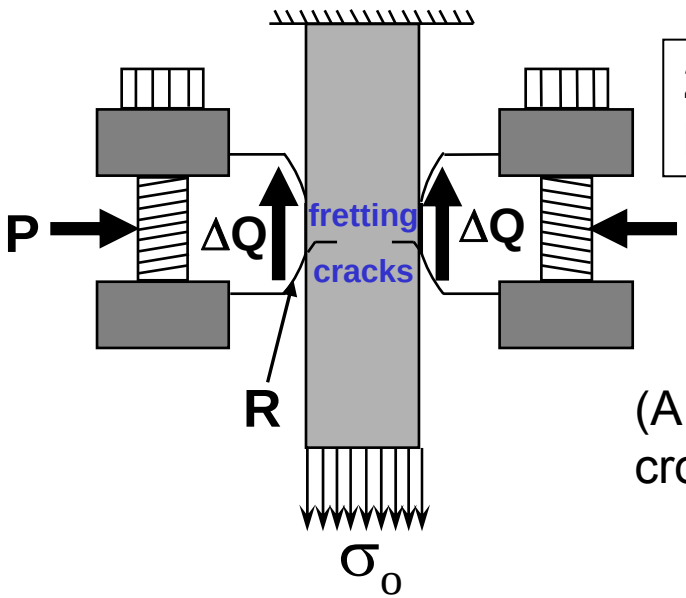








Szolwinski & Farris (1998), *Wear*



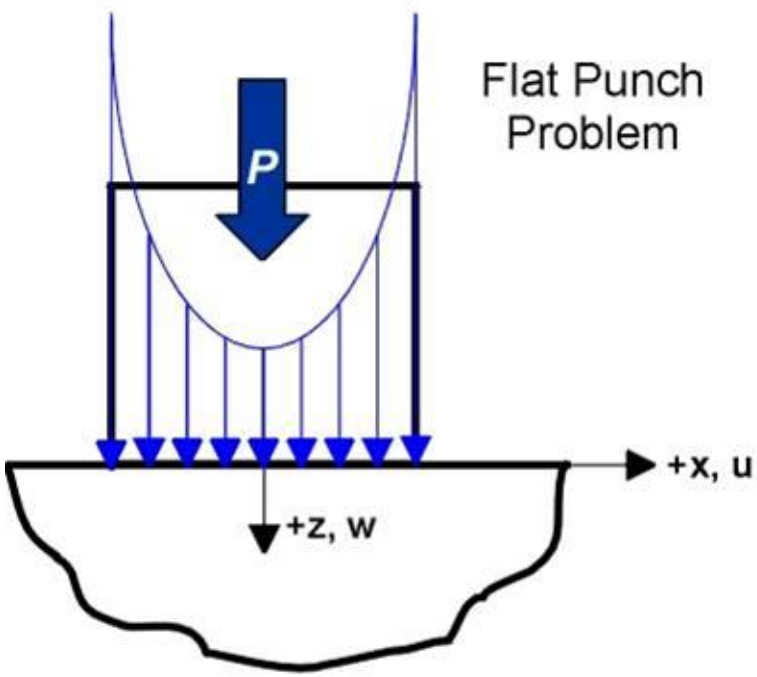
$2\Delta Q = F_o - F$

$F_o = \sigma_o A$

(A is the Area of cross section)

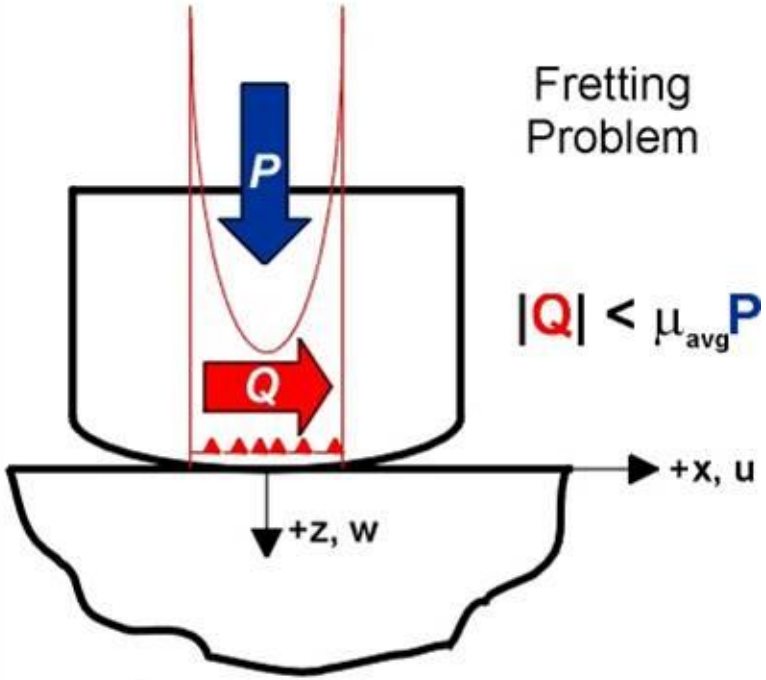
- Oscillating σ_o creates an oscillatory tangential force, ΔQ (fretting contact).
- Specimen is cycled to failure.
- Nominally flat pads are used to simulate blade/disk fretting contact
- The test is designed so that conditions of partial slip exist at the contact interface.
- μ is measured by increasing σ_0 until gross sliding occurs at the contact interface

Mechanics of Fretting



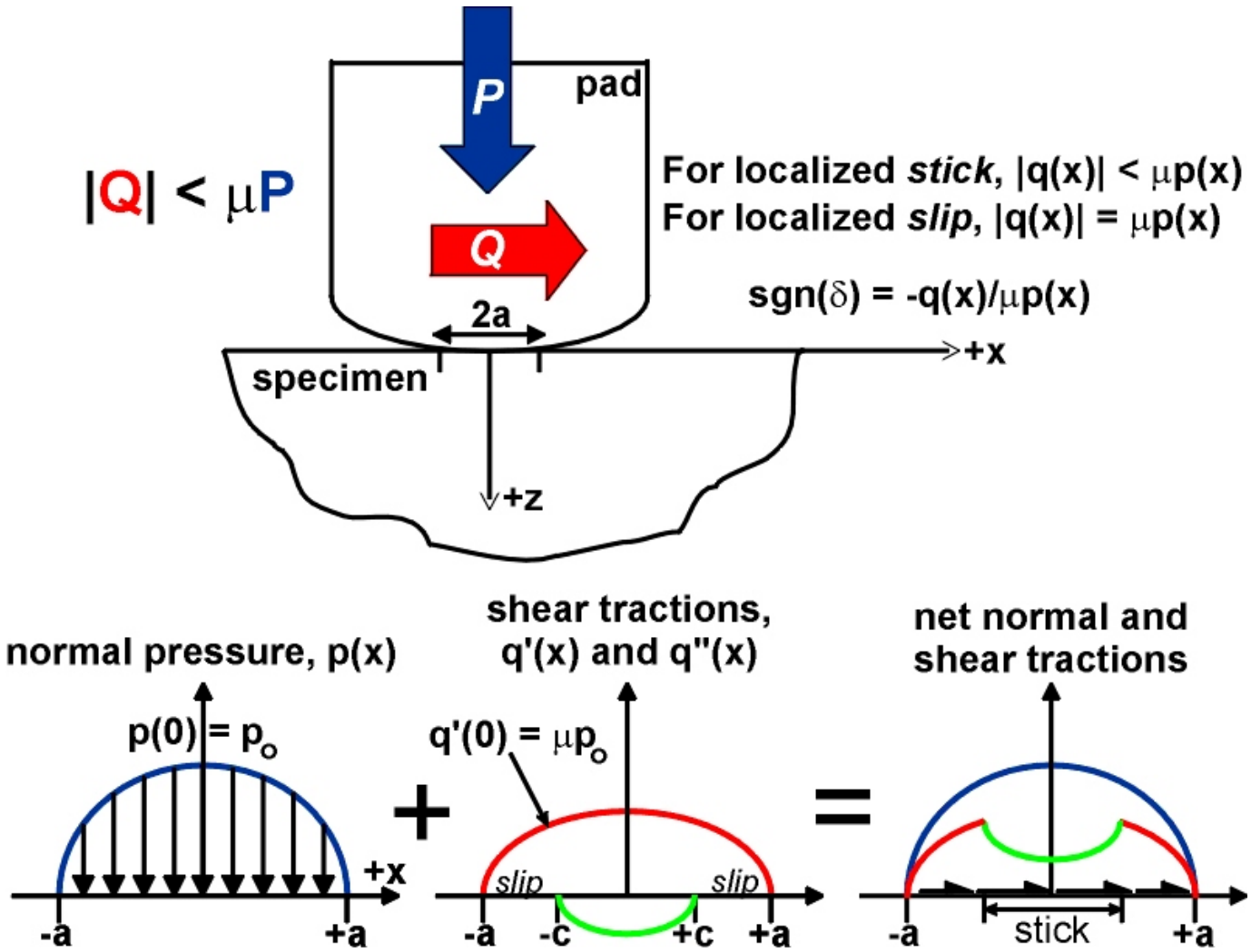
$\frac{dw}{dx} = 0$ at contact surface

infinite peaks in pressure
at edges of contact



$\frac{du}{dx} = 0$ at contact surface for complete stick

infinite shear traction required
at edges of contact


|Q| < μP
P
pad
Q
2a
specimen
+x
+z
For localized stick, |q(x)| < μp(x)
For localized slip, |q(x)| = μp(x)
sgn(δ) = -q(x)/μp(x)
normal pressure, p(x)
p(0) = p_o
+x
-a
+a
shear tractions, q'(x) and q"(x)
q'(0) = μp_o
slip
slip
-a
-c
+c
+a
net normal and shear tractions
-a
stick
+a

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 λ and μ are isothermal Lamé constants

- Heat conduction in terms of strain

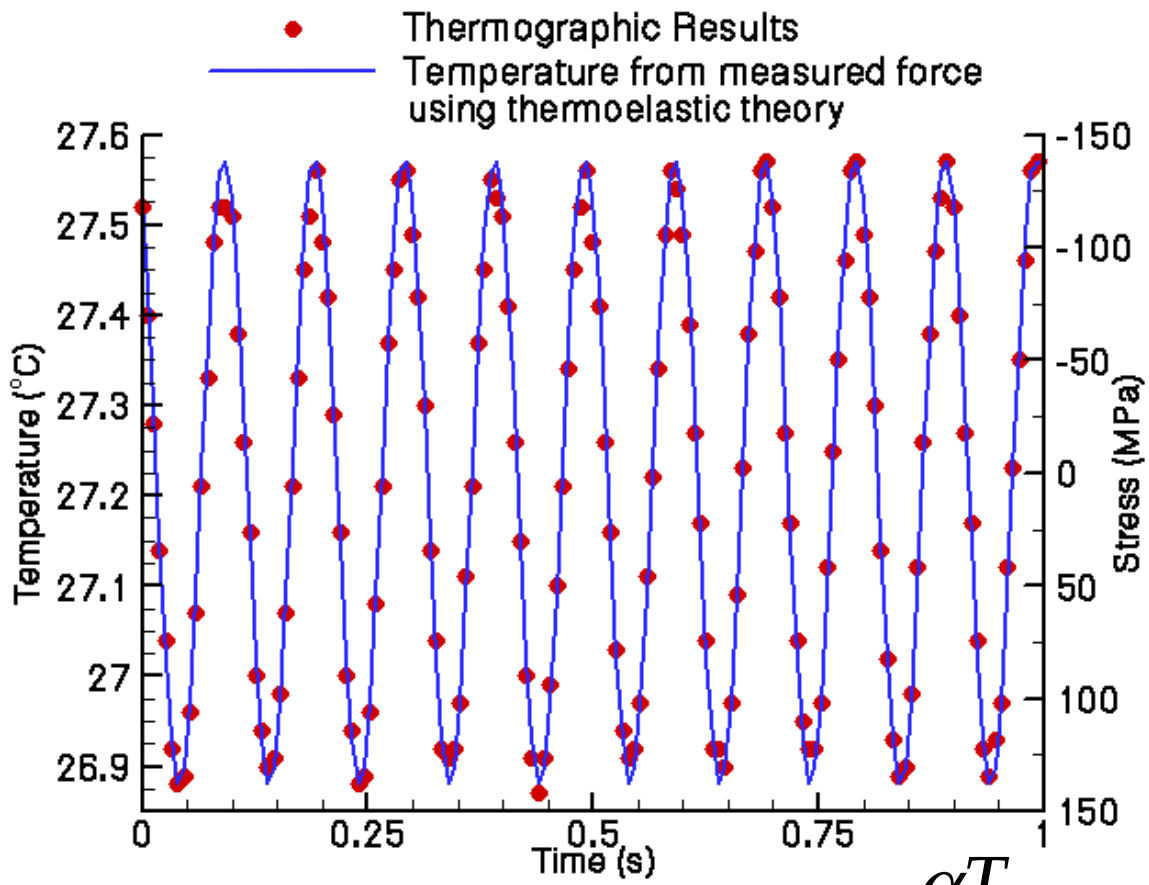
$$k\nabla^2 T = \rho C_v \dot{T} + T\left[\left(3K\alpha - \frac{\partial \lambda}{\partial T}\varepsilon_{kk}\right)\dot{\varepsilon}_{ll} - 2\frac{\partial \mu}{\partial T}\varepsilon_i \dot{\varepsilon}_i\right]$$

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

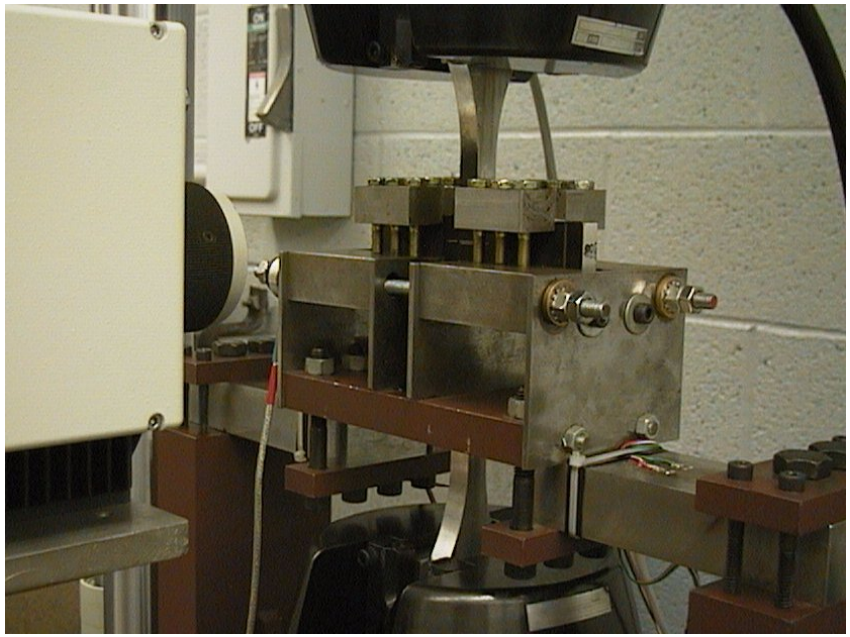
Uniaxial tension

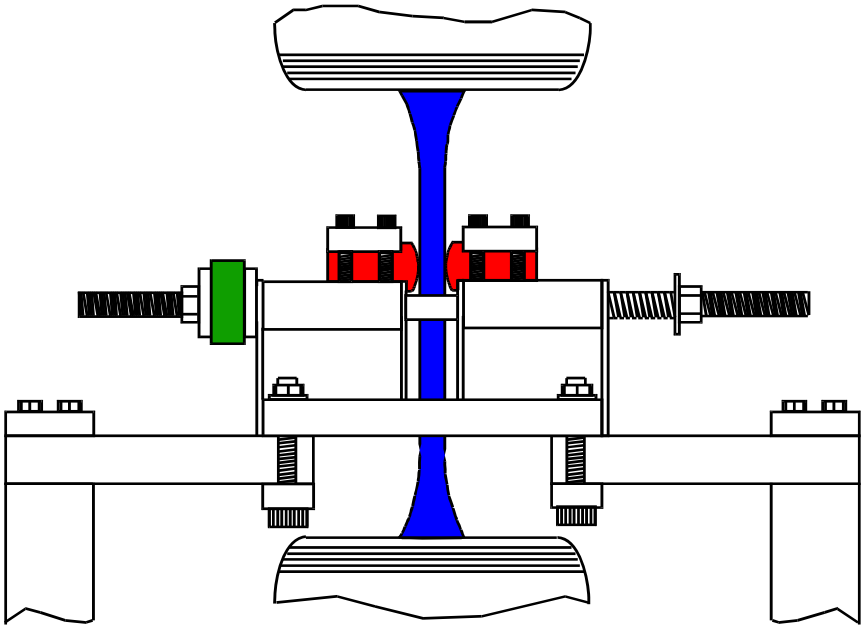


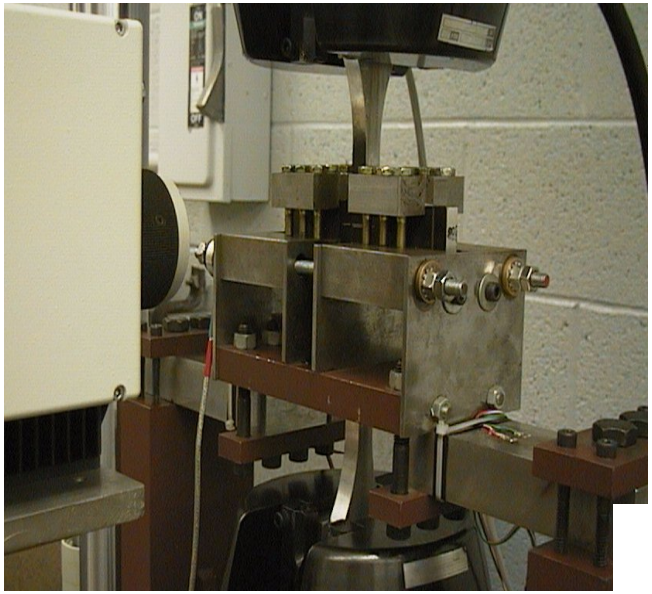
theoretical temperature = $T_o - \frac{\alpha T_o}{\rho C_p}\sigma_{kk}$

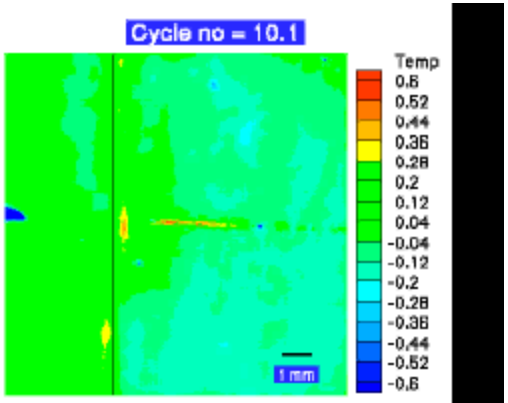
Temperature Measurement

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

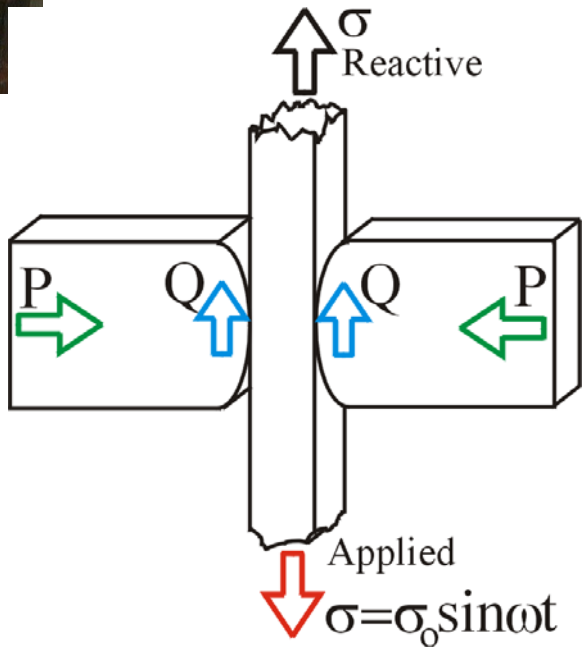




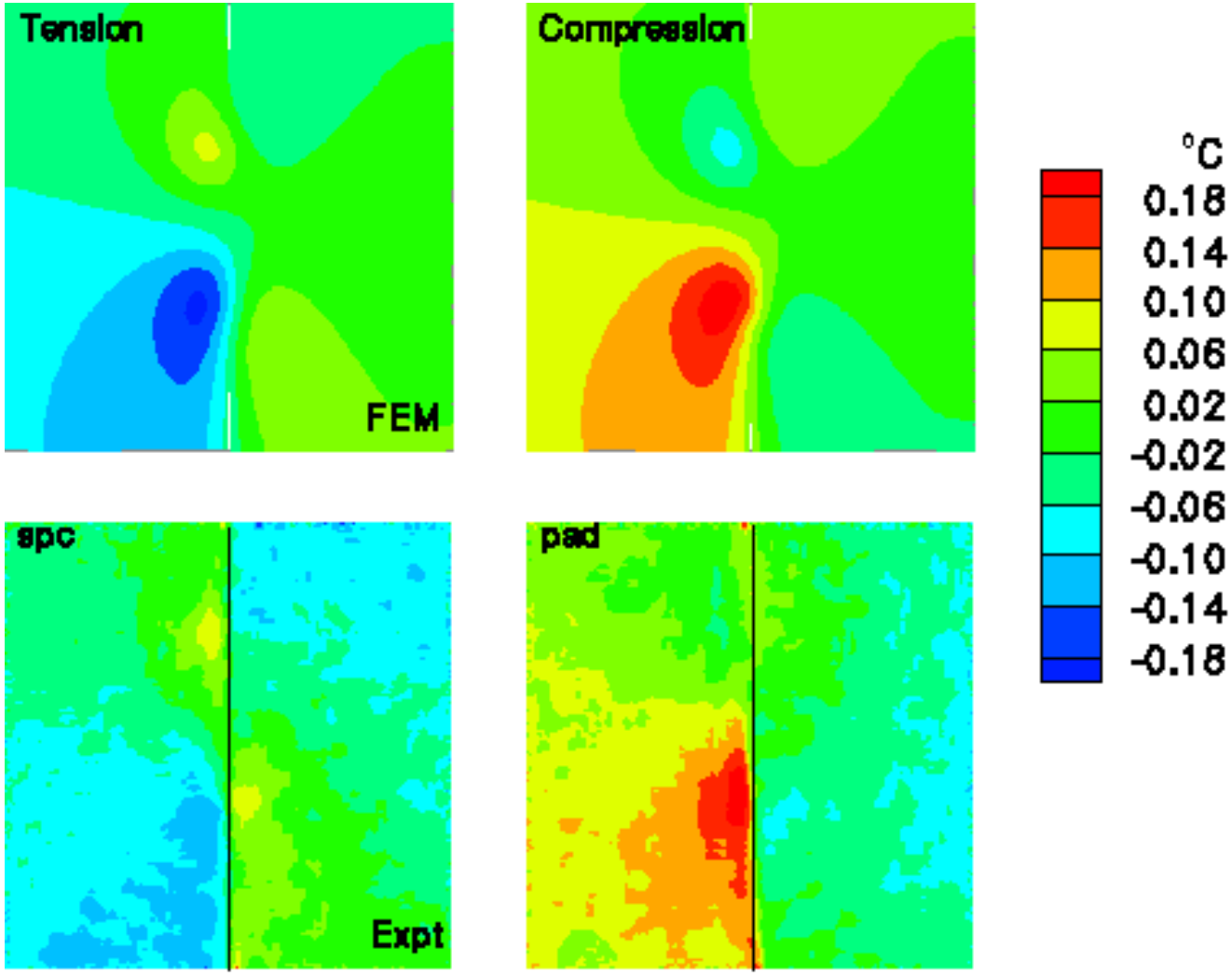




Szolwinski, et al, *ASME JOT* (1999)



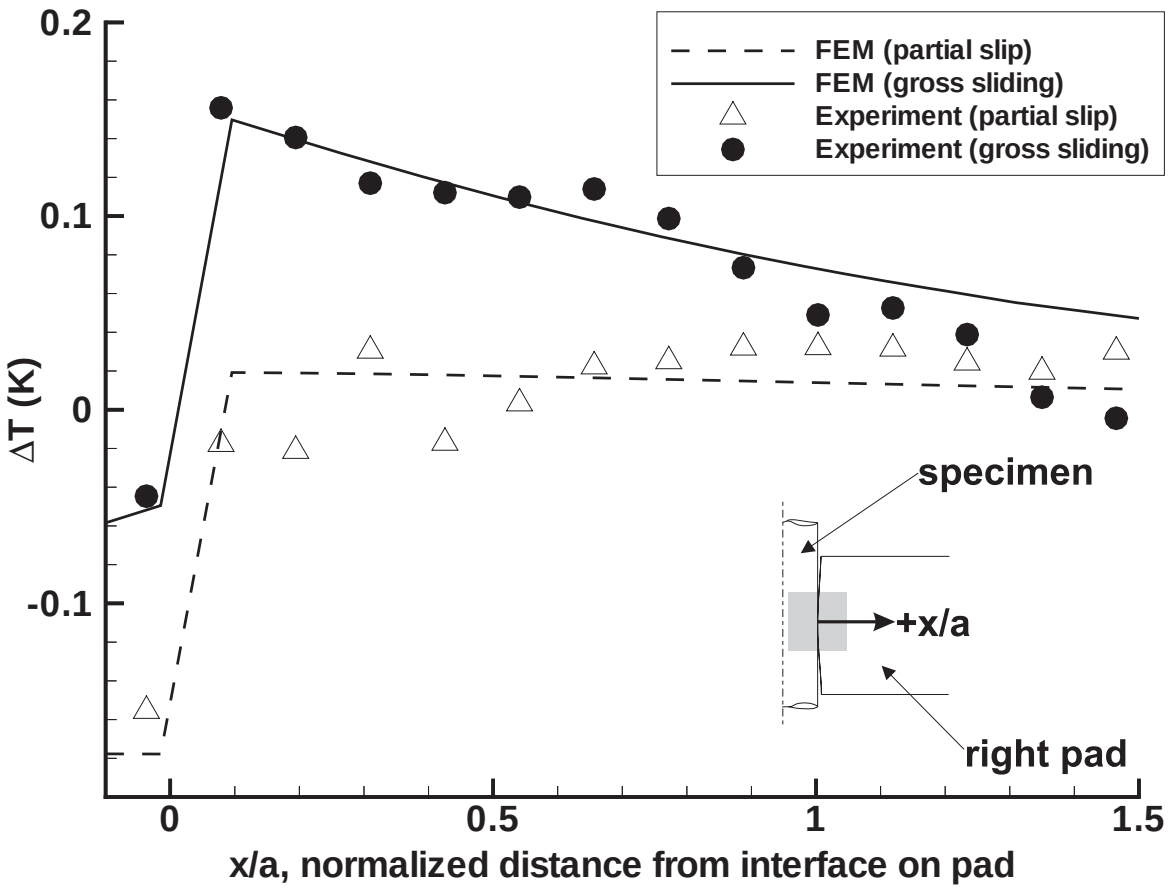
Partial Slip (Ti-6Al-4V)



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

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

Aluminum Temperature



P = 504 N/mm

(Q/P) = 0.34

σ_o = 100 MPa

R-ratio = -1

radius = 178 mm

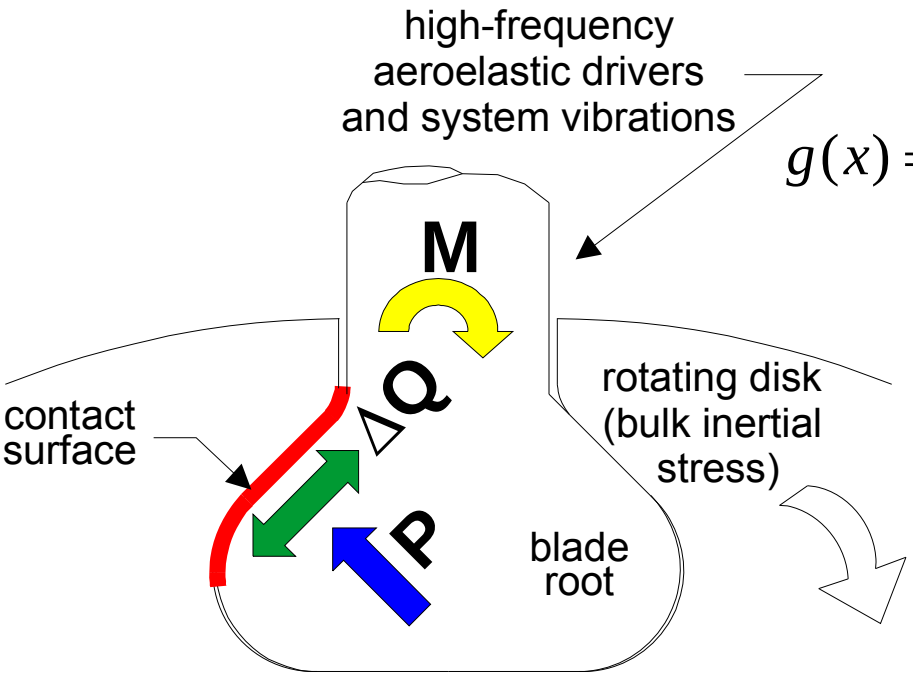
•Harish, et al, *ASTM*,2000

IR Temperature Measurements

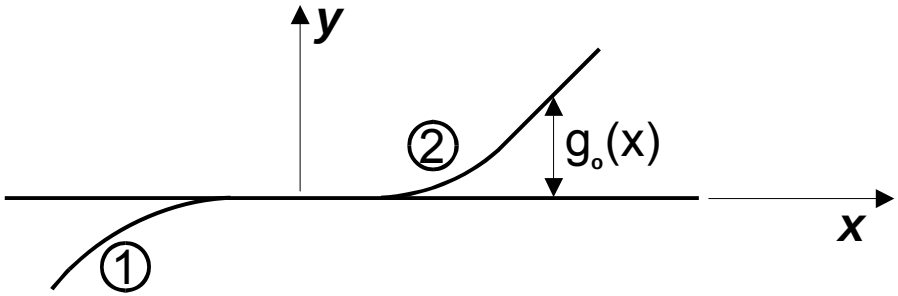
- A full-field real-time in-situ method of characterizing the near-surface temperatures in fretting contacts has been developed
- The prominent features of gross sliding and partial slip contact have been identified from the temperature maps
- A finite element implementation of the coupled thermoelastic 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

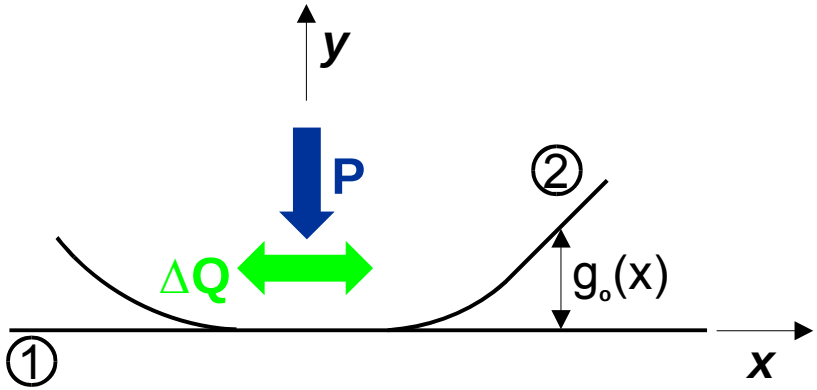


Contact Surface Geometry

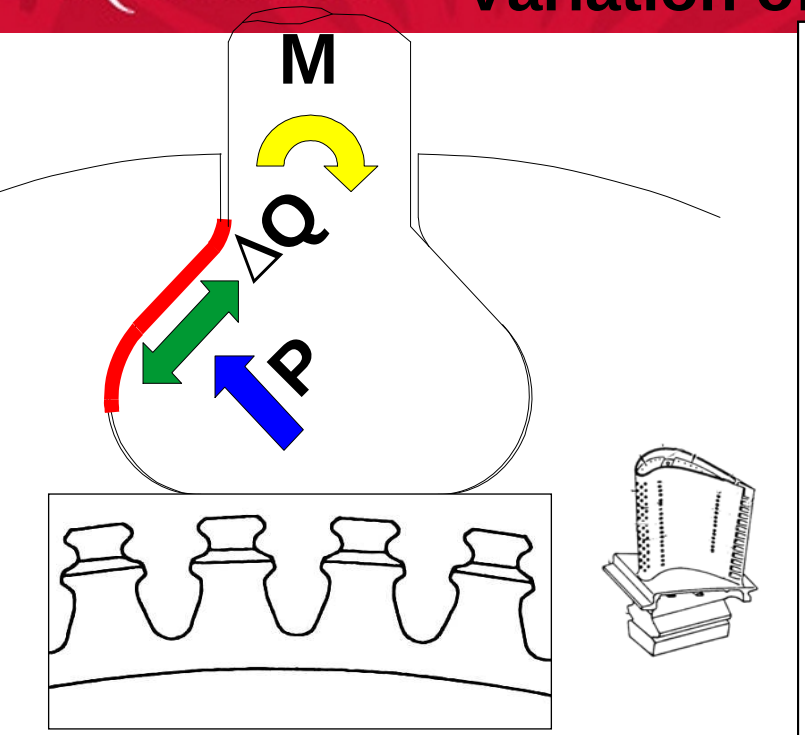


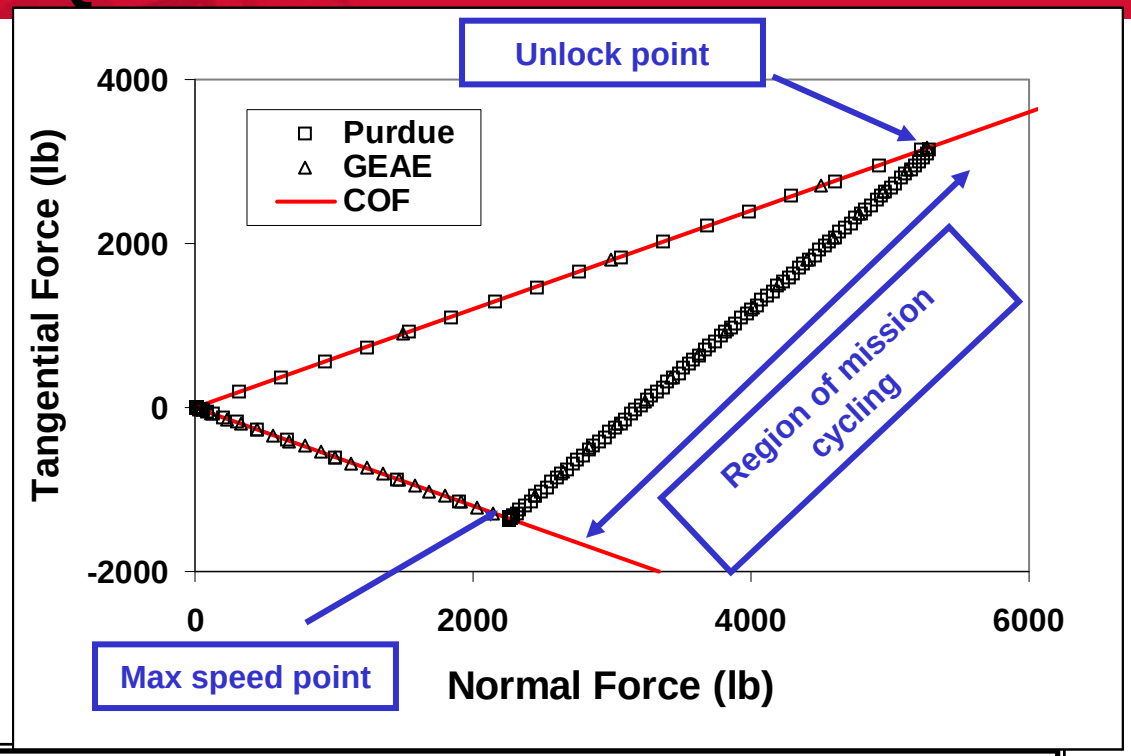
$$g(x) = g_o(x) - u_{y_1}(x,0) + u_{y_2}(x,0) - C_o - C_1 x$$

equivalent contact problem



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 the shear load to normal load exceeds the COF, the blade will slide inward toward the disk bore (Gean and Farris, *JAM*, In-Press)

Modeling Pressure Distribution

Step 1: governing equation

$$-\frac{dg_o}{dx} + C_1 = -\frac{2(\kappa+1)}{4\pi\mu}\int_{-a}^{a}\frac{p(s)ds}{x-s}$$

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

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

Step 5: obtain pressure distribution (FFT)

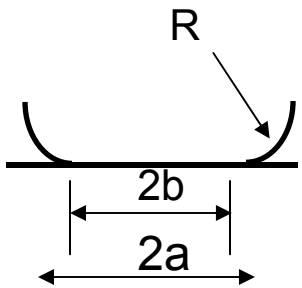
$$p(\theta) = p_o + \sum_{n=1}^{\infty} p_n \sin n\theta / \sin\theta$$

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*

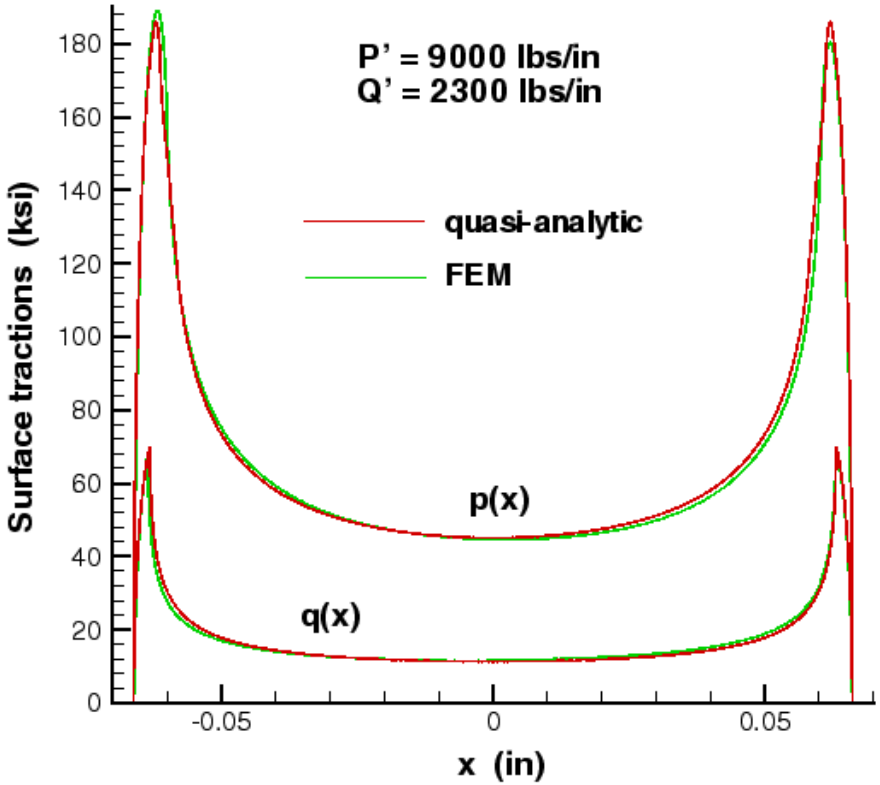
Flat with Rounded Edges

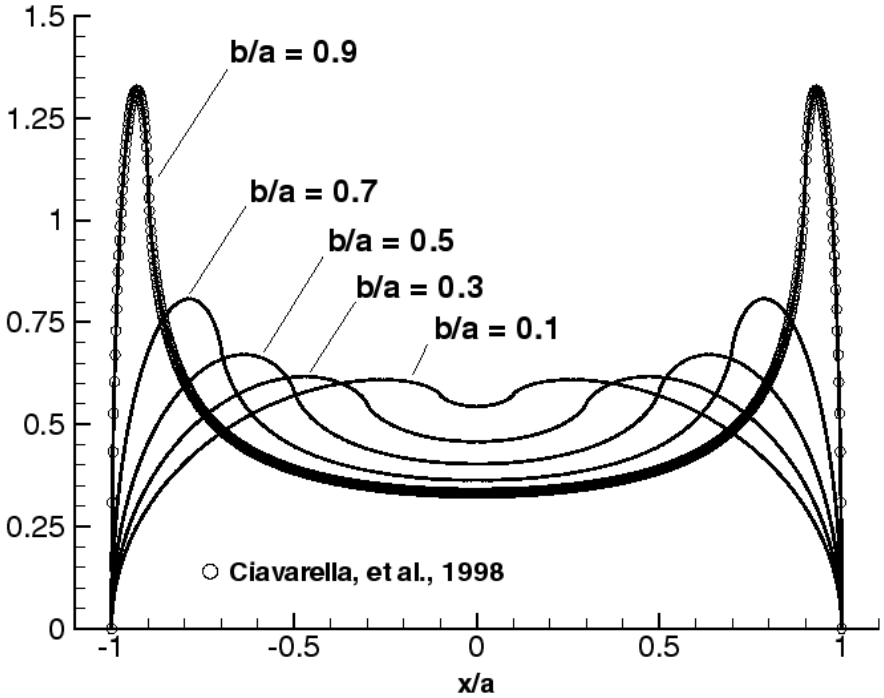
McVeigh etal,
IJF, 1999



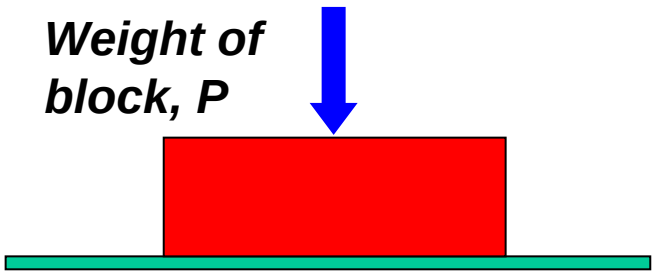
2b = flat length

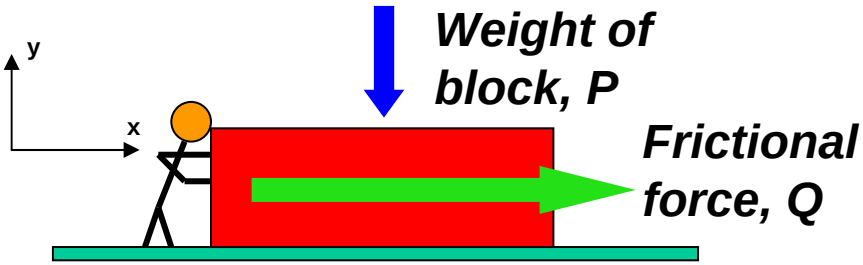
2a = contact length

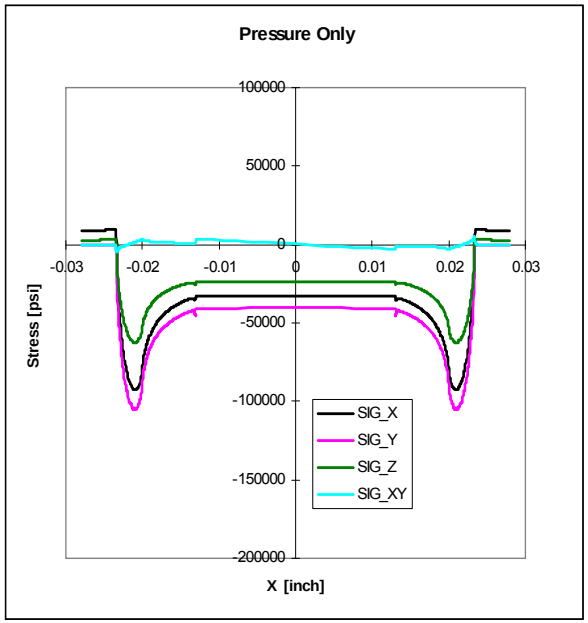


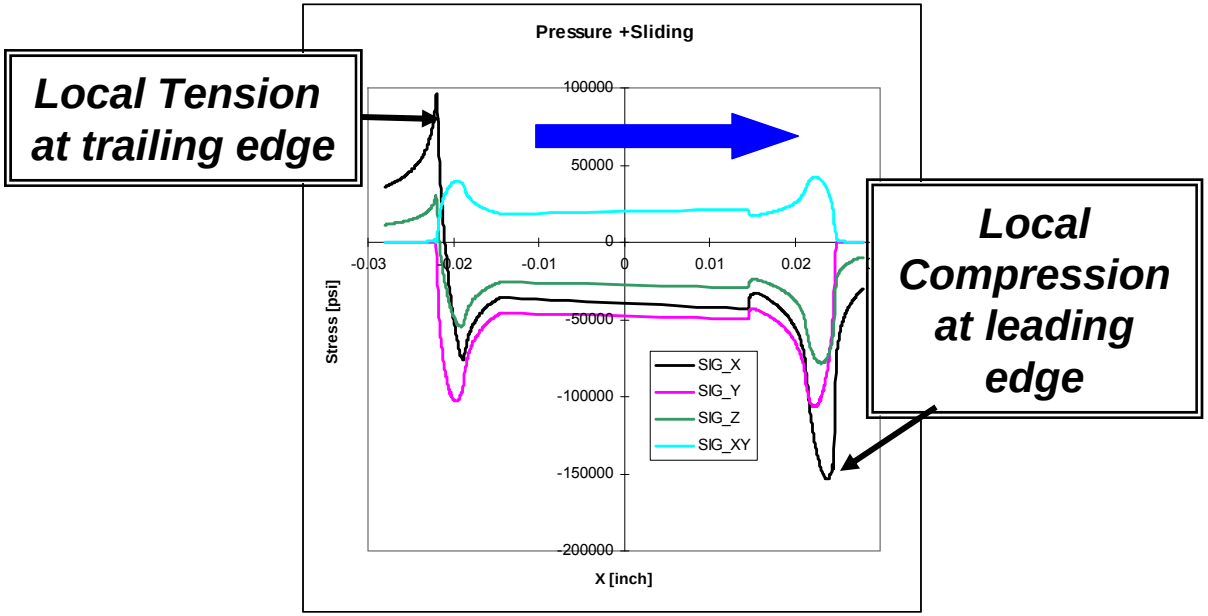


Nominally Flat Contacts



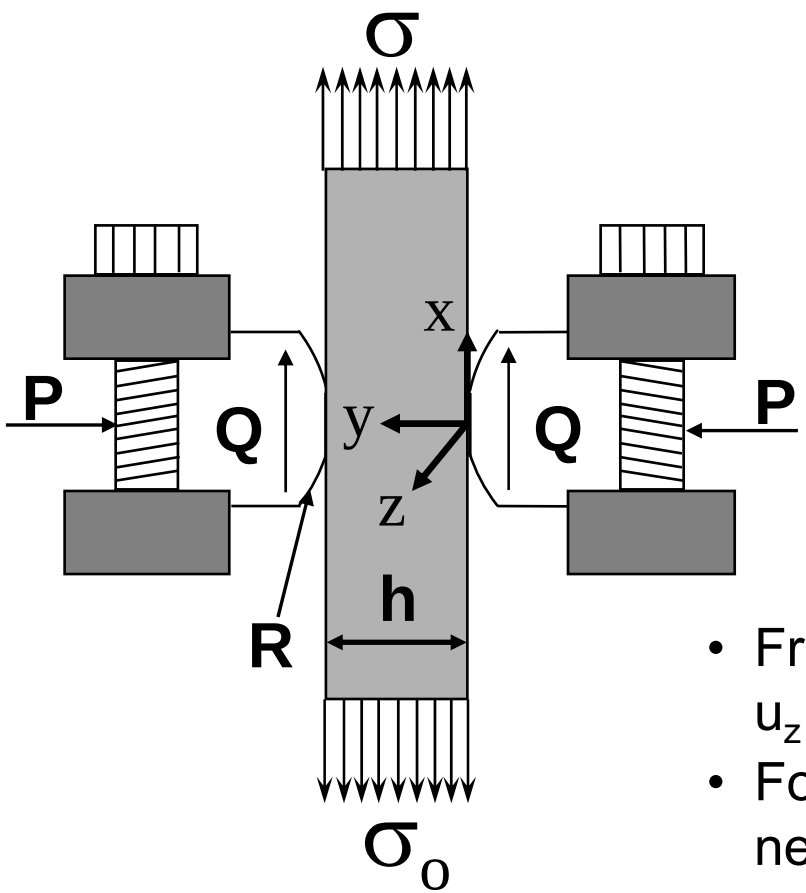






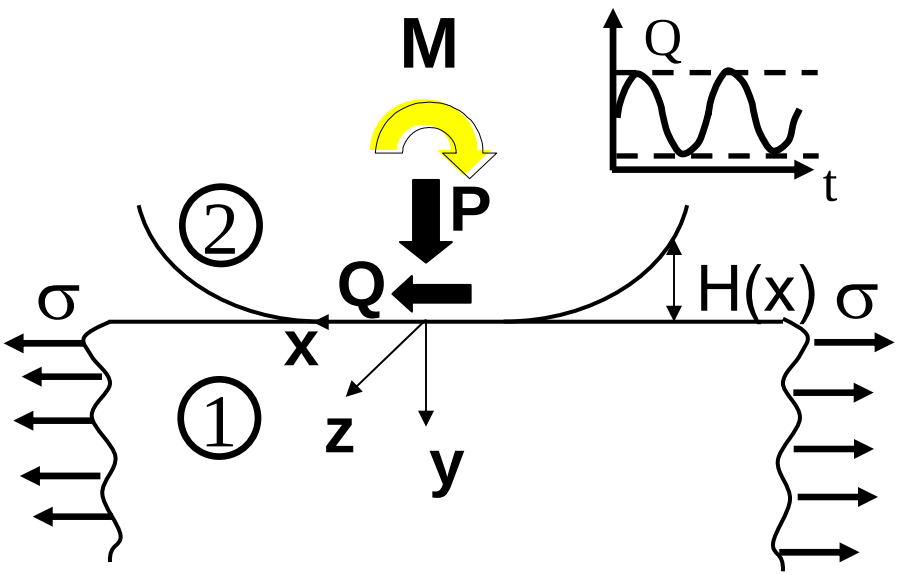
- **Addition of shear load (Q) results in highly localized stress at leading and trailing edges**
- **When the direction of shear load reverses, the leading edge becomes the trailing edge resulting in a very large fatigue cycle**

Analysis of Fretting Experiments



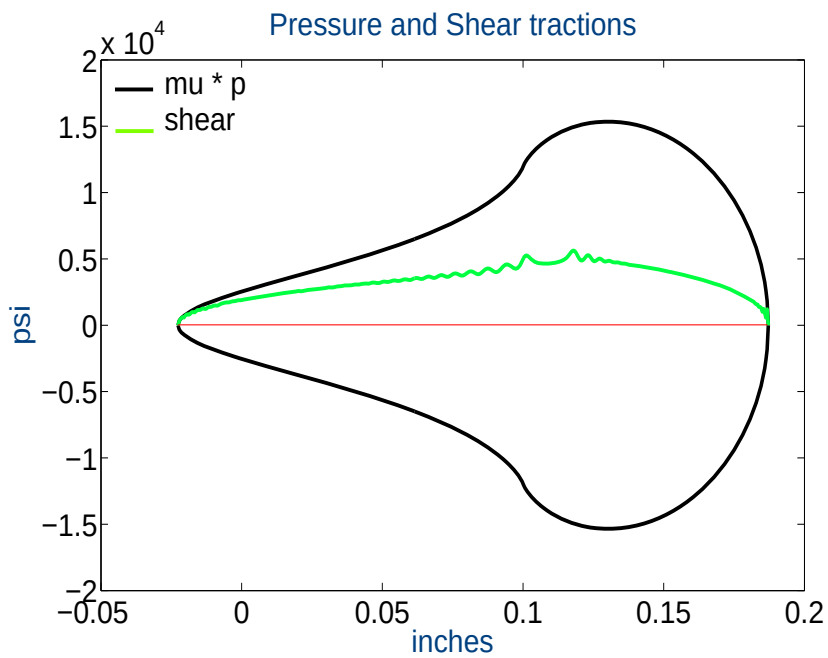
$2Q = h\,(\sigma_0 - \sigma)$

$h = 0.60$ in



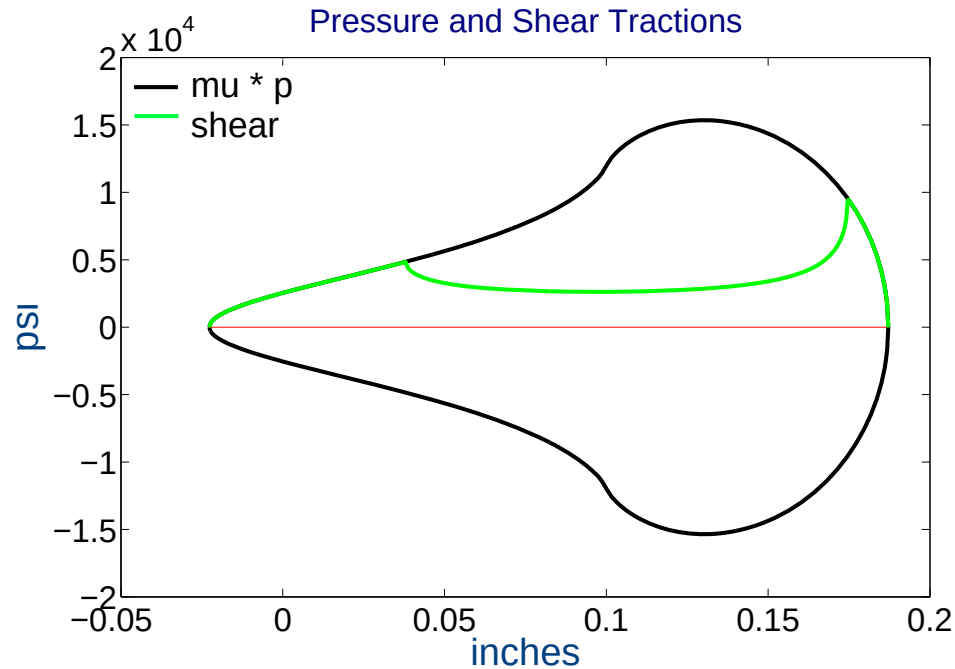
- Fretting contact is modeled as 2D, i.e., u_x, u_y, u_z only depend on x and y.
- For anisotropic materials $u_z(x,y)$ is not necessarily zero $\Rightarrow$ out of plane relative slip $\Rightarrow$ out of plane shear traction.
- The specimen is modeled as a half-space subject to remote stress.

Example Load History Effects



P, M, Q applied simultaneously

No Slip Anywhere



P,M applied followed by Q

Partial Slip

- **The final loads are the same for each of these examples**
- **Integral equations can be used for "Representative" missions can be**
- **For dissiimilar 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)

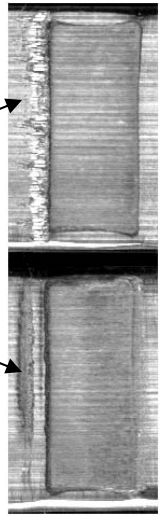
Surface Observations

Right pad

Failure Test

Trailing Edges

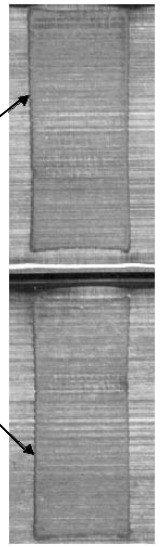
Left pad



Left pad

Trailing Edges

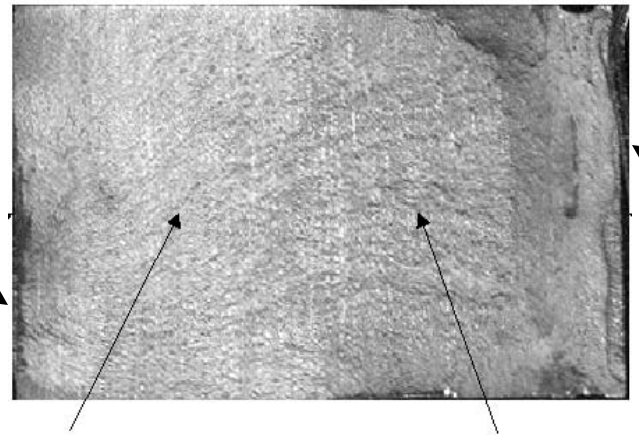
Right pad



Run-out Test

Fracture surface

Fretting debris



Fretting debris

Fatigue crack growth

Fast fracture

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

	Inputs			Measured			Calculated		
Exp.	P (lbs/in)	σ_{max} (ksi)	R_σ	Q_{max} (lbs/in)	Q_{min} (lbs/in)	N_f	σ_{eq} (ksi)	N_i	N_{prop}
PR02	9176	39.7	-0.07	3916	-3337	54,744	67.1	4847	40,957
PR03	9080	32.0	-0.06	3129	-2580	160,628	63.6	6268	197,952
PR04	9104	35.2	-0.02	3220	-2636	144,242	67.1	4847	146,177
PR05	9451	42.7	-0.01	3868	-3204	39,947	68.2	4504	41,327
PR06	9525	40.5	-0.03	3739	-3283	69,279	68.6	4388	54,778
PR07	9099	38.1	-0.05	3479	-3260	93,930	66.1	5197	85,586
PR09	9995	48.1	-0.01	4607	-3775	26,391	71.1	3762	19,146
PR10	9432	48.4	-0.02	3309	-1893	386,049	65.0	5630	232,404
PR11	6669	41.9	0.49	2337	-1425	337,578	56.4	12,427	157,986
PR12	6709	49.8	0.50	2389	-2029	161,986	59.2	9229	68,385
PR16	6677	50.1	0.49	3080	-1461	168,637	58.2	10,208	37,282
PR22	6763	42.1	0.50	2293	-1464	1,285,642	57.4	11,112	135,940
PR23	6787	46.0	0.50	2719	-1369	245,311	57.6	10,875	65,229
PR13	6792	34.8	0.49	1978	-1122	1,728,051	54.8	15,086	471,084
PR14	6768	39.0	0.49	1978	-1524	1,000,038	58.7	9700	595,004
PR17	6717	41.9	0.49	2304	-1472	1,000,863	54.6	15,479	129,113
PR20	6755	39.0	0.49	2436	-1079	1,502,266	57.7	10,749	210,079

Life Prediction

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

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

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

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

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

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

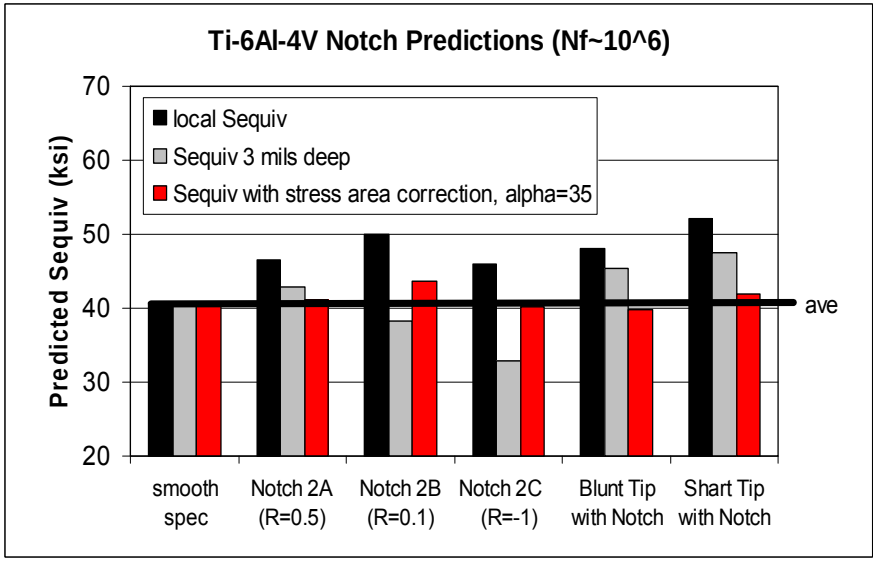
Murthy et al (2001) *Jap. Soc. Mat. Sci*

Stressed Surface Area Approach

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

$$\Delta\sigma_{eq,1} = \left(\frac{Fs_2}{Fs_1}\right)^{\left(\frac{1}{\alpha}\right)} \Delta\sigma_{eq,2}$$

$$Fs_2 = \sum_{i=1}^{n}\left[-\left(\frac{\sigma_i}{\sigma_{i,\max}}\right)^{\alpha}\right]\Delta A_i$$

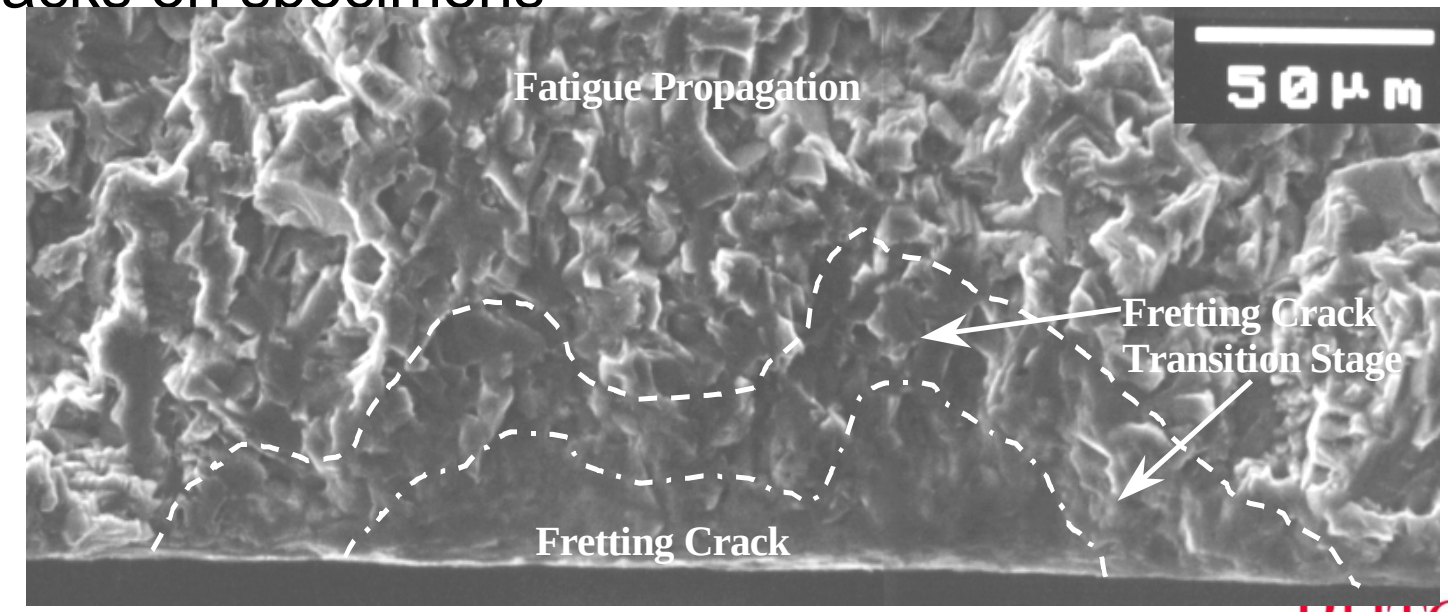


Fs_1 = -0.161 (smooth spec.)
α = 35 (from notch data)

Slavik et al (2001) *6th Nat. HCF Conf.*

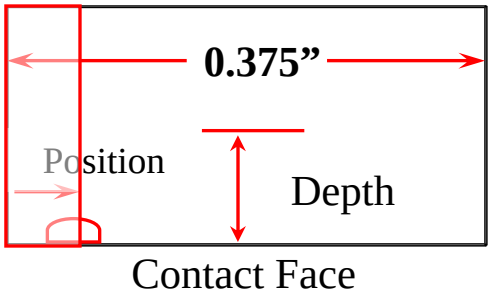
Fretting Pad Fractography

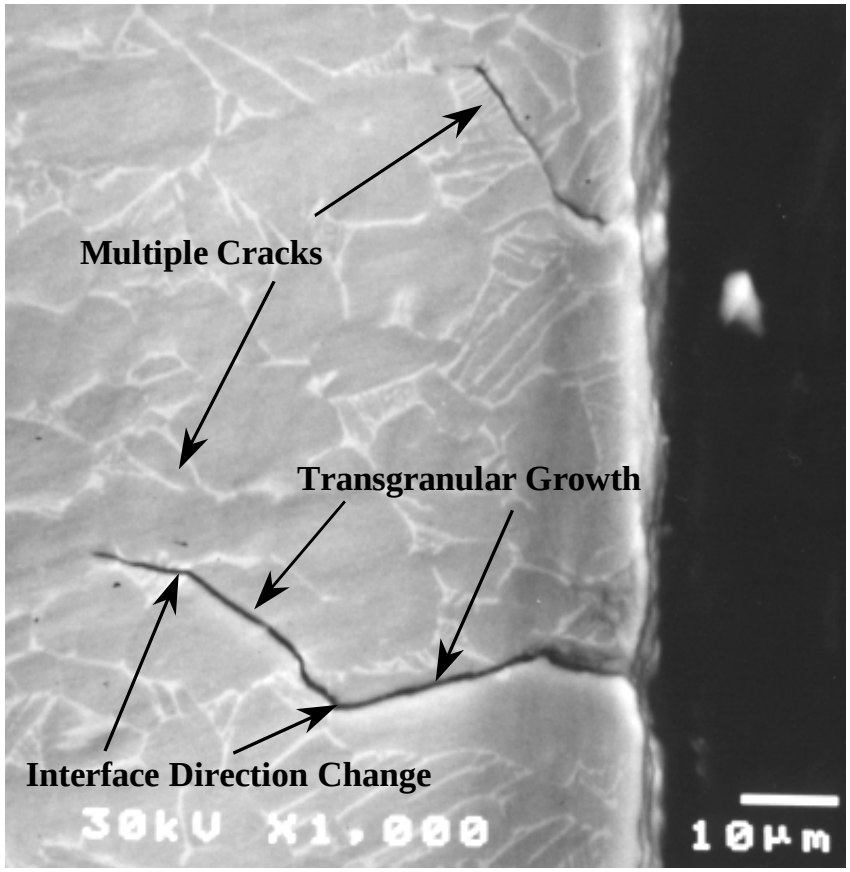
- Heat tinting is useful for identifying cracks
- Featureless fracture surface and transition region
- Fretting fatigue cracks nucleate throughout the edge of contact with similar shapes and sizes
- Transgranular growth perpendicular to surface
- Severe wear and debris obscure fretting fatigue cracks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



Fretting Crack Growth

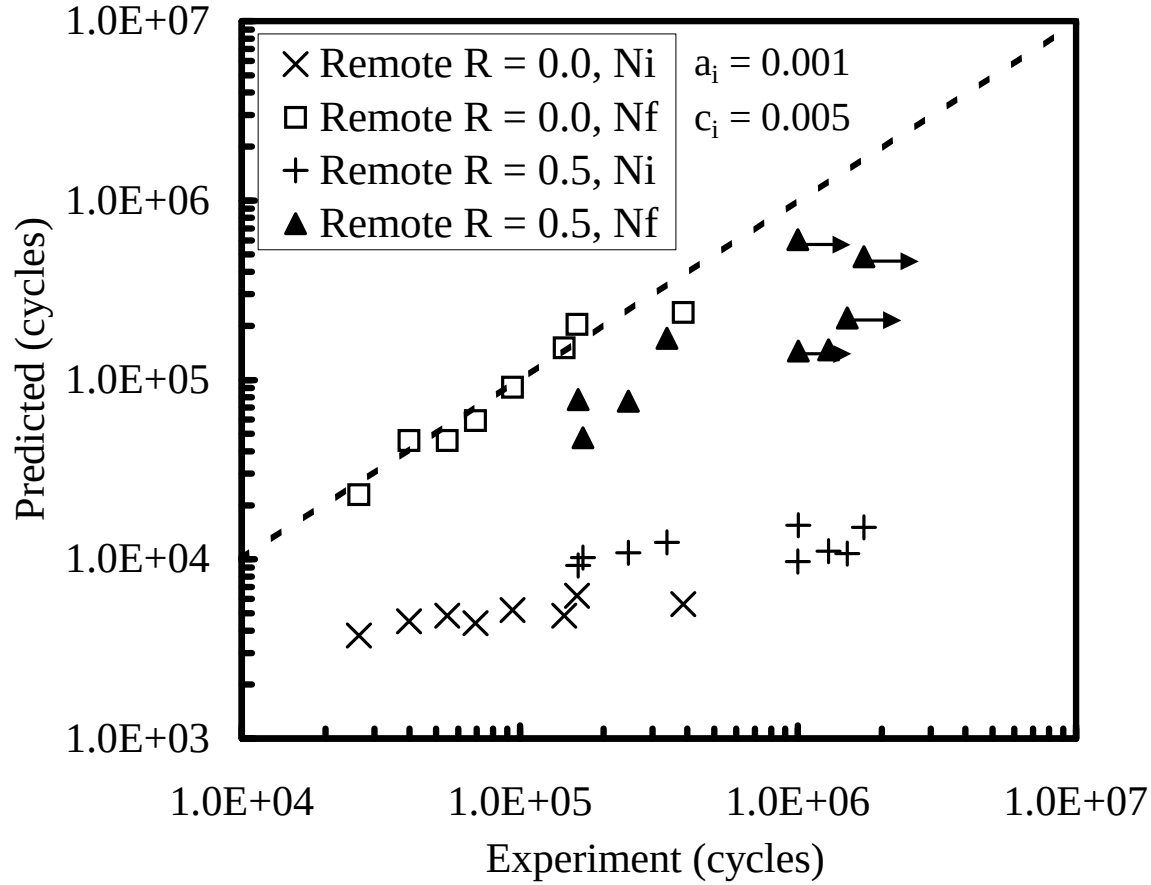
- Transgranular Crack Growth
- Crack Growth perpendicular to surface
- Example at a Polished depth of 0.0365 inches





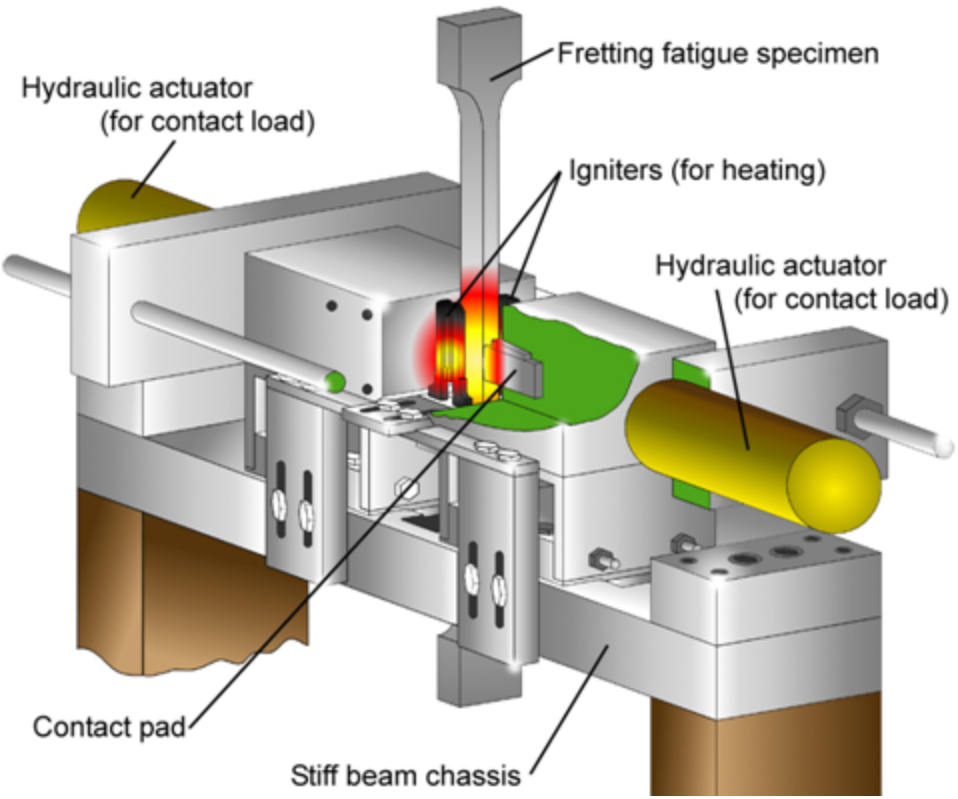
Life Prediction Comparison

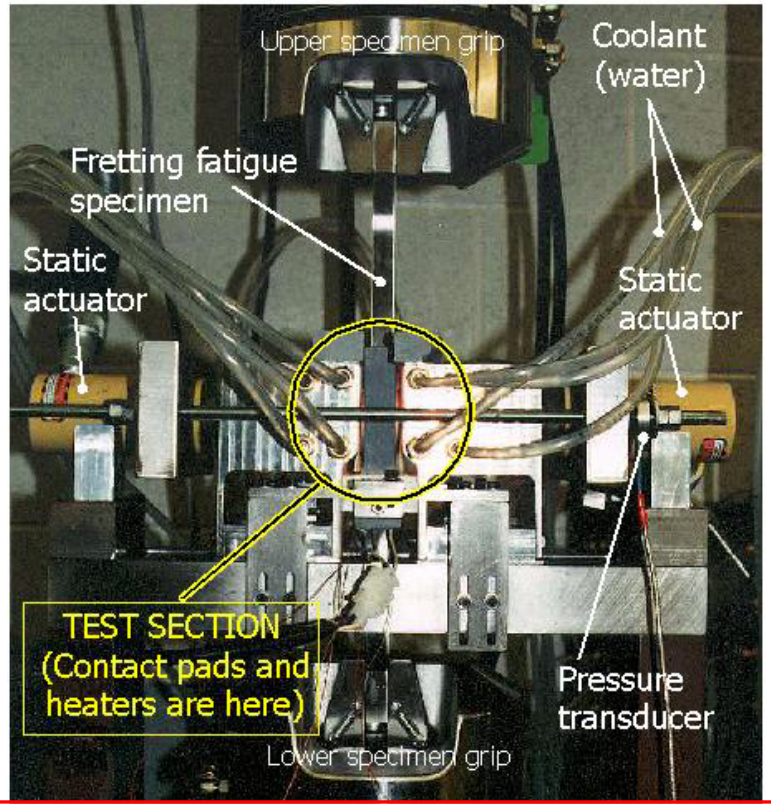
- Golden and Grandt, *Eng Frac Mech*, 2004
- Ti-6-4 on Ti-6-4
  - Two groups
    - P = 9300 lb/in, R = 0
    - P = 6700 lb/in, R = 0.5
- Life predictions
  - $N_f = N_i + N_{prop}$
  - N_i from σ_{eq}
- Total life prediction
  - 1-2 orders of magnitude above N_i
  - Good comparison with experiment using 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)

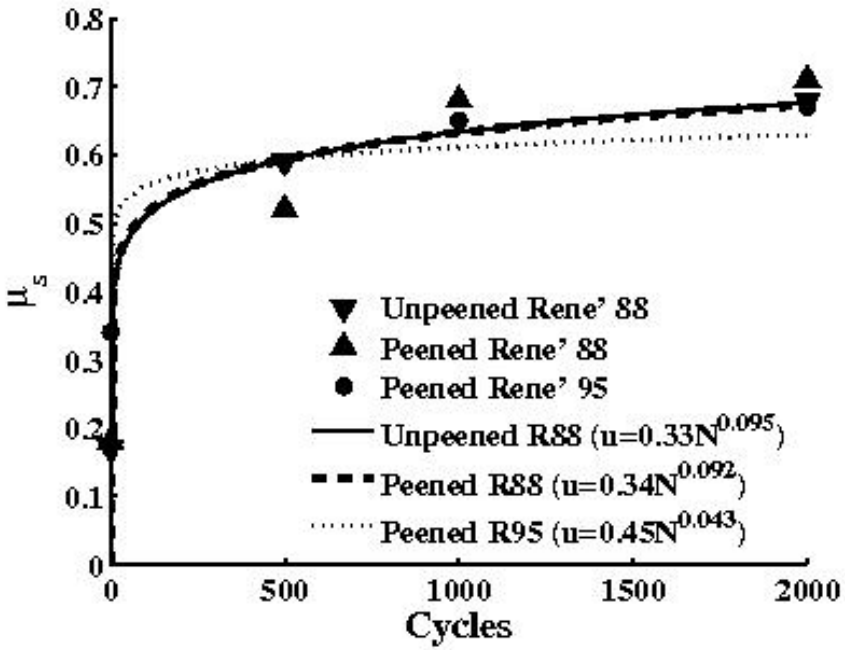
High Temperature Experiments





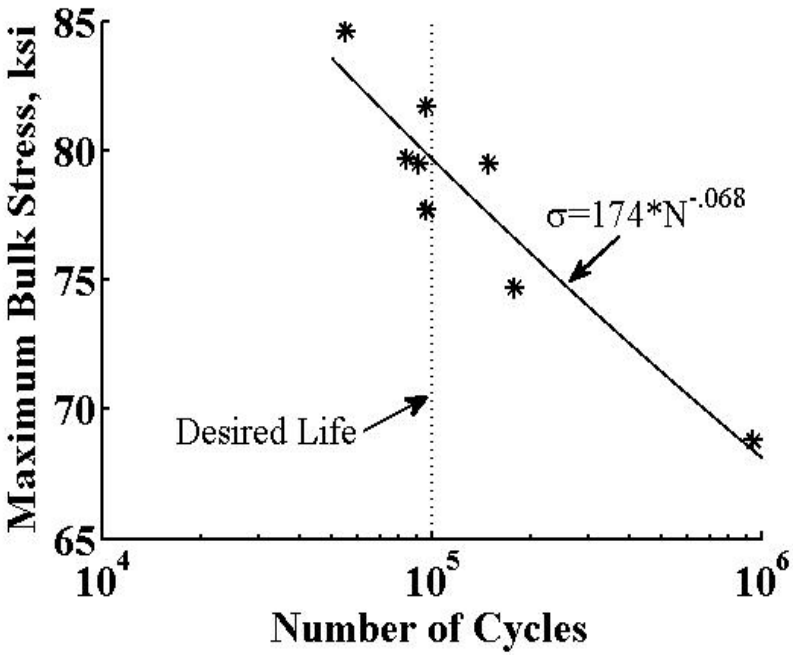
- **Load transfer based on a principle similar to that of room temperature fretting rig**
- **Igniters used for heating the specimen and the pads, locally, to high temperature**
- **Temperature controller unit designed using the output of thermocouple as input signal**
- **Ceramic shields to prevent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

Coefficient of Friction Results



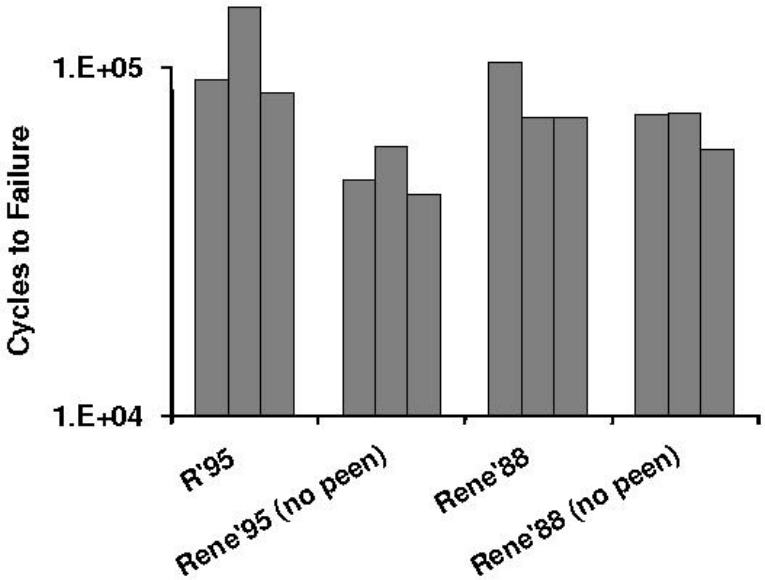
- Similar evolution in μ for peened and unpeened Rene' 88
- More rapid evolution and saturation of μ for Rene' 95
  - Higher initial μ for Rene' 95
  - Similar μ for Rene' 95 after 500-2000 cycles
- Only able to determine μ after 2,000 cycles because of hardware limitations
  - Continued increase in μ after 2,000 minimal
  - Near saturation in μ 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

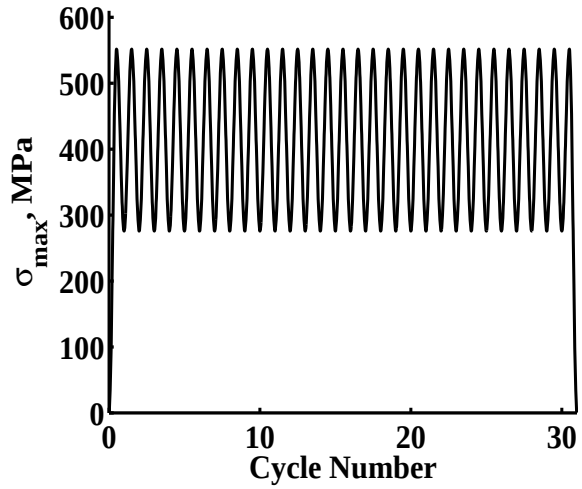
Effect of Material and Surface Treatment

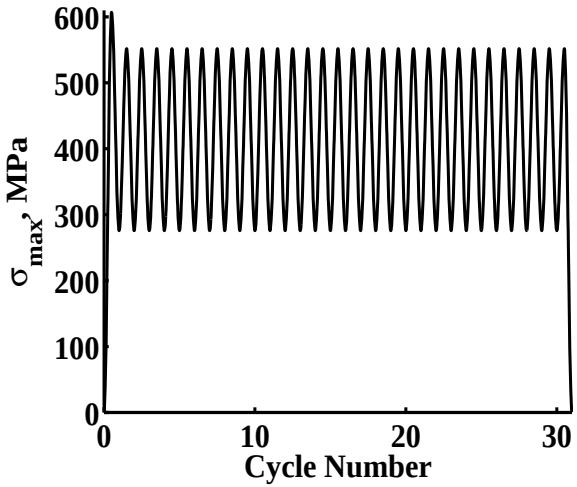


- 2x increase in life between peened/unpeened Rene' 95
  - Elevated temperature (600 ˚F) in Ti-17 shows similar improvement in life, Gean, et al. (2006)
- 10% increase in life between peened/unpeened Rene' 88
- Peened Rene' 95 longer life than peened Rene' 88
- Unpeened Rene' 95 shorter life than unpeened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

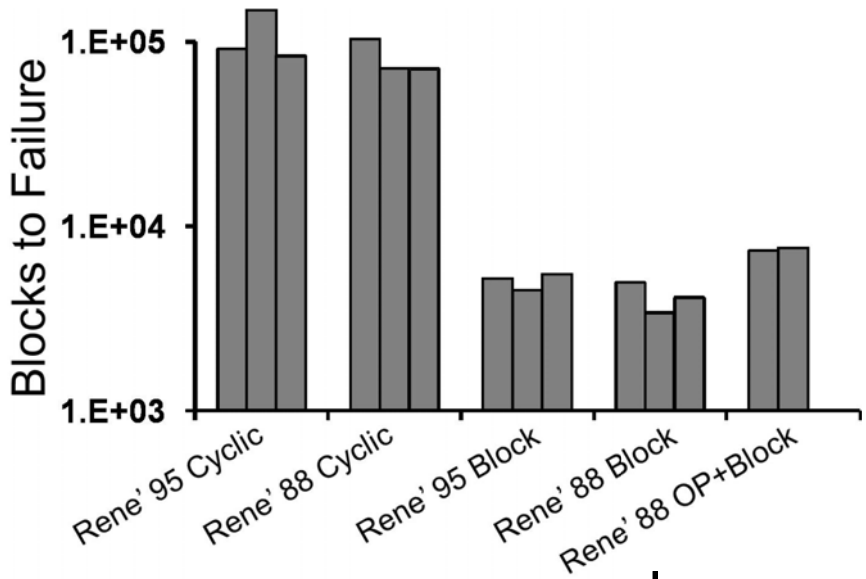
Specimen		Pads		# Exps	Average N	Standard Deviation N
Material	Shot Peen	Material	Shot Peen			
Rene' 88	No	Rene' N5	No	3	68,144	7,264
Rene' 88	7A	Rene' N5	7A	3	82,185	15,001
Rene' 95	No	Rene' 80	No	3	49,774	6,885
Rene' 95	7A	Rene' 80	7A	3	109,707	28,156

Block Loading





- Left plot demonstrates simple block loading
  - 1 Major cycles with σ_{max}~550 MPa
    - R_σ~0
  - 30 Minor cycles with σ_{max}~550 MPa
    - R_σ~.5
- Right plot demonstrates block loading plus overpeak
  - Similar to simple block loading with 10% overload



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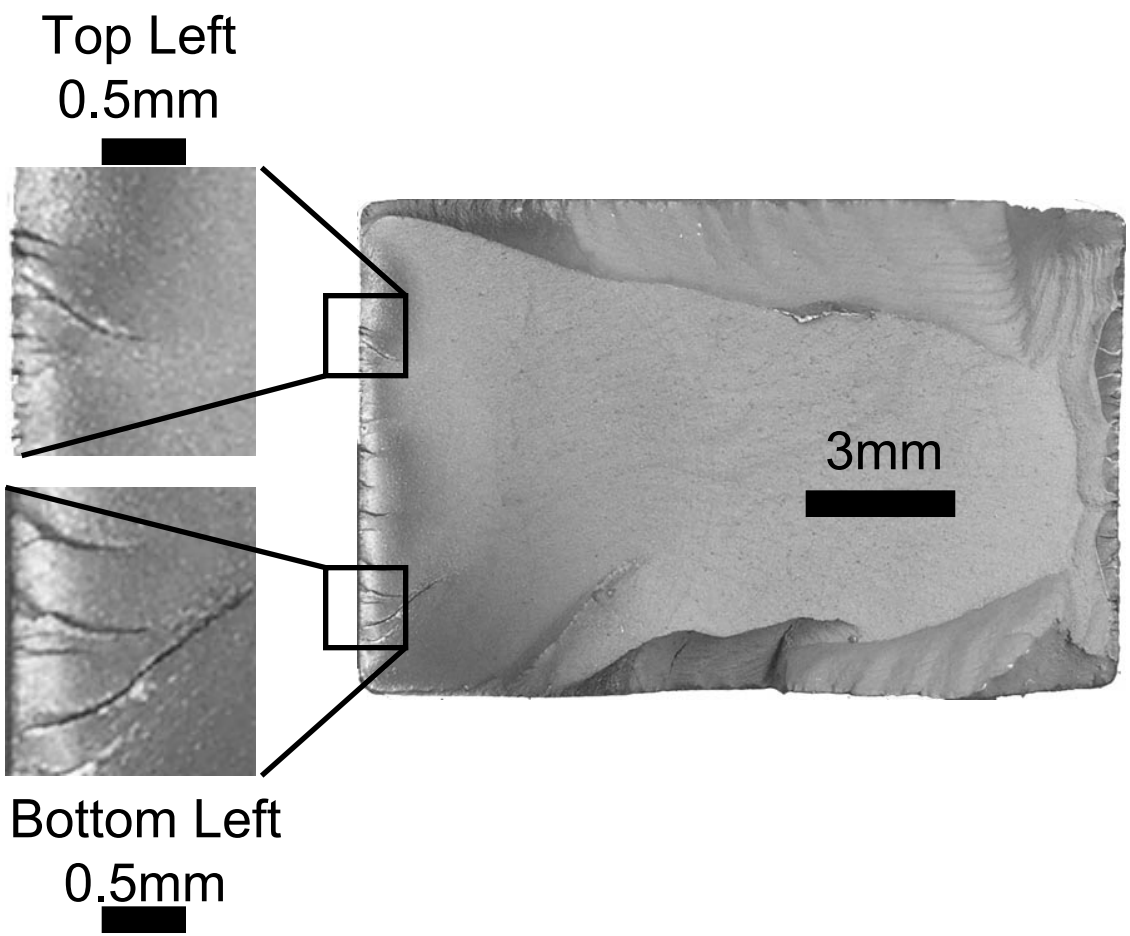
Specimen			Pad		# Exps	Average N	Standard Deviation N
Material	Shot Peen	Load Type	Material	Shot Peen			
Rene' 88	7A	Block	Rene' N5	7A	3	4,139	632
Rene' 88	7A	Block+OP	Rene' N5	7A	2	7,446	159
Rene' 95	7A	Block	Rene' 80	7A	3	5,047	403
Rene' 88	7A	Cyclic	Rene' N5	7A	3	82,185	15,001
Rene' 88	7A	Cyclic	Rene' N5	7A	3	109,707	28,156

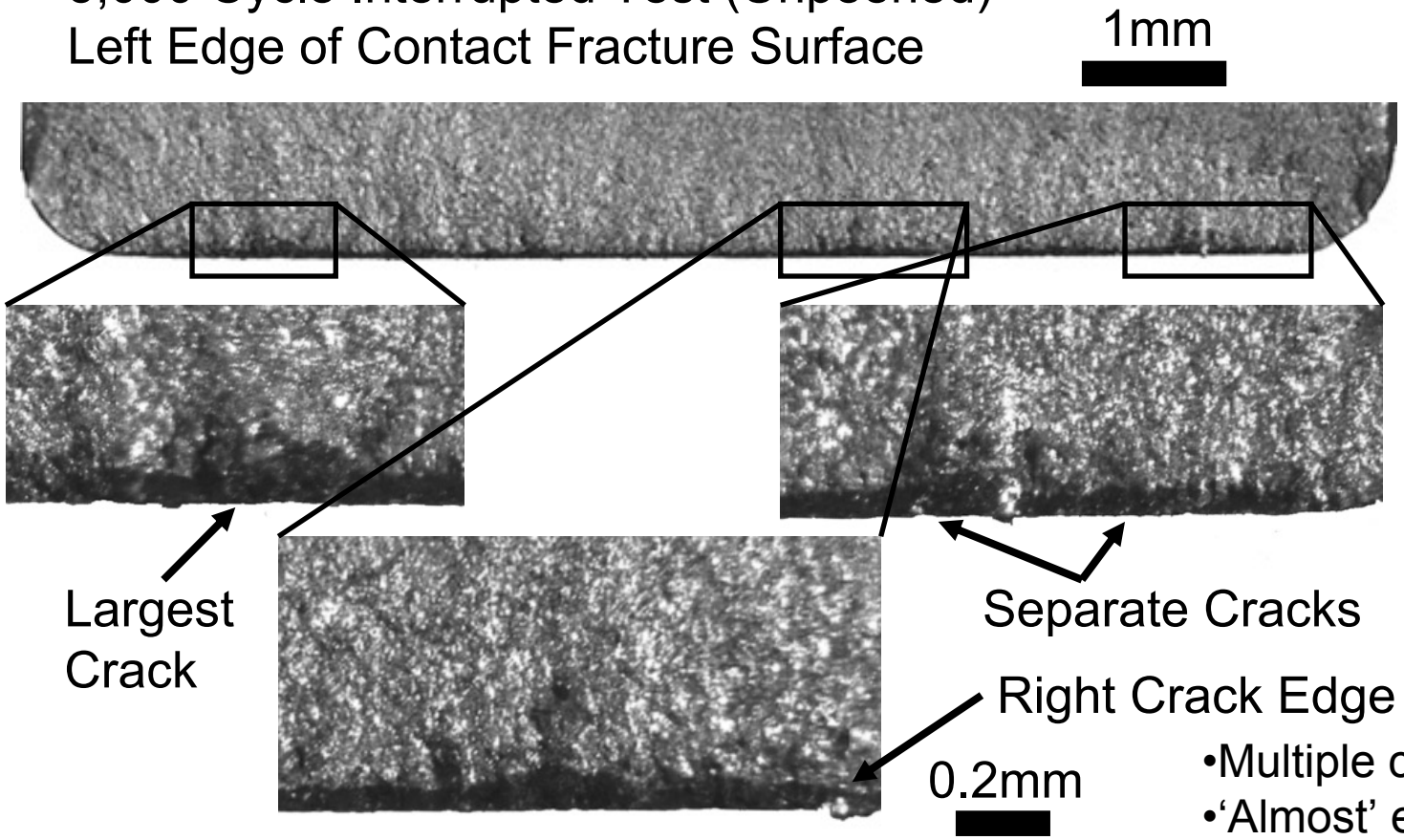
Fretting Fatigue Failure Fracture Surface



- 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



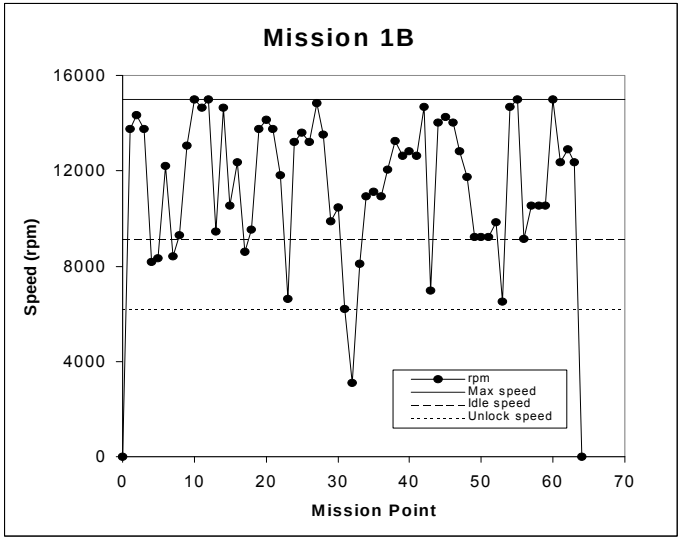
- Multiple cracks
- 'Almost' edge crack
- Shallow depth

Gean, Tate, and Farris, *SDM* 2009

Conclusions

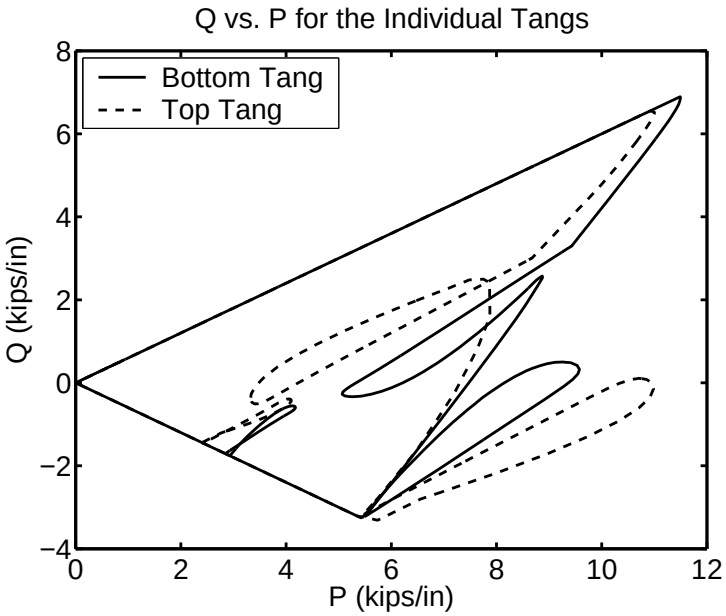
- Attachment fatigue can be reproduced under controlled laboratory conditions
- Characterization of the contact mechanics through a combination of experiments and analysis allows use of conventional life prediction tools
- Analysis tools have been adopted by OEMs
- Robust characterization of load history 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

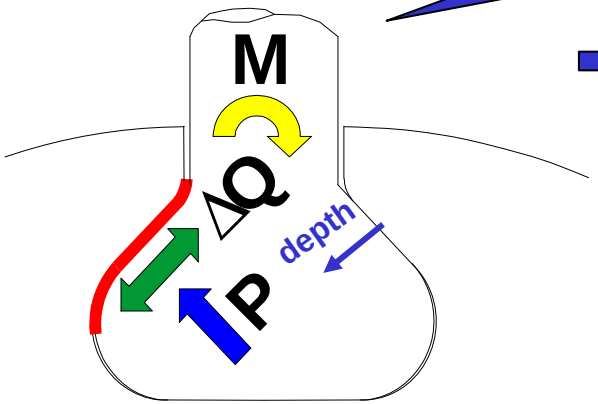
Vision of EoC Implementation by OEMs



"Spring" Model

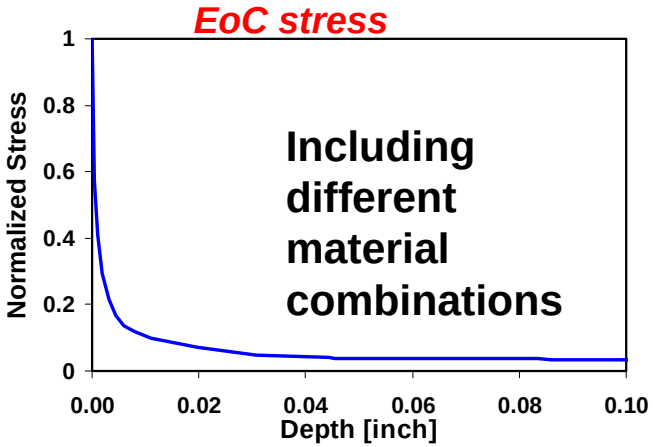
Prediction of contact loads (P,Q,M) through mission history (reduction in FEM analysis)





Integral Equations

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



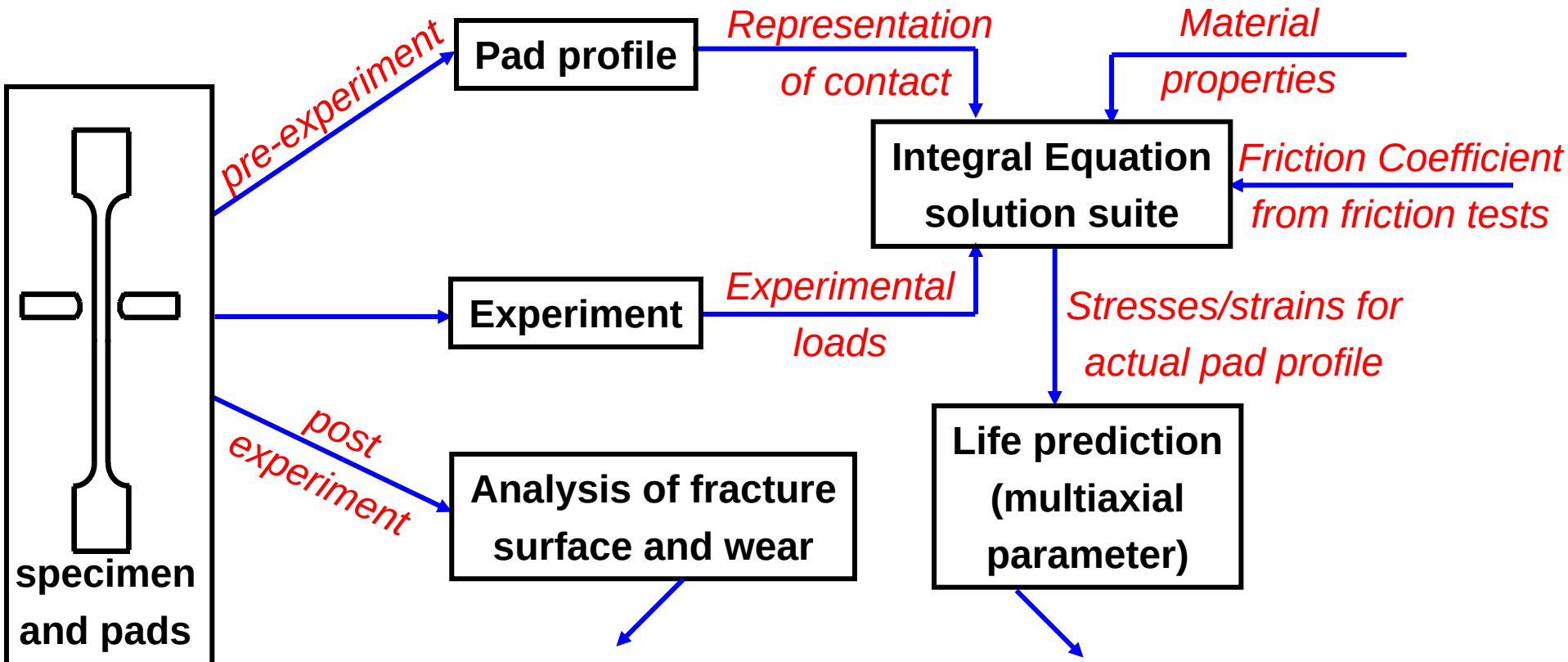
Some of Leon's Academic Grandchildren

- 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

- A.F. Grandt, D.B. Garcia PhD, 2005 SAIC, and P.J. Golden PhD, 2001, AFRL
- M. Okane, TNCT, T. Sakagami, Kobe University
- I. Goryacheva, Russian Academy of Sciences
- Bob VanStone and others at GEAE

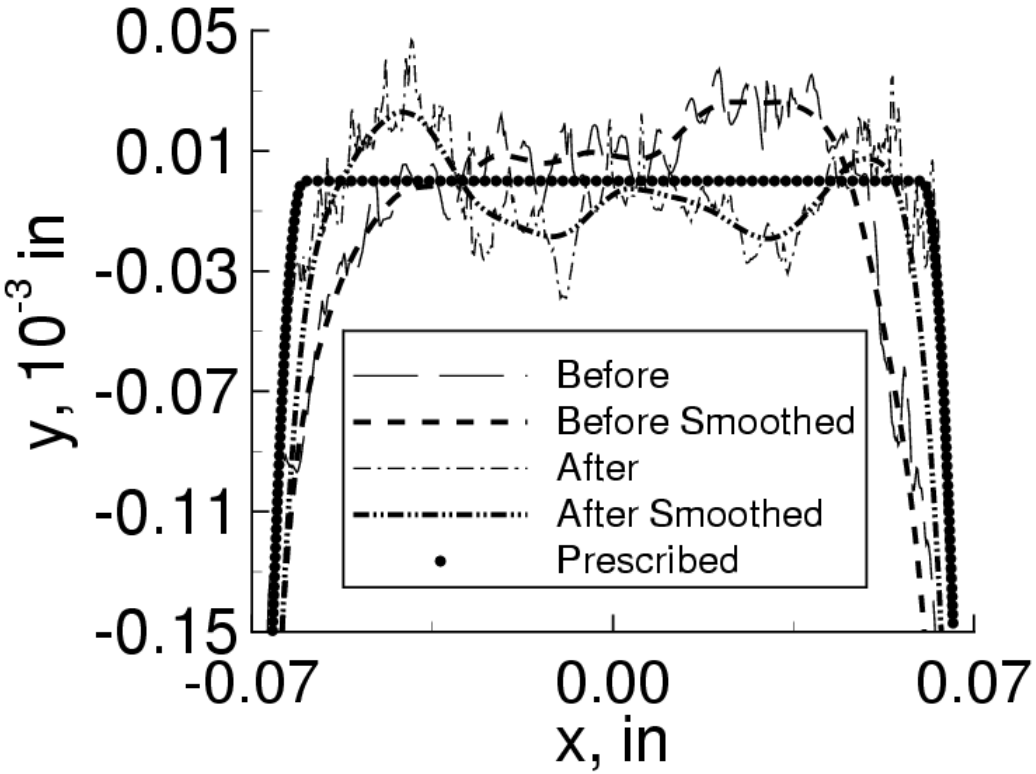
Experimental Flowchart



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

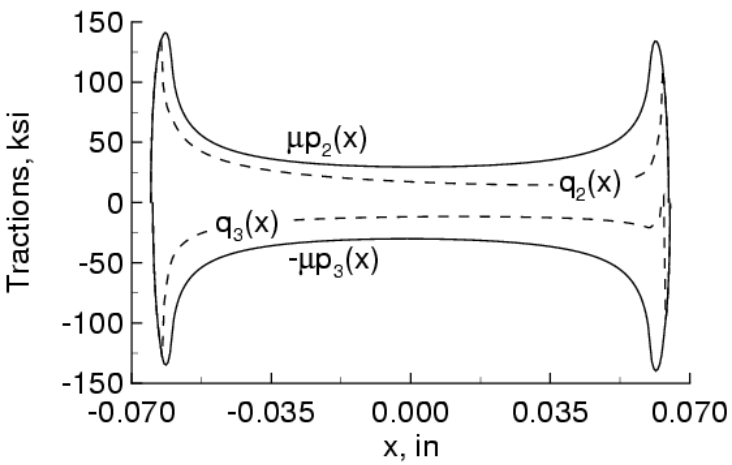
- Life prediction
- Estimation of propagation life
- Comparison with experimental lives

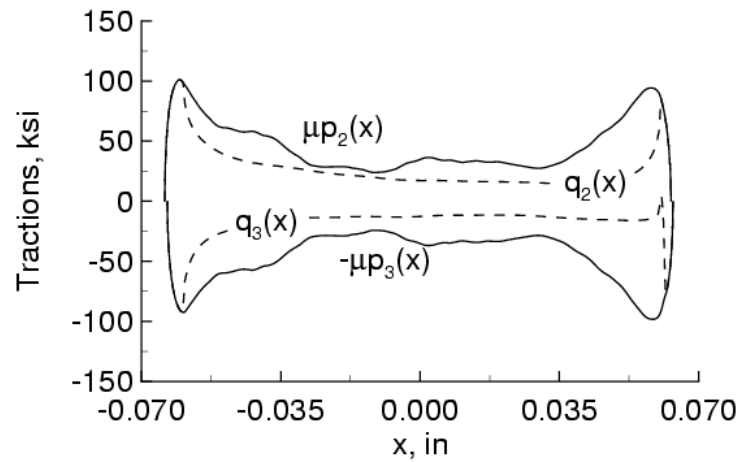
Metrology of Pads



- 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





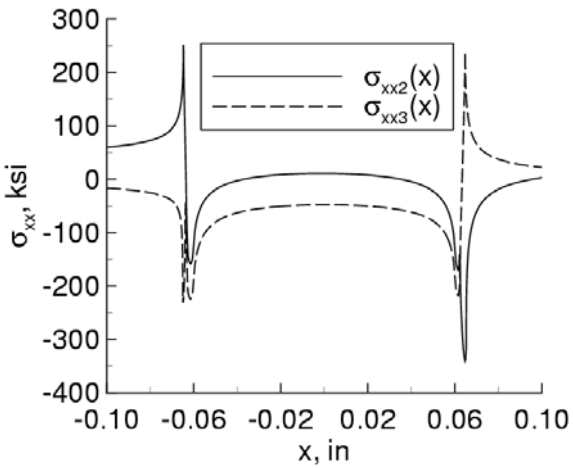
Expt. Fret.02

P = 8160 lb/in

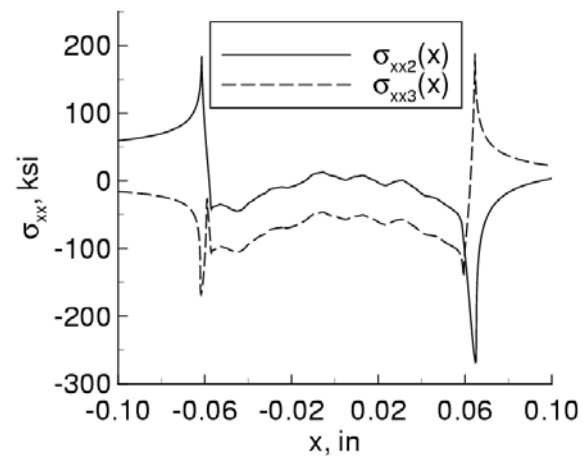
Q_{max} = 3463 lb/in

Q_{min} = -2369 lb/in

σ_{max} = 35.6 ksi

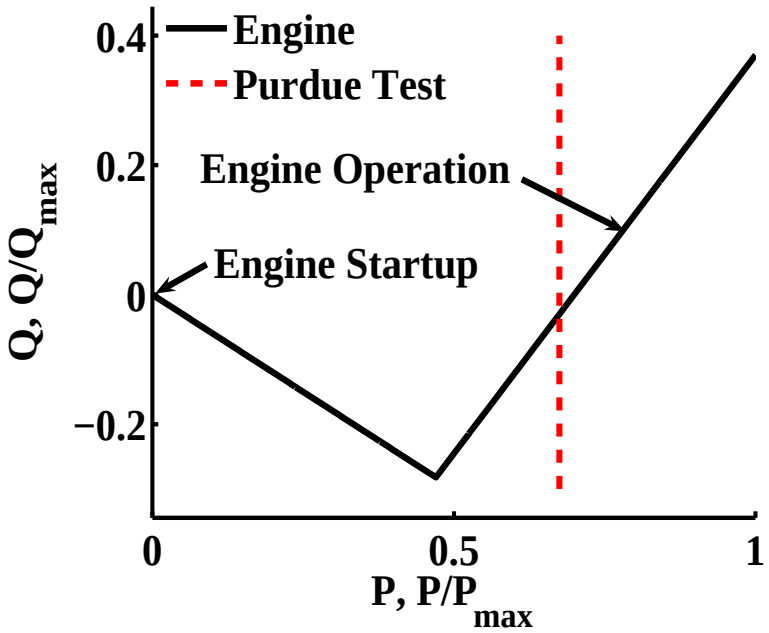


Prescribed



After, smoothed

Load Selection



P=normal load
Q=shear load

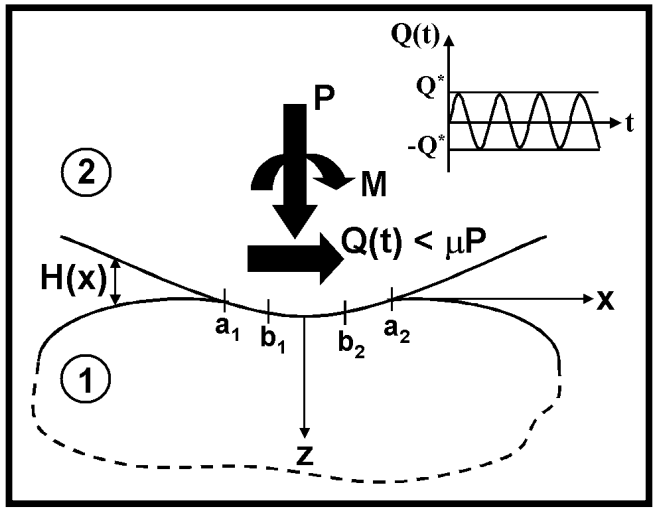
- Dovetail loading coupled normal and shear load
- Fretting Fatigue Experiment
  - Constant normal load
  - Alternating shear load

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

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

2D Fretting Contact Model for SCN



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,

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

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

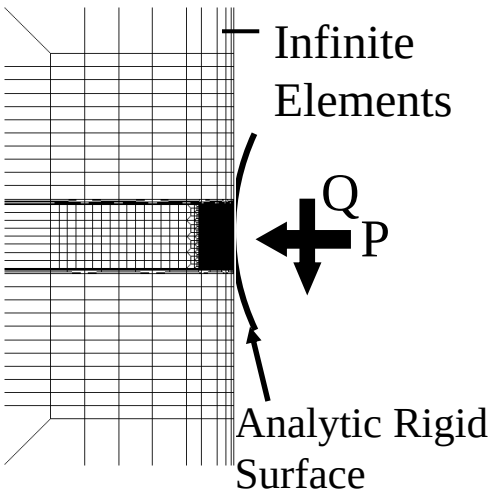
- Incorporating stick/slip behavior in the out-of-plane direction would mean solving **three coupled** SIEs to obtain p(x), $q_x(x)$, $q_z(x)$.
- Problem can be simplified by assuming that the frictional traction acts only to resist motion in the x-direction, i.e., $\mu_x = \mu$ & $\mu_z=0$.
- Since $q_z(x) \equiv 0$, 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,

$$s(x) = s_c(x) - \frac{(1-\nu_{zx}\nu_{xz})}{E_x}\sigma_0 x$$

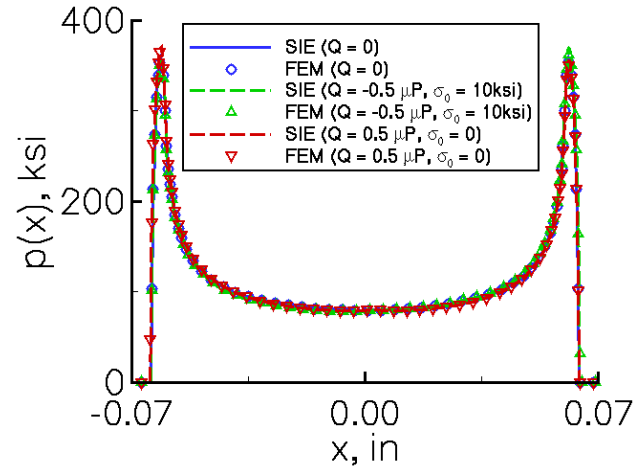
where $s_c(x)$ is the relative slip due to the contact tractions alone and σ_0 is the applied remote stress.

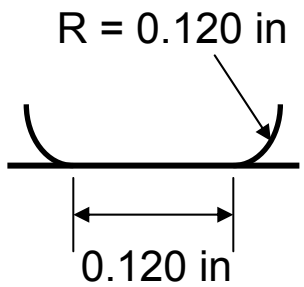
P.T. Rajeev and T. N. Farris, *Journal of Strain Analysis* (2002)

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

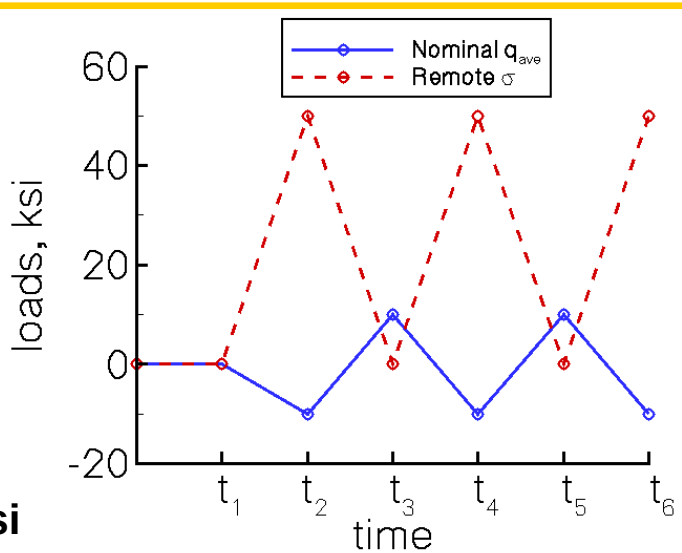


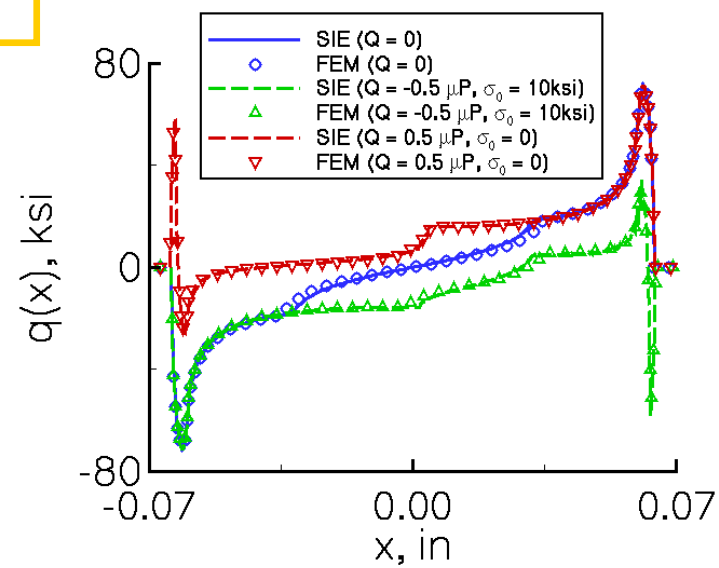


$\mu = 0.2$

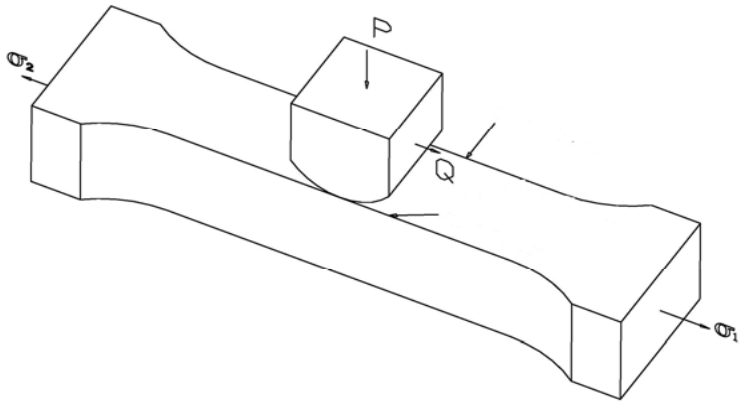
$\theta_z = 45^o, \theta_x = 0^o$

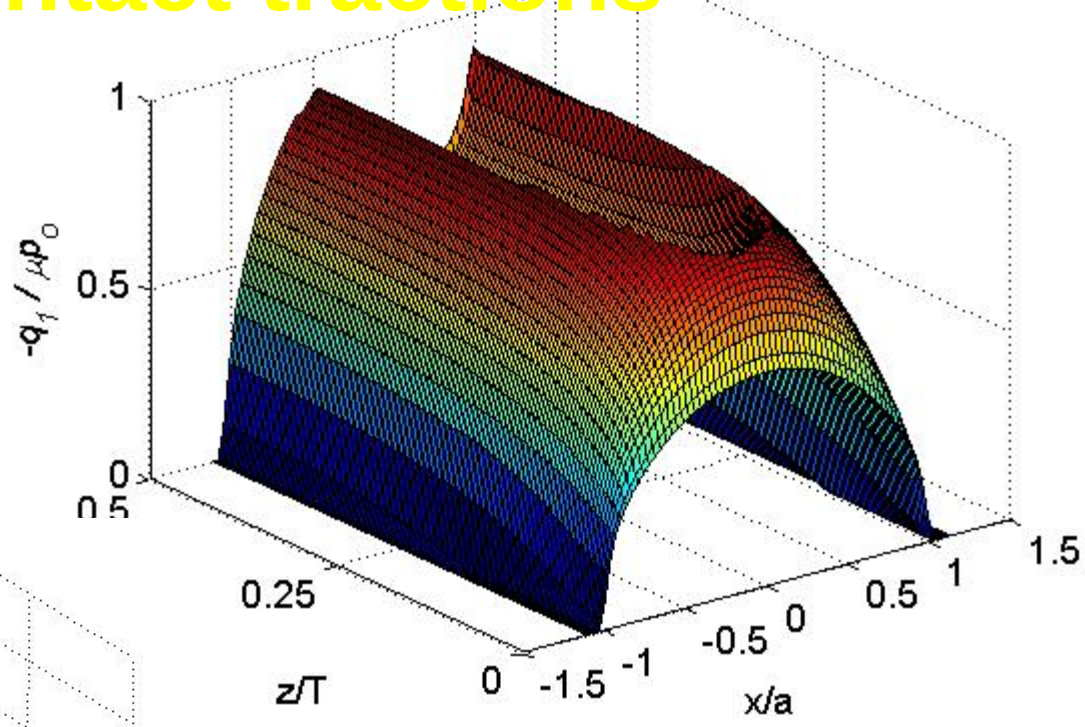
Nominal p_{ave} = 100 ksi

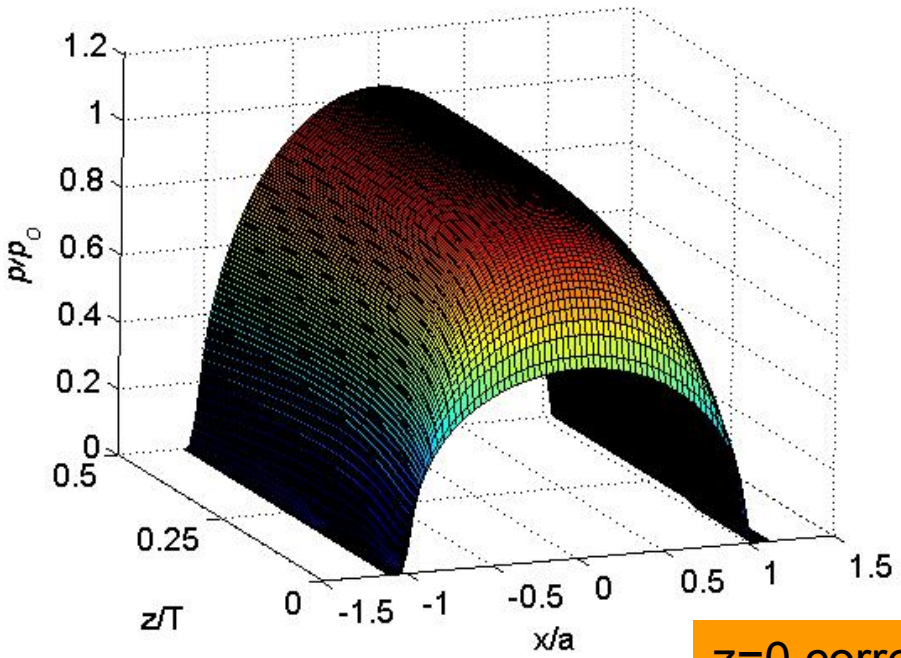




3-D contact tractions



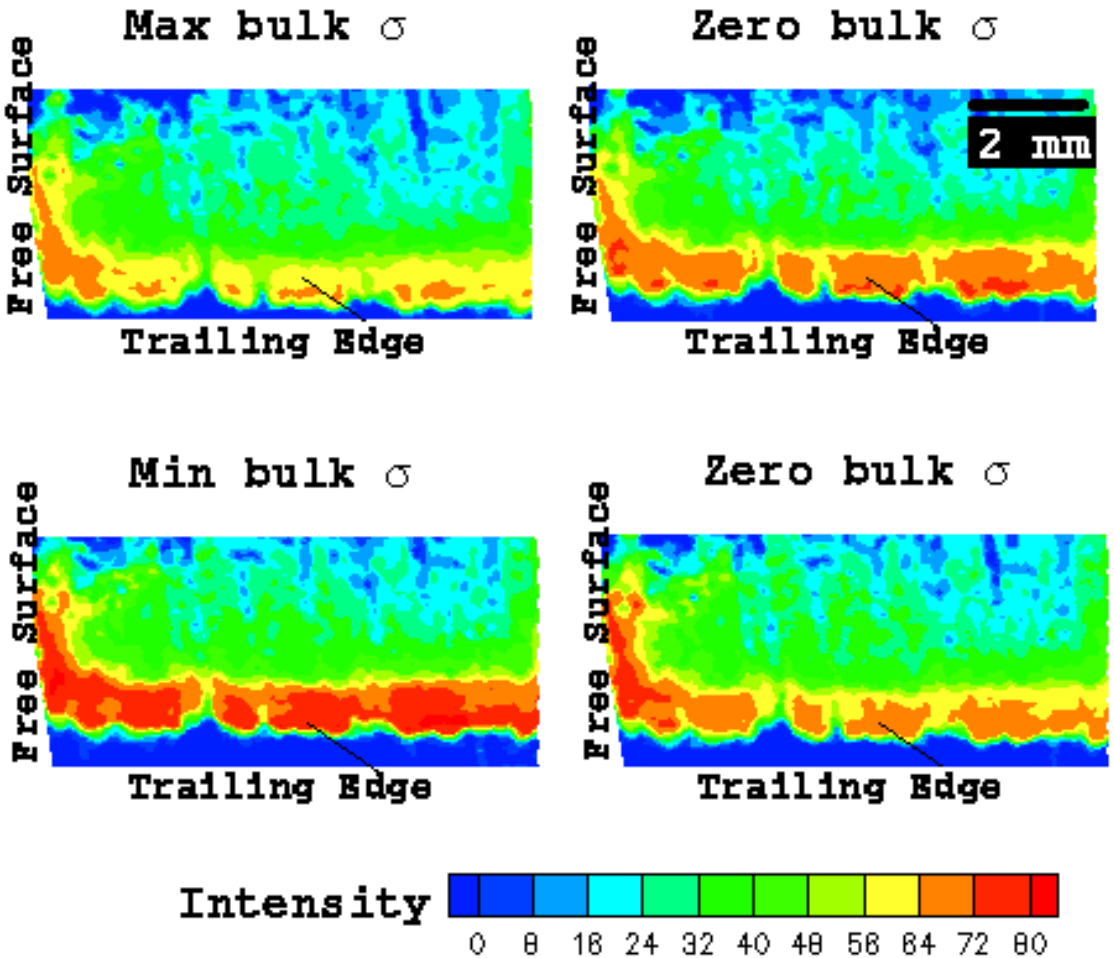




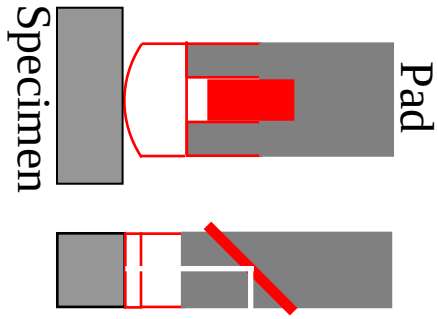
Slip zone in the vicinity of the edge

z=0 corresponds to the edge.

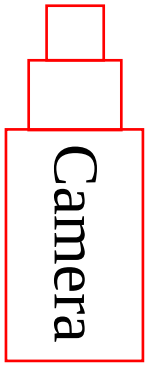
Thermal Imaging of Contact Surface



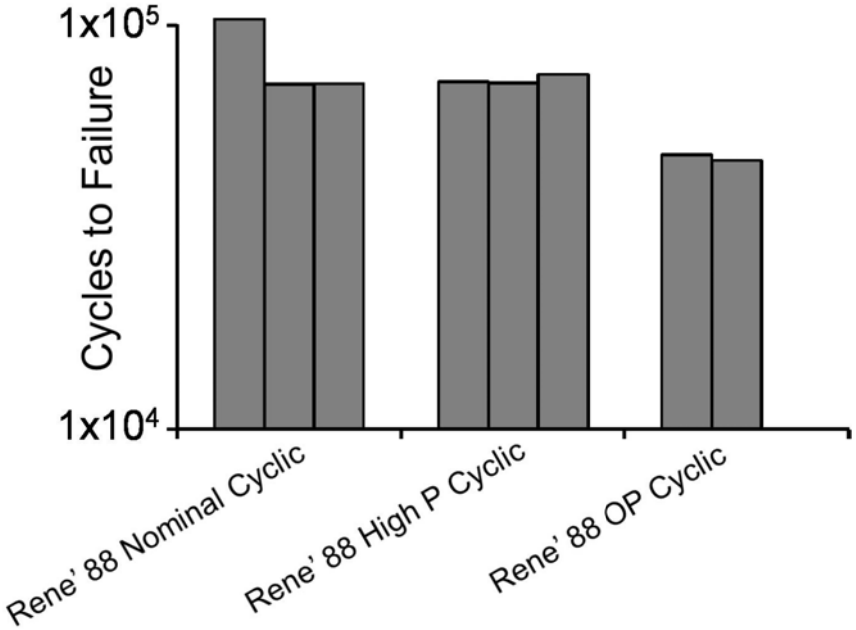
Schematic of surface imaging



Sapphire pad on aluminum specimen



High P and Overpeak Cyclic Results



ic stress level
; life by a
f 2

crease in
load reduces
bout 10%

Specimen			Pad		# Exps	Average N	Standard Deviation N
Material	Shot Peen	Load Type	Material	Shot Peen			
Rene' 88	7A	OP Cyclic	Rene' N5	7A	2	47,057	778
Rene' 88	7A	High P	Rene' N5	7A	3	73,294	1,626
Rene' 88	7A	Cyclic	Rene' N5	7A	3	82,185	15,001