



Parametri indicatori della resistenza a Fatica di Contatto per ingranaggi di elevata durezza

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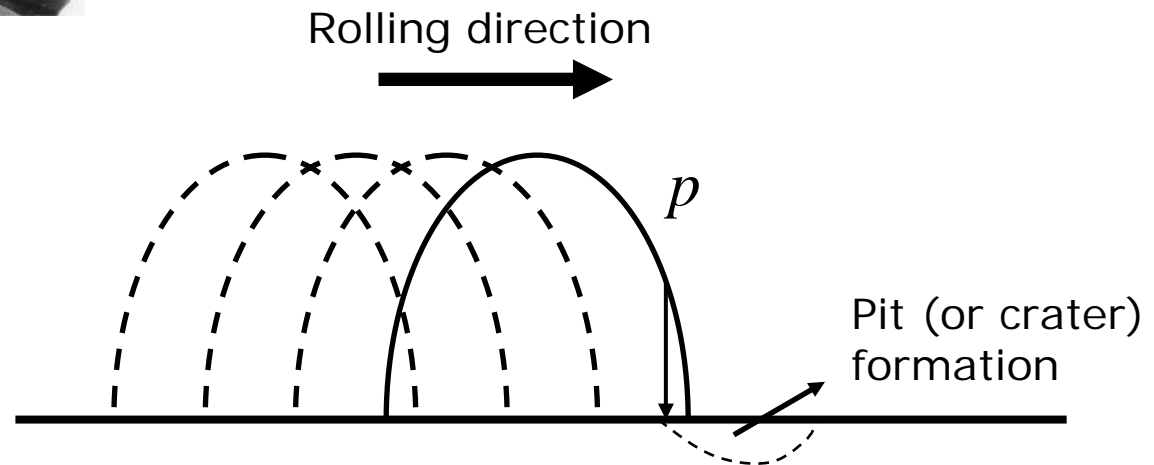
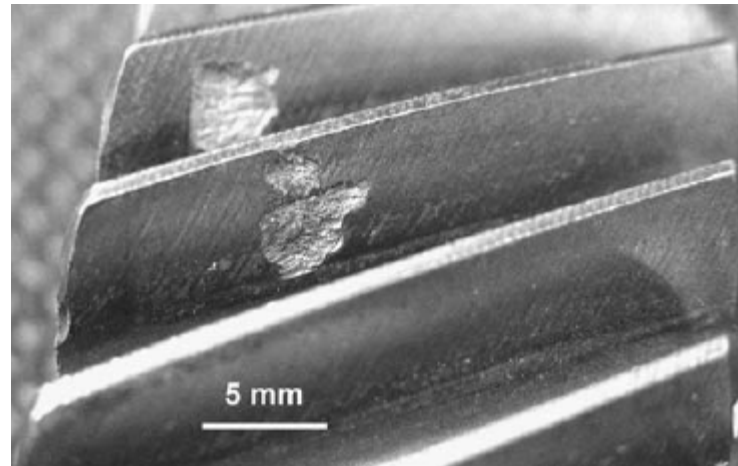
Sommario

- Ricerca bibliografica sulla Fatica di Contatto
 - revisione della nomenclatura
 - classificazione e descrizione dei meccanismi di fatica di contatto

- Definizione di parametri indicatori per ciascun meccanismo

- Approccio alla sperimentazione

Fatica di Contatto, "Rolling Contact Fatigue" (RCF)



Fatica di Contatto, "Rolling Contact Fatigue" (RCF)

Nomenclatura

- Subcase fatigue **Case Crushing** (in surface hardened components);
 - Subsurface originated **Spalling**;
 - Surface originated **Pitting**;
 - Surface originated, but shallower, **Micropitting** (surface distress, frosting, peeling).
- Meccanismi sotto-superficiali
- Meccanismi superficiali
-
- ```
graph TD; MS[Meccanismi sotto-superficiali] --> CC[Case Crushing]; MS --> S[Spalling]; MeS[Meccanismi superficiali] --> P[Pitting]; MeS --> MP[Micropitting];
```



A.V. Olver. The mechanism of rolling contact fatigue: an update. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 219(5):313–330, 2005.

# Origine superficiale / sotto-superficiale

## Sotto-superficiale

buona finitura superficiale  
buona lubrificazione



Ruote dentate di elevata precisione

## Superficiale

scarsa finitura superficiale  
basso rapporto fra spessore del lubrificante (EHD) e  
rugosità superficiale (lubrificazione limite)  
elevate tensioni tangenziali di attrito



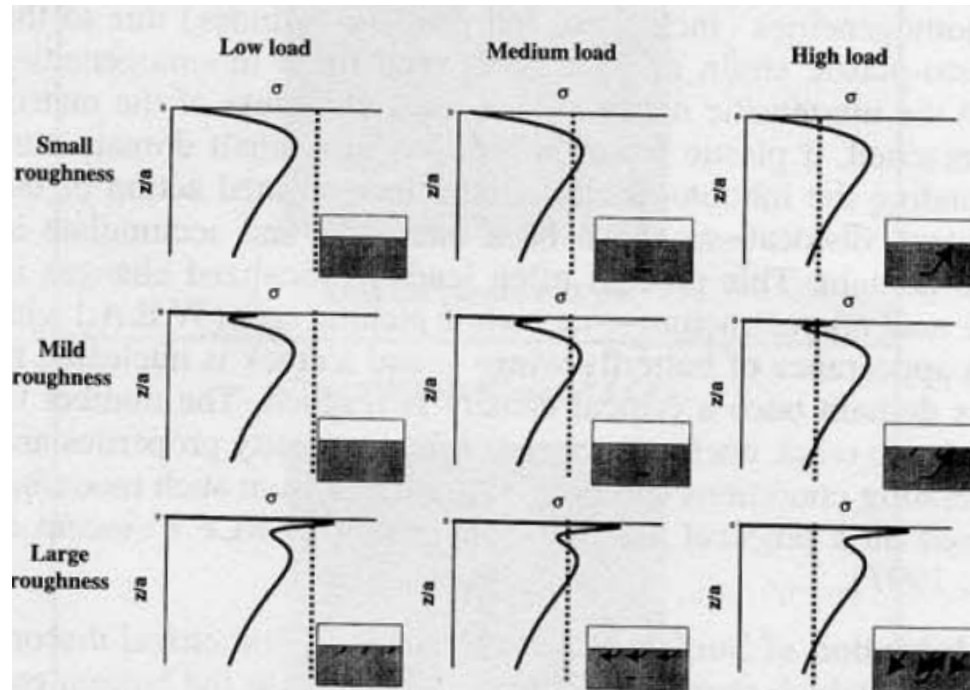
Ruote dentate di qualità comune



T.E. Tallian, Failure Atlas for Hertz Contact Machine Elements, New York, 1992

# Origine superficiale / sotto-superficiale

- “As ground” sempre nucleazione **superficiale**, nonostante slittamento
- “Polished” sempre nucleazione **sotto-superficiale**

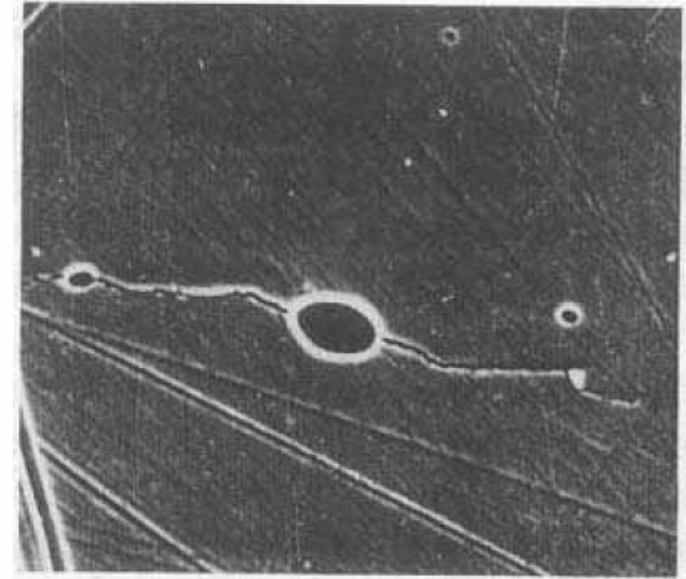
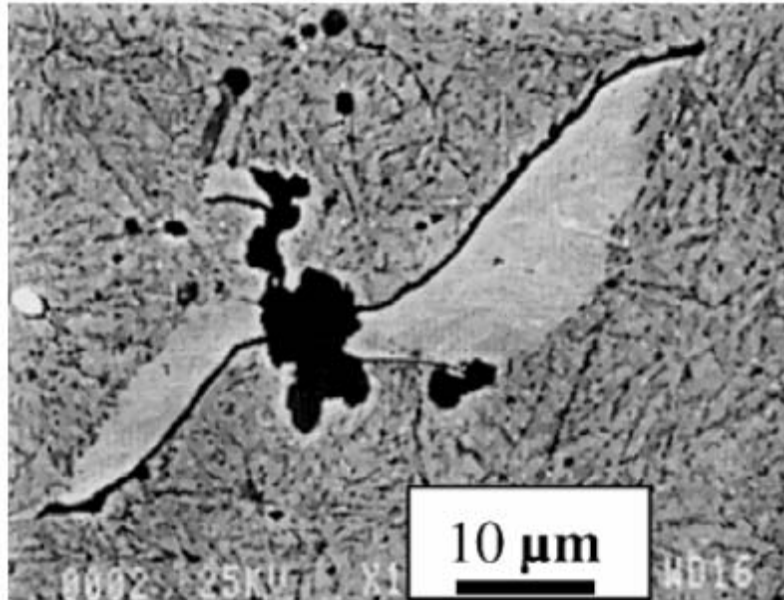


D. Nélias, M.L. Dumont, F. Champiot, A. Vincent, and D. Girodin. Role of inclusions, surface roughness and operating conditions on rolling contact fatigue. *Journal of Tribology*, ASME, 121(2):240–251, 1999.

# Nucleazione sotto-superficiale. Spalling

## Butterfly subsurface initiation

Inclusioni non metalliche: aluminati, carburi

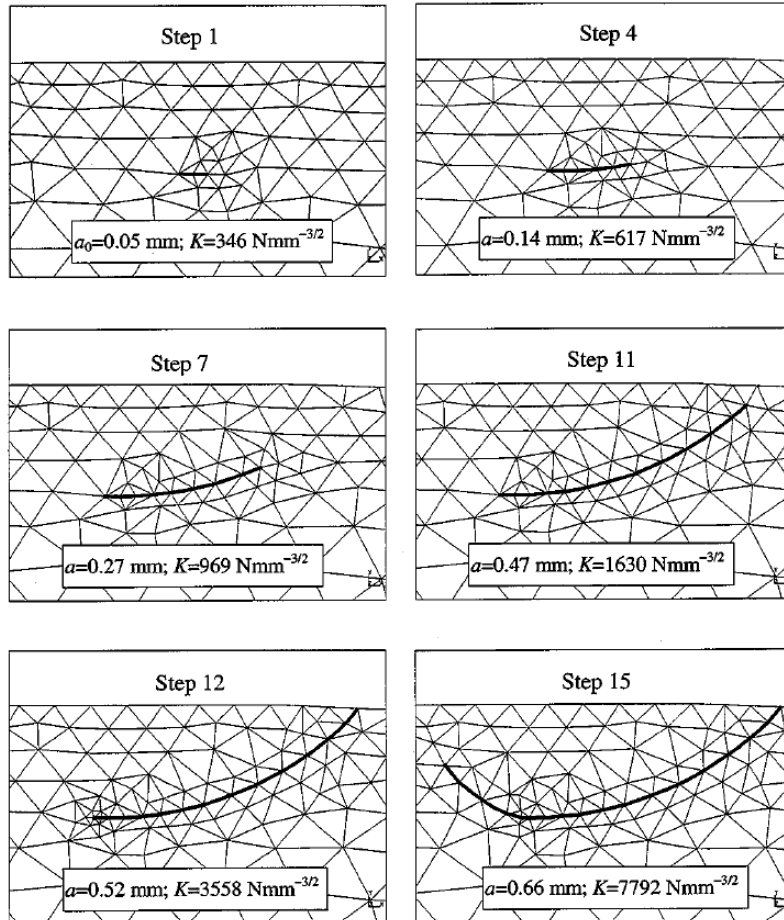


D. Nélias, M.L. Dumont, F. Champiot, A. Vincent, and D. Girodin. Role of inclusions, surface roughness and operating conditions on rolling contact fatigue. *Journal of Tribology, ASME*, 121(2):240–251, 1999.

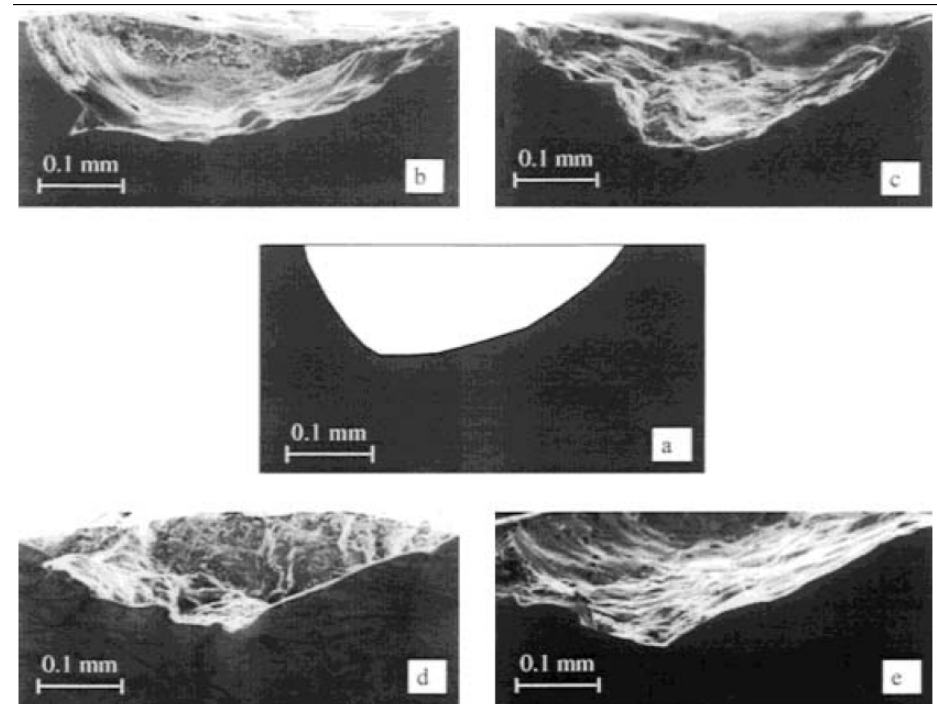


L. Chen, Q. Chen, and E. Shao. Study on initiation and propagation angles of subsurface cracks in GCr15 bearing steel under rolling contact. *Wear*, 133(2):205–218, 1989.

# Propagazione sotto-superficiale. Spalling

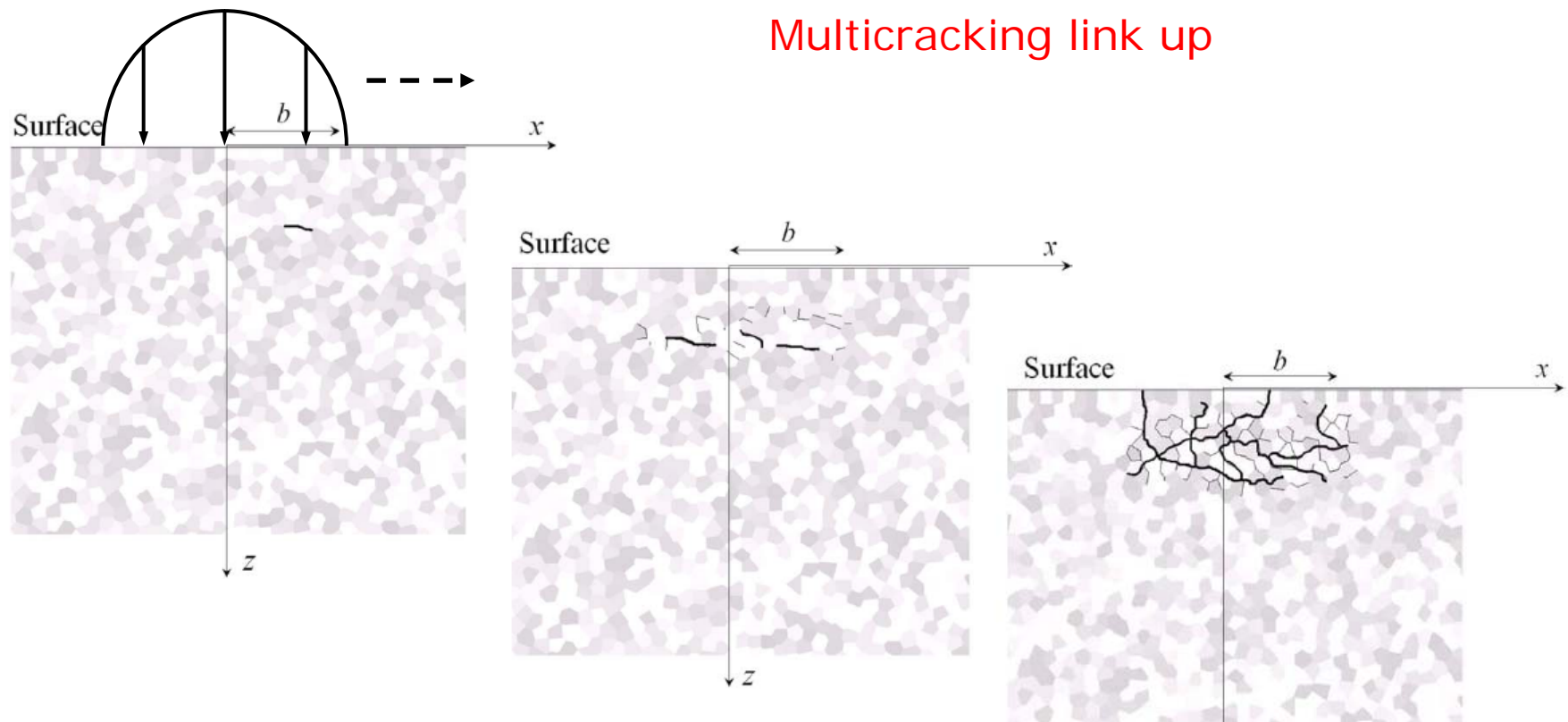


Mode II propagation ( $\Delta K_{II}$ )



S. Glodez, B. Abersek, J. Flasker, Z. Ren. Evaluation of the service life of gears in regard to surface pitting. *Engineering Fracture Mechanics* 71 (2004) 429–438.

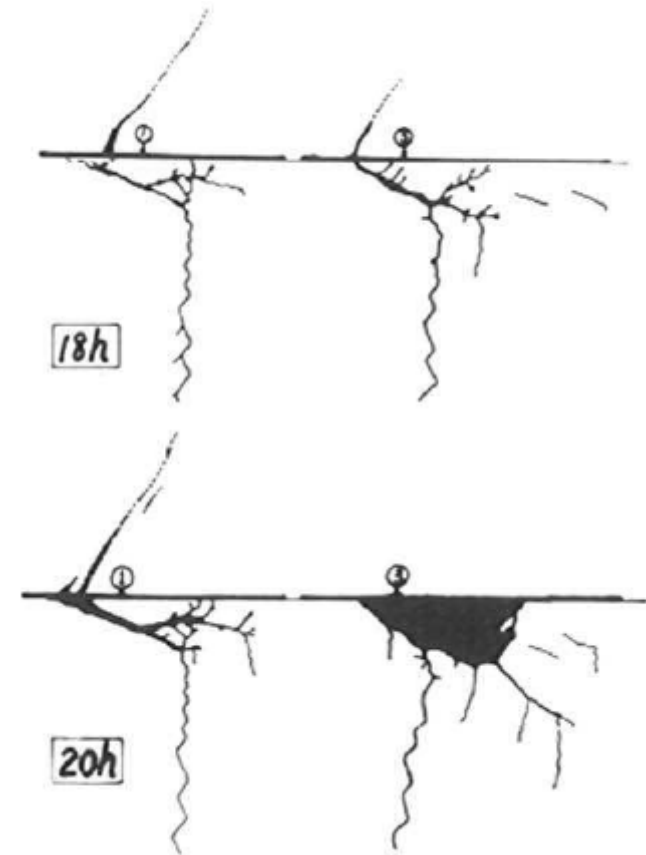
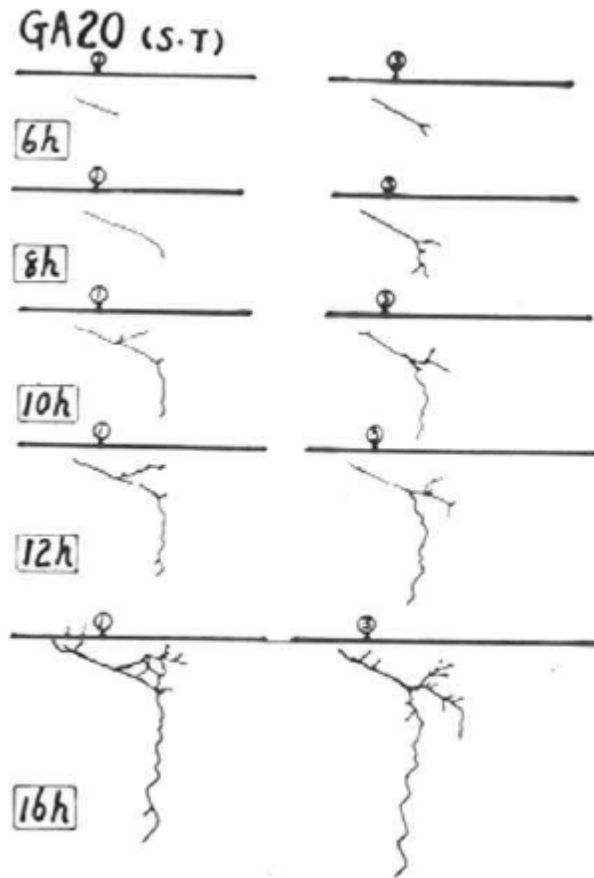
# Propagazione sotto-superficiale. Spalling



N. Raje, T. Slack, and F. Sadeghi. A discrete damage mechanics model for high cycle fatigue in polycrystalline materials subject to rolling contact. *International Journal of Fatigue*, 31(2): 346–360, 2009.

# Propagazione sotto-superficiale. Spalling

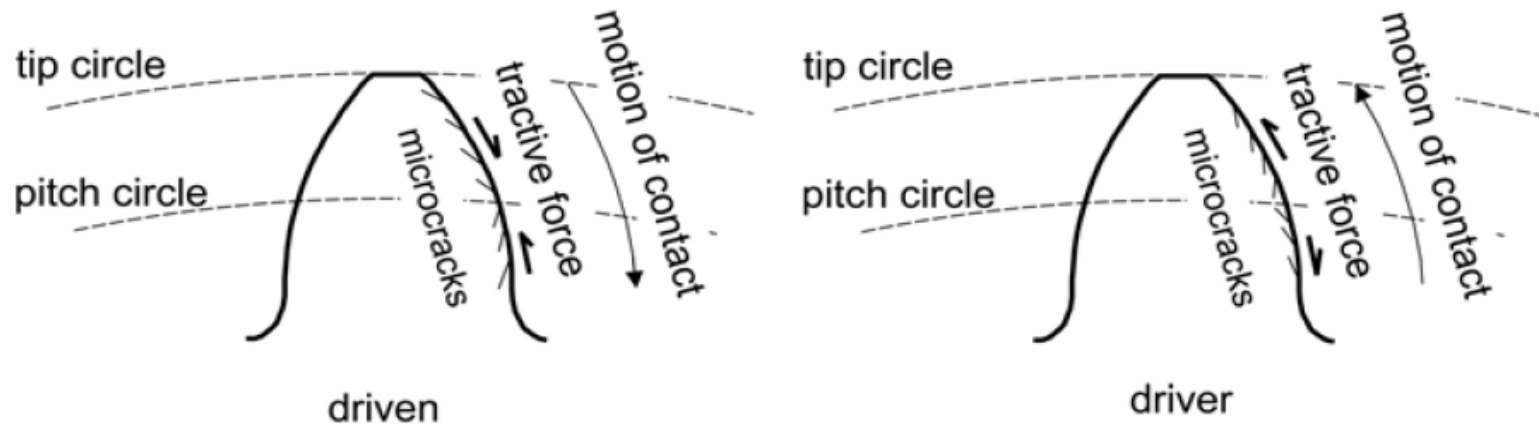
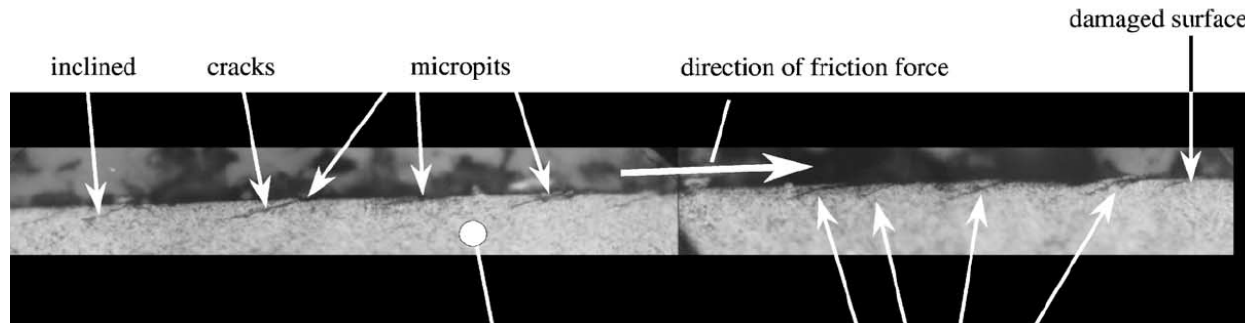
Propagation / branching



L. Chen, Q. Chen, and E. Shao. Study on initiation and propagation angles of subsurface cracks in GCr15 bearing steel under rolling contact. *Wear*, 133(2):205–218, 1989.

# Nucleazione superficiale

Nucleazione di microfessure a basso angolo, orientate in funzione della direzione dell'azione tangenziale di attrito

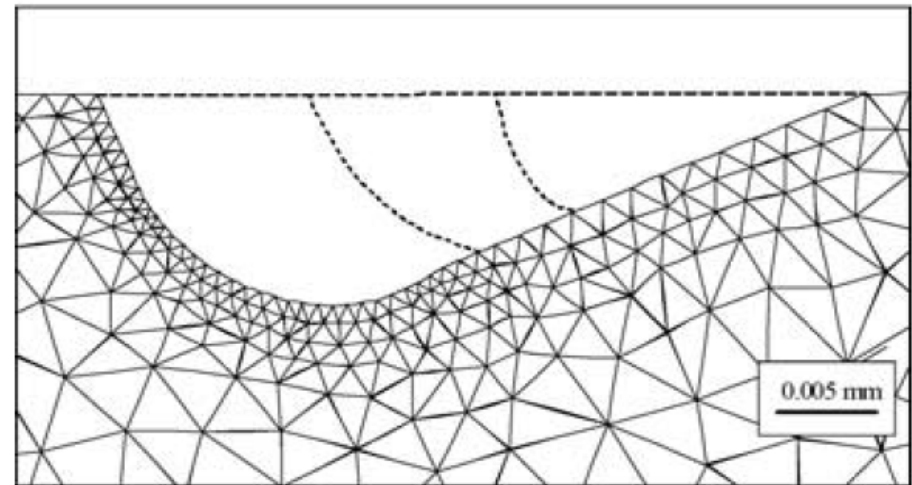
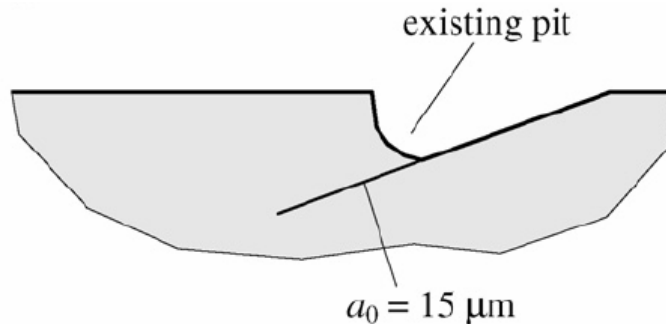
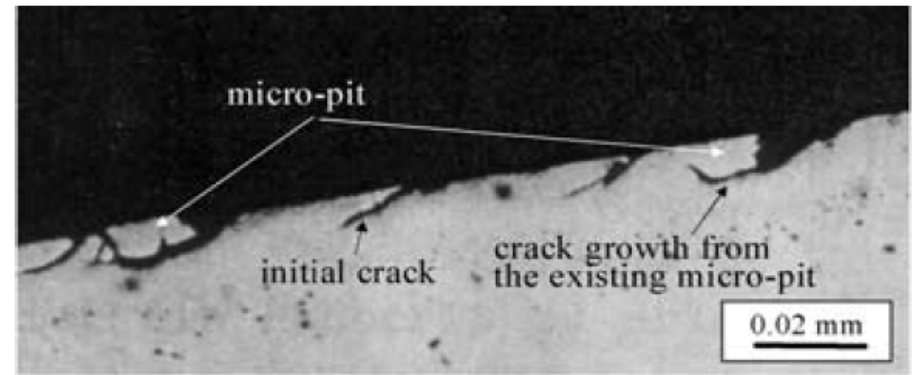


A.V. Olver. The mechanism of rolling contact fatigue: an update. Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology, 219(5):313–330, 2005.

# Pitting / Micropitting

Dopo il distacco di un "micro-cratero" la fessura iniziale può continuare.

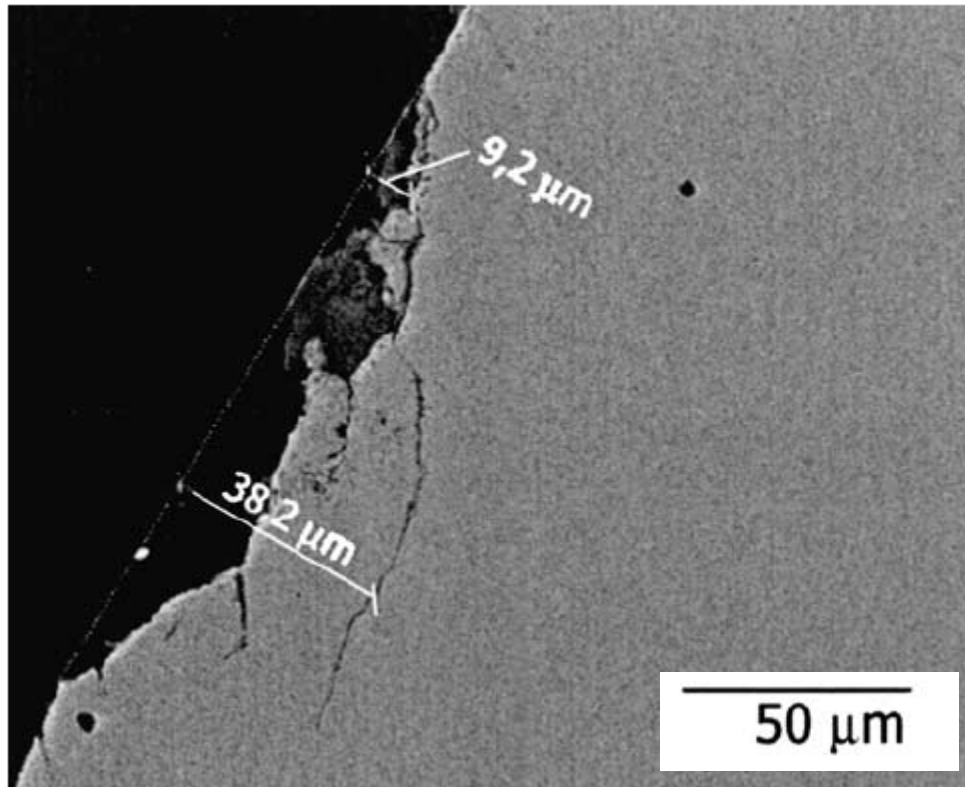
Micropitting => Pitting



G. Fajdiga, S. Glodez and J. Kramar. Pitting formation due to surface and subsurface initiated fatigue crack growth in contacting mechanical elements. *Wear*, 262(9-10):1217–1224, 2007.

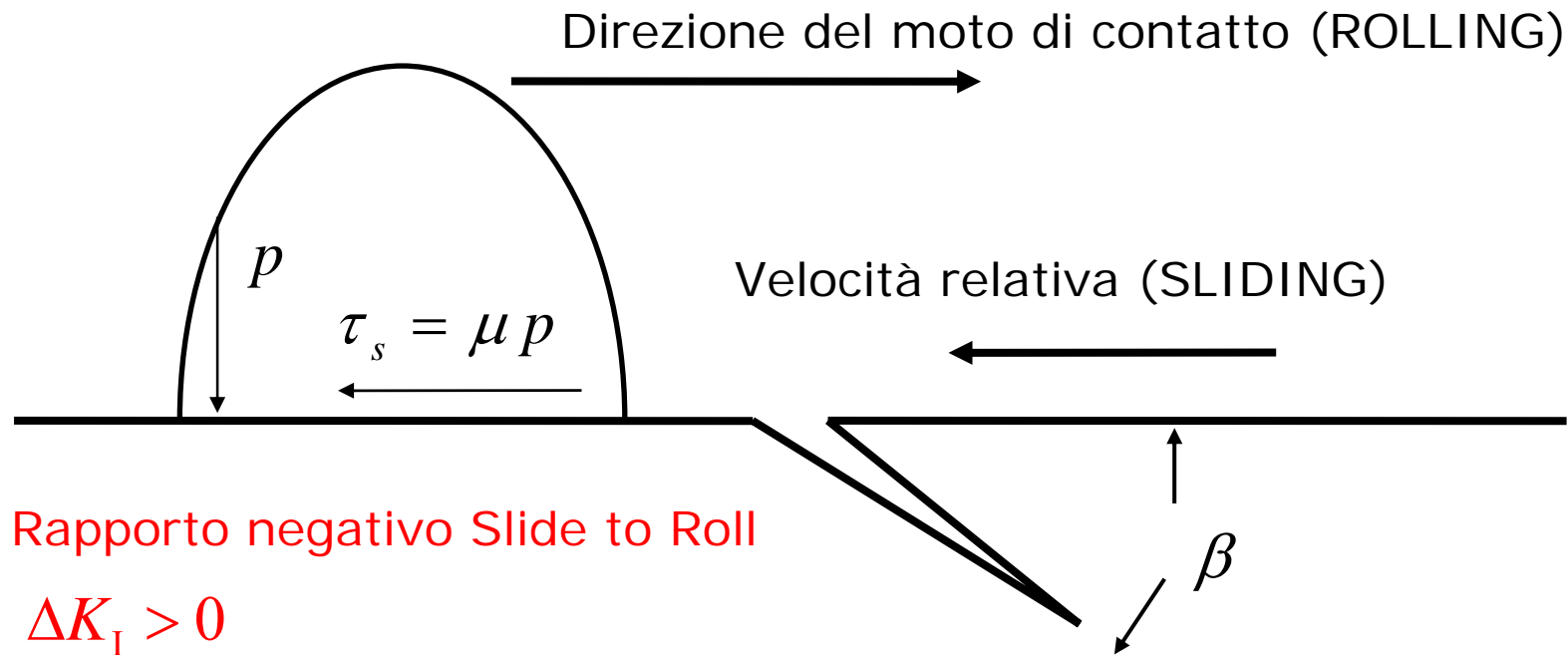
G. Fajdiga, J. Flaker, S. Glodez, and T.K. Hellen. Numerical modelling of micro-pitting of gear teeth flanks. *Fatigue & Fracture of Engineering Materials & Structures*, 26(12):1135-1143, 2003.

# Pitting / Micropitting



M. Boniardi, F. D'Errico, and C. Tagliabue. Influence of carburizing and nitriding on failure of gears – A case study. *Engineering Failure Analysis*, 13(3): 312–339, 2006.

# Pressurizzazione del lubrificante in una fessura superf.

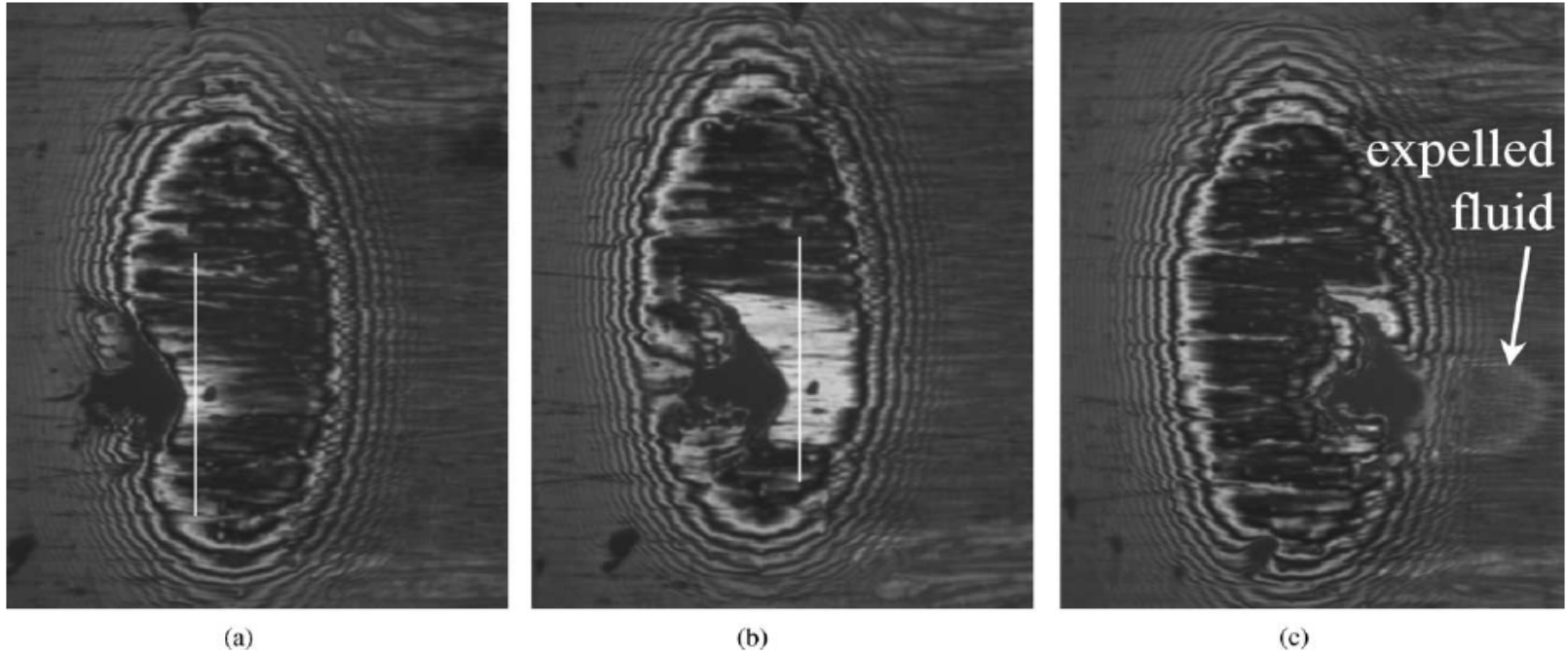


Z. Ren, S. Glodez, G. Fajdiga, and M. Ulbin. Surface initiated crack growth simulation in moving lubricated contact. *Theoretical and Applied Fracture Mechanics*, 38(2):141–149, 2002.

A.V. Olver. The mechanism of rolling contact fatigue: an update. *Proceedings of the Institution of Mechanical Engineers, Part J: Journal of Engineering Tribology*, 219(5):313–330, 2005.

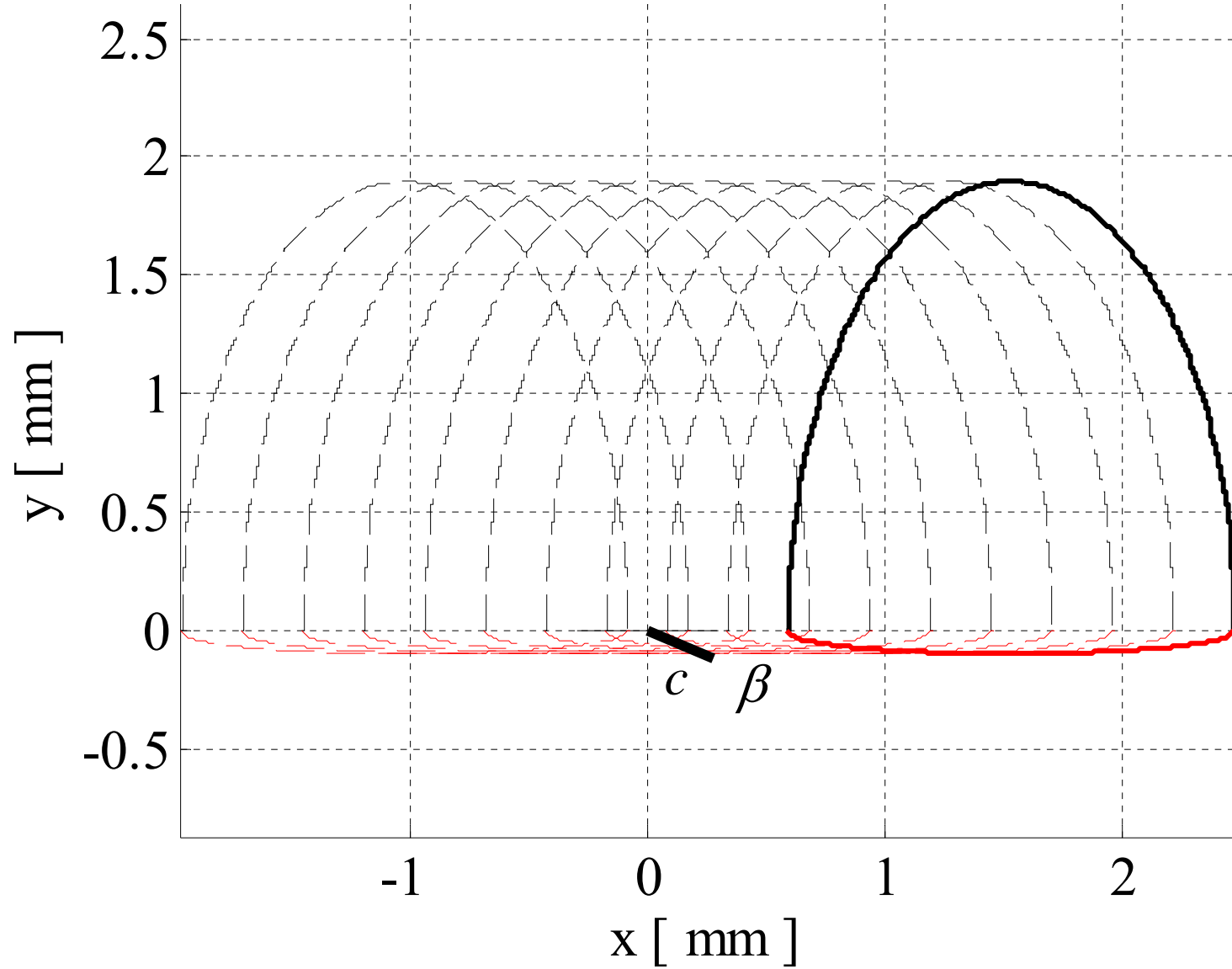
Bower. The Influence of Crack Face Friction and Trapped Fluid on Surface Initiated Rolling Contact Fatigue Cracks. *Journal of Tribology*, 110:704–711, 1988.

# Pressurizzazione, evidenza sperimentale

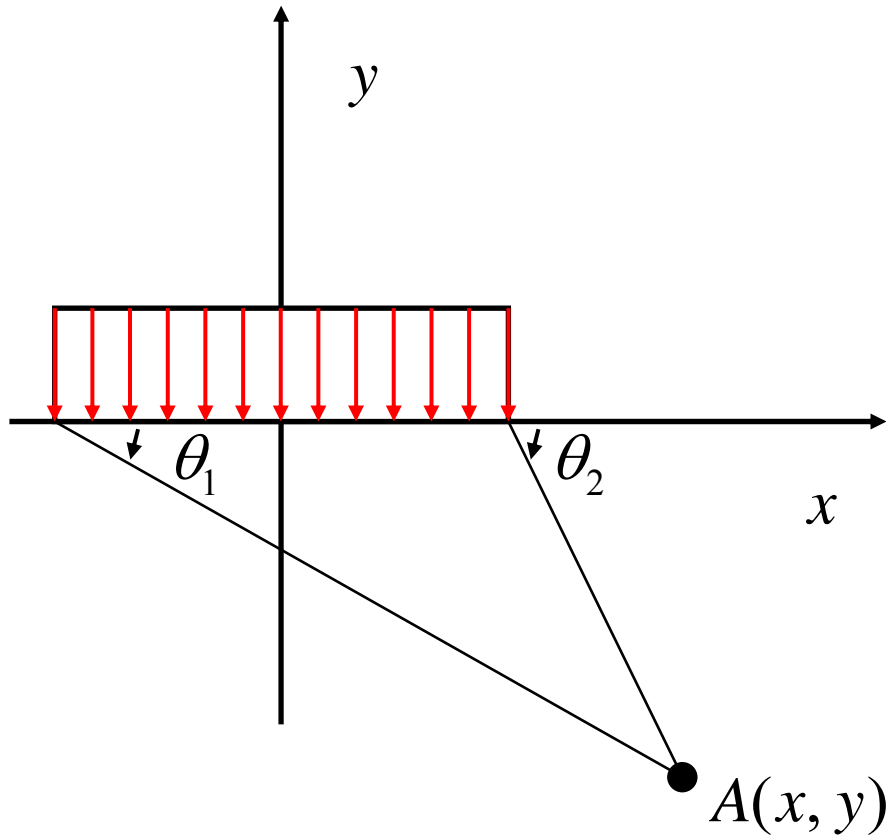


A.V. Olver, L.K. Tiew, S. Medina, and J.W. Choo. Direct observations of a micropit in an elastohydrodynamic contact. *Wear*, 256(1–2):168–175, 2004.

# Pressurizzazione, modellazione con *Weight Functions*



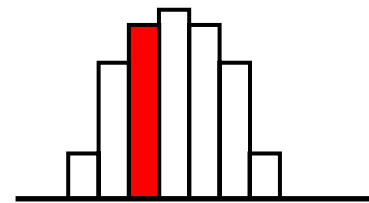
# Pressurizzazione, modellazione con *Weight Functions*



$$\sigma_x = -\frac{p}{2\pi} [2(\theta_1 - \theta_2) + (\sin \theta_1 - \sin \theta_2)]$$

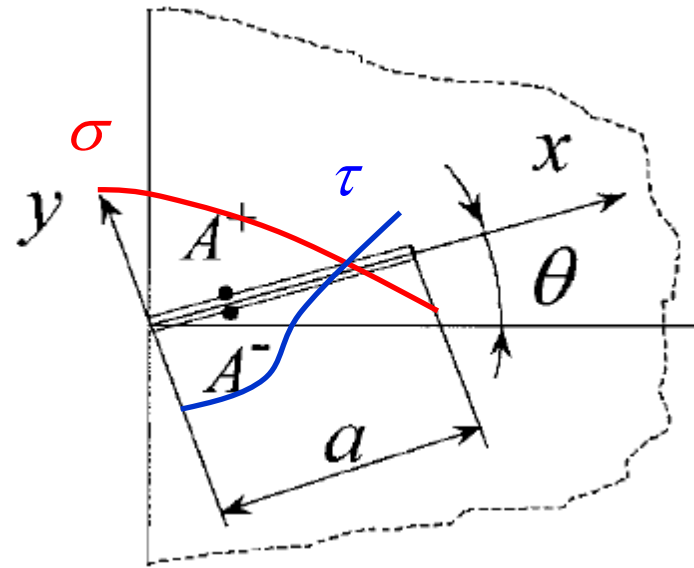
$$\sigma_y = -\frac{p}{2\pi} [2(\theta_1 - \theta_2) - (\sin \theta_1 - \sin \theta_2)]$$

$$\tau_{xy} = -\frac{p}{2\pi} (\cos 2\theta_1 - \cos 2\theta_2)$$



K. L. Johnson. Contact Mechanics. Cambridge University Press. 1985

# Pressurizzazione, modellazione con *Weight Functions*

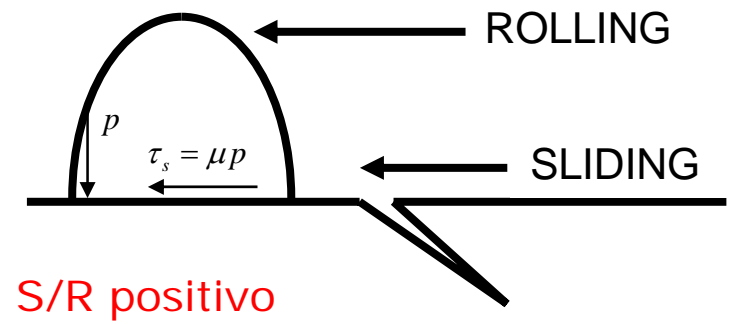
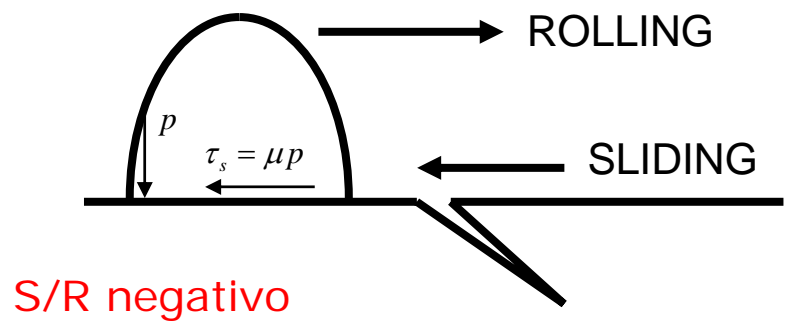
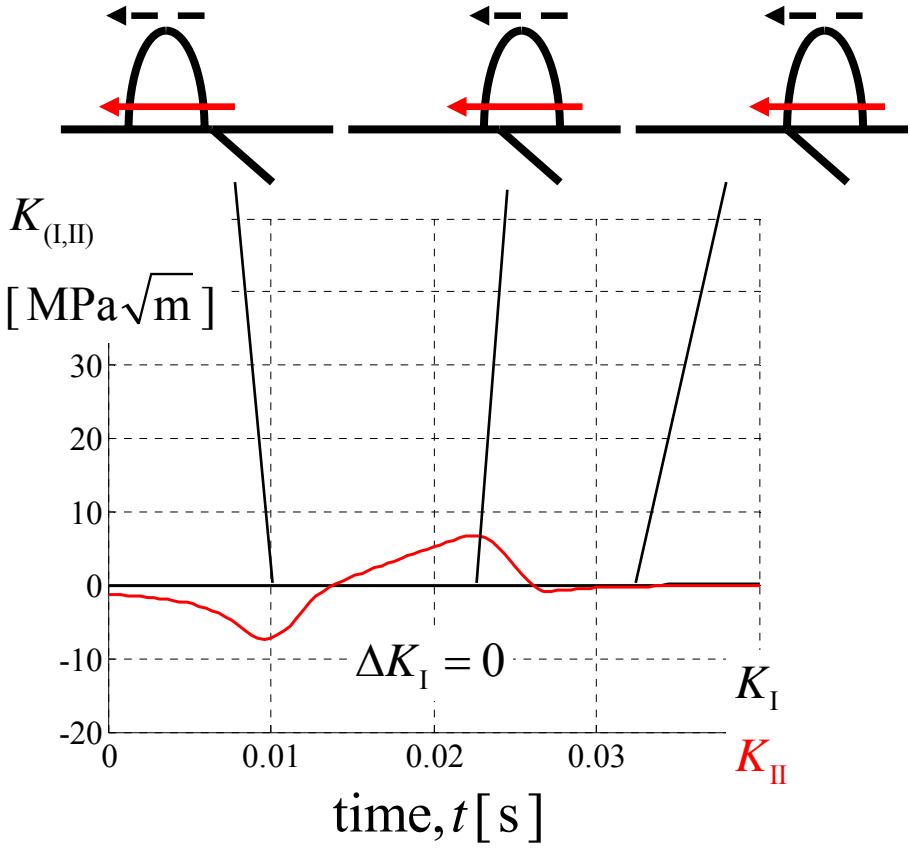
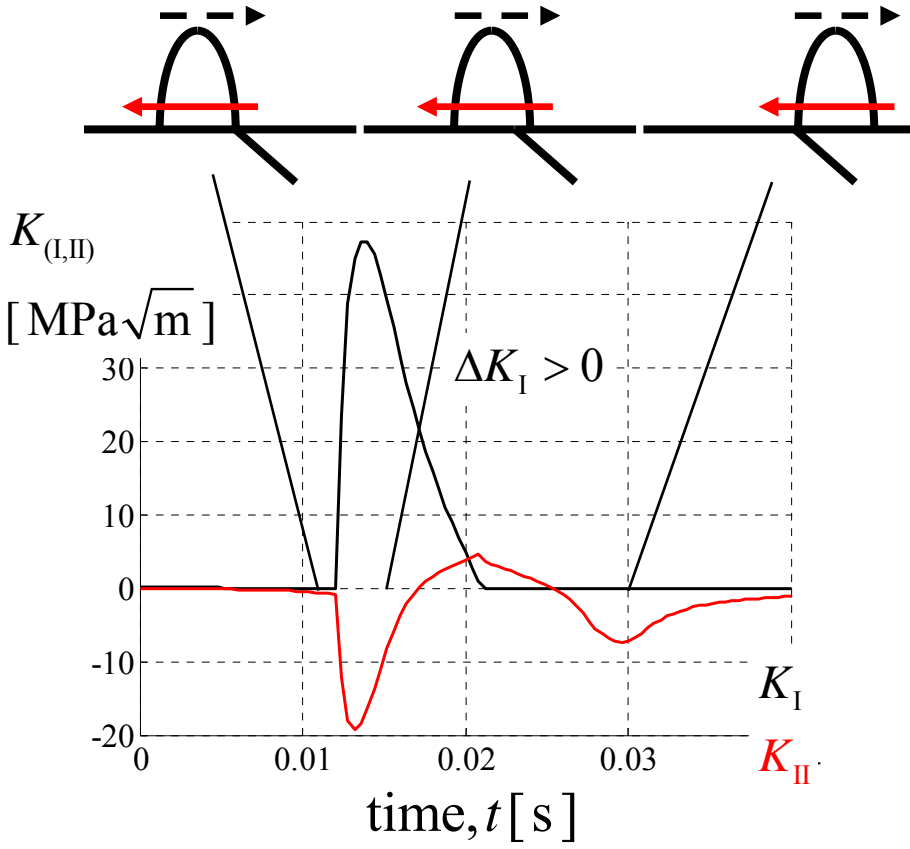


$$\begin{pmatrix} K_I(a) \\ K_{II}(a) \end{pmatrix} = \int_0^a \begin{pmatrix} h_{I\sigma}(x, a) & h_{I\tau}(x, a) \\ h_{II\sigma}(x, a) & h_{II\tau}(x, a) \end{pmatrix} \begin{pmatrix} \sigma(x) \\ \tau(x) \end{pmatrix} dx$$

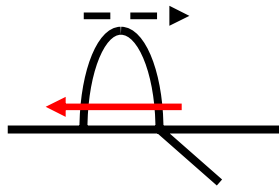


M. Beghini, L. Bertini, V. Fontanari, Weight function for an inclined edge crack in a semiplane. *International Journal of Fracture*, 99: 281–292, 1999.

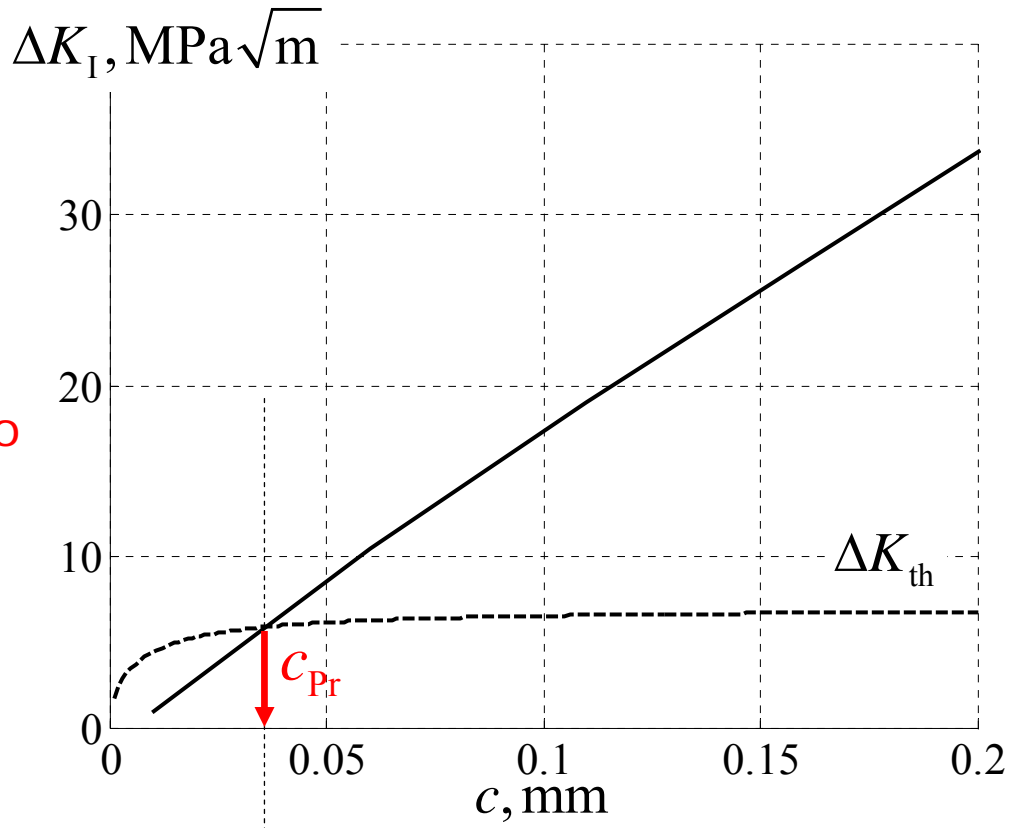
# Pressurizzazione, modellazione con *Weight Functions*



# Dimensione critica della microfessura superficiale



Rapporto negativo  
Slide to Roll



→ Propagazione per pressurizzazione

# Parametri indicatori di danneggiamento, nucleazione o propagazione?

Componenti piccoli  
*High Cycle Fatigue*

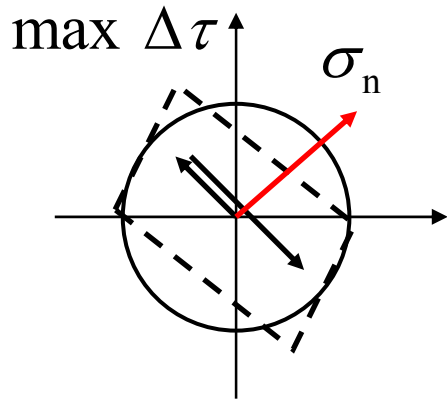
Nucleazione



Componenti grandi  
*Low Cycle Fatigue*

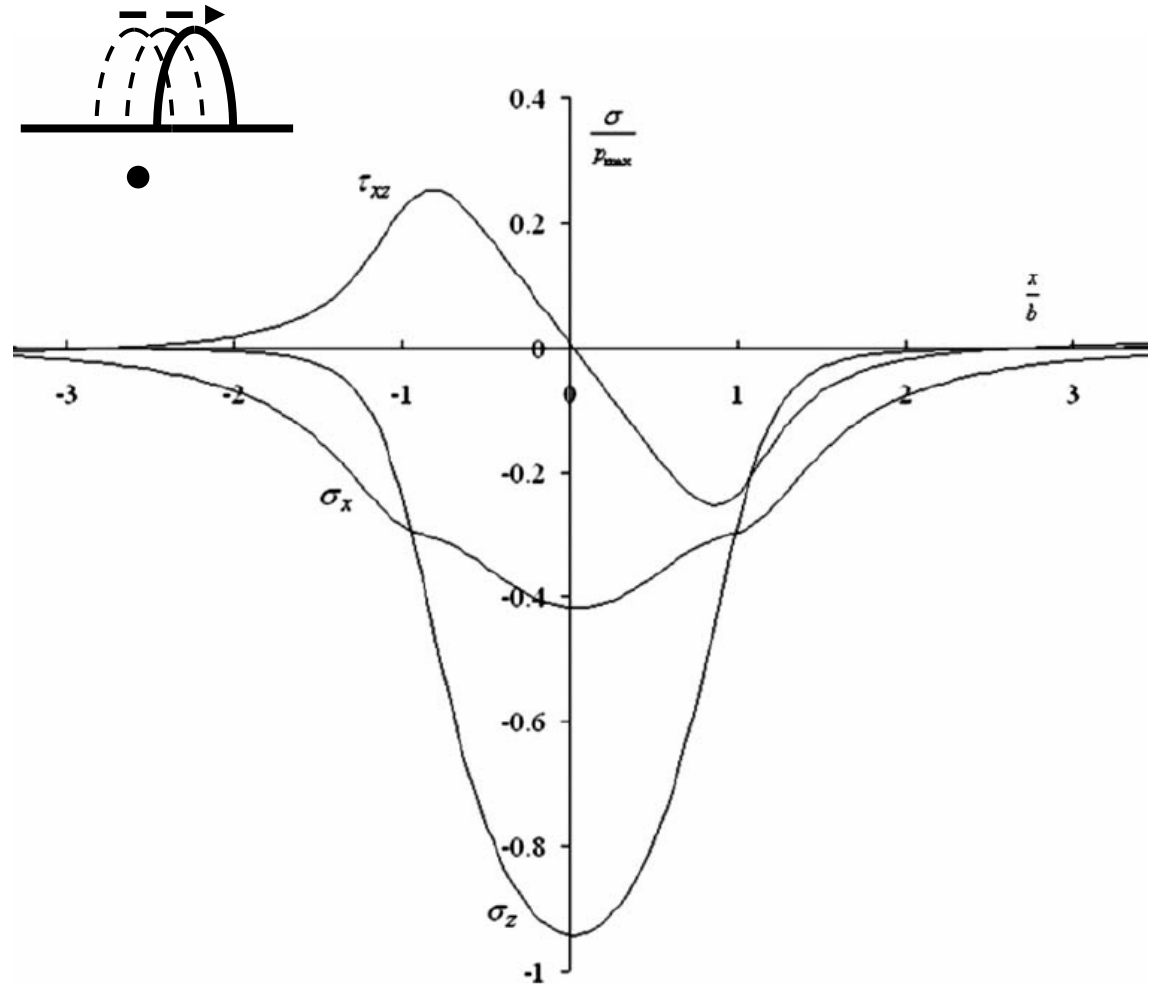
Propagation

# Fatica multiassiale non proporzionale, taglio critico



Piano critico, Findely

$$\Delta \tau + k \sigma_n \leq f$$



D.F. Socie, G.B. Marquis, "Multiaxial Fatigue", SAE, 2000.

# Parametri di danneggiamento, definizione

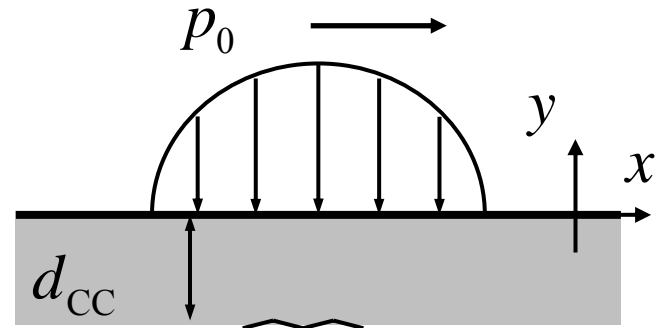
1. CASE CRUSHING; ←  $\Delta\tau_{CC}$

2. Sub-surface originated, SPALLING; ←  $\Delta\tau_{Sp}$

3. MICROPITTING; ←  $\Delta\tau_{MP}$

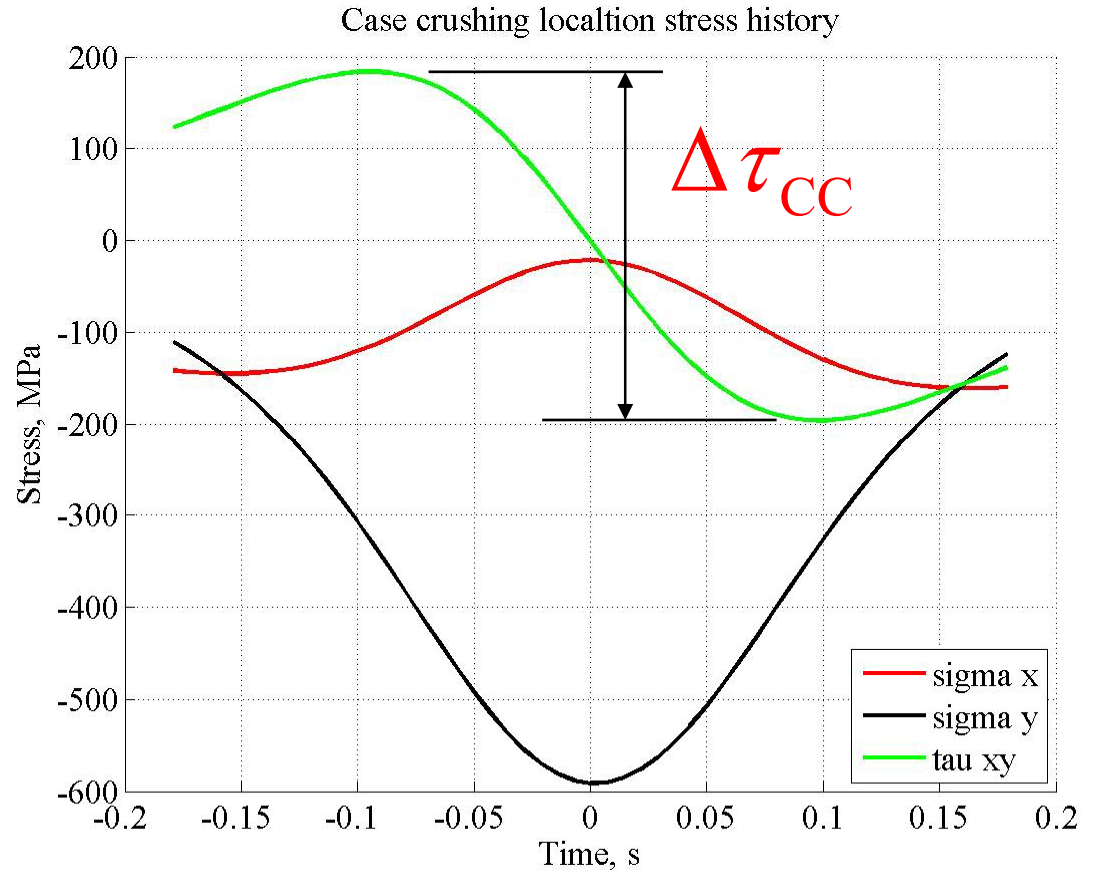
4. Surface originated, PITTING. ←  $\Delta\tau_{Pi}$

# Case Crushing

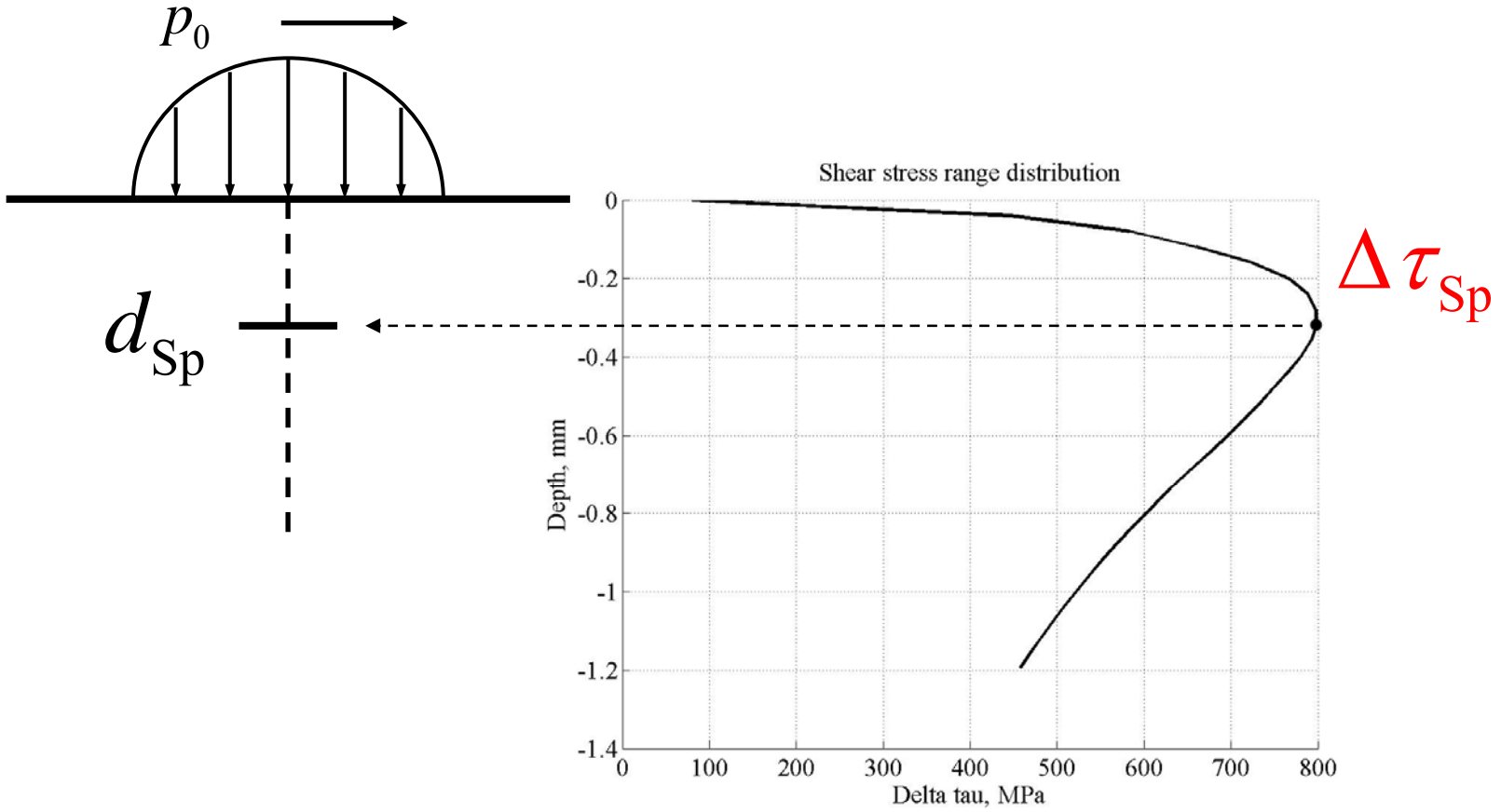


$d_{cc}$  = case hard. depth

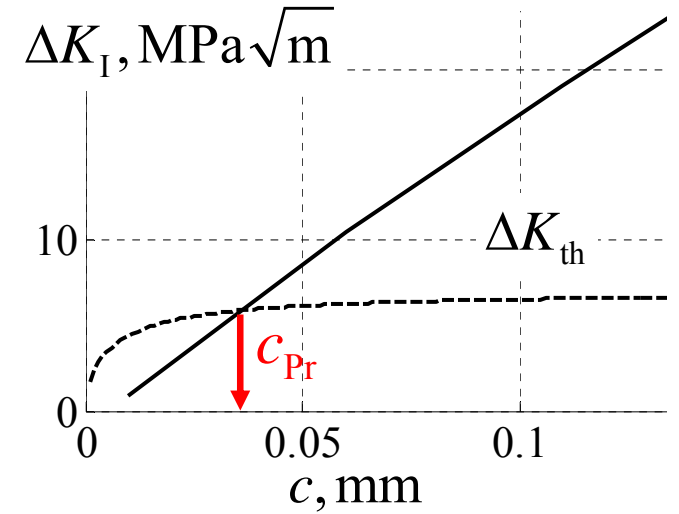
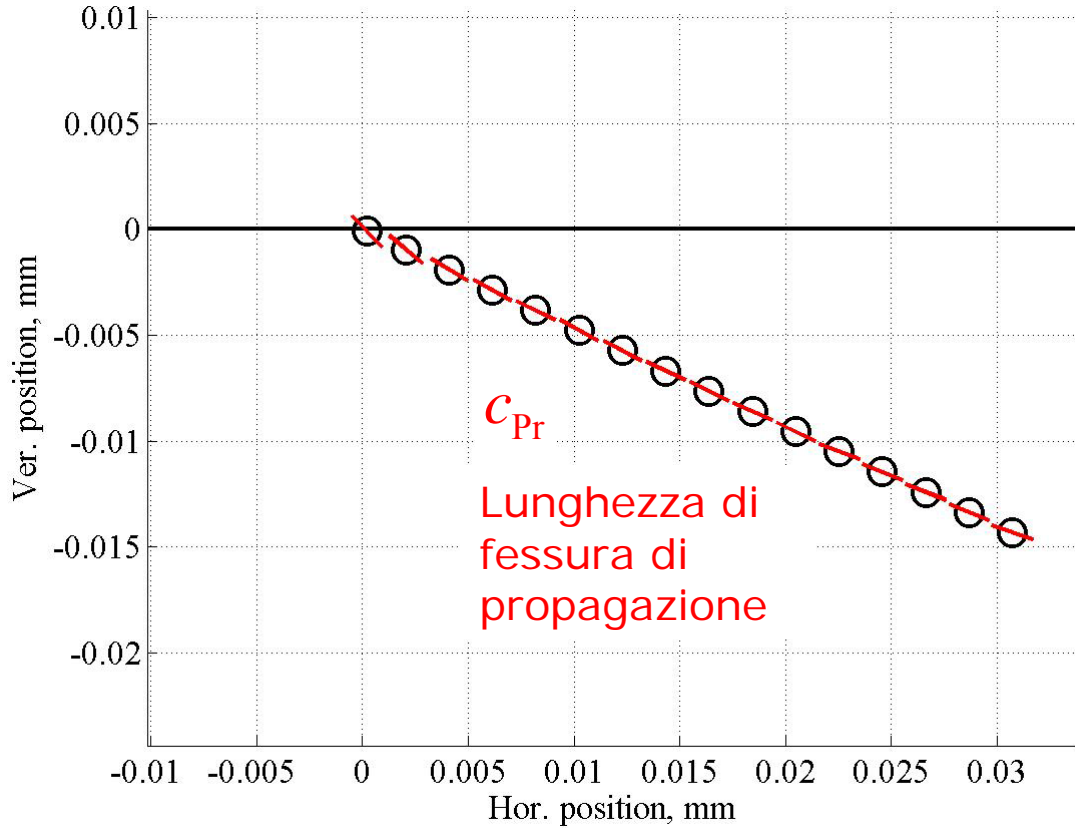
Piano critico,  
coincidente con la  
sup. di delaminazione



# Spalling



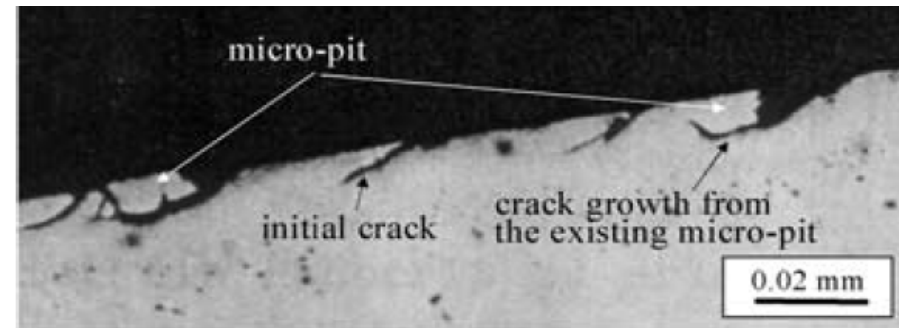
# Pitting



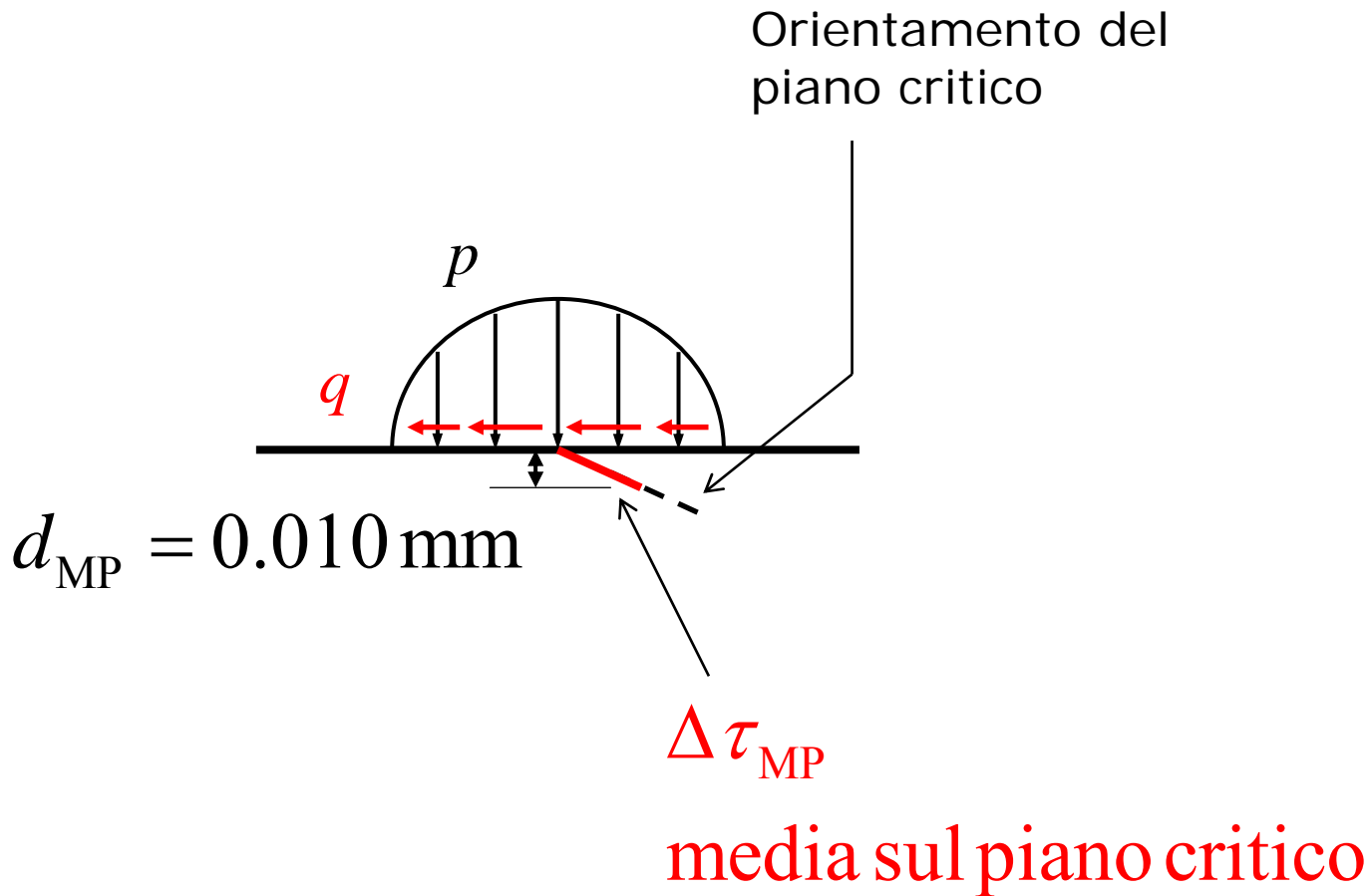
Orientamento del piano critico  $20^\circ$ - $25^\circ$  molto simile alle micro-fessure osservate

$$\Delta \tau_{Pi}$$

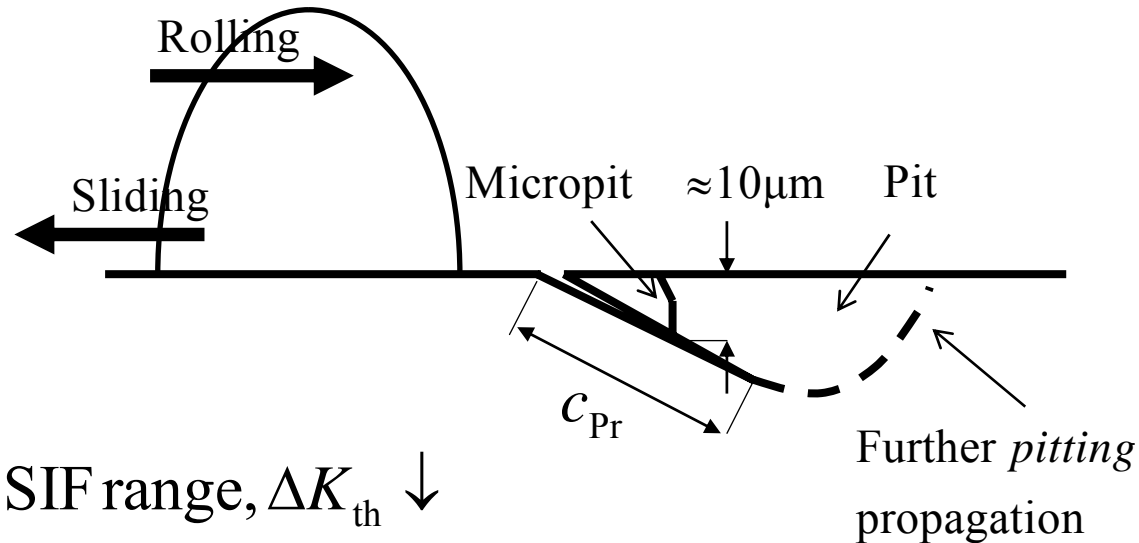
Media taglio ciclico sul piano critico, calcolato sulla lunghezza di propagazione



# Micropitting



# Coincidenza fra Pitting e Micropitting, acciai ad elevata durezza



low threshold SIF range,  $\Delta K_{th} \downarrow$

high pressure,  $p_0 \uparrow$

low eq. radius (small contact halfwidth),  $a \downarrow$

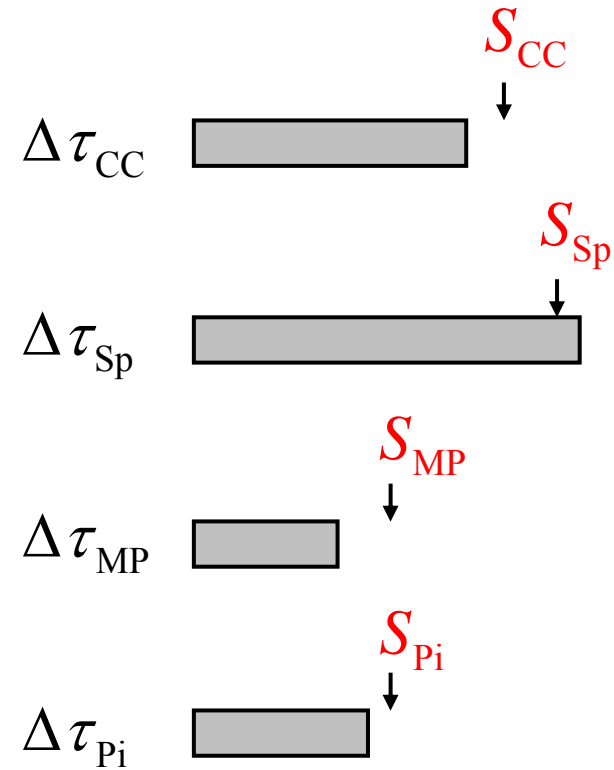
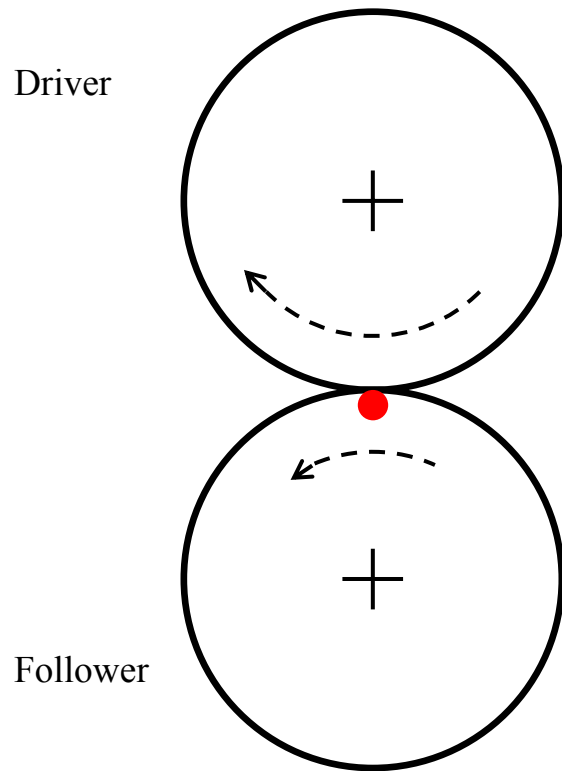
$\Rightarrow$

small critical pitting crack length:  $c_{Pr} \downarrow$

pitting depth can reduce up to  $10\mu\text{m}$ , micropitting size

# Approccio alla sperimentazione

## Banco a dischi



# Conclusioni

- Descrizione dei meccanismi di Fatica di Contatto (ricerca bibliografica).
- Origine superficiale / sotto-superficiale in funzione dell'altezza del meato di lubrif. rispetto all'altezza delle creste.
- Individuazione di una lunghezza di Pitting, limite, di propagazione.
- Coincidenza fra Pitting e Micropitting.
- Definizione di parametri indicatori di danneggiamento, di Nucleazione, per ciascun meccanismo.
- Utilizzo di tali parametri per ottenere i valori di resistenza (allowable stresses) da prove su banco a dischi, per la successiva progettazione di ingranaggi.