

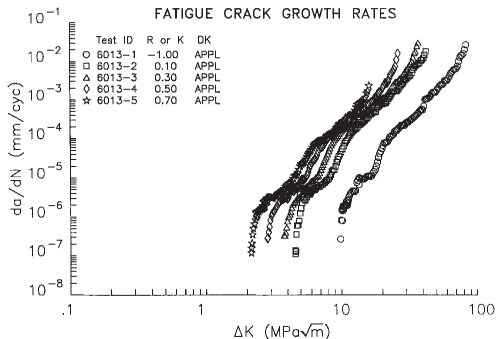
PMT3306 - Módulo “Fadiga operacional” - Material de apoio

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Departamento de Engenharia Metalúrgica e de Materiais
Escola Politécnica da Universidade de São Paulo

14 de novembro de 2021

Curvas de Paris



$$\Delta K = Y\Delta\sigma\sqrt{\pi a}$$

P. C. Paris, H. Tada, J. K. Donald "Service load fatigue – a historical perspective" *Int. J. Fatigue* **21** (1999) S35 – A46.

Princípio da similaridade

“Situações similares, aplicados a sistemas similares, devem resultar nas mesmas consequências.”

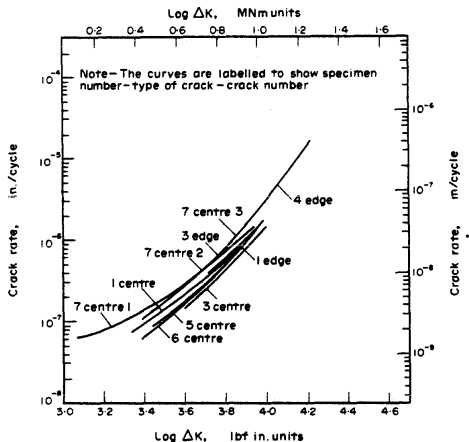
Princípio da similaridade

“O mesmo valor ΔK aplicado a diferentes trincas deve resultar na mesma taxa de propagação.”

Desvios do princípio da similaridade

- Propagação de trincas curtas
- Efeitos de sobrecarga e subcarga

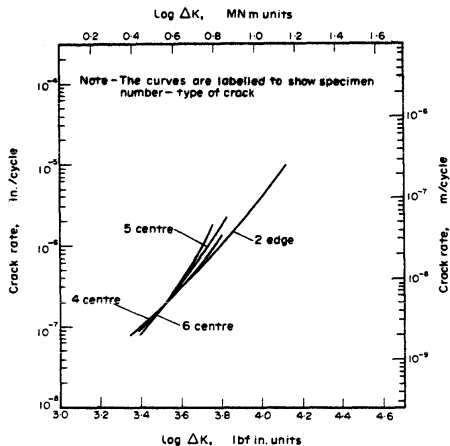
Resultados de Pearson (1975)



S. Pearson "Initiation of fatigue cracks in commercial alloys and the subsequent propagation of very short cracks" *Eng. Frac.*

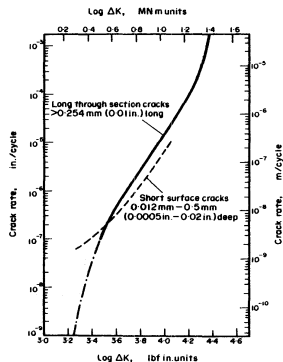
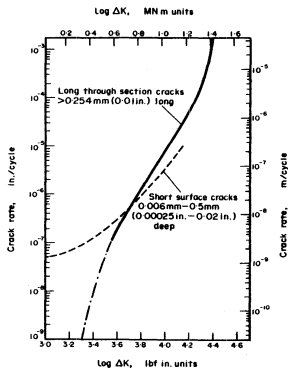
Mech. 7 (1975) 235 – 247.

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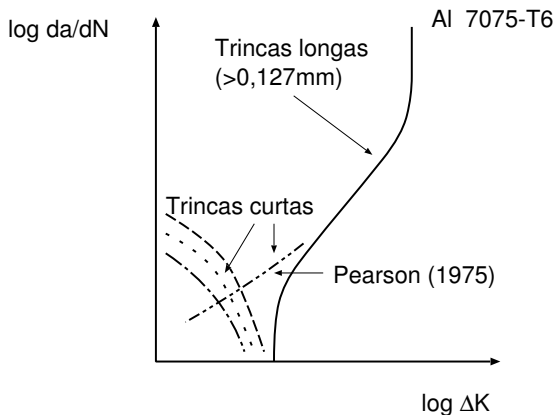


S. Pearson "Initiation of fatigue cracks in commercial alloys and the subsequent propagation of very short cracks" *Eng. Frac.*

Mech. 7 (1975) 235 - 247.

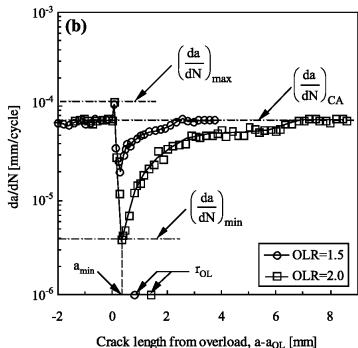
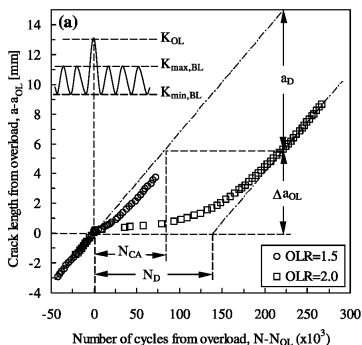
O “problema” da trinca curta

“Short-crack problem”



Efeito de sobrecarga

Al 6082 - T6



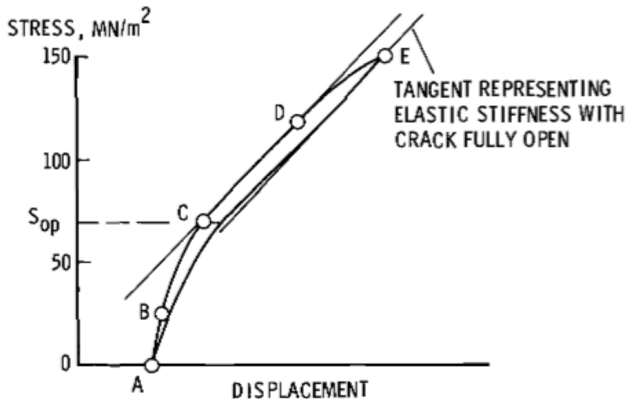
L. Borrego, J. M. Ferreira, J. M. Pinho da Cruz, J. M. Costa "Evaluation of overload effects on fatigue crack growth and closure"

Eng. Frac. Mech. **70** (2003) 1379 – 1397.

Wolf Elber (1941 - 2019)

- Fez seu doutorado na Universidade da Nova Gales do Sul, defendido em 1968 (!!!!)
- Fez sua descoberta quando cortou o ligamento de um corpo de prova, o artigo só foi publicado em 1970
- Voltou para a Alemanha
- Encontrou P. C. Paris em 1968, explicou seu método em um jantar
- Foi contratado para trabalhar na NASA em 1972
- Pesquisador mais influente da história da fadiga na segunda metade do século XX

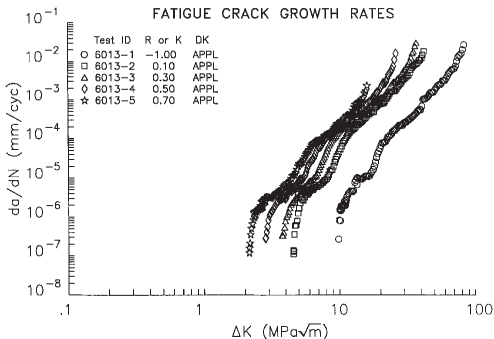
Carga de abertura



$$K_{ef} = Y (\sigma_{max} - \sigma_{OP}) \sqrt{\pi a}$$

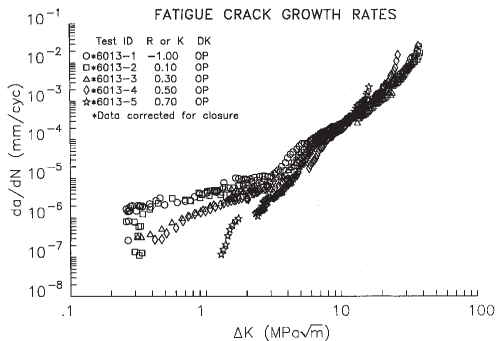
W. Elber "The significance of fatigue crack closure" in: ASTM STP 486 "Damage tolerance in aircraft structures" ASTM:Toronto, 1970, pp.

Efeito do fechamento prematuro de trinça



$$\Delta K = Y \Delta \sigma \sqrt{\pi a}$$

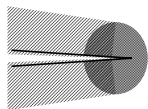
Efeito do fechamento prematuro de trinça



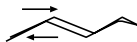
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Mecanismos de fechamento prematuro de trinça



Plasticidade



Rugosidade



Detritos

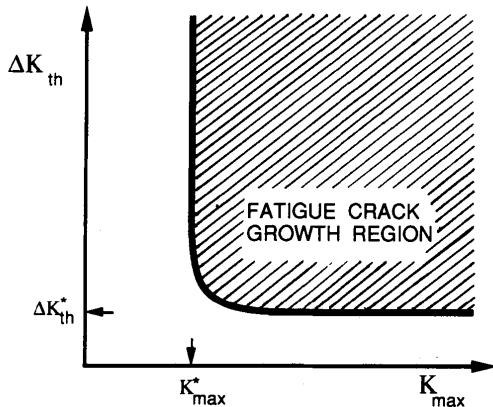
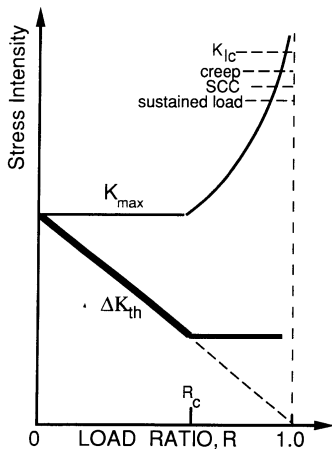
Teoria dos dois parâmetros

Vasudévan e Sadananda:

$$\frac{da}{dN} = f(\Delta K, K_{max})$$

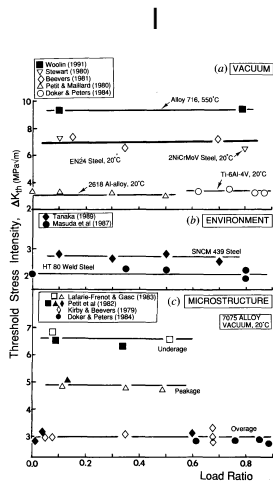
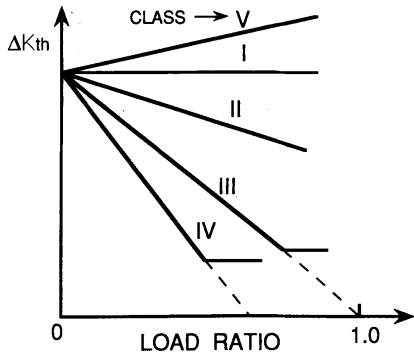
1. Fadiga depende fundamentalmente de dois parâmetros, ΔK e K_{max} , que são as forças motrizes macroscópicas para a propagação da trinca.
2. Existem dois limiares de propagação, ΔK_{th} e K_{max}^* .
3. A existência dos dois limiares torna trivial a dependência de ΔK_{th} com R , portanto é desnecessário postular a ação de fechamento de trinca para justificar o fenômeno.
4. Caso o fechamento de trinca seja importante no processo, ele será caracterizado por um terceiro parâmetro.
5. A força motriz microscópica para o crescimento da trinca é o estado de tensão na ponta da trinca, ou seja, a superposição das tensões geradas pela tensão remota e das tensões residuais de compressão existentes na ponta da trinca.
6. A zona plástica à frente da trinca é uma das principais fontes de tensões residuais de compressão.
7. O efeito básico das tensões residuais é deslocar o valor de σ_m , portanto a dependência em K_{max} é mais sensível a este parâmetro.
8. Efeitos ambientais (ex. corrosão-fadiga) se manifestam fundamentalmente na dependência em K_{max} .

Dependência do limiar de fadiga em R



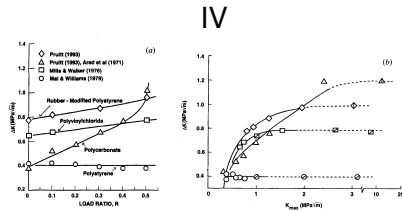
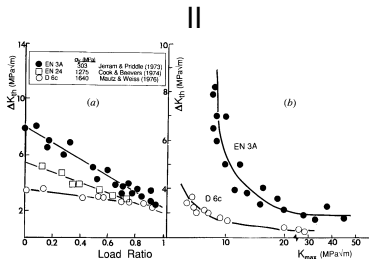
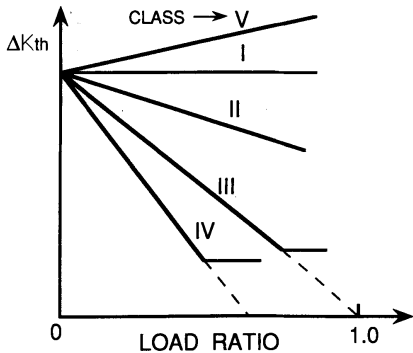
A. K. Vasudévan, K. Sadananda "Classification of fatigue crack growth behavior" *Metall. Mater. Trans. A* **26** (1995) 1221 – 1234.

Classificação dos comportamentos em fadiga



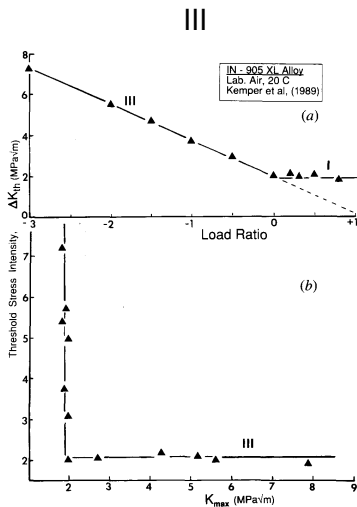
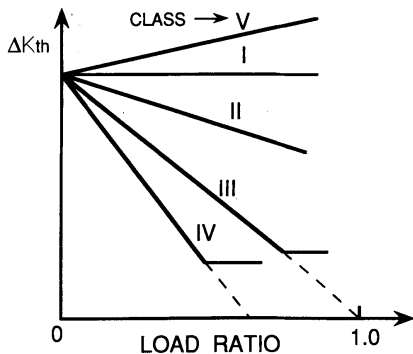
A. K. Vasudévan, K. Sadananda "Classification of fatigue crack growth behavior" *Metall. Mater. Trans. A* **26** (1995) 1221 – 1234.

Classificação dos comportamentos em fadiga



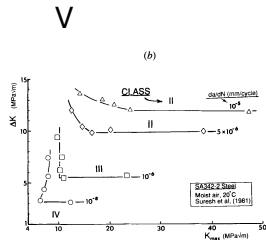
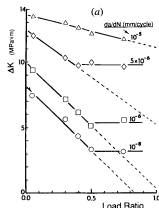
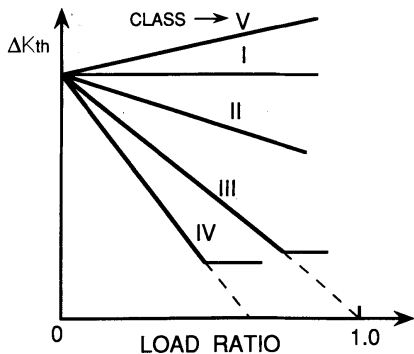
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Classificação dos comportamentos em fadiga



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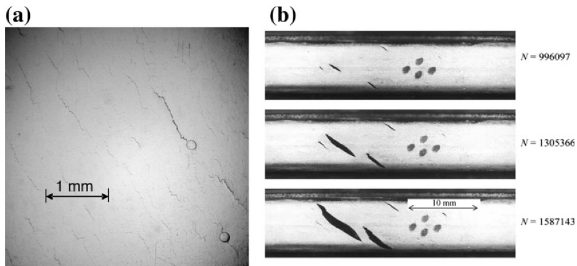
Classificação dos comportamentos em fadiga



A. K. Vasudévan, K. Sadananda "Classification of fatigue crack growth behavior" *Metall. Mater. Trans. A* **26** (1995) 1221 – 1234.

Plano crítico

Torção - tração:

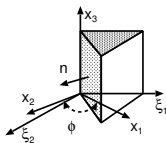
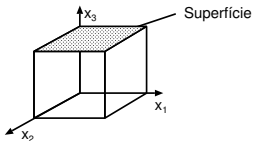


- (a) Aço 1050 cementado, carregamento em fase
- (b) Borracha, carregamento 90° fora de fase

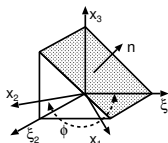
A. Fatemi, N. Shamsaei "Multiaxial fatigue: an overview and some approximation models for life prediction" *Int. J. Fatigue* **33** (2011) 948 – 958.

Plano crítico

Tratamento de Bannantine e Socie



Caso A



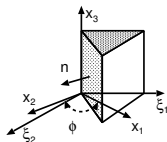
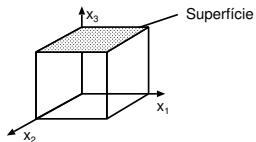
Caso B

Caso A:

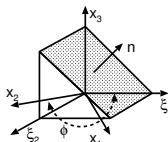
$$D_{BS} = \frac{\Delta \varepsilon}{2} \sigma_{max} = \frac{(\sigma'_f)^2}{E} (2N_f)^{2b} \sigma'_f \varepsilon'_f (2N_f)^{b+c}$$

Plano crítico

Tratamento de Bannantine e Socie



Caso A



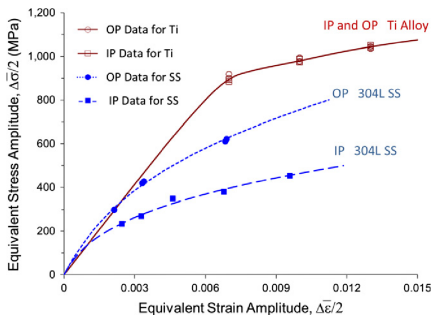
Caso B

Caso B:

$$D_{FS} = \frac{\tau_f'}{G} (2N_f)^b + \gamma_f' (2N_f)^c$$

Carregamentos em fase e fora de fase

Endurecimento

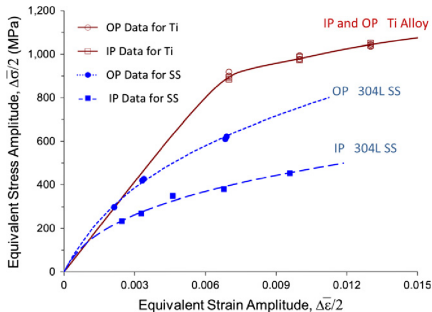


$$\alpha = \frac{\Delta\bar{\sigma}_{0^\circ}}{\Delta\bar{\sigma}_{90^\circ}} - 1$$

A. Fatemi, N. Shamsaei "Multiaxial fatigue: an overview and some approximation models for life prediction" *Int. J. Fatigue* **33** (2011) 948 – 958.

Carregamentos em fase e fora de fase

Endurecimento



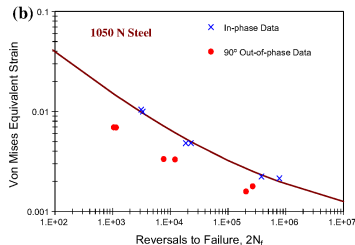
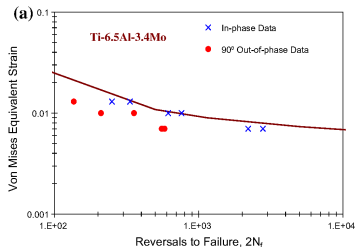
$$\alpha = 1,6 \frac{K}{K'} \left(\frac{\Delta\bar{\epsilon}}{2} \right)^{2(n-n')} - 3,8 \frac{K}{K'} \left(\frac{\Delta\bar{\epsilon}}{2} \right)^{(n-n')} + 2,2$$

A. Fatemi, N. Shamsaei "Multiaxial fatigue: an overview and some approximation models for life prediction" *Int. J. Fatigue* **33**

(2011) 948 – 958.

Carregamentos em fase e fora de fase

Resistência à fadiga



(a) Liga de titânio

(b) Aço 1050 normalizado

Parâmetro de Fatemi - Socie:

$$D_{FS} = \frac{\Delta\gamma_{max}}{2} \left(1 + k \frac{\sigma_{n,max}}{\sigma_e} \right)$$

A. Fatemi, N. Shamsaei "Multiaxial fatigue: an overview and some approximation models for life prediction" *Int. J. Fatigue* **33** (2011) 948 – 958.

Critério MTS

Maximum Tensile Stress

A trinca cresce no plano de máxima tensão normal de tração, quando o dano atinge o valor do limite de fadiga uniaxial

$$\frac{\partial \sigma_{\theta}}{\partial \theta} = 0 \quad \text{e} \quad \frac{\partial^2 \sigma_{\theta}}{\partial \theta^2} < 0$$

Ou ainda:

$$K_I \sin \theta + K_{II} (3 \cos \theta - 1) = 0$$

Critério S

A trinca irá crescer ao longo da direção que apresentar a mínima densidade de energia de deformação, S , e inicia quando esta atinge um valor crítico, S_c . S é definida como:

$$S = a_{11}k_1^2 + 2a_{12}k_1k_2 + a_{22}k_2^2 + a_{33}k_3^2$$

onde os a_{ij} são coeficientes relacionados ao ângulo polar, ao módulo de rigidez e ao coeficiente de Poisson, os k são definidos como:

$$k_i = \frac{K_i}{\pi} \quad (i = \text{I, II, III})$$

Critério J

A trinca cresce orientada de acordo com o vetor:

$$\vec{J} = J_I \vec{i} + J_{II} \vec{j}$$

Onde J_I e J_{II} são as integrais J em modo I e II respectivamente.

Taxa de crescimento de trinca

Segundo Tanaka:

$$\frac{da}{dN} = C (\Delta K_{mix})^m$$

onde:

$$\Delta K_{mix} = \left[\Delta K_I^4 + 8\Delta K_{II}^4 \right]^{0,25}$$

Critérios da abordagem de tensão nominal

Grubisig e Simbürger (flexão - torção com um ângulo de defasagem θ):

$$\bar{\sigma} = \sqrt{1 + \frac{3}{4}K^2} + \sqrt{1 + \frac{3}{2}K^2 \cos \theta + \frac{9}{6}K^4}$$

com

$$K = \frac{2\tau_a}{\sigma_a}$$

sendo

- τ_a : tensão nominal no entalhe devida ao esforço de torção
- σ_a : tensão nominal no entalhe devida ao esforço de flexão

Fonte: D. Liao, S.-P. Zhu, J. A. F. O. Correia, A. M. P. de Deus, F. Berto "Recent advances on notch effects in metal fatigue: A review" *Fatigue Frac. Eng. Mater Struct.* **43** (2020) 637 – 659.

Fim da primeira parte

Gestaltfestigkeit e Betriebfestigkeit

Gestaltfestigkeit (Thum e Bautz, 1935):

“for a high fatigue strength, the shape of the components, as developed by the designer, is much more important than the material itself.”

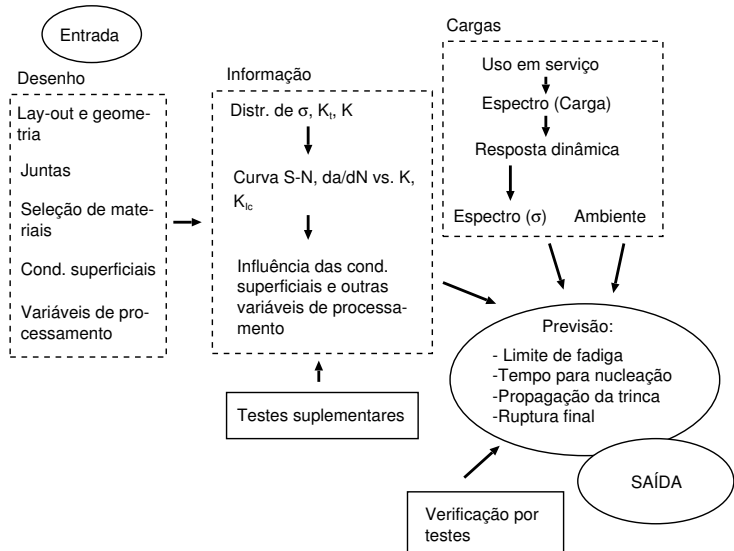
Gestaltfestigkeit e Betriebfestigkeit

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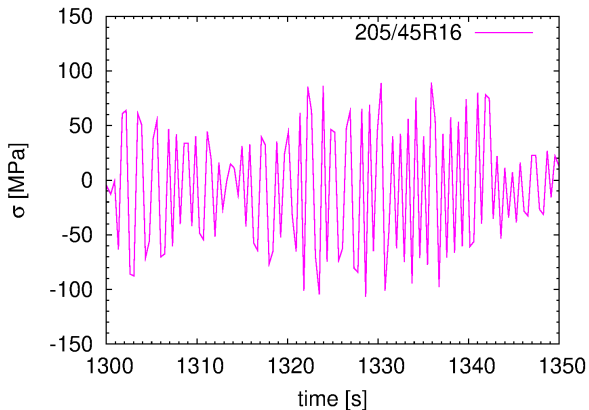
Betriebfestigkeit (Gaßner, 1939): Extensão da *Gestaltfestigkeit* na qual não apenas o componente é ensaiado, mas também é usado o espectro medido em serviço.

Complexidade da fadiga



Espectros

Trecho de um espectro veicular:

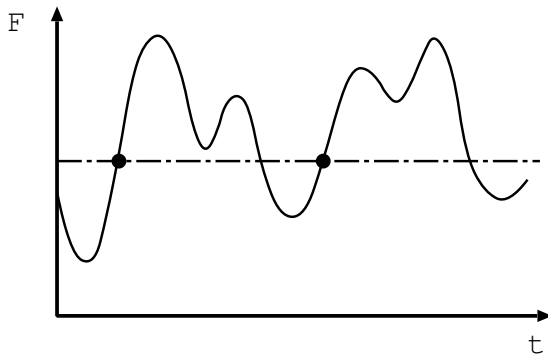


Contagem de ciclos

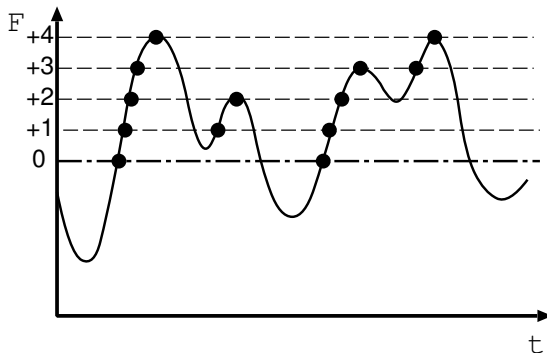
ASTM 1049-85 (reaprovada em 1997):

1. Contagem por cruzamento de nível (*level crossing counting*).
2. Contagem de picos (*peak counting*).
3. Contagem de faixas (*simple-range counting*).
4. *Rainflow* e métodos associados.

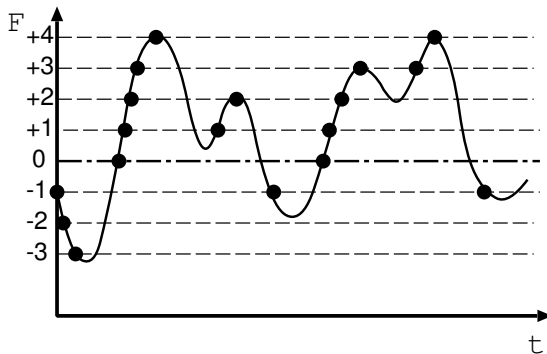
Contagem de níveis



Contagem de níveis



Contagem de níveis



Contagem de níveis

Montamos a tabela de cruzamentos:

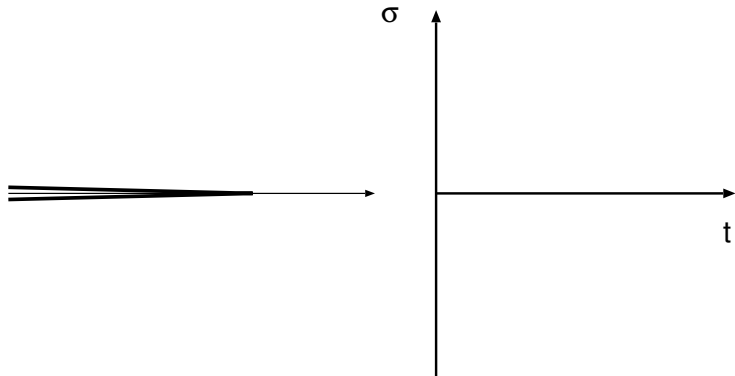
Nível	Cruzamentos
+4	2
+3	3
+2	3
+1	3
0	2
-1	3
-2	1
-3	1

Contagem de níveis

Faixa	Frequência
+7	1
+6	1
+5	0
+4	3
+3	0
+2	2
+1	4

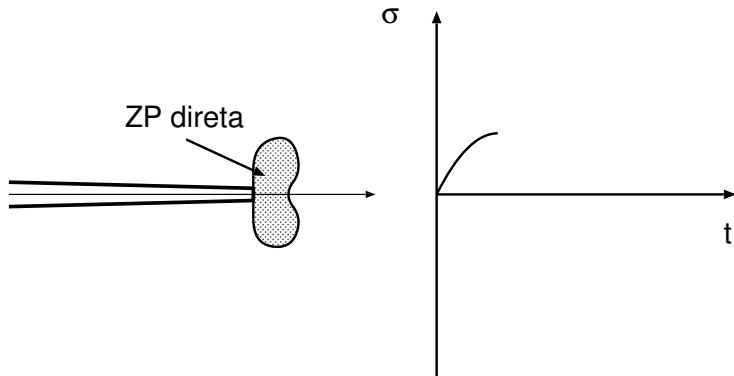
Método *Rainflow*

Plasticidade cíclica



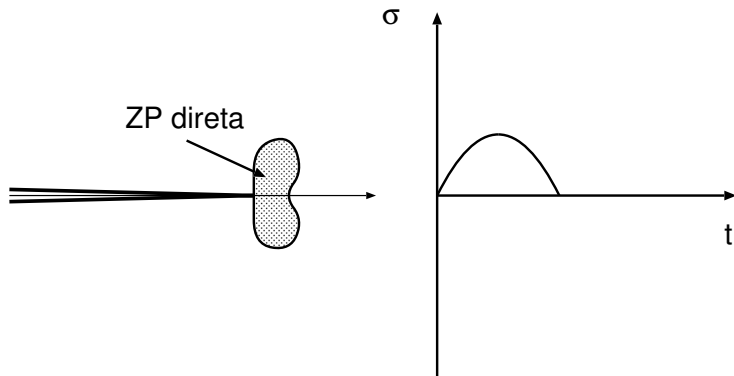
Método *Rainflow*

Plasticidade cíclica



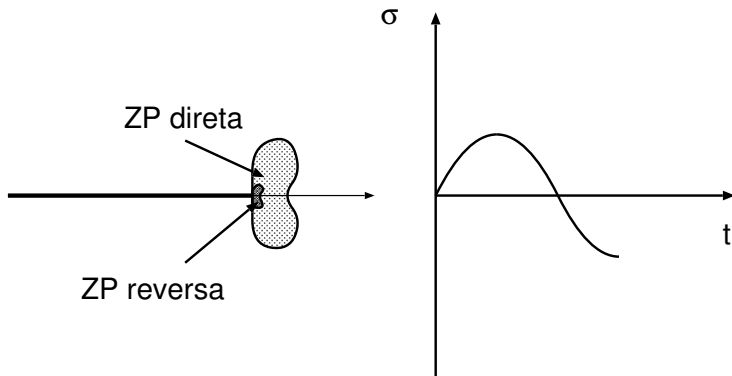
Método *Rainflow*

Plasticidade cíclica



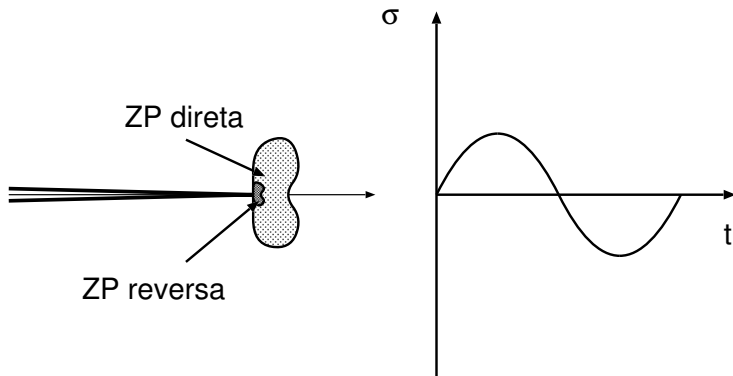
Método *Rainflow*

Plasticidade cíclica



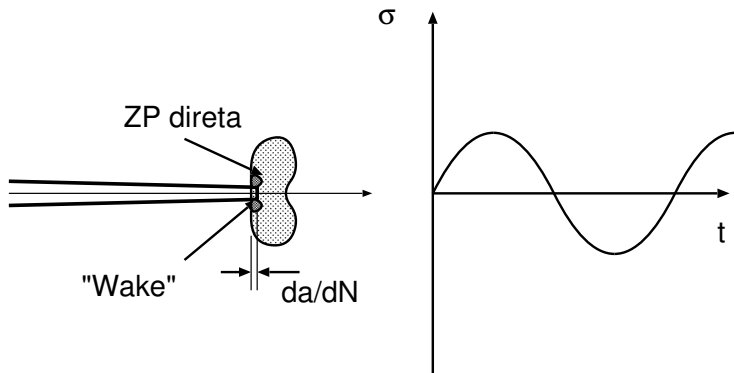
Método *Rainflow*

Plasticidade cíclica



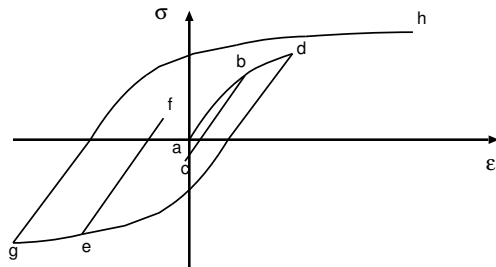
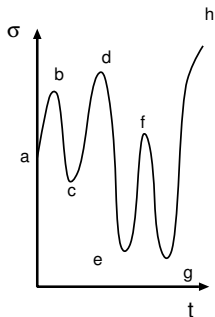
Método *Rainflow*

Plasticidade cíclica



Método *Rainflow*

Plasticidade cíclica

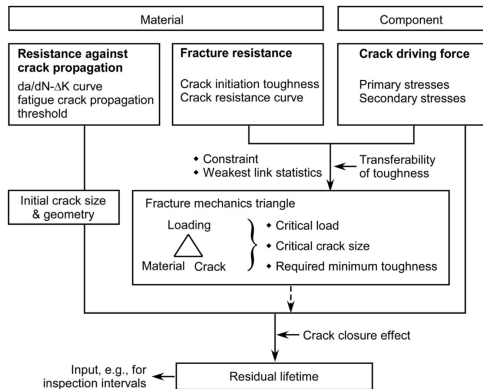


Filosofias de projeto

- *Fail safe* → curva S-N, vida limitada por durabilidade prevista
- *Damage tolerance* → curva da Paris, inspeção
- *Durability design* → interpretação probabilística da fadiga
- *Small crack theory* → considera a microestrutura (e um modelo para trincas curtas)

Schütz → ensaios em protótipos.

Princípio esquemático de uma análise de Mecânica da Fratura



U. Zerbst *et al.* "Review on fracture and crack propagation in weldments — a fracture mechanics perspective" *Eng. Frac. Mech.*

132 (2014) 200 – 276.

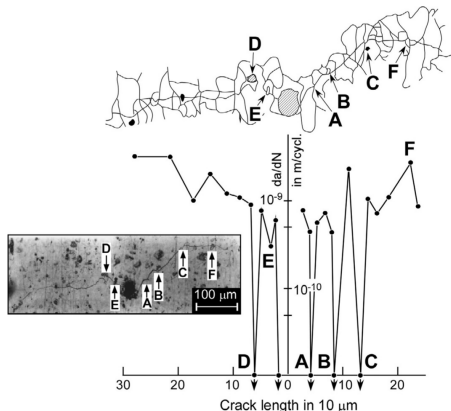
Os dois limiares de fadiga

- O limite de fadiga (σ_F) \rightarrow *safe-life* \rightarrow vida útil
- O limiar de propagação de trinca (ΔK_{th}) \rightarrow *damage tolerance* \rightarrow vida residual

U. Zerbst *et al.* "About the fatigue crack propagation threshold of metals as a design criterion – A review" *Eng. Frac. Mech* **153** (2016) 190 – 243.

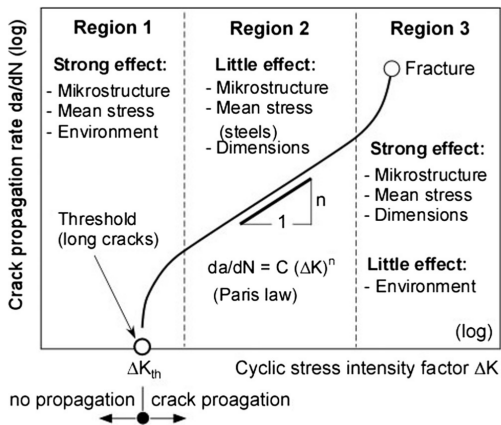
O limite de fadiga

- Visão tradicional:
amplitude de tensão
abaixo da qual
nenhuma trinca, ou ao
menos, nenhuma trinca
perigosa, se formaria
- Recentemente:
amplitude de tensão
abaixo da qual trincas
mesmo formadas não
se propagam (*arrested*)



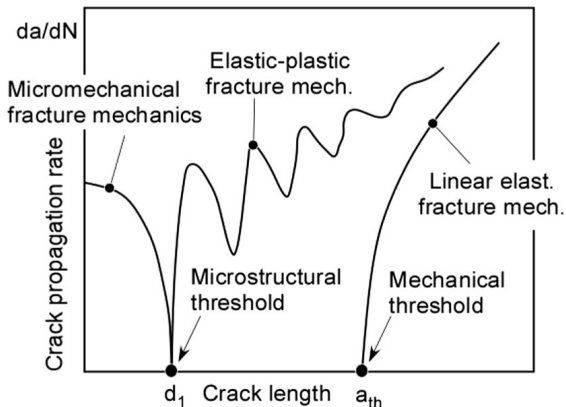
U. Zerbst *et al.* "About the fatigue crack propagation threshold of metals as a design criterion – A review" *Eng. Frac. Mech* **153** (2016) 190 – 243.

O limiar de propagação



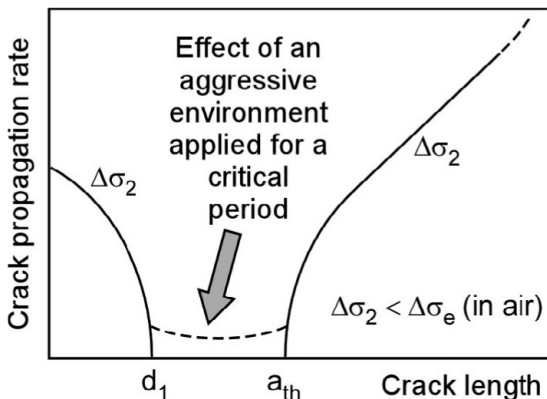
U. Zerbst *et al.* "About the fatigue crack propagation threshold of metals as a design criterion – A review" *Eng. Frac. Mech* **153** (2016) 190 – 243.

O limiar de propagação



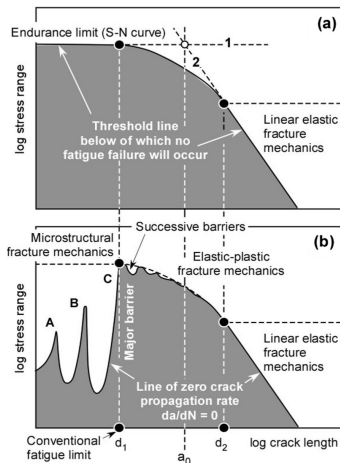
U. Zerbst *et al.* "About the fatigue crack propagation threshold of metals as a design criterion – A review" *Eng. Frac. Mech* **153** (2016) 190 – 243.

O limiar de propagação



U. Zerbst *et al.* "About the fatigue crack propagation threshold of metals as a design criterion – A review" *Eng. Frac. Mech* **153** (2016) 190 – 243.

Diagrama de Kitagawa - Takahashi



O diagrama combina os dois limiares de fadiga.

- (a) Diagrama tradicional
- (b) Diagrama modificado para incluir efeito de trincas curtas

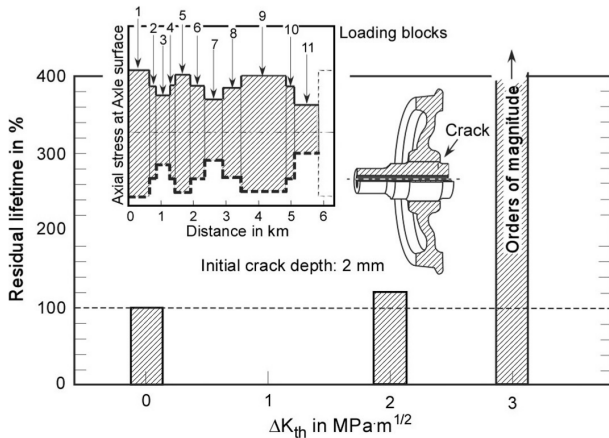
O trecho representando em (1) se refere ao limite de fadiga tradicional, a linha marcada como (2) é o regina da MFLE (ΔK_{th}), a região intermediária é ajustada com a formula

$$\frac{\Delta\sigma_{th}}{\Delta\sigma_f} = \sqrt{\frac{a_0}{a + a_0}}$$

Onde a_0 é um parâmetro de ajuste.

U. Zerbst *et al.* "About the fatigue crack propagation threshold of metals as a design criterion – A review" *Eng. Frac. Mech* **153** (2016) 190 – 243.

A importância da determinação correta do limiar



U. Zerbst *et al.* "About the fatigue crack propagation threshold of metals as a design criterion – A review" *Eng. Frac. Mech* **153** (2016) 190 – 243.

Requisitos para uso da mecânica da fratura

A aplicação da mecânica da fratura à propagação de trincas em juntas soldadas requer:

- Uma definição adequada do tamanho de trinca inicial
- Um tratamento adequado das trincas curtas
- Um tratamento adequado para a nucleação e propagação de múltiplas trincas

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Etapas na propagação de uma trinca de fadiga

Obs.: Definição do Zerbst (BAM).

- (i) iniciação da trinca (normalmente uma fase muito curta)
- (ii) trincas curtas microestruturais (trincas com as dimensões dos entes microestruturais, ex. tamanho de grão)
- (iii) trincas curtas físicas ou mecânicas (a distinção é não ter estabelecido completamente o fechamento, ou não poder ser descrita por um parâmetro com ΔK)
- (iv) Trincas longas

O número total de trincas decresce indo de (i) a (iv).

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Tratamento de trincas curtas mecânicas

- Trinca curta mecânica → tamanho da ordem da zona plástica na sua ponta
- Normalmente é a fase que domina a vida em fadiga do componente
- Não pode ser descrita por mecânica da fratura linear elástica
- Uma força motriz elasto-plástica precisa ser fornecida

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Projeto usando o diagrama de prognóstico de falha

FAD

$$K_r = f(L_r)$$

com

$$K_r = \frac{K}{K_{mat}}$$

e

$$K_{mat} = \begin{cases} \left[\frac{JE}{(1-\nu^2)} \right]^{\frac{1}{2}} & \text{J} \\ \left[\frac{m\delta\sigma_e E}{(1-\nu^2)} \right]^{\frac{1}{2}} & \text{CTOD} \end{cases}$$

com $m = 1,5$.

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132 (2014) 200 – 276.

Soluções para $f(L_r)$

Opção SINTAP 1A: materiais que apresentam escoamento descontínuo:

$$f(L_r) = \begin{cases} [1 + 0,5(L_r)^2]^{\frac{1}{2}} & 0 \leq L_r < 1 \\ [\lambda + \frac{1}{2\lambda}]^{\frac{1}{2}} & L_r = 1 \\ f(1) \times (L_r)^{\frac{n-1}{2n}} & 1 < L_r \leq L_r^{max} \end{cases}$$

Dado:

$$\lambda = 1 + \frac{(E\Delta\varepsilon)}{\sigma_e^-}$$

Deformação de Lüders:

$$\Delta\varepsilon = 0,0375 \left(1 - \frac{\sigma_e^-}{1000}\right)$$

Coefficiente de encruamento:

$$n = 0,3 \left(1 - \frac{\sigma_e^-}{\sigma_u}\right)$$

Carga limite para colapso plástico:

$$L_r^{max} = 0,5 \left[\frac{(\sigma_e^- + \sigma_u)}{\sigma_e^-} \right]$$

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Soluções para $f(L_r)$

Opção SINTAP 1B: materiais não que apresentam escoamento descontínuo:

$$f(L_r) = \begin{cases} \left[1 + 0,5(L_r)^2\right]^{\frac{1}{2}} \times [0,3 + 0,7 \times \exp(-\mu L_r^6)] & 0 \leq L_r < 1 \\ \mu = \min\left(0,001 \frac{E}{\sigma_e}; 0,6\right) & \\ f(1) \times (L_r)^{\frac{n-1}{2n}} & 1 \leq L_r \leq L_r^{max} \end{cases}$$

Coefficiente de encruamento:

$$n = 0,3 \left(1 - \frac{\sigma_e}{\sigma_u}\right)$$

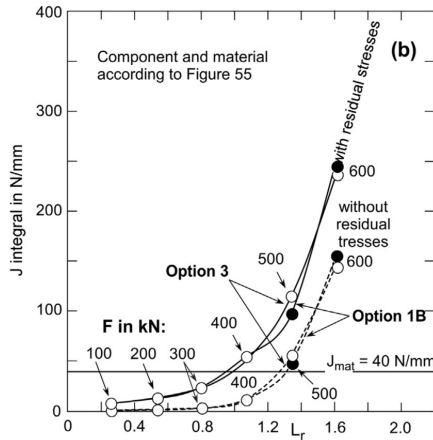
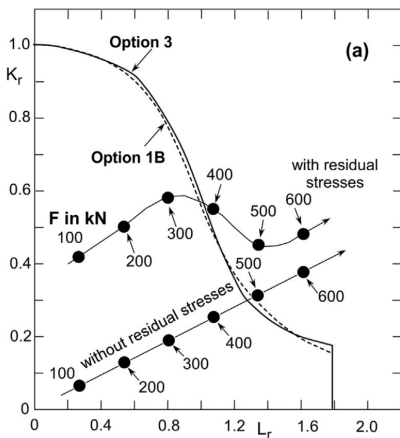
Carga limite para colapso plástico:

$$L_r^{max} = 0,5 \left[\frac{(\sigma_e + \sigma_u)}{\sigma_e} \right]$$

U. Zerbst *et al.* "Review on fracture and crack propagation in weldments — a fracture mechanics perspective" *Eng. Frac. Mech.*

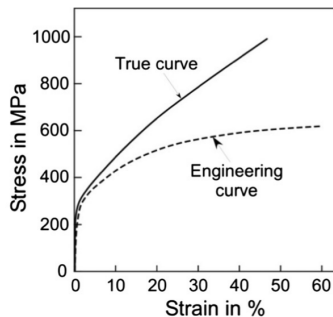
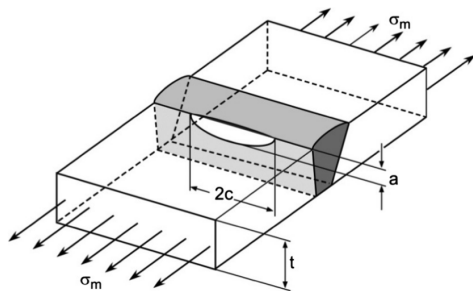
132 (2014) 200 – 276.

Correção para tensões residuais



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Correção para tensões residuais



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132 (2014) 200 – 276.

Tratamento analítico de Zerbst

Trincas curtas mecânicas

- Força motriz para propagação

$$\Delta J = \frac{\Delta K^2}{E'} \times [f(\Delta L_r)]^{-2}$$

- Parâmetro de carga ($\Delta\sigma_{ap}$ é a amplitude de tensão remota aplicada)


$$\Delta L_r = \frac{\Delta\sigma_{ap}}{2\sigma_e}$$

- A função de correção por plasticidade ($\Delta\varepsilon_r$ e $\Delta\sigma_r$ são a amplitude de deformação e a amplitude de tensão de referência)

$$f(\Delta L_r) = \left[\frac{E\Delta\varepsilon_r}{\Delta\sigma_r} + \frac{1}{2} \frac{(\Delta L_r)^2 \Delta\sigma_r}{E\Delta\varepsilon_r} \right]^{-\frac{1}{2}}$$

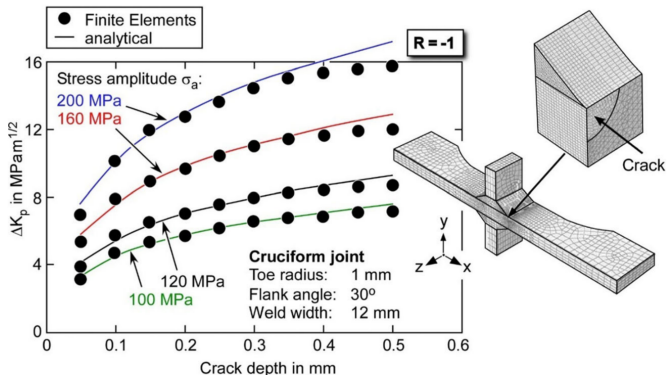
- Fator de intensificação cíclico corrigido por plasticidade

$$\Delta K_p = \sqrt{\Delta J \times E'}$$

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Tratamento analítico de Zerbst

Validação por Elementos Finitos

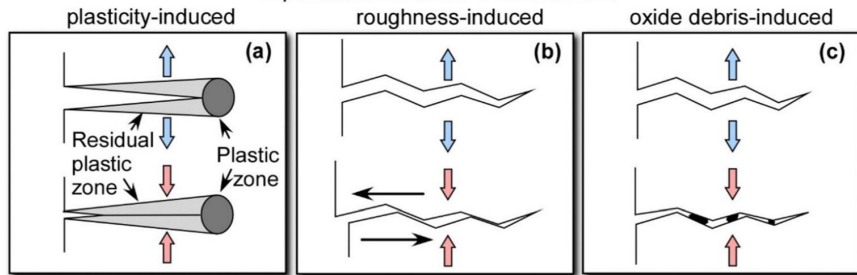


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Trincas curtas físicas

Fechamento de trinca

Important crack closure mechanisms



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Parâmetro de fechamento

- Parâmetro de fechamento

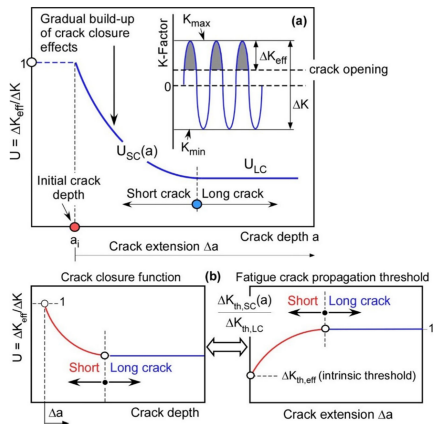
$$U = \frac{\Delta K_{\text{eff}}}{\Delta K}$$

- Conexão com a curva R cíclica

$$\frac{1 - U_{SC}(a)}{1 - U_{LC}} = \frac{\Delta K_{th,SC}(a) - \Delta K_{th,ef}}{\Delta K_{th,LC} - \Delta K_{th,ef}}$$

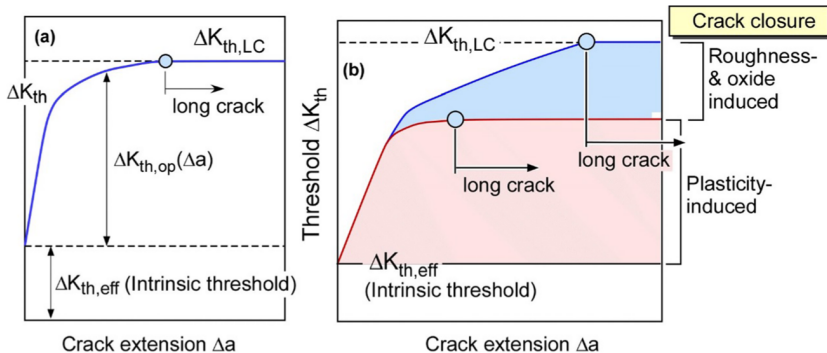
- Limiar intrínseco ($\Delta K_{th,ef}$)

$$\Delta K_{th} = \Delta K_{th,ef} + \Delta K_{th,op}$$



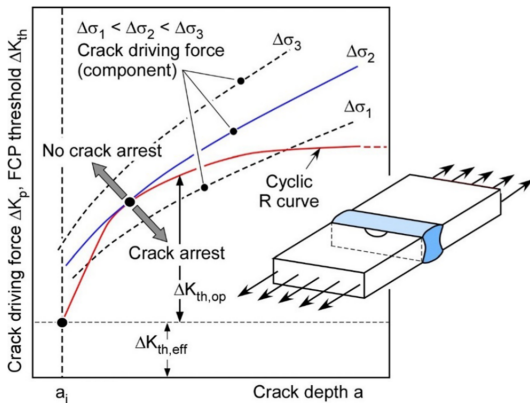
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Curva R cíclica



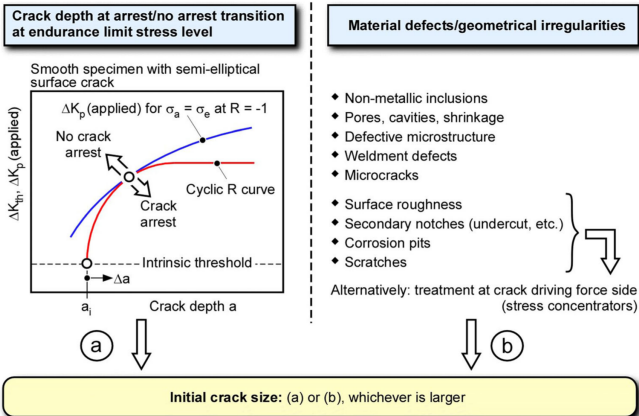
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Curva R cíclica



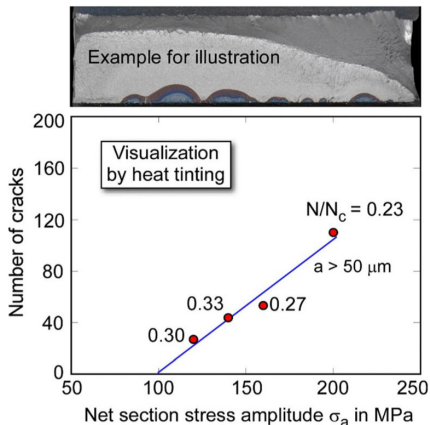
U. Zerbst "Application of fracture mechanics to welds with crack origin at the weld toe — a review. Part 2: welding residual stresses. Residual and total life assessment" *Welding in the World* **64** (2020) 151 – 169.

Determinação do tamanho inicial da trinca



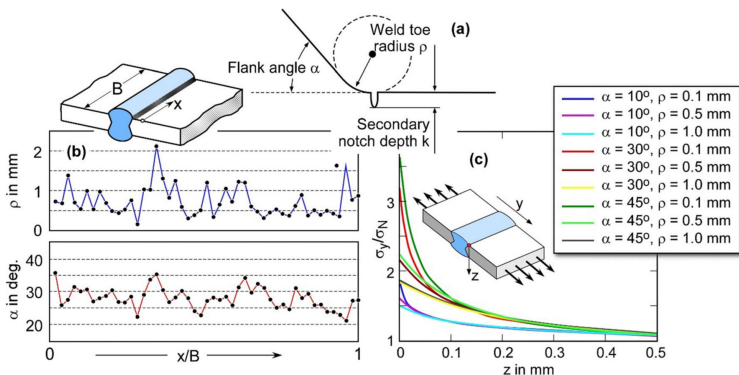
U. Zerbst "Application of fracture mechanics to welds with crack origin at the weld toe — a review. Part 2: welding residual stresses. Residual and total life assessment" *Welding in the World* **64** (2020) 151 – 169.

Múltiplas trincas na margem do cordão



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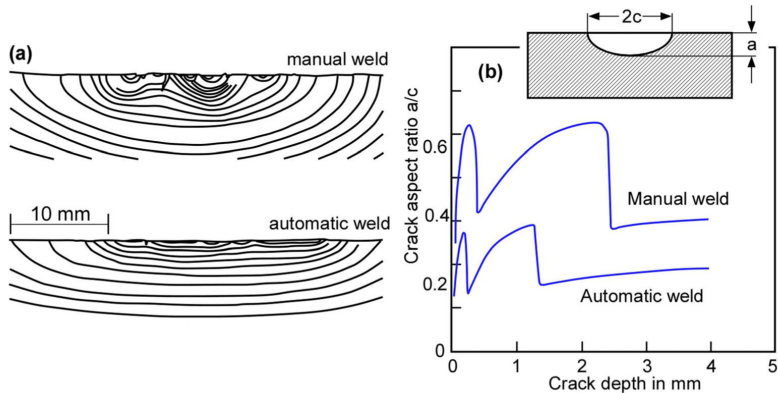
Origem das múltiplas trincas



(a) Parâmetros, (b) variação ao longo de uma margem, (c) concentração de tensão em função dos parâmetros.

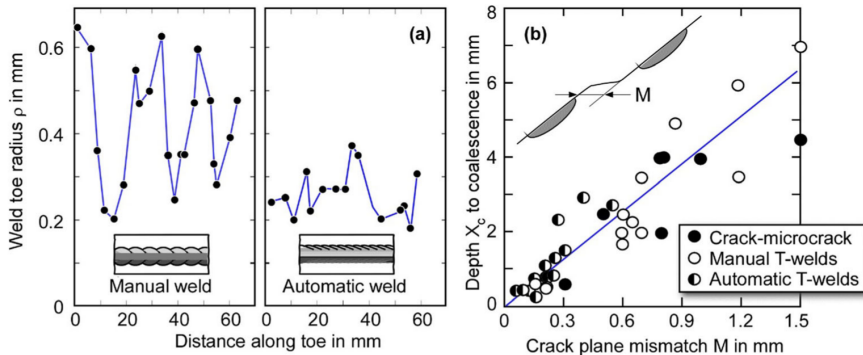
U. Zerbst "Application of fracture mechanics to welds with crack origin at the weld toe — a review. Part 2: welding residual stresses. Residual and total life assessment" *Welding in the World* **64** (2020) 151 – 169.

Consequências



U. Zerbst "Application of fracture mechanics to welds with crack origin at the weld toe — a review. Part 2: welding residual stresses. Residual and total life assessment" *Welding in the World* **64** (2020) 151 – 169.

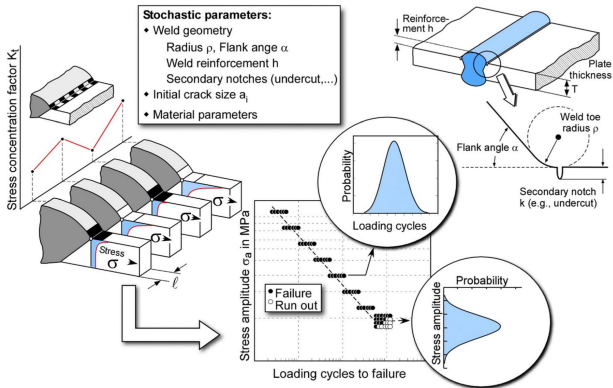
Consequências



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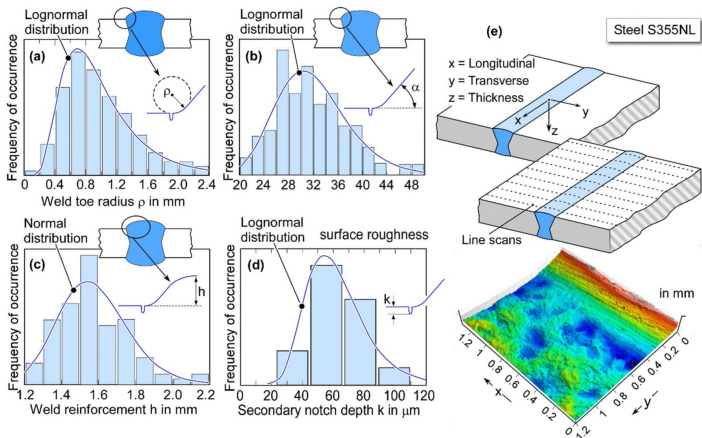
Modelo IBESS

Integrale Bruchmechanische Ermittlung der Schwingfestigkeit von Schweißverbindungen



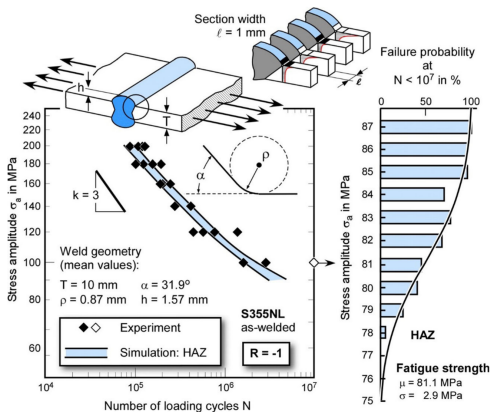
U. Zerbst "Application of fracture mechanics to welds with crack origin at the weld toe — a review. Part 2: welding residual stresses. Residual and total life assessment" *Welding in the World* **64** (2020) 151 – 169.

Natureza estocástica do problema



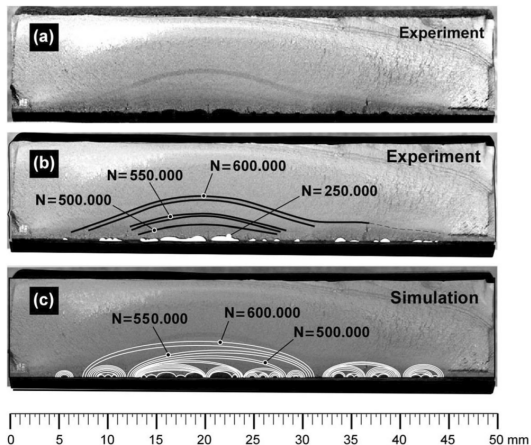
U. Zerbst "Application of fracture mechanics to welds with crack origin at the weld toe — a review. Part 2: welding residual stresses. Residual and total life assessment" *Welding in the World* **64** (2020) 151 – 169.

Resultados do modelo IBESS



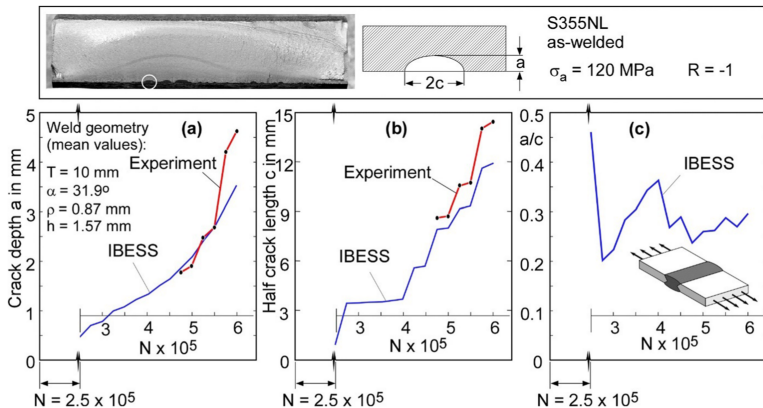
U. Zerbst "Application of fracture mechanics to welds with crack origin at the weld toe — a review. Part 2: welding residual stresses. Residual and total life assessment" *Welding in the World* **64** (2020) 151 – 169.

Resultados do modelo IBESS



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Resultados do modelo IBESS



U. Zerbst "Application of fracture mechanics to welds with crack origin at the weld toe — a review. Part 2: welding residual stresses. Residual and total life assessment" *Welding in the World* **64** (2020) 151 – 169.