UNIVERSIDAD NACIONAL
de MAR DEL PLATA

Facultad de Ingeniería

INTEMA
CONICET
UNMDP

Integridad de Componentes Mecánicos

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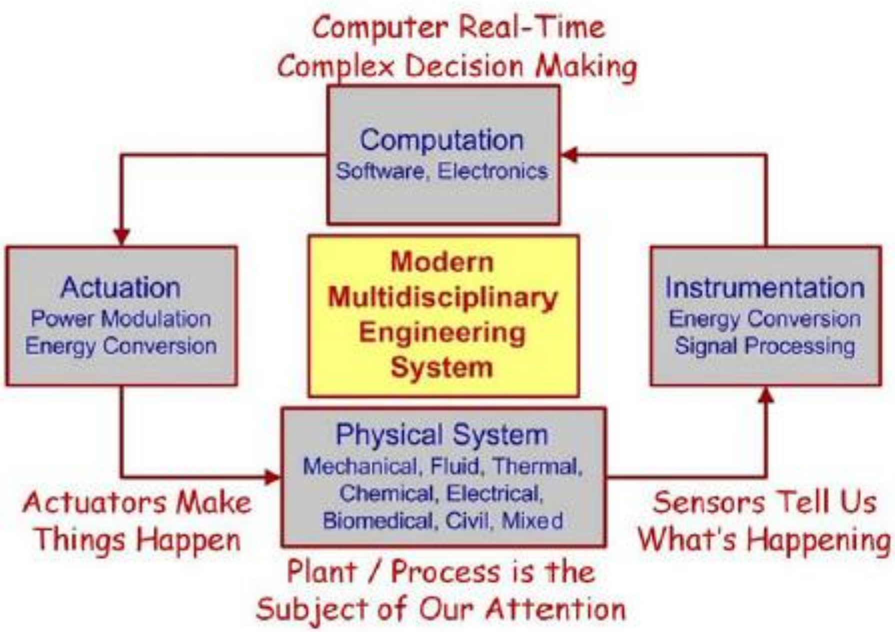
División Mecánica de Materiales
INTEMA (Instituto de Investigaciones en Ciencia y Tecnología de Materiales)
CONICET – Universidad Nacional de Mar del Plata

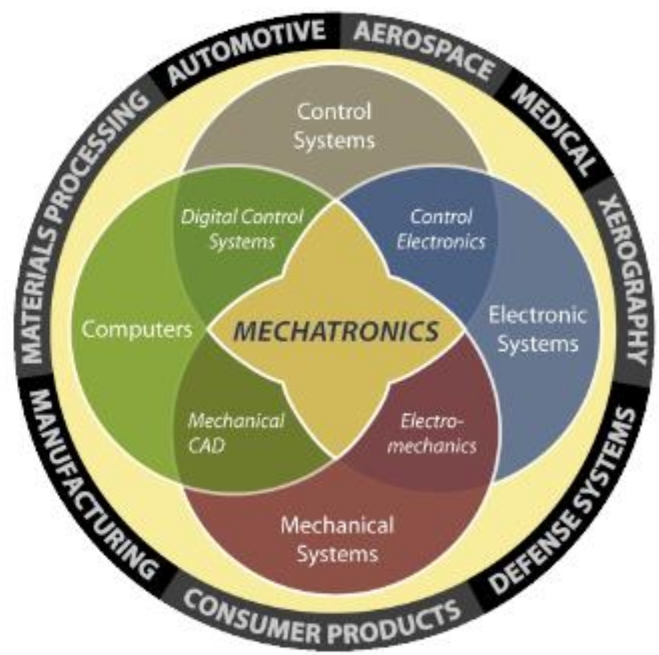
Departamento de Ingeniería Mecánica
Área Mecánica del Sólido

DESIGN PHILOSOPHIES

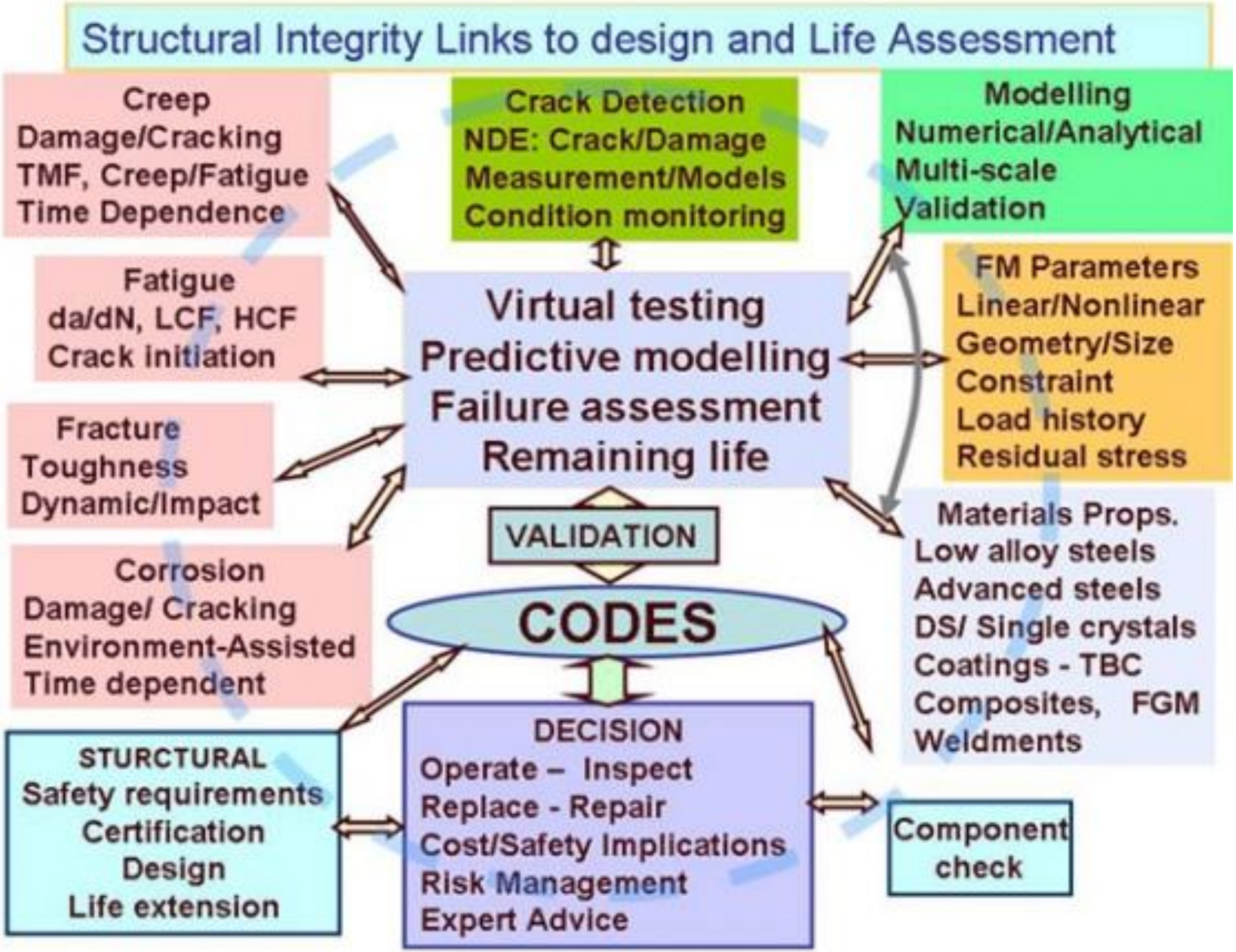
Desert Engineers

Fundamental Principles of Mechanical Design





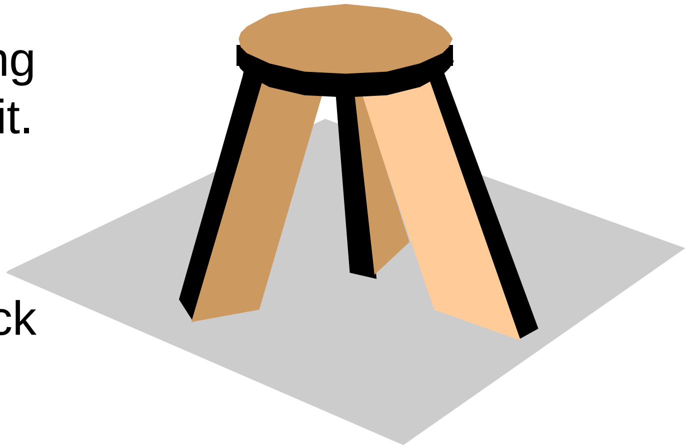
- Design is a mixture of analysis and creative thought.
- Good designs are based on excellent concepts and properly designed details.
- Analogous to physical exercise, analysis is a form of mental exercise that trains the mind to be strong and swift. Many designs would never have even been conceived of if the design engineer did not understand the basic physics behind the process or machine that prompted the need for a new design.
- Design engineers must be good at identifying problems. Once a problem is identified, it will usually yield to an unending barrage of creative thought and analysis.
- In addition to identifying and solving problems, the design engineer must also learn to identify what the customer really needs, which is not necessarily what the customer thinks that he or she needs.



Structural Integrity Links to design and Life Assessment
Creep
Damage/Cracking
TMF, Creep/Fatigue
Time Dependence
Crack Detection
NDE: Crack/Damage
Measurement/Models
Condition monitoring
Modelling
Numerical/Analytical
Multi-scale
Validation
Fatigue
da/dN, LCF, HCF
Crack initiation
Virtual testing
Predictive modelling
Failure assessment
Remaining life
FM Parameters
Linear/Nonlinear
Geometry/Size
Constraint
Load history
Residual stress
Fracture
Toughness
Dynamic/Impact
VALIDATION
Materials Props.
Low alloy steels
Advanced steels
DS/ Single crystals
Coatings - TBC
Composites, FGM
Weldments
Corrosion
Damage/ Cracking
Environment-Assisted
Time dependent
CODES
STURCTURAL
Safety requirements
Certification
Design
Life extension
DECISION
Operate – Inspect
Replace - Repair
Cost/Safety Implications
Risk Management
Expert Advice
Component check

DESIGN PHILOSOPHIES (damage mechanism example: Fatigue)

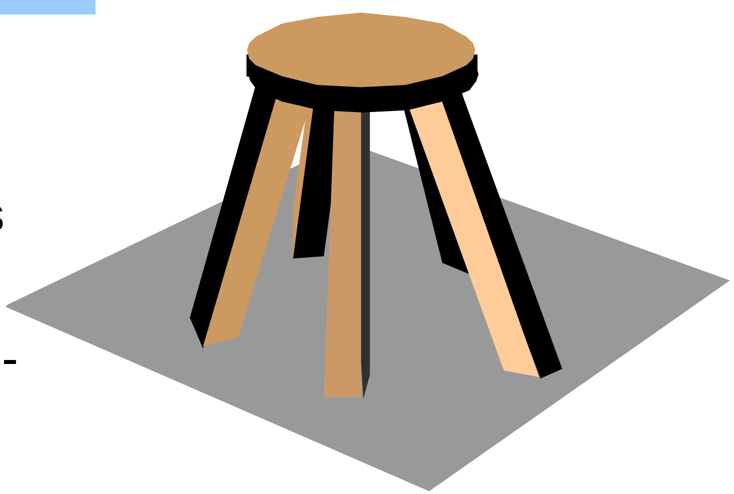
Infinite-Life Design: all expected stress levels during operation will be below the material endurance limit. Safety factors are introduced in the material S-N curves.



Safe-Life Design: the component must remain crack free (without nucleation) during its service life.

Crack nucleation → Crack propagation → Rupture

Fail-Safe: the structure must withstand all loads expected during service time, even if failure occurs in one of its components. It characterizes a redundant structure.



The expressions “single-load path” and “multiple-load path” are closely related to fail-safe design philosophy.

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Fernando Carbone, Gastón Labra

Fatigue Design

Component Resistance $= f\,(C_1, C_2, C_3, \ldots, C_n) \times$ **Material Resistance**

ASTM, ISO, etc

Assumption

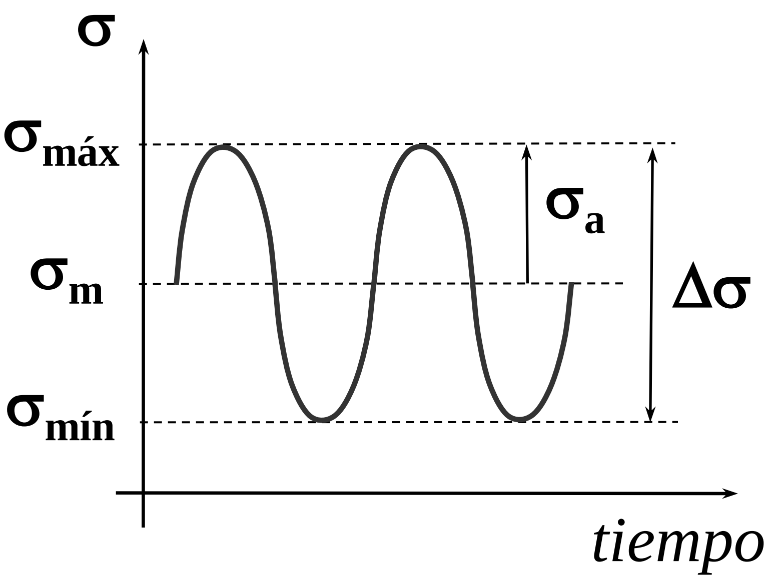
C_n:
- Geometric Concentrators
- Loading Configuration
- Residual Stresses
- Surface Condition
- etc…

In most design applications **C_n** are empirically determined

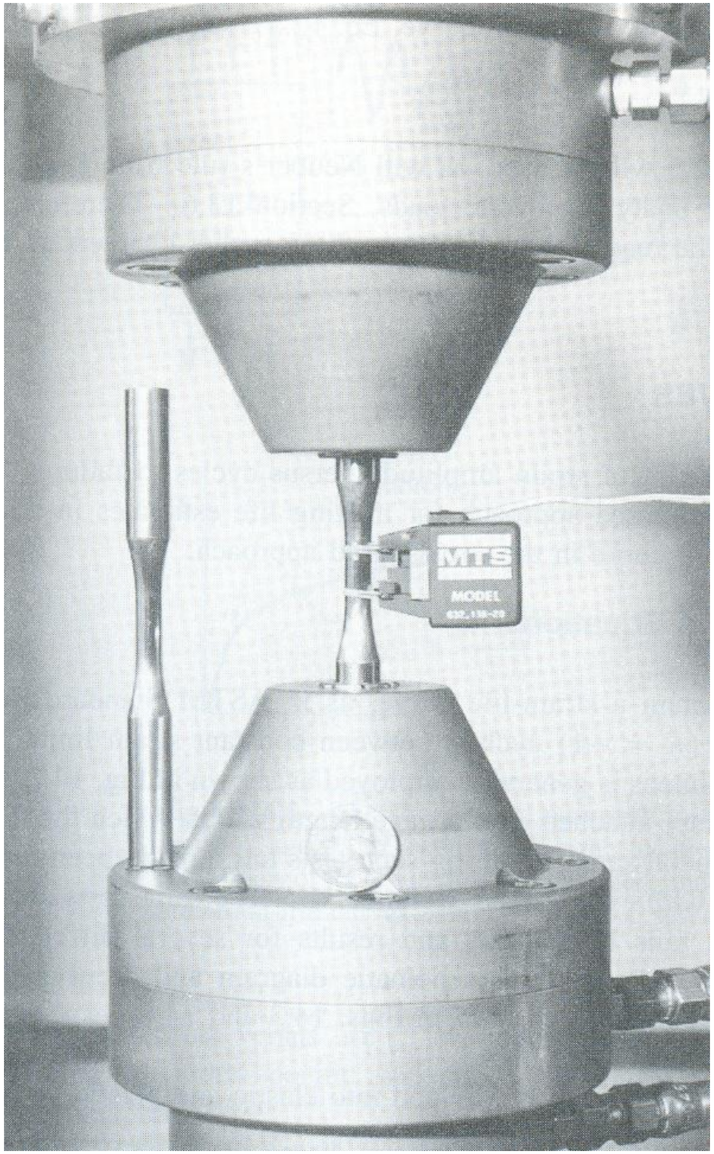
large uncertainties …

Aim: New technologies for fatigue analysis, prediction and design of metallic components

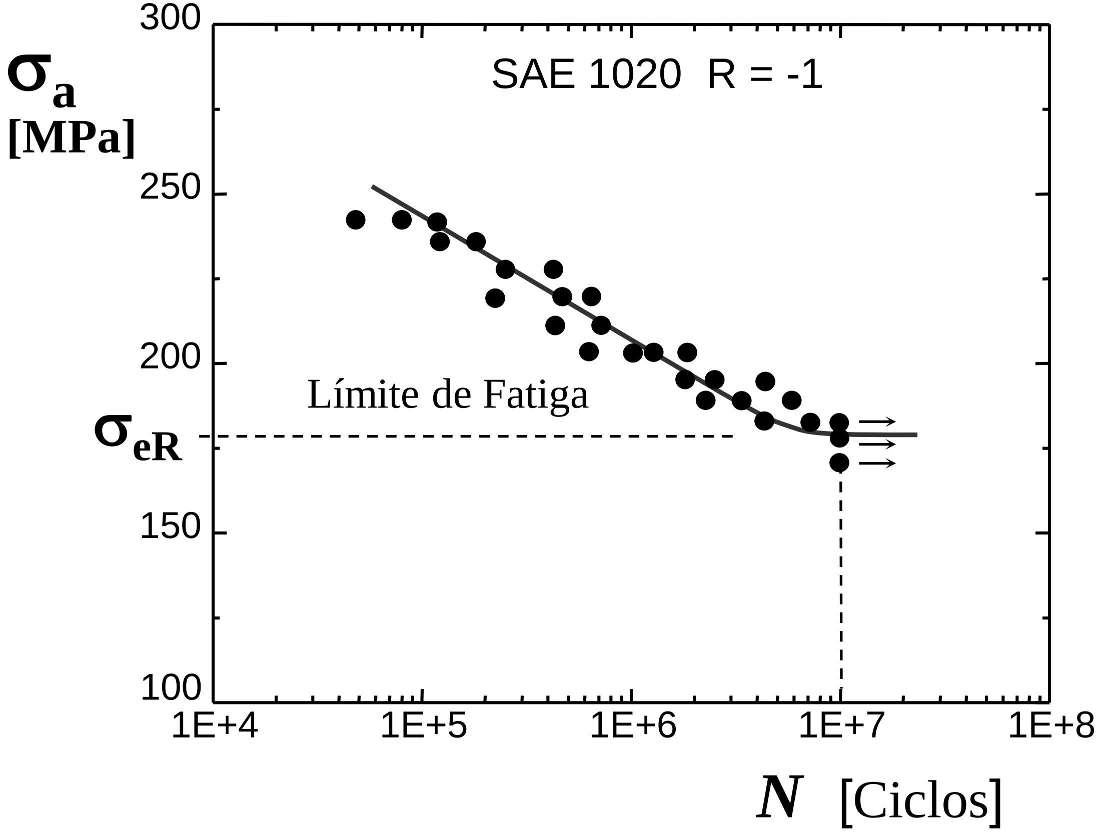
Ciclos de Carga

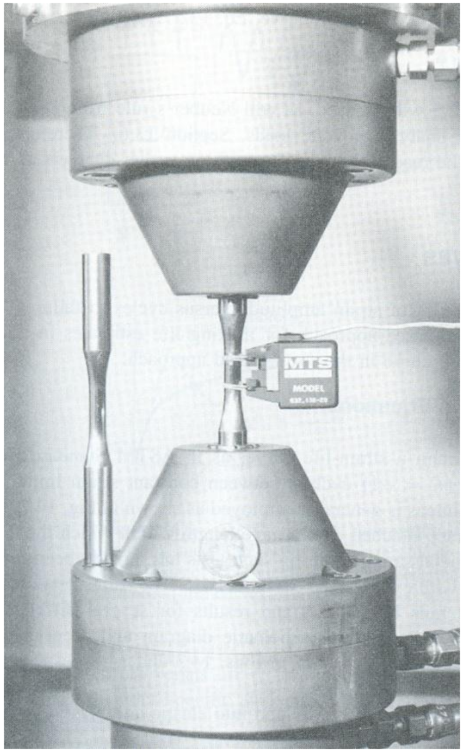


$$R = \frac{P_{\min}}{P_{\max}} = \frac{\sigma_{\min}}{\sigma_{\max}}$$



Curvas S-N


σa
[MPa]
300
250
200
150
100
SAE 1020 R = -1
Límite de Fatiga
σeR
1E+4
1E+5
1E+6
1E+7
1E+8
N [Ciclos]

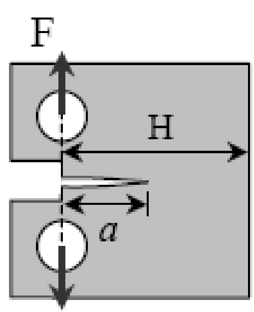

MTS

CRACK PROPAGATION CURVES

- Curve: **da/dN** vs. **ΔK** (*Log-Log*)
- **da/dN** = crack propagation rate (mm/cycle or in./cycle)
- **ΔK** = stress intensity factor variation:
- Lower limit for ΔK: **fatigue crack growth threshold**
- Upper limit for ΔK, region close to instability, where K_{max} is approaching the material fracture toughness.

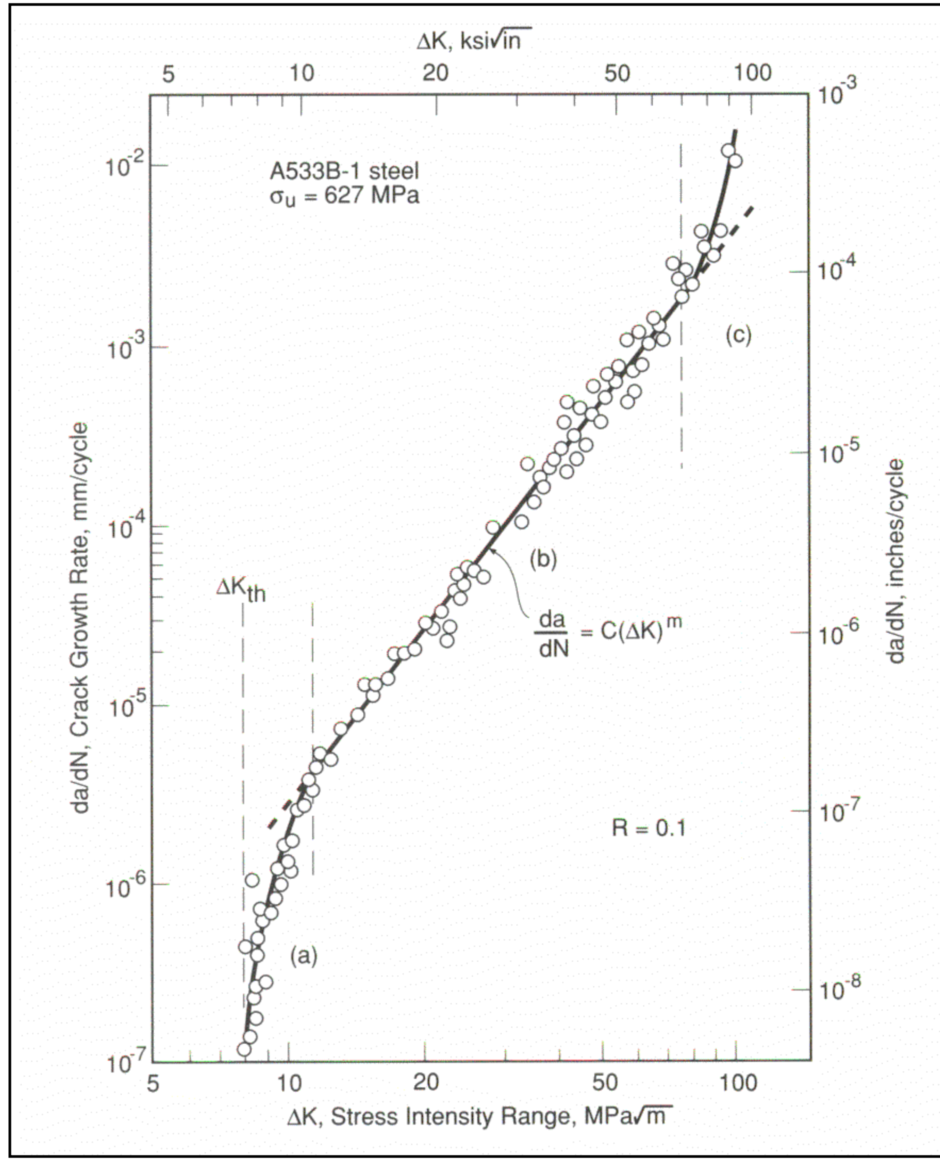
CT

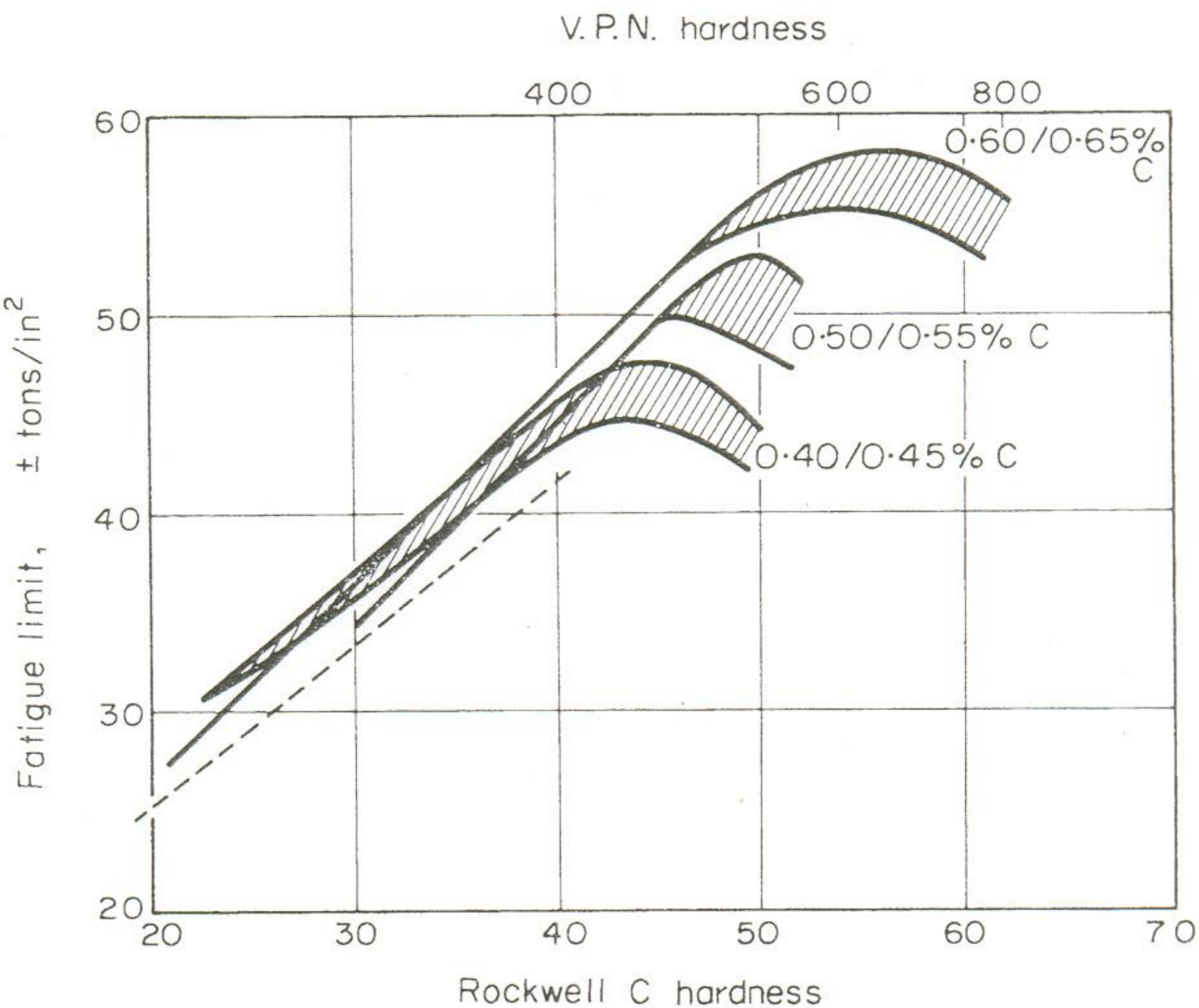
(Compact Tension specimen)



$$K = \beta \Delta S \sqrt{\pi a}$$

$$K = \frac{F}{t\sqrt{H}} f\left(\frac{a}{H}\right)$$

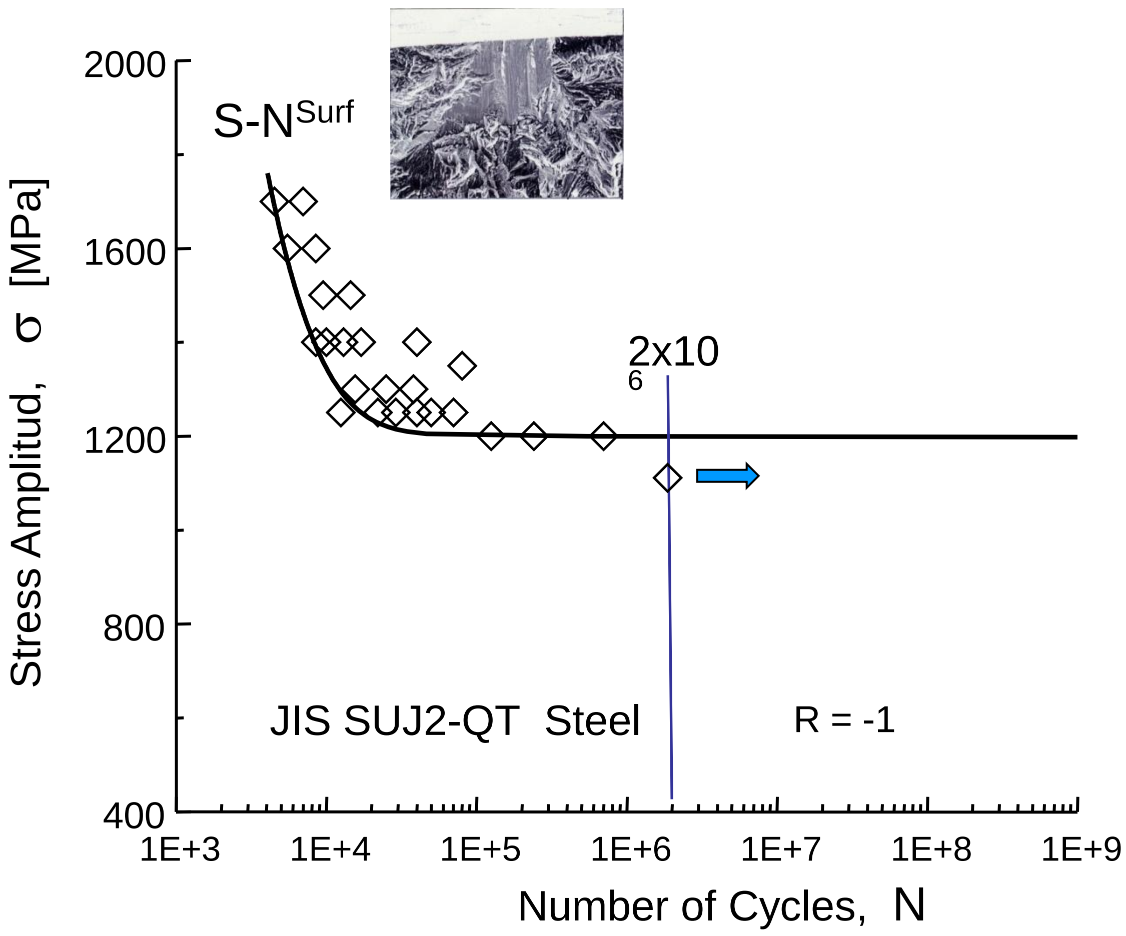




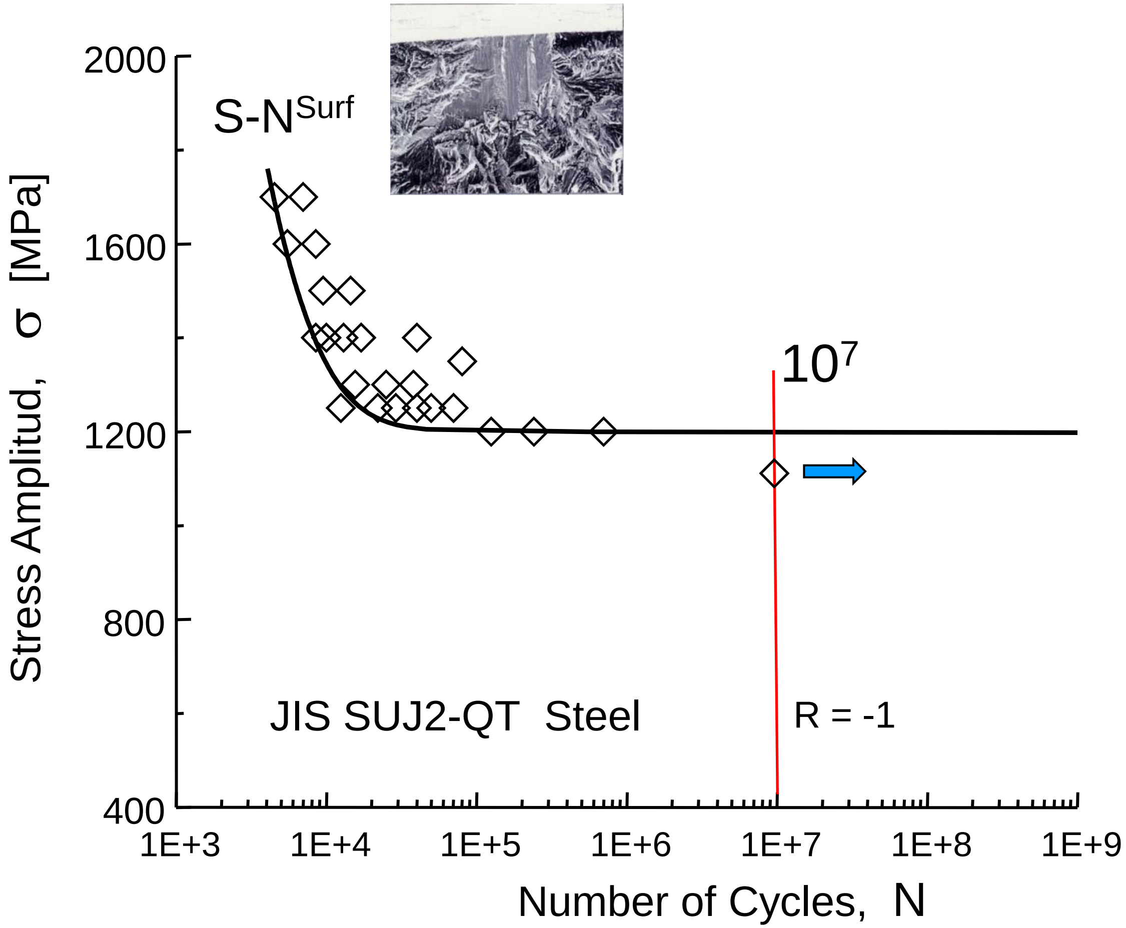
30. Variation of fatigue limit with increasing hardness. (Garwood and others [97])

– – – – – Fatigue ratio 0·5.

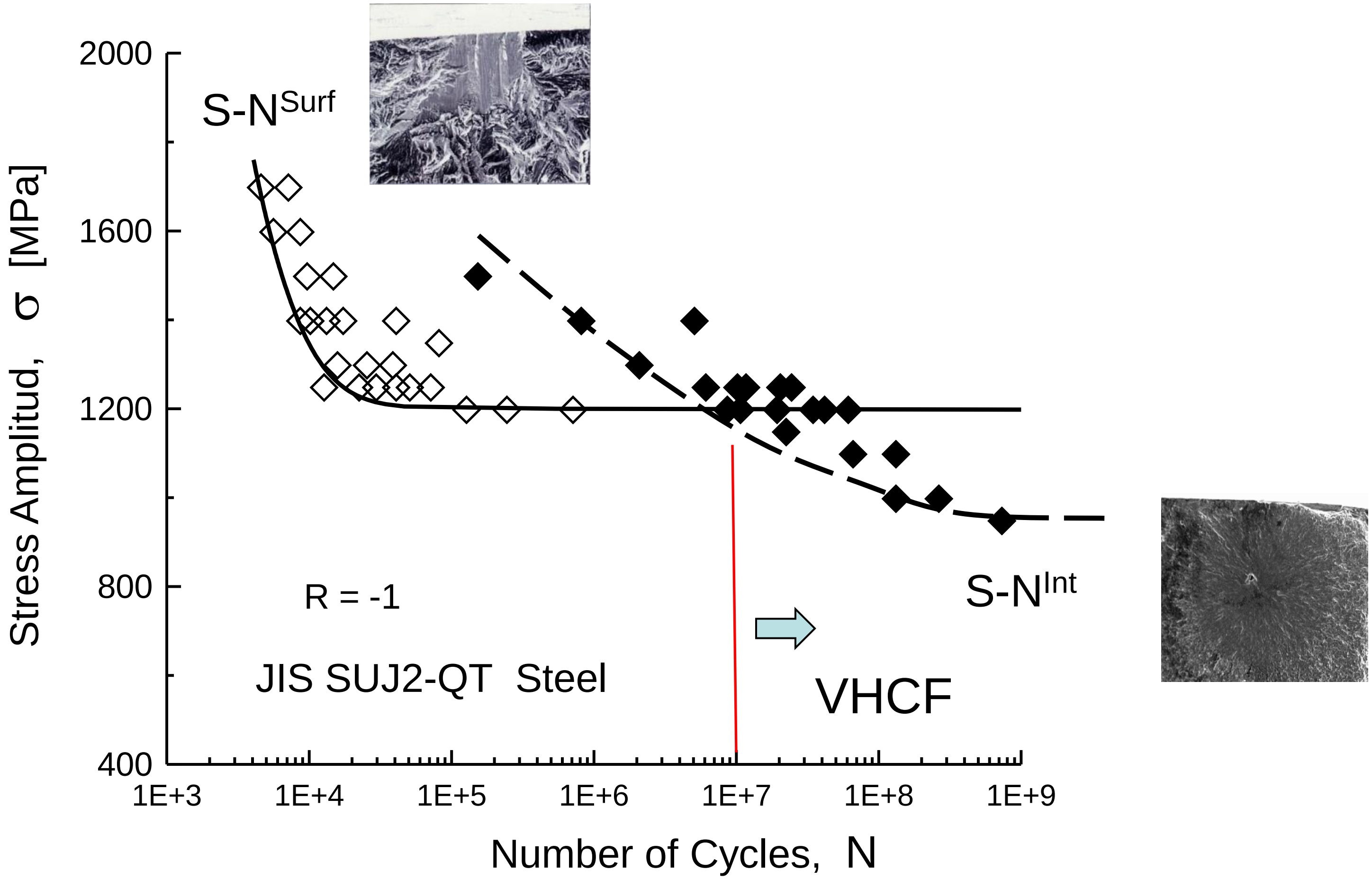
High Cycle Fatigue of High-Strength Carbon Steels



High Cycle Fatigue of High-Strength Carbon Steels

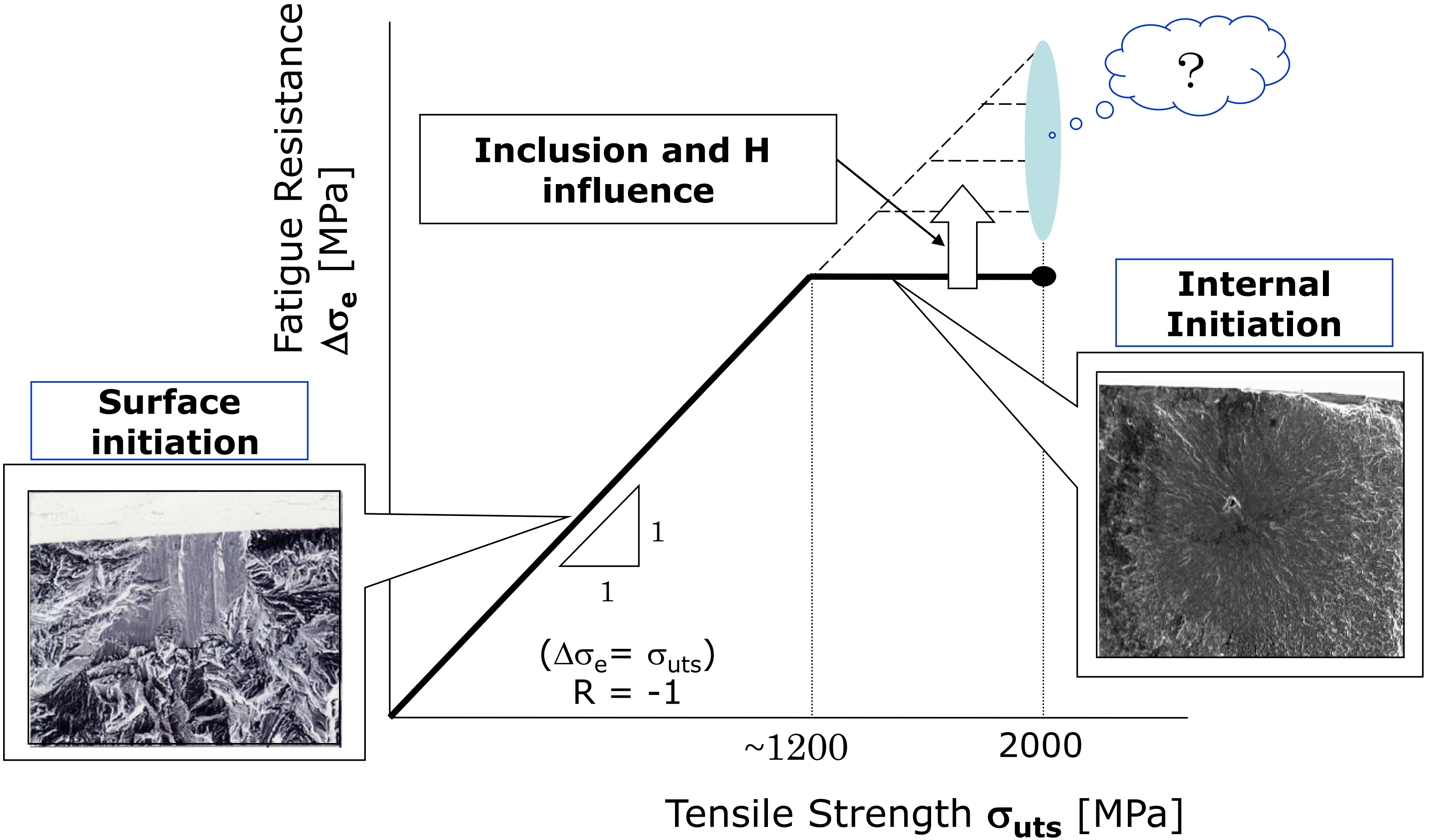


Very-High Cycle Fatigue (VHCF)
of High-Strength Carbon Steels

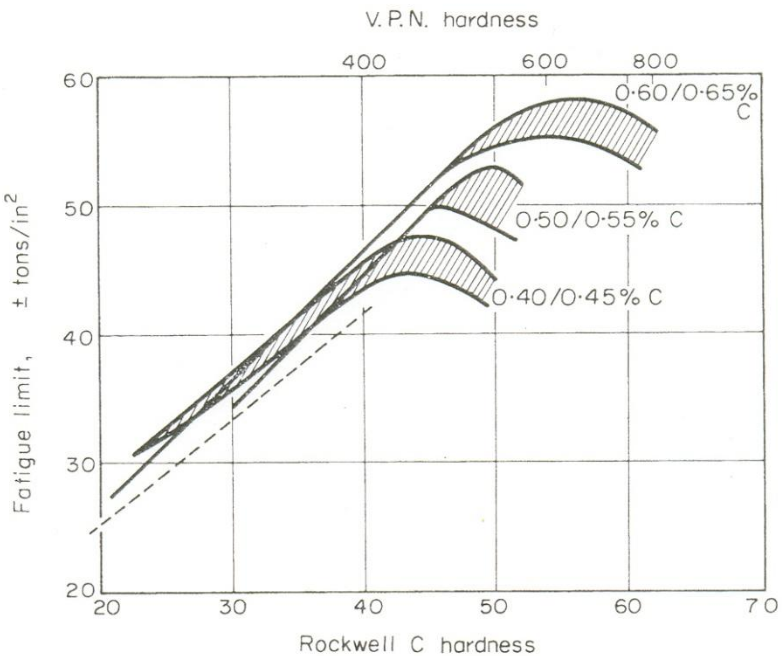


Shiozawa K., Lu L. and Ishihara S. (2001). *Fatigue Fract Engng Mater Struct* Vol.24, pp.781-790.

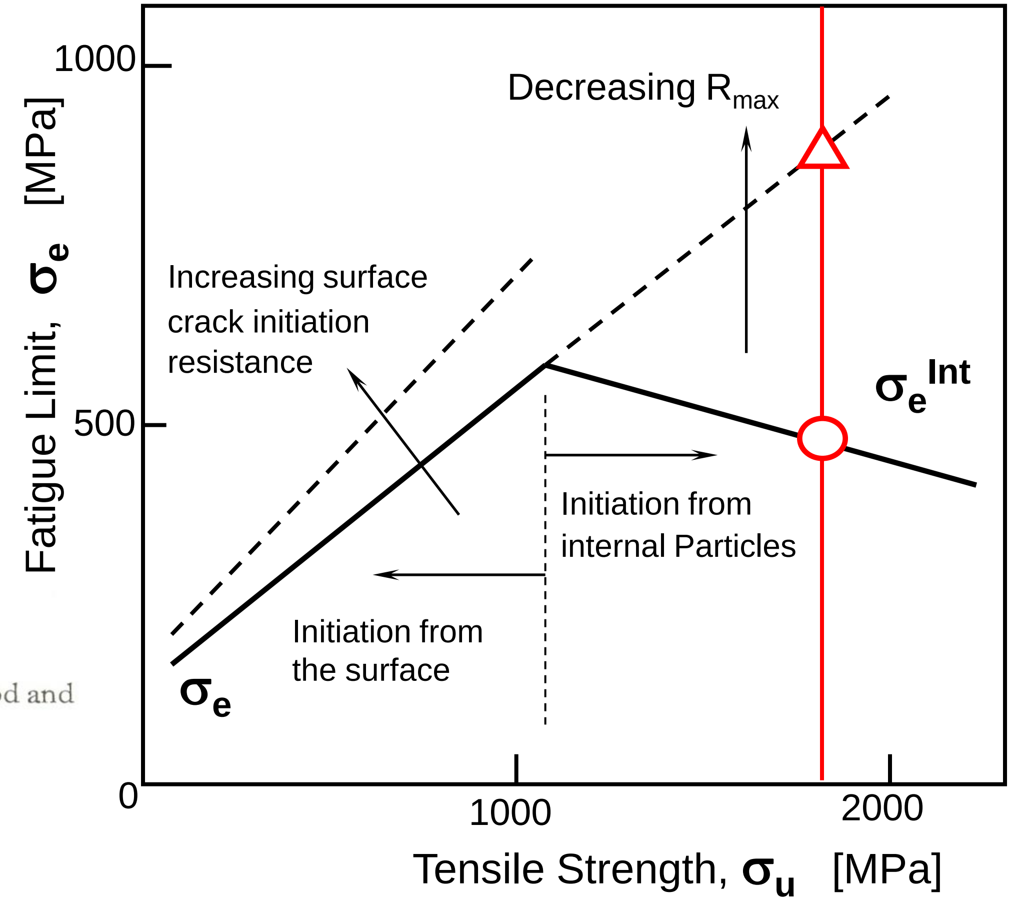
Very-High Cycle Fatigue of High-Strength Carbon Steels

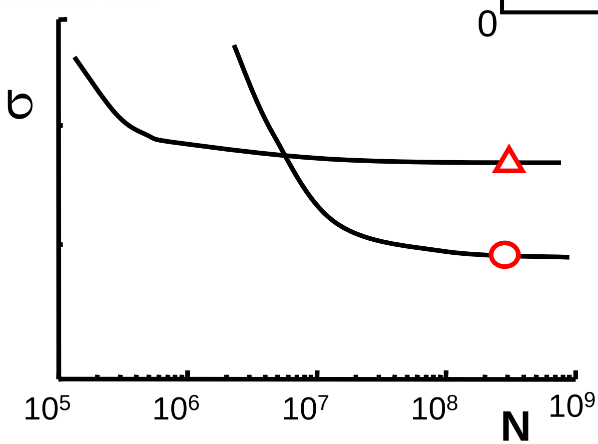


Surface and Internal Fatigue Limits



30. Variation of fatigue limit with increasing hardness. (Garwood and others [97])
— — — — Fatigue ratio 0·5.





$$\sigma_e^{\,Int} = 256\,\frac{\Delta K_{th}}{\sqrt{R_i^{max}}}$$

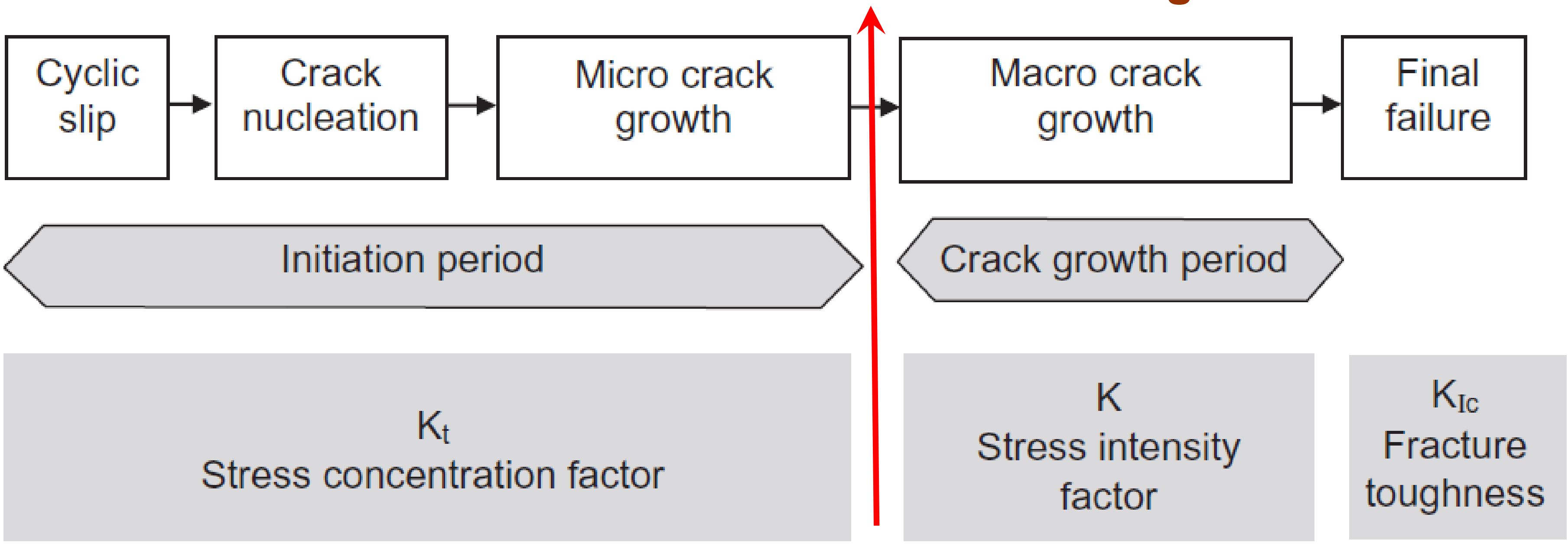
Total Fatigue Life

J. Schijve / International Journal of Fatigue 45 (2012) 31–38
J. Schijve / International Journal of Fatigue 61 (2014) 39–45

The fatigue life of a notched structural element consists of an initial period for crack initiation followed by a crack period of crack growth until final failure, see Fig. 2. Briefly:

$$N = N_{\text{initiation}} + N_{\text{crack growth}}$$

Transition Crack Length ≈ 0.5-1 mm



Different phases of the fatigue life and relevant factors

Schijve J. Fatigue of structures and materials. 2nd ed. Springer; 2009.

Fatigue of welded joints

Key features dominating fatigue strength of welded joints:

- Geometric stress concentrations
- Welding flaws (10-400 μm)
- High tensile residual stresses

Assumption

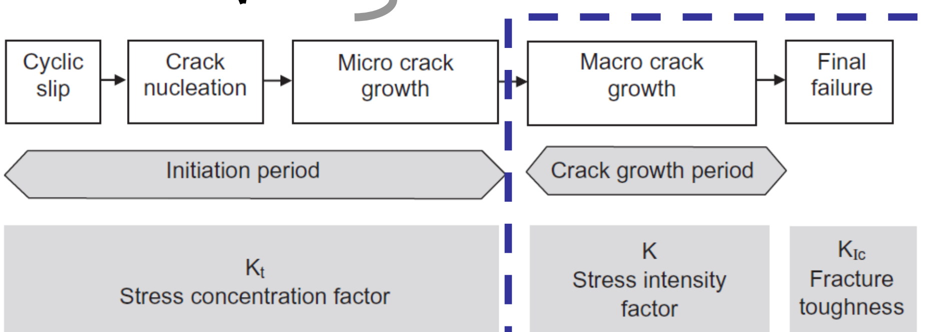
Fatigue life of the welded joint consists mainly of macro-crack growth

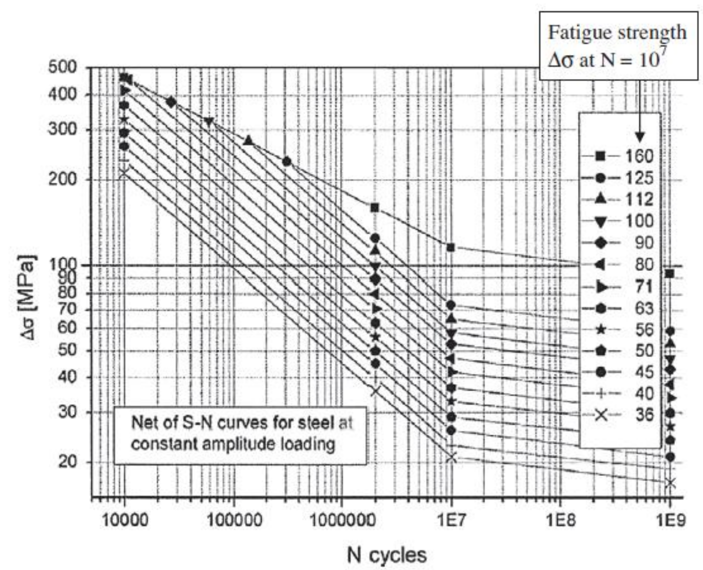
S-N curve can be calculated by integrating the crack growth law

$$\frac{da}{dn} = C\,\Delta K^{m}$$

$$\Delta K = Y\,\Delta\sigma\,\sqrt{\pi\,a}$$

$\Delta\sigma^{m}\,N = Cte$

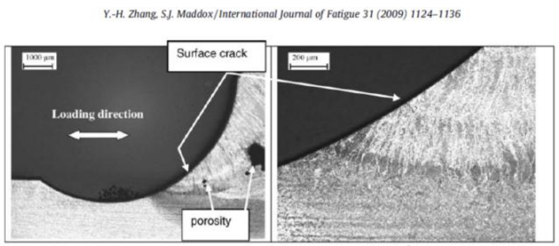




Example -1

Fatigue strength of non-load-carrying transverse fillet welded joints

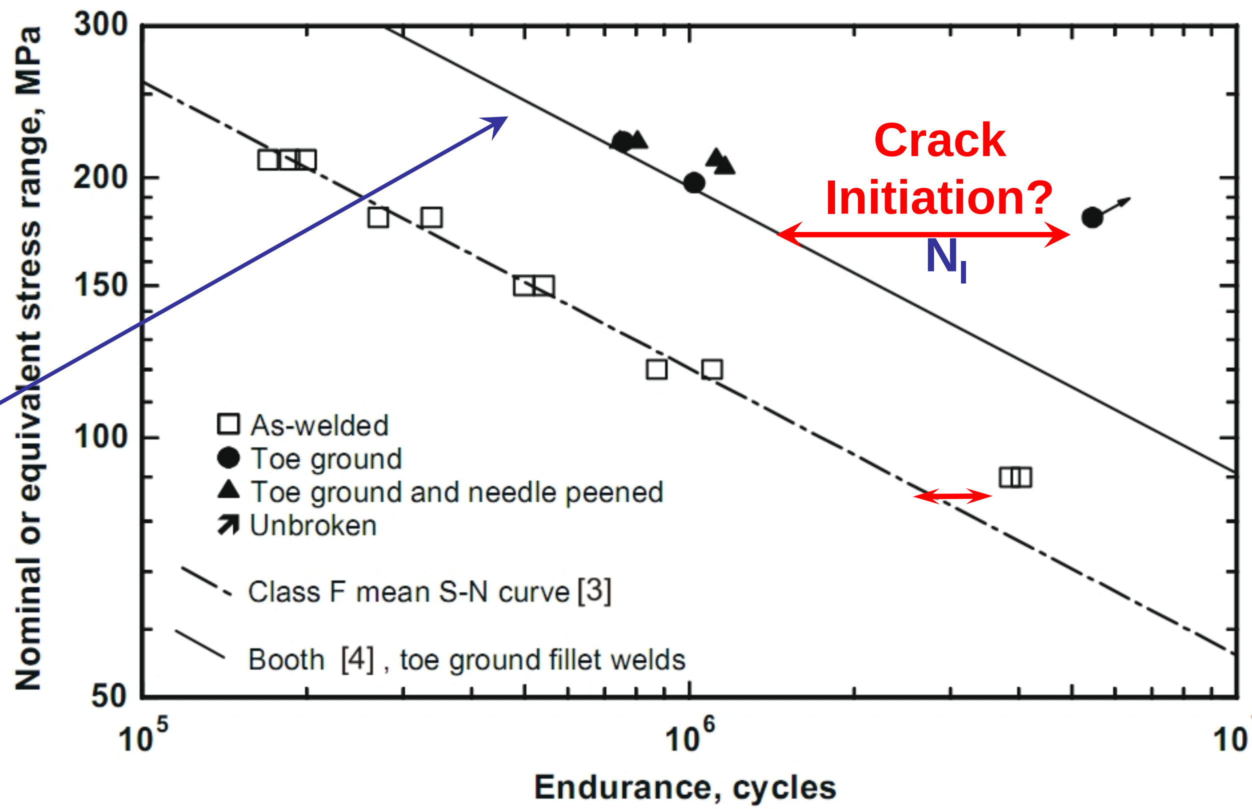
Yan-Hui Zhang, S.J.Maddox, Fatigue life prediction for toe ground welded joints, International Journal of Fatigue, 31, 2009, pp 1124-1136.



Estimation:
Fatigue crack propagation N_P

$$\frac{da}{dN} = A(\Delta K)^m$$

(No fatigue limit)



"…Both the experiments and calculations based on fracture mechanics suggested that the fatigue lives of the toe ground joints that gave **fatigue lives <10^6 cycles were dominated by the crack propagation process**. However, in the long life regime (>10^6 cycles), crack initiation became significant. **Reasonable estimates of the crack initiation period were made using the local stress approach proposed by Lawrence et al**…."

$N_I >> N_P$

Fatigue resistance prediction by applying local fatigue concepts, e.g. the notch strain in combination with the crack propagation approach.

P. Schaumann, M. Collmann.

Center for Wind Energy Research, Institute for Steel Construction. Hannover, Germany

Example -2

Procedia Engineering 66 (2013) 62 – 72. Fatigue Design Conference 2013

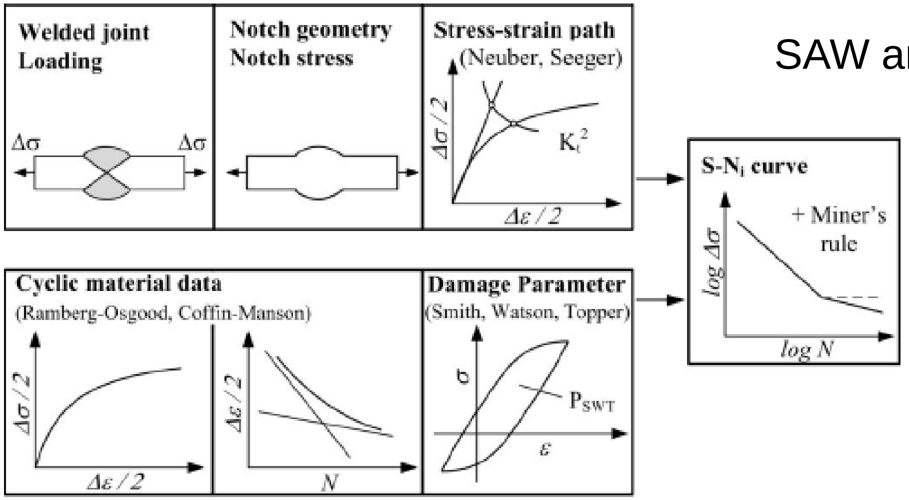
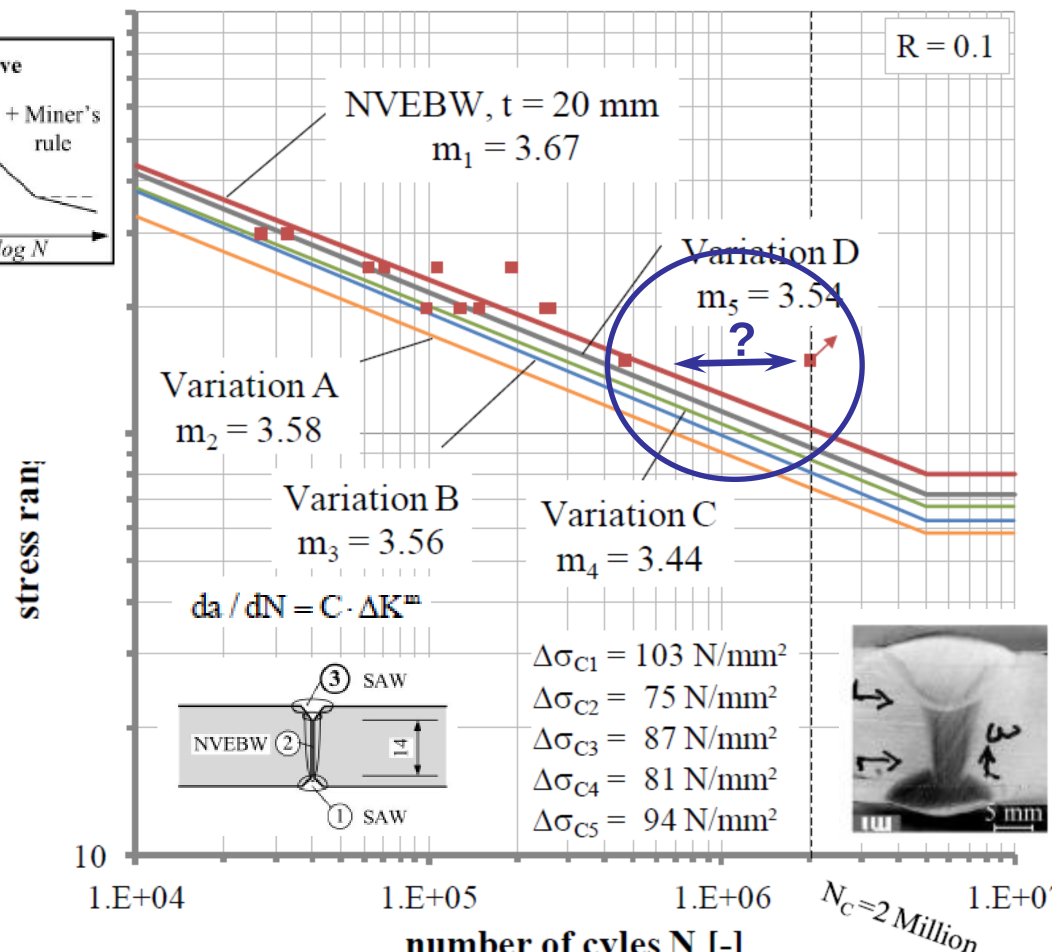


Fig. 5. Notch strain approach according to Seeger; scheme following [12].

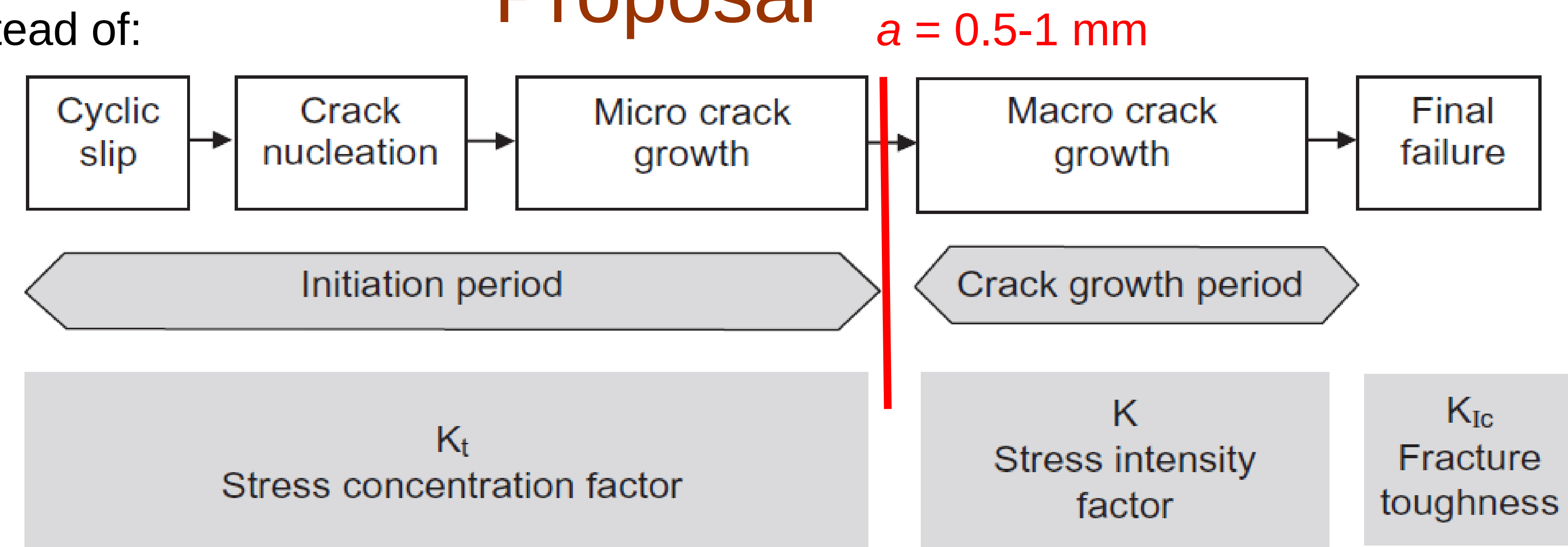
SAW and NVEBW (non-vacuum electron beam welding)



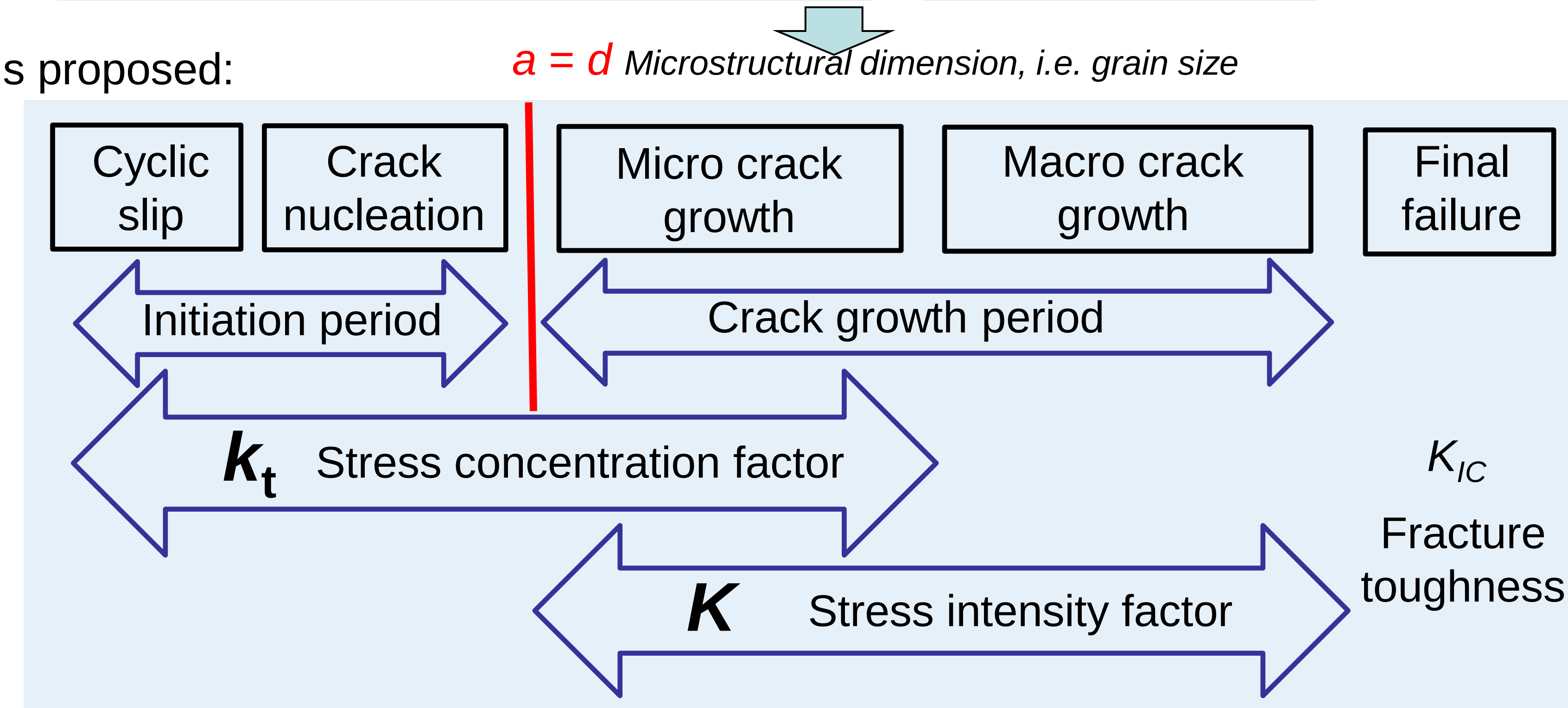
"Basically, it is assumed that total fatigue life Nf of components consists of two major phases: **crack initiation N_I and crack propagation N_P**. With regard to local effects at the fatigue critical detail, the **number of cycles until a small crack with a <u>depth of 0.5 mm</u>** and a width of 1.0 mm is initiated may be modeled by the notch strain approach, e.g. according to Seeger."

Proposal

Instead of:

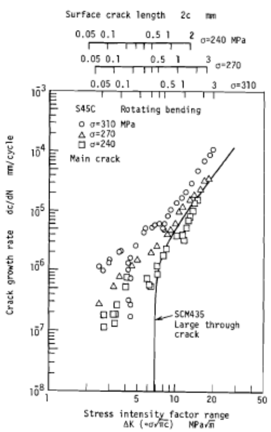


It is proposed:



Estimating Fatigue Crack Propagation Rates and Lives

$$N_P = \int_{a_i}^{a_f} \frac{da}{C\left(\Delta K - \Delta K_{th}(a)\right)^m} \qquad \Delta K = Y\,\Delta\sigma\,\sqrt{\pi a}$$



Growth of microstructurally small fatigue cracks

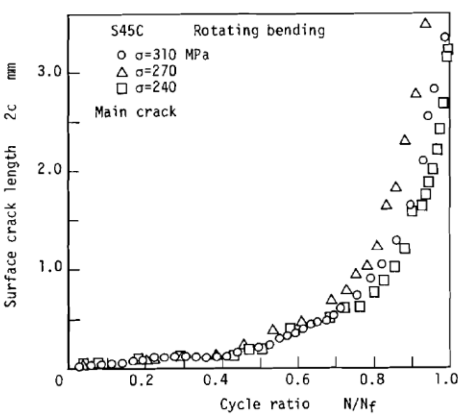
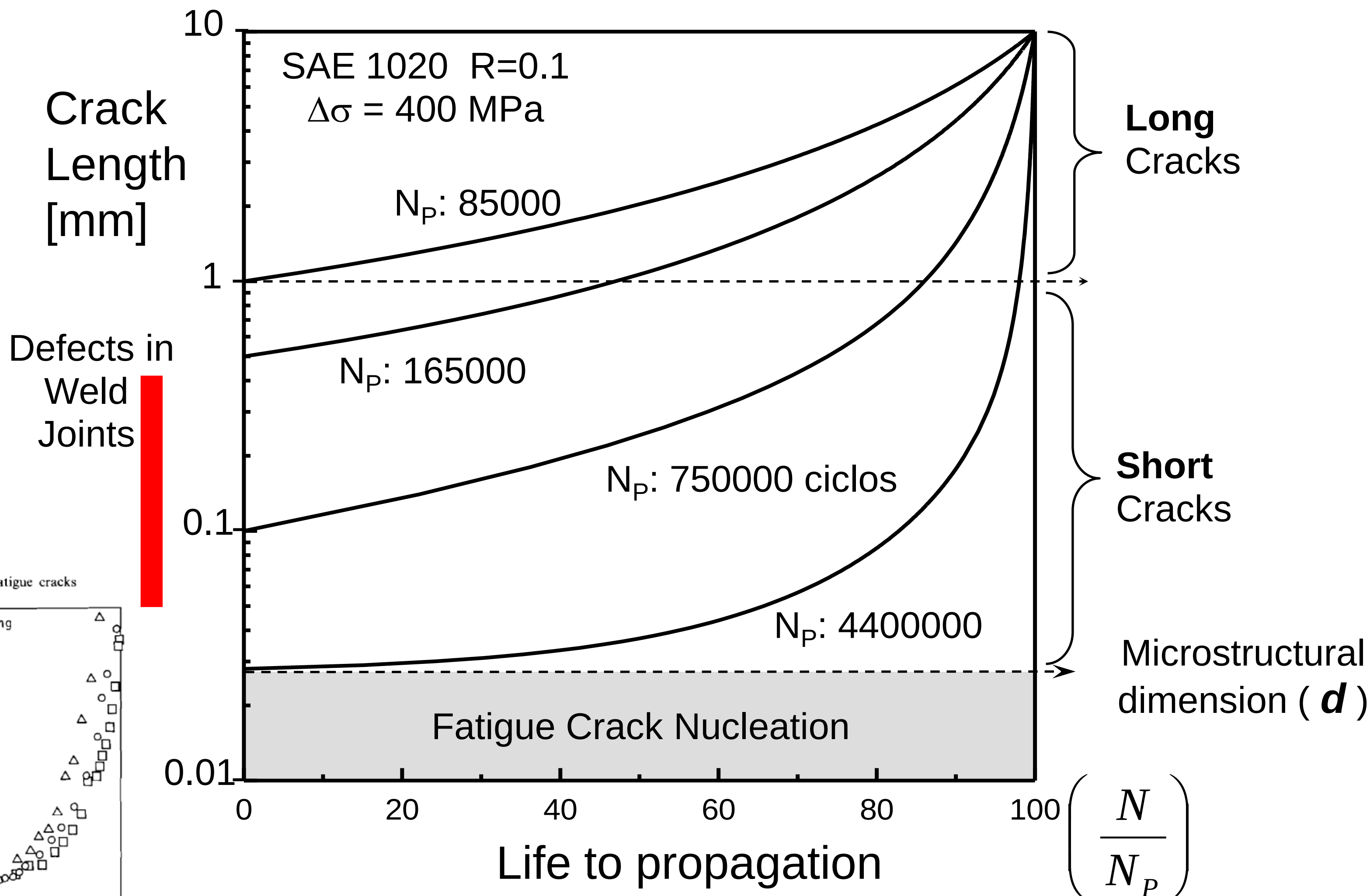


Fig. 2. Crack growth curve for small fatigue cracks.

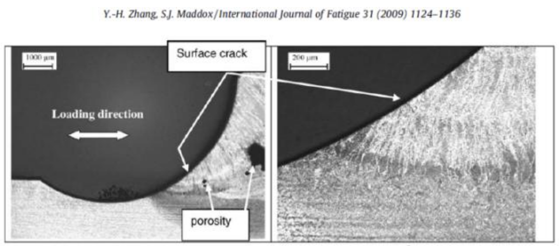


Tokaji and Ogawa. Fatigue Fract Engng Mater Struct, 1988_11_331

Example -1

Fatigue strength of non-load-carrying transverse fillet welded joints

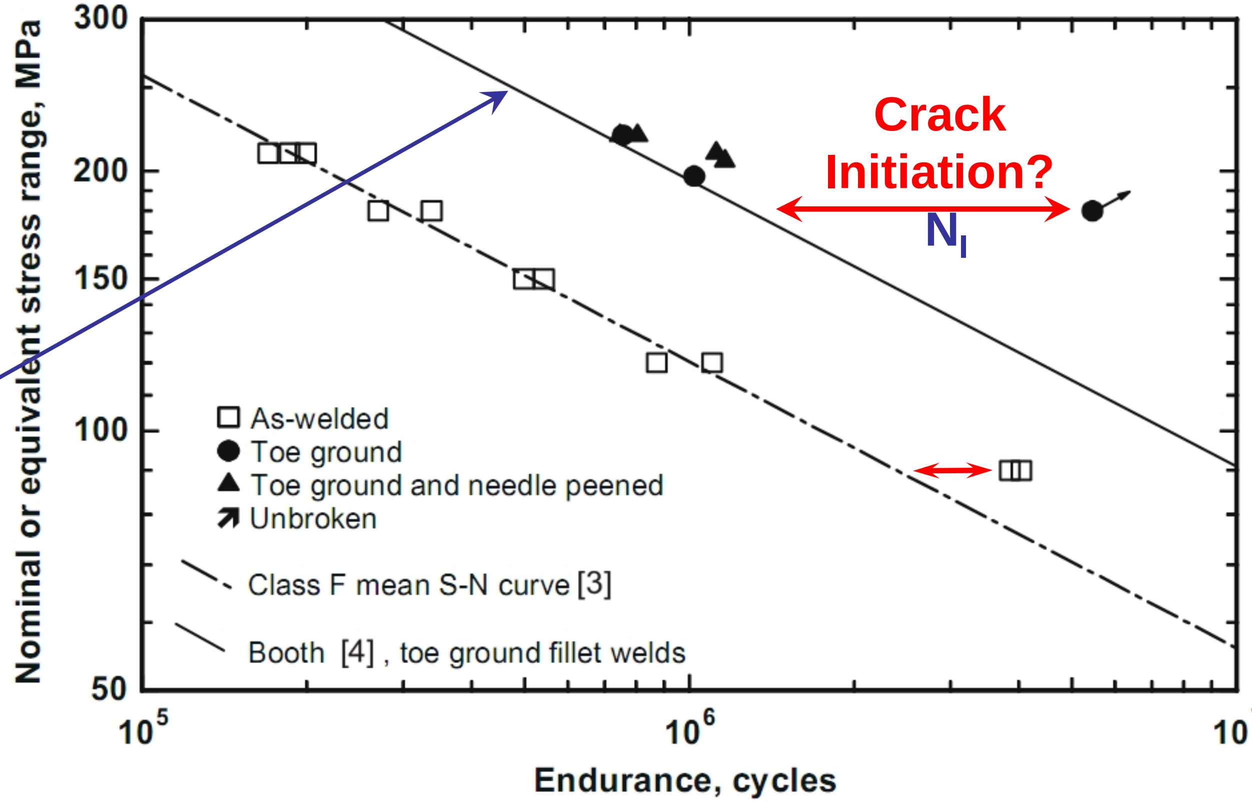
Yan-Hui Zhang, S.J.Maddox, Fatigue life prediction for toe ground welded joints, International Journal of Fatigue, 31, 2009, pp 1124-1136.



Estimation:
Fatigue crack propagation N_P

$$\frac{da}{dN} = A(\Delta K)^m$$

(No fatigue limit)



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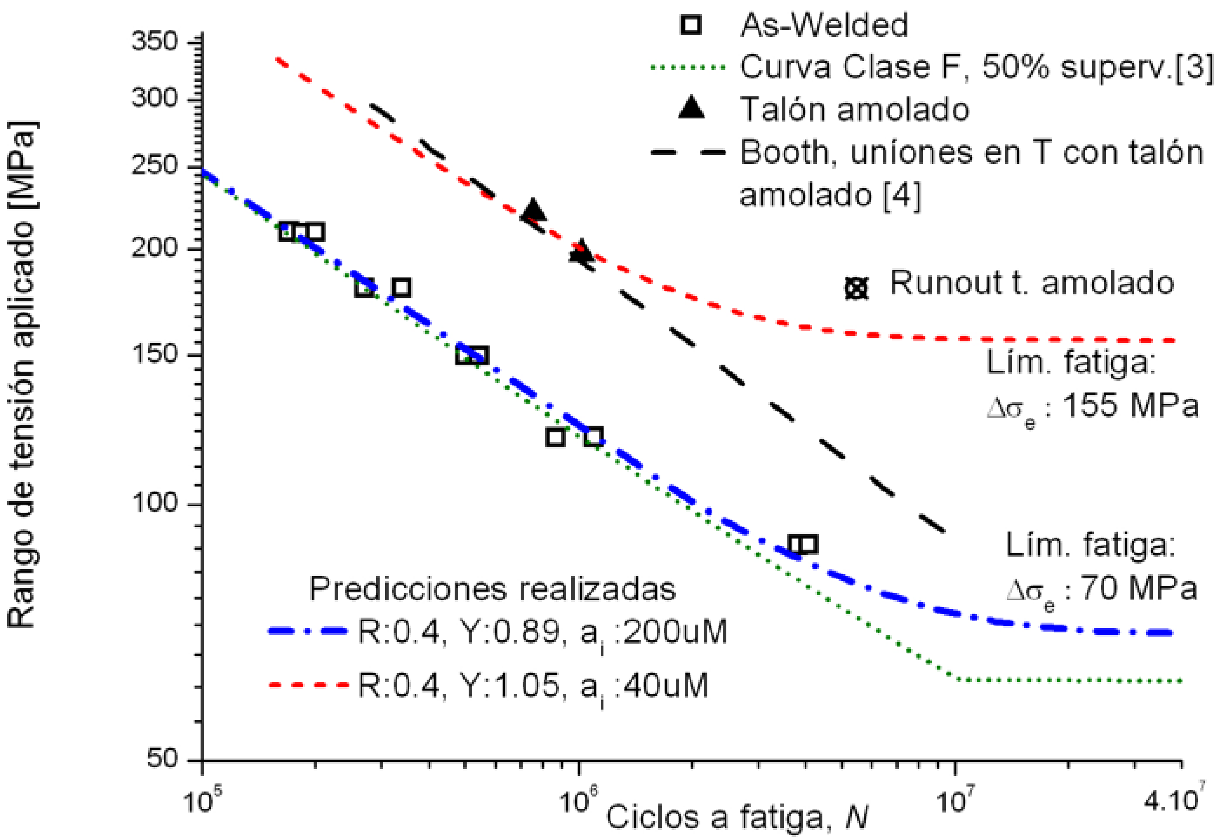
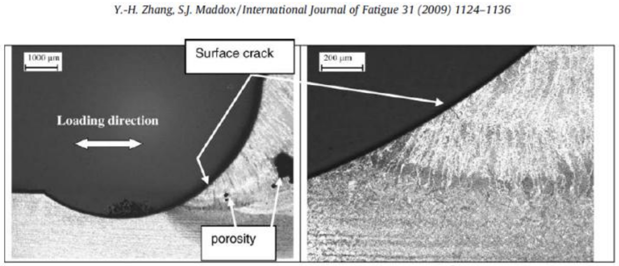
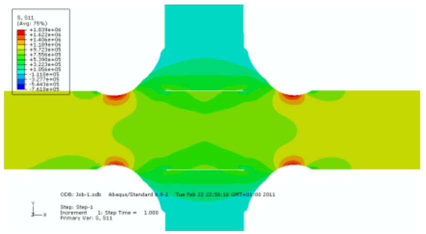
$N_I >> N_P$

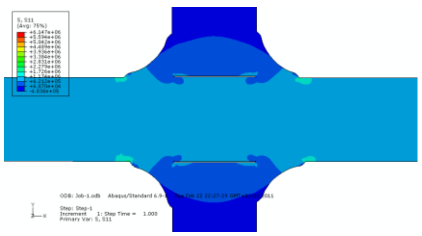
Estimation of fatigue strength of non-load-carrying transverse fillet welded joints

Fatigue behavior prediction of welded joints by using an integrated fracture mechanics approach.
Chapetti, Jaureguizahar. International Journal of Fatigue Vol.43, pp.43-53, 2012.



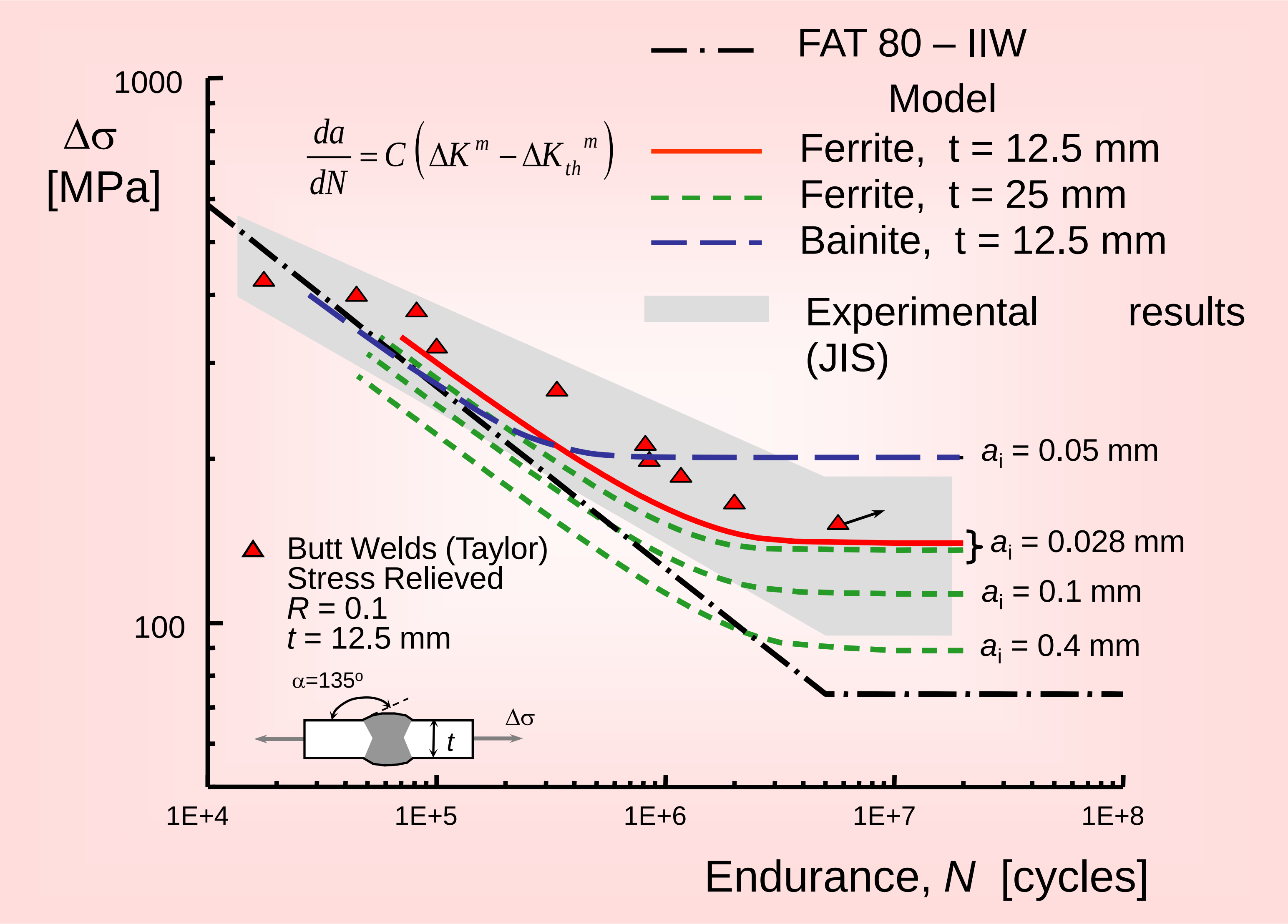






Fatigue strength of butt welds

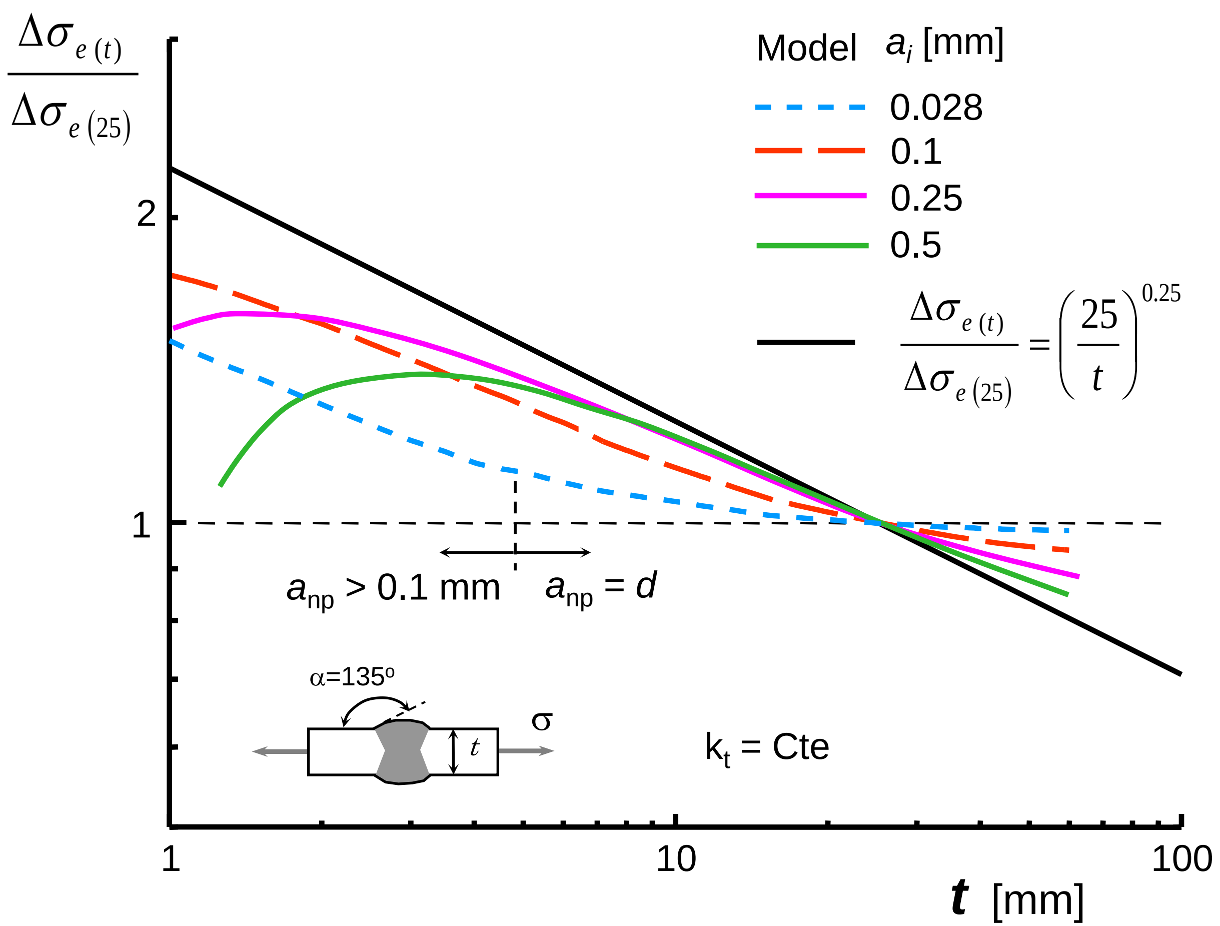
S-N Curves



Fatigue strength of butt welds

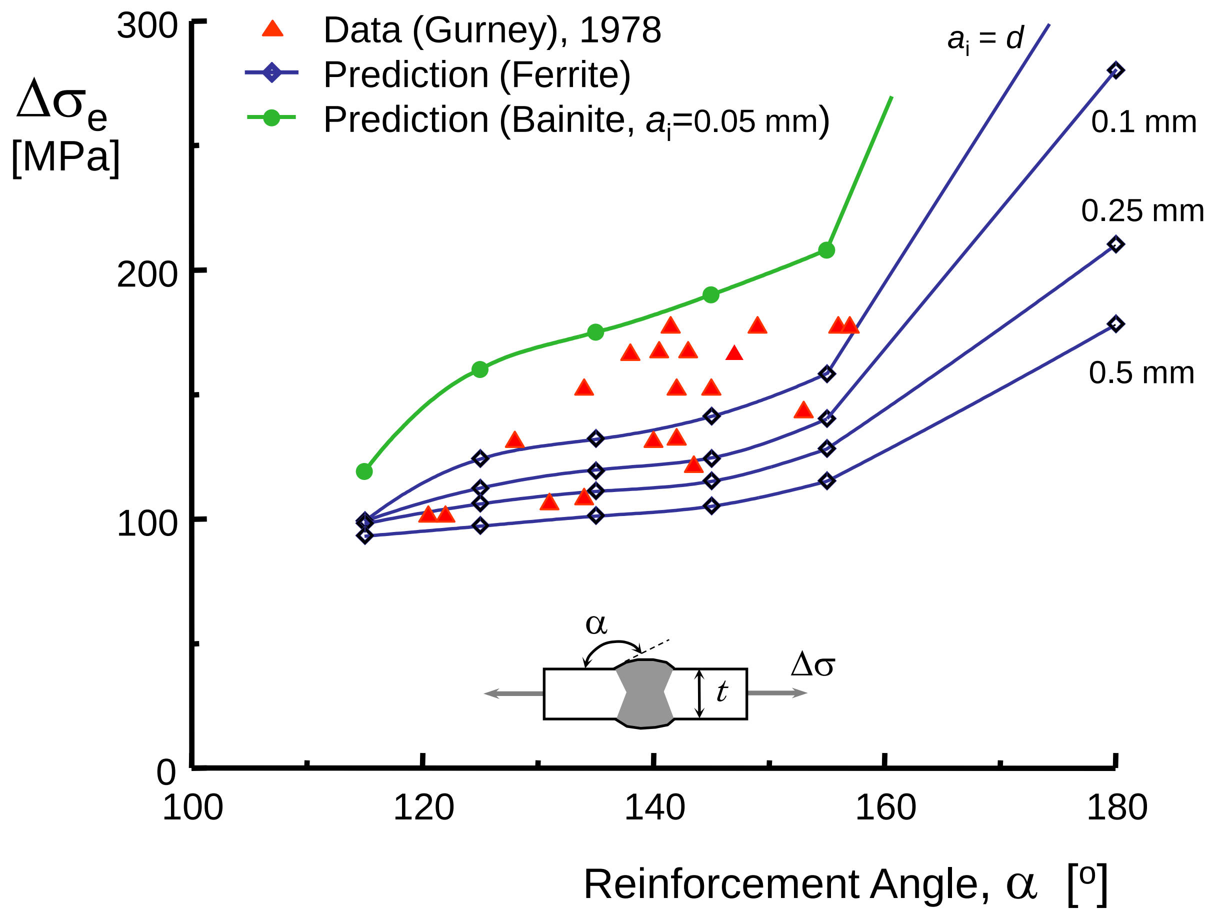
Influence of plate thickness

Estimations using ΔK_{th}

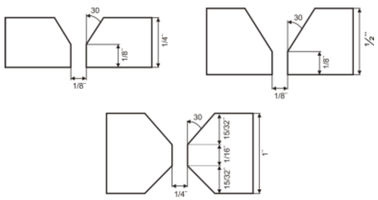


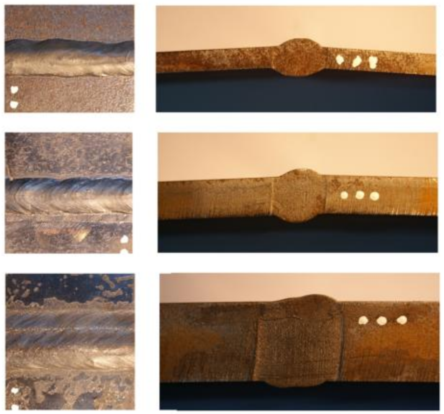
Fatigue strength of butt welds

Influence of reinforcement angle, α



Fatigue strength of butt welds Crack detection and monitoring

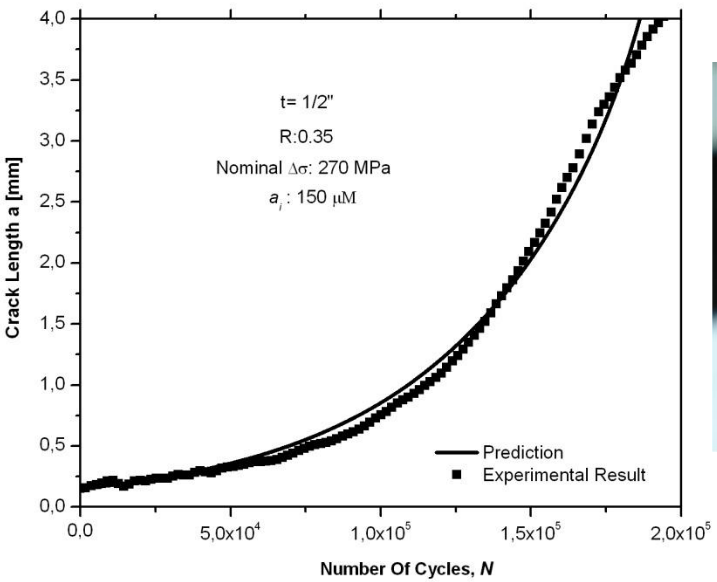


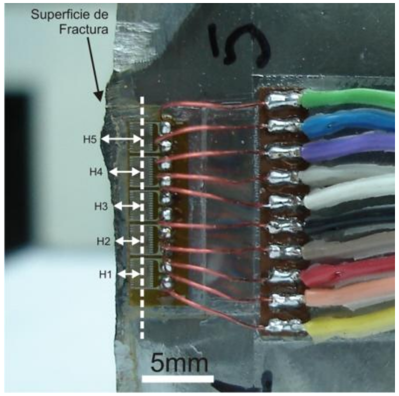


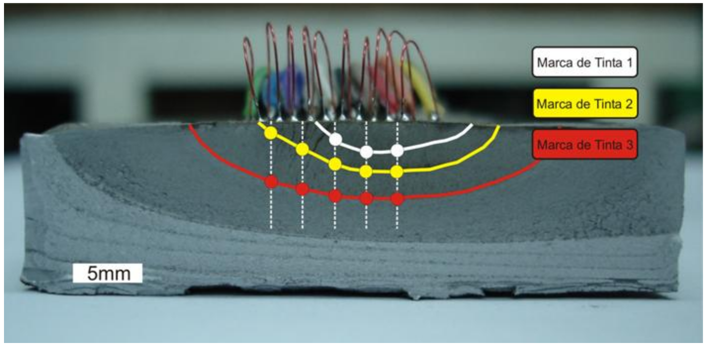
1/4”

½”

1”



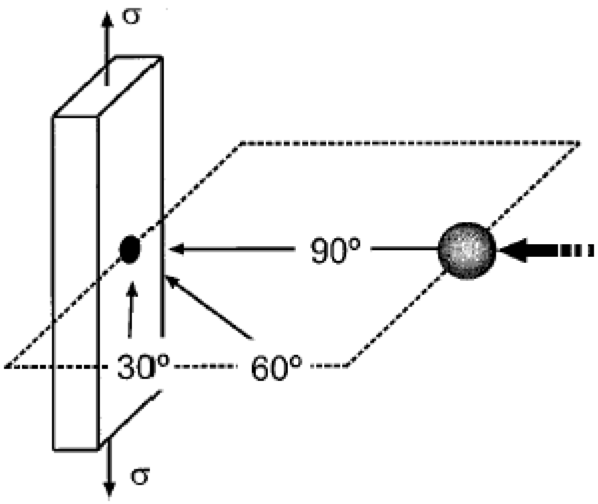




Example 1

Fatigue behaviour of small cracks induced by foreign-object damage (FOD) in Ti-6A-4V

M.D. Chapetti, *International J. of Fatigue* Vol.27, No5, pp.493-501, 2005



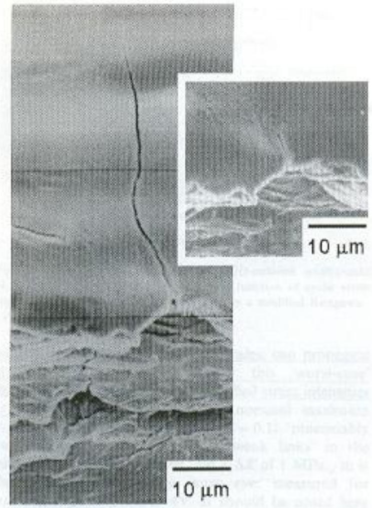


Fig. 3. SEM micrograph of FOD-induced microcracking at the crater rim (insert) and subsequent fatigue-crack growth at such microcrack after 29 000 cycles ($\sigma_{max} = 500$ MPa, $R = 0.1$).

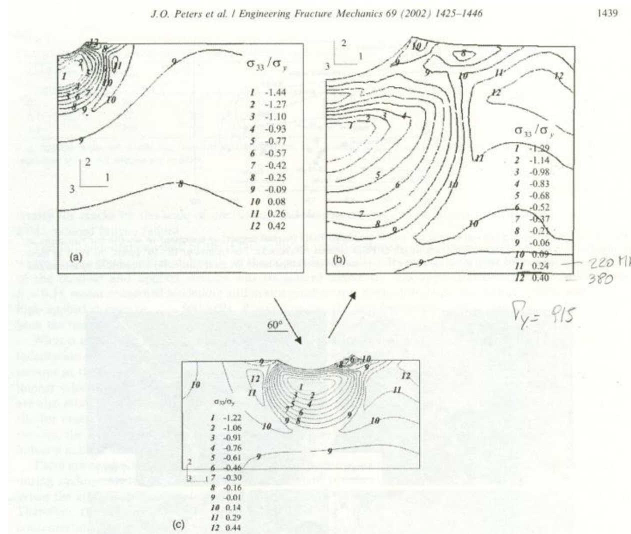
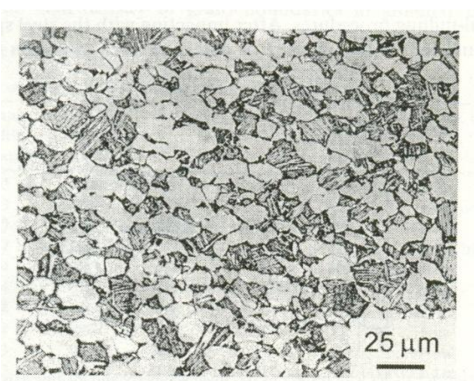
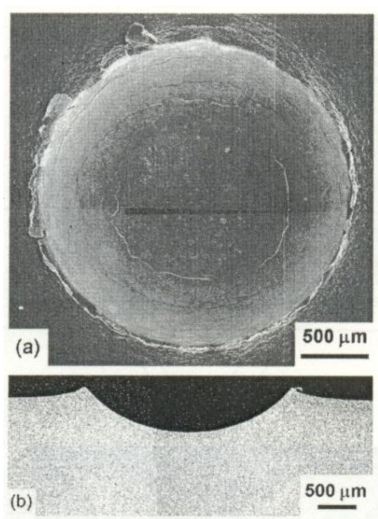


Fig. 12. Residual stress distribution in plane perpendicular to longitudinal axis of K_B specimen, after 300 m/s normal (90°) impact using (a) 1 mm and (b) 3.2 mm diameter steel shot, or (c) 200 m/s inclined (60°) impact using 3.2 mm steel shot. After Chen and Hutchinson [12]. σ_{ll} = normal residual stress, σ_y = yield stress (915 MPa).

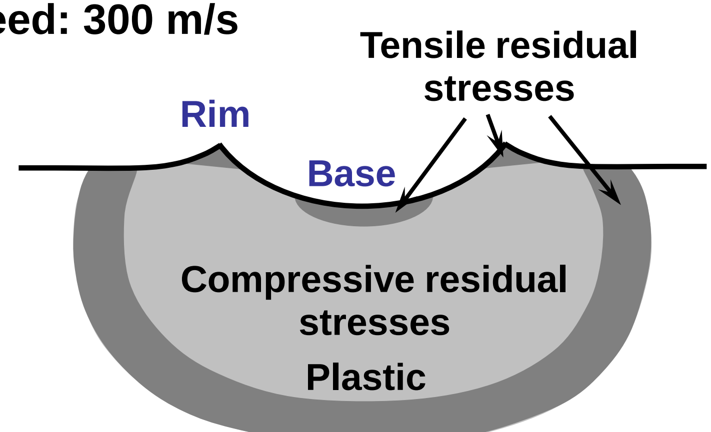
Ti-6Al-4V



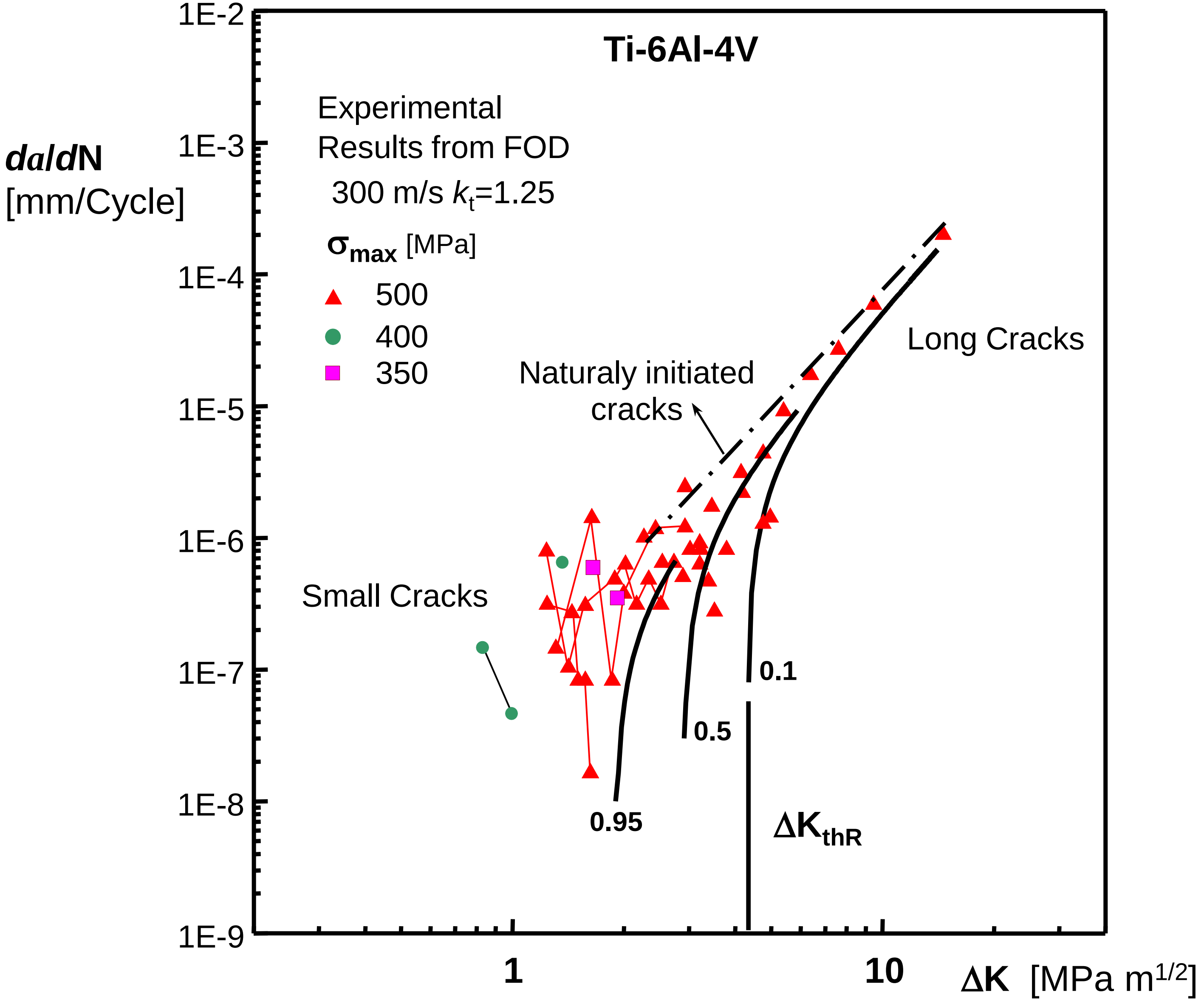


Ball Diameter: 3 mm
Impact Speed: 300 m/s

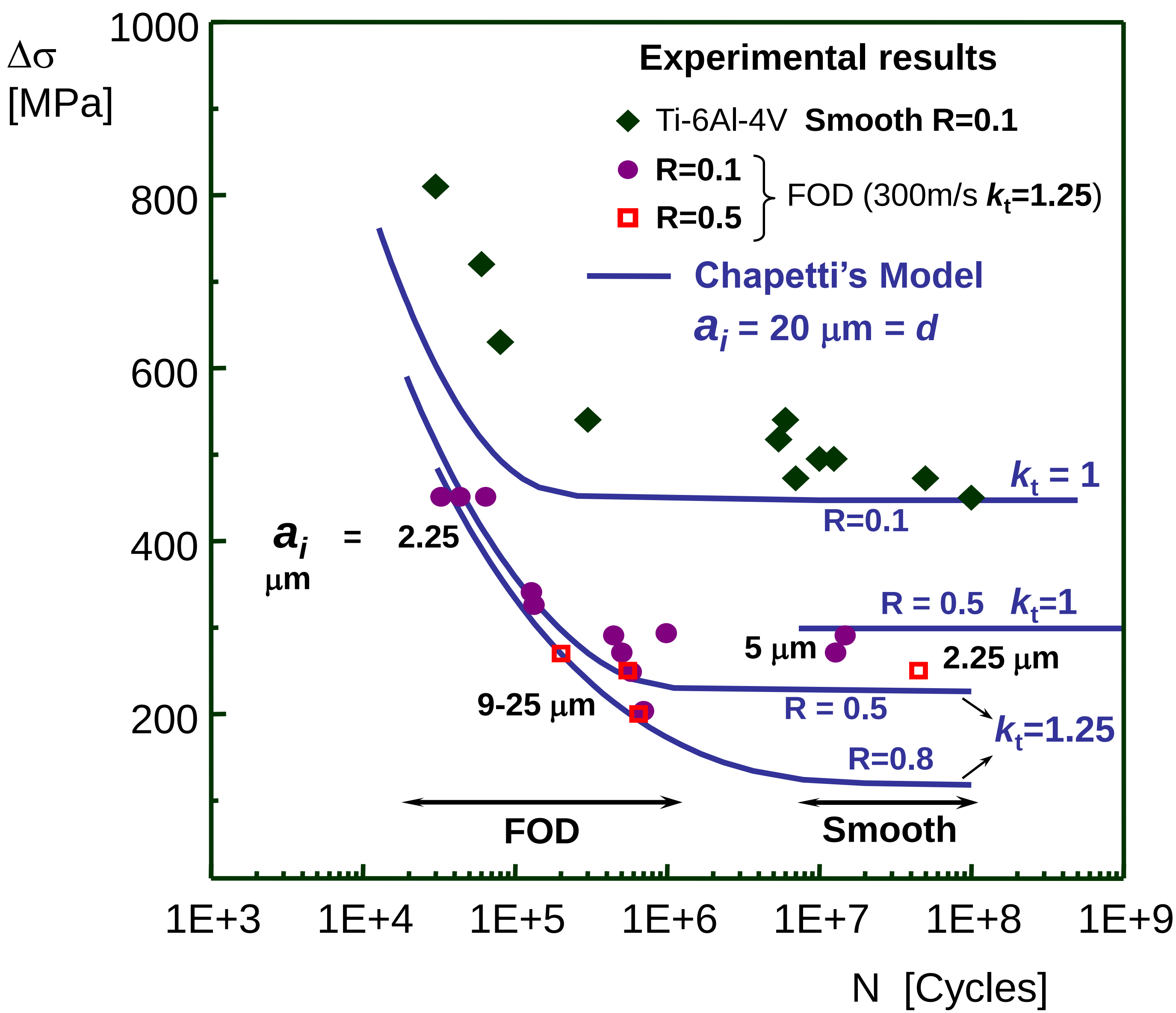
FOD



Fatigue crack propagation



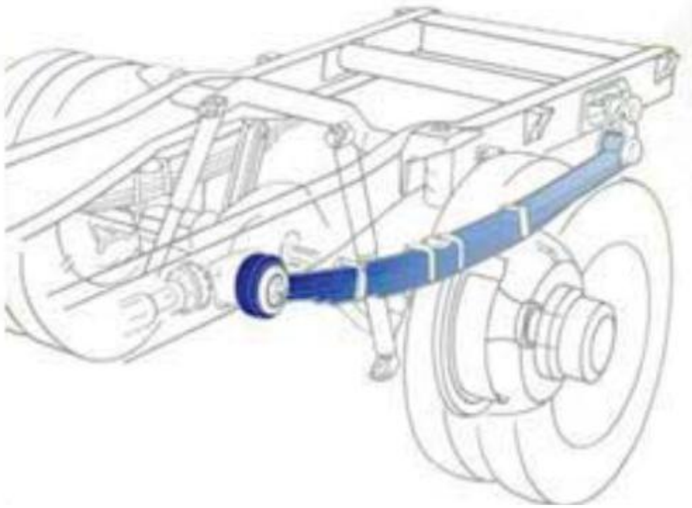
S-N Curves



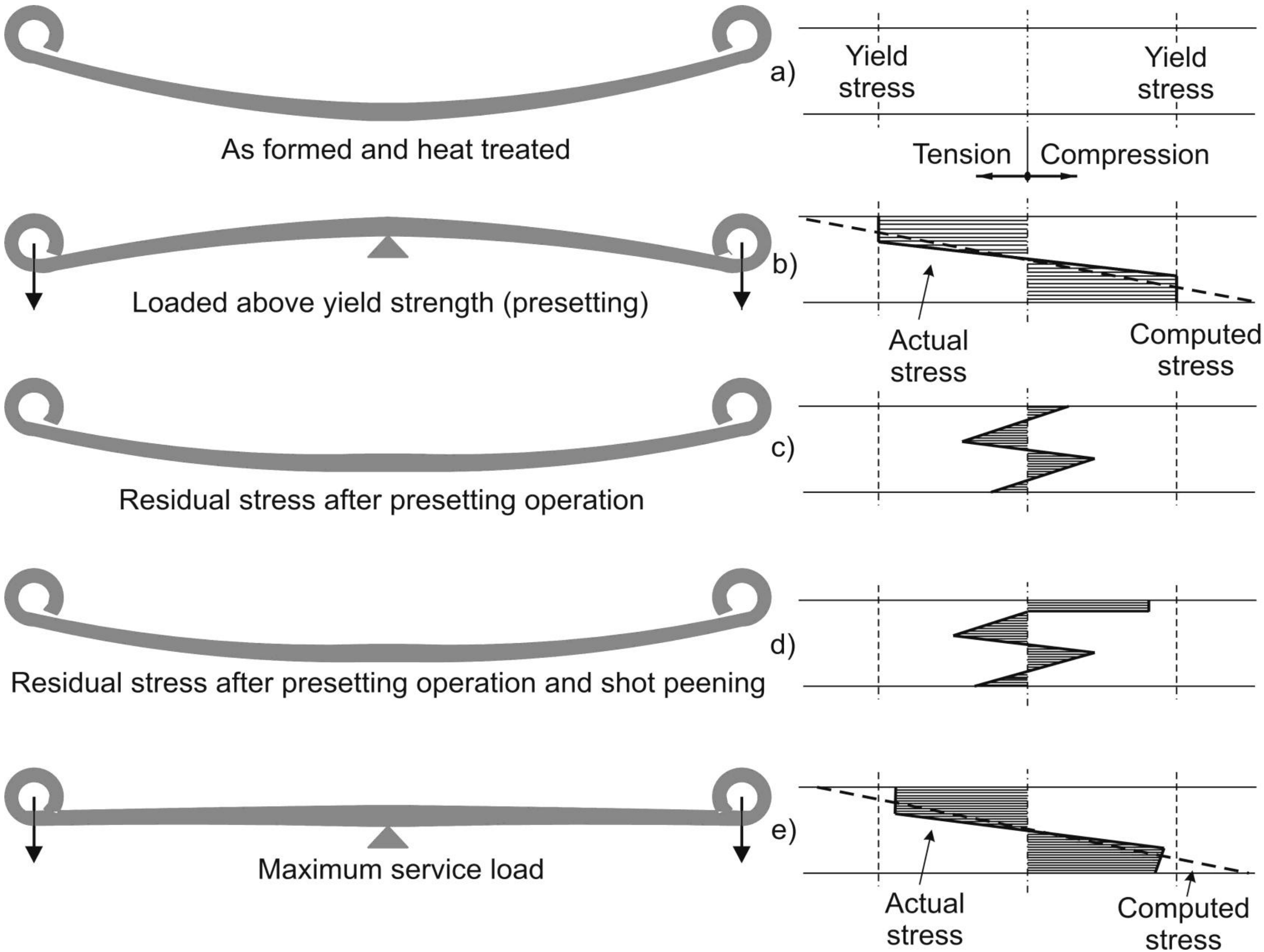
Δσ [MPa]
1000
800
600
400
200
Experimental results
Ti-6Al-4V Smooth R=0.1
R=0.1
R=0.5
FOD (300m/s kt=1.25)
Chapetti's Model
ai = 20 μm = d
kt = 1
R=0.1
ai = 2.25 μm
R = 0.5 kt=1
5 μm
2.25 μm
9-25 μm
R = 0.5
kt=1.25
R=0.8
FOD
Smooth
1E+3
1E+4
1E+5
1E+6
1E+7
1E+8
1E+9
N [Cycles]

Aplication: Analysis of the fatigue behavior of parabolic springs

Example 3



stresses profile from pre-stressing and shot-peening



Residual Stresses

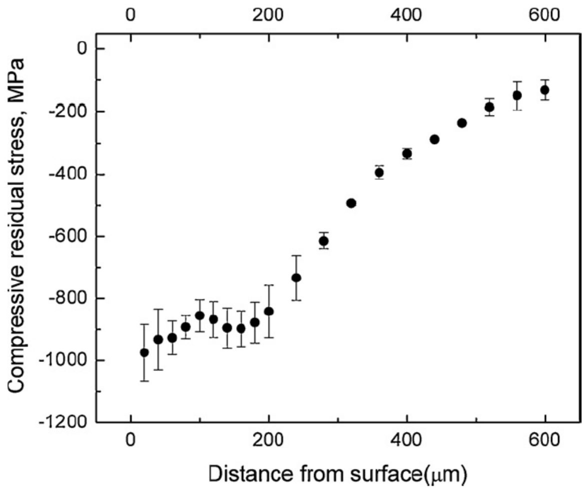
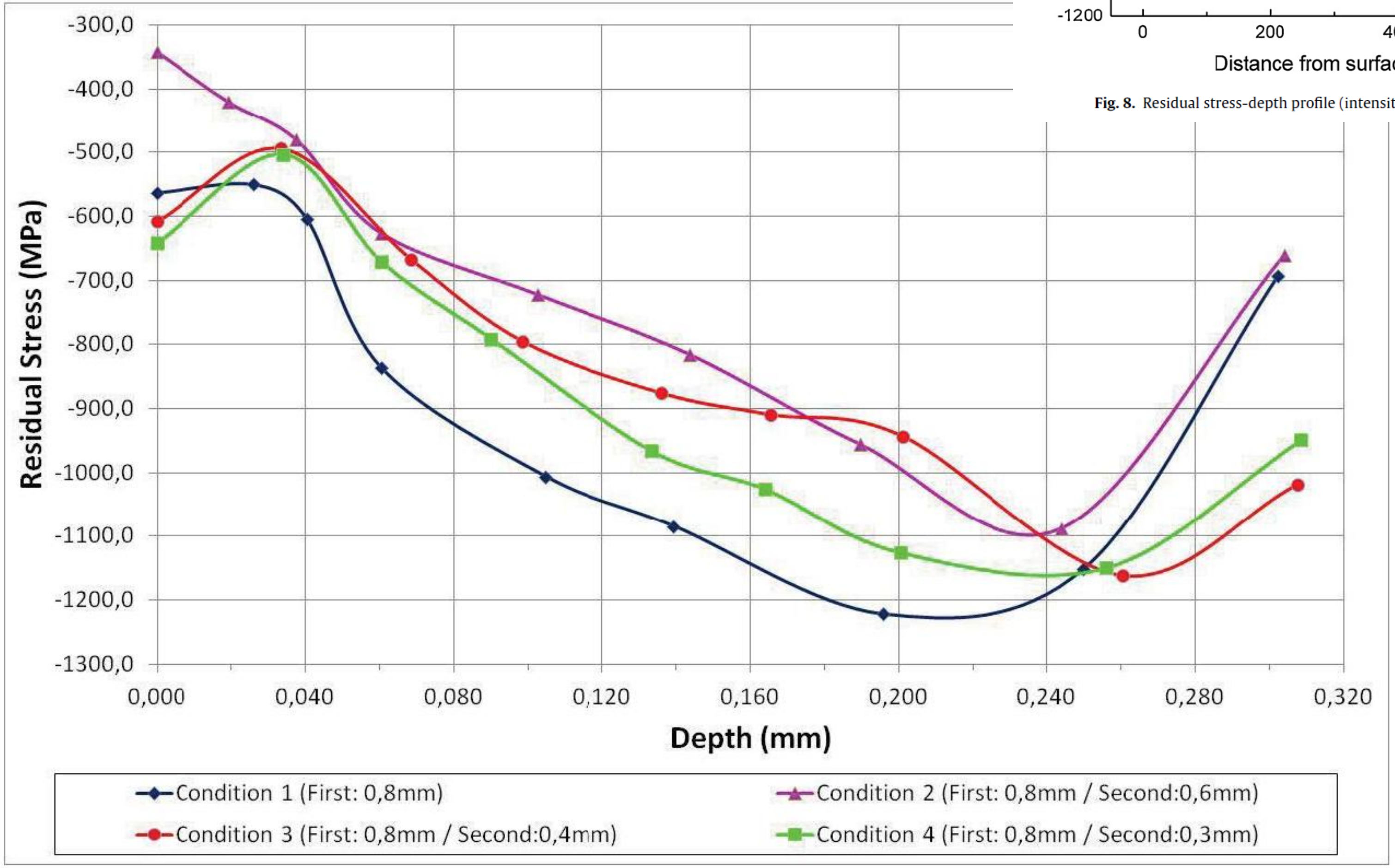


Fig. 8. Residual stress-depth profile (intensity = 0.38 mmA).

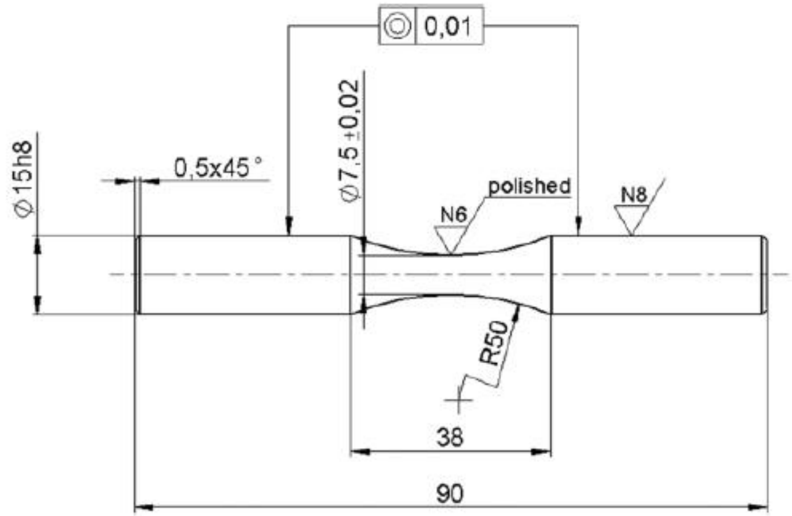
For X-ray residual stress measurement, a Rigaku DMAX 2000 was used, with Cr tube, 40 kV 20 mA as reference. The equipment is from x-ray diffraction lab from IPEN/CNEN-SP, Brazil.

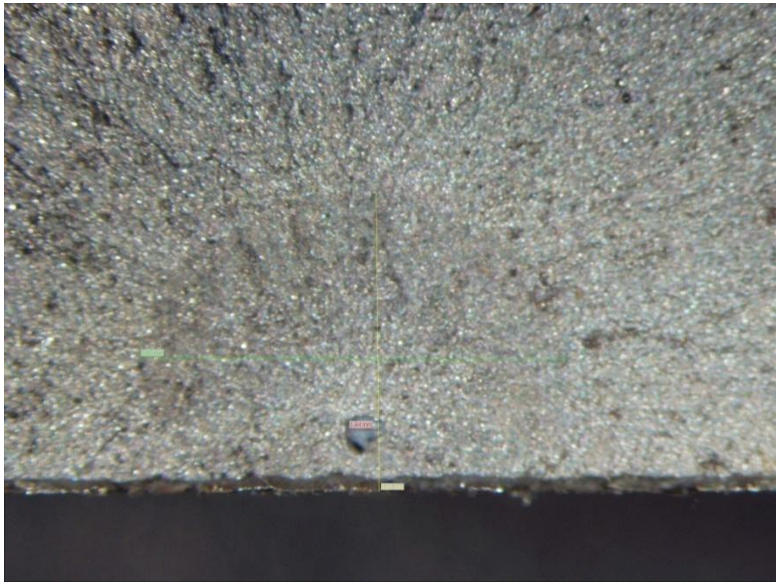


Experimental Tests and Results

size of inclusions varies
between 35 μm to 450 μm

a)

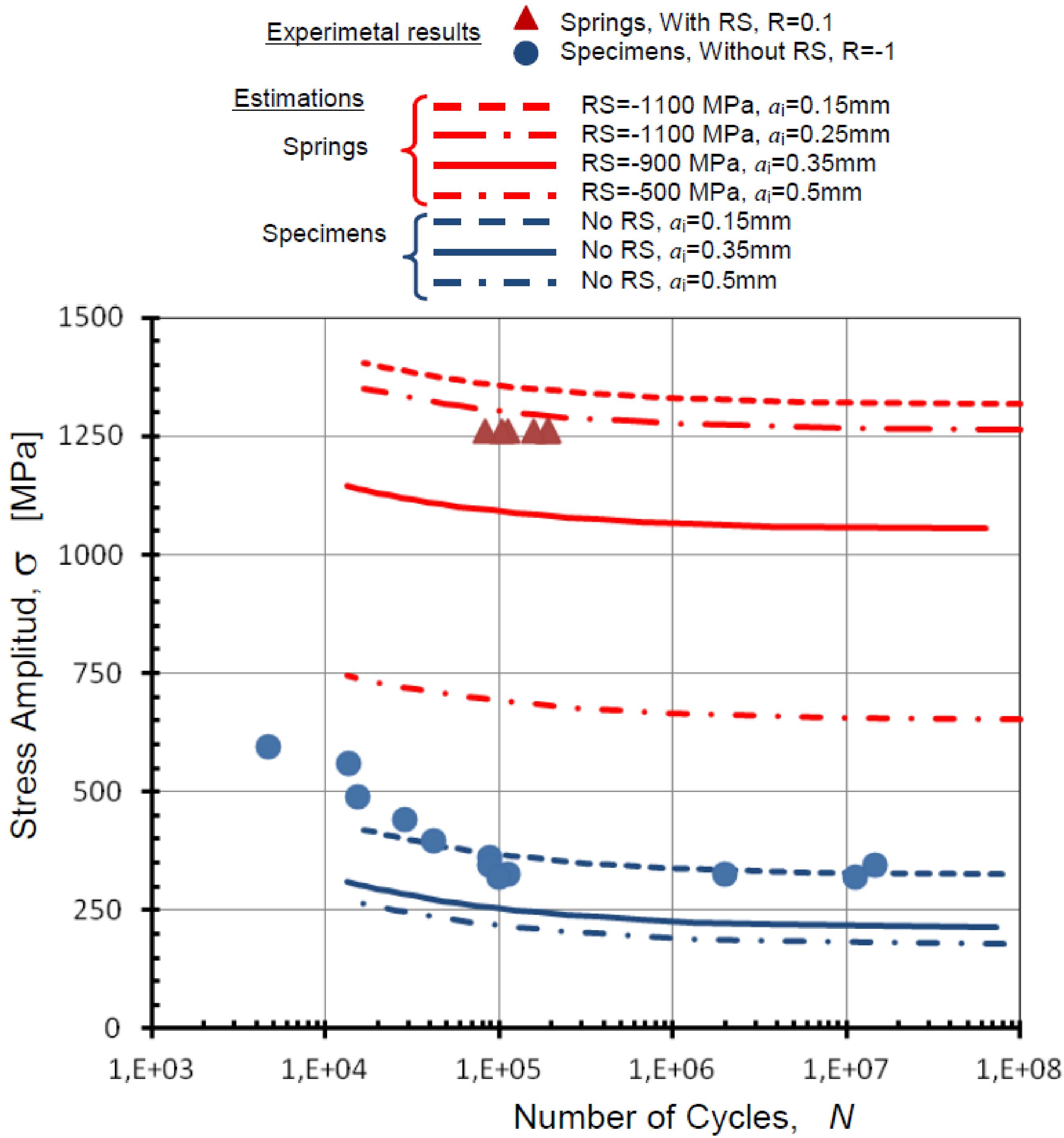




tempered martensite $d = 5$ μm
590 H_V σ_u=1670 ± 25 MPa

b)

Figure 2. a) Rotating bending test specimen, b) Example of the spring test setting



Experimetal results
Springs, With RS, R=0.1
Specimens, Without RS, R=-1
Estimations
Springs
RS=-1100 MPa, a_i=0.15mm
RS=-1100 MPa, a_i=0.25mm
RS=-900 MPa, a_i=0.35mm
RS=-500 MPa, a_i=0.5mm
Specimens
No RS, a_i=0.15mm
No RS, a_i=0.35mm
No RS, a_i=0.5mm
1500
1250
1000
750
500
250
0
Stress Amplitud, σ [MPa]
1,E+03
1,E+04
1,E+05
1,E+06
1,E+07
1,E+08
Number of Cycles, N

Conclusiones:
(Rol de la Universidad)

- Incorporar de forma continua a los cursos de grado y posgrado nuevas herramientas y nuevo conocimiento

  ➡ Condición: - Formación continua de docentes (investigación)
  - Pertinencia (docentes a cargo de áreas, formados).

- Actualización de los planes de estudio regularmente (10-20 años?)

- Elaborar canales de diálogo permanente con autoridades ministeriales

Gracias!!