Notches in Fatigue

Professor Stephen Downing

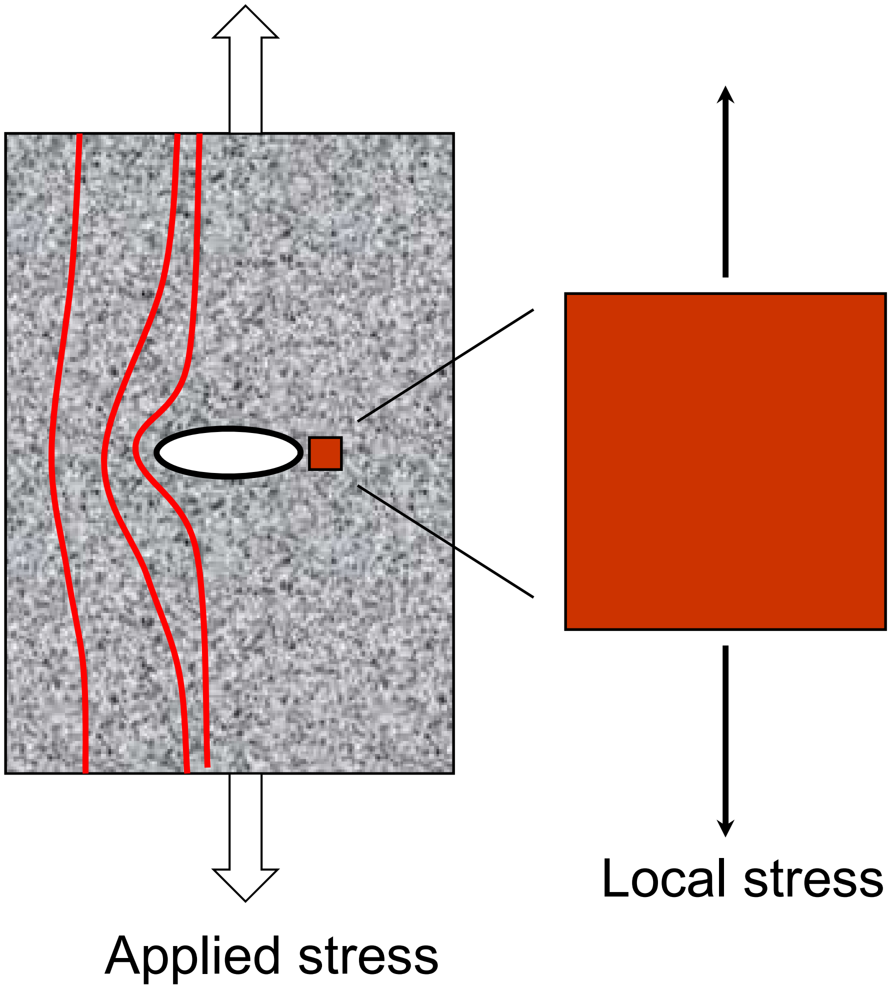
Department of Mechanical Science and Engineering

University of Illinois at Urbana-Champaign

Outline

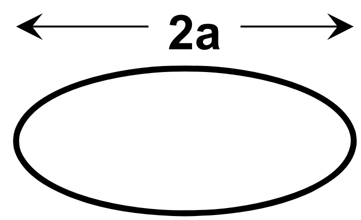
1. Notch Rules
2. Fatigue Notch Factor
3. Stress Intensity Factors for Notches
4. Frost Data and K_f
5. Small Crack Growth
6. Small Notches

Stress Concentration Factor



$$\sigma_{local} = \sigma_{applied}\left(1 + 2\sqrt{\frac{a}{\rho}}\right)$$

Inglis Solution 1910



Notch Rules

Neuber

$$K_t^2 S e = \sigma \varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{\frac{1}{n}}$$

Glinka

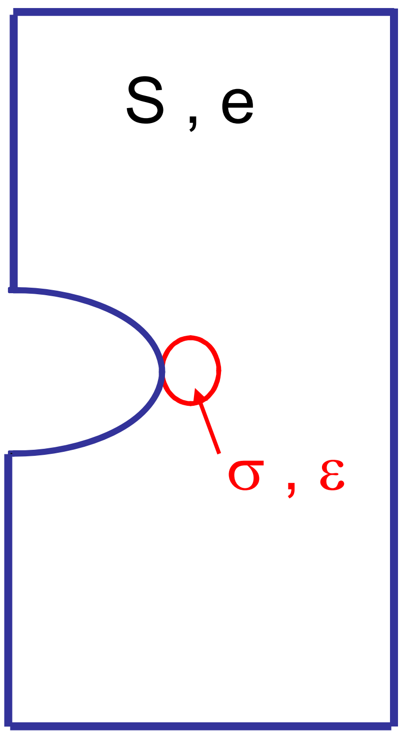
$$K_t^2 S e = \int \sigma \, d\varepsilon = \frac{\sigma}{E} + \frac{1}{1+n}\left(\frac{\sigma}{K}\right)^{\frac{1}{n}}$$

Seeger

$$K_p^2 S^* e^* = \sigma \varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{K}\right)^{\frac{1}{n}}$$

$$K_p = \frac{S_{Limit} K_t}{\sigma_y} \qquad S^* = \frac{K_t}{K_p} S$$

Define K_σ and K_ε after Yielding



Define: nominal stress, S

nominal strain, e

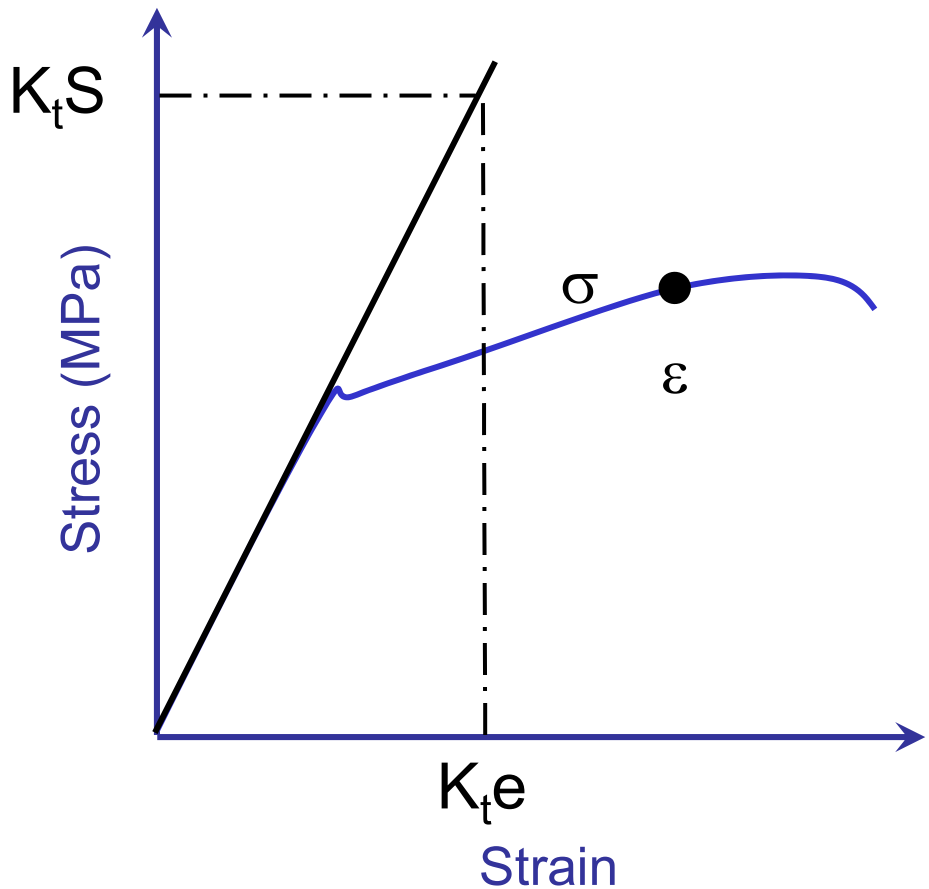
notch stress, σ

notch strain, ε

Stress concentration $K_\sigma = \dfrac{\sigma}{S}$

Strain concentration $K_\varepsilon = \dfrac{\varepsilon}{e}$

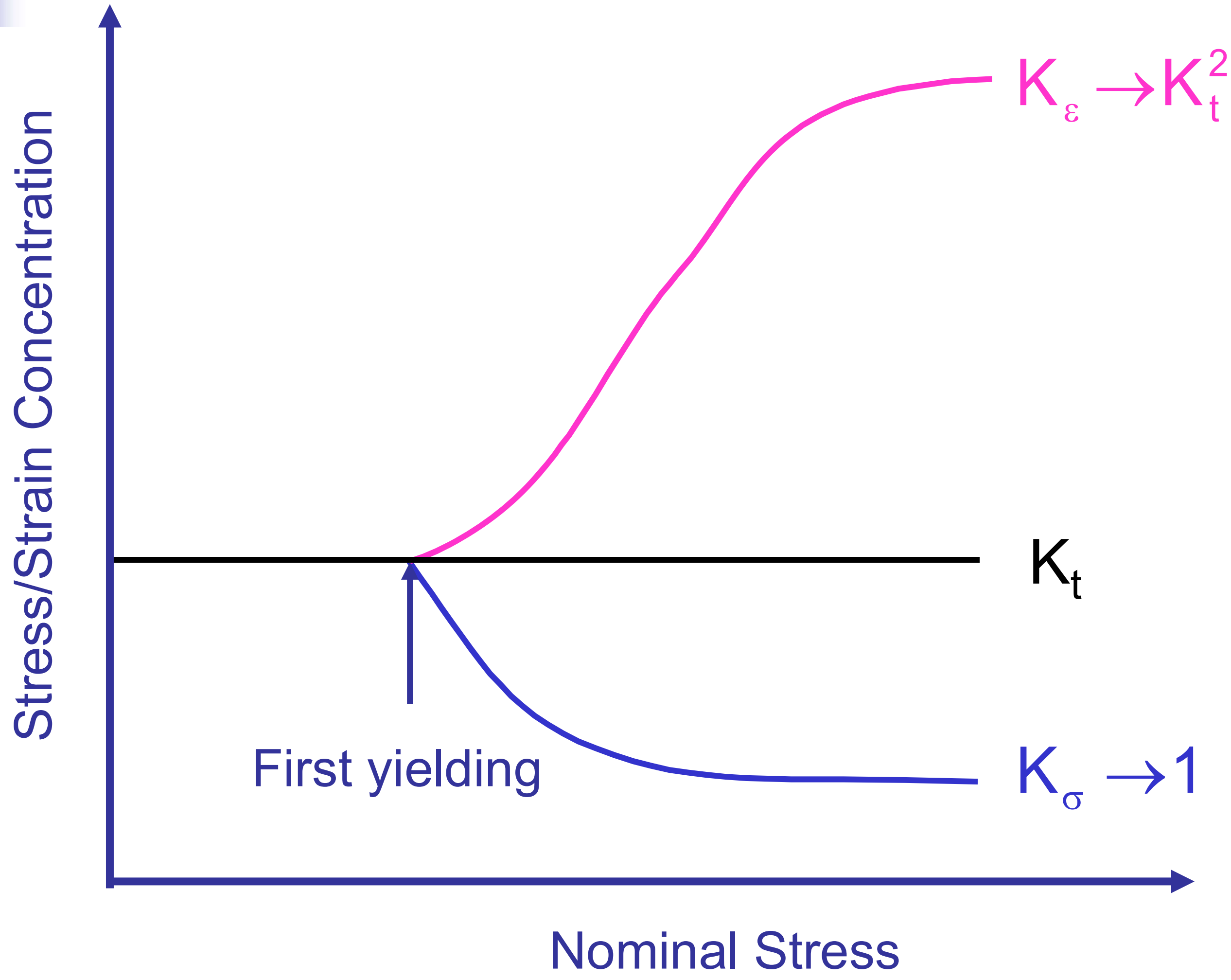
K_σ and K_ε



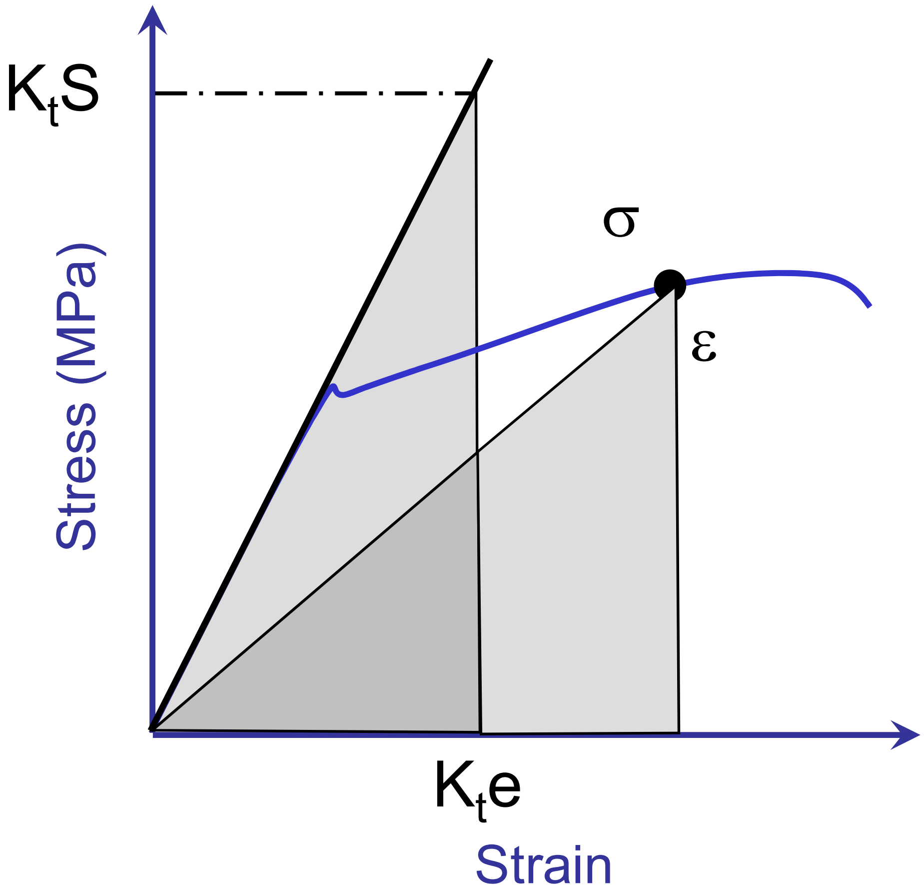
$$K_\sigma = \frac{\sigma}{S}$$

$$K_\varepsilon = \frac{\varepsilon}{e}$$

Stress and Strain Concentration



Neuber's Rule



Actual stress

$$K_t S \, K_t e = \sigma \varepsilon$$

Stress calculated with elastic assumptions

Neuber's Rule for Fatigue

Stress and strain amplitudes

$$\frac{K_t \Delta S \, K_t \Delta e}{2 \qquad 2} = \frac{\Delta\sigma \, \Delta\varepsilon}{2 \quad 2}$$

Elastic nominal stress

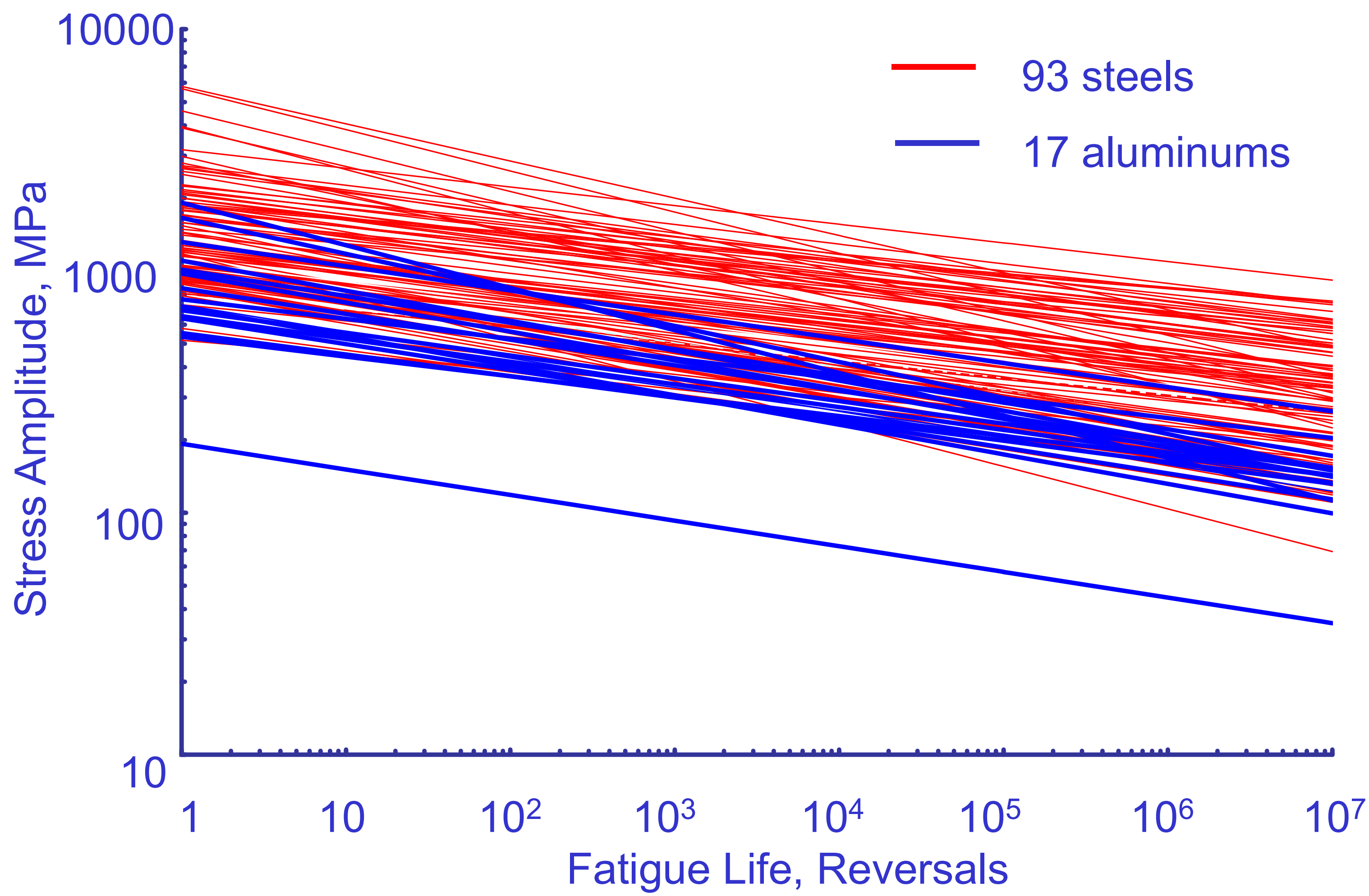
$$\frac{\Delta e}{2} = \frac{\Delta S}{2E}$$

Substitute and rearrange

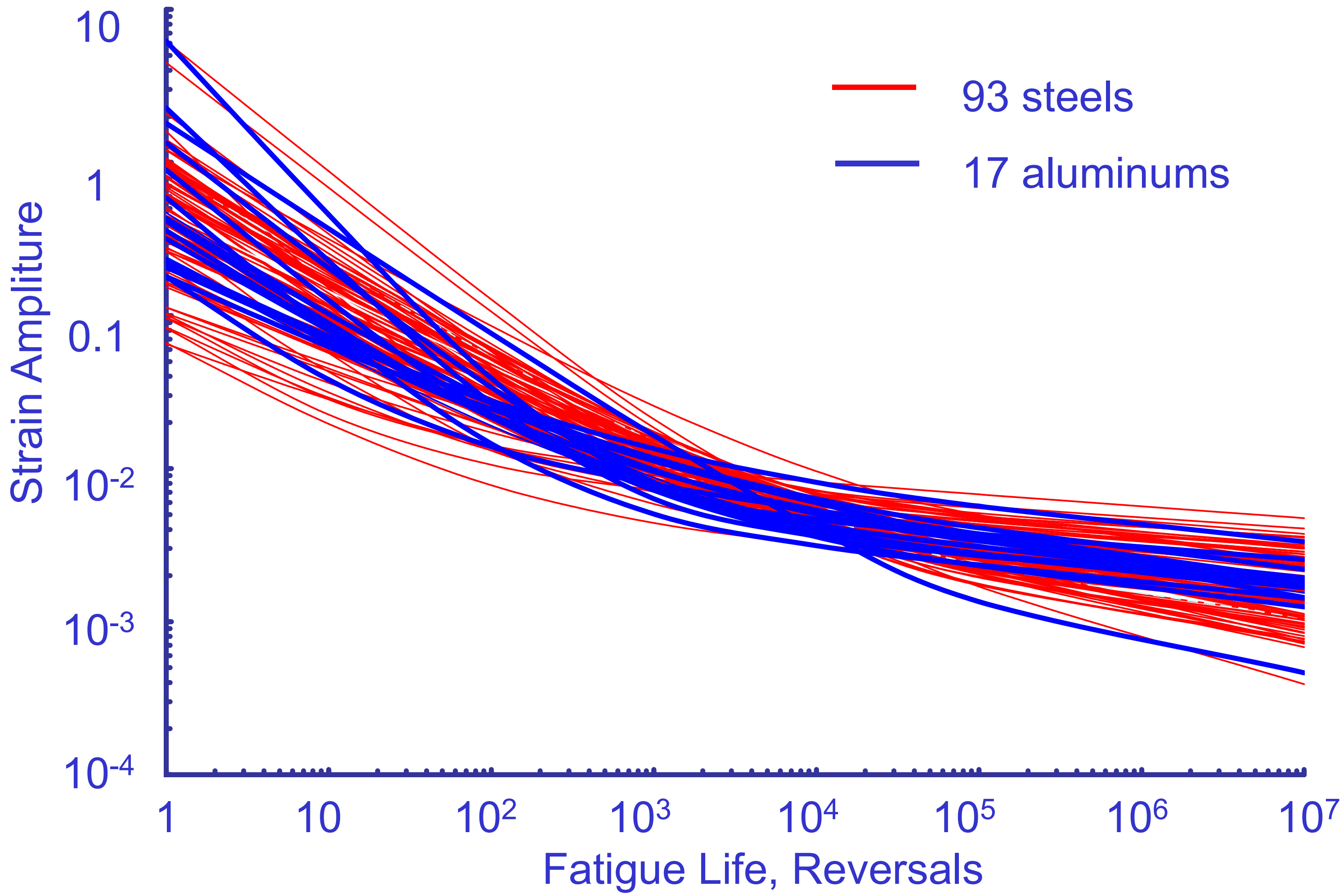
$$K_t \frac{\Delta S}{2} = \sqrt{E \frac{\Delta\sigma}{2} \frac{\Delta\varepsilon}{2}}$$

The product of stress times strain controls fatigue life

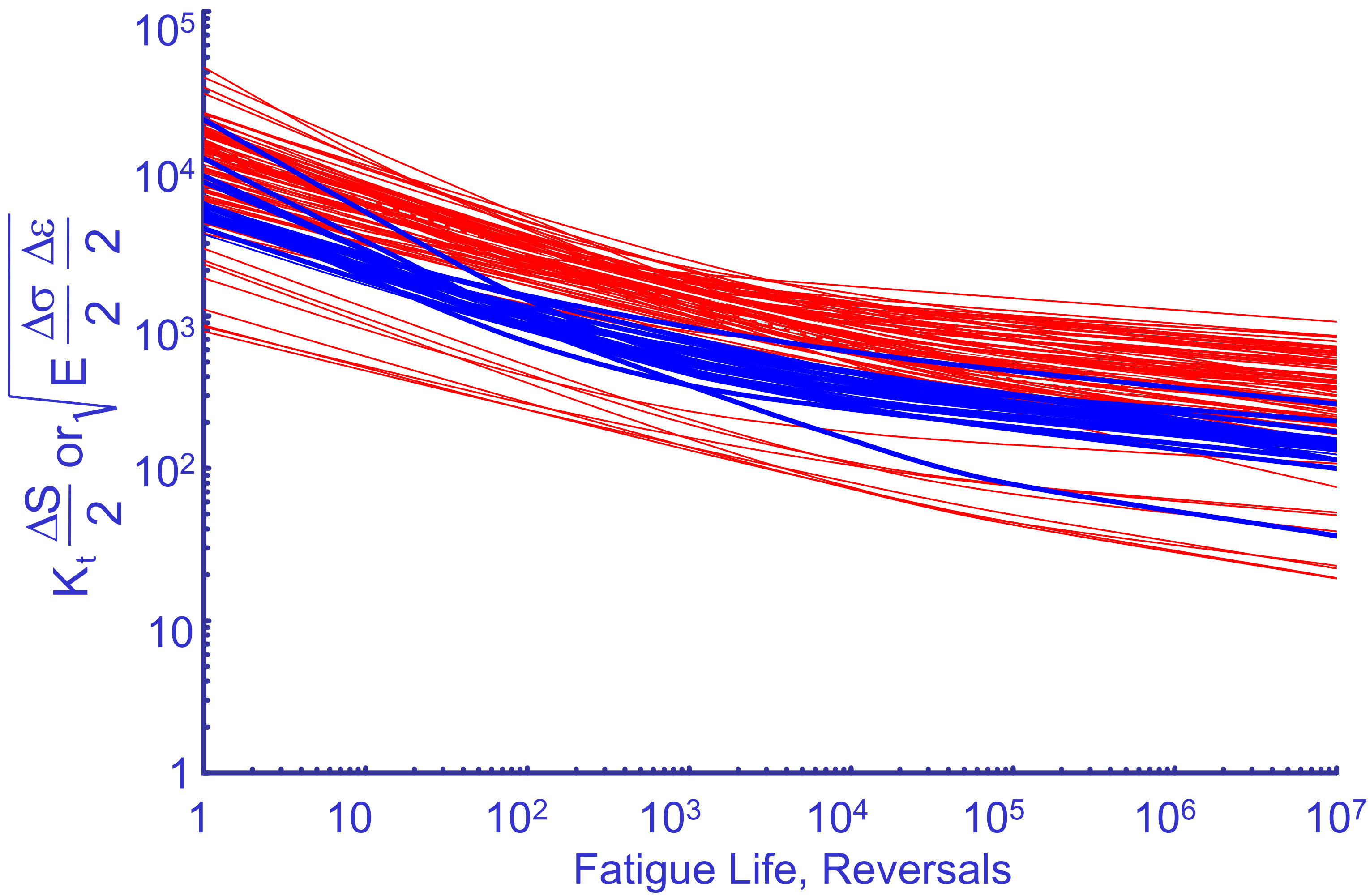
SN Materials Data



εN Materials Data



$$\sqrt{E \frac{\Delta\sigma}{2} \frac{\Delta\varepsilon}{2}}$$



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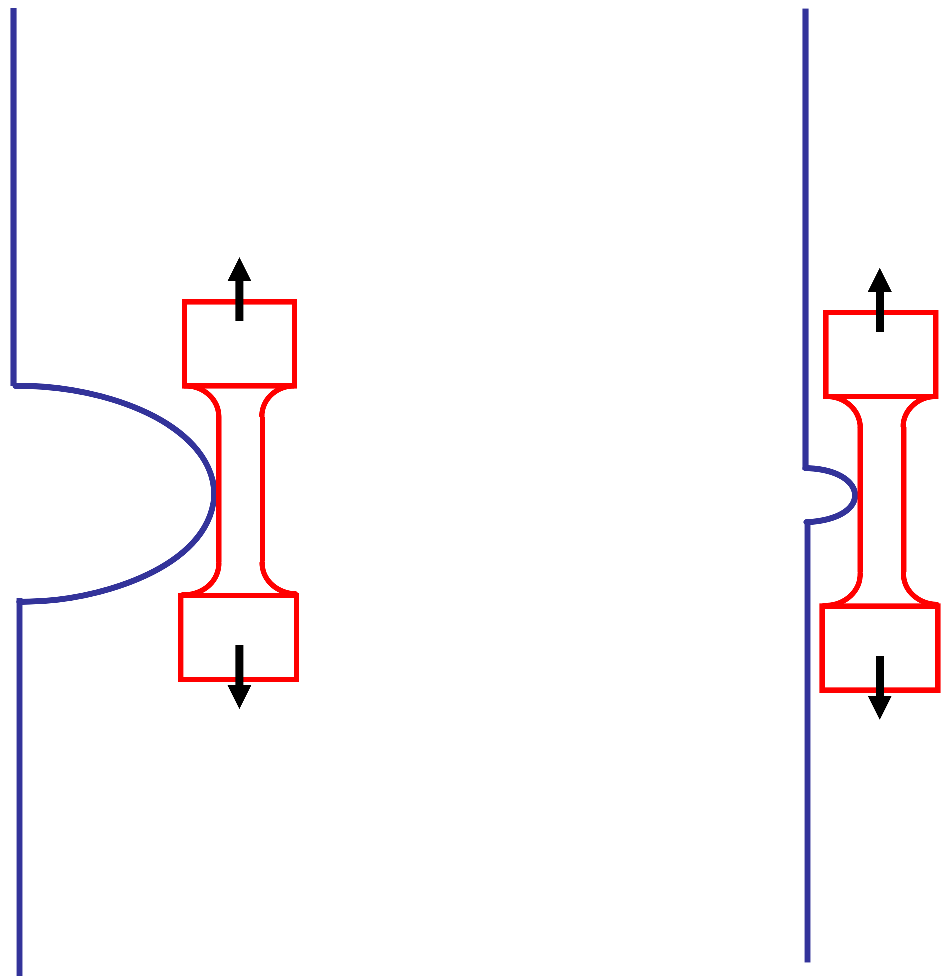
A Dilemma

Stress analysis and stress concentration factors are independent of size and are related only to the ratio of the geometric dimensions to the loads

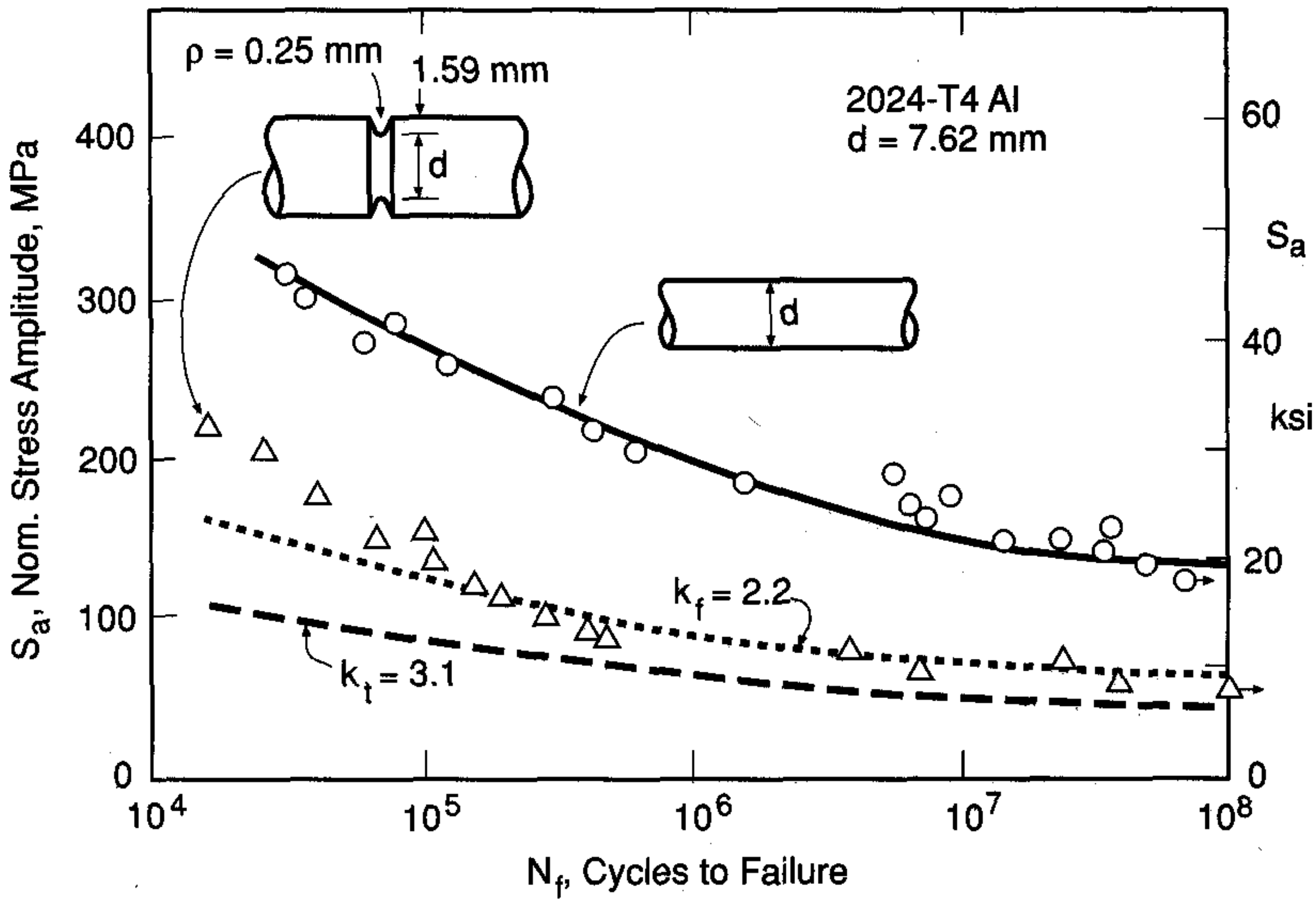
Fatigue is a size dependant phenomena

How do you put the two together ?

Similitude

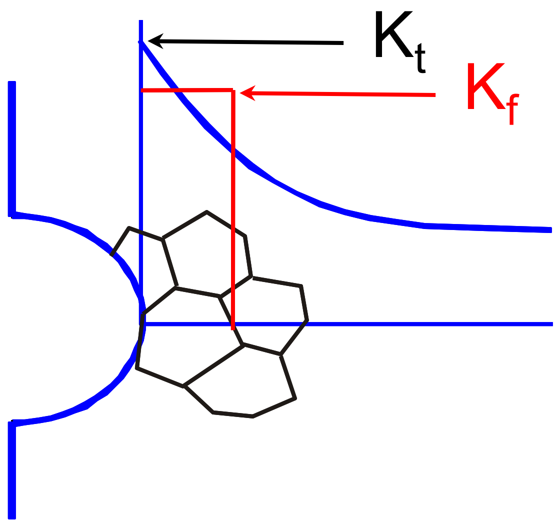


Fatigue of Notches

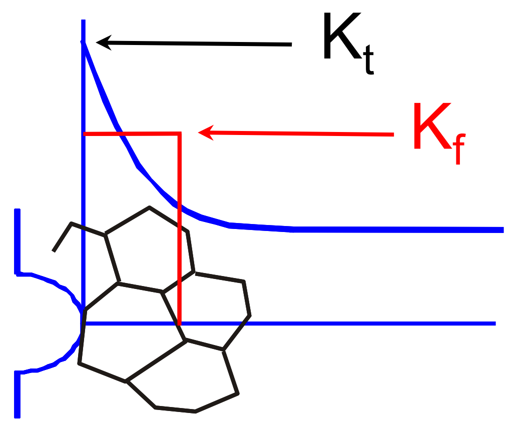


From Dowling, Mechanical Behavior of Materials, 1999

Notch Size

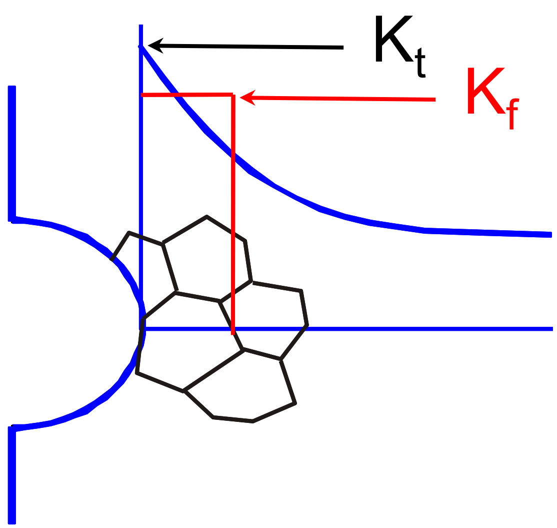


Large Notch

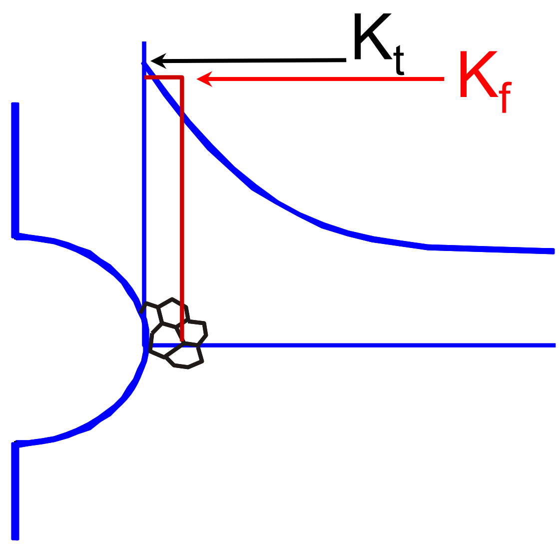


Small Notch

Microstructure Size

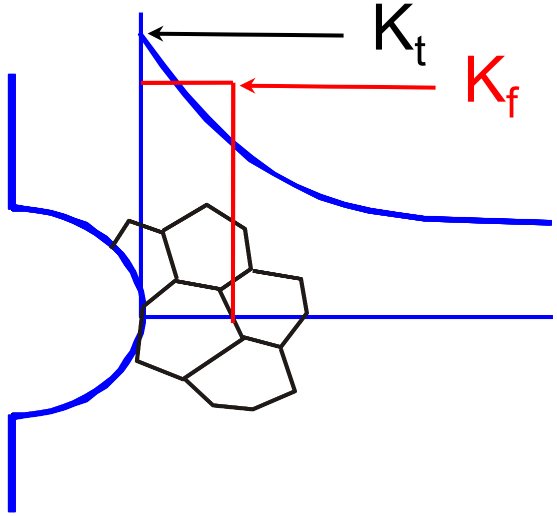


Low Strength

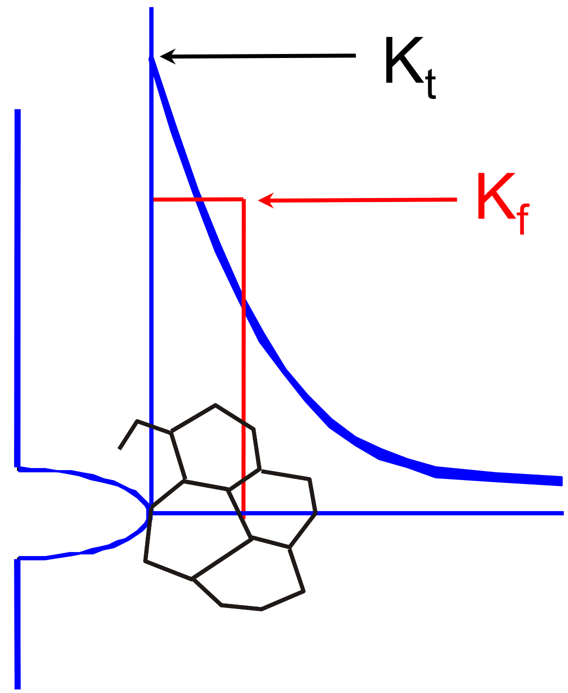


High Strength

Stress Gradient

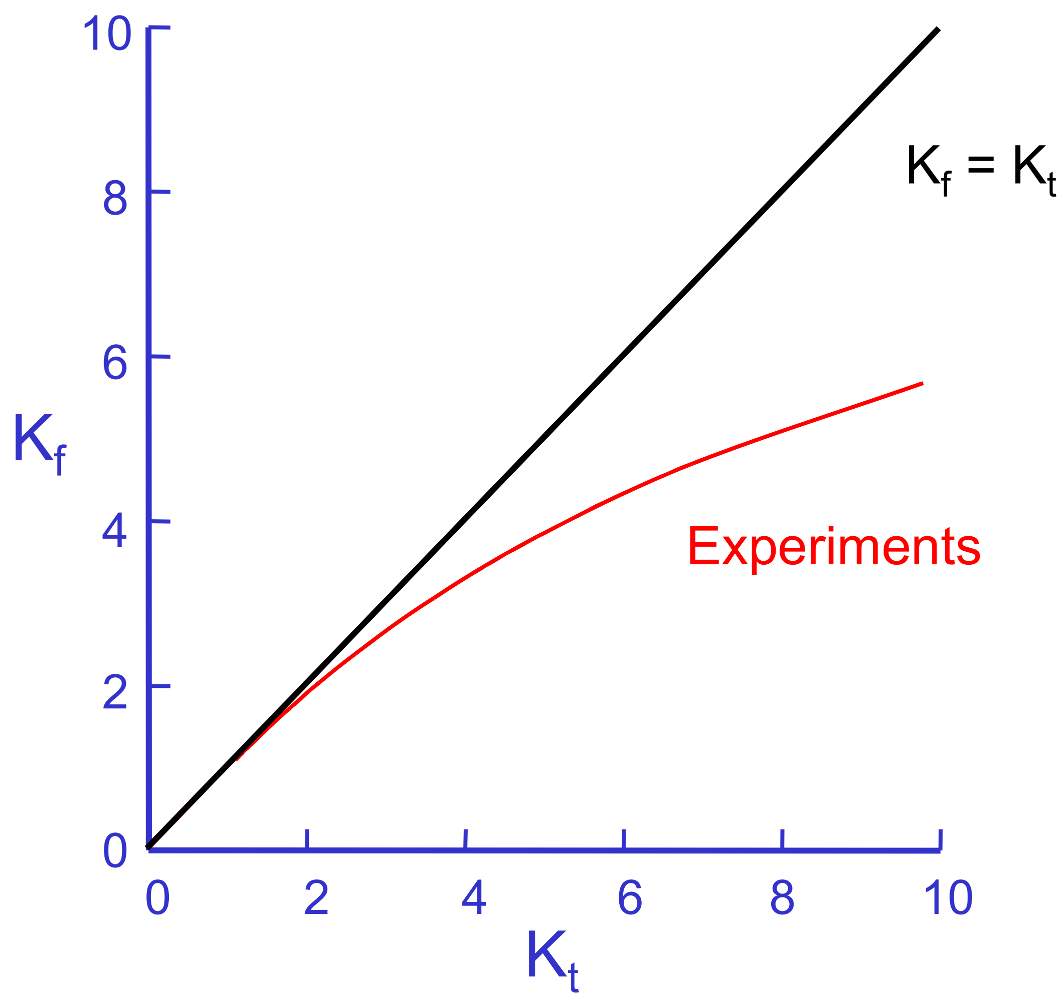


Low K_t



High K_t

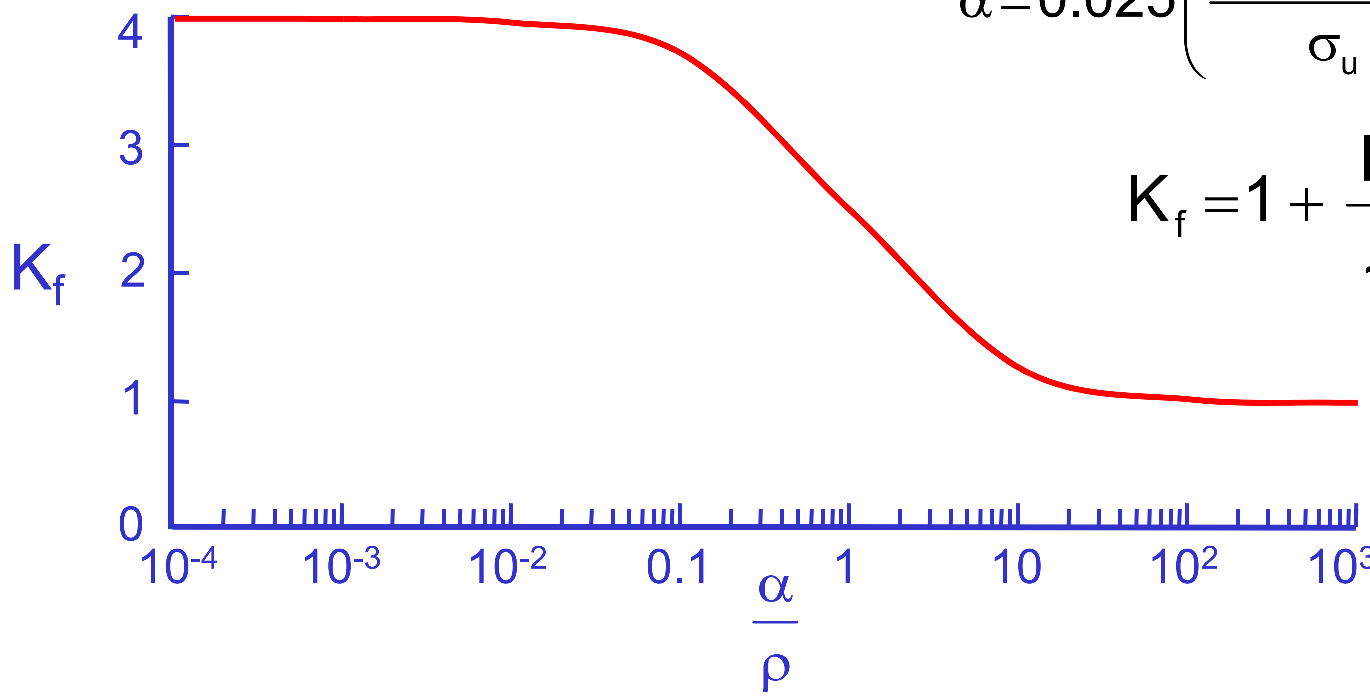
K_t vs K_f



Peterson's Equation

$$\alpha = 0.025\left(\frac{2070\text{MPa}}{\sigma_u}\right)^{1.8}\ \text{mm}$$

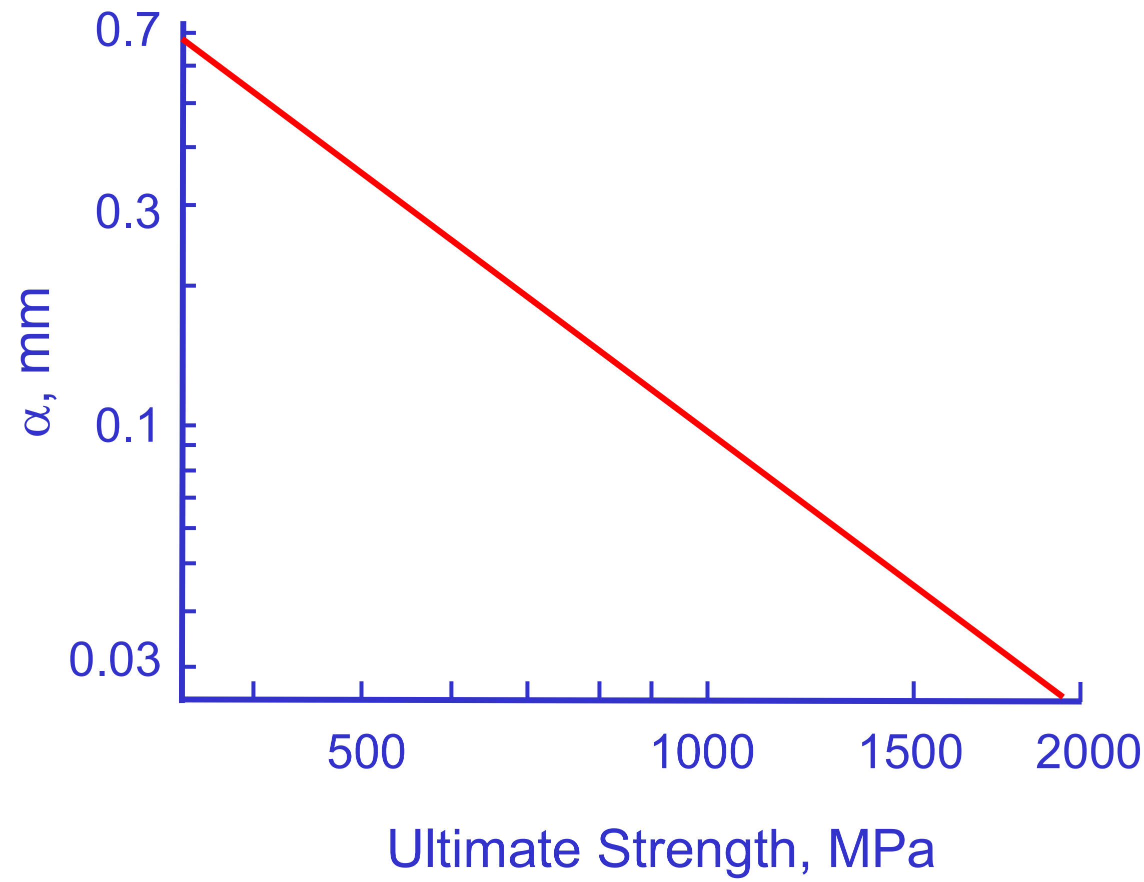
$$K_f = 1 + \frac{K_t - 1}{1 + \frac{\alpha}{\rho}}$$



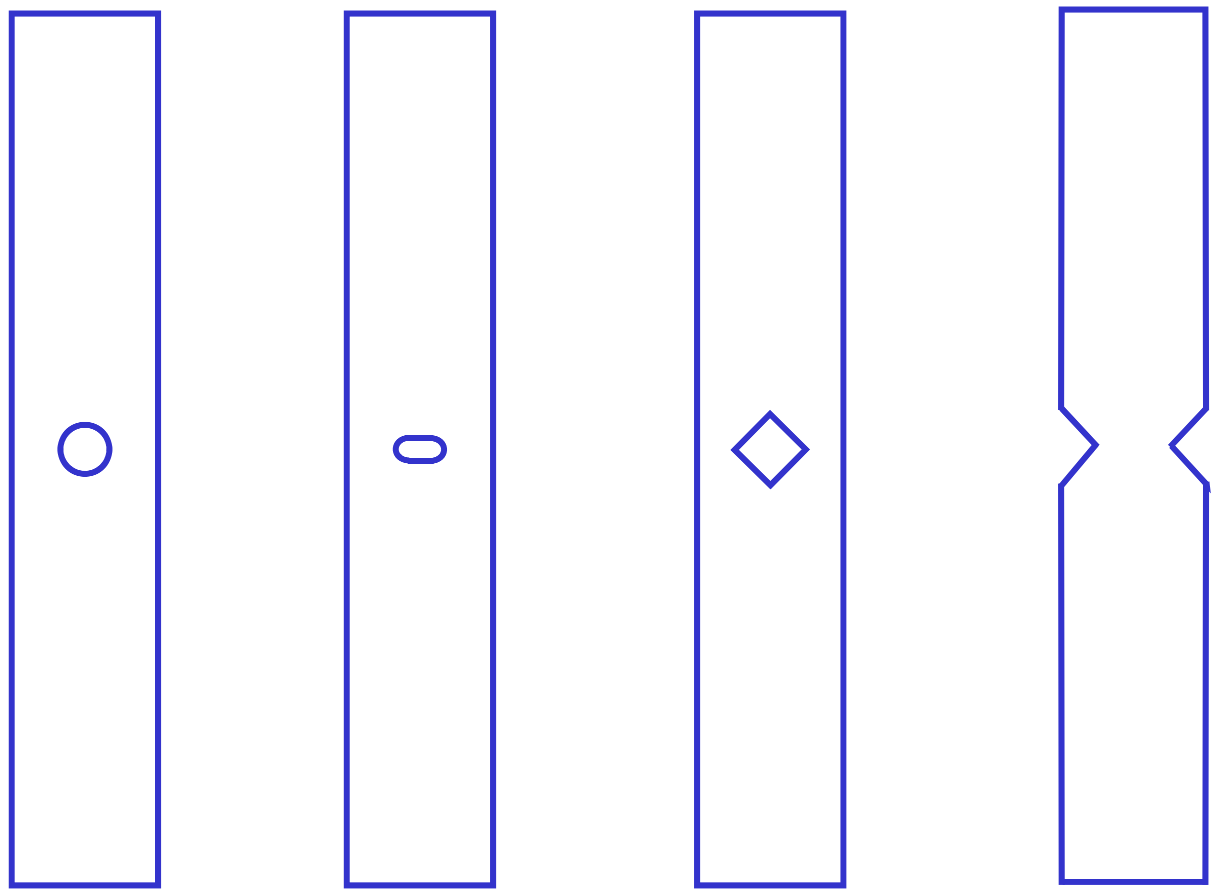
No effect when $\rho \ll \alpha$

Full effect when $\rho \gg \alpha$

Pererson's Constant



Static Strength



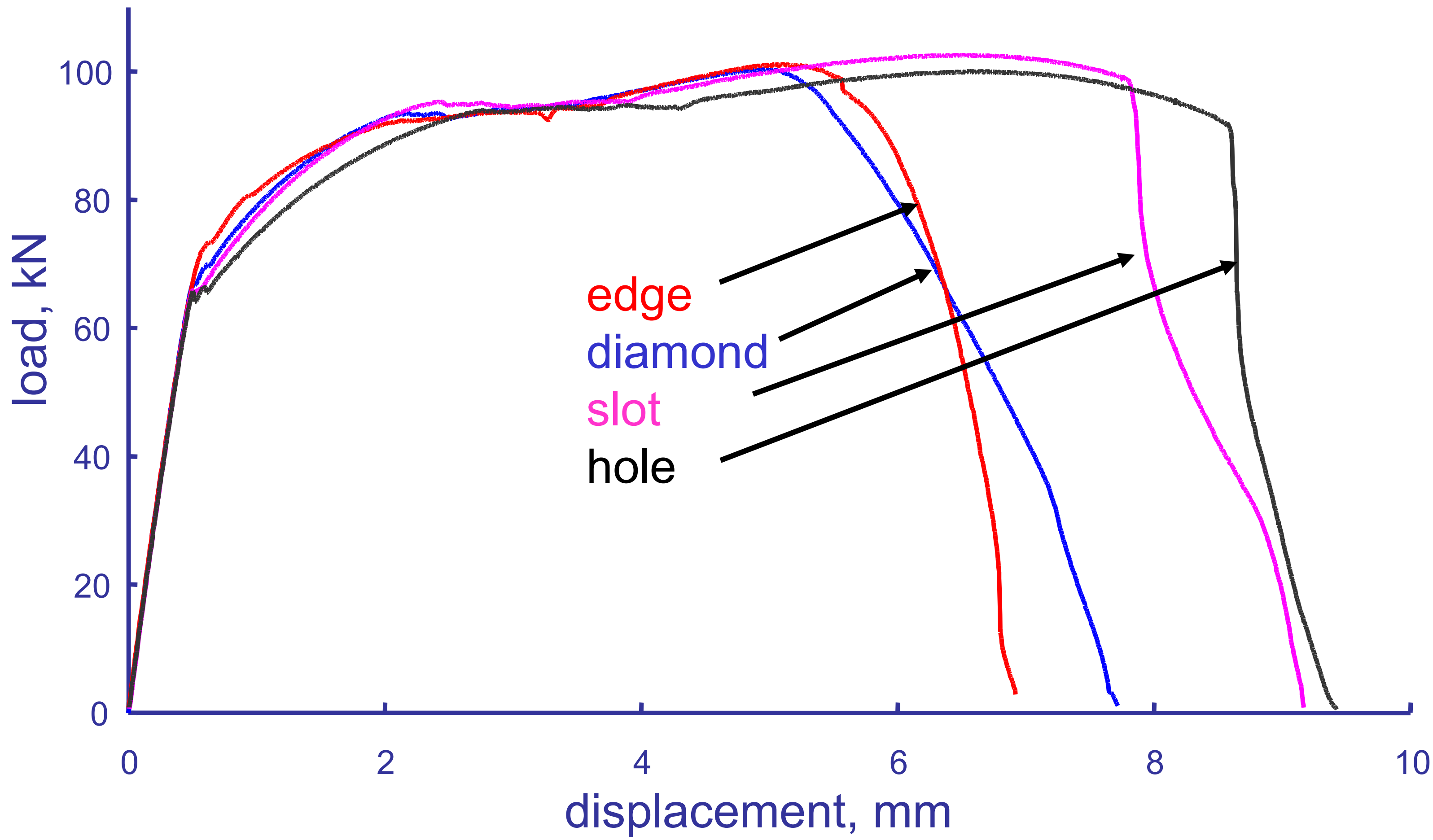
hole $K_t = 2.5$

slot $K_t = 5$

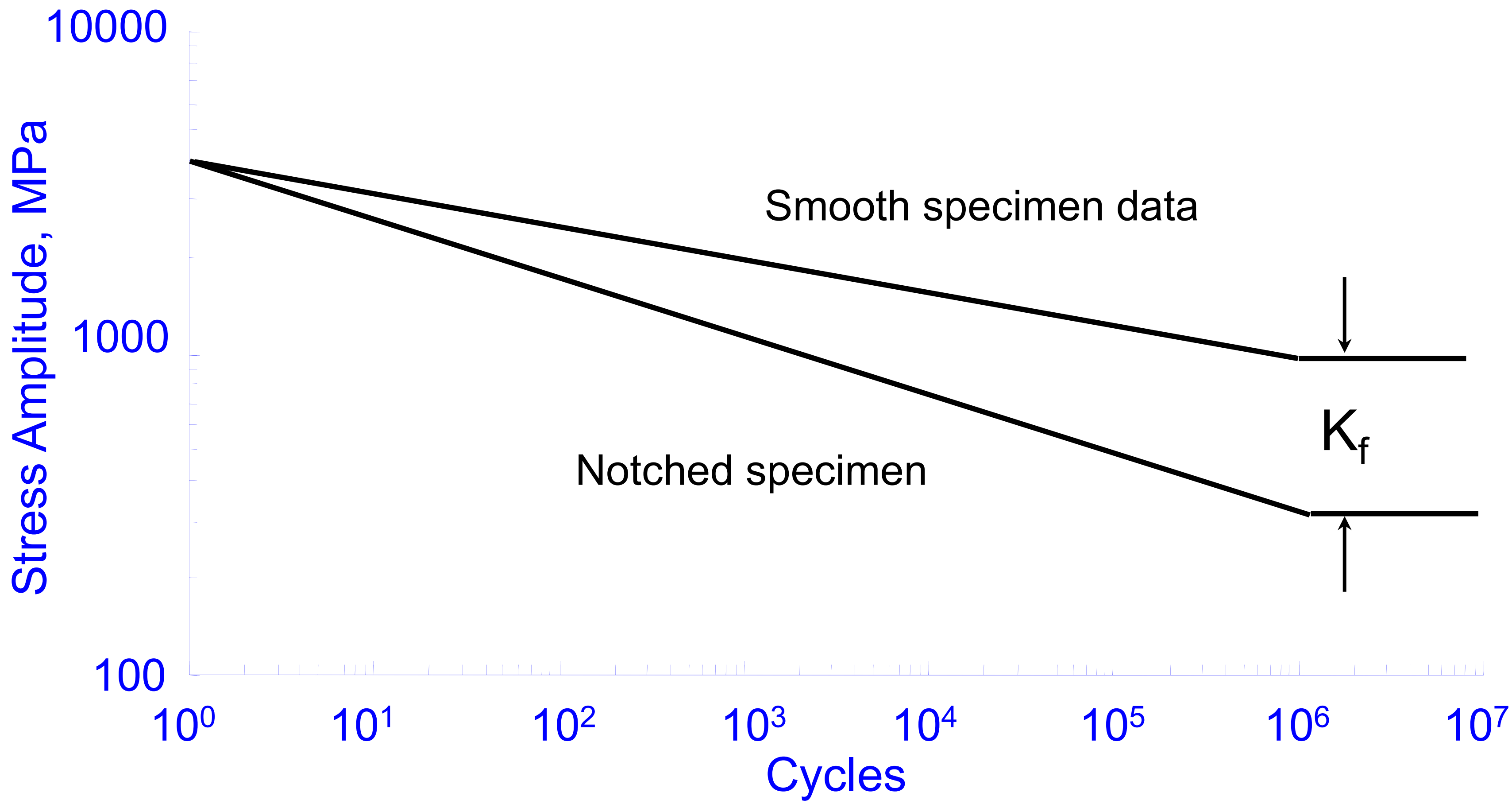
diamond $K_t = 20$

edge $K_t = 20$

1018 Steel Test Data



Notched SN Curve



Stress concentrations are not very important at short lives

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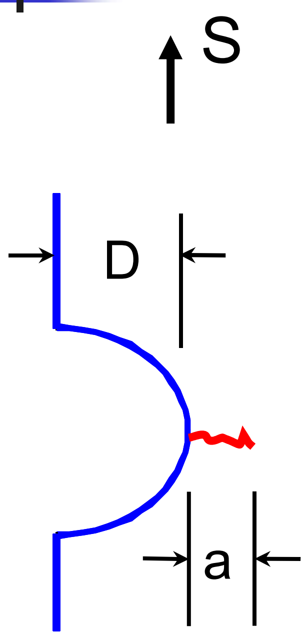
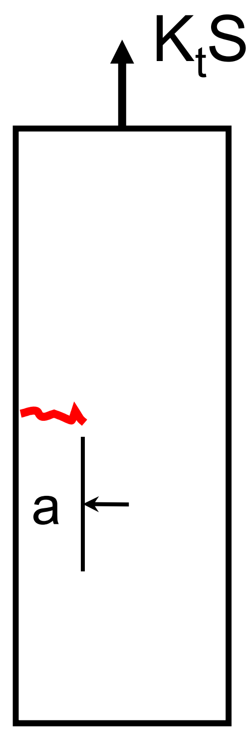
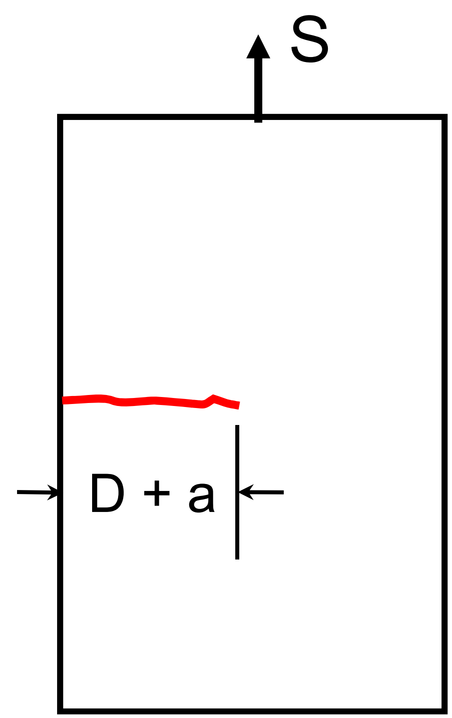
Cracks at Notches







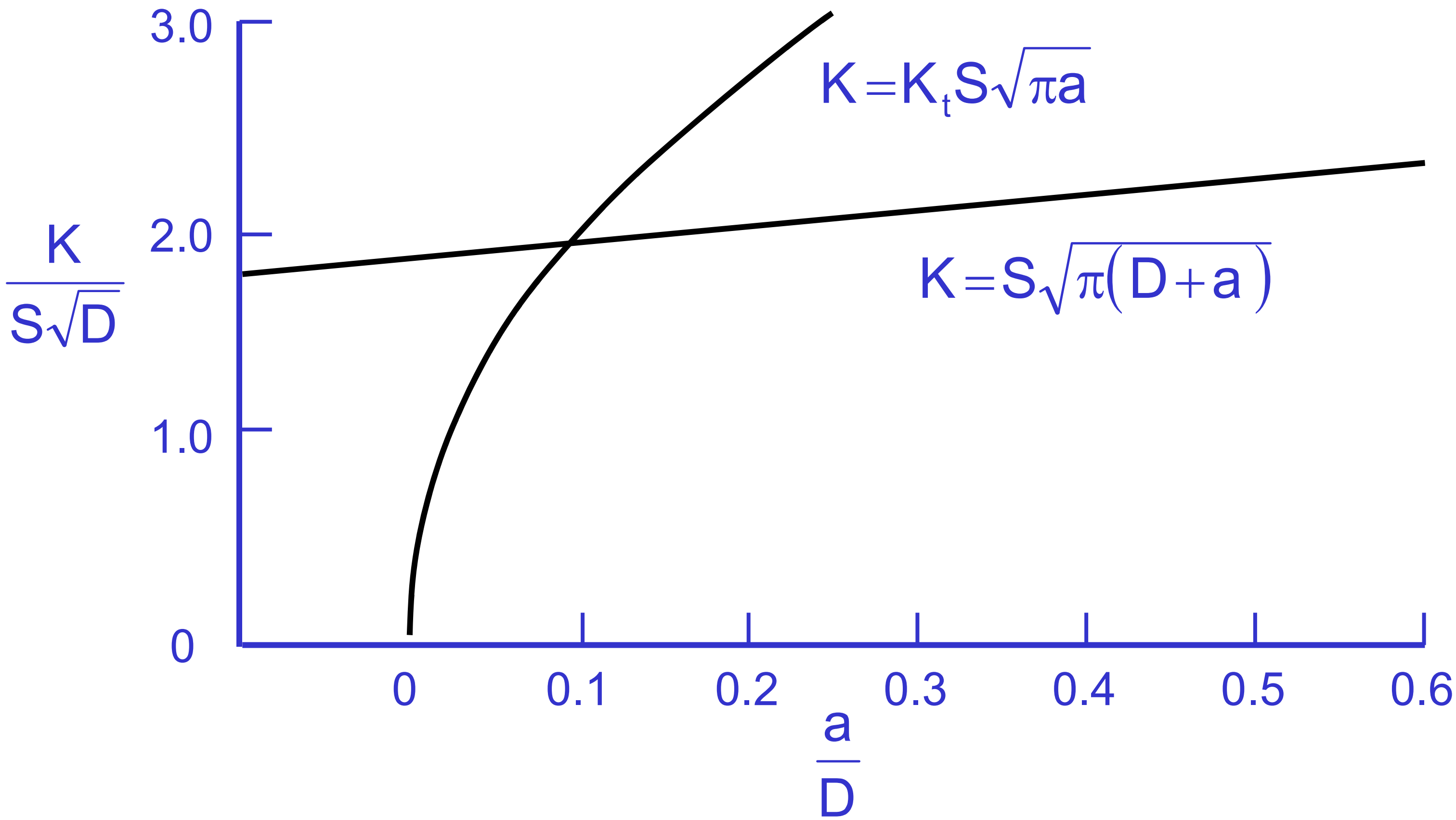
$a << D$

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

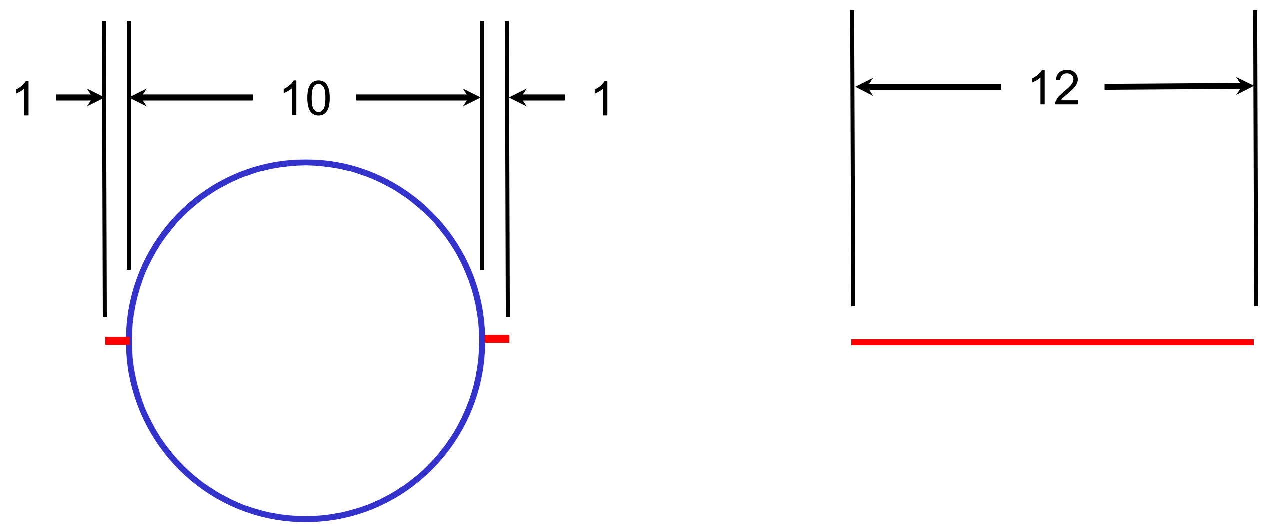
$a >> D$

$$K = S \sqrt{\pi (D + a)}$$

Stress Intensity Factors



Cracks at Holes



Once a crack reaches 10% of the hole radius, it behaves as if the hole was part of the crack

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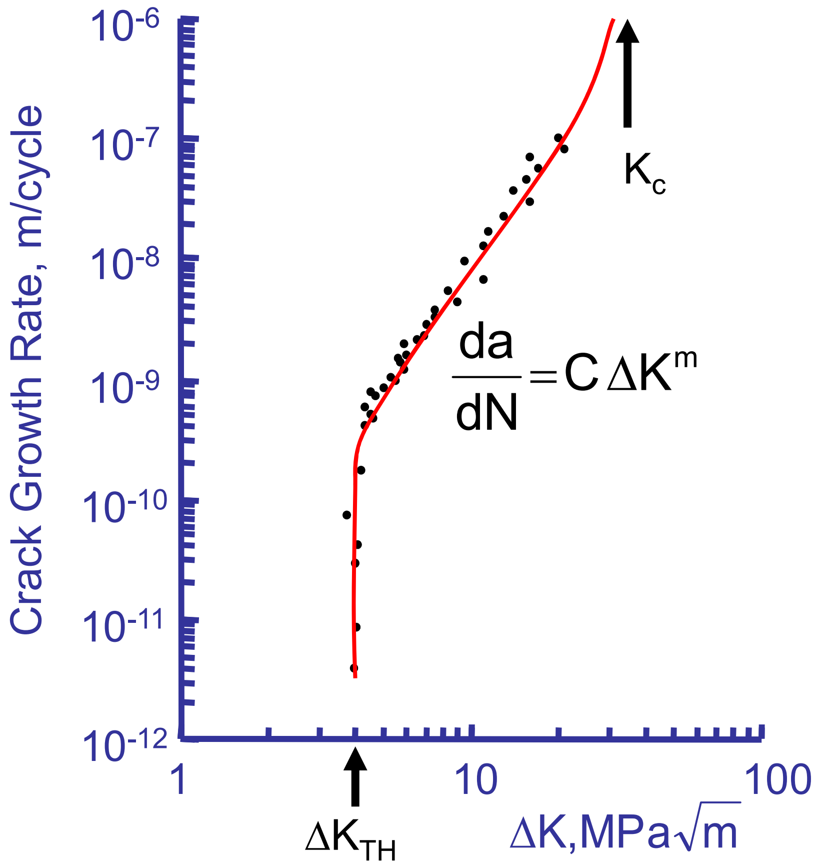
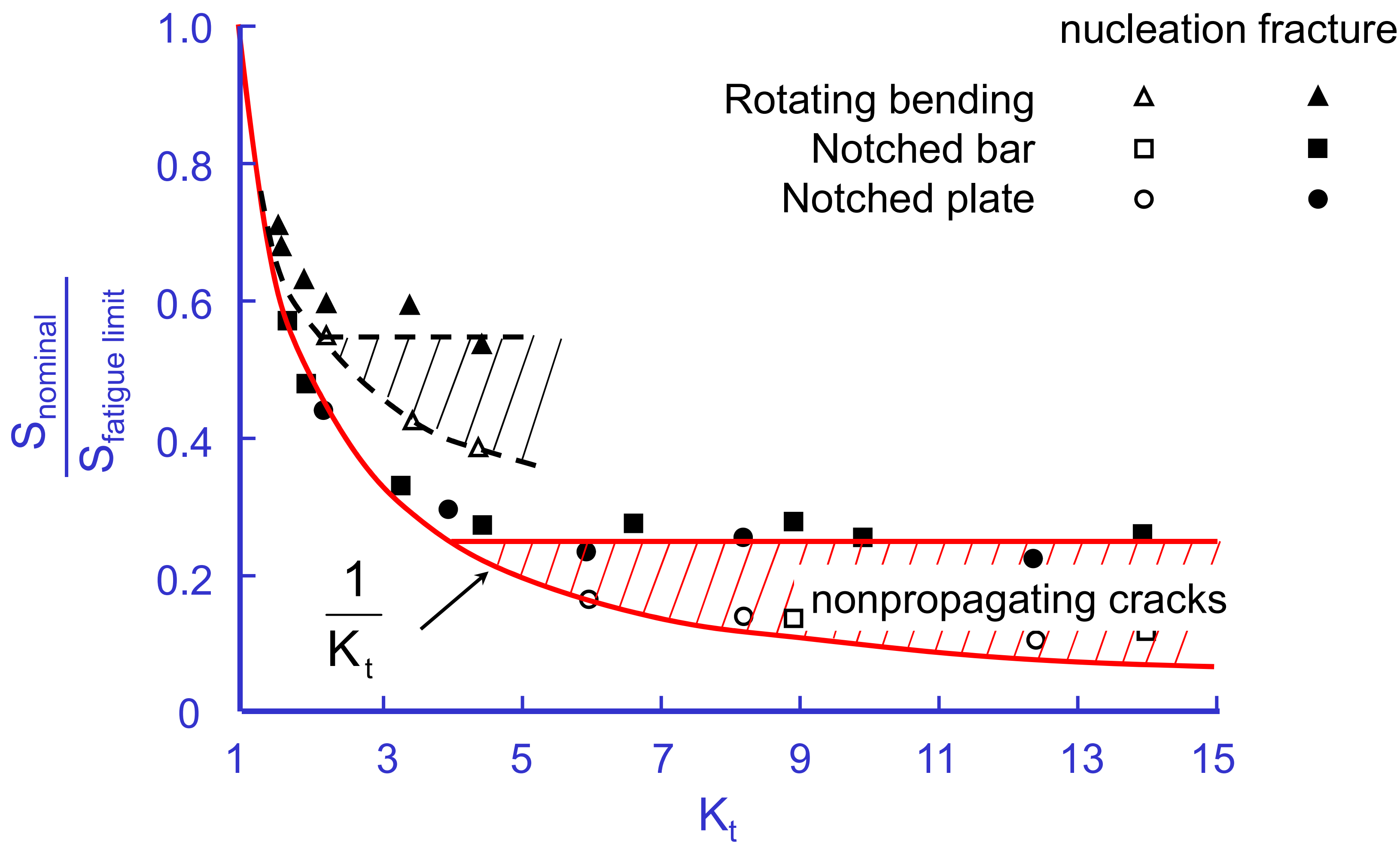
Crack Growth Data



Nonpropagating cracks

$$\Delta K_{TH} > \Delta\sigma 1.12 \frac{2}{\pi}\sqrt{\pi a}$$

Frost Data



Frost, "A Relation Between the Critical Alternating Propagation Stress and Crack Length for Mild Steel" Proceedings of the Institute for Mechanical Engineers, Vol. 173, No. 35, 1959, 811-836

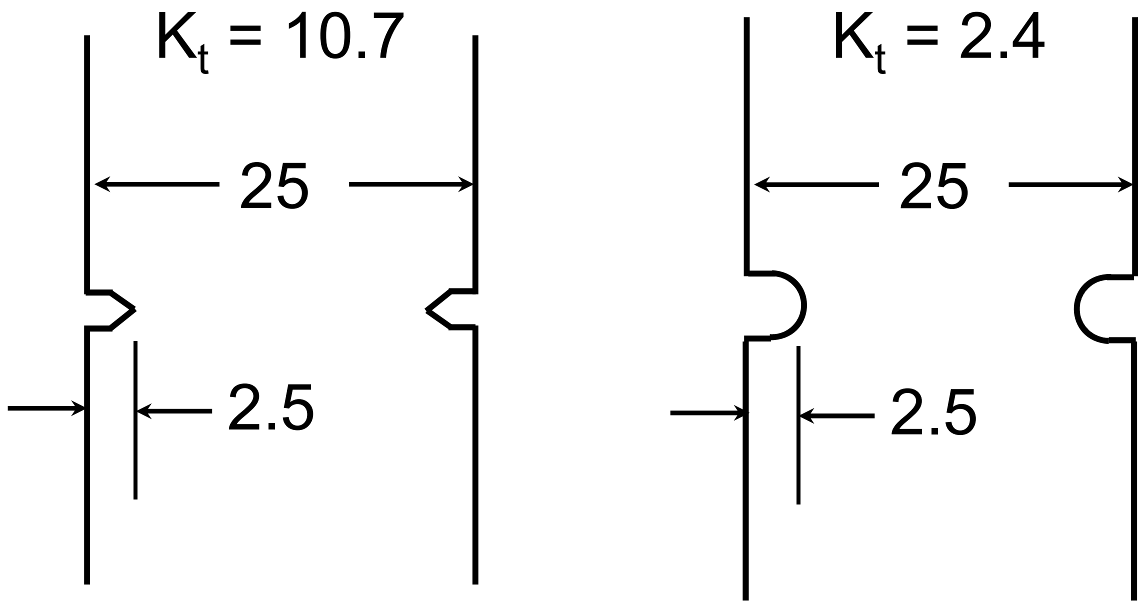
Significance

For $K_t > 4$, the notch acts like a crack with a depth D

$$S_{fl} = \frac{\Delta K_{th}}{\sqrt{\pi D}}$$

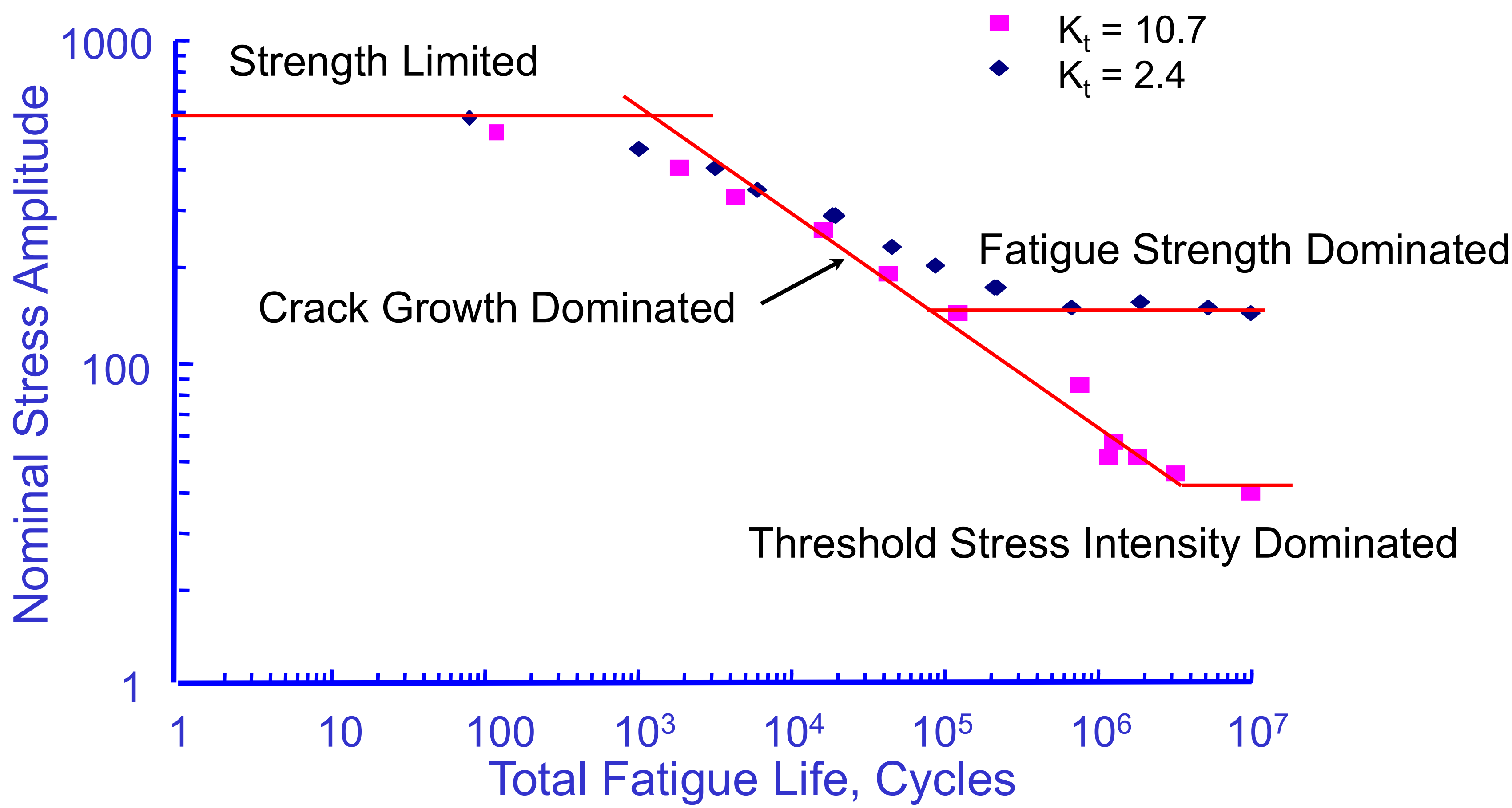
K_t does not play a role for sharp notches !

Specimens with Similar Geometry



Ultimate Strength 780 MPa
Yield Strength 660 MPa

Test Results



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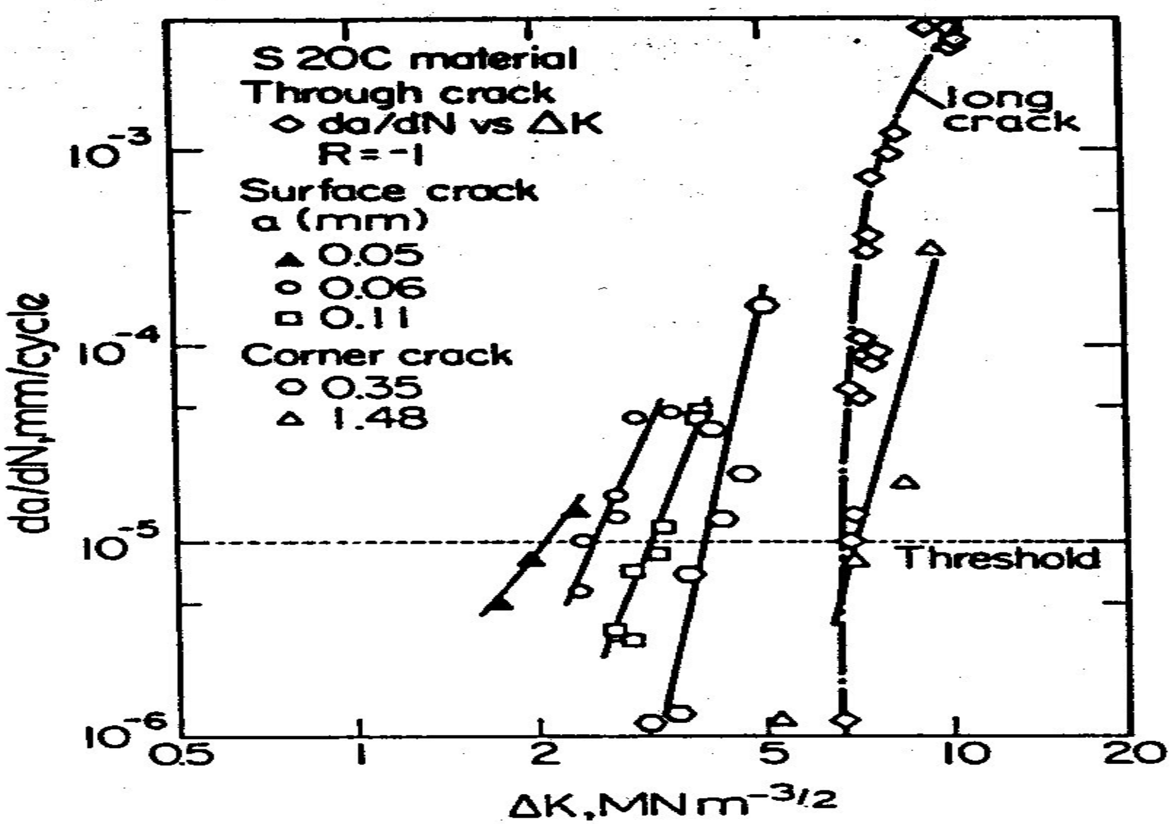
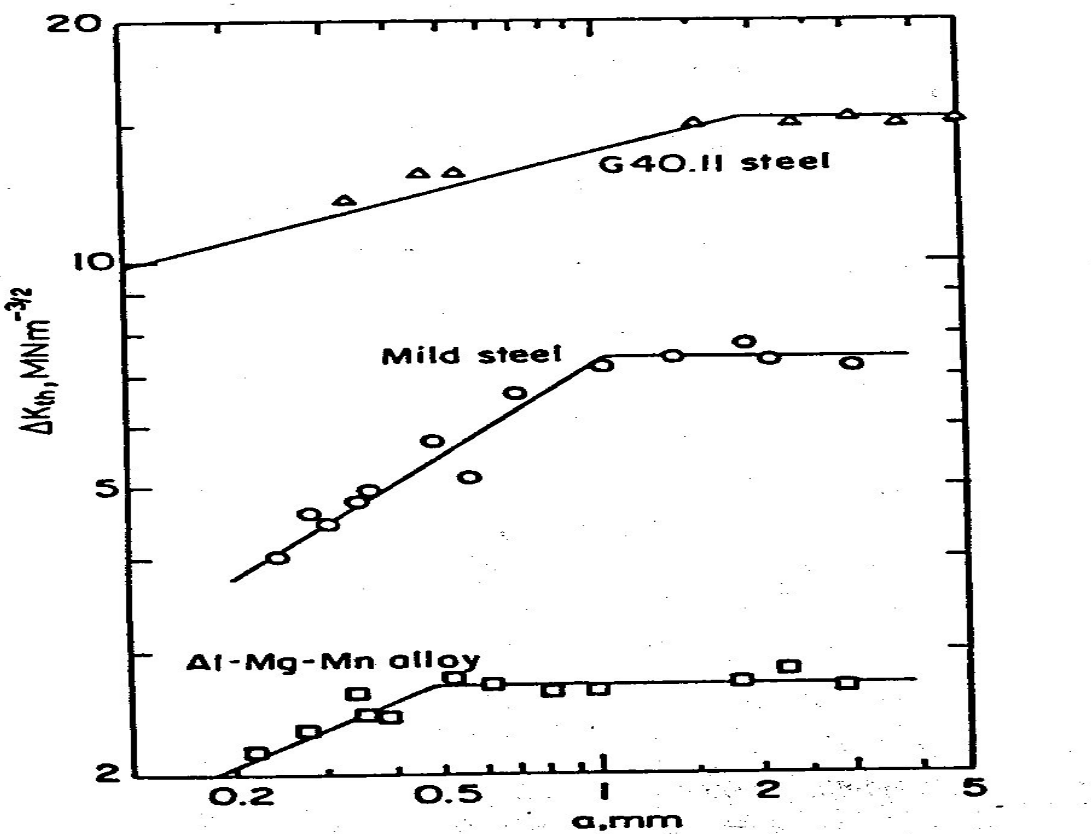
Small Crack Growth



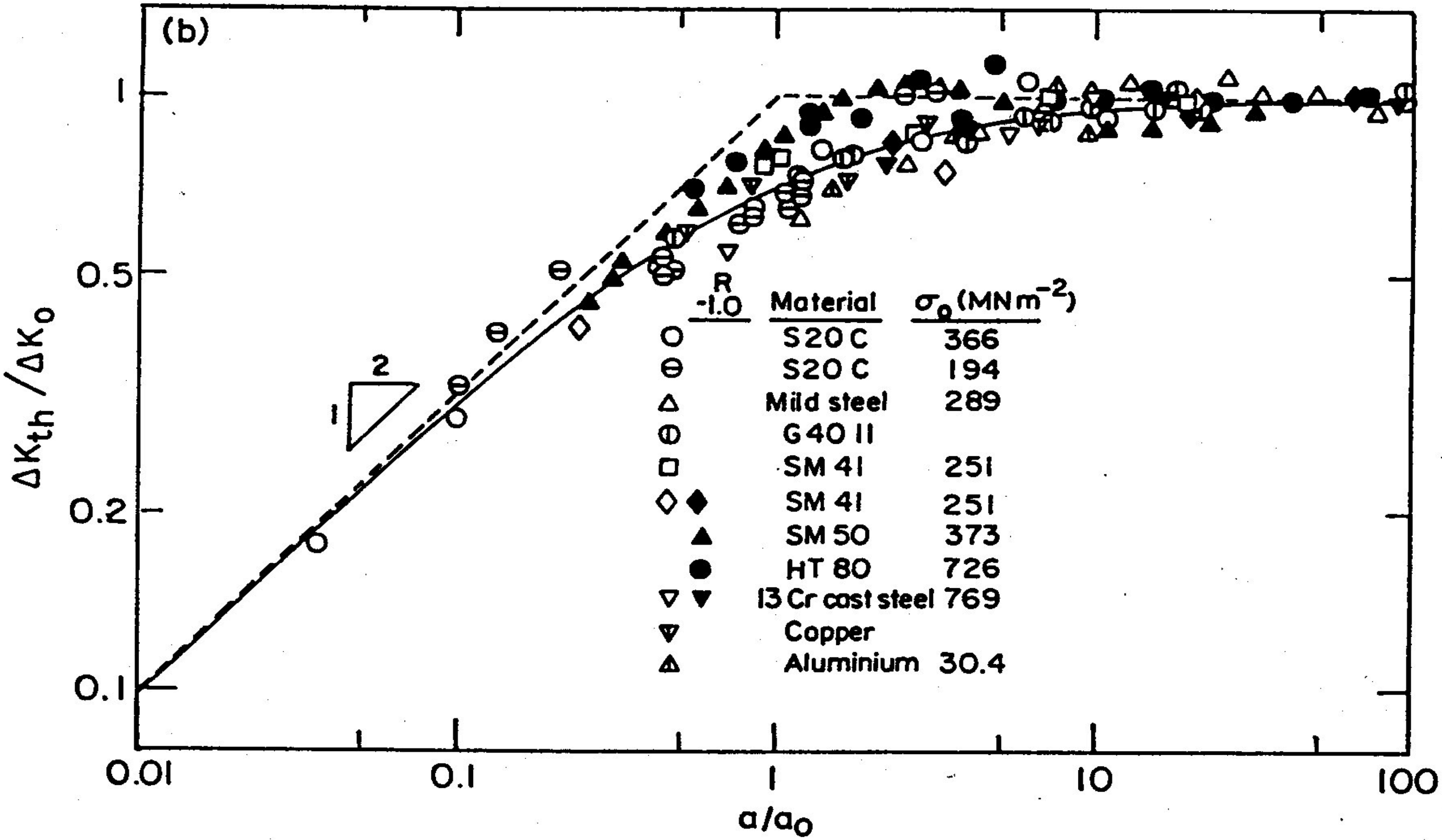
12 Difference in propagation rates da/dN of short and long fatigue cracks as function of stress intensity factor range ΔK for 3%Si iron of yield strength $\sigma_0 = 431$ MNm^{-2} (Ref. 70)

Threshold

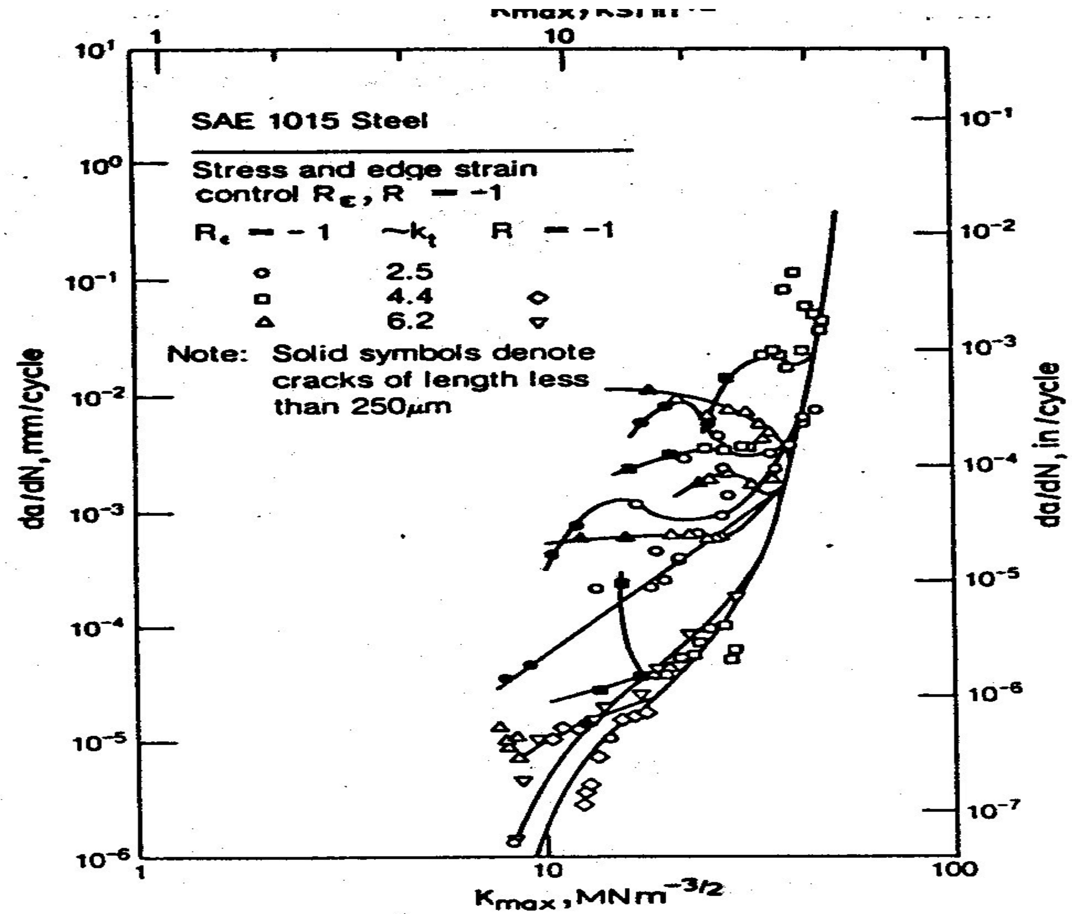


16 Variation of threshold stress intensity range ΔK_{th} with short crack length a in G40.11 austenitic 0.45%C steel, σ_0 = 550 MNm^{-2}, 0.035%C mild steel, σ_0 = 242 MNm^{-2}, and Al—Zn—Mg alloy, σ_0 = 180 MNm^{-2} (Ref. 69)

Normalized Thresholds

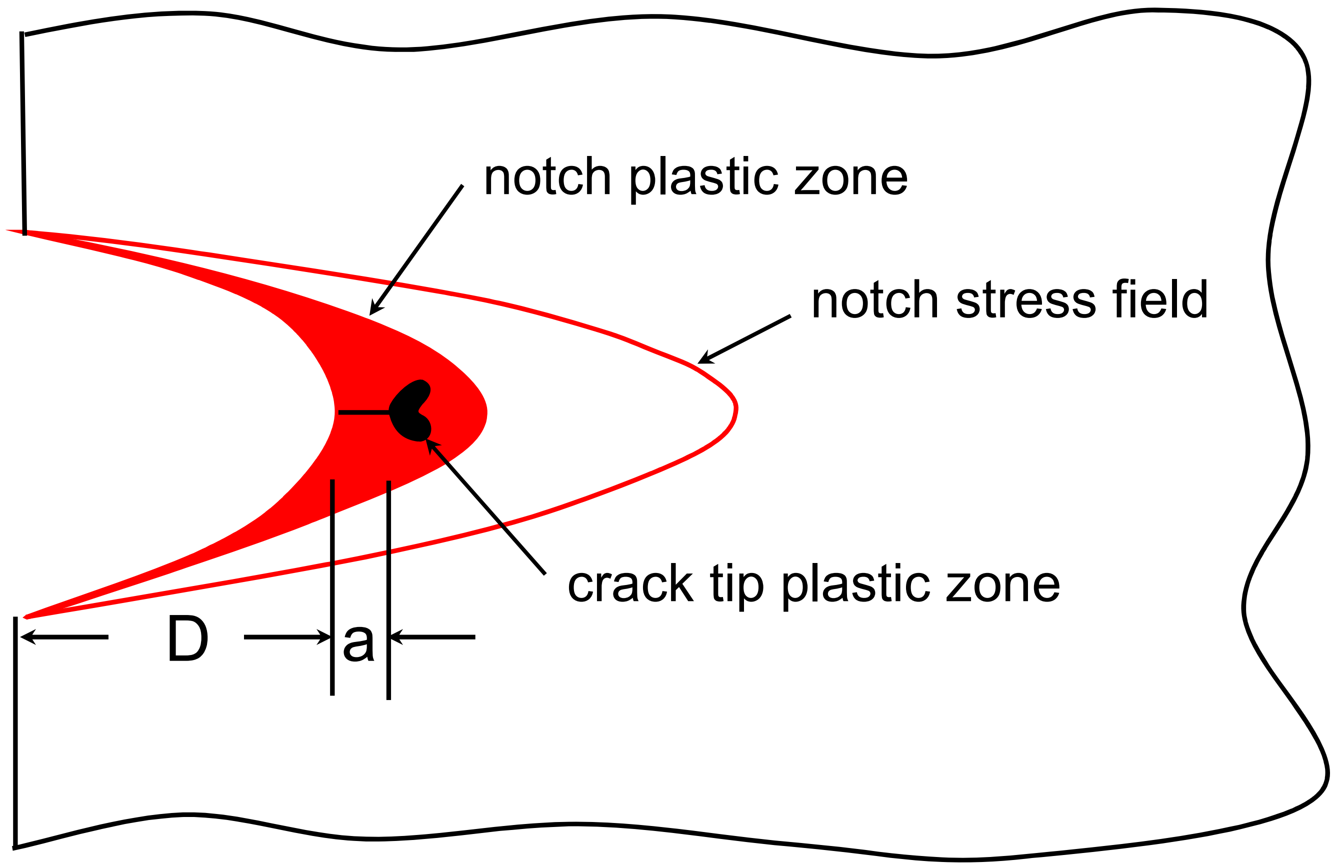


Growth from Notches

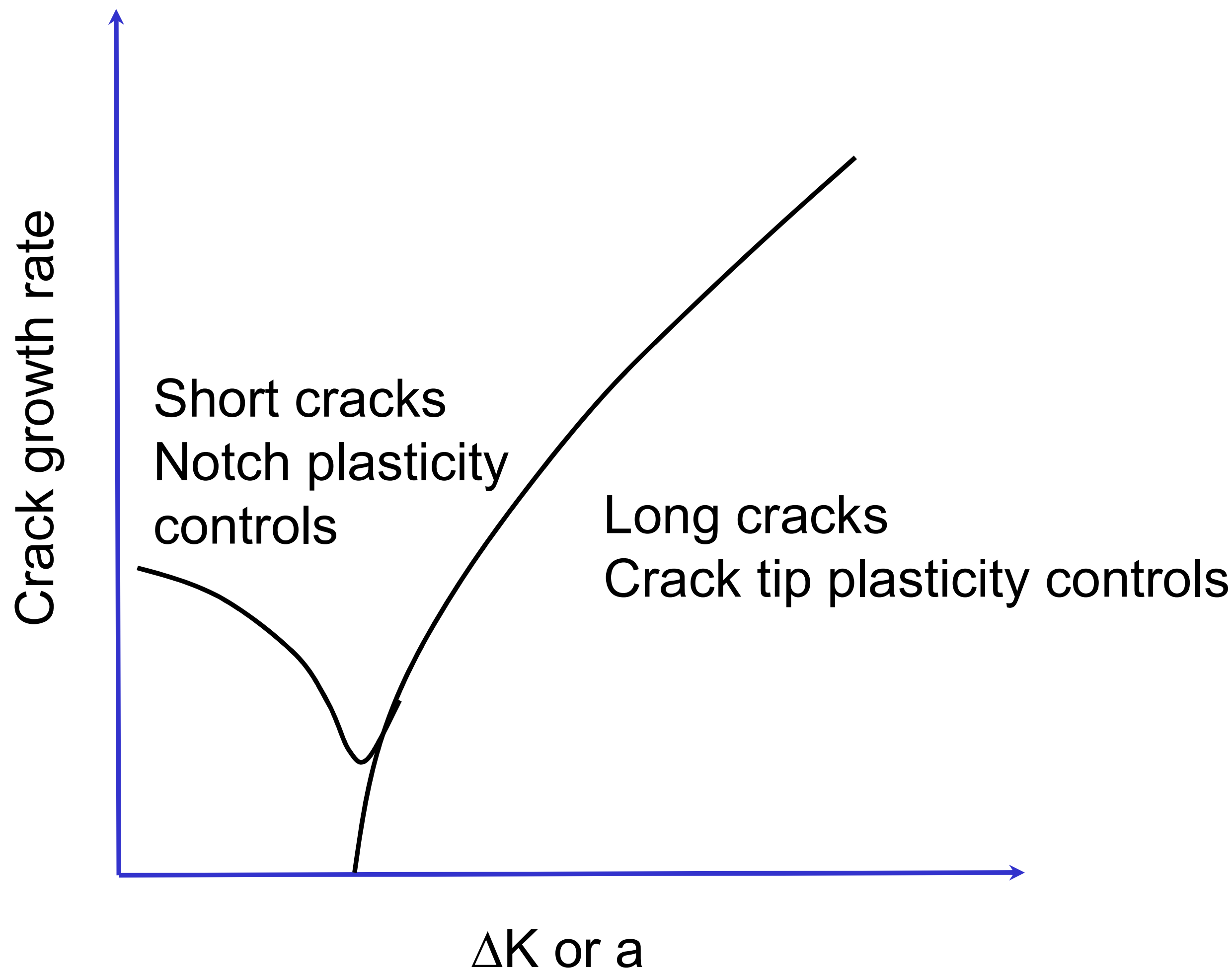


24 Propagation rate da/dN of cracks emanating from notches as function of maximum stress intensity factor K_{max} in 0.15%C mild steel; k_t is theoretical elastic stress concentration factor, R stress ratio, and R_ϵ edge strain ratio[110]

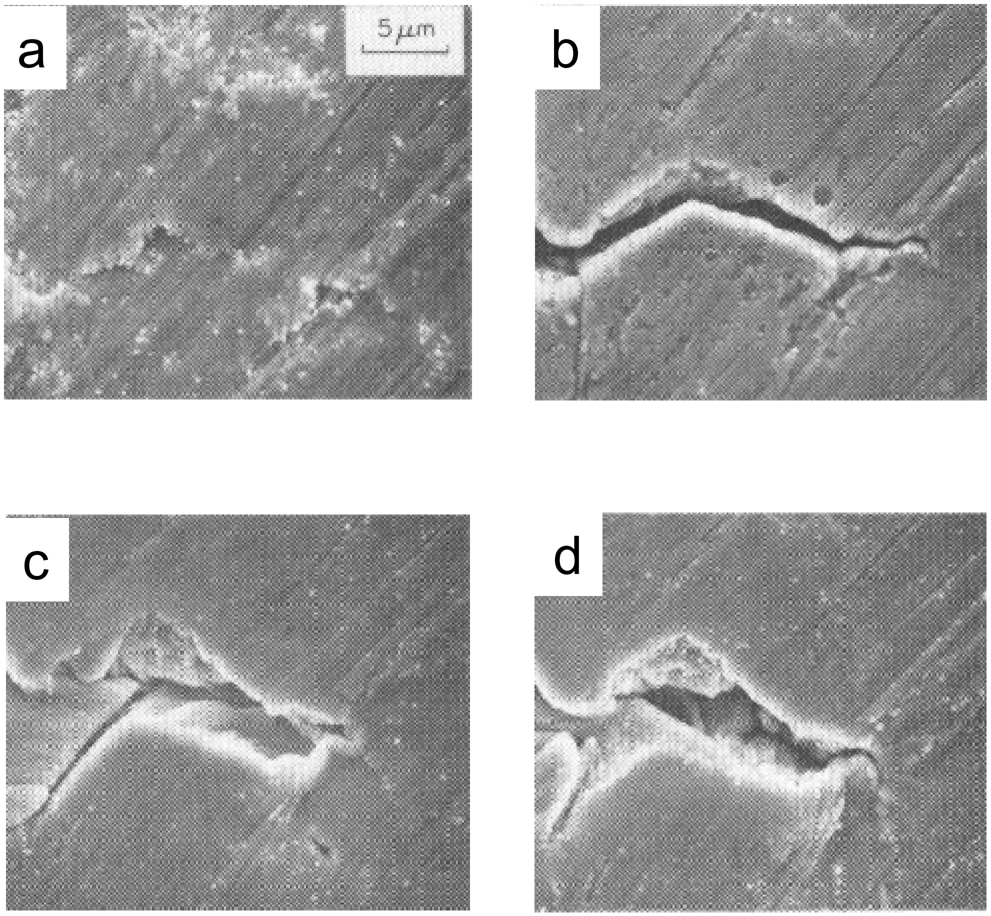
Cracks at Notches

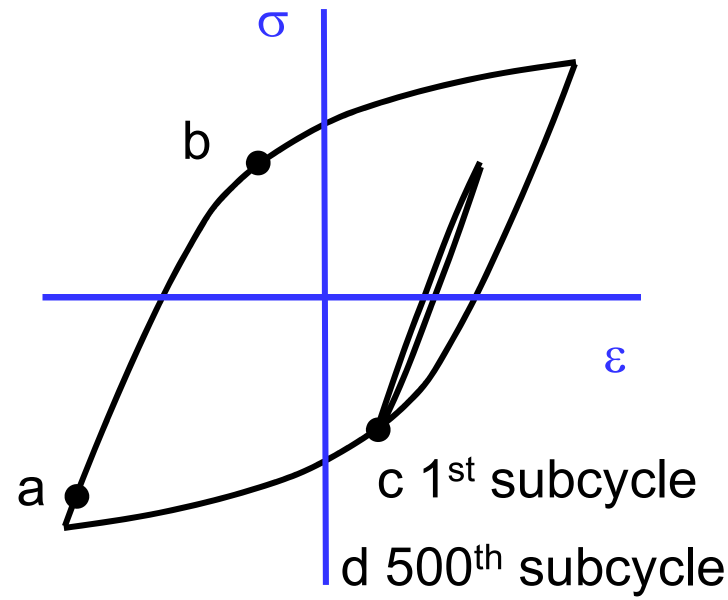


Crack Growth



Closure Observations



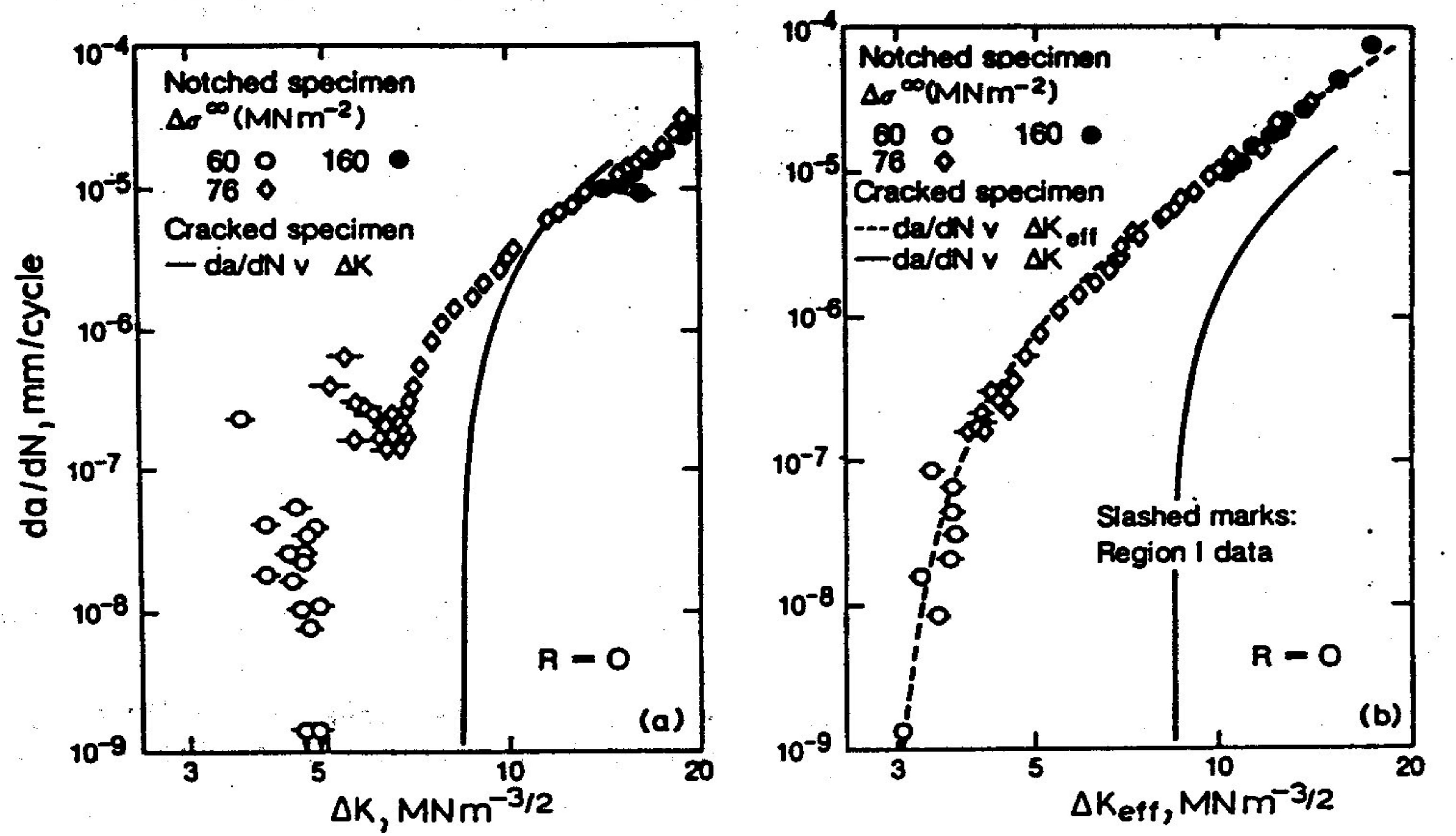


1026 steel

$\Delta\varepsilon_1/2 = 0.005$

$\Delta\varepsilon_2/2 = 0.001$

Closure Correlation



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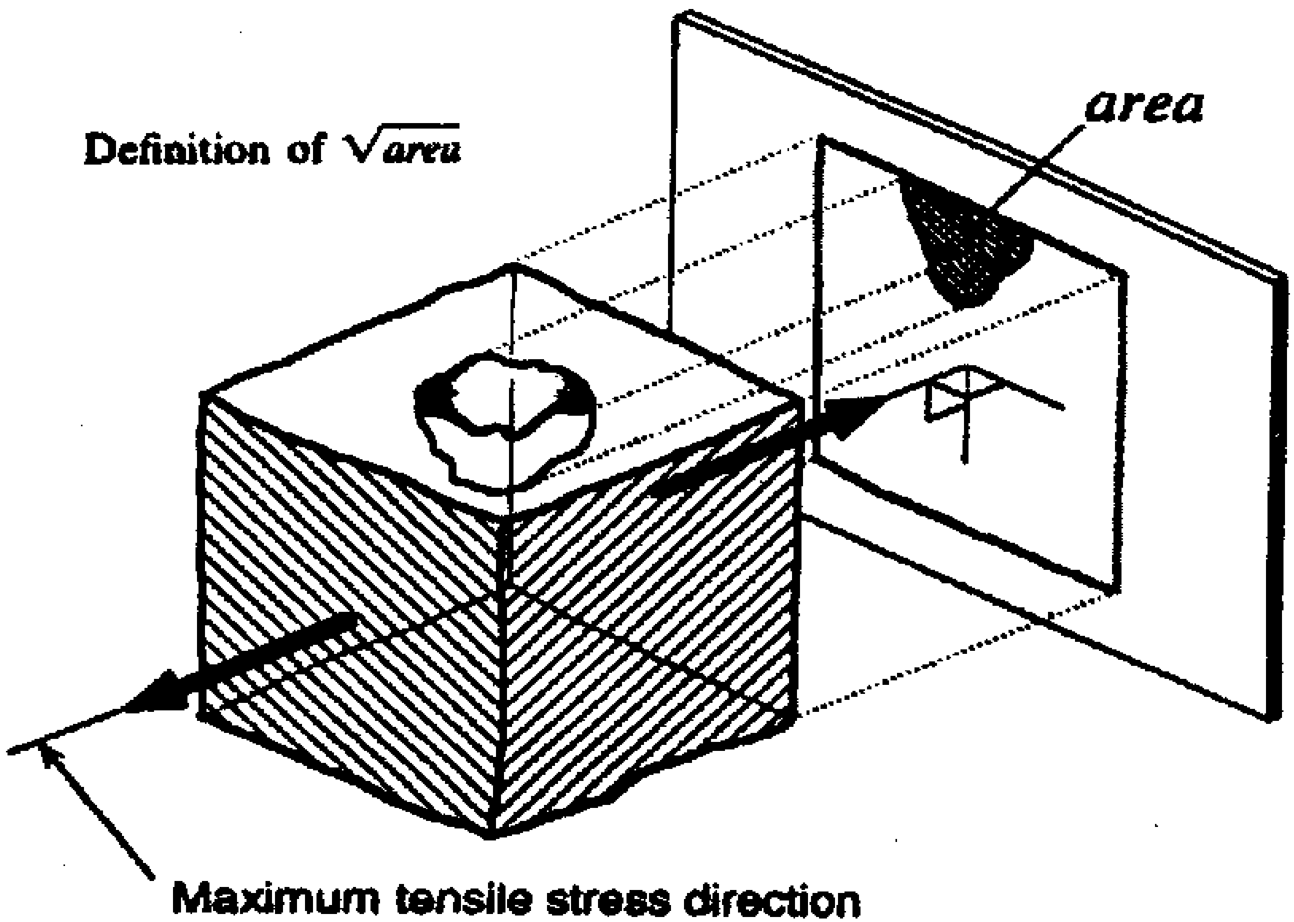
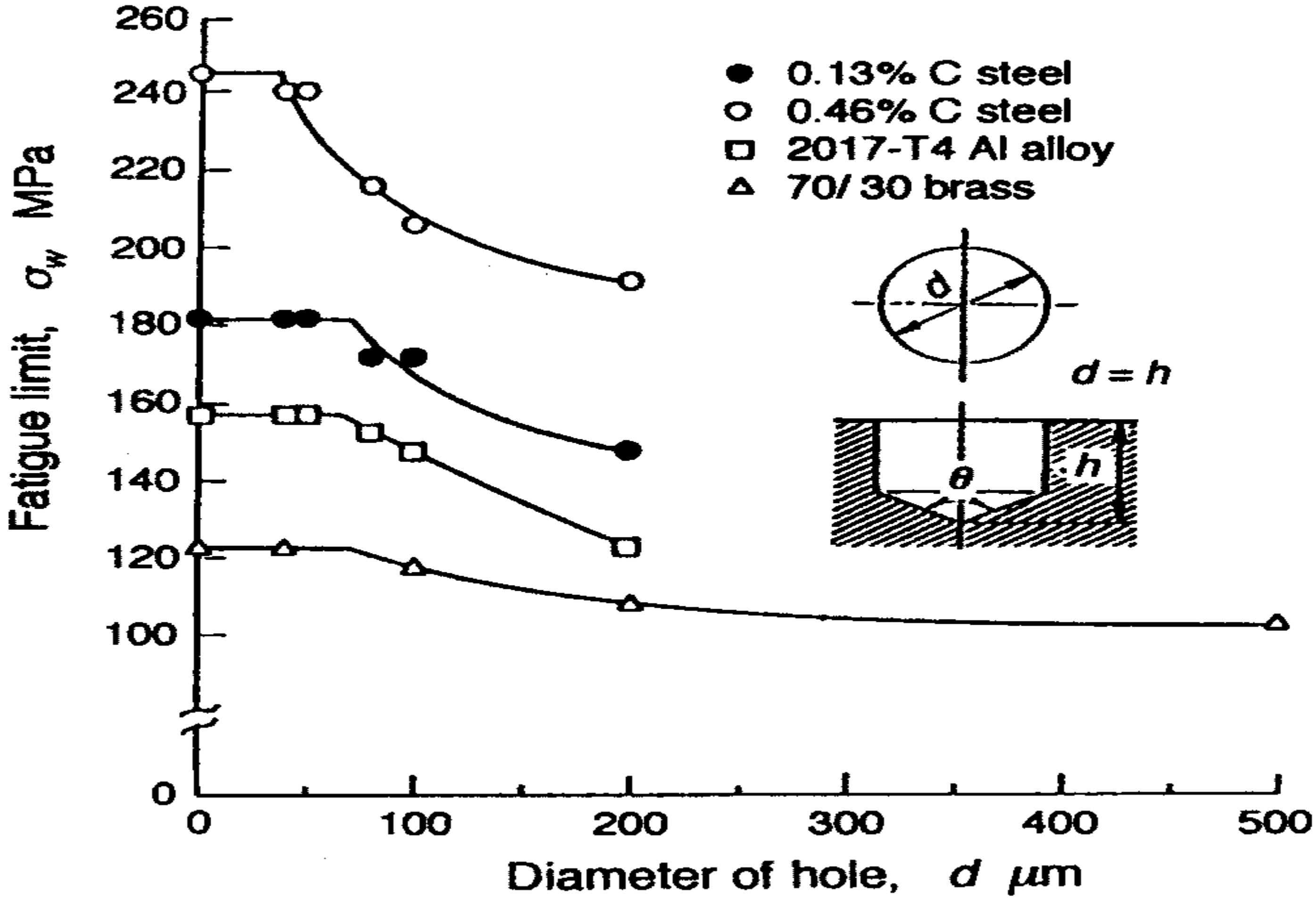
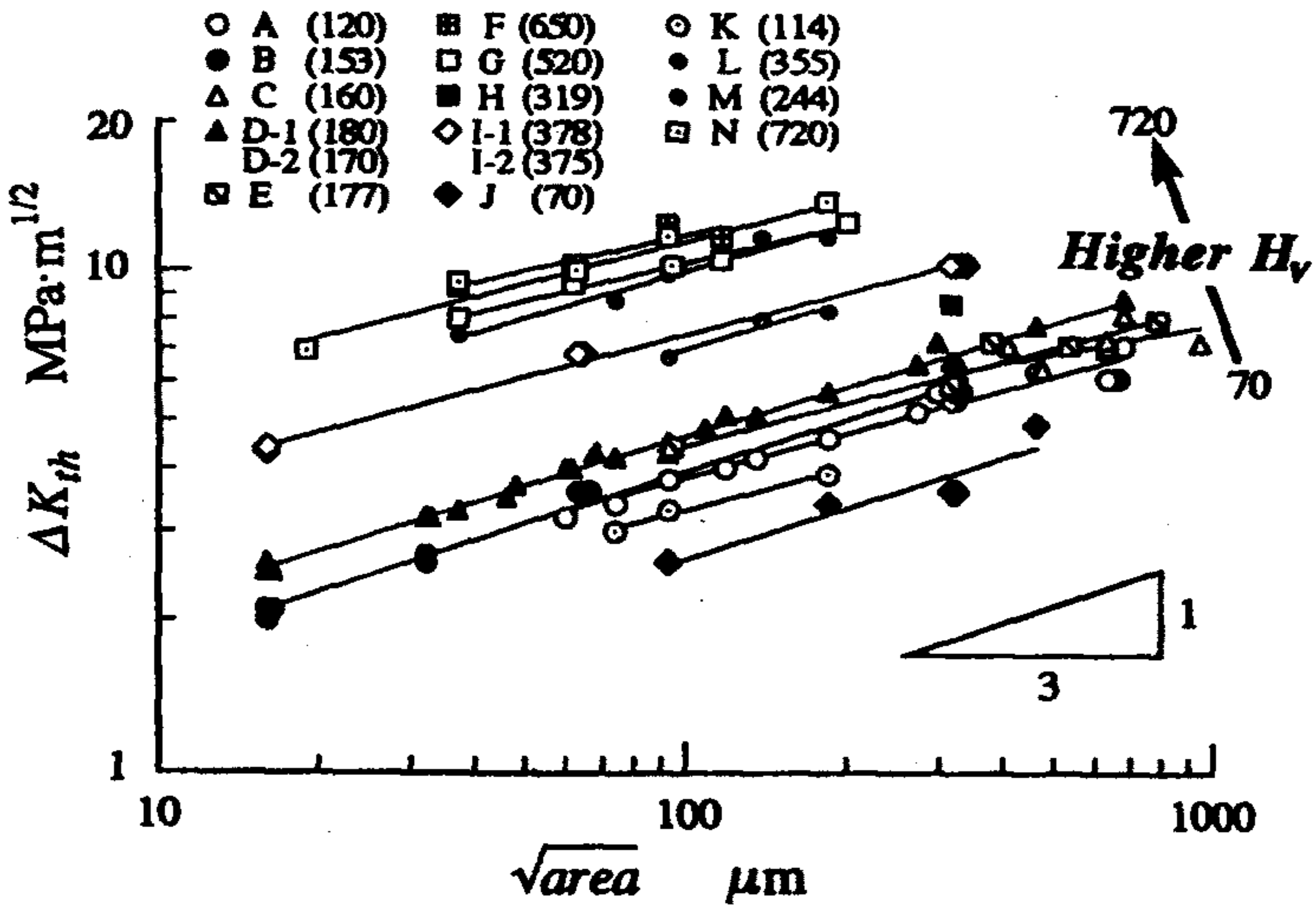


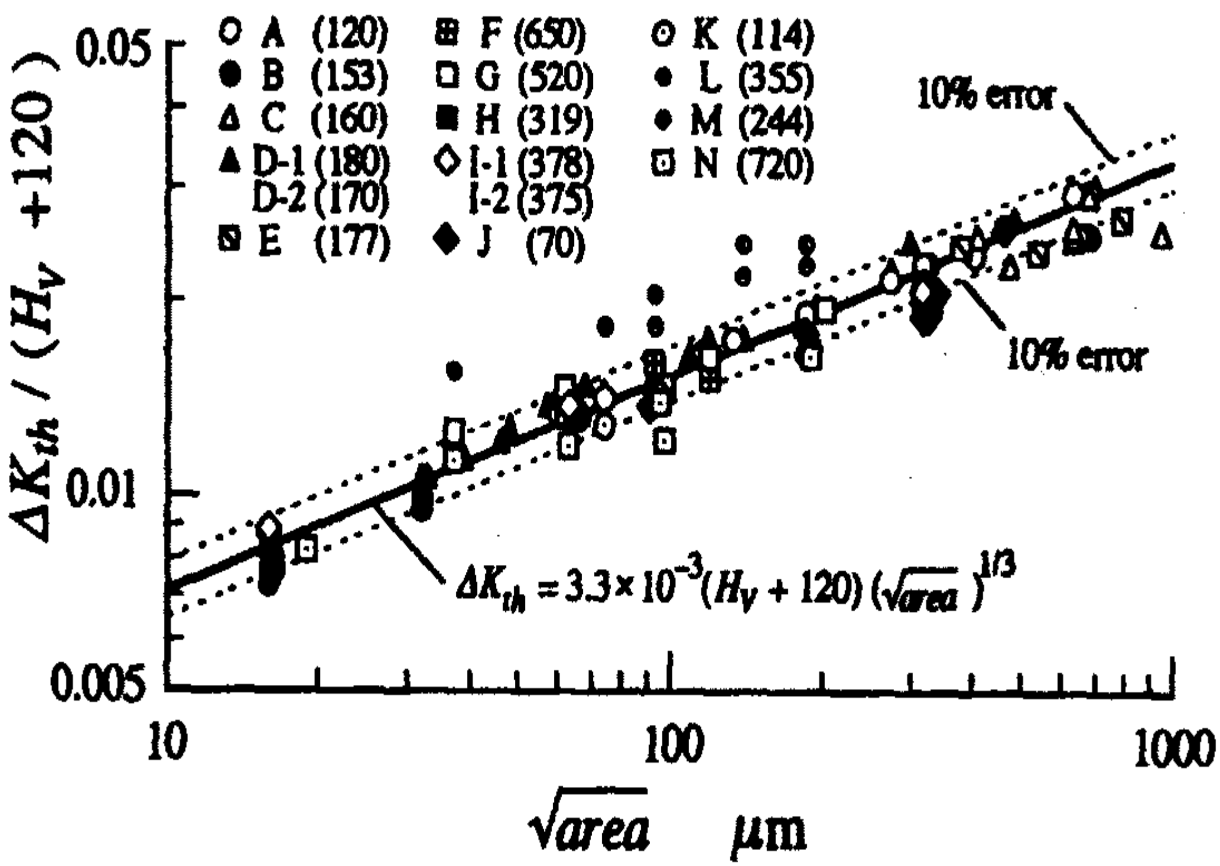
Small Notches



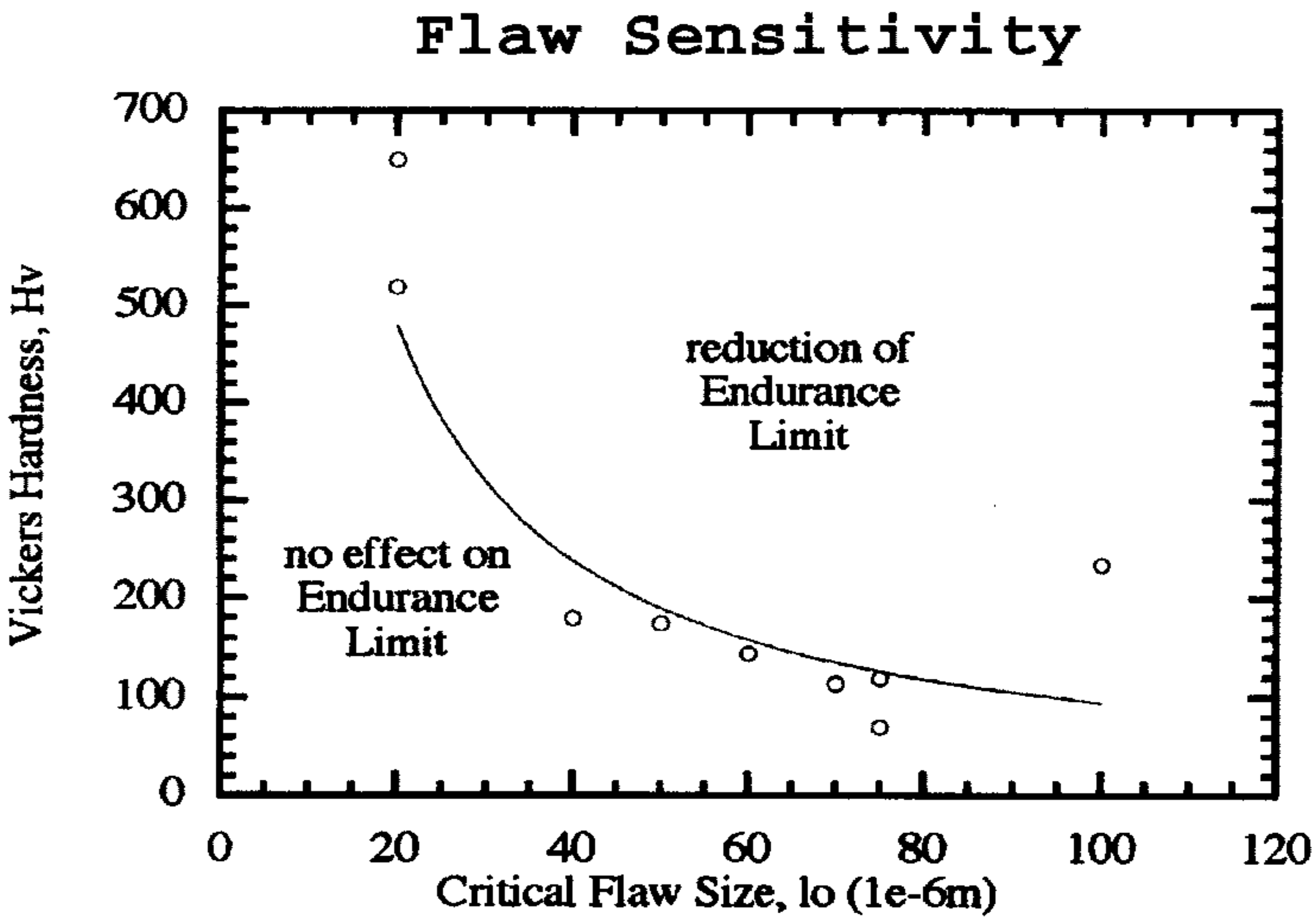
Threshold Stress Intensity



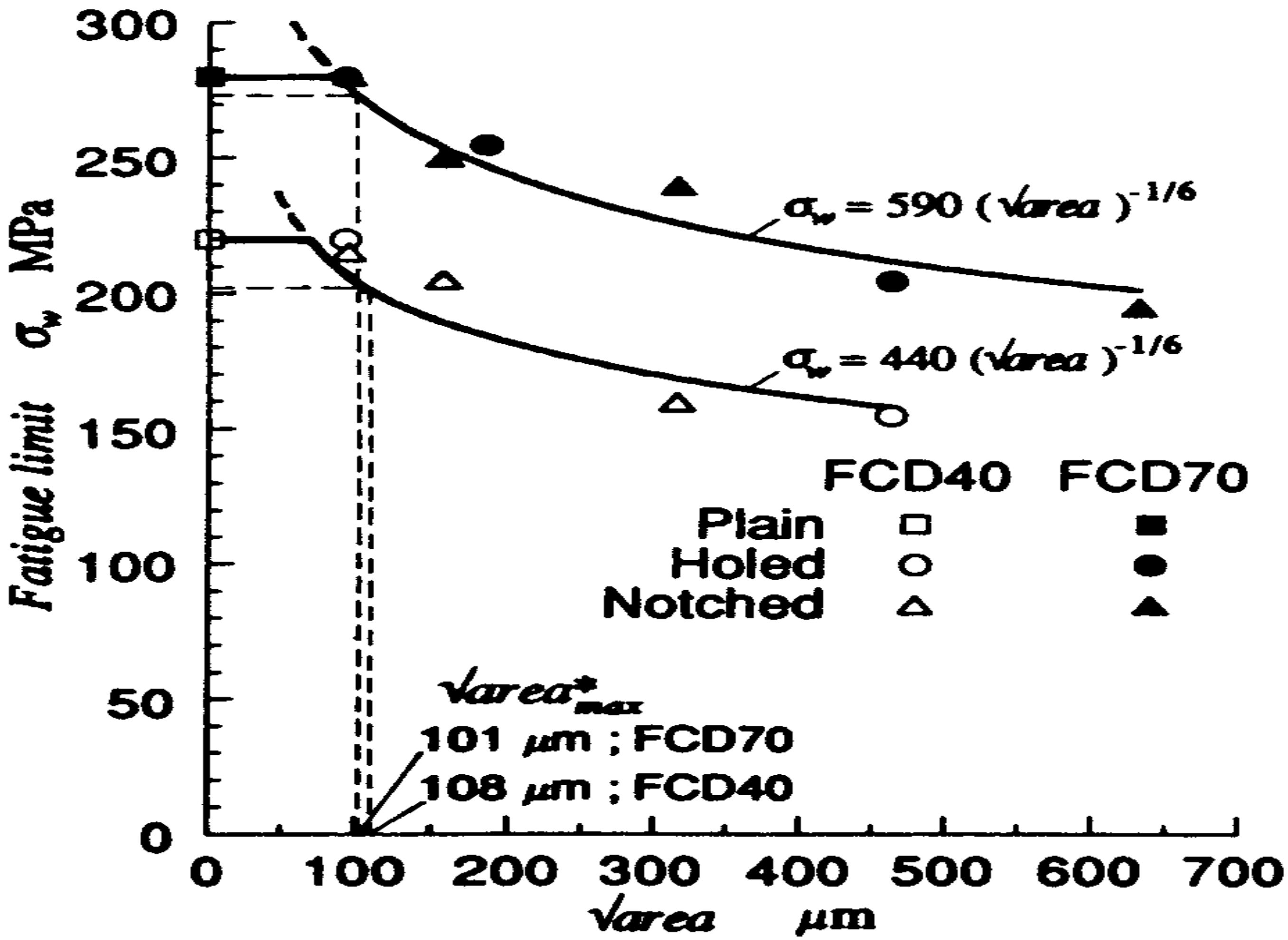
Hardness Corelation



Flaw Sensitivity



Fatigue Limit



Notches in Fatigue