Sequence Effects in Fatigue

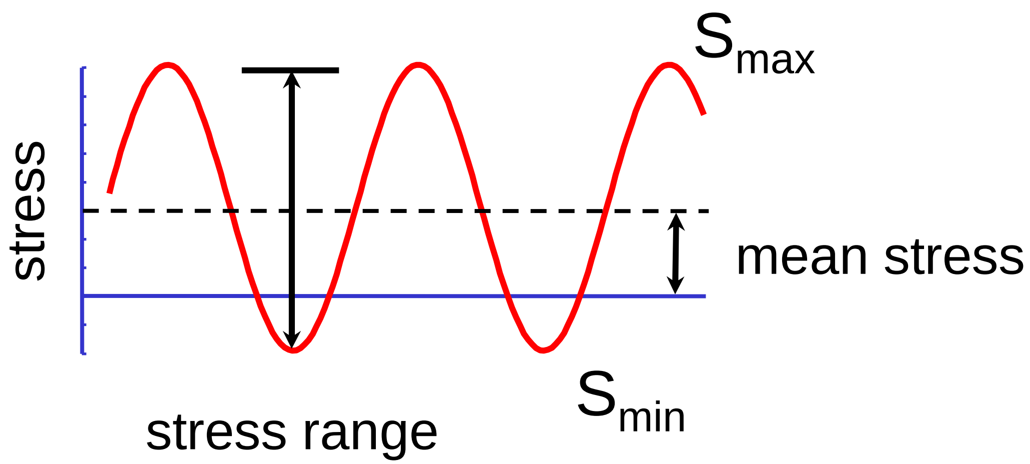
Professor Darrell F. Socie

University of Illinois at Urbana-Champaign

Outline

1. Mean Stress
2. Nonlinear Damage Models
3. Crack Growth Interactions
4. Crack Tip Plasticity Models
5. Crack Closure Models

Mean Stresses



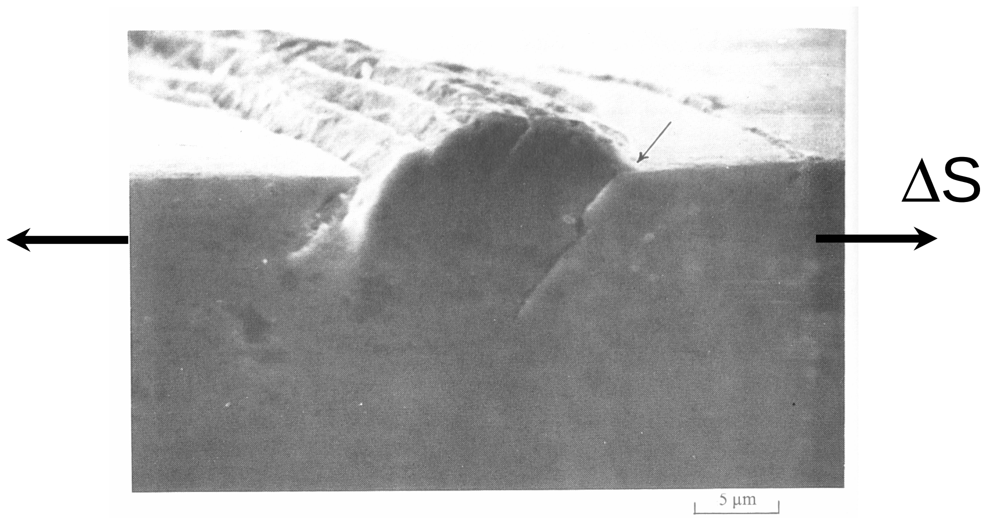
$$S_{mean} = \frac{S_{max} + S_{min}}{2}$$

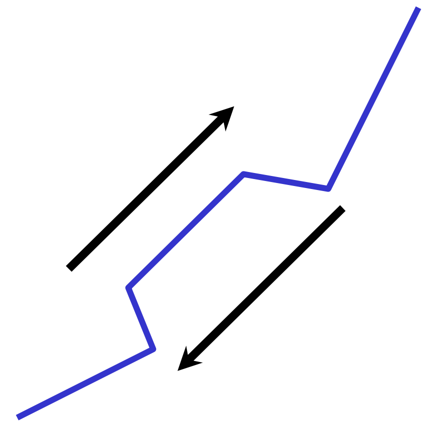
$$R = \frac{S_{min}}{S_{max}}$$

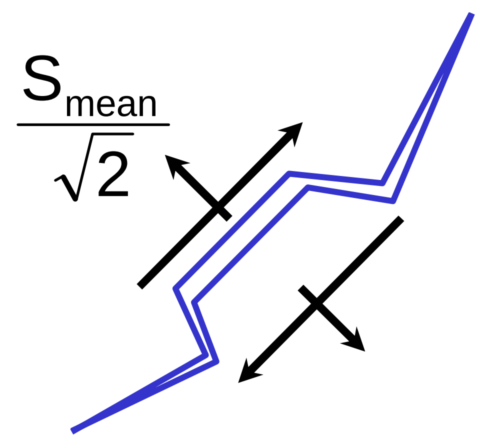
General Observations

- Tensile mean stresses reduce the fatigue life or decrease the allowable stress range
- Compressive mean stresses increase the fatigue life or increase the allowable stress range

Mechanism







Fatigue damage is a shear process

Tensile mean stresses open microcracks and make sliding easier

Goodman 1890

Mechanics Applied to Engineering
John Goodman, 1890

".. whether the assumptions of the theory are justifiable or not …. We adopt it simply because it is the easiest to use, and for all practical purposes, represents Wöhlers data.

$$S_{ultimate} = S_{min} + 2\,\Delta S$$

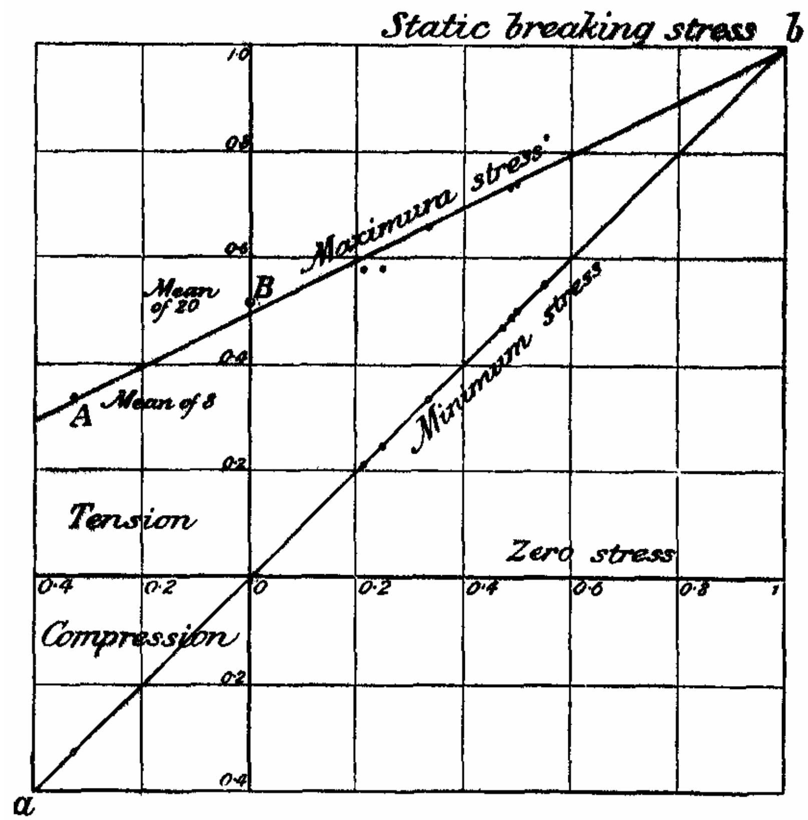
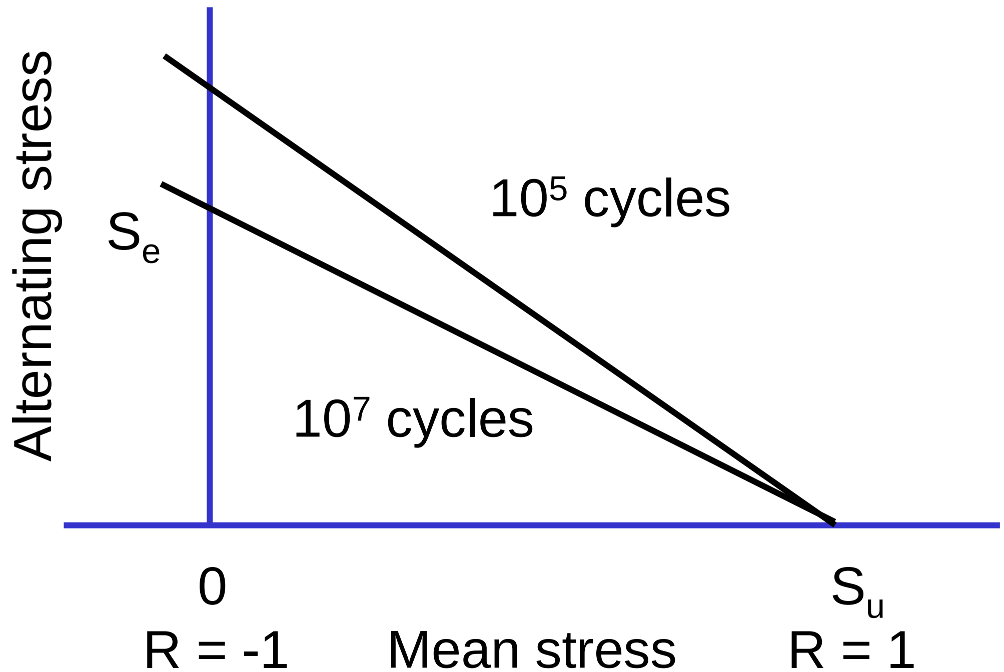


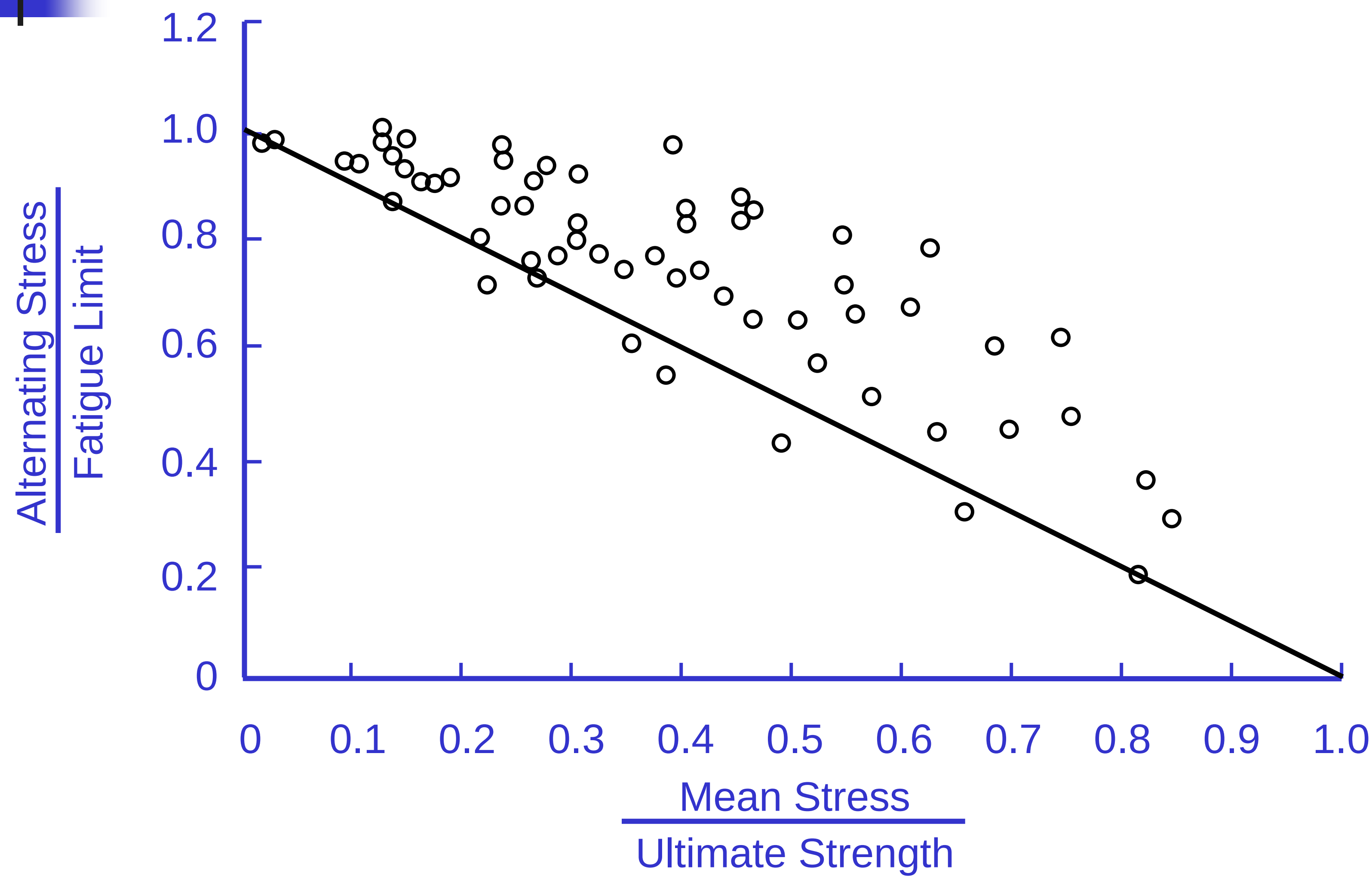
FIG. 517.

Goodman Diagram



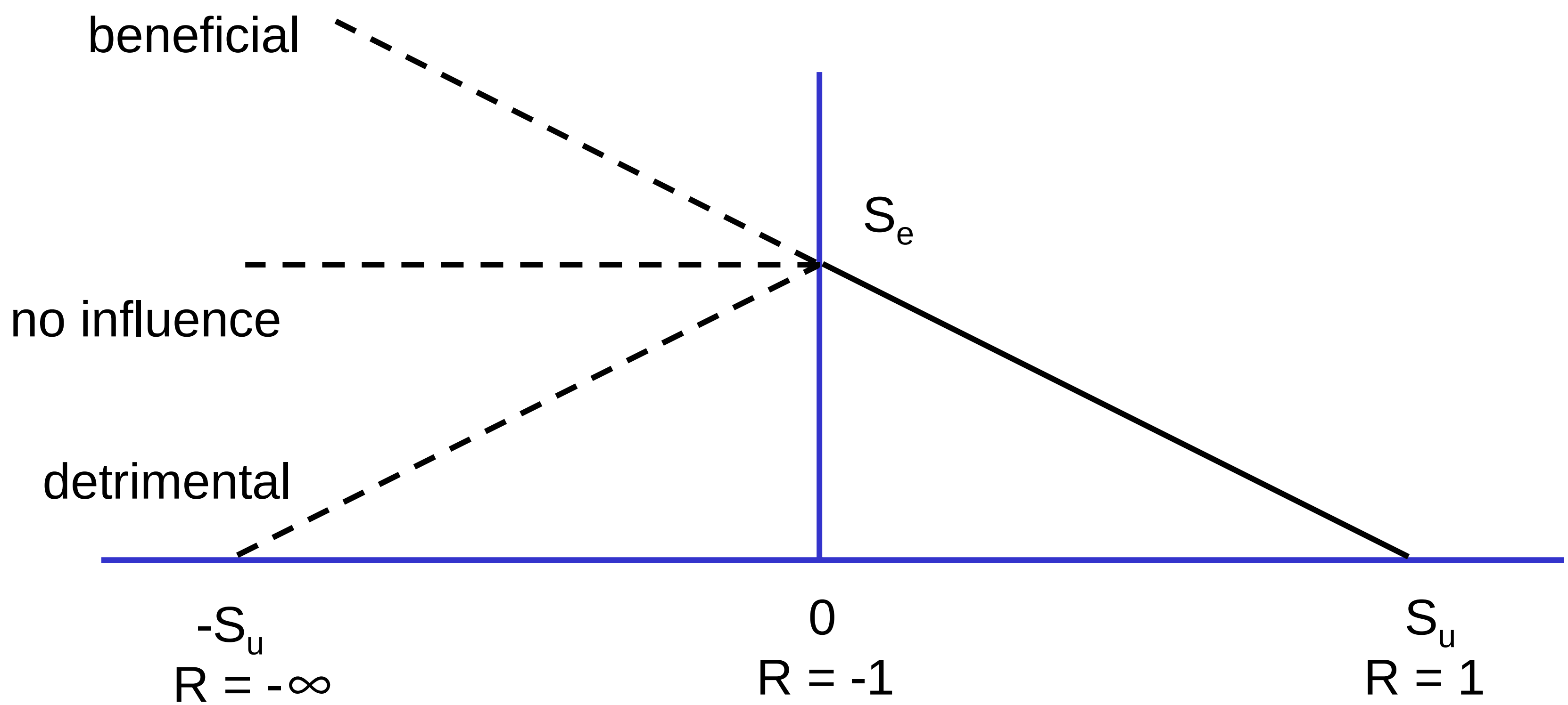
$$\frac{\Delta S}{2} = \left(\frac{\Delta S}{2}\right)_{R=-1}\left(1 - \frac{S_{mean}}{S_{ultimate}}\right)$$

Test Data (1941)

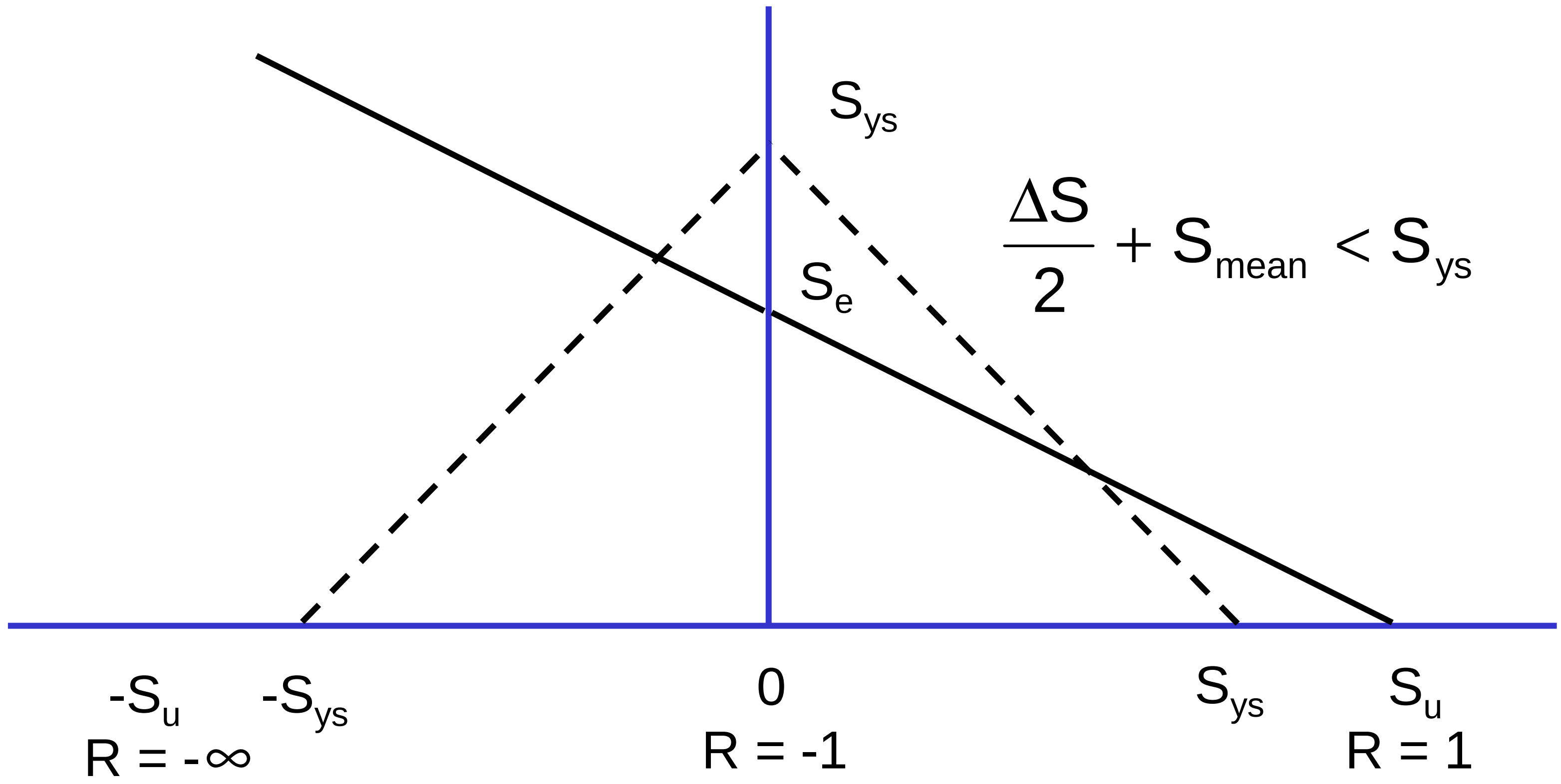


J.O. Smith, The Effect of Range of Stress on the Fatigue Strength of Metals, Engineering Experiment Station Bulletin 334, University of Illinois, 1941

Compression

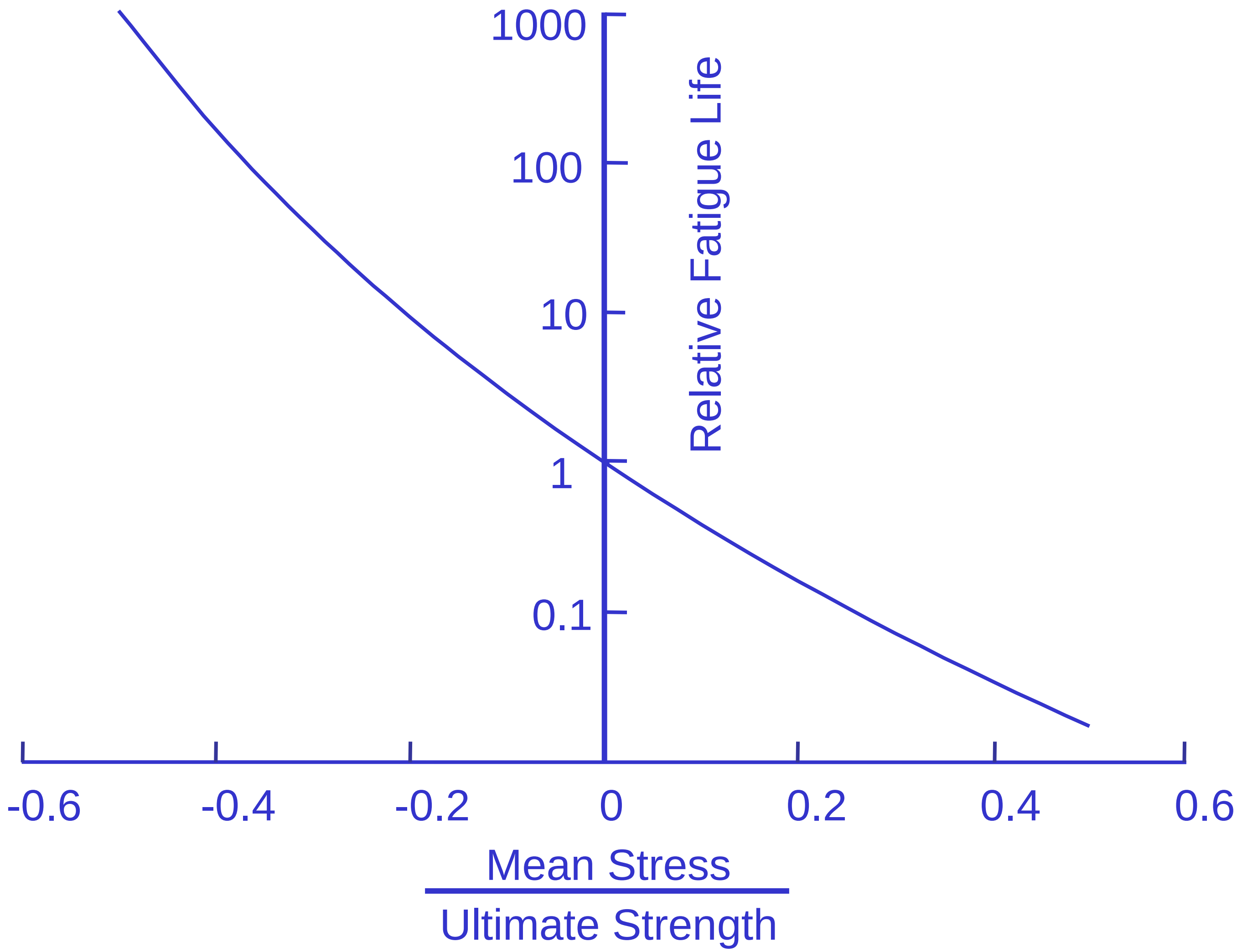


Modified Goodman (no yielding)

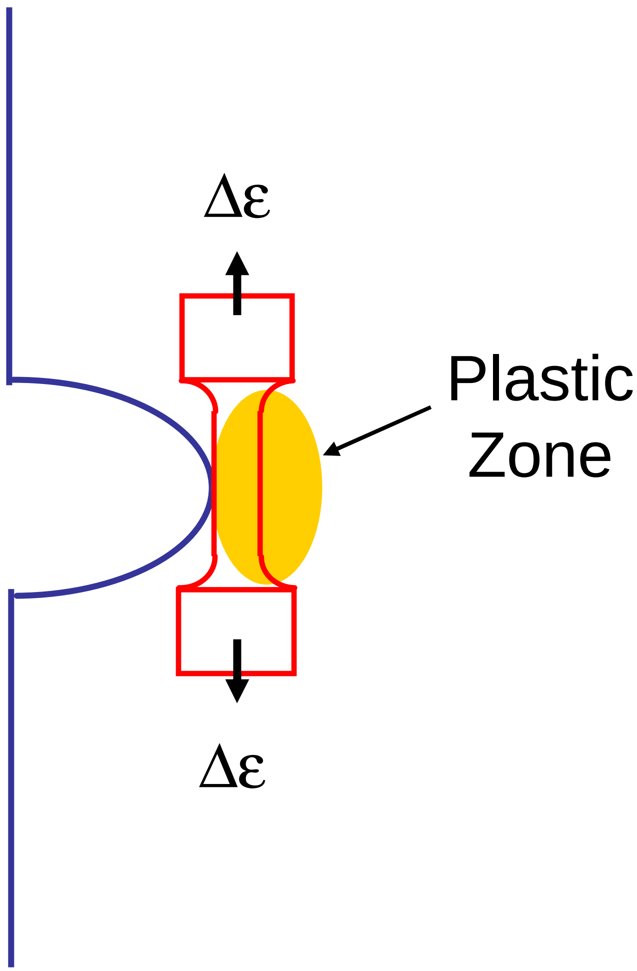


$$\frac{\Delta S}{2} + S_{mean} < S_{ys}$$

Mean Stress Influence on Life

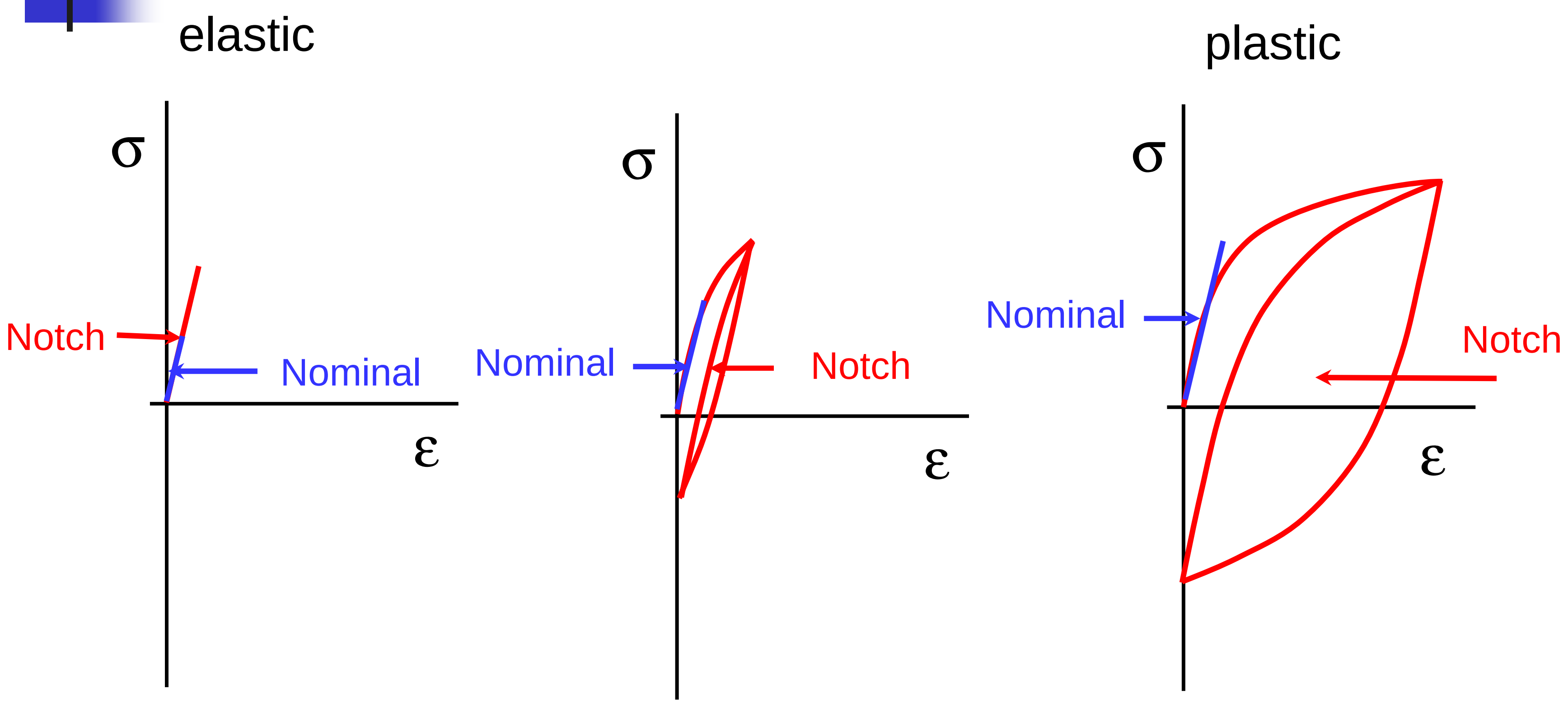


Stress Concentrations



The elastic material surrounding the plastic zone around a stress concentration forces the material to deform in strain control

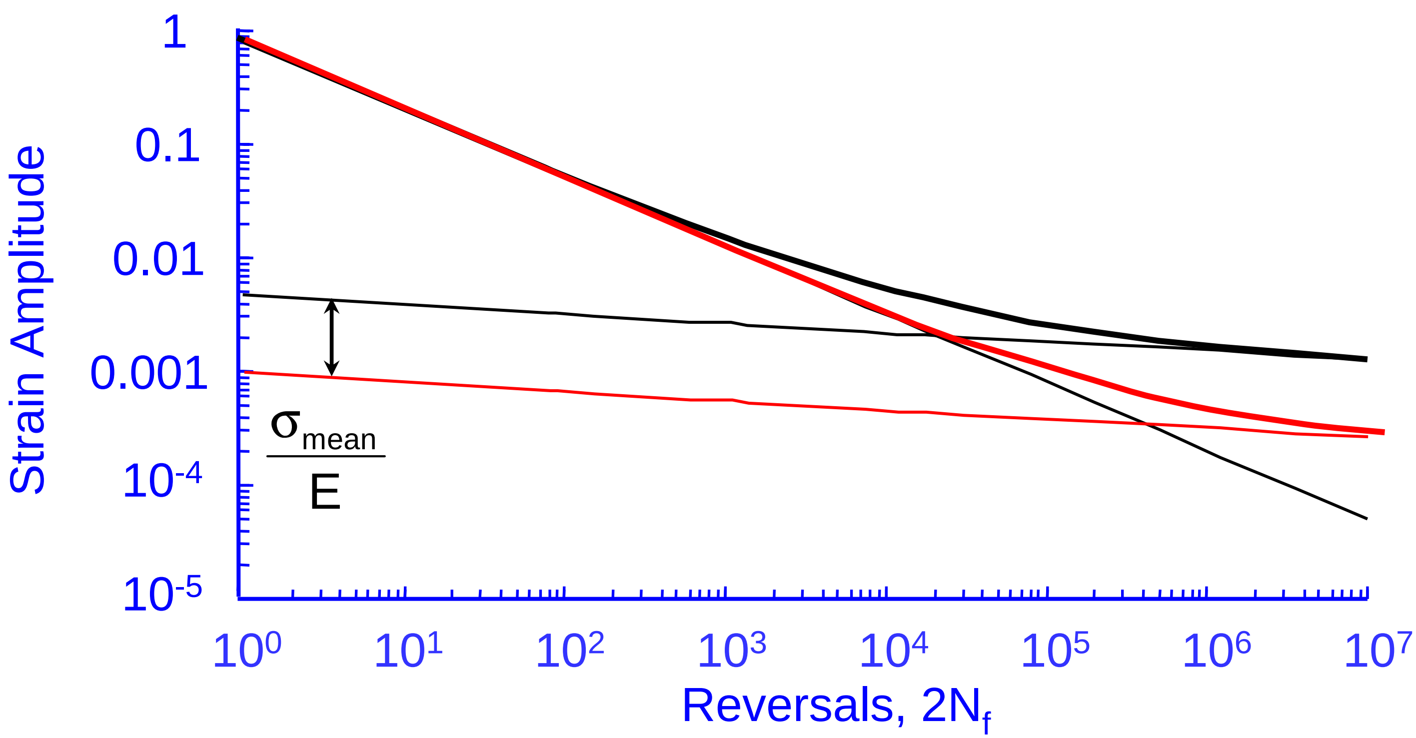
Mean Stresses at Notches



Nominal mean stress is less than notch mean stress

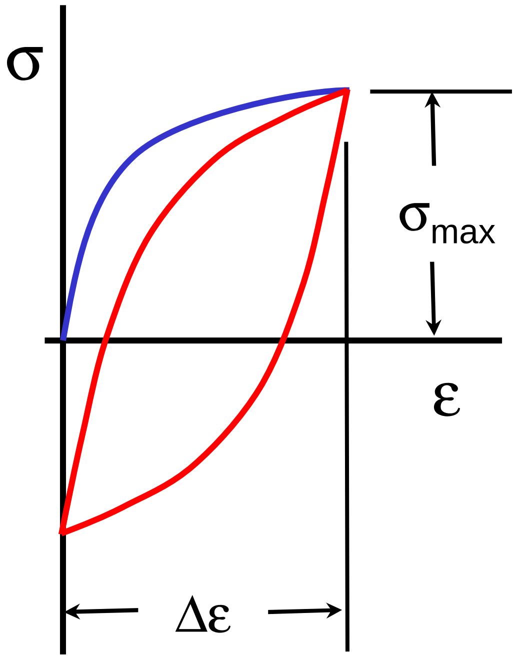
Nominal mean stress is greater than notch mean stress

Morrow Mean Stress Correction



$$\frac{\Delta\varepsilon}{2} = \frac{\sigma_f^{'} - \sigma_{mean}}{E}(2N_f)^b + \varepsilon_f^{'}(2N_f)^c$$

Smith Watson Topper



$$\sigma_{max}\frac{\Delta\varepsilon}{2}=\frac{\sigma_f'^{\,2}}{E}(2N_f)^{2b}+\sigma_f'\varepsilon_f'(2N_f)^{b+c}$$

Mean Stress Relaxation

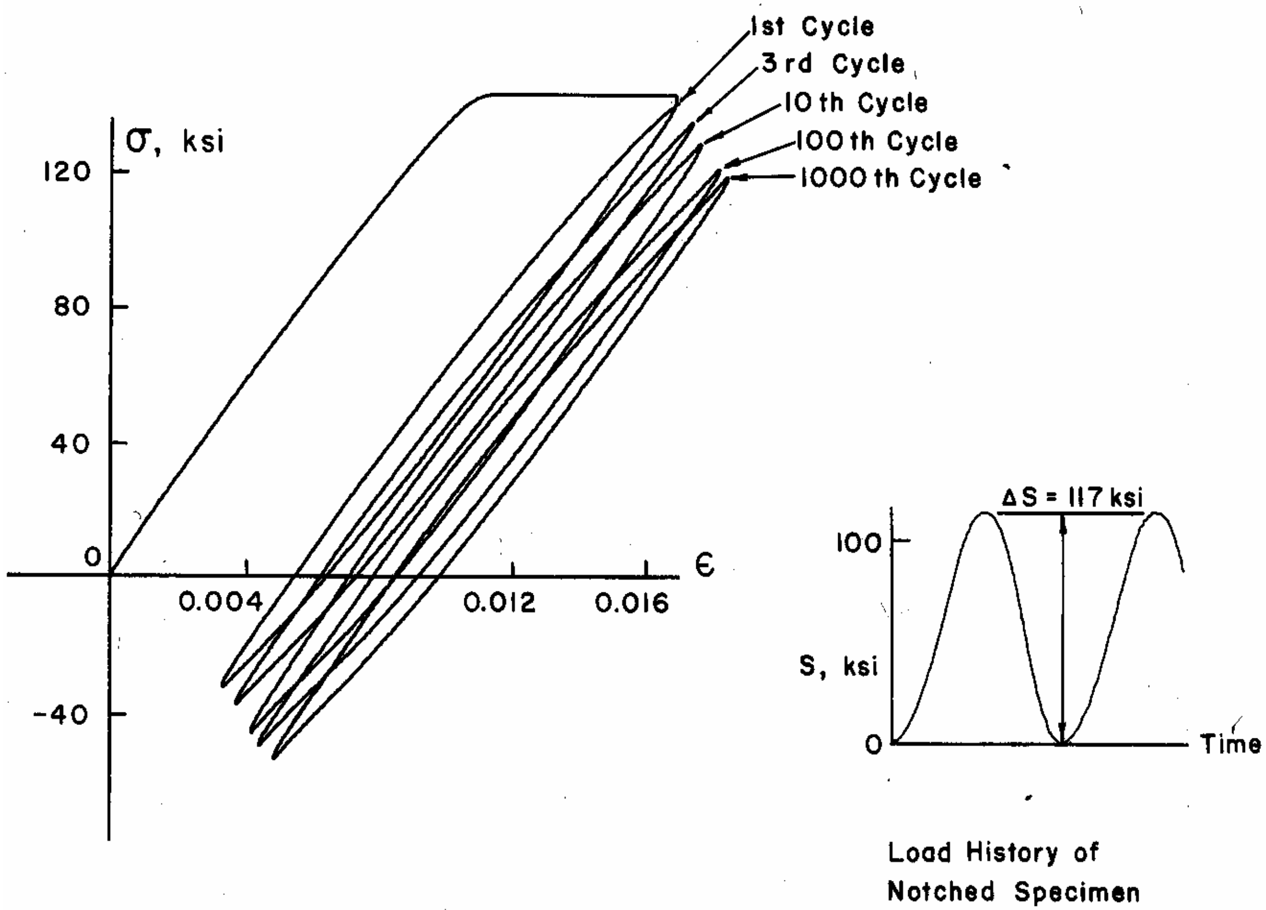
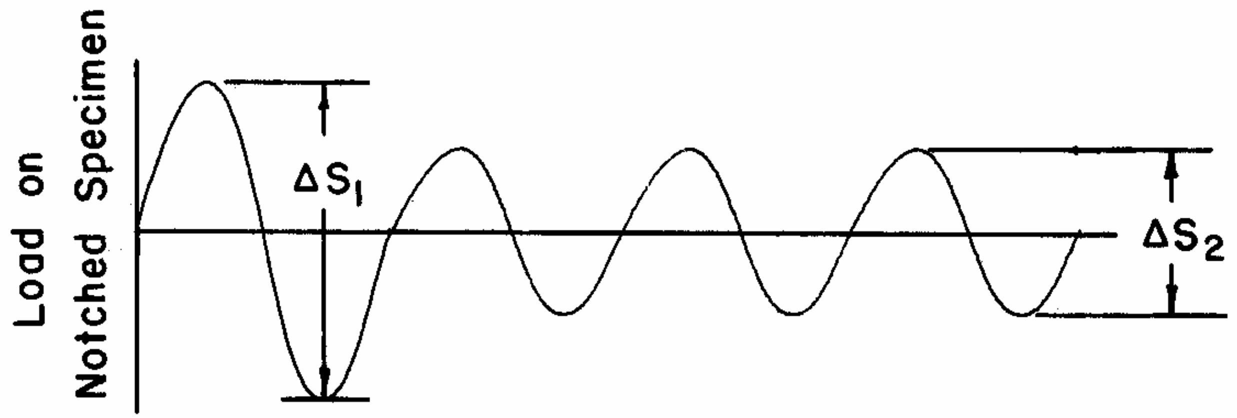


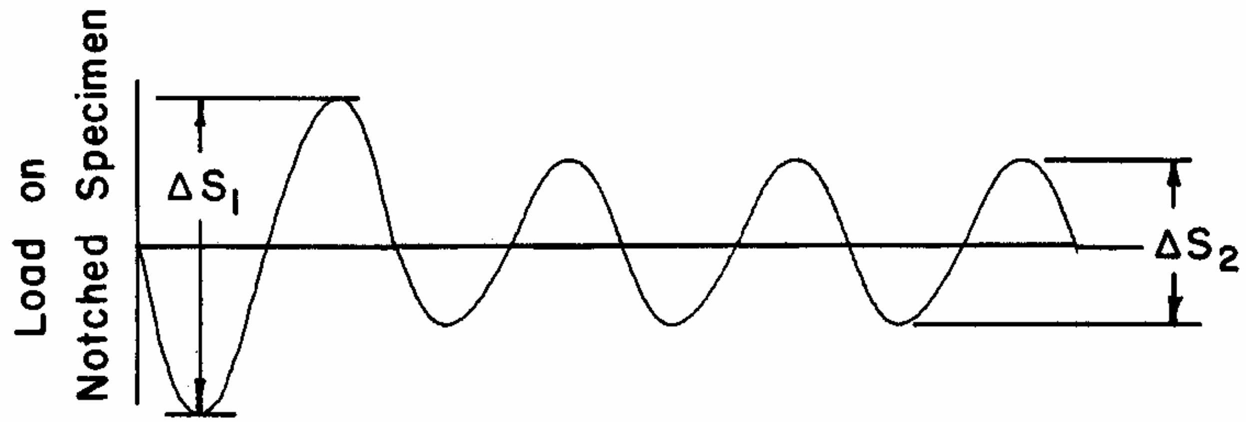
FIG. 7—*Cyclic softening and relaxation of mean stress under Neuber control (Ti-8Al-1Mo-1V,* $K_t = 1.75$*).*

Stadnick and Morrow, "Techniques for Smooth Specimen Simulation of Fatigue Behavior of Notched Members" ASTM STP 515, 1972, 229-252

Loading Histories

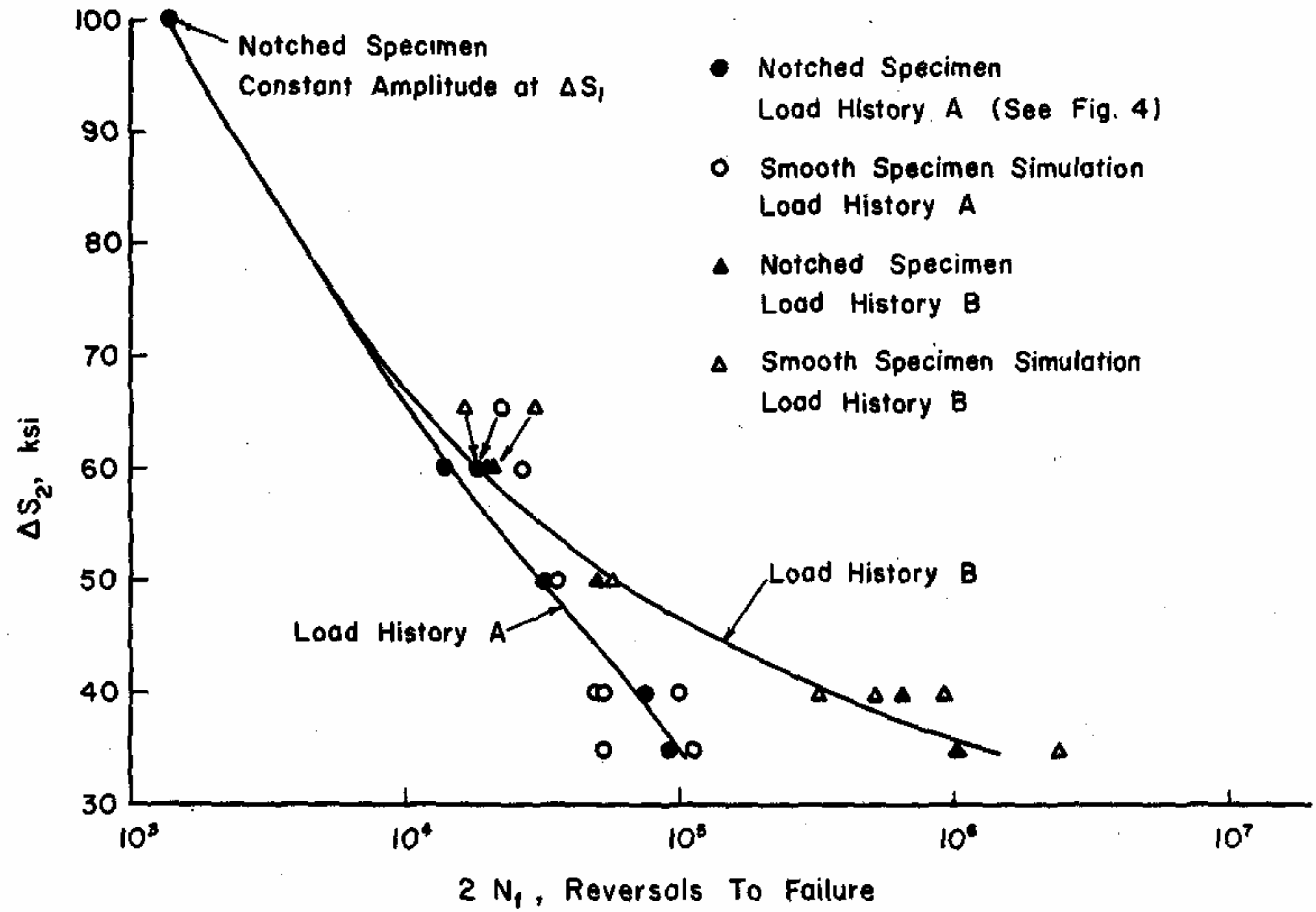


Load History A



Load History B

Test Results

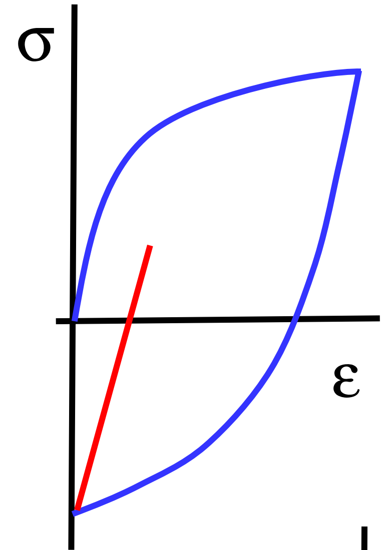


Sources of Mean/Residual Stress

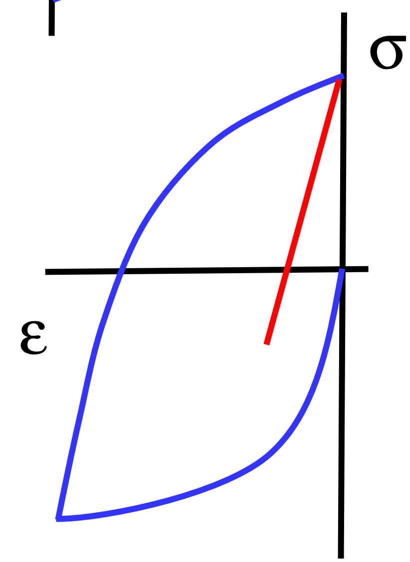
- Loading History
- Fabrication
- Shot Peening
- Heat Treating

Loading History

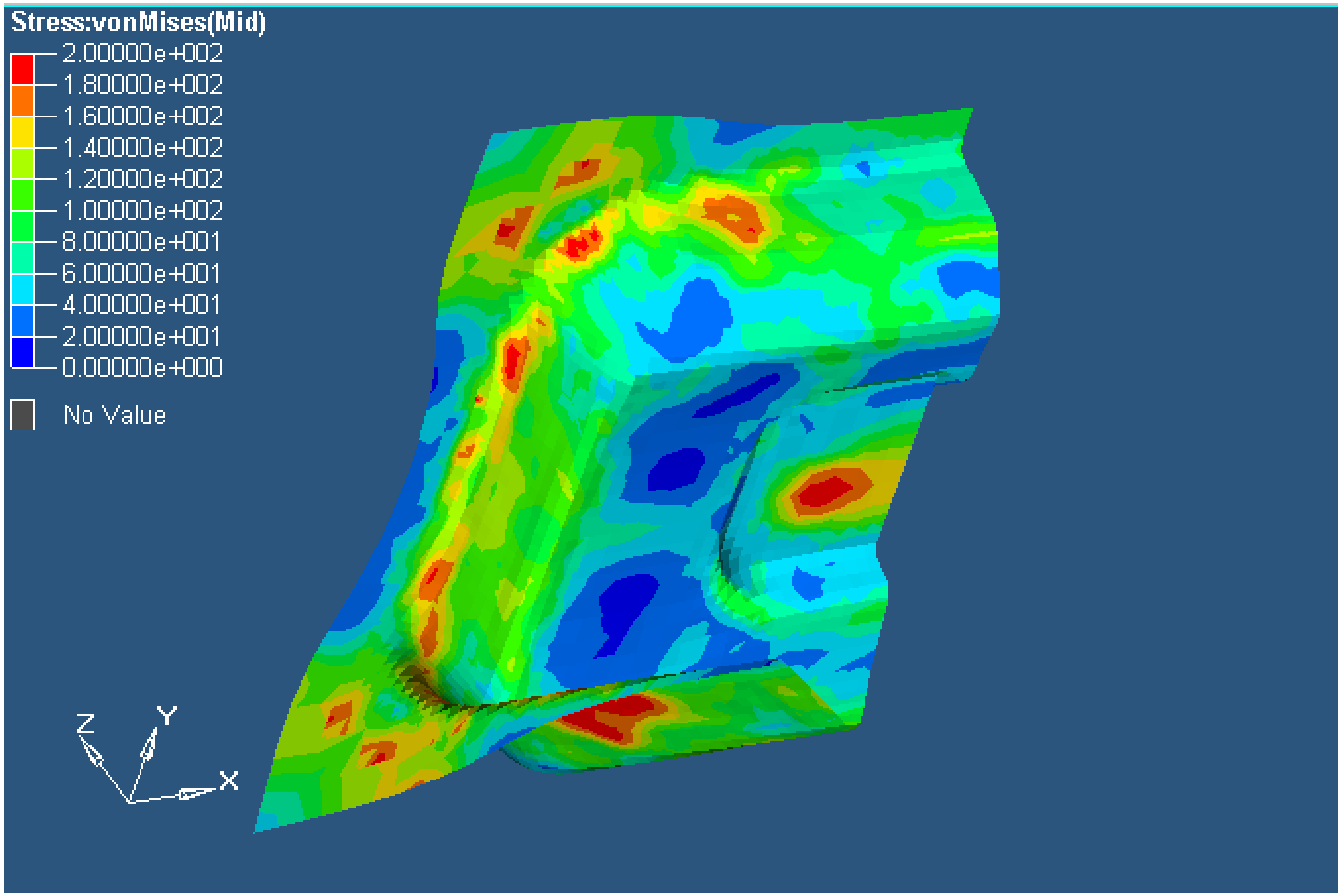
Tension overloads produce favorable compressive residual stress



Compressive overloads produce unfavorable tensile residual stress

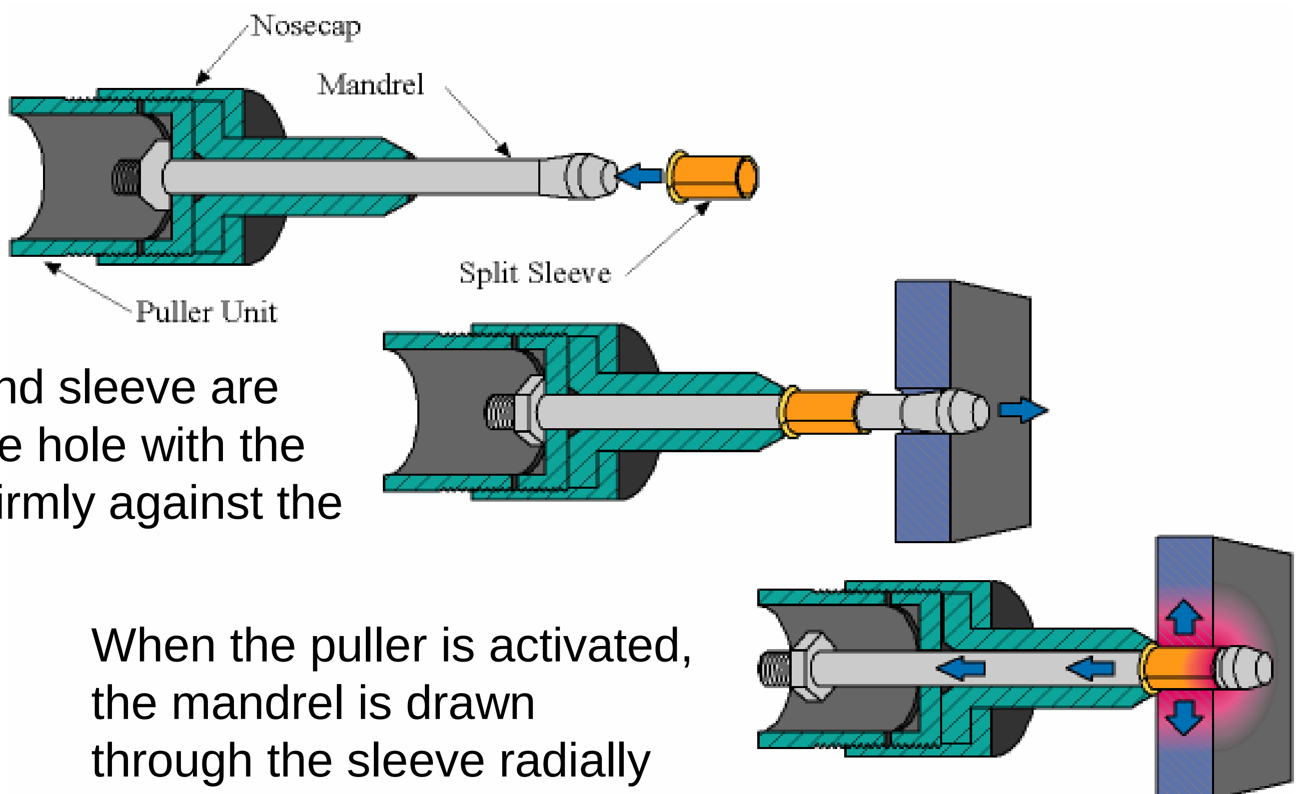


Fabrication



Cold Expansion

1965 Basic Cx process conceptualized (Boeing)



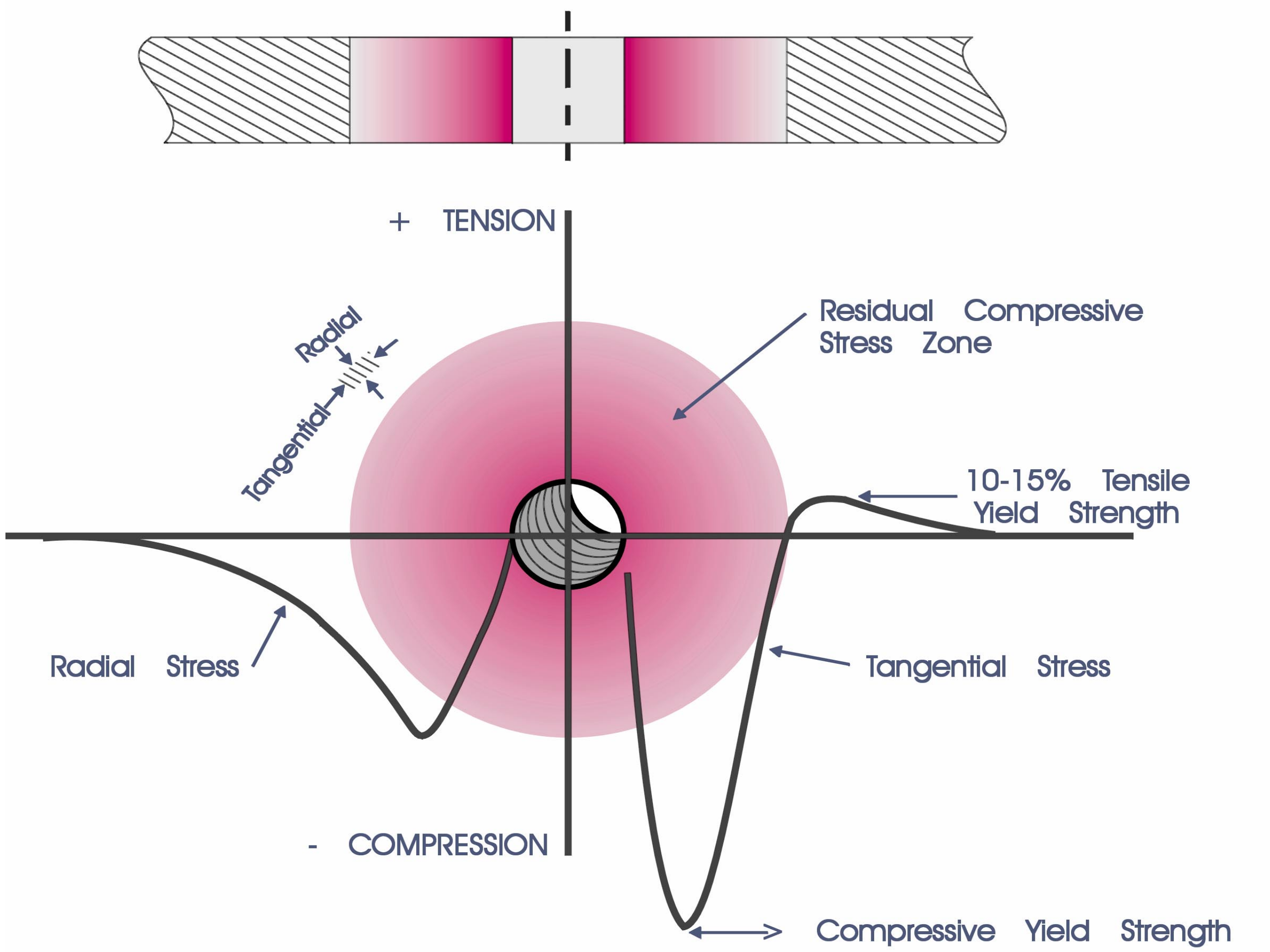
The split sleeve is slipped onto the mandrel, which is attached to the hydraulic puller unit.

The mandrel and sleeve are inserted into the hole with the nosecap held firmly against the workpiece.

When the puller is activated, the mandrel is drawn through the sleeve radially expanding the hole.

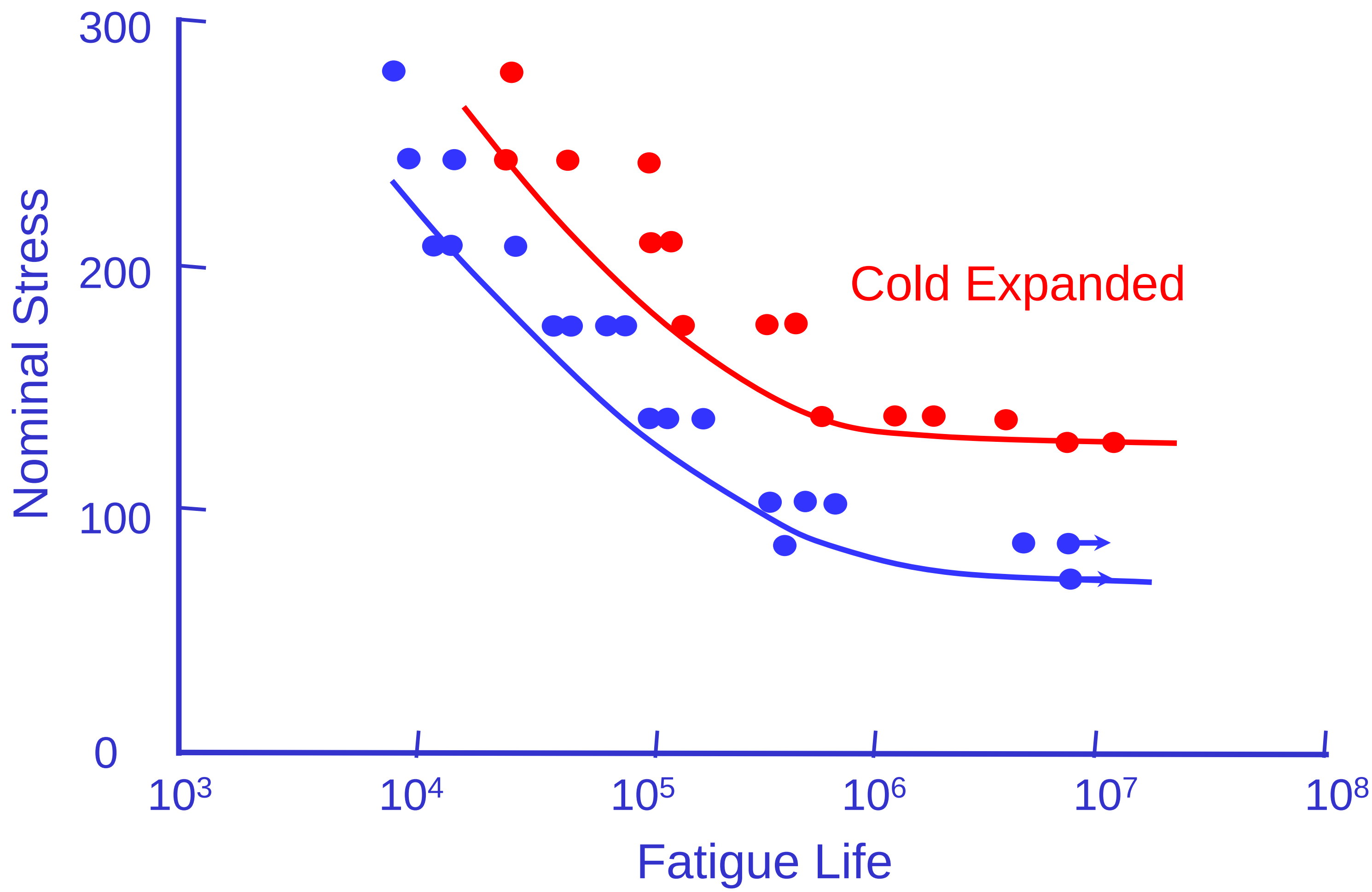
Courtesy of Fatigue Technology Inc.

Theory of Cold Expansion



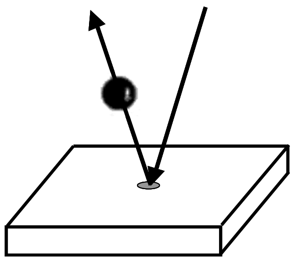
Courtesy of Fatigue Technology Inc.

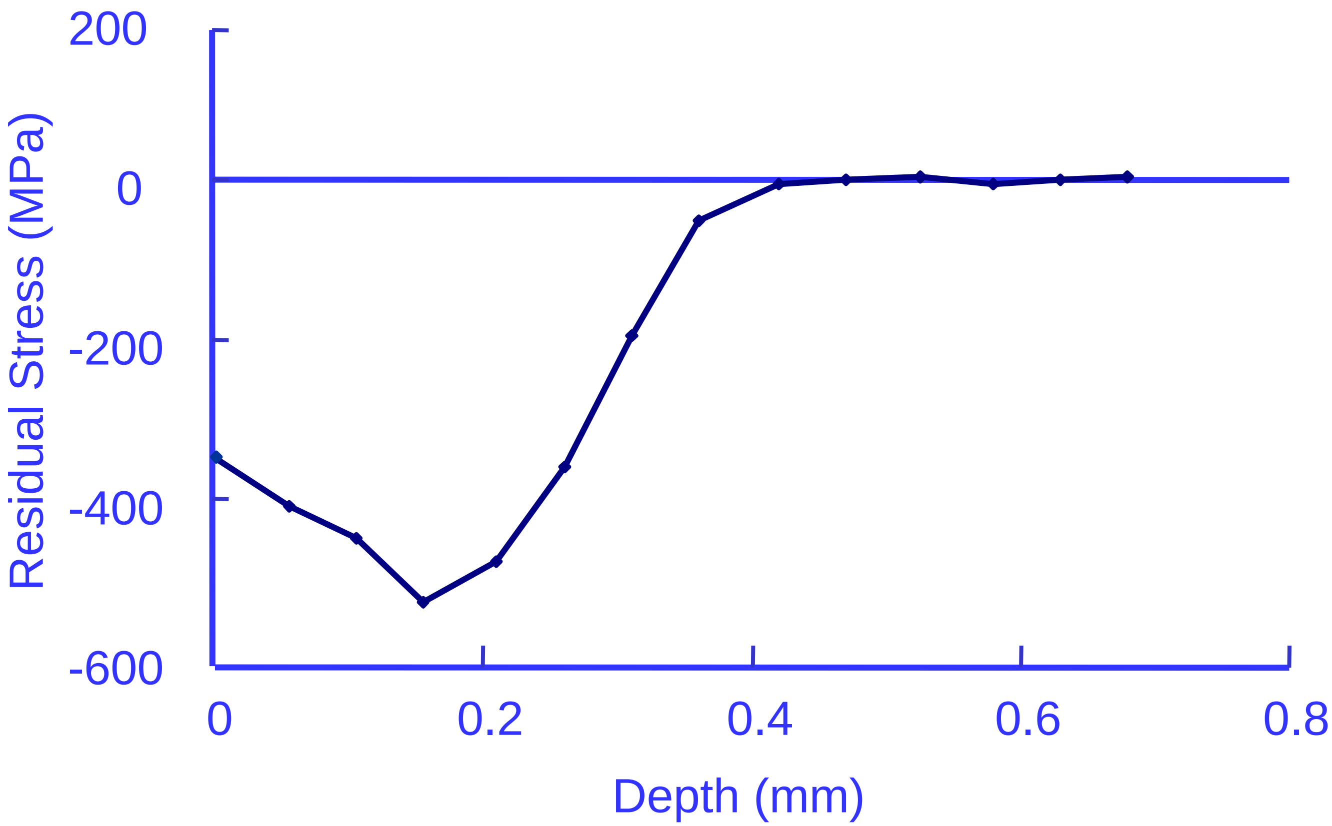
Fatigue Life Improvement



Courtesy of Fatigue Technology Inc.

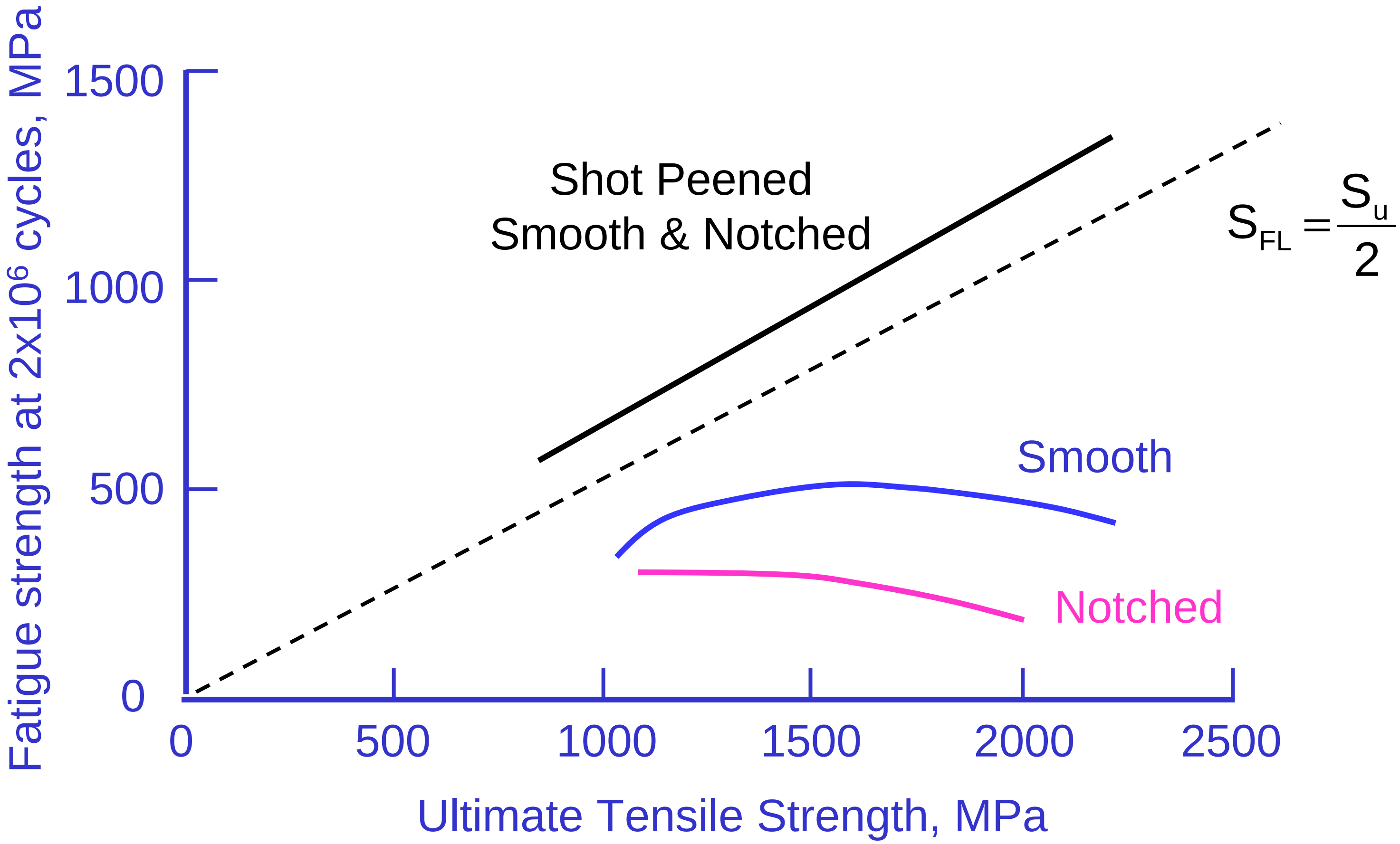
Shot Peening





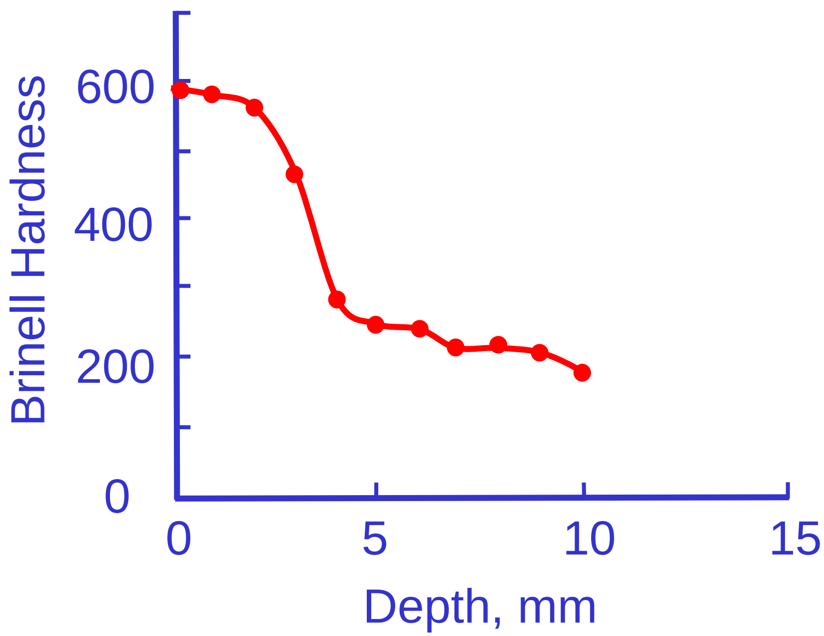
Residual stress in a shot peened leaf spring

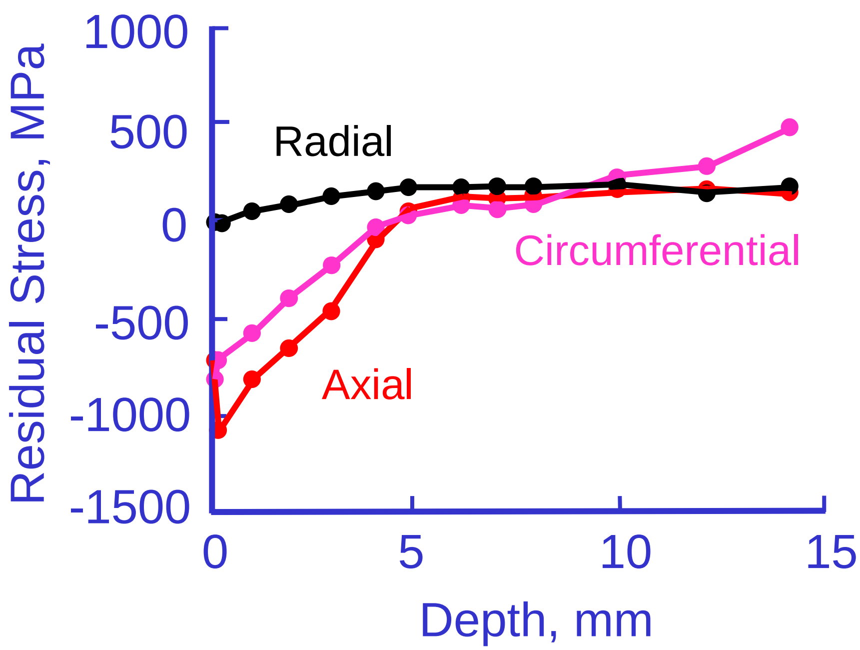
Shot Peening Results



www.metalimprovement.com

Heat Treating





50 mm diameter induction hardened 1045 steel shaft

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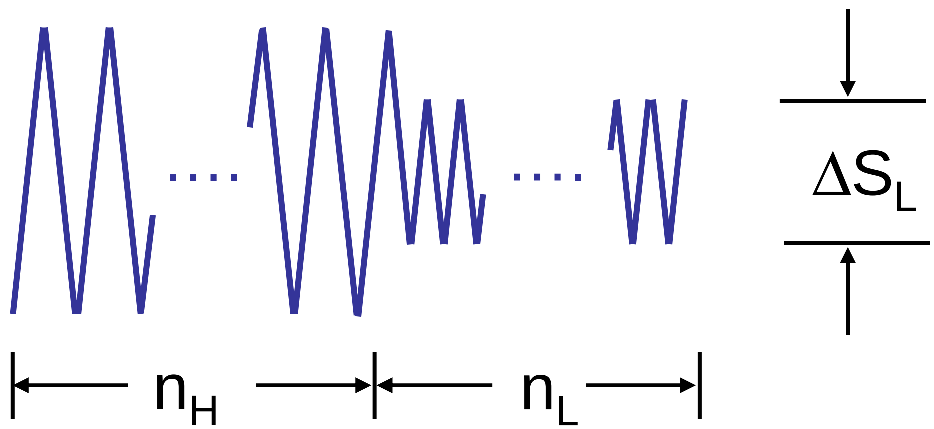
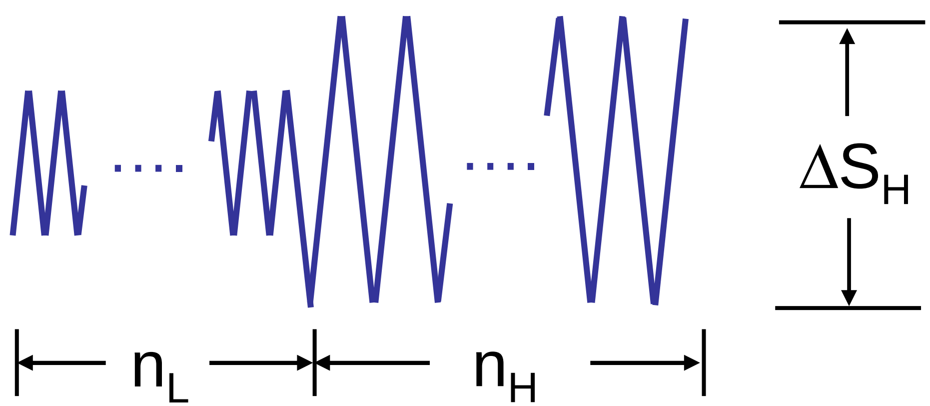
Cumulative Damage

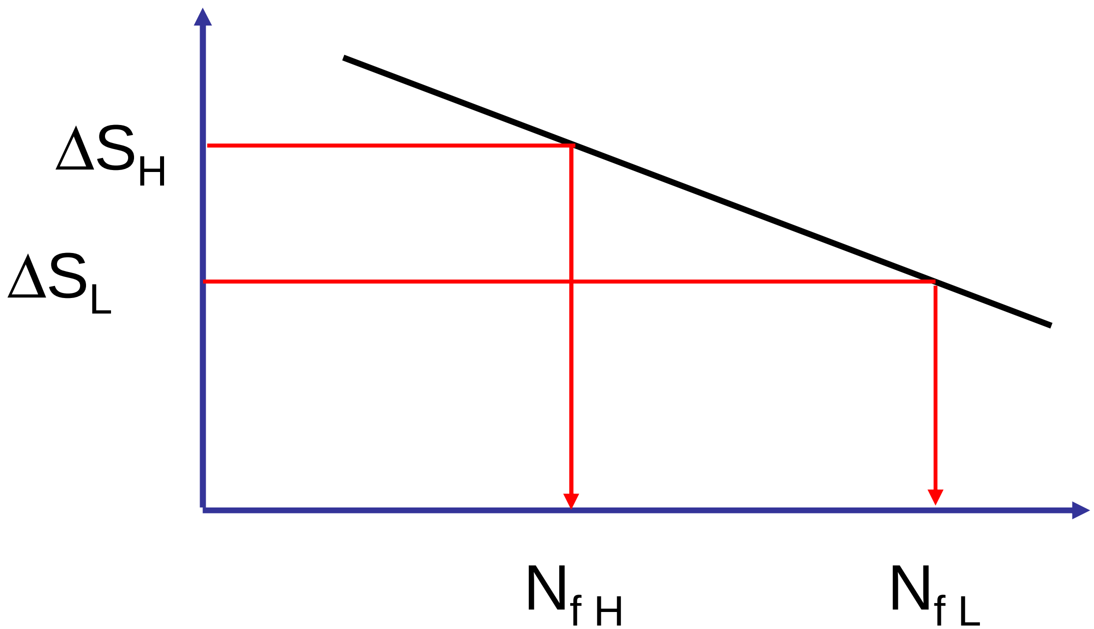
High - Low



Low - High



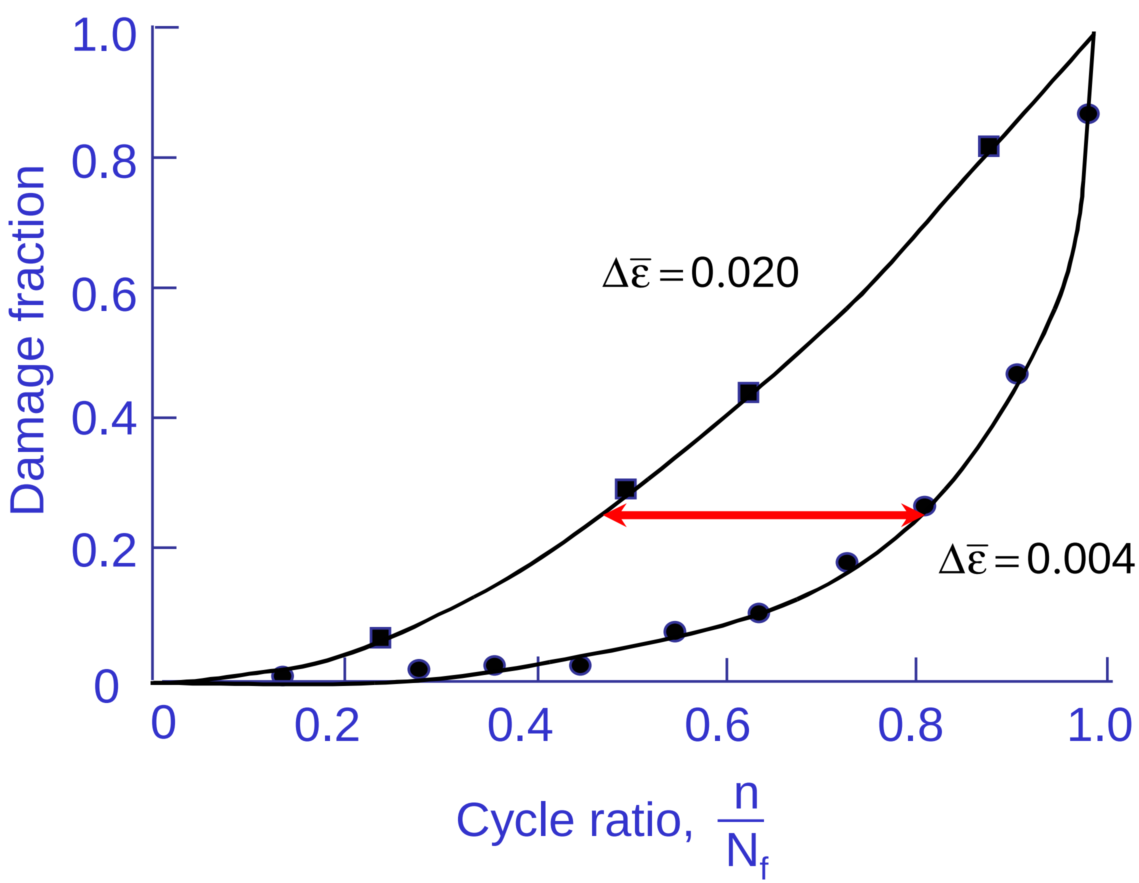
Linear Damage

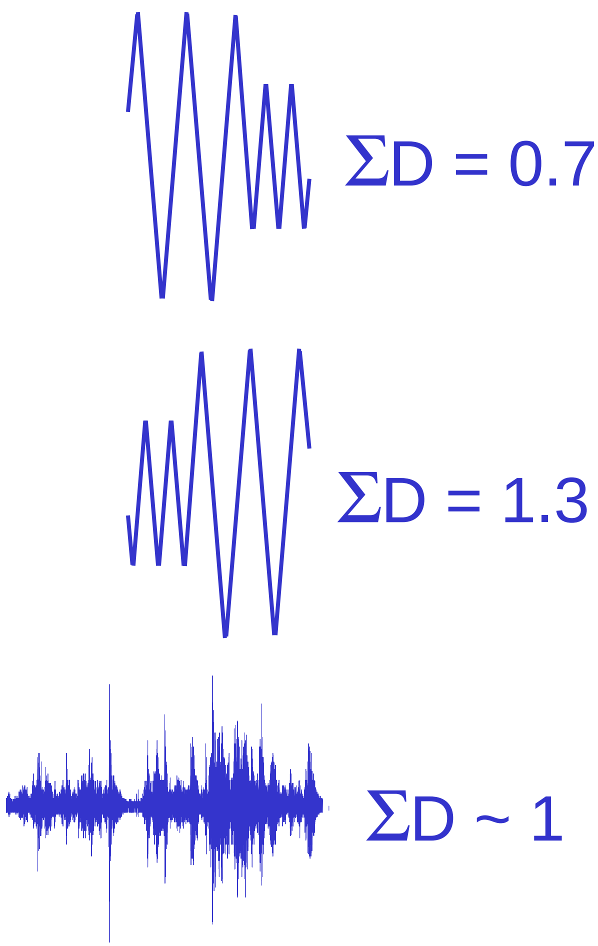


Miners Rule:

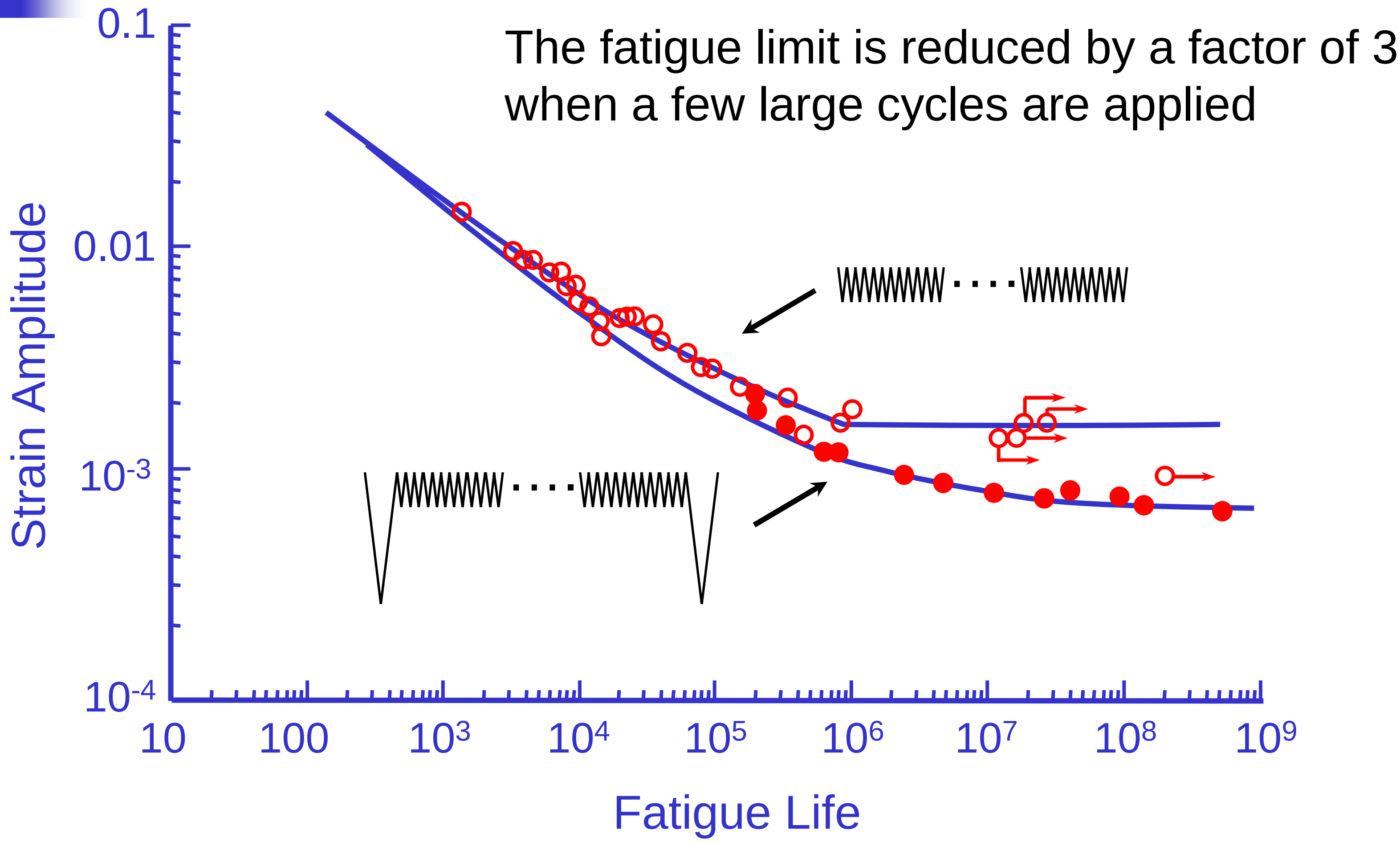
$$Damage = \sum \frac{n}{N_F} = \frac{n_H}{N_{f\,H}} + \frac{n_L}{N_{f\,L}}$$

Nonlinear Damage





Periodic Overload Results



Bonnen and Topper, "The Effects of Periodic Overloads on Biaxial Fatigue of Normalized SAE 1045 Steel" ASTM STP 1387, 2000, 213-231

Relative Miner's Rule

$$\sum D = \sum \frac{n}{N_f} = 0.3$$

Set Miner's damage sum to a number less than 1

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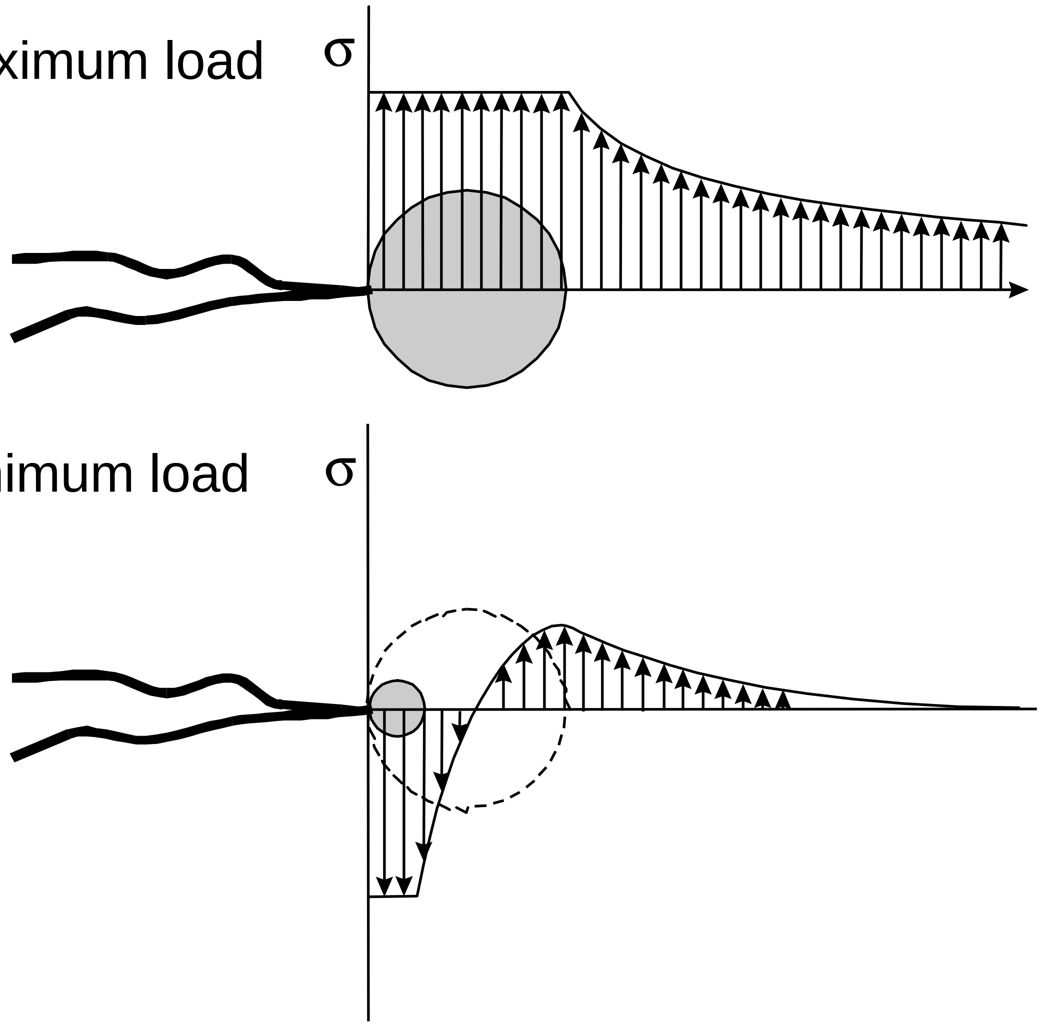
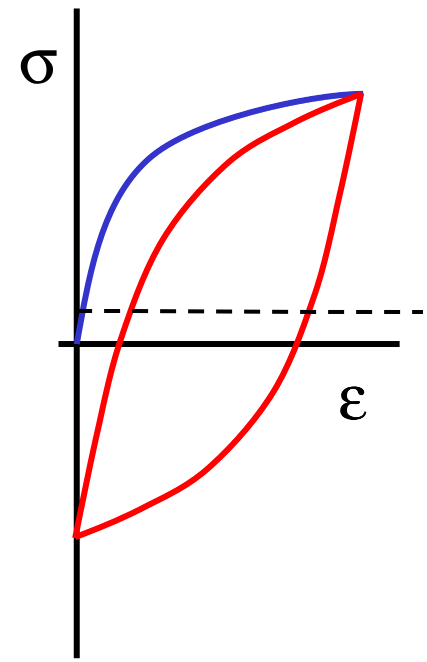
Crack Growth Physics

Maximum load

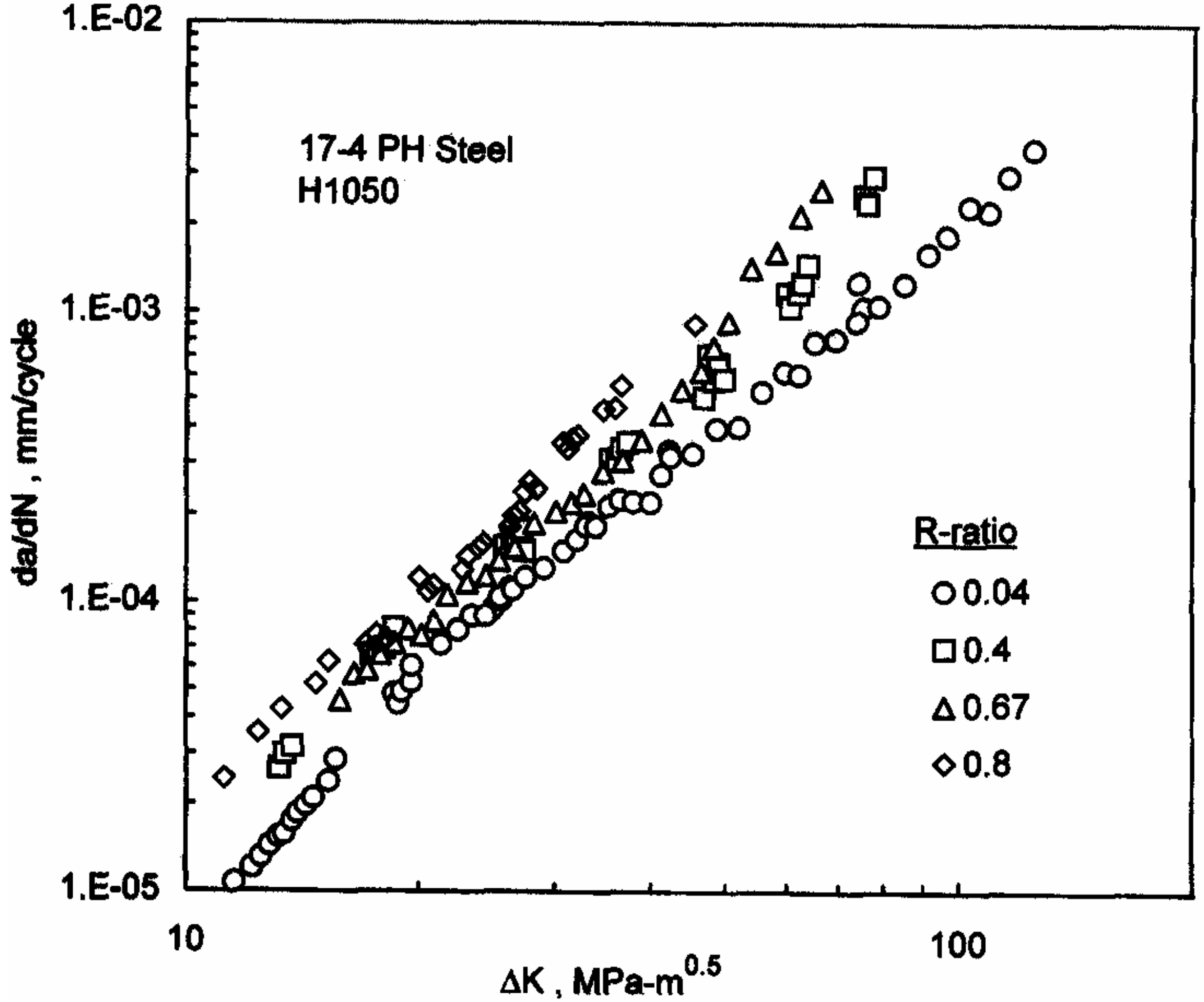
Minimum load





Mean stresses in plastic zone are small

Mean Stress Effects

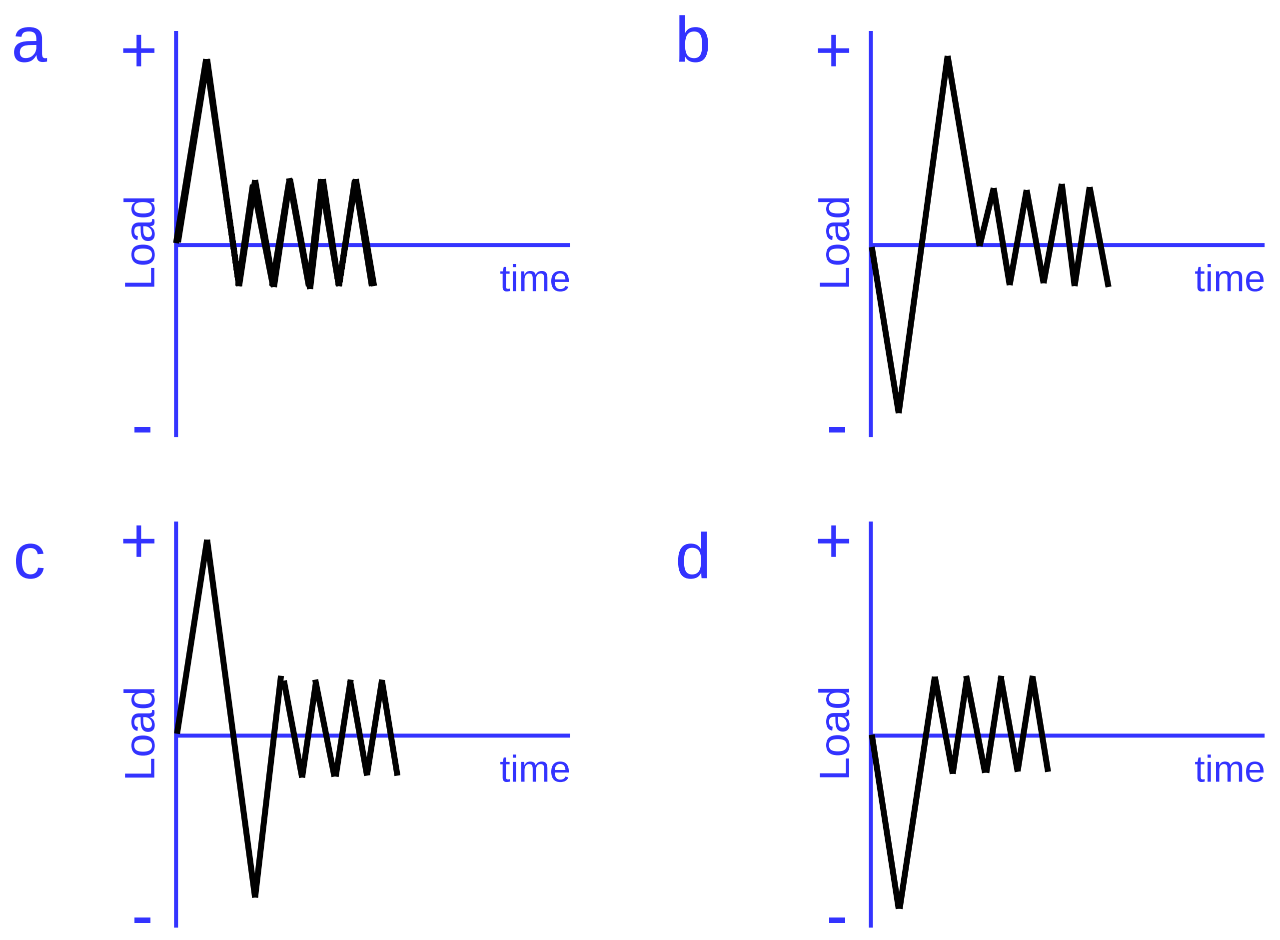


From Dowling, Mechanical Behavior of Materials, 1999

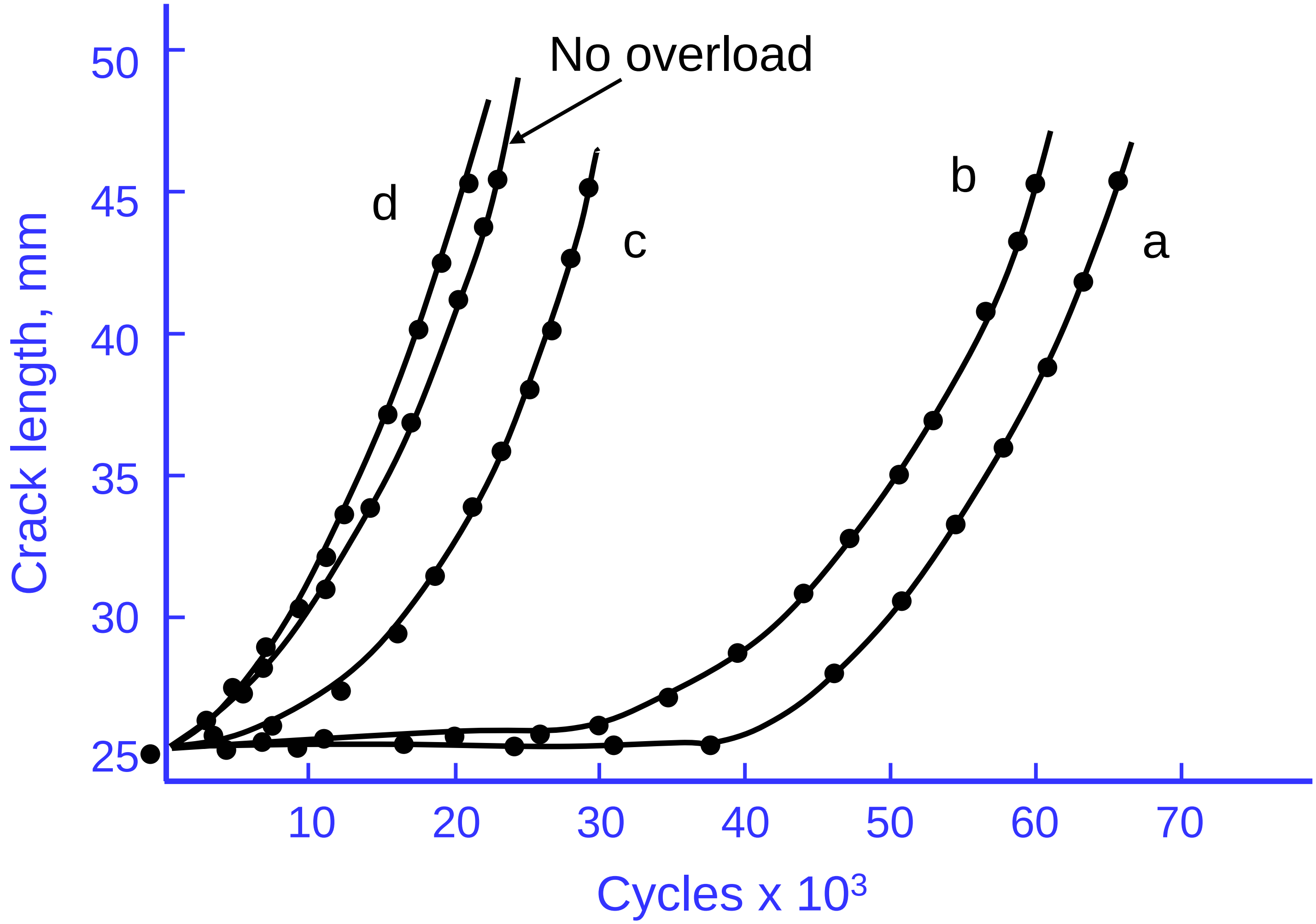
$$\frac{da}{dN} = \frac{C\,\Delta K^{m}}{(1-R)^{\gamma}}$$

$$0 < \gamma < 0.5$$

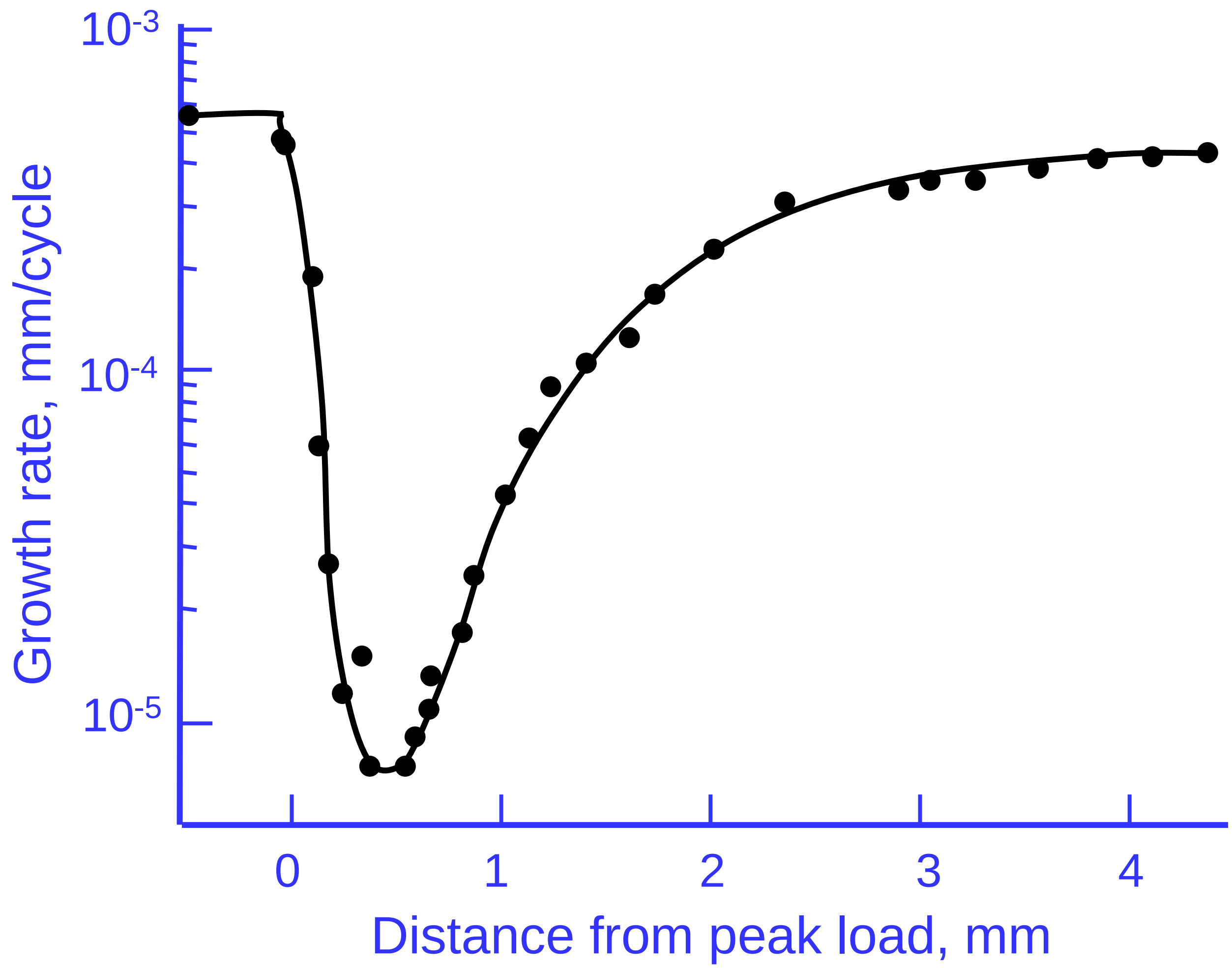
Sequences



Crack Growth



Crack Growth Rate



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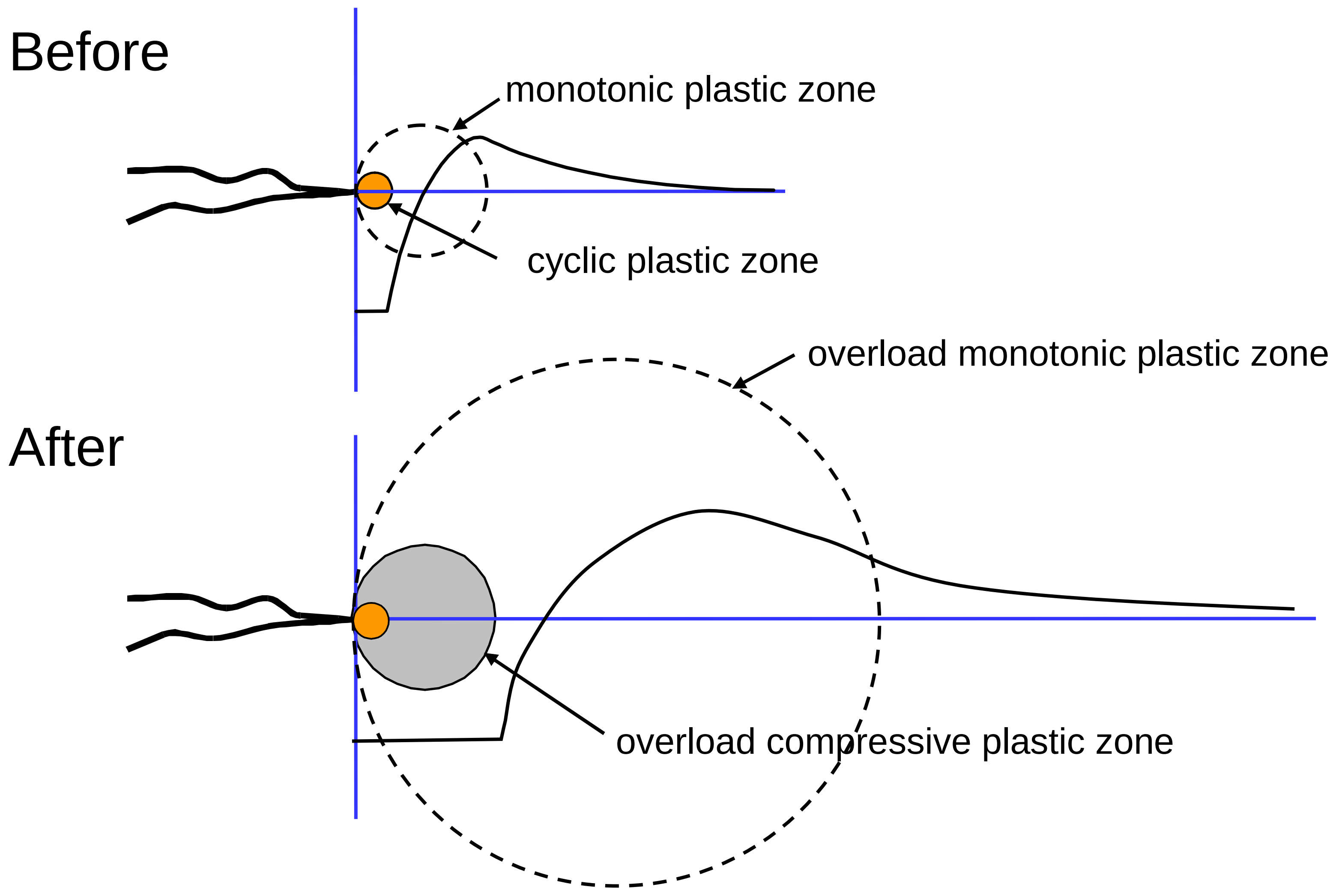
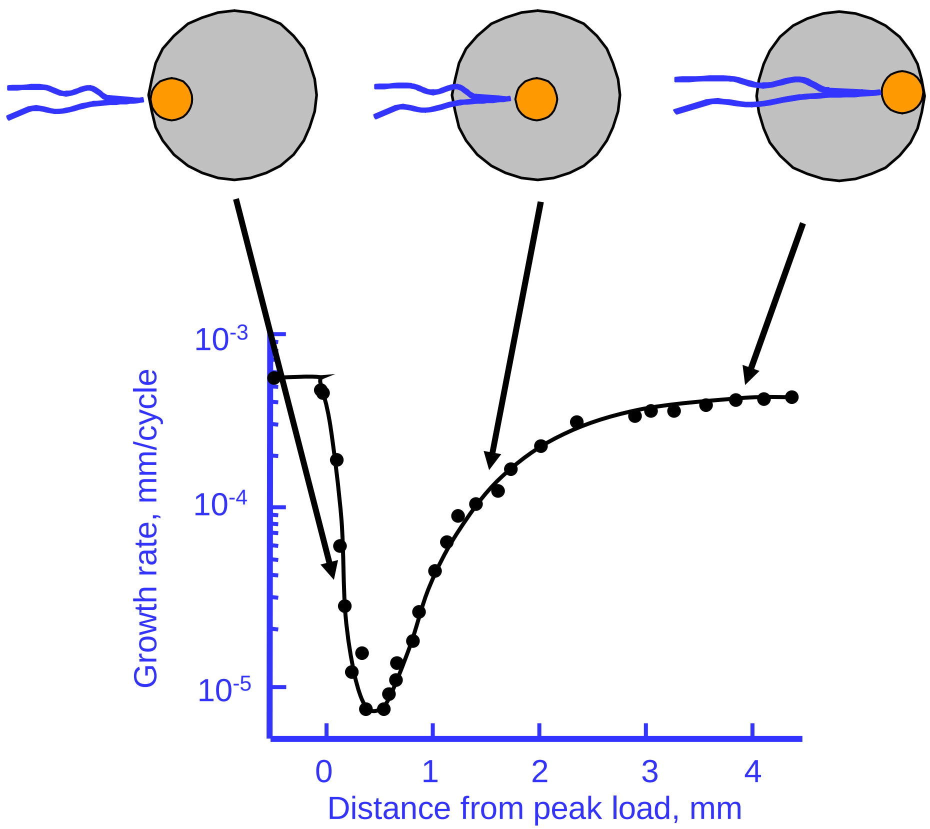
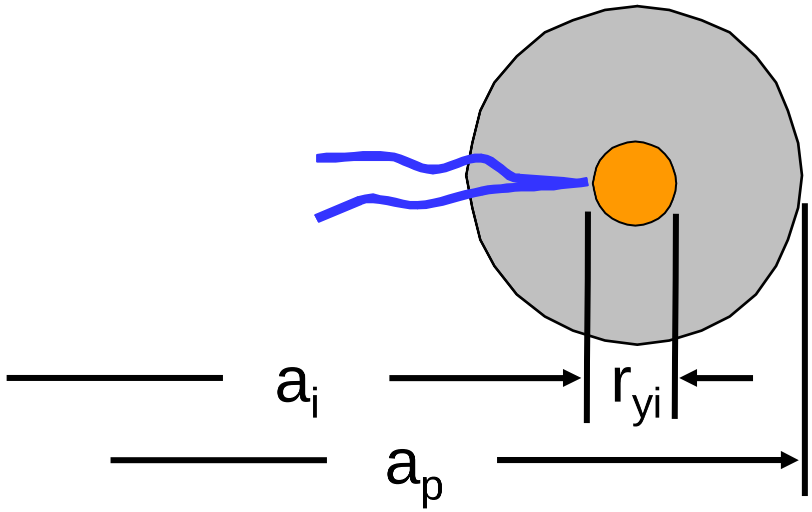
Stress Fields After Overload



Crack Growth Retardation



Wheeler Model



$$\frac{da}{dN} = \left(\frac{r_{yi}}{a_p - a_i}\right)^{\gamma} \left(\frac{da}{dN}\right)_{CA}$$

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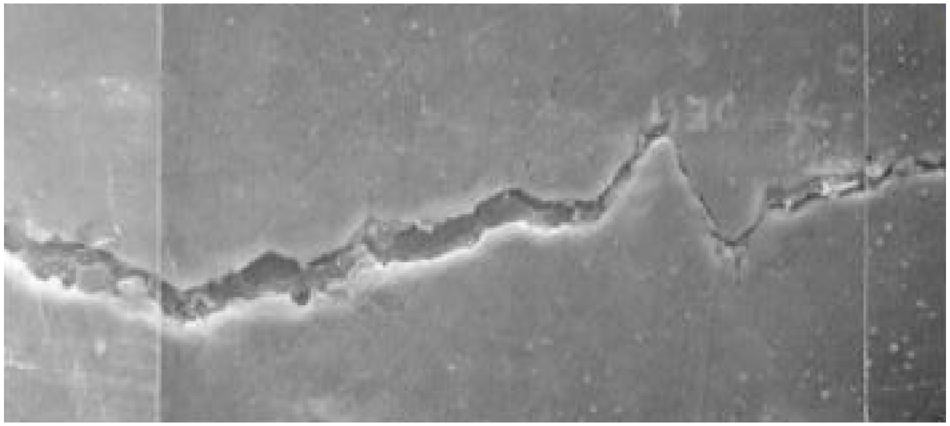
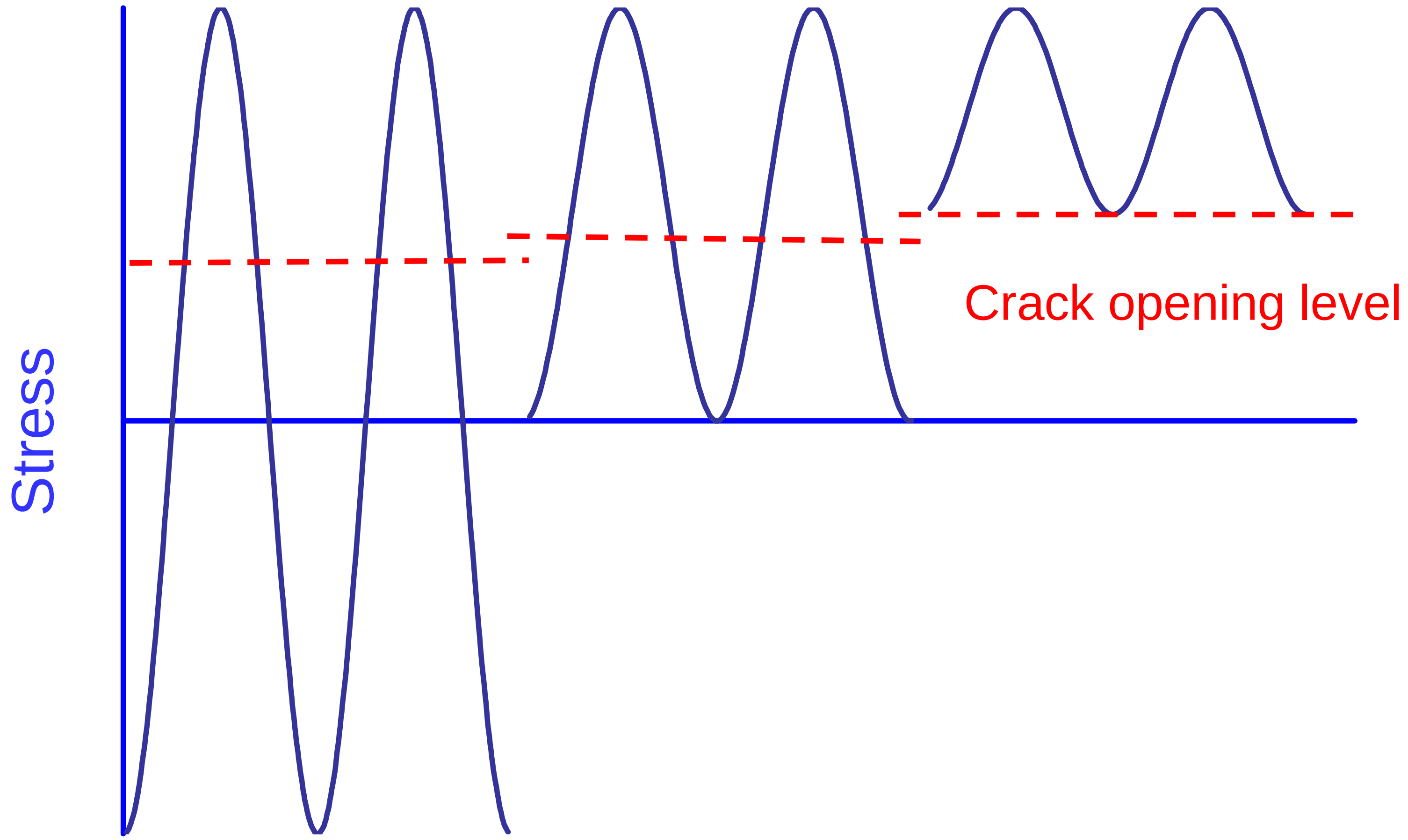
Compression



Crack open

Crack closed

Compressive Stresses

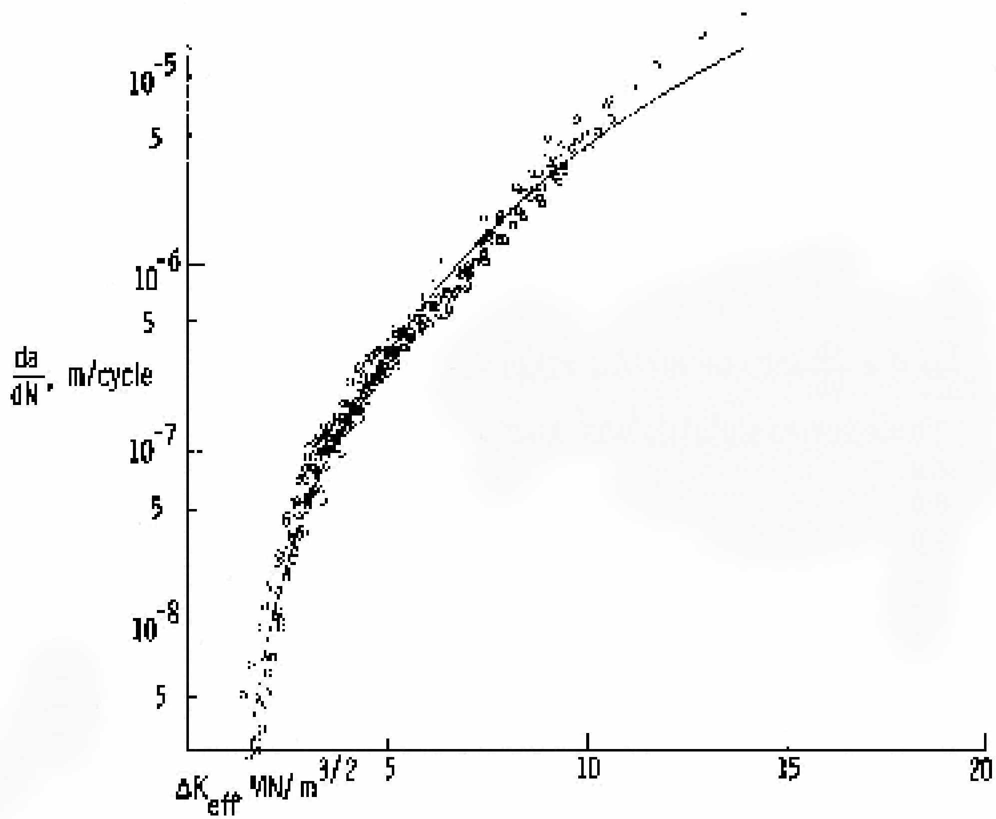


Compressive stresses are not very damaging in crack growth

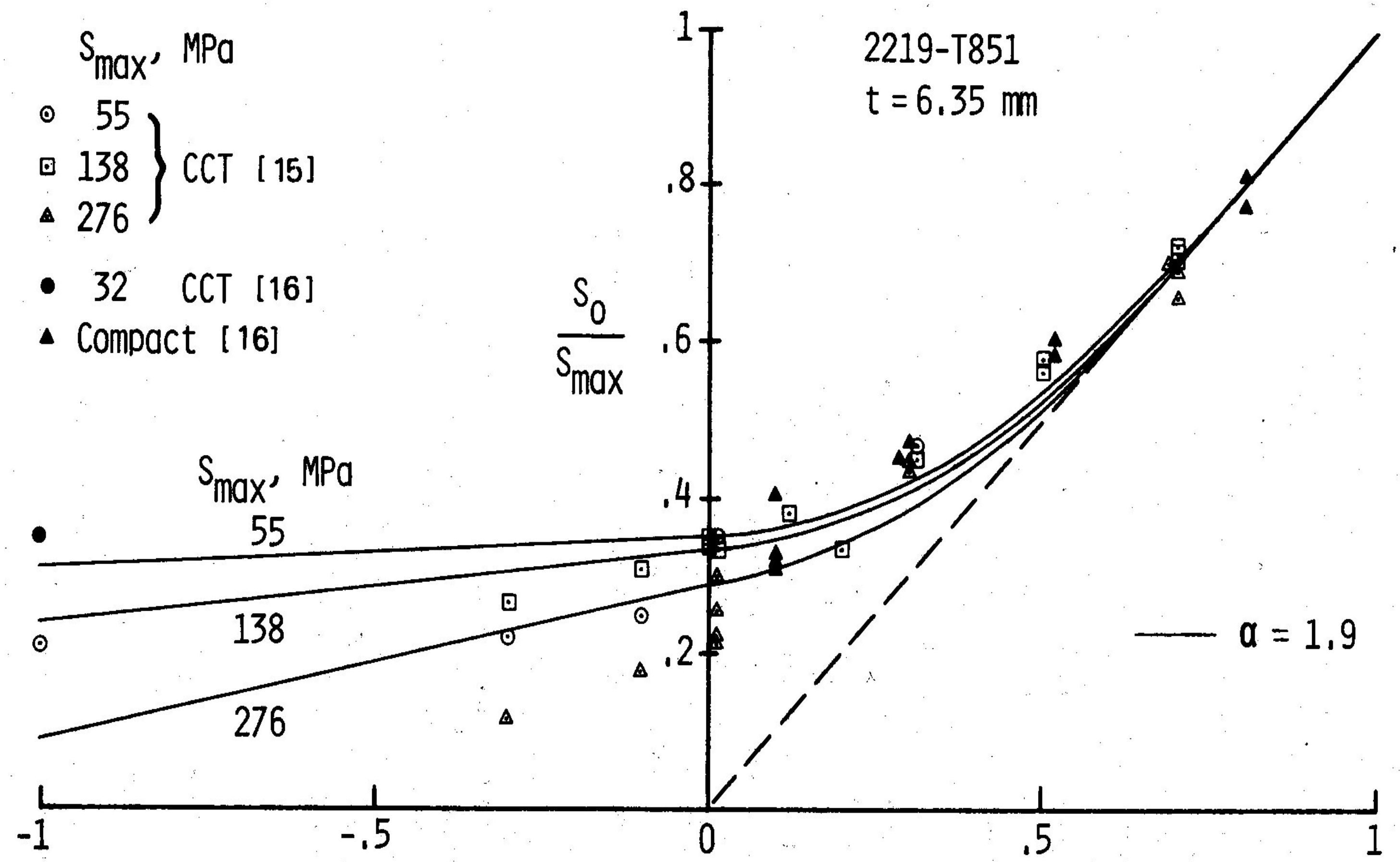
Crack Closure - Elber

$$\Delta K_{eff} = (0.5 + 0.4R)\Delta K$$

$$\frac{da}{dN} = C(\Delta K_{eff})^m$$



Maximum Stress Dependence



Newman Model

$$\Delta K_{eff} = \left[\frac{\left(1 - \dfrac{S_o}{S_{max}}\right)}{1 - R} \right] \Delta K$$

Newman

$$\frac{S_o}{S_{max}} = A_0 + A_1 R + A_2 R^2 + A_3 R^3$$

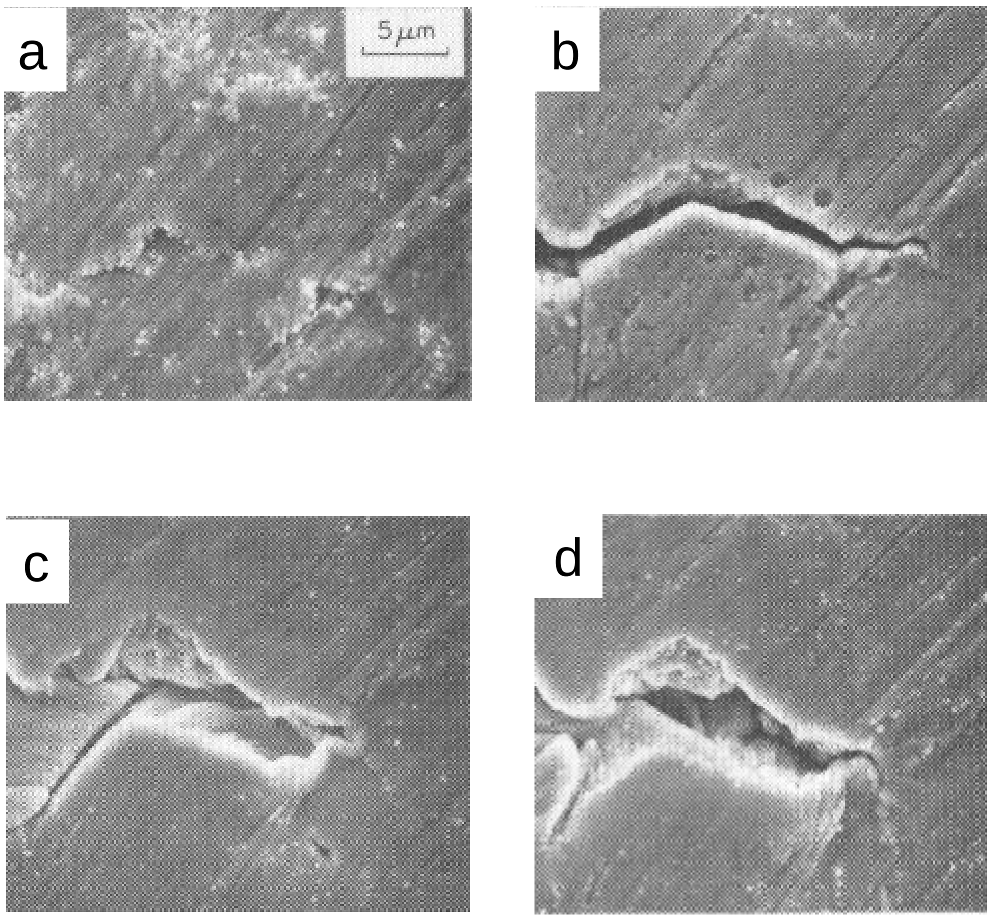
$$A_0 = (0.825 - 0.34\,\alpha + 0.05\,\alpha^2)\left[\cos\left(\frac{\pi S_{max}}{2\sigma_0}\right)\right]^{\frac{1}{\alpha}}$$

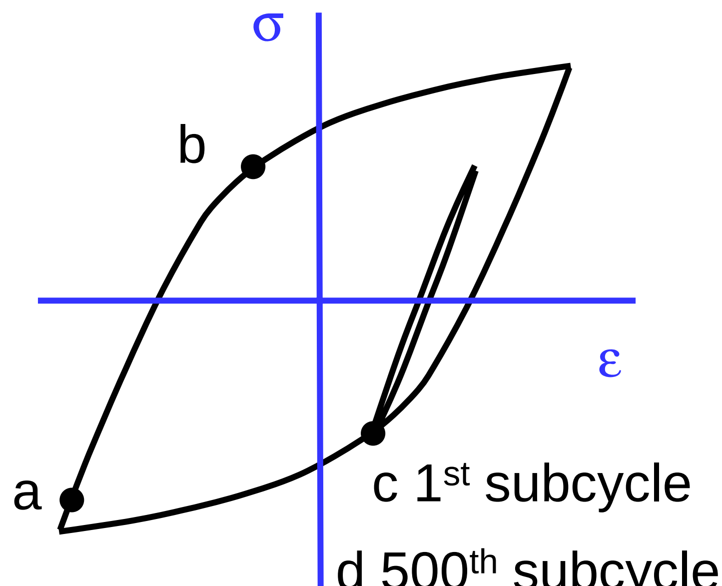
$$A_1 = (0.415 - 0.071\,\alpha)\frac{S_{max}}{\sigma_0}$$

$$A_2 = 1 - A_0 - A_1 - A_3$$

$$A_3 = 2A_0 + A_1 - 1$$

Closure Observations



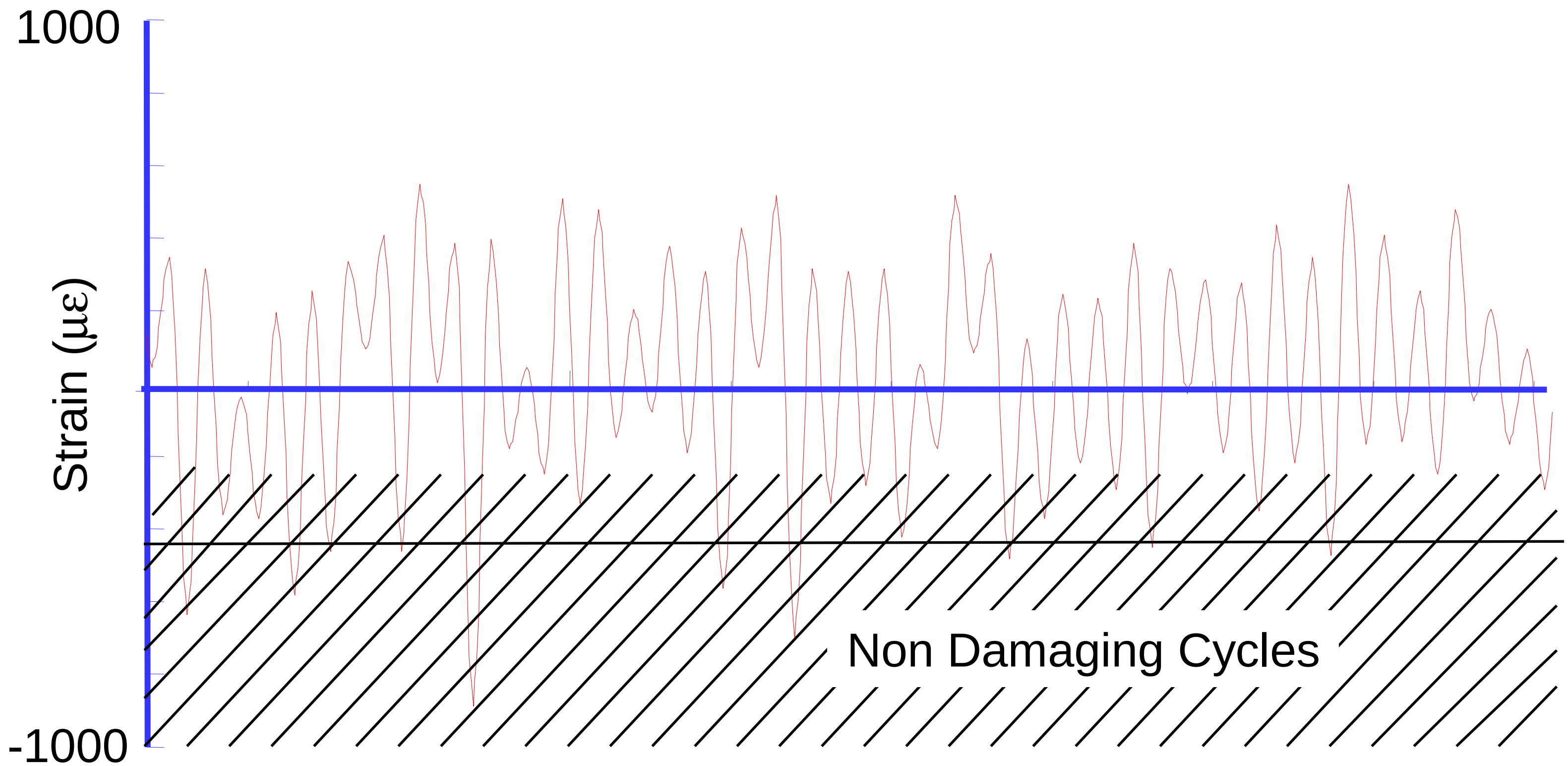


1026 steel

$\Delta\varepsilon_1/2 = 0.005$

$\Delta\varepsilon_2/2 = 0.001$

Spectrum Loading



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