Chapter 4 and 5 Wear Mechanisms

Delamination Wear Mechanisms

- **Four mechanisms of delamination wear**

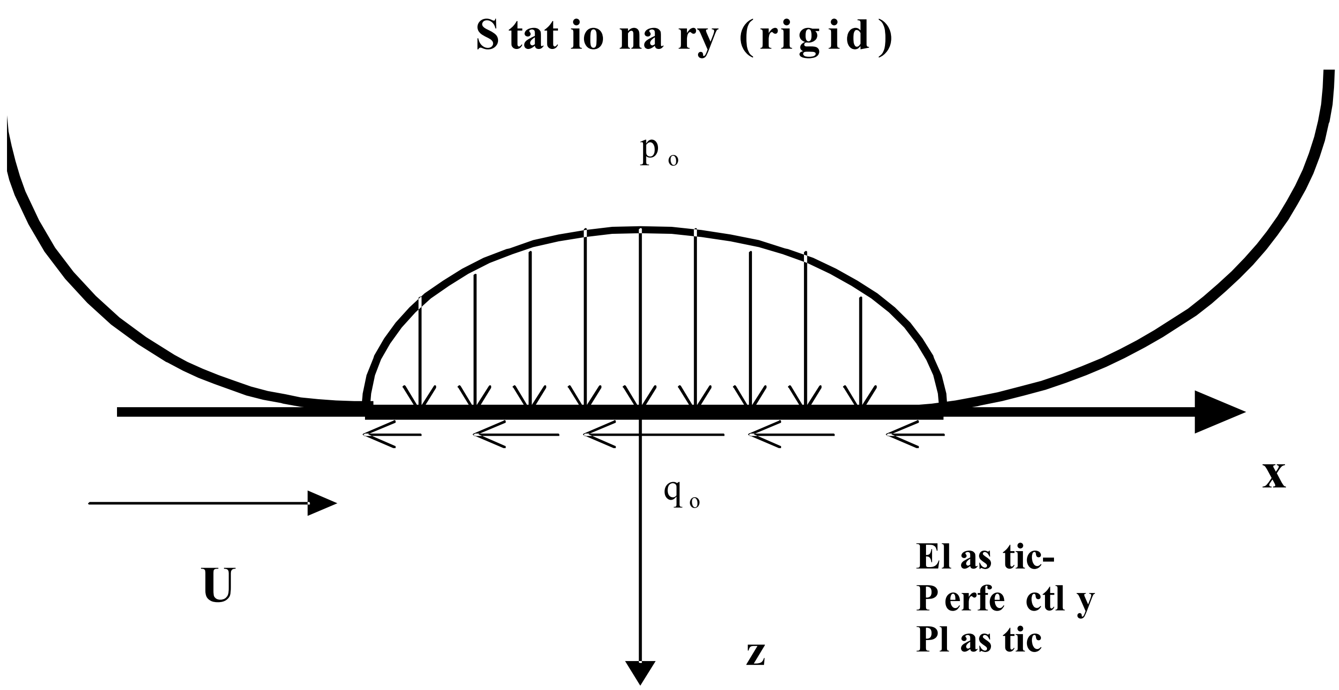
1. Plastic deformation of the surface
2. Crack nucleation at the sub-surface due to plastic deformation
3. Crack propagation from these nucleated cracks due to plastic deformation
4. Creation of loose wear sheets

Plastic Deformation of a Semi-Infinite Elastoplastic Solid

Governing equations

1. Equilibrium condition
2. Yield condition
3. Constitutive relationships for elastic and plastic deformation
4. Geometric compatibility

Plastic Deformation of a Semi-Infinite Elastoplastic Solid



Plastic Deformation of a Semi-Infinite Elastoplastic Solid

- Mises Flow Rule (Yield Criterion)

$$-J'_2 = \frac{1}{2}\sum_{i=1}^{3}\sum_{j=1}^{3}\left(\sigma'_{ij}\sigma'_{ij}\right) = \frac{1}{3}\bar{\sigma}^2 = k^2$$

Plastic Deformation of a Semi-Infinite Elastoplastic Solid

Total strain rate

$$\dot{\varepsilon}_{ij} = \dot{\varepsilon}_{ij}^{e} + \dot{\varepsilon}_{ij}^{p}$$

Prandtl – Reuss Relationship for plastic deformation

$$\dot{\varepsilon}_{ij}^{p} = \frac{\dot{W}^{p}}{2k^{2}}\sigma'_{ij} = \frac{3}{2}\frac{d}{dt}\left(\frac{d\bar{\varepsilon}}{\bar{\sigma}}\right)\sigma'_{ij}$$

$$\dot{W}^{p} = \sum_{i=1}^{3}\sum_{j=1}^{3}\dot{\varepsilon}_{ij}^{p}\sigma'_{ij} = \bar{\sigma}\frac{d}{dt}(\bar{\varepsilon})$$

Plastic Deformation of a Semi-Infinite Elastoplastic Solid

Total strain rate

$$\dot{\varepsilon}_{ij} = \frac{\dot{\sigma}_{ij}}{2G} + \frac{\dot{W}^{p}}{2k^{2}}\sigma'_{ij}$$

Solving for σ'_{ij}

$$\sigma'_{ij} = 2G(\dot{\varepsilon}_{ij} - \frac{\dot{W}^{p}}{2k^{2}}\sigma'_{ij})$$

Plastic Deformation of a Semi-Infinite Elastoplastic Solid

Conversion of the time derivative to gradients:

$$\frac{d}{dt}(\sigma'_{ij};\varepsilon'_{ij};W)=U\frac{\partial}{\partial x}(\sigma'_{ij};\varepsilon'_{ij};W)$$

Plastic Deformation of a Semi-Infinite Elastoplastic Solid

Residual Stress Calculation

$$(\sigma_{xx})_r = f_1(z)$$

$$(\sigma_{zz})_r = f_2(z)$$

$$(\sigma_{yy})_r = \nu[f_1(z) + f_2(z)]$$

$$(\sigma_{xz})_r = f_3(z)$$

Plastic Deformation of a Semi-Infinite Elastoplastic Solid

Residual Stress Calculation -- Equilibrium Equations

$$\frac{\partial(\sigma_{xx})_r}{\partial x} + \frac{\partial(\sigma_{xz})_r}{\partial z} = 0$$

$$\frac{\partial(\sigma_{xz})_r}{\partial x} + \frac{\partial(\sigma_{zz})_r}{\partial z} = 0$$

$$f_3 = c_1$$

$$f_2 = c_2$$

$$(\sigma_{xx})_r = f(z)$$

$$(\sigma_{yy})_r = \nu f(z)$$

$$(\sigma_{zz})_r = 0$$

$$(\sigma_{xz})_r = 0$$

Plastic Deformation of a Semi-Infinite Elastoplastic Solid

Residual Stress Calculation -- Equilibrium Equations

$$(\varepsilon_{zz})_r = -\frac{1-2\nu}{2(1-\nu)G}(\sigma_{zz})'_r$$

$$(\gamma_{xz})_r = -\frac{(\sigma_{xz})'_r}{G}$$

$$(\sigma_{xx})_r = (\sigma_{xx})'_r - \frac{\nu}{1-\nu}(\sigma_{zz})'_r$$

$$(\sigma_{yy})_r = (\sigma_{yy})'_r - \frac{\nu}{1-\nu}(\sigma_{zz})'_r$$

Crack Nucleation

- Crack nucleation criteria
  1. Energy criterion
  2. Strength criterion
- Because of the energy criterion, there is a critical flaw size for crack nucleation, which is satisfied by most flaws in engineering materials.

Crack Nucleation

- Crack nucleation occurs rather readily in multi-phase metals. It takes only 100 to 1,000 cycles. Therefore, it is not the rate-controlling mechanism in these multi-phase metals.

Crack Nucleation

- In single phase metals, crack nucleation at the sub-surface is very difficult. Therefore, in these metals, delamination wear may not be the primary wear mechanism. Wear by plowing of the surface by wear particles may be the primary wear-rate controlling mechanism.

Crack Nucleation

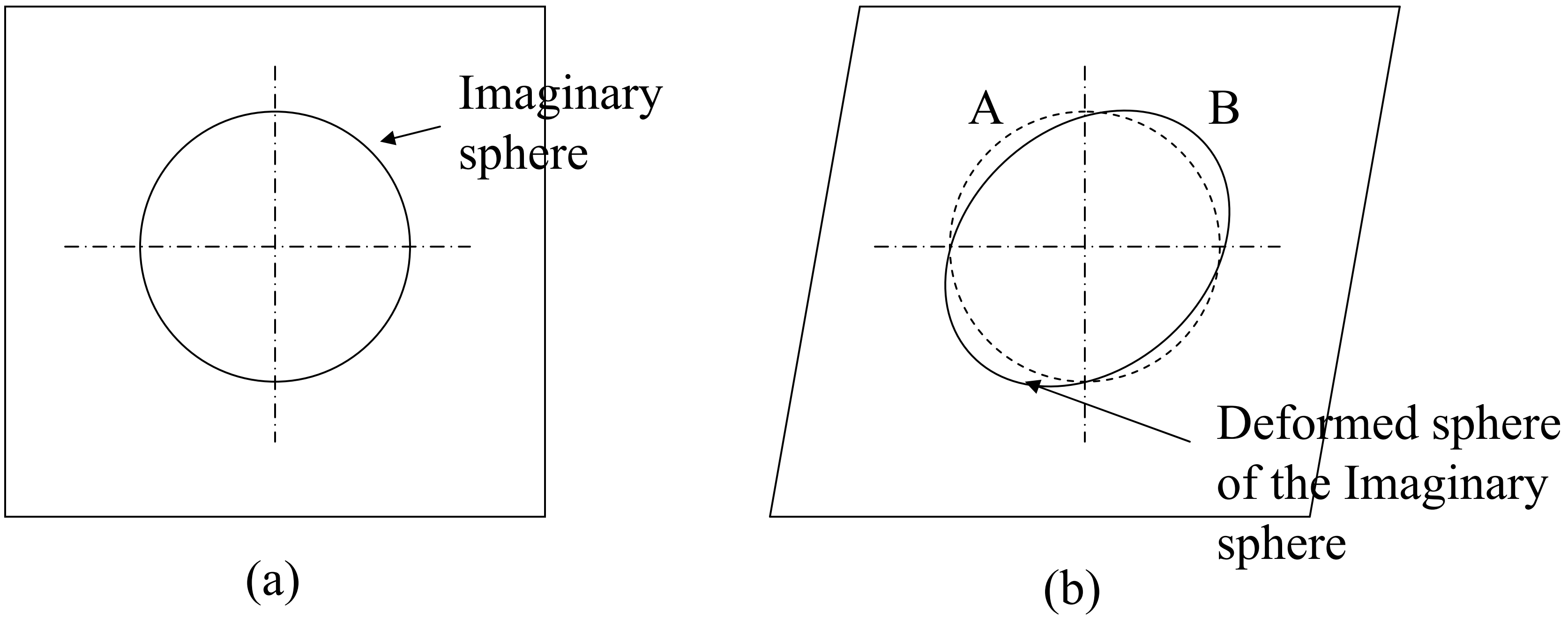


Figure 4.36

Criteria for Crack Nucleation

Energy Criterion and Strength Criterion

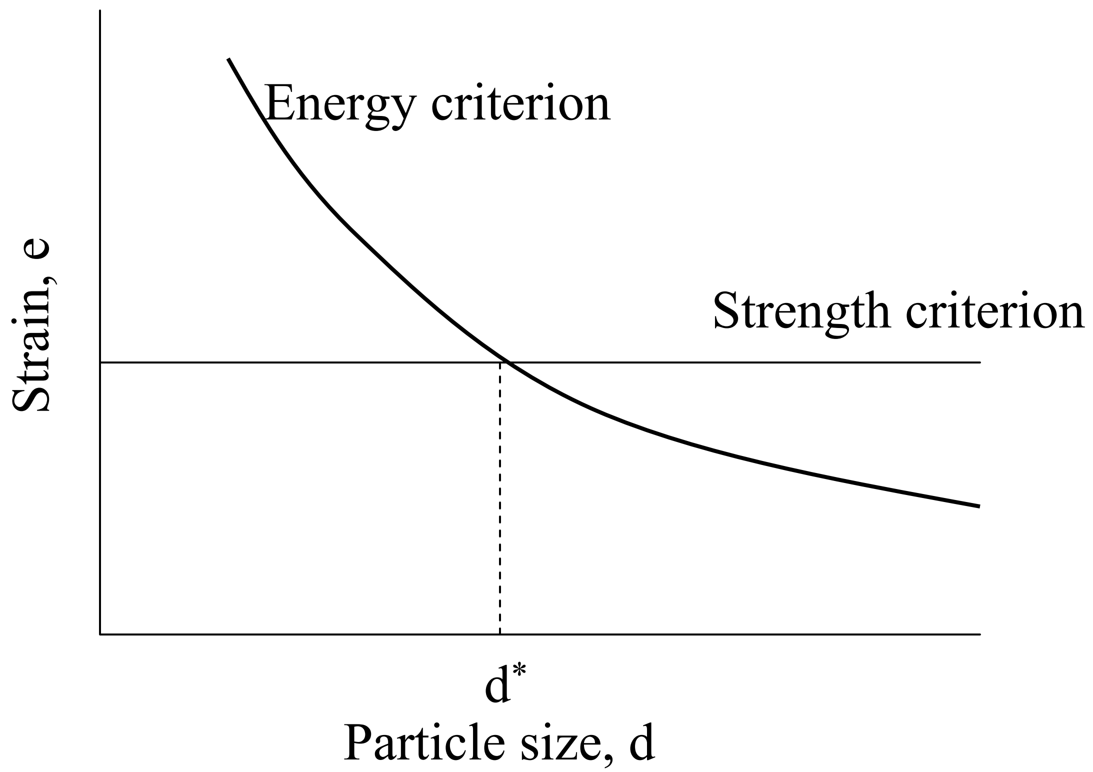


Figure 4.37

Rigid Cylinder under a General State of Stress

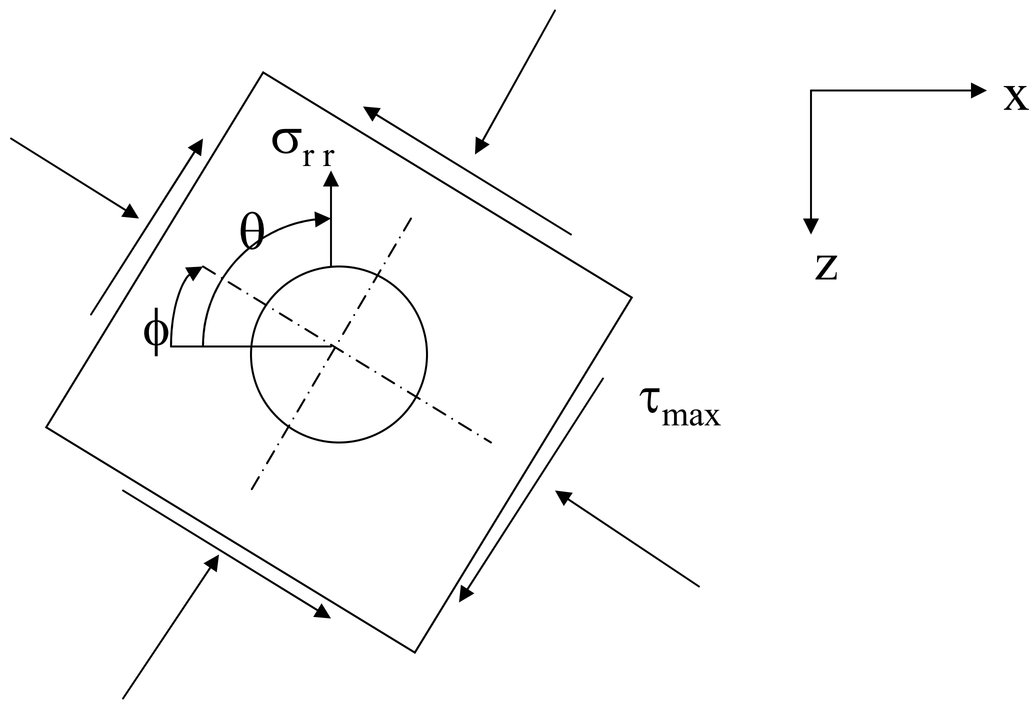


Figure 4.38

Crack Nucleation

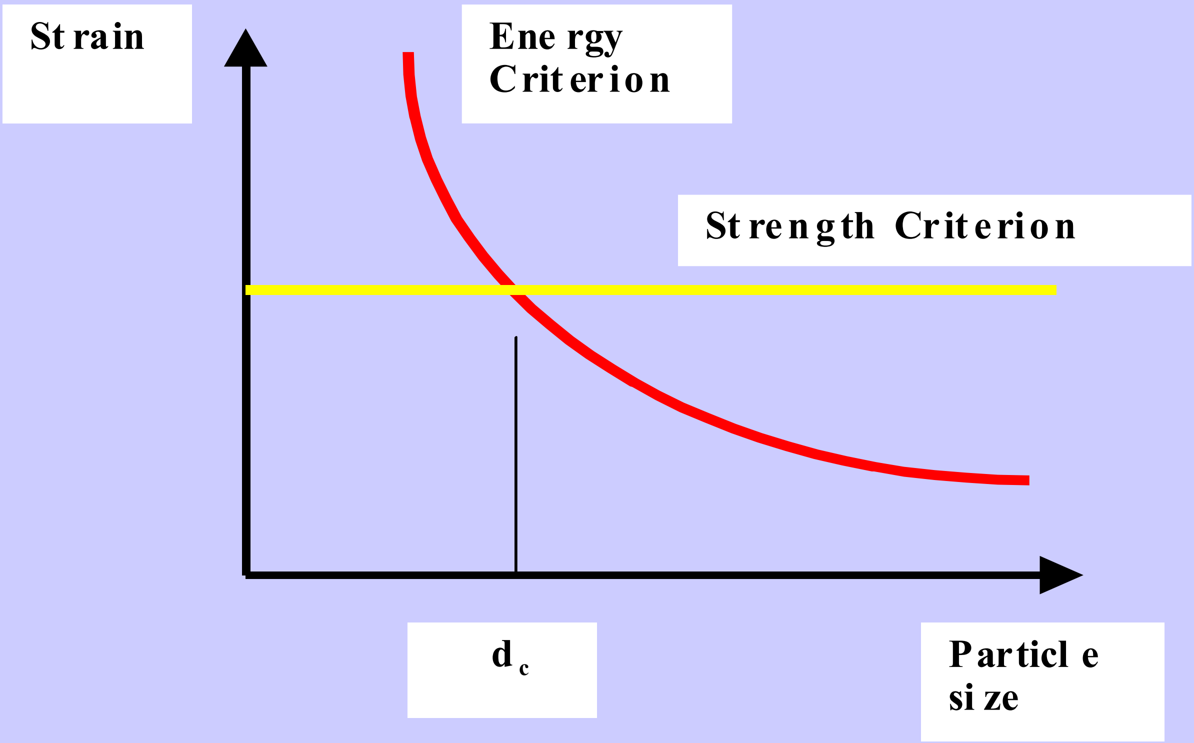
Strength criterion

$$(\sigma_{\mathrm{kk}})_{\max} \geq \sigma_i$$

Energy criterion

$$\mathrm{E}^{\mathrm{s}}_{before} - \mathrm{E}^{\mathrm{s}}_{after} \geq A\,\Delta\gamma$$

Crack Nucleation



Contour of σ_{rr} under a sliding contact

(normalized with respect to k)

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See Figures 4.39-4.41 in [Suh 1986]: Suh, N. P. *Tribophysics*. Englewood Cliffs NJ: Prentice-Hall, 1986. ISBN: 0139309837.

Depth of Void Nucleation Region as a function of μ and p_0

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See Figure 4.42 in [Suh 1986].

Number of passes required for crack nucleation and the depth of crack nucleation at $p_0=4k$

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See Figure 4.43 in [Suh 1986].

Number of passes required for crack nucleation and the depth of crack nucleation at p_0=6k

Graph removed for copyright reasons.
See Figure 4.44 in [Suh 1986].

Crack Propagation

- In fracture mechanics, crack propagation is classified in terms of three modes.

    1. The load is applied perpendicular to the crack.
    2. The load is applied parallel to the crack direction.
    3. The load is applied transversely to the crack direction.

Crack Propagation

- However, crack propagation in sliding wear is due to a combined loading of compression and shear on the crack -- compressive stress on the crack and shear deformation at the crack tip.

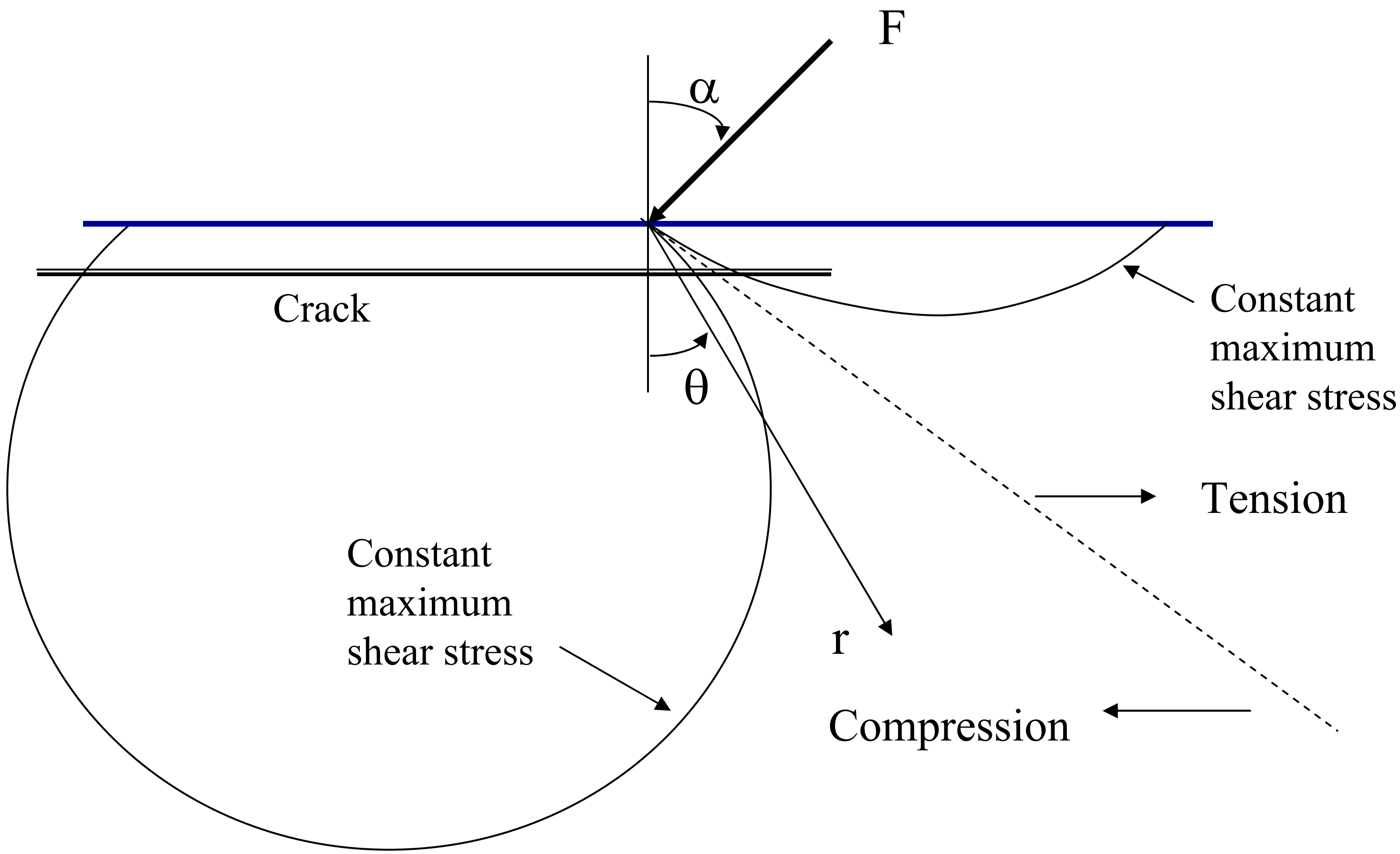
Crack Propagation

- The rate of crack propagation under sliding wear conditions is very slow, being about 30 microns per cycle of crack-tip sliding.
- Therefore, the delamination wear of many multi-phase metals is controlled by the crack propagation rate.

Sliding Wear at Low Speeds

- **Crack propagation rate controls the delamination wear rate.**

Δ(CTSD) ~ 0.003 μm


F
α
Crack
θ
Constant
maximum
shear stress
Tension
r
Constant
maximum
shear stress
Compression

Variation of plastically deformed zone around crack under a moving asperity ($a=10\mu m$, $d=0.5\,a$, $\mu=0.25$, $p_o=4k=980$ MPa)

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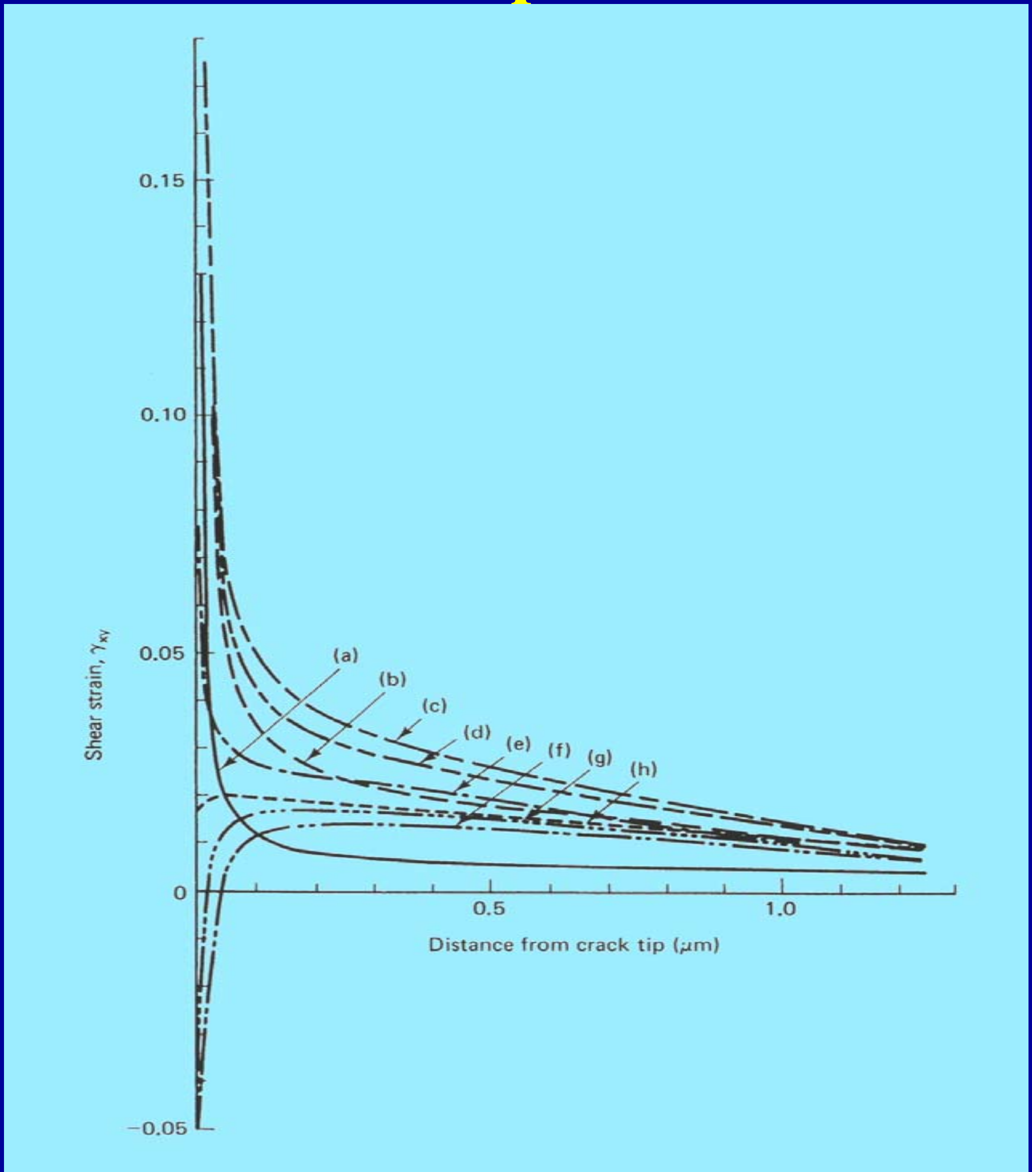
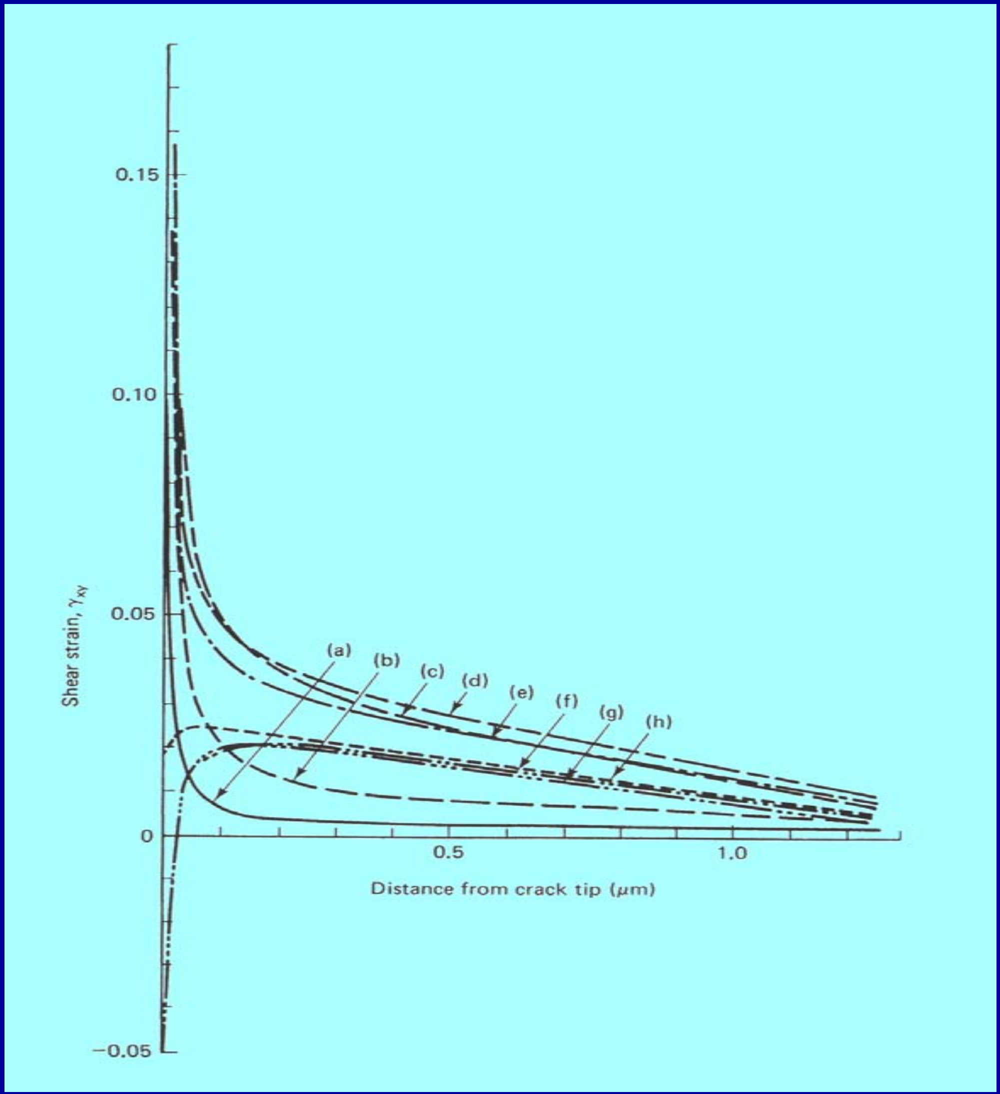
See Figure 4.48 in [Suh 1986].

Shear strain vs. distance from the left crack tip when plastic elements are used.



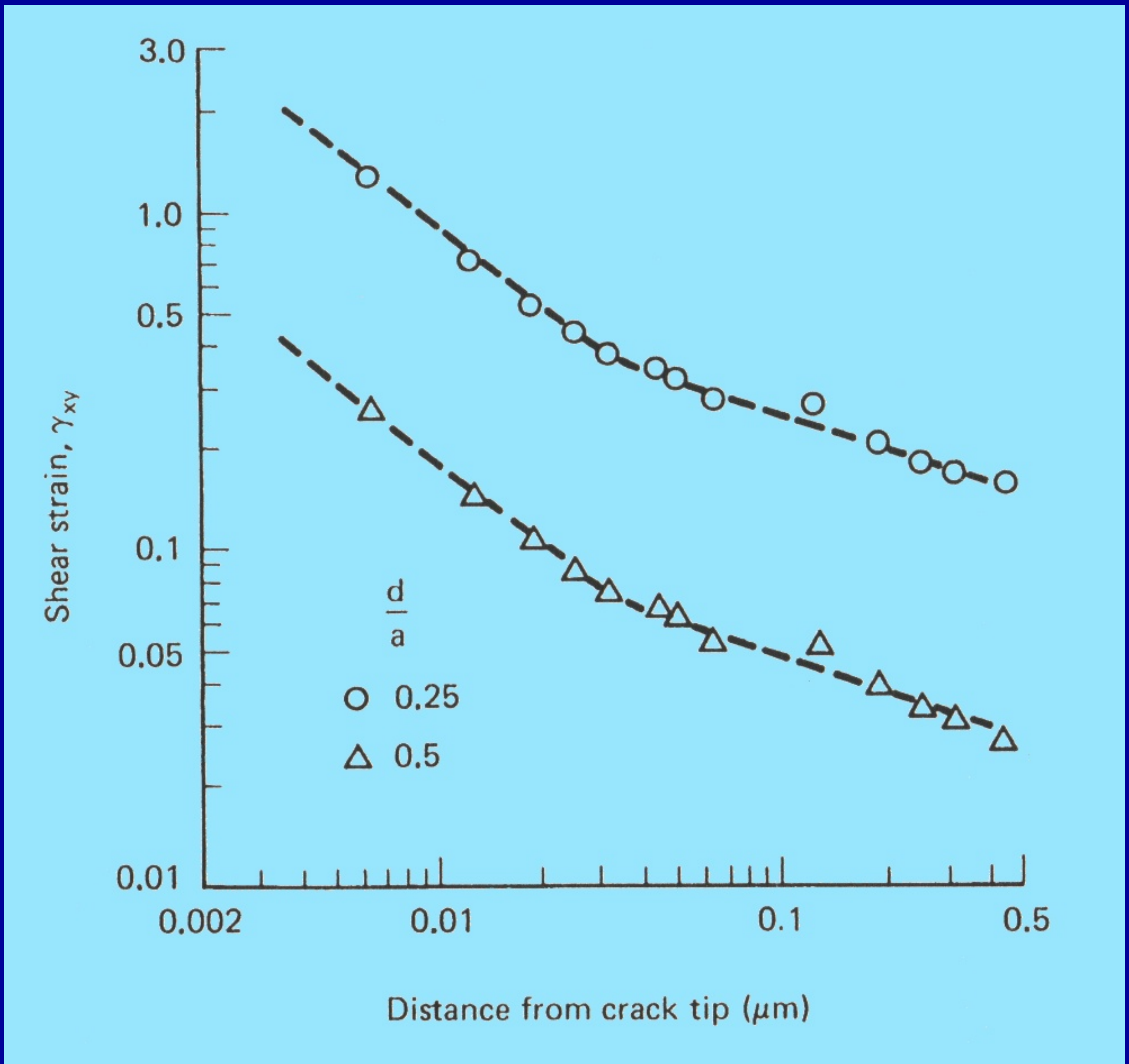
Source: Sin, H-C. “Surface Fraction and Crack Propagation in Delamination Wear.” Ph.D. Thesis, MIT, 1981.

Shear strain vs. distance from the right cracktip when plastic elements are used.



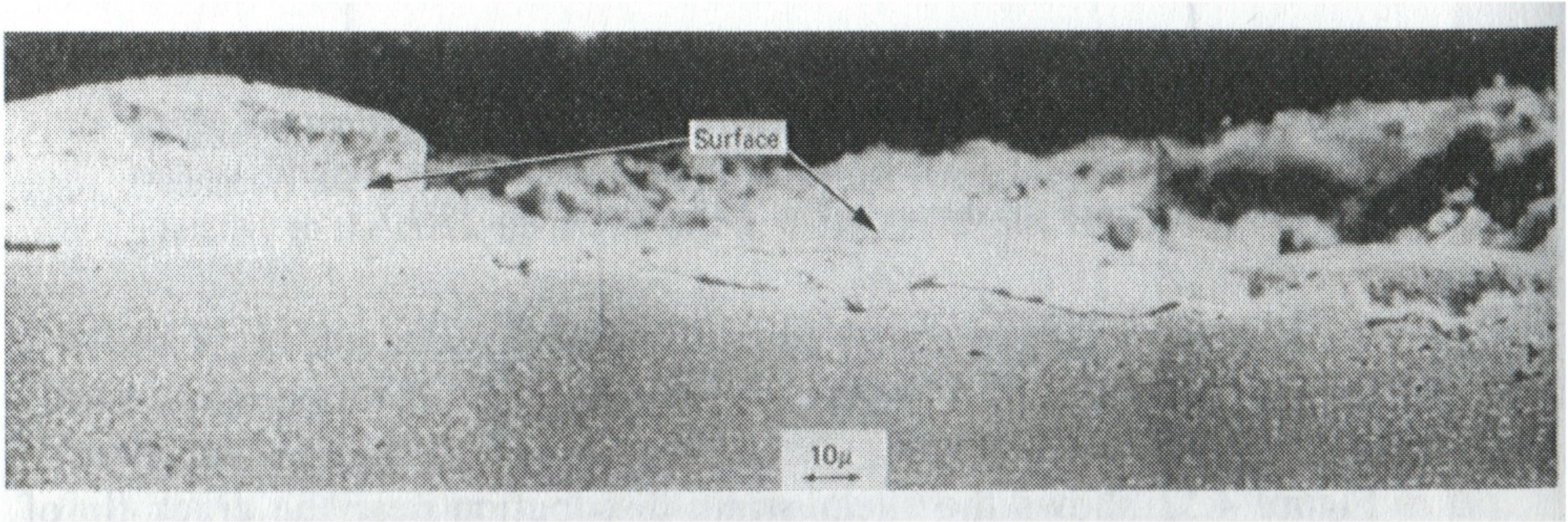
Source: Sin, H-C. "Surface Fraction and Crack Propagation in Delamination Wear." Ph.D. Thesis, MIT, 1981.

Shear strain as a function of distance from the left tip for different depths of crack location

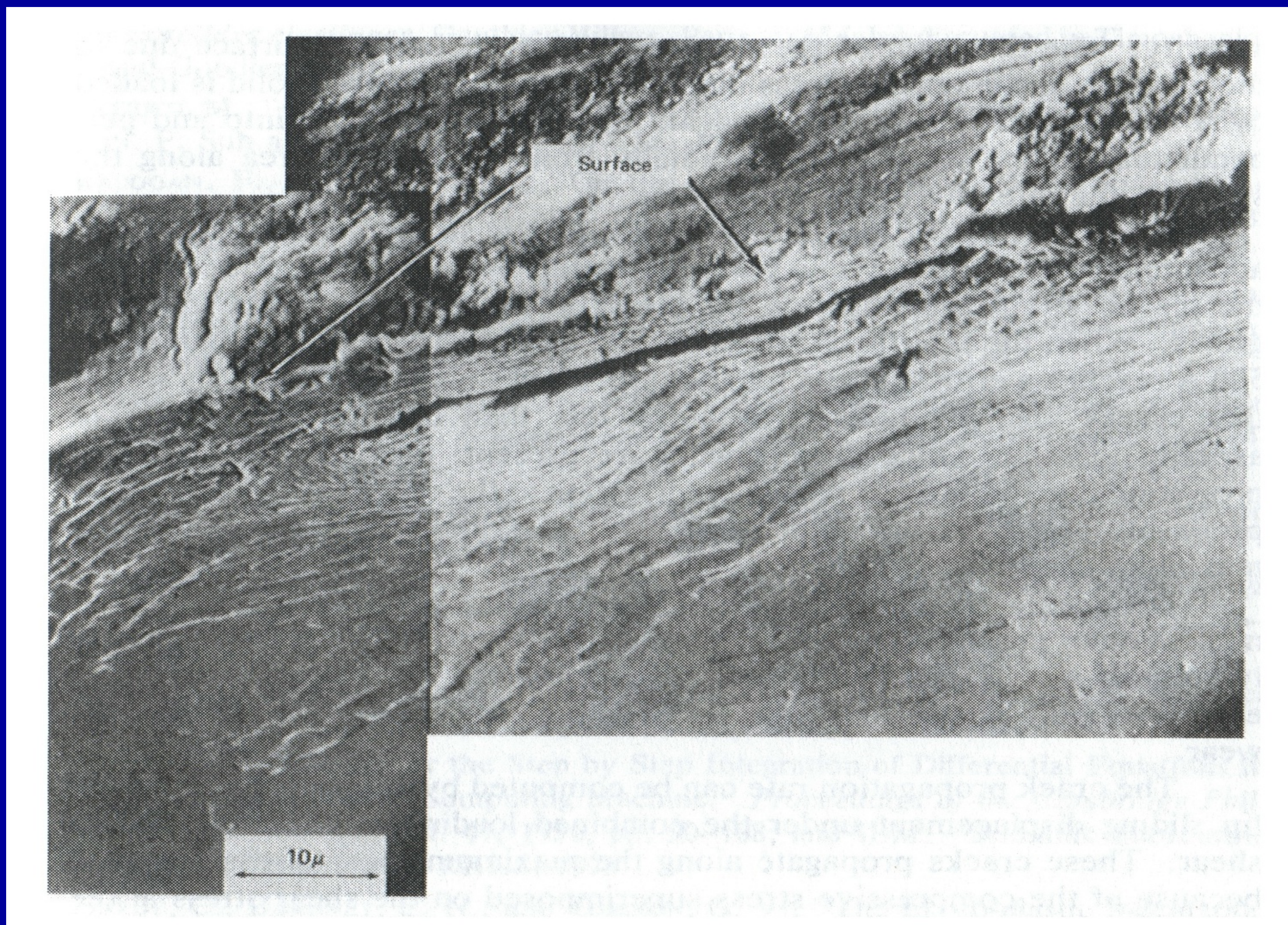


Source: Sin, H-C. "Surface Fraction and Crack Propagation in Delamination Wear." Ph.D. Thesis, MIT, 1981.

Void and crack formation in annealed OFHC copper



Subsurface deformation and crack formation in Fe solid solution



Typical plot of the crack extension per cycle versus the logarithm of the change in the stress intensity factor

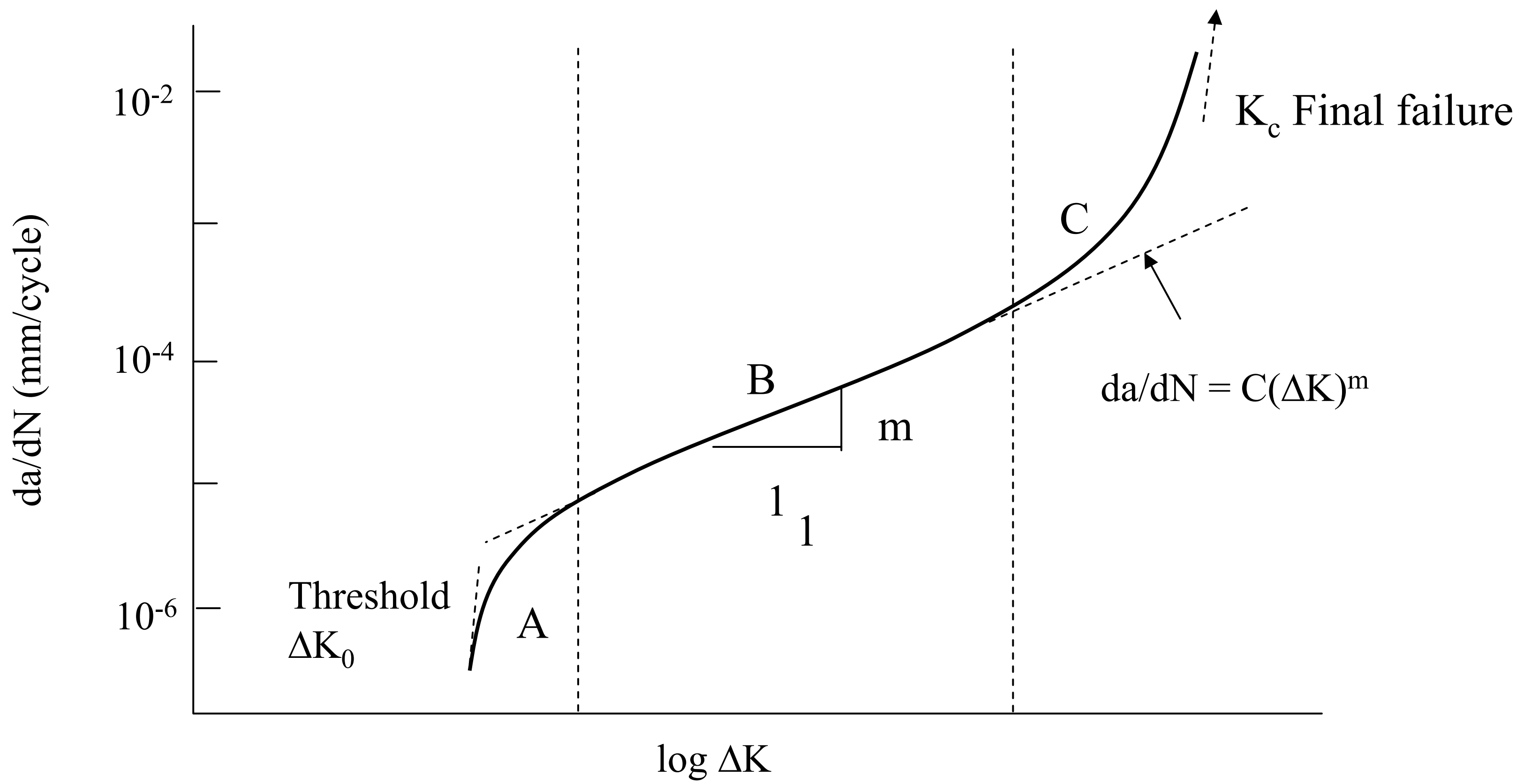


Figure 4.47

Void formation around inclusions and crack propagation from these voids near the surface in annealed Fe-1.3% Mo

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See Figure 4.35 in [Suh 1986].

Subsurface crack under a moving asperity

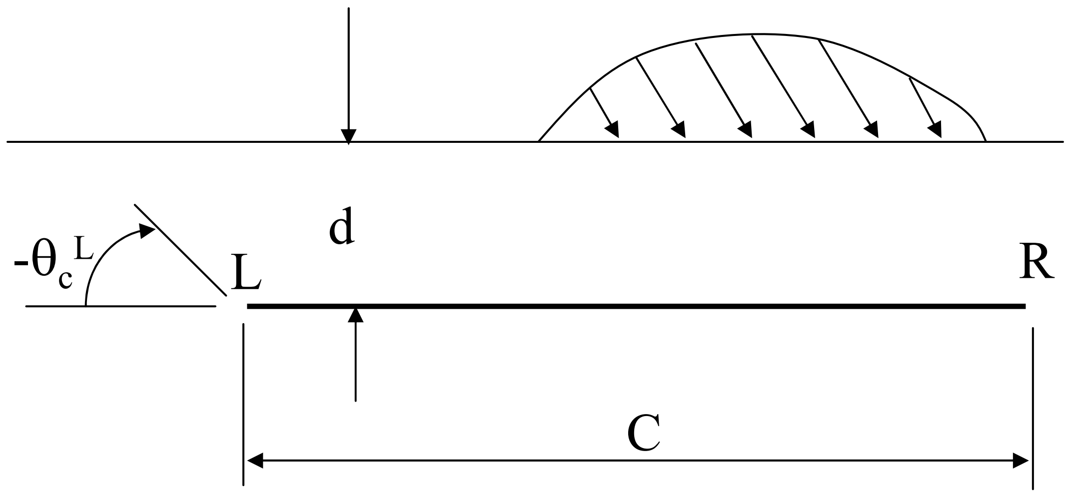

Figure 5.8 Subsurface crack under a moving asperity

Model of wearing specimen

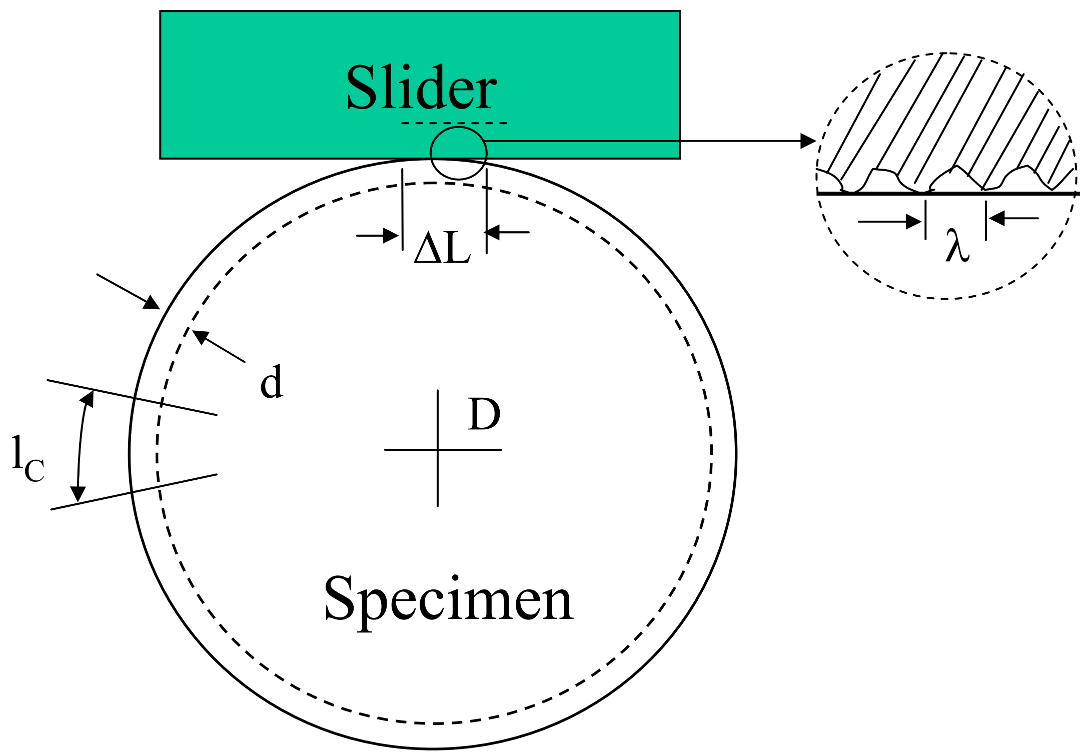

Figure 5.9 Model of wearing specimen and slider

Worn surface of pure iron

(a) sheet formation, (b) shear dimples beneath the wear sheet in (a), © dimpled appearance of wear crater

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See Figure 5.7 in [Suh 1986].

Fretting Wear

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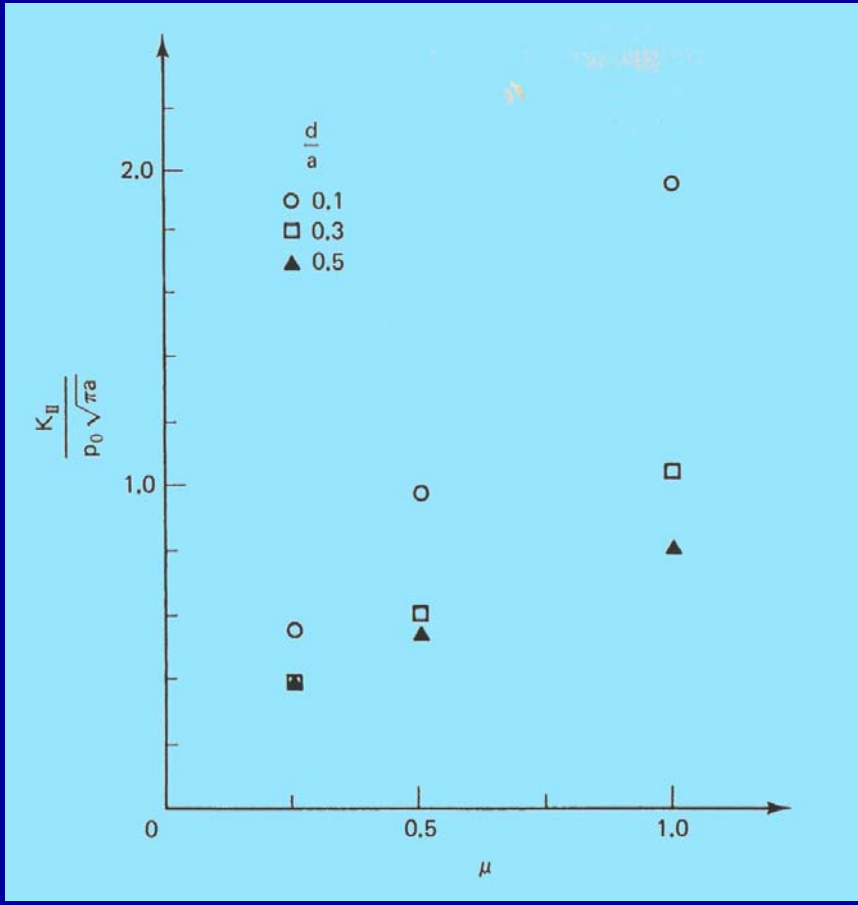
See Figure 5.10 in [Suh 1986].



Source: Sin, H-C. "Surface Fraction and Crack Propagation in Delamination Wear." Ph.D. Thesis, MIT, 1981.

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See Figures 5.12-5.23 in [Suh 1986].