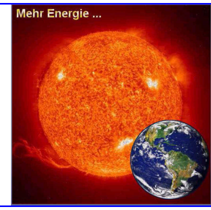
HIGH TEMPERATURE LIFETIME MANAGEMENT

By Petar Agatonovic, Germany



The necessity to increase material application temperatures

- Steam and gas turbines (to increase cycle efficiency)
- Nuclear technology (both Fission and Fusion)
- Space hot structures
- Hydrogen (necessary higher compression)
- Fuel cells
- Solar concentration power station
- Stirling Engine

Increasing temperatures represents a significant challenge to materials technology.

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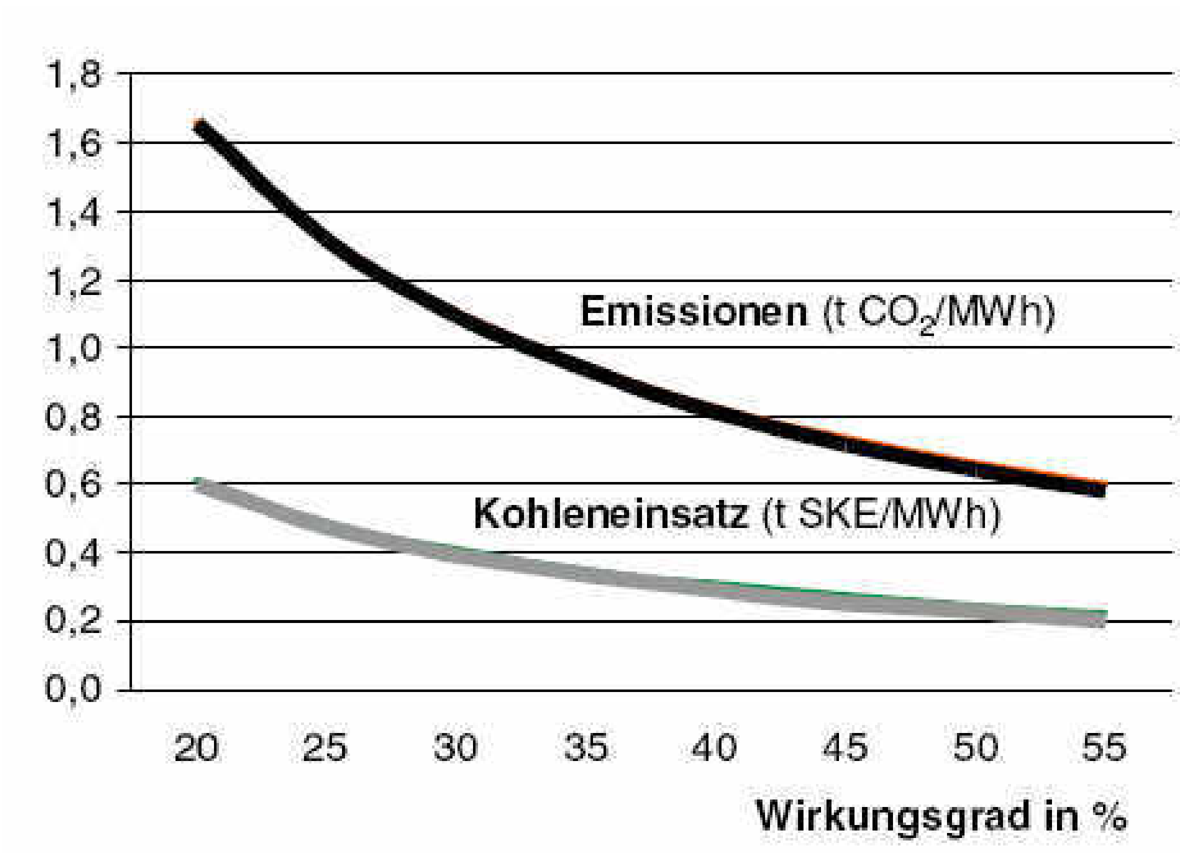
Steam Turbine: Effect of Higher Steam Conditions on Unit Performance

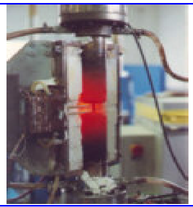
- The potential cycle efficiency gain from elevating steam pressures and temperatures.
- Net thermal efficiency of fossil plants in the case of "**sub-critical plants**" is only max. 37% (but for most of them only 30 %)
- Plants operating under **ultra supercritical** steam conditions of 593℃ 725 MPa improve efficiency to nearly 42% (further improvements are possible by employing a **double, rather than single, reheat cycle)**
- To boost efficiencies above 45%, projects have been carried out in Europe, the United States, and Japan that address steam conditions of 700℃/28 MPa and above.
- The conservative design philosophy requires lasting for 30 – 40 years, despite the high temperatures and stresses.

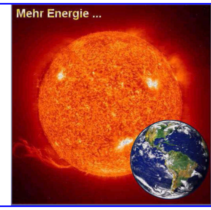
Presuppositions for solution are the **availability of a suitable material, efficient design and adequate testing methods**.

Important effect to the environment and clime

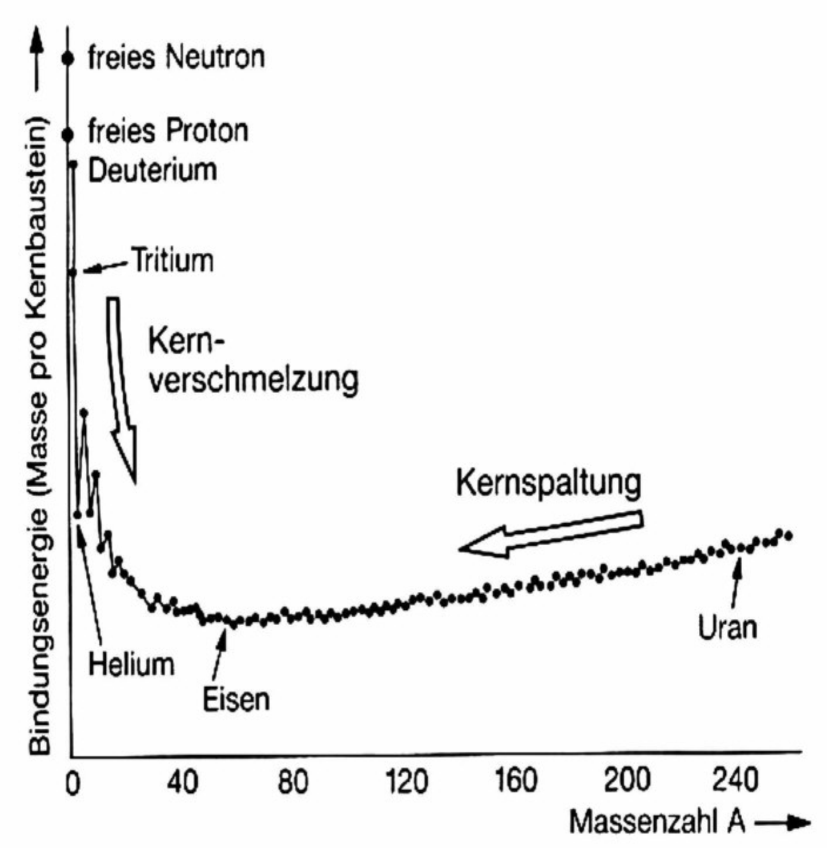


Economics and environmental concerns are the primary driving forces for improvements in the energy industries





Thermonuclear energy (Fusion instead of Fission)

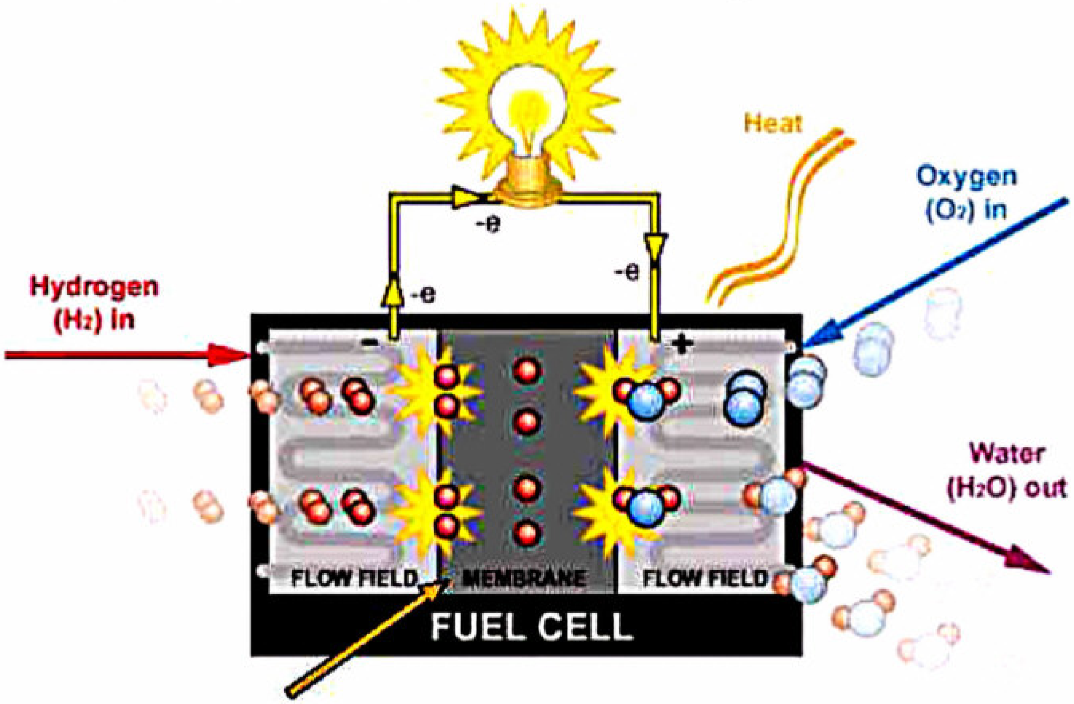


Physical parameters of energy release reaction

Reaction ⇨	***Chemical***	***Fission***	***Fusion***
Used fuel	Coal, oil, gas and air	**UO_2 (3% ^{235}U + 97% ^{238}U)**	Deuterium and Lithium
Formula	$C + O_2$ ⇨ CO_2	**$^{1}n + {}^{235}U$ ⇨ $^{143}Ba + {}^{91}Kr + 2\,{}^{1}n$**	**$D(^{2}H) + T(^{3}n)$ ⇨ $^{4}He + {}^{1}n$**
Typical temp. °K	1000	1000	**100 000 000**
Free energy of kg fuel in (J/kg)	$3{,}3 \times 10^{7}$	$2{,}1 \times 10^{12}$	$3{,}4 \times 10^{14}$

Fuel cells

$2H_2 + O_2 \rightarrow 2H_2O$ + electrical power + heat



Membrane conducts protons from anode to cathode
proton exchange membrane (PEM)

High temperature Fuel cells

- ➔ Solid oxide fuel cells (SOFC) 50 – 65 % efficiency 1000 °C
- ➔ Molten carbonate Fuel cells (MCFC) 45 – 60 % efficiency 800 °C

Necessary temperature for fuel reforming (hydrogen production):

> 800 °C

Using the waste heat ⇨ efficiency up to the 90 % possible

Transport application: Start problem

Solar concentration (for hydrogen production)

Possible solutions

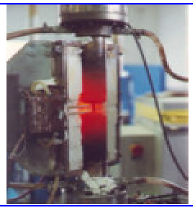
Development of new materials and new design methods

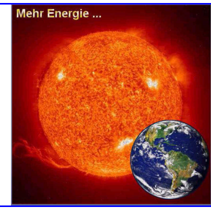
Reactors, gasifiers, pipelines, heat exchangers and many other power-generation structures in the 21st century require new materials that can perform reliably in ever-increasing temperatures and pressures, for longer times, and in a variety of corrosive atmospheres.

The most common reasons for new design methods include:

- ➔ Taking advantage of new materials or processes
- ➔ Improving service performance, including longer life and higher reliability
- ➔ Meeting new legal requirements (Accounting for the changed operating conditions)
- ➔ Reducing cost and making the product more competitive

Both new material and new design methods suffer on long testing and insufficient data for the conventional design





Advanced method should extend the range of application

By improved design

Generally, a simple substitution of one material for another does not produce an optimum solution. This is, because it is not possible to realize the full potential of a new material unless the component is redesigned to exploit its strong points and manufacturing characteristics.

In summary, it is crucial to generate technology for advanced materials and structural analysis that will increase fuel economy, improve reliability, extend life, and reduce operating costs for 21st century application systems.

Results of our examination (BRITE Project 1209)

Stress-strain behaviour modelling and simulation

Stress-strain **history approximation**

“Crack Initiation” replaced with more adequate **damage incubation**

Time - Temperature Substitution approach

Extension of the strain range partitioning method

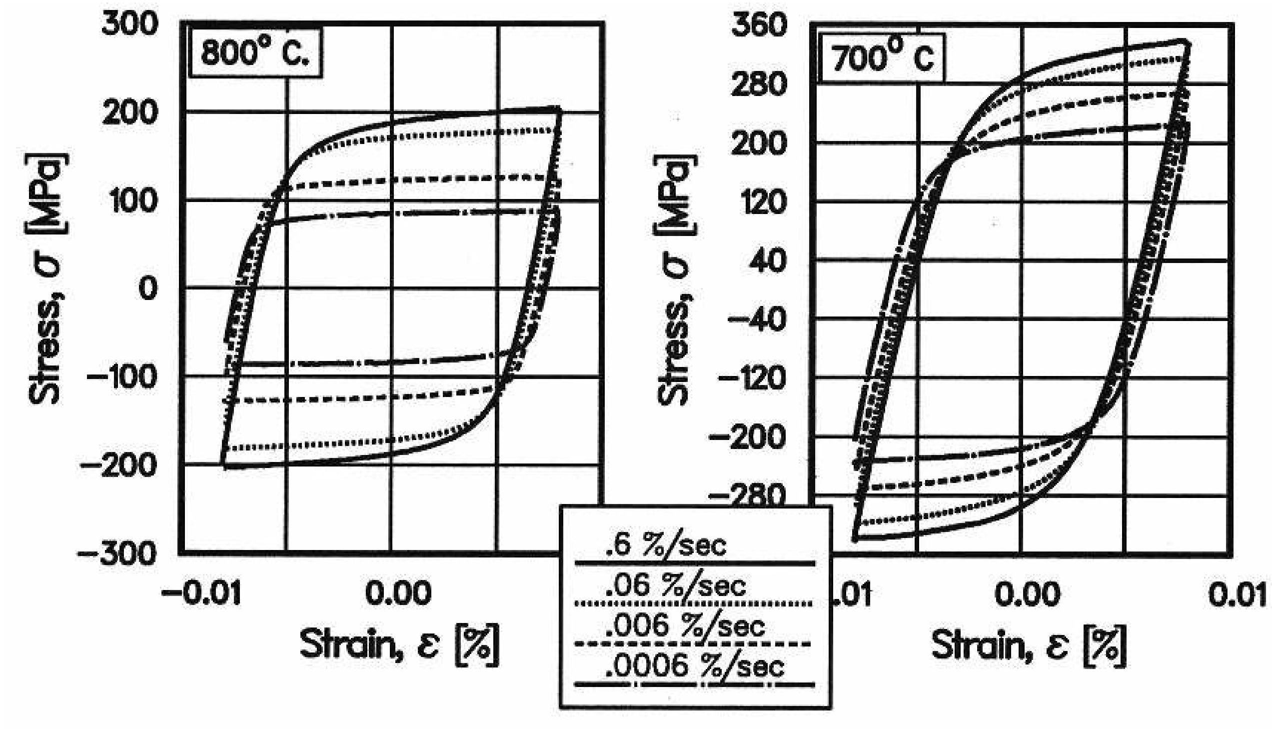
Verification of the method

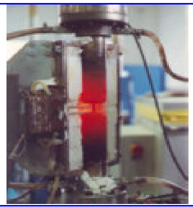
Application to test acceleration

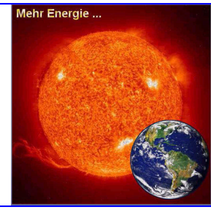
Stress-strain behaviour (for IN 800H)

(Important temperature effects)

The strain rate dependence of the stress-strain behaviour (material softening) - the strain (or strain range) amount increases (and damage)



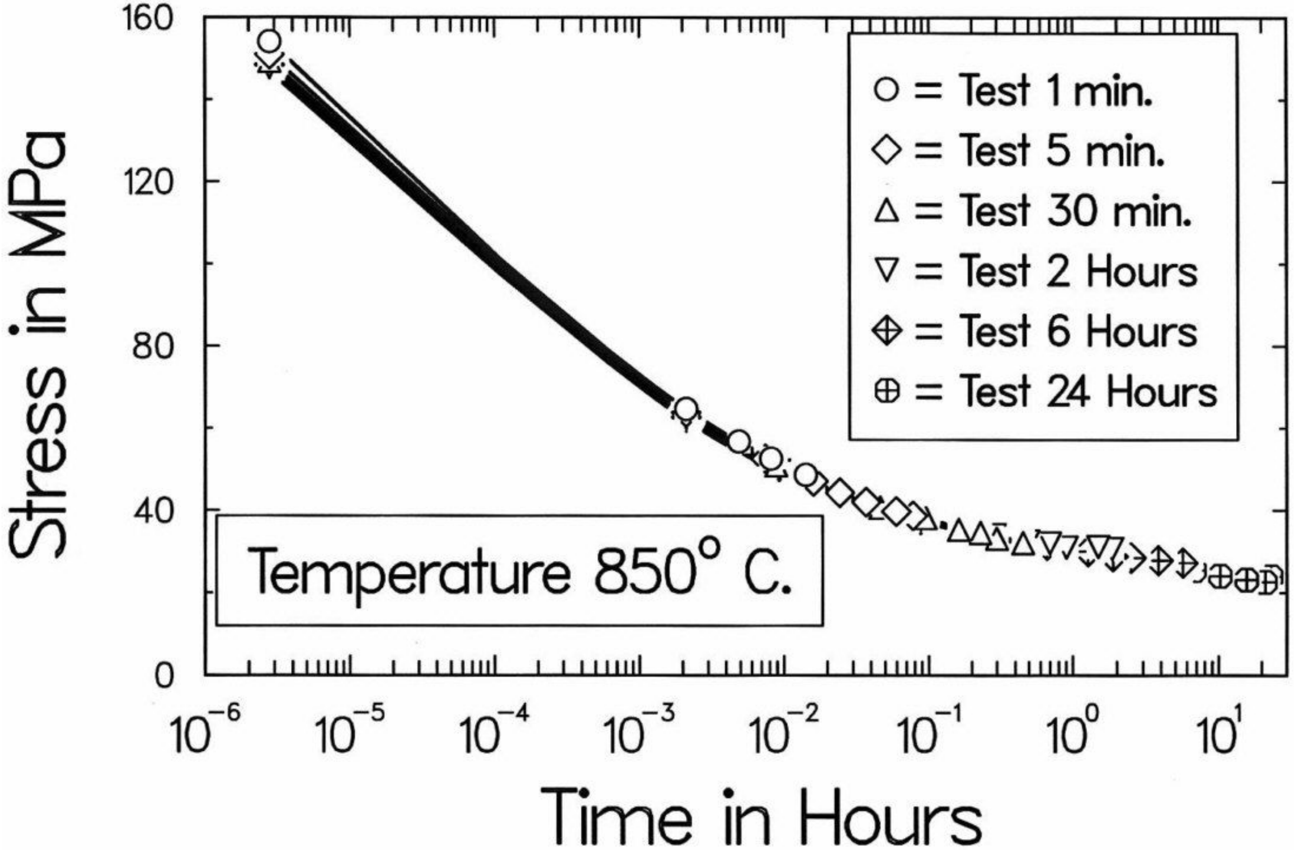




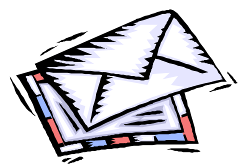
Relaxation behaviour (during dwell)

(Important temperature effects)

Dwell time effects ⇨Relaxation behaviour ("incremental relaxation test")



- ➔ The data for different hold times are seen to coincide
- ➔ The relaxation stress tends towards some threshold value.
- ➔ The threshold stress appears to be independent of the applied stress.



Stress-strain behaviour modelling

In the so-called "unified" theories, the behaviour resulting of both plasticity and creep conditions is described using "state variables" approach.

A general flow rule for the inelastic strain rate (Walker-model) can be expressed as:

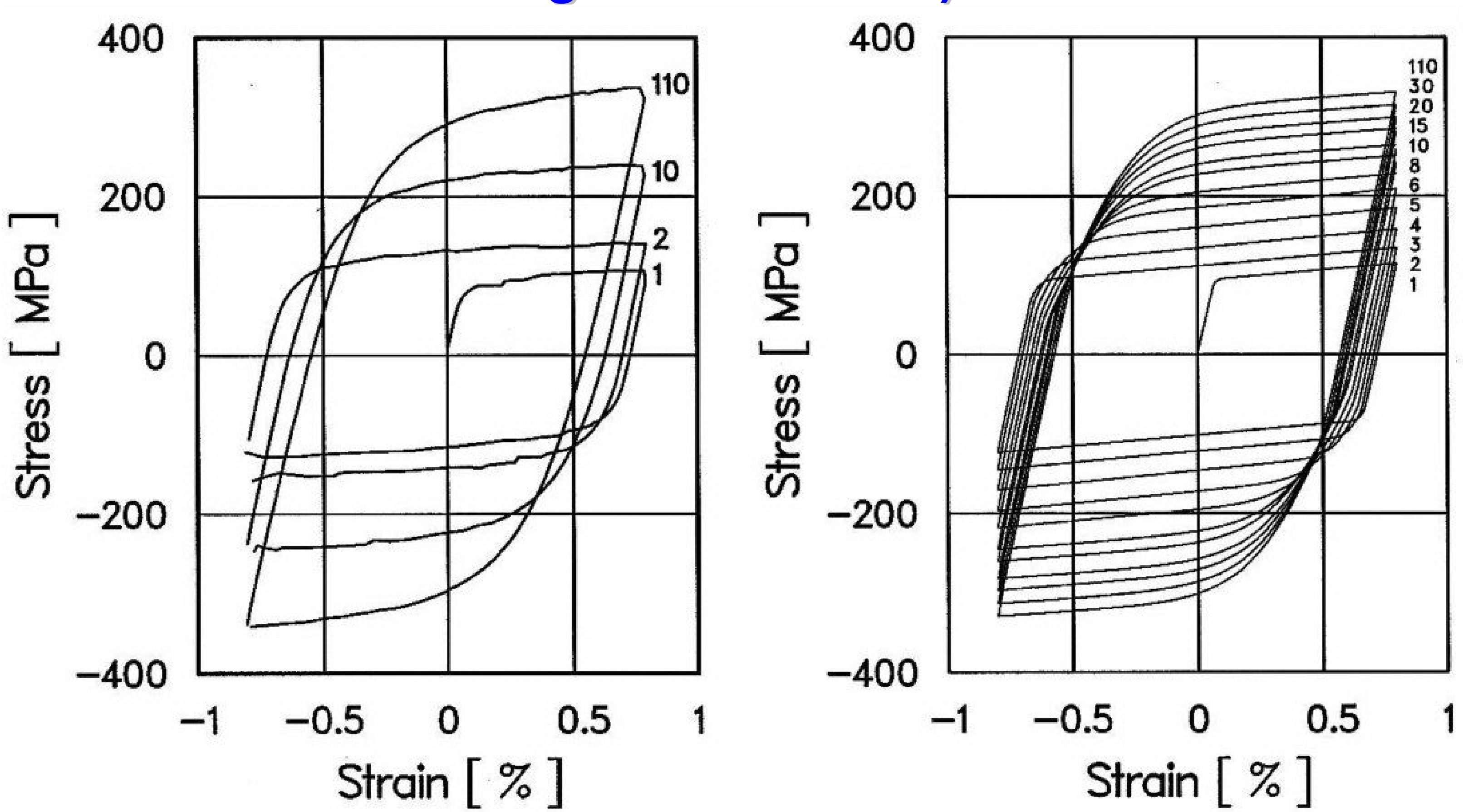
$$\dot{\varepsilon}_{in} = \frac{(\dot{\sigma} - \Omega)^n}{K}$$

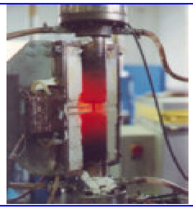
with the two state variables which are:

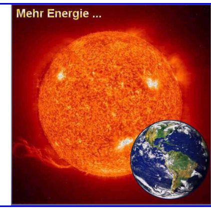
- ➔ the so-called internal stress (Ω), related to the **directional (kinematics) hardening**, and
- ➔ the **isotropic hardening** (**K**), which is a scalar function of the dislocation density.

This allows the description of the different features of the deformation, such as plastic flow, creep and relaxation, as well as hardening, recovery and memory behaviour.

Cyclic hardening simulation by Walker model (left – measurements, right –simulation)





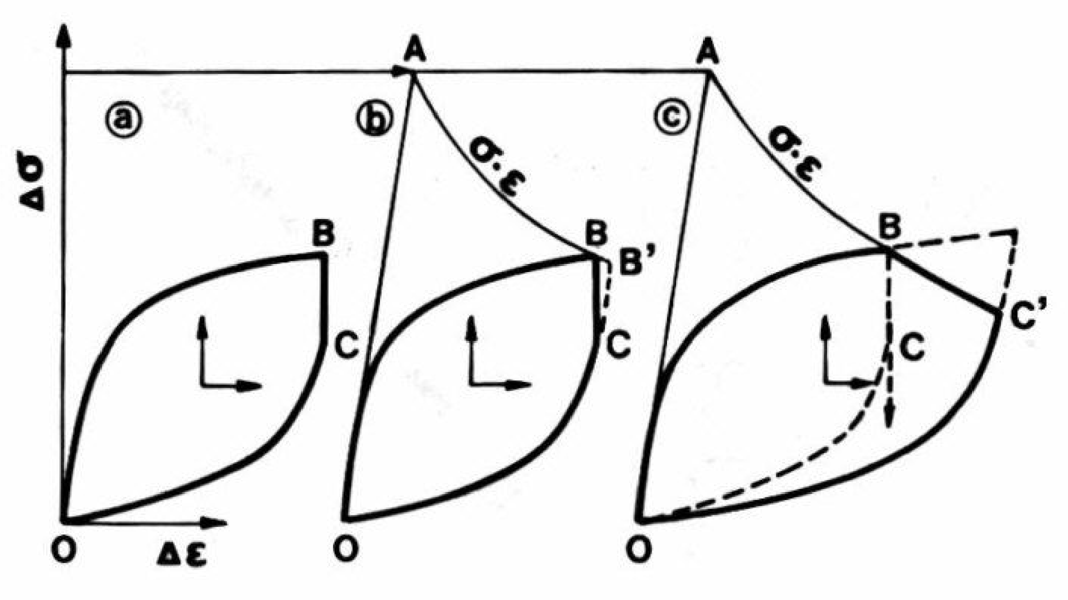


Dwell history simulation

Geometry or Notch Effect

Typical test condition during dwell time

- ➔ Constant strain (relaxation)
- ➔ Both not typical for notch area

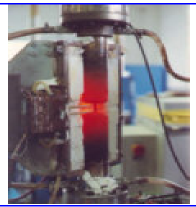


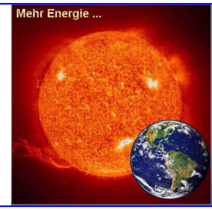
Relaxation behaviour during dwell at notch (or critical area)

Proposed is an approximation by corrected Neuber formula

$$\sigma \cdot \varepsilon^{p} = const.$$

(For p = 1 situation without creep, i.e. pure fatigue)



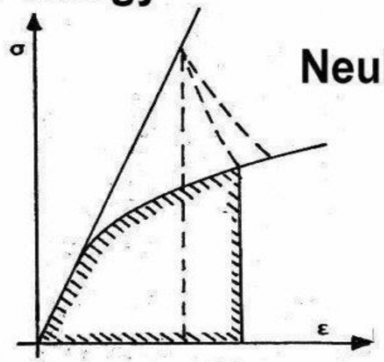


Stress-strain history approximation (approach development)

STRESS-STRAIN HISTORY APPROXIMATION

Equivalent strain energy

$$\frac{1}{2} K_t \sigma_n \varepsilon_n = W_E$$



Neuber's hyperbola

$$K_\sigma K_\varepsilon = K_t$$

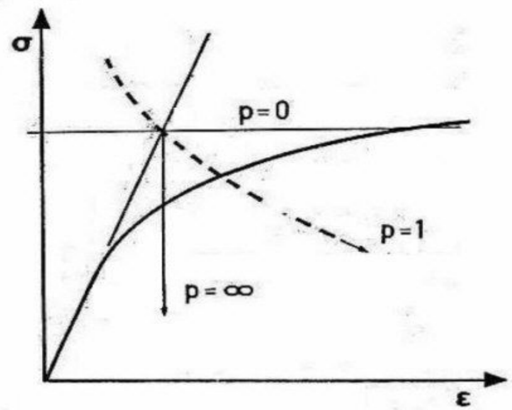
Generalised notch equation

$$K_\sigma . K_\varepsilon \left[\frac{K_\varepsilon}{K_\sigma} \right]^\alpha = K_t^{\ 2}$$

After Substitution $p = \dfrac{1+\alpha}{1-\alpha}$

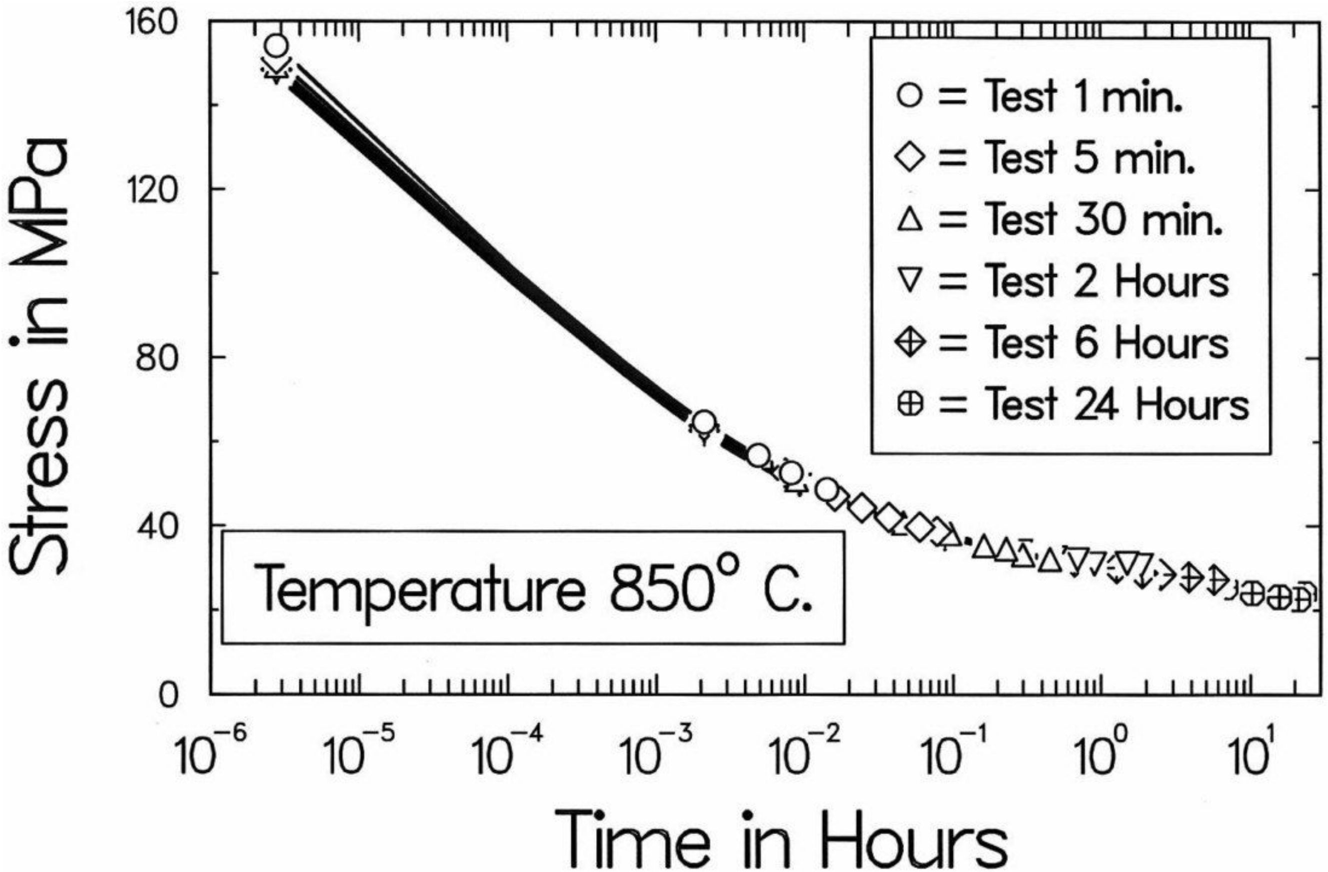
$$K_\sigma K_\varepsilon^{\ p} = K_t^{\ 1+p}$$

or



Material effect

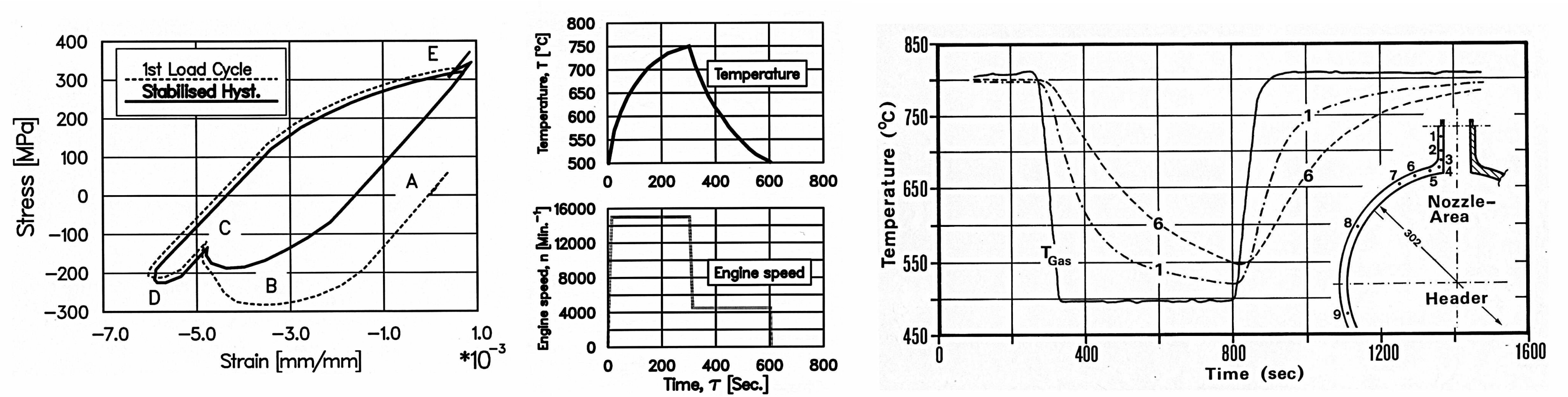
Dwell time effects ⇨ Relaxation behaviour ("incremental relaxation test")



- ➔ The data for different hold times are seen to coincide
- ➔ The relaxation stress tends towards some threshold value.
- ➔ The threshold stress appears to be dwell time dependent.

Thermal transient effects

Start-stop cycle for power equipments: turbine disk (left) or header (right)
⇨ (Examples of non-isotherm working cycles)



For simulation purposes strain rate change could be introduced in the place of a temperature change (test under simple isothermal conditions and in a shorter time), i.e. **slow tension-fast compression** type cycle simulating heating-cooling transient of the original cycle.

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Stress-strain **history approximation**

Crack Initiation or **damage incubation**

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Verification of the method

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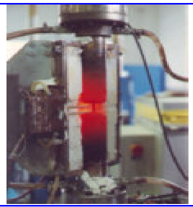
Crack Initiation

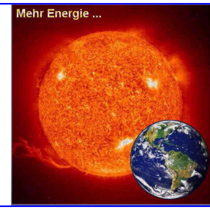
For the safe and economic design of engineering components, it is necessary that the relevant materials can sustain under the imposed service conditions:

(a) without reaching some limiting conditions, or, more usually,
(b) without failure occurring within the planned design lives.

In many applications, the main approach is resting on the so-called **crack initiation**

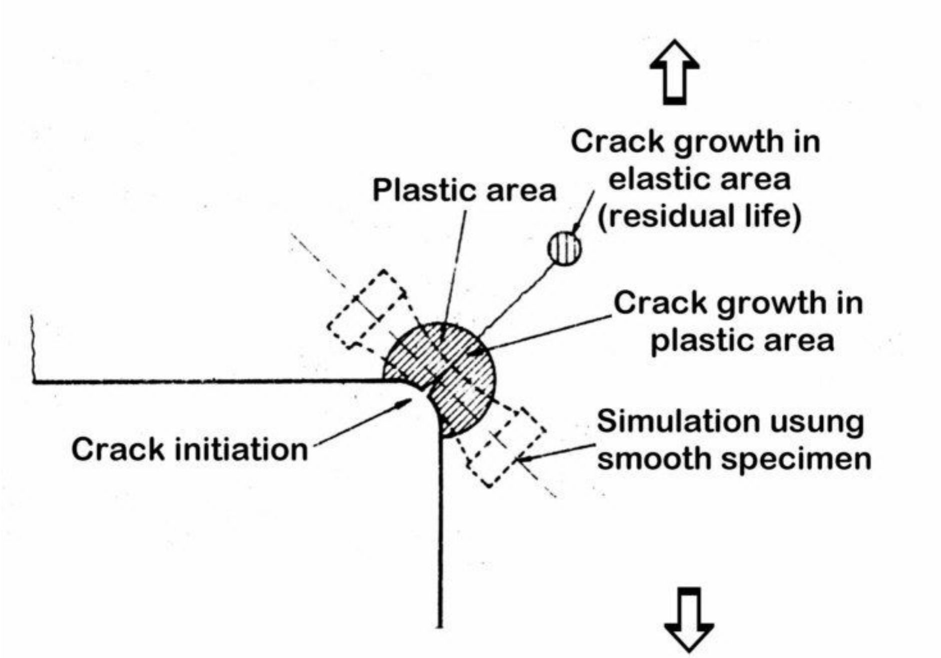
- ➔ This concept is based on a rational simplification of a more complex situation
- ➔ The crack after "initiation" must be geometrically well defined and really predominant (i.e. controllable by fracture mechanics methods)
- ➔ The main advantage is the possibility to incorporate residual life based on crack growth as the safety margin
- ➔ This means, however: short crack behaviour, multiple cracks or cracks in the residual stress field at notches and the likes are ignored.





Notch or critical area simulation (current approach)

Accordingly: Crack initiation life $_{component}$ = Total life $_{smooth\ specimen}$



Smooth specimen (material)

- Plastic load conditions (volume)
- Macro crack growth less than 5 % of total life (less important)

Component

- Stress gradients
- $N_t = N_i + N_{mcg}$
- N_{mcg} (in elastic material) could be calculated using LEFM

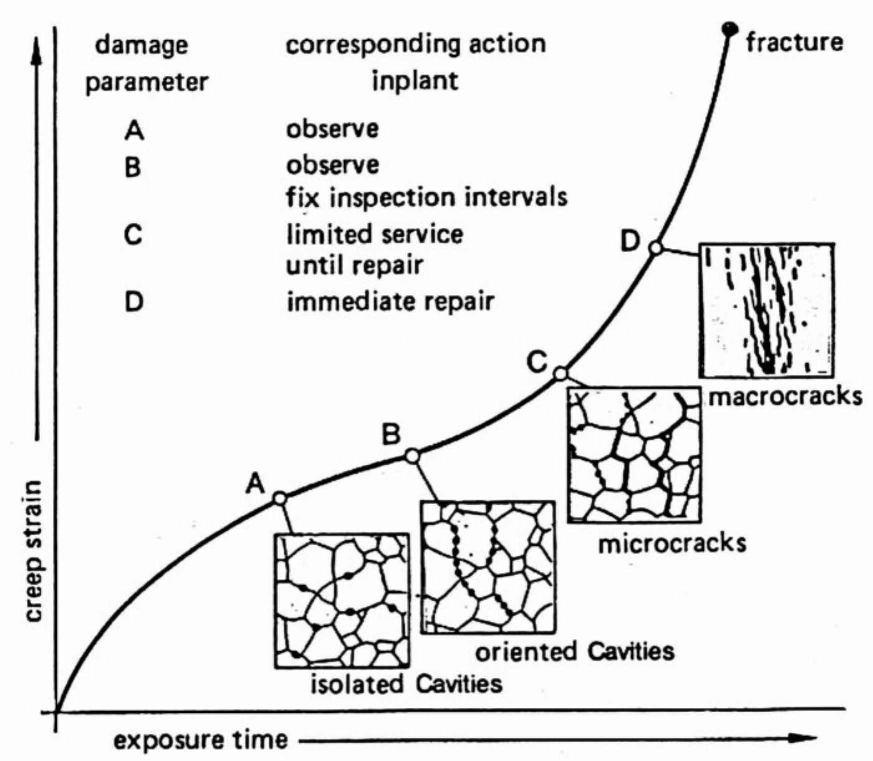
Problem ⇨Initial or welding defects, poor geometry (N_i ~ 0), mean stress

Although much work continues to model the nucleation and growth of the cracks, there are uncertainties in their mechanism and the identification of a failure criterion

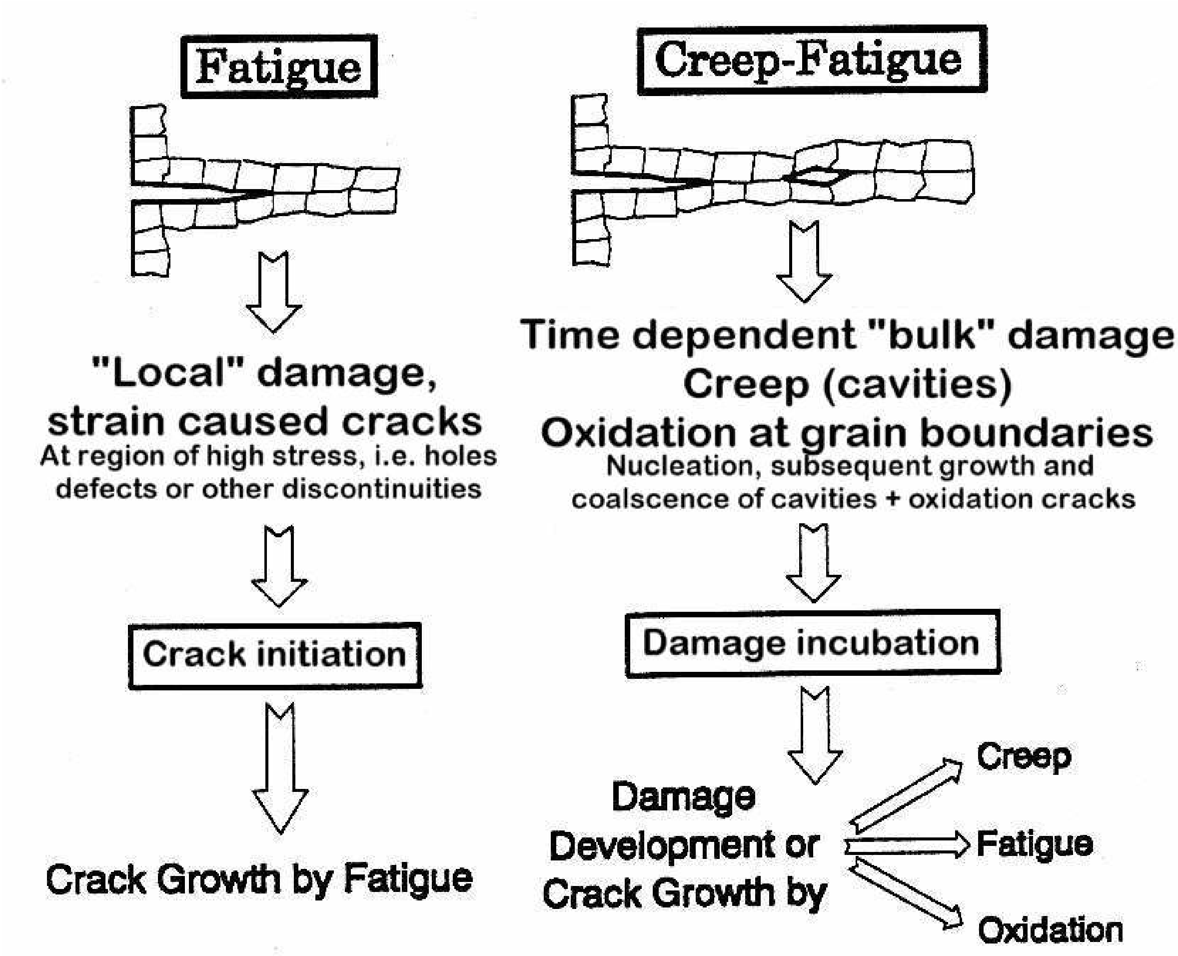
Crack Initiation or damage incubation

Why is the crack initiation in case of high temperatures (creep) problematic?

1. Creep failure is governed by its own mechanism different from fatigue. Creep involves grain boundary sliding with void nucleation and growth in the **bulk of the material**. This provides an indication of damage length **before crack appears.**
2. The combination of **local** crack initiation and growth and creep damage throughout the **material volume** (by void nucleation and growth) makes the separation and corresponding treatment of crack initiation and crack growth for the creep-fatigue life assessment extremely difficult.



3. After "initiation" crack growth is accelerated by **creep** and **environmentally** induced damage ahead of a crack tip. (creep-fatigue interaction)

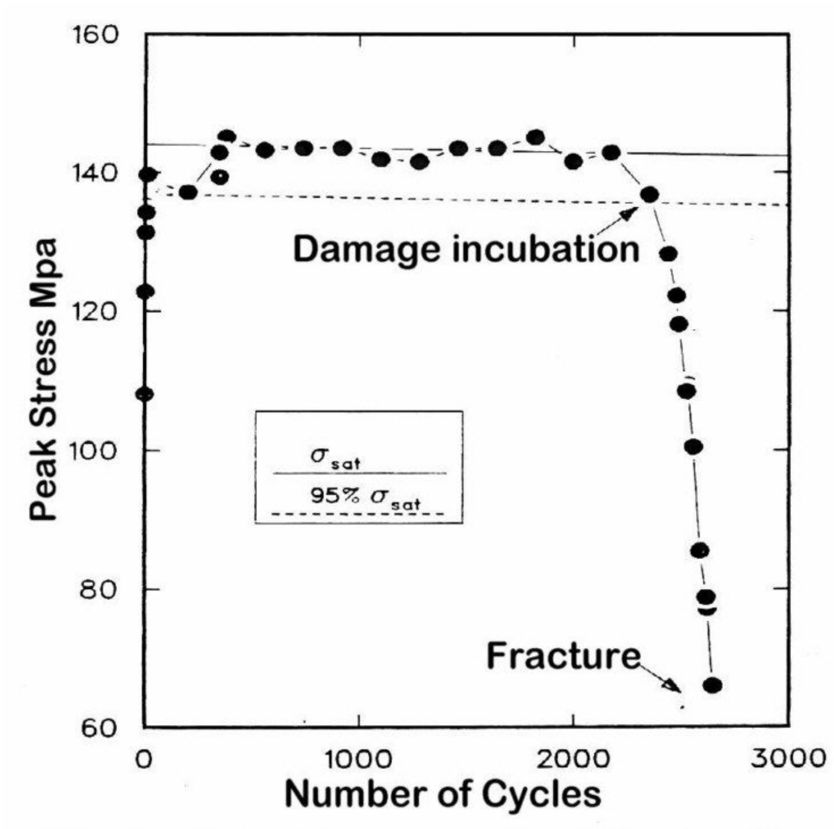


Because of this, at the place of “crack initiation” the conventional "local event" approach has been generalised by considering both interacting processes of a local surface crack development and bulk damage, which is called

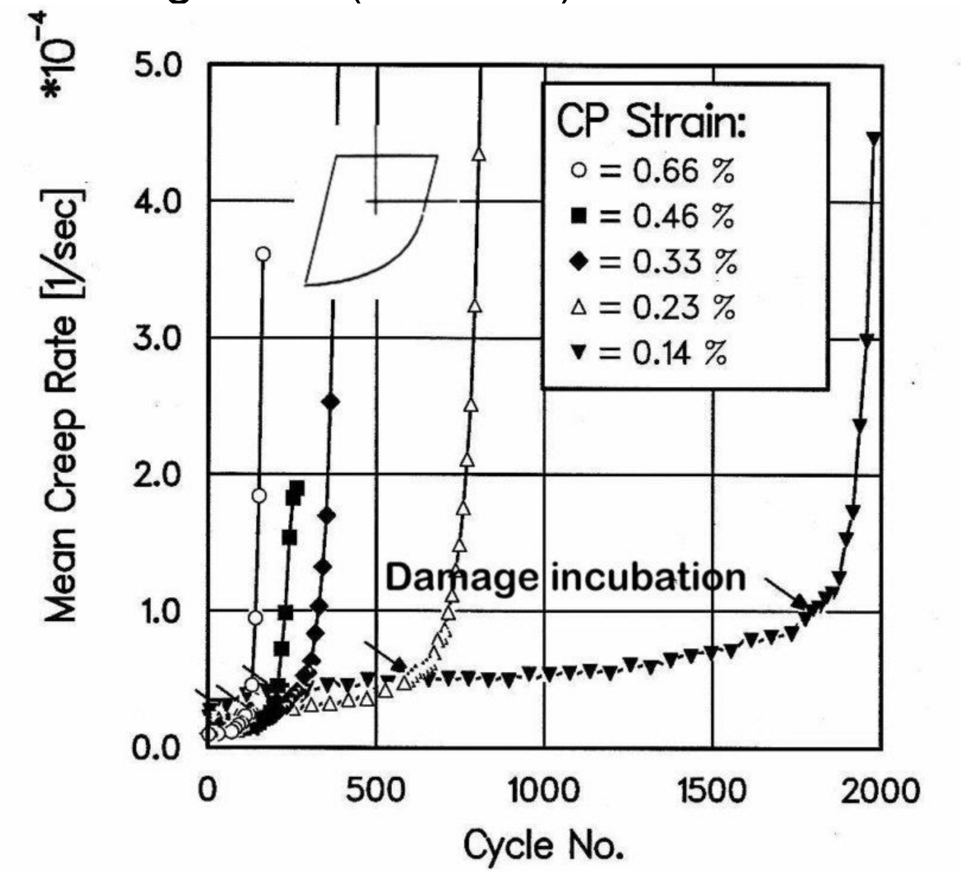
Damage incubation.

Practical Damage incubation criteria (Creep rate instead of peak stress):

Fatigue: Peak cyclic stress reduction 5% ➔ Crack initiation



Cyclic creep: Increase in mean creep rate during dwell (CP-Test) ➔ incubation



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Damage incubation criteria (continued):

It can be shown that the above approach could be related to the creep cavitation **A-parameter.**

Based on typical steady state creep rate relationship

$$\dot{\varepsilon} = b\sigma^n \exp\left\{\frac{-Q}{RT}\right\}$$

one can characterise cavitation through the A-parameter determined as the number fraction of cavitated grain boundaries traversed by a scan parallel to the stress axis of a creep test specimen, which can be considered to have been completely damaged and incapable of supporting load (A as the damage parameter).

The creep rate therefore becomes

$$\dot{\varepsilon} = \frac{b \cdot \sigma^n}{(1-A)^n}$$

Creep-fatigue crack growth

After an initial period of damage incubation we may consider the possibility of the creep-fatigue crack growth, if the corresponding extension of the usable life may be characterised as sufficiently reliable (for example: leak before break).

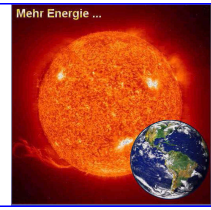
In the simplest case, assuming the availability of the main crack, the total crack growth per cycle can be assessed based on the superposition of the both effects:

$$\frac{da}{dN} = (1.....3) \cdot \left(\frac{da}{dN}\right)_{fatigue} + \frac{1}{f} \cdot \left(\frac{da}{dt}\right)_{creep}$$

Another possible approximation is

$$\frac{da}{dN} = \left(\frac{da}{dN}\right)_{fatigue} + \left(\frac{da}{dN}\right) oxidation$$, (where $(da/dN)_{oxidation} = f(N, t)$)

The application could be dependent on material.



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Time - Temperature Substitution

Results obtained in tests:

- Small material or component, i.e. laboratory specimens
- Test of relatively short duration

Large (and complex) real structure

- Design lives can be up to 250,000 hours (over 30 years),
- Heat-to-heat, load conditions and other variabilities.

Over the years, a tremendous amount of effort has gone into optimising methods of data extrapolation.

Current empirical methods (stress rupture data) limit extrapolation to three times the longest test figures ⇨ expensive test programs required to obtain long-term data.

Reliable procedures

- to provide long-term property estimates, and
- appropriate for the setting of design stresses

⇨ require reliable **methods of extrapolation**.

Time - Temperature Substitution

A methodology has been developed, using generalised time-temperature parameters based on the ways in which creep data can be presented, that are now in the case of static loads in widespread use.

The approach may be applied to achieve the following major design objectives:

- Representation of creep rupture (or creep) data in a compact form
- allowing interpolation of results that are not experimentally determined.
- Provides a simple basis for comparison and ranking of different alloys
- Extrapolation to the time ranges beyond those normally reached.

Theoretical Basis of the Time-Temperature Substitution Approach

Creep strain rate, typically determined by the power law, can be modified to enable the temperature dependence using well known Monkman-Crant relationship

$$\frac{1}{t_r} \propto \varepsilon_S = B' \sigma^n \exp\left(\frac{-Q_C}{RT}\right) \qquad (1)$$

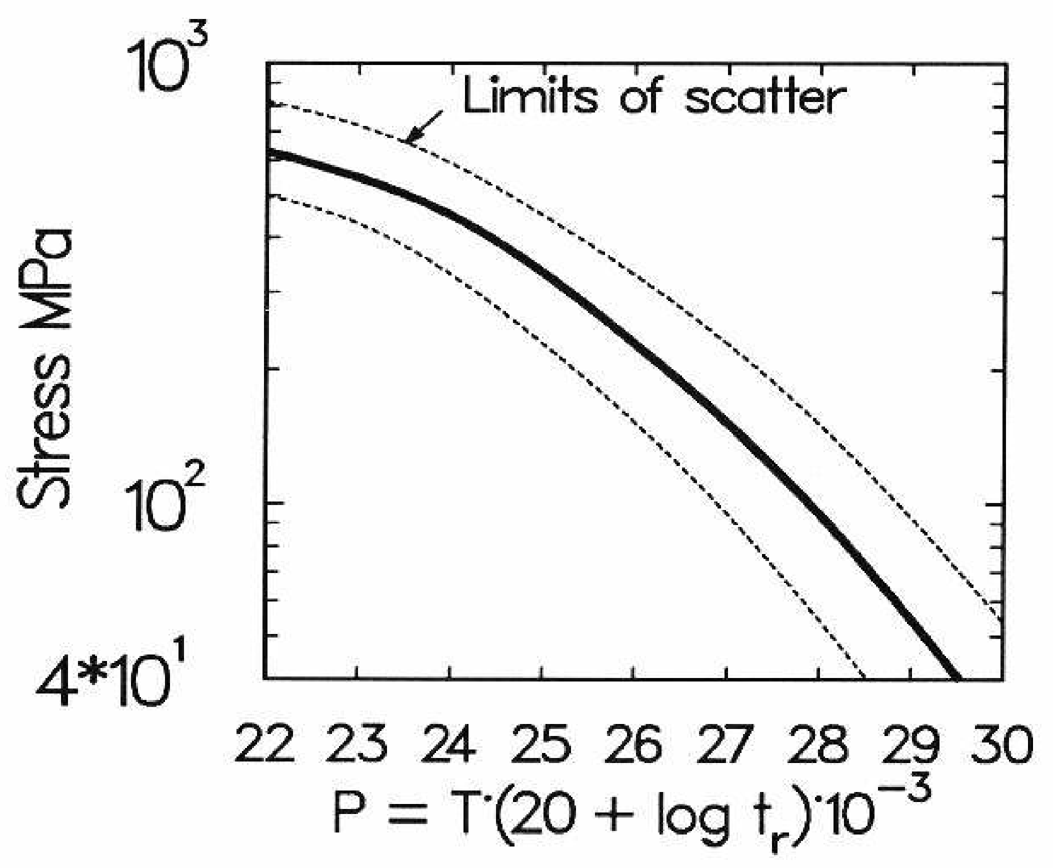
This shows that the basis of the creep process is the thermal activation energy, Q_C describing the temperature influence

The logarithm of the above equation for given σ leads after transformations to the Larson-Miller parameter (LMP) dependence

$$T \cdot (C + \ln t_r) = \frac{Q_C}{R} = F(\sigma)$$

Equation allows adequate representation of the creep response as a single two-dimensional F(σ) "master curve" function on Time-Temperature parameter.

Creep "master curve"



- Data for different temperatures give a unique curve so long as there are no changes in creep mechanism. Useful information can be provided using the so-called deformation-fracture-mechanisms maps.
- The short-time high-temperature data can be used to estimate the long-time behaviour at lower temperature.
- The approach is limited to the creep condition. The solutions for the case of the creep-fatigue-environment interaction are still missing.

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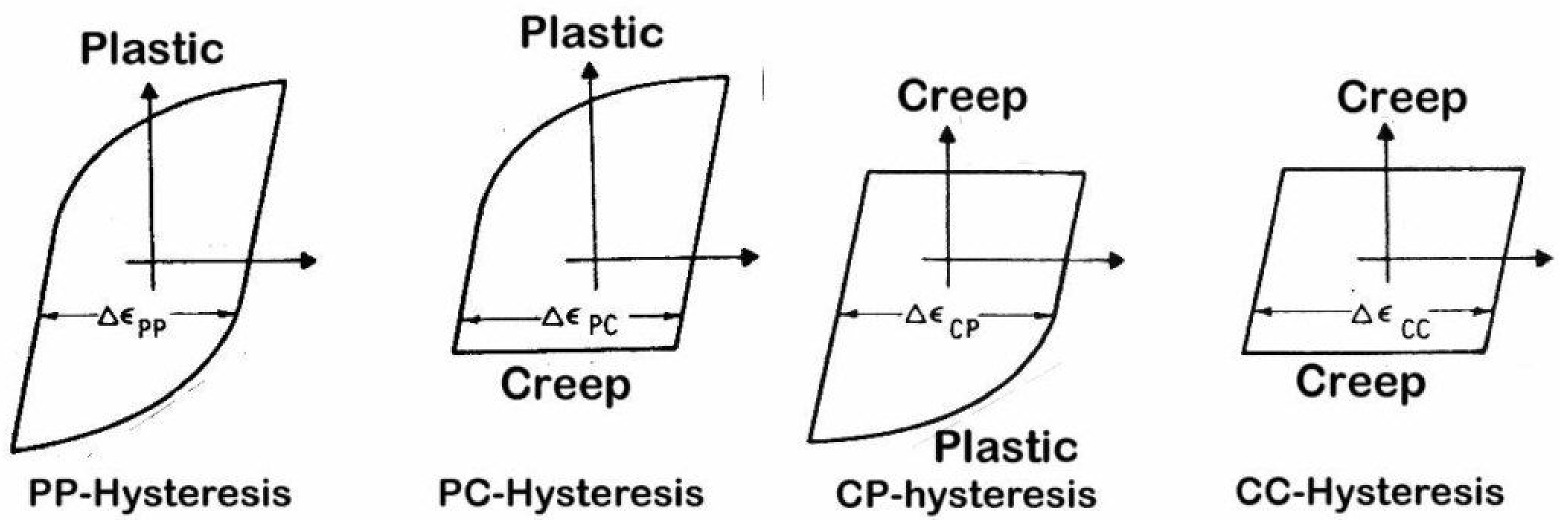
Creep-Fatigue

The life prediction models are

- Purely phenomenological or physically based
- Coffin-Manson law, Strain range Partitioning, Hysteresis Energy and many other

Strain Range Partitioning (SRP):



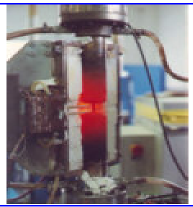
- Most directly relevant to fatigue-with-dwell situations.
- The insensitivity of the material-related constants to temperature changes (application to non-isothermal loading conditions).

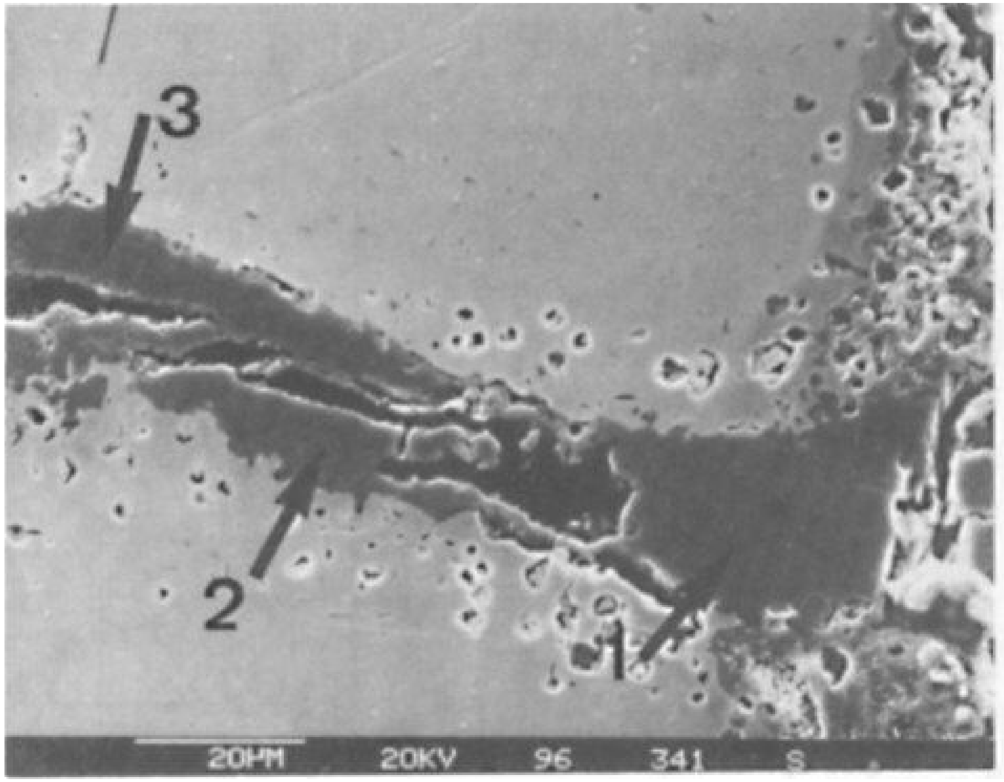
Experience with the application of the classical Strain Range Partitioning Method

Applicable over a large temperature range using the same material input data.

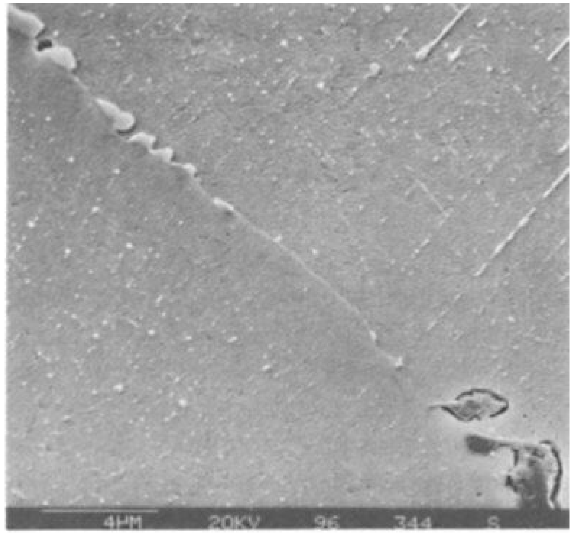
Investigations for creep-fatigue loading conditions at high temperature (850 °C) with the Alloy 800 H within the **BRITE project** shows:

- In contrast to excellent bulk oxidation resistance of the alloy used (800 H) grain boundary carbide precipitation is particularly sensitive to environmental degradation.
- The oxidation due to grain boundary sensitisation by second phase development penetrates deeper than surface oxidation and leads to profound enbrittlement
- Accelerates fatigue crack nucleation (or "damage incubation") significantly shortens the lifetime and it is not considered by classical SRP-Method.

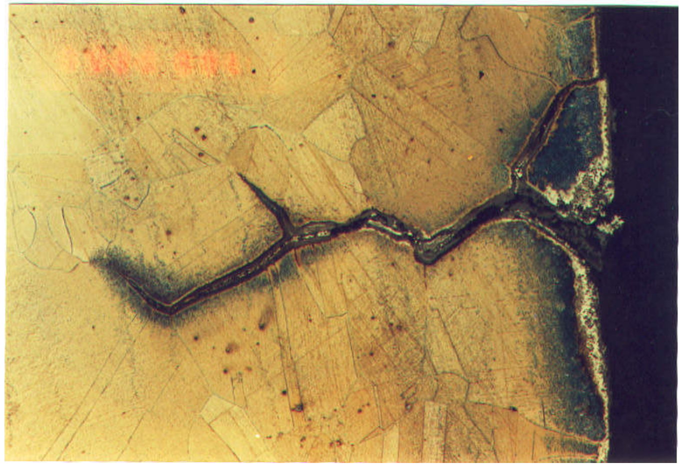




Grain boundary carbide surrounded by an oxidised layer, confirming the sensitising effect of grain boundary carbide formation and sub-surface oxidation damage. ⇨



Far from crack tip: nonoxydised carbides, as is normal for this alloy



Environmental correction of the Strain Range Partitioning method

To consider the effect of the embrittled surface region through the oxidation penetrating along grain boundaries to the fatigue crack initiation we introduce **correction to the Strain Range Partitioning** method, which in the simplest case of tension relaxation dwell gives:

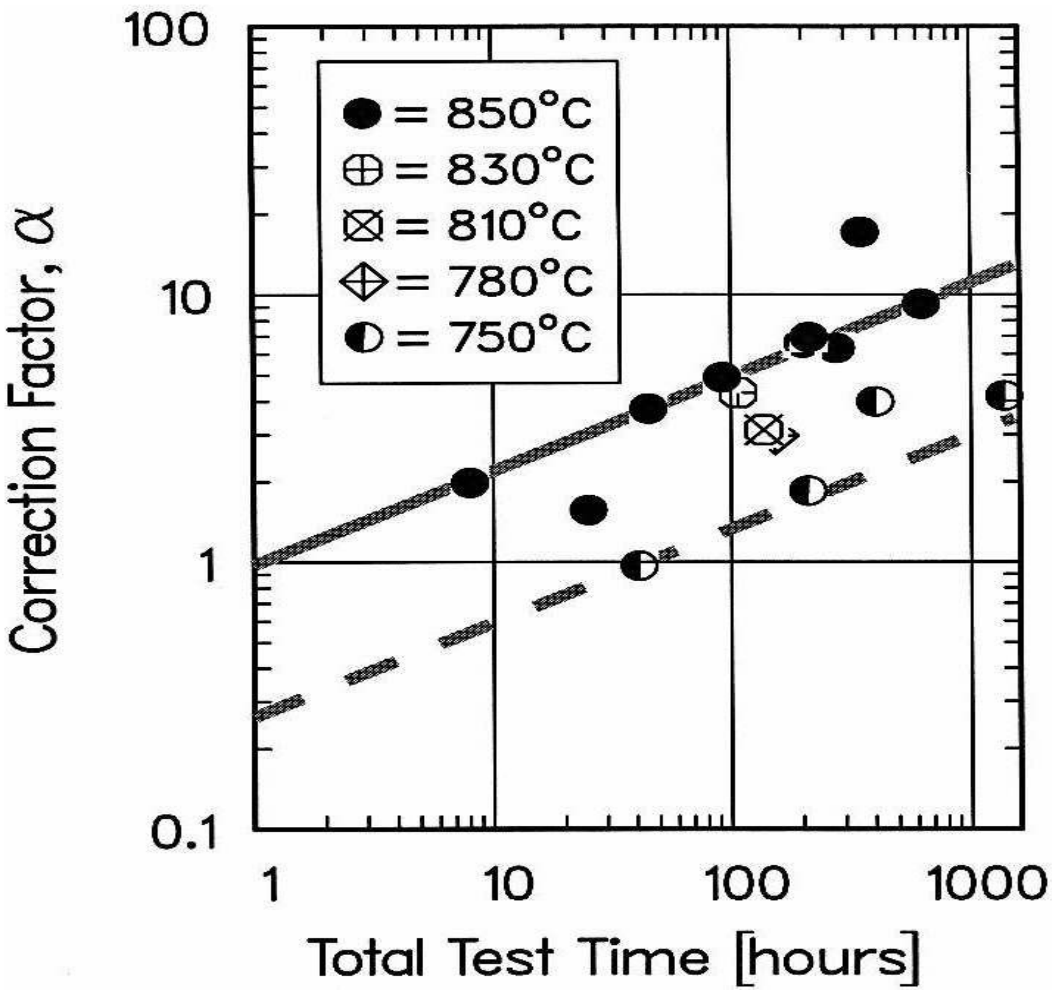
$$\frac{1}{N_i} = \left(\frac{f_{pp}}{N_{pp}}\right) \cdot \alpha + \frac{f_{cp}}{N_{cp}}$$

Here the correction can be represented by the Arrhenius type relationship including time and temperature dependence:

$$\alpha = A \cdot t^n . \exp\left(\frac{-Q}{RT}\right)$$

According to this, for given inelastic strain amplitude the Time-Temperature parametric dependence can be established based on environmental correction α.

Evaluation of the correction factor, α



A series of test (16 specimens) at a temperature in the range 750 to 850 °C with the dwell time up to 2 hours were performed for characterisation.

A. **Test time dependence:**

Based on 850 °C results regression analysis gives:

$$\alpha = a.\tau^{n}$$

where

a = 0.9751 and

n = 0.35213

(with R^2 = 0.99283)

Evaluation of the correction factor, α

B. **Temperature dependence**

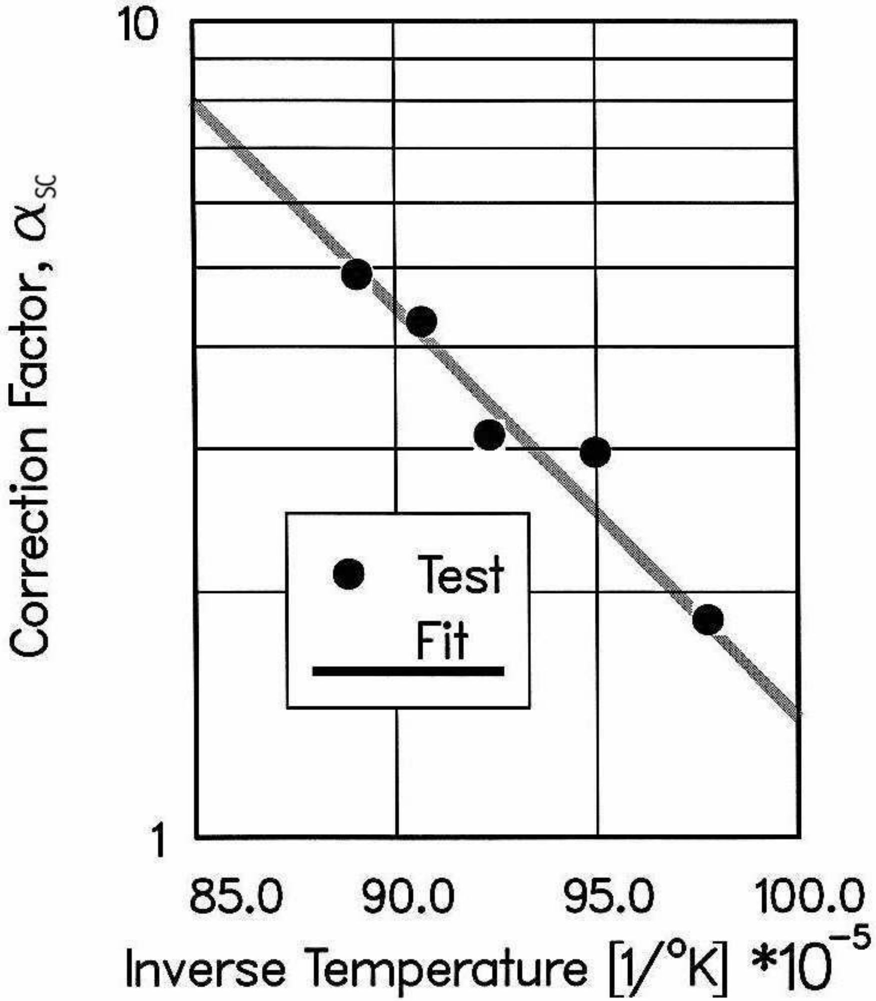
Assuming exponent **n** found is valid for all temperatures and scaling the values for different temperatures

$$\alpha_{sc} = \alpha_T \left(\frac{\tau_{850}}{\tau_T} \right)^n$$

using data for Δε = const. (figure on the right) regression analysis could be performed

$$\alpha = 6{,}515 \cdot 10^5 \cdot \tau^n \exp\left(\frac{-Q}{R \cdot T} \right)$$

where Q = 125,23 kJ/gr, and
R = 8,314 J/gr



Results of examination

Stress-strain behaviour modelling and simulation

Stress-strain **history approximation**

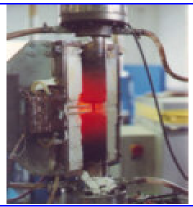
Crack Initiation or **damage incubation**

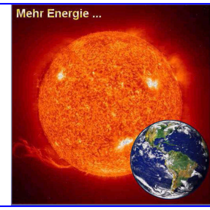
Time - Temperature Substitution approach

Extension of the strain range partitioning method

Verification of the method

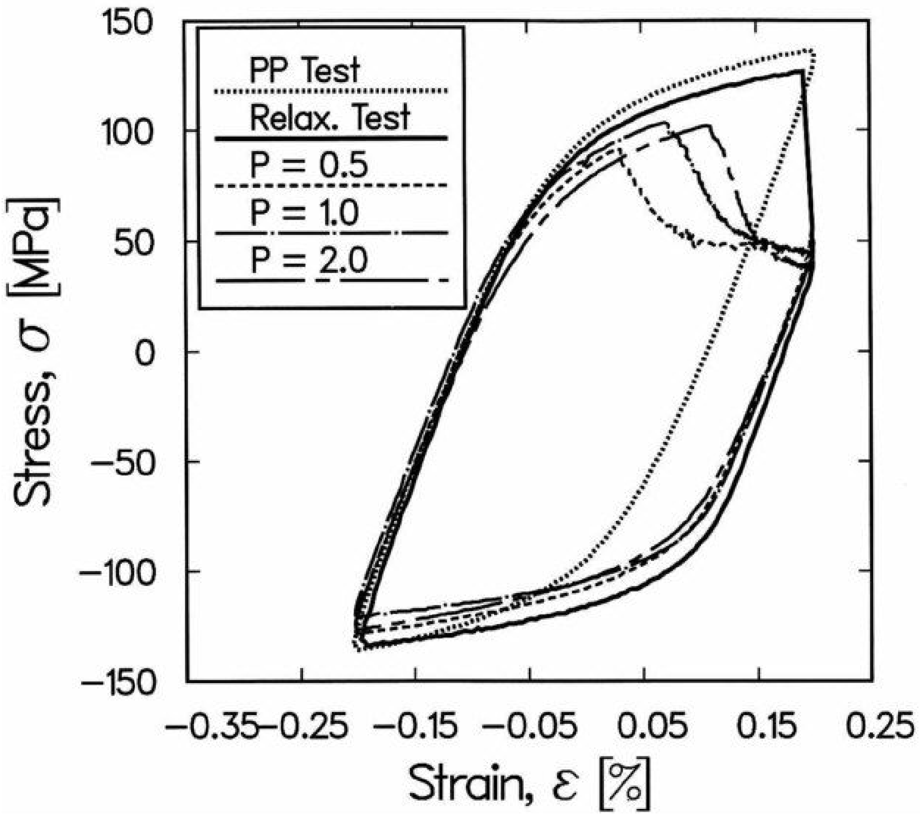
Application to test acceleration



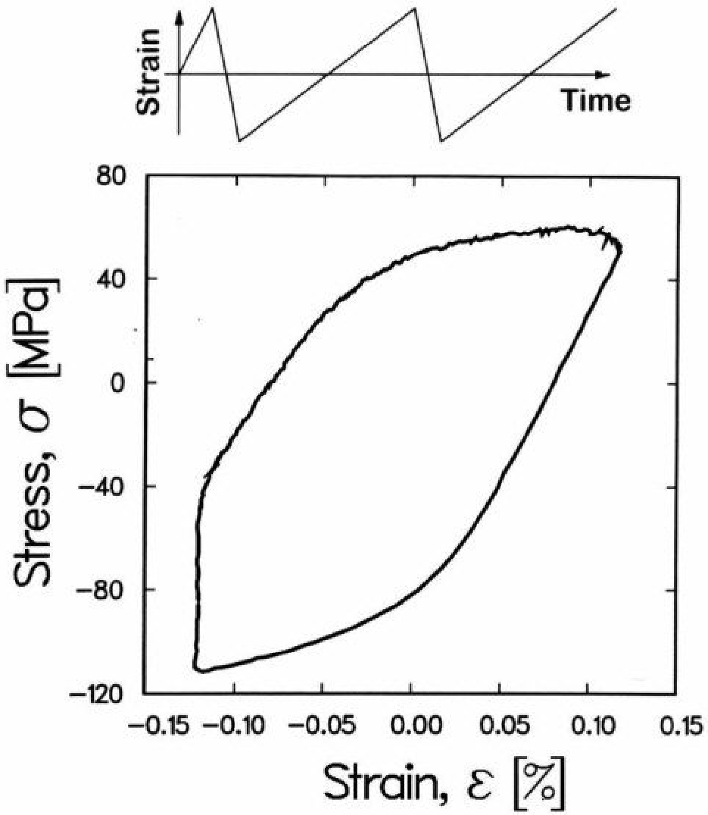


Tests procedures for the verification of the method

"Notch" test

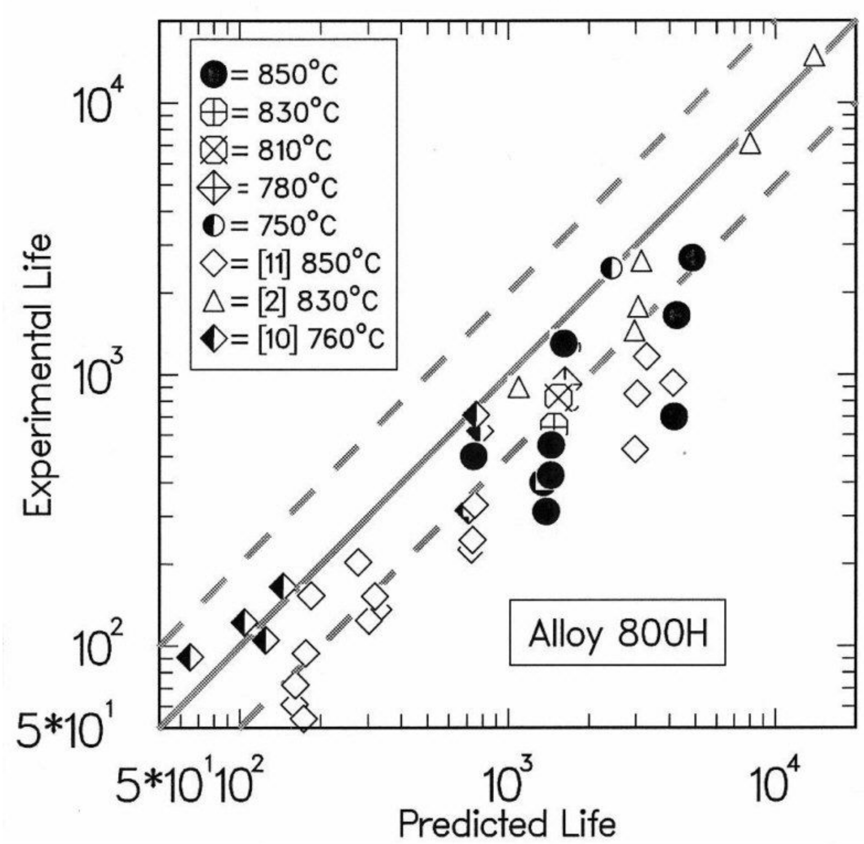


"Slow-Fast" Test

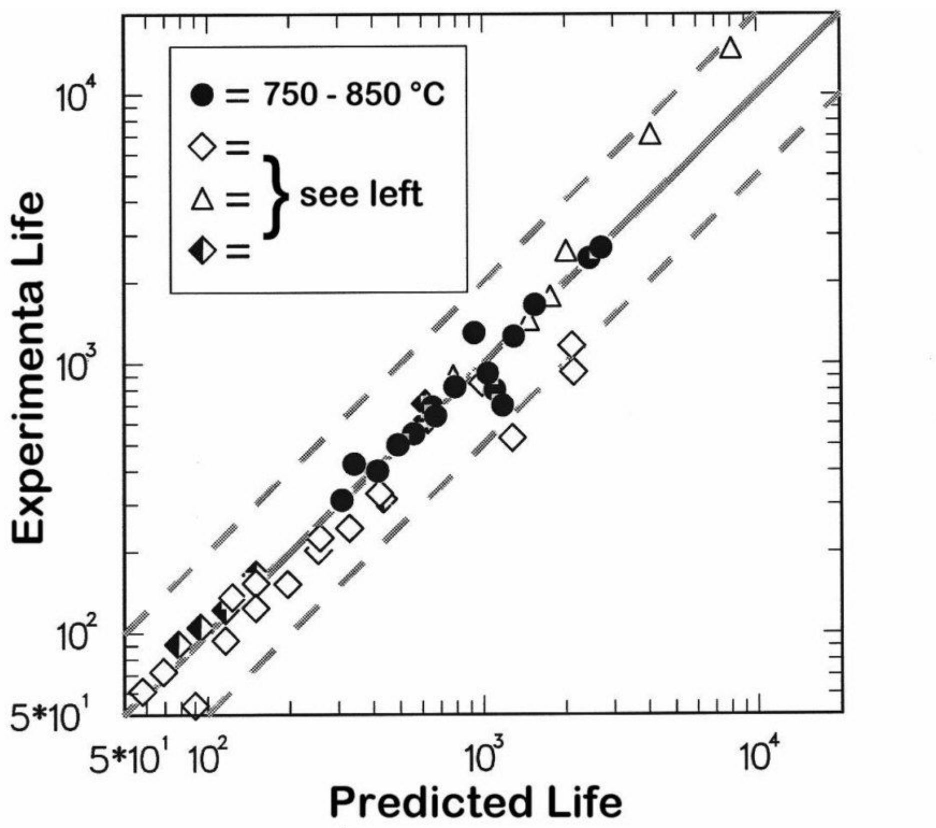


Results of the verification

Excellent results have been achieved using also available literature tensile dwell data, covering a number of different material lots, treatment and testing conditions



Left = conventional SRP



Right = with the correction

Results of examination

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Service testing

If we wish to simulate service complexity in our material testing, there is in fact a hierarchy of increasing complexity and expense.

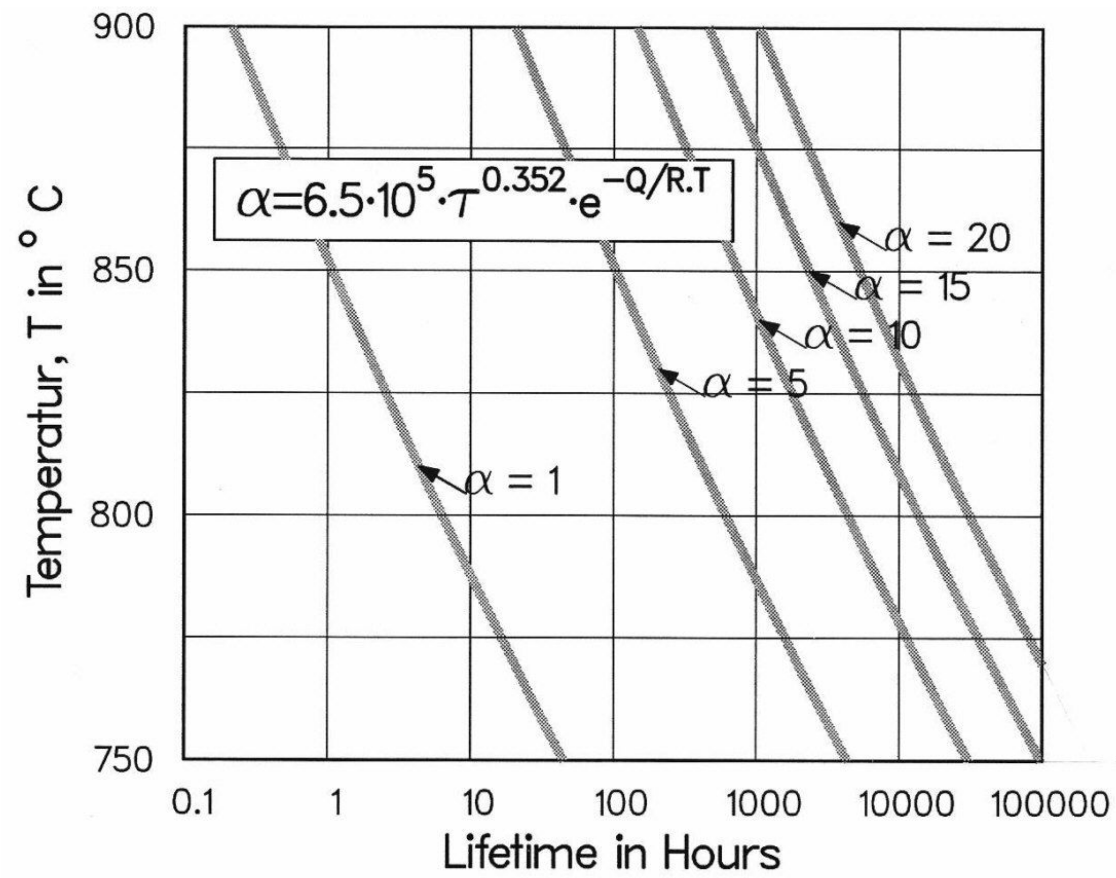
Long term fatigue or creep tests are clearly insufficient ⇨ Additionally account for non-steady test conditions, complex stresses, cyclic stresses, environmental effects, and synergism among them is necessary.

- On the other hand, achievement of the health of the structures is crucial to maintain operational availability and productivity, reduce maintenance cost, and prevent catastrophes
- I.e. structures such as transportation systems and vehicles (spacecraft, aircraft, helicopters, ground vehicles, etc.), civil structures (bridges, highways, power plants, tunnels, etc.), and high-valued manufactured products (satellites, launch systems, semiconductor equipment, etc.), require high reliability.
- Thus, major concerns in the operation of in-service structures are the reliability of the structures and the cost associated with maintaining reliability.

Why accelerated testing ?

- Traditional life analysis involves analysing times-to-failure data obtained under normal operating conditions to quantify the life characteristics of the product, system or component.
- In many situations, and for many reasons, such life data (or times to-failure data) is very difficult, if not impossible, to obtain.
- Therefore, to meet increasing competition, get products to market in the shortest possible time, and satisfy customer expectations, traditional test methods are no longer sufficient
- Given this difficulty, and the need to observe failures of products to better understand their failure modes and their life characteristics, design practitioners have attempted to devise methods to force these products to fail more quickly than they would under normal use conditions. In other words, they have attempted to accelerate their failures. Over the years, the term accelerated life testing has been used to describe all such practices.

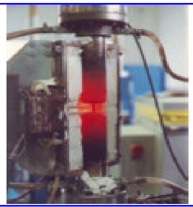
Application of correction factor α to test acceleration

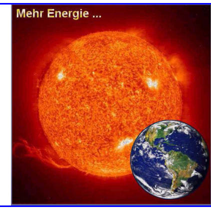


For equal inelastic strain range, the increase in temperature for 60 ℃ allows the reduction of the test duration, from 10000 to 1000 hours.

If the number of cycles has to be unchanged, the dwell time should be reduced according to the time reduction factor.

Thus, the method can help to reduce the amount of experimental effort in the design of components for operation under creep-fatigue conditions and their optimisation and efficient re-design.





CONCLUSIONS

The results reported here have focused on practical aspects of applying an integrated approach to high temperature component life prediction. In particular, different parameter influencing a reliable life prediction method at high temperatures have been examined.

Several significant advances have been made applicable to the better understanding of the behaviour and to a more efficient high temperature component design:

- ➔ Life prediction method considering creep-fatigue-environment damage.
- ➔ Modelling of material deformation behaviour using a "unified" viscoplastic theory and its application to the numerical analysis.
- ➔ Component life simulation by creation and use of the efficient methods for accelerated simulation of actual component stress-strain histories.

In using the proposed method, even with the consideration of environmental attack, there is no longer a need to run fatigue test with long time dwell and the design approach becomes faster, cheaper, and more accurate.