A. BASIC CONCEPTS

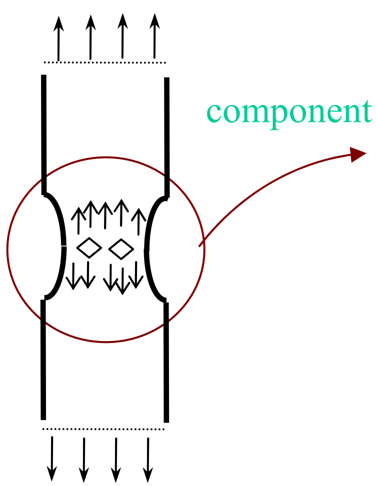
F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UNIVERSIDAD DE CANTABRIA

FRACTURE BEHAVIOUR

INTRODUCTION

The final fracture of structural components is associated with the presence of macro or microstructural defects that affect the stress state due to the loading conditions.

Fracture occurs when this state reaches at local level a critical condition.



Material + Geometry and defects + loading Vs. Toughness

Stress state (local) Vs. Critical local condition to fracture

F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UNIVERSIDAD DE CANTABRIA

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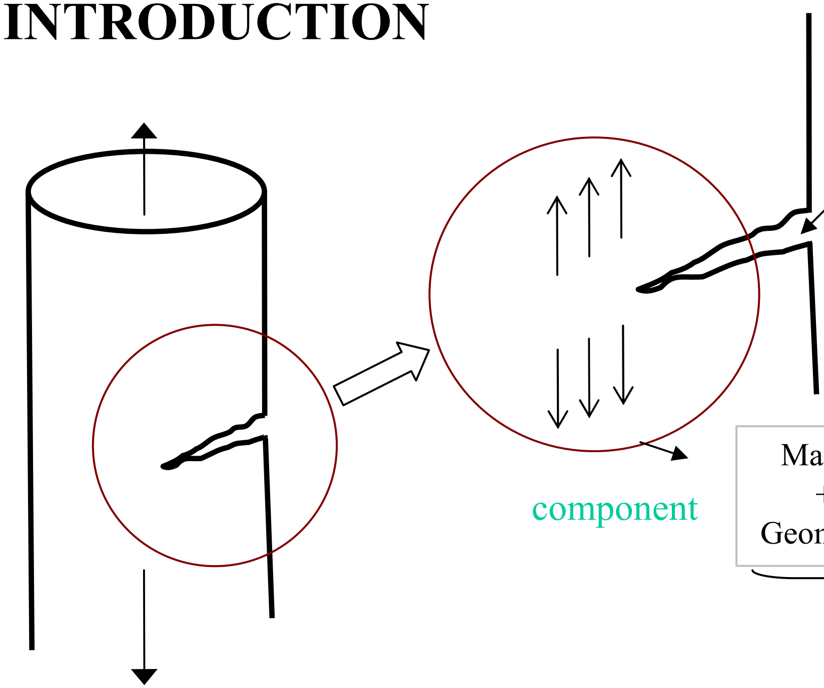
INTRODUCTION



Crack (defect): produced by
- Processing
- Cracking processes
- Operation damage

Material + Geometry and defects + loading → Stress state (local) Vs. Toughness

Vs. Critical local condition to fracture

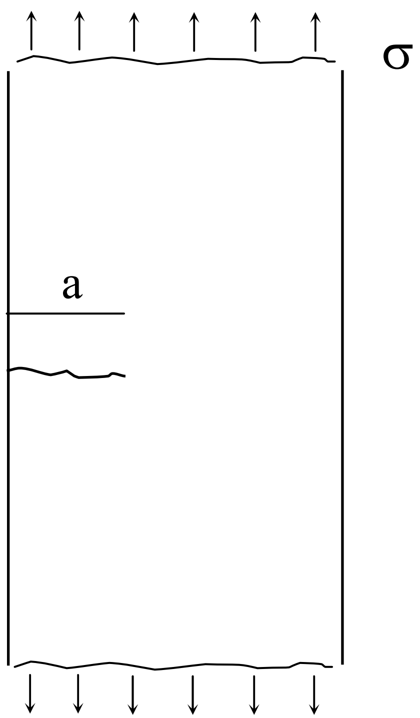
Fracture analysis → **FRACTURE MECHANICS**

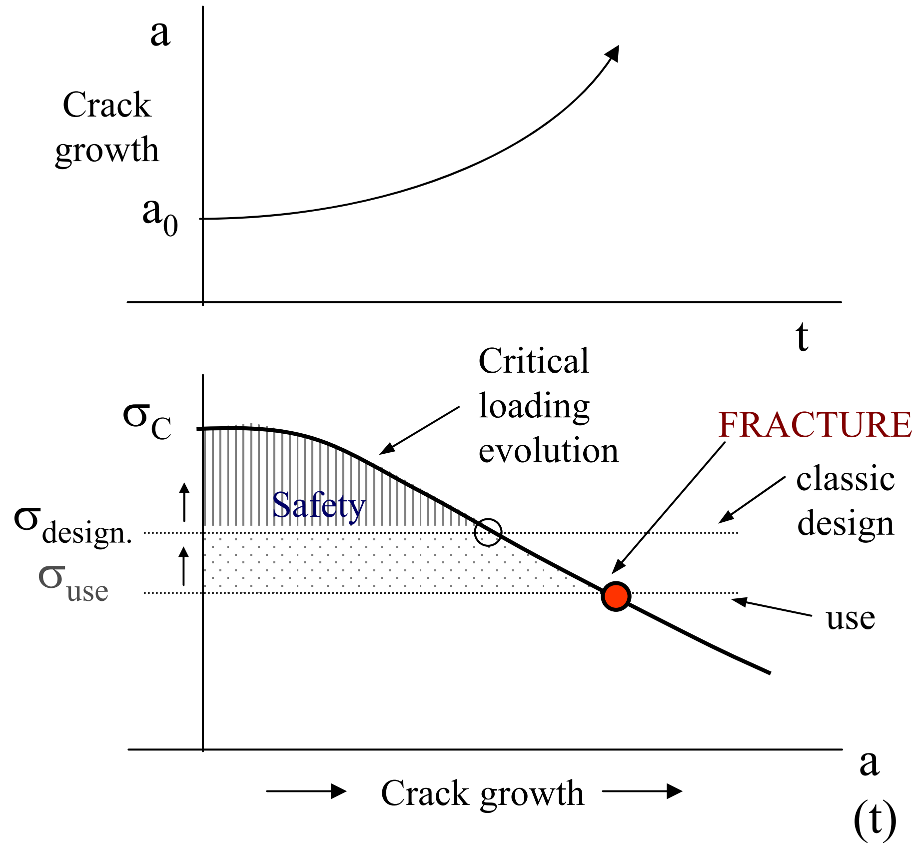
F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UNIVERSIDAD DE CANTABRIA

FRACTURE BEHAVIOUR

INTRODUCTION

Fracture Mechanics





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S. CICERO
J.A. ALVAREZ
R. LACALLE
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INTRODUCTION

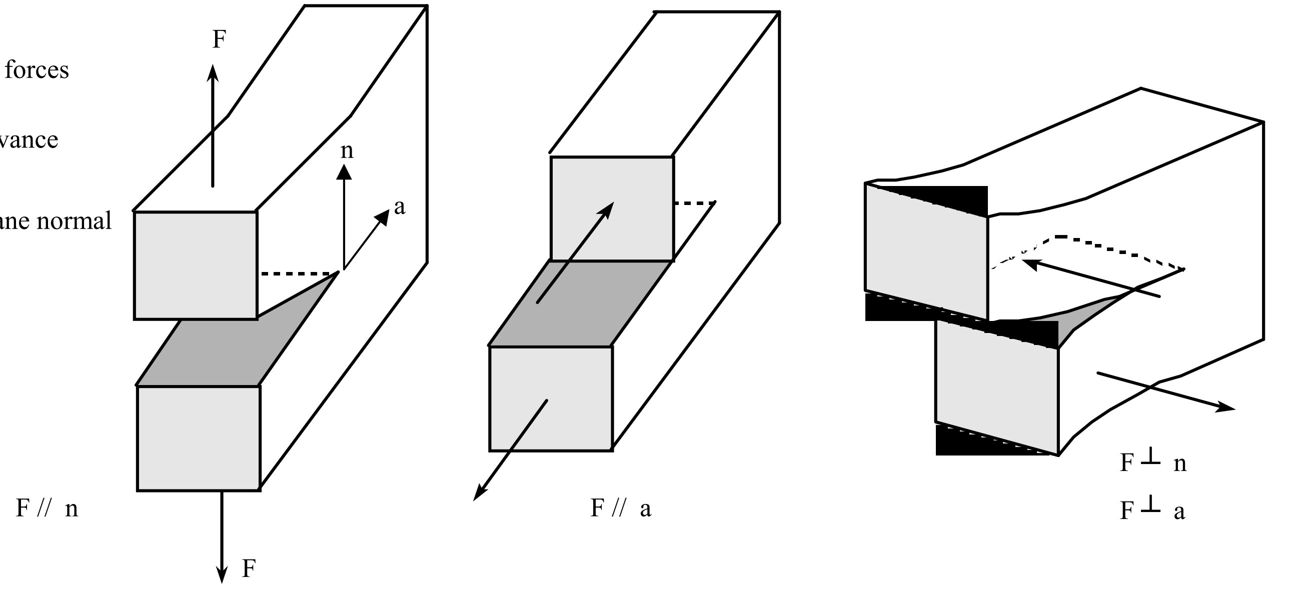
Fracture Modes

F: Loading forces

a: crack advance

n: crack plane normal

a ⊥ n



MODE I
Tensile

MODE II
Shear

MODE III
Torsion

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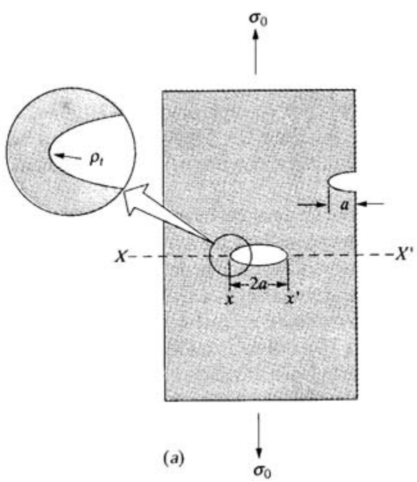
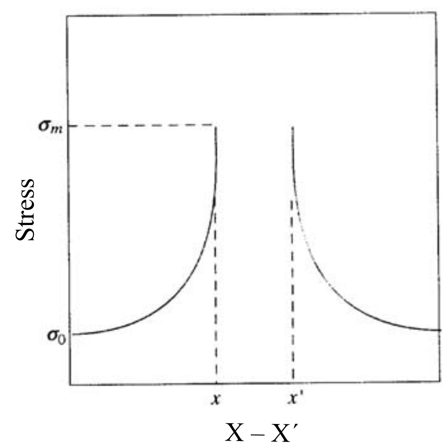
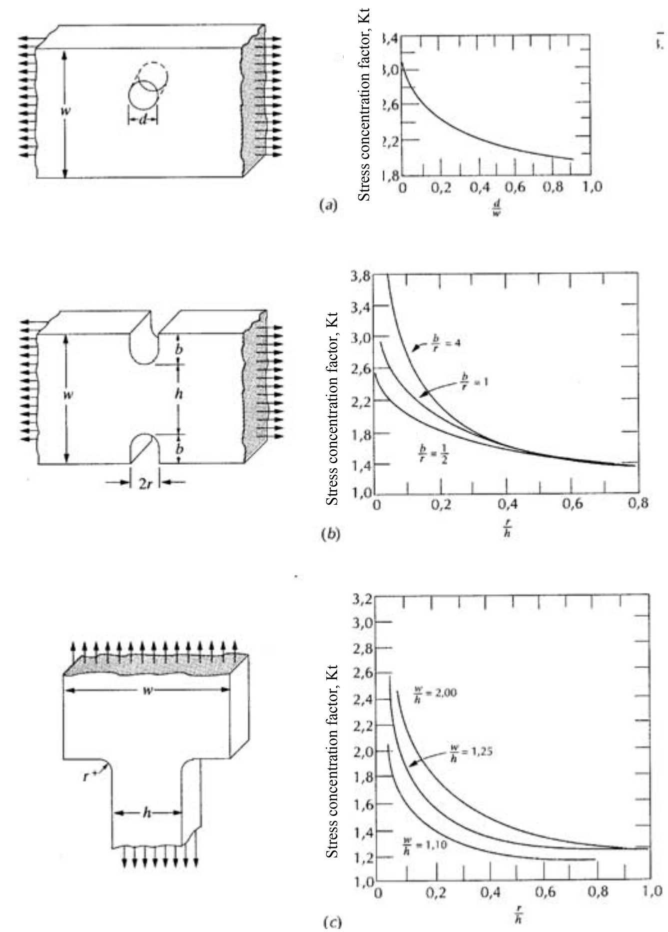
FRACTURE CRITERIA

Stress state in a crack front

Stress concentration







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S. CICERO
J.A. ALVAREZ
R. LACALLE
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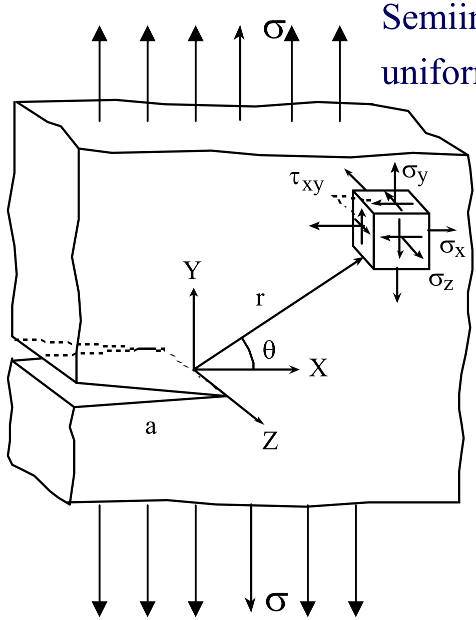
FRACTURE BEHAVIOUR

FRACTURE CRITERIA

Local stress and strain states

in a crack front (Irwin)

Semiinfinite plate,
uniform stress (MODE I)



STRESSES

Plane solution

$$\sigma_x = \sigma\sqrt{\frac{a}{2r}}\left[\cos\frac{\theta}{2}\left(1-\operatorname{sen}\frac{\theta}{2}\operatorname{sen}\frac{3\theta}{2}\right)\right]$$

$$\sigma_y = \sigma\sqrt{\frac{a}{2r}}\left[\cos\frac{\theta}{2}\left(1+\operatorname{sen}\frac{\theta}{2}\operatorname{sen}\frac{3\theta}{2}\right)\right]$$

$$\tau_{xy} = \sigma\sqrt{\frac{a}{2r}}\left[\cos\frac{\theta}{2}\operatorname{sen}\frac{\theta}{2}\cos\frac{3\theta}{2}\right]$$

$$\sigma_{ij}^{I} = \sigma\sqrt{\frac{a}{2r}}\,f_{ij}^{I}(\theta)$$

Plane stress (PSS): $\sigma_z = 0$

Plane strain (PSN): $\sigma_z = \nu\,(\sigma_x + \sigma_y)$

DISPLACEMENTS

$$u = \frac{\sigma}{2E}\sqrt{\frac{ar}{2}}(1+\nu)\left[(2\kappa-1)\cos\frac{\theta}{2} - \cos\frac{3\theta}{2}\right]$$

$$v = \frac{\sigma}{2E}\sqrt{\frac{ar}{2}}(1+\nu)\left[(2\kappa+1)\operatorname{sen}\frac{\theta}{2} - \operatorname{sen}\frac{3\theta}{2}\right]$$

$\kappa = 3 - 4\nu$ (PSS) $\qquad \kappa = \frac{3-\nu}{1+\nu}$ (PSN)

$$w = -\frac{\nu}{E}\int(\sigma_x + \sigma_y)\,dz$$

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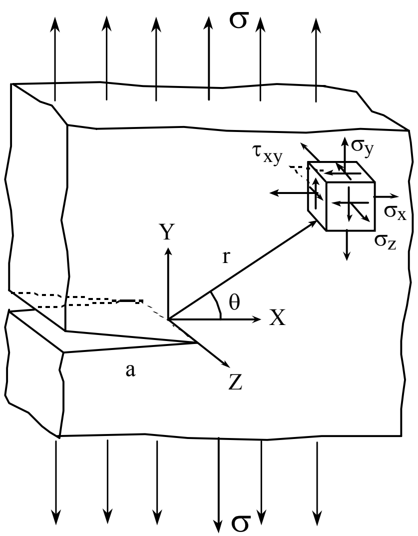
FRACTURE CRITERIA

Stress state in a crack front. Stress Intensity Factor



$$\sigma_{ij}^{I} = \sigma\sqrt{\frac{a}{2r}}\,f_{ij}^{I}(\theta) = \sigma\sqrt{\pi a}\;\frac{1}{\sqrt{2\pi r}}\,f_{ij}^{I}(\theta)$$

$$\sigma_{ij}^{I} = K_I\,\frac{1}{\sqrt{2\pi r}}\,f_{ij}^{I}(\theta)$$

Position

Stress Intensity Factor

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

K_I defines the stress state in the crack front

F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UNIVERSIDAD DE CANTABRIA

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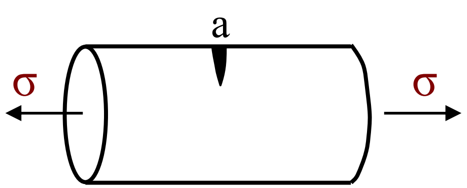
FRACTURE CRITERIA

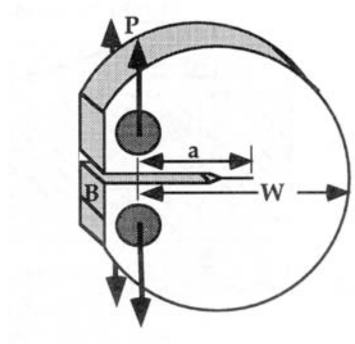
Stress state in a crack front ≡ Stress Intensity Factor

For any component
(geometry + defects)



$$K_I = f\sigma\sqrt{\pi a} \quad \text{or} \quad f\sigma\sqrt{\pi g(a)}$$

f: geometric factor



(b) Disk shaped compact specimen.

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

$$\frac{2+\frac{a}{W}}{\left(1-\frac{a}{W}\right)^{3/2}}\left[0.76 + 4.8\left(\frac{a}{W}\right) - 11.58\left(\frac{a}{W}\right)^2 + 11.43\left(\frac{a}{W}\right)^3 - 4.08\left(\frac{a}{W}\right)^4\right]$$

For other modes
analogously ...

$$K_{II} = f_{II}\tau\sqrt{\pi g(a)}$$

FRACTURE BEHAVIOUR

FRACTURE CRITERIA

Stress fracture criterion

If $\sigma\uparrow \Rightarrow K_I \uparrow \Rightarrow \sigma_{ij}$ (local) $\uparrow$

If σ_{ij} (local) = σ_{ij} (critical) — Local fracture criterion

$\downarrow$ — $\downarrow$

$K_I = K_I^C$ — Sress fracture criterion

- If fracture critical conditions (K_I^C) only depend on material

$\downarrow$

K_{Ic} (Fracture Toughness)

Stress Fracture Criterion $K_I = K_{Ic}$

F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UNIVERSIDAD DE CANTABRIA

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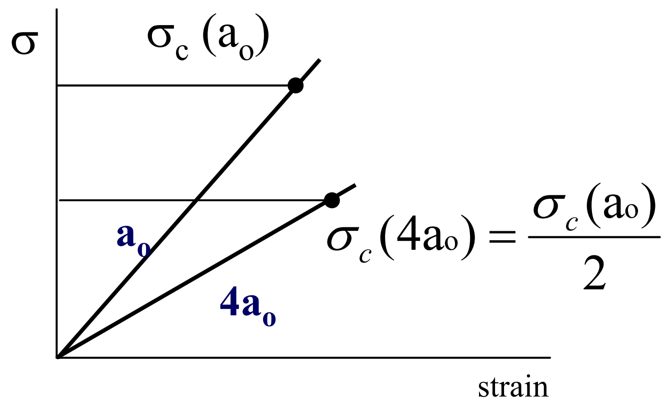
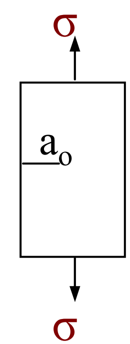
FRACTURE CRITERIA

Stress fracture criterion





$K_I = K_{Ic}$

↓

Fracture occurs with σ_c (a)

Another observation:

The compliance of the component increases with the length of the defects.

Compliance: Indicates the length of the defects.

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S. CICERO
J.A. ALVAREZ
R. LACALLE

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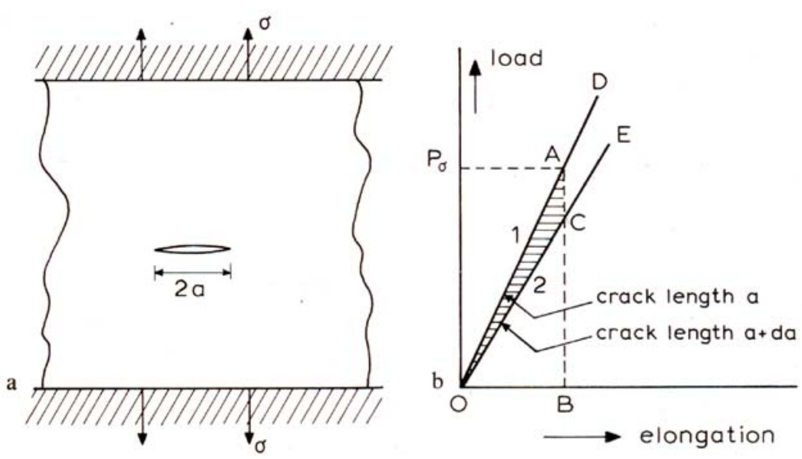
FRACTURE CRITERIA

Energetic fracture criterion (Griffith)

Comparison between the energy that is released in crack extension and the energy that is necesary to generate new surfaces because of that extension.



$$\frac{d(U)}{da} \geq \frac{dE\gamma}{da} \longrightarrow \text{Crack grows (Fracture)}$$

unitary thickness

$$\frac{d(U)}{Bda} \geq \frac{dE\gamma}{Bda} = 2\gamma$$

γ: surface energy of the material

(Energy per unit of generated surface)

FRACTURE BEHAVIOUR

FRACTURE CRITERIA

Energetic fracture criterion (Griffith)

As a geometry function $f(\sigma, a, E) \geq 2\gamma$

Semiinfinite plate $G = \dfrac{\pi\sigma^2 a}{E} \geq G_c$

$G = G_c$ Fracture criterion

G: Energy release rate

G_c: Fracture Toughness

Where: $G = \alpha \dfrac{K_I^2}{E}$ $\begin{cases} \alpha = 1 & \text{(Plane stress)} \\ \alpha = (1-\upsilon^2) & \text{(Plane strain)} \end{cases}$

$G_c = \begin{cases} 2\gamma \text{ in very brittle materials} \\ >> 2\gamma \text{ in materials with plasticity before fracture} \end{cases}$

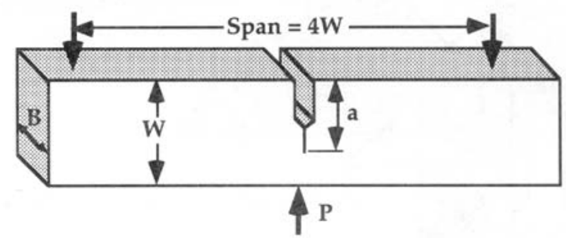
F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE

FRACTURE BEHAVIOUR

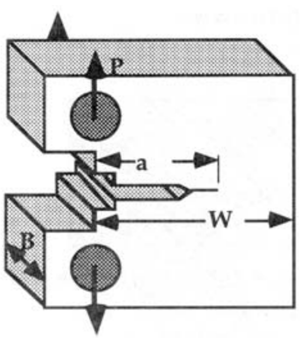
FRACTURE TOUGHNESS

Fracture Toughness Characterisation

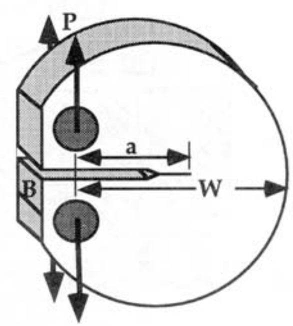
A) Standardised specimens



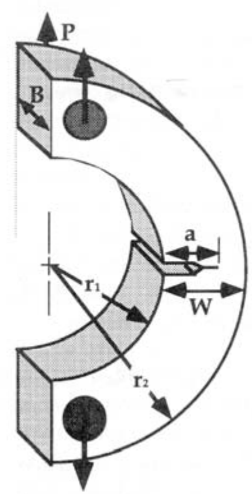
(c) Single edge notched bend (SENB) specimen.



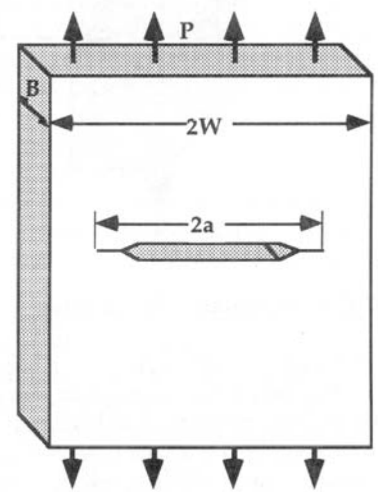
(a) Compact specimen.



(b) Disk shaped compact specimen.



(d) Arc shaped specimen



(e) Middle tension (MT) specimen.

B) Fatigue precracked specimens : a

(a as initial crack length)

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S. CICERO
J.A. ALVAREZ
R. LACALLE
UC UNIVERSIDAD DE CANTABRIA

FRACTURE BEHAVIOUR

FRACTURE TOUGHNESS

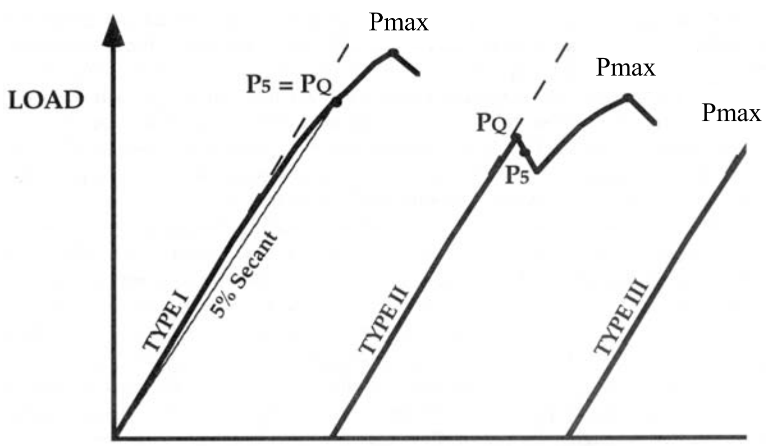
Fracture Toughness Characterisation

C) Mechanical Testing → P_Q (Load on Fracture initiation)

$$\Downarrow$$

$$K_Q = f\,(P_Q, a, \text{geometry})$$

$$K_Q = \left(\frac{P_Q}{B \cdot W^{\frac{1}{2}}}\right) \cdot f\left(\frac{a}{W}\right) \qquad \text{for CTs}$$



- **a** measured on fracture surface

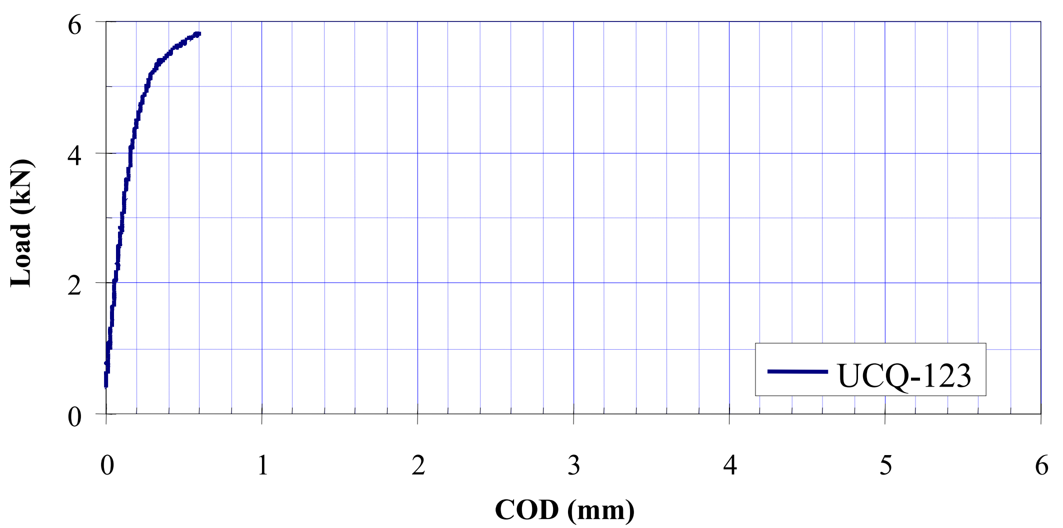
$\mathbf{K_Q = K_{Ic}}$ (toughness), if some normalised conditions are fulfilled

F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UNIVERSIDAD DE CANTABRIA

FRACTURE BEHAVIOUR

FRACTURE TOUGHNESS

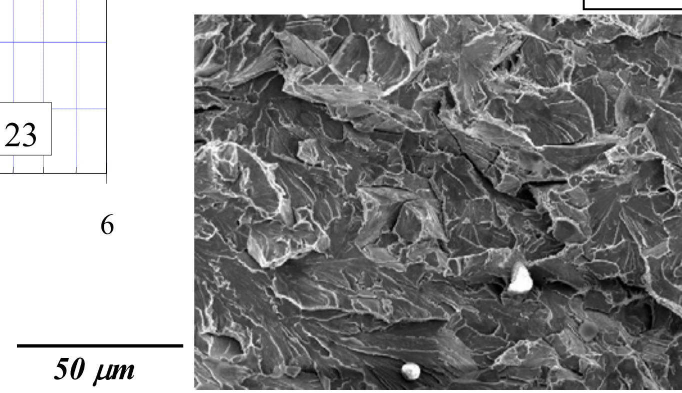
Fracture Toughness Characterisation



Fatigue crack profile

a

Fracture mechanisms



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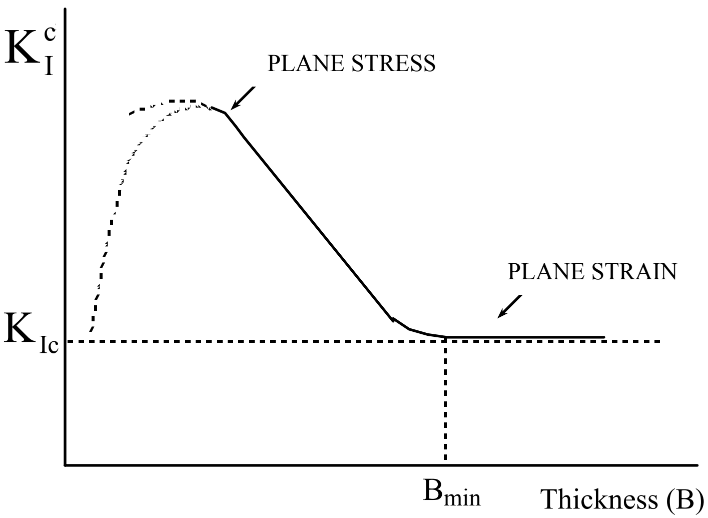
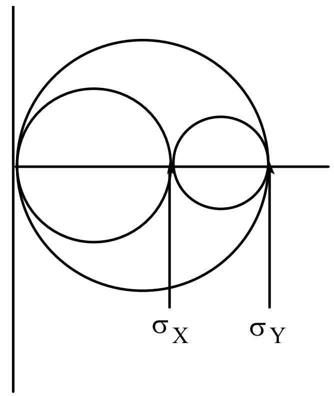
FRACTURE TOUGHNESS

Thickness effect

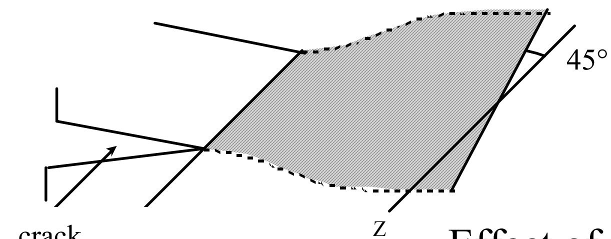


$$B_{min}\ (P.Strain) = 2.5\left[\frac{K_{Ic}^2}{\sigma_Y^2}\right]$$



PLANE STRESS $\sigma_Z = 0$

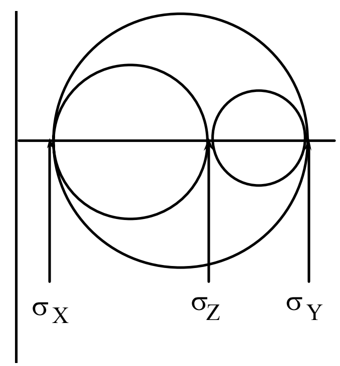
Fracture at 45º with respect to the original crack plane



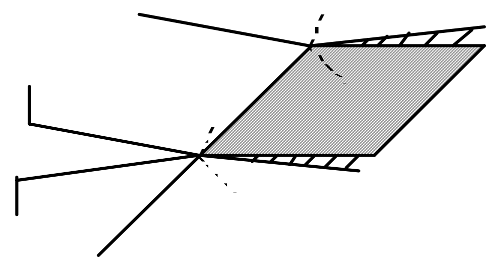
Effect of Plastic Zone

+

Fracture in crack plane



PLANE STRAIN



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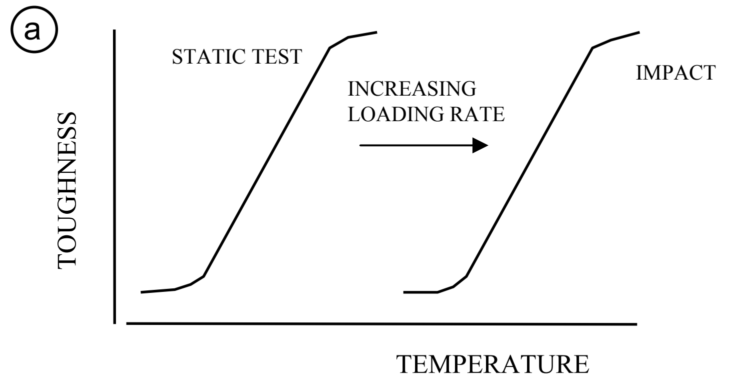
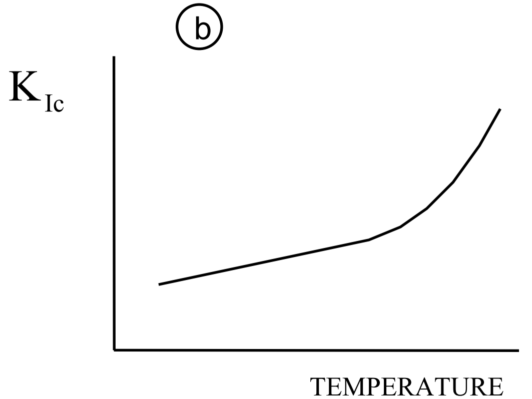
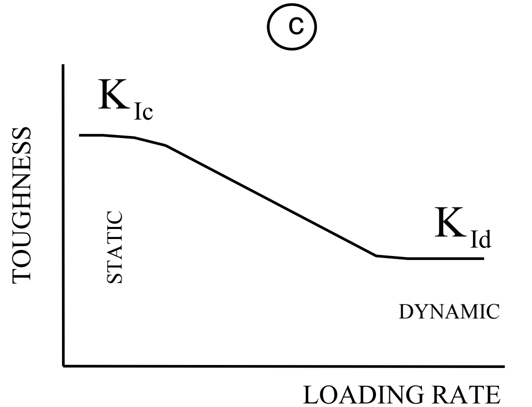
FRACTURE TOUGHNESS

Effect of temperature and loading rate







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S. CICERO
J.A. ALVAREZ
R. LACALLE
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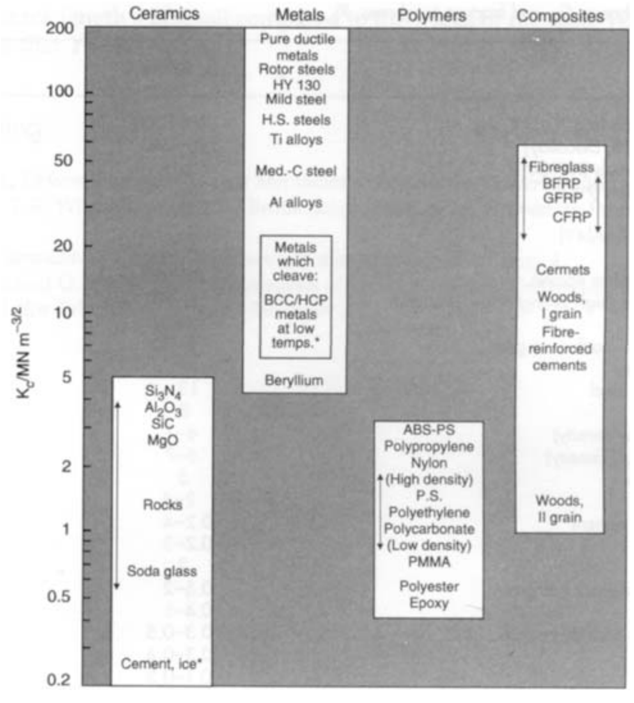
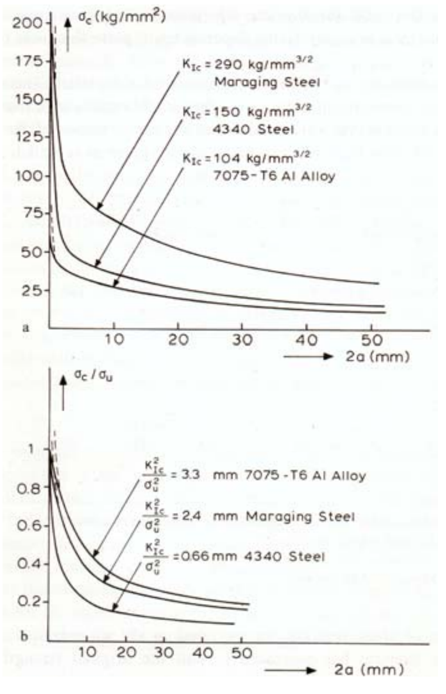
MATERIAL TOUGHNESS

Value It depends on microstructure and external variables → Environment (temperature) (degradation) / Loading rate





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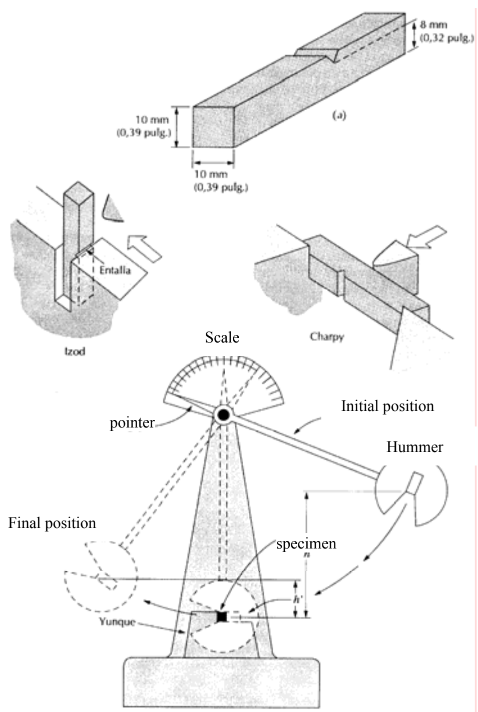
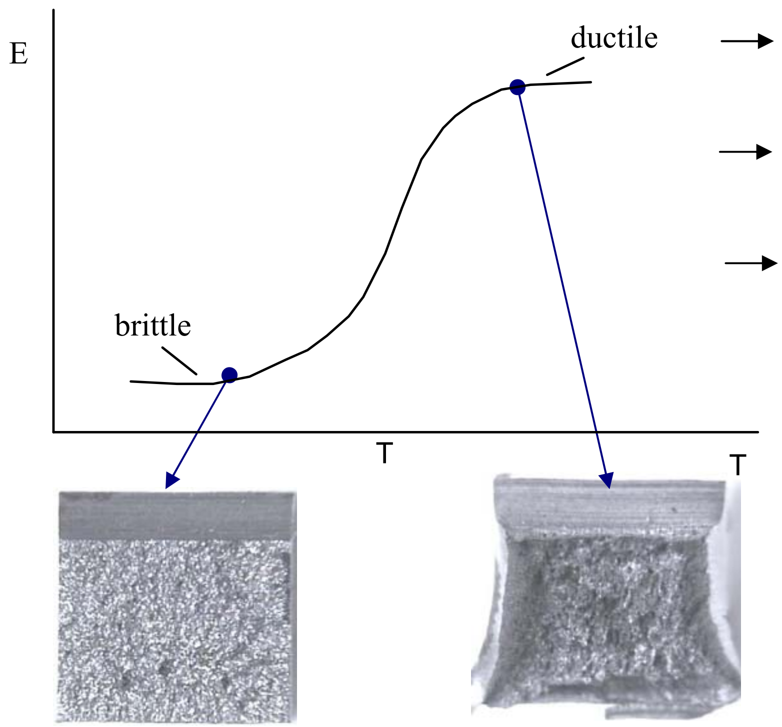
FRACTURE TOUGHNESS

Impact Toughness: Charpy Test





- → Absorbed Energy (E)
- → % Ductile fracture
- → % Lateral expansion

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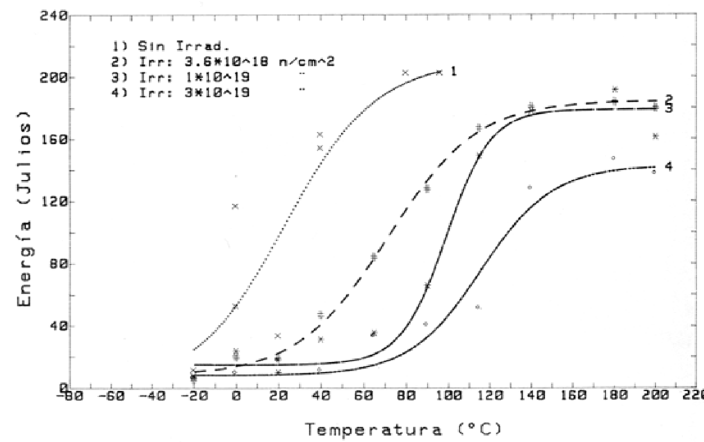
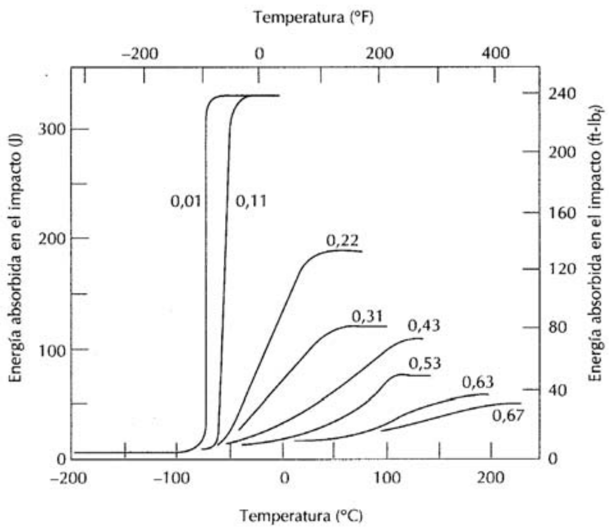
FRACTURE TOUGHNESS

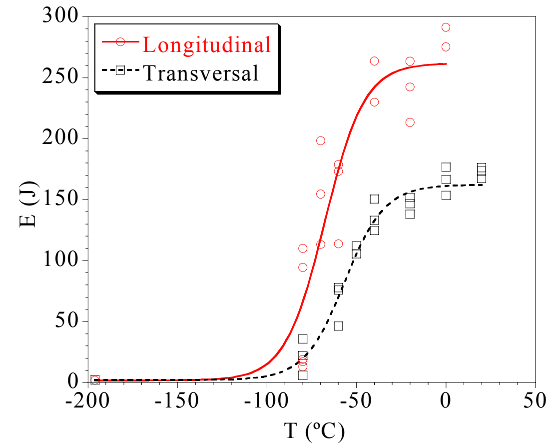
Impact Toughness: Examples of the effect of different variables



Influence of Irradiation



Influence of Carbon Content



Influence of microstructural orientation

F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UC UNIVERSIDAD DE CANTABRIA

FRACTURE BEHAVIOUR

PLASTICITY ON FRACTURE

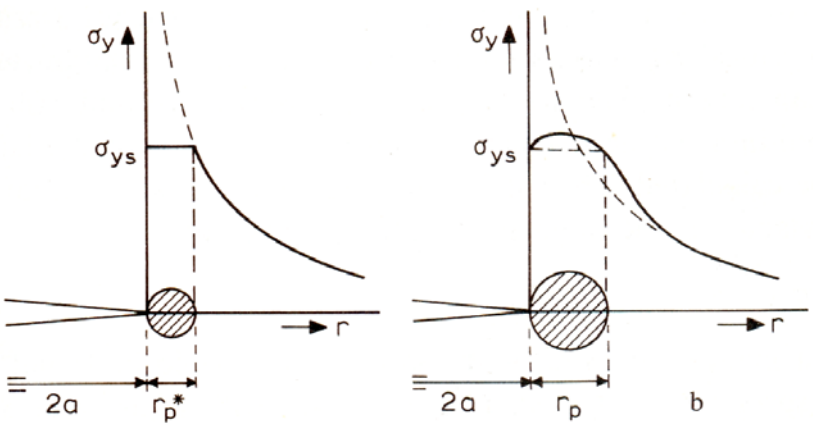
Plasticity in a crack front

$$\sigma_y = \frac{K_I}{\sqrt{2\pi r}} \cdot \cos\left(\frac{\theta}{2}\right) \cdot \left[1 + sen\left(\frac{\theta}{2}\right) \cdot \cos\left(3\frac{\theta}{2}\right)\right]$$

Linear elastic solution

(LEFM)

For $\theta = 0$ (crack plane): $\sigma_y = \frac{K_I}{\sqrt{2\pi r}}$



1st plastic zone model

If $\sigma_y \geq \sigma_Y$ plastic zone: $\sigma_y = \sigma_Y$

$$r_Y = \frac{1}{2\pi} \cdot \frac{K_I^2}{\sigma_Y^2}$$

(problem: there is no stress equilibrium)

2nd plastic zone model (Irwin correction)

$$r_P = \frac{1}{\pi} \cdot \frac{K_I^2}{\sigma_Y^2}$$

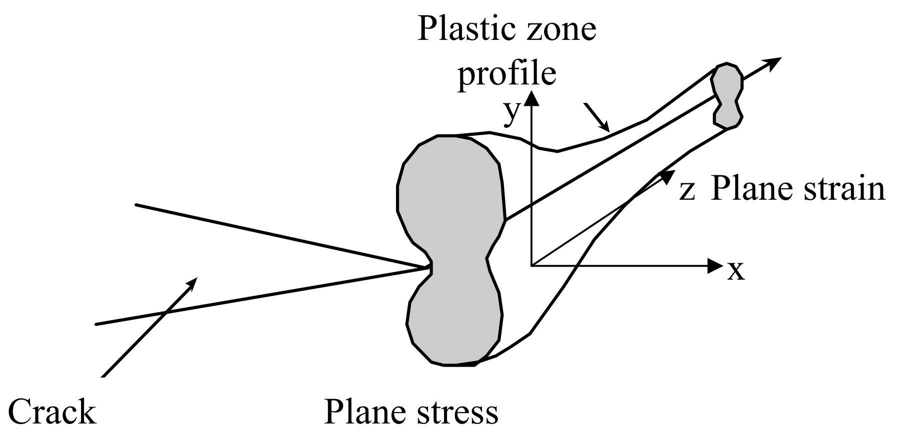
(stress redistribution)
(approximate solution)

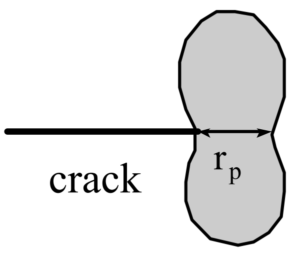
F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UC UNIVERSIDAD DE CANTABRIA

FRACTURE BEHAVIOUR

PLASTICITY ON FRACTURE

Plastic Zones on Plane Stress and Plane Strain





Plane Stress. Yield stress for $\sigma_y = \sigma_Y$

$$r_P = \frac{1}{\pi} \cdot \frac{K_I^2}{\sigma_Y^2}$$

Plane Strain. Yield stress for $\sigma_y \cong 3\sigma_Y$

$$r_P = \frac{1}{9\pi} \cdot \frac{K_I^2}{\sigma_Y^2}$$

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S. CICERO
J.A. ALVAREZ
R. LACALLE
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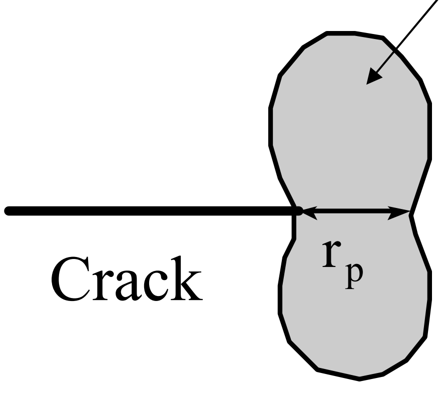
FRACTURE BEHAVIOUR

PLASTICITY ON FRACTURE

Corrections on Linear Elastic Fracture Mechanics (LEFM)

If the plastic zone is small and it is constrained:



$r_P << a$, defect
$r_P << B$, thickness
$r_P << (W-a)$, residual ligament

$$K_I = K_I(a_{ef}) = K_I(a + \Delta a_P)$$

Effective defect = Real defect + Δa_P

Δa_P: plastic correction to crack length

$$\Delta a_P = f(r_P) = \frac{1}{n\pi} \cdot \frac{K_I^2}{\sigma_Y^2}$$

n = 6 Plane Strain

n = 2 Plane Stress

An iterative calculation is required to obtain K_I

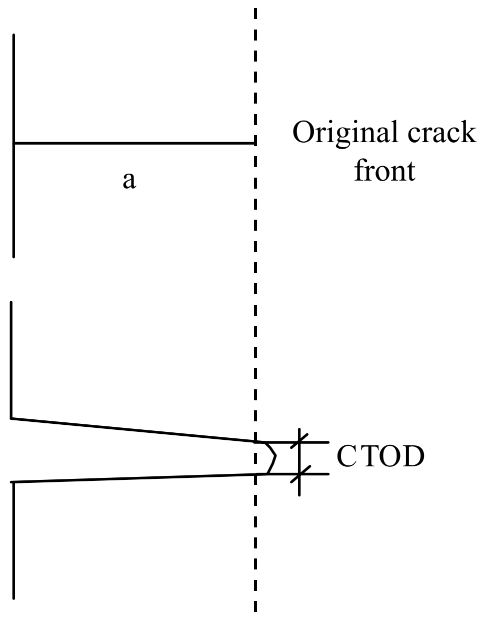
F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UNIVERSIDAD DE CANTABRIA

FRACTURE BEHAVIOUR

PLASTICITY ON FRACTURE

Elastic-Plastic Fracture Mechanics (EPFM)

If plastic zone has important dimensions:



Parameters and fracture criteria change because of local condition changes

- Physical parameters and criteria

$CTOD = CTOD_c$

- Energetic parameters and criteria

J-Integral

$J = J_{Ic}$

(equivalent to G in linear elastic conditions)

F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UNIVERSIDAD DE CANTABRIA

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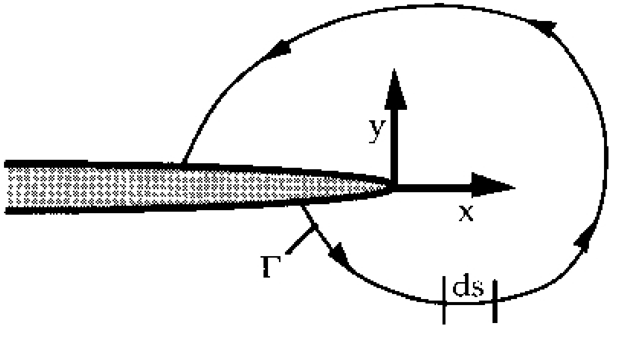
Elastic-Plastic Fracture Mechanics (EPFM)

The non linear energy release rate , J, can be written as a path-independent line integral. Considering an arbitrary counter-clockwise path (Γ) arround the tip of the crack, the J integral is given by:

$$J = \int_{\Gamma} \left(w dy - T_i \frac{\partial u_i}{\partial x} ds \right)$$



Arbitrary contour around the tip of the crack

F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UC UNIVERSIDAD DE CANTABRIA

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Elastic-Plastic Fracture Mechanics (EPFM)

J can also be seen as a Stress Intensity Parameter for Elastic-Plastic problems as long as the variation of stress and strain ahead of the crack tip can be expressed as:

$$\sigma_{ij} = k_1 \left(\frac{J}{r} \right)^{\frac{1}{n+1}}$$

$$\varepsilon_{ij} = k_2 \left(\frac{J}{r} \right)^{\frac{n}{n+1}}$$

Where k_1 and k_2 are proportionally constants and n is the strain hardening component.

F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UNIVERSIDAD DE CANTABRIA

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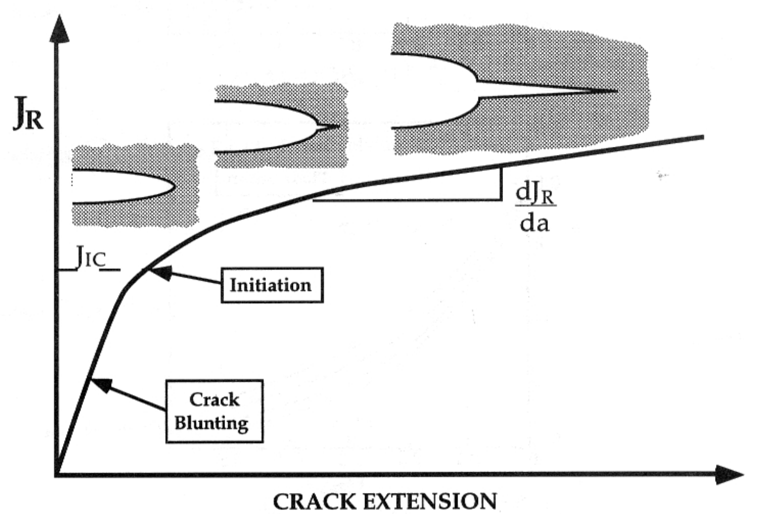
Elastic-Plastic Fracture Mechanics (EPFM)

Many materials with high toughness do not fail catastrophically at a particular value of J or CTOD. In contrast, these materials exhibit a rising R curve, where J and CTOD increase with crack growth.

The figure illustrates a typical J resistance curve for a ductile material.



F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UNIVERSIDAD DE CANTABRIA

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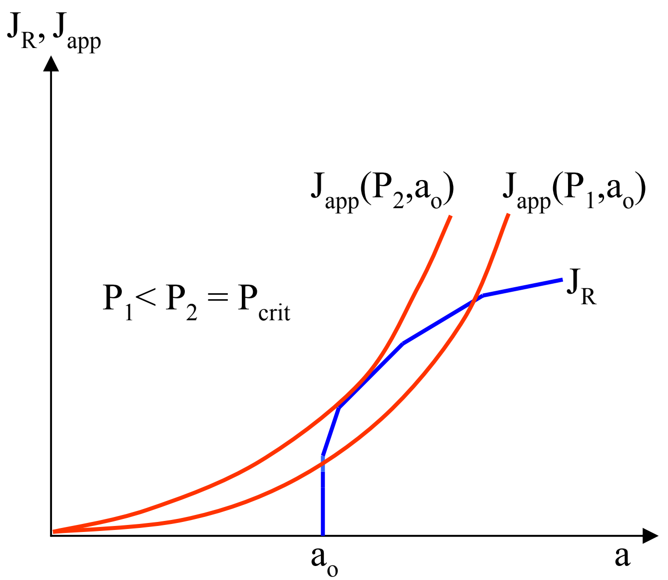


CRACK DRIVING FORCE DIAGRAM

Local conditions in the component

$$J_{app}(P,a) = J_e(P,a) + J_p(P,a)$$

Characterises the local state

Critical conditions in the material

$$J_R(\Delta a)$$

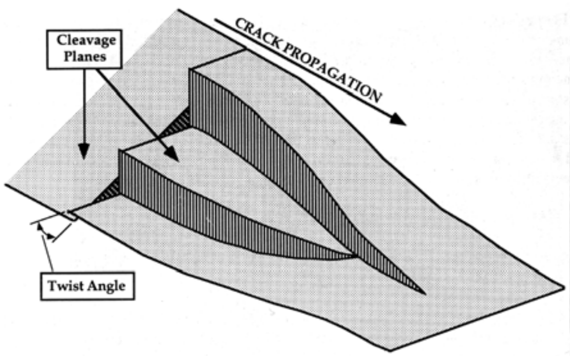
Characterises the strength of the material to cracking

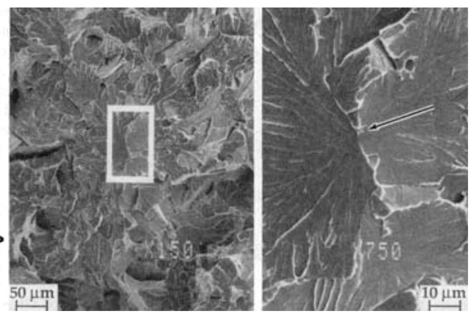
F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UC UNIVERSIDAD DE CANTABRIA

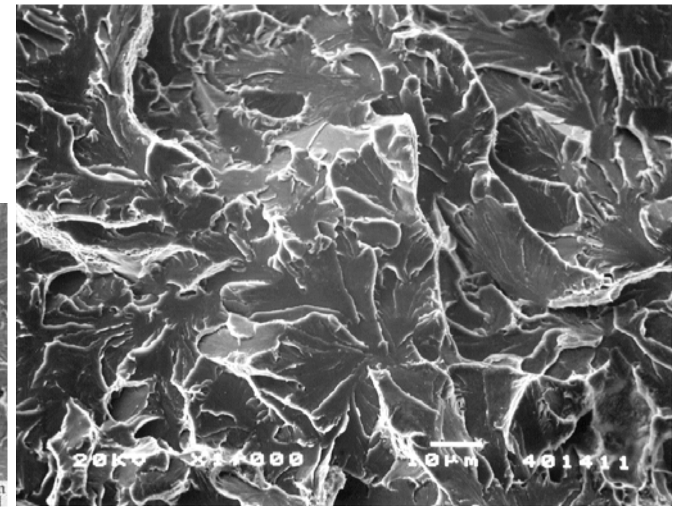
FRACTURE BEHAVIOUR

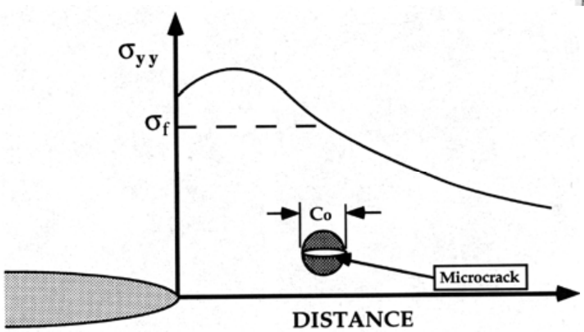
FRACTURE MICROMECHANISMS

Brittle Fracture: Cleavage









It occurs on metallic material with brittle behaviour

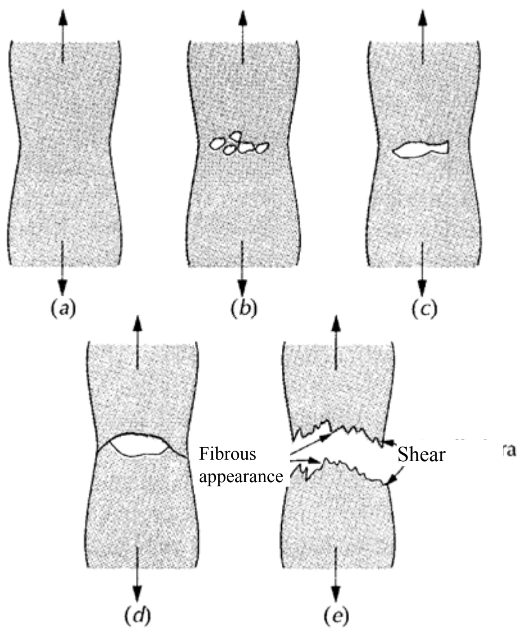
- favoured by low temperatures and high loading rates
- favoured in materials with high σ_Y

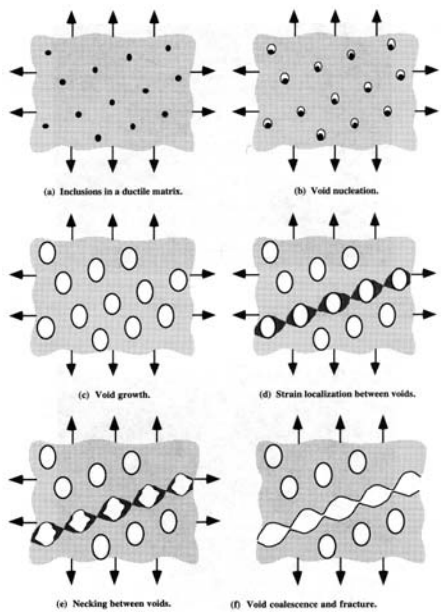
F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UNIVERSIDAD DE CANTABRIA

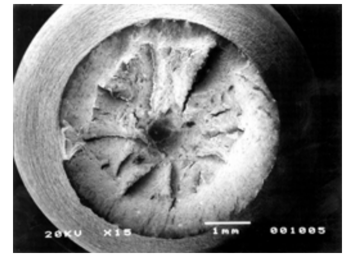
FRACTURE BEHAVIOUR

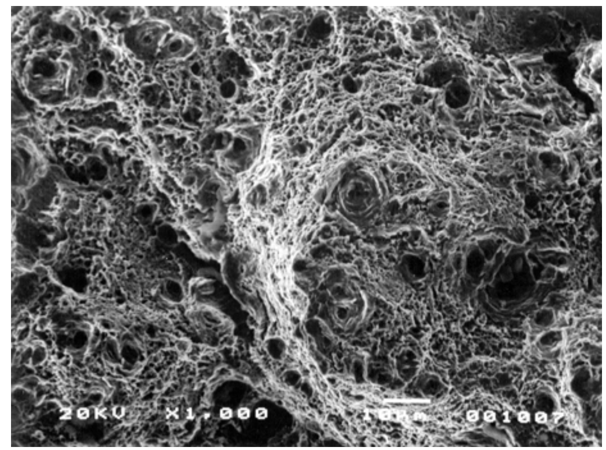
FRACTURE MICROMECHANISMS

Ductile Fracture: Void nucleation and coalescence









Metallic materials with plastic behaviour

- favored by T $\uparrow$, $\sigma_Y \downarrow$, $\dot{\sigma} \downarrow$

F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE

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FRACTURE MICROMECHANISMS

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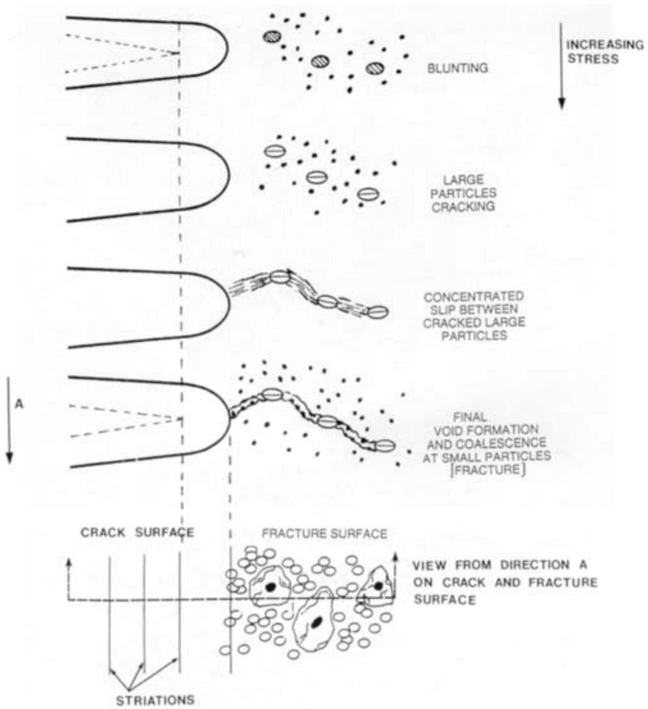
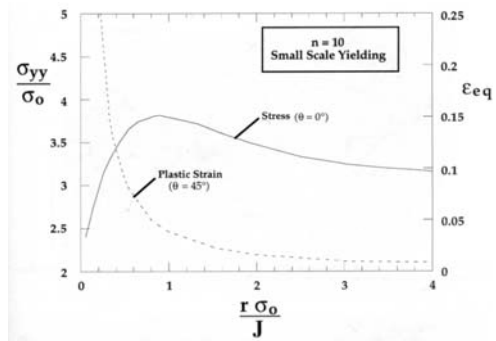
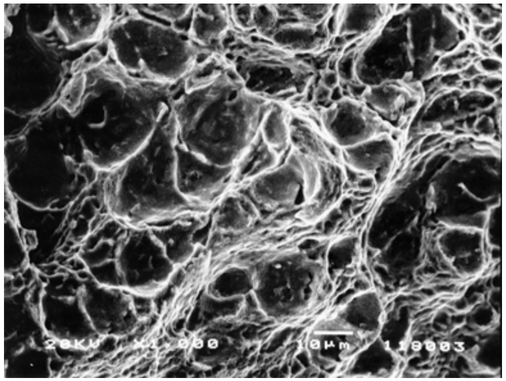




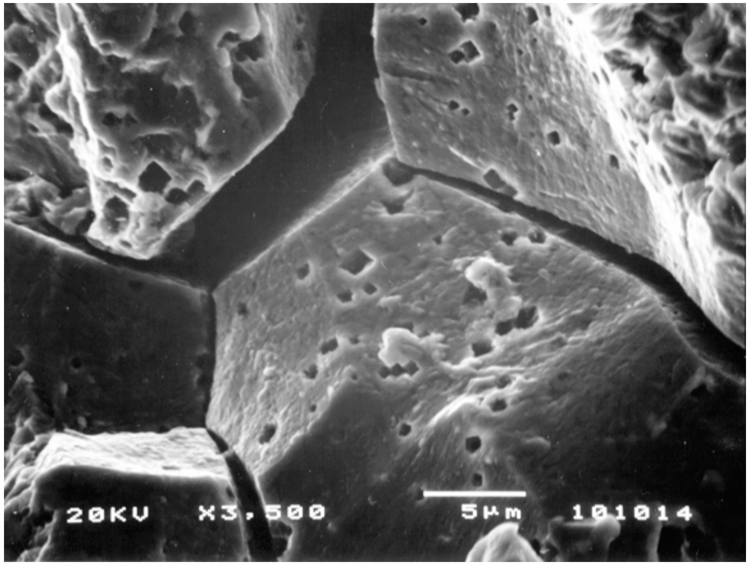


F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UNIVERSIDAD DE CANTABRIA

FRACTURE BEHAVIOUR

FRACTURE MICROMECHANISMS

Intergranular fractures



→ Because of the environment or grain boundary segragations

F. GUTIÉRREZ-SOLANA
S. CICERO
J.A. ALVAREZ
R. LACALLE
UNIVERSIDAD DE CANTABRIA

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