Lifetime prediction of welded structures by means of welding simulation

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- Motivation
- Fatigue of metals and welds
- Fracture mechanics and life expectancy
- Application for large structures: case study - marine diesel engines
- Conclusions

Motivation: safety and economy

Fatigue damage estimated to cause 90% of all mechanical failures.

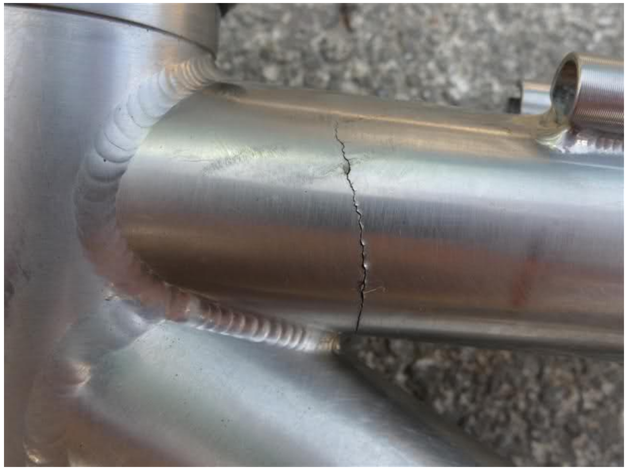
American Society for Metals

Estimated costs for failure to be $119 billion in 1982 (4% of US GDP).

National Bureau of Standards

Brittle fracture on 1250 Liberty ships initiated at welds (50th)

Collapse of the Seongsu bridge due to the welding failure (1994)



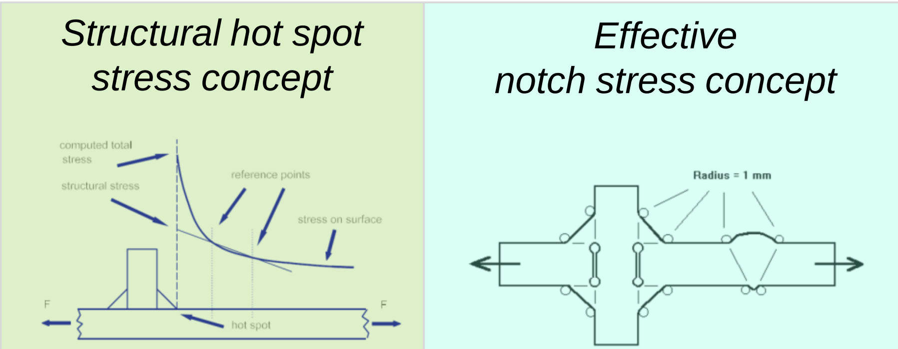
Crack on a bike frame starting from weld seam

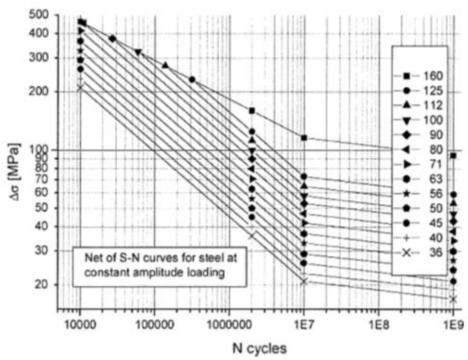
Practical experience clearly shows that fatigue damage generally originates from welds, which are considered to be the weakest link of welded structures.

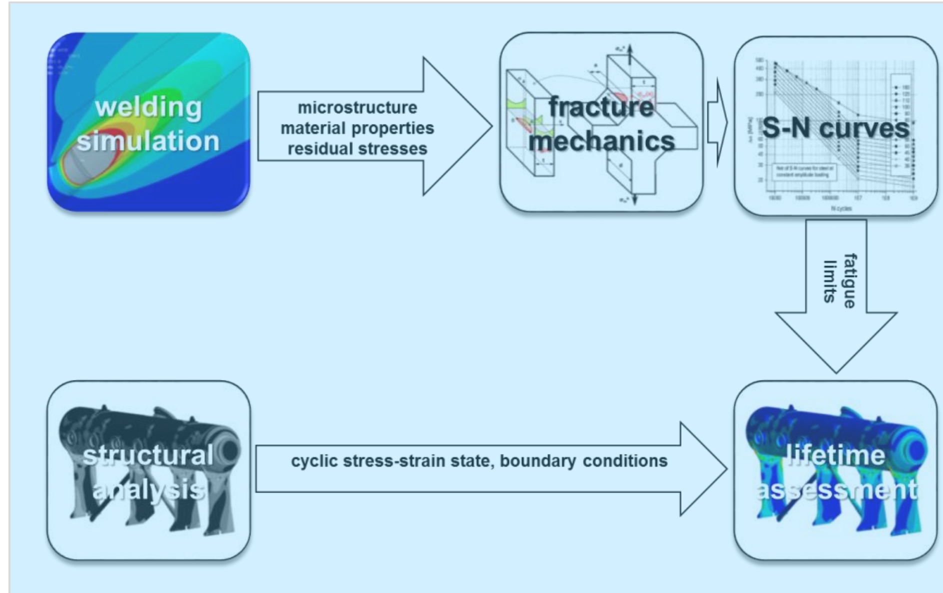
Goal: enhanced fatigue assessment

International Institute of Welding
A world of joining experience

Coupled welding-fatigue analysis







+ simple and fast
+ widely accepted

- many assumptions → suboptimal design
- generalization of material, welding process and geometry
- exotic weld types missing

+ specific material and welding process
+ prediction of residual stresses and microstructure
+ understanding of phenomena and their interactions

- comprehensive modeling and material characterization

Fatigue of metals

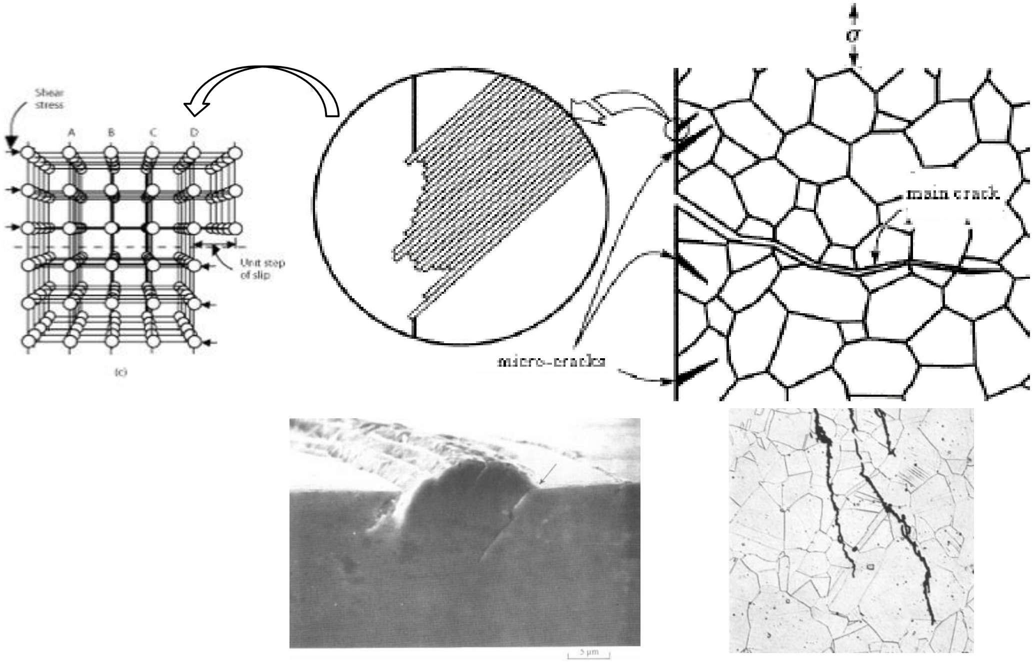
For metals the whole life span can be split into three stages:

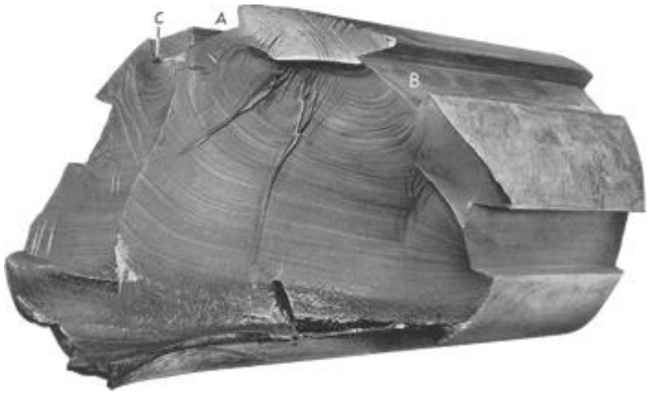
(I) Crack initiation - nucleation at inclusions, persistent slip bands

(II) Crack propagation - incremental crack growth (inter- and transcrystalline)

(III) Failure - final rapid crack propagation

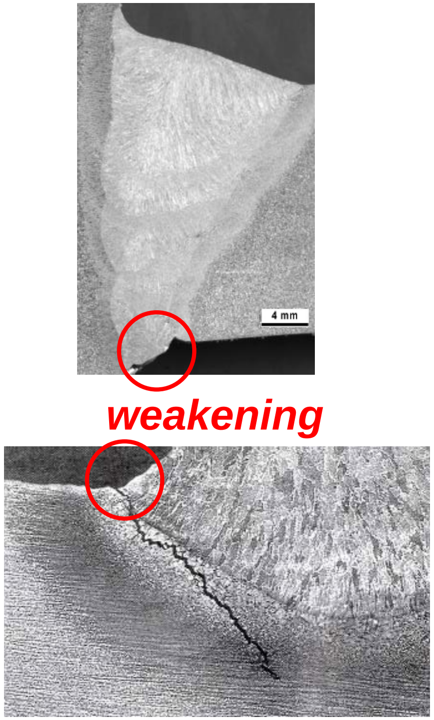
initiation propagation collapse

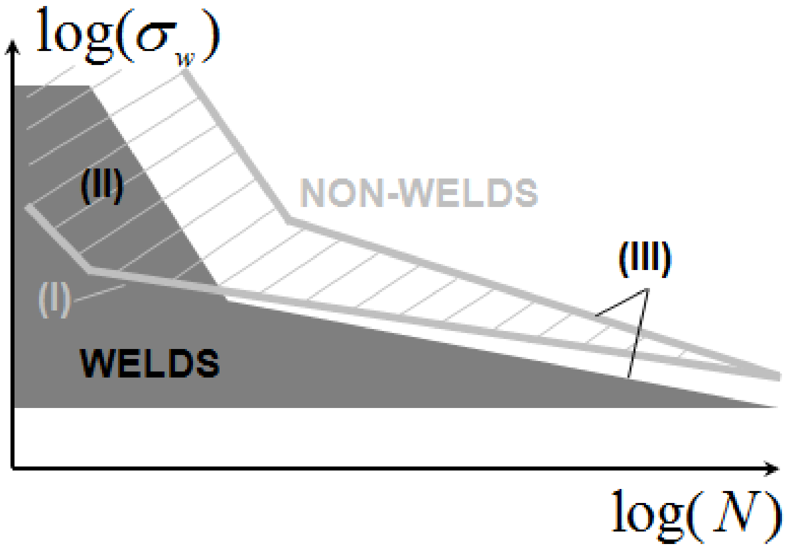




Fatigue of welds

High probability of crack-like flaws after the welding process, heterogeneity of microstructure and residual stresses lead to significant differences in fatigue assessment of welds compared to non-welded structures.

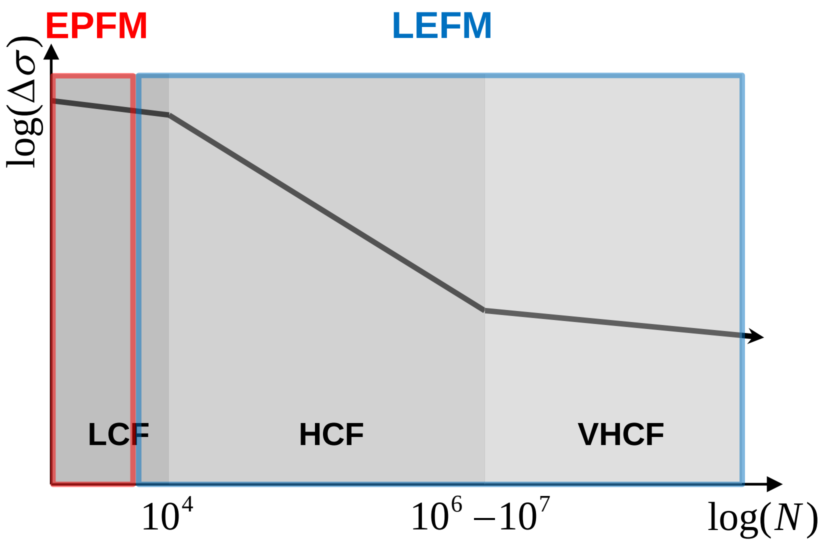


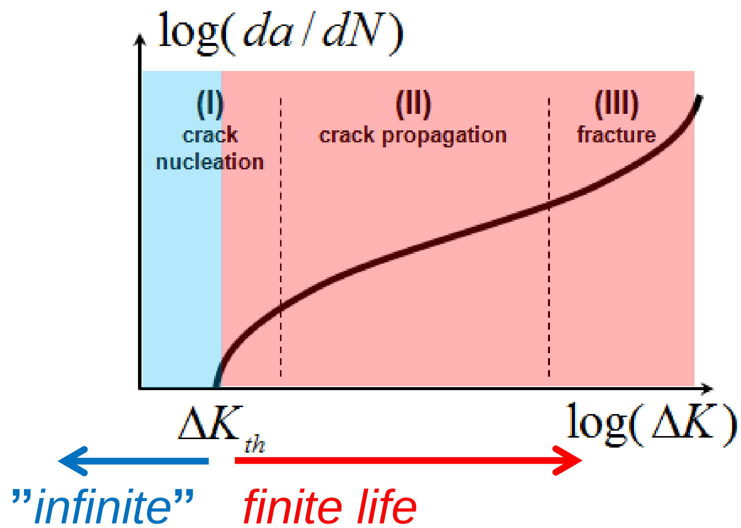


The stage of crack initiation is relatively insignificant for welds.

Fracture mechanics

Fracture mechanics deals with cracks and can be used for the estimation of fatigue crack growth. Depending on the size of the plastic zone at a crack tip a linear-elastic (LEFM) or elastic-plastic fracture mechanics (EPFM) has to be applied.



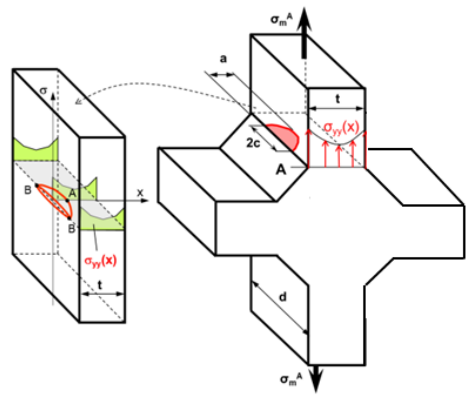


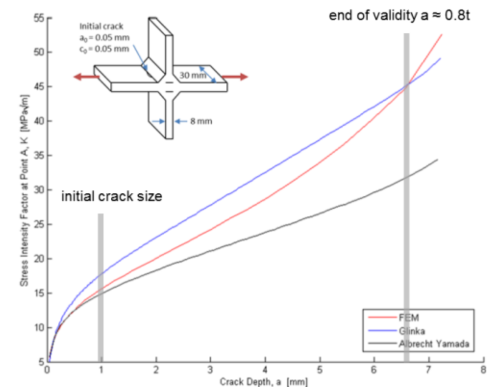
Let us focus on LEFM since it covers the most relevant fatigue regimes.
The threshold for the initial crack propagation can be taken as a criterion for VHCF, whereas crack growth can be used for HCF and LCF.
If the maximum allowable flaw size is known (e.g. manufacturing process with NDT), a deterministic approach instead of a stochastic can be applied.

Weight function method

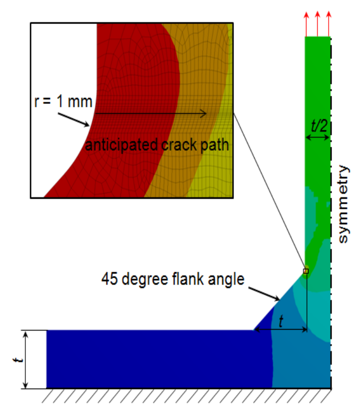
For a rapid estimation of crack growth the weight function method can be used. The stress intensity factor for Mode I is obtained by integrating the product of the stress distribution σ(x) and the weight function m(x,a):

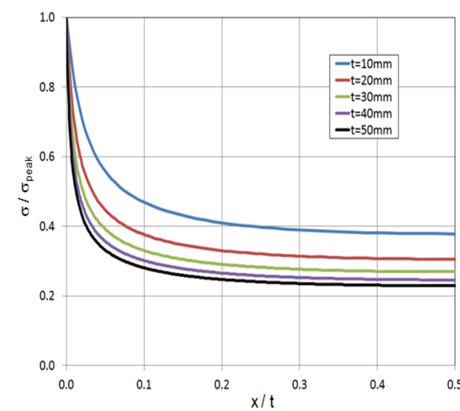
$$\Delta K_{A,B} = \int_0^a \Delta\sigma(x) m_{A,B}(x,a)dx$$





Stress distribution through the plate thickness is crucial for the crack growth analysis.

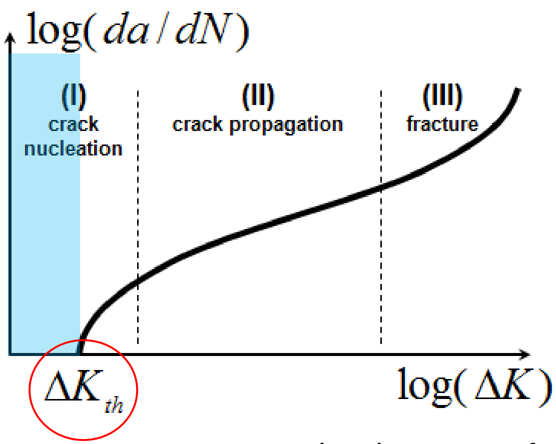


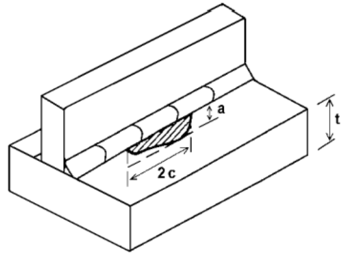


Courtesy of Winterthur Gas & Diesel Ltd.

DYNA MORE SWISS

Very High Cycle Fatigue





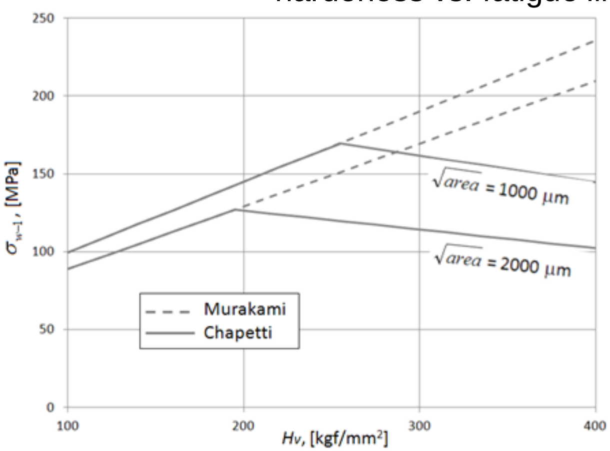
$$\sigma_{w,-1} = \frac{\Delta K_{th,-1}}{2.3\;10^{-3}\left(\sqrt{area}\right)^{1/2}}$$

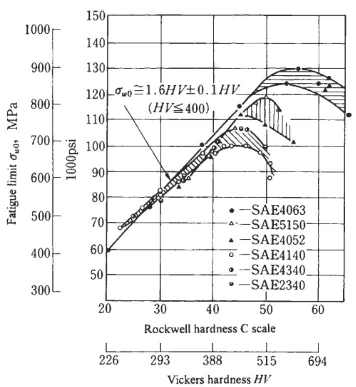
$$\Delta K_{th,-1} = \min\left\{\Delta K_{th,-1}^{short},\;\; \Delta K_{th,-1}^{long}\right\}$$

Short cracks (Murakami): $\Delta K_{th,-1}^{short} = 3.3\;10^{-3}(H_V + 120)(\sqrt{area})^{1/3}$

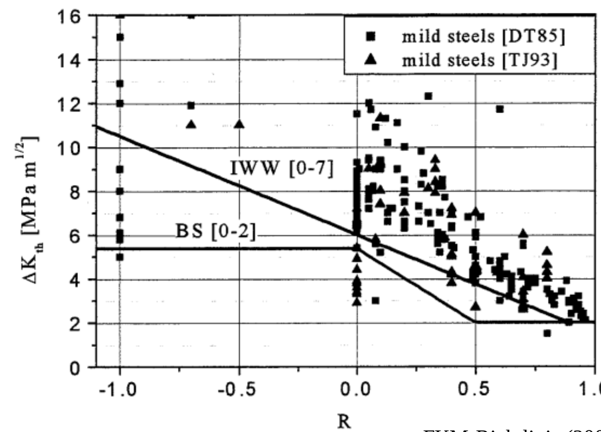
Long cracks (Chapetti): $\Delta K_{th,-1}^{long} = -0.01239\;\; H_V + 15.5$

hardeness vs. fatigue limit





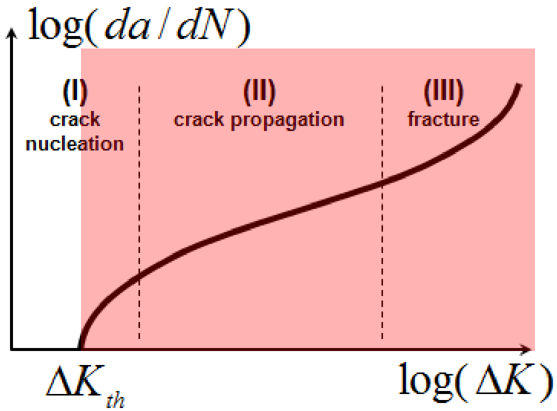
R-value dependency



FKM-Richtlinie (2002)

$$\Delta\sigma_{w,R}^{VHCF} = \frac{\Delta K_{th,R}}{\max\left\{\int_0^{a_0} f(x,t)m_A(x,a)dx,\;\; \int_0^{a_0} f(x,t)m_B(x,a)dx\right\}}$$

High & Low Cycle Fatigue



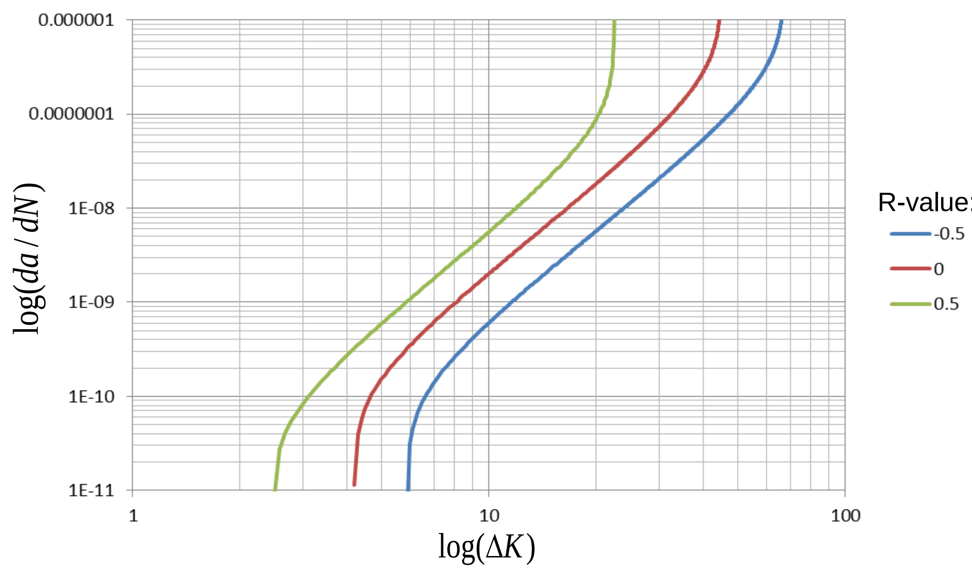
NASGRO:

$$\frac{da}{dN} = C\Delta K^{m-p}\left(\frac{1-f}{1-R}\right)^{m} \frac{(\Delta K-\Delta K_{th})^{p}}{(1-\frac{\Delta K}{(1-R)K_c})^{q}}$$

Paris law:

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

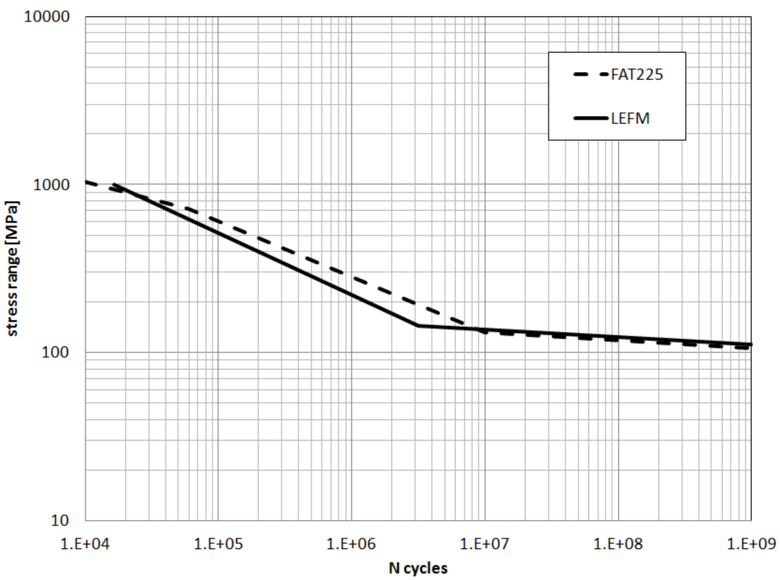
$$\Delta\sigma^{HCF}_{w,R} = \sqrt[m]{\frac{1}{C\ N}\int_{a_0}^{a_f}\left[\int_0^a f(x,t)\ m_A(x,a)dx\right]^{-m} da}$$



In case the exact residual stress distribution, including its alternation as well as gradient of microstructure are unknown, a constant R=0.5 can be assumed as the worst case.

Fatigue life prediction

$$\Delta\sigma_{w,R} = \begin{cases} \dfrac{\Delta K_{th,R}}{\max\left\{ \int_0^{a_0} f(x,t) m_A(x,a)dx,\ \int_0^{a_0} f(x,t) m_B(x,a)dx \right\}} & - \ VHCF \\ \sqrt[m]{\dfrac{1}{C\ N} \int_{a_0}^{a_f} \left[\int_0^{a} f(x,t)\ m_A(x,a)dx \right]^{-m} da} & - \ HCF \end{cases}$$

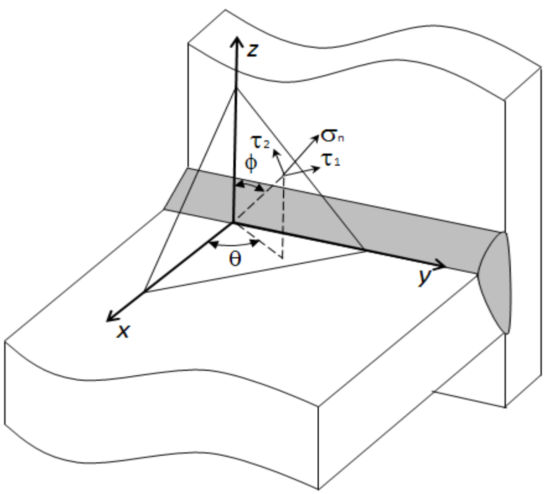


S235JR
HV213
C = 9.71E-9
m = 2.71
semi-elliptical surface crack
a_0 = 1 mm
a_0/c_0 = 0.1
a_f = 0.8t
crack opening Mode I
R=0.5, no crack closure

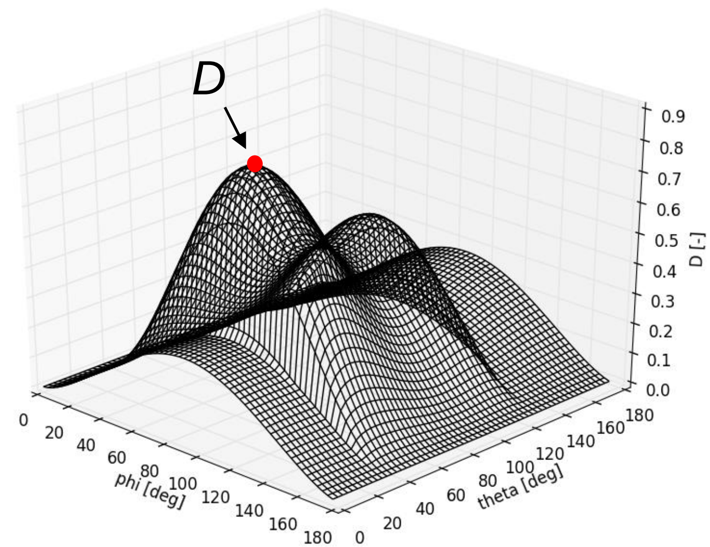
LEFM based model with worst case assumptions can properly reproduce S-N curves from standards – with one essential difference – it is for a particular material, welding process and stress state.

Multiaxial and non-proportional loading

Due to the complex loading and geometry, multiaxial and non-proportional stress history is very common for real structures. Critical plane approach combined with appropriate stress criterion can be applied. Assuming the crack opening Mode I as dominating, the maximum normal stress amplitude has to be evaluated:



$$D = \frac{\max_{\phi,\theta \in [0;\pi]} \left\{ \Delta\sigma_n \right\}}{\Delta\sigma_{w,R}} \leq 1$$



Size effect

So far the model was deterministic, based on the maximum allowable flaw size. If the probability density function for defects is known, a stochastic approach can be applied. In this case the probability of failure increases with the length of weld seam – this is very important for real structures.

Weakest link theory:

Survival probability of a system is a product of reliabilities of each link

$$R_S = \prod_{i=1}^{n} R_i$$

Failure probability for each link

$$P_i = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\lambda_i} e^{-\frac{x^2}{2}} dx$$

Effective stress area

$$A_{eff} = \Sigma_{i=1}^{n} \frac{\ln R_i}{\ln R_s} A_i$$

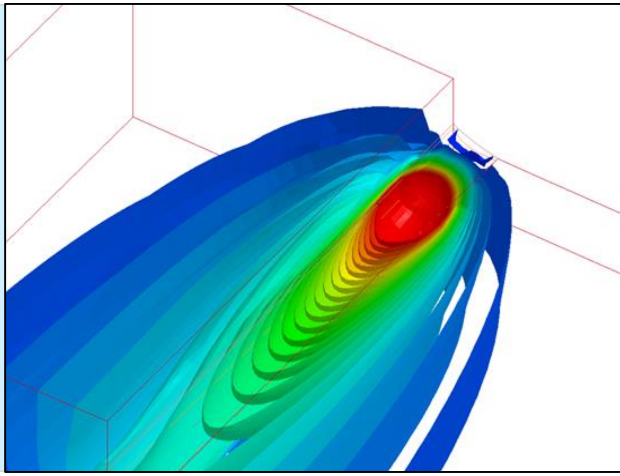
Statistical size factor used to scale fatigue limit

$$n = \max\left\{ \frac{A_{ref}}{A_{eff}} ; \frac{A_{eff}}{A_{ref}} \right\} \qquad R = \sqrt[n]{R_S} \qquad \boxed{K_{size} = e^{-\lambda \sigma_{\ln}}}$$

Fatigue of welds

Important factors:

- service loading (asymmetry, non-proportionality, multiaxiality)
- weld seam geometry (notch radius and angle)
- microstructure (phase, grain size)
- mechanical properties (hardness, hardening)
- residual stresses

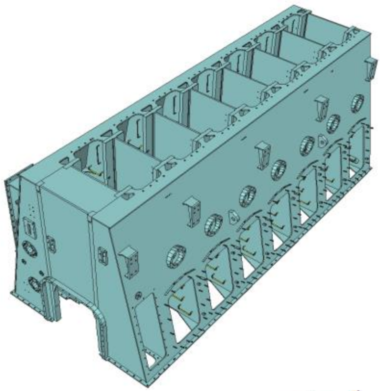


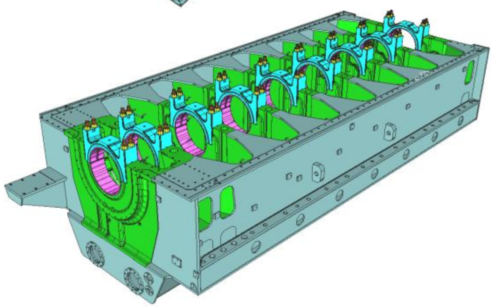
Welding simulation provides totally new possibilities for improved fatigue analysis.

Case study: 2-stroke marine diesel engine

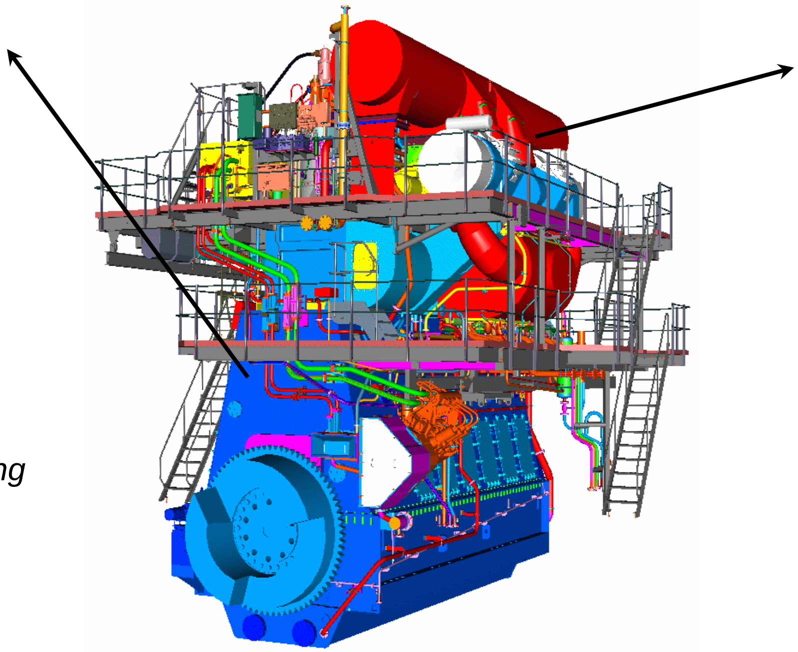
manual multi-pass MAG weldings
S235JR
plate thicknesses 8 – 60 mm

engine frame

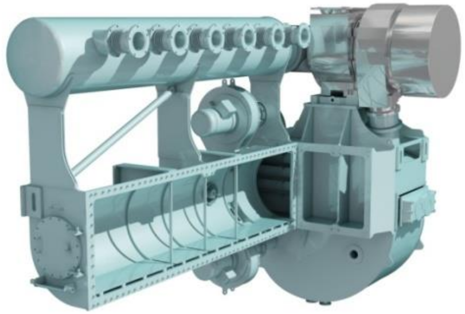




- *room temperature*
- *VHCF*
- *non-proportional multiaxial loading*



exhaust gas system

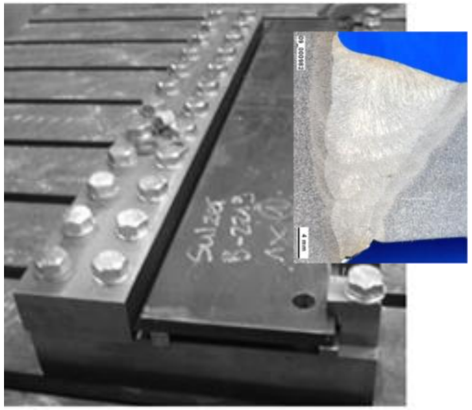


- *high temperature*
- *LCF, VHCF, TMF*
- *high cycle fatigue*

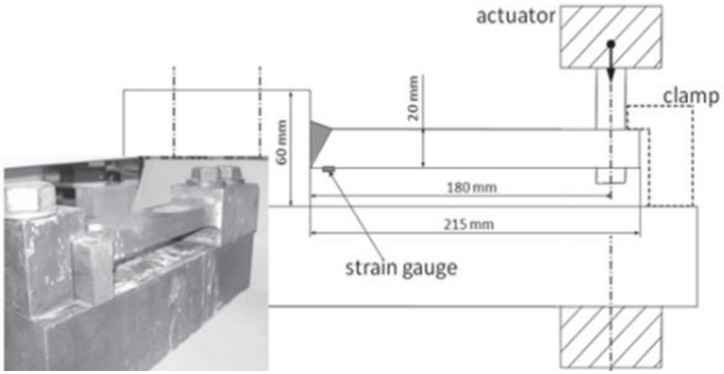
Courtesy of Winterthur Gas & Diesel Ltd.

Single bevel butt weld

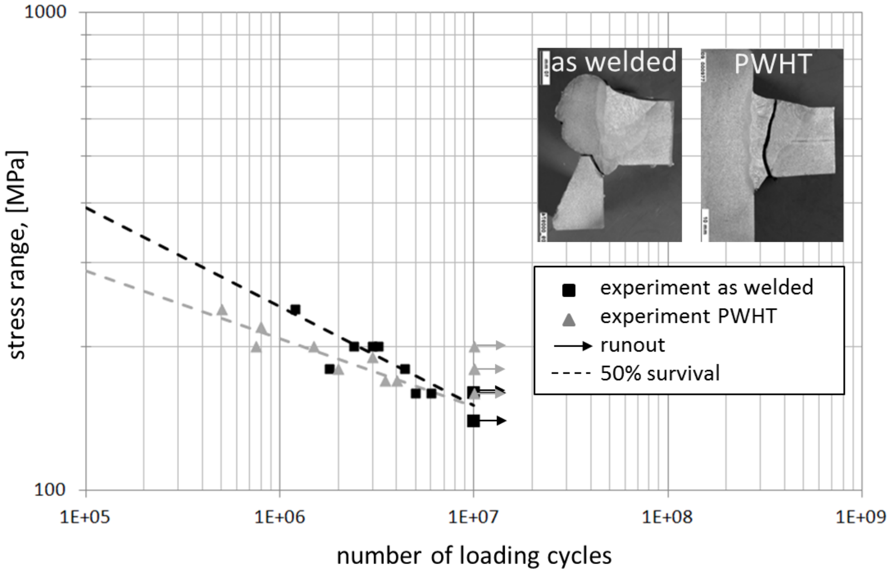
Welding



Fatigue tests

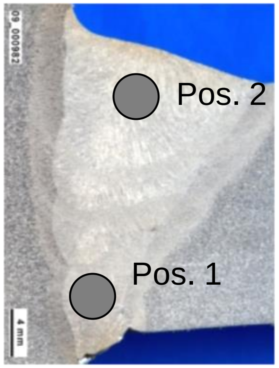


S-N curves



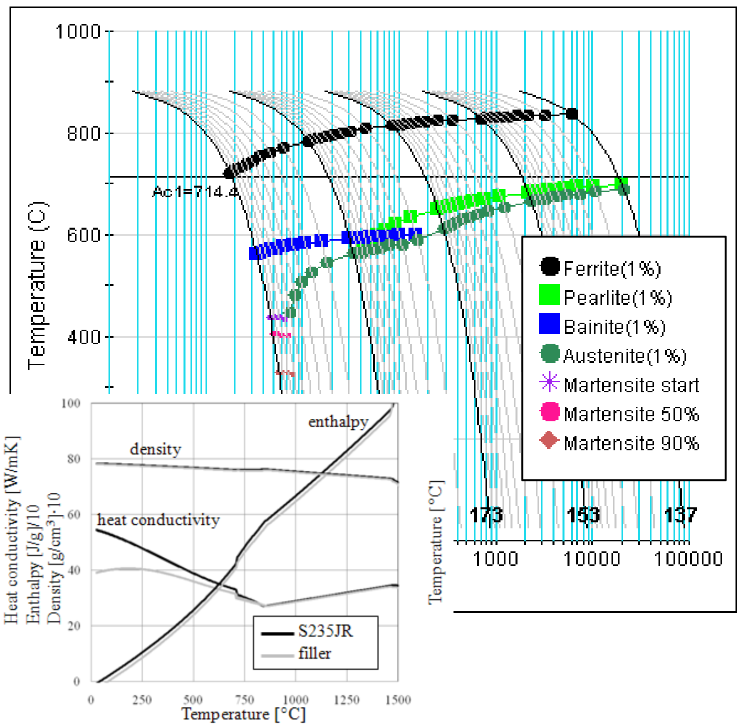
Courtesy of Winterthur Gas & Diesel Ltd.

Material characterization

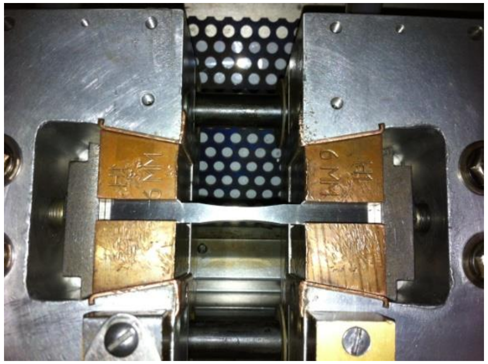


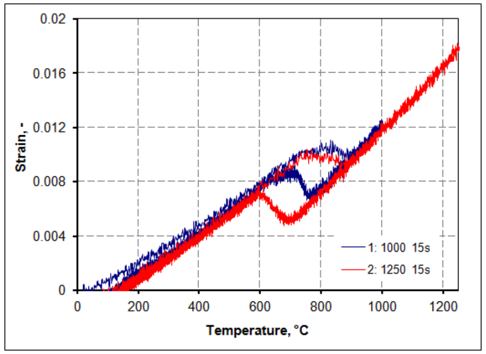
	C	Si	Mn	P	S	Co	Cr	Mo	Ni	V	Cu
S235JR	0.14	0.2	0.75	0.016	0.014	<0.01	0.02	<0.01	<0.02	<0.01	<0.01
Pos. 1 (solid wire)	0.11	0.62	1.13	0.013	0.016	<0.05	0.05	<0.01	0.02	<0.02	0.078
Pos. 2 (flux-cored wire)	0.105	0.61	1.14	0.013	0.009	<0.05	0.036	<0.01	0.042	<0.02	0.11

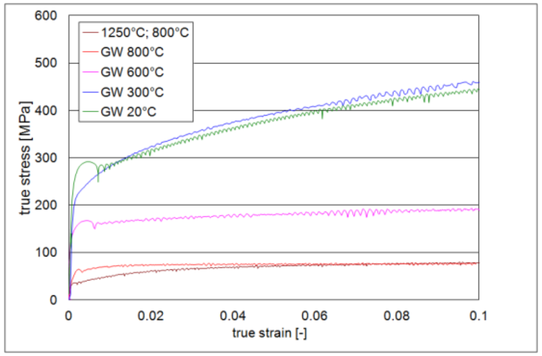
CCT S235JR (JMatPro)



Gleeble simulator







Courtesy of Winterthur Gas & Diesel Ltd.

Welding simulation

Material model

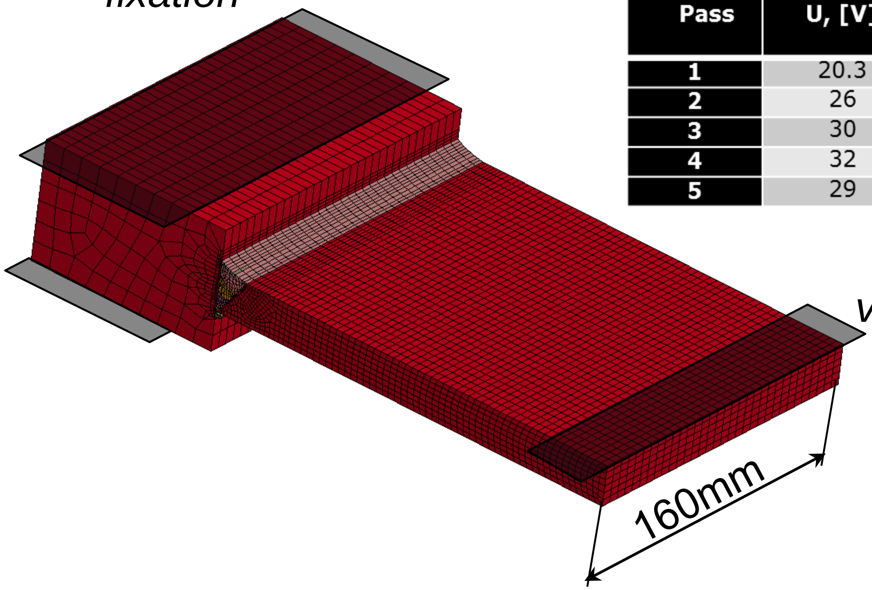
$$\dot{\boldsymbol{\varepsilon}} = \dot{\boldsymbol{\varepsilon}}_{el} + \dot{\boldsymbol{\varepsilon}}_{vp} + \dot{\boldsymbol{\varepsilon}}_{th} + \dot{\boldsymbol{\varepsilon}}_{tr} + \dot{\boldsymbol{\varepsilon}}_{tp}$$

Multi-phase Leblond:

$$\dot{P}(T) = n\left(\frac{P_{eq}(T) - P_i(T)}{\tau(T)}\right)\left(\ln\left(\frac{P_{eq}(T)}{P_{eq}(T) - P_i(T)}\right)\right)^{\frac{n(T)-1}{n(T)}}$$

Koistinen-Marburger:

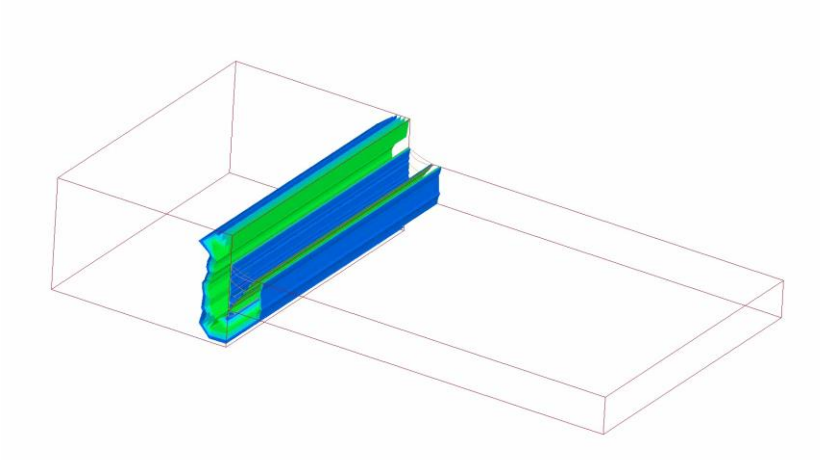
$$P(T,t) = 1 - e^{-b(M_s - T(t))}$$



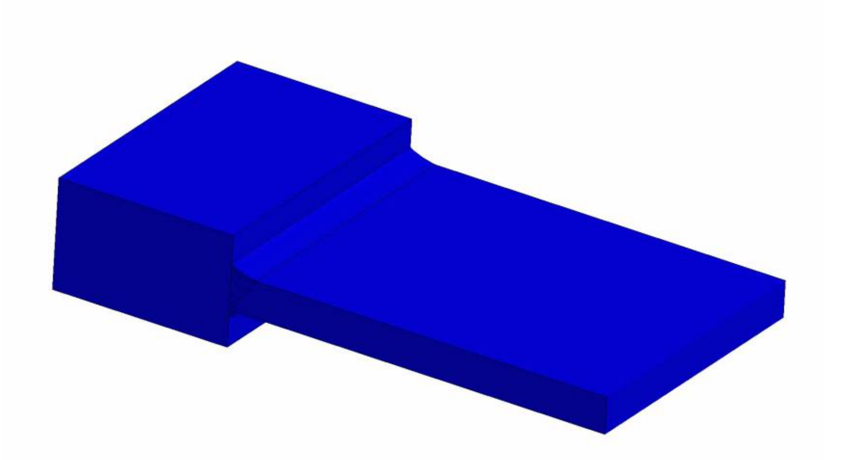
Pass	U, [V]	I, [A]	Speed, [cm/min]	Gas	Heat input, [kJ/m]	Thermal efficiency factor
1	20.3	140	10	CO_2	1614	0.95
2	26	230	27	CO_2	1316	0.85
3	30	280	18	CO_2	2772	0.69
4	32	320	22	CO_2	2765	0.75
5	29	290	20	CO_2	2523	0.82

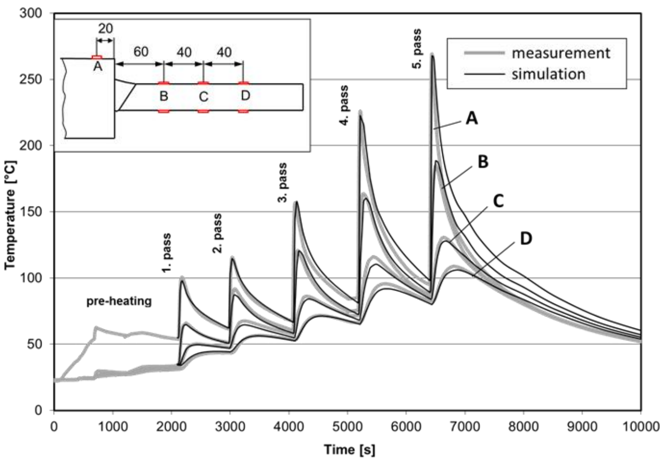
Welding simulation

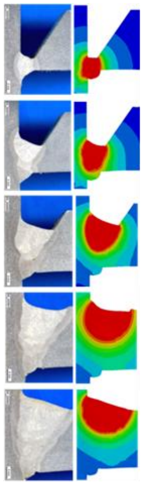
temperature

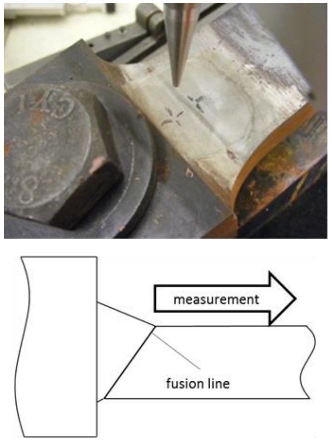


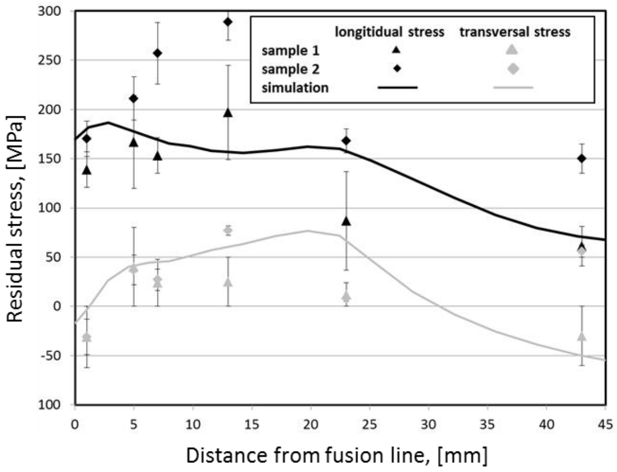
stress









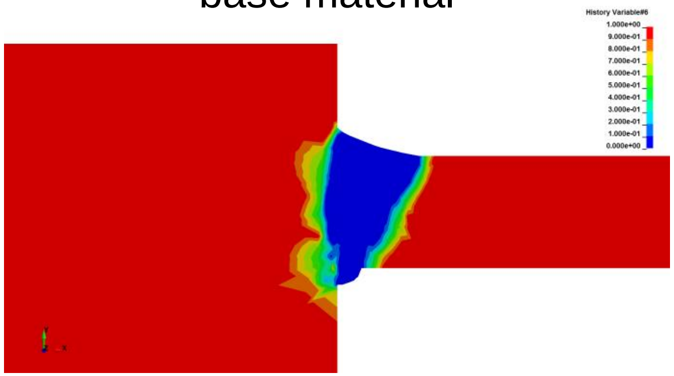


Courtesy of Winterthur Gas & Diesel Ltd.

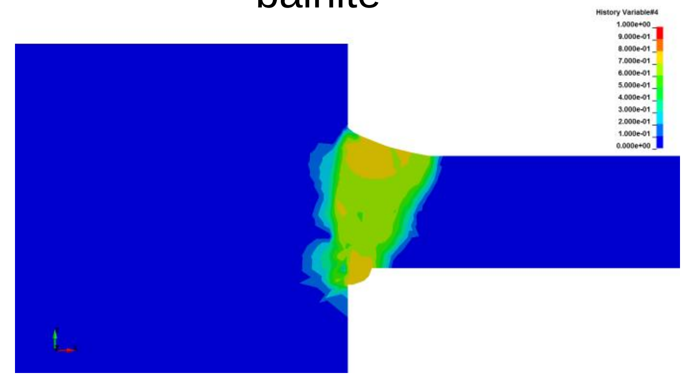
Simulation predicts measured temperature evolution and residual stresses.

Microstructure prediction

base material



bainite

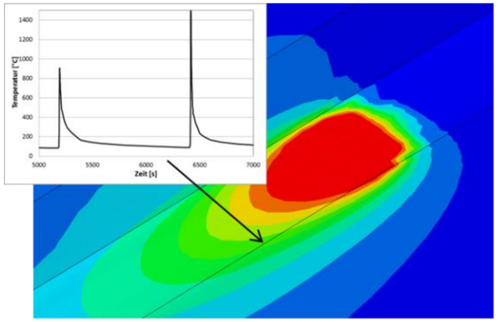


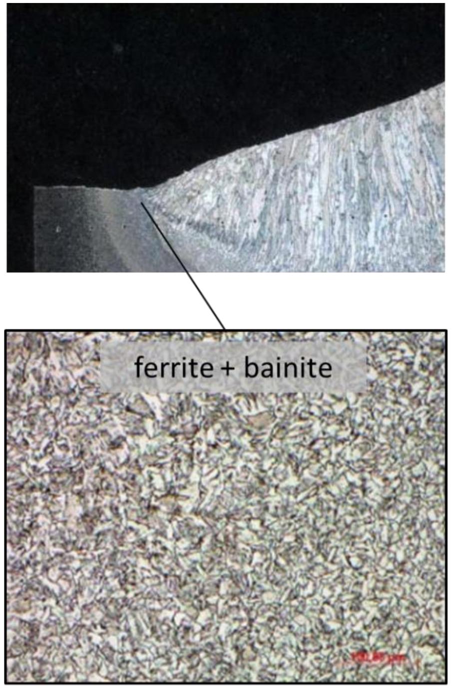
ferrite

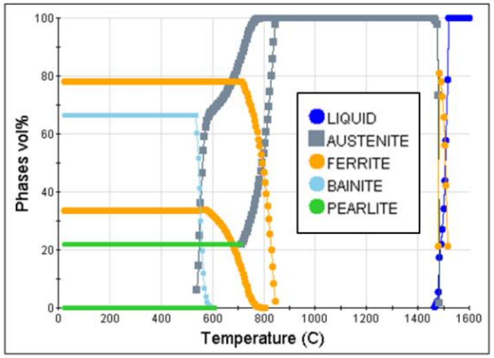
perlite

Material properties on weld notch

microstructure prediction (JMatPro)

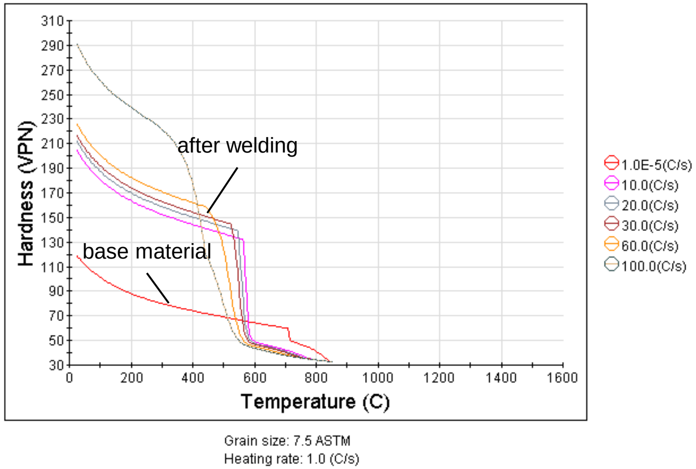


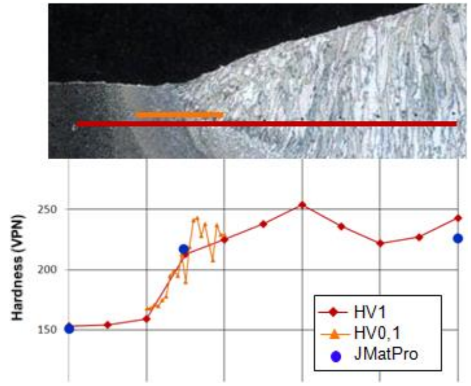




Courtesy of Winterthur Gas & Diesel Ltd.

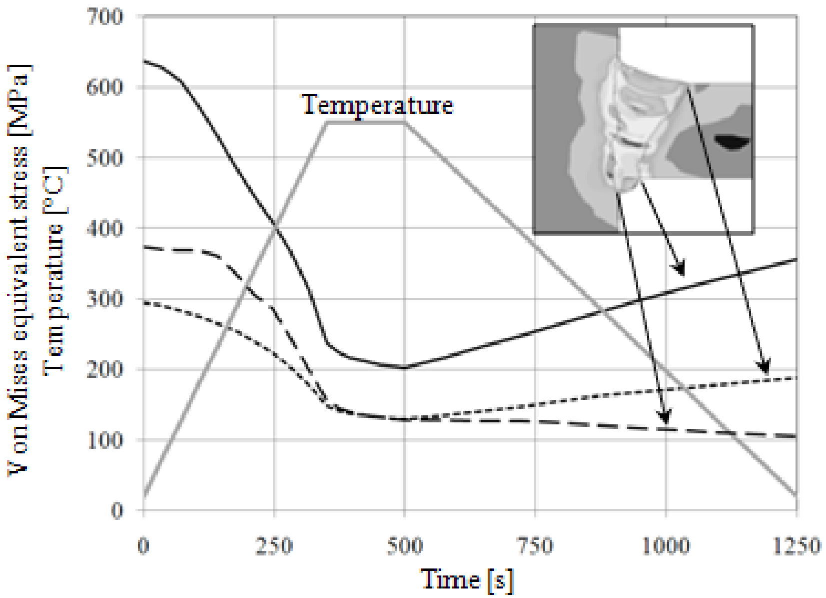
thermo-mechanical properties (JMatPro)

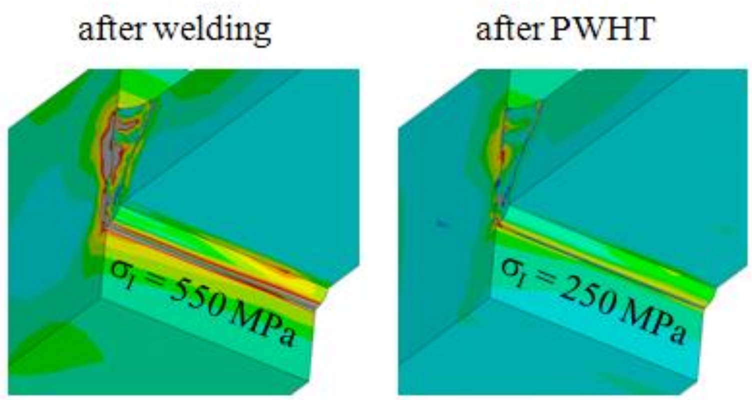




Fast thermal simulation can provide a lot of valuable information about the microstructure and mechanical properties on weld notches.

Post-weld heat treatment

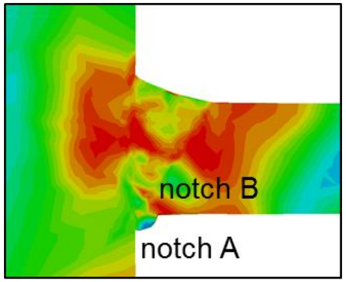


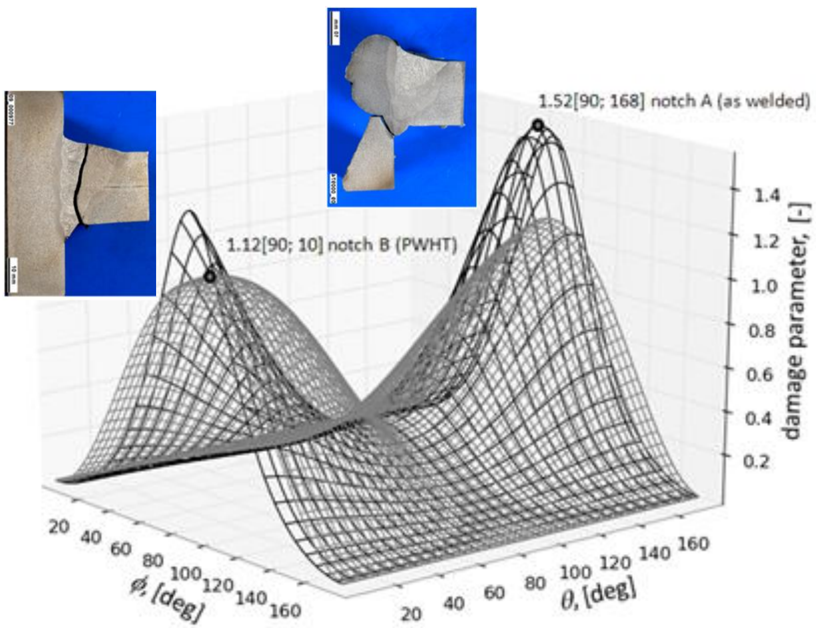


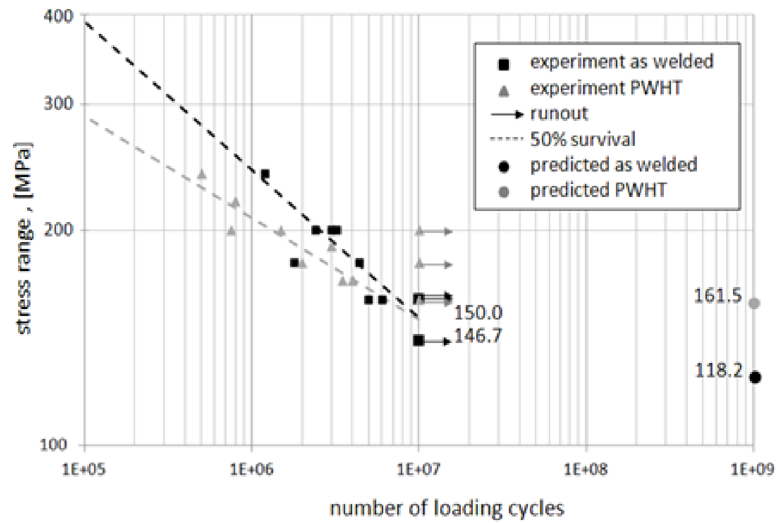
Courtesy of Winterthur Gas & Diesel Ltd.

Post-weld heat treatment can significantly influence residual stress distribution and so the fatigue limit.

Cyclic bending test







Courtesy of Winterthur Gas & Diesel Ltd.

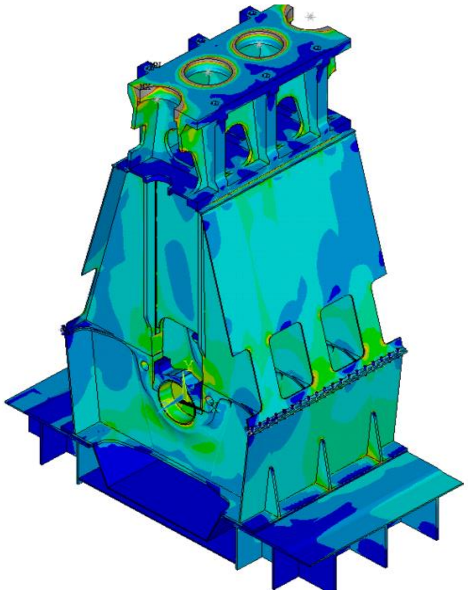
Coupled welding-fatigue analysis is able to explain fracture behavior observed in experiments.

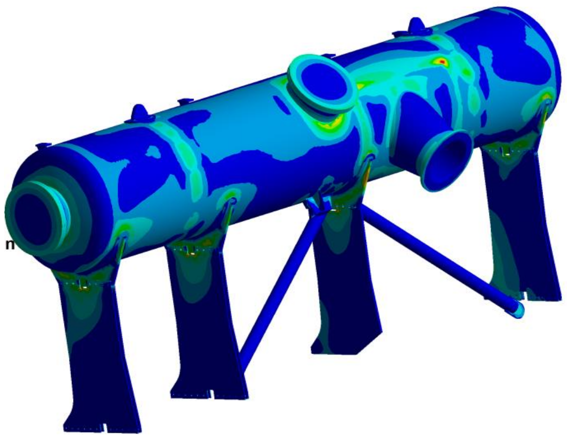
Large structures

In order to rapidly identify critical areas the following relation can be applied for large structures (assuming proportional plane stress state):

$$D = \frac{\Delta\sigma_n}{\Delta\sigma_{w,R}} \leq 1$$

$$\Delta\sigma_n = \frac{\Delta\sigma_{11} + \Delta\sigma_{22}}{2} + \sqrt{\left(\frac{\Delta\sigma_{11} - \Delta\sigma_{22}}{2}\right)^2 + \Delta\sigma_{12}^2}$$





Courtesy of Winterthur Gas & Diesel Ltd.

Conclusions

- welding process simulation can be effectively used for the prediction of microstructure, mechanical properties and residual stresses
- based on the worst case assumptions regarding the loading and initial flaw size, LEFM can be successfully applied for estimating fatigue limits at VHCF- and LCF-regimes
- coupled welding-fatigue analysis is able to accurately predict fatigue behavior of welded structures
- derived by this approach S-N curves can be successfuly used for fatigue assessment of large welded structures