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Basics of Fracture Mechanics as Applied to Structural Integrity of RPVs

SERVER William Leon

ATI Consulting
24 Glenbarr Court, P.O. Box 5769, Pinhurst 28374
NC
U.S.A.

Strada Costiera 11, 34151 Trieste, Italy - Tel.+39 040 2240 111; Fax +39 040 224 163 - sci_info@ictp.it

Basics of Fracture Mechanics as Applied to Structural Integrity of RPVs

William L. Server
ATI Consulting

Presentation Outline

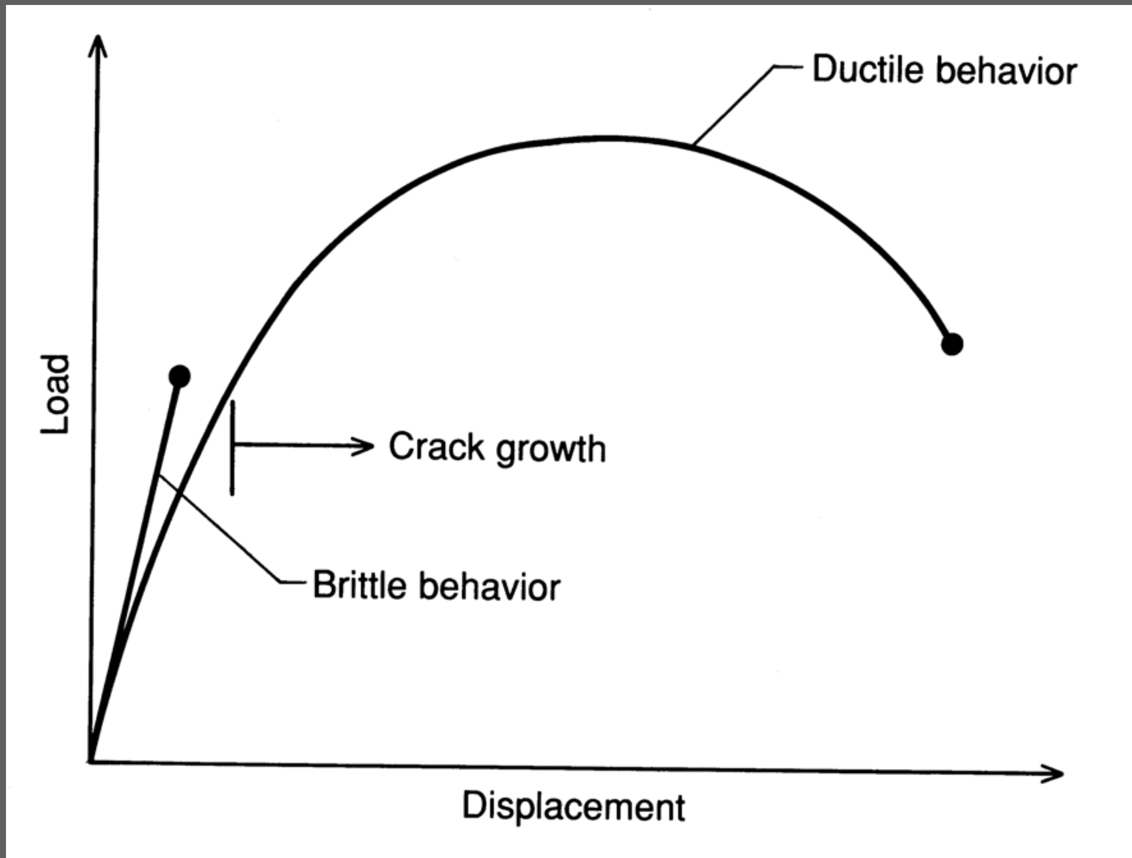
- Overview of fracture
- Linear elastic fracture mechanics (LEFM)
- Elastic-plastic fracture mechanics (EPFM)
- High temperature time dependent fracture mechanics (HTTDFM)

Overview of fracture

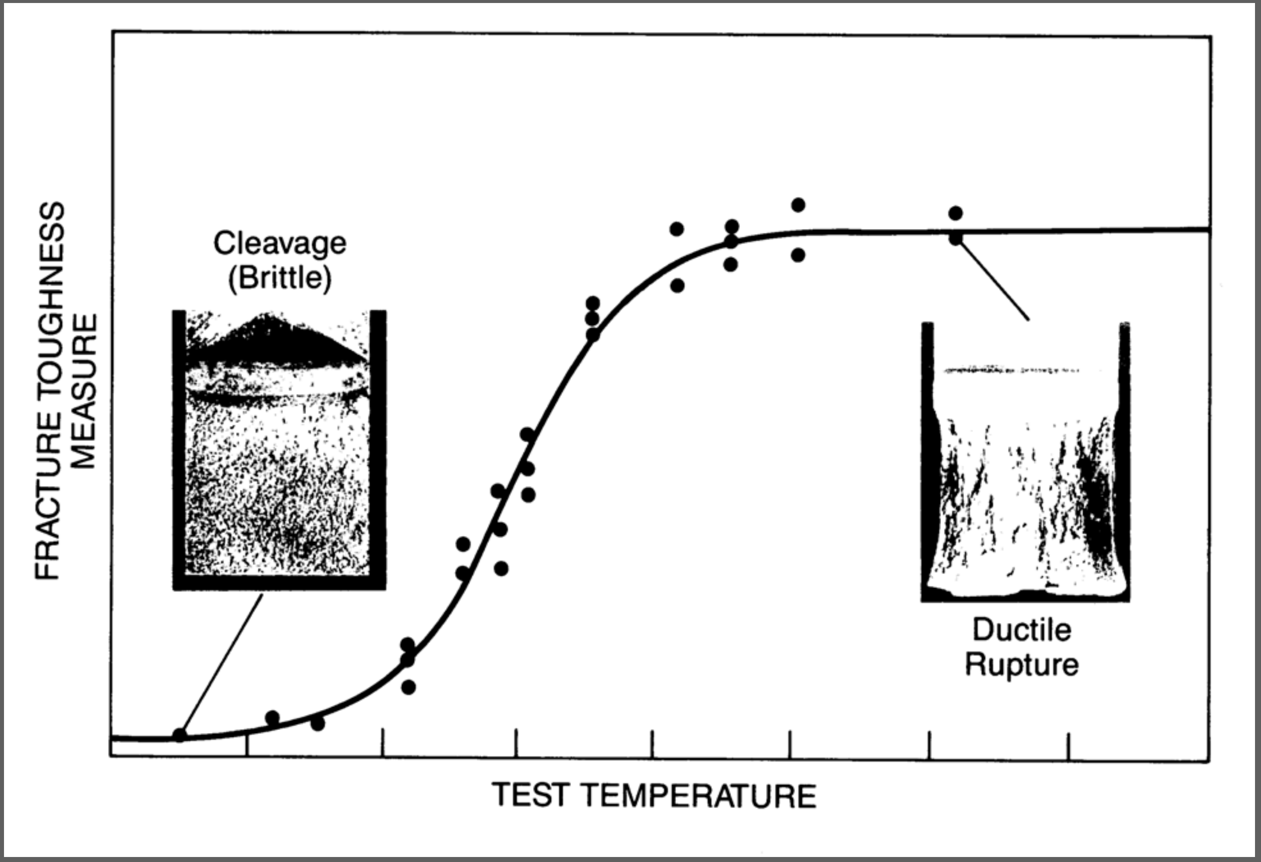
Fracture

- Fracture is a deformation process whereby regions of a material body separate and load-carrying capacity decreases significantly approaching zero
- 3 different levels of definition:
  - Macro dimensions (on the order of a visual crack in a body, $\simeq$ 1 mm); movement of a crack from area of stress and/or environmental concentration through the bulk material
  - Micro dimensions (on the order of metallic grain size, $\simeq$ 1 μm); passage of micro-crack through or around grains/imperfections
  - Nano dimensions (on the order of atomic dimensions, $\simeq 10^{-3}$ μm); breaking of atomic bonds across a fracture plane creating a new surface

Brittle vs. Ductile Fracture



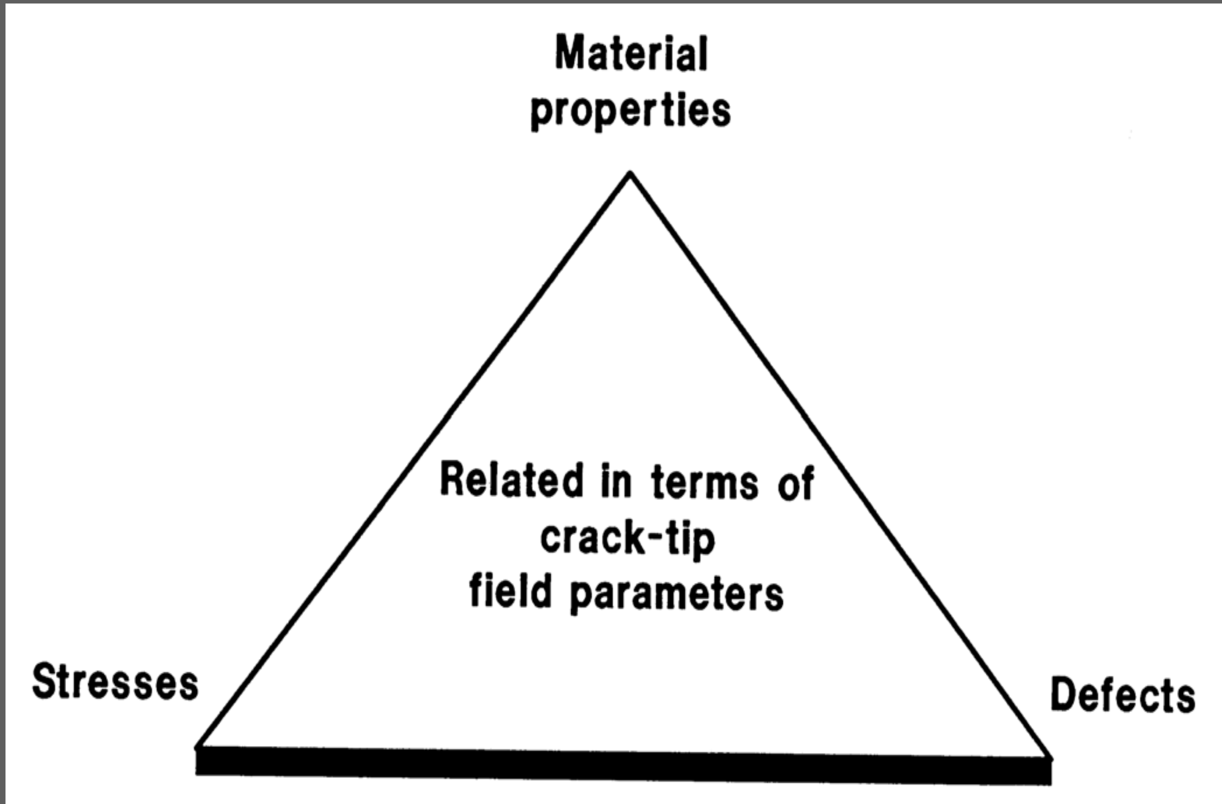
Brittle Cleavage Progressing to Ductile Rupture Fracture in Ferritic Materials



Fracture Mechanics

- Fracture is defined when the applied loading of a cracked body (crack driving force) exceeds the material's resistance to failure (fracture toughness)
- Fracture toughness is a material property for a given material condition
- Crack driving force is a function of the applied stresses, the size of the crack in the subject body, and body geometry factors

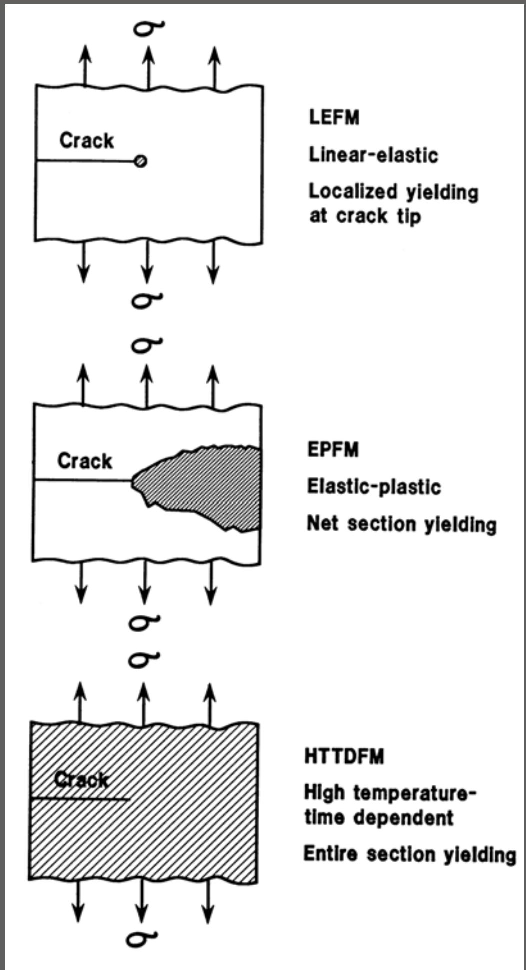
Link Between Material Toughness, Defects, and Stresses



Variables Affecting Material Fracture Toughness

- External and mechanical variables
  - Temperature
  - Loading rate
  - Environment (neutron irradiation, corrosive, etc.)
- Material variables
  - Chemical composition/impurities
  - Heat treatment
  - Microstructure
  - Strength level
  - Fabrication (welding method, rolling practice, etc.)
  - Time-temperature metallurgical changes (temper embrittlement)

General Categories of Fracture Mechanics of Cracked Bodies

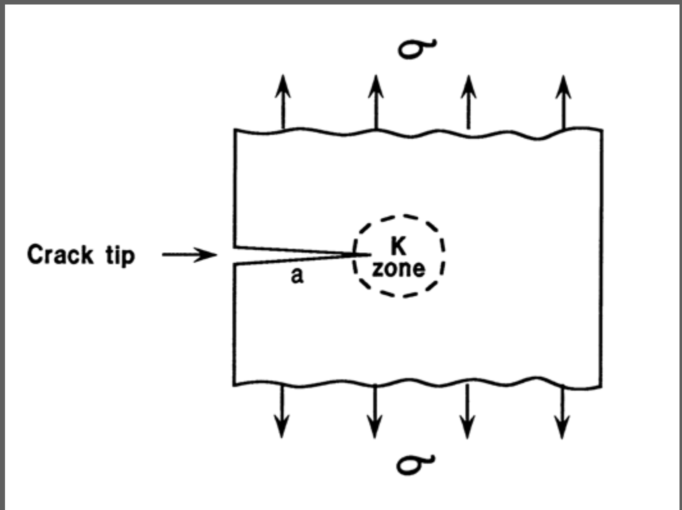


Defect Tolerant Structural Integrity

- Based on use of fracture mechanics to assure that no failures will occur
- Requires knowledge of:
  - Initial defect size(s) – NDE capabilities
  - Consideration of crack growth – cyclic and/or environmental
  - Global stresses acting on the cracked body (structure), including residual stresses
  - Geometric localized considerations near the crack
  - Material fracture toughness

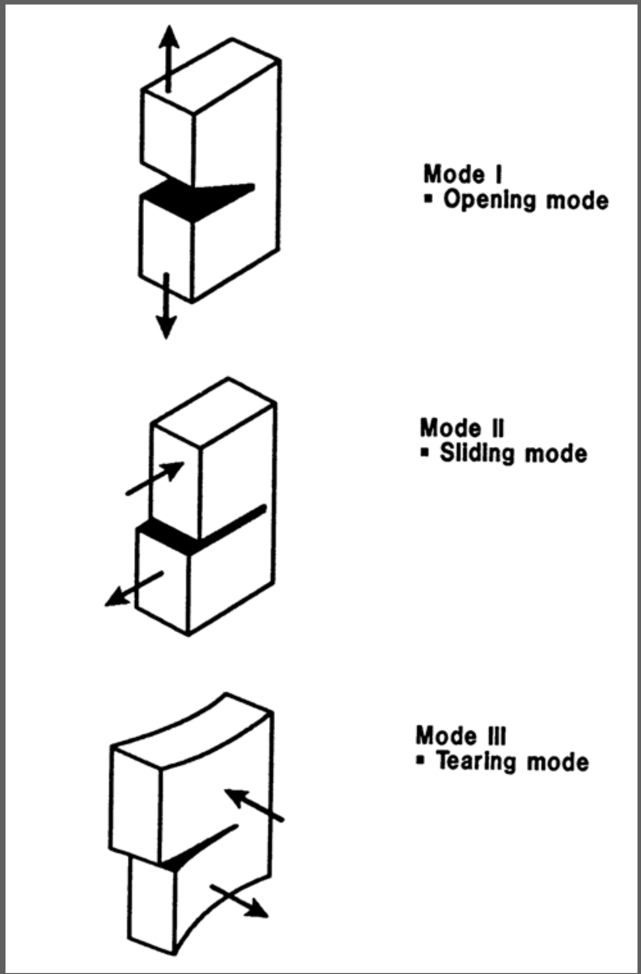
Linear elastic fracture mechanics (LEFM)

Basis of LEFM

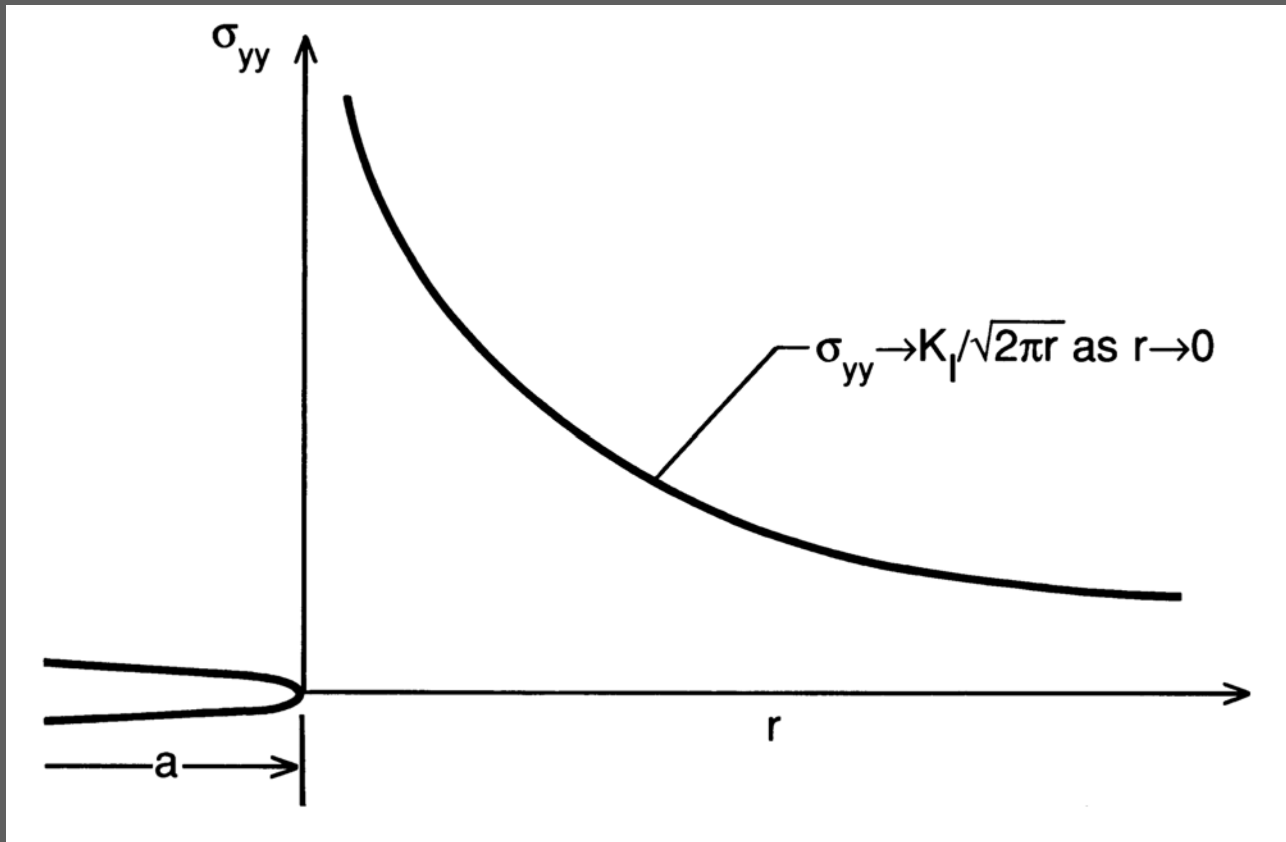


- K is the stress intensity factor (MPa-m$^{1/2}$)
  - Defines magnitude of intensification of elastic stresses at the crack tip using a unique singularity term
  - $K = f\,[\sigma\, a^{1/2}\, \mathcal{G}]$
    - Externally applied load (σ)
    - Crack length (a)
    - Geometry of cracked body and load application ($\mathcal{G}$)
- Crack initiation occurs if applied K is greater than the material toughness (K_{Ic})

Modes of Crack Extension

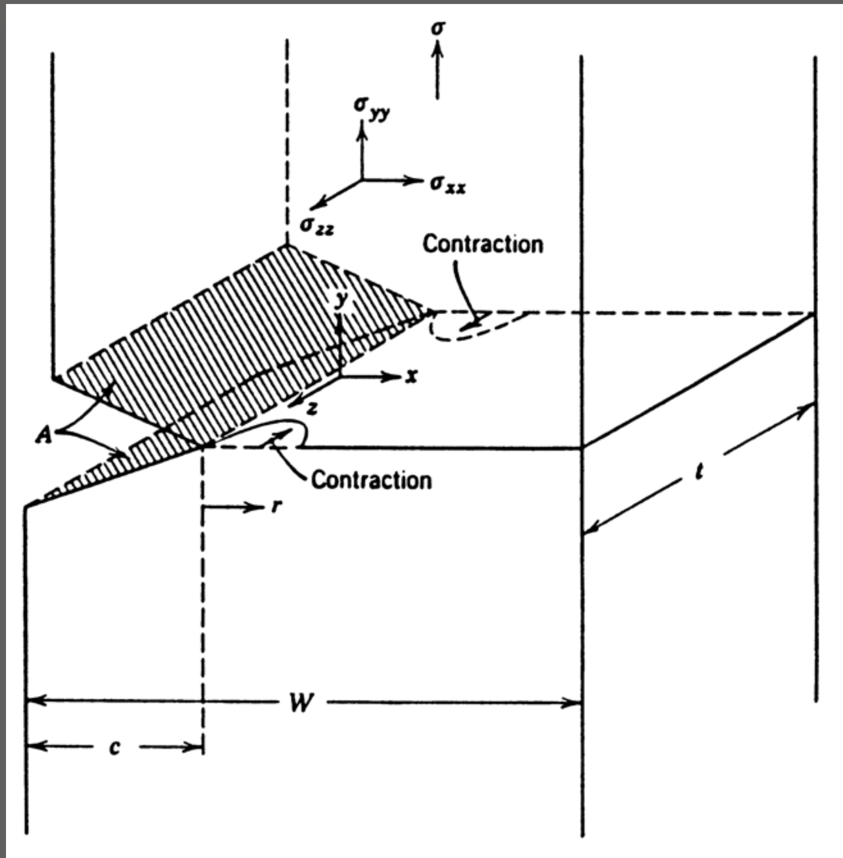


Mode I Loading Local Tensile Stress (σ_{yy}) Ahead of Crack Tip

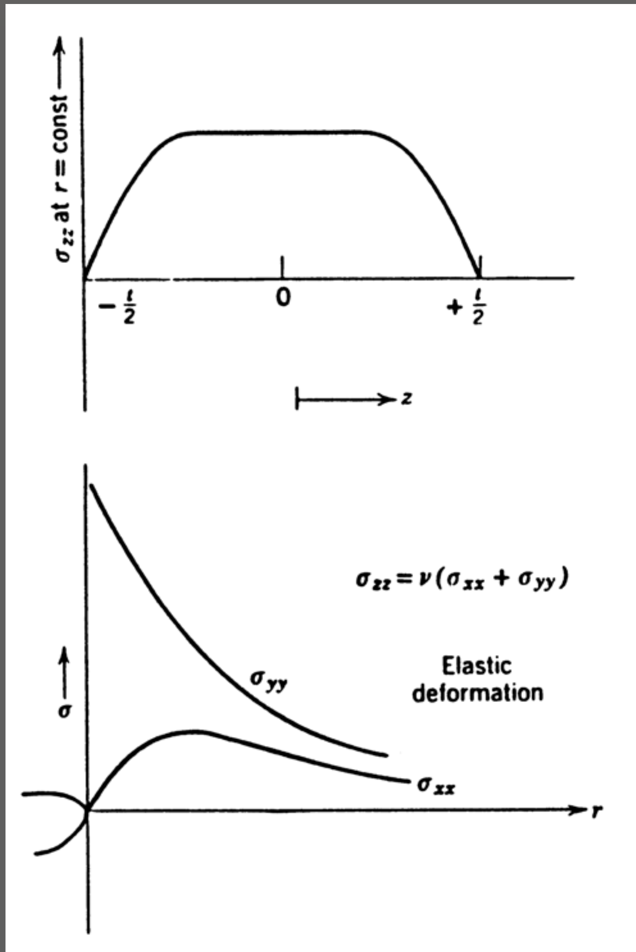


Local Conditions Ahead of the Crack

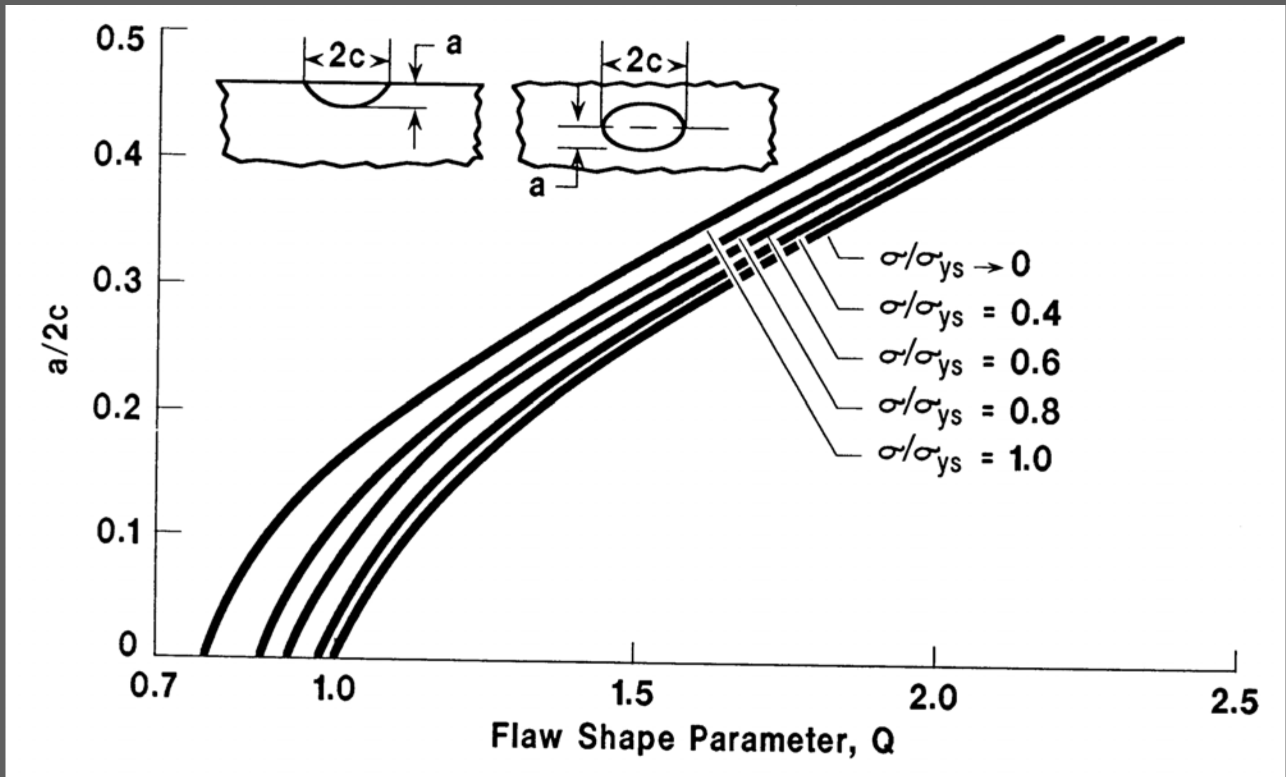
- Transverse contractions are opposed by unyielding faces of fatigue crack area resulting in transverse stresses σ_{xx} and σ_{zz} ahead of the crack
- Plane strain is when $\varepsilon_{zz} = 0$
- Plane stress is when $\sigma_{zz} = 0$



Local Stresses Ahead of the Crack

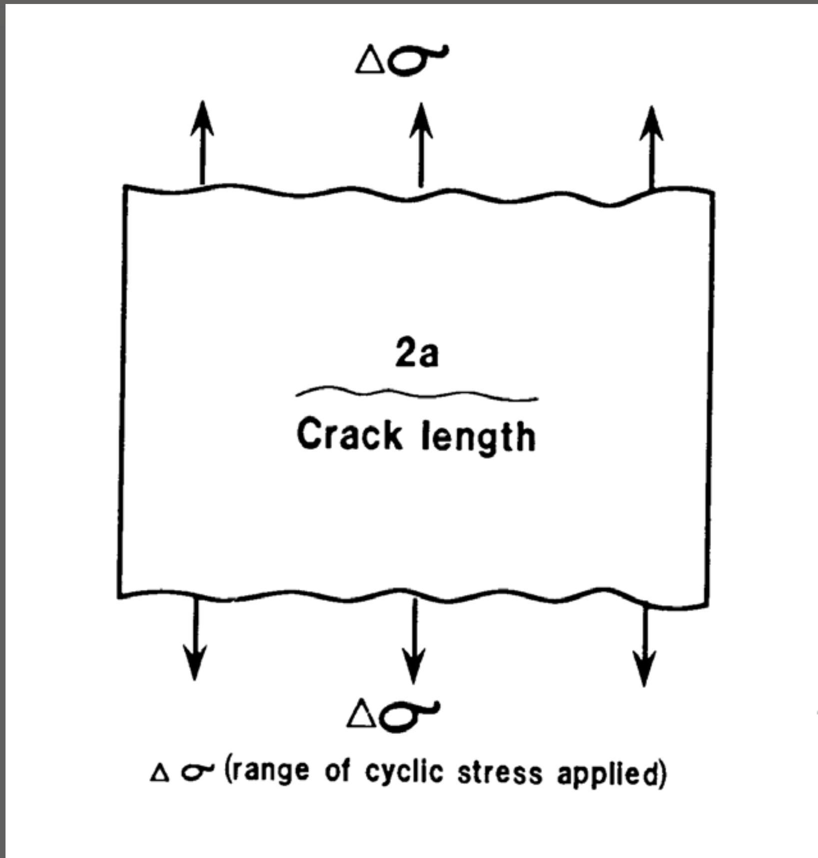


Flaw Shape Parameter for Surface and Internal Cracks



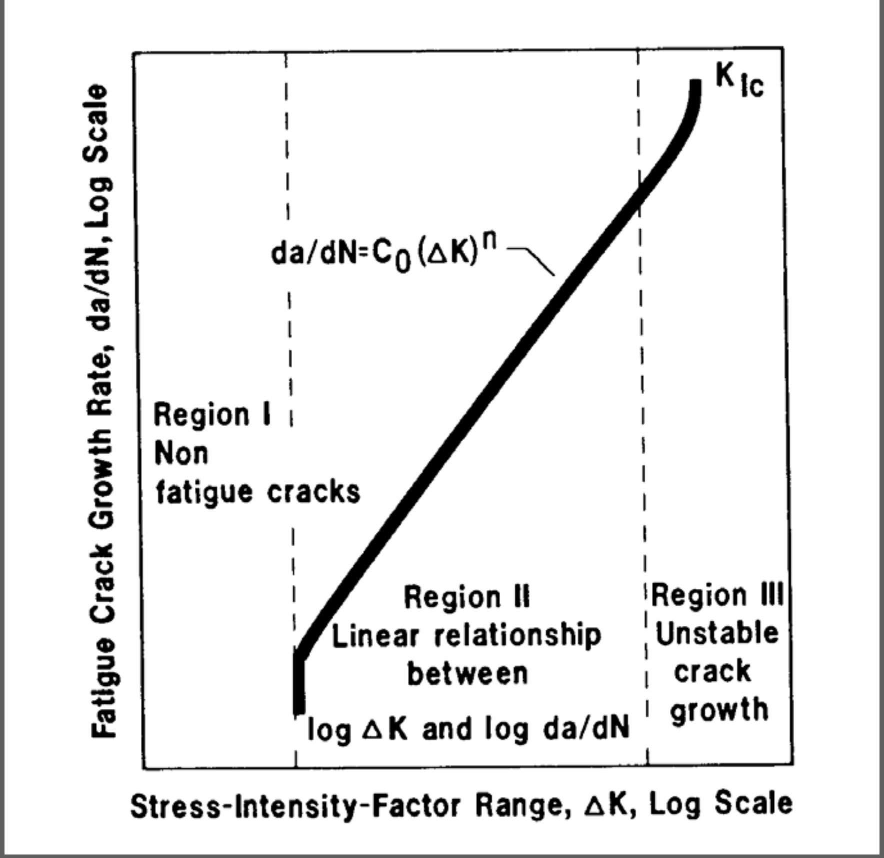
Surface Crack: $K = 1.1\,\sigma\,[\pi\,a / Q]^{1/2}$ Internal Crack: $K = \sigma\,[\pi\,a / Q]^{1/2}$

Fatigue Crack Growth

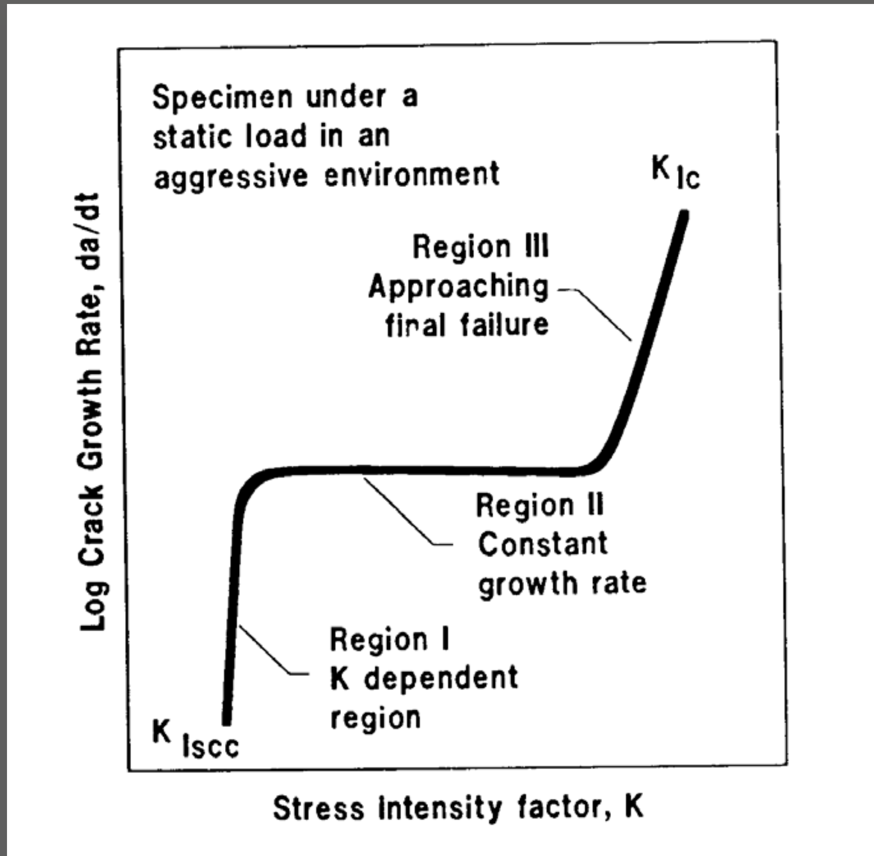


$$\Delta K_I = \Delta \sigma [\pi a]^{1/2}$$

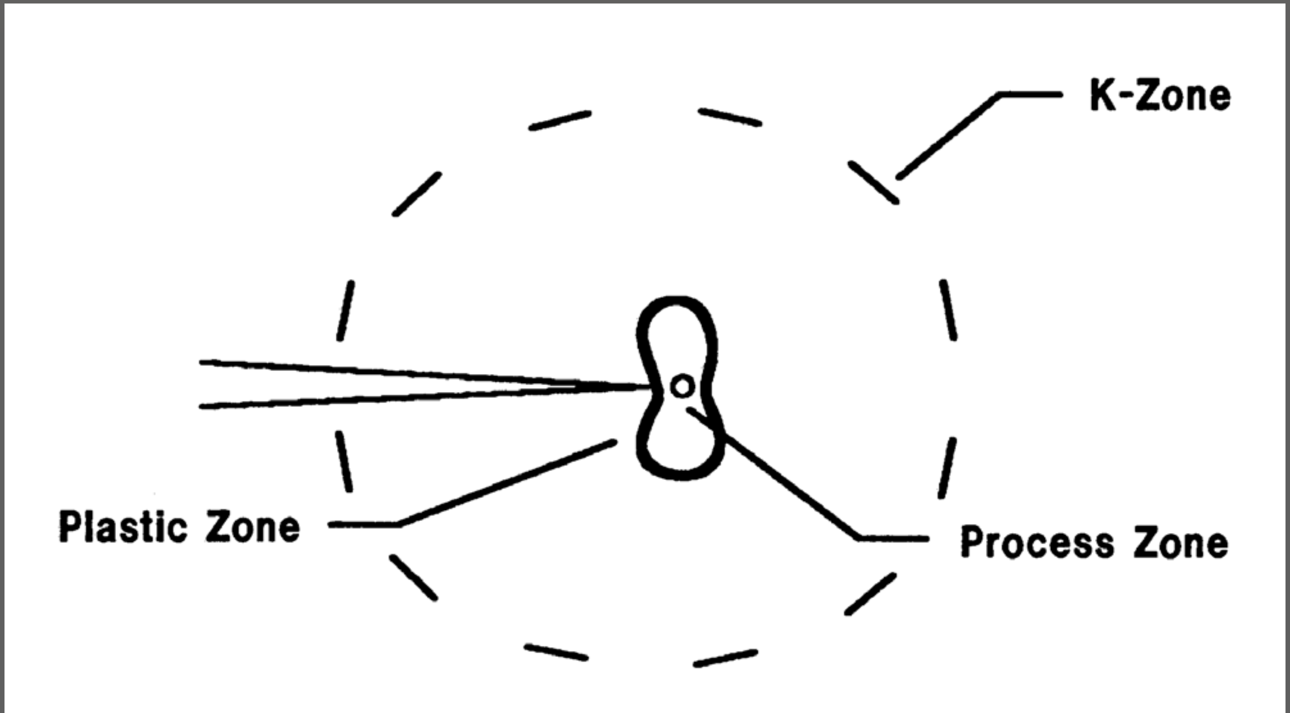
Fatigue Crack Growth in Non-Hostile Environment



Stress Corrosion Cracking



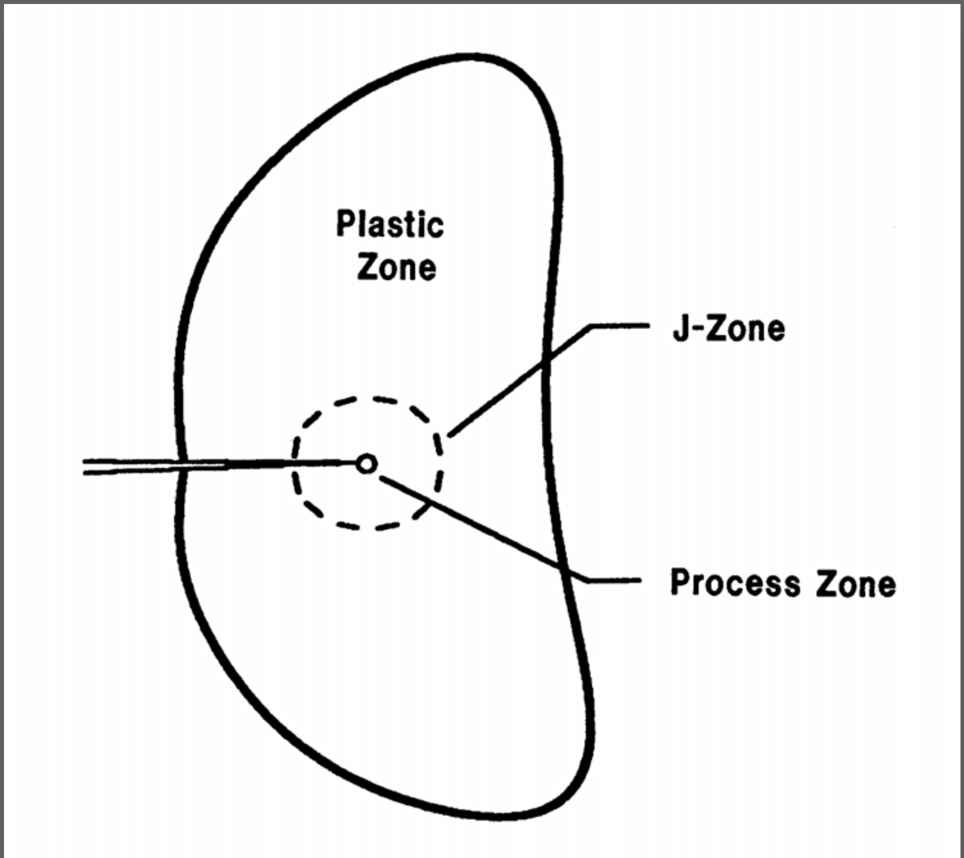
Small-Scale Yielding Conditions Approximating LEFM



For plane strain conditions, the plastic zone size (r_y) can be approximated as: $r_y = [1 / 6 \pi] [K_I / \sigma_{ys}]^2$

Elastic-plastic fracture mechanics (EPFM)

EPFM Involves a Larger Plastic Zone Size



$$\sigma_{yy} = \sigma_o \left[E J / \sigma_o^2 r \right]^{n/(n+1)} \text{ as } r \rightarrow 0$$

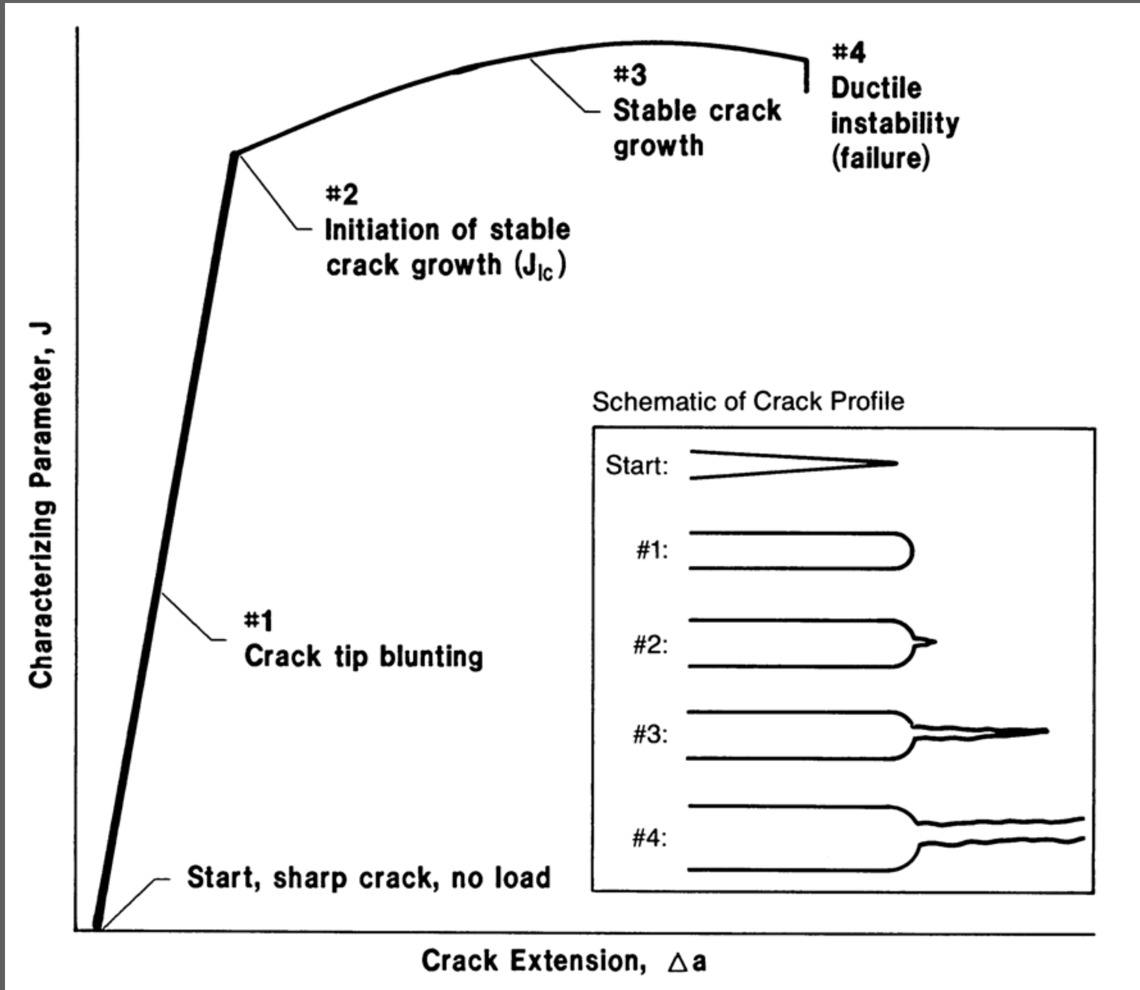
Generalizations for EPFM vs. LEFM

EPFM	LEFM
Beyond small-scale yielding	Small-scale yielding applies
Lower strength materials	High strength materials
Tough, ductile materials	Brittle materials
Small thickness	Large thickness
Plane stress	Plane strain
High temperatures	Low temperatures
Slow loading rates	High loading rates
Mechanical freedom	Mechanical restraint

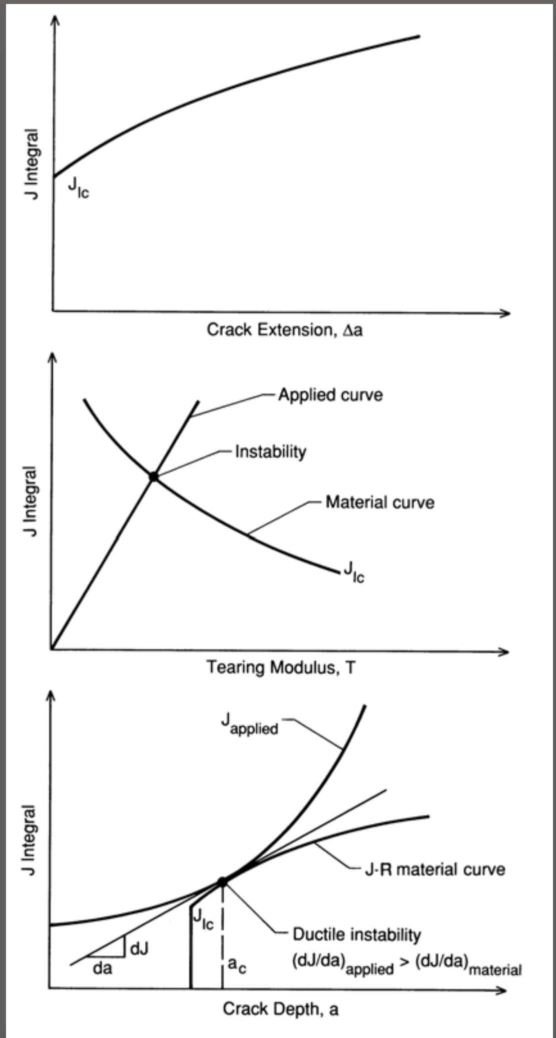
Ductile Fracture Process (J-Resistance Curve)

J_{Ic} is the initiation value of J and can be equated to an equivalent value of K: $K_{Jc} = [\ E' J_{Ic}\ ]^{½}$

E' is Young's Modulus (E) for plane stress or $E / (1 - \nu^2)$ for plane strain



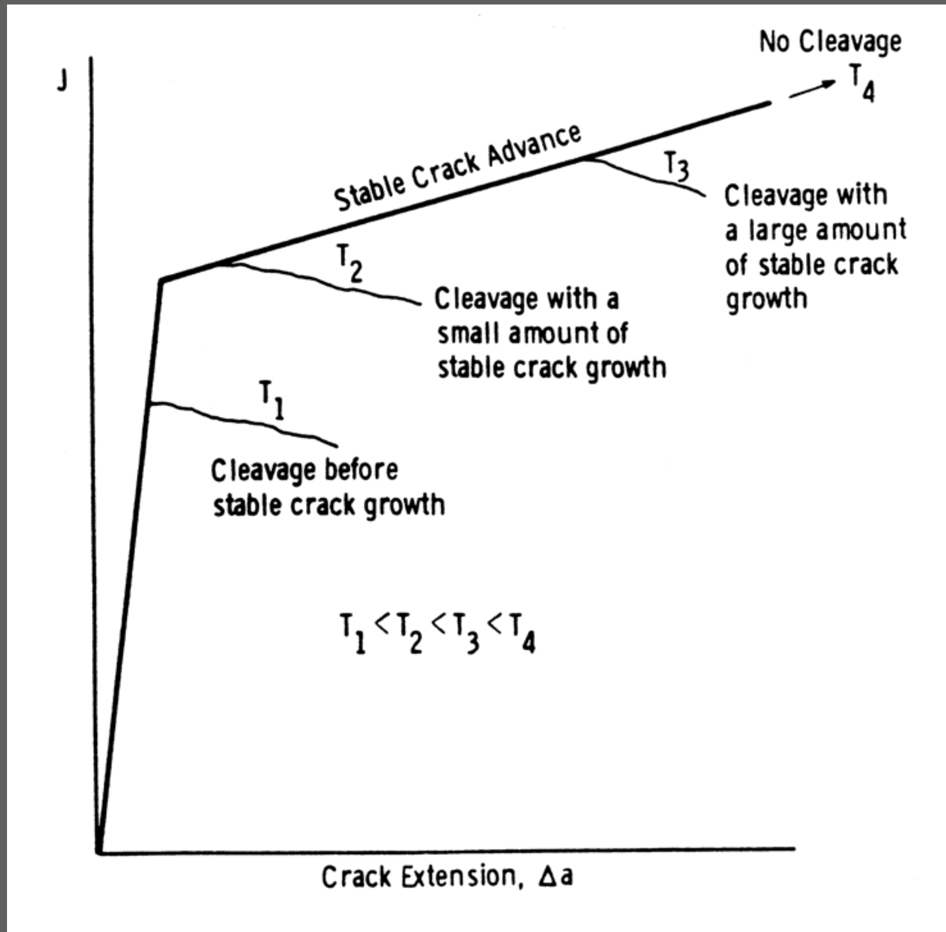
Characterizing Ductile Crack Growth and Instability



- J-Δa curve is termed the J-resistance or J-R curve
- Slope of J-R curve is converted to the Tearing Modulus (T):

  $T = [\, dJ / da \,] [\, E / \sigma_o^2 \,]$
- Ductile instability occurs when the applied T is reaches the material T

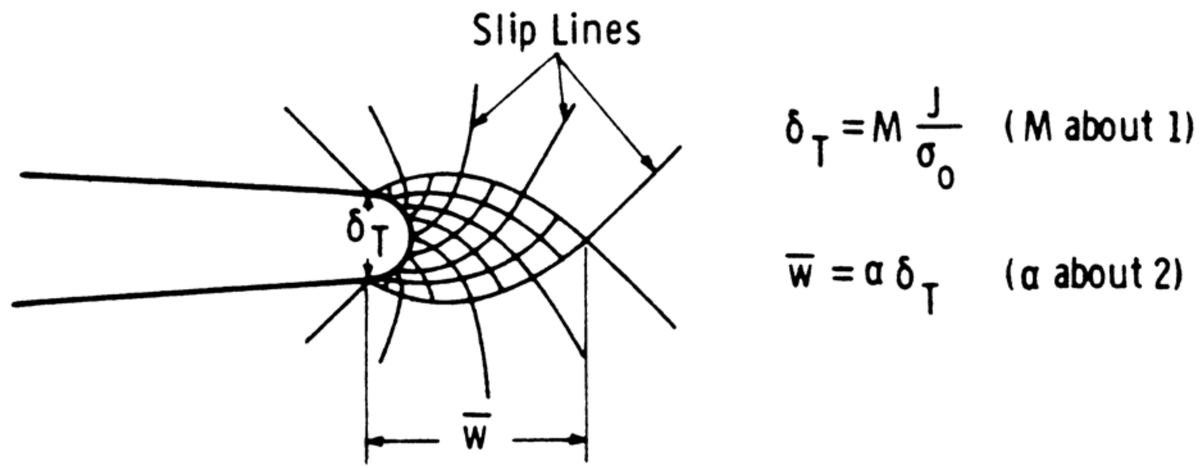
Stable Crack Growth Can Be Interrupted by Cleavage



Other EPFM Parameters

- Crack opening displacement at the crack tip (CTOD)
- Crack opening angle (COA)
- Crack tip force
- Crack tip work, similar to G
- Energy supplied to fracture process zone
- Multi-parameter characterization
- Failure Assessment Diagram

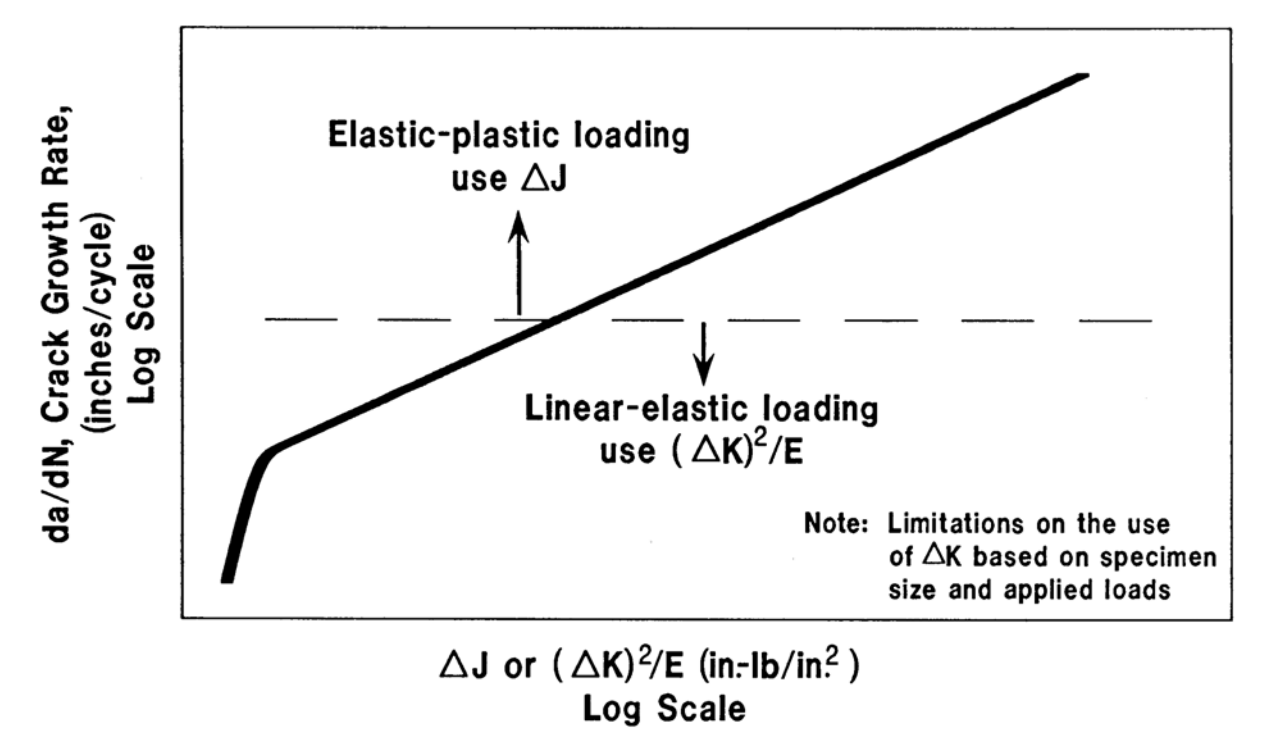
Crack Tip Opening Displacement



Crack tip parameter, CTOD (δ_T)

J-integral and CTOD are directly related

EPFM Fatigue Crack Growth



High temperature time dependent fracture mechanics (HTTDFM)

High Temperature, Time-Dependent Fracture

- Time derivative of J called C* has been used to characterize the rate of crack growth under steady-state creep conditions
- $C^* = \sigma\, a\, [d\varepsilon / dt]\, \mathcal{H}$

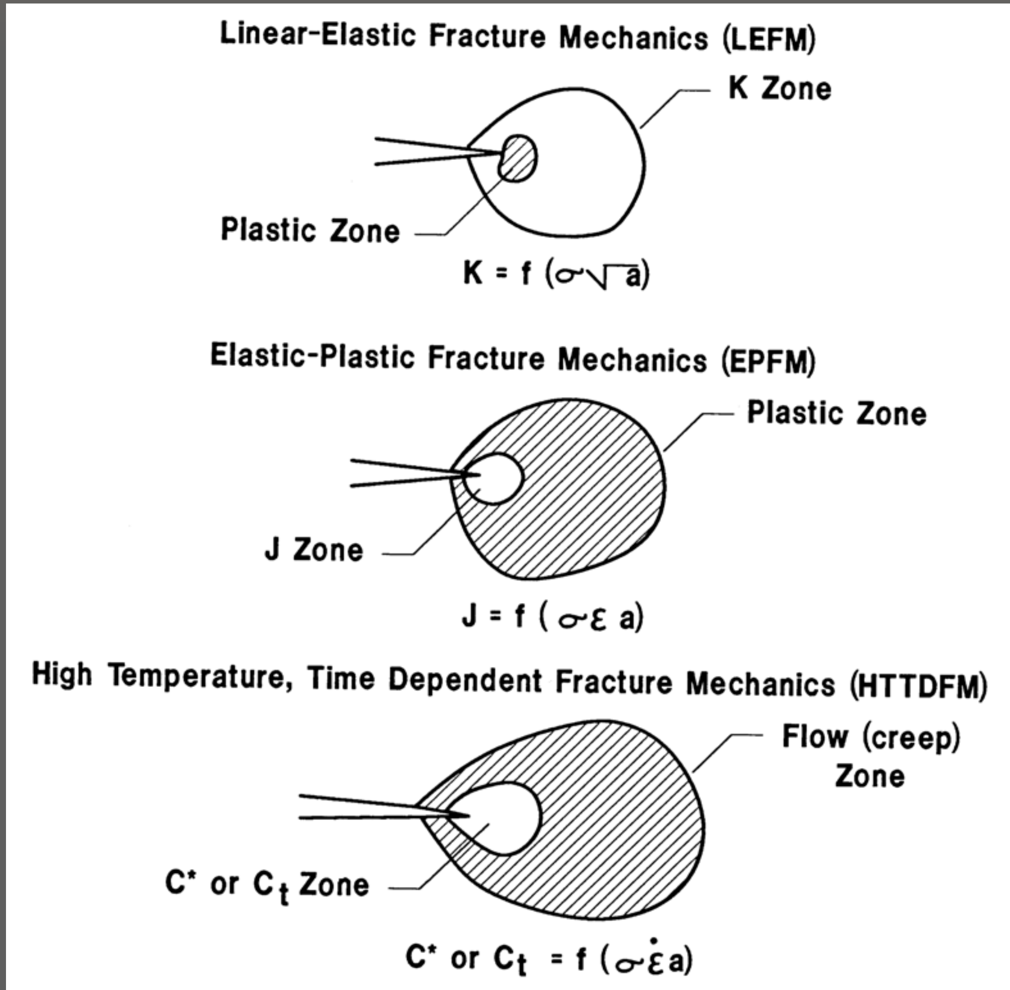
  σ is the nominal stress

  a is the crack depth

  $d\varepsilon / dt$ is the strain rate

  $\mathcal{H}$ is a function of geometry and the creep exponent, n
- Prior to steady-state, crack tip stresses are controlled by C_t, which varies with time; as time increases, C_t approaches C*

Summary of Crack Tip Characterization Parameters

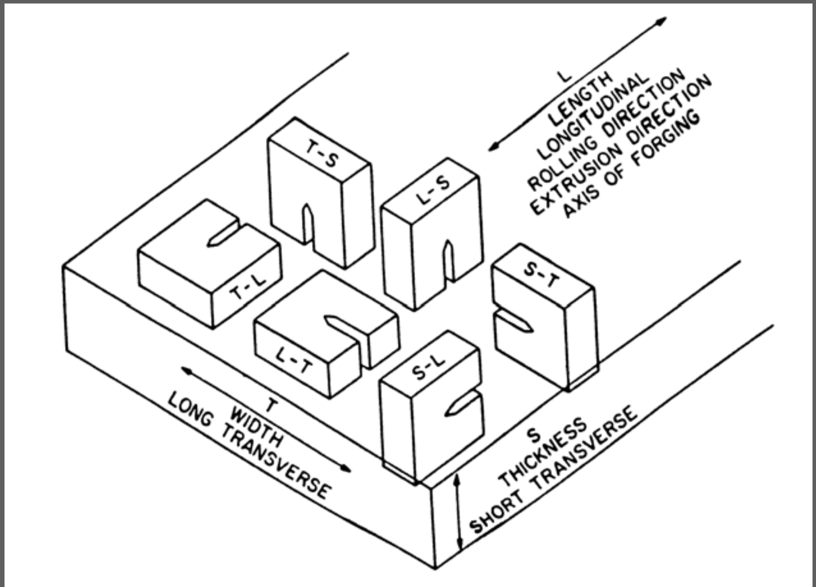


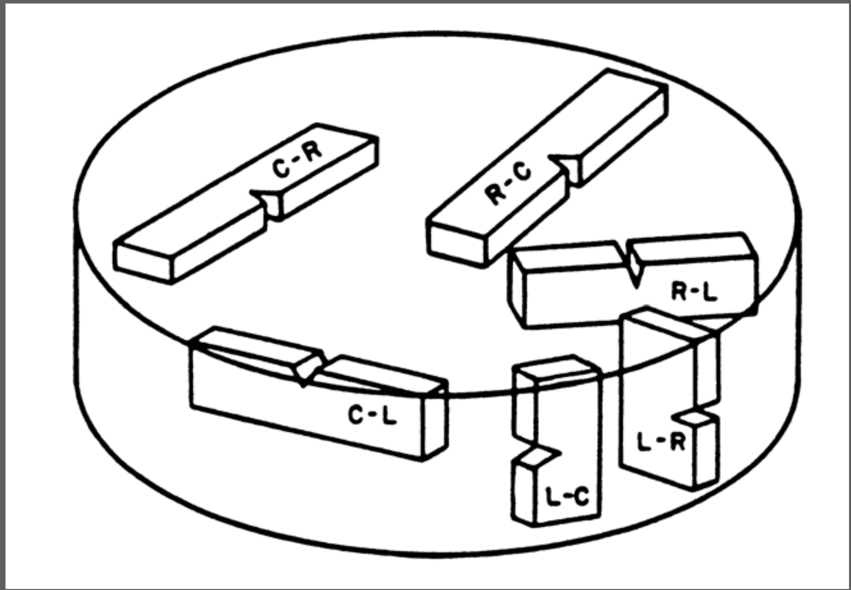
Measurement and application of fracture toughness

LEFM Parameters and Test Methods

Parameter	Characterizes	Comments	ASTM Test Method
K_{Ic}	Plane strain, brittle fracture toughness	Material property, static & dynamic	E 399-09, E 1820-08a (unified)
K_{Ia}	Plane strain, crack arrest toughness	K_I when running crack is arrested	E 1221-06
K_{ISCC}	Threshold for SCC propagation	Sustained loading and environment	E 1681-03 (2008)
da/dt vs. K	Growth rate for SCC	Sustained loading and environment	Under development
ΔK_{th}	Fatigue crack growth threshold	Region I crack growth	Under development
da/dn vs. ΔK	Fatigue crack growth rates	Region II crack growth	E 647-08

Specimen Orientation is Important

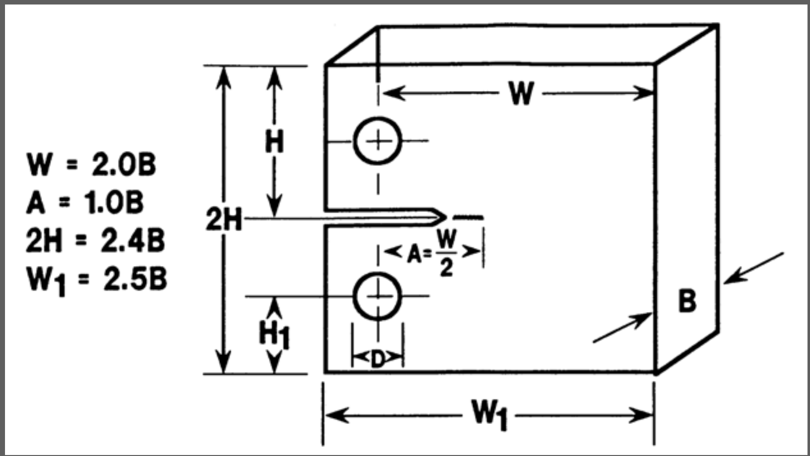




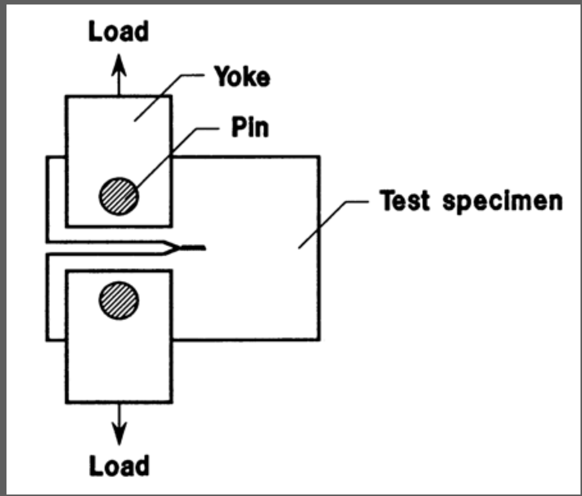
Plates

Forgings

Measurement of Plane Strain Fracture Toughness

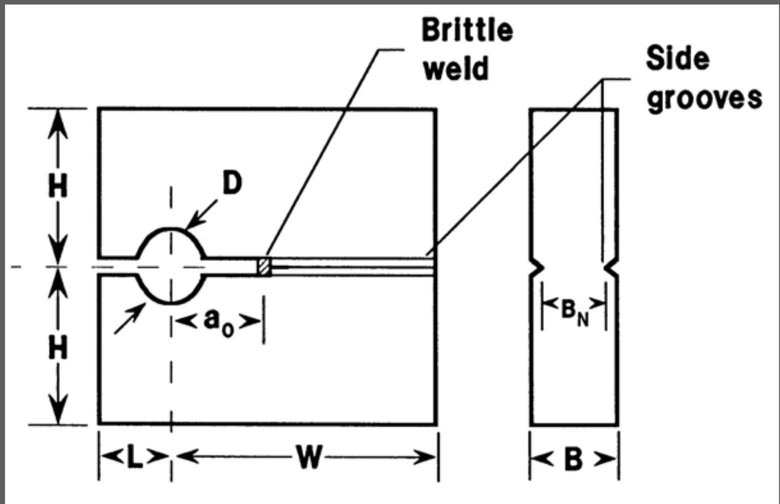


Compact Tension Specimen

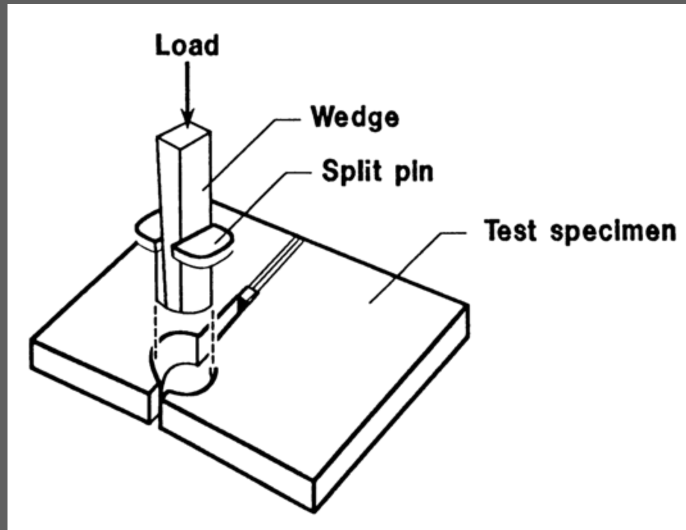


Loading Arrangement

Measurement of Crack Arrest Toughness

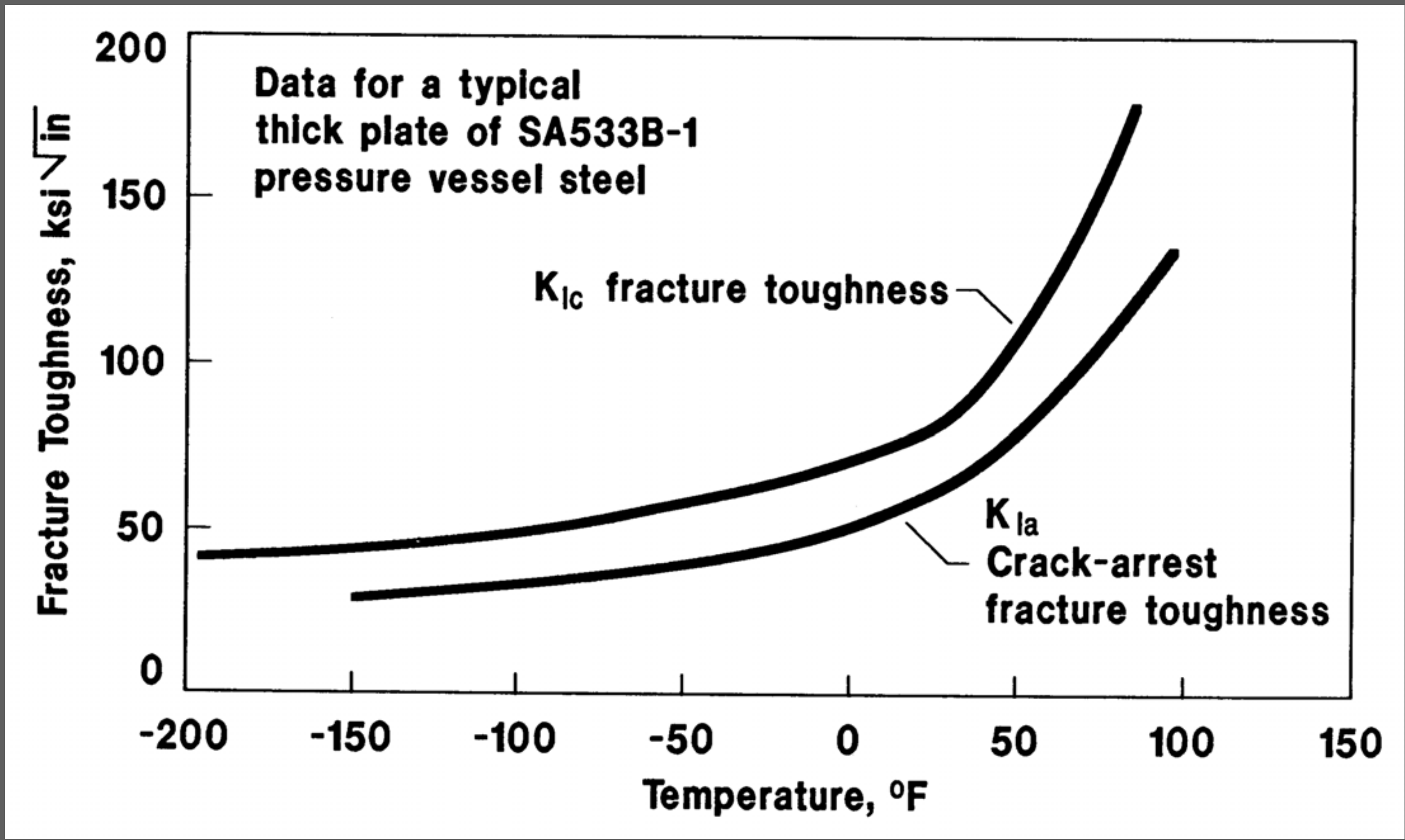


Compact Crack Arrest Specimen

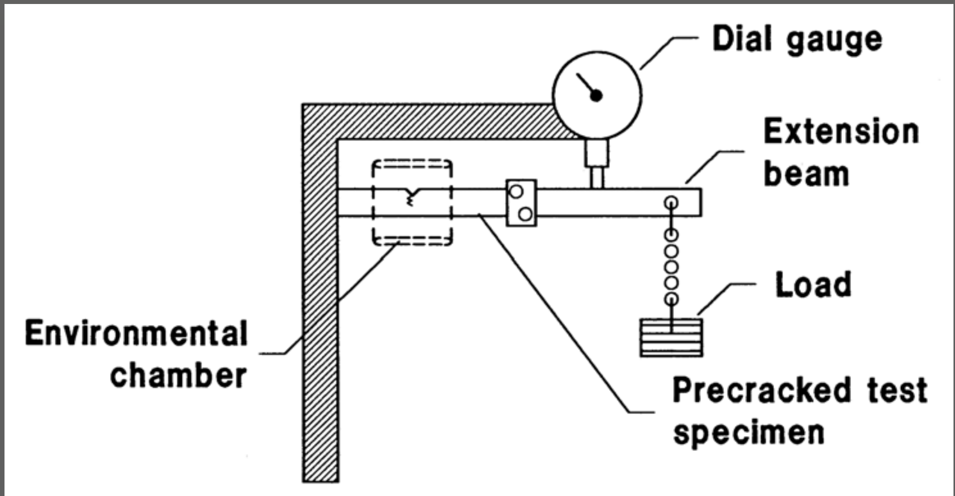


Split Pin Loading

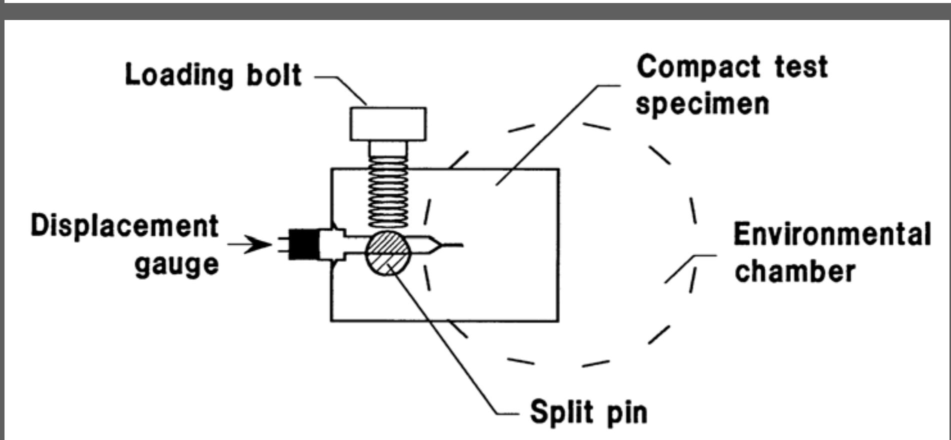
Comparison of Static K_{Ic} and Crack Arrest K_{Ia} Results



Measurement of Threshold K_{ISCC}

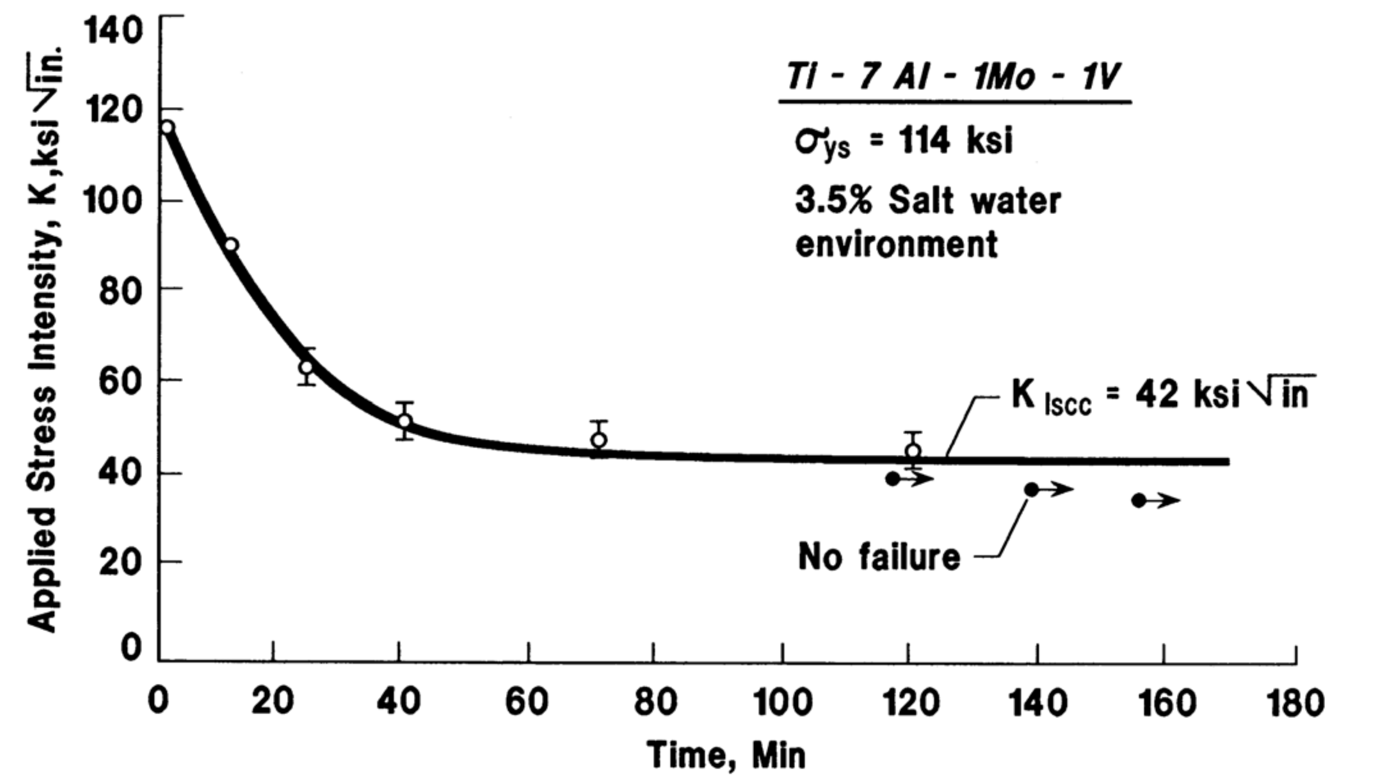


Constant load, cantilever bend test

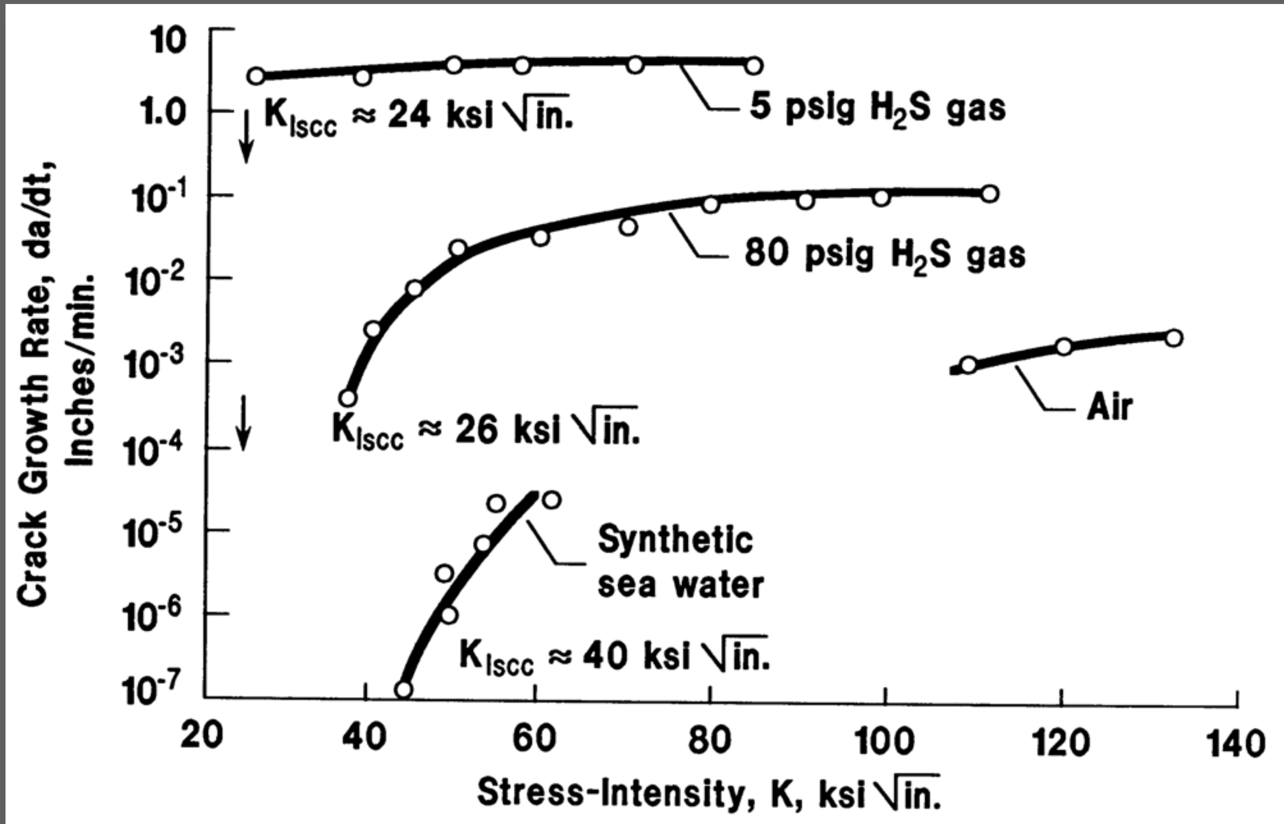


Constant deflection, bolt-loaded compact test

K_{Iscc} Results from Cantilever Bend Tests



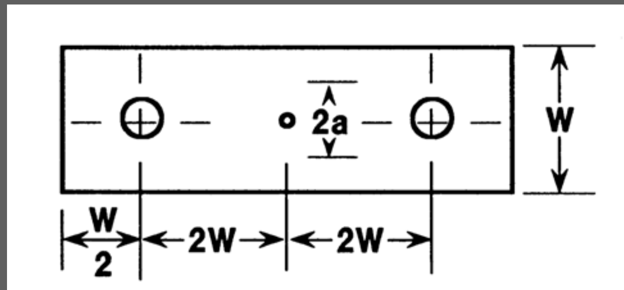
Static Load Crack Growth Rate



4340 Steel: σ_{ys} = 180 ksi; K_{Ic} = 140 ksi-in$^{1/2}$

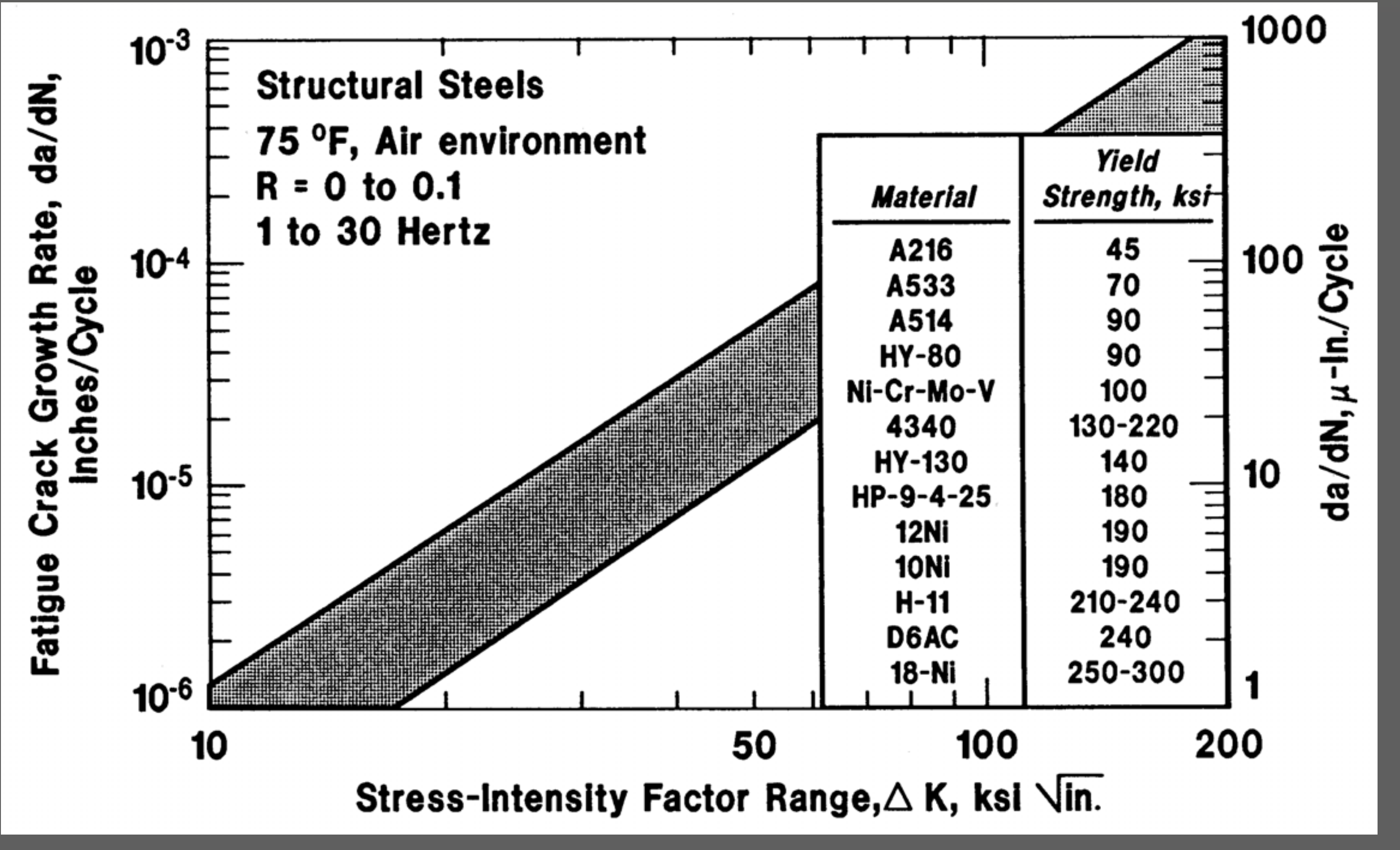
Measurement of Fatigue Crack Growth Rate

- Most common specimen types are compact tension (CT) and center-cracked-tension (CCT)
- Recommended thickness (B) for both specimen types is (W/20) $\leq$ B $\leq$ (W/4)
- ΔK_{th} test methods are not standardized; primarily applicable to Region II fatigue



CCT specimen

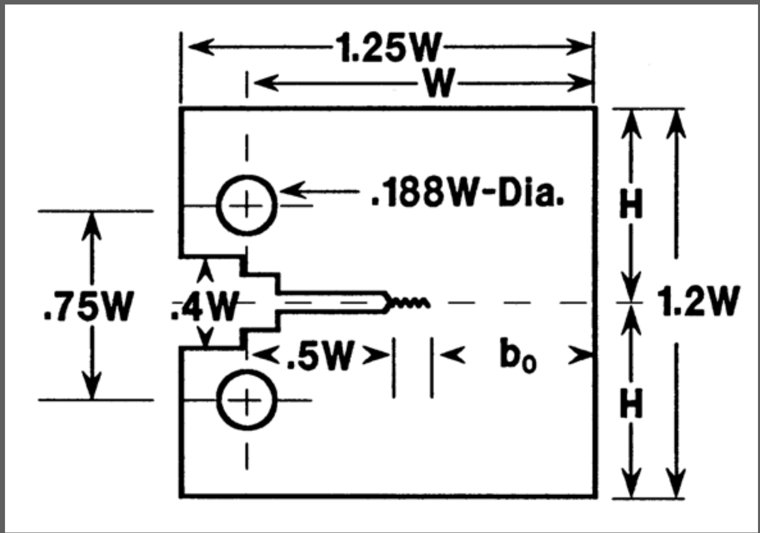
Fatigue Crack Growth Data for Structural Steels

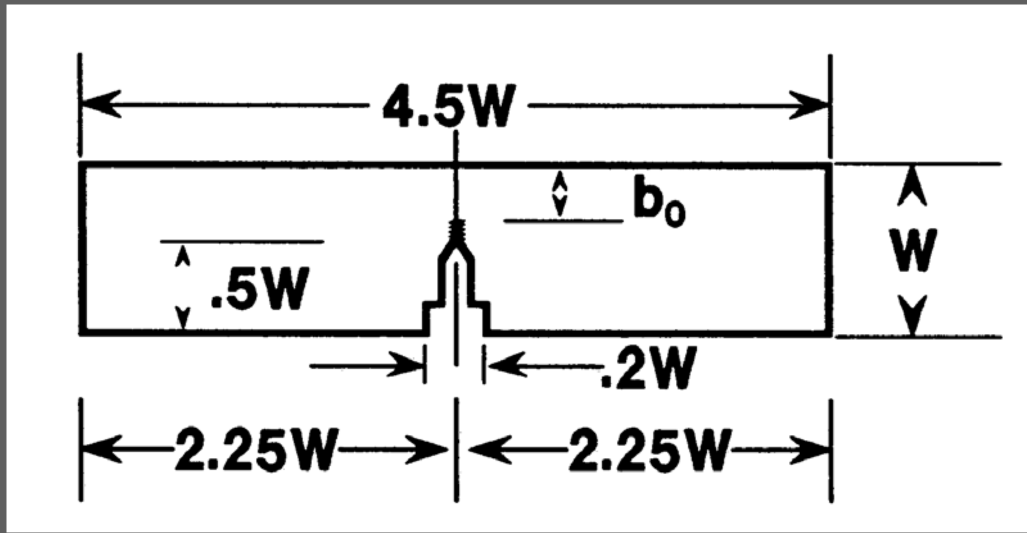


EPFM Parameters and Test Methods

Parameter	Characterizes	Comments	ASTM Test Method
J_{Ic}	Initiation J for ductile crack extension	Material property, static & dynamic	Old E 813, now E 1820-08a (unified)
J-R Curve	Resistance to stable, ductile crack growth	J-Δa under monotonic loading	Old E 1152, now E 1820-08a (unified)
T	Tearing modulus	$T = (dJ/da)\ E / \sigma_o^2$	Comes from J-R curve above
T_o	Ductile-cleavage transition temperature	Master Curve application	E 1921-09c
da/dn vs. ΔJ	Fatigue crack growth rates	Crack extension per cycle of ΔJ	Under consideration
da/dt vs. C* or C_t	Creep crack growth rate	High temperature, time-dependent	E 1457-07e2

Measurement of Ductile Initiation J_{Ic}

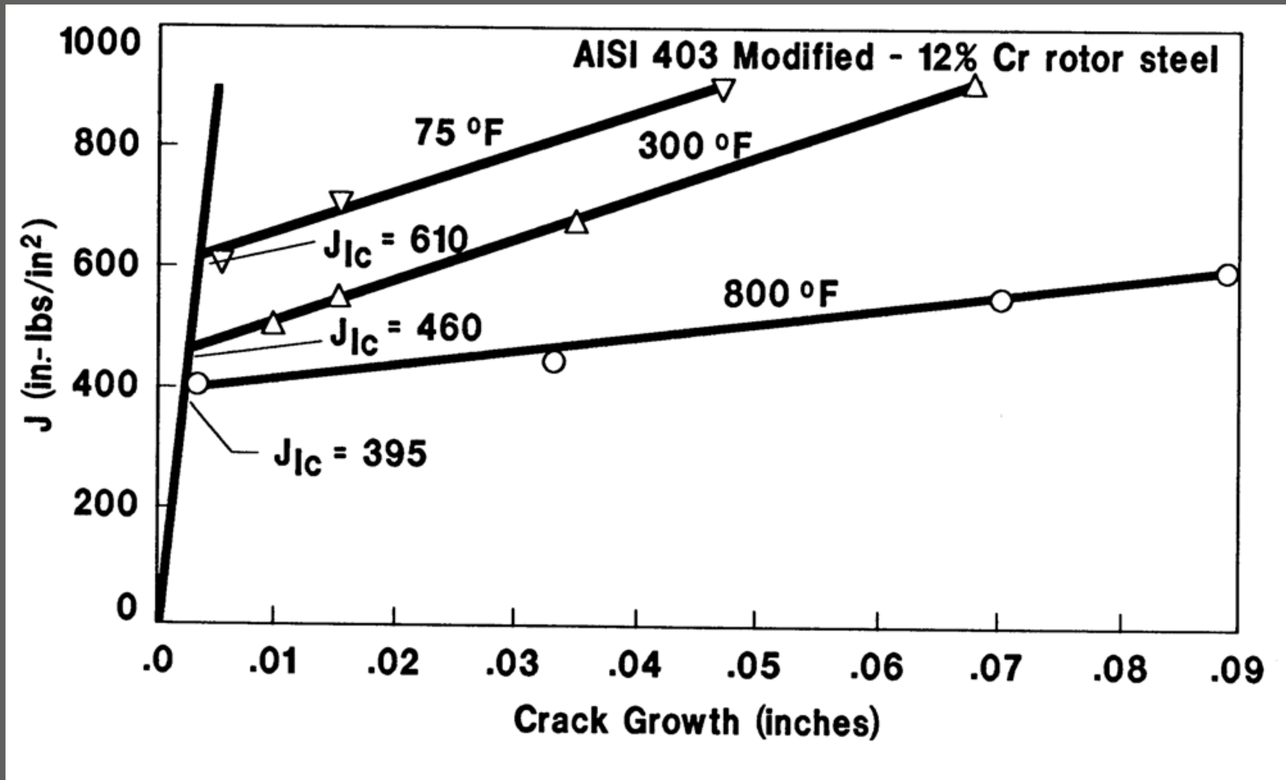




Modified Compact Tension and Three-point Bend Specimens

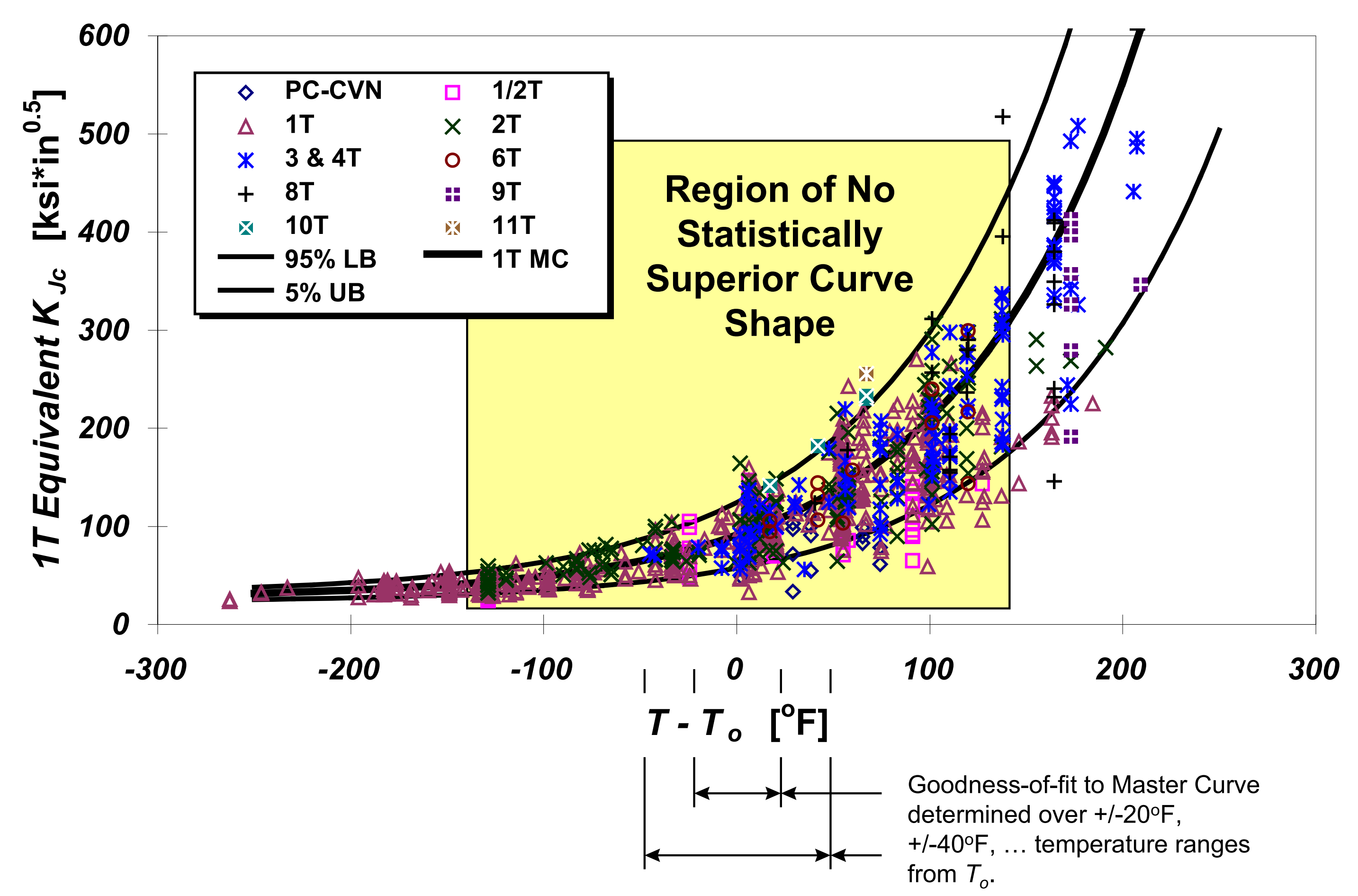
B is nominally 0.5W, but bend specimens with B=W are acceptable

Effect of Temperature on J_{Ic} and J-R Curve from Multi-Specimens



Most J-R curves are developed using unloading compliance or electric potential methods for measuring ductile crack growth

Cleavage Initiation J_{Ic} Used to Determine T_o via *Master Curve*



Definition of Master Curve

- T_o is temperature where median fracture toughness of 1T specimen equals 100 MPa√m (90.9 ksi√in)
- Using weakest link theory and Weibull statistics, the median value of K_{Jc} toughness ($K_{Jc(med)}$) is measured at a temperature or temperatures usually different from T_o
- Master Curve is used to determine T_o :

$$K_{Jc(med)} = 30 + 70 \exp [\, 0.019\, (T - T_o\,)],\ \text{MPa}\sqrt{m}$$

For single T $$T_o = T - (0.019)^{-1} \ln [(\, K_{Jc(med)} - 30\,) / 70\,],\ ^oC$$

Weibull Model Used for the Master Curve

- Three parameter Weibull model with two parameters fixed (P_f is the probability that any arbitrary test result of thickness B will produce a toughness $\geq K_{Jc}$):

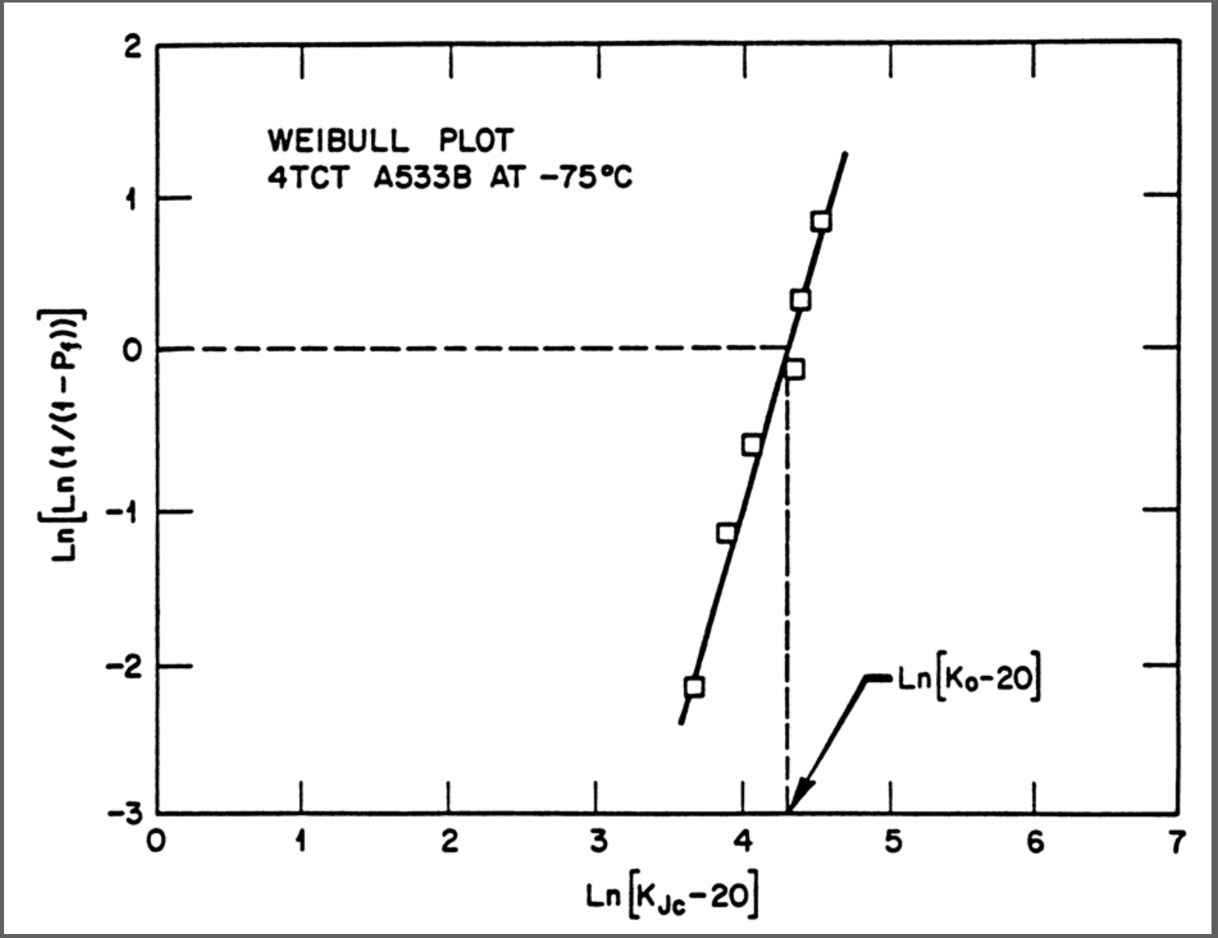
$$P_f = 1 - \exp\{-(B / B_o)\,[(K_{Jc} - K_{min}) / (K_o - K_{min})]^b\}$$

K_{min} is fixed at 20 MPa-m $^{1/2}$ and b is fixed at 4

B_o is the reference thickness chosen for normalization (typically 1T as in ASTM E 1921)

K_o is a scale parameter from a Weibull plot

Typical Weibull Plot Identifying K_o



Multi-Temperature Determination of T_0

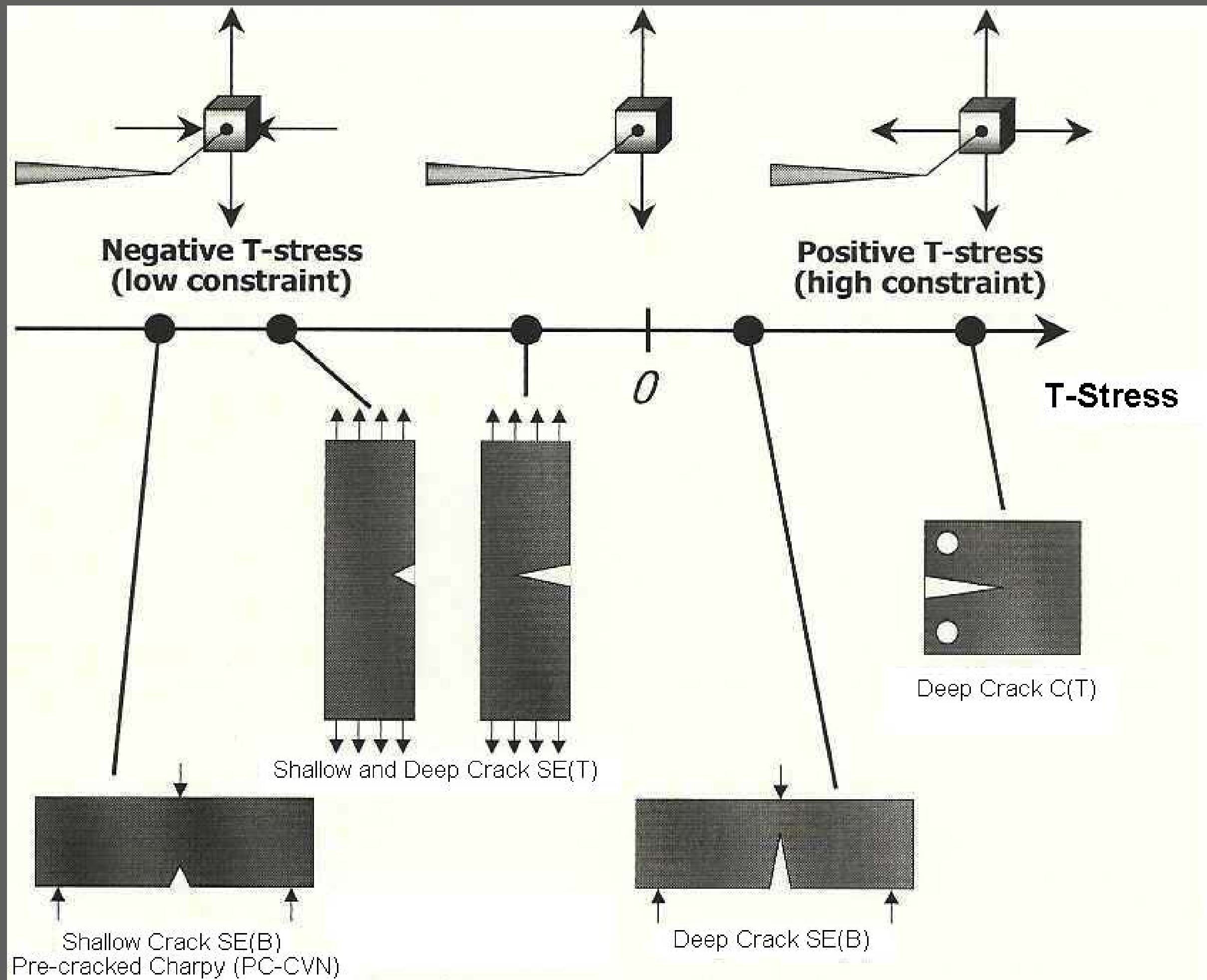
- T_0 is solved iteratively

$$\sum_{i=1}^{n} \frac{\delta_i \cdot \exp\{0.019 \cdot [T_i - T_0]\}}{11 + 77 \cdot \exp\{0.019 \cdot [T_i - T_0]\}} - \sum_{i=1}^{n} \frac{(K_{Jc\,i} - K_{min})^4 \cdot \exp\{0.019 \cdot [T_i - T_0]\}}{(11 + 77 \cdot \exp\{0.019 \cdot [T_i - T_0]\})^5} = 0$$

- Master Curve is defined as:

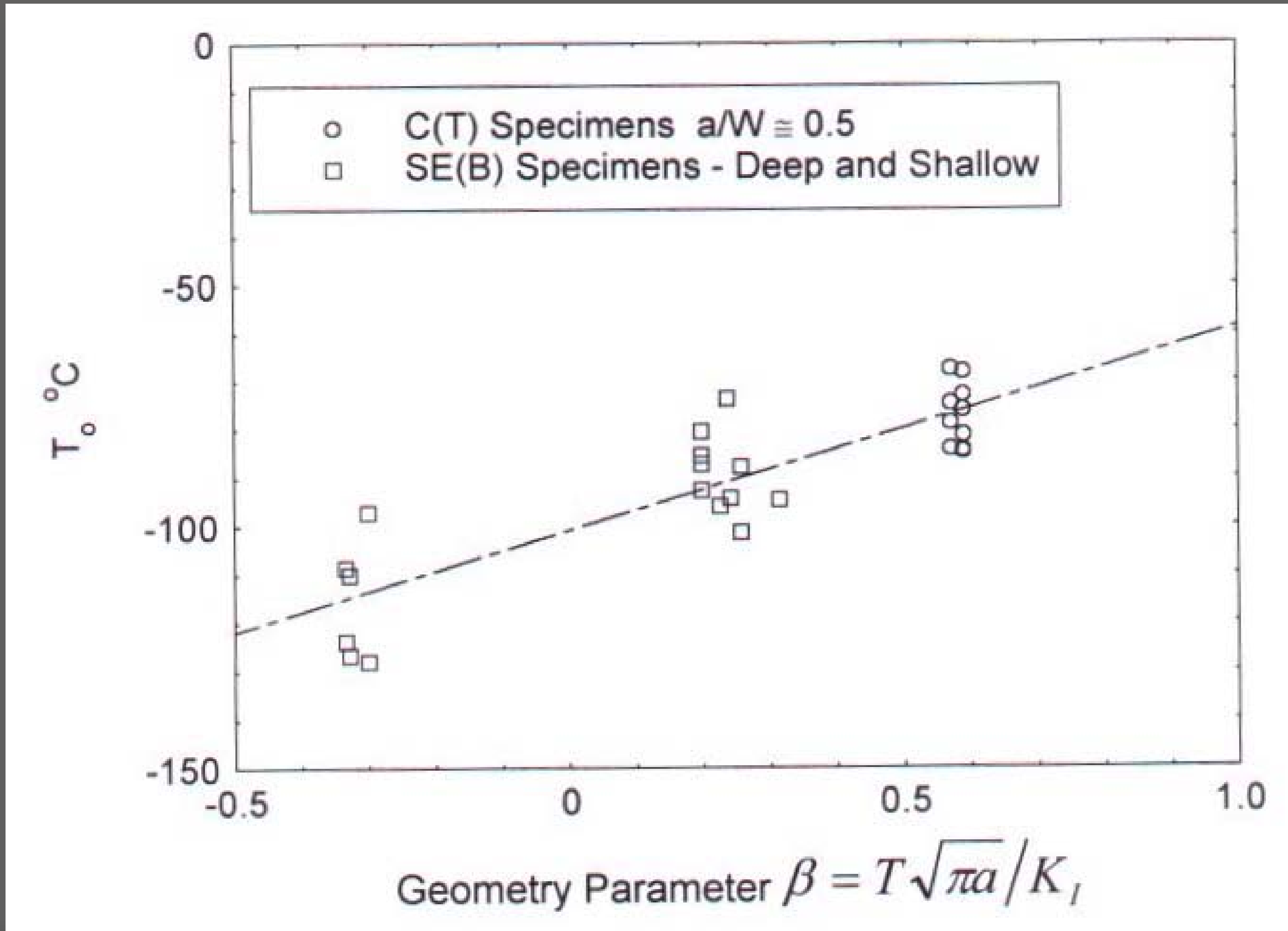
$$K_{Jc(0.xx)} = 20 + \left[\ln\left(\frac{1}{1 - 0.xx}\right)\right]^{1/4} \{11 + 77 \cdot \exp[0.019 \cdot (T - T_0)]\}$$

Effect of T-Stress on Specimen Crack Tip Loading

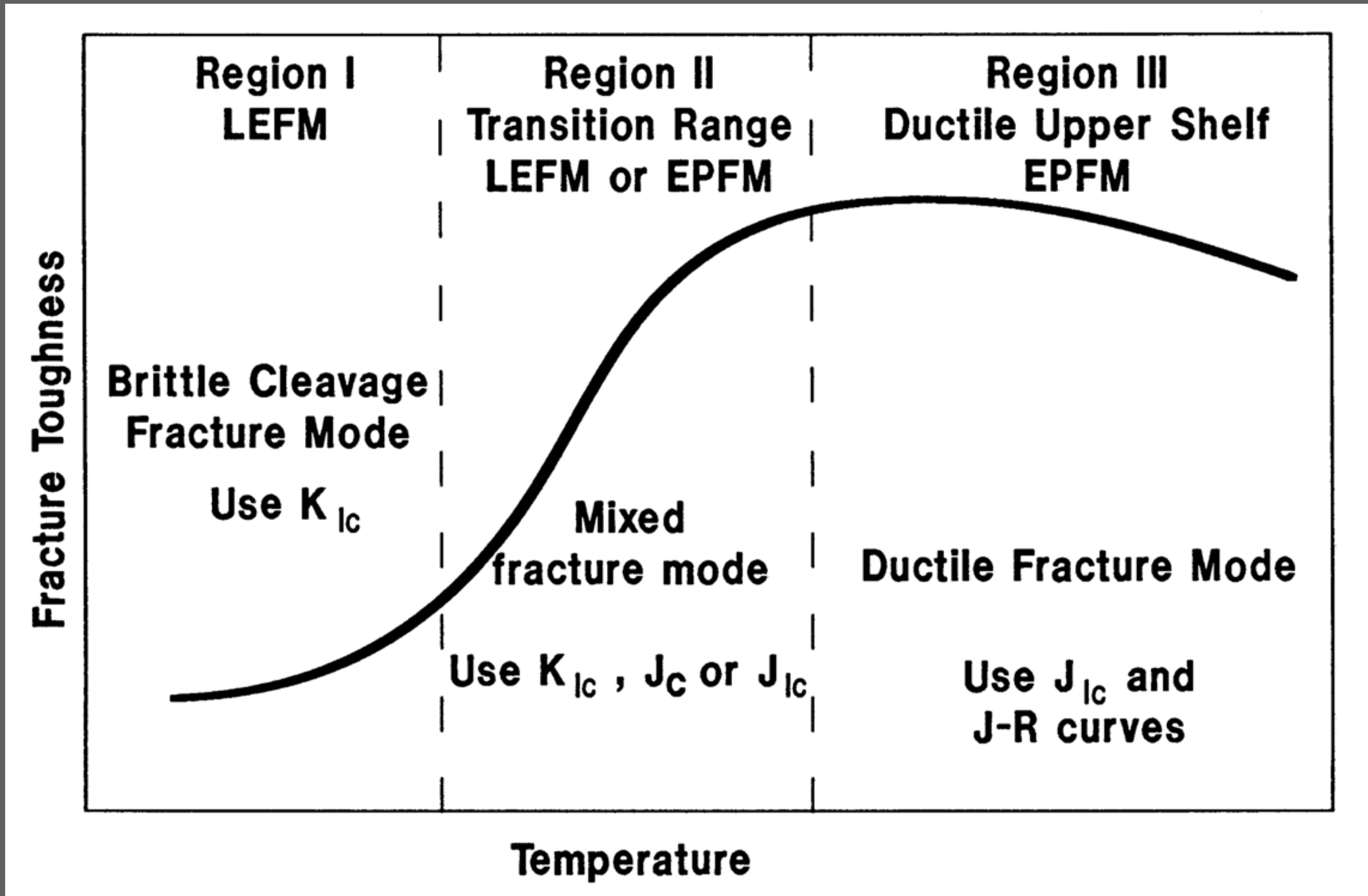


Effects of T-Stress on T_o

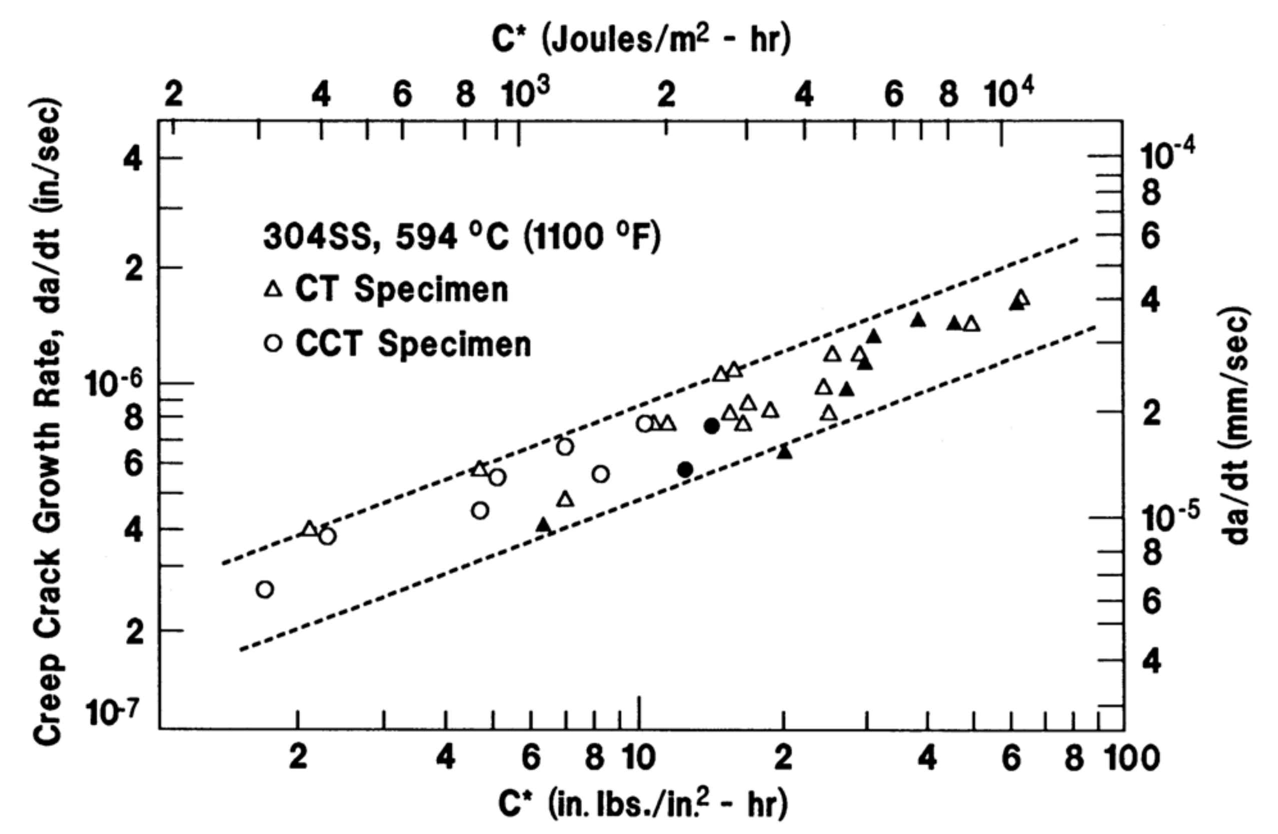
(Reported by Tregoning and Joyce for A533B)



Transition from LEFM to EPFM



Creep Crack Growth Rate as Function of C*



Crack growth measured using electric potential

Overall Approach to Structural Integrity for Flaw Tolerance