

Module #22

FRACTURE OF MATERIALS

Fundamentals of Fracture and Fracture Mechanics

READING LIST

▶ DIETER: Ch. 7, all; Ch. 11, all; and Ch. 14, all

- Chapters 7-9 in Meyers & Chawla, 1st ed.
- J. Knott and P. Withey, *Fracture Mechanics: Worked Examples*, Institute of Materials (1993)
- D. Broek, <u>Elementary Engineering Fracture Mechanics</u>, 4th <u>revised edition</u>, Nijhoff (1986).



Fracture

• Separation or fragmentation of an object under stress.

- Fracture proceeds via two processes:
 - Crack initiation
 - Crack propagation

Types of Fracture

• Brittle / fast fracture

Structural elements fail with little or no plastic deformation; often without warning.

- Ductile fracture
 - Appreciable plastic deformation occurs prior to and during the fracture process.

Classification

• Strain to fracture

– Ductile or brittle

<u>Appearance of fracture surface*</u>

– Fibrous or granular

Crystallographic mode of fracture*

* We shall address these topics in great detail later

FRACTURE MODES

Fracture mode = function:

material Temp. stress state & rate environment

Types of Engineering Fractures

Low T tensile fracture	separation of atomic bonds under static loading
High T tensile fracture	atomic bond separation assisted by diffusional flow
Fatigue fracture	cyclic stress induced
Embrittlement	environmentally aided fracture H ₂ , liquid metal embrittlement



Fig. 11.20 Schematic classification of major fracture mechanisms. From R. Phillips, <u>*Crystals, Defects and Microstructures: Modeling across Length Scales*</u>, (Cambridge, 2001) p. 619. Originally adapted from Ashby, Gandhi and Taplan, "Overview No. 3: Fracture-mechanism maps and their construction for F.C.C. metals and alloys," *Acta Metallurgica* **27** (1979) 699-729.



Why/how do materials fail?

Are typical loading conditions severe enough to rupture interatomic bonds?

Since we know the stress that is required to break bonds, why do materials fail in service?

What about materials are perfect?

Why/how do materials fail?

Are typical loading conditions severe enough to rupture interatomic bonds?

NO!

Since we know the stress that is required to break bonds, why do materials fail in service?

DEFECTS or FLAWS

concentrate stress locally, levels high enough to rupture bonds

What about materials are perfect?

NOTHING

For almost all engineering applications there is always some statistical distribution of flaws.

Defects act as stress concentrators





CONSIDER AN ELIPTICAL CRACK IN A LARGE PLATE

 σ_{max} = stress at the ends of the major axis of the crack

 σ_{nom} = average stress away from the crack

$$\frac{\sigma_{\max}}{\sigma_{\min}} = 1 + \frac{2c}{b}$$

The radius of curvature at the end of the crack is:

$$\rho = \frac{b^2}{c} \therefore b = \sqrt{\rho c}$$

$$\sigma_{\max} = \sigma_{\max} \left[1 + 2\sqrt{\frac{c}{\rho}} \right]$$

For very sharp cracks (*I.e.*, where $c >> \rho$), we can neglect the "1" in the brackets, which leaves us with:



The term in brackets represents a stress concentration factor.

If we let
$$K_T = 2\sqrt{\frac{c}{\rho}}$$
,
then $\sigma_{max} = \sigma_{nom}K_T$

As crack length increases or the radius of curvature decreases, K_T increases and thus σ_{max} increases



 $\sigma_{\rm max}$ = stress at the ends of the major axis of the crack

Stress distribution around flaws





Griffith Theory for brittle fracture <u>1920</u>

- Proposed that brittle materials contain a population of small cracks that act as stress concentrators.
- The theoretical cohesive strength is reached locally at the crack tip.
- Cracks propagate at stress levels far below the theoretical cohesive strength of the solid.

TO EXTEND A CRACK, WORK MUST BE DONE.

You are creating two new free surfaces when you extend the crack.

The source of this work is the elastic strain energy released when the crack grows!



As the crack extends, new surface area (dc) is created. There is a strain energy term, γ , associated with this new area For in infinitely large plate containing an elliptical crack as illustrated previously, the change in potential energy (decrease) due to the presence of a crack is:

$$J_E = -\frac{\pi \sigma^2 c^2 t}{E}$$

where 2c is the length of the center of the crack and t is the thickness of the material.

The change in potential energy (increase) of the plate due to an increase in the length of the crack is:

$$U_{\rm S} = 2c2t\gamma$$

where γ is the surface energy for a brittle material.

$$\Delta U = U_E + U_S = -\frac{\pi \sigma^2 c^2 t}{E} + 4ct\gamma$$

The *equilibrium crack length* can be determined by differentiating the potential energy expression with respect to *c* and setting the result equal to zero.

$$\frac{\partial \Delta U}{\partial c} = 0 = -\frac{2\pi\sigma^2 ct}{E} + 4t\gamma$$

$$\int \sigma = \sqrt{\frac{2E\gamma}{\pi c}} \quad \leftarrow \quad \text{This is the stress required to propagate a length of crack c in a brittle material.}$$



With it, we can calculate the maximum tolerable crack dimension (*i.e.*, flaw size) for a given state of stress

-or-

The maximum allowable stress if the maximum crack dimension is known

These equations apply **ONLY** to brittle elastic solids

We must develop other relationships for plastic solids

What about "plastic" solids?

- Metals that fail in a completely brittle fashion undergo some plastic deformation prior to fracture.
- The fracture strengths of a material that undergo plastic deformation before fracture is greater than that for a perfectly brittle elastic solid.

- <u>Plastic deformation at the root of the crack</u> <u>increases</u> the <u>radius of curvature at the crack</u> <u>tip</u>, which reduces the stress concentration at the crack tip.
- This <u>increases</u> the <u>fracture</u> <u>strength</u> of the material (according to the Orowan equation).

OROWAN (1952)

Suggested that a plastic work term γ_P should be added to the Griffith equation to make it applicable to metallic materials.

 γ_P represents the plastic work necessary to extend the crack front.

This modified Griffith equation becomes:

$$\sigma_{F} = \sqrt{\frac{2E(\gamma + \gamma_{P})}{\pi c}}$$

For ductile materials (*i.e.*, metals and most polymers),

$$\gamma \simeq 10^{-4} \gamma_P$$

(*i.e.*, $\gamma_P \gg \gamma$)

Thus we can neglect γ in ductile materials.

IRWIN (1958)

replaced the $2\gamma_P$ in Orowan's modification with \mathcal{G} where \mathcal{G} is defined as the "strain energy release rate" or "crack extension force."

$$\sigma_{F} = \sqrt{\frac{E\mathcal{G}}{\pi c}}$$

The parameter G represents the <u>rate of transfer of</u> <u>energy</u> from the elastic stress field in the cracked structure or sample to the crack extension process.

THE CRITICAL VALUE OF \mathcal{G} THAT MAKES THE CRACK PROPAGATE TO FRACTURE IS \mathcal{G}_c

 \mathcal{G}_c is a material parameter called the "critical strain energy release rate", "toughness", or "crack resistance force".

Some books (such as Dieter) call this term the fracture toughness. They are incorrect!

The conditions for crack growth can be represented as:

 $\sigma_{F}\sqrt{\pi c} = \sqrt{E G_{c}}$

This term represents the driving force for crack propagation.

Let $K_c = \sigma_F \sqrt{\pi c}$

(the critical stress intensity factor)



K_c is a material parameter known as the *fracture toughness*.

Values of K_c depend upon many factors including:

- 1. Type of loading on the crack face
- 2. The material being loaded
- 3. Geometry of the sample or structure



Tensile forces are the most important in fracture

WHY?

They tend to open up cracks and to make them propagate.



Stress analysis at crack tips

- Introduction of a crack into a solid causes a redistribution of stress.
- Westergaard (1939) and Irwin (1957)
 - Related stresses in front of a crack tip to the stress intensity.

$$\sigma_{tip} = \frac{K}{\sqrt{2\pi r}} F(\theta)$$

Figure

Coordinates specified from leading edge of crack and components of stress in crack tip stress field.



$$\sigma_{xx} = \frac{K}{\sqrt{2\pi r}} \left[\cos \frac{\theta}{2} \left(1 - \sin \frac{\theta}{2} \sin \frac{3\theta}{2} \right) \right]$$

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

$$T_{xy} = \frac{K}{\sqrt{2\pi r}} \left[\sin \frac{\theta}{2} \cos \frac{\theta}{2} \cos \frac{3\theta}{2} \right]$$

$$\tau_{xz} = \tau_{yz} = 0$$

$$\sigma_{zz} = 0, \text{ plane stress}$$

$$\sigma_{zz} = v \left(\sigma_{xx} + \sigma_{yy} \right) 0, \text{ plane strain}$$

General Expression



• Allows calculation of maximum allowable stress for a given flaw size.

Design Philosophy

 $K_{Ic} = Y \sigma_{app} \sqrt{\pi c_c}$

Material <u>Property</u> Materials selection

Design stress

Allowable flaw size or NDT flaw detection



Plane-strain fracture toughness of selected alloys

	ŀ	< _{lc}	σ	ys	c	c
Material	MPa·m ^{1/2}	ksi∙in¹/2	MPa	ksi	mm	in.
2024-T3	~44	~40	345	50	~21	~0.82
2024-T851	26.4	24	455	66	4.3	0.17
Ti-6Al-4V	115.4	105	910	132	20.5	0.81
Ti-6Al-4V	55	50	1035	150	3.6	0.14
4340	98.9	90	860	125	16.8	0.66
4340	60.4	55	1515	220	2	0.08
350 Maraging	55	50	1550	225	1.6	0.06
350 Maraging	38.5	35	2240	325	<0.4	<0.02

Brittle Fracture of Single Crystals

- Fracture is related to the resolved normal stress on a cleavage plane.
- Sohncke's law:
 - Fracture occurs when the resolved normal stress reaches a critical value.
 - See the next page.

Sohncke's law



$$\sigma_c = \frac{F\cos\phi}{A/\cos\phi} = \frac{F}{A}\cos^2\phi$$

- This law is generally accepted.
- Variations from it might be due to the occurrence of slip prior to fracture.

Metallographic aspects of fracture

- Observations show that Griffith cracks don't exist in undeformed metallic materials.
- Microcracks <u>can</u> <u>be</u> produced during plastic deformation.
- Defects such as inclusions are often the cause for microcracking.
- Etc...

Process for cleavage fracture in metals

- Crack initiation in single phase material:
 - Plastic deformation produces dislocation pileups at grain boundaries.
 - Stress concentration might become large enough to induce microcracking in neighboring grains.
 - Cracks propagate under the applied stress.

Crack nucleation for MgO



Figure 10.28

(a) Microcracks formed in MgO at tips of slip bands impinging on a grain boundary. Magnification, $1170 \times$. (b) Cracks in MgO that formed at the intersection of slip bands. This photograph shows two adjacent sides of a crystal that meet at a common edge (i.e., the dark vertical line). The crack is associated with the intersection of the crystal faces.

Initiation of microcracks (1)

- Can be greatly influenced by second phase particles (see *Metall. Trans.*, v.4, pp. 2495-2518, 1973).*
- When second phase particles are easily sheared (cut) by moving dislocations, slip becomes planar resulting in large dislocation pileups.
- The high stress at the tip of the pileup can nucleate microcracks which can then grow.

^{*} NOTE: Dieter cites this incorrectly on page 252 of his text.

Initiation of microcracks (2)

- When second phase particles cannot be sheared by moving dislocations (i.e., they are impenetrable),
 - Slip distance of dislocations is reduced
 - Large dislocation pileups don't form
 - Cracks (if they do form) are forced to move between particles which increases resistance to fracture; "cracks must follow a more tortuous path."

Grain boundary precipitates

- Precipitates often form at grain boundaries in polycrystalline materials.
- When the precipitates are brittle and don't wet the primary phase, brittle intergranular fracture will occur.



[Dieter]

Figure 7-10 Model of microcrack formation at a pileup of edge dislocations.



Microcrack formation in metals. Also possible in other semi-brittle solids such as MgO

Figure 8.3 Grouping of dislocations piled up at a barrier and leading to the formation of a microcrack (Zener–Stroh crack).



[Dieter]

Figure 7-11 Smith's model of microcrack formation in grain boundary carbide film.

Some Metallographic Aspects of Fracture



Fig. 1. Fracture mechanisms. (a) cleavage; (b) rupture by necking; (c) rupture by shear; (d) microvoids; (e) intergranular microvoids; (f) intergranular cleavage.⁽⁷⁾

> From R.M.N. Pelloux, "Fractography," in <u>Atomistics of</u> <u>Fracture</u>, edited by R.M. Latanision and J.R. Pickens, Plenum Press (1981) pp. 241-251

Transgranular





Transgranular cleavage fracture in low carbon steel (1300 X). From R.M.N. Pelloux, "Fractography," in <u>Atomistics of Fracture</u>, edited by R.M. Latanision and J.R. Pickens, Plenum Press (1981) pp. 241-251.

Intergranular





Intergranular cleavage fracture in sintered tungsten. From R.M.N. Pelloux, "Fractography," in <u>Atomistics of Fracture</u>, edited by R.M. Latanision and J.R. Pickens, Plenum Press (1981) pp. 241-251.

Intergranular



Transgranular





Brittle fracture in polycrystalline NiAl

Mixture of intergranular and transgranular

(arrowed)

• Multiple modes are possible.

Failure by shear rupture



Figure 8.7 Sequence of deformation processes leading to the formation of chisel-edge fracture shown in Fig. 8.6: (a) orientation of crystal and active <111> Burgers vectors. (b) development of intense shear bands in the neck. (c) Geometry of shear bands and chisel-edge fracture after final separation.





(a)

(c)



(b)

Figures 8.6 and 8.7 adapted from D. Hull, <u>Fractography: Observing,</u> <u>Measuring and Interpreting Fracture</u> <u>Surface Topography</u>, Cambridge University Press (1999). **Figure 8.6** Side view of a chisel-edge fracture in a [110] single crystal of Fe-3%Si tested in tension at 473 K.

Failure of a single crystal via cleavage **Figure 6.1** Cleavage fracture of a single crystal of Mo tested in tension, normal to (001), at 293 K. Geometry of specimen is illustrated in Fig. 6.2.



Figure 6.2 Geometry of crystal and test configuration for cleavage fracture shown in Fig. 6.1. A spark-induced starter crack nucleated a new crack at E that propagated slowly to F. An unstable crack nucleated at F and un-zipped along tip of slow growth crack.







Images from D. Hull, <u>Fractography: Observing, Measuring and</u> <u>Interpreting Fracture Surface Topography</u>, Cambridge University Press (1999) pp.158-160.

Ductile fracture

- Up to this point we've defined it as fracture occurring with appreciable gross plastic deformation.
- Necking begins at a point of elastic instability.
- Voids grow and coalesce, ultimately leading to failure.



Figure 8.13 Low magnification (center) and high magnification images of an AISI 1008 steel specimen fractured in tension. Note the equiaxed dimples in the central region and elongated dimples in the shear walls (i.e., sides of cup). [From Meyers & Chawla]

Ductile microvoid coalescence



Figure 8.16 Light microscope photograph of a polished section, parallel to tensile axis, through center of a necked copper bar. Holes formed in necked region. Largest holes are in center of neck and some have joined to form a crack. From Puttick, *Phil. Mag.*, 1951, **4**, 964-9.

Figure 8.17 Cup and cone fracture in a steel bar tested in uniaxial tension, showing central flat region formed by coalescence of holes and outer rim of 'shear lip' fracture. From Bridgman, in *Fracturing of Metals*, 1948, ASM, Cleveland, pp. 246-61.





Images from D. Hull, <u>Fractography: Observing, Measuring and</u> <u>Interpreting Fracture Surface Topography</u>, Cambridge University Press (1999) pp.233. Ductile fracture is influenced by the presence of particles or inclusions



Figure 7.35 Schematic representation of ductile fracture. (a) Voids nucleate at inclusions. (b) Voids elongate as the specimen extends. (c) Voids coalesce to cause fracture when their length 2h is about equal to their separation (after Ashby et al., 1979).

[R.E. Smallman and A.H.W. Ngan, Physical Metallurgy and Advanced Materials, 7th Ed., (2007) p. 435]



Ductile microvoid coalescence

inclusions

From R.M.N. Pelloux, "Fractography," in Atomistics of Fracture, edited by R.M. Latanision and J.R. Pickens, Plenum Press (1981) pp. 241-251



Fig. 4. Ductile fracture by microvoids (1400 X).

Process can be enhanced by inclusions WHY?



Fig. 5. Ductile fracture channels in Zircaloy. The channels which are called 'flutes' are parallel to [0002]. (1800 X)

	Туре	Principal Factors	Materials
Increasing K _c [Meyers & Chav	Brittle	Bond rupture	Structures of type diamond, ZnS, silicates, alumina, mica, boron, carbides, and nitrides
	Semibrittle	Bond rupture, dislocation mobility	Structures of type NaCl, ionic crystals, hexagonal compact metals, majority of body-centered cubic metals, glassy polymers
	Ductile awla]	Dislocation mobility	Face-centered cubic metals, nonvitreous polymers, some body-centered cubic
			melais

TABLE 8.1 Materials of Various Degrees of Brittleness^a

^aAdapted with permission from B. R. Lawn and T. R. Wilshaw, *Fracture of Brittle Solids* (Cambridge: Cambridge University Press, 1975), p. 17.)

Increasing fracture toughness is related to increase in work required to initiate and propagate a crack.



Figure 9.16

Several sample geometries suitable for measuring plane strain fracture toughness. $K_{\rm Lc}$ is defined by $\sigma_F(\pi c)^{1/2} f(c/a)$, where σ_F is the fracture stress and f(c/a) is a function of the test sample geometry. The crack length (c) used in calculating $K_{\rm Lc}$ is that of the initial machined notch (c') plus the increment provided by sharpening of the crack tip prior to testing. Specifications for producing plane strain conditions are noted. However, the sheet thickness should always be compared to the plastic zone size $(r_y \cong K_c^2/2\pi\sigma_y^2)$ calculated from the measured fracture toughness to verify that plane strain conditions have been met.

[Courtney]

Ductile to Brittle Transition

- In some materials the fracture mode changes from brittle to ductile as you increase temperature.
 - BCC Steels
 - Intermetallics
 - Others???



Charpy Impact Test

• Qualitative way to establish the fracture resistance of a material.



Change in Fracture Morphology at the DBTT

SEM fractographis of ductile (D) and brittle (B) fractures in Charpy V-notch impact specimens shown at top. (500 x magnification).

[ASM Handbook, Desk Edition, 2nd Edition, J.R. Davis editor, ASM International, Materials Park,OH, 1998) p. 1215]



