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AP 298r

WEDNESDAY, FEBRUARY 25, 2004

STRENGTH, FATIGUE & FRACTURE

JOHN HUTCHINSON

- PLASTICITY & STRENGTH
- FATIGUE ~ S-N TESTS
- FRACTURE
  - STRESS INTENSITY FACTORS & ENERGY RELEASE RATES
  - FRACTURE TOUGHNESS
  - FRACTURE ANALYSIS
  - FATIGUE CRACK GROWTH ~ $\frac{da}{dN}$ DATA

NONLINEAR BEHAVIOR (PLASTICITY)

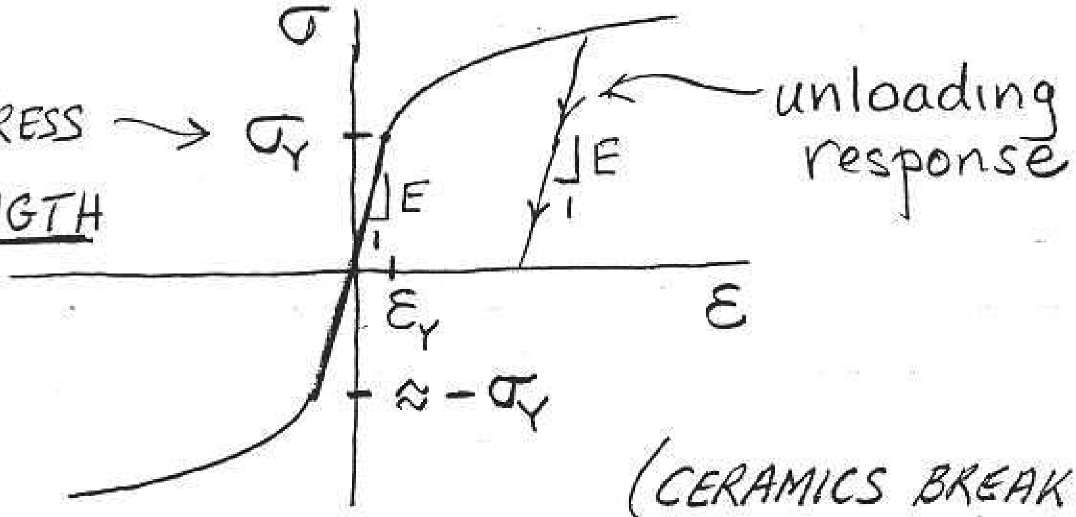
HIGH TEMPERATURES $\Longrightarrow$ TIME-DEPENDENT BEHAVIOR, CREEP, ...

$T < \frac{1}{2} T_{melt} \Longrightarrow$ BEHAVIOR OF METALS + CERAMICS $\approx$ INDEPENDENT OF TIME

UNIAXIAL BEHAVIOR OF METALS + POLYMERS IN TIME-INDEPENDENT REGIME

YIELD STRESS → σ_Y

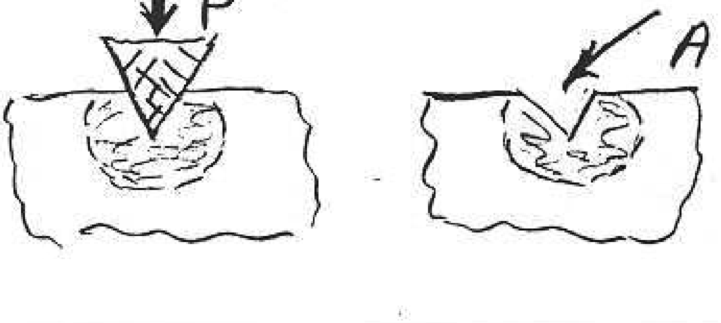
OR STRENGTH (Pa)



(CERAMICS BREAK IN TENSION!)

$\varepsilon_Y \equiv \frac{\sigma_Y}{E}$ FOR MOST METALS + POLYMERS $10^{-3} < \varepsilon_Y < 10^{-2}$

INDENTATION TEST FOR HARDNESS



$$H = \frac{P}{A} \approx 3\sigma_Y$$

(Pa)

STRENGTH $\sigma_s \leftarrow$ Pa

BRITTLE MATERIALS IN TENSION:
CERAMICS, GLASSES, ...

σ_s ~ catastrophic fracture due to small flaws

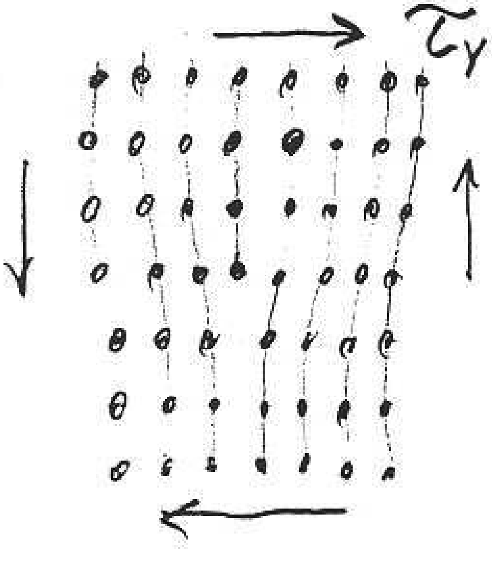
IN COMPRESSION A VARIETY OF MECHANISMS, INCLUDING PLASTIC FLOW

$$(\sigma_s)_{compression} \gg (\sigma_s)_{Tension}$$

DUCTILE METALS (TENSION OR COMPRESSION)

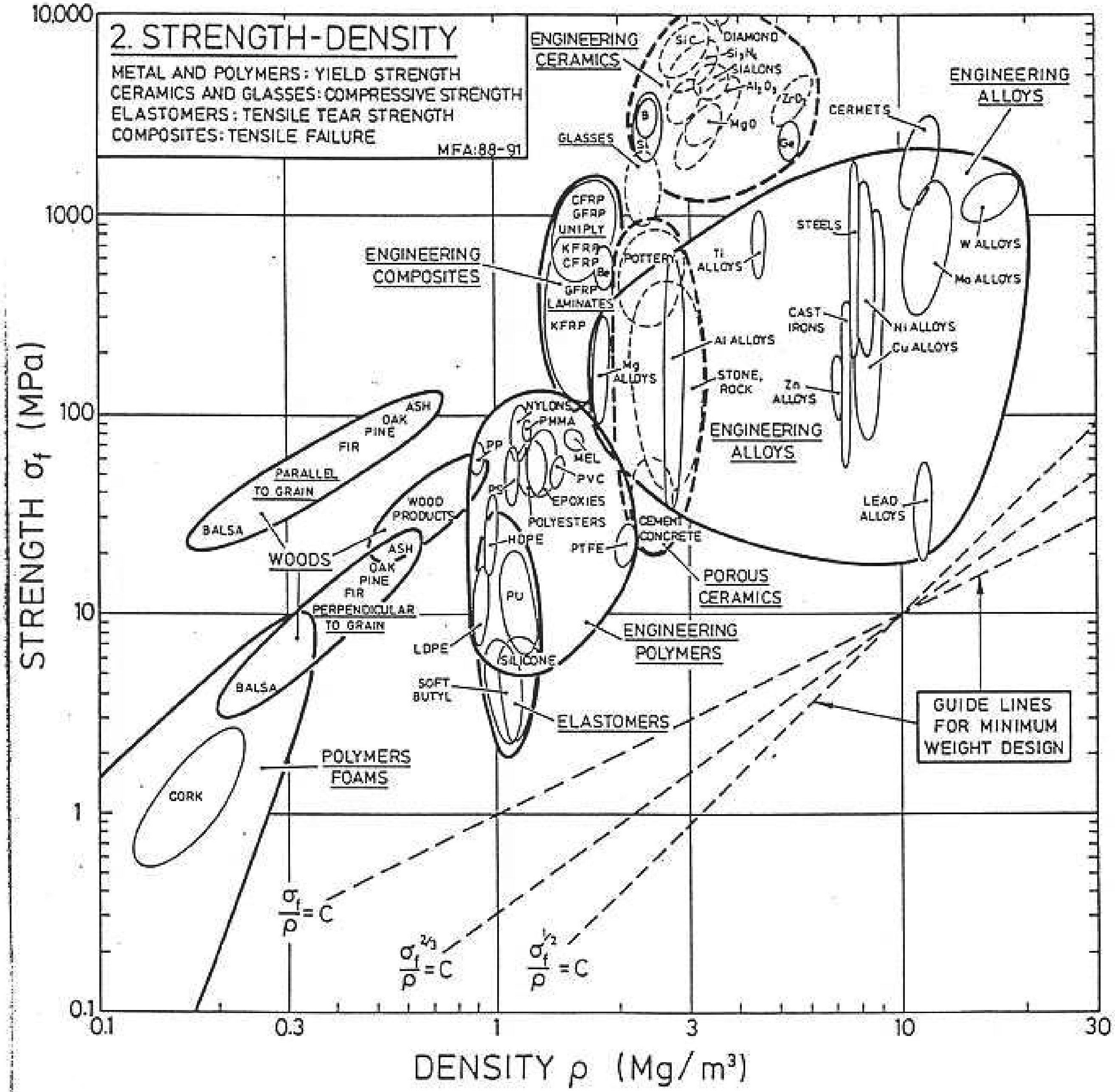
$\sigma_s \equiv \sigma_Y$ ~ stress for plastic yielding

plastic flow due to dislocation motion



$$\tau_Y \ll \mu/10$$

4,

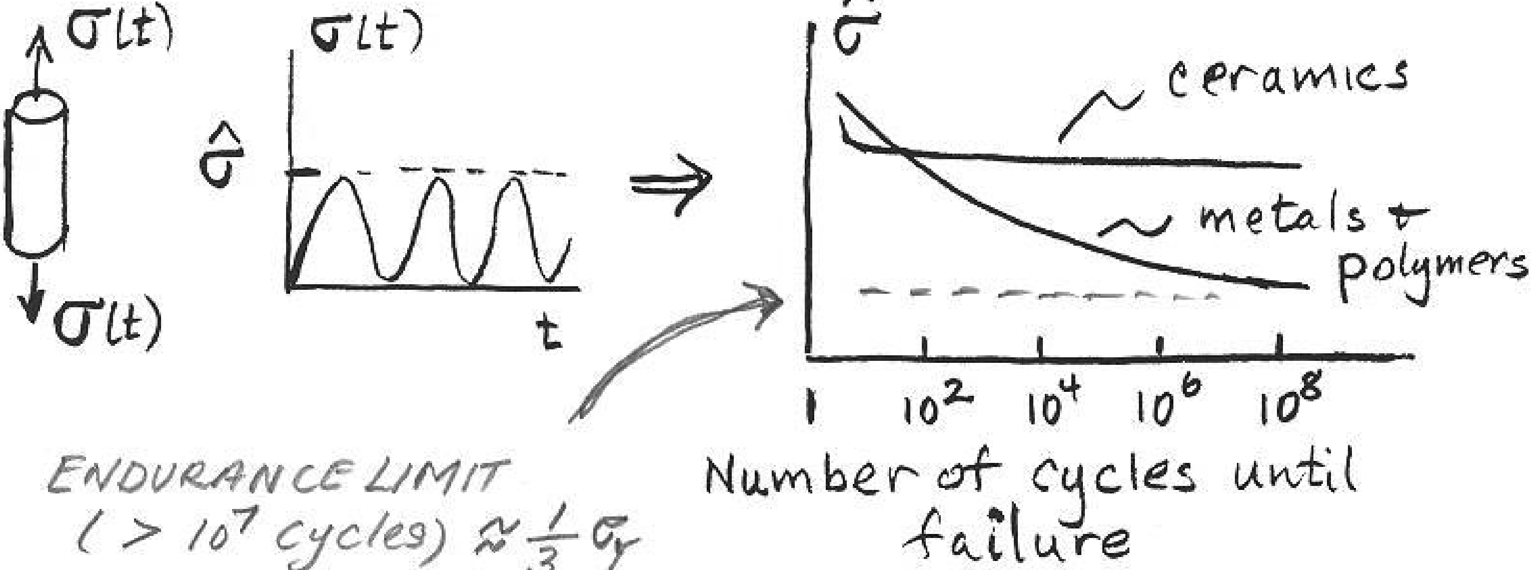


From M.F. Ashby, 1992

FATIGUE → FATIGUE CRACK INITIATION

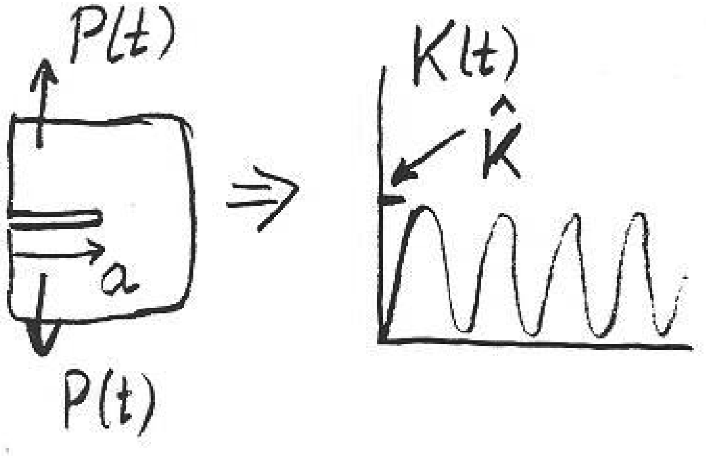
FATIGUE → FATIGUE CRACK GROWTH (GROWTH UNDER CYCLIC LOADING)

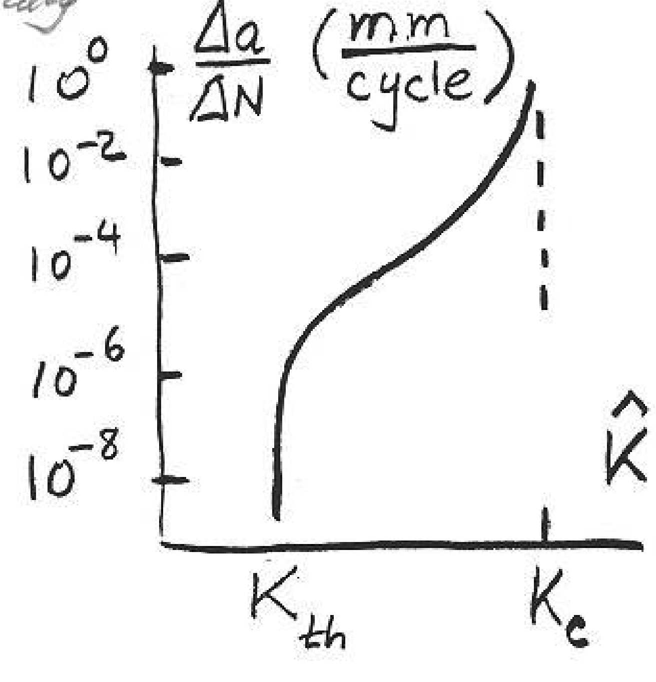
FATIGUE TESTING (INITIATION OF CRACKS)



ENDURANCE LIMIT
(> 10^7 cycles) $\approx \frac{1}{3}\sigma_Y$ ← typically

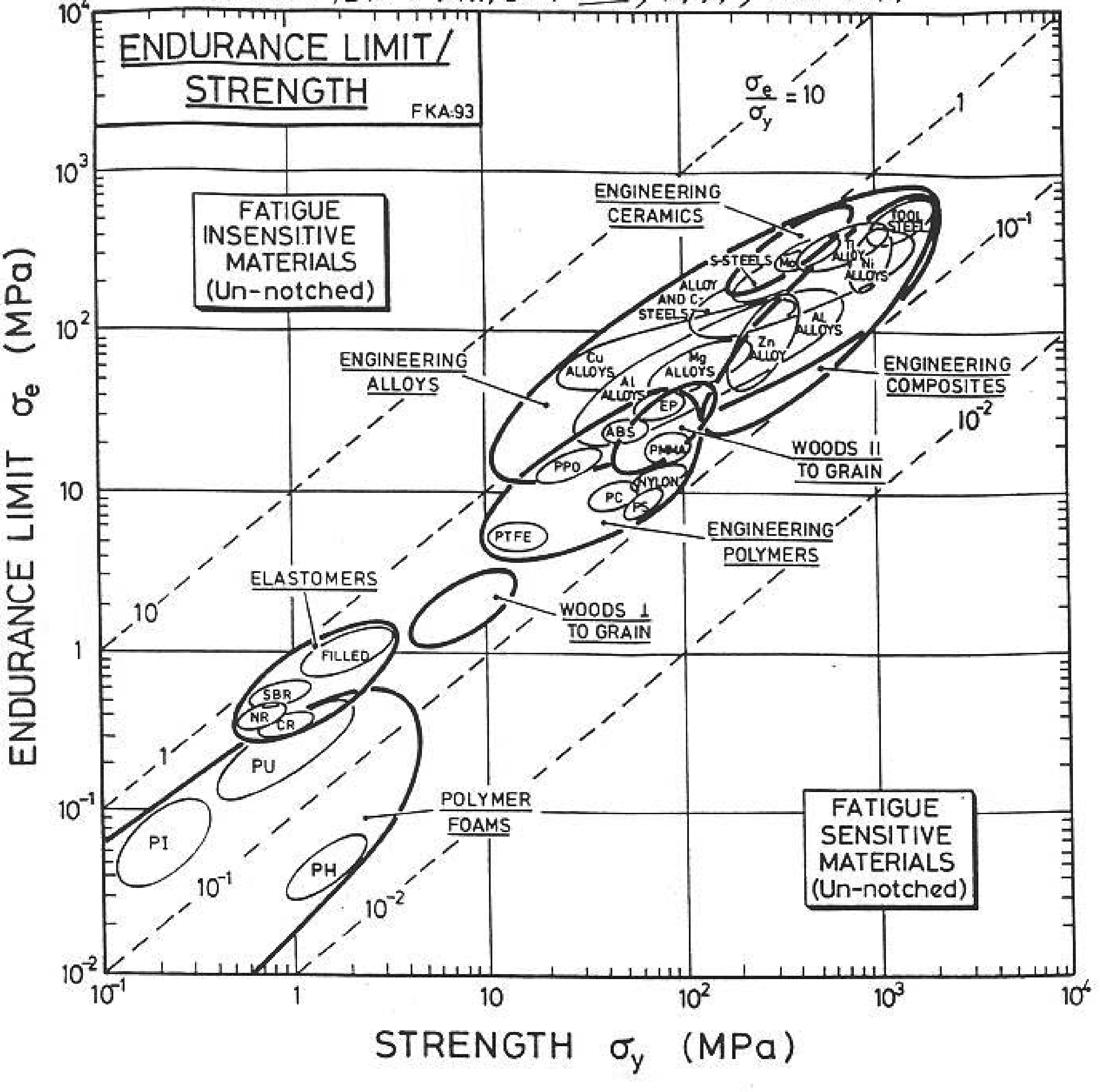
FATIGUE CRACK GROWTH





ENDURANCE LIMIT $\Leftrightarrow$ SURVIVAL TO MORE THAN 10^7 CYCLES
(Depending on application)

ACTA MET. + MATER. 42, 1994, 365-381.



MICROSCOPIC FATIGUE MECHANISM IN METALS ~ IRREVERSIBLE LOCAL SLIP

RELATED TO HETEROGENITY

GRAINS

ANISOTROPIC ELASTIC CRYSTALS

INTERACTION WITH SURFACE

DEVELOPS INTO A MICRO-CRACK

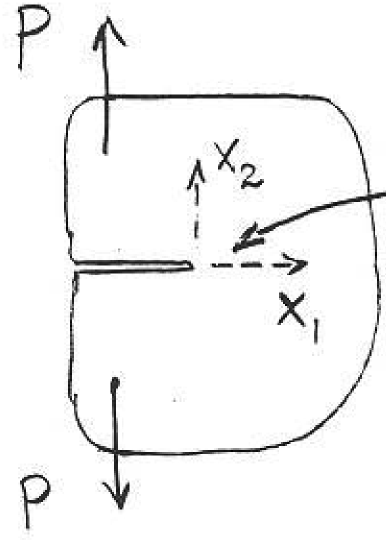
MICRO-CRACK → "SHORT" CRACK → "LONG" CRACK

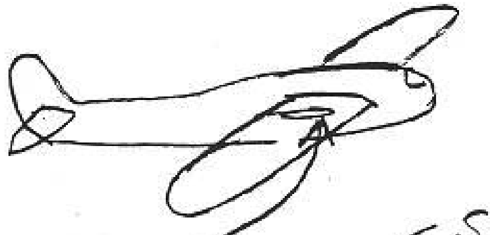
RELEVANT RELATED PHENOMENA

- CYCLIC STRAIN HARDENING OR SOFTENING
- ENVIRONMENTAL EFFECTS, CORROSION

FRACTURE TOUGHNESS ~ PRELIMINARIES

TWO RESULTS FROM ELASTICITY THEORY OF CRACKS:





$$\sigma_{22} \rightarrow \frac{K}{\sqrt{2\pi X_1}}$$

STRESS INTENSITY FACTOR

(NEAR TIP)

UNIVERSAL STRESS DISTRIBUTION AHEAD OF CRACK TIP

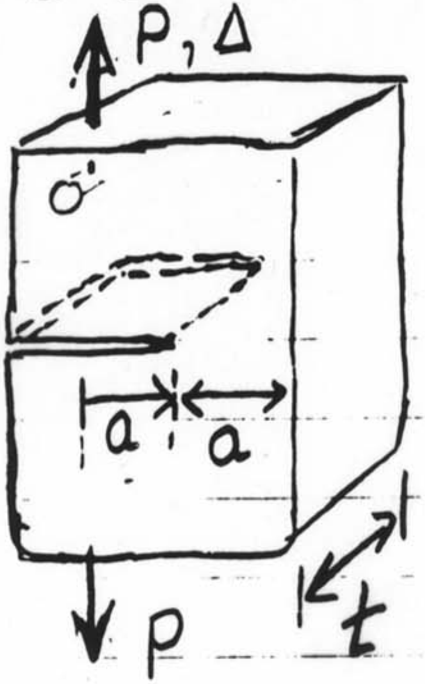
ENERGY RELEASE RATE (elastic energy made available to fracture processes / unit advance of crack)

$$\mathcal{G} = \frac{(1-\nu^2)}{E} K^2$$

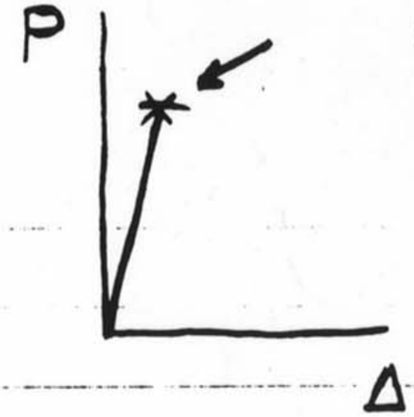
$$\boxed{\begin{array}{l} K \leftrightarrow \frac{Nt}{m^2}\sqrt{m} \equiv Pa\sqrt{m} \\ \mathcal{G} \leftrightarrow \frac{Nt\text{-}m}{m^2} \equiv \frac{\text{JOULES}}{m^2} \end{array}}$$

SOLUTIONS FOR K ARE AVAILABLE FOR MANY GEOMETRIES & LOADINGS

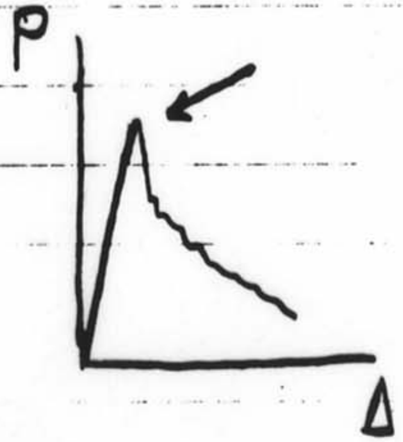
FRACTURE TOUGHNESS TEST : K_c OR Γ_c



COMPACT TENSION SPECIMEN

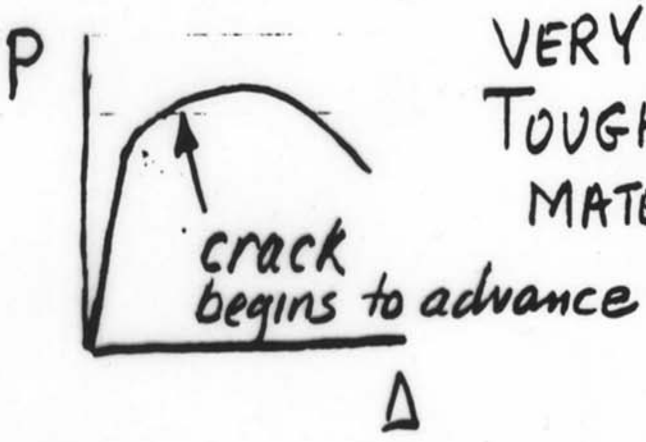


VERY BRITTLE MATERIAL

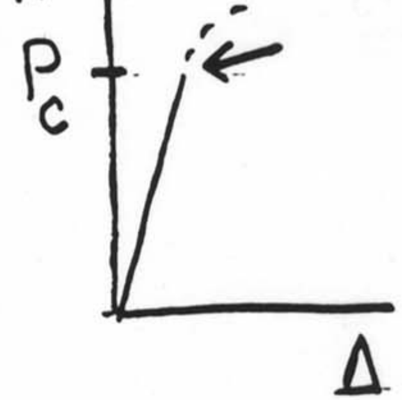


MODERATELY BRITTLE TO MODERATELY TOUGH

$$K = 6.9 \frac{P}{t\sqrt{a}}$$

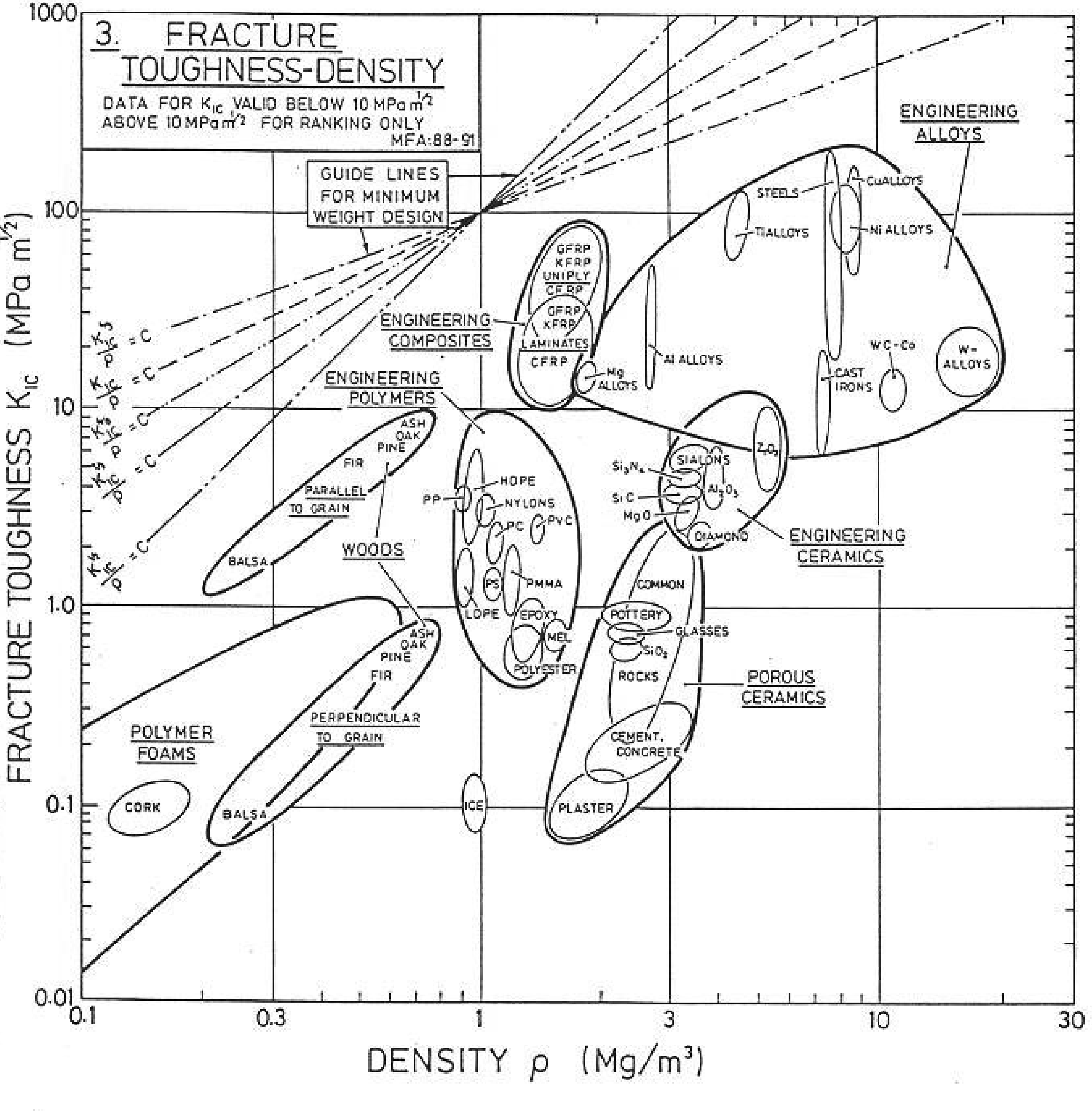


VERY TOUGH MATERIAL



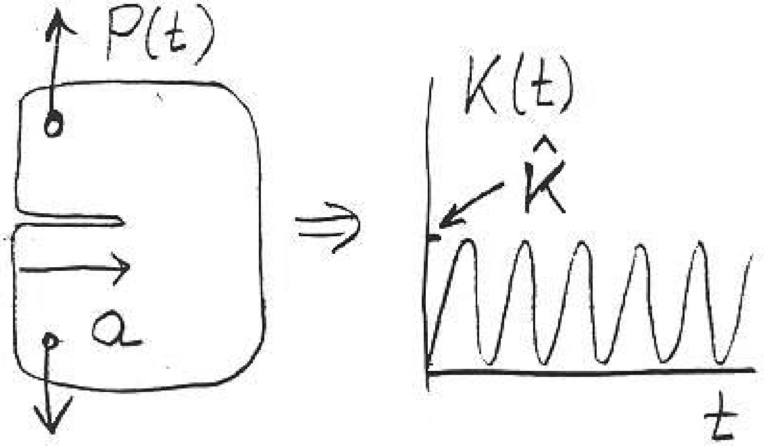
$$P_c \rightarrow \overset{Pa\sqrt{m}}{K_c} \quad \text{or} \quad \overset{J/m^2}{\Gamma_c} \equiv \frac{1-\nu^2}{E} K_c^2$$

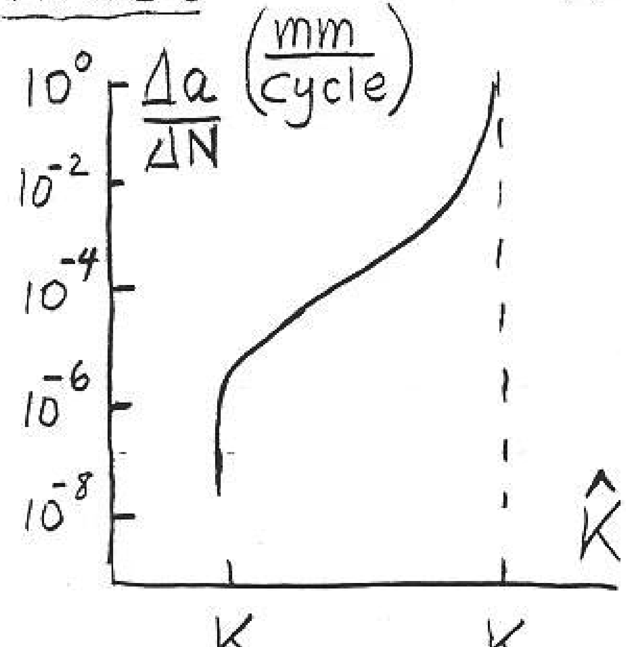
Called <u>Fracture Toughness</u>

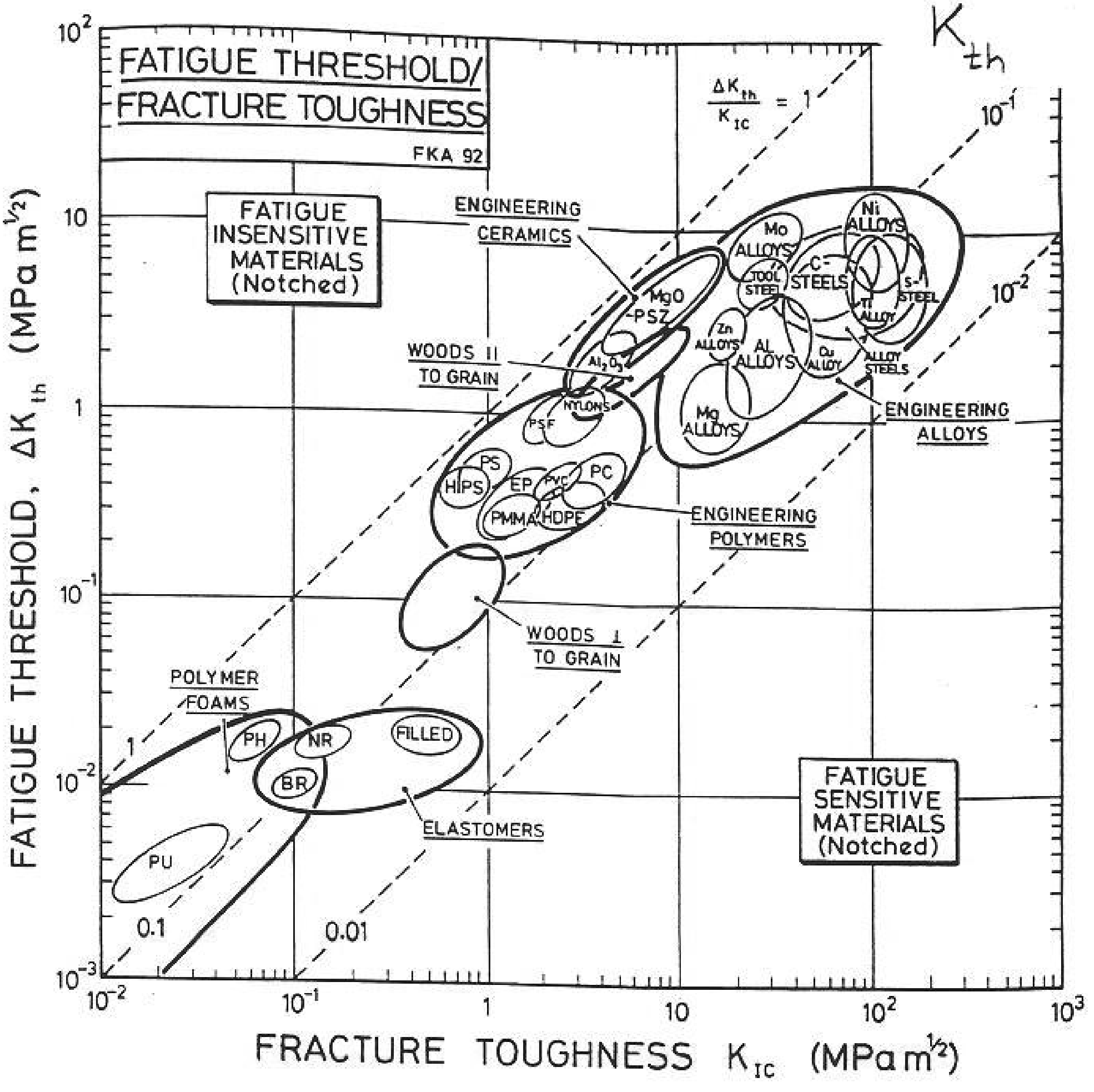


From M.F. Ashby, 1992

FATIGUE CRACK GROWTH RATES FOR "LONG" CRACKS





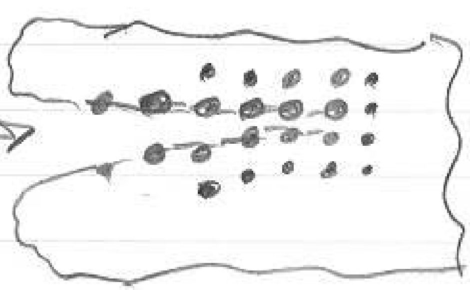


Fleck, et al., Acta Met. Mater. 1994, 42, 365-381,

FRACTURE MECHANISMS

ASSUMING $T < \frac{1}{2} T_M$, the two most common fracture mechanisms in structural metal alloys are cleavage & void nucleation, growth & coalescence (VNG+C)

CLEAVAGE ~ separation of atomic lattice



For almost all metals & ceramics

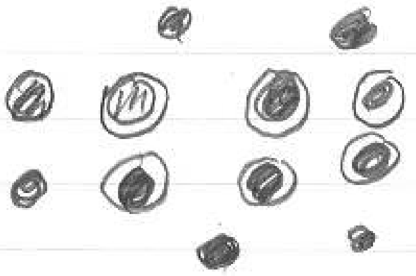
↓

Atomic Work of separation $\Gamma_0 \approx 1 \ J/m^2$

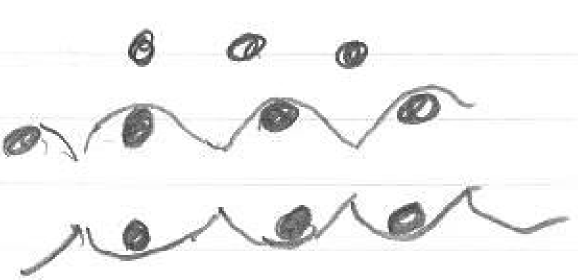
FOR A STEEL THAT CLEAVES $\Gamma_c \approx 10^4 \ J/m^2$

(plasticity!)

(VNG+C)



second phase particles debond & nucleate micron-sized voids, These grow & coalesce to form crack.



$\Gamma_c \approx 10^4$ to 10^5 J/m^2