

PMT3306 - Módulo “Fadiga dos materiais” - Parte 2 - Material de apoio

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Nucleação da trinca

- Nucleação em descontinuidades
 - Superfícies
 - Contornos de grão
 - Interfaces matriz/precipitado (inclusões)
- Estruturas complexas de deformação → *persistent slip bands* (PSBs)

Nucleação em partículas

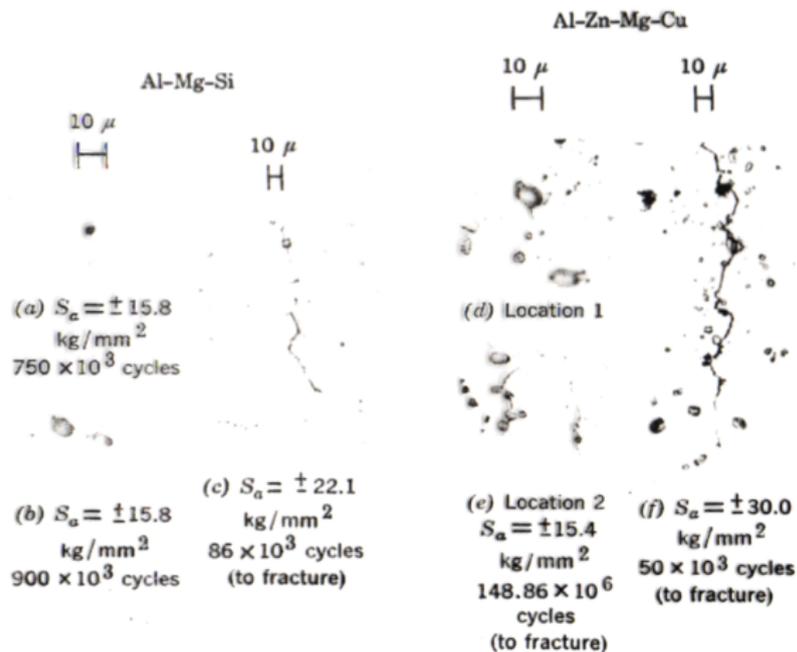
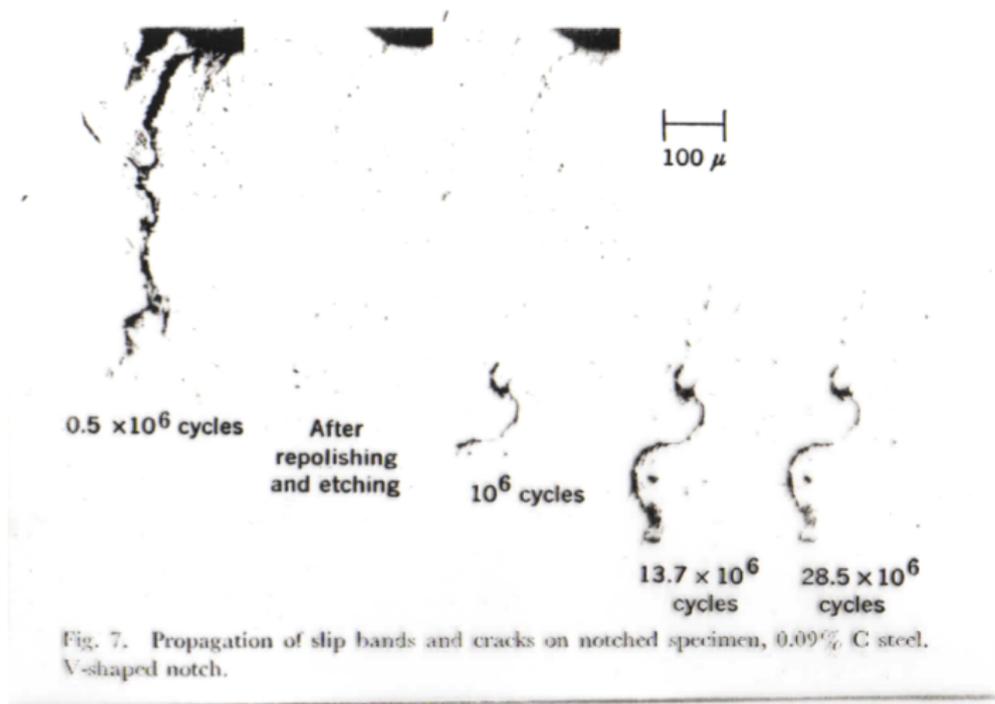


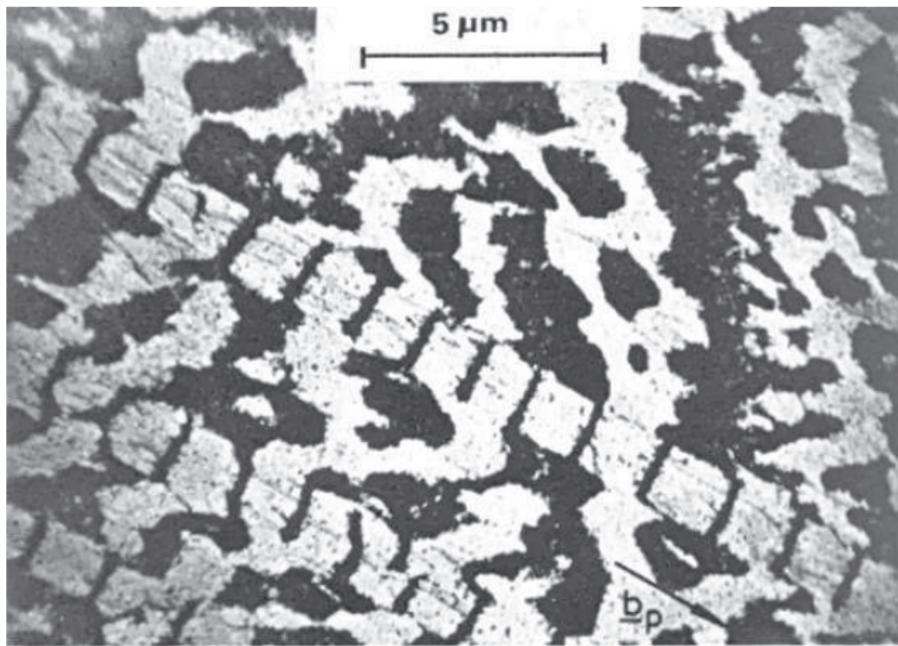
Fig. 24. Starting of cracks on inclusions in cyclically stressed specimens of Al-Mg-Si and Al-Zn-Mg-Cu alloys.

Bandas persistentes

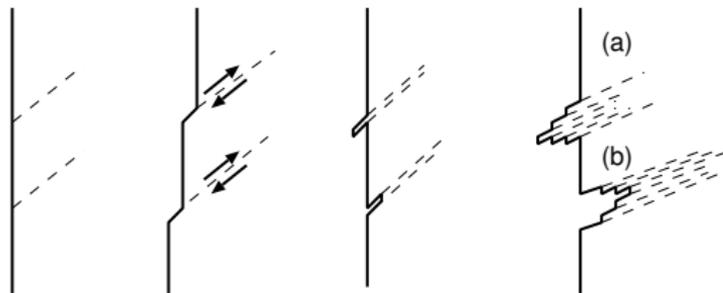
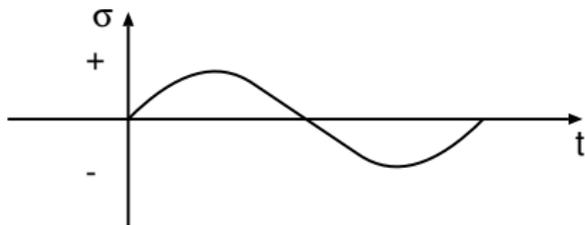


Bandas persistentes de escorregamento

PSBs



Intrusões e extrusões



----- Planos
de escorregamento

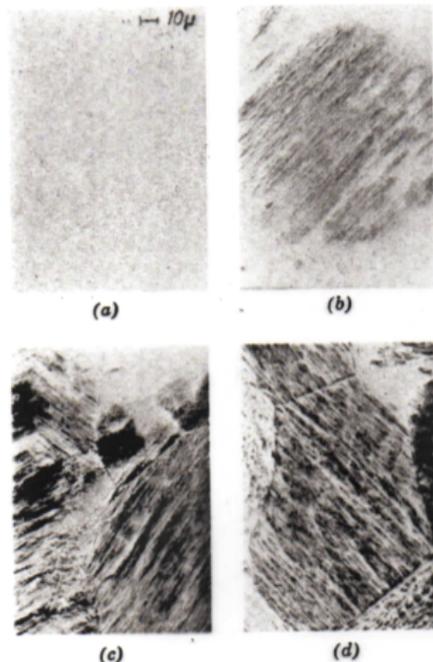


Fig. 16. Effect of increasing stress level on the appearance of slip markings in pure aluminum at a constant number of cycles, 0.25×10^6 : $S_n = (a) \pm 0.73 \text{ kg/mm}^2$, $(b) \pm 0.93 \text{ kg/mm}^2$, $(c) \pm 1.34 \text{ kg/mm}^2$, $(d) \pm 1.74 \text{ kg/mm}^2$.

Intrusões e extrusões

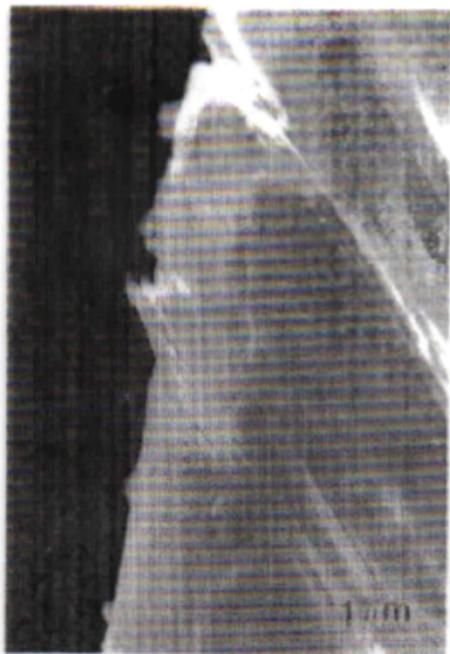


Figure 14.13 SEM of extrusions and intrusions in a copper sheet. (Courtesy of M. Judelwicz and B. Ilchner)

Relevo superficial

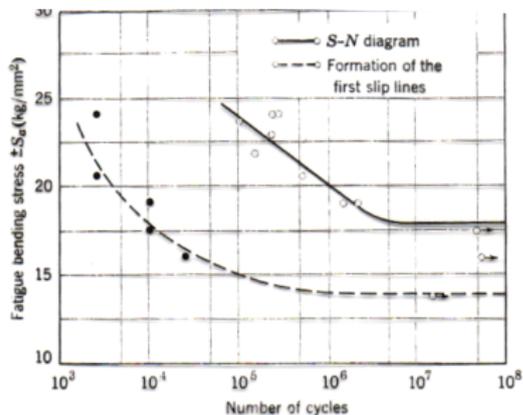


Fig. 3. Occurrence of the first slip lines on unnotched flat specimens of 0.09% C steel.

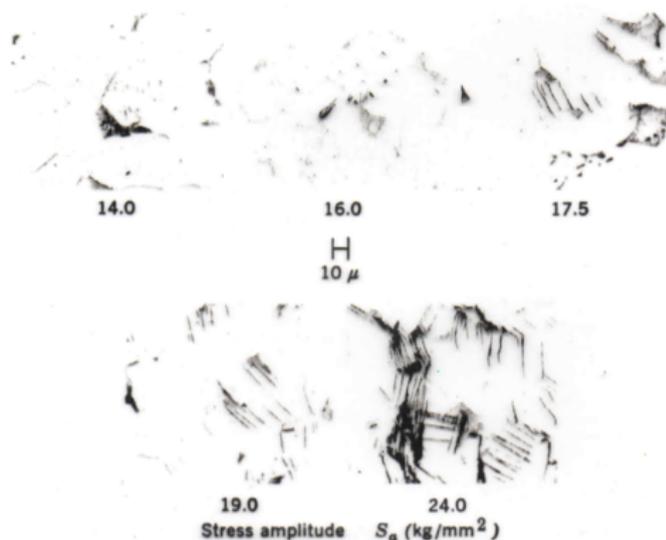


Fig. 4. Formation of slip bands dependent on the stress $\pm S_a$. 0.25×10^6 cycles.

Relevo superficial

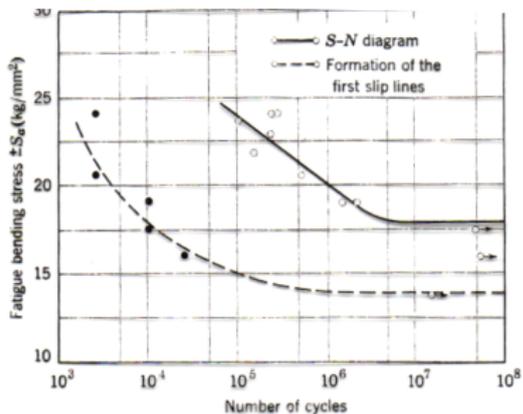
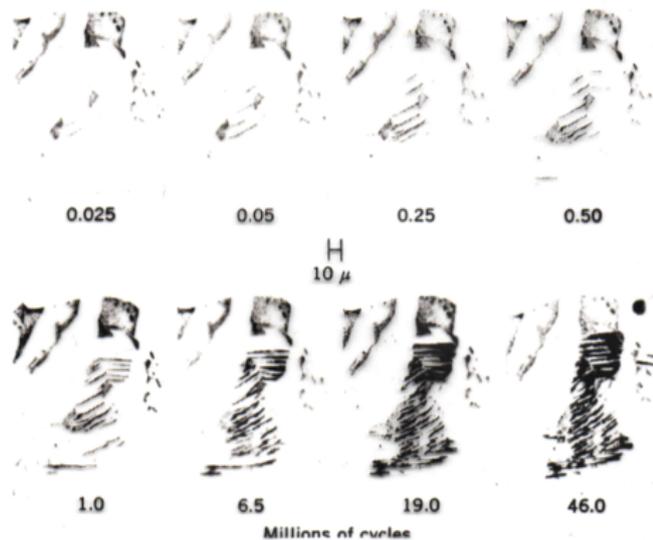


Fig. 3. Occurrence of the first slip lines on unnotched flat specimens of 0.09% C steel.

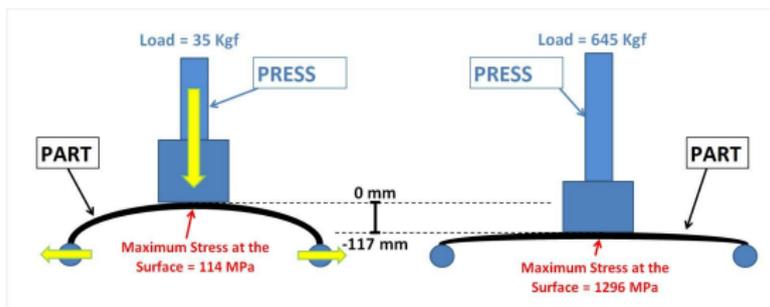


Qualidade da superfície

- Polimento
- Introdução de tensões residuais de compressão
 - *Shot peening*
 - Componentes cementados ou nitretados
 - Deposição de filmes finos

Estudo de caso

shot peening em molas de lâmina



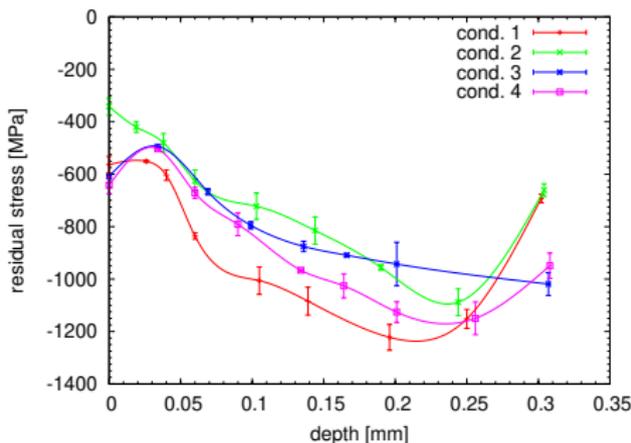
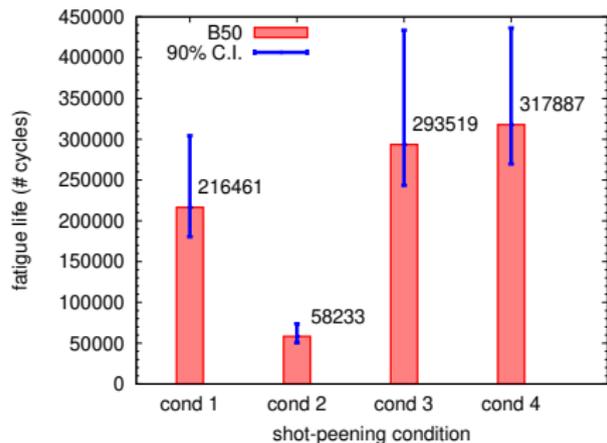
	CS1 (nominal)	CS2 (nominal)
Condition 1	0.8 mm \varnothing	none
Condition 2	0.8 mm \varnothing	0.6 mm \varnothing
Condition 3	0.8 mm \varnothing	0.4 mm \varnothing
Condition 4	0.8 mm \varnothing	0.3 mm \varnothing

B. G. Scuracchio, N. B. Lima, C. G. Schön "Role of residual stresses induced by double peening on fatigue durability of automotive leaf springs" *Materials & Design* **47** (2013) 672 – 676.

Estudo de caso

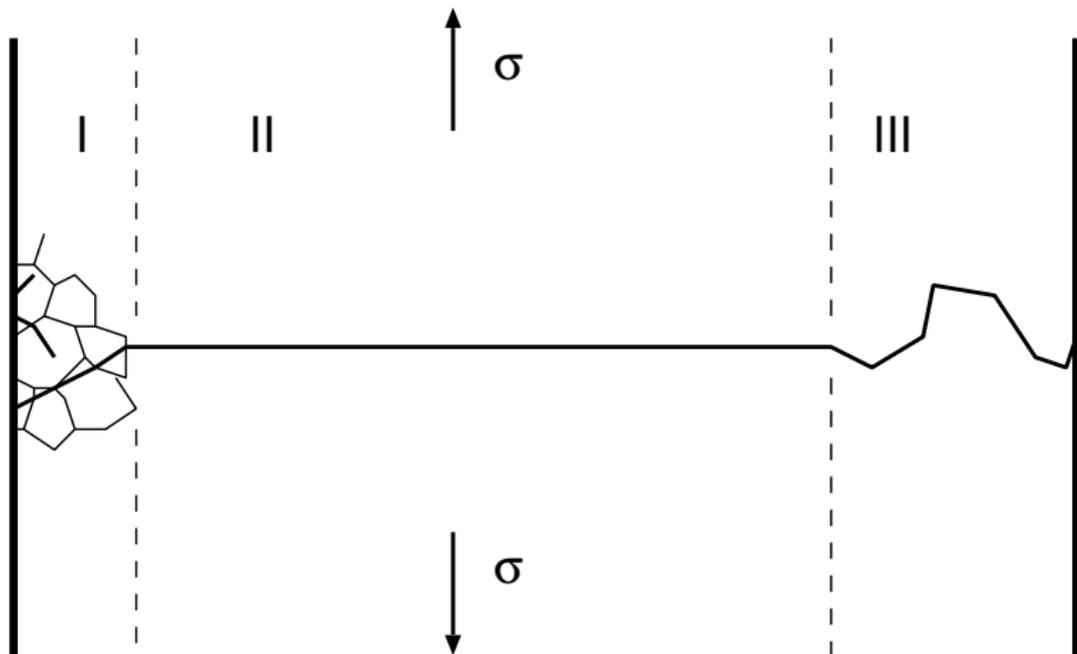
shot peening em molas de lâmina

Médias de dez molas por condição:



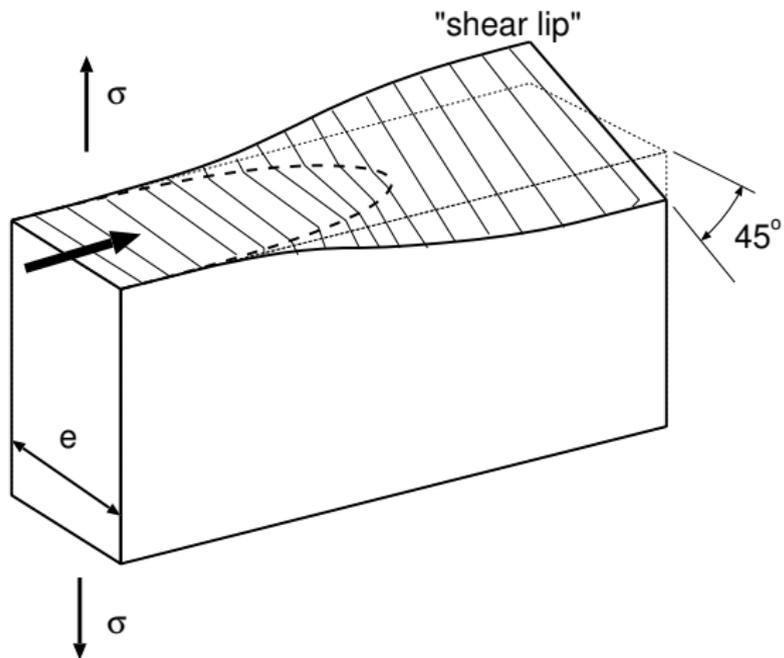
B. G. Scuracchio, N. B. Lima, C. G. Schön "Role of residual stresses induced by double peening on fatigue durability of automotive leaf springs" *Materials & Design* **47** (2013) 672 – 676.

Propagação da trinca

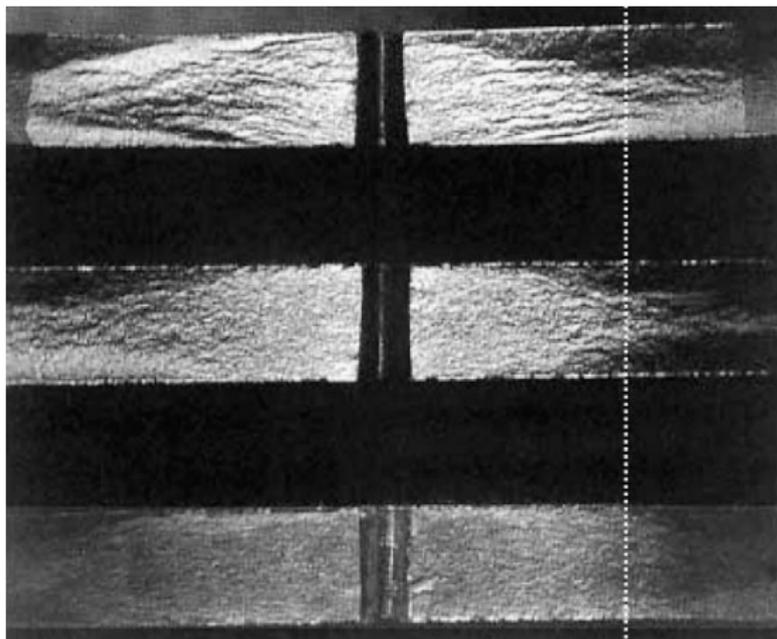


Efeito do estado de tensão

Shear lips



Efeito do ambiente



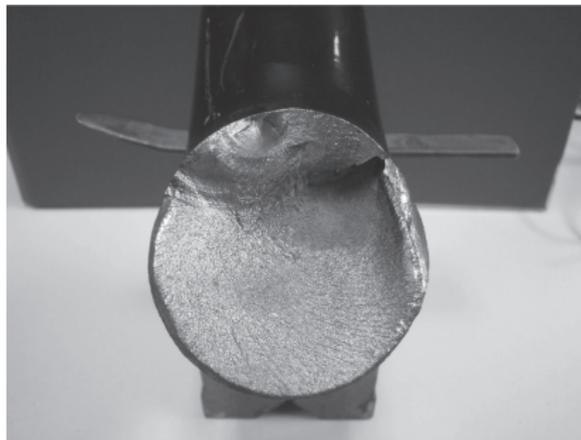
Al 7075-T6 com 6 mm de espessura, trincas centrais simétricas, $\sigma_{max} = 98$ MPa, $R = 0,1$.

- Acima: vácuo
- Centro: atmosfera
- Abaixo: solução salina concentrada

R. Sunder "Spectrum load fatigue – underlying mechanisms and their significance in testing analysis" *Int. J. Fatigue* **25** (2003) 971 – 981.

Marcas de praia

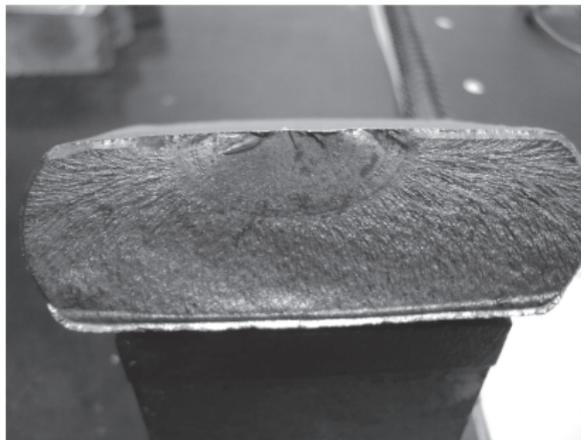
Beach marks



Barra estabilizadora

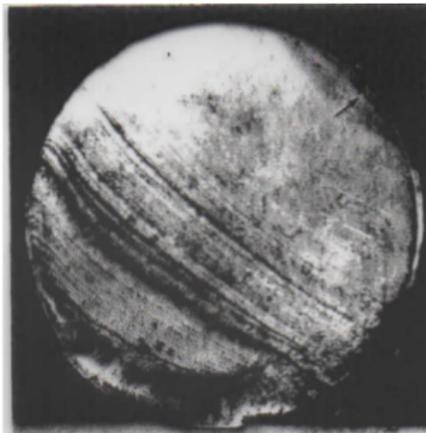
Marcas de praia

Beach marks



Lâmina de mola

Interpretação



Stress condition Case	No stress concentration		Mid stress concentration		High stress concentration	
	Low overstress	High overstress	Low overstress	High overstress	Low overstress	High overstress
One-way bending load						
Two-way bending load						
Reversed bending and rotation load						

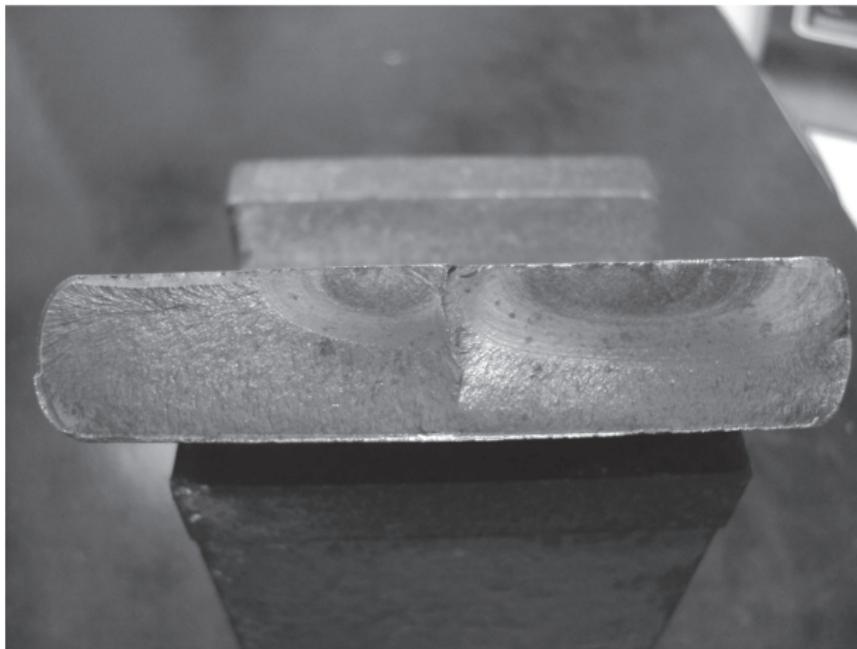
Interpretação



Stress condition Case	No stress concentration		Mild stress concentration		High stress concentration	
	Low overstress	High overstress	Low overstress	High overstress	Low overstress	High overstress
One-way bending load						
Two-way bending load						
Reversed bending and rotation load						

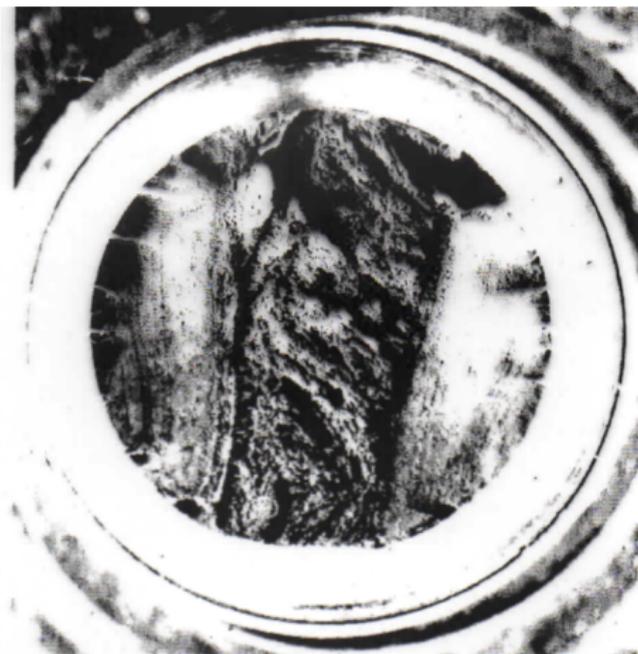
Marcas de catraca

Ratchet marks

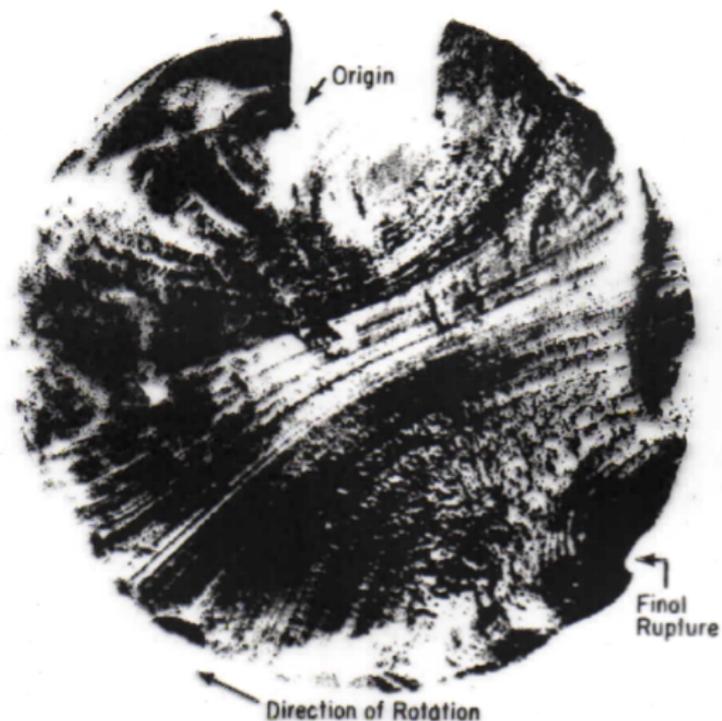


Marcas de catraca

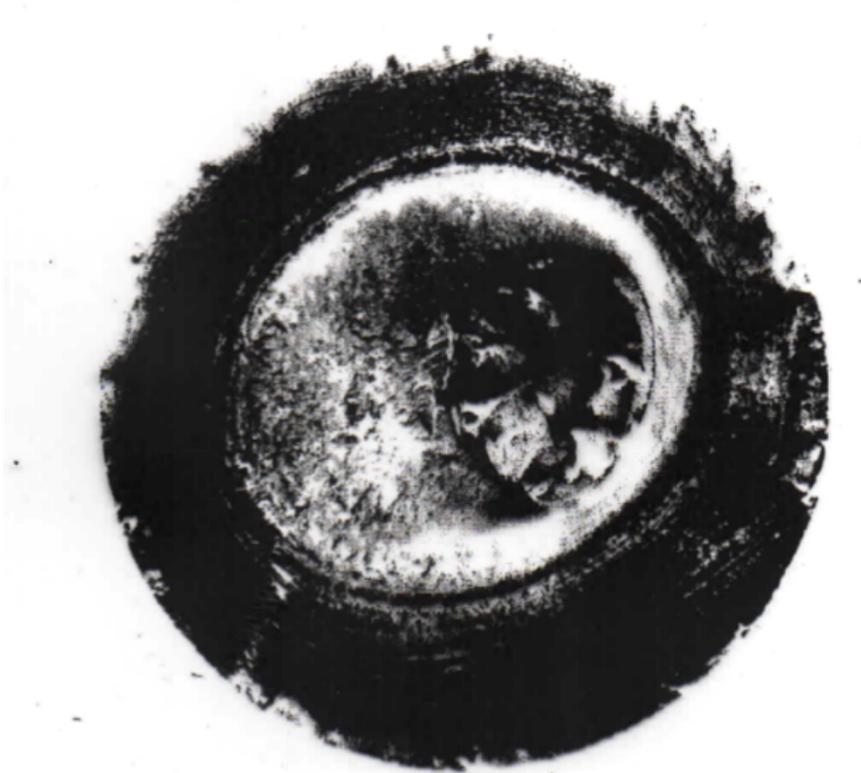
Ratchet marks



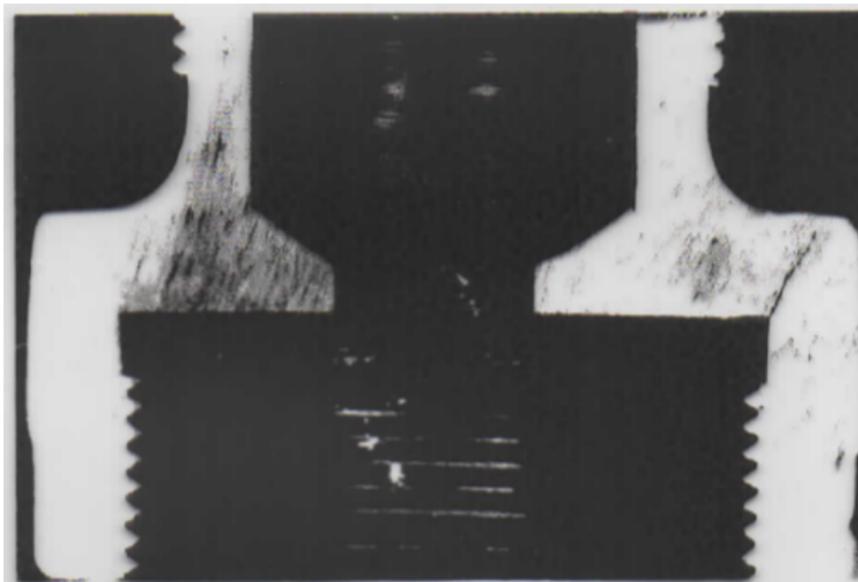
Efeito de concentradores de tensão



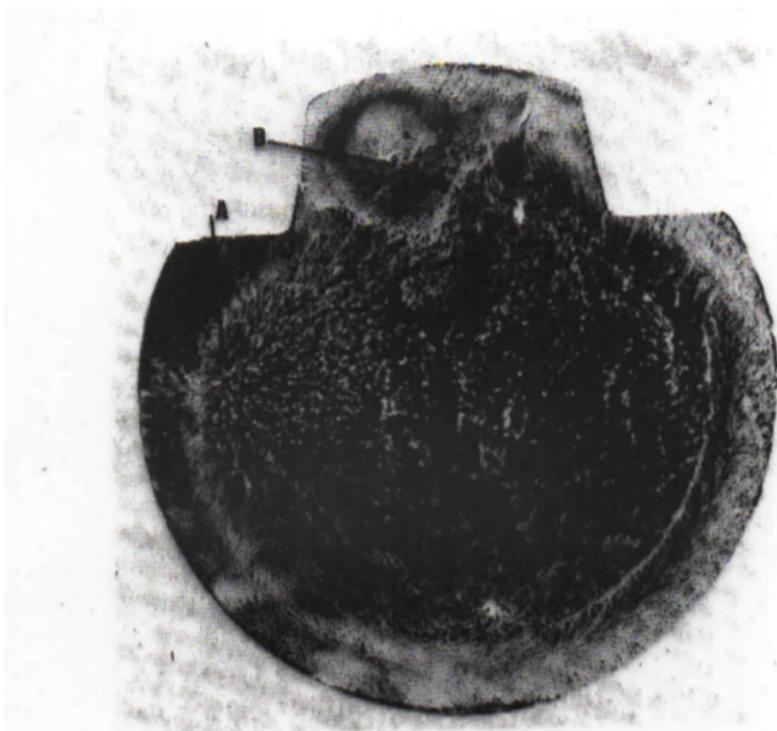
Efeito de concentradores de tensão



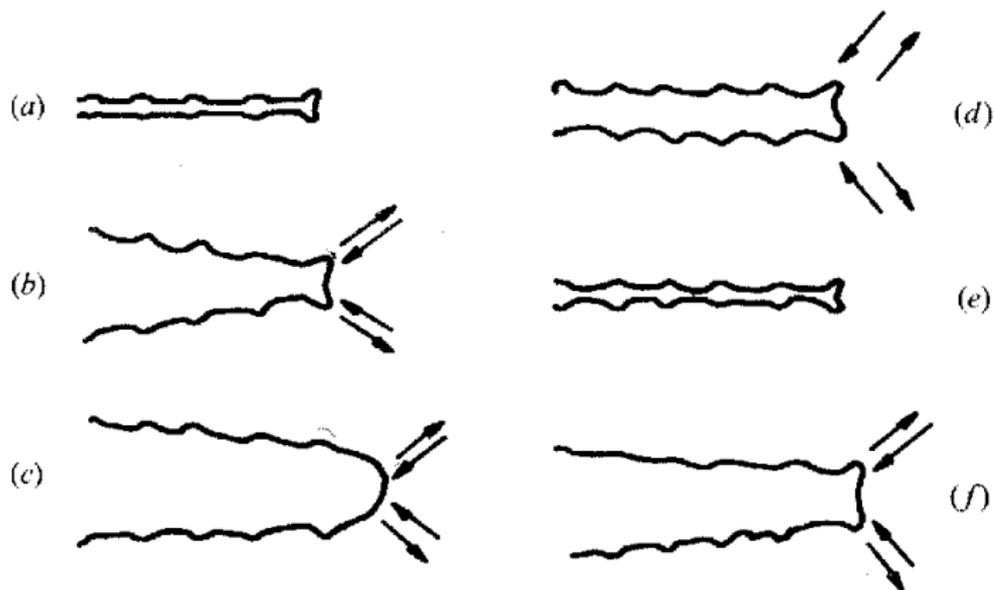
Efeito de concentradores de tensão



Efeito de concentradores de tensão



Estrias de fadiga



Tipos de estrias

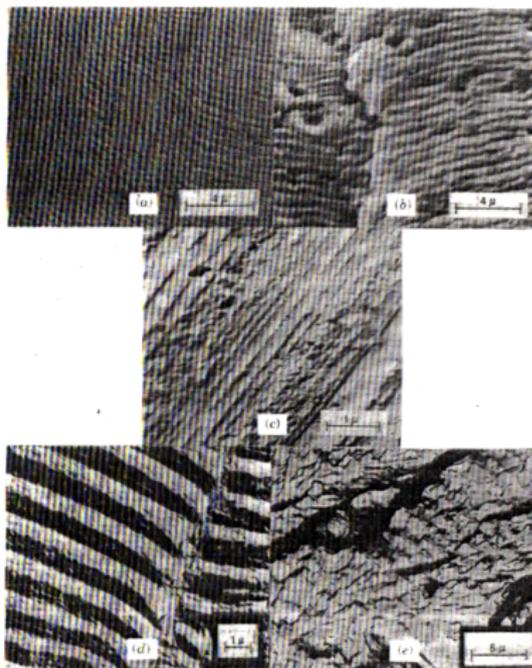
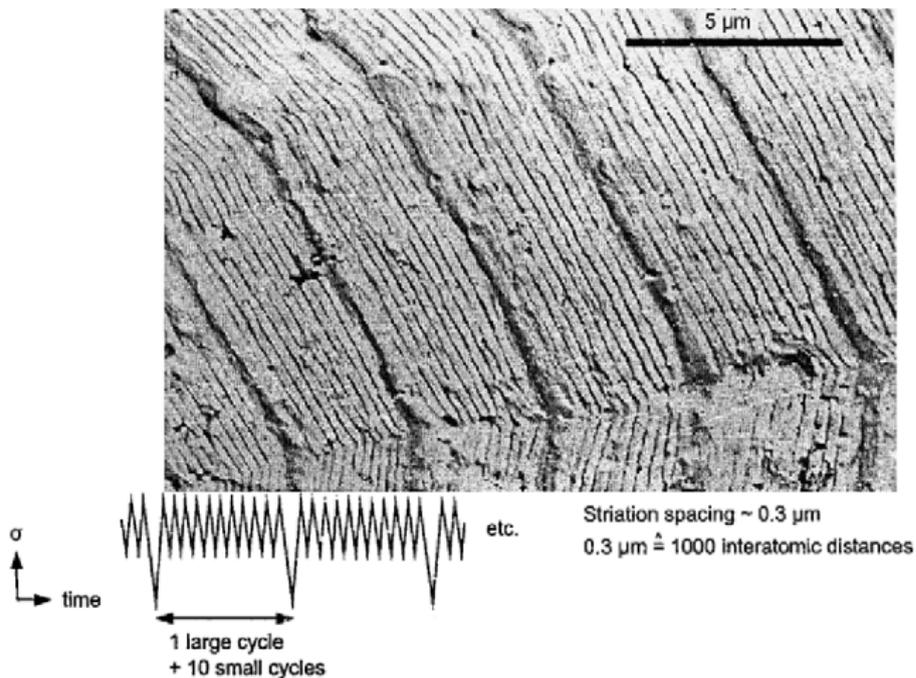


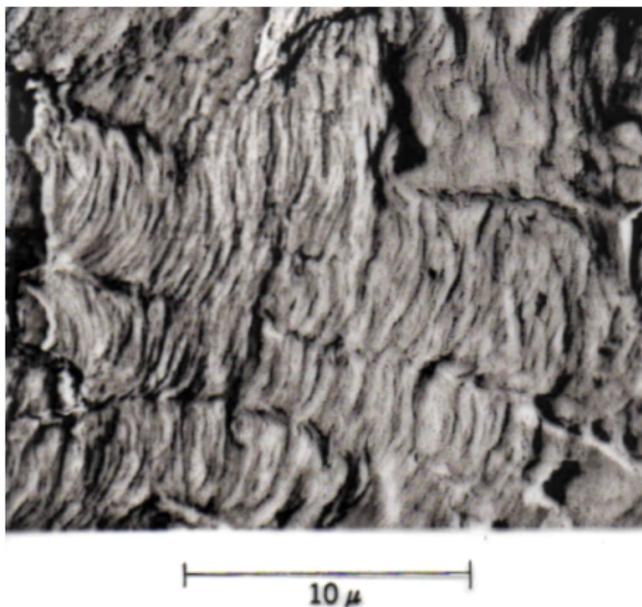
FIGURE 13.11 Electron fractographs revealing fatigue striations found on fracture surface and within macroscopic bands (Figs. 12.1, 12.3, 13.42). (a) TEM, constant load range; (b) SEM, constant load range; (c) TEM, random loading; (d) TEM, ductile striations;²² (e) TEM, brittle striations.²² (Reprinted with permission of the American Society for Testing and Materials from copyrighted work.)

- (a) Transmissão (réplica), amplitude constante
- (b) Varredura, amplitude constante
- (c) Transmissão (réplica), amplitude variável
- (d) Transmissão (réplica), estrias “dúcteis”
- (e) Transmissão (réplica), estrias “frágeis”

Correlação entre estrias e posição da trinca

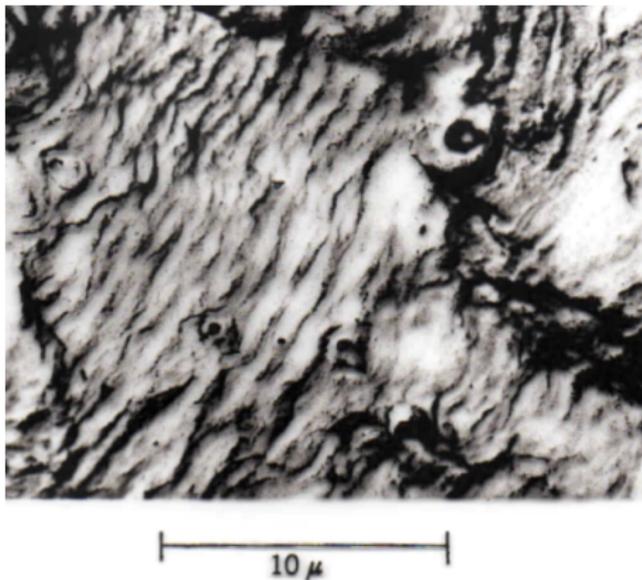


Exemplos



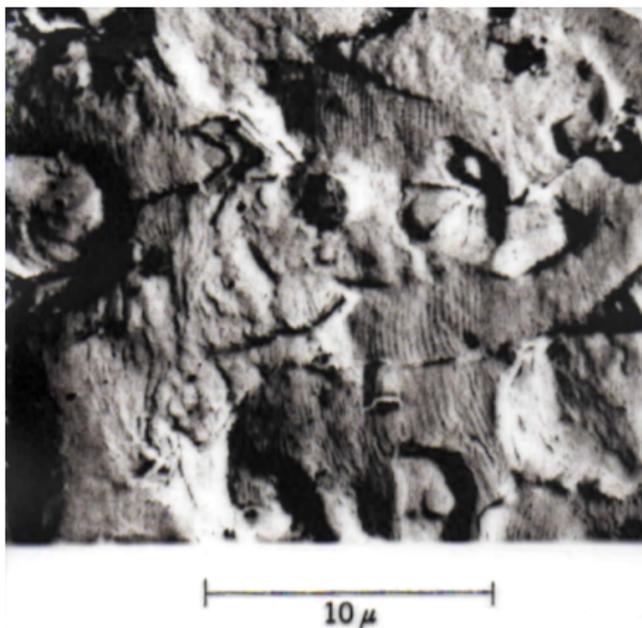
Aço carbono, $\Delta\sigma = 190$ MPa, $\sigma_m = 120$ MPa, $N_f = 0,63 \times 10^6$.

Exemplos



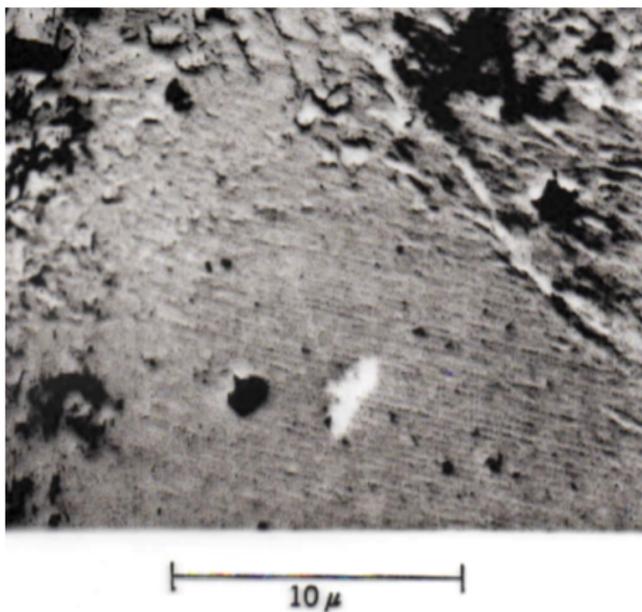
Aço inoxidável 18 - 8, $\Delta\sigma = 230$ MPa, $\sigma_m = 0$ MPa, $N_f = 0,77 \times 10^6$.

Exemplos



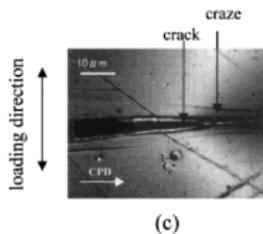
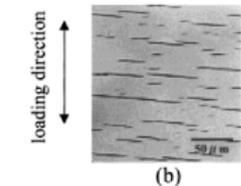
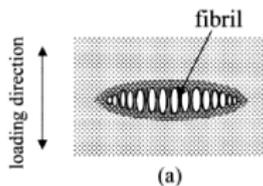
Alumínio AA20204-T6, $\Delta\sigma = 70$ MPa, $\sigma_m = 0$ MPa, $N_f = 0,27 \times 10^6$.

Exemplos



Aço inoxidável 18 - 8, flexão rotativa, $\Delta\sigma = 240$ MPa, $\sigma_m = 0$ MPa,
 $N_f = 0,84 \times 10^6$.

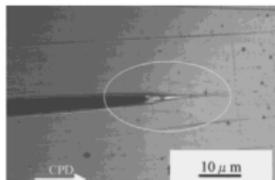
Dano cíclico em polímeros



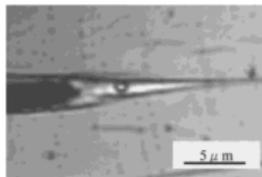
- (a) Representação esquemática de um *craze*
- (b) *Crazes* na superfície de PMMA
- (c) *Craze* na ponta de uma trinca em PMMA, CPD = direção de propagação da trinca

C. Ishiyama, T. Asai, M. Kobayashi, M. Shimojo, Y. Higo "Fatigue crack propagation mechanism in poly(methyl metacrylate) by *in situ* observation with scanning laser microscope" *J. Polym. Sci. B* **39** (2001) 3103 – 3113.

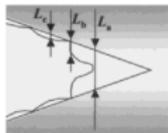
Dano cíclico em polímeros



(a)



(b)

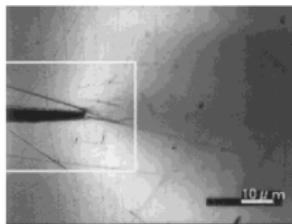


(c)

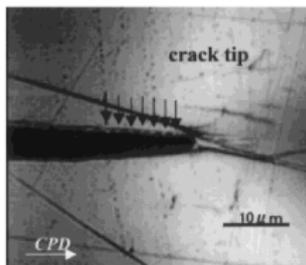
- (a) trinca em PPMA contendo um *craze* na ponta
- (b) detalhe do *craze* na ponta da trinca em PMMA
- (c) representação esquemática indicando as variáveis

C. Ishiyama, T. Asai, M. Kobayashi, M. Shimojo, Y. Higo "Fatigue crack propagation mechanism in poly(methyl methacrylate) by *in situ* observation with scanning laser microscope" *J. Polym. Sci. B* **39** (2001) 3103 – 3113.

Crescimento da trinca



(a)



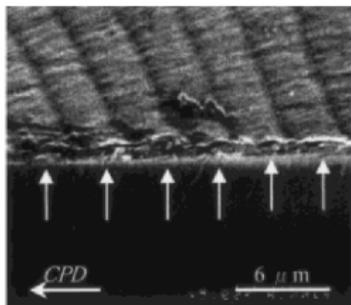
(b)

Trinca de fadiga com $K_{max} = 0,7 \text{ MPa m}^{\frac{1}{2}}$ e $R = 0,1$, com a trinca propagando a uma taxa de $2 \mu\text{m ciclo}^{-1}$

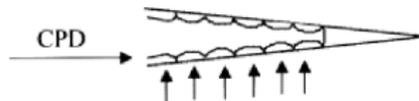
- ⓐ Trinca no máximo de carregamento, que acabou de propagar
- ⓑ Detalhe das rugosidades deixadas na trazeira da trinca

C. Ishiyama, T. Asai, M. Kobayashi, M. Shimojo, Y. Higo "Fatigue crack propagation mechanism in poly(methyl metacrylate) by *in situ* observation with scanning laser microscope" *J. Polym. Sci. B* **39** (2001) 3103 – 3113.

Estrias



(a)

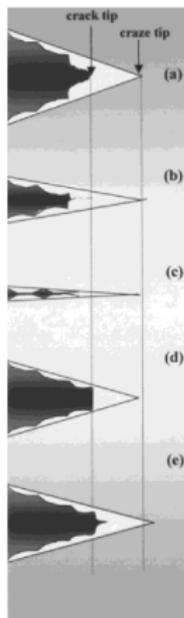


(b)

- (a) imagem de MEV mostrando as rugosidades
- (b) representação esquemática da formação da rugosidade

C. Ishiyama, T. Asai, M. Kobayashi, M. Shimojo, Y. Higo "Fatigue crack propagation mechanism in poly(methyl metacrylate) by *in situ* observation with scanning laser microscope" *J. Polym. Sci. B* **39** (2001) 3103 – 3113.

Mecanismo de crescimento da trinca



Mecanismo proposto para formação das rugosidades

- (a) Trinca no máximo de carregamento, que acabou de propagar
- (b) Descarregamento
- (c) Mínimo de carga
- (d) Novo carregamento
- (e) Novo máximo de carga, com nova etapa de propagação

C. Ishiyama, T. Asai, M. Kobayashi, M. Shimojo, Y. Higo "Fatigue crack propagation mechanism in poly(methyl methacrylate) by *in situ* observation with scanning laser microscope" *J. Polym. Sci. B* **39** (2001) 3103 – 3113.