Fatigue Prediction for Aluminum Materials

C. Broeckmann[1]

F. Klubberg, N. A. Giang

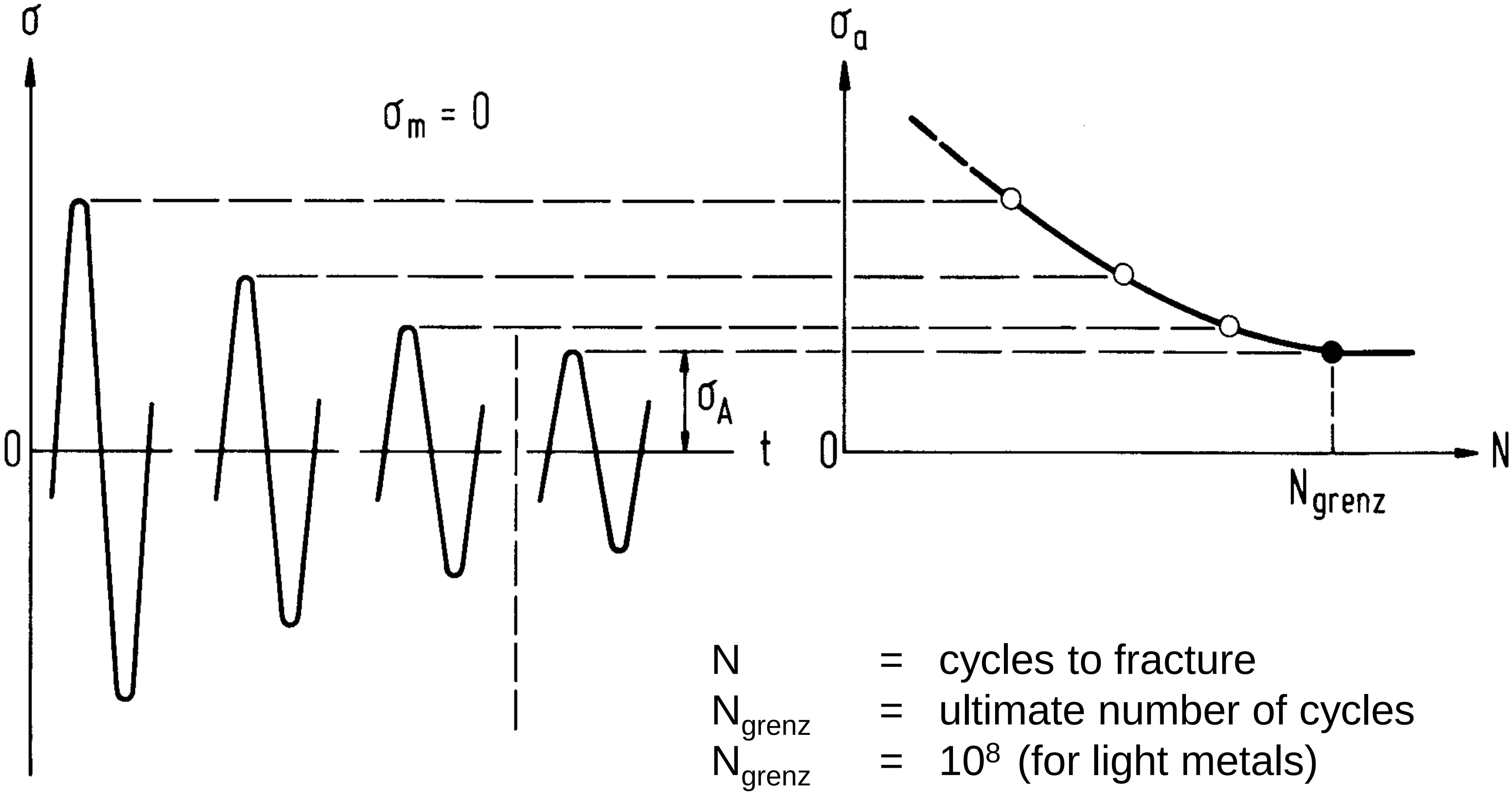
Institute for Materials Applications in Mechanical Engineering , RWTH Aachen

AMAP Colloquium, Aachen, January 15, 2015

Outline

1. Introduction
2. Fatigue prediction of aluminum components based on S-N-diagrams
3. Fatigue prediction based on the simulation of crack initiation and growth
4. Summary

S-N diagram (Wöhler curve)



N	=	cycles to fracture
N_{grenz}	=	ultimate number of cycles
N_{grenz}	=	10^8 (for light metals)

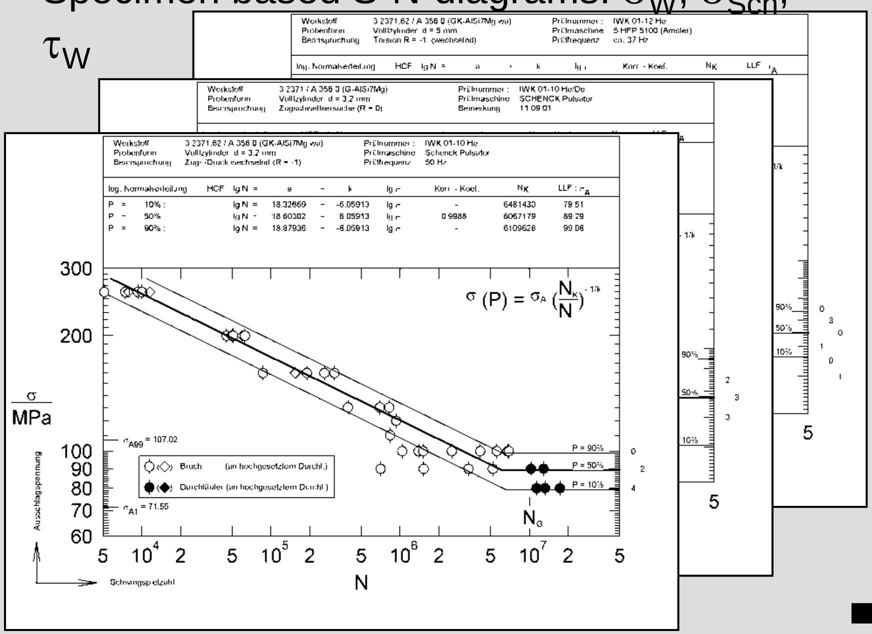
Conventional fatigue evaluation of components
example: brake calliper

material
(composition, heat treatment, strength, inhomogenity)

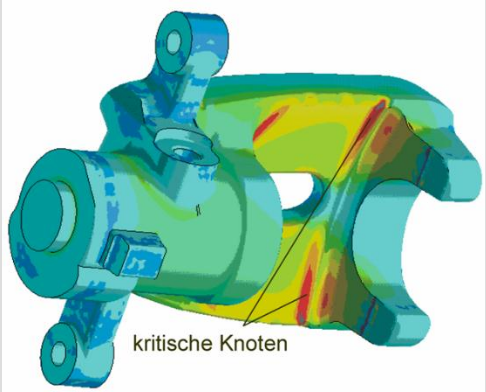
component
(geometry, surface, machining porosity, corrosion,)

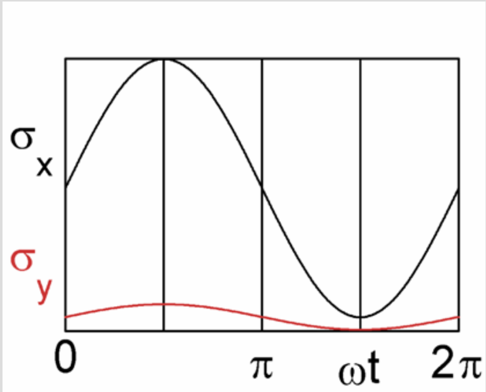
Service condition
(direction of loading, collective, multiaxial loading)

Specimen based S-N-diagrams: σ_W, σ_{Sch}, τ_W



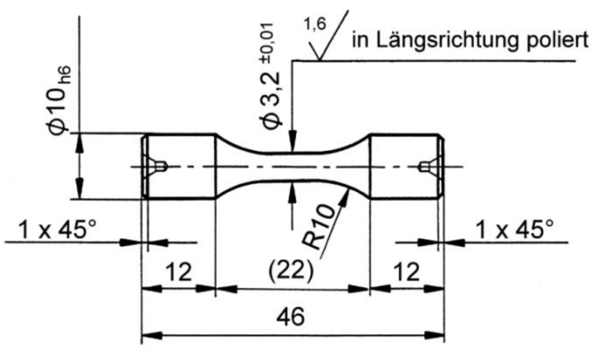
Loading of component
Stess analysis (FEA), local stress





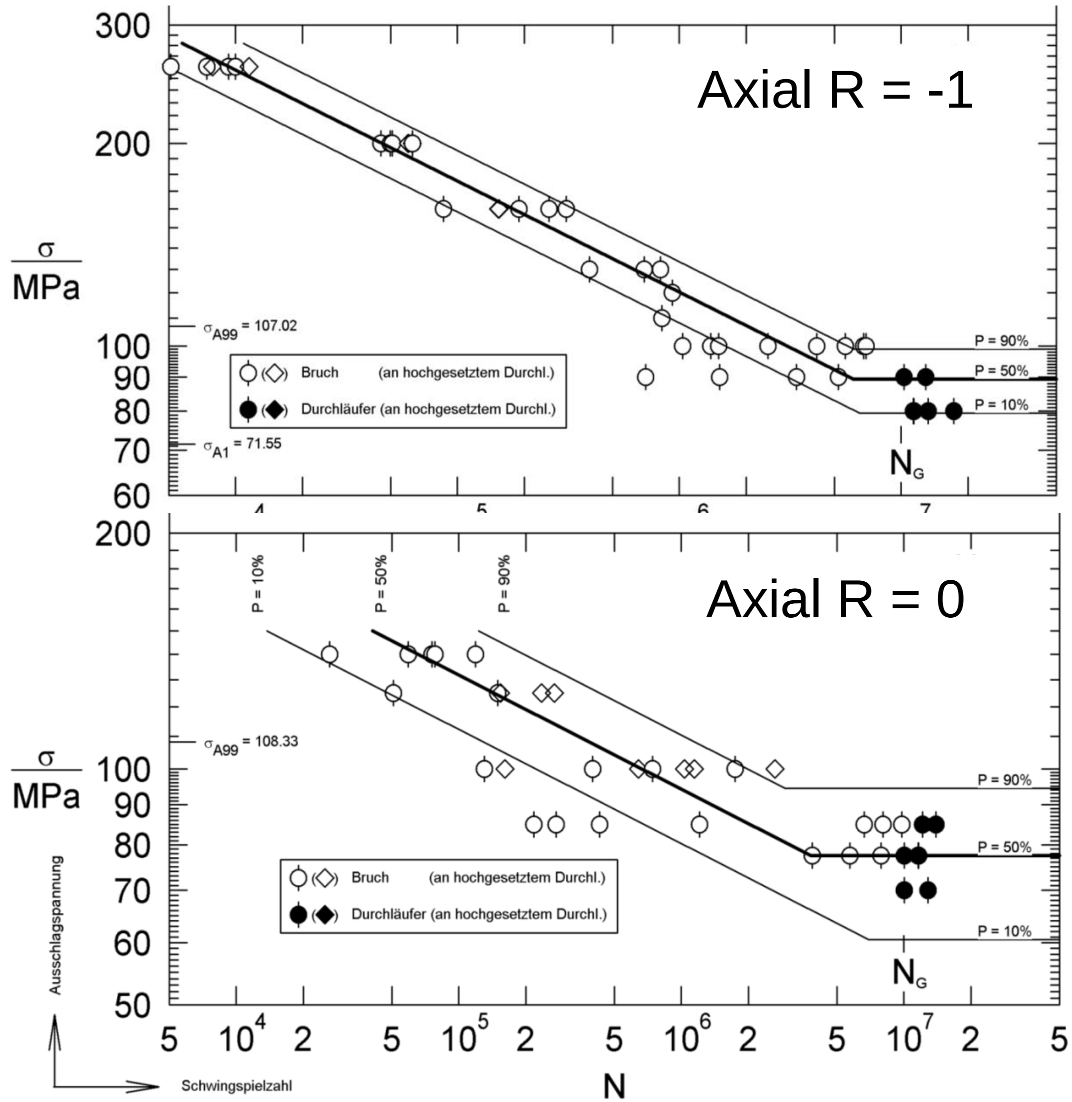
Multiaxial fatigue model

Specimen for axial testing



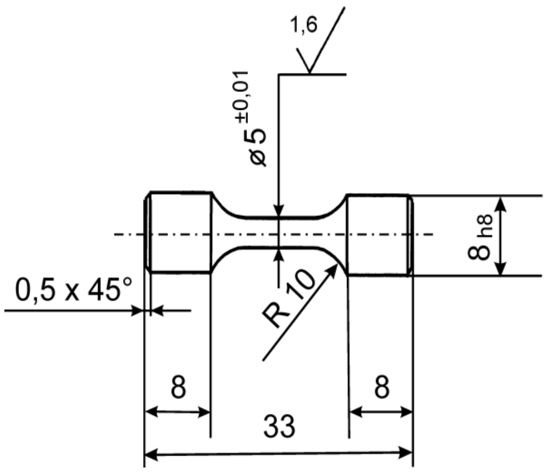
stress ratio:

$$R = \frac{\sigma_u}{\sigma_o}$$

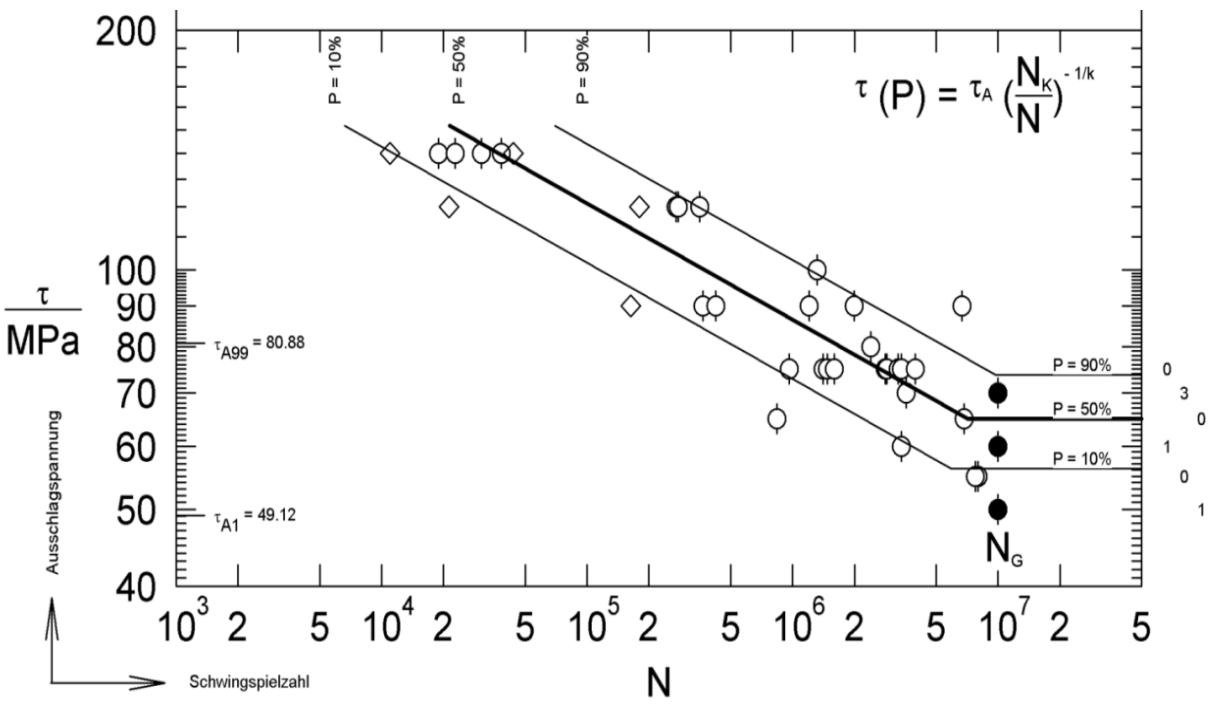


S-N-diagram for torsional loading

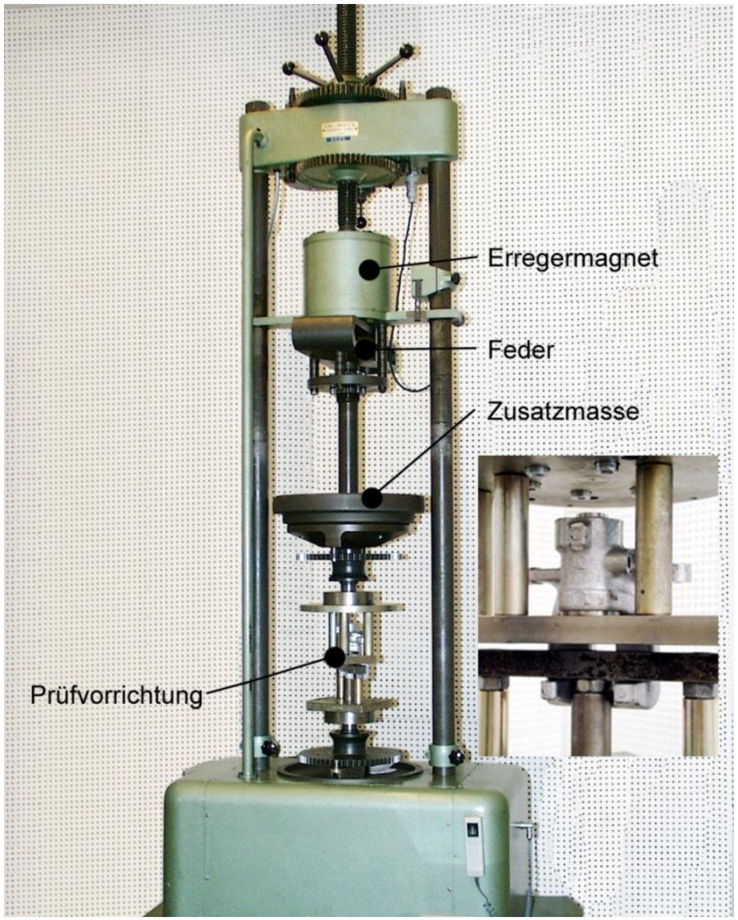
Specimen for torsion



R = -1



Testing of components

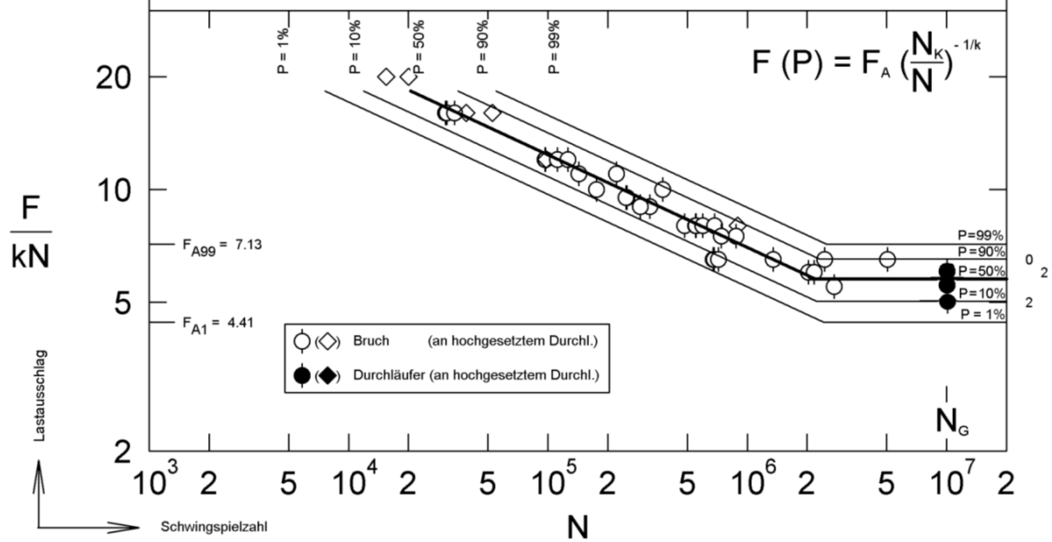


S-N diagram of component (R = 0,05)

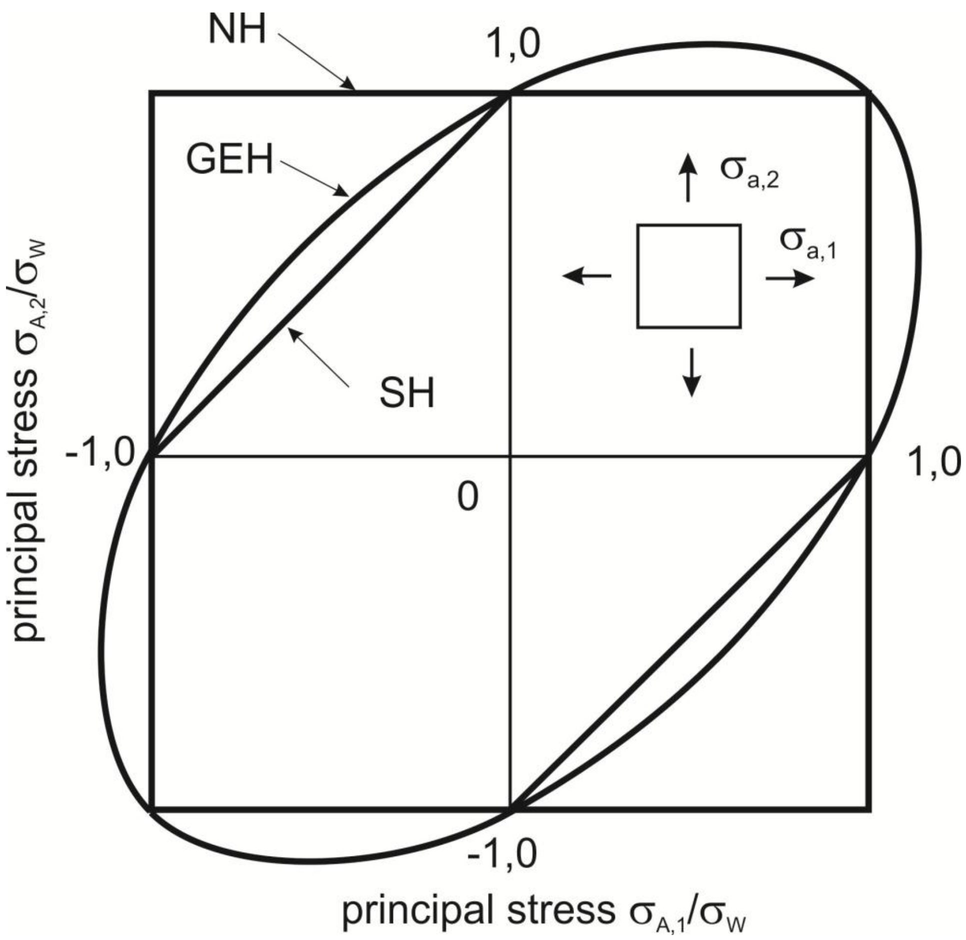
material: AlSi7Mg

Werkstoff :	3.2371.62 / A356.0 (GK-AlSi7Mg wa)	Prüfnummer :	IWK 01-14 He
Probenform :	Bremssattel	Prüfmaschine :	15 HFP 422
Beanspruchung :	Bauteilprüfung	Bemerkung :	R = 0,05

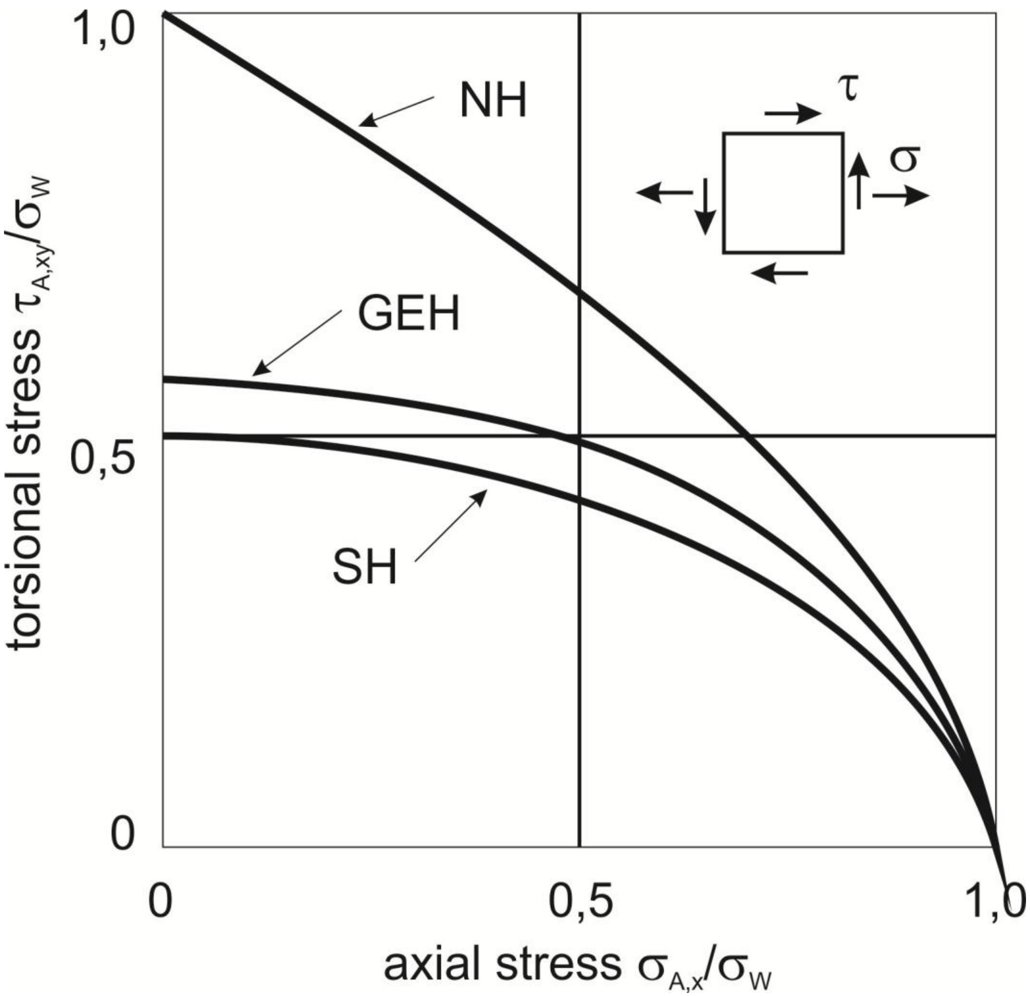
log. Normalverteilung	HCF : lg N =	a	+	k	lg F	|Korr. - Koef.|	N_K	LLF : F_A
P = 1% :	lg N =	8.99020	+	-4.04481	lg F	-	2415179	4.41
P = 10% :	lg N =	9.18293	+	-4.04481	lg F	-	2229753	5.02
P = 50% :	lg N =	9.41933	+	-4.04481	lg F	0.9994	2191540	5.77
P = 90% :	lg N =	9.65573	+	-4.04481	lg F	-	2306838	6.52
P = 99% :	lg N =	9.84846	+	-4.04481	lg F	-	2503982	7.13



Endurance limit under biaxial stesses



NH:	maximum prinicpal stress criterion
GEH:	von Mises criterion
SH:	maximum shear stress criterion (Tresca)



biaxiality ratio:

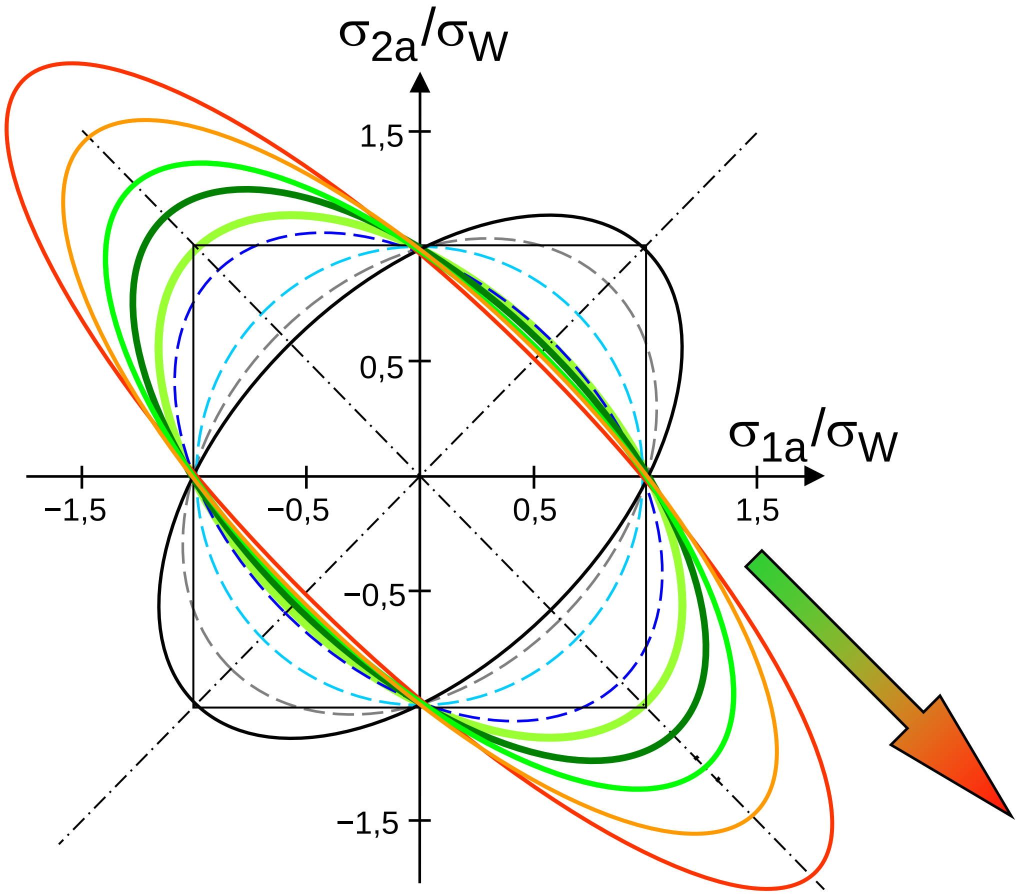
$$f_{W,\tau} = \frac{\tau_W}{\sigma_W}$$

NH: $f_{W,\tau}$ = 1,0

SH: $f_{W,\tau}$ = 0,5

GEH: $f_{W,\tau}$ = = 0,577

Fatigue endurance limit for biaxial reversed stress states



$$\sigma_{ij}(t) = \begin{pmatrix} \sigma_x(t) & \tau_{yx}(t) \\ \tau_{xy}(t) & \sigma_y(t) \end{pmatrix} = \begin{pmatrix} \sigma_1(t) & 0 \\ 0 & \sigma_2(t) \end{pmatrix}$$

$$\left.\begin{aligned} \sigma_x(t) &= \sigma_{xa} \sin\omega t \\ \sigma_y(t) &= \sigma_{ya} \sin\omega t \\ \tau_{xy}(t) &= \tau_{xya} \sin\omega t \end{aligned}\right\} \text{fully reversed loading case}$$

$$\sigma_v = \sqrt{\sigma_{xa}^2 + \sigma_{ya}^2 - \sigma_{xa}\sigma_{ya} + \left(\frac{\sigma_W}{\tau_W}\right)^2 \tau_{xya}^2}$$

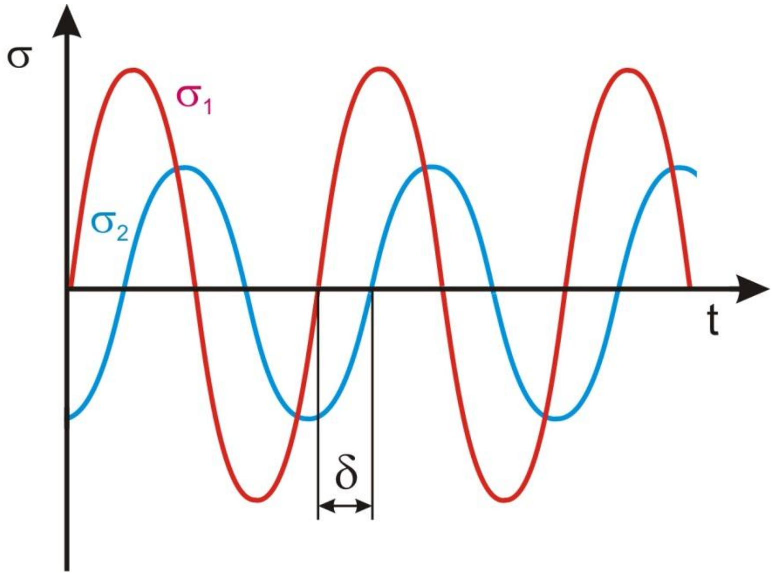
$$= \sqrt{I_1^2 - \left(\frac{\sigma_W}{\tau_W}\right)^2 I_2} \qquad \text{(invariants)}$$

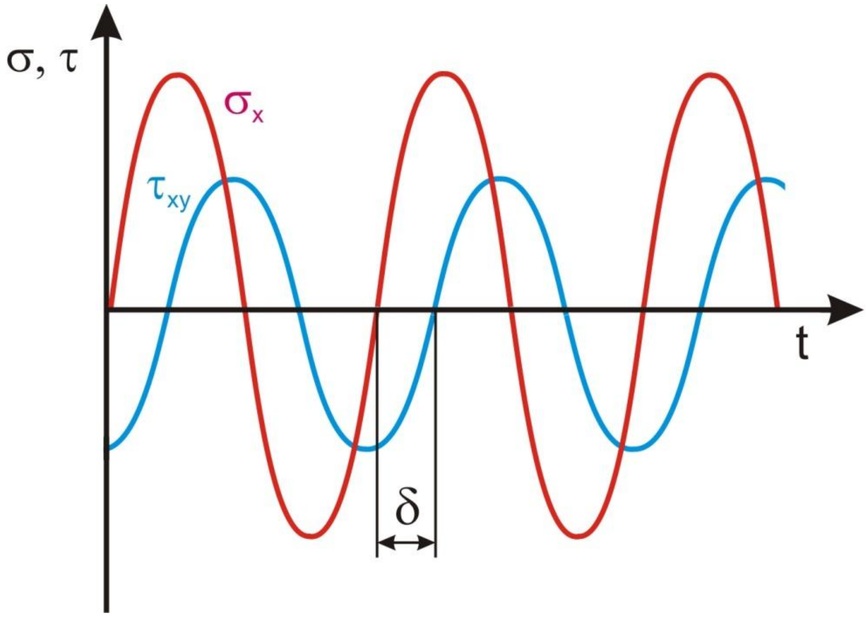
$$\frac{\sigma_{xA}}{\sigma_W} = \frac{1}{2}\sqrt{1 - \left(\frac{1}{f_{W,\tau}}\right)^2 \left(\frac{\sigma_{yA}}{\sigma_W}\right)^2}$$

$$f_{W,\tau} = \frac{\tau_W}{\sigma_W}$$

Prediction of fatigue strength under non proportional multiaxial loading (I)

examples for non proportional loading situations:





→ rotation of principal coordinate system

Prediction of fatigue strength under non proportional multiaxial loading (II)

- static stress components $\sigma_{i,m}$ and
- variable stress components $\sigma_{i,a}$ with <u>constant</u> principal stress direction

1. Sines criterion:

$$\sigma_{A,v(GEH)} = f(\sigma_{hm}) \qquad \sigma_{A,v(GEH)} + \alpha\,\sigma_{hm} = \beta$$

2. Dang Van creiterion:

$$\tau_{A2} = f(\sigma_{hmax}) \qquad \tau_{A2} + \alpha\,\sigma_{hmax} = \beta$$

σ_{hm} = average of static stress
σ_{hmax} = maximum of static stress

Failure criteria for nonproportional multiaxial fatigue under out-of-phase loading

1. Criteria using integral material effort

   criterion of Simbürger
   criterion of shear stress intensity (SIH)

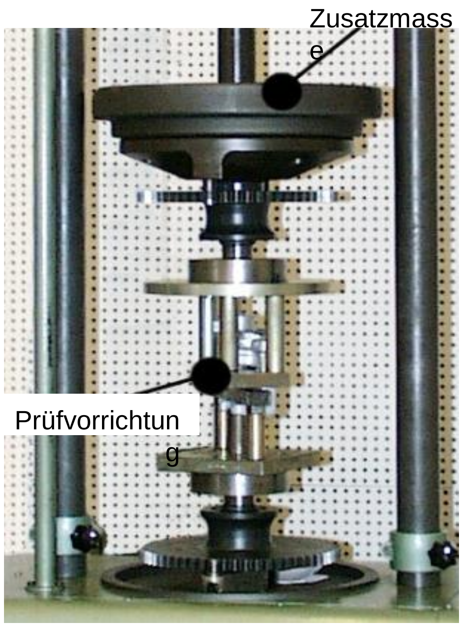
2. Criteria using critical plane approaches

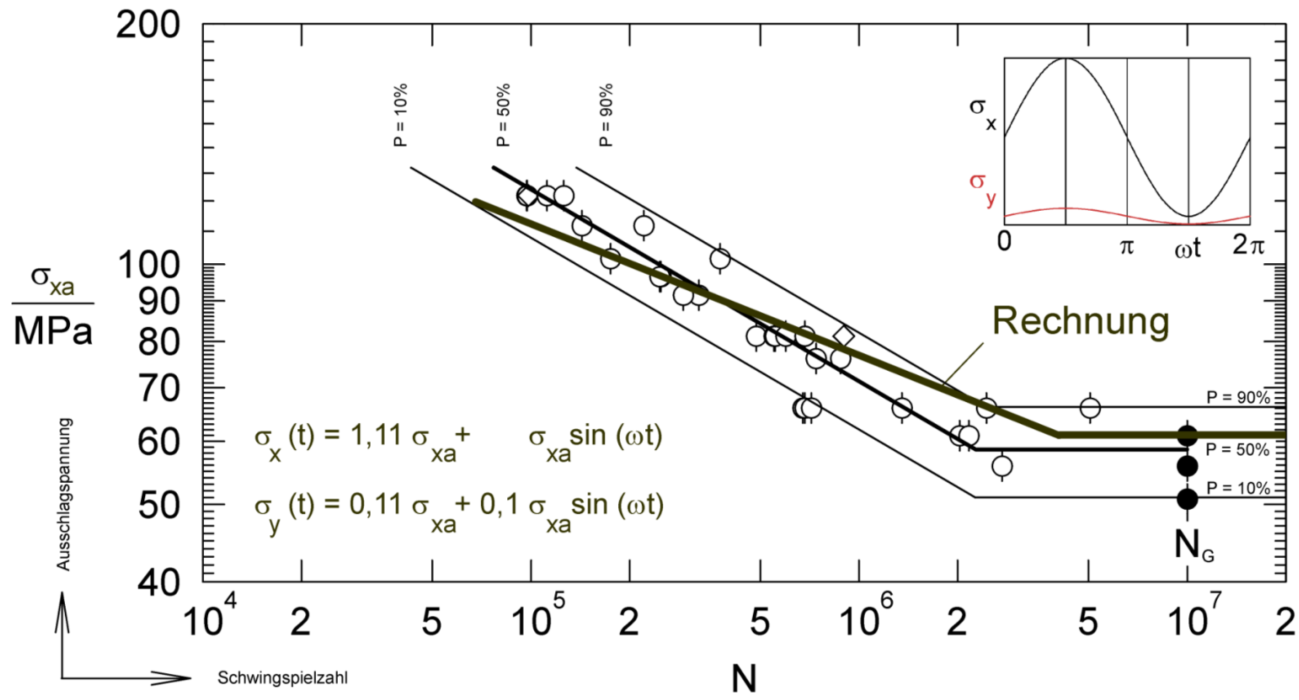
   generalized criterion of Dang Vang
   criterion of Nokebly
   criterion of Bongbhibhat
   criterion of Fatemi-Socie

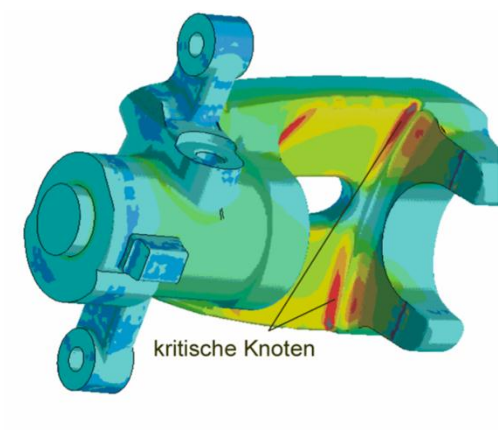
3. Combination of both approaches

   criterion of quadratic failure potential (QVH)

Prediction of component endurance limit





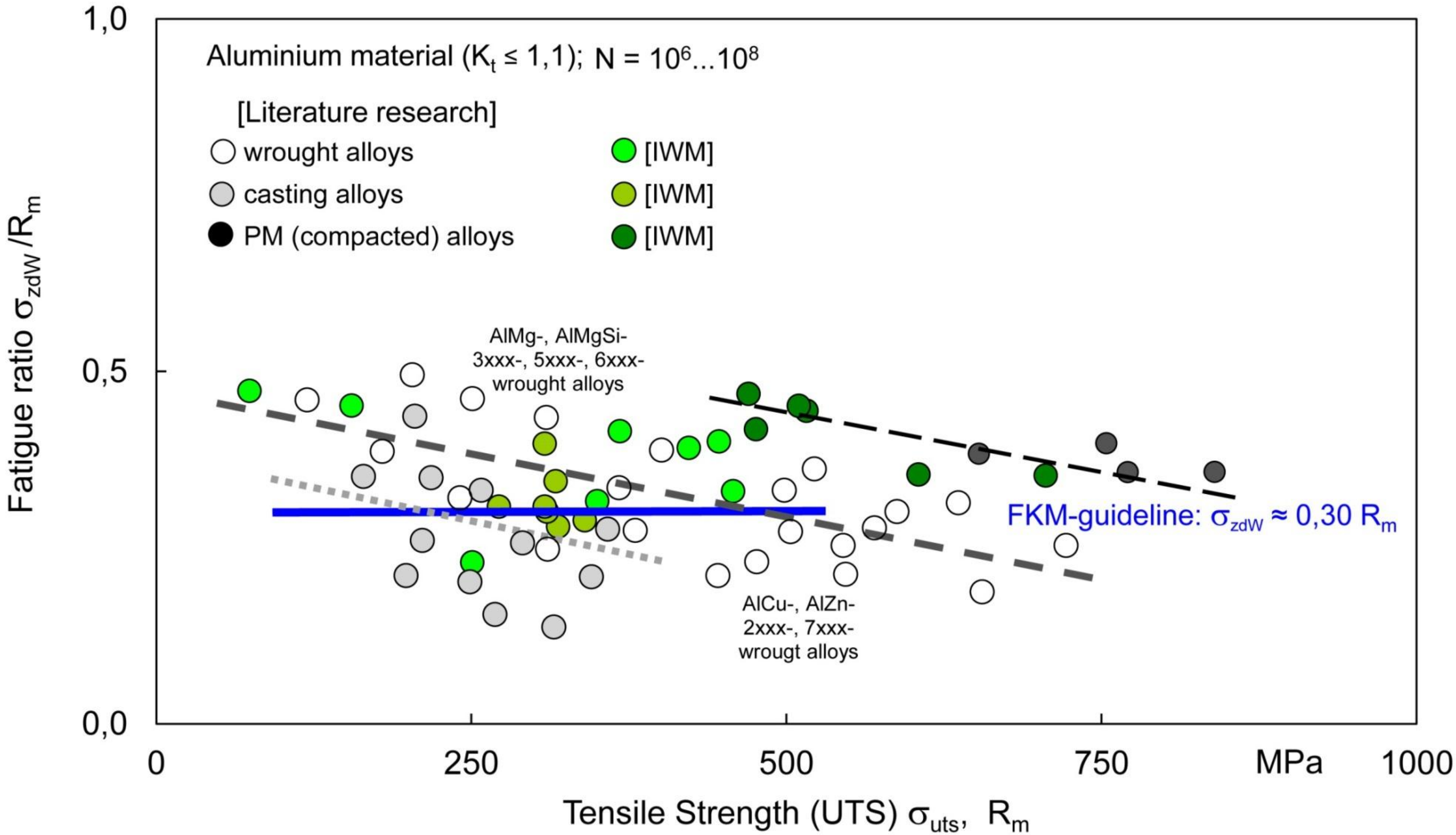


Stress tensors for amplitude and mean component at critical areas:

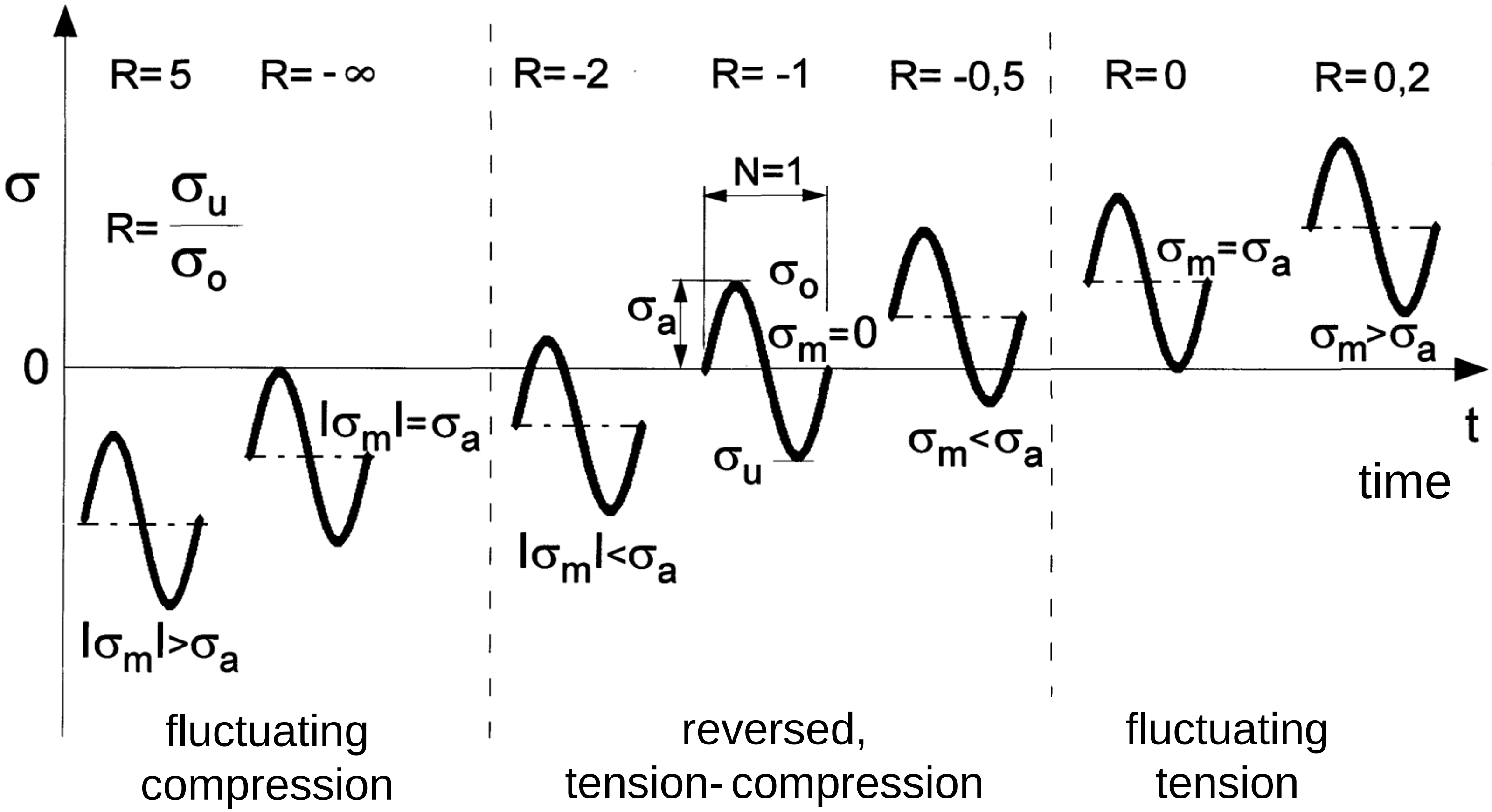
$$\sigma_{ij,a} = \begin{pmatrix} 58{,}9 & 0{,}0 \\ 0{,}0 & 9{,}5 \end{pmatrix}, \quad \sigma_{ij,m} = \begin{pmatrix} 65{,}1 & 0{,}0 \\ 0{,}0 & 10{,}5 \end{pmatrix}$$

Endurance ratio of Aluminum alloys

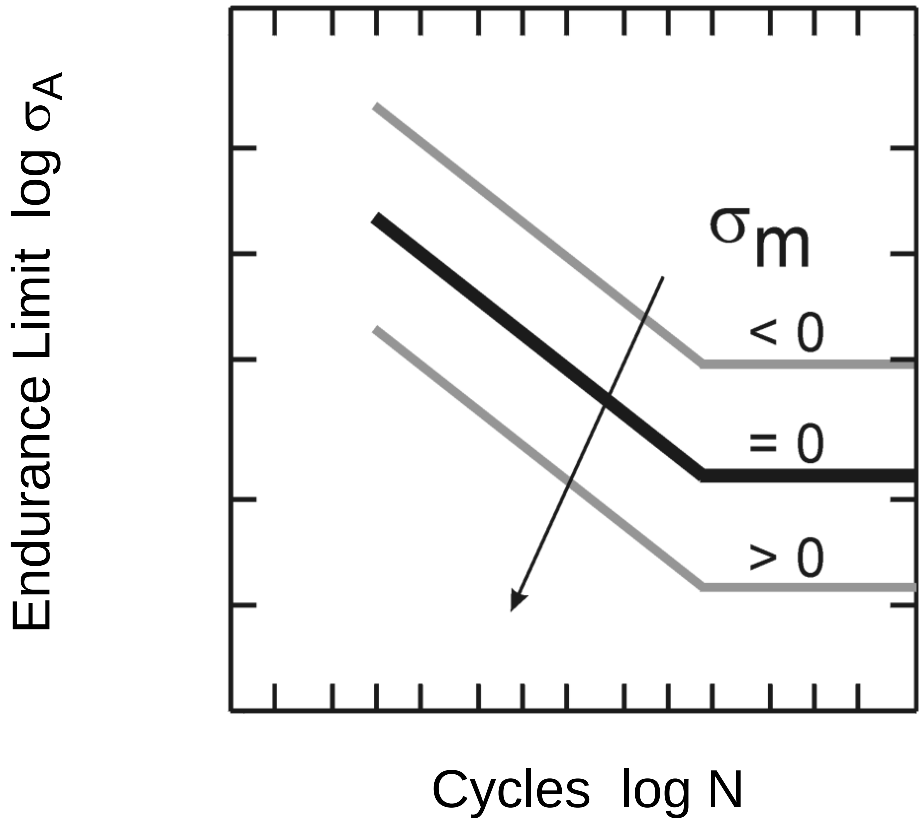
Alternating axial tension-compression



Mean stress sensitivity of fatigue strength (I)
Definition of load ratio

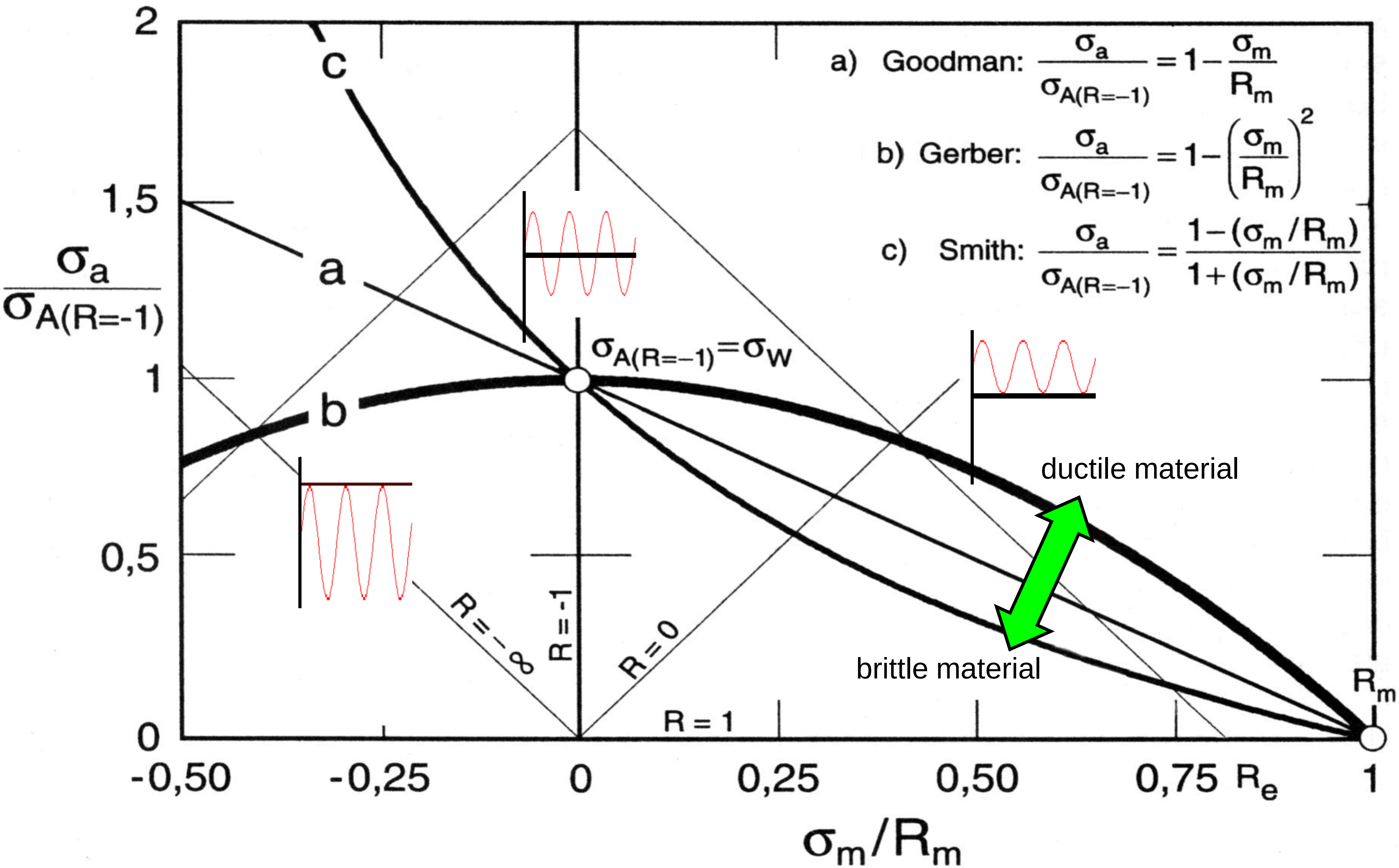


Haigh diagram

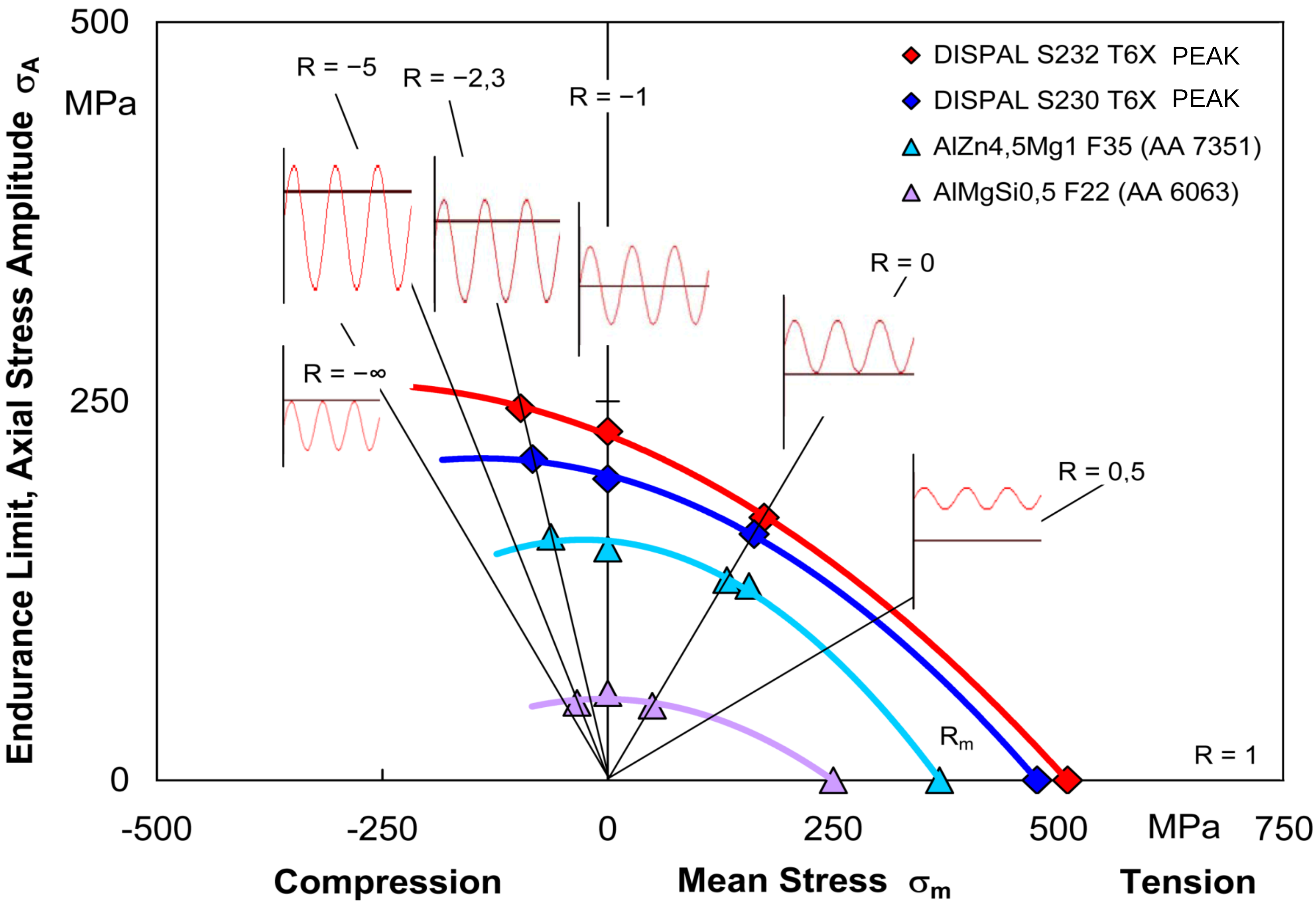


The endurance limit decreases with increasing static mean stress !

Nondimensional form of Haigh diagram

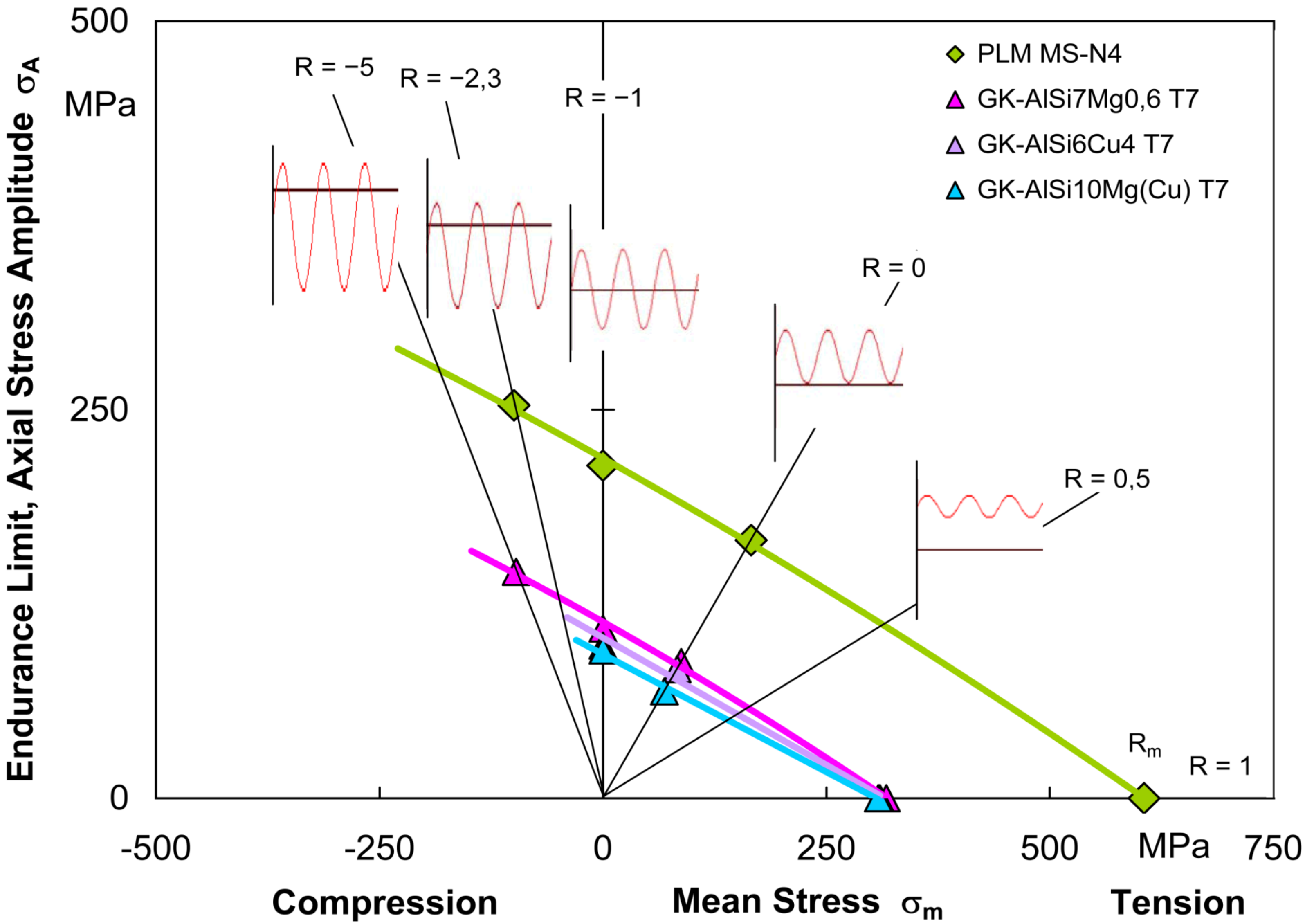


Haigh diagram of aluminium materials ductile behaviour



[F. Klubberg, I. Klopfer, C. Broeckmann, R. Berchtold, P. Beiss: Fatigue testing of materials and components under mean load conditions. XXVIII. GEF Encuentro del Grupo Español de Fractura, Gijón, 6. – 8. April 2011]

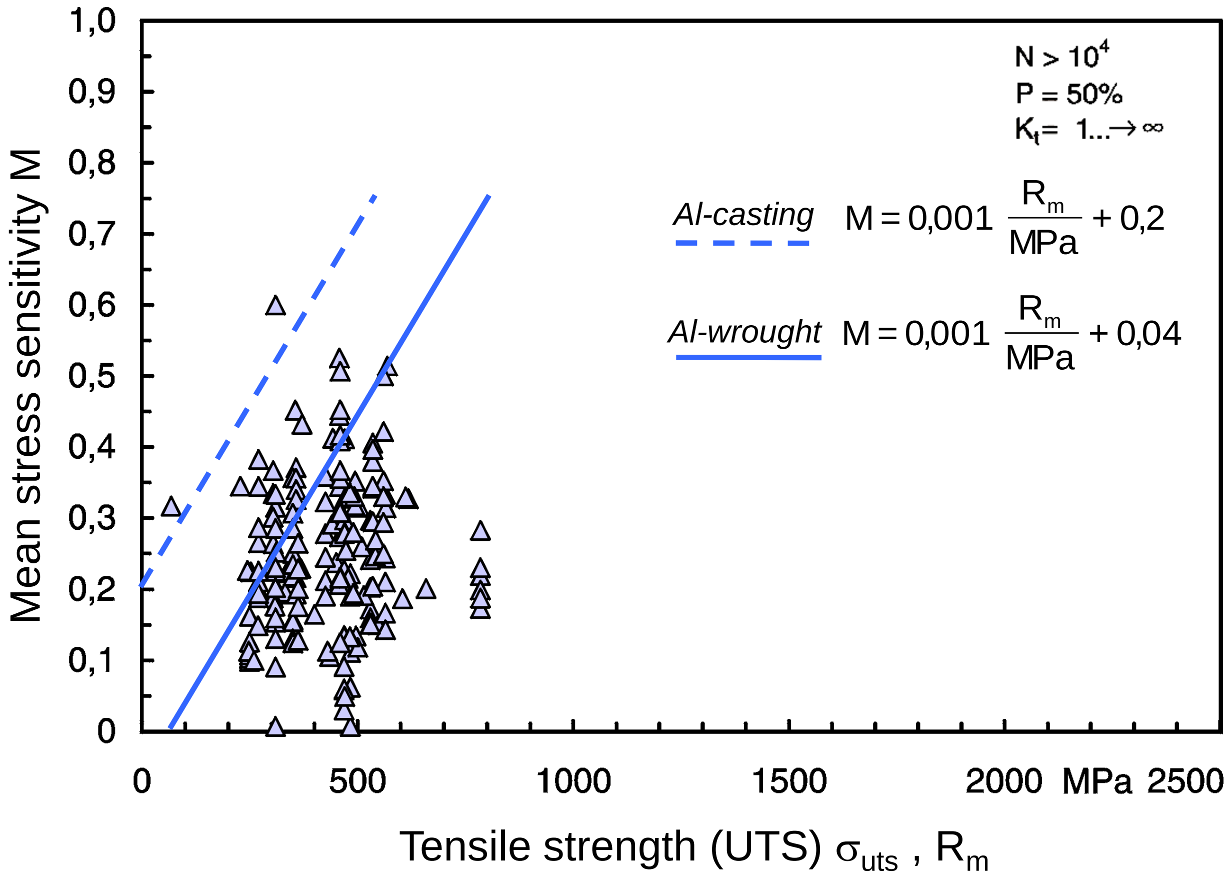
Haigh diagram of aluminium materials brittle behaviour



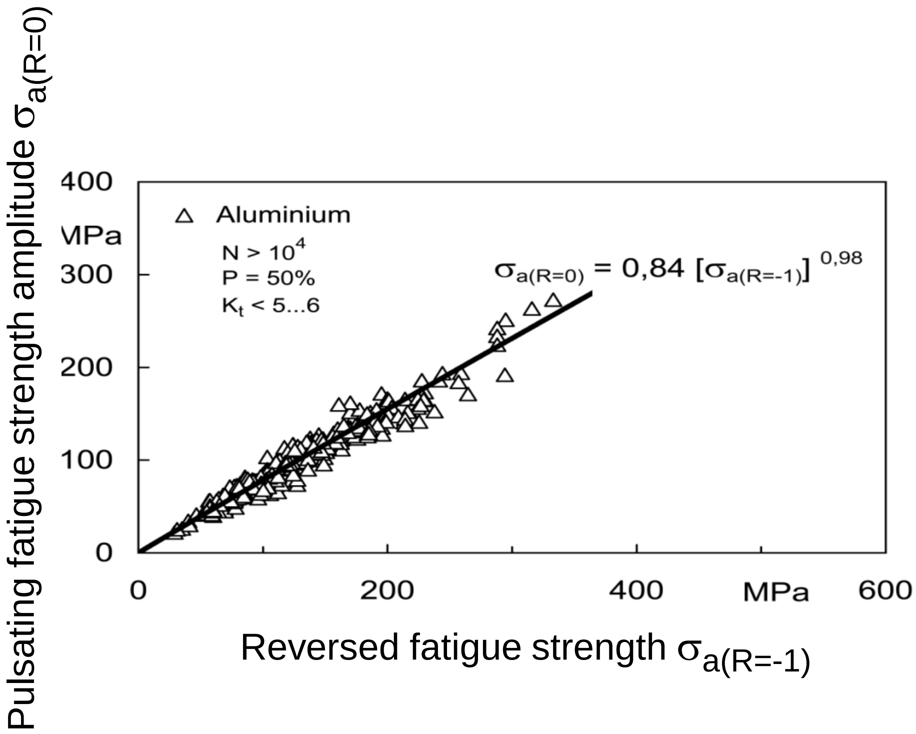
[F. Klubberg, I. Klopfer, C. Broeckmann, R. Berchtold, P. Beiss: Fatigue testing of materials and components under mean load conditions. XXVIII. GEF Encuentro del Grupo Español de Fractura, Gijón, 6. – 8. April 2011]

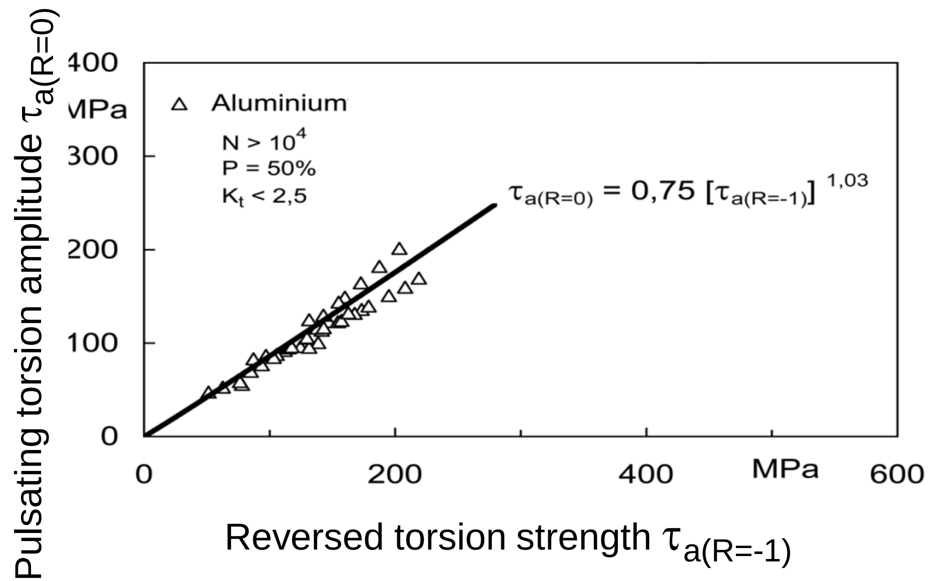
Mean stress sensitivity according to FKM-guideline compared to results obained in fatigue tests

$$\text{Mean stress sensitivity } M_{(exp)} = \frac{\sigma_{a(R=-1)}}{\sigma_{a(R=0)}} - 1$$



Correlation between pulsating and fully reverse fatigue strength

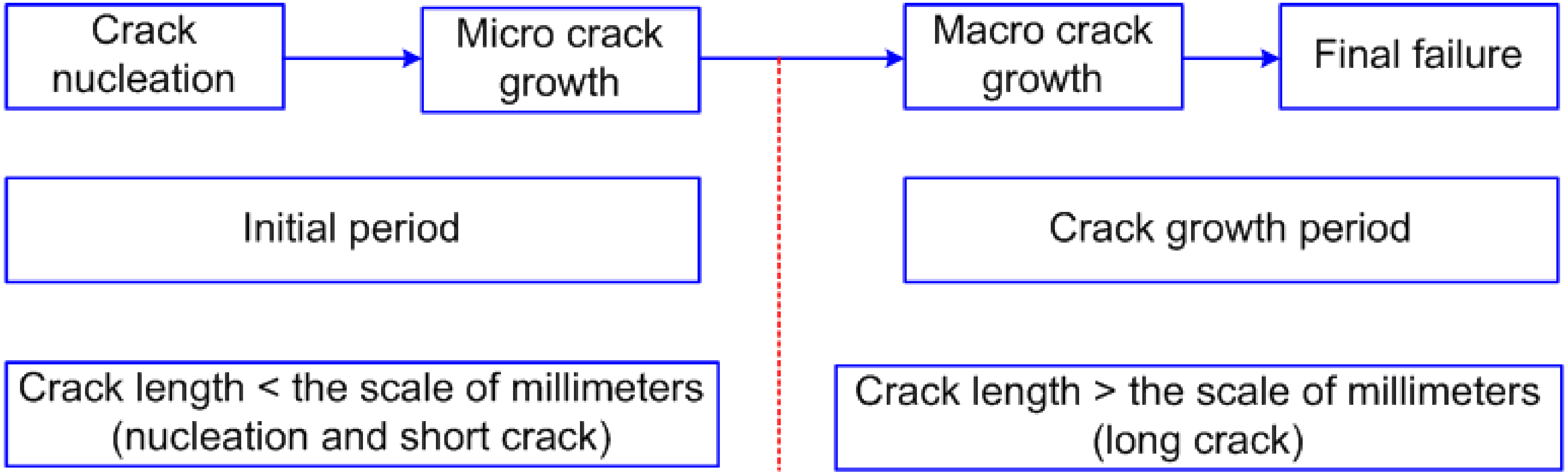




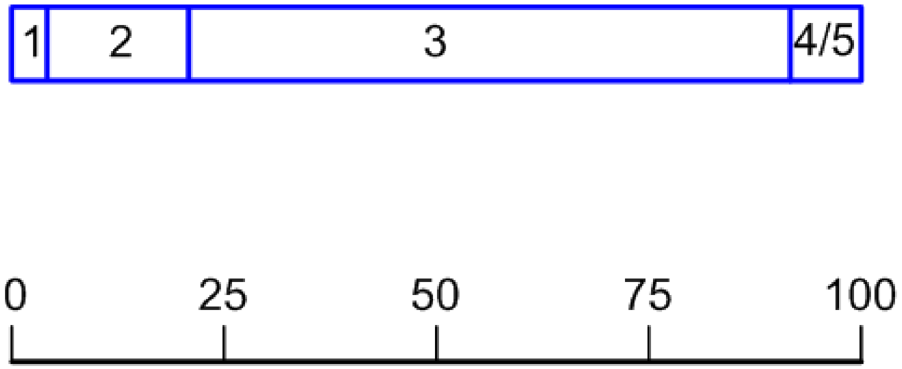
Outline

1. Introduction
2. Fatigue prediction of aluminum components based on S-N-diagrams
3. Fatigue prediction based on the simulation of crack initiation and growth
4. Summary

Different stages of fatigue life



Stages of Fatigue



1: No crack present

2: Nucleation

3: Micro-crack

4/5: Macro-crack and failure

time spent in stages of crack growth
(molybdenum alloy)

[S. P. Wilson and D. Taylor, “Reliability assessment from fatigue micro-crack data,” *IEEE Transactions on reliability*, vol. 46, pp. 165–172, 1997.

Lifetime prediction based on crack growth

prediction of the total lifetime:

$$N_T = N_{inc} + N_{msc/psc} + N_{lc}$$

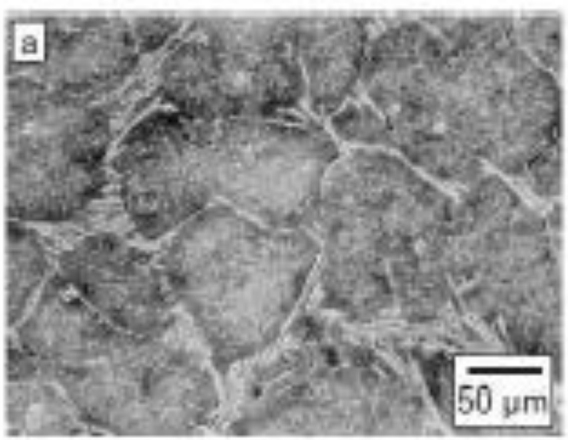
N_T	total lifetime
N_{inc}	incubation time
$N_{msc/psc}$	short crack growth
N_{lc}	long crack growth

High speed steel AISI M3:2 (HS6-5-3)

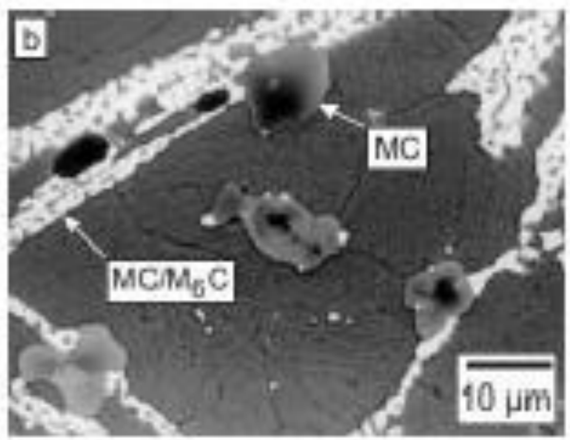
Chemical composition

AISI	C	Si	Cr	W	Mo	V	Mn
Cast M3:2	1.19	0.72	4.4	6.9	4.6	2.9	0.29
Forged M3:2	1.21	0.44	4.0	6.1	4.8	2.8	0.25
PM M3:2	1.31	0.60	3.9	5.9	4.9	2.9	0.47

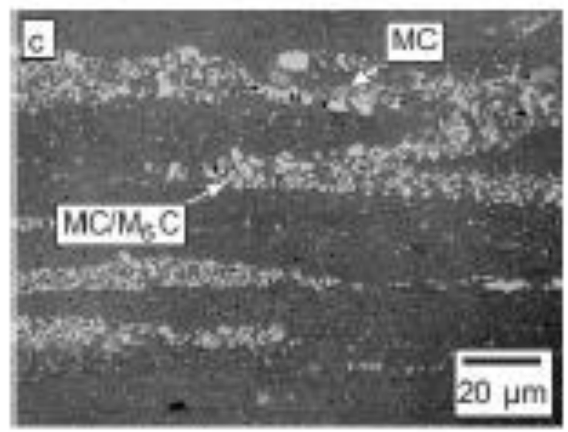
Microstructure



as cast



as cast (details)



as forged

Mechanical properties for mesoscopic FEA-modelling

Phase	E[GPa]	ν[-]	σ_{y0}[MPa]	σ_{ult}[MPa]	c[GPa]	r[MPa]	σ_∞[MPa]	κ[-]
carbide	400	0.25	-	1604	-	-	-	-
matrix	210	0.3	1500	-	112.1	200	417	137

Carbide: MC and M_6C
Matrix: tempered martensite

σ_{y0}	yield strength
σ_{ult}	ultimate tensile stress
C	kinematic modulus
r	dynamic modulus of rate of back stress tensor
σ_∞ and κ	coefficient and exponent of flow stress

J. L. Mishnaevsky, N. Lippmann, and S. Schmauder, “Experimental-numerical analysis mechanisms of damage initiation in tool steel,” in *Proceeding 10th international Conference Fracture*, (Milan, Italy), pp. 1–10, 2001..

R. Prasannavenkatesan, *Microstructure-sensitive fatigue modeling of heat treated and shot peened martensitic gear steels*. Ph.D. thesis, Georgia Institute of Technology, USA, 2009...

Estimation of the incubation lifetime N_{inc}

Fatemi-Socie parameter :

$$\Delta\Gamma = \frac{\Delta\gamma_{max}^{p*}}{2}\left(1 + K^* \frac{\sigma_n^{max}}{\sigma_{ys}}\right)$$

$\frac{\Delta\gamma_{max}^{p*}}{2}$: maximum plastic shear strain range on the critical plane

σ_n^{max}: normal stress on the critical plane

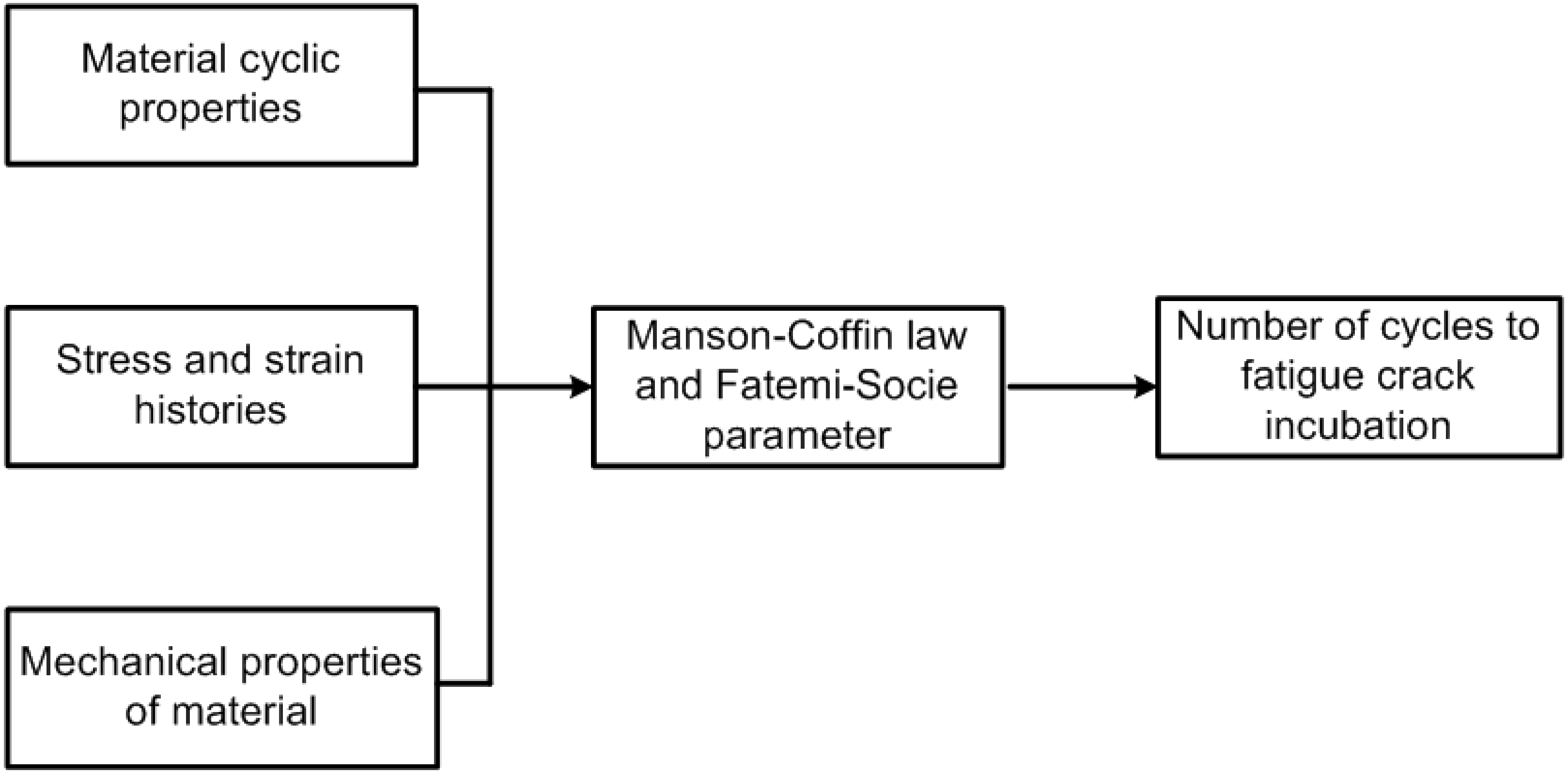
K^*: interaction between torsion an tension fatigue ductility

relationship between Fatemi-Socie parameter and Manson-Coffin law:

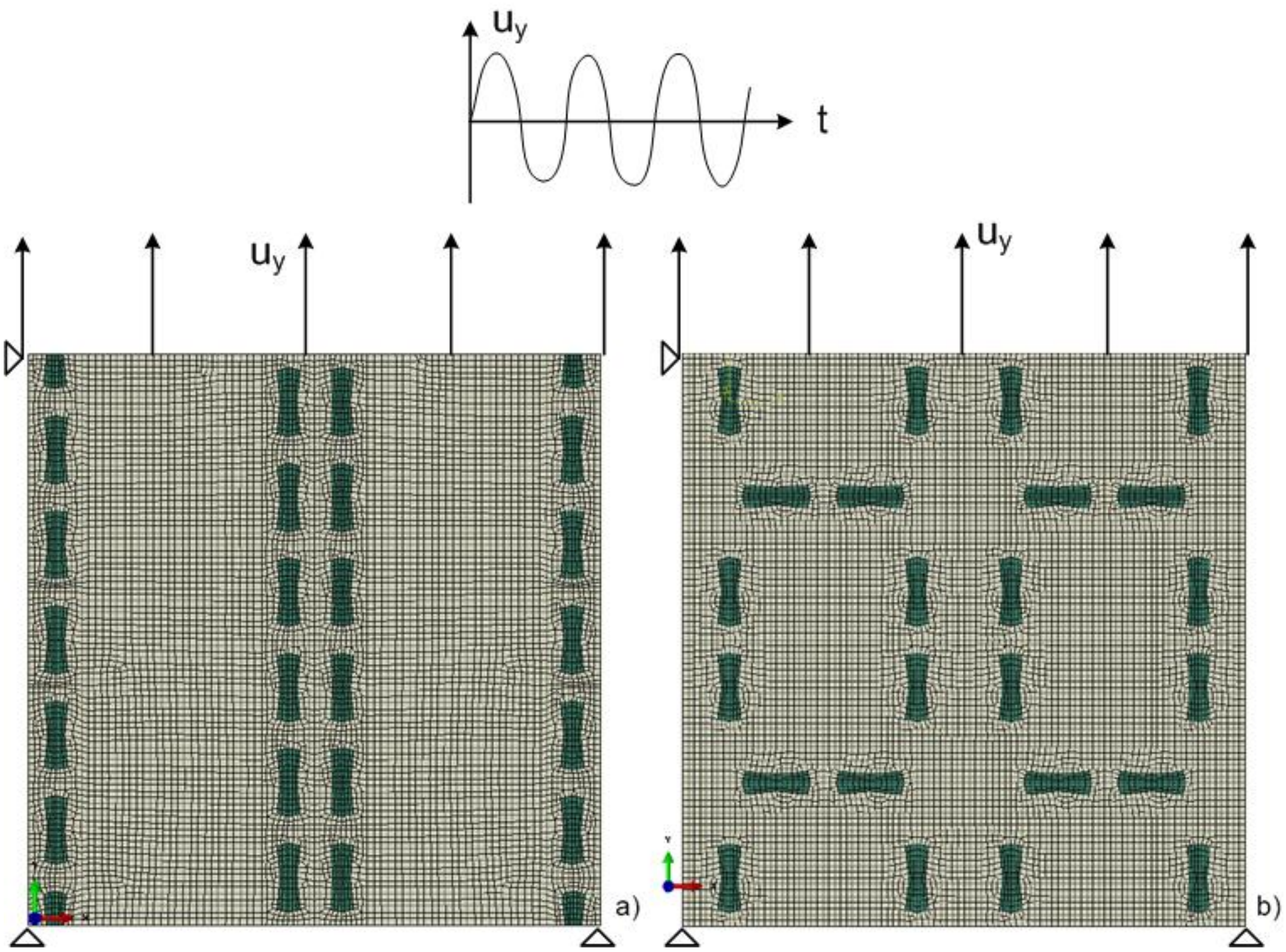
$$\Delta\Gamma = C_{inc}(2N_{inc})^{\alpha}$$

C_{inc} and α parameters to be determined in unit cell studies

Flow chart for the prediction of the incubation lifetime



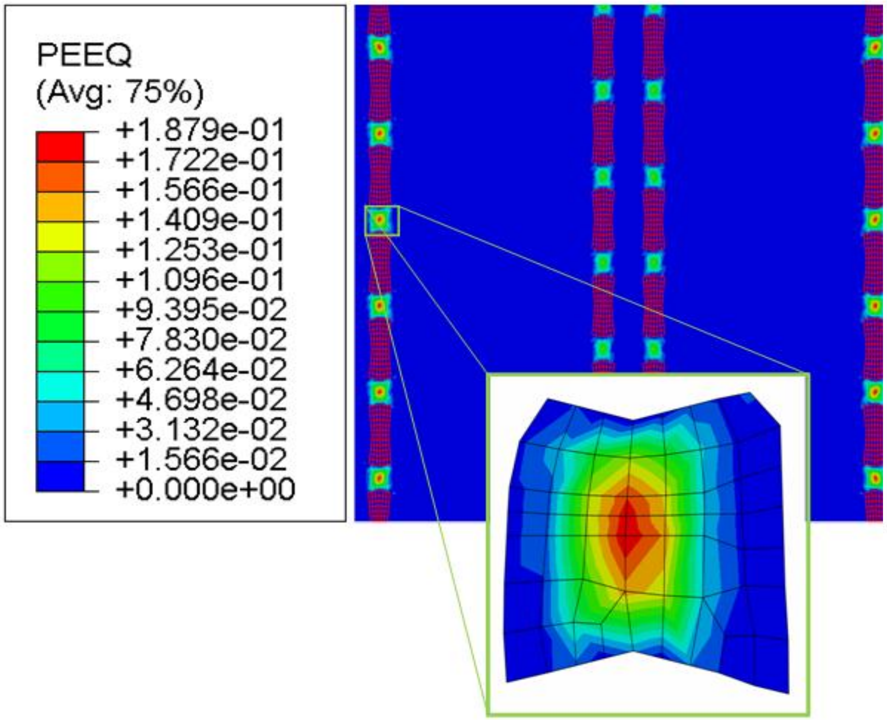
RVE models for forged and cast tool steel



as forged as cast

Lifetime up to crack initiation

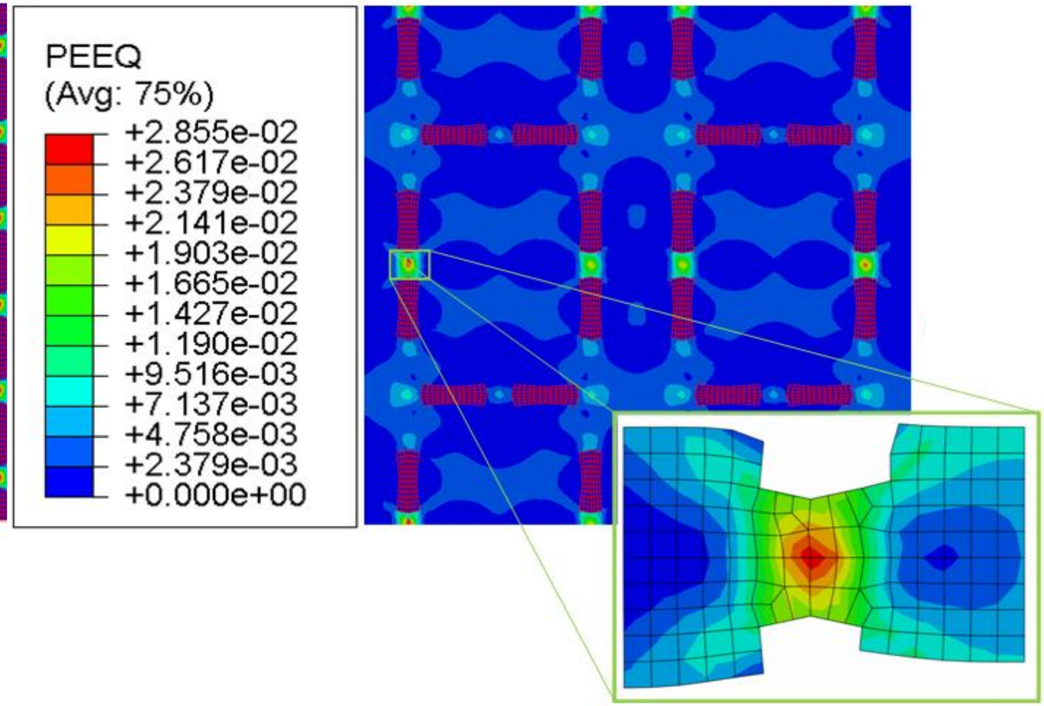
as forged



$$\Delta\Gamma = 0.00175$$

N_{inc} = 715,000

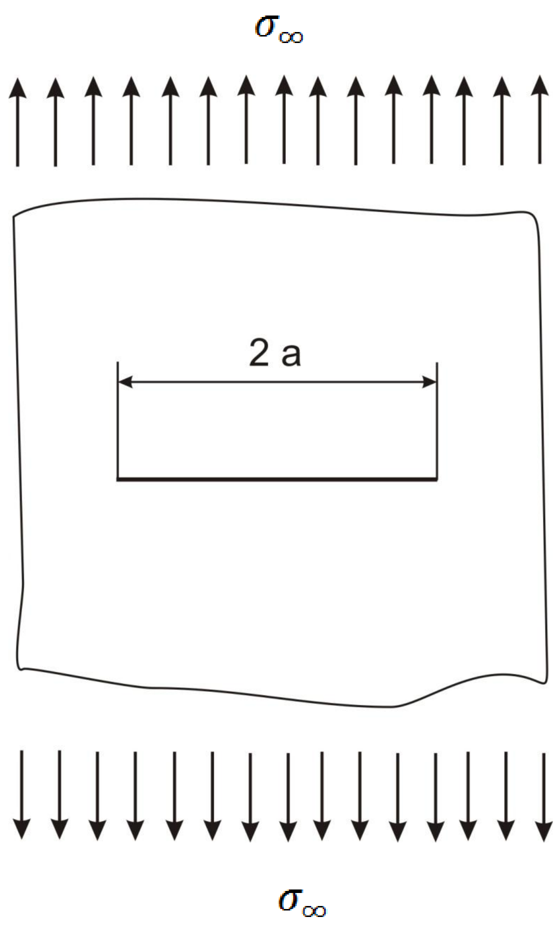
as cast

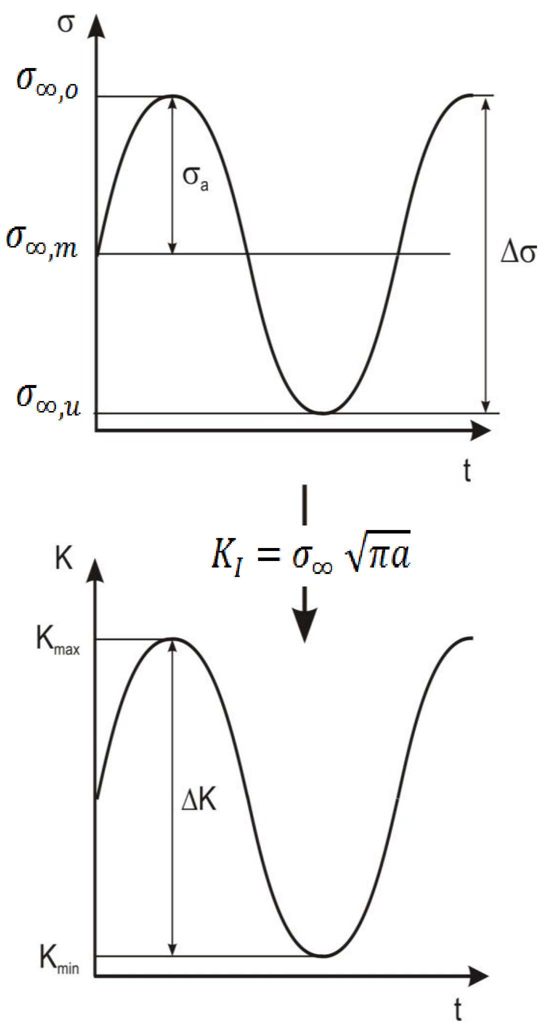


$$\Delta\Gamma = 0.00160$$

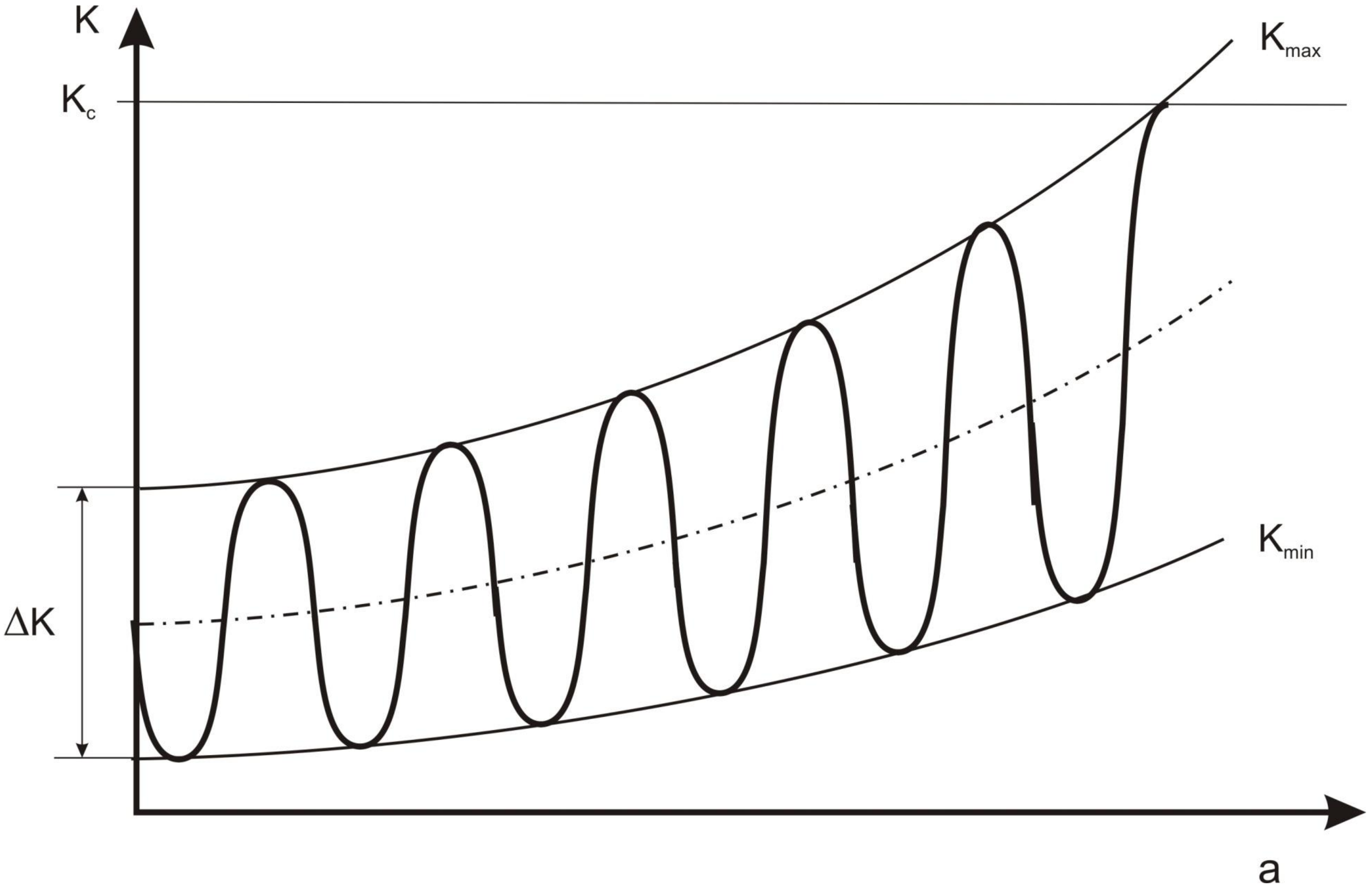
N_{inc} = 890,000

The cyclic stress intensity factor

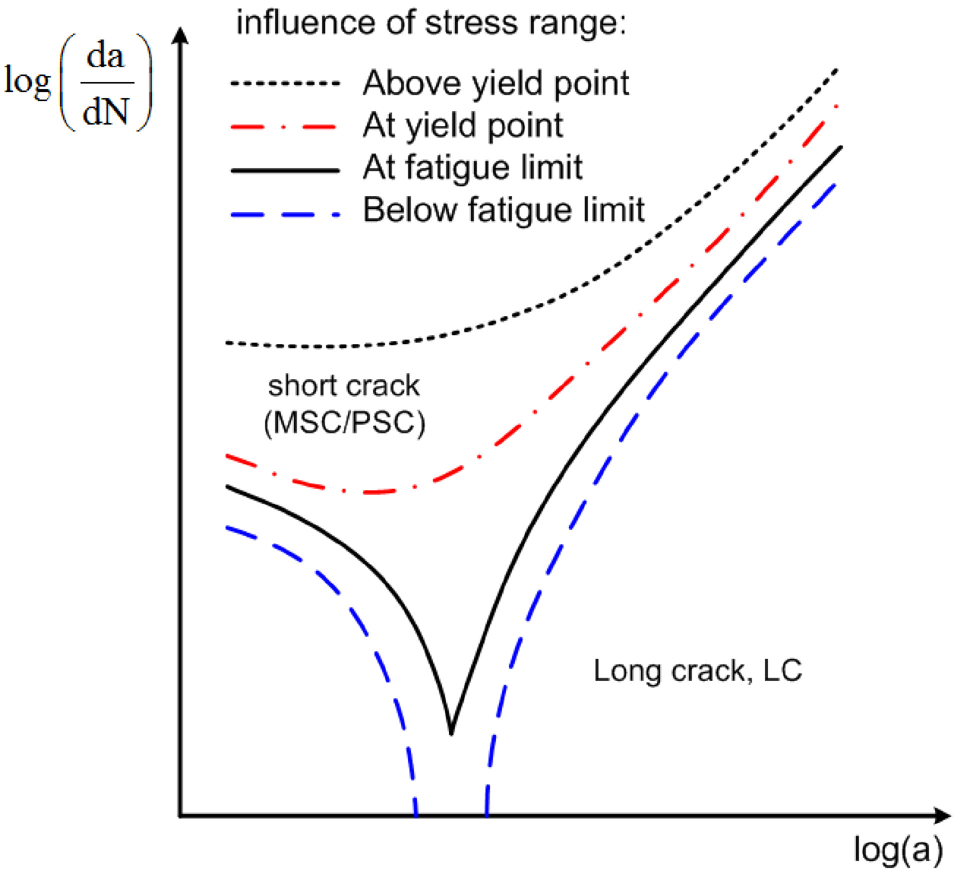




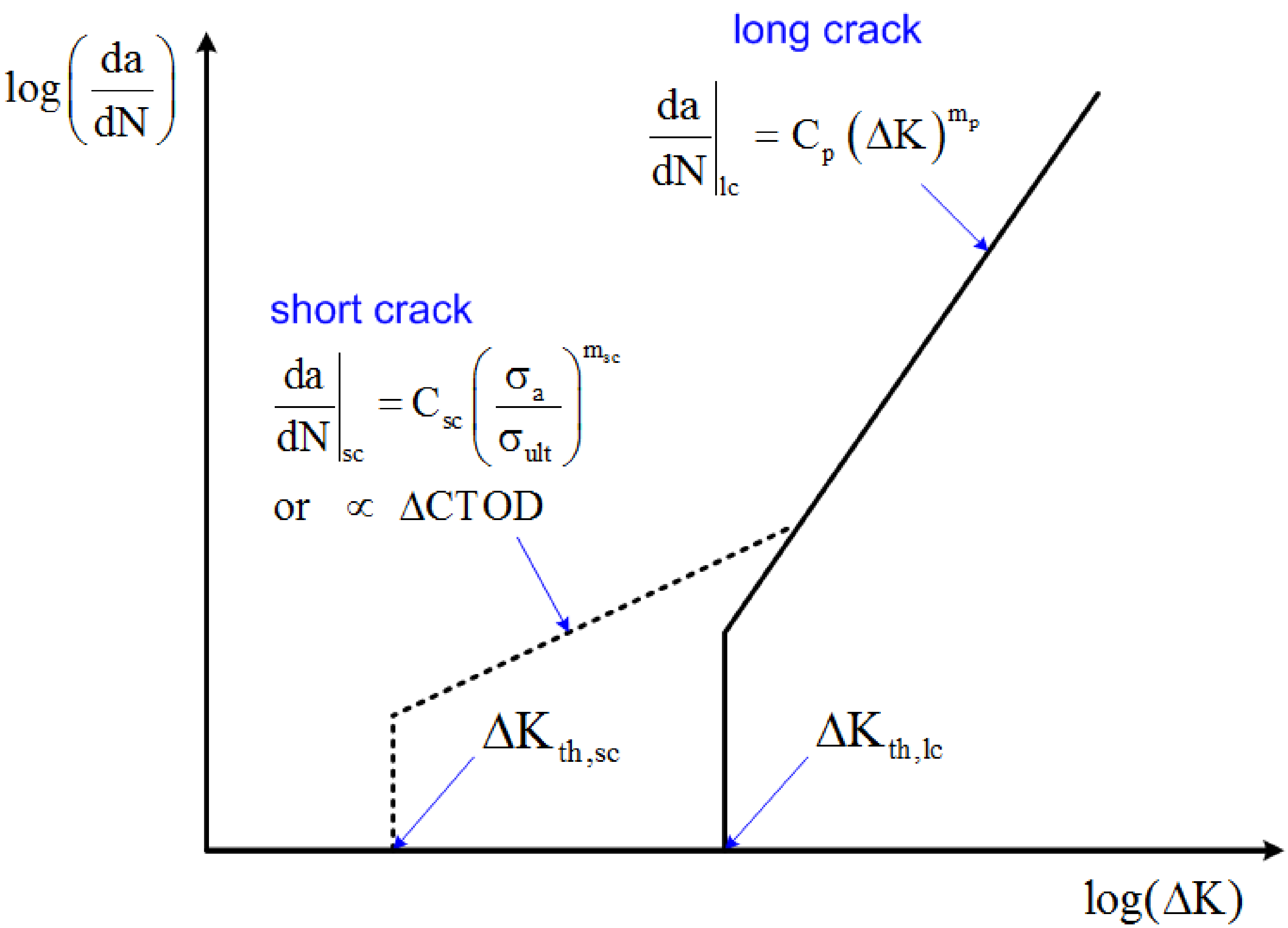
Increase of ΔK with the growing crack



Crack growth rate for short and long cracks



Short crack growth and long crack growth



Short crack growth based on Chan‘s model

$$\left.\frac{da}{dN}\right|_{sc} = \xi^{\frac{1}{b}}(2s_{sp})^{1-\frac{1}{b}}\left[\frac{\Delta K - \Delta K_{th,sc}}{E}\right]^{\frac{2}{b}}$$

with $\xi = \dfrac{E s_{sp}}{4\sigma_y \varepsilon_f' d_o}$

s_{sp}: striation spacing

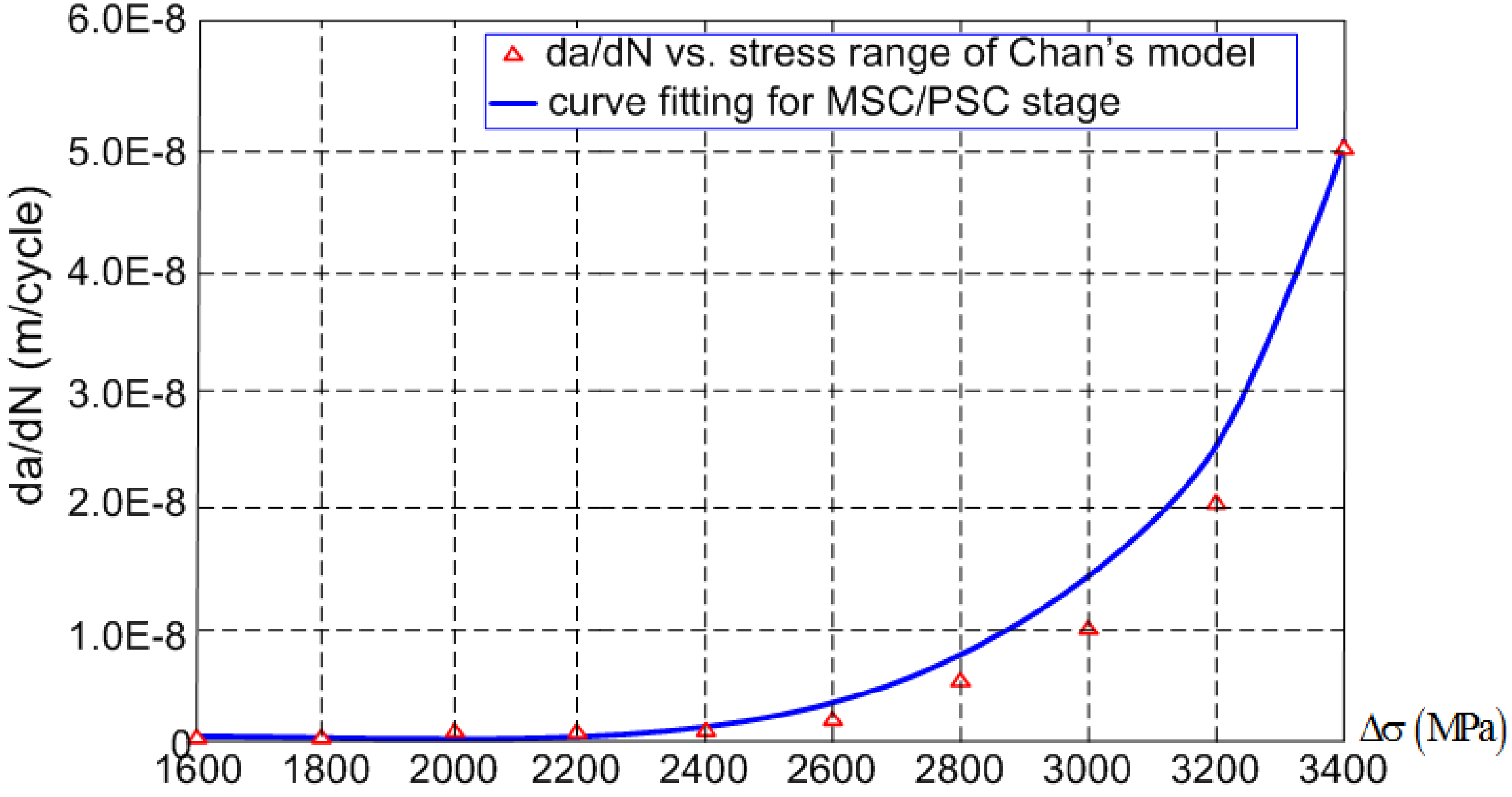
d_o: dislocation barrier spacing

$$\Delta K_{th,sc} = \Delta K_{th,lc}\sqrt{\frac{a}{a+a_D}} = (1-R)\sigma'_{p,M}\sqrt{2S_p\left(\frac{a}{a+a_D}\right)}$$

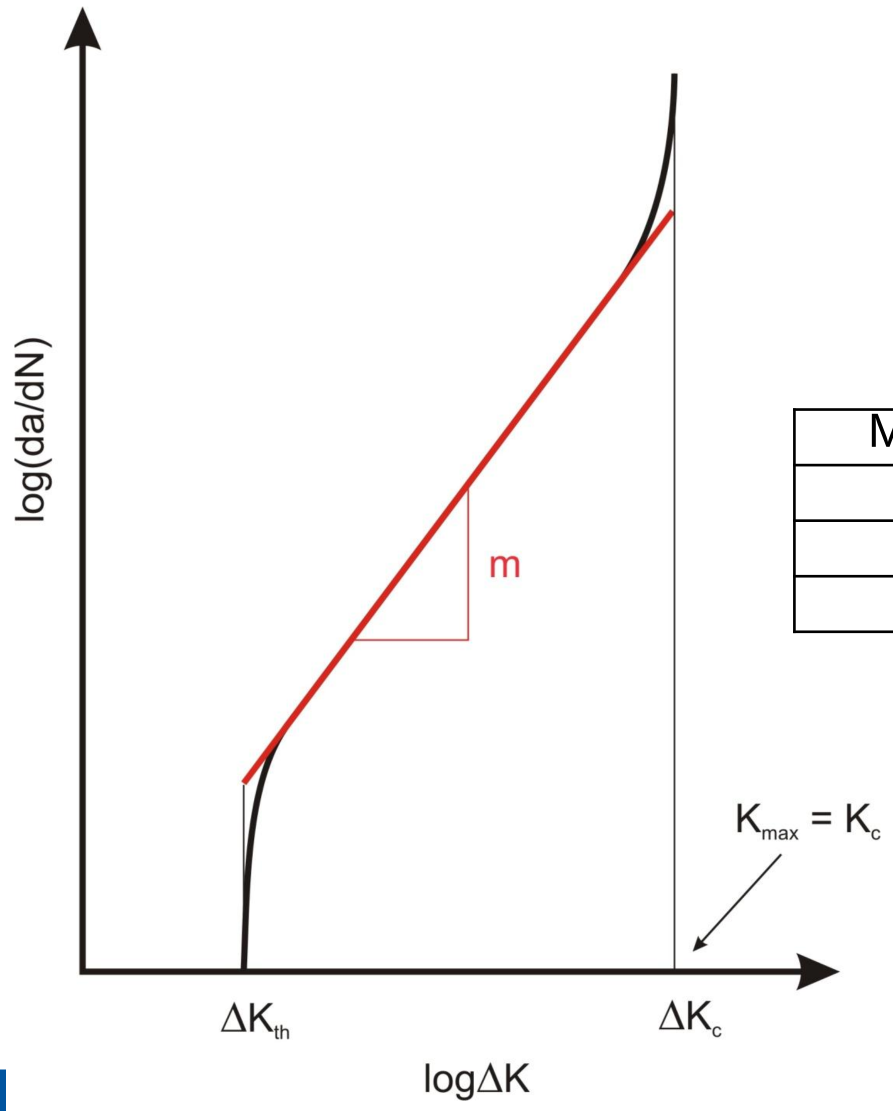
a_D: critical defect

S_p: carbide spacing

Short crack growth in forged M3:2 steel



Paris law of stable crack growth



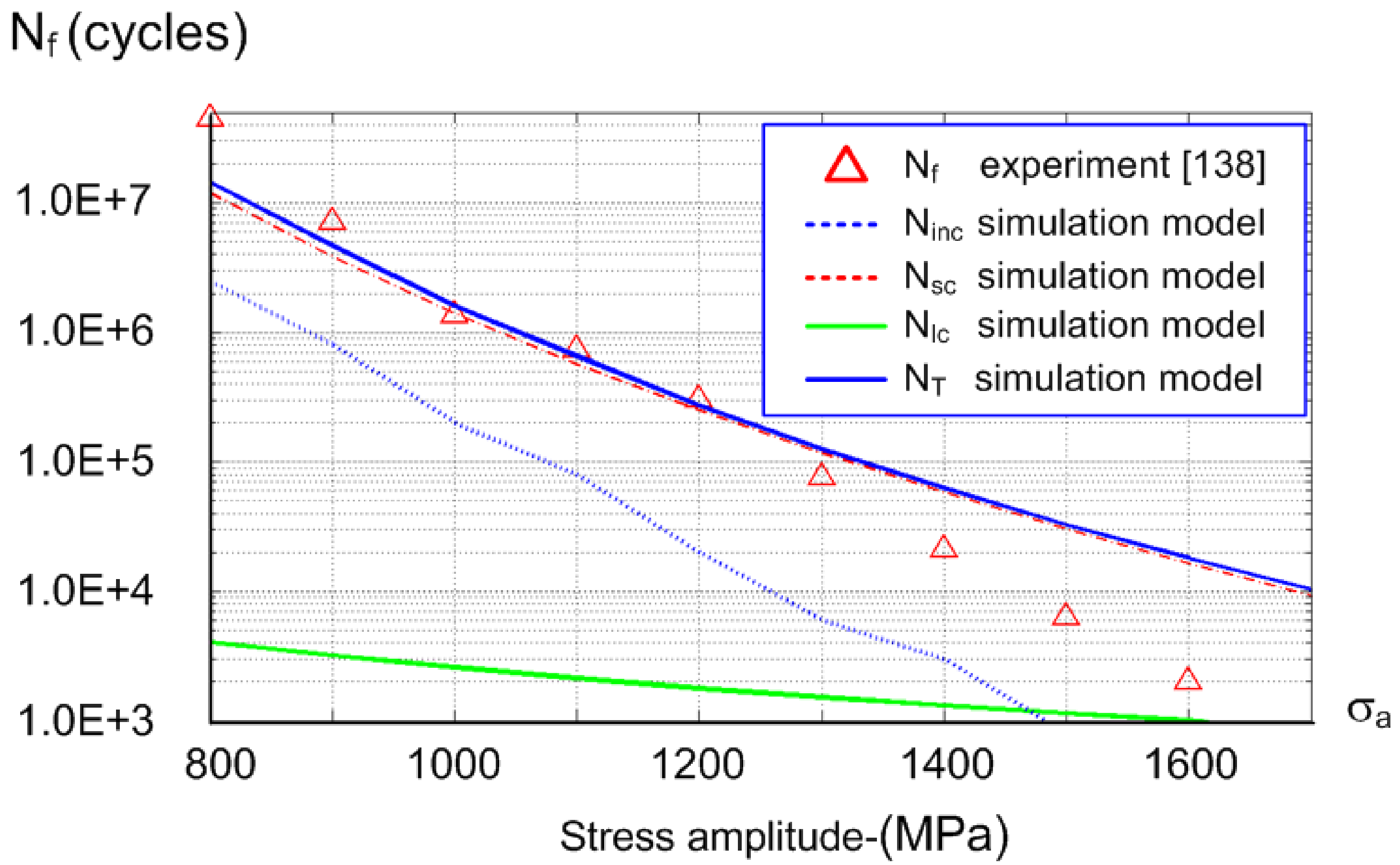
$$\frac{da}{dN} = C\,\Delta K^m$$

Materials group	m	C
Steel	2,25	$5{,}79 \cdot 10^{-11}$
Al-alloys	3,00	$9{,}82 \cdot 10^{-12}$
Ti-alloys	4,00	$3{,}56 \cdot 10^{-15}$

acc. to Clark

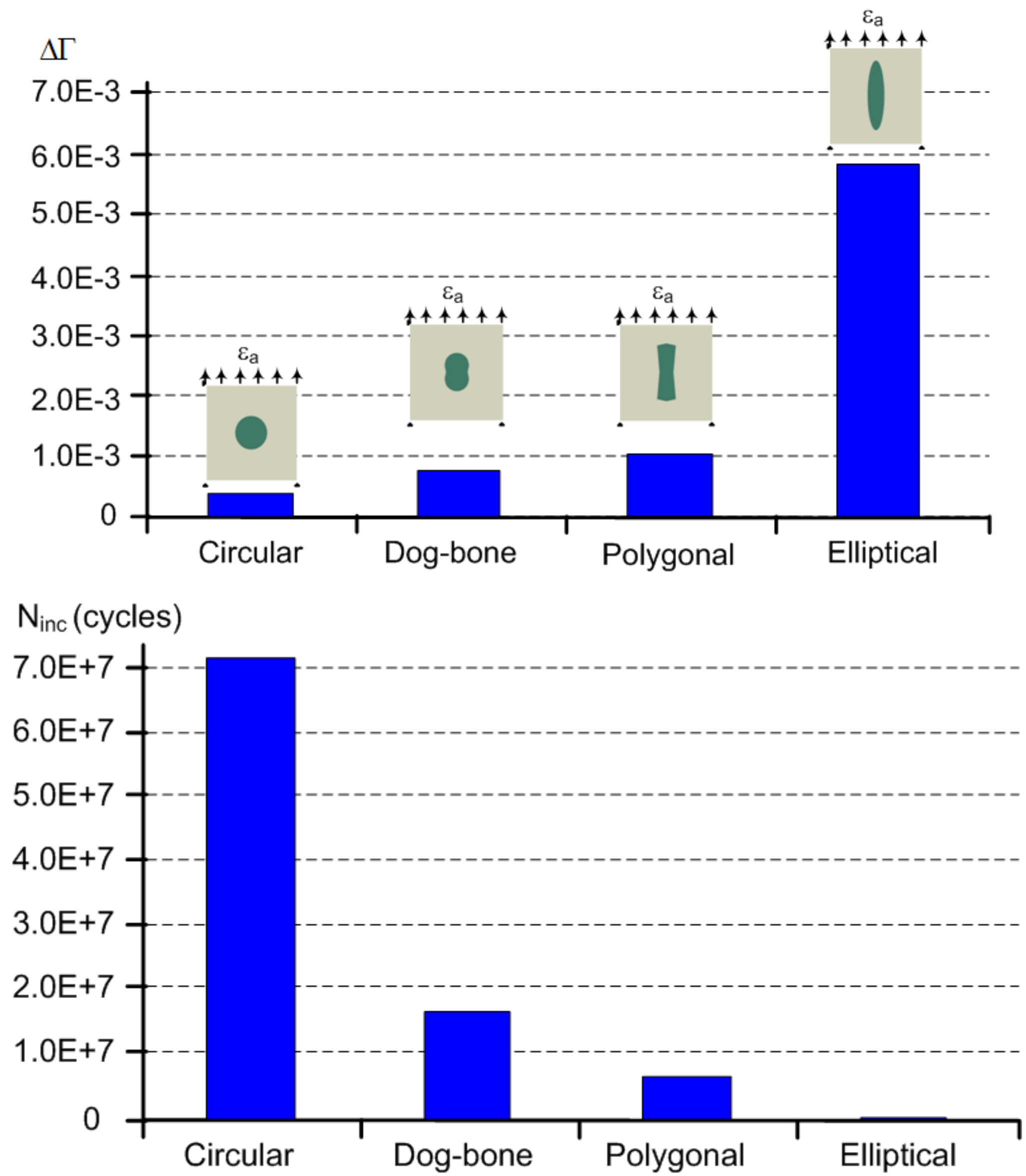
da/dN in mm and ΔK in N/mm$^{3/2}$

Predicted S-N-diagram in comparison to experimental data

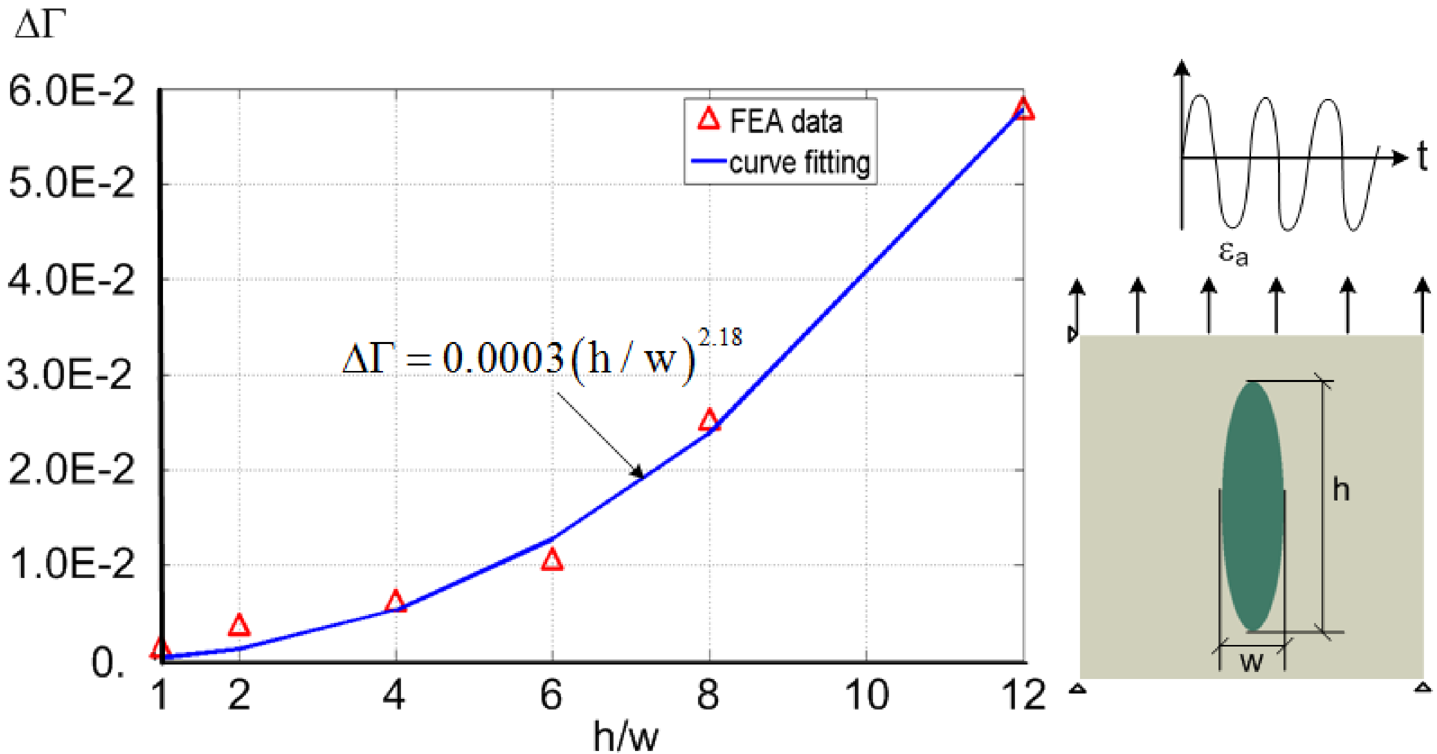


[138] P. Brondsted and P. Skov-Hansen, “Fatigue properties of high-strength materials used in cold-forging tools,” *International Journal of Fatigue*, vol. 20, pp. 373–381, 1998.

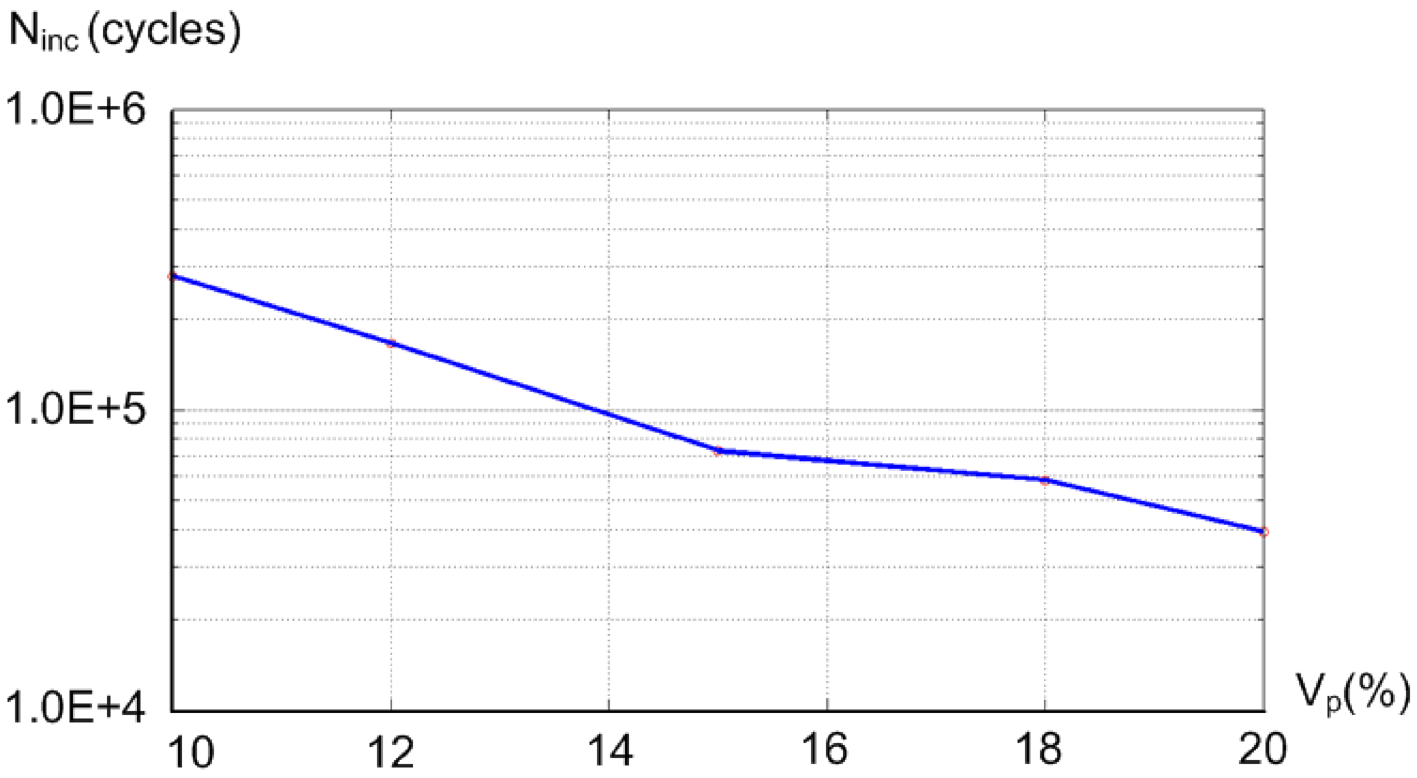
Effect of carbide shape on ΔΓ and N_{inc}



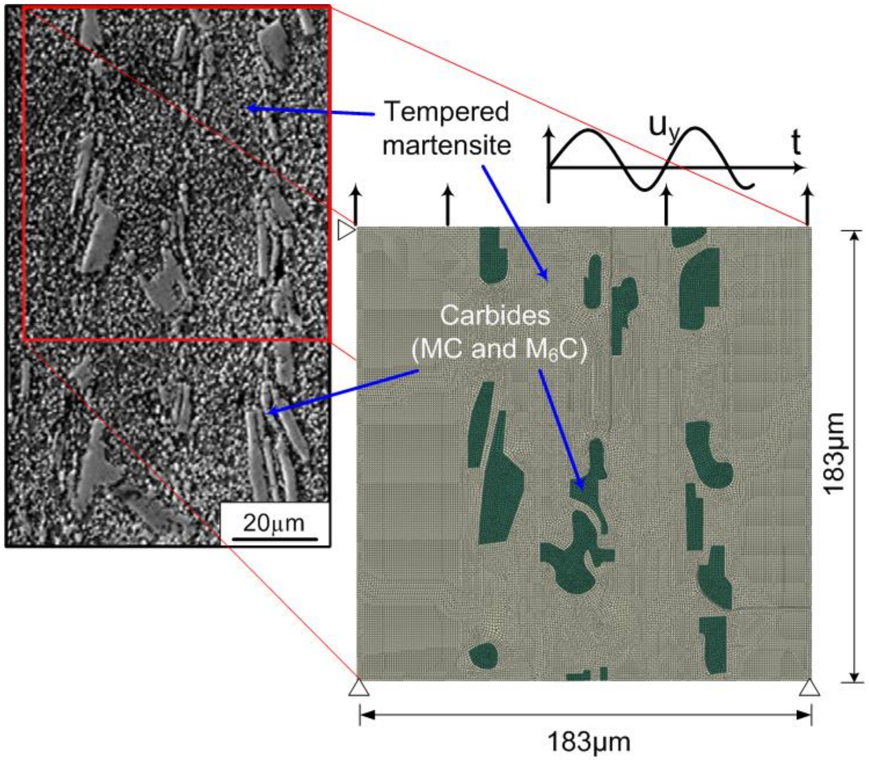
Effect of aspect ratio on ΔΓ

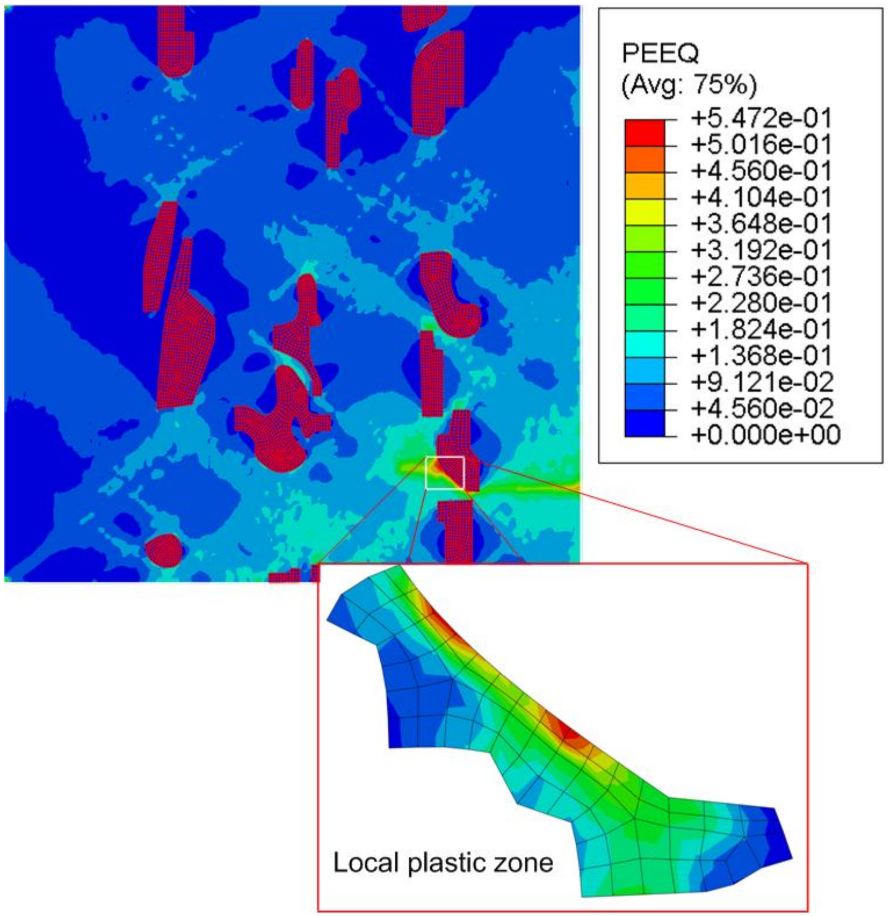


Effect of particle volume fraction on N_{inc}



Local plastic defomations





Summary

- Fatigue strength of aluminum components can be estimated based on material fatigue strength data and appropriate multiaxial failure criteria.
- Experimental investigation of a huge number of aluminum alloys show a dependence of fatigue strength on static strength, stress state, mean stress and production technology.
- The simple rule, given by FKM-guideline does not reflect all these influences.
- A multistage, multiscale model has been developed to predict fatigue life based on crack initiation and crack propagation.
- This model has been used to investigate microstructural features on fatigue strength.

Thank you for your attention!

Prof. Dr.-Ing. Christoph Broeckmann

IWM – Institute for Materials Applications in Mechanical Engineering
RWTH Aachen University
Augustinerbach 4
52062 Aachen

www.iwm.rwth-aachen.de