

FRATURA DOS METAIS

AULA V: FRATURA EM ELEMENTOS TRINCADOS

MECÂNICA DA FRATURA LINEAR ELÁSTICA E ELASTOPLÁSTICA

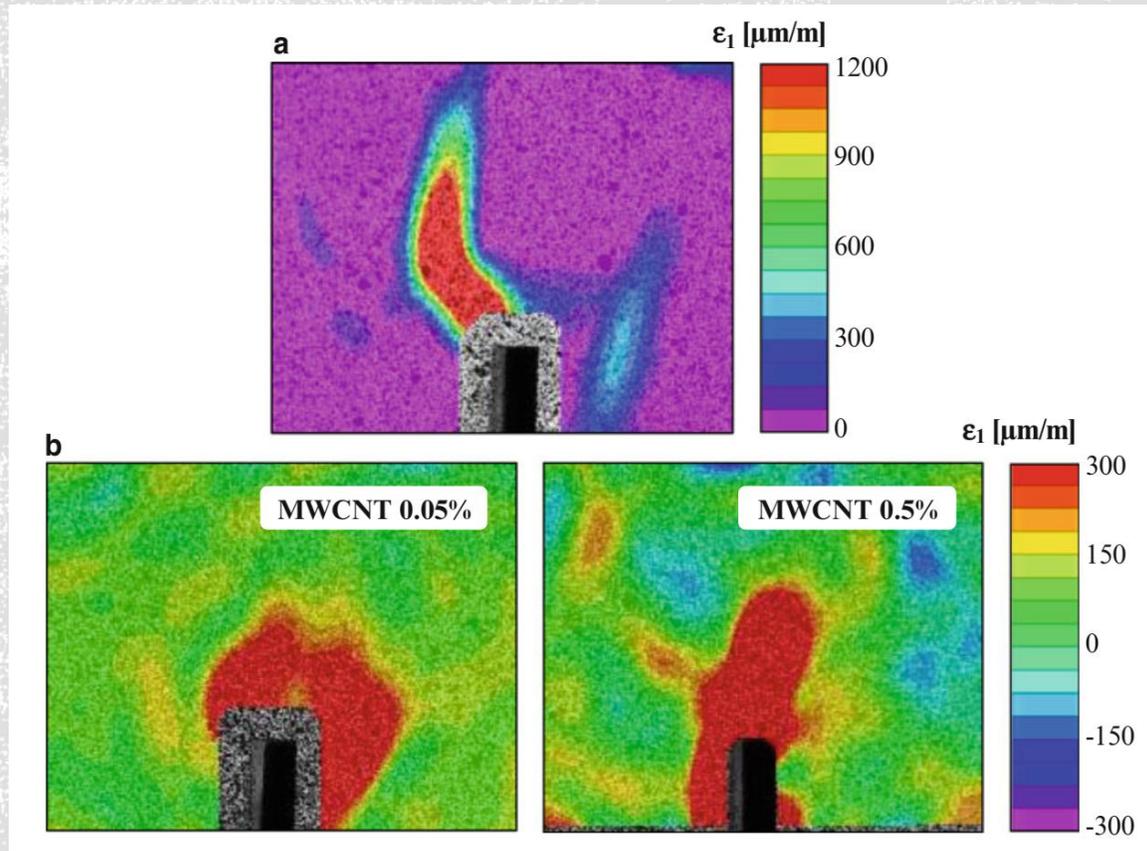


Fig. 10.5 Representative DIC principal tensile strain map in cement paste notched beam specimens in post-peak load stage: (a) unreinforced (control) beam; and (b) MWCNT reinforced beams



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NESTA AULA

Fratura em elementos trincados:

- Discussão preliminar
- Conceitos matemáticos
- Aplicação do fator K no desenho e análises
- Tópicos adicionais na aplicação do fator K
- Tenacidade à fratura – valores e tendências
- Tamanho da zona plástica, e limitações da plasticidade no LEFM (*Linear Elastic Fracture Mechanics*)
- Ensaio de tenacidade à fratura
- Mecânica da fratura além da elasticidade linear



OCORRÊNCIA DE TRINCAS

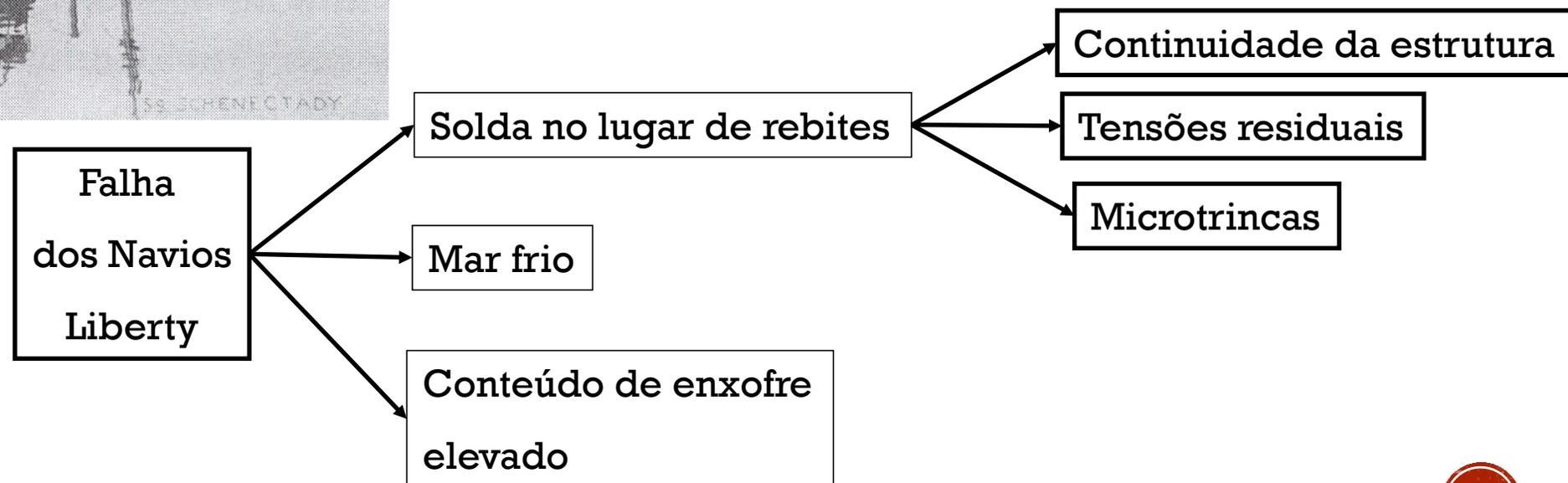
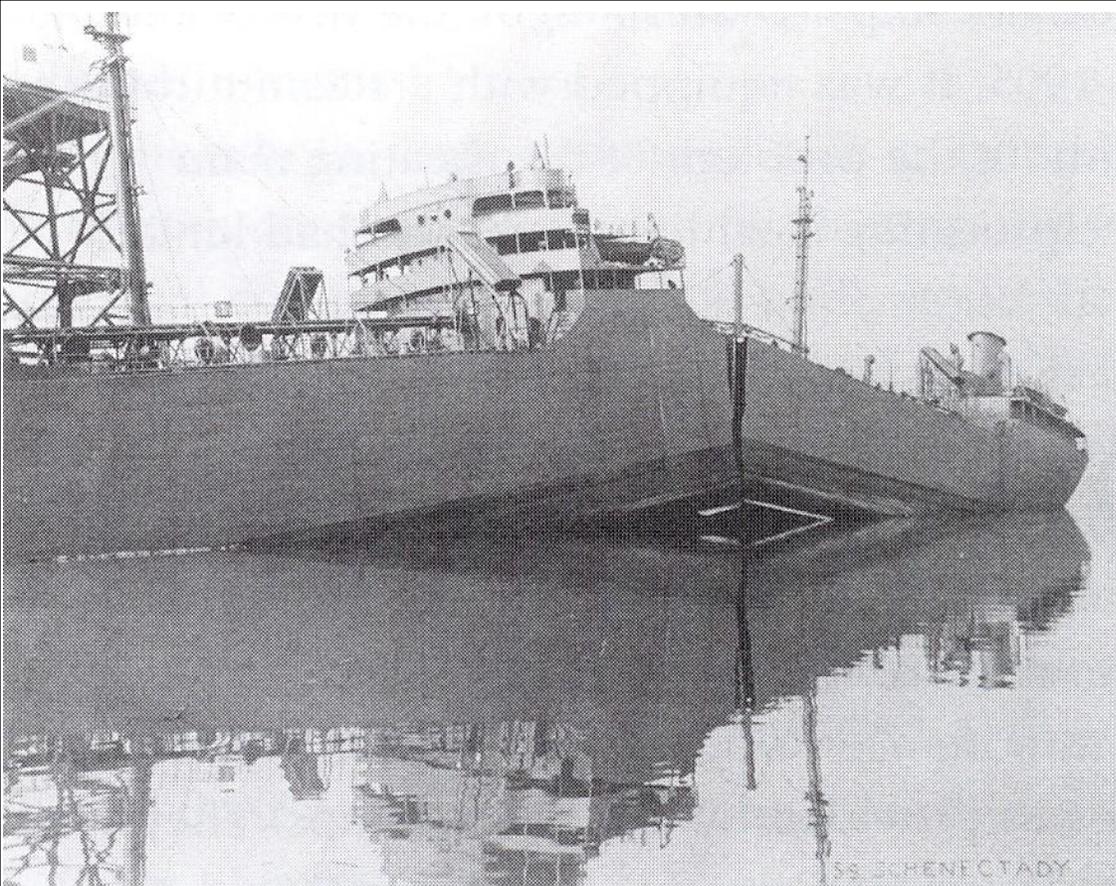
Primeira ocorrência de falhas:

- Em estruturas de ferro e aço durante a Revolução Industrial (primeiro componente estrutural projetado para suportar tensões trativa; novos projetos estruturais)
- Solução: usar fatores de segurança incrivelmente altos (10 ou mais).

O efeito da amostragem (volume) observado por Leonardo Da Vinci da uma explicação qualitativa para a causa de tais fratura (base da teoria estatística de Weibull para fratura).

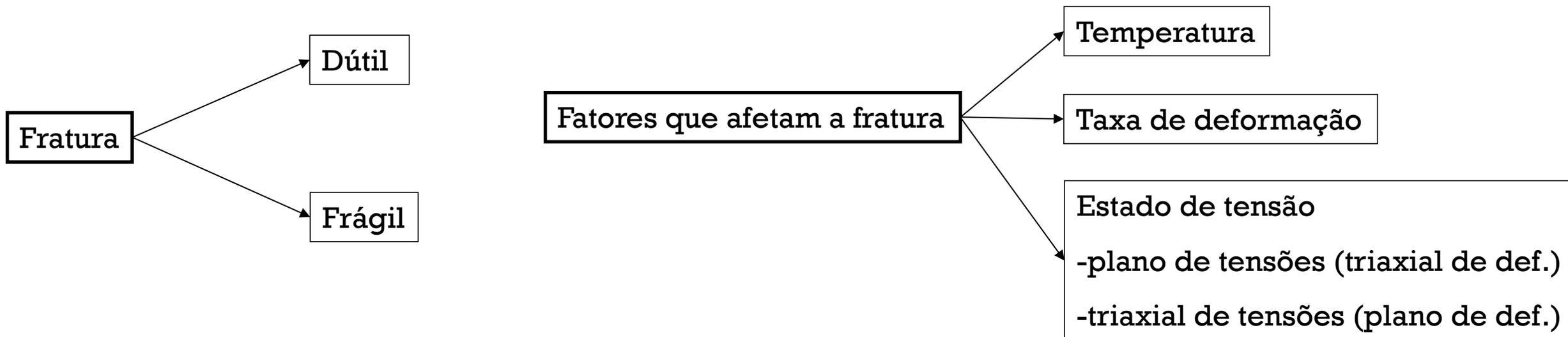
FIGURE 1.6 The Tower Bridge in London, completed in 1894. Note the modern beam design, made possible by the availability of steel support girders.

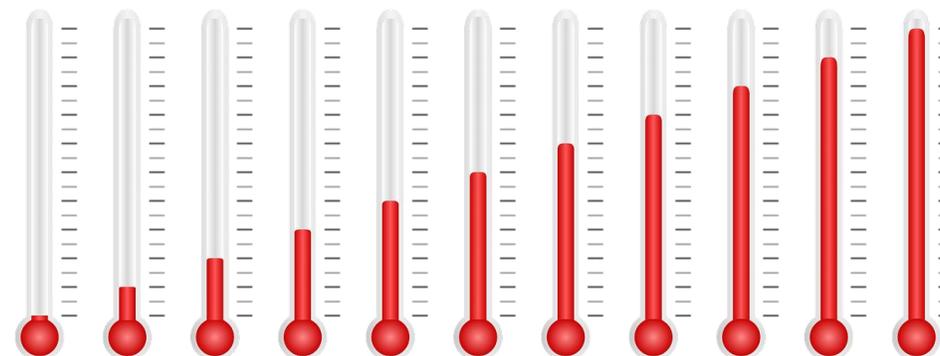
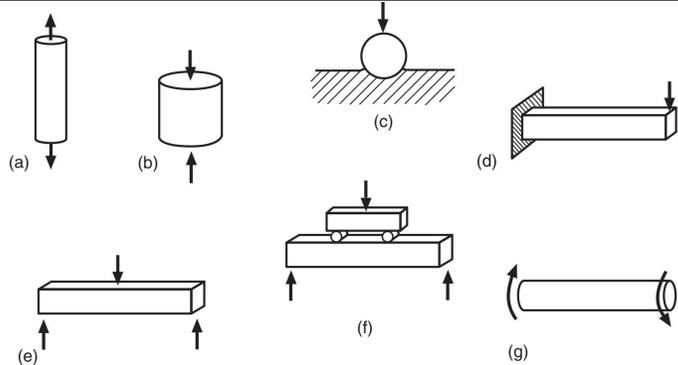




FRATURA

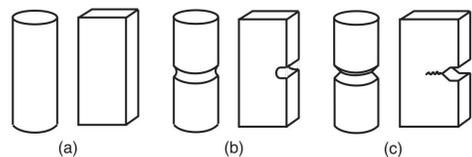
“É a separação ou fragmentação de um corpo sólido em duas ou mais partes sob ação de uma tensão devido ao início e propagação de uma trinca”





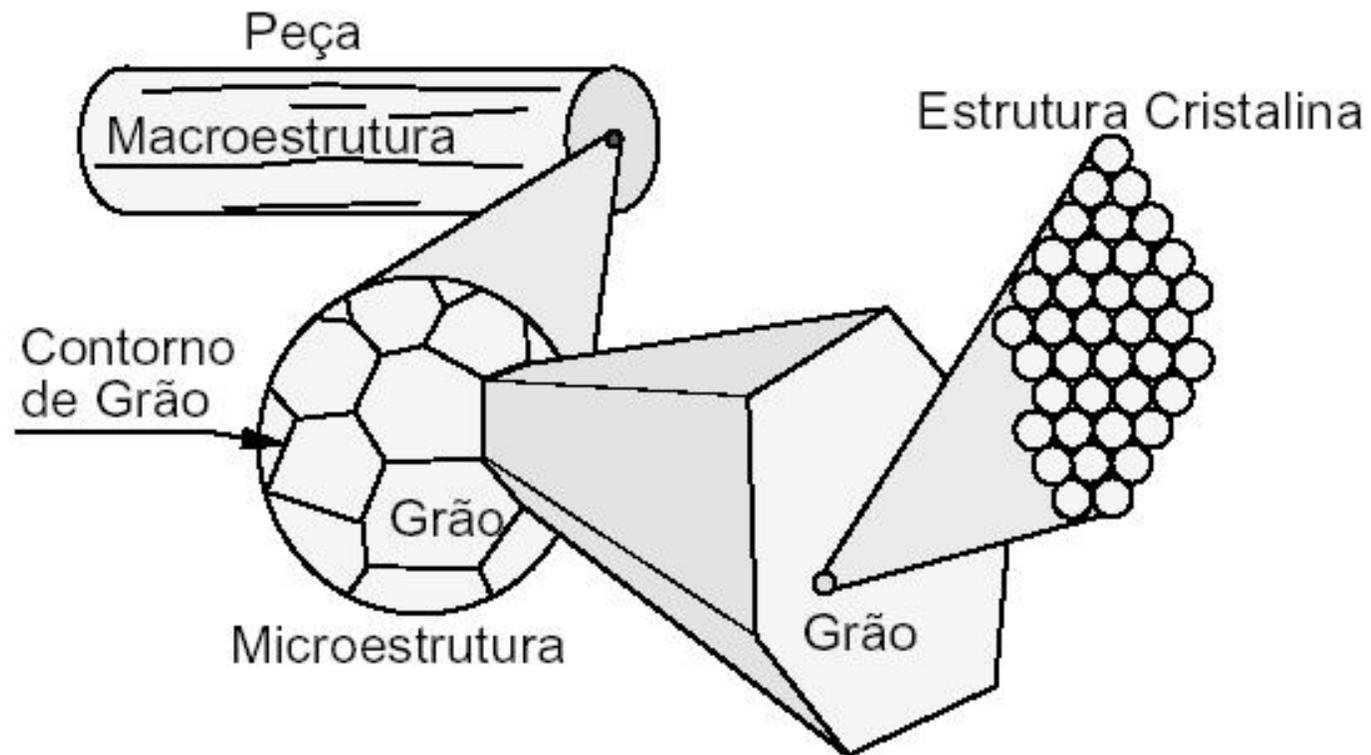
Condições de Fratura

- Tração
- Torção
- Fadiga
- Fluência
- Fratura frágil em Temperaturas Baixas
- Fragilização no Trat. Térm.
- Fragilização por Hidrogênio

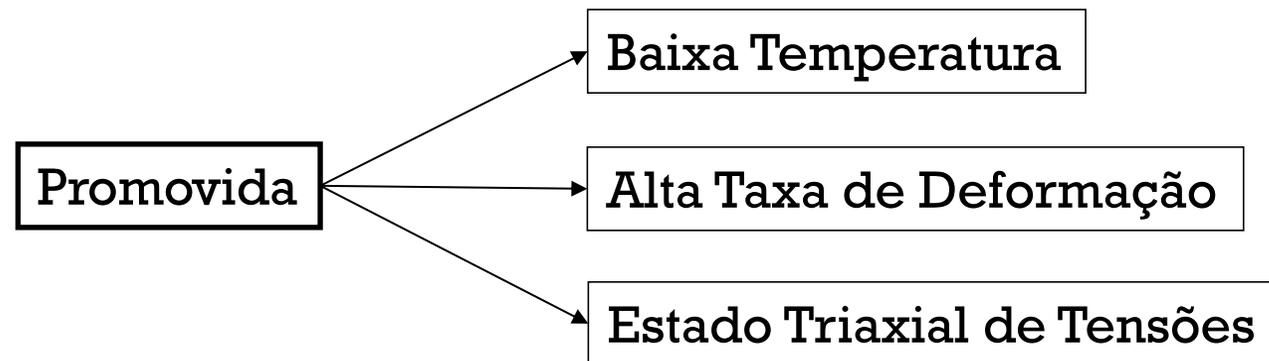
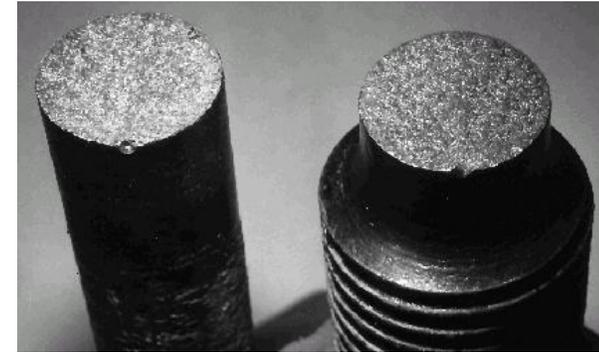
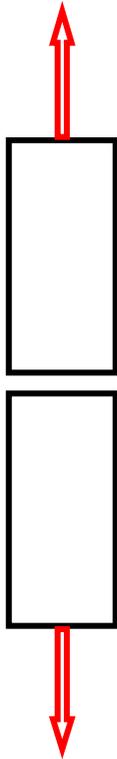


COMPORTAMENTO DESCRITO	TERMOS USADO	
Modo cristalográfico	Cisalhamento	<i>Clivagem</i>
Aparência da superfície de fratura	Fibrosa	<i>Granular / brilhante</i>
Deformação até fratura	Dútil	<i>Frágil</i>
Caminho	Transgranular	<i>Intergranular</i>

FRATURA: ASPECTO MACRO E MICROGRÁFICO



FRATURA FRÁGIL : ASPECTO MACROGRÁFICO



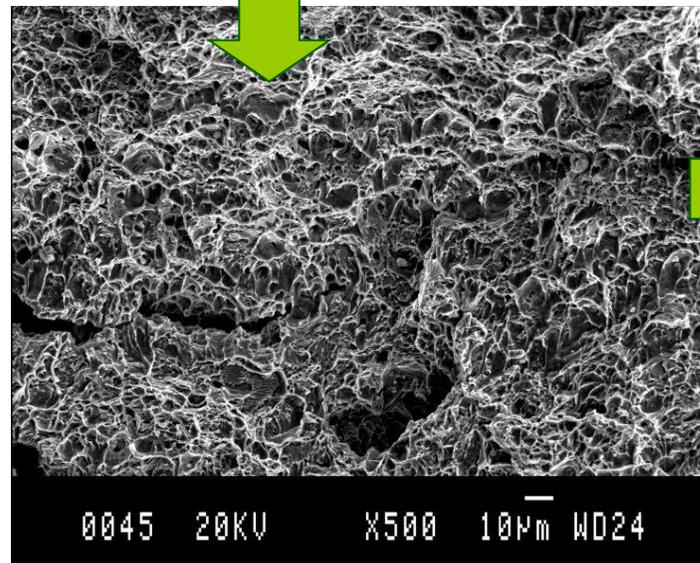
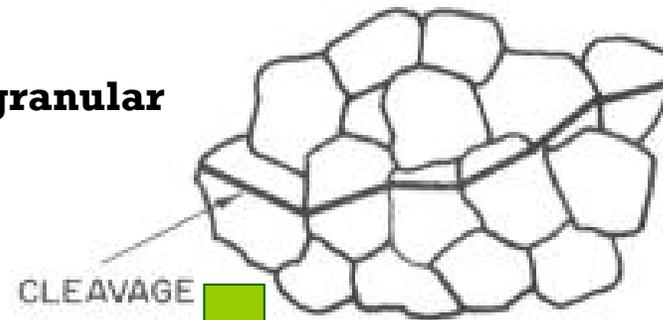
FRATURA FRÁGIL : ASPECTO MACROGRÁFICO

- É caracterizada por uma ou mais trincas diretas na estrutura.
- Pouca ou nenhuma deformação.
- A trinca se propaga pelo caminho de menor resistência.
- Observada em monocristais e materiais policristalinos.
- Observada em metais com estrutura CCC e HC mas não em metais CFC*.
- Tem aparência brilhante enquanto a fratura dúctil tem aspecto escuro e acinzentado.
- Aumenta com a diminuição da temperatura, a taxa de deformação e o estado triaxial tensões.

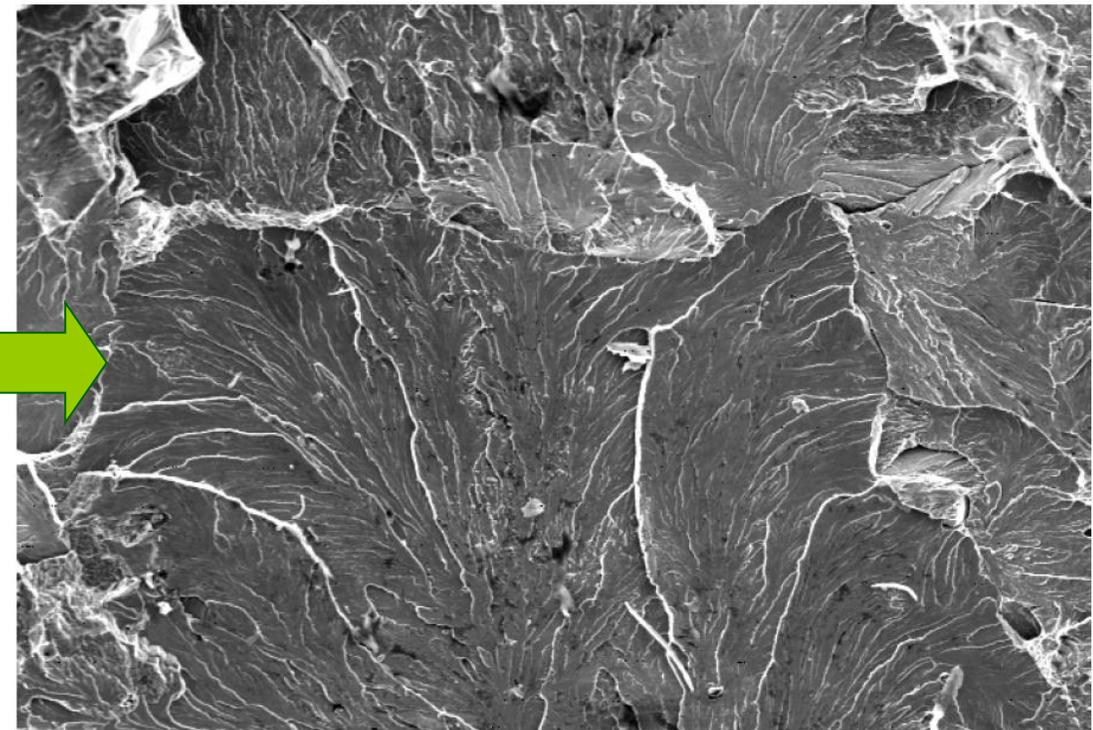
FRATURA FRÁGIL ASPECTO MICROGRÁFICO

- A clivagem ocorre na direção cristalográficas dos planos
- As faces de clivagem aparecem grãos com alta reflexividade que dão um aspecto de fratura brilhante.

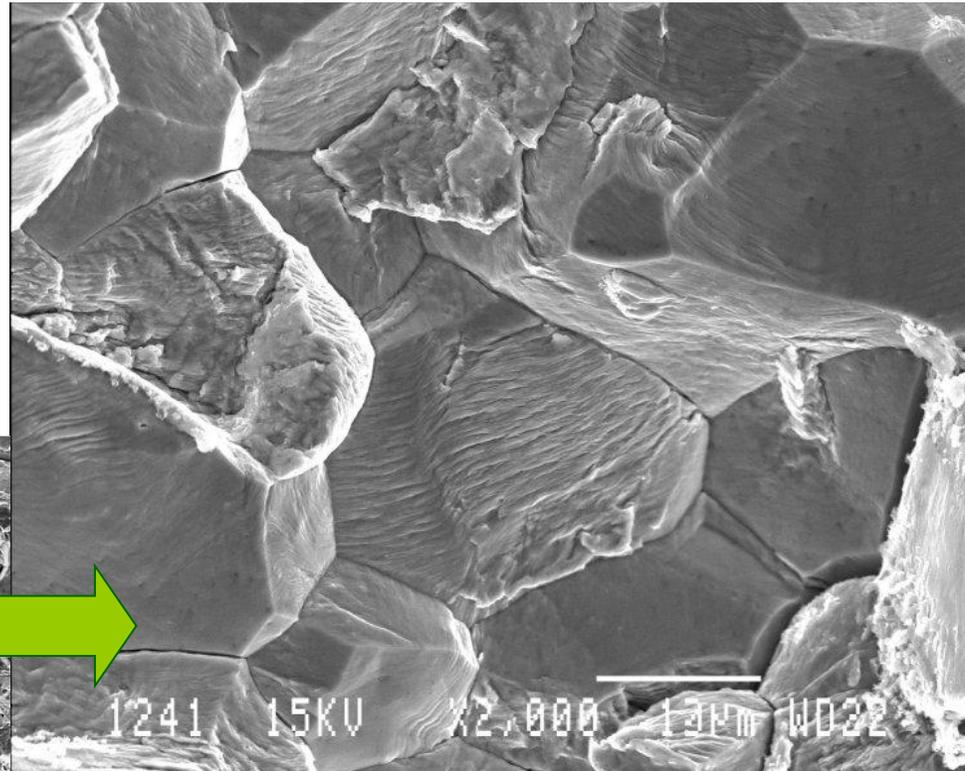
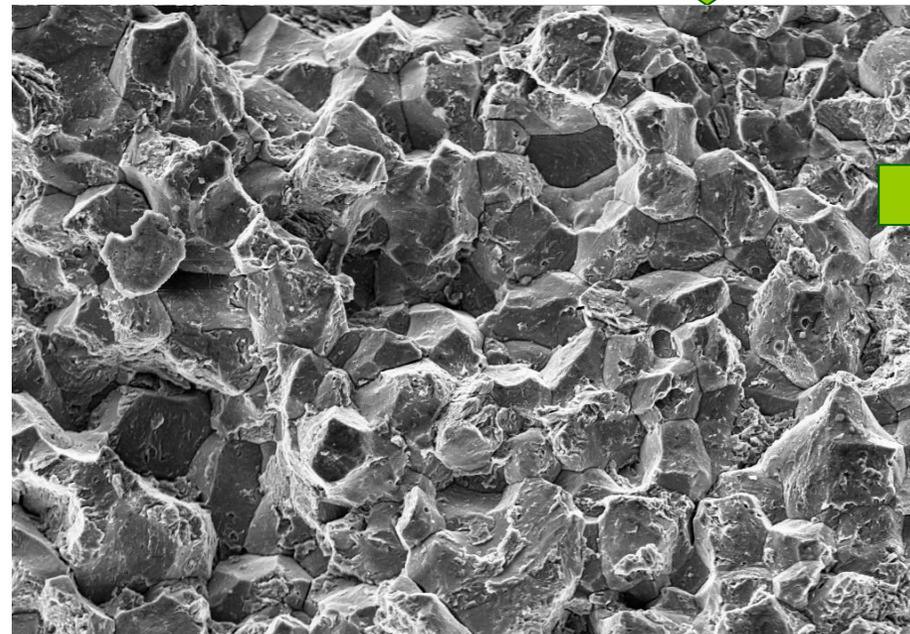
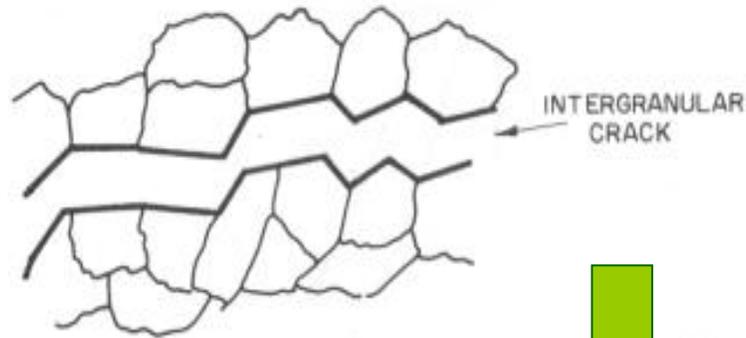
Transgranular



Fratura por Clivagem

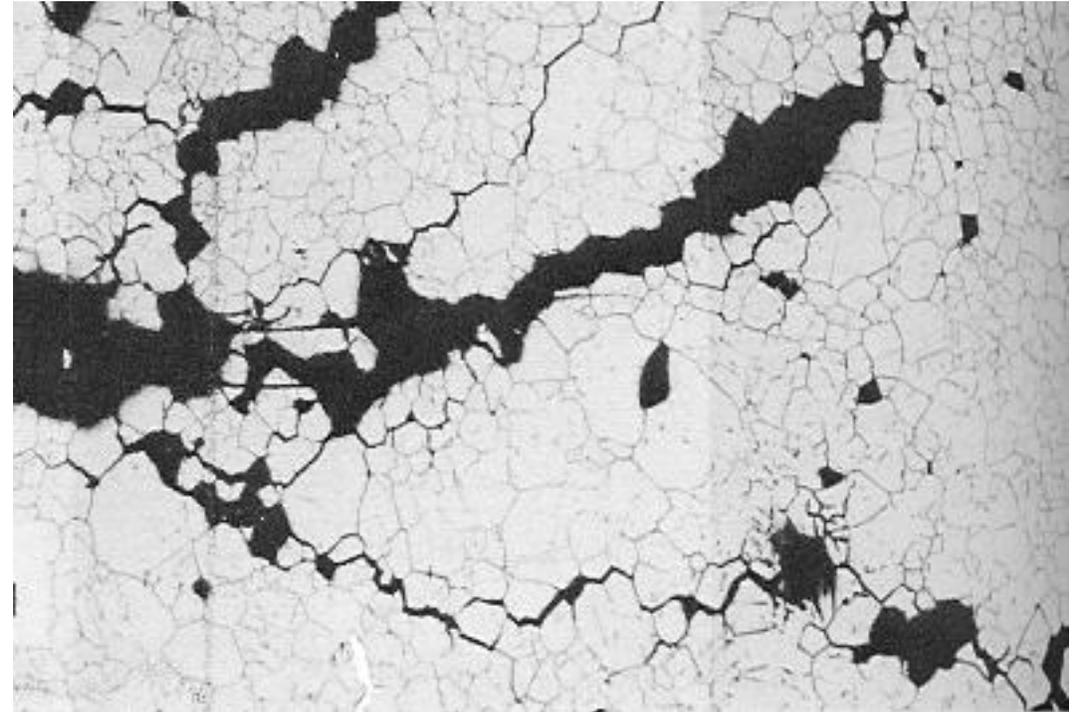


FRATURA INTERGRANULAR É UM MODO DE FRATURA COM BAIXA ENERGIA



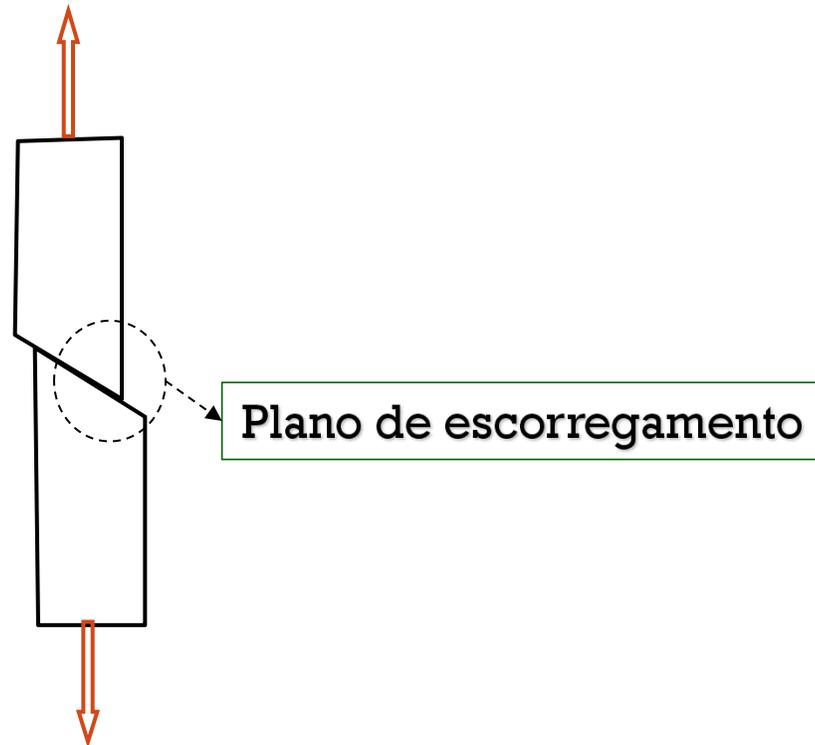


Fratura Intergranular

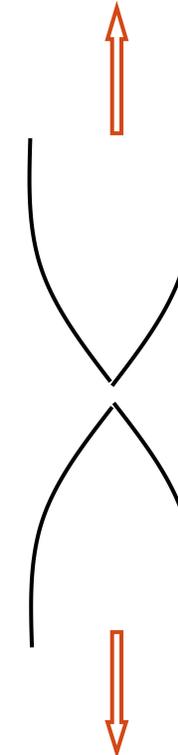


Transgranular

FRATURA DÚCTIL : ASPECTO MACROGRÁFICO

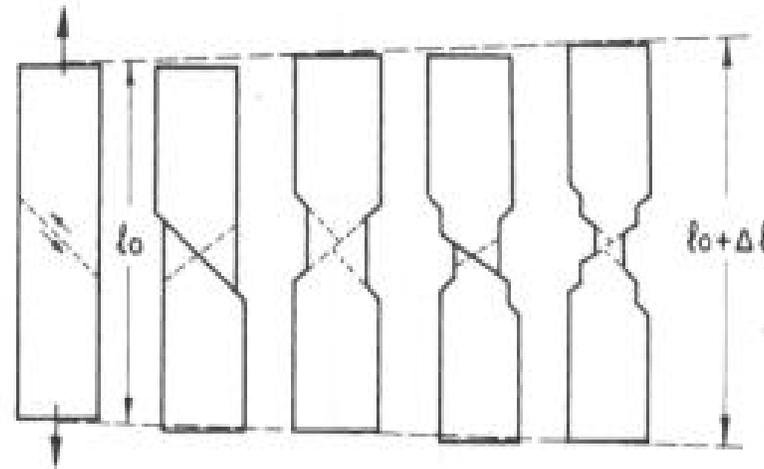


Fratura cisalhante de monocristal dúctil.
Não observada em policristais.



Fratura completamente dúctil em policristais → ruptura
Metais muito dúcteis como ouro e chumbos

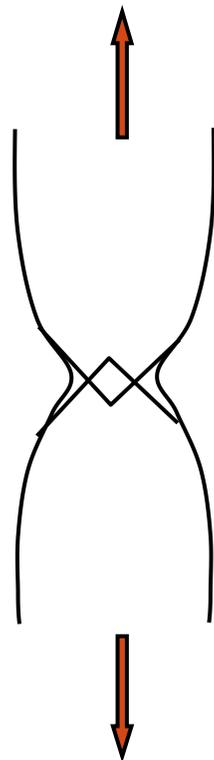
- Considerando um simples cristal, o cobre, um metal dúctil.
- Não há nucleação de trincas e os cristais deformam plasticamente até iniciar a estabilidade plástica, chamada de pescoçamento.
- A deformação é concentrada na região de instabilidade plástica até a separação cristalina ao longo de uma linha ou um ponto.



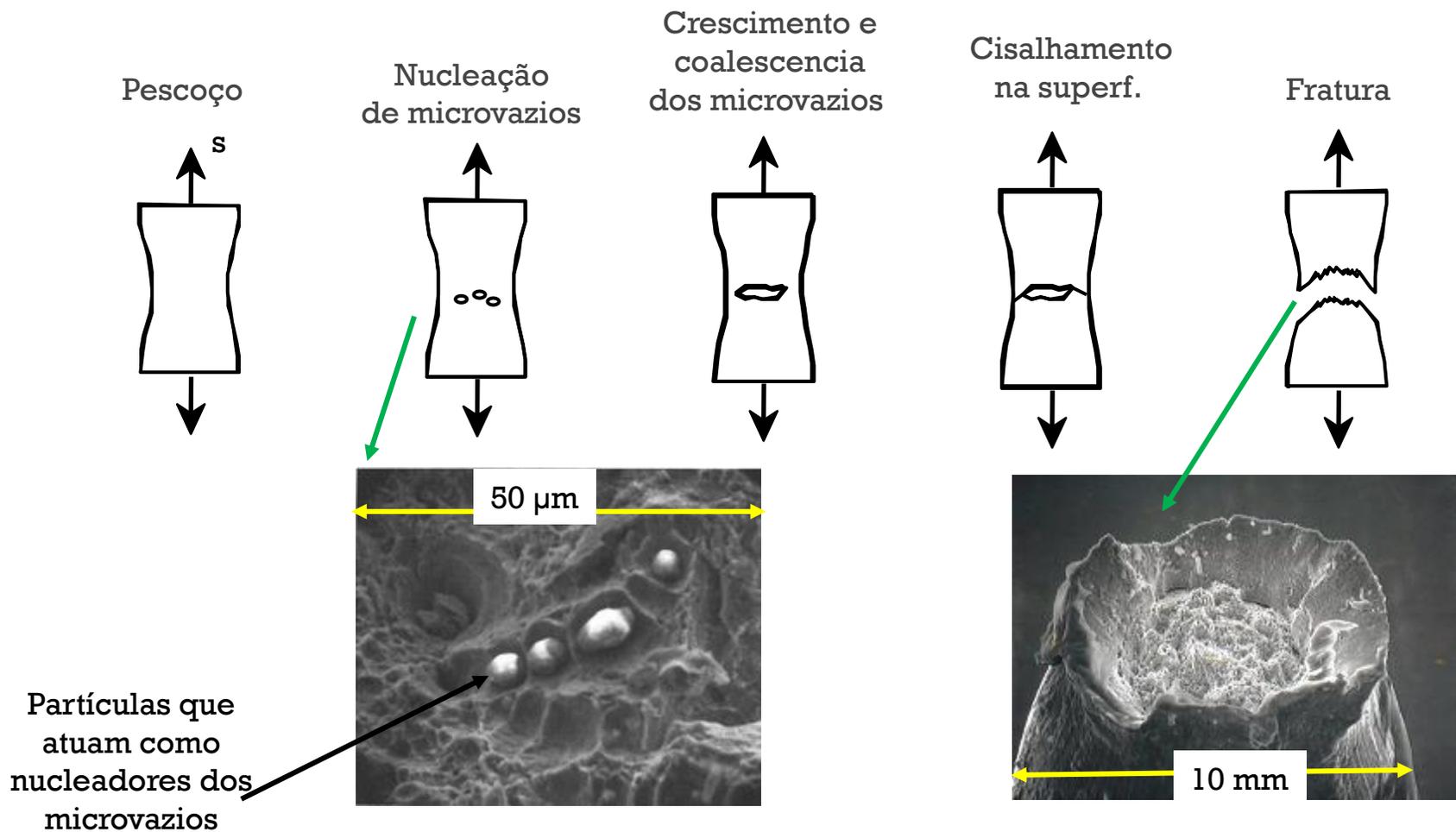
Cisalhamento de um “metal puro” – Ex.: Cobre

FRATURA DÚTIL EM METAIS POLICRISTALINOS

- **Fratura Taça – Cone:** O empescoçamento leva a um estado triaxial de tensões e a trinca nucleia em partículas frágeis (formação de vazios na interface matriz - partícula)
- Aspecto escuro e acinzentado



EVOLUÇÃO DA FALHA



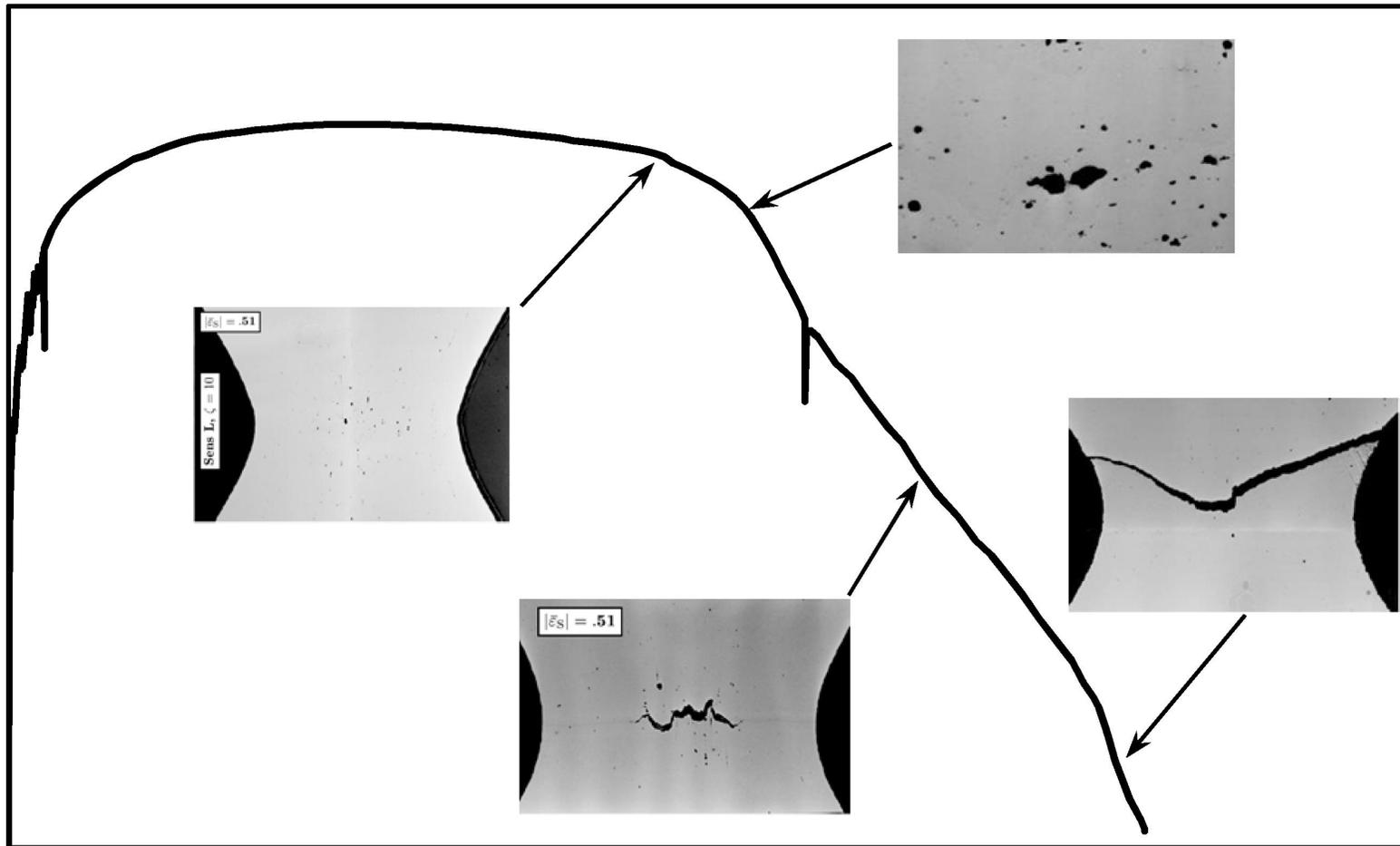
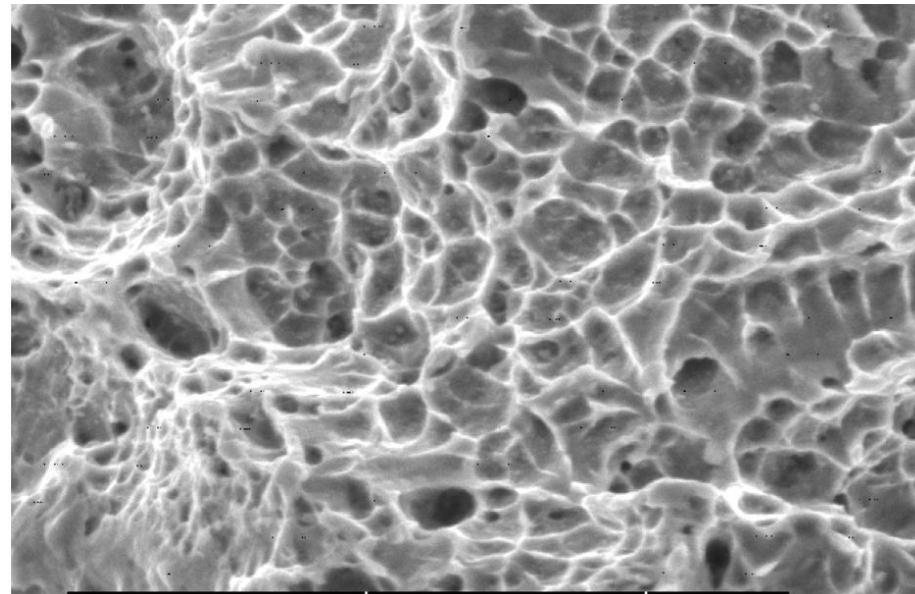


Figure 1. Typical example of micro-cracks coalescence in metals leading to the softening branch and to the final failure of a specimen tested in uniaxial tension (taken from [7,8]).

FRATURA DÚCTIL ASPECTO MICROGRÁFICO

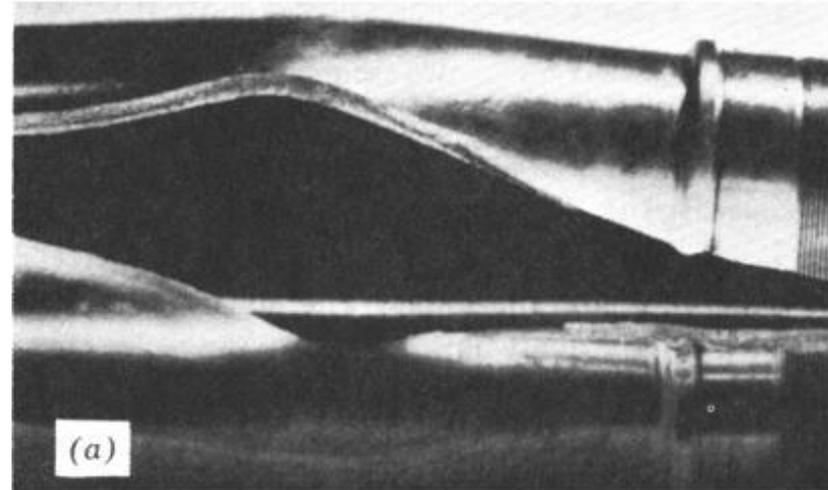


Dimples - Coalescência de microvazios

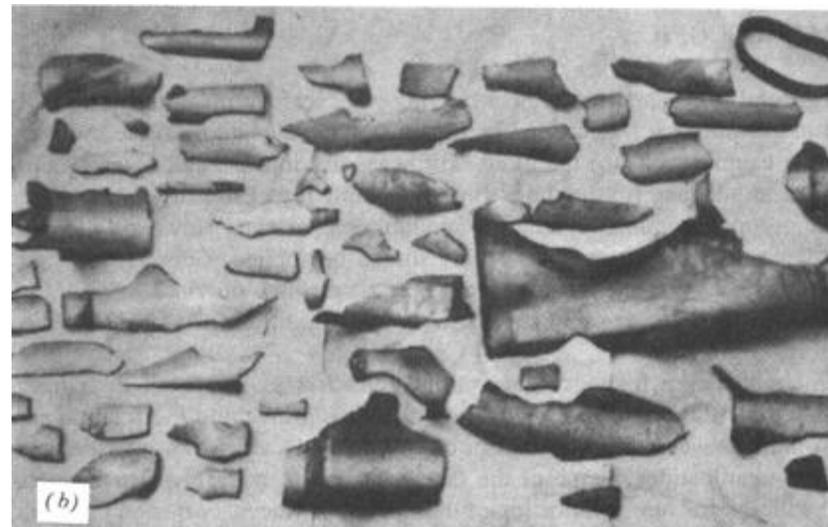


EXEMPLO: FALHA EM UM TUBO

- **Falha Dúctil:**
 - um pedaço
 - grande deformações



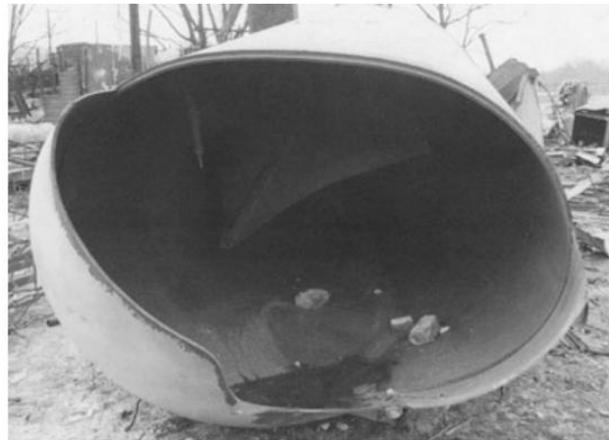
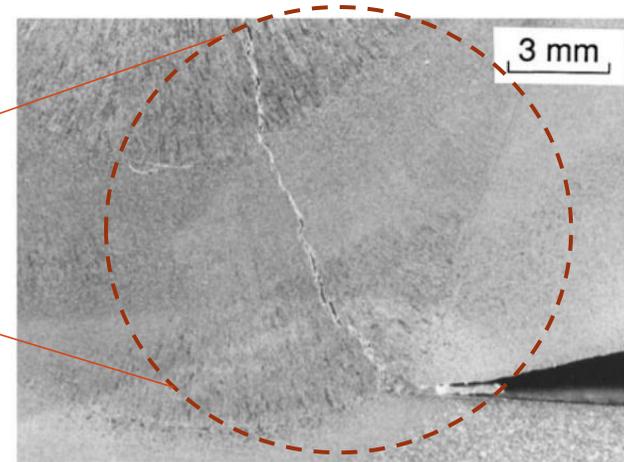
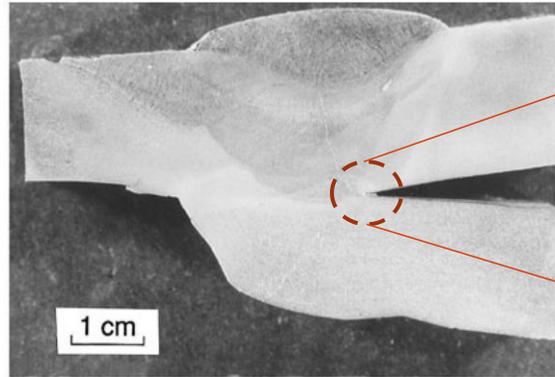
- **Falha Frágil:**
 - vários pedaços
 - pouca deformação



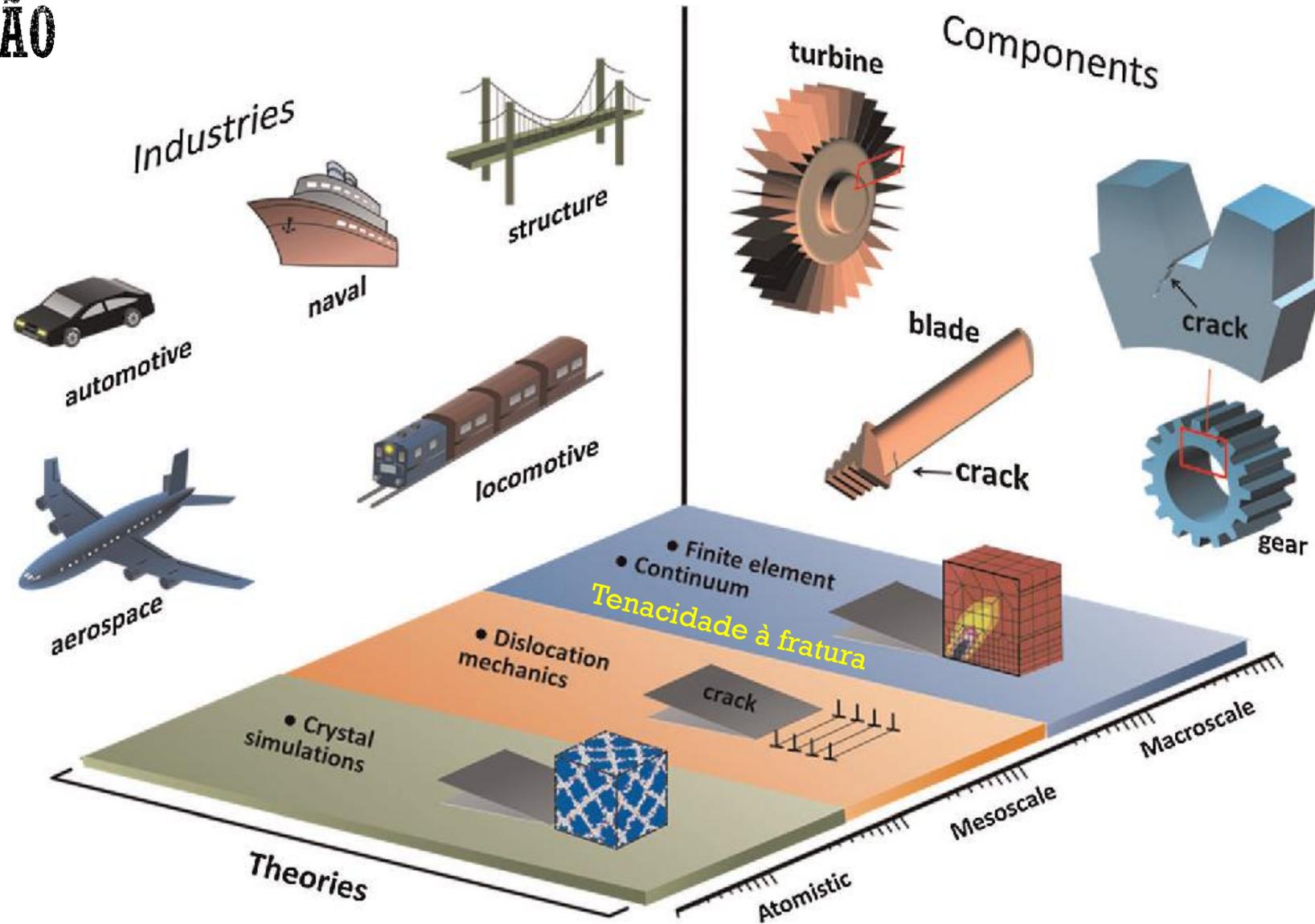
Observe a quantidade de deformação plástica.

Figure 8.1 Photographs from a propane tank truck that exploded due to fracture from initial environmental cracks in welds. Typical initial cracks are shown from a region that did not participate in the final failure. (Photos courtesy of H. S. Pearson, Pearson Testing Labs, Marietta, GA, lower left, upper and lower right, published in [Pearson 86]; copyright c ASTM; reprinted with permission.)

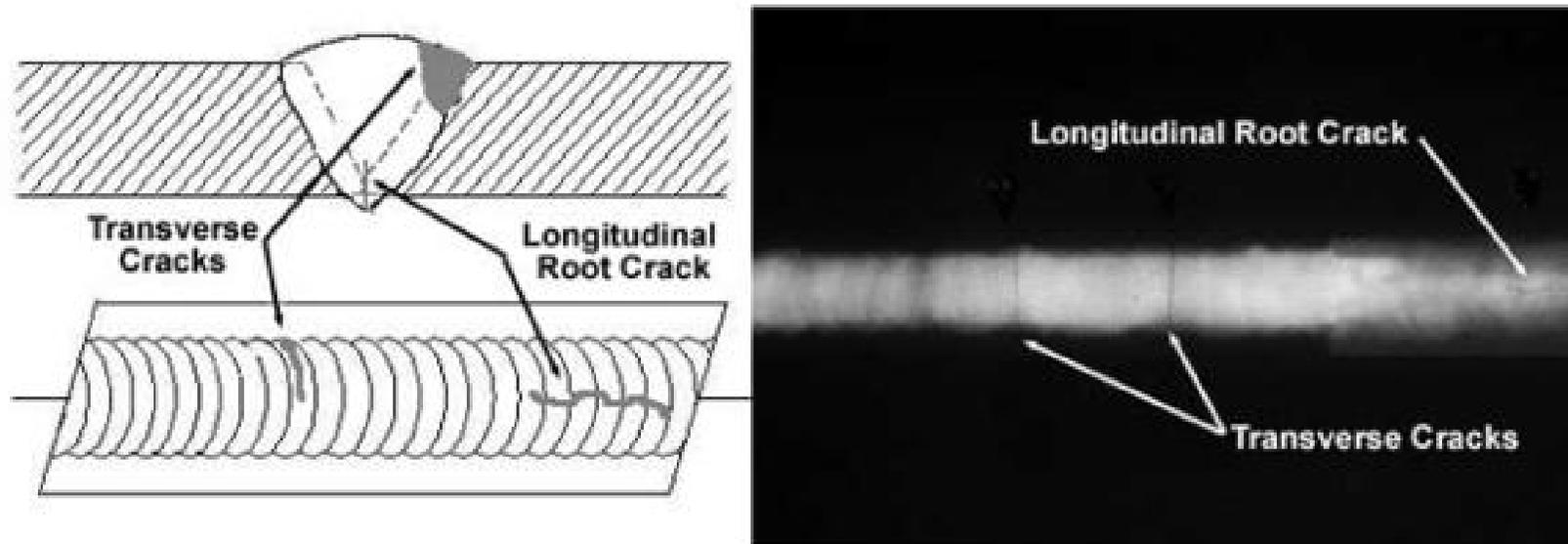
MECÂNICA DA FRATURA



INTRODUÇÃO



- O coeficiente de segurança não leva em conta a falha por fratura frágil ou rápida.
- Entretanto a falha total de componentes e/ou estruturas ocorre devido à presença de **defeitos ou trincas** e em condições de **carregamento bem abaixo do nível especificado no projeto**.



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AVALIAÇÃO DE DEFETOS

X-ray micro-computed tomography (1-CT)

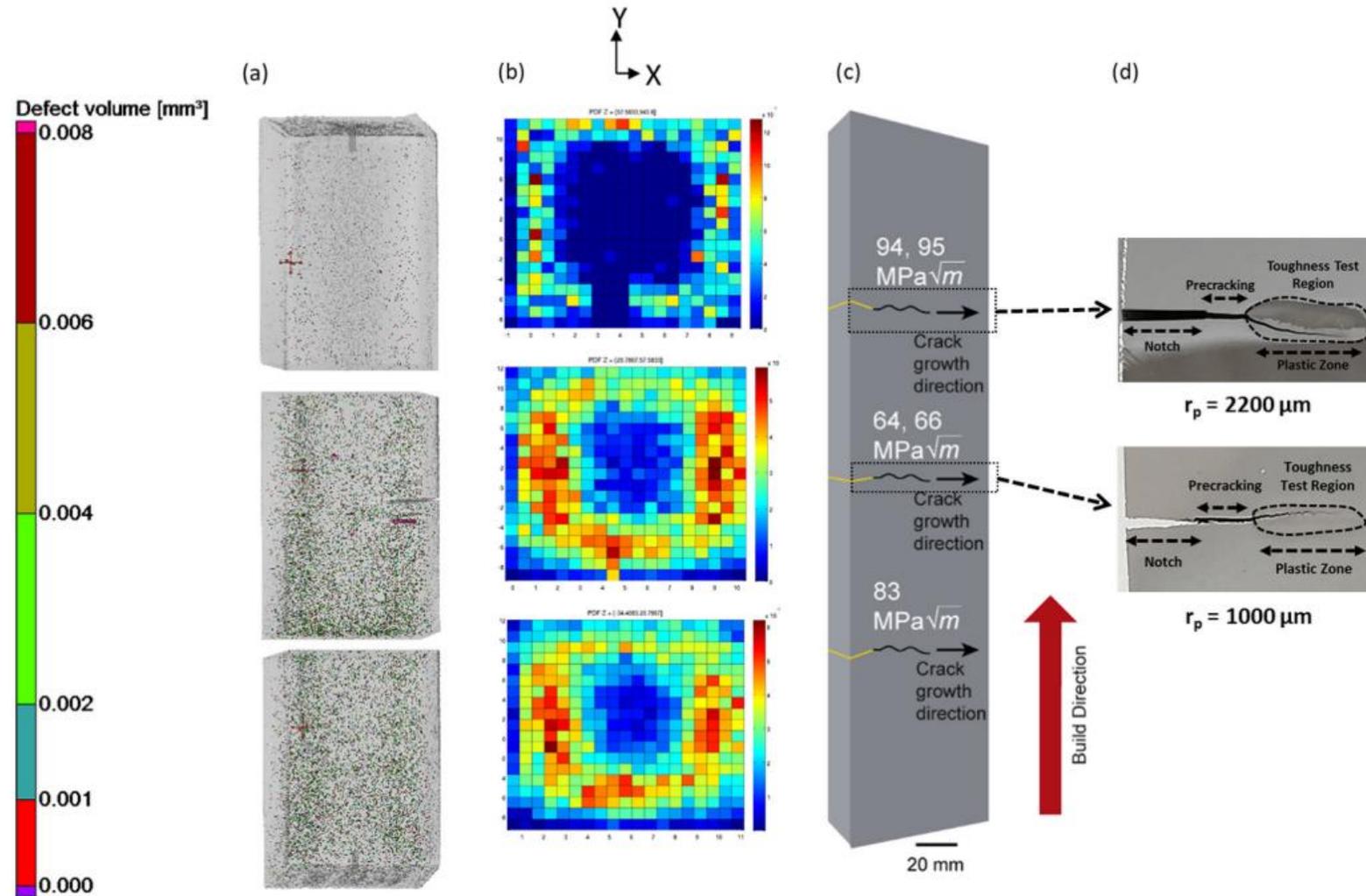
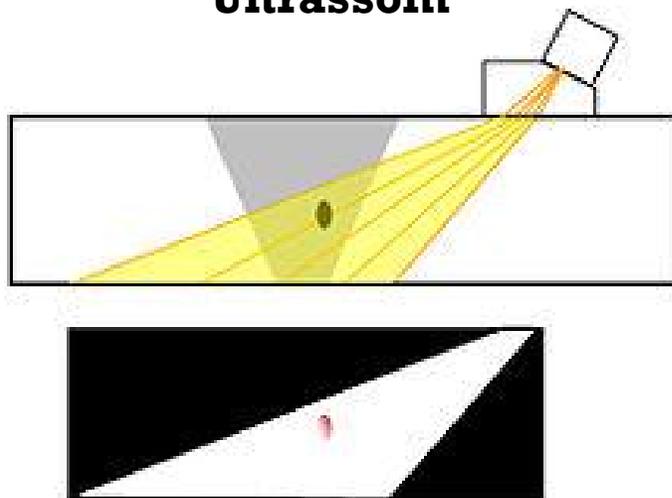


Fig. 14. (a) Defect spatial distribution for A2-processed SL sample in as-deposited condition. (b) Defect histogram for A2-processed SL sample at START, MIDDLE and END of the build. (c) Fracture toughness variation throughout the build. (d) Extent of plastic zone size at high toughness region and low toughness region is shown.

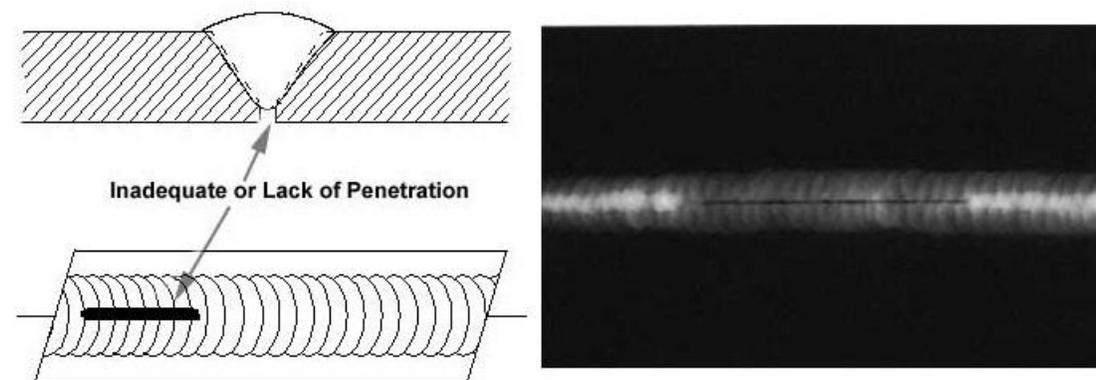
AVALIAÇÃO DE DEFEITOS

Ultrassom



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Radiografia



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- Trincas ou Defeitos tipo trinca são bastante comuns de ocorrerem:
 - Riscos profundos;
 - Vazios em soldas;
 - Inclusões ou partículas estranhas em fundidos ou forjados;
 - Delaminações em materiais formados por camadas.
- Em estruturas:
 - Aviões;
 - Navios;
 - Vasos de Pressão;
 - Pontes;
 - Tubos;
 - Veículos terrestres.
- Antes do desenvolvimento da Mecânica da Fratura nos anos de 1950 – 1960, a análise de trincas em componentes ou estruturas não era possível.
- O projeto era baseado a partir de resultados de testes de ensaios de tração, flexão e compressão, conjuntamente com os critérios apresentados para corpos sem trincas.

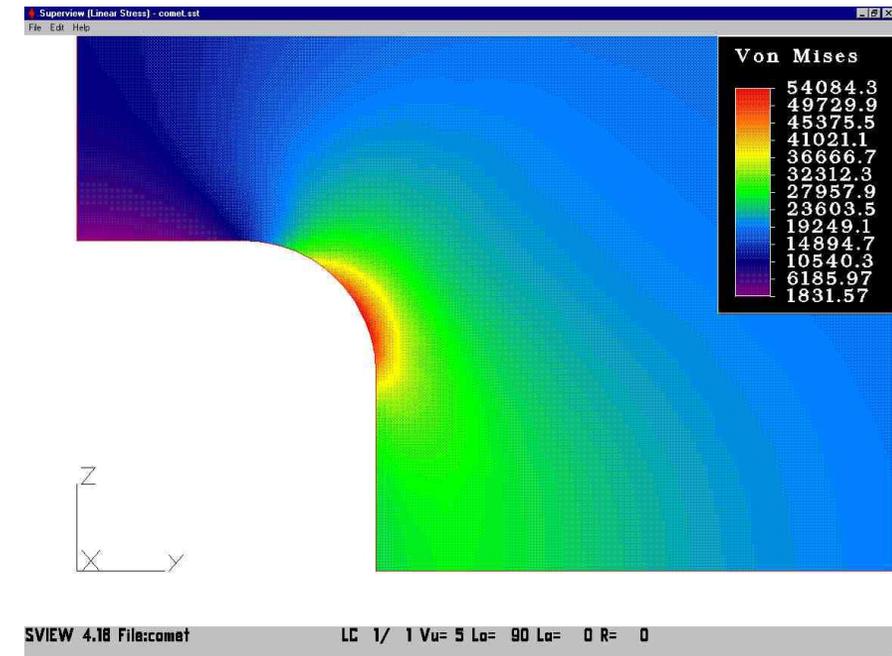
CONCENTRADORES DE TENSOES

Concentração de tensões. K_t :

- Fundo de filetes de rosca
- Rasgos de chavetas
- Furos
- Raios de concordância
- Entalhes. etc.

Outros exemplos típicos de defeitos semelhantes a trincas são :

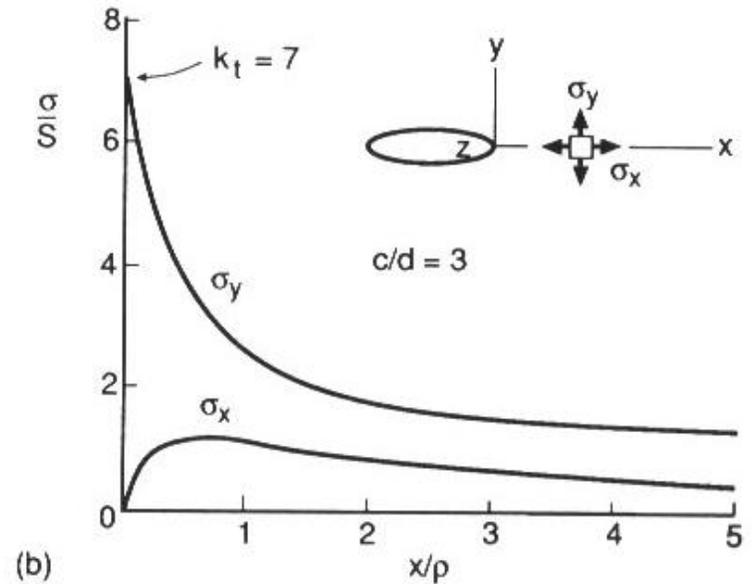
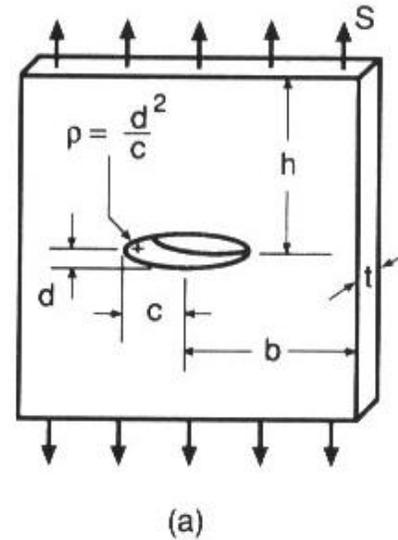
- Trincas de solidificação em peças fundidas e metais de solda.
- Trincas por hidrogênio em zonas termicamente afetadas pelo calor. em regiões soldadas.
- Decoção lamelar em torno de inclusões em placas de aço laminadas e barras forjadas.
- Trinca nucleada por mecanismos de fadiga ou corrosão sob tensão. com tamanho sub-crítico.



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CONCENTRADOR DE TENSÕES - TRINCA

- Considere o furo muito menor que a largura da placa
- O efeito do furo é muito relevante para a direção y-y.
- Quando d tende a zero (trinca), s_y vai para o infinito, e assim K_t .
- Assim, uma trinca aguda causa uma severa concentração de tensão e a tensão seria teoricamente infinita.

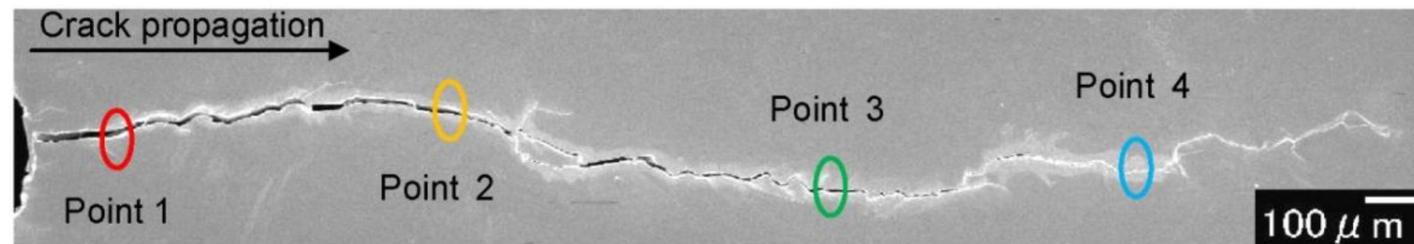


$$\sigma_y = S \left[1 + 2 \frac{c}{d} \right] = S \left[1 + 2 \sqrt{\frac{c}{\rho}} \right]$$

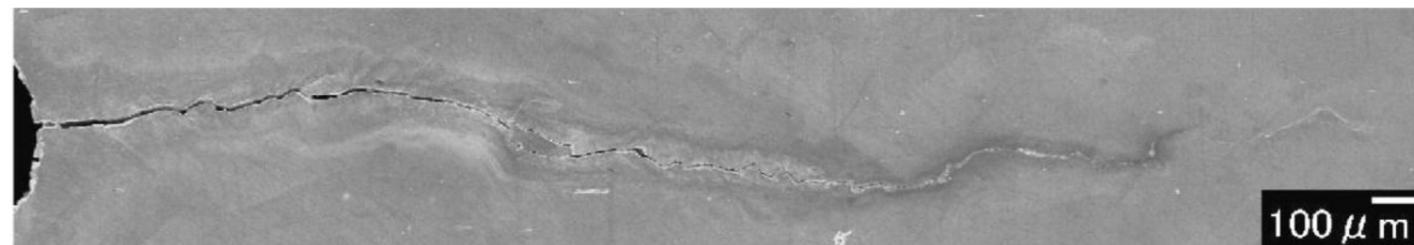
$$k_t = \frac{\sigma_y}{S} = 1 + 2 \frac{c}{d} = 1 + 2 \sqrt{\frac{c}{\rho}}$$

Mecânica da fratura é uma disciplina de engenharia que:

- Quantifica as **condições** sob as quais um sólido sob ação de um carregamento pode ir ao colapso devido à **propagação de uma trinca contida nesse sólido**.
- Possibilita a obtenção de **informações quantitativas** de problemas específicos relativos a trincas em estruturas e componentes de engenharia.



(a)



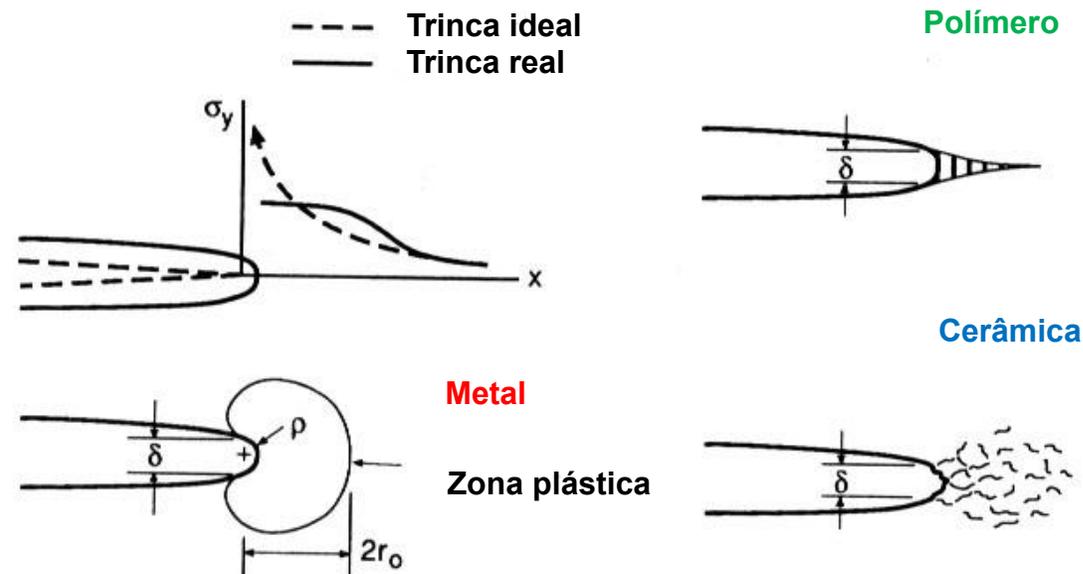
(b)

Mecânica de fratura

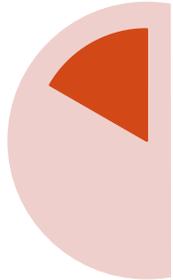
- Pode-se determinar o grau de segurança que um determinado componente ou estrutura possui com relação à ocorrência de uma possível falha por fratura frágil.
- Os parâmetros da Mecânica de Fratura que indiretamente medem a capacidade do material de resistir à fratura rápida são denominados de tenacidade à fratura :
 - K_{IC}
 - J_{IC}
 - CTOD
- Estes valores são obtidos em laboratório por meio de ensaios de carregamento até a fratura

As tensões em materiais verdadeiros não podem ir para o infinito!

- Se a carga aplicada não for muito elevada, o material pode acomodar a presença de uma trinca aguda de tal forma que o valor teórico infinito de tensão é reduzido para um valor finito.
- A região de intensa deformação na frente de trincas reais é formada devido a plasticidade. “crazing” ou microtrincamento



DESENVOLVIMENTO DA MECÂNICA DA FRATURA



1920 - Griffith

Usou a primeira lei da termodinâmica para formular a teoria da fratura baseada em um simples balanço de energia.

O modelo de Griffith prevê a relação entre resistência e tamanho de falha em vidro.

A modificação ao modelo de Griffith somente veio em 1948.



Década de 50

Após estudar os trabalhos de Inglis, Griffith e outros, Irwin modificou o modelo de Griffith para permitir sua aplicação em metais

Em 1956 desenvolveu o conceito de taxa de alívio de energia.



1960 e 1980

•1960: Os fundamentos da Mecânica da Fratura Linear Elástica (MFLE) foram estabelecidos e os pesquisadores voltaram-se para a plasticidade na ponta da trinca.

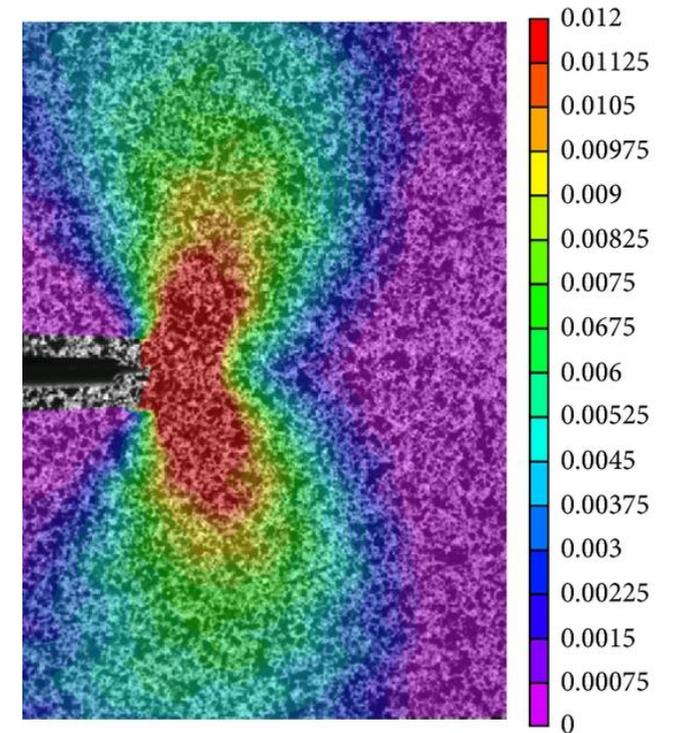
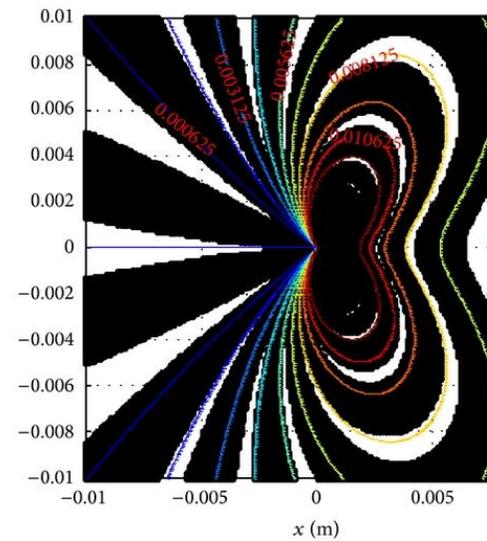
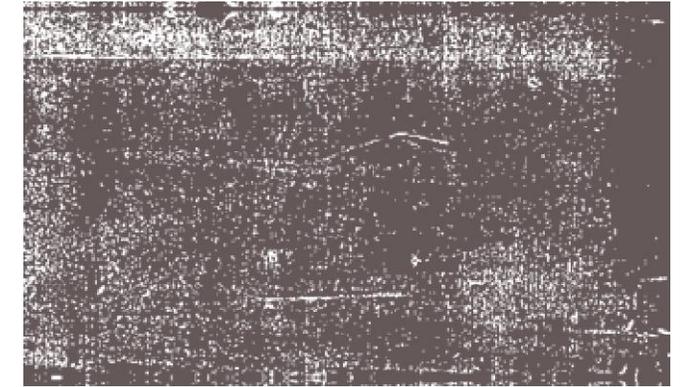
•1961: Wells identificou que os aços estruturais eram muito dúcteis para o uso da MFLE. → desenvolveu o conceito de CTOD (Mecânica da Fratura Elasto-plástica – MFEP).

•1965: Foi criado o Comitê de Mecânica da Fratura da ASTM.

•1968: Rice desenvolveu o conceito para caracterizar materiais com comportamento dúcteis → Integral J

MECÂNICA DE FRATURA

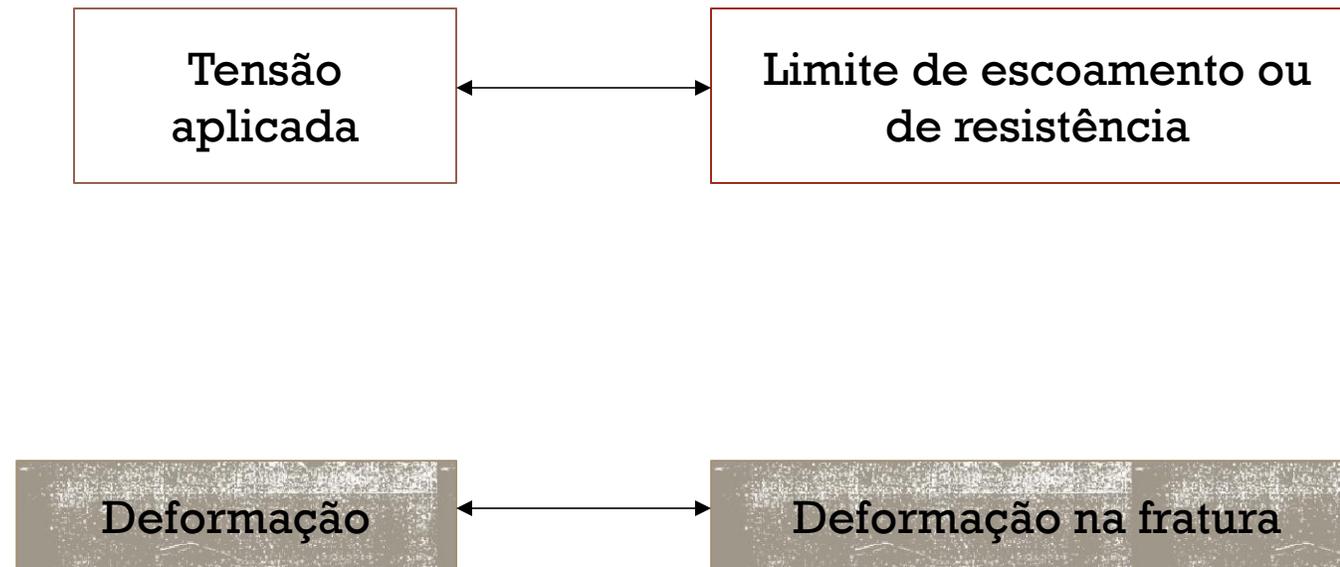
Traz o desenvolvimento teórico e experimental para se prever se um determinado defeito, de uma dada dimensão, poderá propagar-se de uma maneira catastrófica, sob a ação de um carregamento conhecido.



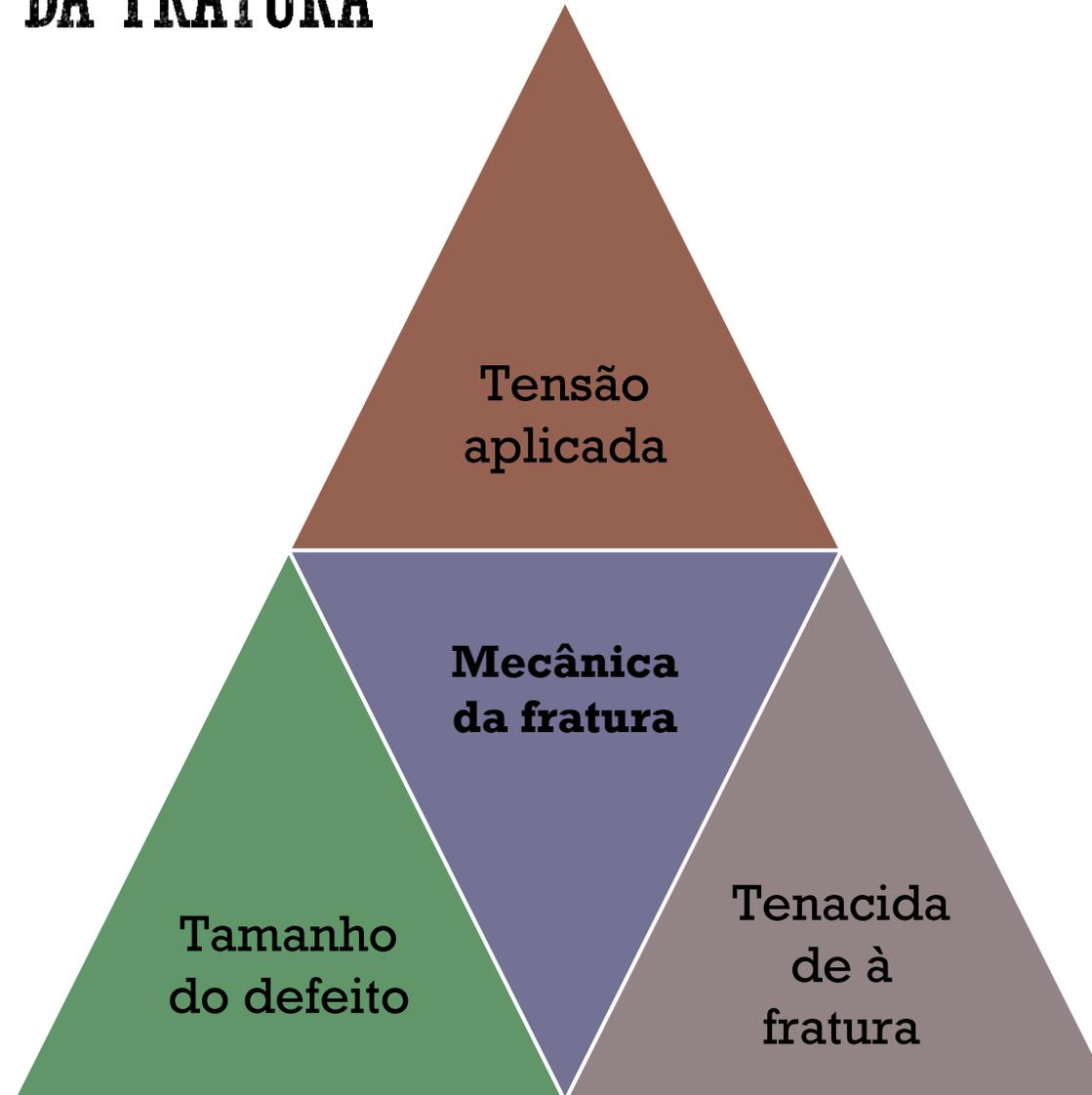
PROJETOS CONVENCIONAIS

- Projetos convencionais → geralmente especificadas pelo limite de escoamento (σ_E) e limite de resistência (σ_R).
- Na seleção de um material para uma dada aplicação:
 - é comparado o valor calculado da tensão que atua no componente com os valores tabelados das propriedades citadas acima.
- Fator de segurança ($FS = S_{critico} / S_{projeto}$):
 - ❑ 1.5 para aços beneficiados utilizados em aplicações tais como vasos de pressão e caldeiras
 - ❑ 4 para aços fundidos para aplicações similares
 - ❑ 5 a 10 para tirantes de suportes, elevadores e guindastes.

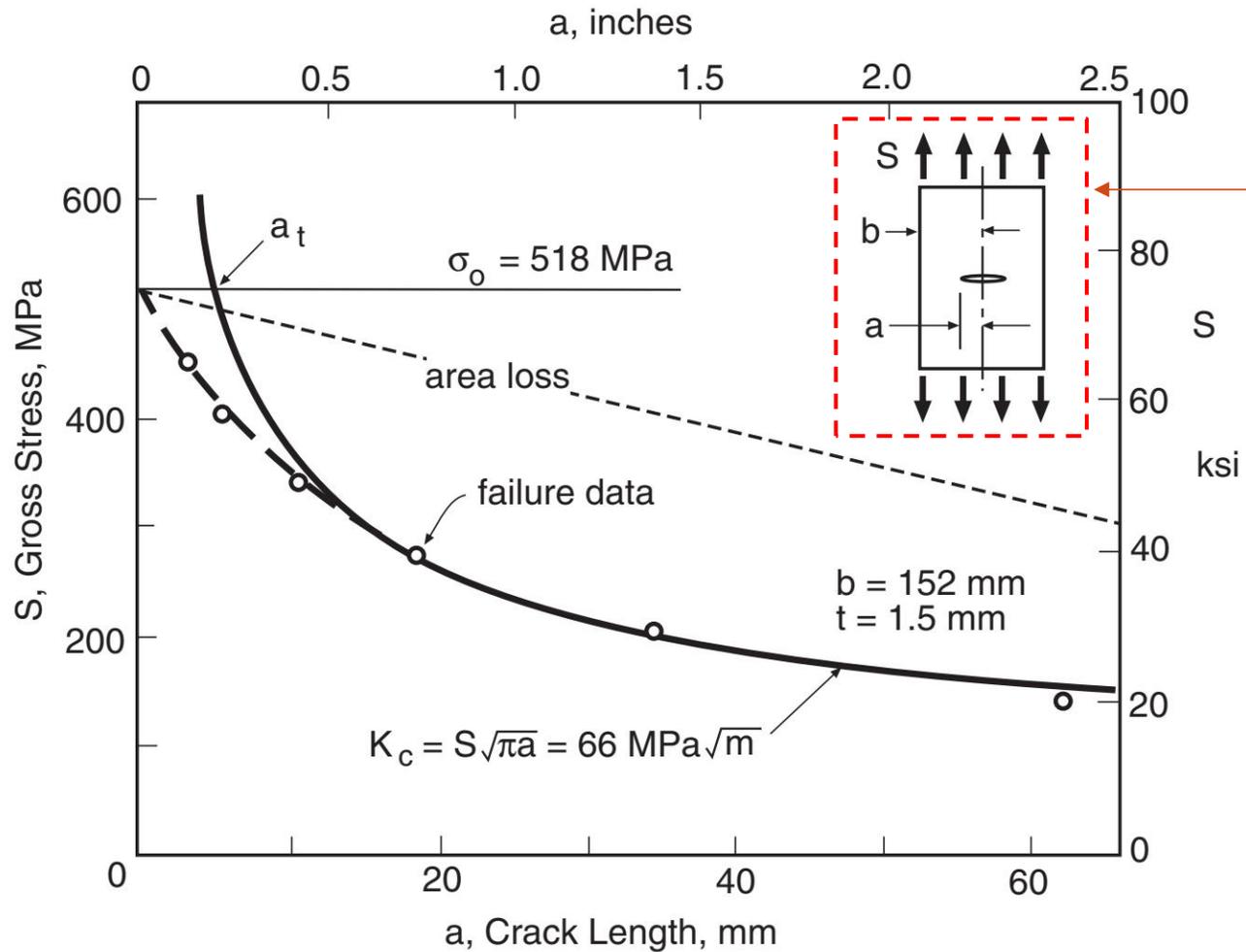
MÉTODO DE RESISTÊNCIA DOS MATERIAIS - PROJETOS CONVENCIONAIS



MÉTODO DA MECÂNICA DA FRATURA



FATOR DE INTENSIDADE DE TENSÕES, K



$$K = S\sqrt{\pi a}$$

Figure 8.5 Failure data for cracked plates of 2014-T6 Al tested at -195°C . (Data from [Orange 67].)

COMPARAÇÃO ENTRE MATERIAIS FRÁGEIS E DÚCTEIS

$$a_t = \frac{1}{\pi} \left(\frac{K_c}{\sigma_o} \right)^2$$

$$K = S \sqrt{\pi a}$$

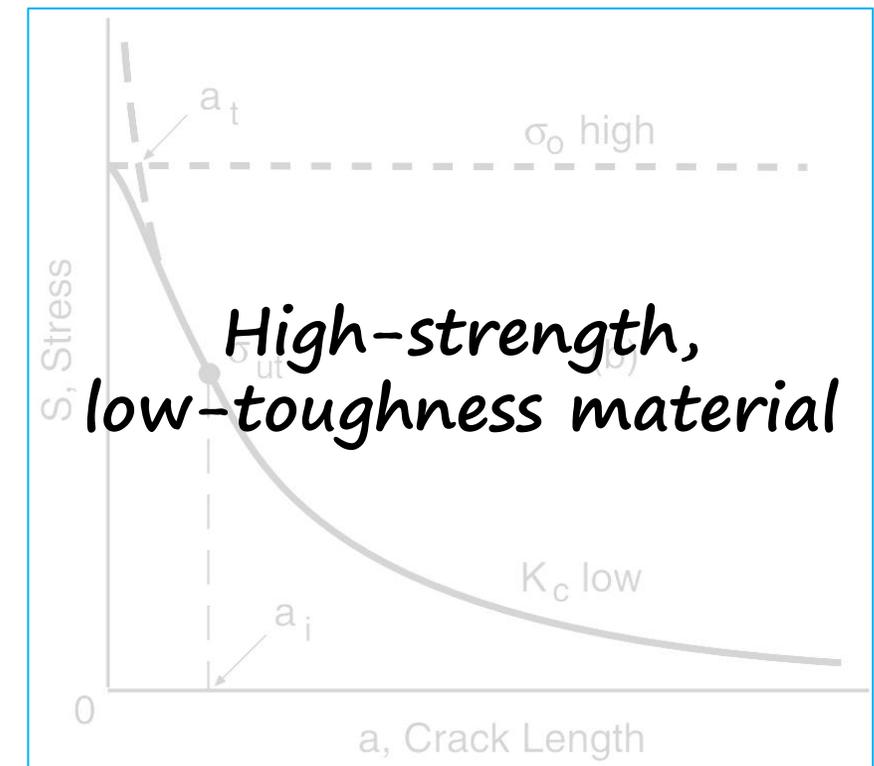
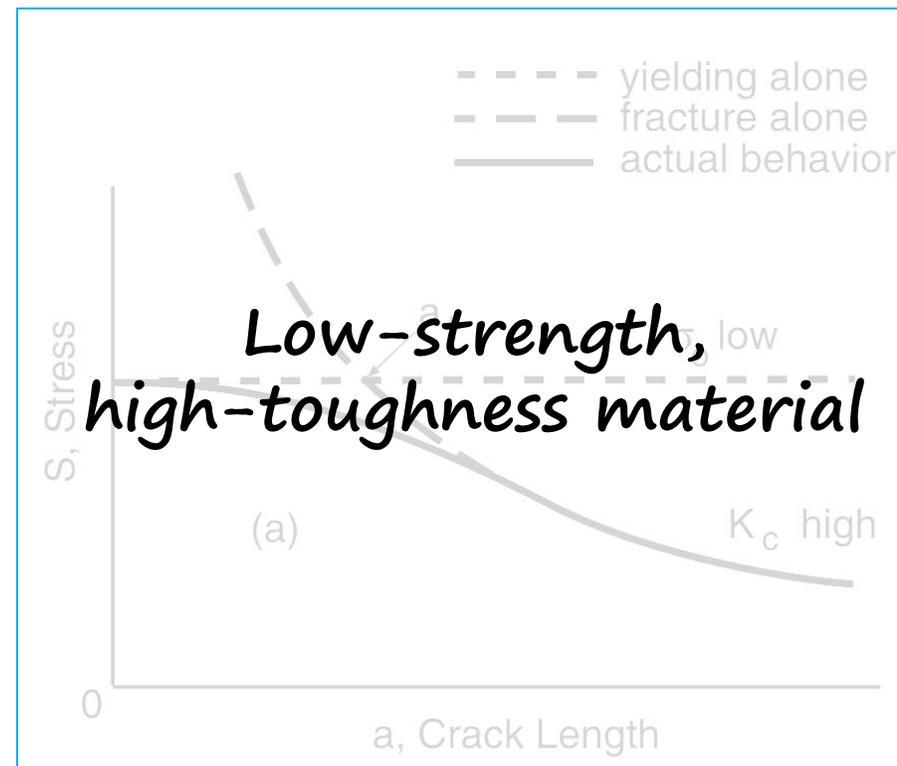


Figure 8.6 Transition crack length a_t for a low-strength, high-toughness material (a), and for a high-strength, low-toughness material (b). If (b) contains internal flaws a_i , its strength in tension σ_{ut} is controlled by brittle fracture.

COMPARAÇÃO ENTRE MATERIAIS FRÁGEIS E DÚCTEIS

$$a_t = \frac{1}{\pi} \left(\frac{K_c}{\sigma_o} \right)^2$$

$$K = S \sqrt{\pi a}$$

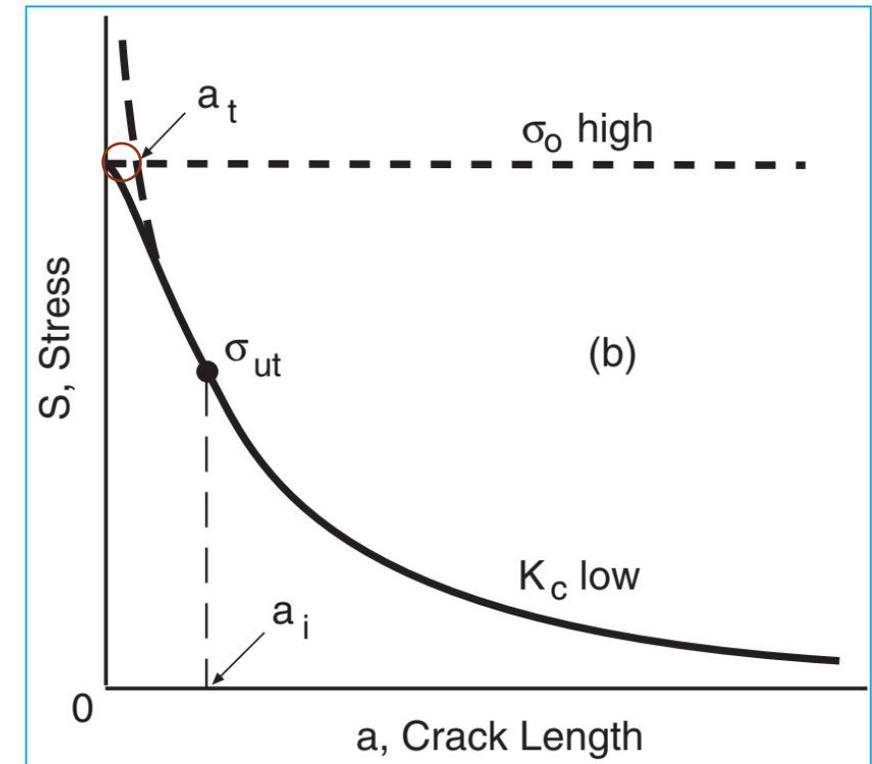
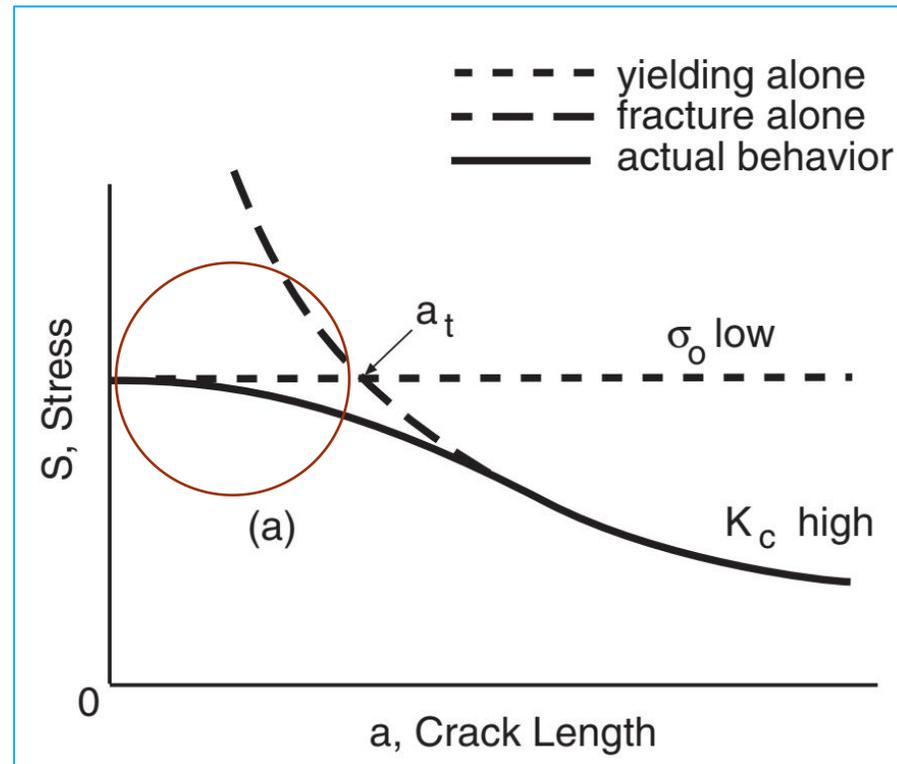
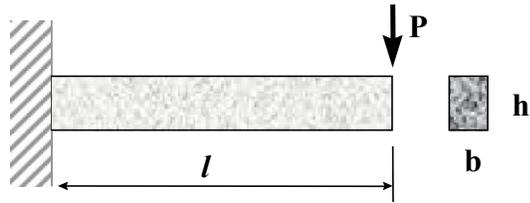


Figure 8.6 Transition crack length a_t for a low-strength, high-toughness material (a), and for a high-strength, low-toughness material (b). If (b) contains internal flaws a_i , its strength in tension σ_{ut} is controlled by brittle fracture.

MECÂNICA DA FRATURA VERSUS RESISTÊNCIA DOS MATERIAIS

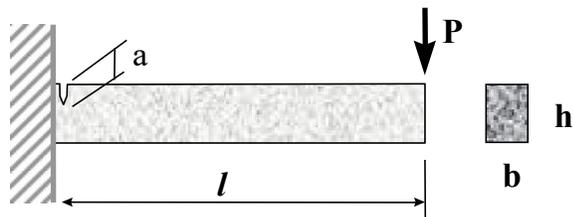


$$M = Pl$$

$$W = \frac{bh^2}{6}$$

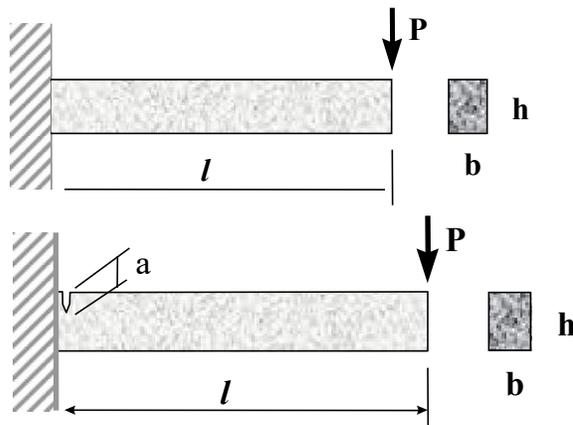
γ : fator de segurança

$$\sigma_{\max} = \frac{Pl}{bh^2/6} \leq \frac{\sigma_y}{\gamma} \Rightarrow P \leq \frac{bh^2}{6\gamma l} \sigma_y$$



$$K_I = 1.12 \sigma_{\max} \sqrt{\pi a} = 1.12 \frac{Pl}{bh^2/6} \sqrt{\pi a} \leq \frac{K_{Ic}}{\gamma}$$

$$\Rightarrow P \leq \frac{bh^2}{6\gamma l} \frac{K_{Ic}}{1.12\sqrt{\pi a}}$$



$$L = 250 \text{ mm}$$

$$h = 50 \text{ mm}$$

$$b = 25 \text{ mm}$$

$$a = 10 \text{ mm}$$

$$s_y = 550 \text{ MPa}$$

$$K_{IC} = 80 \text{ MPa m}^{1/2}$$

$$S = 1.0$$

Projeto convencional:

$$P \leq \frac{bh^2}{6\gamma l} \sigma_y$$

$$P_{\max} = \frac{BH^2}{6SL} \sigma_y \approx 2340 \text{ kgf}$$

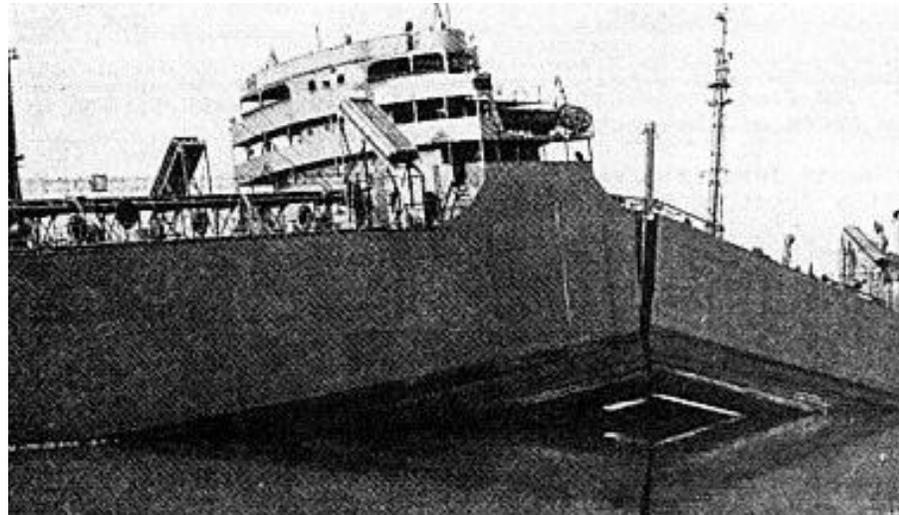
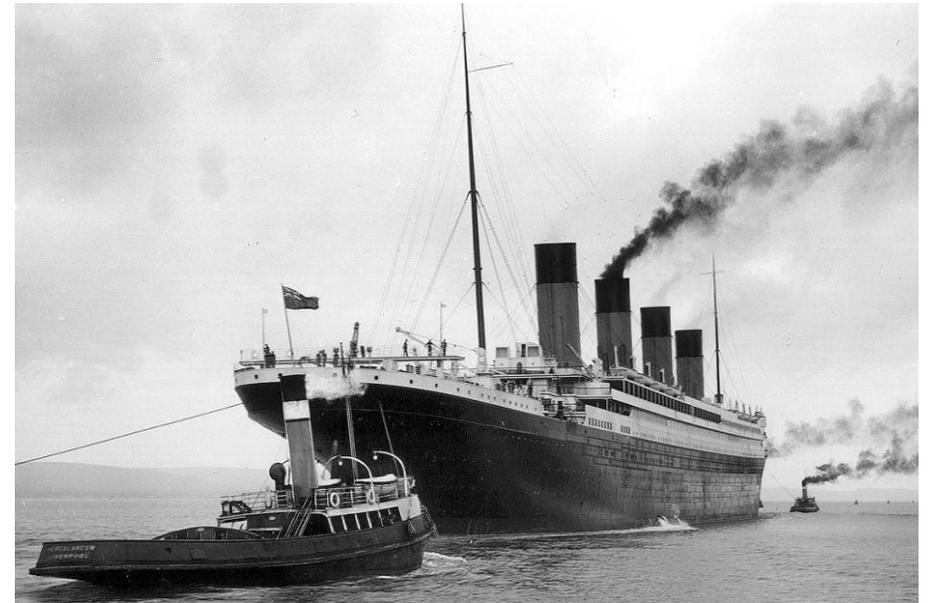
Projeto com mecânica da fratura:

$$P \leq \frac{bh^2}{6\gamma l} \frac{K_{IC}}{1.12\sqrt{\pi a}}$$

$$P_{\max} = \frac{BH^2}{6LS} \frac{K_{IC}}{1,12\sqrt{\pi a}} \approx 1715 \text{ kgf}$$

NOVOS MATERIAIS = NOVOS PROBLEMAS 1900-1950

- Titanic, 1912.
- <https://www.tms.org/pubs/journals/JOM/9801/Felkins-9801.html>
- Failure in Boston in 1919 of a large tank.
- <http://www.bbc.com/future/story/20160817-the-killer-flood-made-of-molasses>;
<https://www.theatlantic.com/photo/2015/01/on-this-day-the-boston-molasses-disaster-in-1919/384573/>
- Liberty ships, 1943.
- <https://www.linkedin.com/pulse/how-liberty-ships-wwii-contributed-study-fracture-mechanics-pinell/>



NOVOS MATERIAIS = NOVOS PROBLEMAS 1950-1960

British-made Comet passenger airliner:

1954

“There were two fatal flaws with the aircraft,” says Hodgson.

I. “First was the method of construction – the skin of the aircraft was made as thin as possible to save weight.” “The Comet flew very high, and it needed to be pressurised so the passengers inside can breathe,” says Hodgson. “If you do that, it’s like taking a toy balloon and blowing it up and deflating it constantly – eventually it’s going to tear.”

II. The second problem concerned the rectangular windows. “If you have a square opening in a sheet of metal, like the skin of an airliner, and you stress it, the place where the crack is going to start is at the corner,” Hodgson explains.



NOVOS MATERIAIS = NOVOS PROBLEMAS 1950-1960

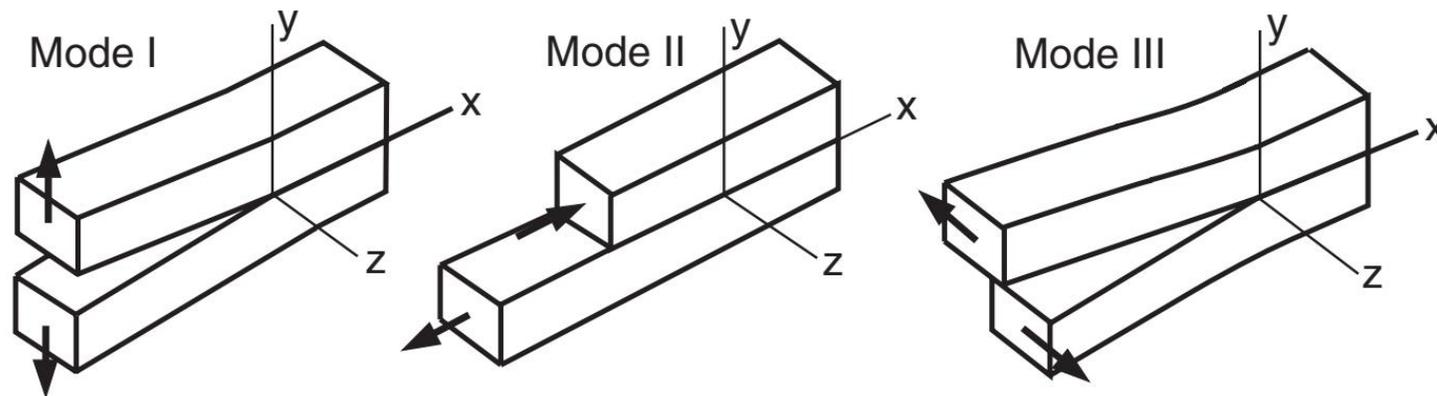
- 1950s failures of rocket motor cases for the Polaris missile
- F-111 aircraft crash in 1969

Such failures accelerated the development of fracture mechanics and led to its adoption by the U.S. Air Force as the basis of their *damage tolerant design* requirements.

Conceitos da mecânica da fratura

Um corpo trincado pode ser carregado em um ou combinação dos seguintes modos de carregamentos.

- Modo I: abertura ou modo trativo (as superfícies da trinca são tracionadas a parte);
- Modo II: deslizamento ou cisalhamento no plano (as superfícies da trinca deslizam uma sobre a outra)
- Modo III: rasgamento ou cisalhamento fora do plano (as superfícies da trinca se move paralelamente frente da trinca e uma a outra)



- Muitos problemas de trincas em componentes de engenharia envolve primariamente o modo I de carregamento (tensões trativas)



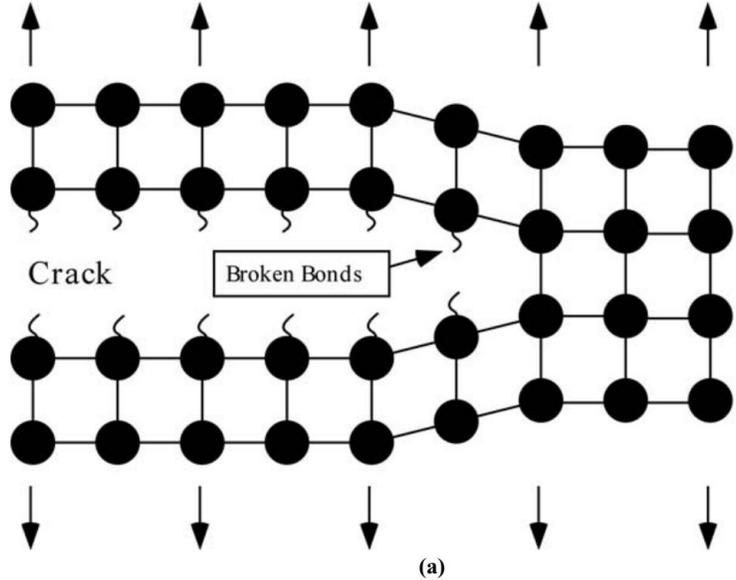
Mecânica de Fratura Elástica Linear (MFEL)

Esta metodologia é expressa em termos da **taxa de alívio de energia de deformação (G)**.

Trabalhos adicionais levaram o desenvolvimento do **fator de intensidade de tensão. K**.

Balanco de energia (1920, Griffith)

Alan Arnold Griffith



Balanco de energia (1920, Griffith)

$$\frac{dE}{dA} = \frac{d\Pi}{dA} + \frac{dW_s}{dA} = 0 \qquad -\frac{d\Pi}{dA} = \frac{dW_s}{dA}$$

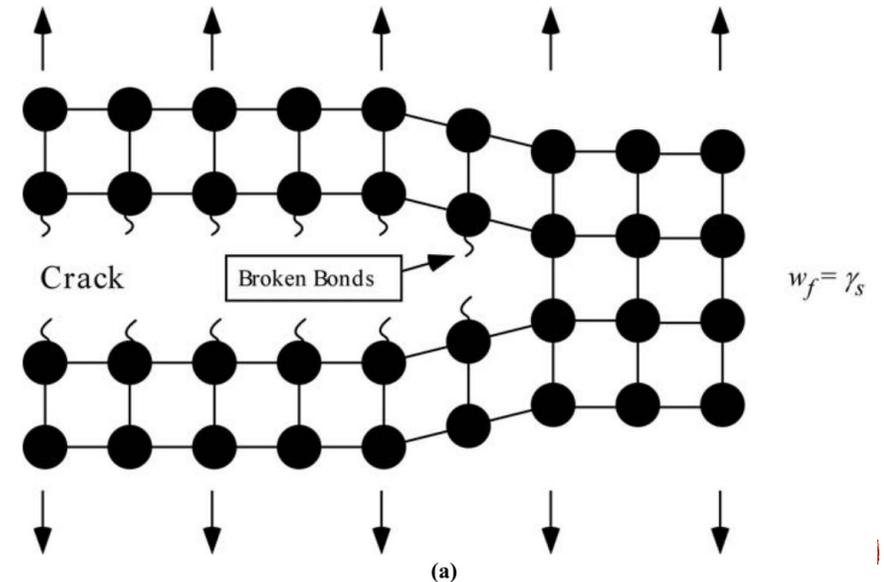
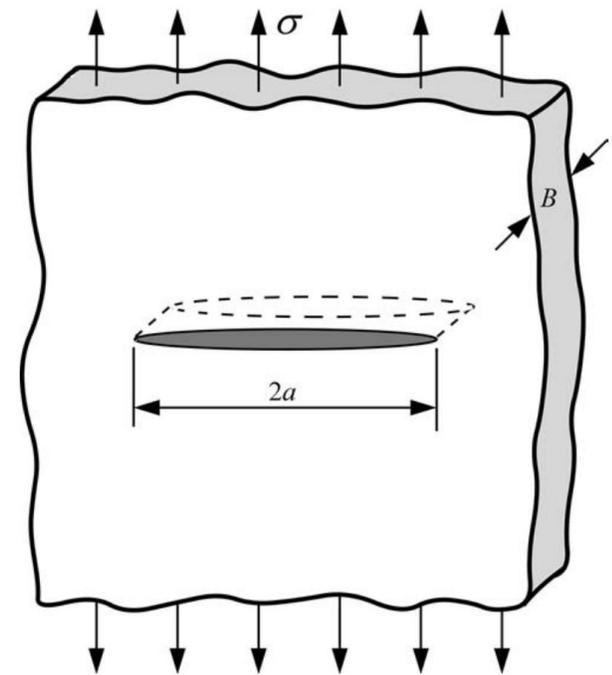
E = total energy

Π = potential energy supplied by the internal strain energy and external forces

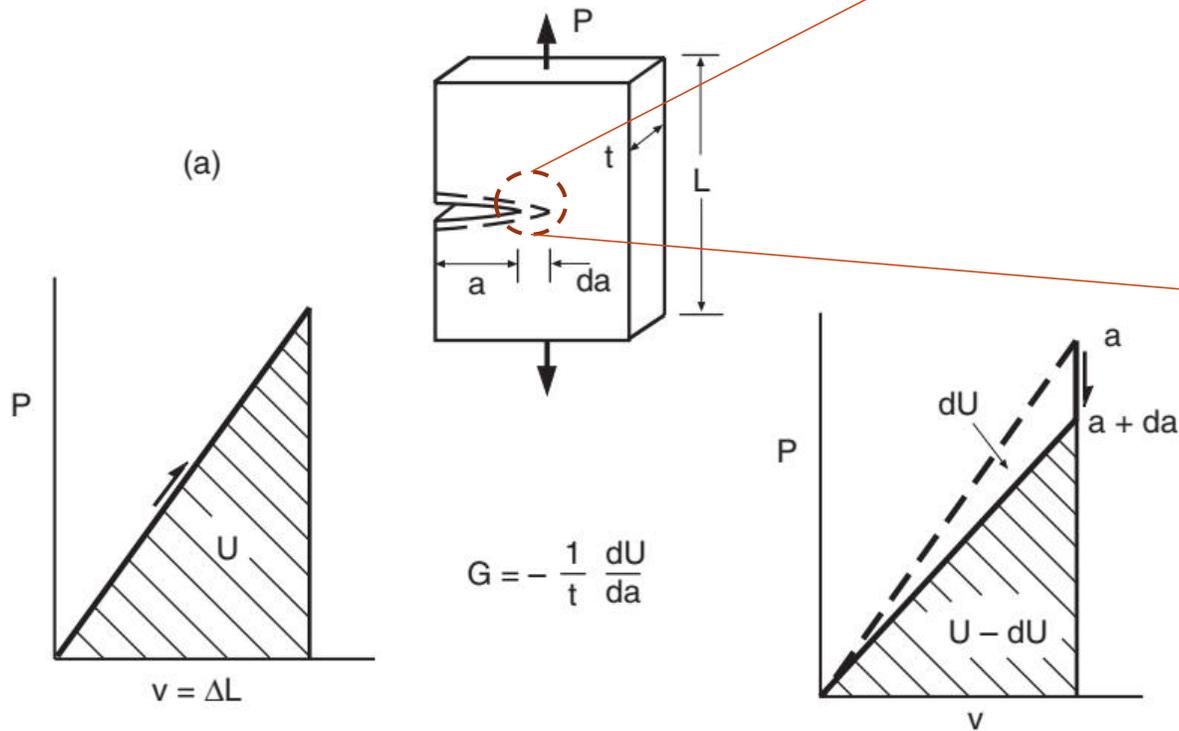
W_s = work required to create new surfaces

$$W_s = 4aB\gamma_s \qquad -\frac{d\Pi}{dA} = \frac{\pi\sigma^2 a}{E} \qquad \frac{dW_s}{dA} = 2\gamma_s$$

$$\sigma_f = \left(\frac{2E\gamma_s}{\pi a} \right)^{1/2}$$

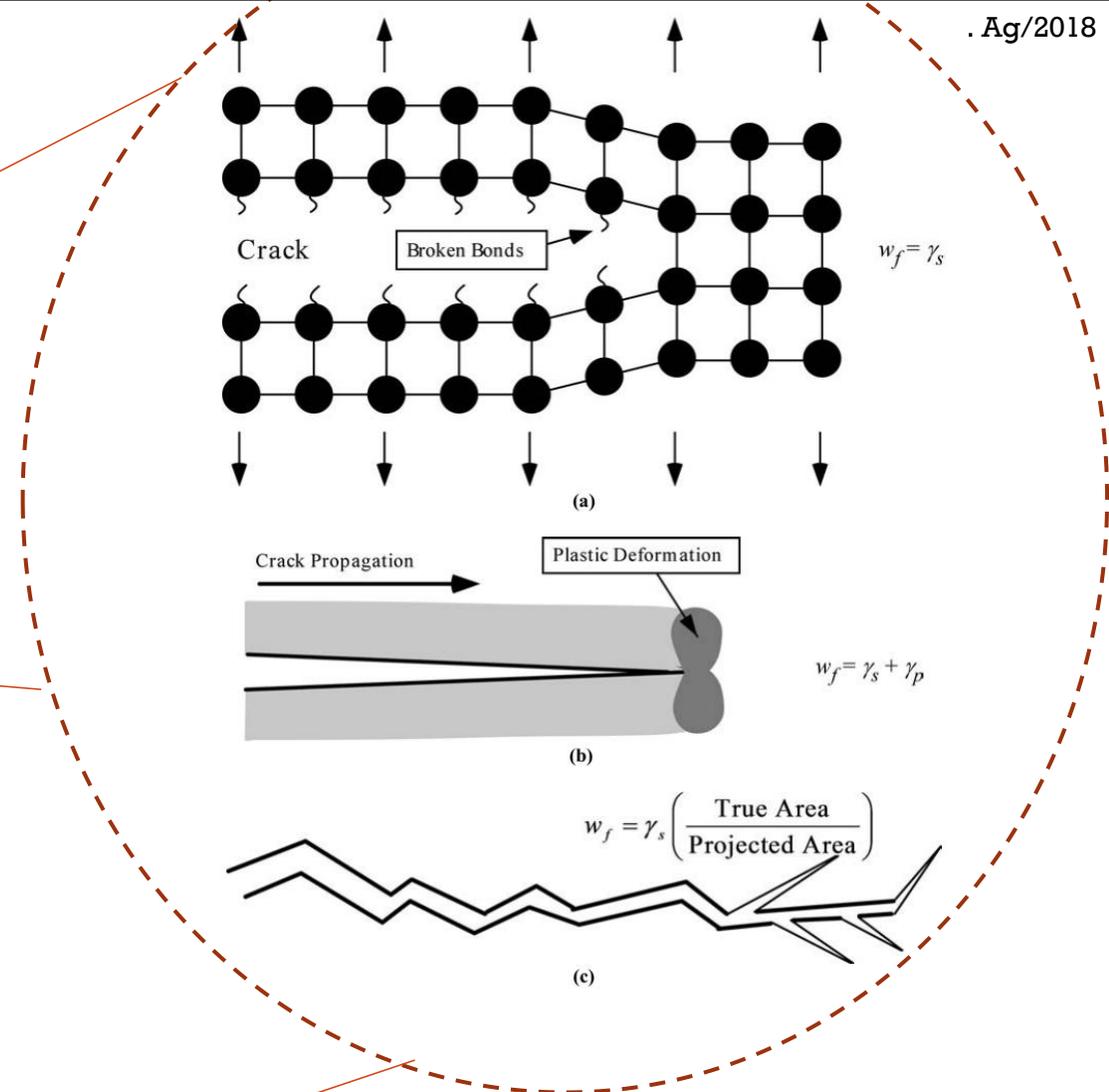


Taxa de alívio de energia, G (Irwin 1956)



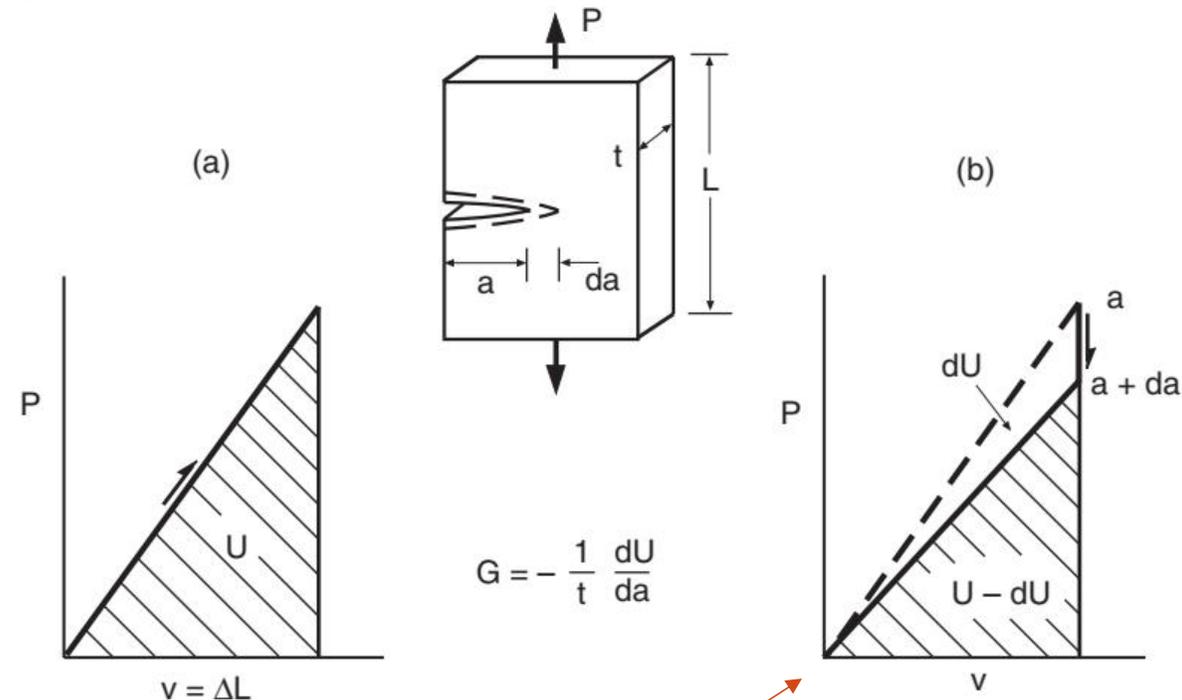
$$U = Pv/2$$

$$G = \frac{dU_p}{da}$$



Taxa de alívio de energia, G (Irwin 1956)

- Considere um corpo contendo uma trinca de tamanho a , carregado no Modo I com a carga P e que este tenha um comportamento elástico linear
- De maneira similar a uma mola, a energia potencial elástica armazenada neste corpo é denominada de U_p .
- Se a trinca se propaga por uma quantidade da (em deslocamento constante ou carregamento constante), a rigidez do sistema diminui, resultando em um decréscimo na energia potencial de dU_p .



É a taxa de variação da energia potencial com a área da trinca, ou seja, a força motriz.

$$G = \frac{dU_p}{da}$$

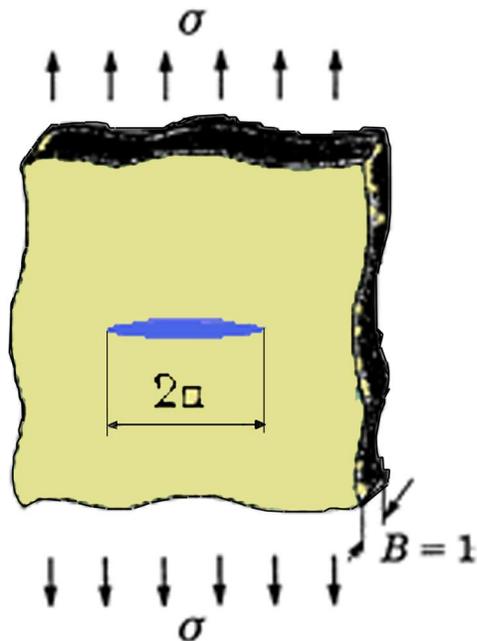
Figure 8.9 Potential energies for two neighboring crack lengths and the energy change dU used to define the strain energy release rate G .

- A equação inicial de Griffith é válida somente para materiais idealmente frágeis. Assim, ele obteve resultados bons para vidros mas não para metais.
- Irwin e Orowan independentemente modificaram a equação de Griffith, para que esta fosse capaz de levar em conta o escoamento plástica e assim aplicá-la a metais.

$$\sigma_F = \sqrt{\frac{E(2\gamma_s + \gamma_p)}{\pi a_c}}$$

- Onde γ_p é o trabalho plástico por unidade de área da superfície criada e é >>>> γ_s

CRITÉRIO DE ENERGIA DE GRIFFITH (1920)



$$U_t = U_0 + U_a + U_s - F$$

$$U_p = U_0 + U_a - F$$

U_t = Energia Total

U_0 = Energia total da placa sem trinca

U_a = Variação da energia de deformação elástica

U_p = Energia potencial fornecida pela deformação interna e forças externas

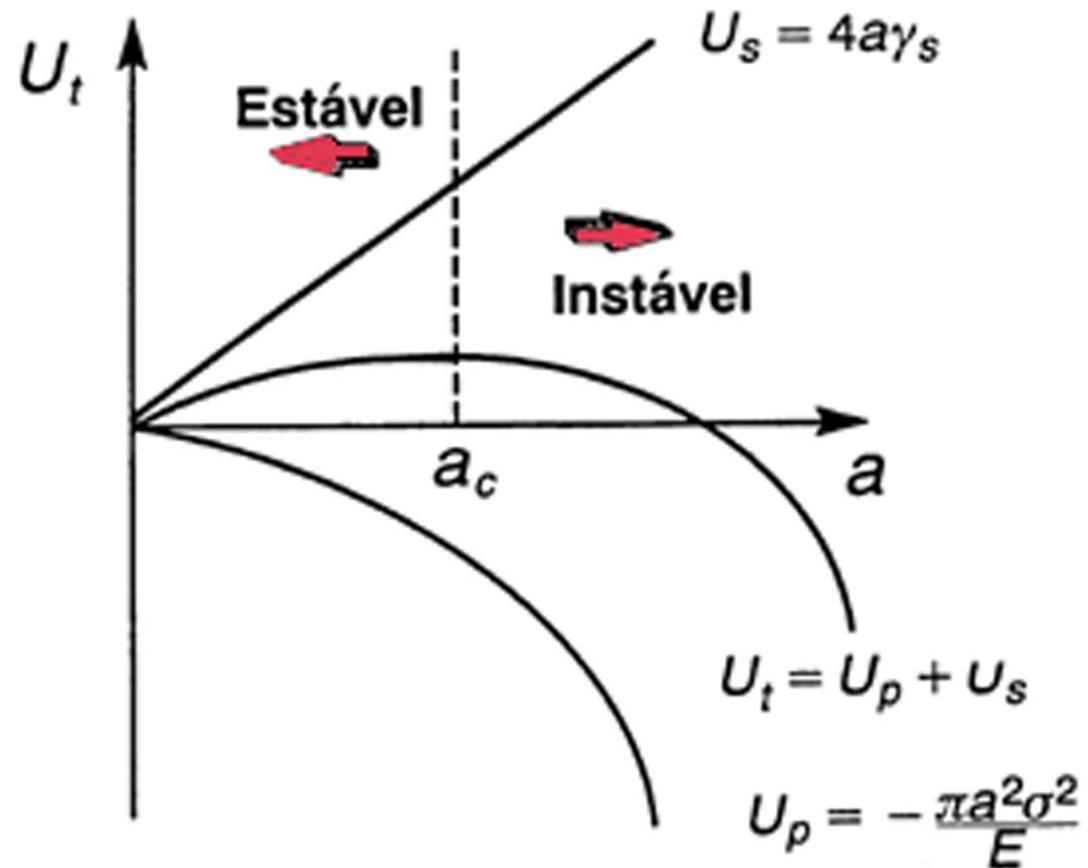
U_s = Variação da energia de superfície.

γ_s = Energia de superfície por unidade de área

Em controle de deslocamento, $F=0$ para a placa da figura. Griffith mostrou que:

$$U_p = U_0 - \frac{\pi a^2 \sigma^2}{E} \Rightarrow \frac{dU_p}{da} = -\frac{2\pi a \sigma^2}{E}$$

$$U_s = 2(2a \times 1)\gamma_s \Rightarrow \frac{dU_s}{da} = 4\gamma_s$$



$$\frac{dU_t}{da} = \frac{dU_p}{da} + \frac{dU_s}{da} = 0$$

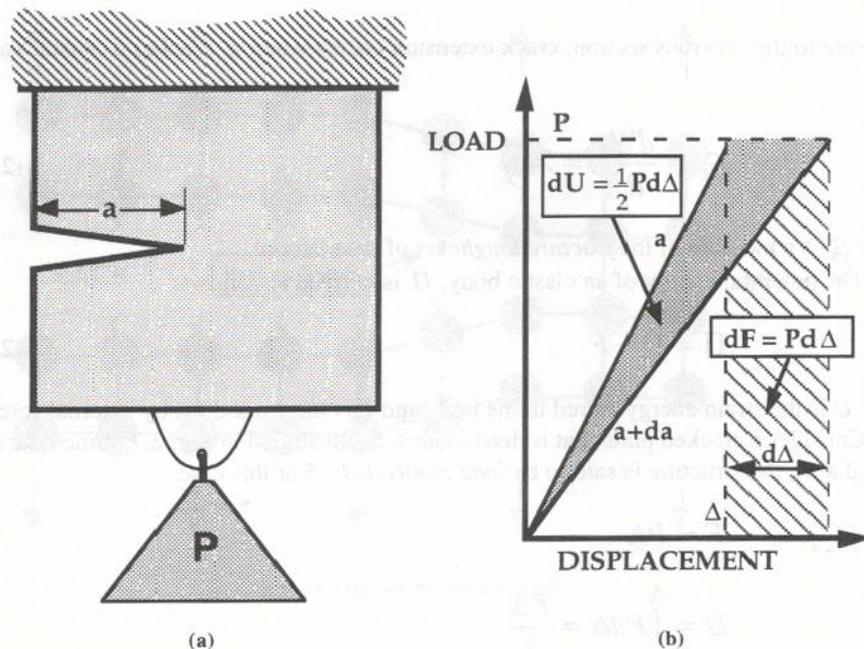
$$-\frac{2a\pi\sigma_F^2}{E} + 4\gamma_s = 0$$

$$\sigma_F = \sqrt{\frac{2\gamma_s E}{\pi a_c}}$$

$$U_p = U - F$$

U = Energia de deformação armazenada pelo corpo
F = Trabalho das forças externas

Considere que o CP de espessura B seja carregado em controle de carga:



$$F = P\Delta$$

$$U = \int_0^{\Delta} P d\Delta = \frac{P\Delta}{2}$$

$$U_p = -U$$

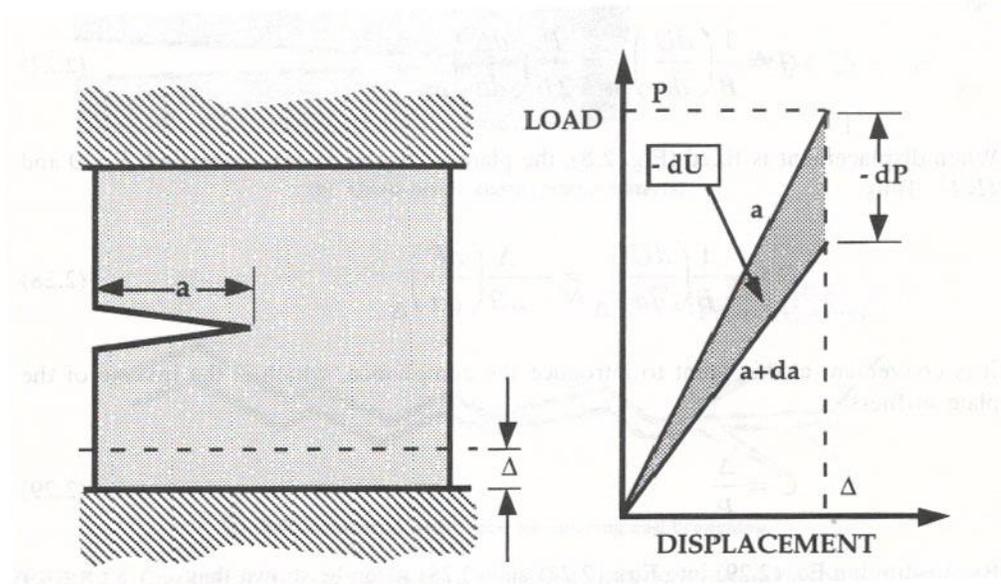
$$G = \frac{1}{B} \left(\frac{dU}{da} \right)_P = \frac{P}{2B} \left(\frac{d\Delta}{da} \right)_P$$

$$U_p = U - F$$

U = Energia de deformação armazenada pelo corpo

F = Trabalho das forças externas

Considere CP com espessura B seja carregado em controle de deslocamento:



$$F = 0$$

$$U = \int_0^{\Delta} P d\Delta = \frac{P\Delta}{2}$$

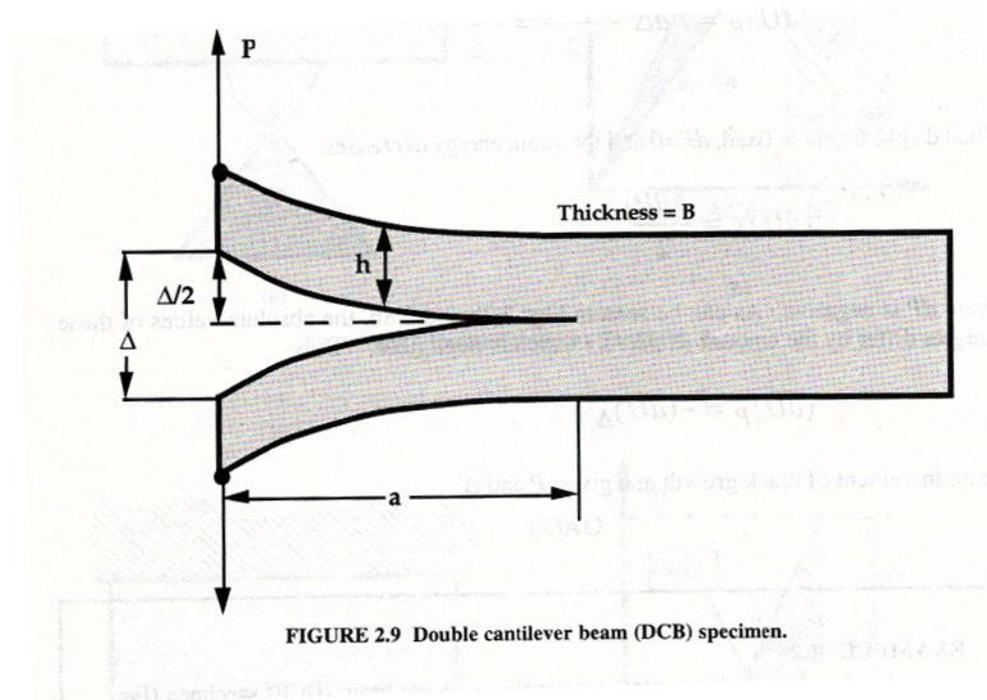
$$U_p = U$$

$$G = -\frac{1}{B} \left(\frac{dU}{da} \right)_{\Delta} = -\frac{\Delta}{2B} \left(\frac{dP}{da} \right)_{\Delta}$$

$$G = \frac{P^2}{2B} \left(\frac{dC}{da} \right)$$

EXEMPLO 2.2 ANDERSON

- Determine a taxa de alívio de energia para um corpo de prova DCB (double cantilever beam).



Substituindo (II) em (III) teremos

$$G = \frac{P^2 a^2}{BEI} = \frac{12 P^2 a^2}{B^2 h^3 E}$$

$$\frac{\Delta}{2} = \frac{P a^3}{3EI} \text{ onde } I = \frac{B h^3}{12} \quad (I)$$

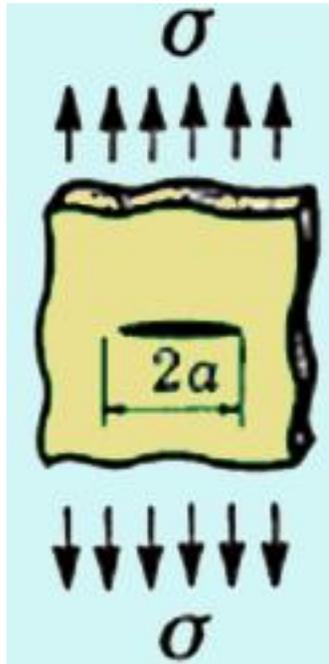
O compliance elástico é dado por:

$$C = \frac{\Delta}{P} = \frac{2a^3}{3EI} \quad (II)$$

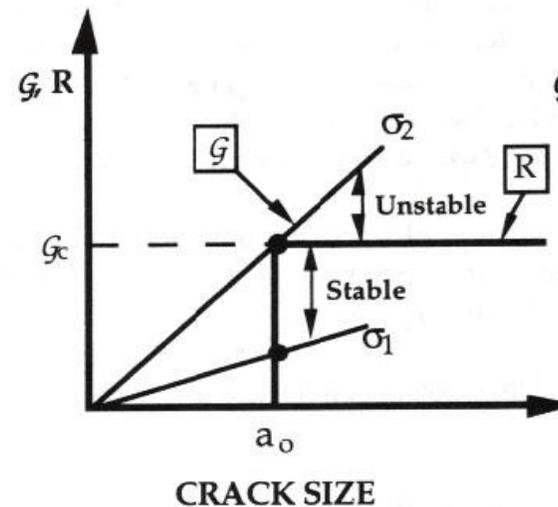
Como:

$$G = \frac{P^2}{2B} \left(\frac{dC}{da} \right) \quad (III)$$

CURVAS DE RESISTÊNCIA CURVAS-R

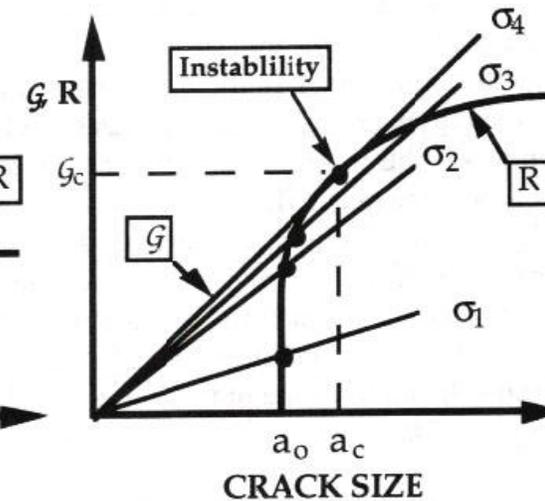


R constante com crescimento



(a) Flat R curve

R varia com crescimento



(b) Rising R curve

G = a força motriz (drive force) para a extensão da trinca

R = a resistência à extensão da trinca

Ponto P ocorre instabilidade. então $G=R$ e (cresc. instavel) . mas este ponto de tangência depende da forma de G que depende da configuração da estrutura. para a figura acima ela é linear mas para o DCB ela varia com a^2 . portanto não possui uma propriedade única.

INSTABILIDADE

$$G = -\frac{dU_p}{da} = \frac{\pi \sigma^2 a}{E}$$

$$G_c = \frac{dU_s}{da} = 2\gamma_s = R$$

$$G_c = \frac{\pi}{E} \sigma_F^2 a_c$$

Controle de carga versus controle deslocamento

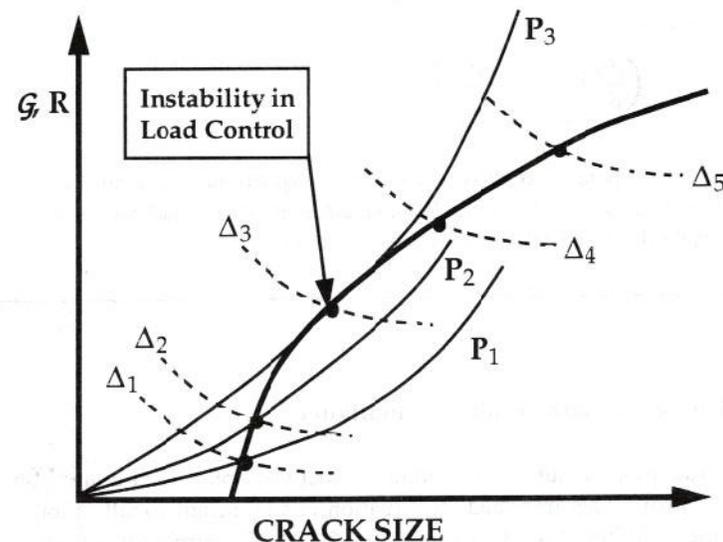


FIGURE 2.11 Schematic driving force/R curve diagram which compares load control and displacement control.

- A estabilidade do crescimento da trinca depende da taxa variação de G . isto é. da segunda derivada da energia potencial U .

- O controle de deslocamento tende a ser mais estável do que o controle em carga. Em algumas configurações . G diminui com o crescimento da trinca em controle de deslocamento.

EXEMPLO

- Determine a estabilidade relativa para um corpo de prova DCB em controle de carga e em controle de deslocamento. Dado:

$$\frac{\Delta}{2} = \frac{P a^3}{3EI} \Rightarrow P = \frac{3EI\Delta}{2a^3} \quad G = \frac{P^2 a^2}{BEI} = \frac{12P^2 a^2}{B^2 h^3 E}$$

Solução

- 1) A partir da equação calculada no exercício anterior. a inclinação (derivada) da força motriz em controle de carga será dada por:

$$\left(\frac{dG}{da} \right)_P = \frac{2P^2 a}{BEI} = \frac{2G}{a}$$

- 2) Para avaliar o controle de deslocamento. é necessário expressar G em termos de Δ e a. A partir da teoria da viga. carga é relacionada com deslocamento como segue:

$$G = \frac{9\Delta^2 EI}{2a^3} \quad \text{Logo:} \quad \left(\frac{dG}{da} \right)_\Delta = -\frac{9\Delta^2 EI}{Ba^3} = -\frac{4G}{a}$$

CONTINUAÇÃO EXERCÍCIO ANTERIOR:

Controle de Carga

$$\left(\frac{dG}{da} \right)_P = \frac{2P^2 a}{BEI} = \frac{2G}{a}$$

Controle de deslocamento

$$\left(\frac{dG}{da} \right)_\Delta = -\frac{9\Delta^2 EI}{Ba^3} = -\frac{4G}{a}$$

Conclusão do exercício

Portanto, a força motriz (G) aumenta com o crescimento da trinca em controle de carga e decresce em controle de deslocamento. Para a curva R do tipo plana (Flat), o crescimento da trinca em controle de carga é sempre instável, enquanto em controle de deslocamento é sempre estável.

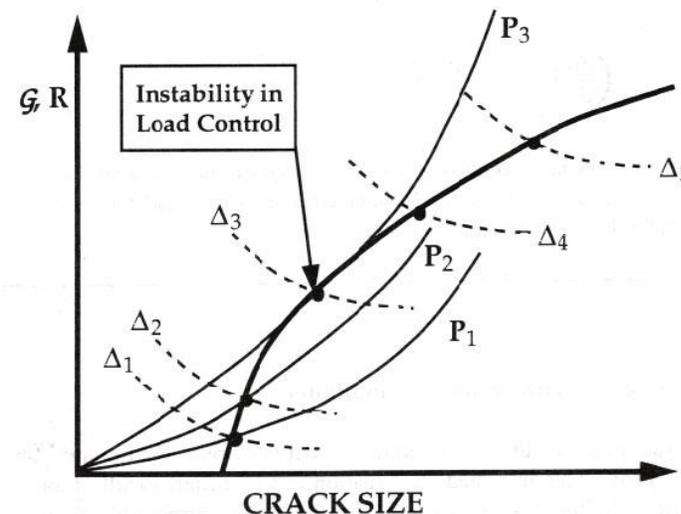
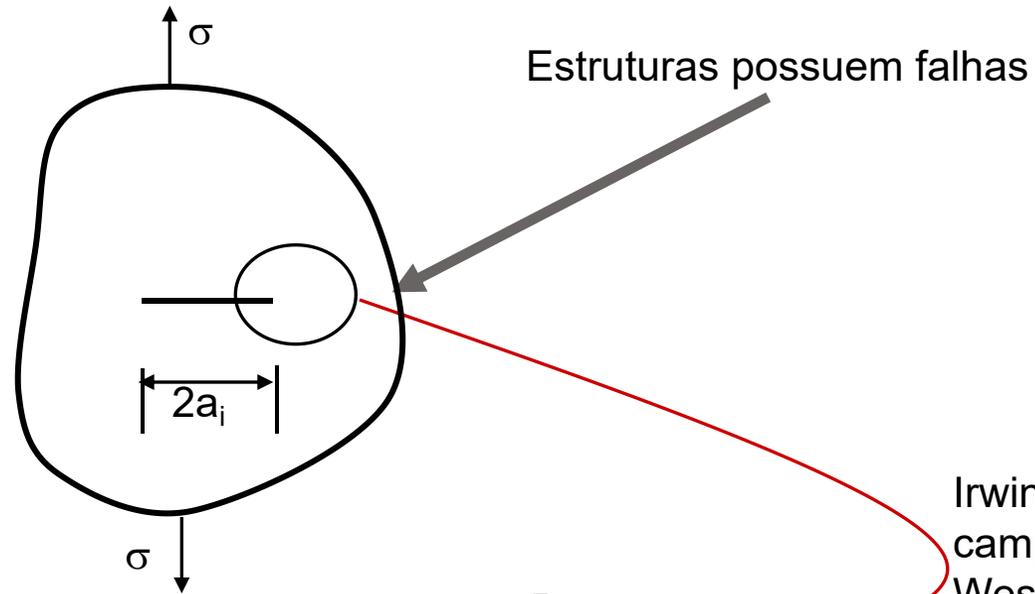
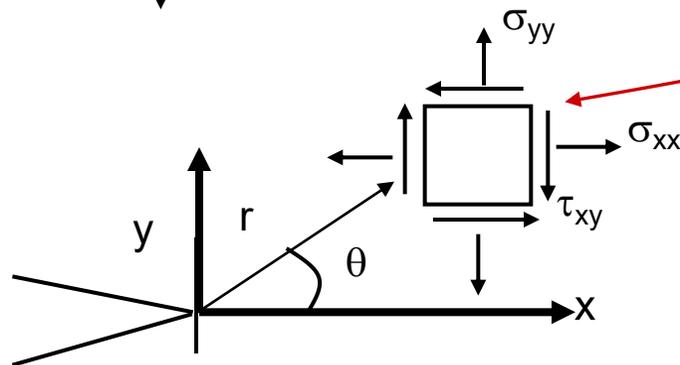


FIGURE 2.11 Schematic driving force/R curve diagram which compares load control and displacement control.

Teoria do campo de tensões elásticas

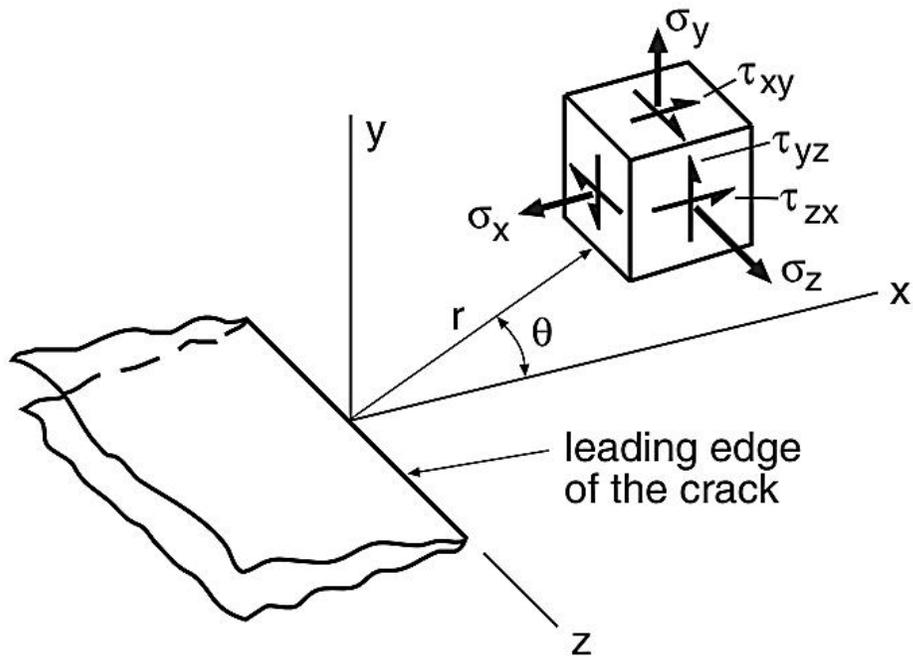


Irwin (1957) obteve as equações para o campo de tensões baseado no método de Westergaard (1930).



r e θ são coordenadas cilíndricas do ponto considerado e K é denominado de fator de intensidade de tensão.

$$\sigma_{ij} = \frac{K}{\sqrt{2\pi r}} f_{ij}(\theta)$$



$$\sigma_x = \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left[1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right] + \dots \quad (a)$$

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \left[1 + \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right] + \dots \quad (b)$$

$$\tau_{xy} = \frac{K_I}{\sqrt{2\pi r}} \cos \frac{\theta}{2} \sin \frac{\theta}{2} \cos \frac{3\theta}{2} + \dots \quad (c)$$

$$\sigma_z = 0 \quad (\text{plane stress}) \quad (d)$$

$$\sigma_z = \nu (\sigma_x + \sigma_y) \quad (\text{plane strain; } \epsilon_z = 0) \quad (e)$$

$$\tau_{yz} = \tau_{zx} = 0 \quad (f)$$

Termos
pequenos

Figure 8.10 Three-dimensional coordinate system for the region of a crack tip. (Adapted from [Tada 85]; used with permission.)

- K_I é o fator de intensidade de tensão no modo I de carregamento.
- Uma vez que K é determinado, todas as tensões $s_{x,y}$, $s_{x,y}$ e $\tau_{y,x}$ em qualquer ponto na frente da trinca (r, θ) são estabelecidas.

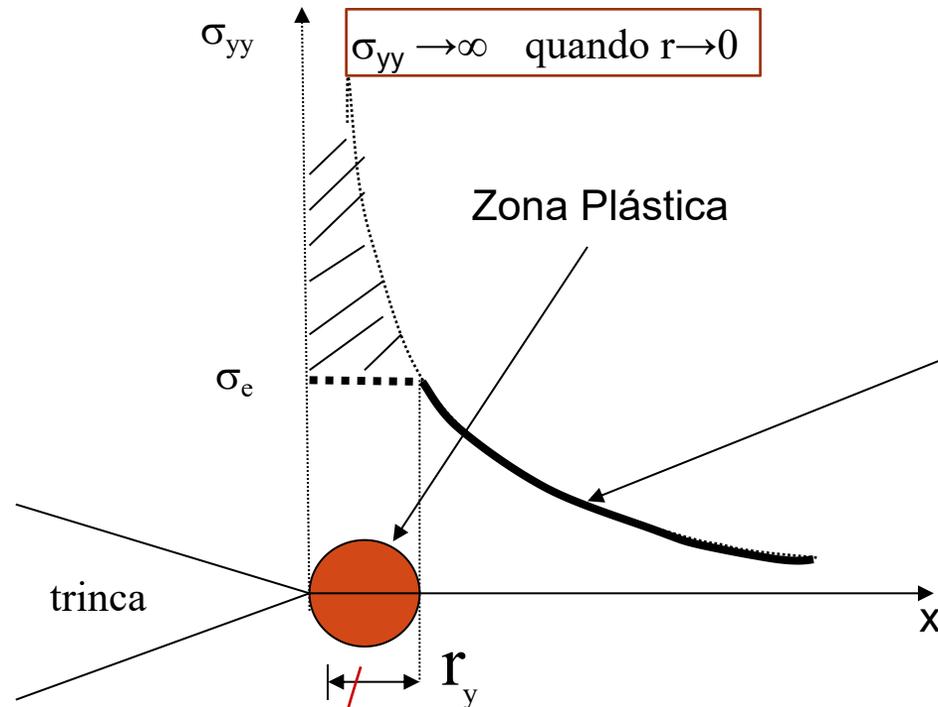
Considere o componente de tensão. σ_{yy}

$$\sigma = \frac{K_I}{\sqrt{\pi r}} \left[1 + \frac{1}{2} \left(\frac{r}{a} \right)^2 \right]$$

Ao longo do eixo X. $\theta = 0$:

$$\sigma_{\infty} = \frac{K_I}{\sqrt{2\pi r}} \cos(\theta/2) \left[1 + \sin(\theta/2) \sin(3\theta/2) \right]$$

$$\sigma = \frac{K_I}{\sqrt{\pi r}}$$



Raio da zona plástica

$$\left\{ \begin{array}{l} r_p = \frac{1}{2\pi} \left(\frac{K_I}{\sigma_e} \right)^2 \text{ tensão plana} \\ r_p = \frac{1}{6\pi} \left(\frac{K_I}{\sigma_e} \right)^2 \text{ Def. plana} \end{array} \right.$$

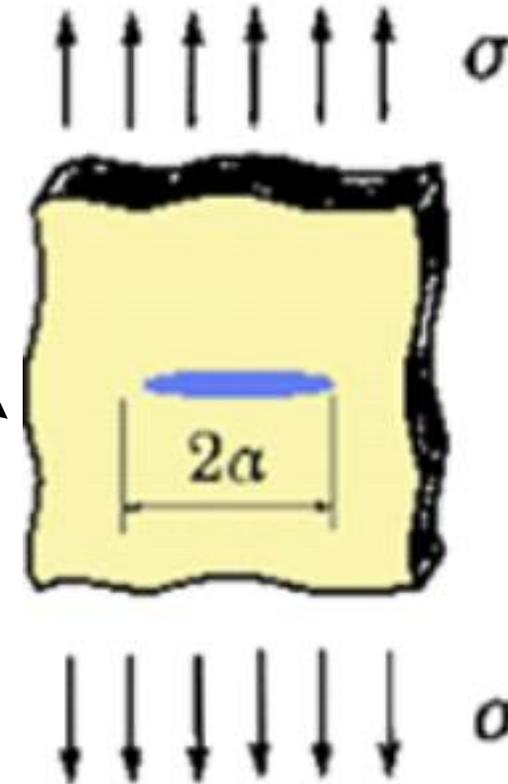
$r_p \ll$ as dimensões de a e do CP

Modo I (Tração)

$$K_I = \lim_{r \rightarrow 0} \left\{ \sqrt{2\pi r} \sigma_{yy} \right\}$$

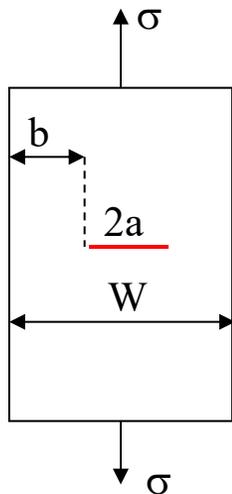
$$K_I = \sigma \sqrt{\pi a}$$

$$K_I = Y \sigma \sqrt{\pi \cdot a} \quad [\text{MPa}\sqrt{\text{m. ksi}\sqrt{\text{in}}}]$$



Y = fator de correção (das geometrias do corpo e da trinca). Soluções de K podem ser encontradas em vários livros: Tada, Paris e Irwin(1973); Rooke e Cartwright (1975); Sih (1973), entre outros.

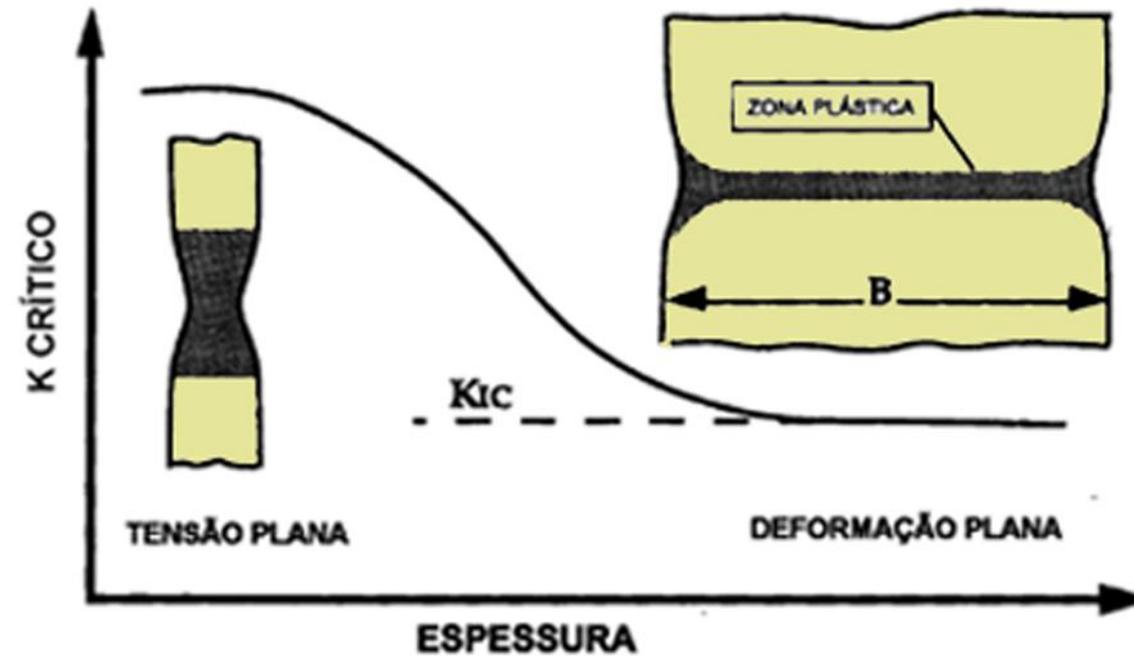
Critério de fratura



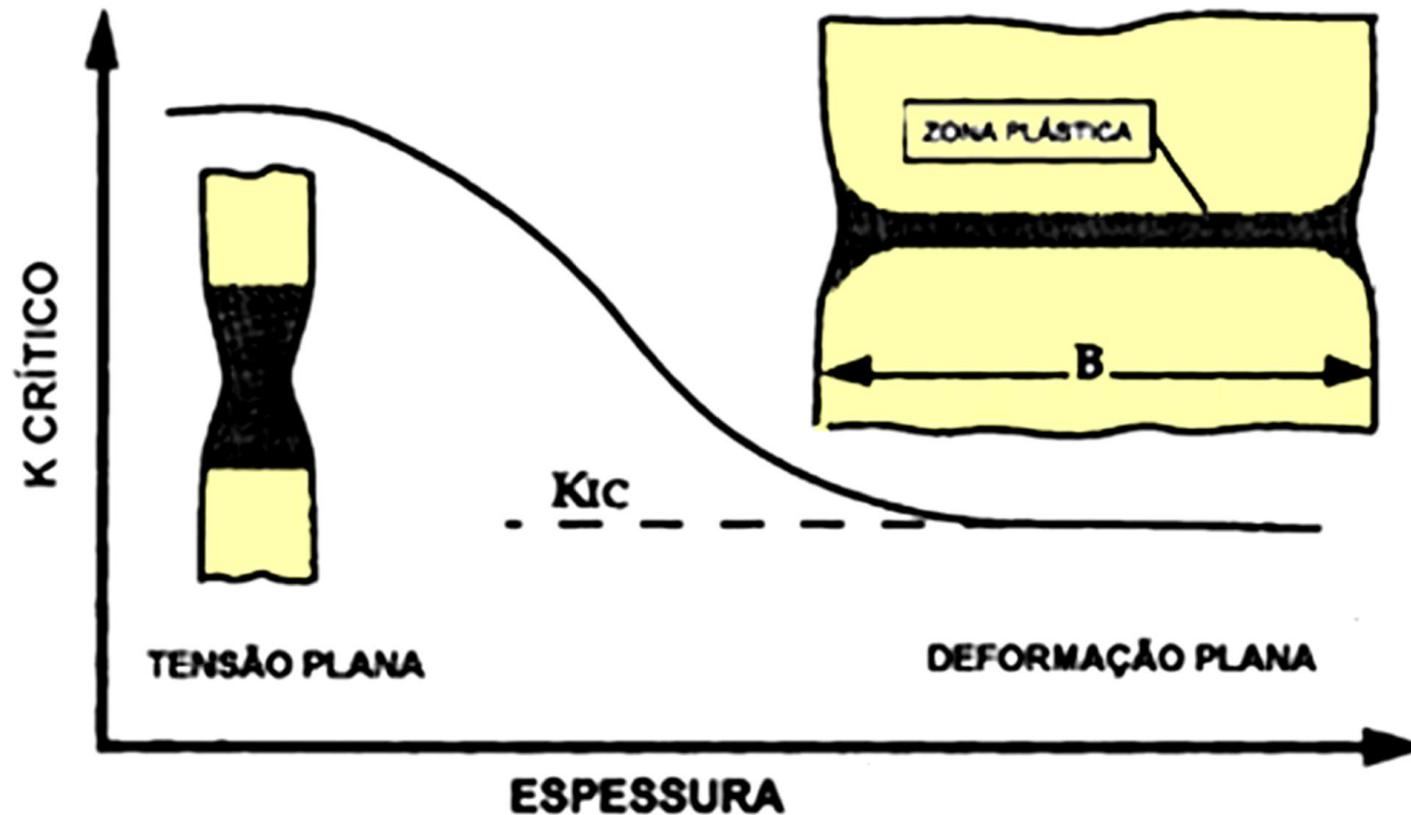
$$K = Y\sigma\sqrt{\pi a}$$

$K = K_C \rightarrow$ fratura instável

Tenacidade à Fratura.



Critério de fratura



Verifica Deformação Plana

Para que K_C seja considerado K_{IC} , a Norma ASTM E399 – Método Normalizado de Ensaio de Tenacidade à Fratura no Estado de Def. Plana de Materiais Metálicos.

$$a, B, b \geq 2,5 \left(\frac{K_I}{\sigma_e} \right)^2$$

Table 8.1 Fracture Toughness and Corresponding Tensile Properties for Representative Metals at Room Temperature

Material	Toughness K_{Ic}	Yield σ_o	Ultimate σ_u	Elong. $100\varepsilon_f$	Red. Area $\%RA$
	MPa \sqrt{m} (ksi \sqrt{in})	MPa (ksi)	MPa (ksi)	%	%
<i>(a) Steels</i>					
AISI 1144	66 (60)	540 (78)	840 (122)	5	7
ASTM A470-8 (Cr-Mo-V)	60 (55)	620 (90)	780 (113)	17	45
ASTM A517-F	187 (170)	760 (110)	830 (121)	20	66
AISI 4130	110 (100)	1090 (158)	1150 (167)	14	49
18-Ni maraging air melted	123 (112)	1310 (190)	1350 (196)	12	54
18-Ni maraging vacuum melted	176 (160)	1290 (187)	1345 (195)	15	66
300-M 650°C temper	152 (138)	1070 (156)	1190 (172)	18	56
300-M 300°C temper	65 (59)	1740 (252)	2010 (291)	12	48

(b) Aluminum and Titanium Alloys (L-T Orientation)

2014-T651	24 (22)	415 (60)	485 (70)	13	—
2024-T351	34 (31)	325 (47)	470 (68)	20	—
2219-T851	36 (33)	350 (51)	455 (66)	10	—
7075-T651	29 (26)	505 (73)	570 (83)	11	—
7475-T7351	52 (47)	435 (63)	505 (73)	14	—
Ti-6Al-4V annealed	66 (60)	925 (134)	1000 (145)	16	34

Sources: Data in [Barsom 87] p. 172, [Boyer 85] pp. 6.34, 6.35, and 9.8, [MILHDBK 94] pp. 3.10–3.12 and 5.3, and [Ritchie 77].

Table 8.2 Fracture Toughness of Some Polymers and Ceramics at Room Temperature

Material Polymers ¹	K_{Ic}		Material Ceramics ²	K_{Ic}	
	MPa \sqrt{m}	(ksi \sqrt{in})		MPa \sqrt{m}	(ksi \sqrt{in})
ABS	3.0	(2.7)	Soda-lime glass	0.76	(0.69)
Acrylic	1.8	(1.6)	Magnesia, MgO	2.9	(2.6)
Epoxy	0.6	(0.55)	Alumina, Al ₂ O ₃	4.0	(3.6)
PC	2.2	(2.0)	Al ₂ O ₃ , 15% ZrO ₂	10	(9.1)
PET	5.0	(4.6)	Silicon carbide	3.7	(3.4)
Polyester	0.6	(0.55)	SiC		
PS	1.15	(1.05)	Silicon nitride	5.6	(5.1)
PVC	2.4	(2.2)	Si ₃ N ₄		
PVC	3.35	(3.05)	Dolomitic limestone	1.30	(1.18)
rubber mod.			Westerly granite	0.89	(0.81)
			Concrete	1.19	(1.08)

Notes: ^{1,2}See Tables 4.3 and 3.10, respectively, for additional properties of similar materials.

Sources: Data in [ASM 88] p. 739, [Karfakis 90], [Kelly 86] p. 376, [Shah 95] p. 176, and [Williams 87] p. 243.

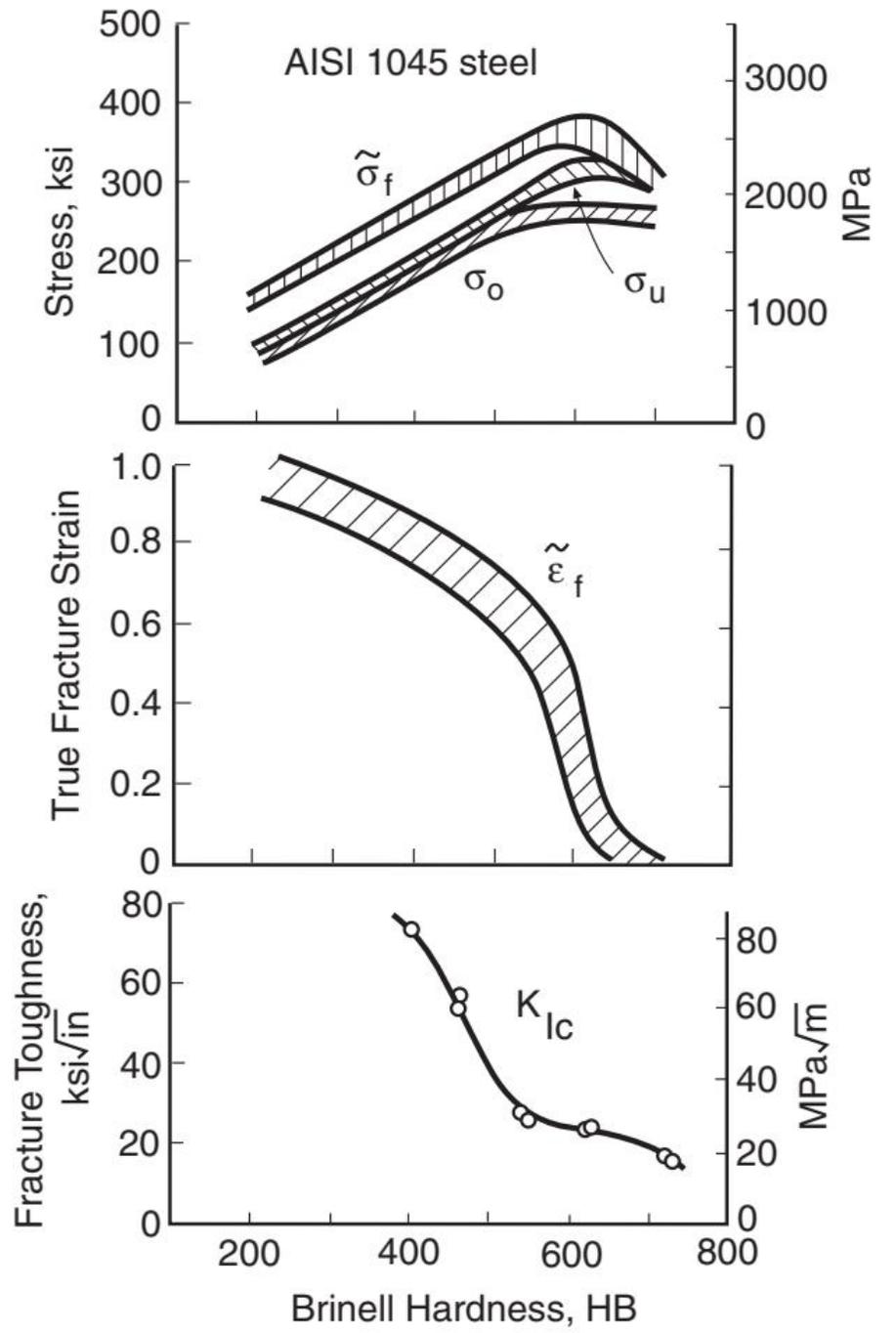
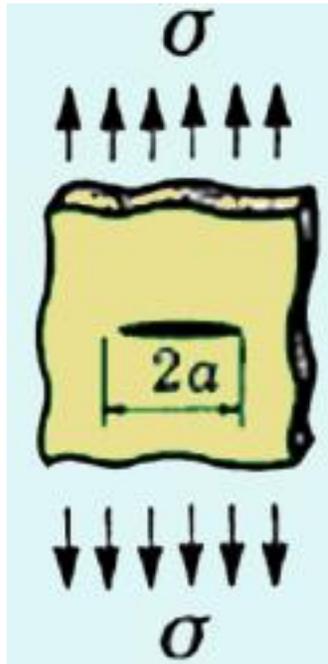


Figure 8.7 Comparison of properties from tension tests and fracture toughness tests for AISI 1045 steel, all plotted as functions of hardness, which is varied by heat treatment. (Illustration courtesy of R. W. Landgraf, Howell, MI.)

RELAÇÃO ENTRE K E G



$$G = \frac{K^2}{E'}$$

$$E' = E \quad (\text{plane stress; } \sigma_z = 0)$$

$$E' = \frac{E}{1 - \nu^2} \quad (\text{plane strain; } \varepsilon_z = 0)$$

Qualquer que seja a configuração.

APLICAÇÃO DE K EM PROJETOS E ANÁLISE DE PROBLEMAS DE FRATURA

- Para uso prático o valor de K dever ser determinado para geometrias de trincas existentes em componentes estruturais
- Neste aspecto um trabalho extensivo tem sido desenvolvido e o resultado pode ser encontrado em Handbooks:
 - Kujawski. D. Estimation of Stress Intensity Factors for small cracks and notches.
 - Murakami. Y. Stress Intensity Factors Handbook.
 - Newman. J. C. and I. Raju. Stress Intensity Factor Equations for Cracks in Three Dimensional Bodies Subjected to Tension and Bending Loads.
 - Outros.

EQUAÇÕES PARA K

$$K_I = F S \sqrt{\pi a}$$

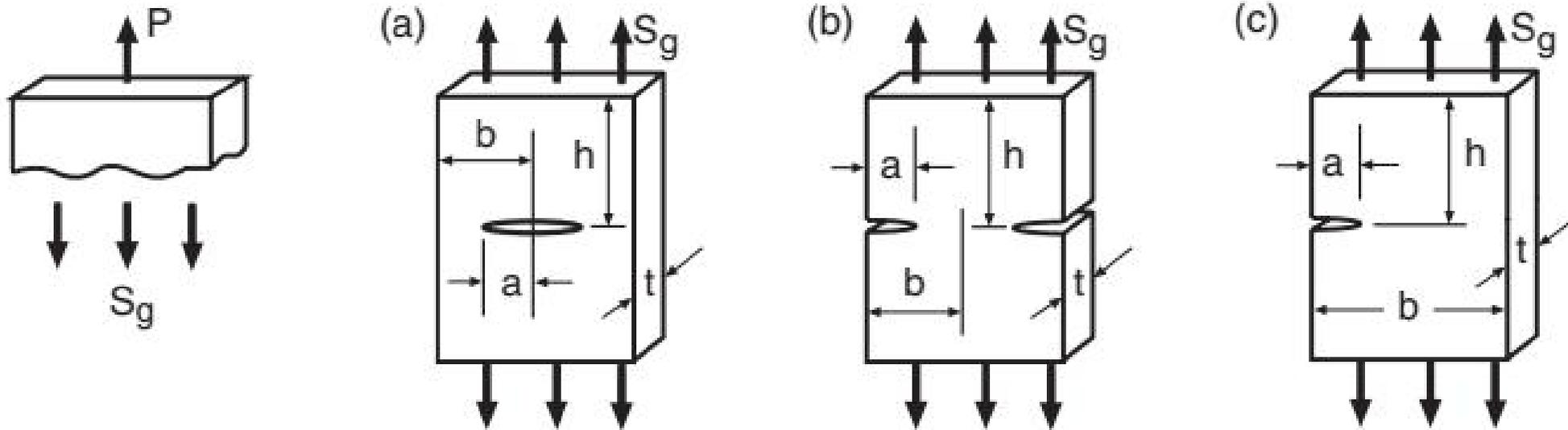


Figure 8.12 Stress intensity factors for three cases of cracked plates under tension. Geometries, curves, and equations labeled (a) all correspond to the same case, and similarly for (b) and (c). (Equations as collected by [Tada 85] pp. 2.2, 2.7, and 2.11.)

EQUAÇÕES PARA K

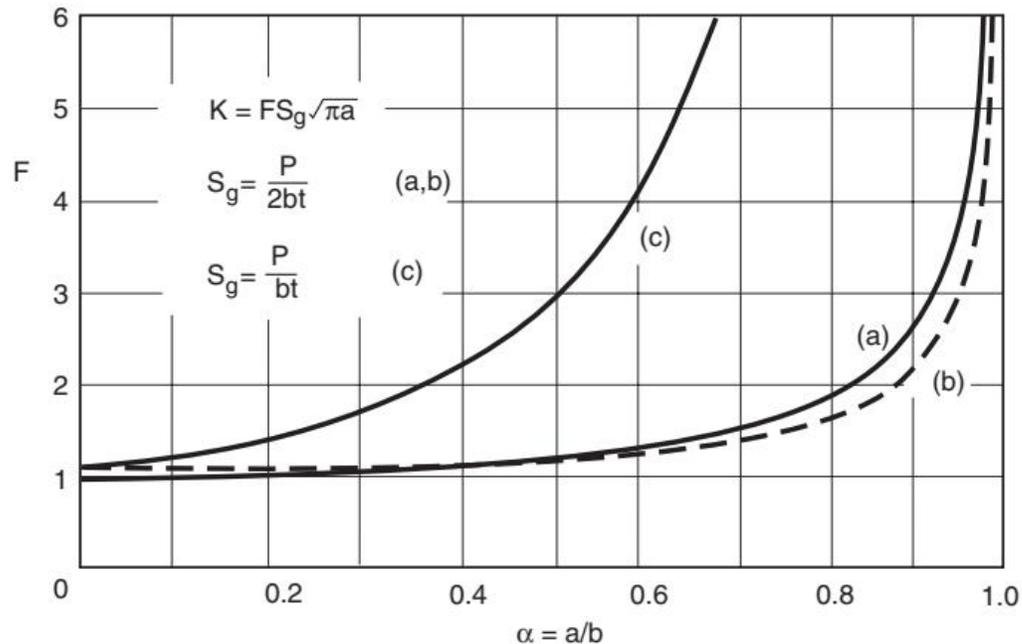
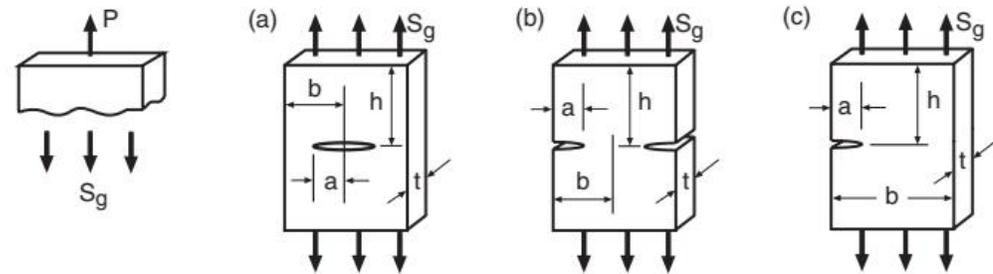


Figure 8.12 Stress intensity factors for three cases of cracked plates under tension. Geometries, curves, and equations labeled (a) all correspond to the same case, and similarly for (b) and (c). (Equations as collected by [Tada 85] pp. 2.2, 2.7, and 2.11.)

$$K_I = FS\sqrt{\pi a}$$

Values for small a/b and limits for 10% accuracy:

$$(a) \quad K = S_g\sqrt{\pi a}$$

$$(a/b \leq 0.4)$$

$$(b) \quad K = 1.12S_g\sqrt{\pi a}$$

$$(a/b \leq 0.6)$$

$$(c) \quad K = 1.12S_g\sqrt{\pi a}$$

$$(a/b \leq 0.13)$$

Expressions for any $\alpha = a/b$:

$$(a) \quad F = \frac{1 - 0.5\alpha + 0.326\alpha^2}{\sqrt{1 - \alpha}}$$

$$(h/b \geq 1.5)$$

$$(b) \quad F = \left(1 + 0.122 \cos^4 \frac{\pi\alpha}{2}\right) \sqrt{\frac{2}{\pi\alpha} \tan \frac{\pi\alpha}{2}}$$

$$(h/b \geq 2)$$

$$(c) \quad F = 0.265(1 - \alpha)^4 + \frac{0.857 + 0.265\alpha}{(1 - \alpha)^{3/2}}$$

$$(h/b \geq 1)$$

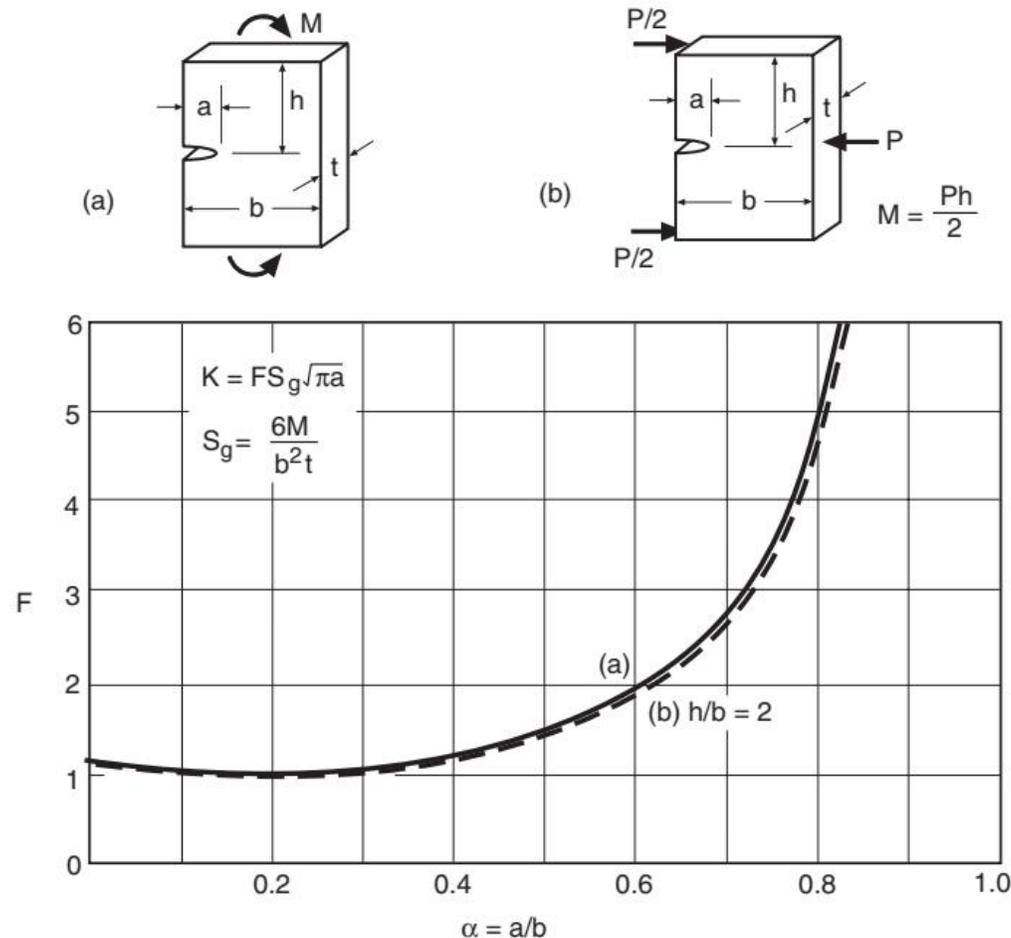


Figure 8.13 Stress intensity factors for two cases of bending. Geometries, curves, and equations labeled (a) all correspond to the same case, and similarly for (b). Case (b) with $h/b = 2$ is the ASTM standard bend specimen. (Equations from [Tada 85] p. 2.14, and [ASTM 97] Std. E399.)

Values for small a/b and limits for 10% accuracy:

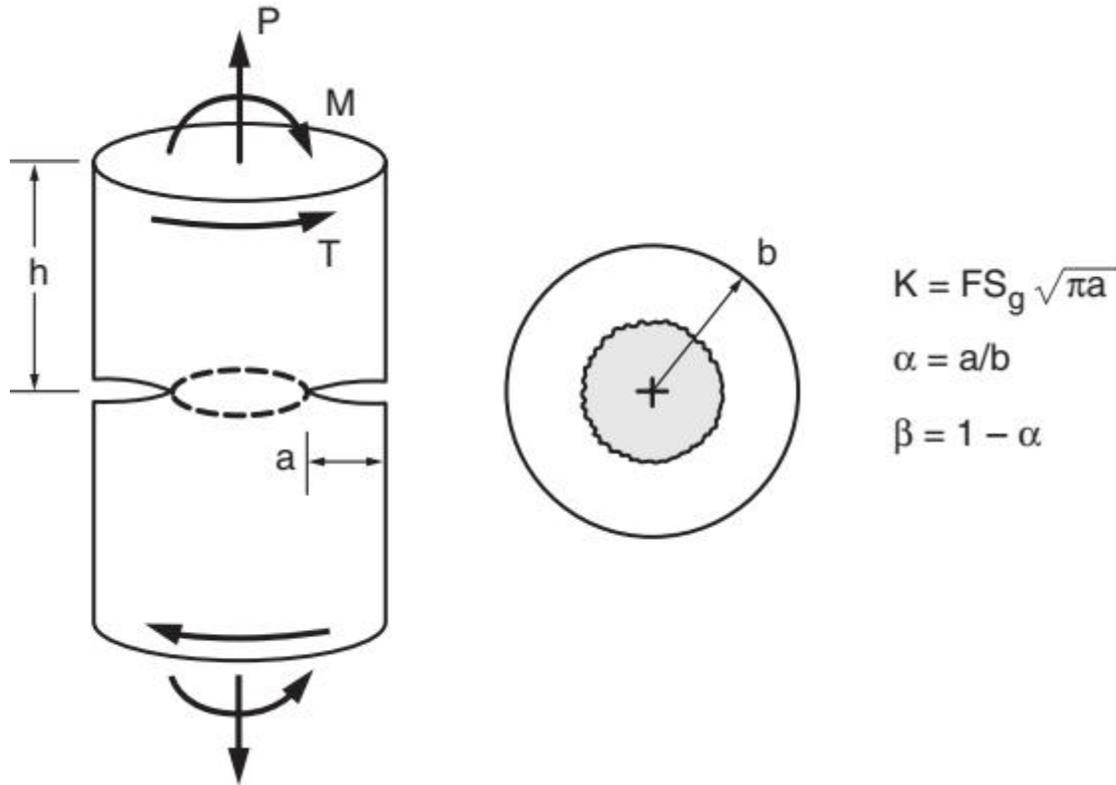
$$(a, b) \quad K = 1.12S_g\sqrt{\pi a} \quad (a/b \leq 0.4)$$

Expressions for any $\alpha = a/b$:

$$(a) \quad F = \sqrt{\frac{2}{\pi\alpha} \tan \frac{\pi\alpha}{2}} \left[\frac{0.923 + 0.199 \left(1 - \sin \frac{\pi\alpha}{2}\right)^4}{\cos \frac{\pi\alpha}{2}} \right] \quad (\text{large } h/b)$$

(b) F is within 3% of (a) for $h/b = 4$, and within 6% for $h/b = 2$, at any a/b :

$$F = \frac{1.99 - \alpha(1 - \alpha)(2.15 - 3.93\alpha + 2.7\alpha^2)}{\sqrt{\pi}(1 + 2\alpha)(1 - \alpha)^{3/2}} \quad (h/b = 2)$$



(a) Axial load P : $S_g = \frac{P}{\pi b^2}$, $F = 1.12$ (10%, $a/b \leq 0.21$)

$$F = \frac{1}{2\beta^{1.5}} \left[1 + \frac{1}{2}\beta + \frac{3}{8}\beta^2 - 0.363\beta^3 + 0.731\beta^4 \right]$$

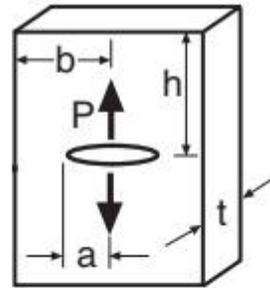
(b) Bending moment M : $S_g = \frac{4M}{\pi b^3}$, $F = 1.12$ (10%, $a/b \leq 0.12$)

$$F = \frac{3}{8\beta^{2.5}} \left[1 + \frac{1}{2}\beta + \frac{3}{8}\beta^2 + \frac{5}{16}\beta^3 + \frac{35}{128}\beta^4 + 0.537\beta^5 \right]$$

(c) Torsion T , $K = K_{III}$: $S_g = \frac{2T}{\pi b^3}$, $F = 1.00$ (10%, $a/b \leq 0.09$)

$$F = \frac{3}{8\beta^{2.5}} \left[1 + \frac{1}{2}\beta + \frac{3}{8}\beta^2 + \frac{5}{16}\beta^3 + \frac{35}{128}\beta^4 + 0.208\beta^5 \right]$$

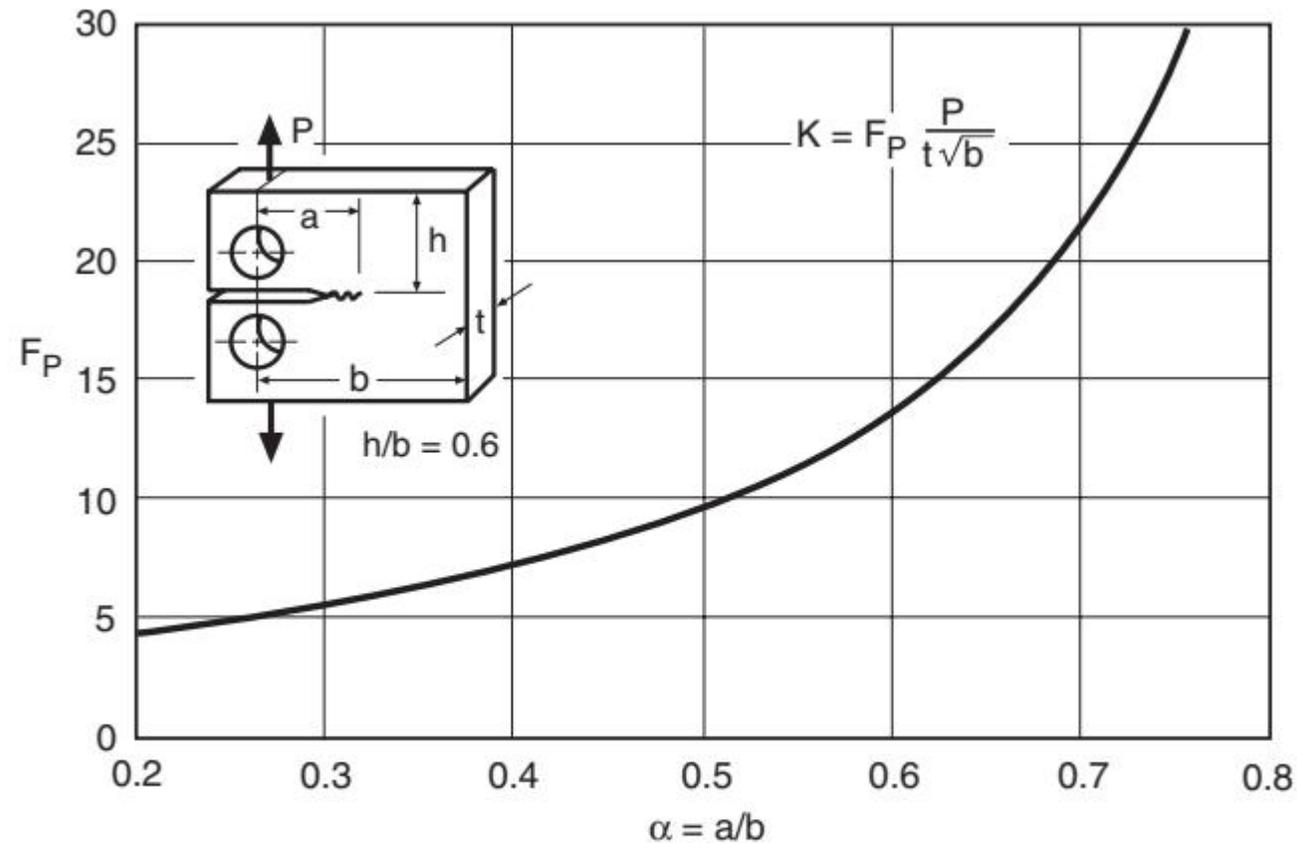
Figure 8.14 Stress intensities for a round shaft with a circumferential crack, including limits on the constant F for 10% accuracy and expressions for any $\alpha = a/b$. For torsion (c), the stress intensity is for the shear Mode III. (Equations from [Tada 85] pp. 27.1, 27.2, and 27.3.).



$$K = F_P \frac{P}{t\sqrt{b}}, \quad \alpha = \frac{a}{b}, \quad F_P = \frac{1}{\sqrt{\pi\alpha}} \quad (10\%, \frac{a}{b} \leq 0.3)$$

$$F_P = \frac{1.297 - 0.297 \cos \frac{\pi\alpha}{2}}{\sqrt{\sin \pi\alpha}} \quad (0 \leq \frac{a}{b} \leq 1)$$

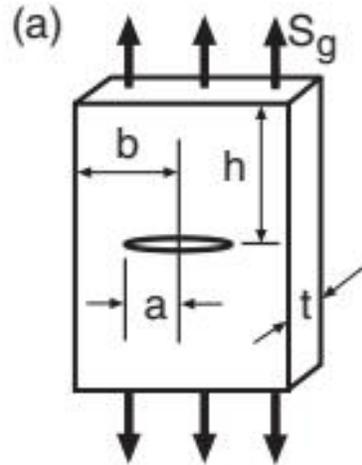
Figure 8.15 Stress intensity factor for forces applied to the faces of a central crack in a plate with $h/b \geq 2$. A simple expression is given for F_P that is within 10% for a limited range of $\alpha = a/b$, as is an expression valid for any α . (Equations from [Tada 85] pp. 2.22 and 2.23.).



$$F_P = \frac{2 + \alpha}{(1 - \alpha)^{3/2}} (0.886 + 4.64\alpha - 13.32\alpha^2 + 14.72\alpha^3 - 5.6\alpha^4) \quad (a/b \geq 0.2)$$

Figure 8.16 Stress intensity factor for the ASTM standard compact specimen, as determined from $F_P = F_P(\alpha)$, where $\alpha = a/b$. (Equation from [Srawley 76].)

EXAMPLE 8.1



Values for small a/b and limits for 10% accuracy:

$$\begin{array}{lll} \text{(a) } K = S_g \sqrt{\pi a} & \text{(b) } K = 1.12 S_g \sqrt{\pi a} & \text{(c) } K = 1.12 S_g \sqrt{\pi a} \\ (a/b \leq 0.4) & (a/b \leq 0.6) & (a/b \leq 0.13) \end{array}$$

Expressions for any $\alpha = a/b$:

$$\begin{array}{ll} \text{(a) } F = \frac{1 - 0.5\alpha + 0.326\alpha^2}{\sqrt{1 - \alpha}} & (h/b \geq 1.5) \\ \text{(b) } F = \left(1 + 0.122 \cos^4 \frac{\pi\alpha}{2}\right) \sqrt{\frac{2}{\pi\alpha} \tan \frac{\pi\alpha}{2}} & (h/b \geq 2) \\ \text{(c) } F = 0.265 (1 - \alpha)^4 + \frac{0.857 + 0.265\alpha}{(1 - \alpha)^{3/2}} & (h/b \geq 1) \end{array}$$

Example 8.1

A center-cracked plate, as in Fig. 8.12(a), has dimensions $b = 50 \text{ mm}$, $t = 5 \text{ mm}$, and large h ; a force of $P = 50 \text{ kN}$ is applied.

- What is the stress intensity factor K for a crack length of $a = 10 \text{ mm}$?
- For $a = 30 \text{ mm}$?
- What is the critical crack length a_c for fracture if the material is 2014-T651 aluminum?

Solution (a) To calculate K for $a = 10 \text{ mm}$, using Fig. 8.12(a), we need

$$S_g = \frac{P}{2bt} = \frac{50,000 \text{ N}}{2(50 \text{ mm})(5 \text{ mm})} = 100 \text{ MPa}, \quad \alpha = \frac{a}{b} = \frac{10 \text{ mm}}{50 \text{ mm}} = 0.200$$

Since $\alpha \leq 0.4$, it is within 10% to use $F = 1$. Thus,

$$K = S_g \sqrt{\pi a} = (100 \text{ MPa}) \sqrt{\pi (0.010 \text{ m})} = 17.7 \text{ MPa}\sqrt{\text{m}} \quad \text{Ans.}$$

where crack length a is entered in units of meters to obtain the desired units for K of $\text{MPa}\sqrt{\text{m}}$.

(b) For $a = 30 \text{ mm}$, we have $\alpha = a/b = (30 \text{ mm})/(50 \text{ mm}) = 0.600$. This does not satisfy $\alpha \leq 0.4$, so the more general expression for F from Fig. 8.12(a) is needed:

$$F = \frac{1 - 0.5\alpha + 0.326\alpha^2}{\sqrt{1 - \alpha}} = 1.292$$

$$K = F S_g \sqrt{\pi a} = 1.292 (100 \text{ MPa}) \sqrt{\pi (0.030 \text{ m})} = 39.7 \text{ MPa}\sqrt{\text{m}} \quad \text{Ans.}$$

EXAMPLE 8.1

(c) Table 8.1 gives $K_{Ic} = 24 \text{ MPa}\sqrt{\text{m}}$ for 2014-T651 Al. Since a_c is not known, F cannot be determined directly. First, assume that $\alpha \leq 0.4$ is satisfied, in which case $F \approx 1$. Then

$$K_{Ic} \approx S_g \sqrt{\pi a_c}$$

Solving for a_c gives

$$a_c \approx \frac{1}{\pi} \left(\frac{K_{Ic}}{S_g} \right)^2 = \frac{1}{\pi} \left(\frac{24 \text{ MPa}\sqrt{\text{m}}}{100 \text{ MPa}} \right)^2 = 0.0183 \text{ m} = 18.3 \text{ mm} \quad \text{Ans.}$$

This corresponds to $\alpha = a_c/b = (18.3 \text{ mm})/(50 \text{ mm}) = 0.37$, which satisfies $\alpha \leq 0.4$, so that the estimated $F \approx 1$ is acceptable and the result obtained is reasonably accurate.

If it is not desired to use the 10% approximation on F , an iterative solution is needed. Toward that end, substitute the expression for F into the equation for K :

$$K = \frac{1 - 0.5(a/b) + 0.326(a/b)^2}{\sqrt{1 - (a/b)}} S_g \sqrt{\pi a}$$

Then, using the values $K = K_{Ic} = 24 \text{ MPa}\sqrt{\text{m}}$, $b = 0.050 \text{ m}$, and $S_g = 100 \text{ MPa}$, solve for a by trial and error, Newton's method, or another numerical procedure, as implemented in various widely available computer software. The result is

$$a_c = 0.01627 \text{ m} = 16.3 \text{ mm} \quad \text{Ans.}$$

which value is seen to differ somewhat from the previous one. (The actual value of F that corresponds to this a_c is $F_c = 1.061$.)

A graphical procedure could also be used to obtain this result: Select a number of values of a , and for each of these calculate $\alpha = a/b$. Then calculate F by using the polynomial-type expression as in (b), and calculate K , obtaining values such as those in Table E8.1. Next, plot the resulting values of K versus a as in Fig. E8.1. Finally, enter this graph with the desired value of $K = K_{Ic} = 24 \text{ MPa}\sqrt{\text{m}}$, and read the corresponding crack length as accurately as the graph permits, giving $a_c = 16.3 \text{ mm}$ (Ans.).

Table E8.1

Calc. No.	a mm	$\alpha = a/b$	F	$K = FS_g\sqrt{\pi a}$ MPa $\sqrt{\text{m}}$
1	10	0.20	1.021	18.1
2	15	0.30	1.051	22.8
3	20	0.40	1.100	27.6

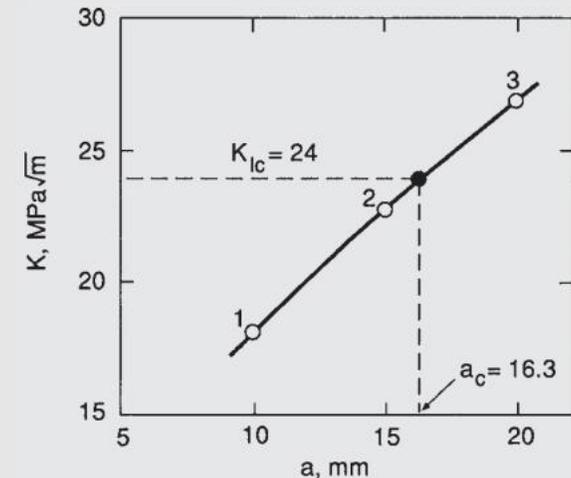


Figure E8.1

Comment For (c), an iterative or graphical solution is optional in this case, but is necessary in other cases where a limit on α for 10% accuracy in K is exceeded.

FATOR DE SEGURANÇA

Fatores com relação ao faturamento frágil:

$$X_K = \frac{K_{Ic}}{K} = \frac{K_{Ic}}{F S_g \sqrt{\pi a}}$$

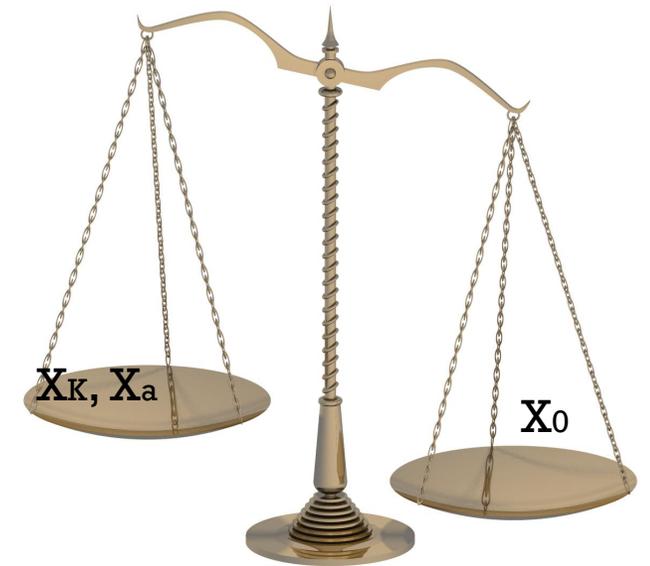
$$K_{Ic} = F_c S_g \sqrt{\pi a_c}$$

$$X_a = \frac{a_c}{a} = \left(\frac{F}{F_c} X_K \right)^2$$

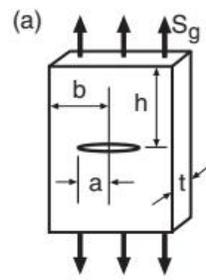
Fatores com relação ao escoamento:

$$X_o = \sigma_o / S_g$$

$$X'_o = P_o / P, \quad X'_o = M_o / M$$



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Example 8.2

Consider the situation of Ex. 8.1, where a center-cracked plate of 2014-T651 aluminum, with dimensions $b = 50$ and $t = 5$ mm, is subjected in service to a force of $P = 50$ kN.

- What is the largest crack length a that can be permitted for a safety factor against fracture of 3.0 in stress?
- What safety factor on crack length results from the safety factor in stress of (a)?
- What is the safety factor against yielding?

Solution (a) Equation 8.15 gives the highest value of K that can be allowed:

$$K = \frac{K_{Ic}}{X_K} = \frac{24 \text{ MPa}\sqrt{\text{m}}}{3.0} = 8.0 \text{ MPa}\sqrt{\text{m}}$$

Hence, this K is employed to obtain the largest crack length that can be permitted:

$$K = F S_g \sqrt{\pi a}, \quad 8.0 \text{ MPa}\sqrt{\text{m}} = F(100 \text{ MPa})\sqrt{\pi a}$$

Assuming that $F = 1$ is sufficiently accurate, solving for a gives

$$a = 2.04 \text{ mm} \quad \text{Ans.}$$

Since $\alpha = a/b = (2.04 \text{ mm})/(50 \text{ mm}) = 0.0408$, we are well within the limit for 10% accuracy on K , and this result is reasonably accurate. If F is allowed to vary, as in Ex. 8.1(c), essentially the same result is obtained: $a = 2.03$ mm (Ans.).

(b) In Ex. 8.1(c), the crack length causing failure at the service stress is calculated to be $a_c = 16.3$ mm. Comparing this with the value of a from part (a) of this example gives the safety factor on crack length:

$$X_a = a_c/a = (16.3 \text{ mm})/(2.03 \text{ mm}) = 8.03 \quad \text{Ans.}$$

(c) The safety factor against yielding, calculated as if no crack is present, is given by Eq. 8.18 and is

$$X_o = \sigma_o/S_g = (415 \text{ MPa})/(100 \text{ MPa}) = 4.15 \quad \text{Ans.}$$

where the yield strength value is from Table 8.1. A more detailed calculation that uses the fully plastic limit force as in Eq. 8.19 is

$$X'_o = \frac{P_o}{P} = \frac{2bt\sigma_o(1 - a/b)}{P} = \frac{2(50 \text{ mm})(5 \text{ mm})(415 \text{ MPa})}{50,000 \text{ N}} \left(1 - \frac{2.03 \text{ mm}}{50 \text{ mm}}\right) = 3.98 \quad \text{Ans.}$$

where the expression for P_o is obtained from Fig. A.16(a), and P is the actual service force.

Comments The safety factor on crack length is rather large, as expected. Either of the safety factors against yielding is higher than $X_K = 3.0$, indicating that this member is closer to brittle fracture than to yielding; that is, $X_K = 3.0$ is the controlling safety factor.

EXAMPLE 8.3

Example 8.3

An engineering member made of titanium 6Al-4V (annealed) is a plate loaded in tension that may have a crack in one edge, as shown in Fig. 8.12(c). The applied force is $P = 55$ kN, the width is $b = 40$ mm, and the crack may be as long as $a = 6$ mm. If a safety factor of 3.0 in stress is required, what minimum plate thickness t is required?

Solution The stress intensity $K = FS_g\sqrt{\pi a}$ must be below K_{Ic} by a safety factor $X_K = 3.0$. Noting this and substituting the expression for S_g from Fig. 8.12(c) gives

$$K = \frac{K_{Ic}}{X_K} = F \frac{P}{bt} \sqrt{\pi a}, \quad \frac{66 \text{ MPa}\sqrt{\text{m}}}{3.0} = F \frac{55,000 \text{ N}}{(40 \text{ mm})(t, \text{ mm})} \sqrt{\pi(0.006 \text{ m})}$$

where K_{Ic} is from Table 8.1. Note that $F = 1.12$ with 10% accuracy up to $\alpha = 0.13$. But $\alpha = a/b = (6 \text{ mm})/(40 \text{ mm}) = 0.15$ is beyond this limit, so F must be calculated by substituting this α into the appropriate polynomial-type expression. The result is

$$F = 0.265(1 - \alpha)^4 + \frac{0.857 + 0.265\alpha}{(1 - \alpha)^{3/2}} = 1.283$$

Substituting this F and solving gives $t = 11.01$ mm (**Ans.**).

However, we need to check that the safety factor is also met for yielding. The fully plastic limit force, from Fig. A.16(d), is

$$P_o = bt\sigma_o \left[-\alpha + \sqrt{2\alpha^2 - 2\alpha + 1} \right]$$

$$P_o = (40 \text{ mm})(11.01 \text{ mm})(925 \text{ MPa}) \left[-0.15 + \sqrt{2(0.15)^2 - 2(0.15) + 1} \right] = 290,400 \text{ N}$$

where the yield strength is from Table 8.1. Hence, the safety factor against yielding is

$$X'_o = \frac{P_o}{P} = \frac{290.4 \text{ kN}}{55 \text{ kN}} = 5.28$$

which exceeds the required value, so the preceding result of $t = 11.01$ mm is the final answer.

EXEMPLO 3.1 - RESISTÊNCIA VS. TENACIDADE

- A tenacidade à fratura do material diminui, muitas vezes dramaticamente quando o limite de escoamento do material aumenta. Por exemplo, para um liga Ti-6Al-4V, com o limite de escoamento de 130 ksi a tenacidade à fratura é 105 ksi $\sqrt{\text{pol}}$. Se o limite de escoamento é aumentado para 150 ksi, a tenacidade à fratura diminui para 50 ksi $\sqrt{\text{pol}}$.

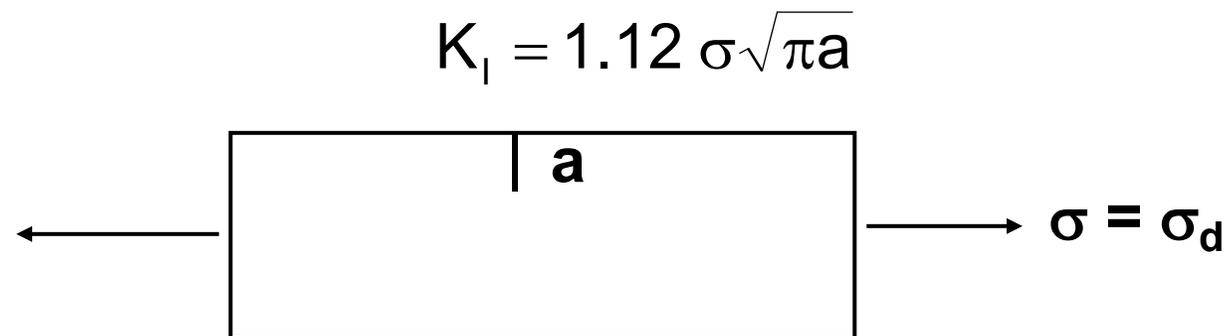
Um engenheiro é desafiado com o seguinte problema:

- A empresa dele fabrica um componente na forma de uma chapa ou placa grande usando a liga acima na condição que o limite de escoamento é de 130 ksi. Tem sido sugerido uma redução de peso que poderia ser obtido pelo uso de uma liga com limite de escoamento de 150 ksi. O ensaio não destrutivo do componente pode prontamente detectar uma trinca 0,2 pol. Assim, os requisitos do projeto especifica que a trinca de canto pode ser maior do que esta medida de trinca (0,2 pol) de maneira que ela possa ser detectada antes da fratura catastrófica. Em adição, um fator de segurança de 2 é especificado para uma tensão de projeto.

A tensão de projeto deve ser menor ou igual a metade do limite de escoamento. Ele tem sido perguntado a analisar a proposta de mudar de material.

- a) Deve ele aceitar a proposta? Verifique com cálculos e comentários.
- b) Qual é a máxima tensão de projeto que pode ser usada com o material de máxima resistência?
- c) O uso de um material de mais alta resistência levará a redução de peso?

Para esta geometria:



a) Material Original:

A tensão de projeto é baseada no escoamento $\sigma_d = \sigma_{ys}/2 = 65$ ksi

Fratura irá ocorrer quando $K_I = K_{IC}$; dado $K_{IC} = 105$ ksi $\sqrt{\text{pol}}$

$$1.12 \sigma_d \sqrt{\pi a_{cr}} = 105 \quad \Rightarrow \quad a_{cr} = 0.66 \text{ pol}$$

IND/END pode detectar qualquer trinca maior do que 0.2 pol, i.e., uma trinca de 0.2 pol ou menor escapará da inspeção.

Em um projeto de 65 ksi, um comprimento de 0.66 pol produzirá falha catastrófica. Isto não irá acontecer porque nenhuma trinca de comprimento 0.2 pol ou maior escapa da inspeção.

O projeto é seguro contra fratura frágil!!

Novos Materiais: $\sigma_d = 150/2 = 75$ ksi

Falha por fratura se $K_I = K_{IC}$; dado. $K_{IC} = 50$ ksi $\sqrt{\text{pol}}$

$$1.12 (75) \sqrt{\pi a_{cr}} = 50 \Rightarrow \boxed{a_{cr} = 0.113''}$$

IND/END pode detectar qualquer trinca maior do que 0.2 pol.. i.e.. uma trinca de 0.113 pol escapará a inspeção!!

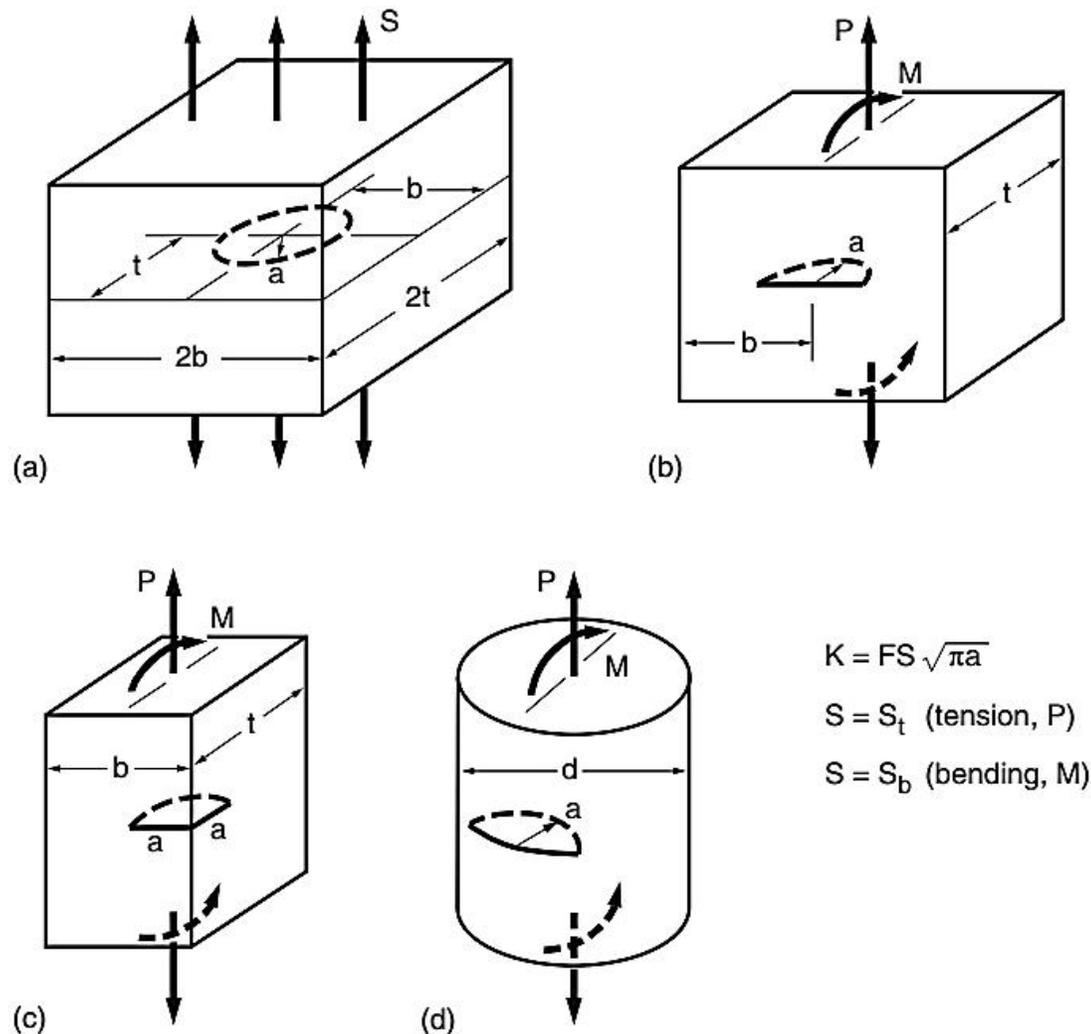
A trinca pode tornar-se crítica antes de ser detectada se $\sigma_d = 75$ ksi. O novo projeto é baseado no escoamento e não será seguro contra fratura frágil.

Qual é então a tensão de projeto baseada na fratura (assumindo que todos os componentes contêm um trinca de 0.2 pol?)

$$K_I = K_{IC} = 1.12 \sigma_d \sqrt{\pi(0.2)} = 50 \quad \boxed{\sigma_d = 56.3 \text{ ksi}}$$

Menor do que σ_d para o material original

CASOS DE INTERESSE ESPECIAL PARA APLICAÇÕES PRÁTICAS



$$K = FS\sqrt{\pi a}$$

$$S = S_t \text{ (tension, P)}$$

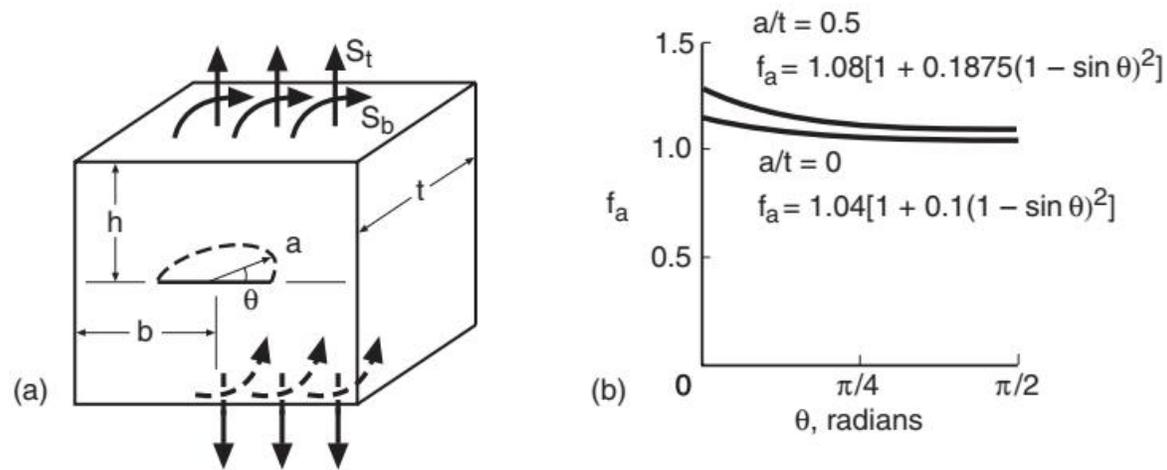
$$S = S_b \text{ (bending, M)}$$

Considerando a 10% de acuracidade

Case	S_t	S_b	F for small a	Limits for $\pm 10\%$ on F
(a)	$\frac{P}{4bt}$	—	$\frac{2}{\pi} = 0.637$	$\frac{a}{t}, \frac{a}{b} < 0.5$
(b)	$\frac{P}{2bt}$	$\frac{3M}{bt^2}$	0.728	$\frac{a}{t} < 0.4, \frac{a}{b} < 0.3$
(c)	$\frac{P}{bt}$	$\frac{6M}{bt^2}$	0.722	$\frac{a}{t} < 0.35, \frac{a}{b} < 0.2$
(d)	$\frac{4P}{\pi d^2}$	$\frac{32M}{\pi d^3}$	0.728	$\frac{a}{d} < 0.2$ or 0.35^1

Note: ¹Different limits for tension or bending, respectively.

Figure 8.17 Stress intensity factors for (a) an embedded circular crack under uniform tension normal to the crack plane, and related cases: (b) half-circular surface crack, (c) quarter-circular corner crack, and (d) half-circular surface crack in a shaft, where the latter is more precisely a portion of a circular arc with center on the surface. (Based on [Newman 86] and [Raju 86].)



Functional forms for $a/b < 0.5$, $h/b > 1$:

$$K = f_a f_w \frac{2}{\pi} (S_t + f_b S_b) \sqrt{\pi a}, \quad f_w = \sqrt{\sec\left(\frac{\pi a}{2b} \sqrt{\frac{a}{t}}\right)}$$

$$\text{where } f_a = f_a(a/t, \theta), \quad f_b = f_b(a/t)$$

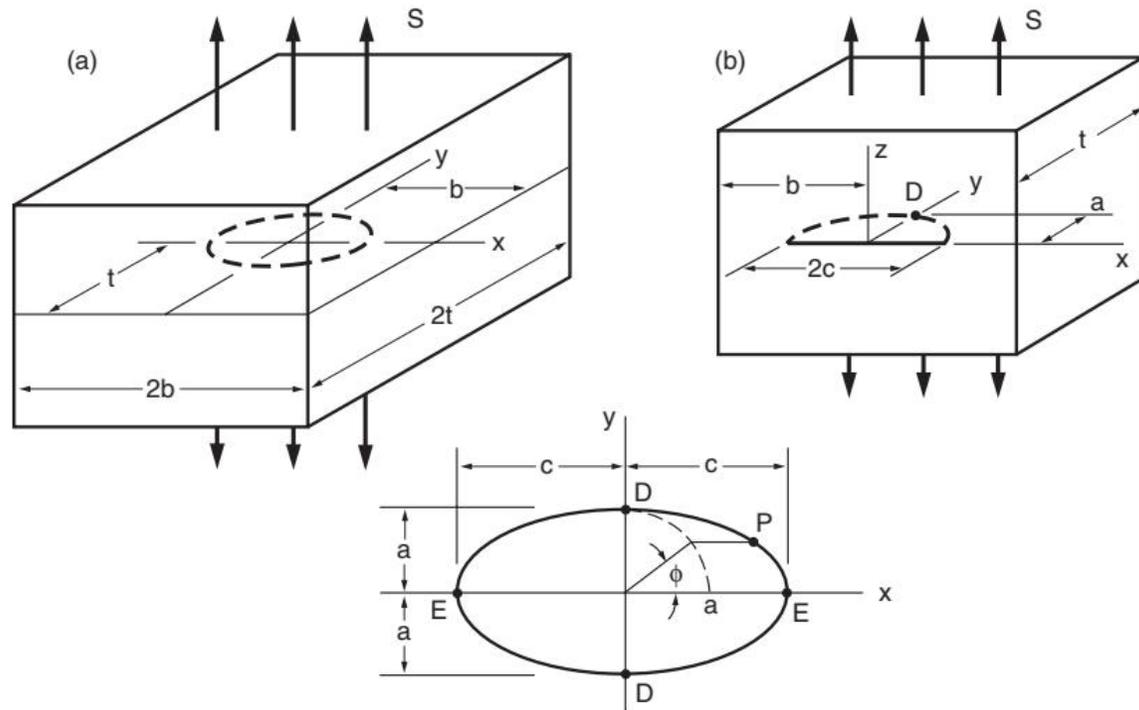
Expressions for $\theta = 0$ and 180° (surface) for any $\alpha = a/t$:

$$f_a = (1.04 + 0.2017\alpha^2 - 0.1061\alpha^4)(1.1 + 0.35\alpha^2), \quad f_b = 1 - 0.45\alpha$$

Expressions for $\theta = 90^\circ$ (deepest point) for any $\alpha = a/t$:

$$f_a = 1.04 + 0.2017\alpha^2 - 0.1061\alpha^4, \quad f_b = 1 - 1.34\alpha - 0.03\alpha^2$$

Figure 8.18 Stress intensity factors for rectangular cross sections as in (a) for half-circular surface cracks under tension and/or bending. The general form for K is given, as well as particular equations for the surface and deepest point for any a/t . Also, (b) shows the variation with θ for $a/t = 0$ and 0.5 as given by f_a . (Equations from [Newman 86].)



$$K_D = F_D S \sqrt{\frac{\pi a}{Q}}, \quad Q \approx 1 + 1.464 \left(\frac{a}{c}\right)^{1.65} \quad (a/c \leq 1)$$

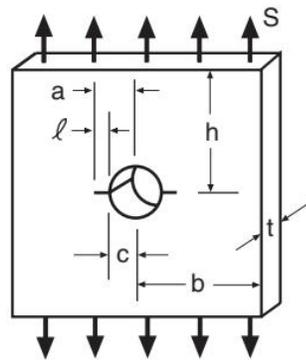
Case	Values for small $a/t, c/b$	Limits for 10% accuracy
(a)	$F_D = 1$	$a/t < 0.4, c/b < 0.2$
(b)	$F_D \approx 1.12$	$a/t < 0.3,^1 c/b < 0.2$

Note: ¹Except limit to $a/t < 0.16$ if $a/c < 0.25$.

Figure 8.19 Stress intensity factors for (a) an embedded elliptical crack and (b) a similar half-elliptical surface crack. The equations give K_D at point D for a uniform tension normal to the crack plane. (Based on [Newman 86].)

TRINCA CRESCENDO A PARTIR DE UM CONCENTRADOR DE TENSÕES

- Se a trinca for pequena comparada com o raio, a solução é a mesma para uma trinca superficial em um corpo infinito.
- Uma vez que a trinca cresce para longe do campo de tensão do concentrador, esta passa a ser considerada uma trinca longa de comprimento $2a$



$$K = F_d S \sqrt{\pi l}, \quad d = \frac{l}{a} = \frac{l}{c+l}$$

$$F_d = 0.5(3-d)[1 + 1.243(1-d)^3]$$

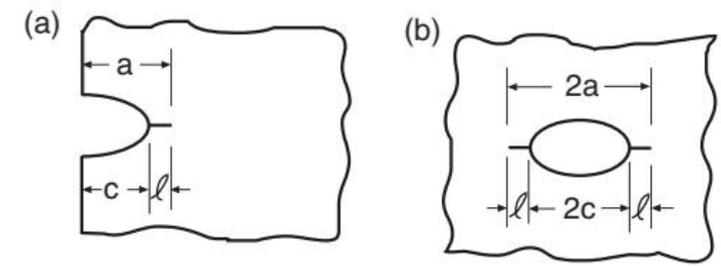
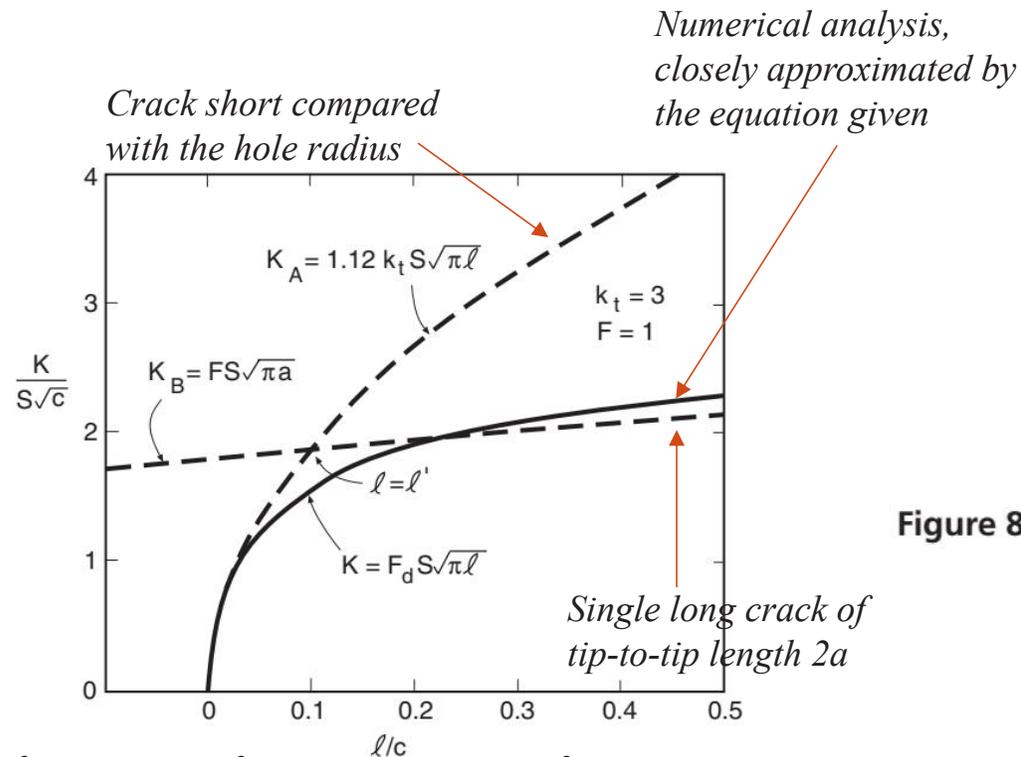


Figure 8.21 Nomenclature for cracks growing from notches.

$$l' = \frac{c}{\left(1.12 \frac{k_{tg}}{F}\right)^2 - 1}$$

Figure 8.20 Stress intensities for a pair of cracks growing from a circular hole in a remotely loaded wide plate, a , b , h . (Equation from [Tada 85] p. 19.1.)

EXAMPLE 8.4

Example 8.4

A pressure vessel made of ASTM A517-F steel operates near room temperature and has a wall thickness of $t = 50$ mm. A surface crack was found in the vessel wall during an inspection. It has an approximately semi-elliptical shape, as in Fig. 8.19(b), with surface length $2c = 40$ mm and depth $a = 10$ mm. The stresses in the region of the crack, as calculated without considering the presence of the crack, are approximately uniform through the thickness and are $S_z = 300$ MPa normal to the crack plane and $S_x = 150$ MPa parallel to the crack plane, where the coordinate system of Fig. 8.19 is used. What is the safety factor against brittle fracture? Would you remove the pressure vessel from service?

Solution From Table 8.1(a), we see that this material has a fracture toughness of $K_{Ic} = 187$ MPa $\sqrt{\text{m}}$ and a yield strength of $\sigma_o = 760$ MPa at room temperature. The K for the given stresses and crack can be estimated from Fig. 8.19(b). Since $c = 20$ mm, we have $a/c = 0.5$. Also, we have $a/t = 0.2$ and large b , for which $F_D = 1.12$ is a reasonable approximation. The quantity Q is needed:

$$Q = 1 + 1.464 \left(\frac{a}{c} \right)^{1.65} = 1.466$$

Hence, the maximum K , which occurs at the point of maximum depth of the elliptical crack, is approximately

$$K = K_D = F_D S_z \sqrt{\frac{\pi a}{Q}} \approx 1.12(300 \text{ MPa}) \sqrt{\frac{\pi(0.010 \text{ m})}{1.466}} = 49.2 \text{ MPa}\sqrt{\text{m}}$$

The stress-based safety factor against brittle fracture is

$$X_K = \frac{K_{Ic}}{K} = \frac{187}{49.2} = 3.80 \quad \text{Ans.}$$

This is a reasonably high value, so it would be safe to continue using the pressure vessel until repairs are convenient. However, the crack should be checked frequently to be sure that it is not growing. In addition, the ASME or other design code for pressure vessels is likely to apply, and it should be consulted in this situation.

Comment Stresses parallel to the plane of a crack do not affect K , so the given S_x does not enter the calculation. (See Section 8.5.4 for further discussion of this point.)

Example 8.5

A spherical pressure vessel is made of ASTM A517-F steel and operates at room temperature. The inner diameter is 1.5 m, the wall thickness is 10 mm, and the maximum pressure is 6 MPa. Is the leak-before-break condition met? What is the safety factor on K relative to K_{Ic} , and what is the safety factor against yielding?

Solution From Fig. A.7(b), the maximum stress in the vessel wall is

$$\sigma_t = \frac{pr_1}{2t} = \frac{(6 \text{ MPa})(750 \text{ mm})}{2(10 \text{ mm})} = 225 \text{ MPa}$$

Combining this value with $K_{Ic} = 187 \text{ MPa}\sqrt{\text{m}}$ from Table 8.1, the critical crack length is

$$c_c = \frac{1}{\pi} \left(\frac{K_{Ic}}{\sigma_t} \right)^2 = \frac{1}{\pi} \left(\frac{187 \text{ MPa}\sqrt{\text{m}}}{225 \text{ MPa}} \right)^2 = 0.220 \text{ m} = 220 \text{ mm}$$

This far exceeds the wall thickness of $t = 10 \text{ mm}$, so the leak-before-break condition is met.

When the vessel leaks, the crack length along the surface is $2c = 2t$, so that $c = t = 10 \text{ mm}$. At this point, the stress intensity factor is

$$K = FS\sqrt{\pi a} = 1(225 \text{ MPa})\sqrt{\pi(0.01 \text{ m})} = 39.9 \text{ MPa}\sqrt{\text{m}}$$

Here, the situation is treated as a center crack in a wide plate, as in Fig. 8.12(a), with substitutions $F = 1$, $S = \sigma_t$, and $a = c$. Hence, the safety factor on K is

$$X_K = \frac{K_{Ic}}{K} = \frac{187 \text{ MPa}\sqrt{\text{m}}}{39.9 \text{ MPa}\sqrt{\text{m}}} = 4.69 \quad \text{Ans.}$$

This is a reasonable value, so the vessel is safe from brittle fracture.

Noting that the principal stresses are $\sigma_1 = \sigma_2 = 225 \text{ MPa}$ and $\sigma_3 \approx 0$, we conclude that the effective stress from Eq. 7.21 is $\bar{\sigma}_S = 225 \text{ MPa}$, and the safety factor against yielding is

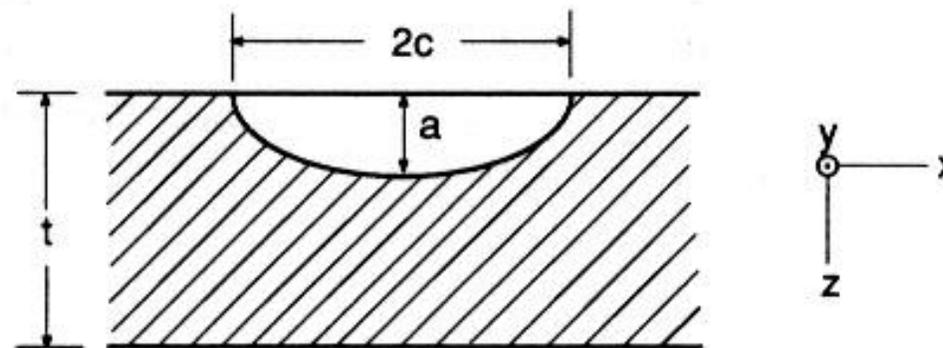
$$X_o = \frac{\sigma_o}{\bar{\sigma}_S} = \frac{760 \text{ MPa}}{225 \text{ MPa}} = 3.38 \quad \text{Ans.}$$

where the yield strength is also from Table 8.1. Hence, yielding is unlikely.

EXERCÍCIO

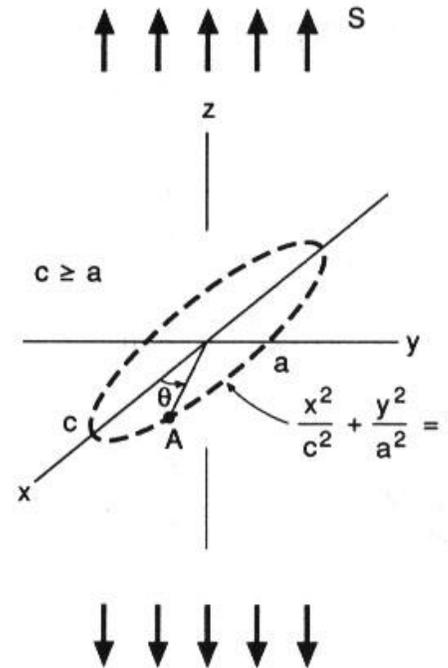
Um vaso de pressão feito de um aço ASTM A517-F opera próximo a temperatura ambiente e possui uma espessura de parede de $t = 50 \text{ mm}$. Uma trinca como mostrada na figura abaixo foi encontrada durante uma inspeção. Ela possui uma forma aproximadamente semi-elíptica com um comprimento do eixo maior $2c = 40 \text{ mm}$ e profundidade $a = 10 \text{ mm}$. As tensões na região da trinca, quando calculada sem a mesma, são aproximadamente uniforme através da espessura e são $S_y = 300 \text{ MPa}$, normal ao plano da trinca e $S_x = 150 \text{ MPa}$, paralela ao plano da trinca.

- Qual seria o fator de segurança contra a fratura frágil (relação K_{IC}/K)? Você retiraria este vaso de pressão de serviço? Dados: $K_{IC} = 187 \text{ MPa}\cdot\text{m}^{1/2}$; $\sigma_e = 760 \text{ MPa}$; $\sigma_R = 830 \text{ MPa}$ e $E = 200 \text{ GPa}$.



SOLUÇÃO 1:

O valor de K pode ser estimado pela aplicação do fator de correção para uma trinca elíptica embebida como o da figura abaixo. O fator de correção é necessário devido a superfície que livre criada pelo seccionamento da geometria de trinca elíptica e devido a um $a/t = 0.2$.



Onde o máximo valor acontece para $\theta = \pm\pi/2$. e para $S_y = 300$ MPa e S_x não afeta por ser paralelo a trinca. Assim, para $a/c = 0.5$ (10mm/20mm). tem-se que $E(k) = 1.21$

$$K = F_s \frac{S\sqrt{\pi a}}{E(k)}$$

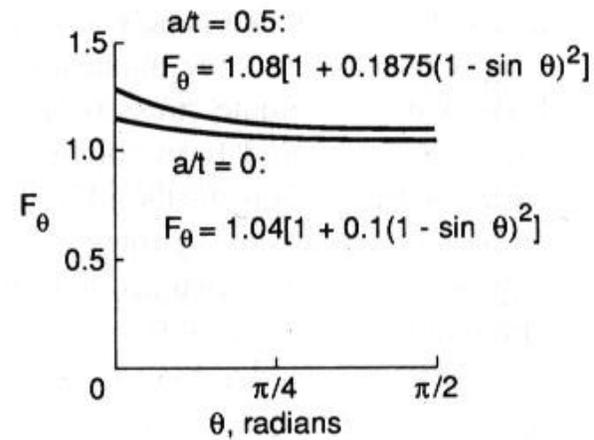
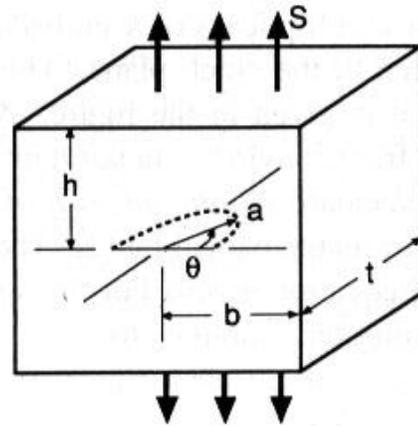
$$E(k) = \sqrt{1 + 1,464 \left(\frac{a}{c}\right)^{1,65}}$$

$$a = 10 \text{ mm}$$

$$2c = 40 \text{ mm}$$

$$t = 50 \text{ mm.}$$

Como uma estimativa. sabendo-se $a/t = 0.2$ (10mm/50mm) assumo que não possui nenhum efeito, o que é razoável considerando uma metade de trinca circular da figura abaixo e grande valor de b (tamanho da placa).



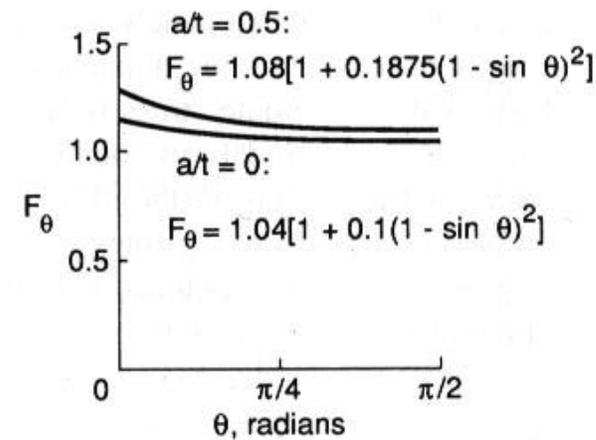
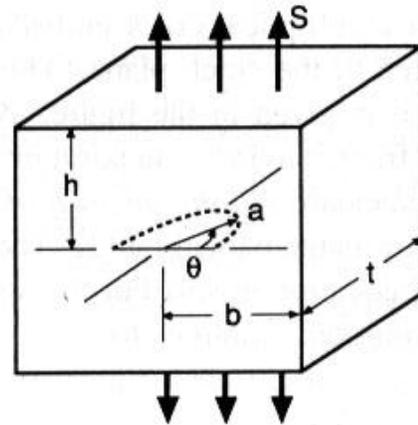
$$K = F_{\theta} \frac{2}{\pi} S \sqrt{\pi a} \quad (a \ll b, h)$$

Assim, considerando uma trinca passante. $F_S = 1.12$

$$K = F_s \frac{S \sqrt{\pi a}}{E(k)} = 1,12 \frac{300 \sqrt{\pi(0,01)}}{1.21} = 49,2 \text{MPa} \sqrt{m}$$

$$X_s = \frac{K_{IC}}{K} = \frac{187}{49,2} = 3,80$$

Como uma estimativa. assuma que $a/t = 0.2$ não possui nenhum efeito, o que é razoável considerando uma metade de trinca circular da figura abaixo.



$$K = F_{\theta} \frac{2}{\pi} S \sqrt{\pi a} \quad (a \ll b, h)$$

Assim, considerando uma trinca passante. $F_S = 1.12$

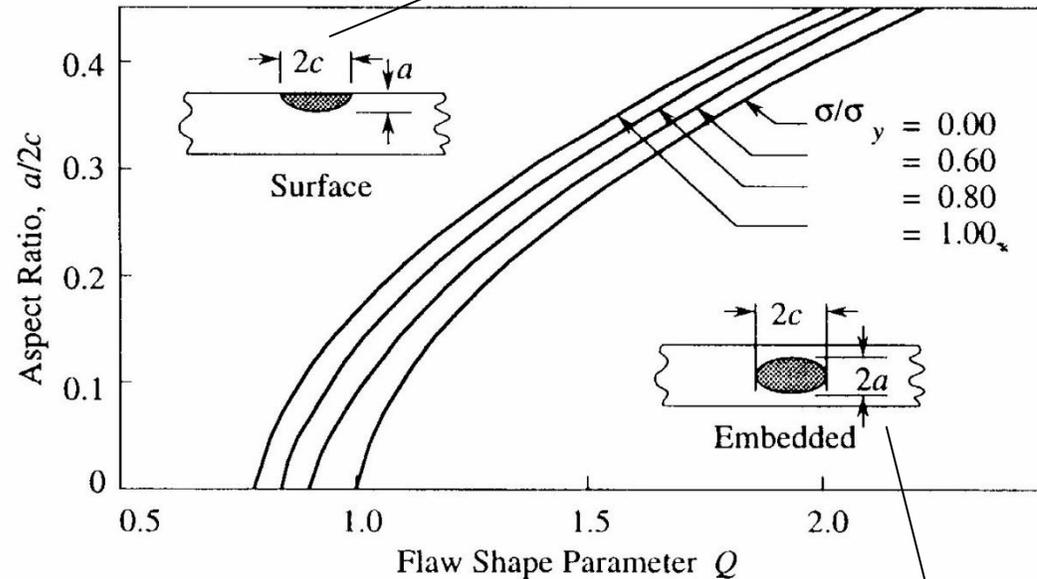
$$K = F_S \frac{S \sqrt{\pi a}}{E(k)} = 1,12 \frac{300 \sqrt{\pi(0,01)}}{1.21} = 49,2 \text{MPa} \sqrt{m}$$

$$X_S = \frac{K_{IC}}{K} = \frac{187}{49,2} = 3,8$$

RESOLUÇÃO 2

$$Q = 1 + 1,464 \left(\frac{a}{c} \right)^{1,65} = 1,466$$

Trinca superficial $K = 1,1\sigma \left(\frac{\pi a}{Q} \right)^{\frac{1}{2}}$



Trinca interna

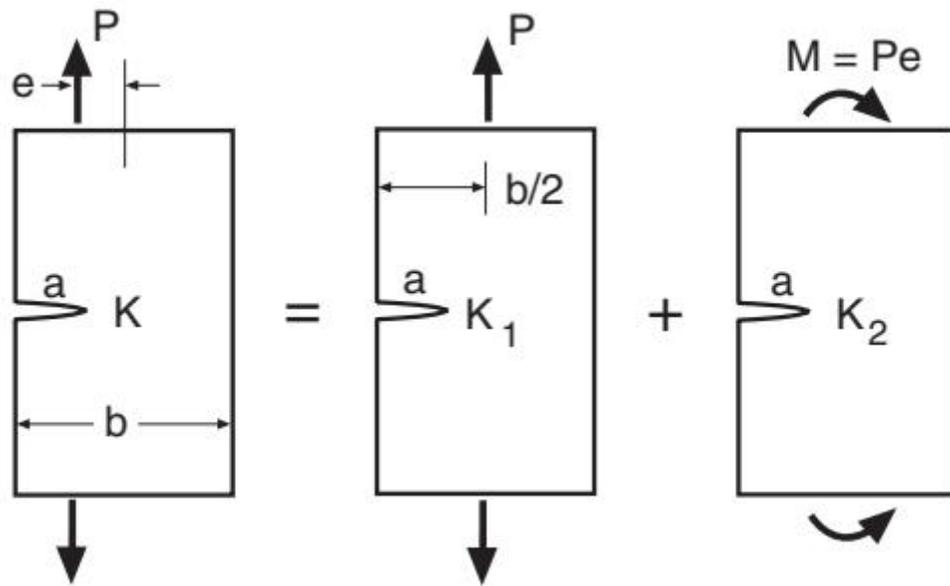
$$K = \sigma \left(\frac{\pi a}{Q} \right)^{\frac{1}{2}}$$

$$K = 1,1 * 300 \left(\frac{3,1415 * 0,01}{1,466} \right)^{1/2} = 48,30 MPa^{1/2}$$

$$X_s = \frac{KIC}{K} = \frac{187}{48,30} = 3,87$$

Superposição para carregamentos combinados

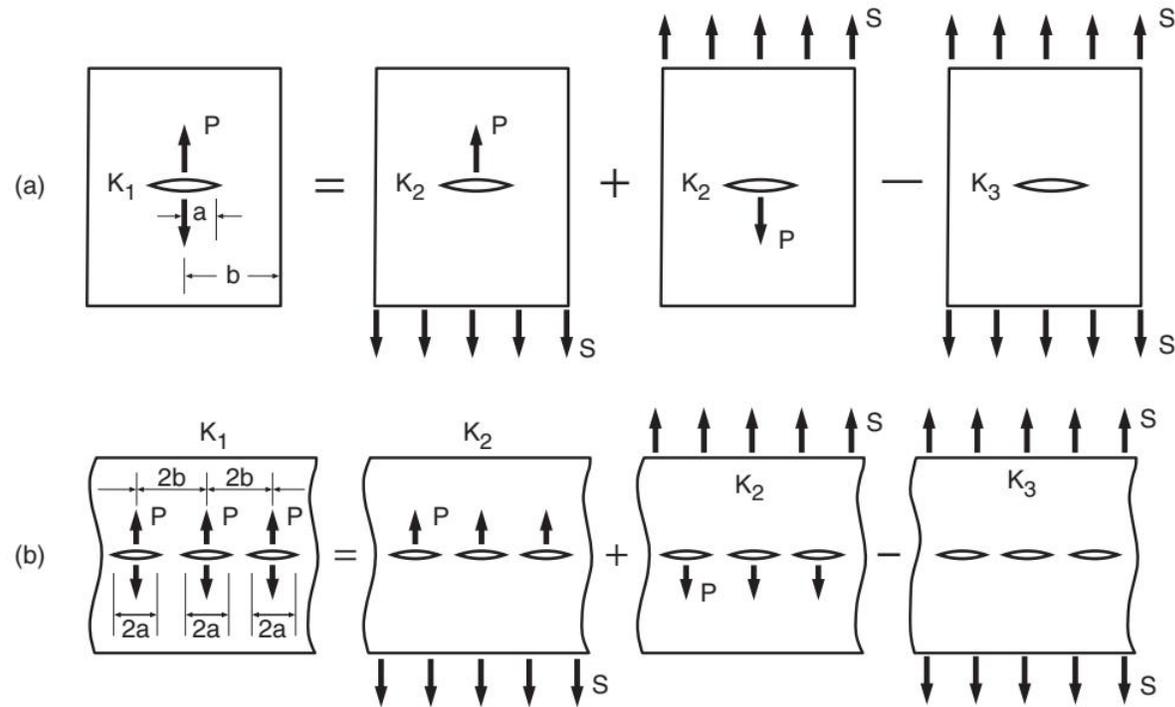
- Adição da contribuição de K para cada componente de carregamento individual.



$$K_1 = F_1 S_1 \sqrt{\pi a}, \quad S_1 = \frac{P}{bt}$$

$$K_2 = F_2 S_2 \sqrt{\pi a}, \quad S_2 = \frac{6M}{b^2 t} = \frac{6Pe}{b^2 t}$$

$$K = K_1 + K_2 = \frac{P}{bt} \left(F_1 + \frac{6F_2 e}{b} \right) \sqrt{\pi a}$$



Superposition for either (a) or (b): (t = thickness)

$$K_1 = K_2 + K_2 - K_3, \quad \text{so that } K_2 = \frac{1}{2}(K_1 + K_3), \quad \text{where } S = \frac{P}{2bt}$$

(a) Single crack in finite-width plate for any $\alpha = a/b$:

$$K_1 = F_{P1} \frac{P}{t\sqrt{b}}, \quad K_3 = F_3 S \sqrt{\pi a}, \quad K_2 = \frac{P}{2t\sqrt{b}} \left(F_{P1} + \frac{F_3 \sqrt{\pi a}}{2} \right)$$

F_{P1} is F_P from Fig. 8.15, and F_3 is F from Fig. 8.12(a).

(b) Infinite array of collinear cracks, exact solutions for any $\alpha = a/b$:

$$K_1 = \frac{P}{t\sqrt{b}} \frac{1}{\sqrt{\sin \pi \alpha}}, \quad K_3 = S \sqrt{2b \tan \frac{\pi \alpha}{2}}, \quad K_2 = \frac{P}{2t\sqrt{b}} \left(\frac{1}{\sqrt{\sin \pi \alpha}} + \sqrt{\frac{1}{2} \tan \frac{\pi \alpha}{2}} \right)$$

Approximations within 10%: (Note limits for (a) or (b), respectively, below each equation.)

$$K_2 = \frac{P}{2t\sqrt{b}} \left(\frac{1}{\sqrt{\pi \alpha}} + \frac{\sqrt{\pi \alpha}}{2} \right), \quad K_2 = \frac{0.89P}{t\sqrt{b}}$$

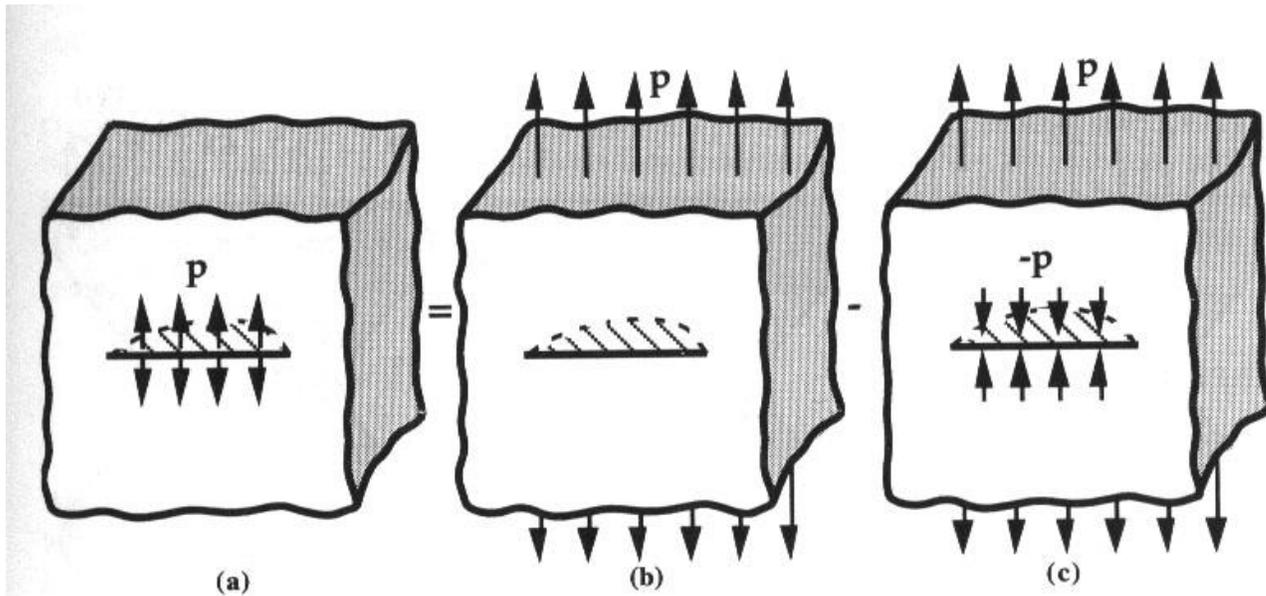
$$(\alpha \leq 0.32 \text{ or } 0.38)$$

$$(0.12 \leq \alpha \leq 0.57 \text{ or } 0.65)$$

Figure 8.23 Superposition to obtain solutions for cases of a single crack (a), or a row of cracks (b), loaded on one side. (Arguments of trigonometric functions are in radians.)

SUPERPOSIÇÃO PARA CARREGAMENTOS COMBINADOS

- O uso da superposição algumas vezes permite as soluções dos Handbooks serem usados em casos não tão óbvios.
- Considere o caso de uma trinca central em uma placa. sendo esta trinca carregada localmente com a pressão p .



$$K = K_1 + K_2 = \frac{p\sqrt{\pi a}}{E(k)} \left[\text{sen}^2 \beta + \left(\frac{a}{c} \right)^2 \text{cos}^2 \beta \right]^{1/4} - 0$$

$$\beta = \tan^{-1} \left(\frac{c}{a} \tan g \theta \right)$$

$$E(k) = \sqrt{1 + 1,464 \left(\frac{a}{c} \right)^{1,65}}$$

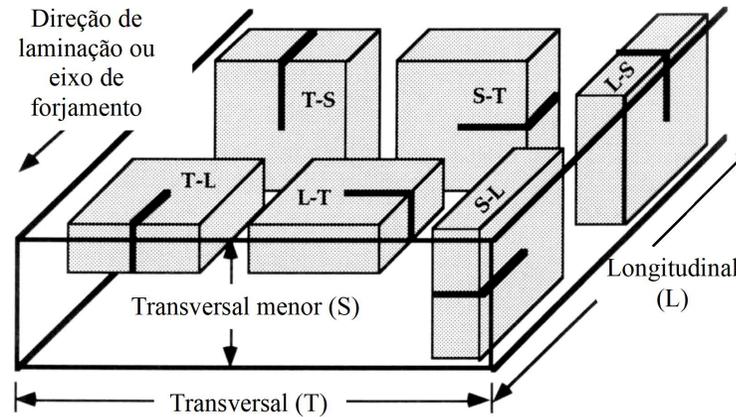


PARTE EXPERIMENTAL

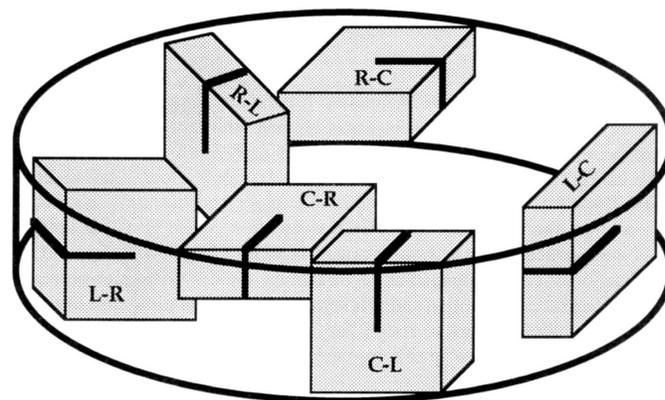
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ENSAIO DE TENACIDADE À FRATURA - KIC

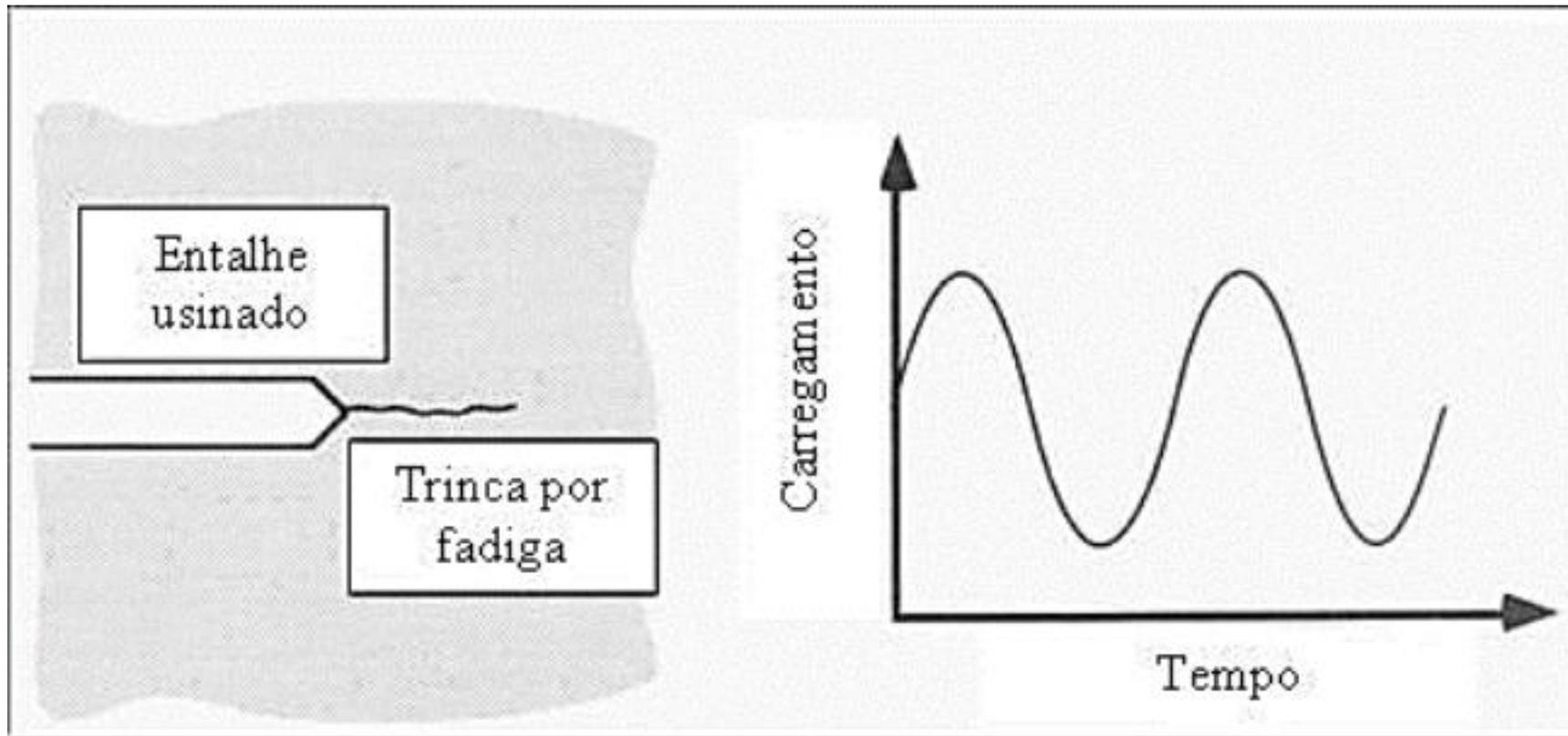
- Os ensaios são realizados conforme a norma ASTM E399 ou E1820



As letras L, T e S denotam as direções: longitudinal, transversal e transversal menor



As direções de simetria nesse caso são: circunferência, radial e longitudinal (C, R e L, respectivamente)

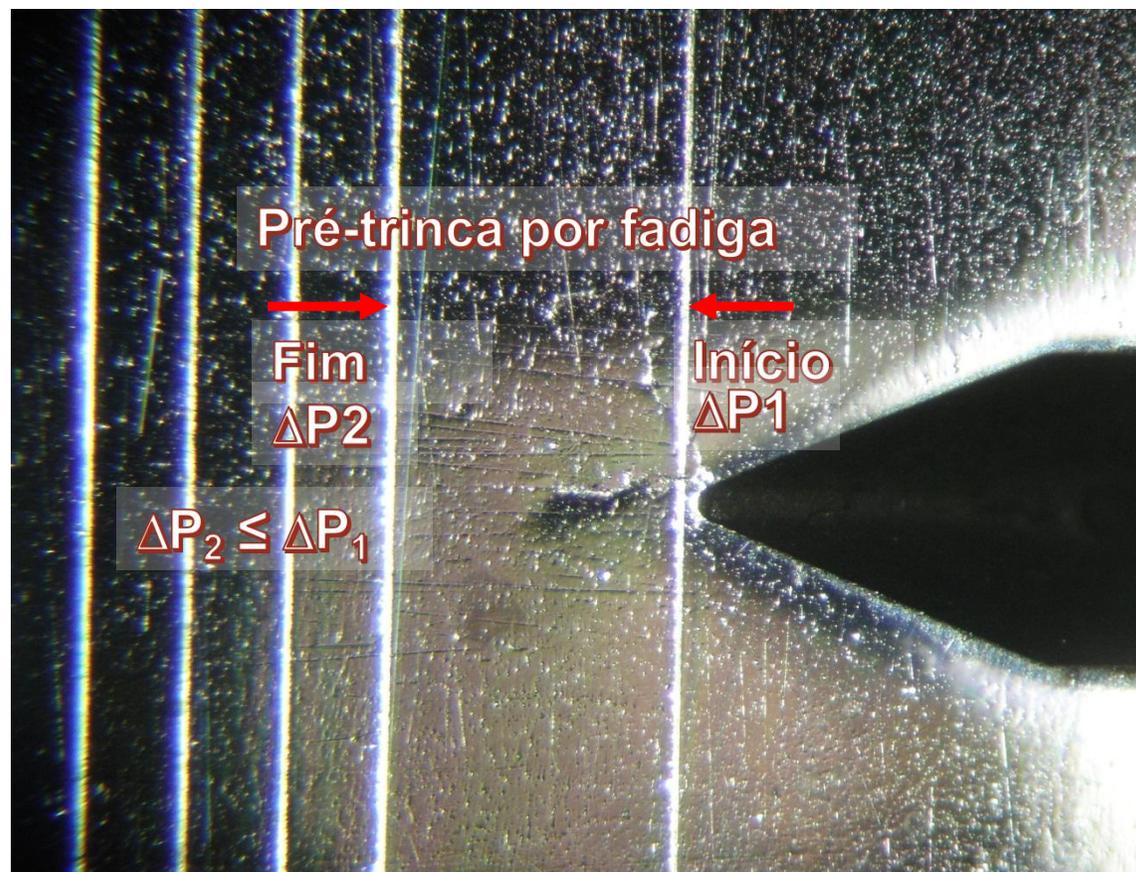
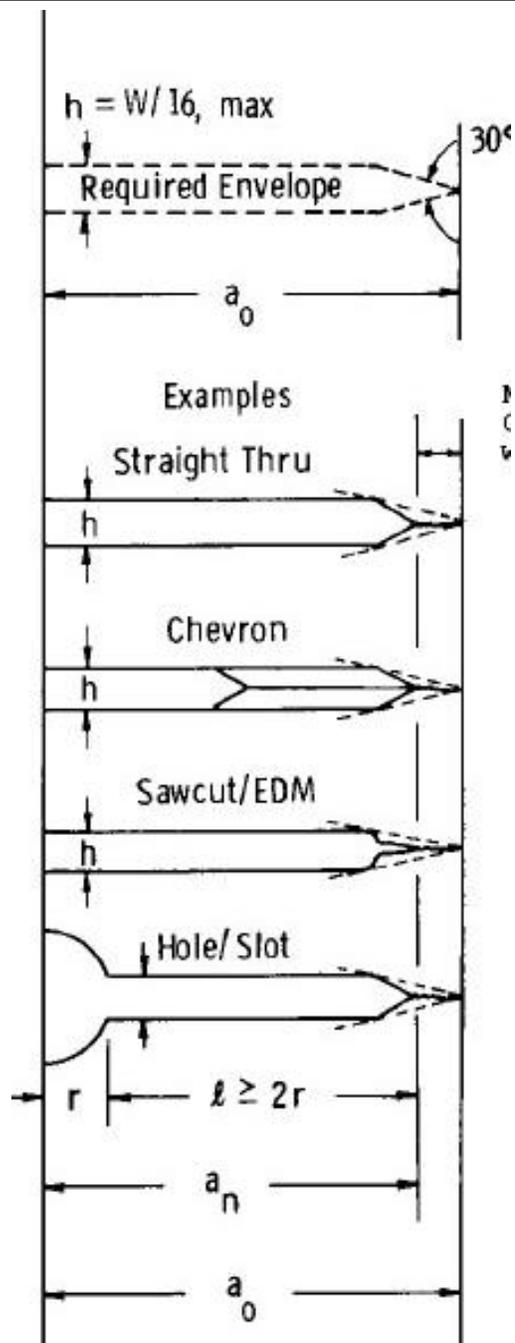


Uma trinca por fadiga é introduzida na ponta do entalhe usinado por meios de carregamento cíclico.

Pré-trinca por Fadiga

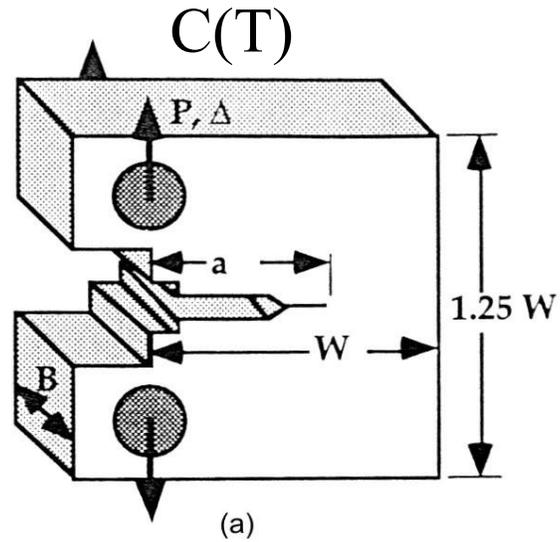
Tamanho pre-trinca = $0.45 \leq a/W \leq 0.551$

$$P_f = \frac{0,4 * B * b_o^2 \sigma_y}{(2 * W + a_o)}$$



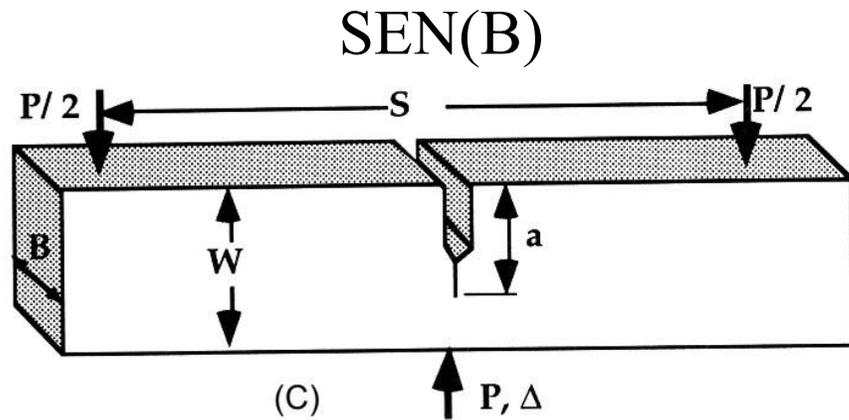
Terminar pré-trinca com $\Delta K \leq \Delta K$ de início do ensaio

Tamanho da Zona Plástica



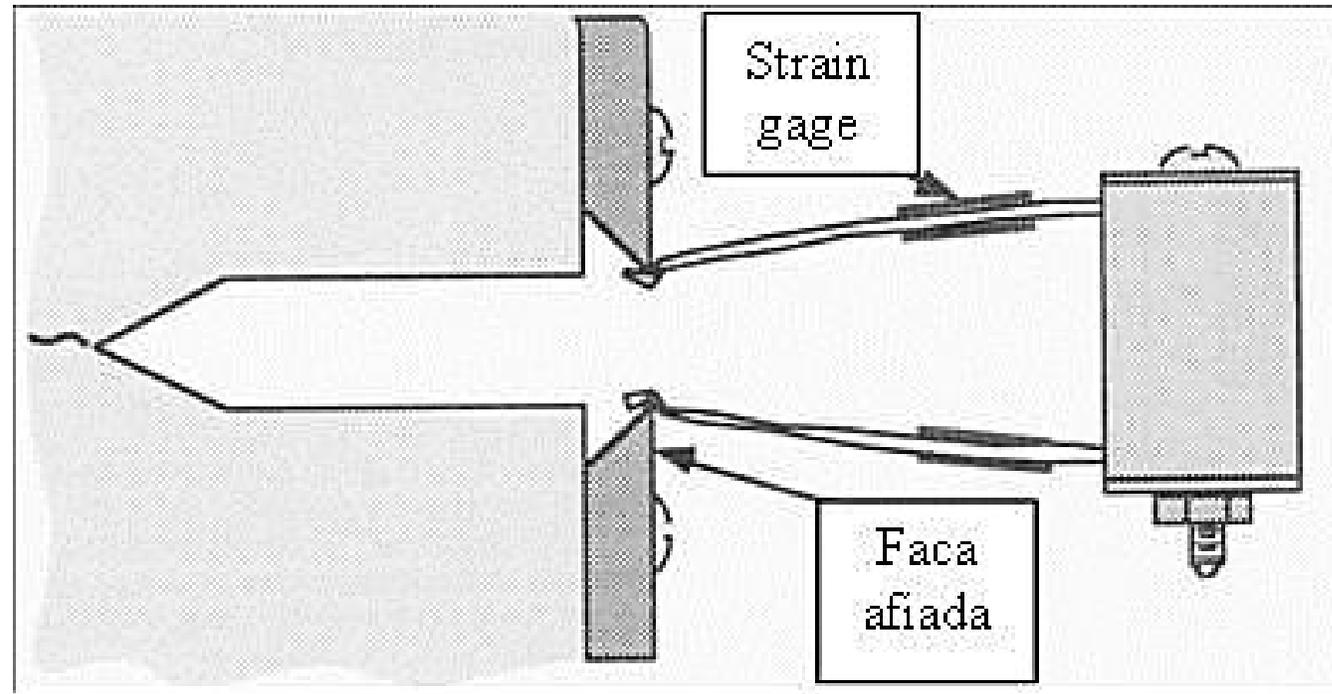
$$K = \frac{P}{B\sqrt{W}} Y$$

$$Y = f\left(\frac{a}{W}\right) = \frac{2 + \frac{a}{W}}{\left(1 - \frac{a}{W}\right)^{\frac{3}{2}}} \left[0,886 + 4,64\left(\frac{a}{W}\right) - 13,32\left(\frac{a}{W}\right)^2 + 14,72\left(\frac{a}{W}\right)^3 - 5,6\left(\frac{a}{W}\right)^4 \right]$$

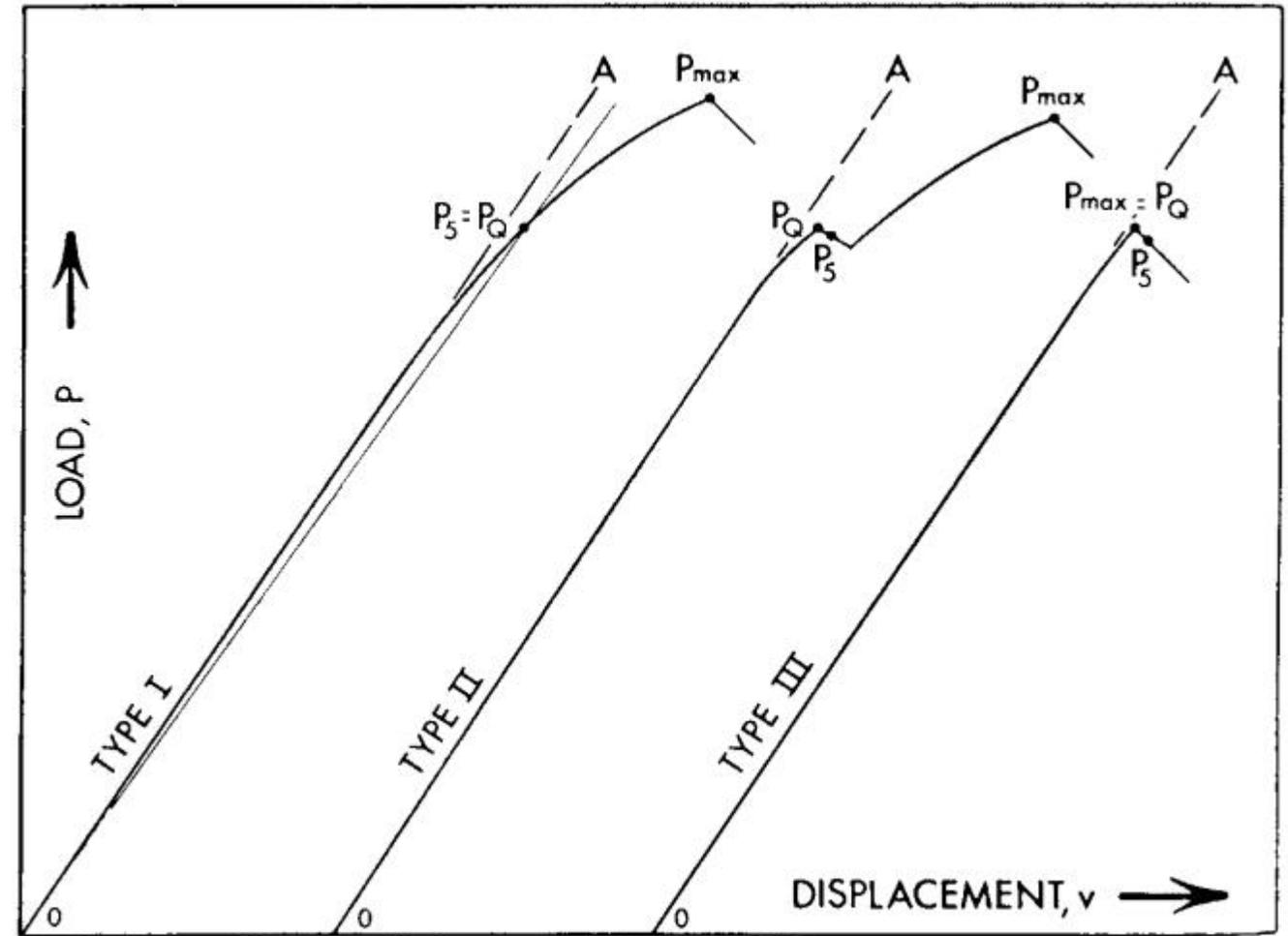
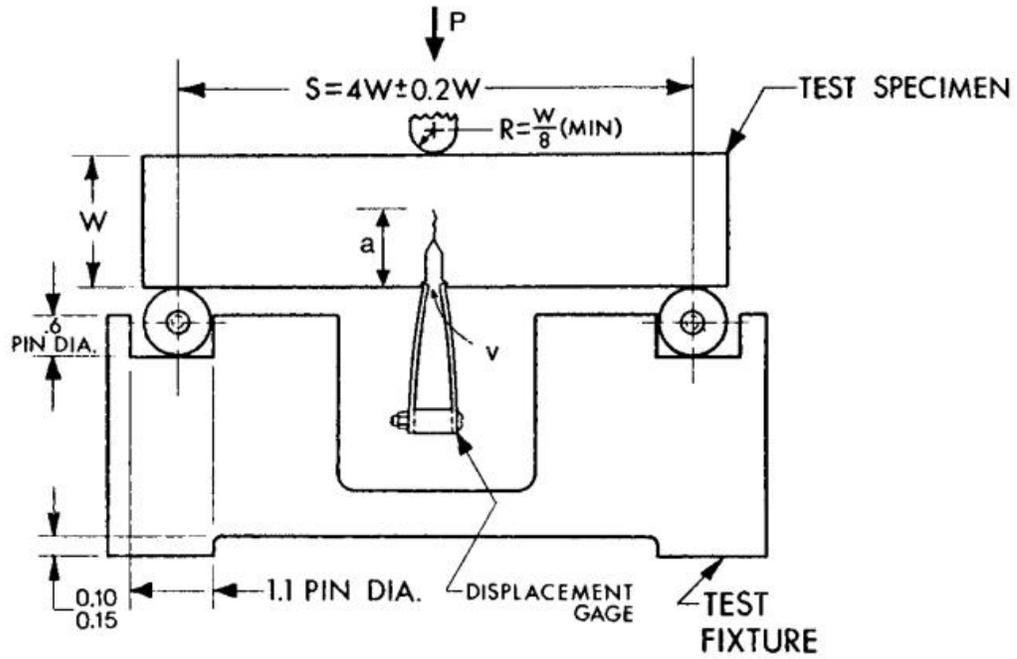


$$K = \frac{P}{B\sqrt{W}} Y$$

$$Y = f\left(\frac{a}{W}\right) = \frac{3 \frac{S}{W} \sqrt{\frac{a}{W}}}{2 \left(1 + 2 \frac{a}{W}\right) \left(1 - \frac{a}{W}\right)^{\frac{3}{2}}} \left[1,99 - \frac{a}{W} \left(1 - \frac{a}{W}\right) \left\{ 2,15 - 3,93 \left(\frac{a}{W}\right) + 2,7 \left(\frac{a}{W}\right)^2 \right\} \right]$$

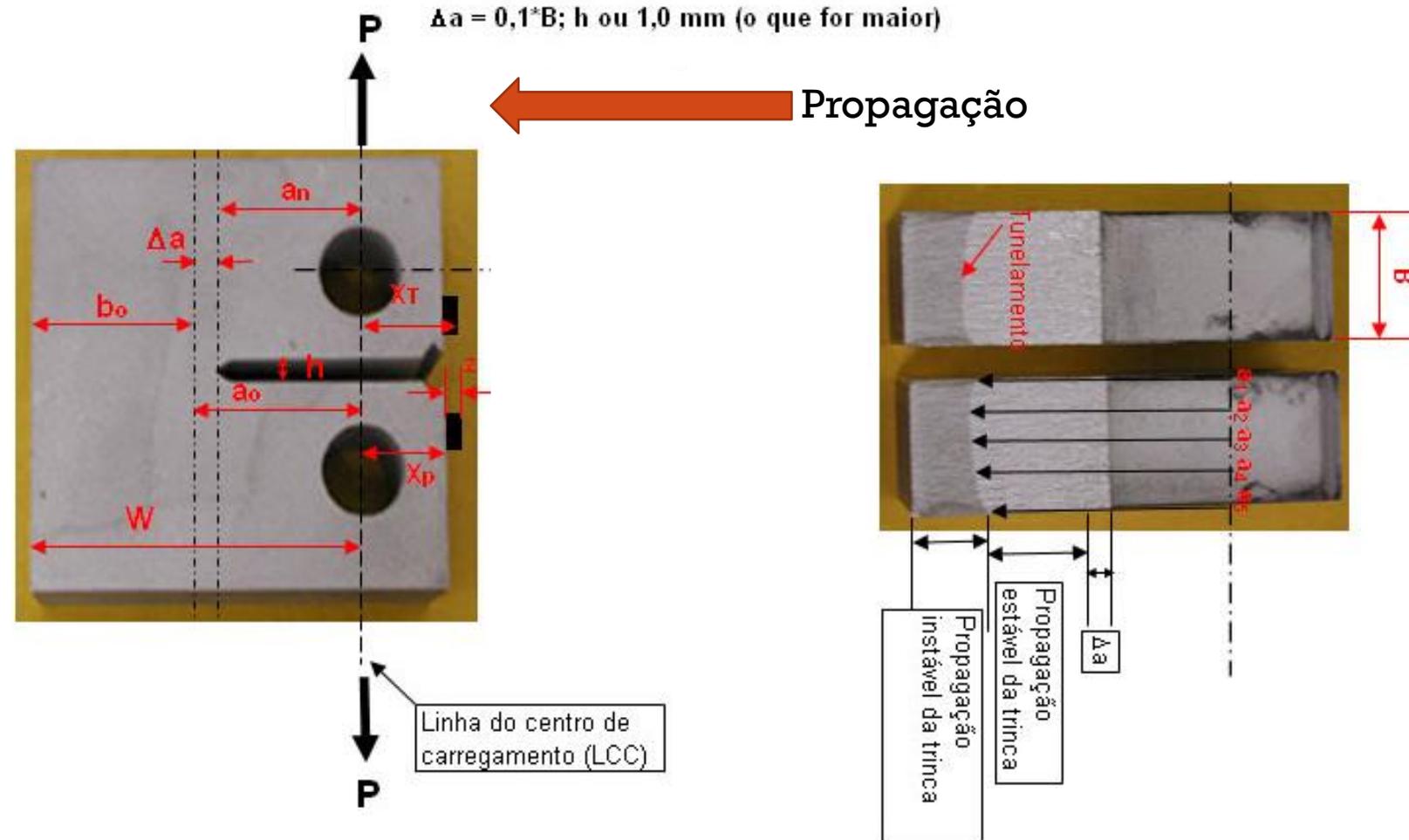


Medida do deslocamento da abertura da trinca : “clip gage”.
Medida do carregamento: células de carga da própria máquina.



$$P_{max} \leq 1.10P_q$$

Nomenclatura Usuais



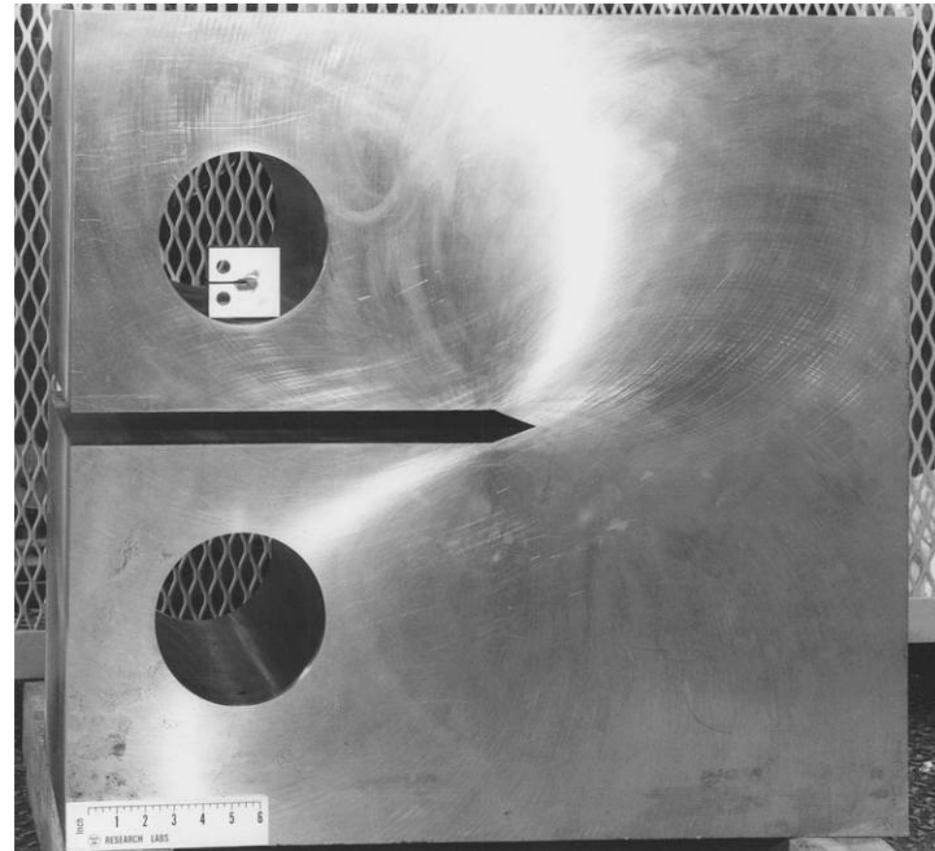
- W = Distância da LCC ao final do CP
- $b_o = (W - a_o)$ = Ligamento
- B = espessura do CP
- X_T = Altura da faca
- h = Altura do entalhe
- Δa = Tamanho da propagação
- a_n = Tamanho do entalhe
- a_o = Tamanho da trinca

Para satisfazer o teste:

- Condição de deformação plana e o corpo de prova precisa se comportar de maneira linearmente elástica.

$$B, a, (W - a) \geq 2,5 \left(\frac{K_Q}{\sigma_{YS}} \right)^2$$

σ_{ys} – Limite de escoamento



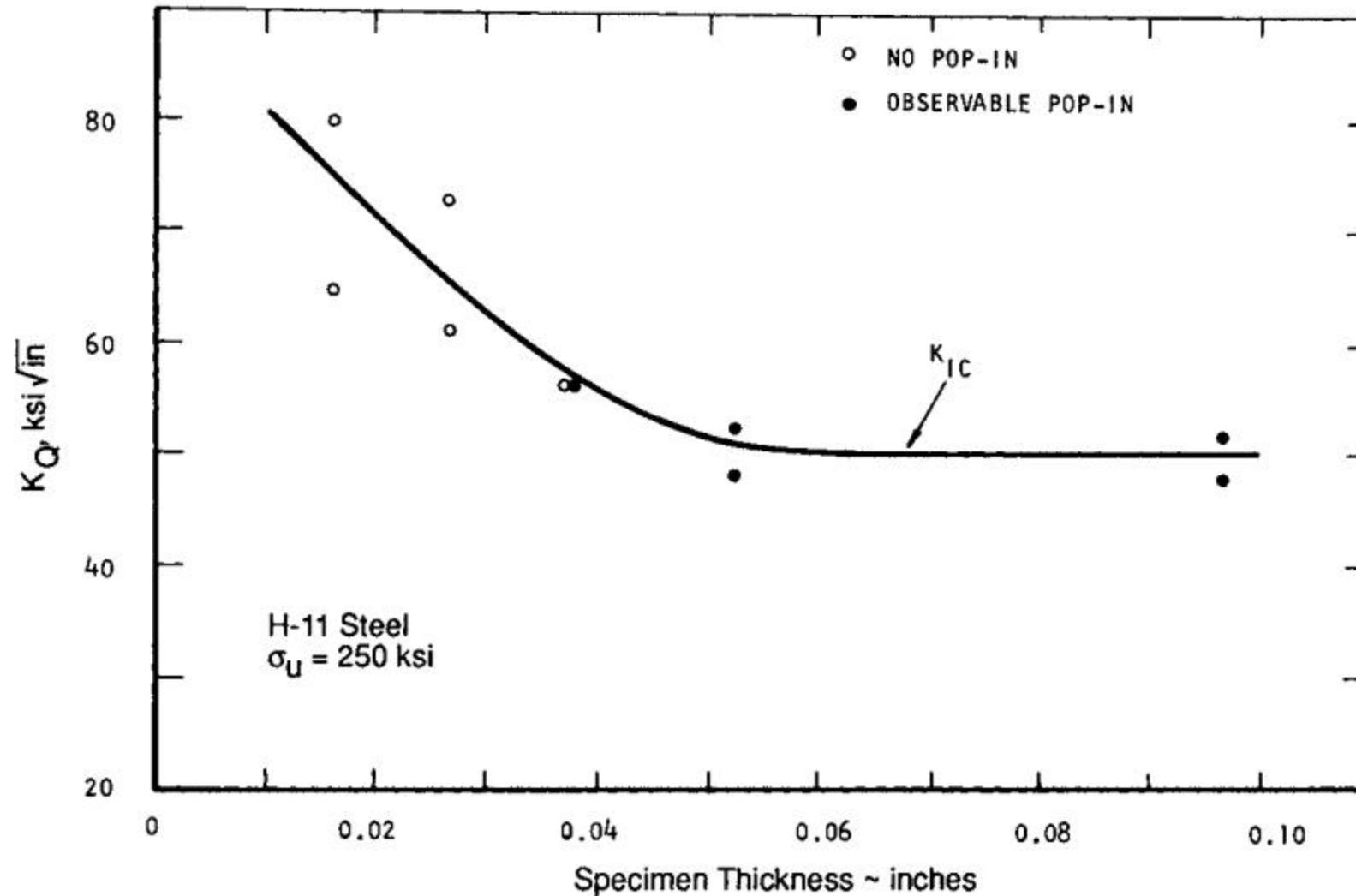
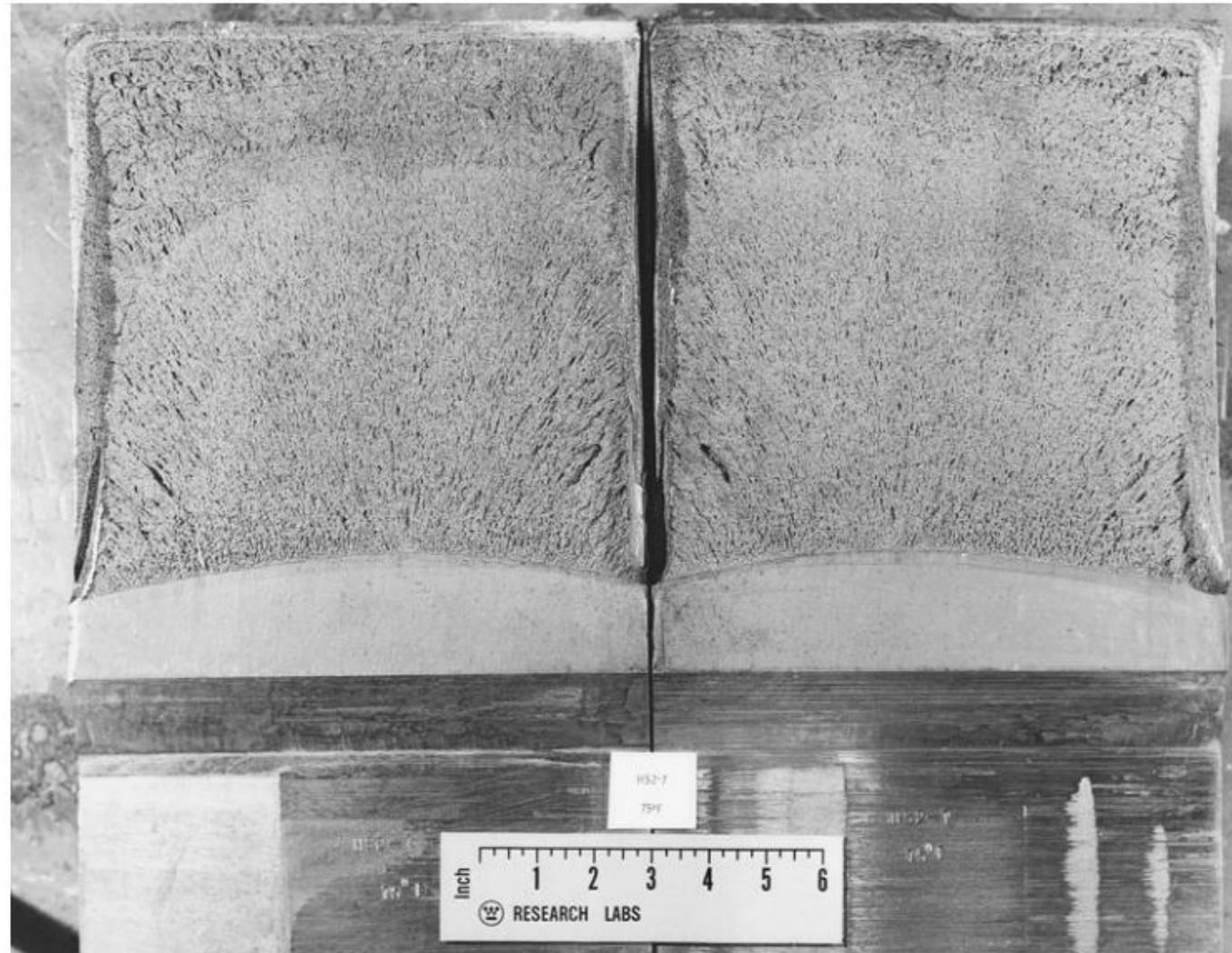


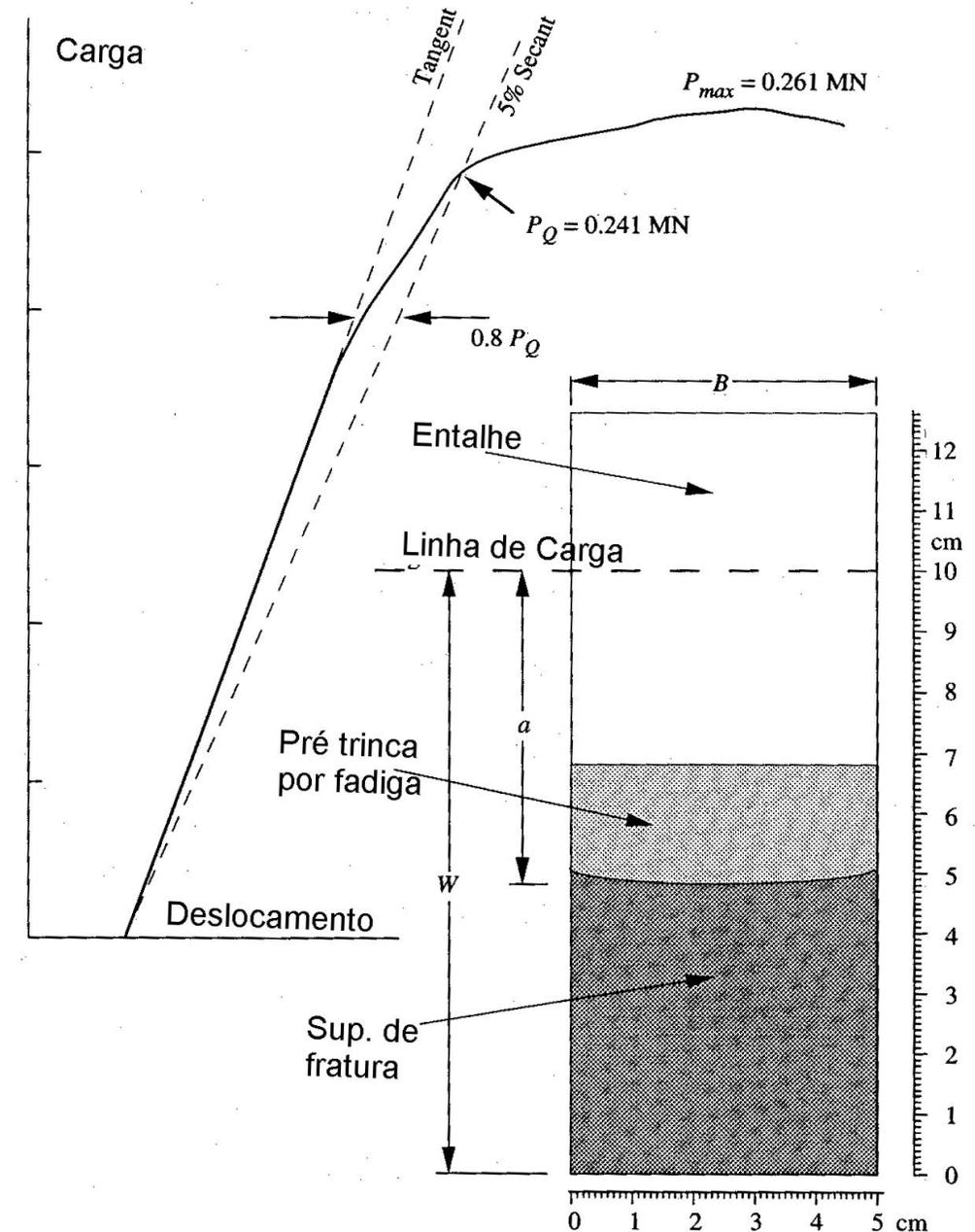
Figure 8.31 Effect of thickness on fracture toughness of an alloy steel heat treated to the high strength of $\sigma_u = 1720$ MPa. (Adapted from [Steigerwald 70]; copyright c ASTM; reprinted with permission.)

$$0.45 \leq a/W \leq 0.55$$

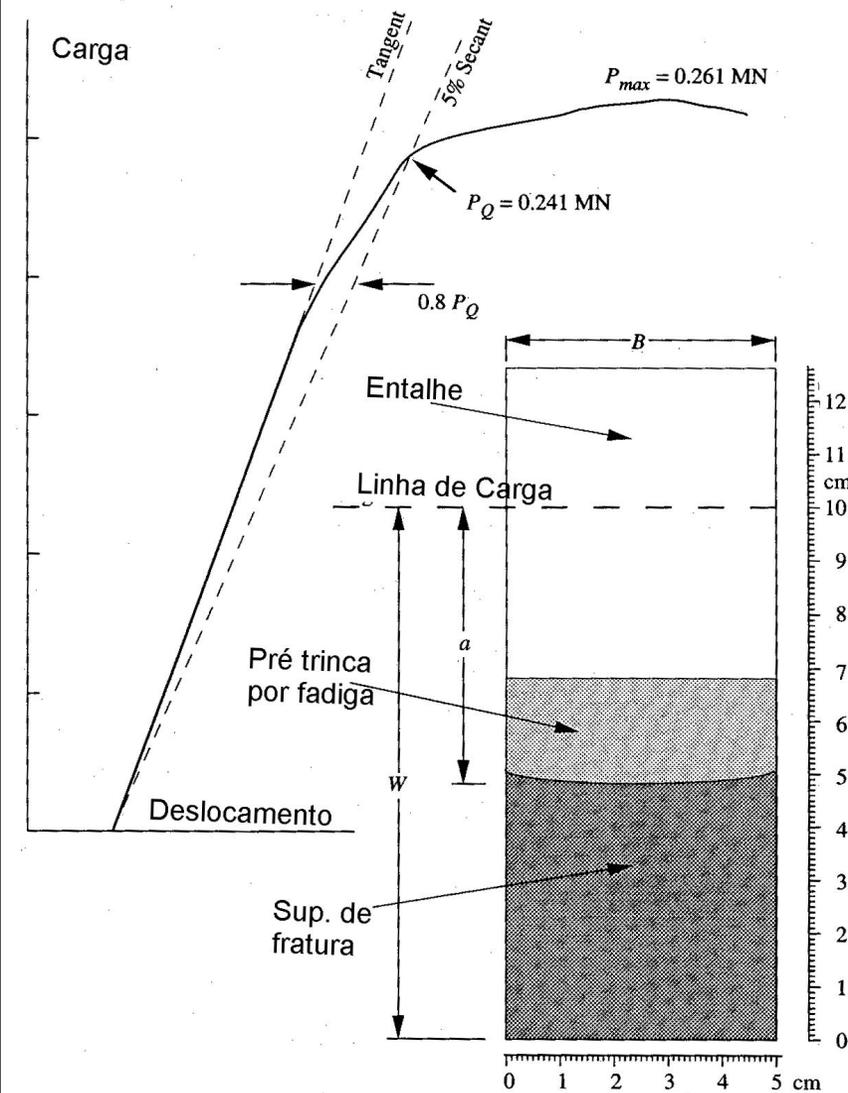


EXERCÍCIO KNOTT "FRACTURE MECHANICS WORKED EXAMPLES"

A figura abaixo mostra a curva carga versus deslocamento obtidas a partir do ensaio de um corpo de prova do tipo C(T), executado de um material forjado com tensão limite de escoamento de 1050 MPa. Um esquema da fratura deste corpo de prova é mostrado na figura. Determine se o teste fornece um resultado válido de K_{IC} .



EXERCÍCIO KNOTT "FRACTURE MECHANICS WORKED EXAMPLES"



Preferível trabalhar nas unidades do SI (m. MPam^{1/2}. N)

$$a_m = \frac{\sum_{ai=1}^{ai=5} ai}{5} = 52,10 \text{ mm}$$

$$0,45 \leq a_m / W \leq 0,55$$

$$0,45 \leq 0,521 \leq 0,55 \text{ (OK)}$$

$$W = 100 \text{ mm}$$

$$P_m / P_Q \leq 1,10 \therefore 0,261 / 0,241 = 1,083 \text{ (OK)}$$

$$B = 49,98 \text{ mm}$$

$$P_m = 0,261 \text{ MN}$$

$$P_Q = 0,241 \text{ MN}$$

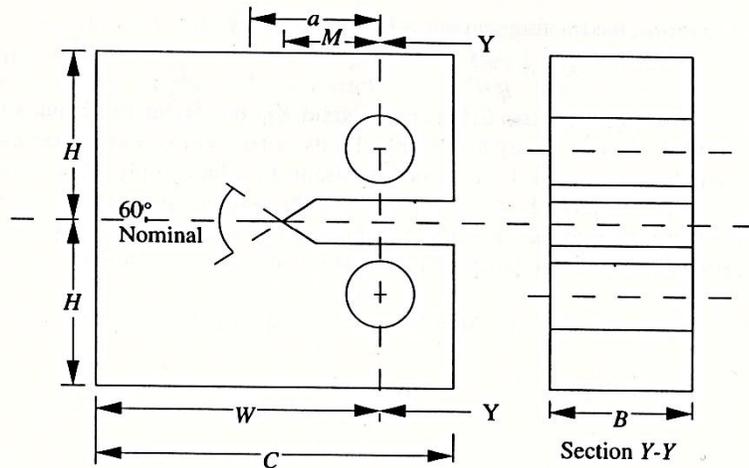
$$K_Q = \frac{P_Q}{B\sqrt{W}} Y = \frac{0,241 * Y}{0,04998 * \sqrt{0,1}}$$

$$Y = \frac{2 + \frac{a}{W}}{\left(1 - \frac{a}{W}\right)^{\frac{3}{2}}} \left[0,886 + 4,64\left(\frac{a}{W}\right) - 13,32\left(\frac{a}{W}\right)^2 + 14,72\left(\frac{a}{W}\right)^3 - 5,6\left(\frac{a}{W}\right)^4 \right]$$

$$Y = 10,32 \text{ Logo } K_Q = 158 \text{ MPa}^{1/2}$$

CONTINUAÇÃO EXERCÍCIO

Poderíamos utilizar a tabela abaixo para o calculo do Y



Net Width = W
 Total width C = $1.25W$
 Thickness B = $0.5W$
 Half height H = $0.6W$
 Hole diameter = $0.25W$
 Effective notch length M = $0.25W$ to $0.40W$
 Effective crack length a = $0.45W$ to $0.55W$
 Dimensions in mm.

Values of Y_2 as a function of a/W for a compact tension testpiece

a/W	0.000	0.001	0.002	0.003	0.004	0.005	0.006	0.007	0.008	0.009
	Stress Intensity factor coefficient, Y_2									
0.450	8.34	8.36	8.39	8.41	8.43	8.46	8.48	8.51	8.53	8.56
0.460	8.58	8.60	8.63	8.65	8.68	8.70	8.73	8.75	8.78	8.80
0.470	8.83	8.86	8.88	8.91	8.93	8.96	8.99	9.01	9.04	9.07
0.480	9.09	9.12	9.15	9.17	9.20	9.23	9.26	9.29	9.31	9.34
0.490	9.37	9.40	9.43	9.45	9.48	9.51	9.54	9.57	9.60	9.63
0.500	9.66	9.69	9.72	9.75	9.78	9.81	9.84	9.87	9.90	9.93
0.510	9.96	10.00	10.03	10.06	10.09	10.12	10.16	10.19	10.22	10.25
0.520	10.29	10.32	10.35	10.39	10.42	10.45	10.49	10.52	10.56	10.59
0.530	10.63	10.66	10.70	10.73	10.77	10.80	10.84	10.87	10.91	10.95
0.540	10.98	11.02	11.06	11.10	11.13	11.17	11.21	11.24	11.29	11.33
0.550	11.36	-----	-----	-----	-----	-----	-----	-----	-----	-----

$$a_m / W \leq 0,5204$$

$$Y = 10,32$$

Calculando Validade de deformação plana

$$B, a, (W - a) \geq 2,5 \left(\frac{K_Q}{\sigma_{YS}} \right)^2$$

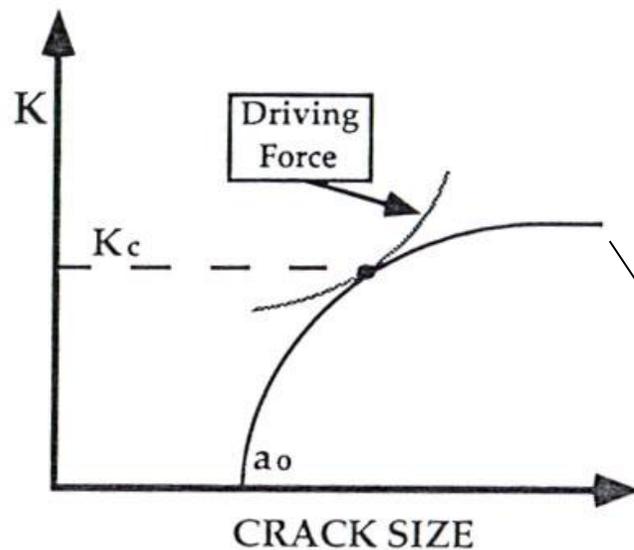
$$B, a, (W - a) \geq 2,5 \left(\frac{158}{1050} \right)^2 \geq 56 \text{ mm}$$

Portanto como $B=49,98$ mm que é menor que 56 mm e $a_m = 52,10$ mm que é menor que 56 mm. não é valido. (Não OK!!!!)

Logo para validar o ensaio teremos que aumentar ligeiramente a espessura para no mínimo 56 mm

CURVA K-R – ASTM E561

Este método de ensaio é frequentemente aplicado para materiais do tipo placa com resistência elevada, onde o comportamento em fratura é *linear elástico* em *tensão plana* e não em deformação plana como o ensaio de K_{IC} . Portanto, geralmente é realizado para materiais com espessuras pequenas onde o K varia com a espessura. Logo, o resultado advindo deste ensaio depende da geometria do CP.

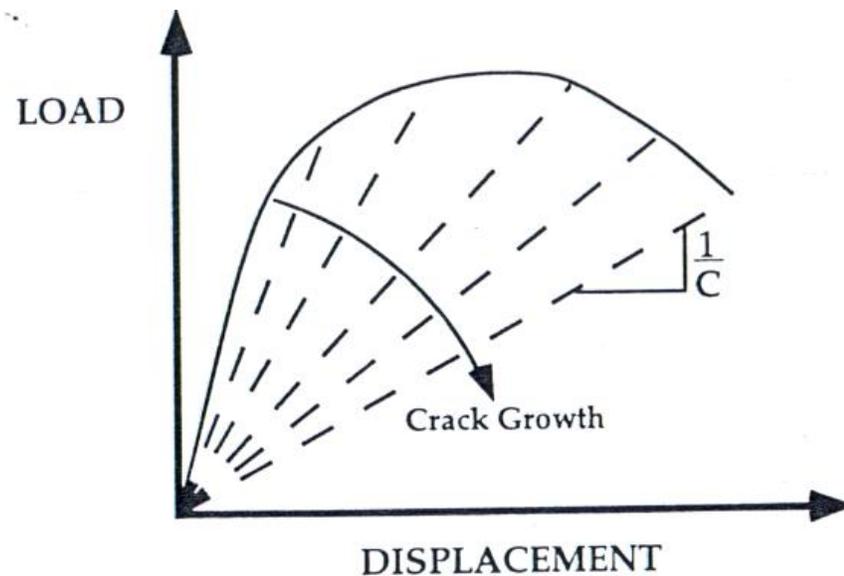


Curva K-R esquemática; K_c ocorre a um ponto de tangência entre a força motriz (drive force) e a curva R. O ponto de instabilidade K_c não é uma propriedade do material pois depende da posição da força motriz o que é governado pela geometria e forma do CP.

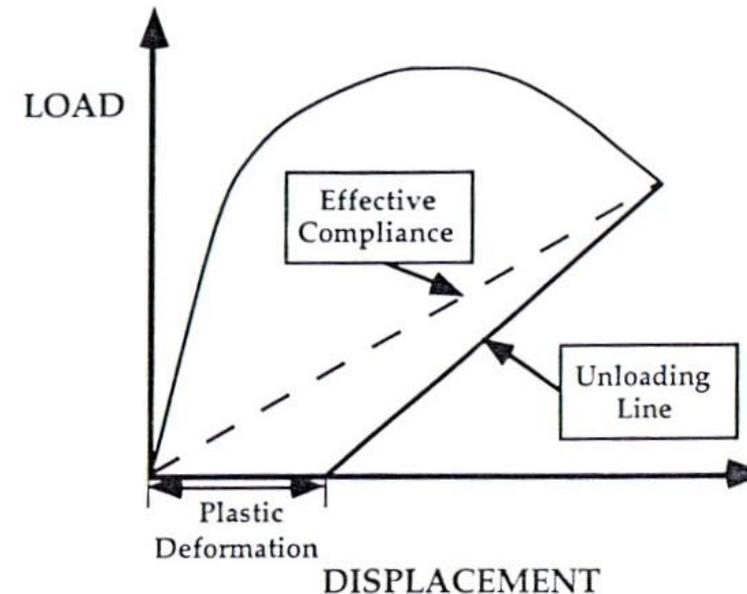
K aumenta com aumento de a até alcançar um comportamento reto

MEDIADAS EXPERIMENTAIS PARA OBTENÇÃO DA CURVA K-R

A norma ASTM E561 nos fornece uma série de métodos alternativos para o cálculo de K_I e a na curva R. mas o resultado mais apropriado dependerá do tamanho relativo da trinca e do tamanho da zona plástica.

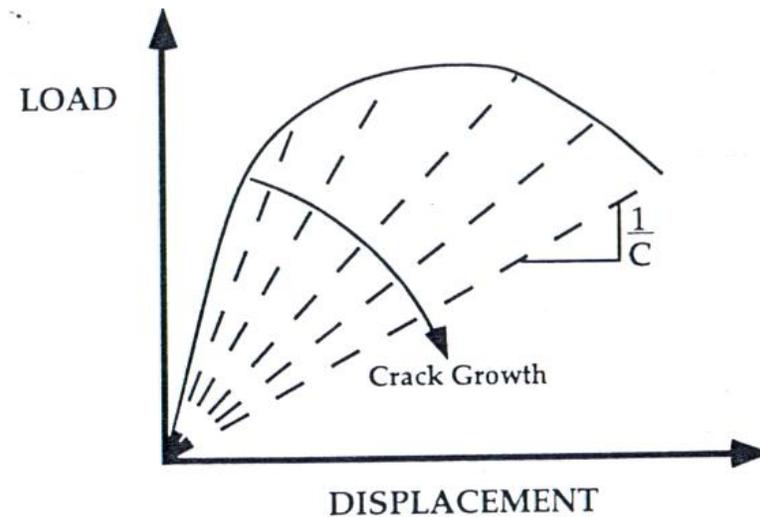


Curva carga versus deslocamento para o crescimento da trinca na ausência de plasticidade



Curva carga versus deslocamento para o crescimento da trinca com plasticidade

1º Caso – Sem plasticidade



Com o descarregamento a curva retornará ao ponto de origem como indicado pela linha pontilhada.

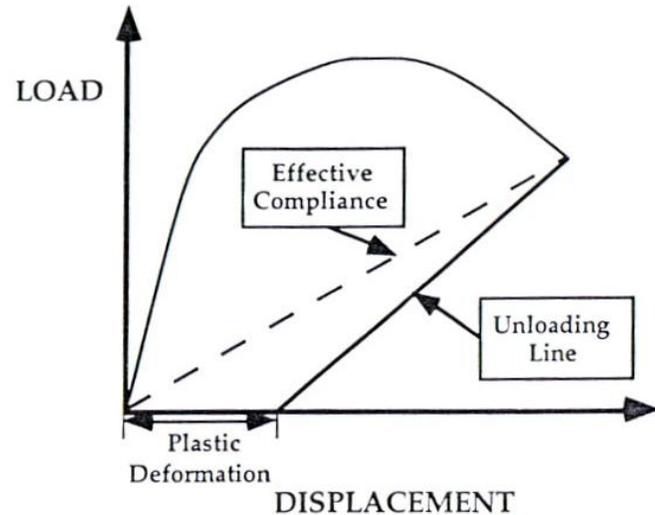
A trinca pode ser medida pela técnica do Compliance ou opticamente por luneta

Compliance = Deslocamento / Carga – O C muda pois a trinca cresce.

Para o calculo do fator de intensidade de tensão. equação abaixo. será usado o valor instantâneo da carga e da trinca e a geometria do CP.

$$K_I = \frac{P}{B\sqrt{W}} f(a/W)$$

2º Caso – Com plasticidade



Não linearidade da curva de descarregamento devido a uma combinação do tamanho da trinca e da plasticidade. pois a plasticidade na ponta da trinca provoca uma parcela finita de deformação permanente.

O Tamanho da trinca físico pode ser medido pela técnica do “compliance” ou oticamente.

O fator de intensidade de tensão deverá ser corrigido tendo em vista os efeitos de plasticidade pela determinação do tamanho de trinca efetivo, a_{eff} .

A norma ASTM sugere dois tipos de correção para cálculo de a_{eff} :

- Correção pela zona plástica de Irwin (válida para pequenas zonas plásticas);
- Correção pelo método da secante (para zonas plásticas maiores)

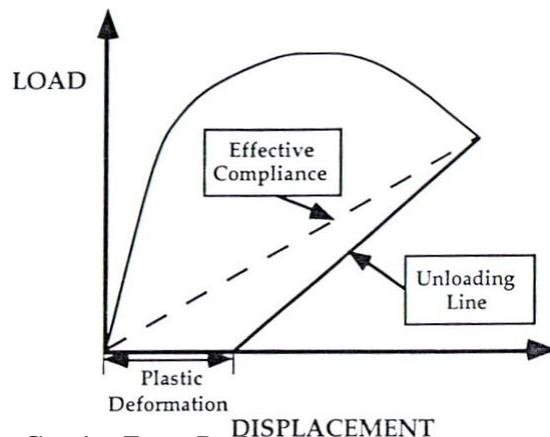
- Correção pela zona plástica de Irwin (válida para pequenas zonas plásticas);

$$a_{eff} = a + \frac{1}{2\pi} \left(\frac{K}{\sigma_{YS}} \right)^2$$

$$K_{eff} = \frac{P}{B\sqrt{W}} f(a_{eff} / W)$$

- Correção pelo método da secante (para zonas plásticas maiores)

O método da secante consiste em determinar o tamanho da trinca efetivo a partir do “compliance” efetivo o que é igual ao total deslocamento dividido pela carga segundo figura abaixo



ASTM E561 não requer condições no tamanho do CP ou o máximo tamanho de trinca permitido. logo não tem garantia que a curva K-R realizada de acordo com a norma produzirá uma propriedade do material independente da geometria.

RELAÇÕES ENTRE MICROESTRUTURA E K_{Ic}

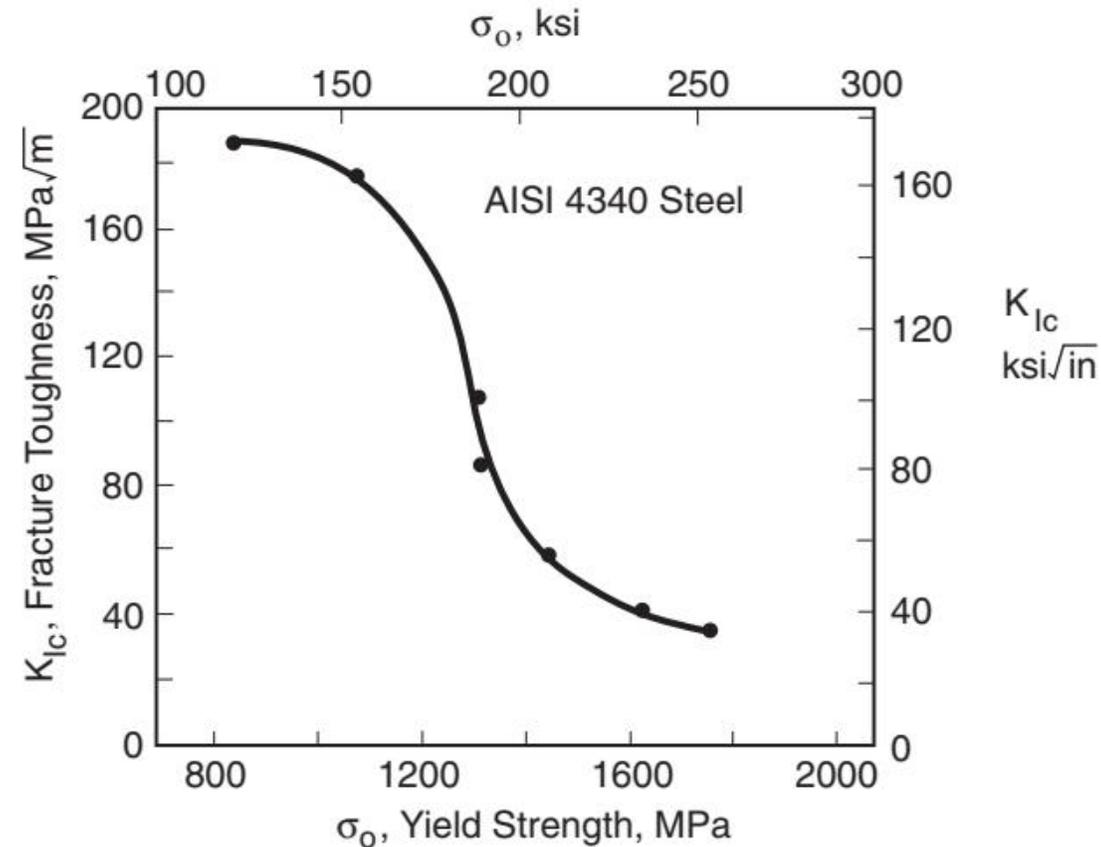


Figure 8.32 Fracture toughness vs. yield strength for AISI 4340 steel quenched and tempered to various strength levels. (Adapted from an illustration courtesy of W. G. Clark, Jr., Westinghouse Science and Technology Ctr., Pittsburgh, PA.)

EFEITO DA TEMPERATURA

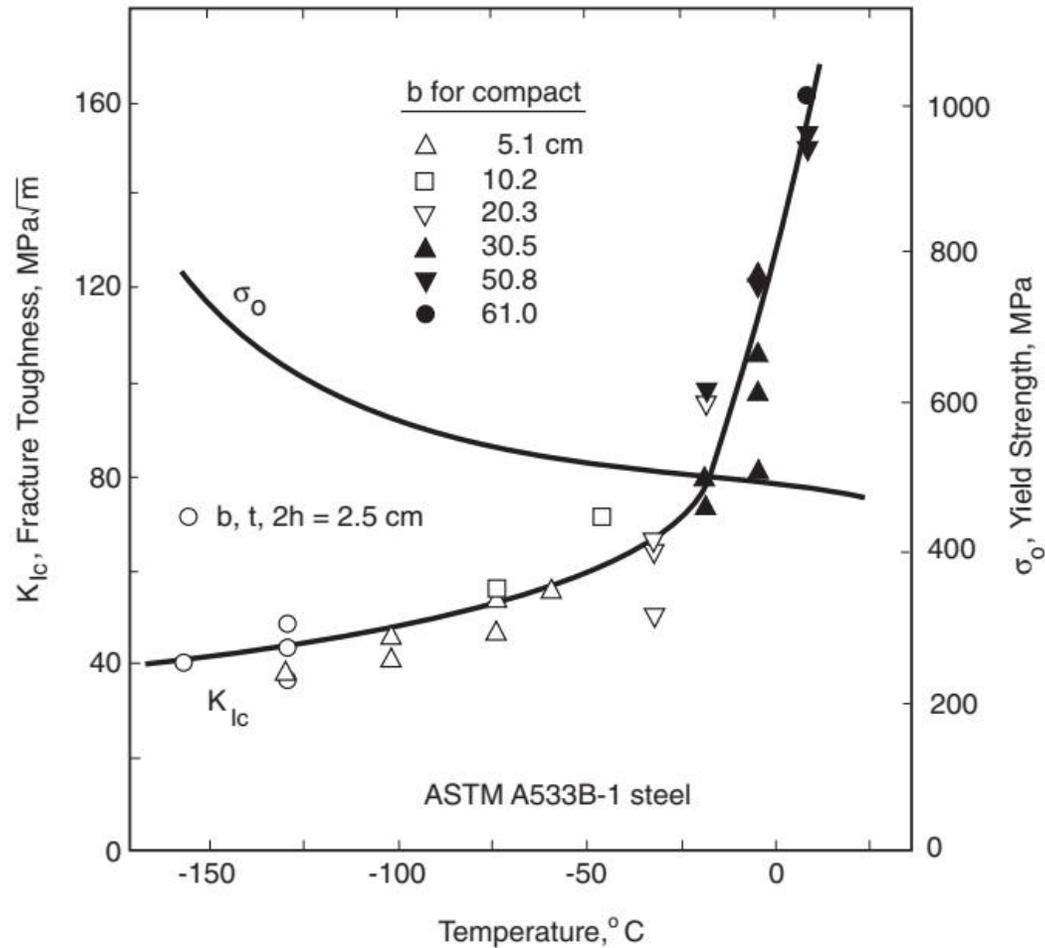


Figure 8.33 Fracture toughness and yield strength versus temperature for a nuclear pressure vessel steel. Compact specimens and one nonstandard geometry were used in sizes indicated. (Adapted from [Clark 70]; copyright c ASTM; reprinted with permission.)

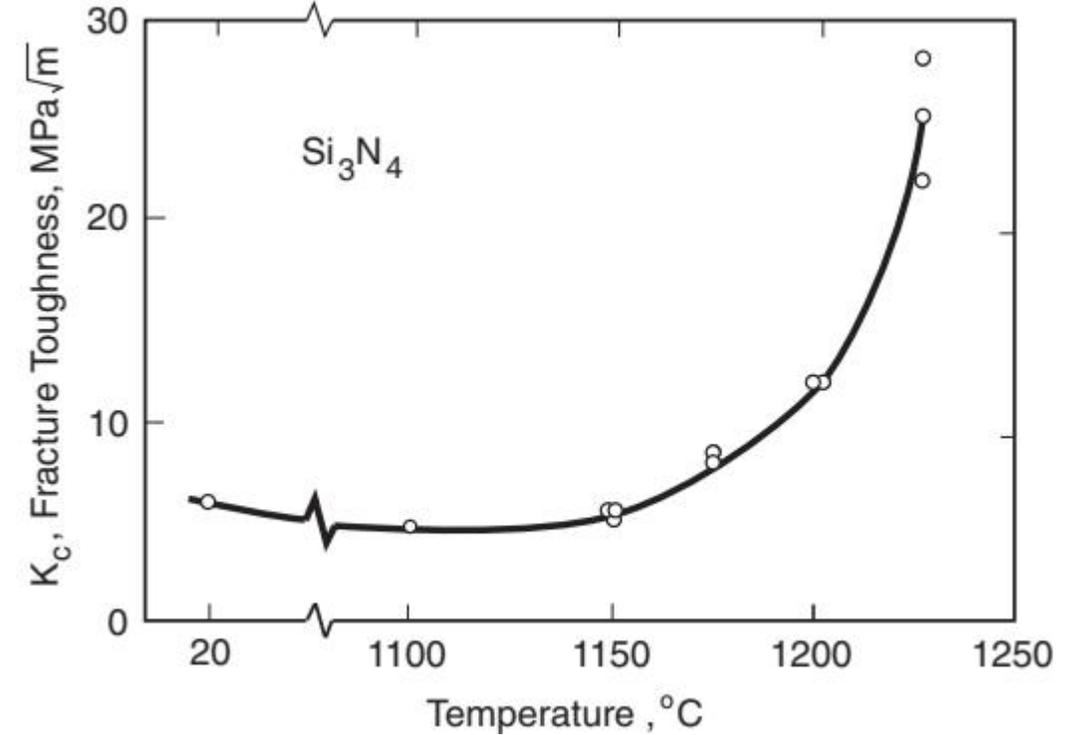


Figure 8.34 Fracture toughness vs. temperature for a silicon nitride ceramic. (Adapted from [Munz 81]; copyright c ASTM; reprinted with permission.)

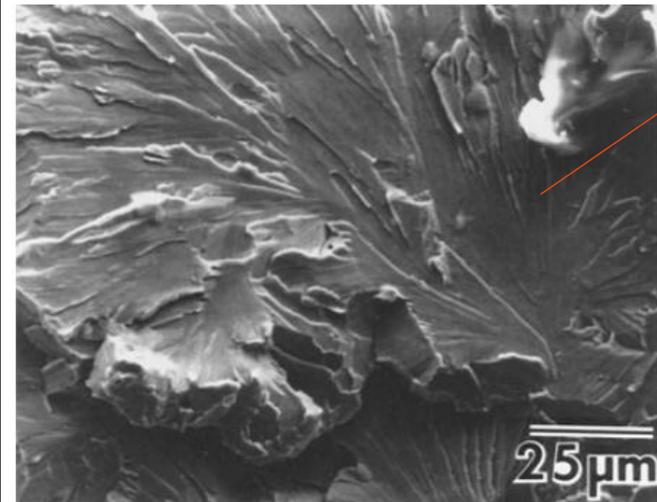
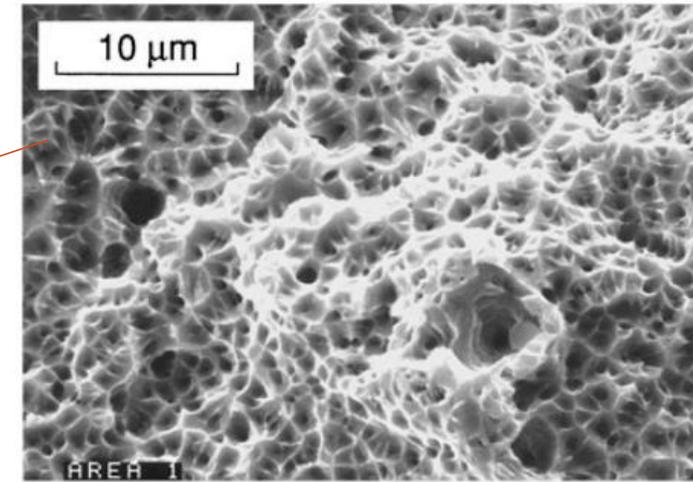
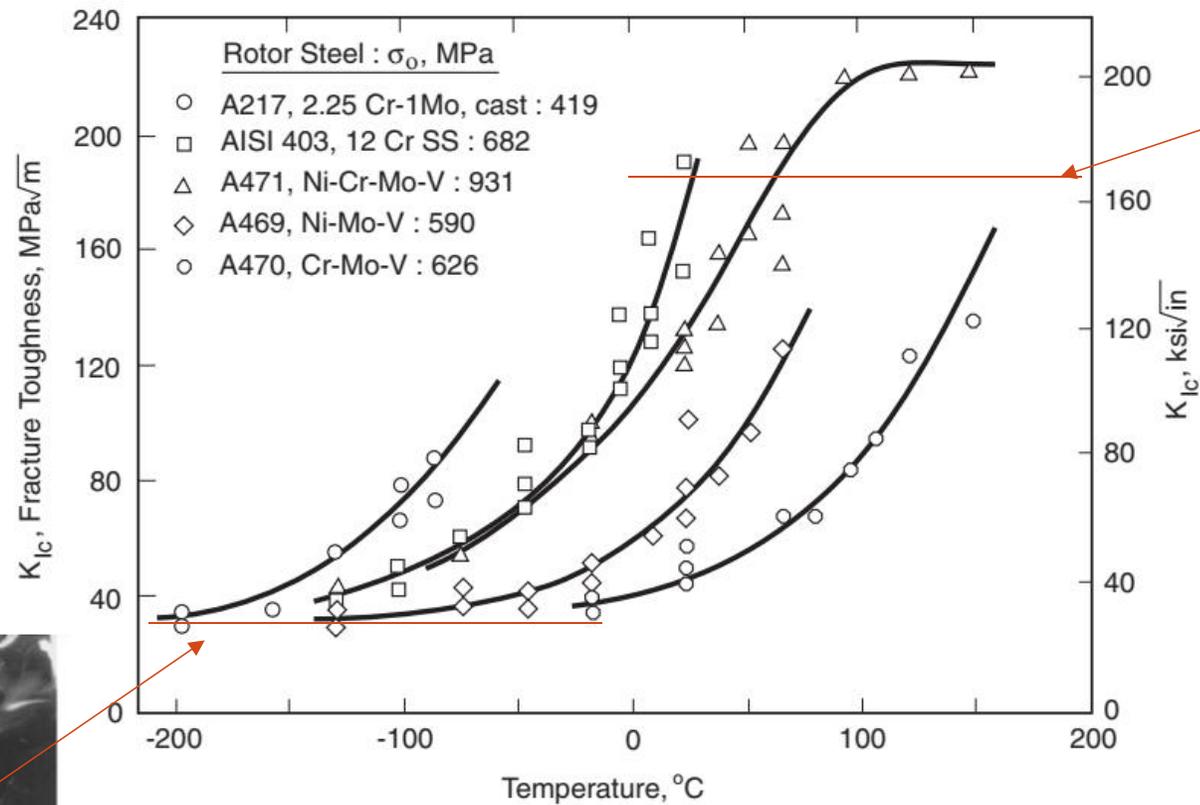


Figure 8.35 Fracture toughness vs. temperature for several steels used for turbine-generator rotors. (Data from [Logsdon 76].)

Figure 8.36 Cleavage fracture surface (left) in a 49Co-49Fe-2V alloy, and dimpled rupture (right) in a low-alloy steel. (Photos courtesy of A. Madeyski, Westinghouse Science and Technology Ctr., Pittsburgh, PA.).

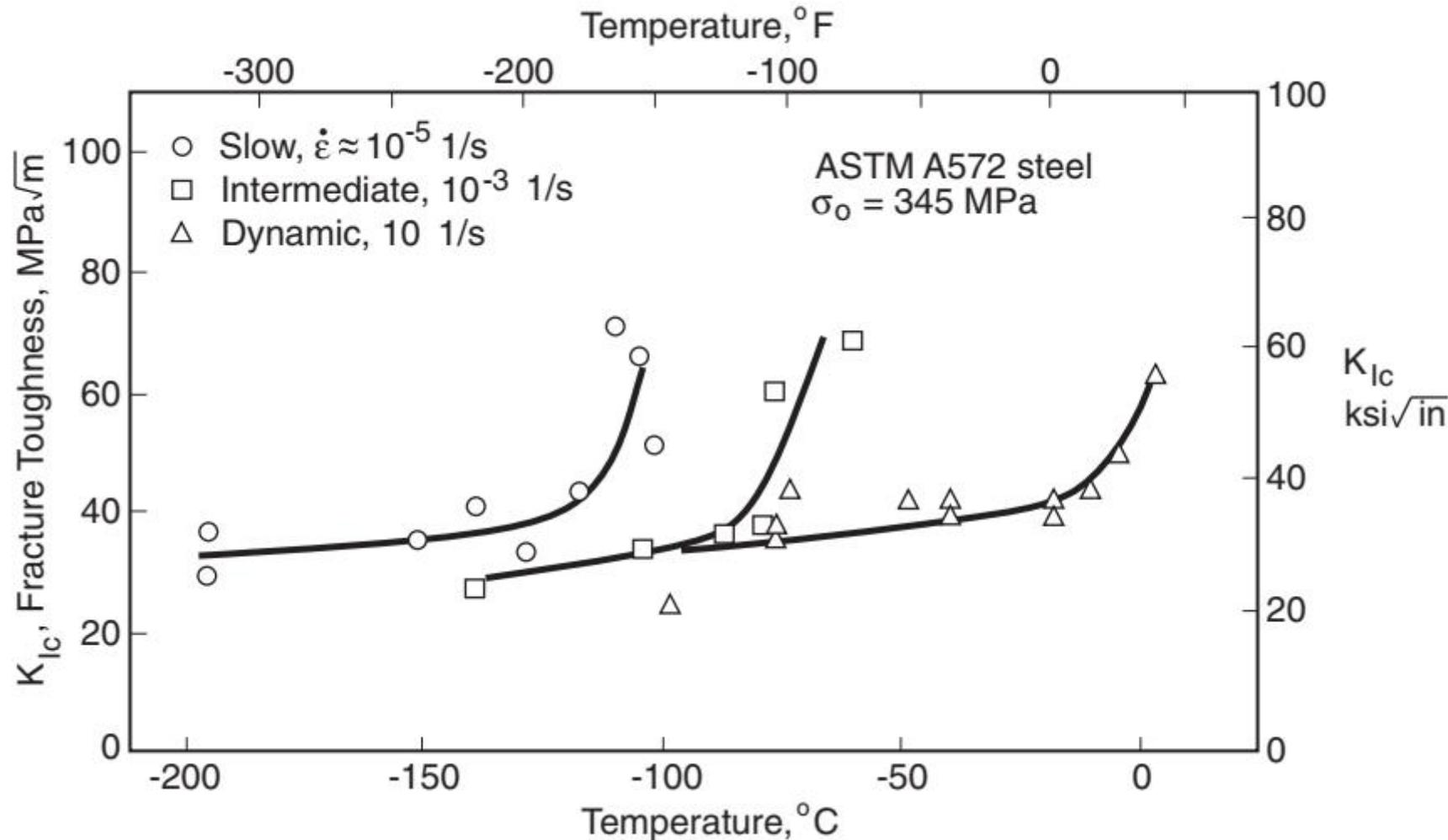


Figure 8.37 Effect of loading rate on the fracture toughness of a structural steel. Approximate strain rates at the edge of the plastic zone are given; the slowest corresponds to an ordinary test. (Adapted from [Barsom 75]; reprinted with permission from *Engineering Fracture Mechanics*; c 1975 Elsevier, Oxford, UK.).

TENACIDADE AO IMPACTO VS TENACIDADE À FRATURA

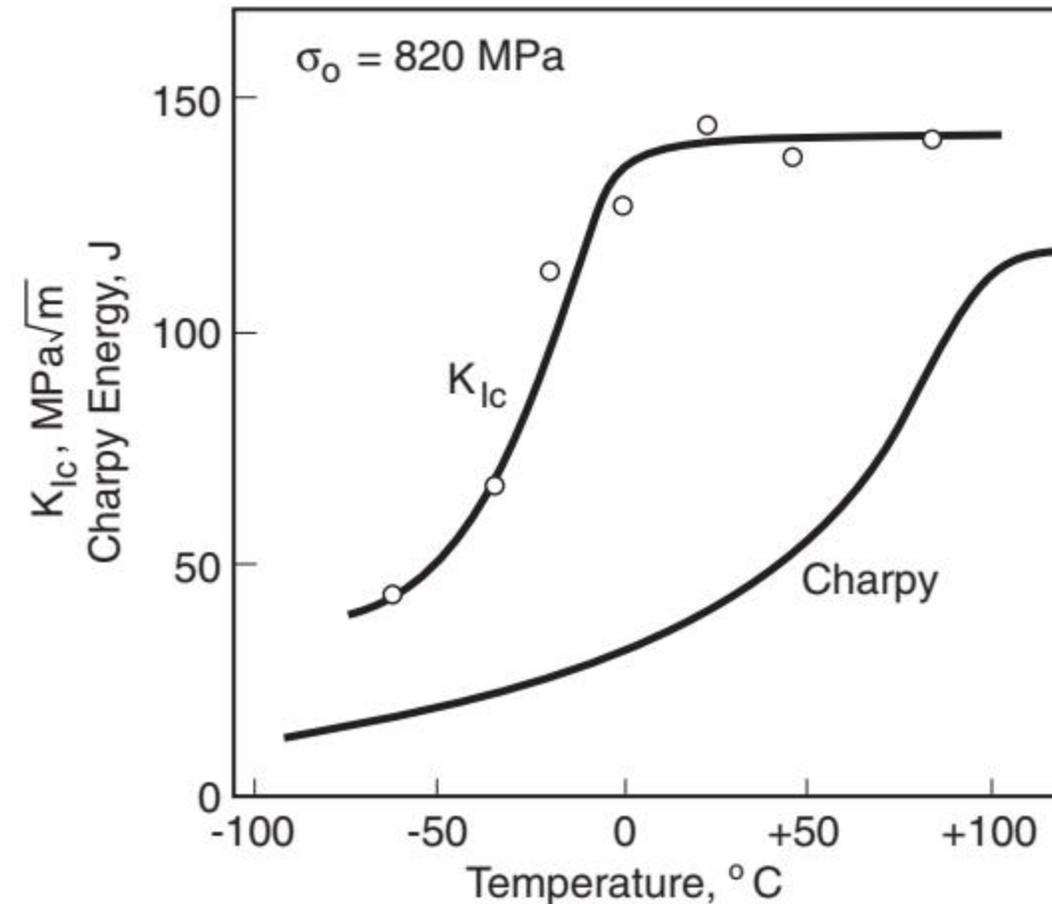


Figure 8.38 Comparison of temperature-transition behaviors for K_{Ic} and Charpy tests on a 2.25Cr-1Mo steel. (Adapted from [Marandet 77]; copyrightc ASTM; reprinted with permission.).

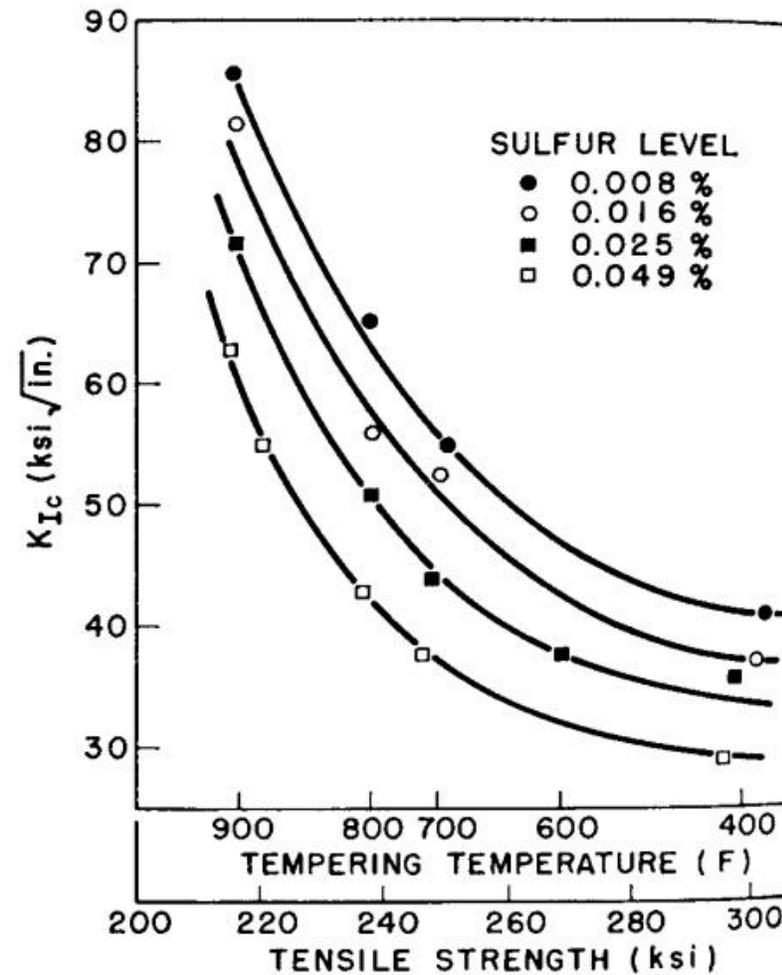
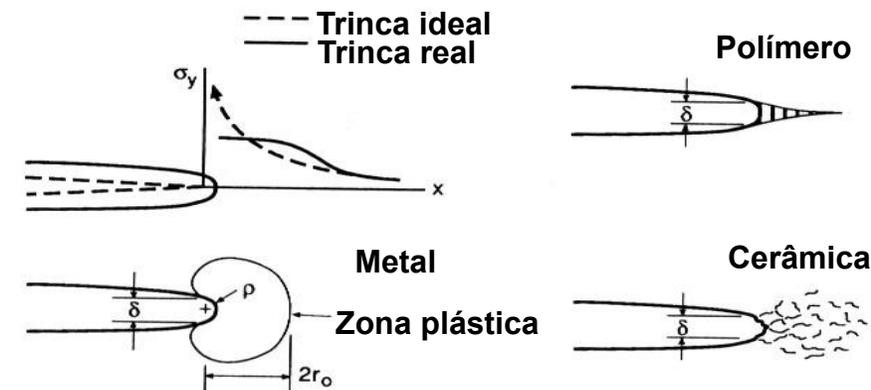
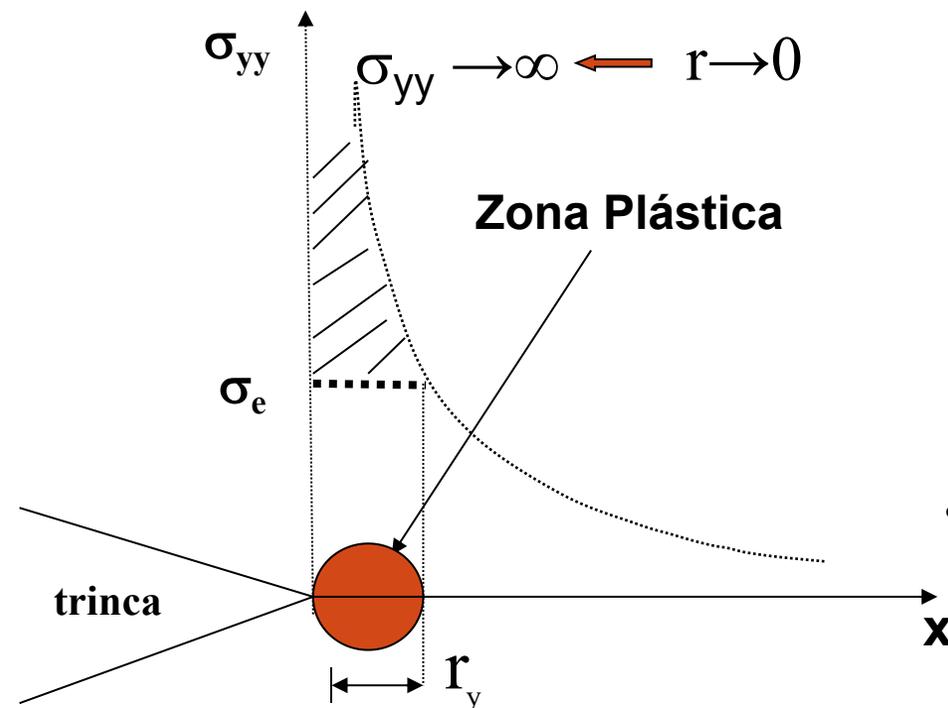


Figure 8.39 Effect of sulfur content on the fracture toughness of AISI 4345 steel. (From [Wei 65]; copyright c ASTM; reprinted with permission.)

TAMANHO DA ZONA PLÁSTICA

No início foi mostrado que o material não pode suportar tensões infinitas na ponta da trinca. desta forma no carregamento a ponta da trinca torna-se arredondada e é formada **uma região de escoamento em metais**, crazing (polímeros) e microtrincas (cerâmicas).



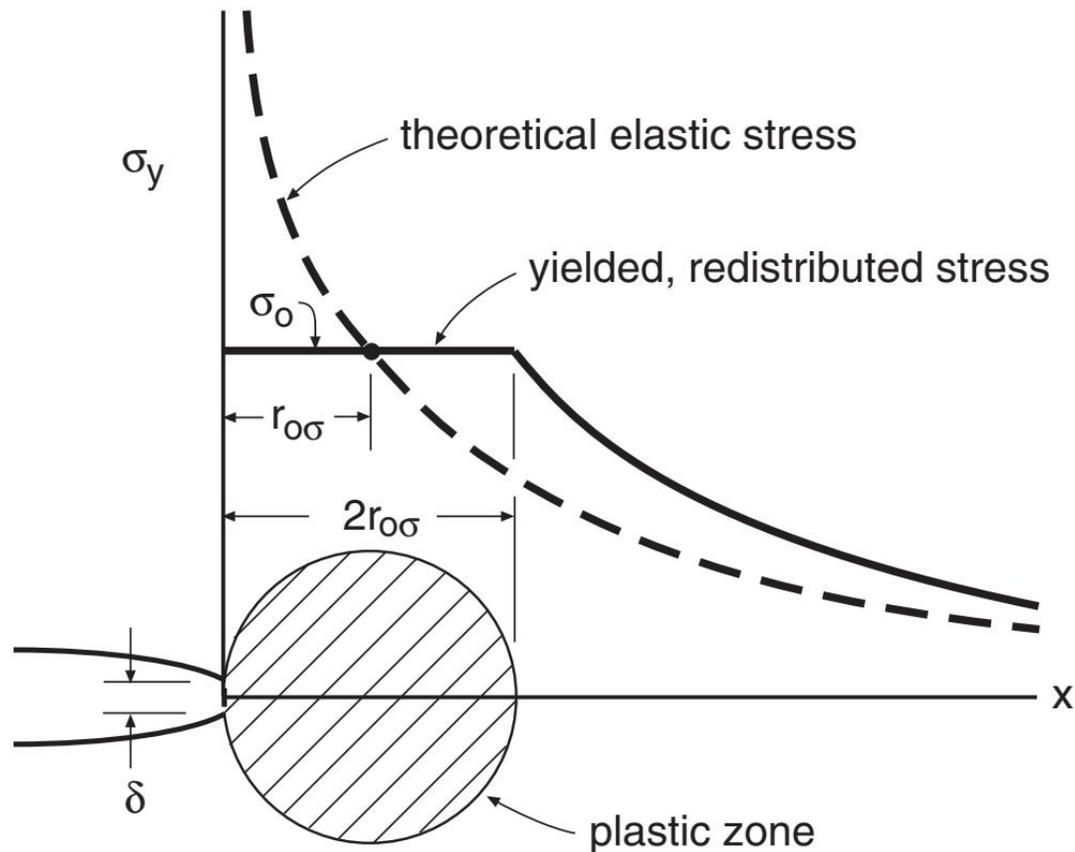
- **Relaxamento das tensões na frente da trinca**

Ajuste da zona plástica (*ainda aplica MFEL*)

- Com a formação da ZP a análise de tensões fica imprecisa.
- Correções simples para a MFEL são disponíveis. desde que ZP é pequena.
- O tamanho da ZP pode ser estimado de duas formas: O **método de Irwin** e o **modelo de Dugdale**.
- **Método de Irwin:** no plano da trinca $\theta=0$
 - O limite entre a comportamento plástico e elástico ocorre quando a equação satisfaz o critério de escoamento.
 - No estado plano de tensão o escoamento irá ocorrer quando $\sigma_{yy} = \sigma_{ys}$ e a singularidade de tensão é truncada pelo escoamento na frente da trinca.
- Quando o escoamento ocorre, as tensões devem ser redistribuídas para satisfazer o equilíbrio.
- A zona plástica deve aumentar em tamanho para acomodar estas forças.

$$a, (b - a), h \geq \frac{4}{\pi} \left(\frac{K}{\sigma_o} \right)^2 \quad (\text{LEFM applicable})$$

Ajuste da zona plástica (*ainda aplica MFEL*)



$$K = FS\sqrt{\pi a}$$

$$K_e = F_e S \sqrt{\pi a_e} = F_e S \sqrt{\pi (a + r_{o\sigma})},$$

$$\text{where } r_{o\sigma} = \frac{1}{2\pi} \left(\frac{K_e}{\sigma_o} \right)^2$$

$$F_e = \bar{F} (a_e/b)$$

$$K_e = \frac{K}{\sqrt{1 - \frac{1}{2} \left(\frac{FS}{\sigma_o} \right)^2}}$$

It is suggested that the use of plastic zone adjustments be limited to loads below 80% of the fully plastic force or moment—that is, below $0.8P_o$ or $0.8M_o$.

ESTADO PLANO DE TENSÃO VERSUS ESTADO PLANO DE DEFORMAÇÃO

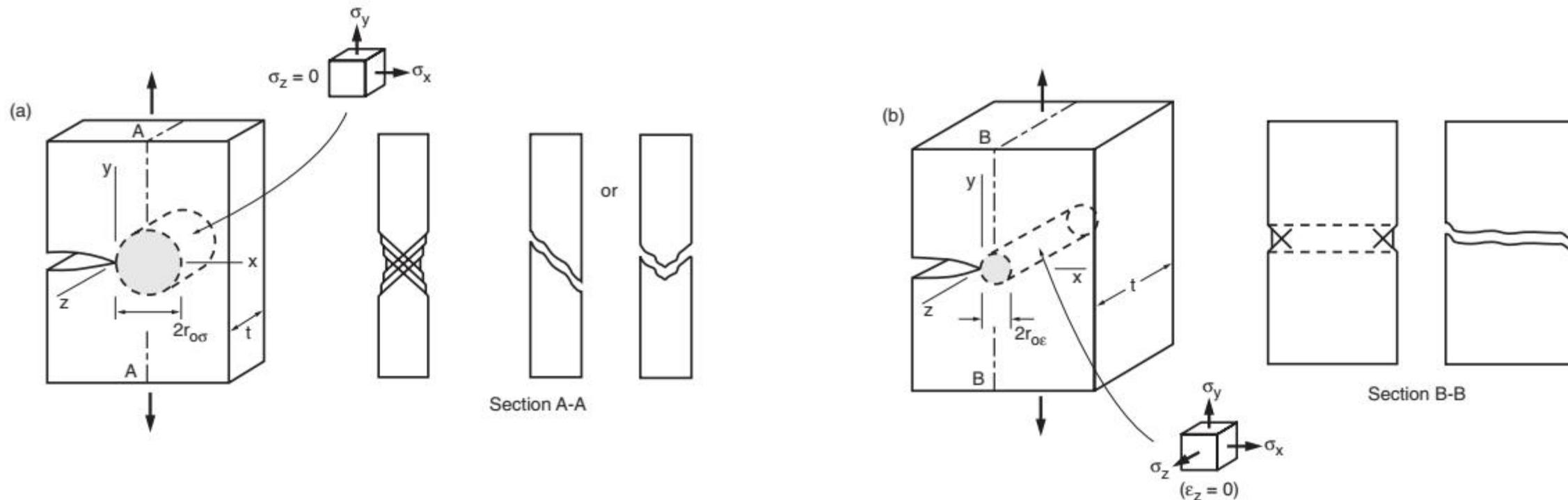


Figure 8.44 Plastic zone, stress state, and fracture mode for (a) plane stress and (b) plane strain.

ZONA PLÁSTICA NUMA CHAPA GROSSA

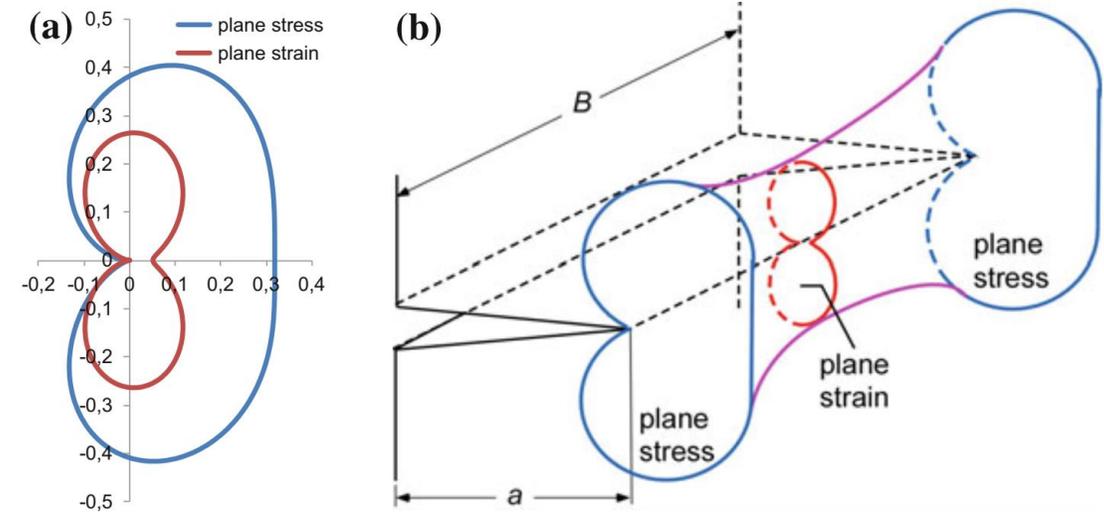
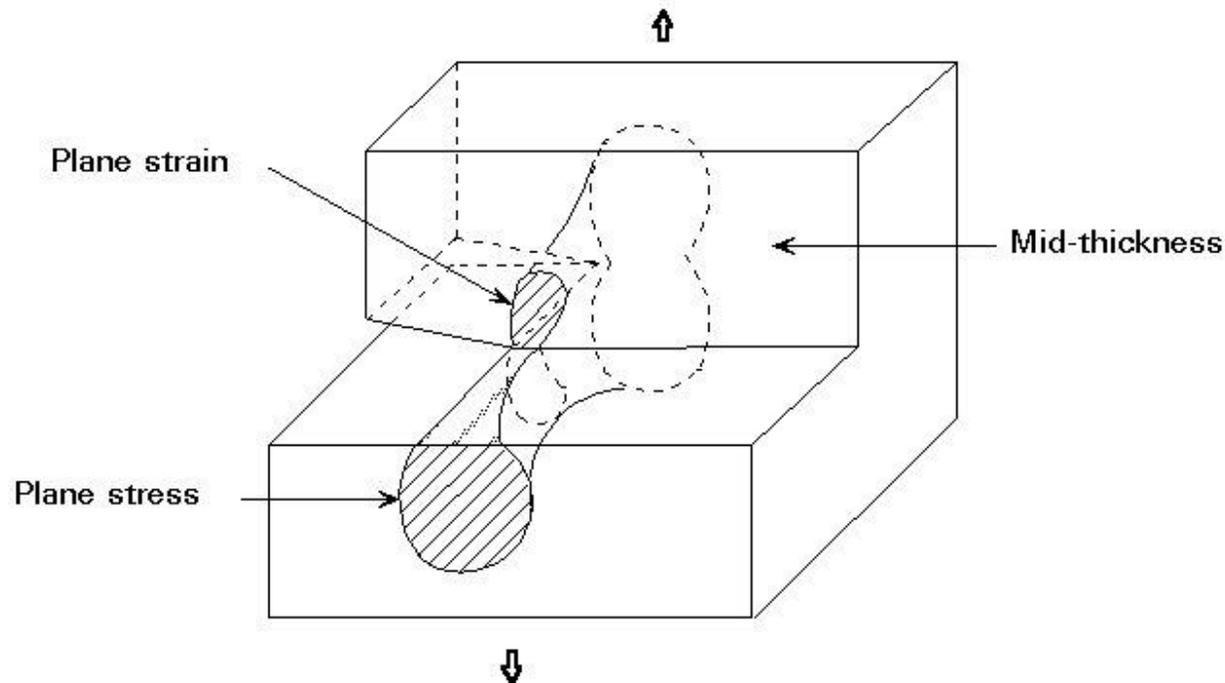


Fig. 4.3 a Shape of the plastic zones in plane stress and plane strain: abscissa and ordinate normalised by $(K_I/R_0)^2$; b "dog-bone" model

Limitações da MFEL devido a plasticidade

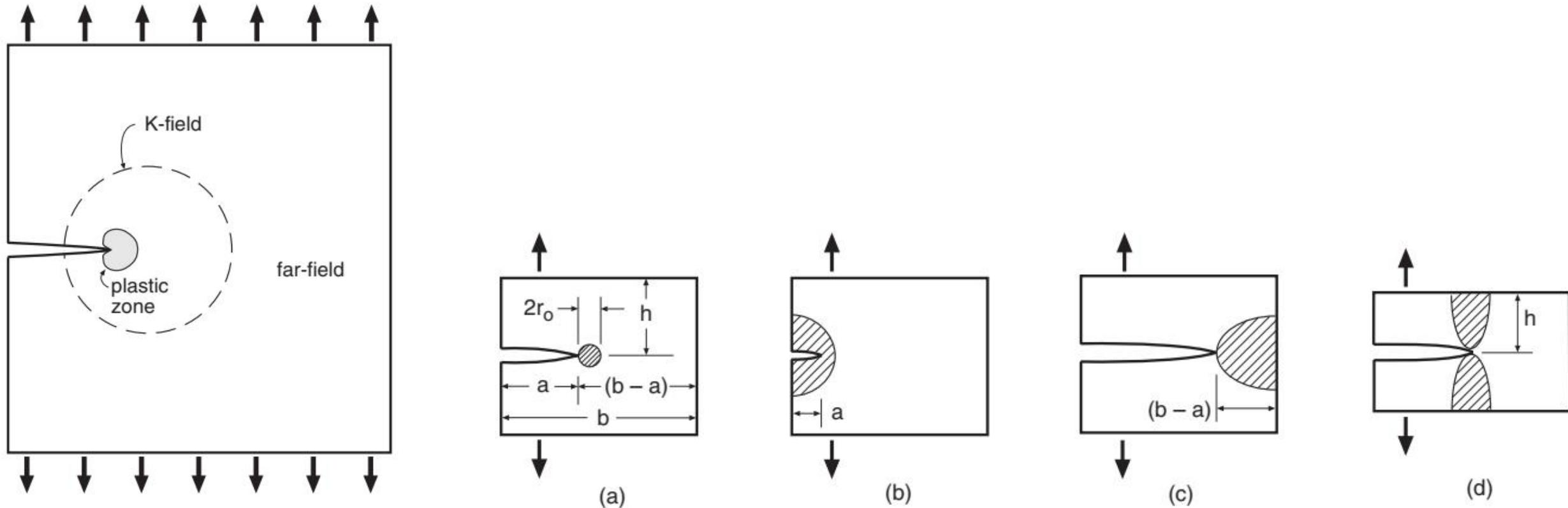
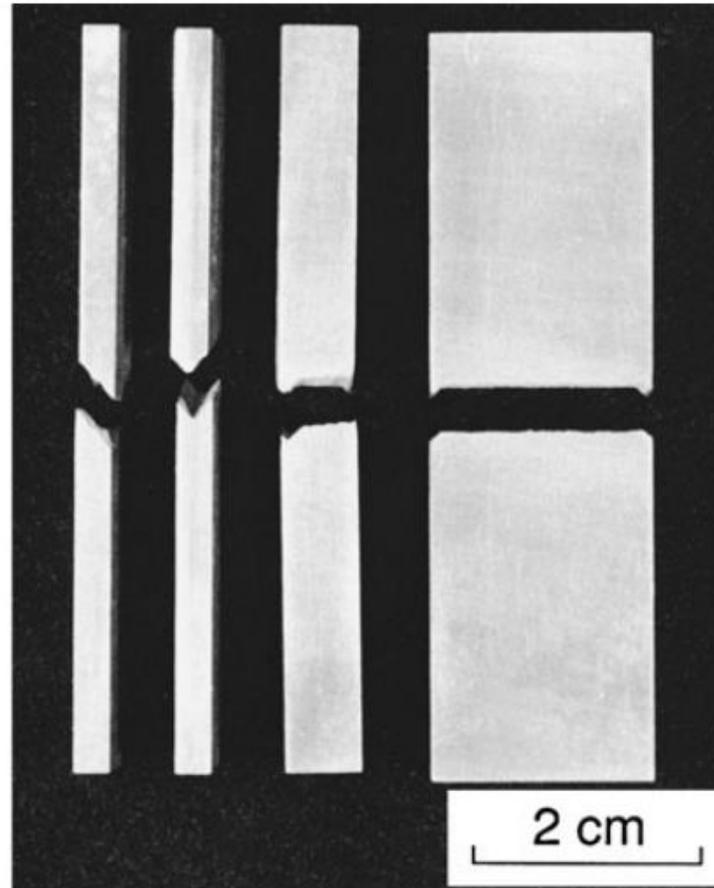
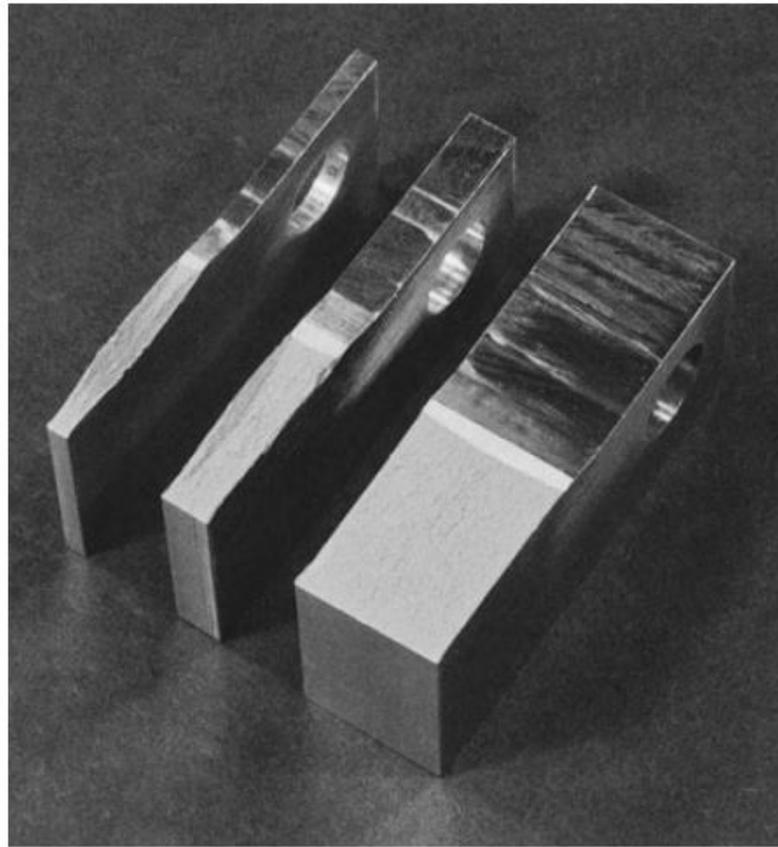


Figure 8.45 A crack and its plastic zone, and the larger K-field that must exist for LEFM to be applicable.

Figure 8.46 Small plastic zone compared with planar dimensions (a), and situations where LEFM is invalid due to the plastic zones being too large compared with (b) crack length, (c) uncracked ligament, and (d) member height.

Limitações da MFEL devido a plasticidade



$$t, a, (b - a), h \geq 2.5 \left(\frac{K}{\sigma_o} \right)^2 \quad (\text{plane strain})$$

Figure 8.47 Fracture surfaces (left) and cross sections showing profiles of fractures (right) for toughness tests on compact specimens ($b = 51$ mm) of 7075-T651 aluminum. The thinnest specimens shown have typical plane stress fractures on inclined planes; the intermediate thickness has mixed behavior; and the thickest specimens have flat plane-strain fractures. (Photos by R. A. Simonds.)

EXAMPLE 8.6

Example 8.6

For the situation of Ex. 8.1:

- (a) For $a = 10$ mm, determine whether or not plane strain applies and whether or not LEFM is valid. Also estimate the plastic zone size.
- (b) Do the same for the estimated $a_c = 16.3$ mm.

Solution (a) Plane strain applies if Eq. 8.40 is satisfied. Use $t = 5$ mm, $b = 50$ mm, and K as calculated in Ex. 8.1(a), and also $\sigma_o = 415$ MPa for 2014-T651 Al, to obtain

$$t, a, (b - a), h \geq 2.5 \left(\frac{K}{\sigma_o} \right)^2 = 2.5 \left(\frac{17.7 \text{ MPa}\sqrt{\text{m}}}{415 \text{ MPa}} \right)^2 ?$$

$$5, 10, 40, \text{ large } h \geq 0.0045 \text{ m} = 4.5 \text{ mm?}$$

Yes, the test is successful, so *plane strain applies and LEFM is applicable (Ans.)*. The plastic zone size is then estimated as the value for plane strain from Eq. 8.38:

$$2r_{o\varepsilon} = \frac{1}{3\pi} \left(\frac{K}{\sigma_o} \right)^2 = \frac{1}{3\pi} \left(\frac{17.7 \text{ MPa}\sqrt{\text{m}}}{415 \text{ MPa}} \right)^2 = 0.19 \text{ mm} \quad \text{Ans.}$$

- (b) For $a_c = 16.3$ mm and $K = K_{Ic} = 24 \text{ MPa}\sqrt{\text{m}}$, the plane strain test is similarly applied.

$$5, 16.3, 33.7, \text{ large } h \geq 2.5 \left(\frac{24 \text{ MPa}\sqrt{\text{m}}}{415 \text{ MPa}} \right)^2 = 8.4 \text{ mm?}$$

No, the test fails, and *plane strain does not apply (Ans.)*. But LEFM may still be applicable if Eq. 8.39 is satisfied. Thus, we ask,

$$a, (b - a), h \geq \frac{4}{\pi} \left(\frac{K}{\sigma_o} \right)^2 = \frac{4}{\pi} \left(\frac{24 \text{ MPa}\sqrt{\text{m}}}{415 \text{ MPa}} \right)^2 ?$$

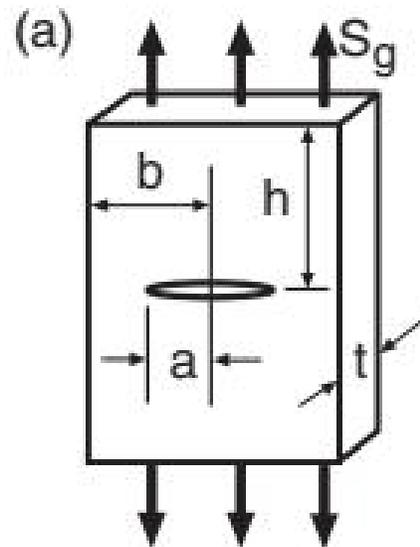
$$16.3, 33.7, \text{ large } h \geq 4.3 \text{ mm?}$$

Yes, the test is successful, and *LEFM is applicable (Ans.)*. The plastic zone size is then estimated as the value for plane stress from Eq. 8.37:

$$2r_{o\sigma} = \frac{1}{\pi} \left(\frac{K}{\sigma_o} \right)^2 = \frac{1}{\pi} \left(\frac{24 \text{ MPa}\sqrt{\text{m}}}{415 \text{ MPa}} \right)^2 = 1.06 \text{ mm} \quad \text{Ans.}$$

Comment Due to the state of plane stress in (b), the use of K_{Ic} is conservative. The actual K_c may be somewhat higher than K_{Ic} , and the a_c value therefore larger than estimated.

Example 8.1 (lembrando)



Example 8.1

A center-cracked plate, as in Fig. 8.12(a), has dimensions $b = 50$ mm, $t = 5$ mm, and large h ; a force of $P = 50$ kN is applied.

- What is the stress intensity factor K for a crack length of $a = 10$ mm?
- For $a = 30$ mm?
- What is the critical crack length a_c for fracture if the material is 2014-T651 aluminum?

Solution (a) To calculate K for $a = 10$ mm, using Fig. 8.12(a), we need

$$S_g = \frac{P}{2bt} = \frac{50,000 \text{ N}}{2(50 \text{ mm})(5 \text{ mm})} = 100 \text{ MPa}, \quad \alpha = \frac{a}{b} = \frac{10 \text{ mm}}{50 \text{ mm}} = 0.200$$

Since $\alpha \leq 0.4$, it is within 10% to use $F = 1$. Thus,

$$K = S_g \sqrt{\pi a} = (100 \text{ MPa}) \sqrt{\pi(0.010 \text{ m})} = 17.7 \text{ MPa}\sqrt{\text{m}} \quad \text{Ans.}$$

where crack length a is entered in units of meters to obtain the desired units for K of $\text{MPa}\sqrt{\text{m}}$.

(b) For $a = 30$ mm, we have $\alpha = a/b = (30 \text{ mm})/(50 \text{ mm}) = 0.600$. This does not satisfy $\alpha \leq 0.4$, so the more general expression for F from Fig. 8.12(a) is needed:

$$F = \frac{1 - 0.5\alpha + 0.326\alpha^2}{\sqrt{1 - \alpha}} = 1.292$$

$$K = F S_g \sqrt{\pi a} = 1.292 (100 \text{ MPa}) \sqrt{\pi(0.030 \text{ m})} = 39.7 \text{ MPa}\sqrt{\text{m}} \quad \text{Ans.}$$

Example 8.7

Problem 8.48 concerns a test on a double-edge-cracked plate of 7075-T651 aluminum, for which $a = 5.7$, $b = 15.9$, and $t = 6.35$ mm. A value of $K_Q = 37.3 \text{ MPa}\sqrt{\text{m}}$ is calculated for the force $P_Q = 50.3$ kN, but the test for applicability of LEFM (Eq. 8.39) is not met. Calculate the fully plastic force. If it is reasonable to do so, also apply the plastic zone adjustment to obtain a revised value of K_Q .

Solution Figure A.16(a) also applies to the geometry of Fig. 8.12(b), so that the fully plastic load is

$$P_o = 2bt\sigma_o \left(1 - \frac{a}{b}\right)$$

$$P_o = 2(0.0159 \text{ m})(0.00635 \text{ m})(505 \text{ MPa}) \left(1 - \frac{5.7 \text{ mm}}{15.9 \text{ mm}}\right)$$

$$P_o = 0.0654 \text{ MN} = 65.4 \text{ kN}$$

Ans.

where the yield strength of 7075-T651 Al from Table 8.1 is used. Comparing P_o with P_Q gives

$$\frac{P_Q}{P_o} = \frac{50.3 \text{ kN}}{65.4 \text{ kN}} = 0.77$$

Since this ratio is less than 0.80, it is reasonable to apply the plastic zone adjustment.

From Fig. 8.12(b), the value $\alpha = a/b = 0.358$ that applies is well within the range $\alpha \leq 0.6$, where $F \approx 1.12$. Hence, F can be taken as unchanged for a_e and Eq. 8.43 applies. Thus, we have

$$K_{Qe} = \frac{K_Q}{\sqrt{1 - \frac{1}{2} \left(\frac{FS}{\sigma_o}\right)^2}} = \frac{37.3 \text{ MPa}\sqrt{\text{m}}}{\sqrt{1 - \frac{1}{2} \left(\frac{1.12 \times 249 \text{ MPa}}{505 \text{ MPa}}\right)^2}} = 40.5 \text{ MPa}\sqrt{\text{m}} \quad \text{Ans.}$$

where $S = S_g = P_Q/2bt$ is used.

Comment This adjusted K is 40% above the value from Table 8.1 of $K_{Ic} = 29 \text{ MPa}\sqrt{\text{m}}$. The probable explanation for the difference is that K_{Qe} includes an effect of increased toughness for plane stress.

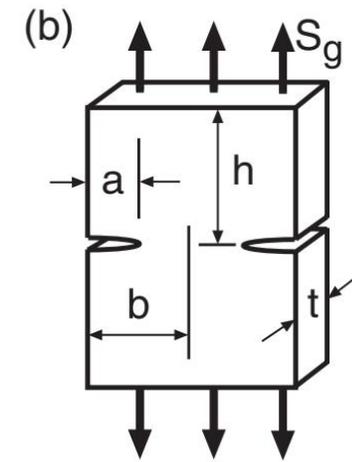


Figura 12.b

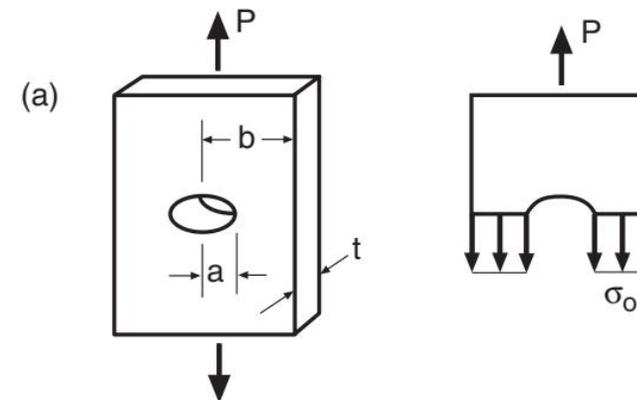


Figura A.16

Fully plastic force or moment for given $\alpha = a/b$.

$$(a) P_o = 2bt\sigma_o (1 - \alpha)$$

Crack length at fully plastic yielding for given load, where, for (c) and (d), $P = P/(bt\sigma_o)$:

$$(a) a_o = b \left[1 - \frac{P}{2bt\sigma_o}\right]$$



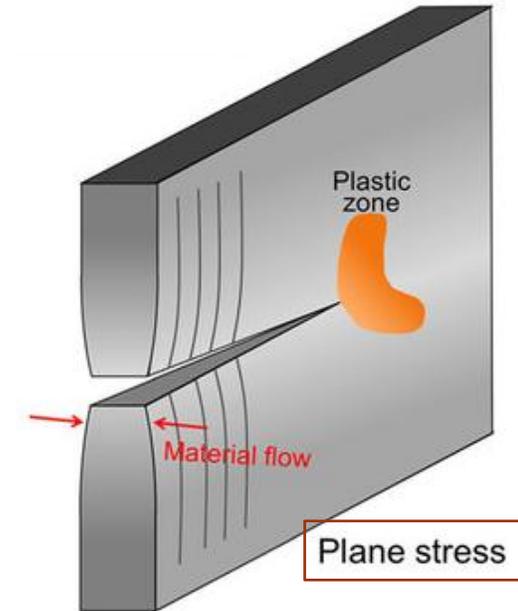
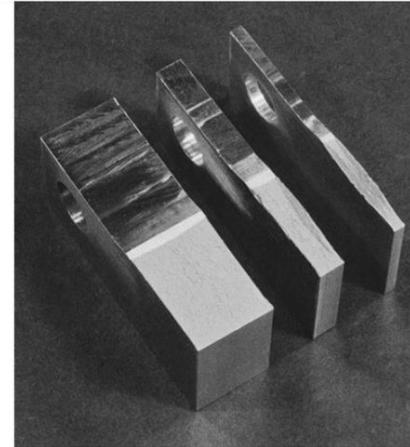
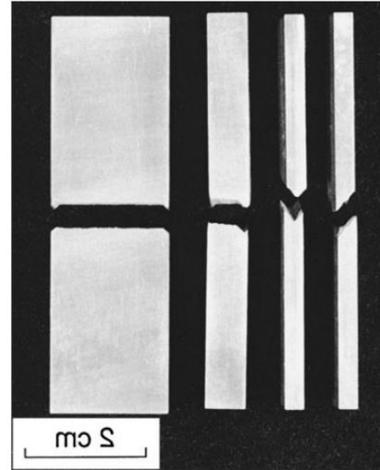
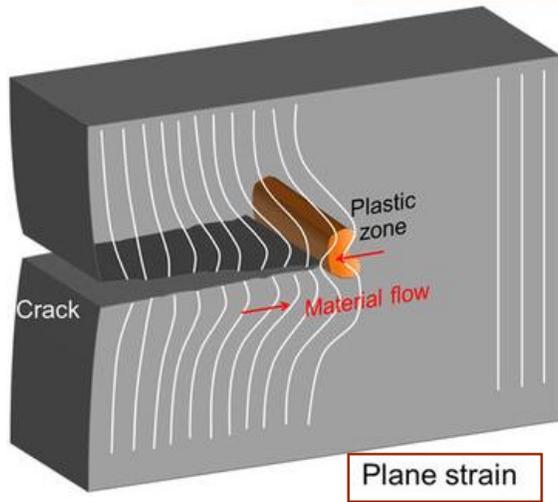
Mecânica da fratura: Linear elástica (MFLE) vs Elastoplástica (MFEP)

136

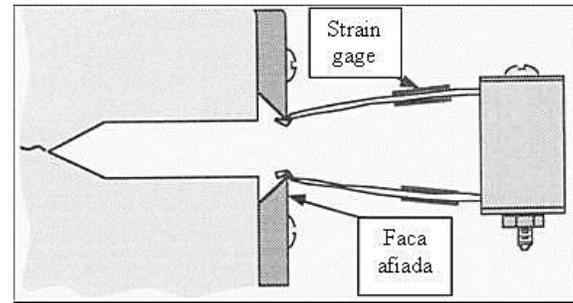
Figure 5.2 Fractured components and devices. (a) Ruptured beer barrel

Mecânica da fratura: Linear elástica (MFLE)

vs Elastoplástica (MFEP)



A principal diferença está no tamanho da região plástica gerada na ponta da trinca



k_{ic}

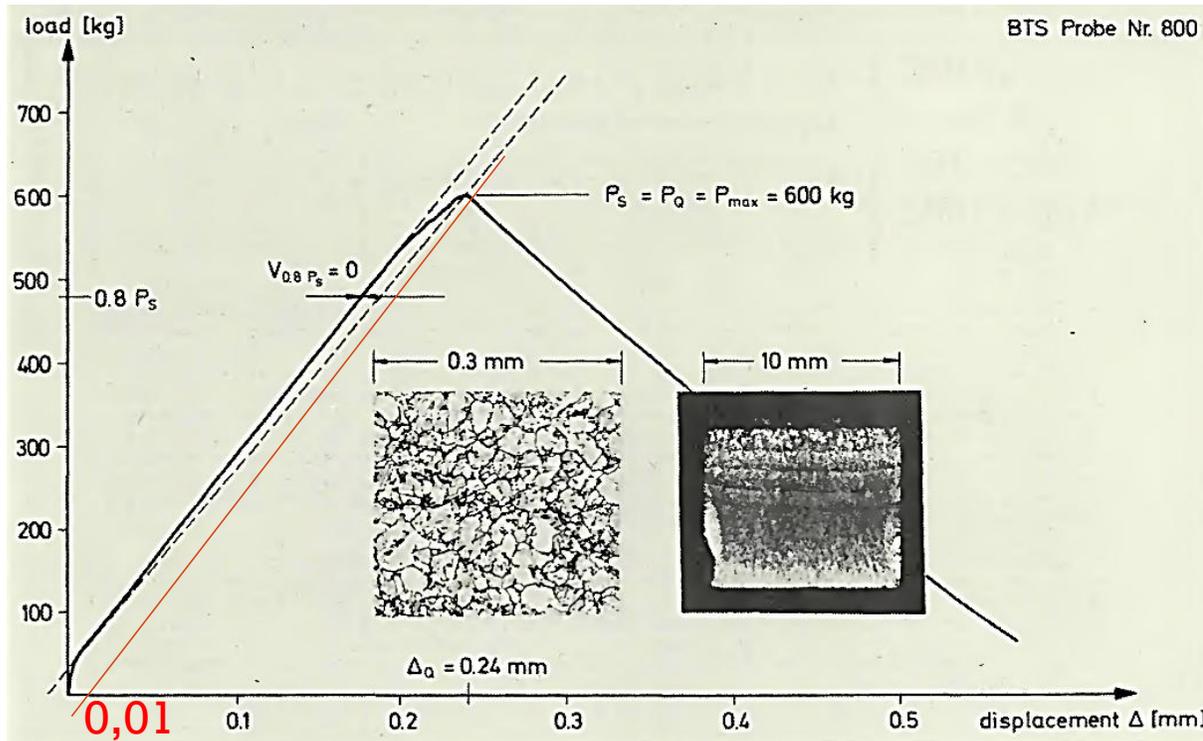
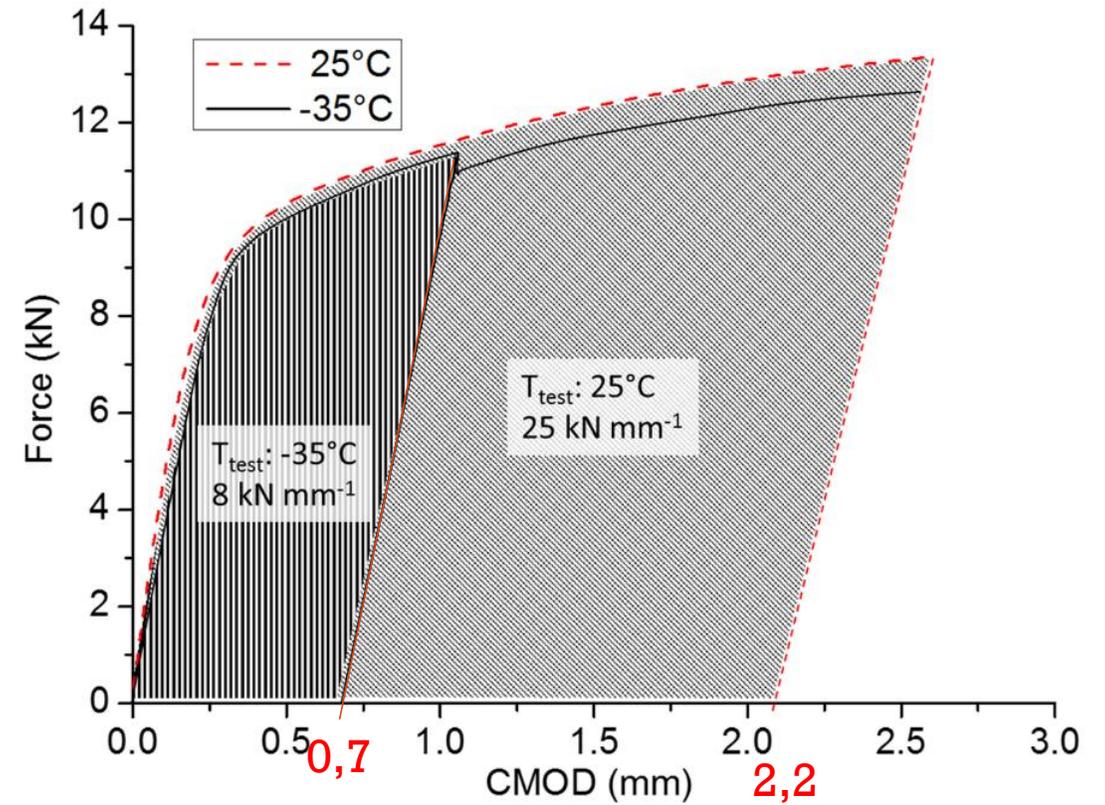
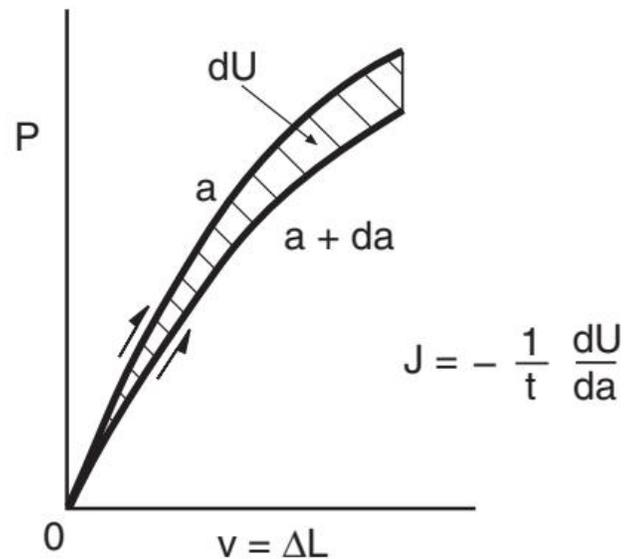
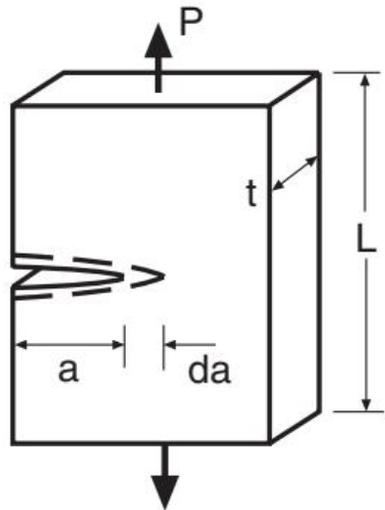


Fig. 12 — Load-displacement curve of a fracture mechanics test of the transformed structure in the HAZ of a GTA weld, together with the microstructure in the region of the fatigue crack tip and a macrograph of the crack surface

CTOD, integral-J



INTEGRAL J



$$K_{IcJ} = \sqrt{J_{Ic} E'}$$

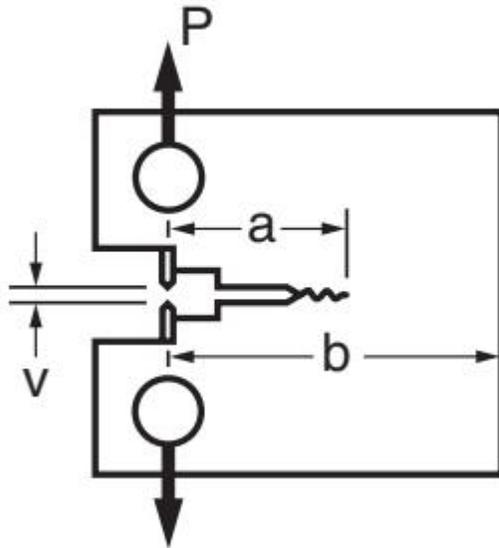
$$K_J = \sqrt{J E},$$

$$K_J \approx K \sqrt{1 + \frac{\epsilon_p}{\epsilon_e \sqrt{n}}}$$

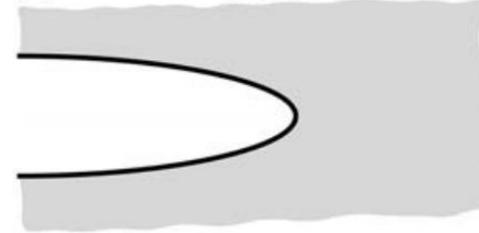
Figure 8.49 Definition of the J -integral in terms of the potential energy difference for cracks of slightly different length.

Here, $K = S\sqrt{\pi a}$ is from LEFM, and ϵ_e and ϵ_p are the elastic and plastic strains corresponding to the applied stress. The quantity n is the strain-hardening exponent for a stress versus plastic strain relationship of the form $\sigma = H\epsilon_p^n$, where $n \approx 0.1$ to 0.2 is typical for metals.

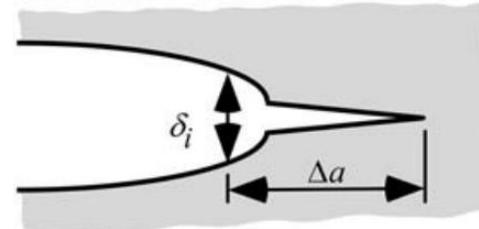
INTEGRAL J - ENSAIO



(1) Crack Blunting



(2) Fracture Initiation



(3) Steady State Crack Growth

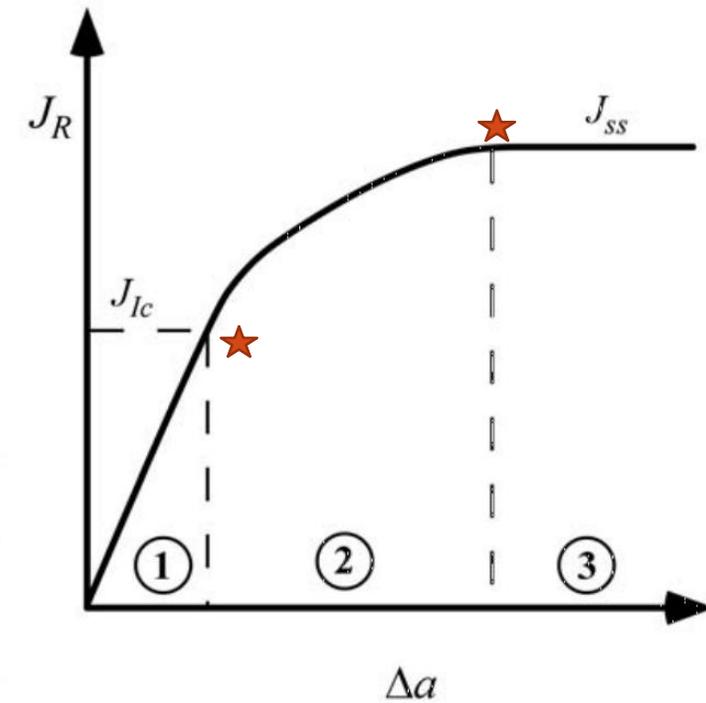
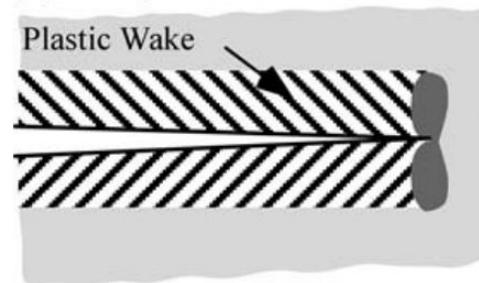
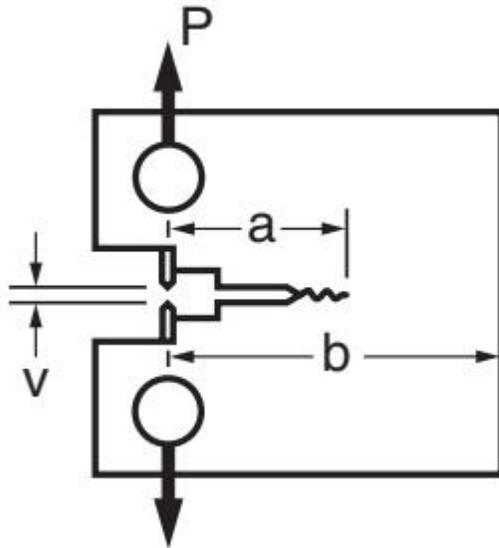


FIGURE 3.25 Three stages of crack growth in an infinite body

INTEGRAL J - ENSAIO



$$J = J_{el} + J_{pl}, \quad J_{el} = \frac{K^2(1 - \nu^2)}{E}$$

$$J_{pl} = \frac{\eta A_{pl}}{t(b - a)}$$

$$\frac{J}{\Delta a} = 2\sigma_Y \quad \text{where } \sigma_Y = \frac{\sigma_o + \sigma_u}{2}$$

$$t, (b - a) > 10 \left(\frac{J_Q}{\sigma_Y} \right)$$

$$K_{IcJ} = \sqrt{J_{Ic} E'}$$

INTEGRAL J - ENSAIO

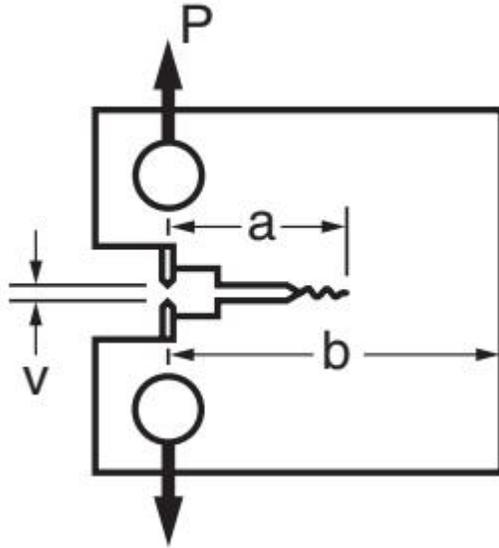
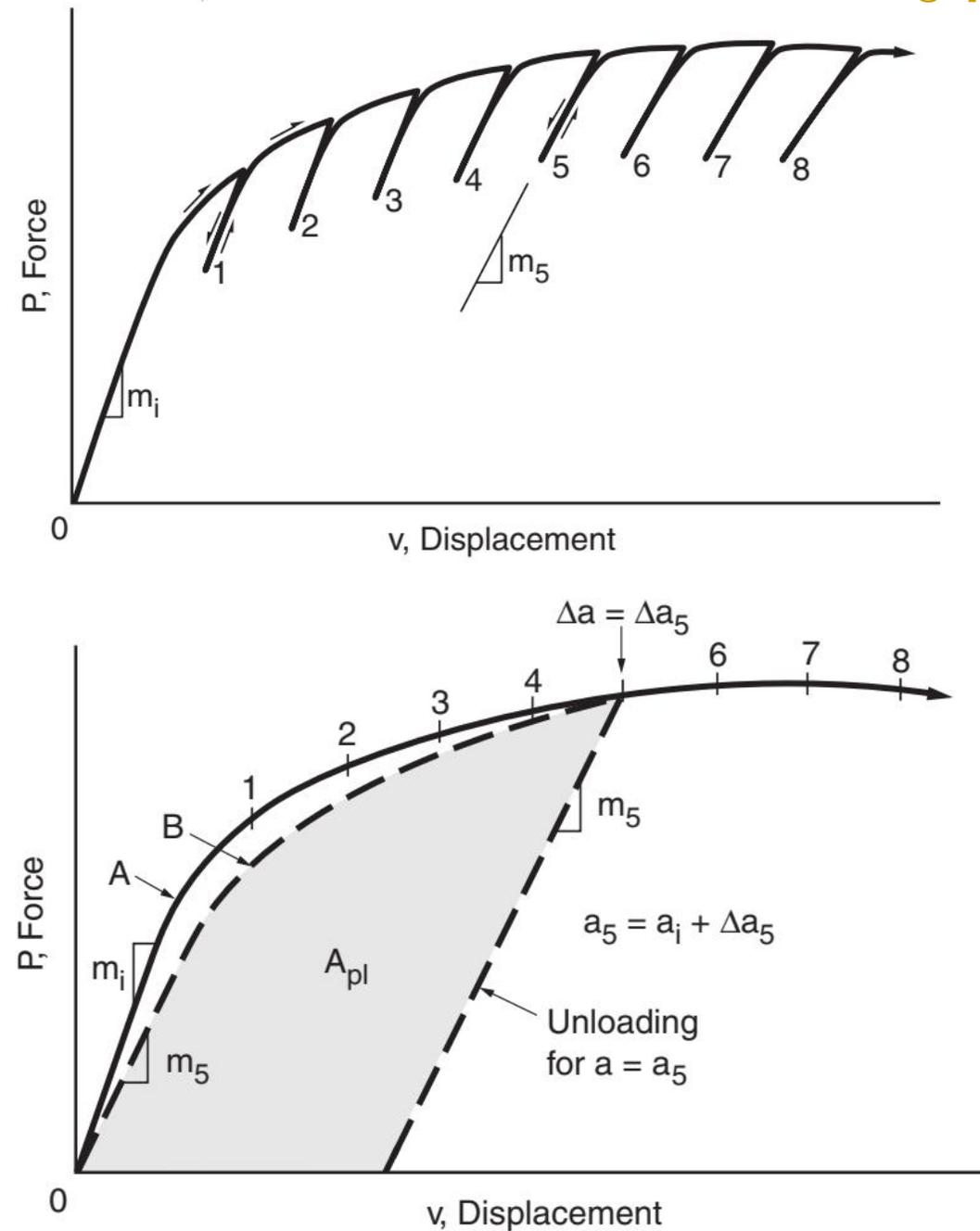
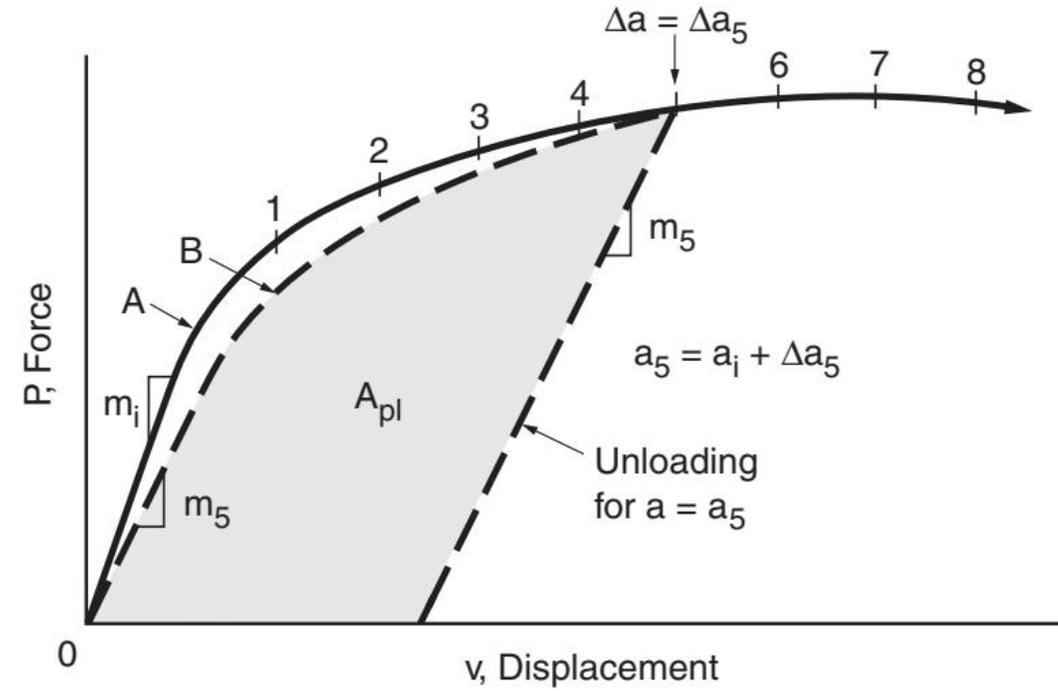
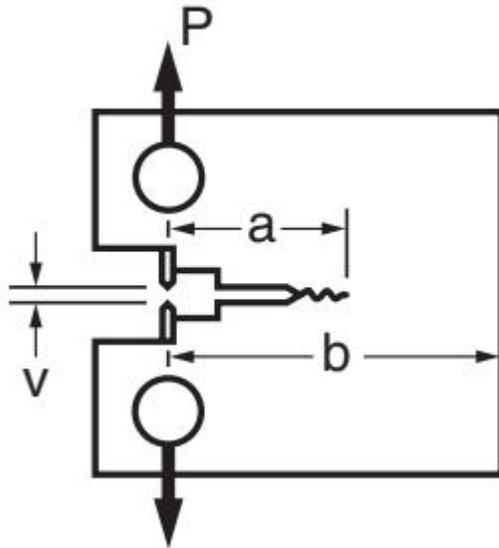


Figure 8.51 Area A_{pl} for calculating the J -integral. Curve A is the actual P - v record for the growing crack, whereas curve B is the hypothetical P - v curve for a stationary (nongrowing) crack of length a_5 .

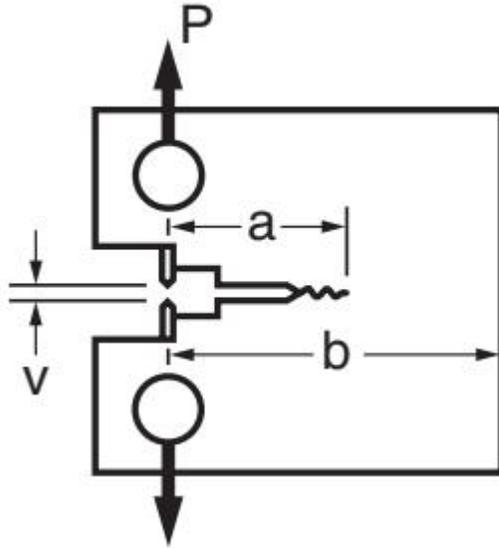


INTEGRAL J - ENSAIO



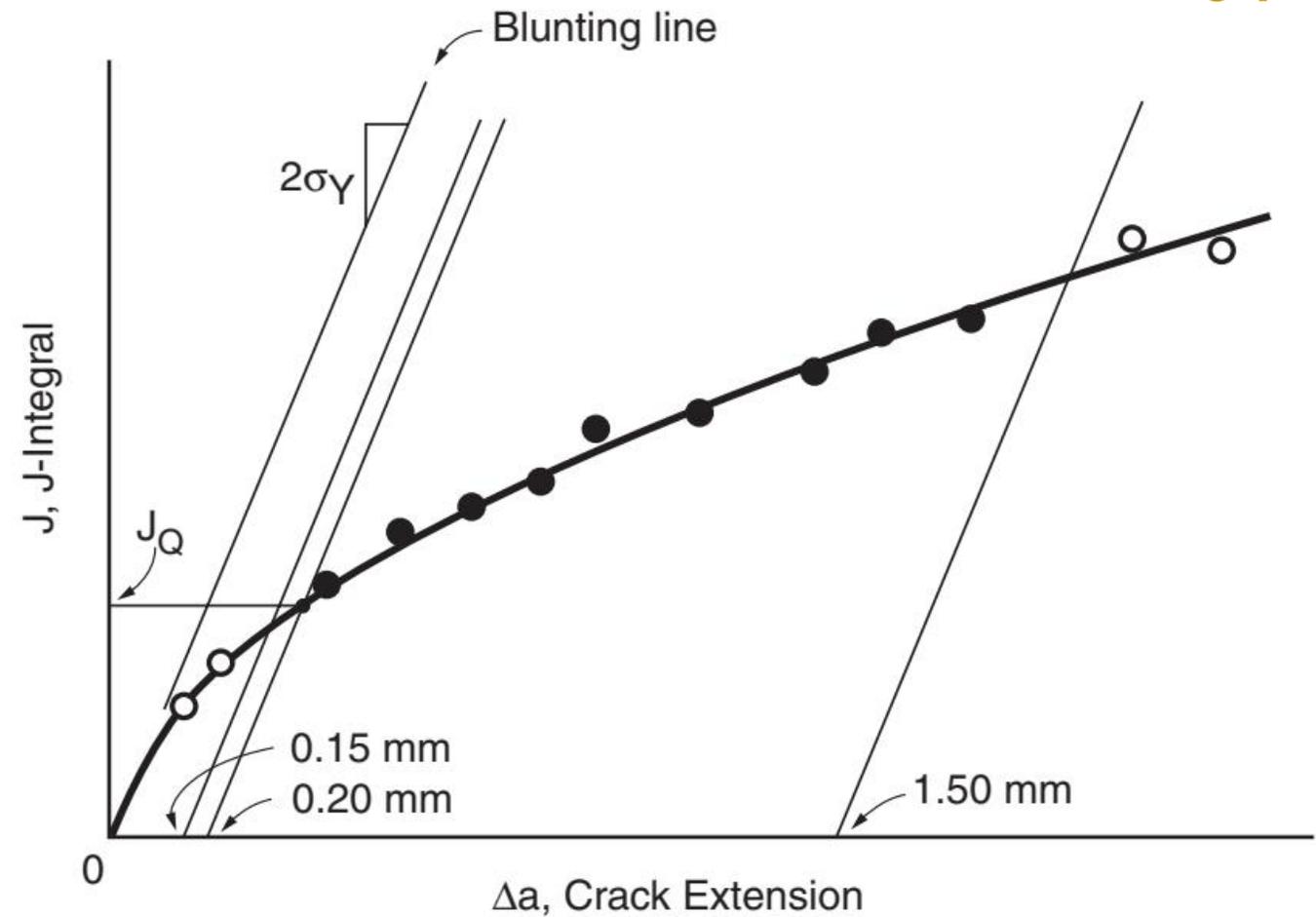
$$J = J_{el} + J_{pl}, \quad J_{el} = \frac{K^2(1 - v^2)}{E}$$

INTEGRAL J - ENSAIO



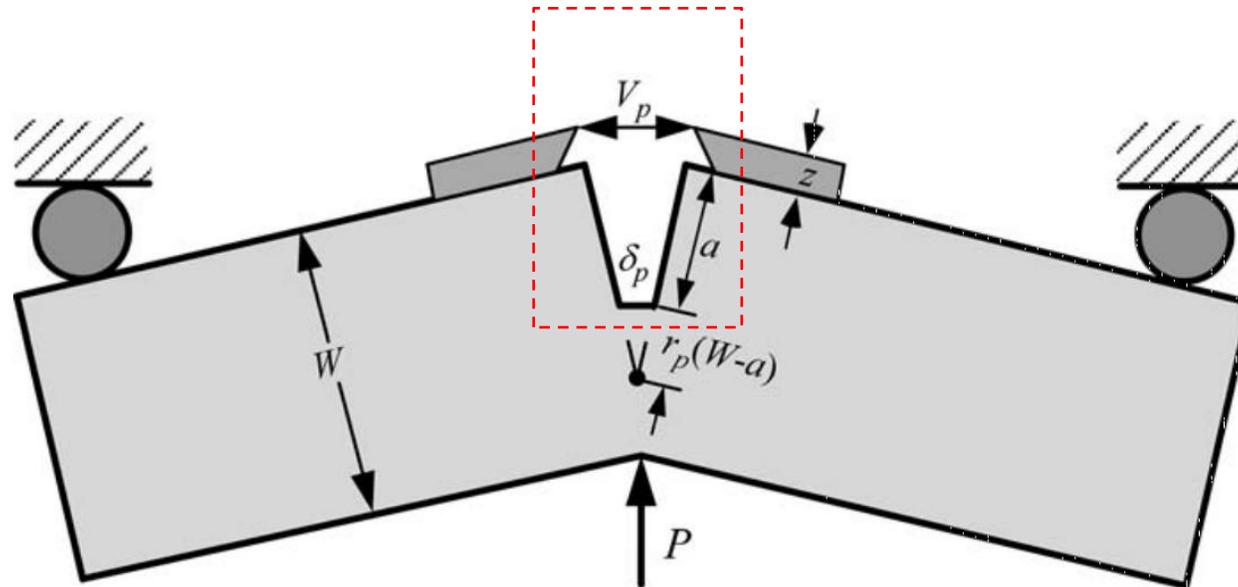
$$J = J_{el} + J_{pl}, \quad J_{el} = \frac{K^2(1 - \nu^2)}{E}$$

$$J_{pl} = \frac{\eta A_{pl}}{t(b - a)}$$



CTOD - ENSAIO

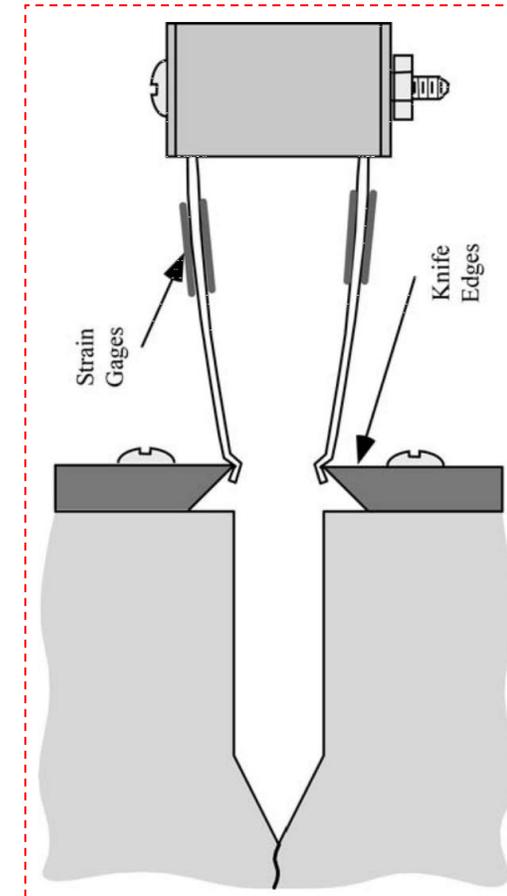
Crack Tip Opening Displacement



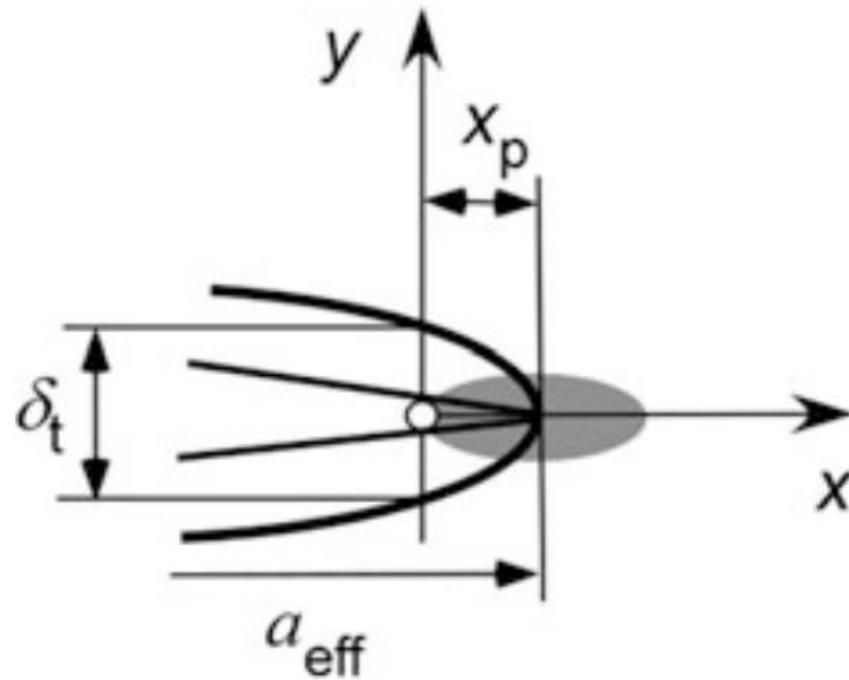
$$\text{CTOD } (\delta) = \delta_{el} + \delta_{pl}$$

$$\delta_{el} = \frac{K^2(1-\nu^2)}{2\sigma_{YS}E}$$

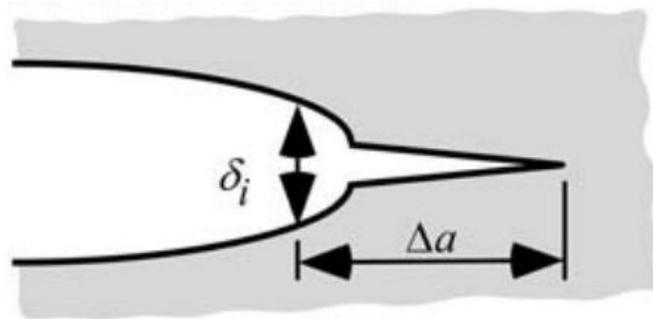
$$\delta_{pl} = \frac{r_p(W-a_o)V_p}{r_p(W-a_o) + a_o + z}$$



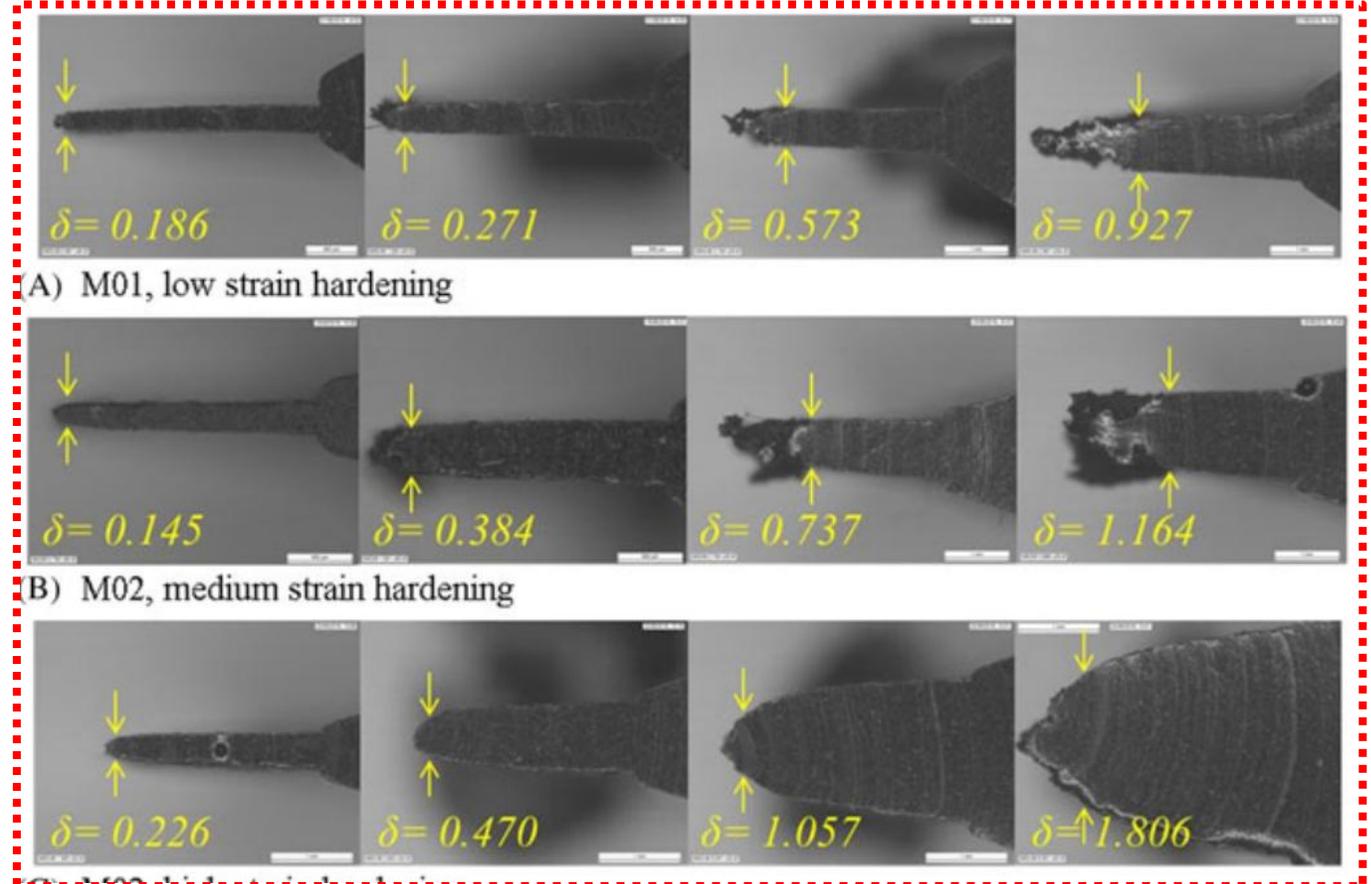
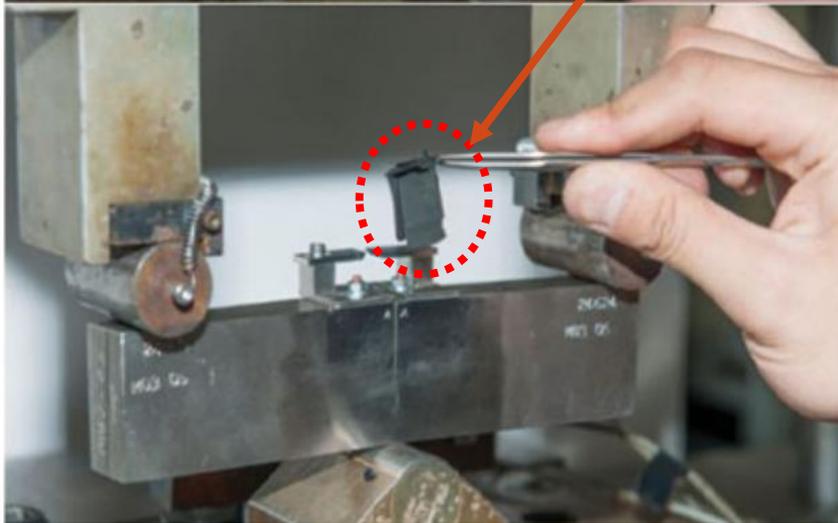
CALCULO DO CTOD A PARTIR DA INTEGRAL J

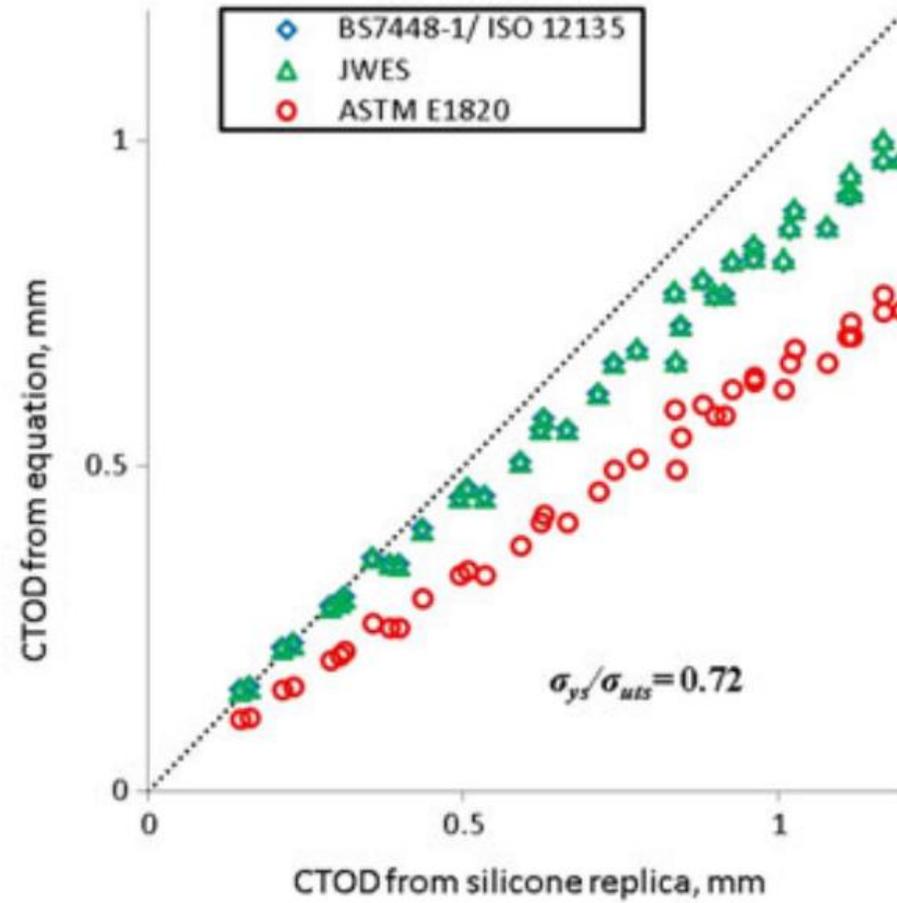
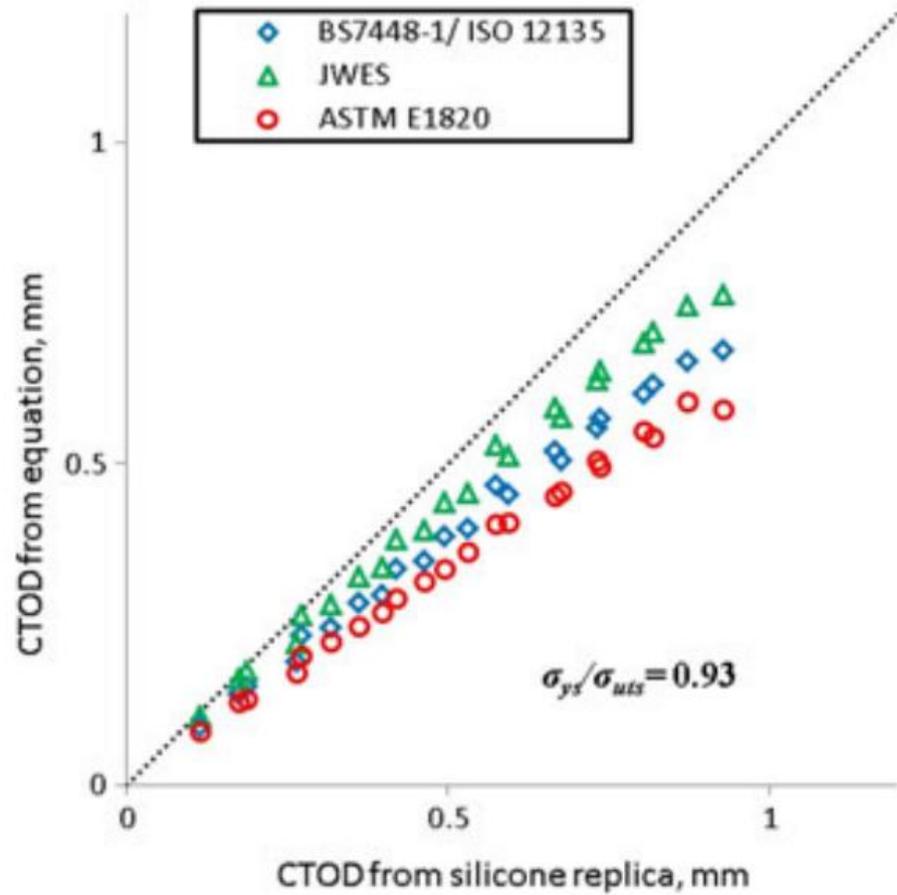


$$\delta \approx \frac{K^2}{E\sigma_0} \approx \frac{J}{\sigma_0}$$



Replicas





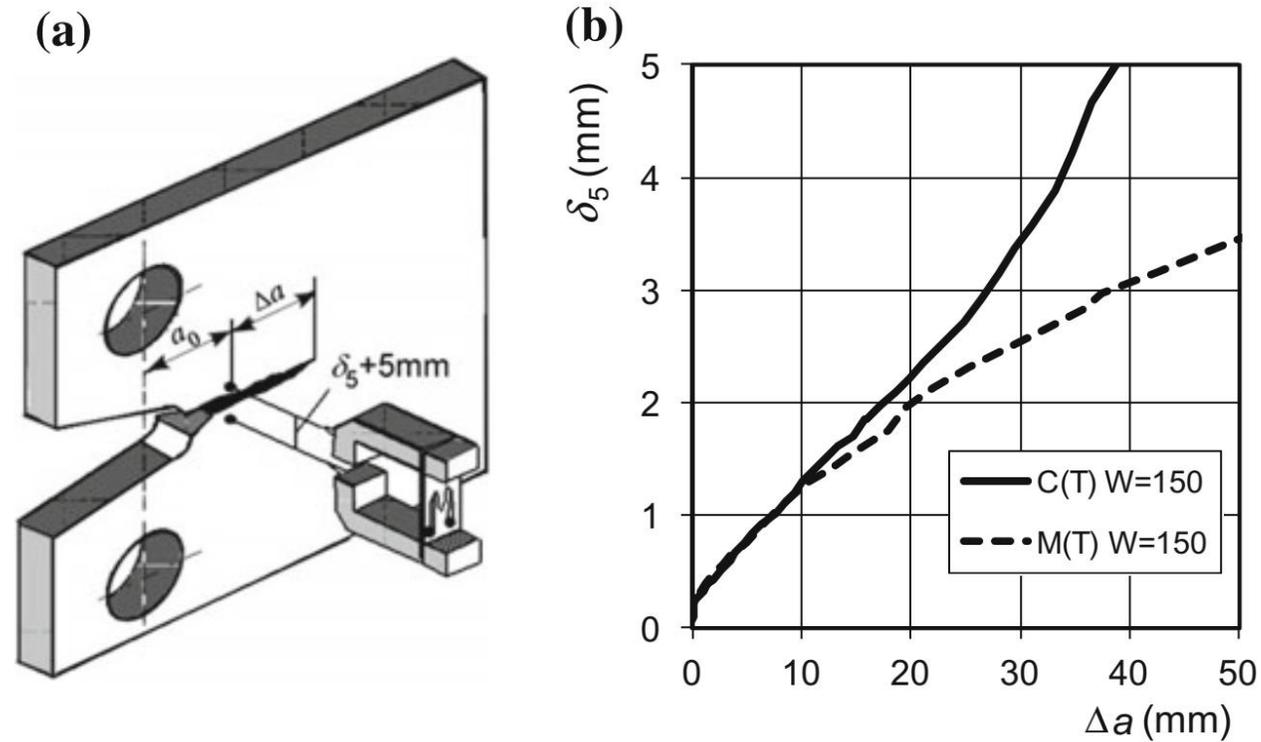
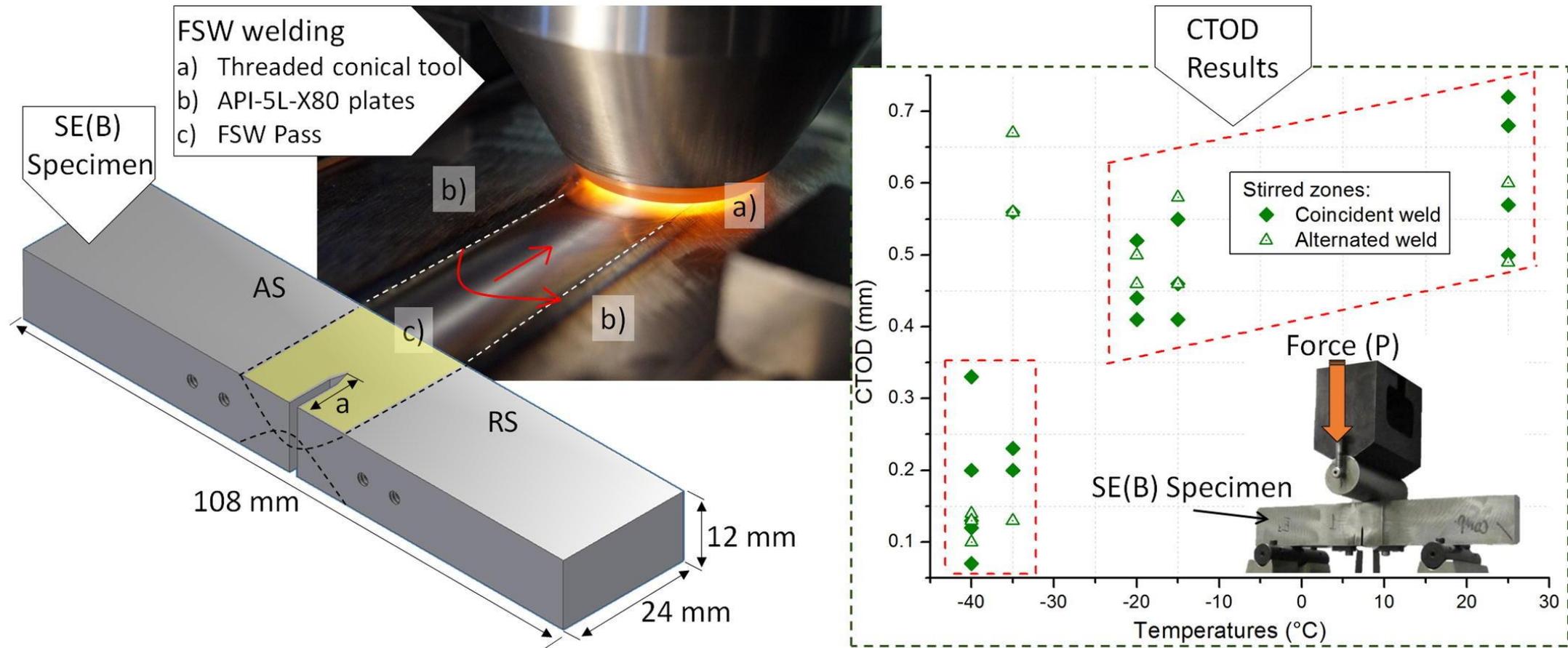


Fig. 5.17 CTOD δ_5 according to Schwalbe [74]: **a** Clip gauge and specimen arrangement; **b** δ_{5R} -curves for C(T) and M(T), same material as in Fig. 5.10, Scheider et al. [73]



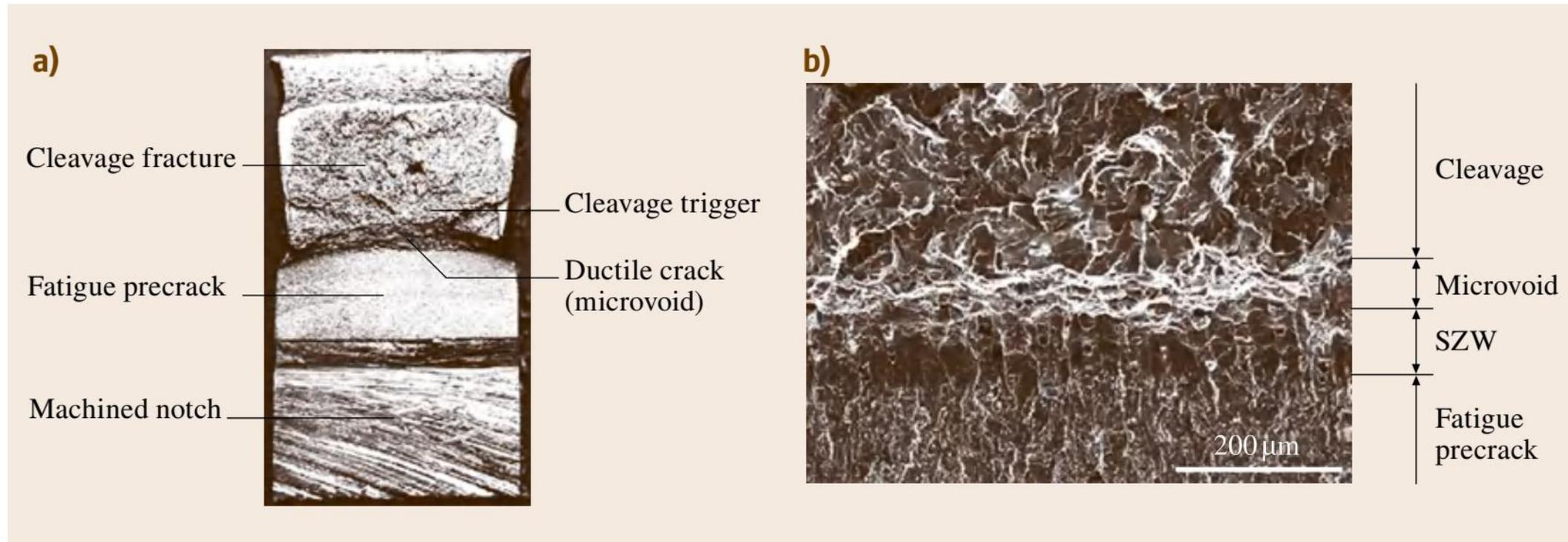


Fig. 7.102a,b Fracture appearance of toughness specimen in low carbon steel: **(a)** macroscopic observation, and **(b)** microscopic observation

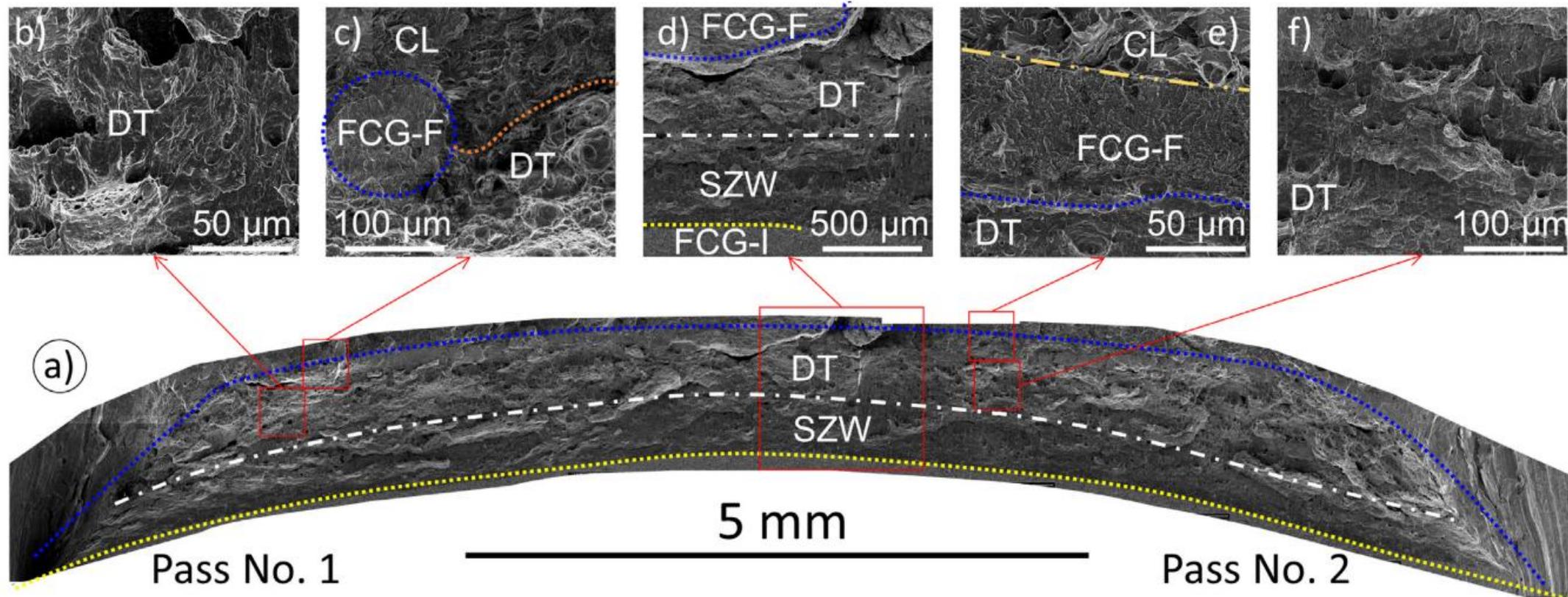


Figure 4. Typical fracture surfaces of a API X80 steel two-passes FSW joint SE(B) specimen, thickness of 15 mm and notch located at the center line (stirred zone) through the thickness. CTOD: 0.59 mm, test temperature of 0 °C. Abbreviations: FCG-I: Initial fatigue crack growth; SZW: stretch zone wide; DT: ductile tearing; FCG-F: final fatigue crack growth; CL: final fracture surface by impact showing cleavage.

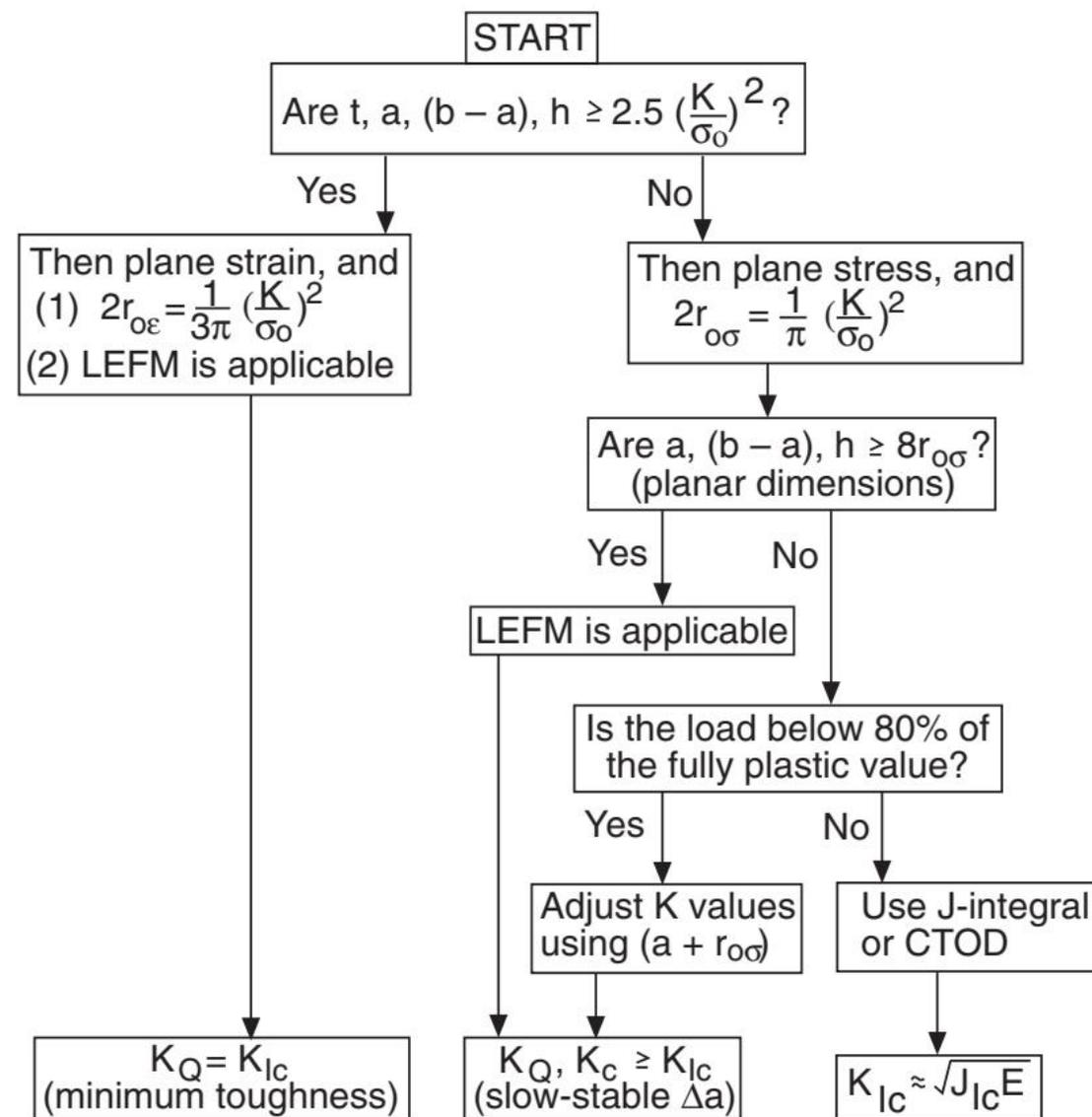


Figure 8.53 Flowchart for distinguishing between plane stress and plane strain, for deciding what fracture mechanics approach is needed, and for identifying what is expected from toughness testing.

Material	Specimen Thickness, mm	Test	Yield/ 0.2% Proof Strength, MPa	Tensile Ratio	BS 7448-1/ ISO 12135 CTOD, mm	WES 1108 CTOD, mm	ASTM E1820 CTOD, mm
		Temperature, °C					
18MND5 (A533B)	24.9-25.1	-100	651	0.89	0.01 to 0.07	0.01 to 0.08	0.01 to 0.06
9%Cr-1%Mo	4.7	7	520	0.75	0.25 to 0.34	0.36 to 0.50	0.14 to 0.20
ABS AH 36	20.0-58.6	70 to -10	341 to 443	0.62 to 0.72	0.02 to 2.25	0.02 to 2.04	0.01 to 1.62
ABS AH/DH/EH 32	15.5-43.7	-10	317 to 402	0.67 to 0.73	0.24 to 1.89	0.28 to 1.78	0.14 to 1.64
API X-grade	8.0-30.0	-20 to 22	349 to 540	0.5 to 0.86	0.01 to 1.11	0.00 to 1.34	0.00 to 1.10
ASTM A105/A106	23.0-23.1	0 to 290	216 to 339	0.46 to 0.60	0.05 to 0.72	0.04 to 0.59	0.03 to 0.49
ASTM A131 grade E	20.0-28.0	-10	312 to 358	0.63 to 0.66	0.60 to 1.12	0.64 to 1.13	0.43 to 0.88
BS 7191 grade 355E	45.2-25.3	-10	377	0.70	1.82 to 2.22	1.75 to 2.14	1.42 to 1.79
Duplex SS	25.0-35.1	-50 to -3	543 to 625	0.74 to 0.76	0.08 to 0.95	0.07 to 1.09	0.06 to 0.80
Grade 12.9 bolt	27.0-27.2	0 to 100	1205 to 1231	0.90	0.01 to 0.04	0.01 to 0.04	0.01 to 0.02
GS-13 MnNi 64	45.0-45.1	-10	327	0.65	1.41 to 1.76	1.28 to 1.60	0.99 to 1.30
INCOLOY 800	5.7	20 to 22	381	0.52	0.95 to 0.98	1.01 to 1.06	0.48 to 0.50
Macalloy	10.0	-20 to 30	950 to 963	0.86	0.00 to 0.01	0.01 to 0.01	0.00 to 0.00
Super duplex SS	28.0-53.1	-46 to 20	576 to 660	0.71 to 0.77	0.08 to 0.75	0.08 to 0.78	0.06 to 0.61

REALIZAÇÃO DE ENSAIOS

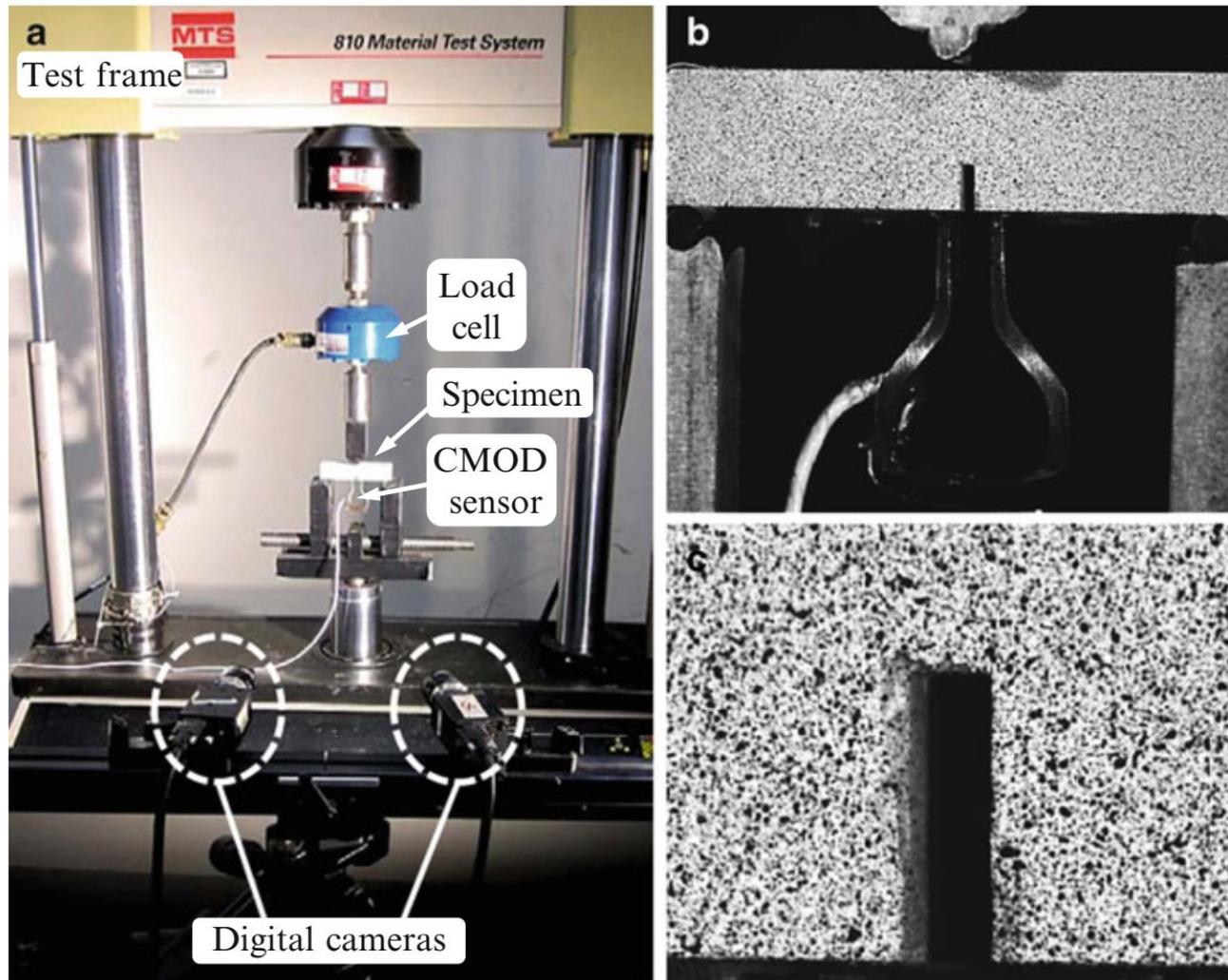
Maiores detalhes no seminário da Bruna:

Escopo:

Ensaio e análise de resultados do ensaio de tenacidade à fratura: K, J e CTOD. (Papers: 1. <http://dx.doi.org/10.1590/0104-9224/SI2103.05> ; 2. An introductory approach to fracture mechanics analyses <https://doi.org/10.1016/j.engfracmech.2014.09.008>) --> Bruna

REFERÊNCIAS

- Dowling, Norman E. Mechanical Behavior of Materials, Engineering Methods for Deformation, Fracture and Fatigue. 3a Edição. Pearson Prentice Hall, 2007, 890p.
- Anderson, T. L. Fracture Mechanics – Fundamentals and Applications, Second Edition, CRC Press, 680p. 2005.
- Hertzberg, R. W., Deformation and Fracture Mechanics of Engineering Materials, 4th Edition, John Wiley & Sons, 1996. (2) Anderson, T. L., Fracture Mechanics: Fundamentals and Applications, 2th Edition, CRC Press, 1995.
- Hull, Derek. Fractography: Observing, Measuring and Interpreting Fracture Surface Topography, 1st Edition, Cambridge University Press, 386p. 1999.
- Meyers, Marc; Chawla, Krishan. Mechanical Behavior of Materials. 2 edition, Cambridge University Press, 856 p, 2008.
- François, Dominique; Pineau, André; Zaoui, André. Mechanical Behavior of materials. Volume II: Fracture mechanics and damage, Springer Netherlands, 622 p, 2013.



OBRIGADO!!!

Fig. 10.1 Fracture mechanics testing and DIC measurement: (a) test setup; (b) close-up photograph of notched beam specimen; and (c) close-up view of speckle pattern around 2 × 6 mm notch

https://doi.org/10.1007/978-3-319-06977-7_10