Basic Aspects of High Temperature Strength: Creep Fundamentals

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Fundamental Aspects of Materials Science and Engineering (FAMSE)

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materials science and engineering

Objective of this lecture:

We want to understand the importance of deformation at high temperature through creep. We focus on the concept of steady state creep which is the most important in high temperature applications.

(1) Deformation mechanisms at high temperature

(2) Steady state creep

(3) Sherby-Dorn equation

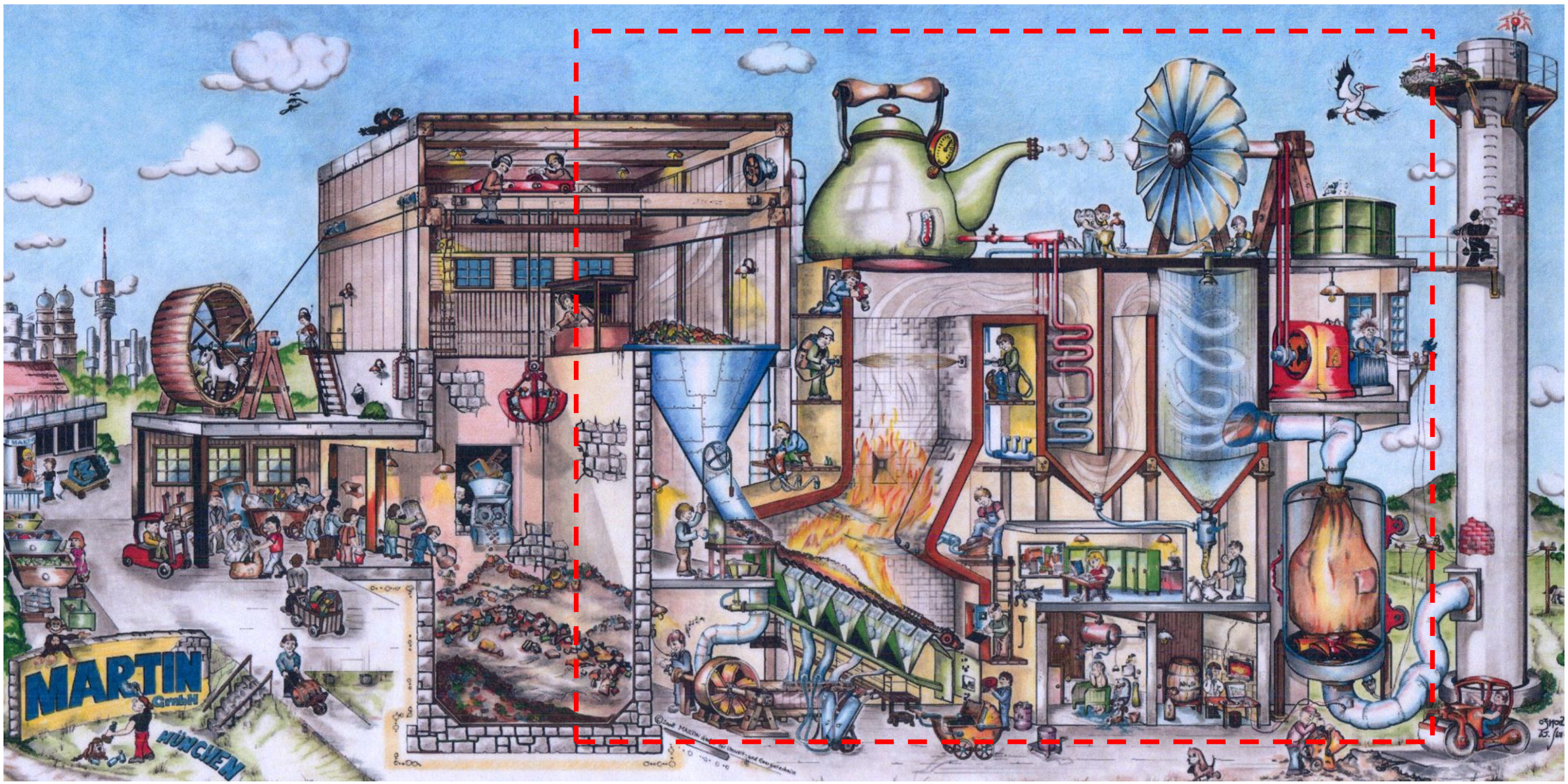
(4) Creep concepts

Text books/recommended reading

- Frank Garofalo, Fundamentals of Creep and Creep Rupture, Macmillan, New York 1965
- Bernhard Ilschner, Hochtemperaturplastizität, Springer-Verlag, Berlin 1973
- Jean-Paul Poirier, Plasticité a haute température des solides cristallins, Editions Eyrolles, Paris 1976
- Jean-Paul Poirier, Creep of crystals – High-temperature deformation processes in metals, ceramics and minerals, Cambridge University Press, 1985
- Russel W.Evans, Brian Wilshire, Creep of Metals and Alloys, Institute of Metals, London 1995
- F.R.N.Nabarro, H.L. de Villiers, The Physiscs of Creep, Creep and Creep Resistant Alloys, Taylor and Francis, UK, 1995
- Josef Ćadek, Creep of Metallic Materials, Elsevier, Amsterdam 1988
- Michael E. Kassner, Maria-Teresa Perez-Prado, Fundamentals of Creep in Metals and Alloys, Elsevier, Amsterdam, 2004
- R. Viswanathan, F. Abe, T.U. Kern, Creep-resistant steels, CRC Press, Boca Raton, USA, 2008
- many others

Service life of components which operate in the creep range – creep rupture plots

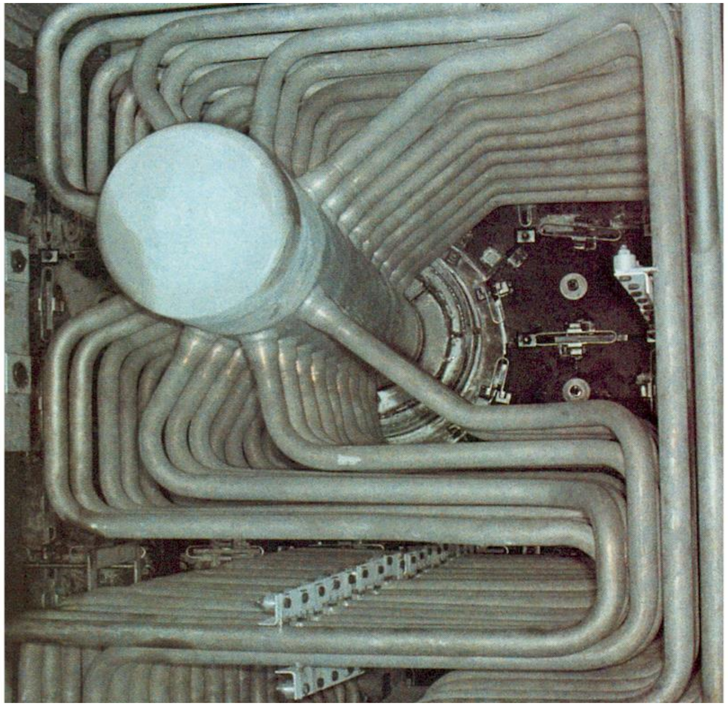
Example: Coal fired power plant



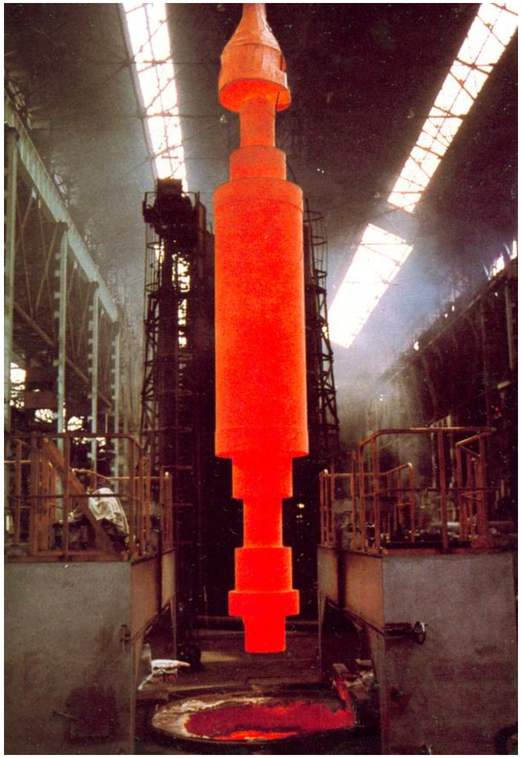
Source: Martin GmbH München, vom Internet

Critical components in coal fired power plant

Temperature range:
600°C



Boiler plant/Dampferzeuger:
Steam header, Sammlerrohr
Source: CEGB, UK

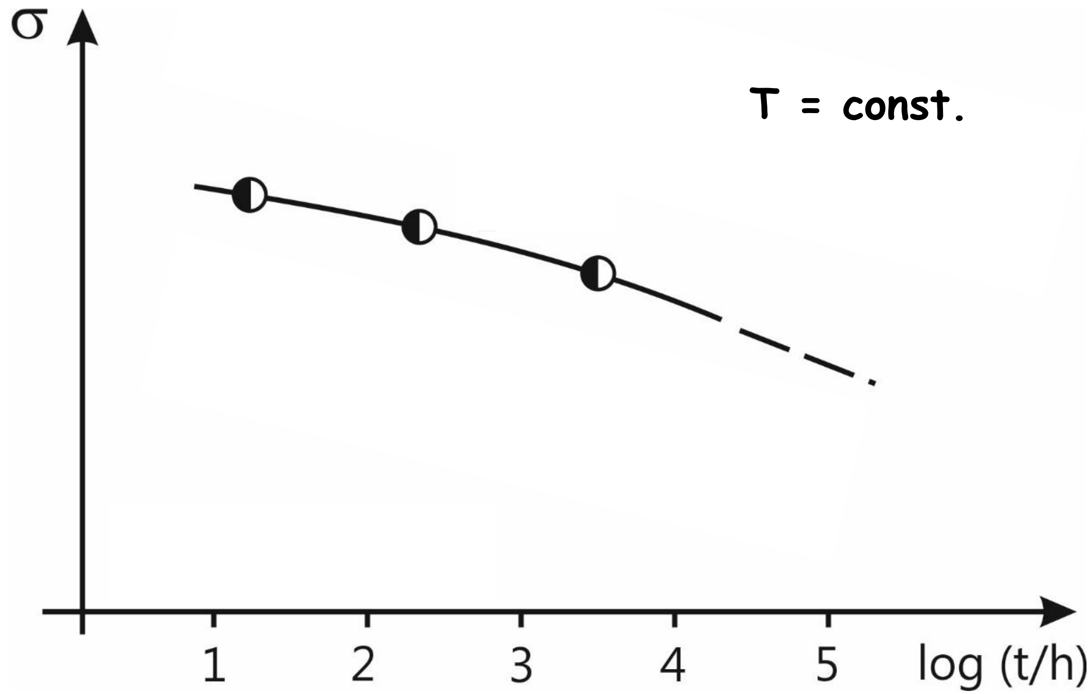


Turbine
Rotor
Source: Prof. Fujita, JP

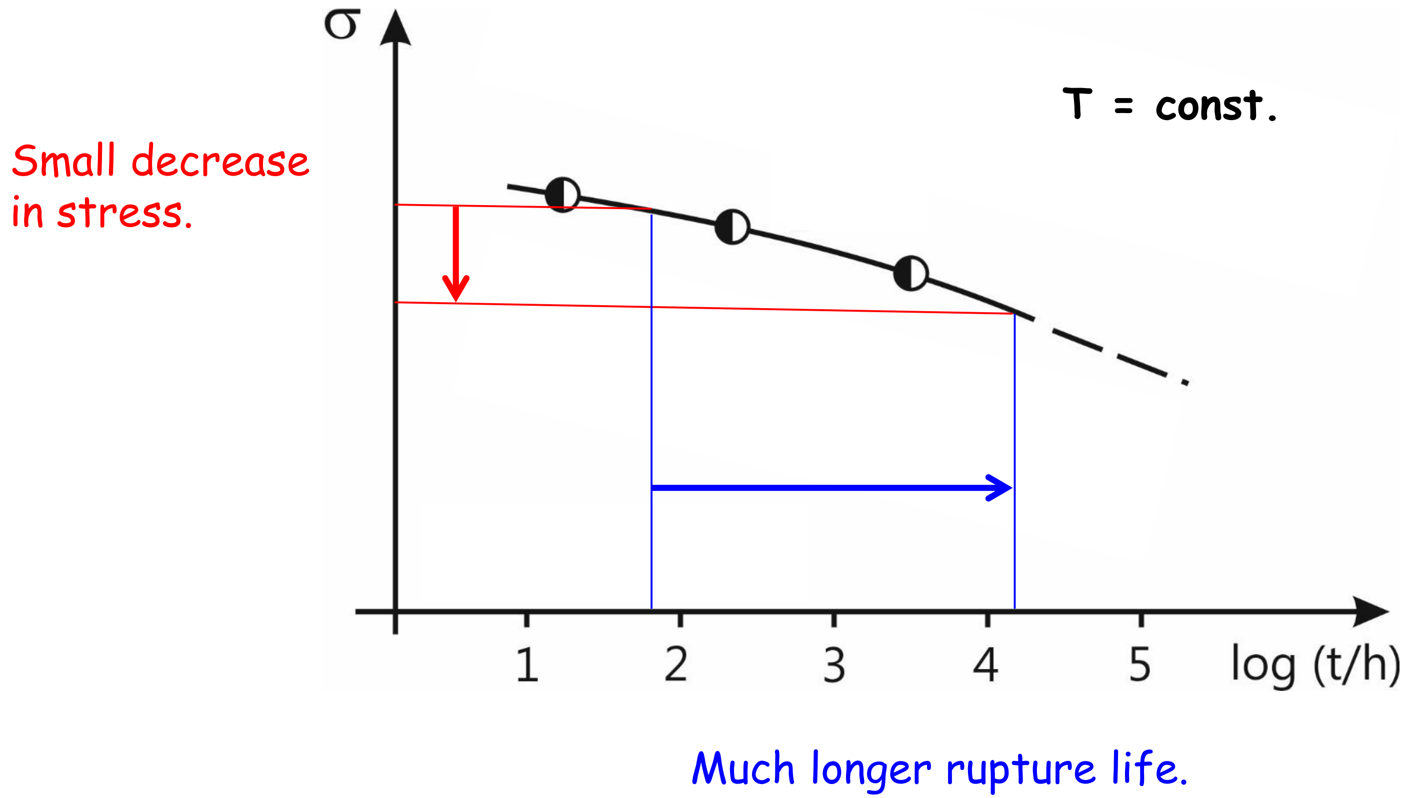
Creep is the time dependent plastic deformation of metals and alloys which can lead to rupture.

No longer: Below a critical stress (yield stress) nothing happens.

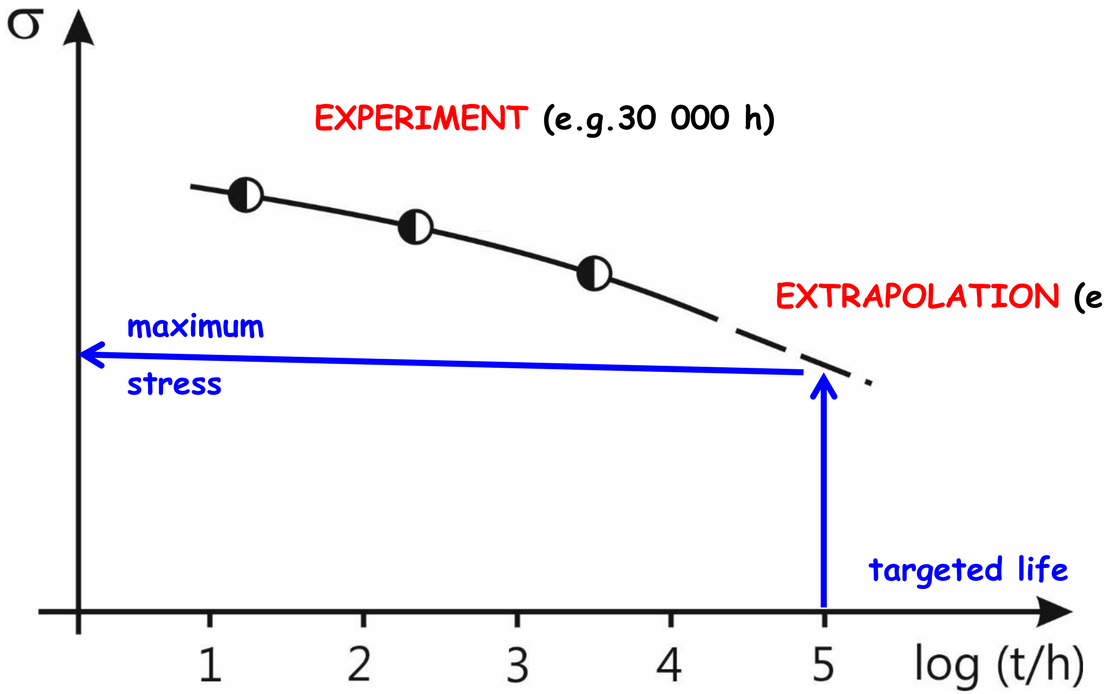
Instead: For a given combination of stress and temperature a component which operates in the creep range has a limited service life. First look at materials behaviour: Stress-rupture plot.



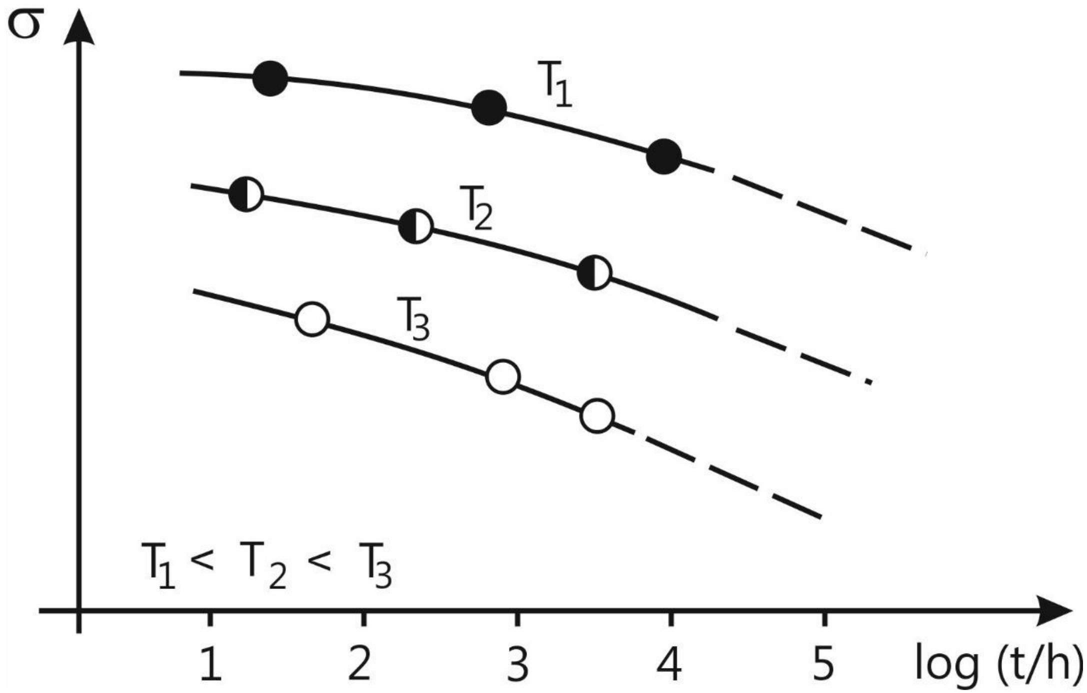
Stress-rupture plot


σ
T = const.
Small decrease
in stress.
1
2
3
4
5
log (t/h)
Much longer rupture life.

T = const.


σ
EXPERIMENT (e.g.30 000 h)
EXTRAPOLATION (e.g. 100 000 h)
maximum
stress
targeted life
1
2
3
4
5
log (t/h)

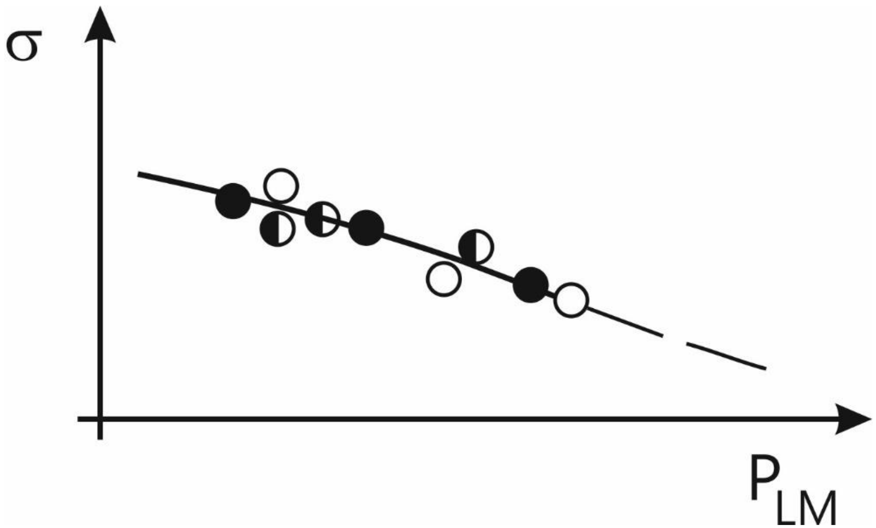
Higher temperatures yield shorter rupture times.



Creep rupture diagram

There are phenomenological parameters like the Larson Miller parameter, which allow to plot experimental results from different temperatures onto one master curve.

Larson-Miller plot



$$P_{LM} = T \cdot (C + \log t)$$

LARSON MILLER PARAMETER:

T = temperature

C = constant (often: 20)

t = time

Companies/institutes where creep is important:

- Aero space companies
- Energy plant manufacturers
- Energy suppliers / utilities
- Control organizations, monitoring agencies, specialists for component life assessment
- Companies building motors, furnaces, plant accessories, systems for waste combustion
- Companies running hight temperature plant (Metallurgy, chemical industry, …)
- Research institutes

Creep curves and creep rates

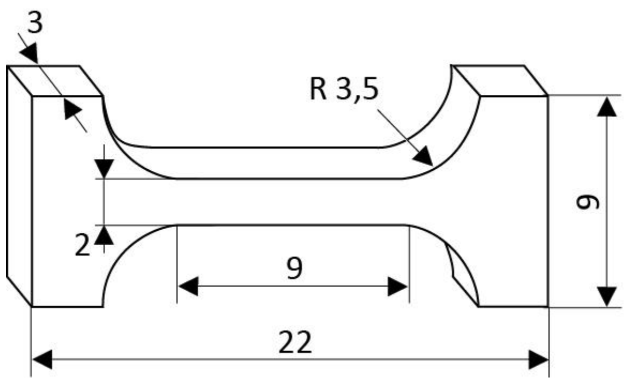
Rupture is important.

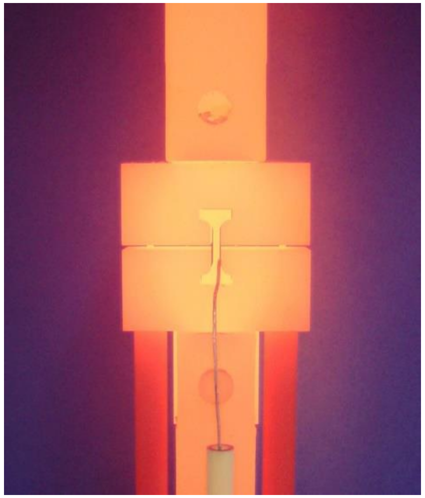
But we also want to know, how much creep strain has accumulated after a given time.

There are cases, where a maximum allowable strain limits the service life of components.

—> Creep curve.

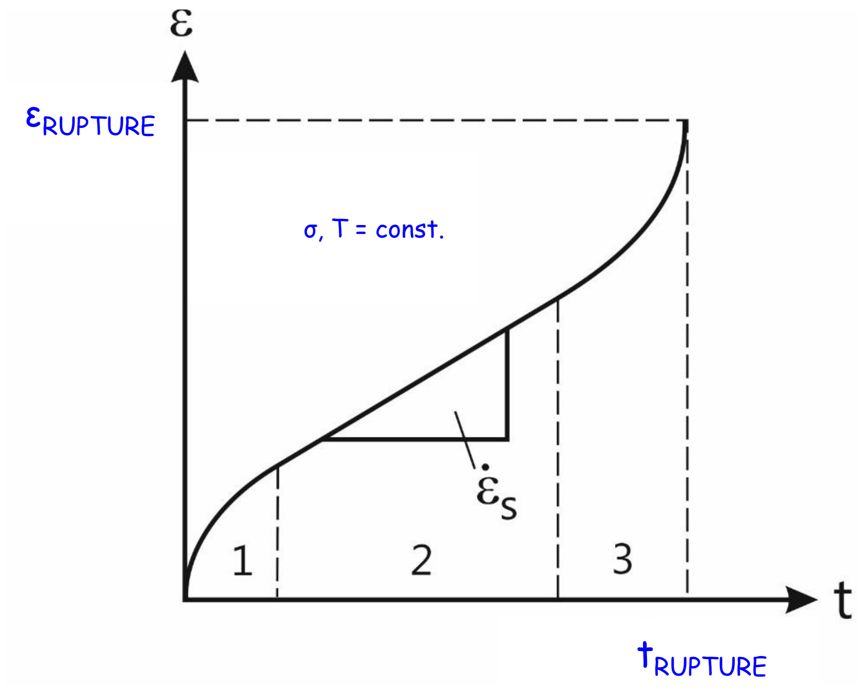
Creep testing





We adjust temperature, we apply a load, we measure strain ε as a function of time t.

Creep curve

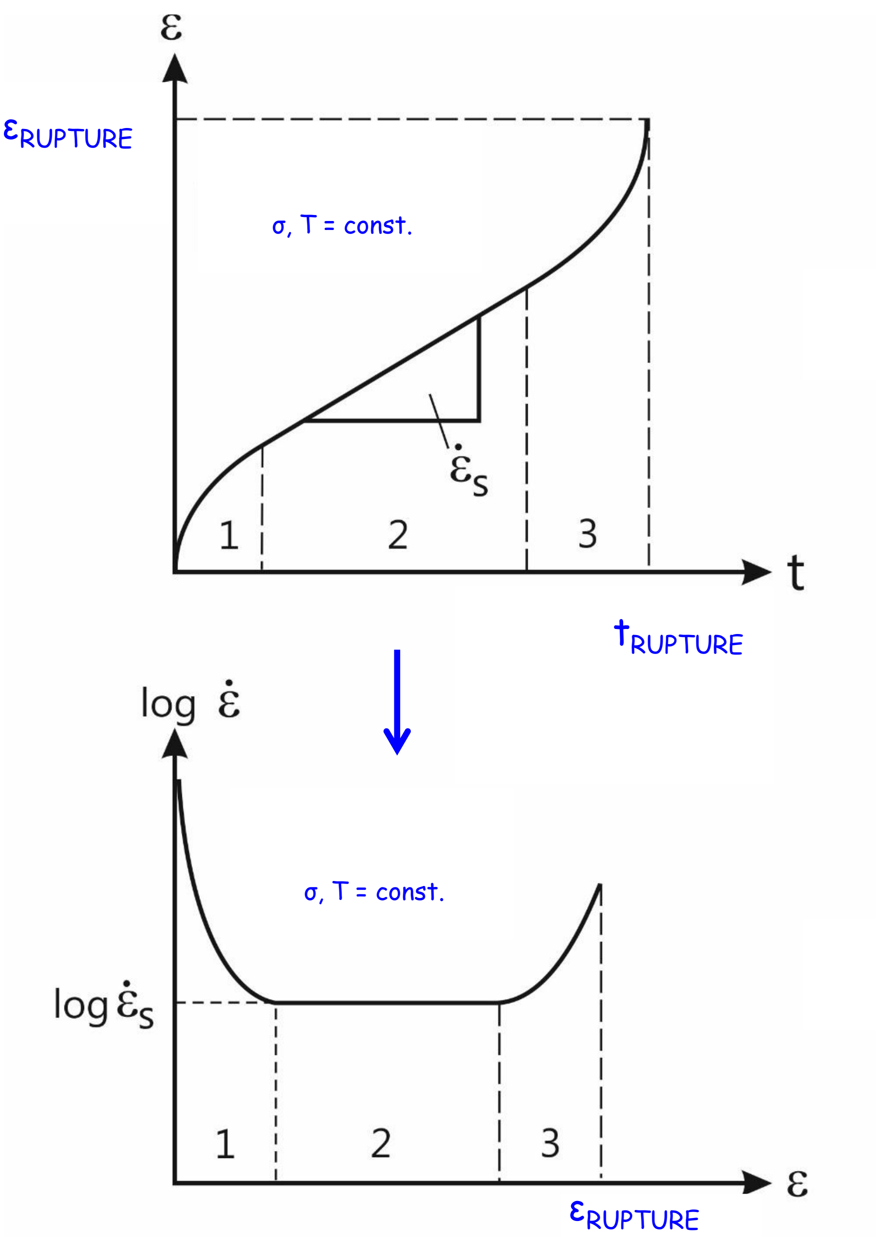


The three regions of a creep curve:

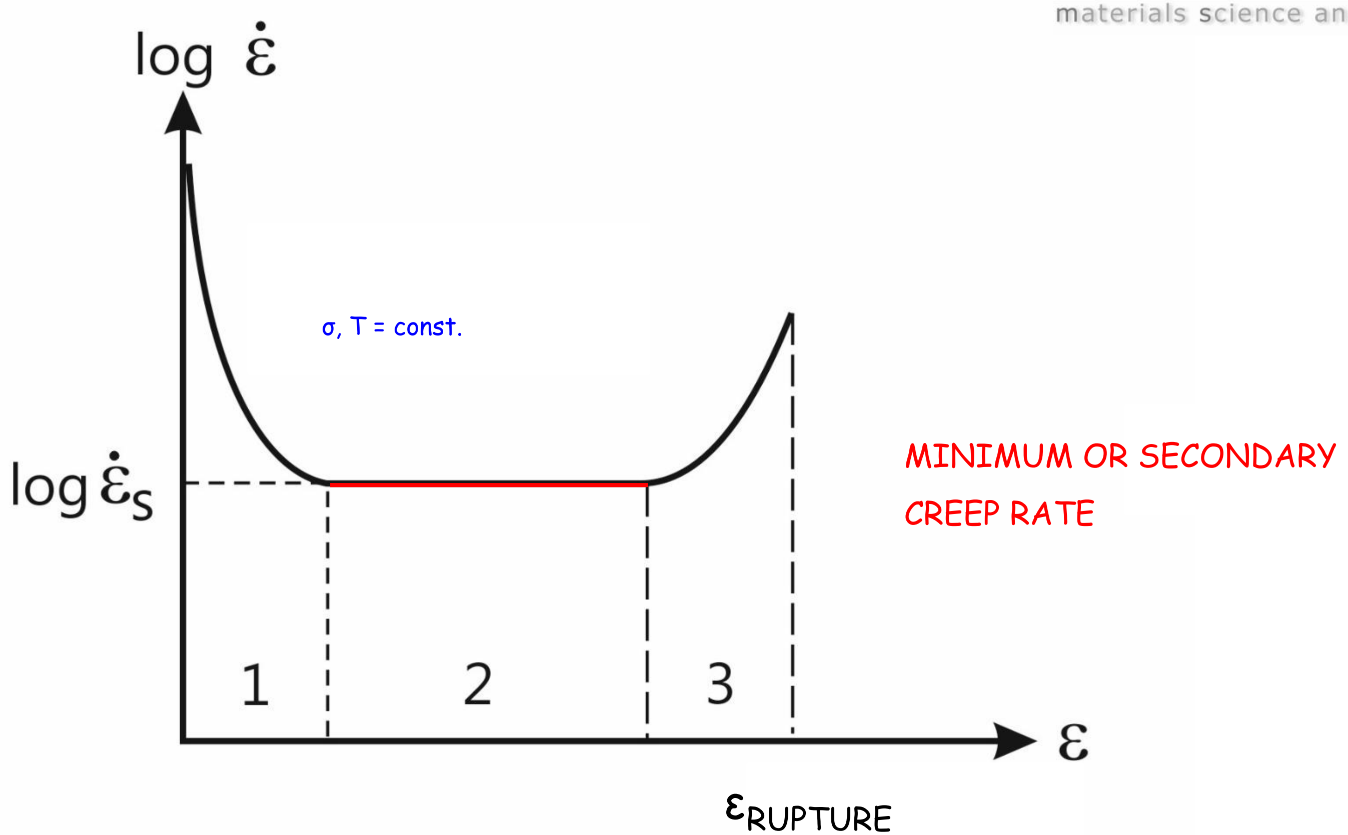
1 – decreasing creep rate – primary creep

2 – minimum creep rate – secondary creep

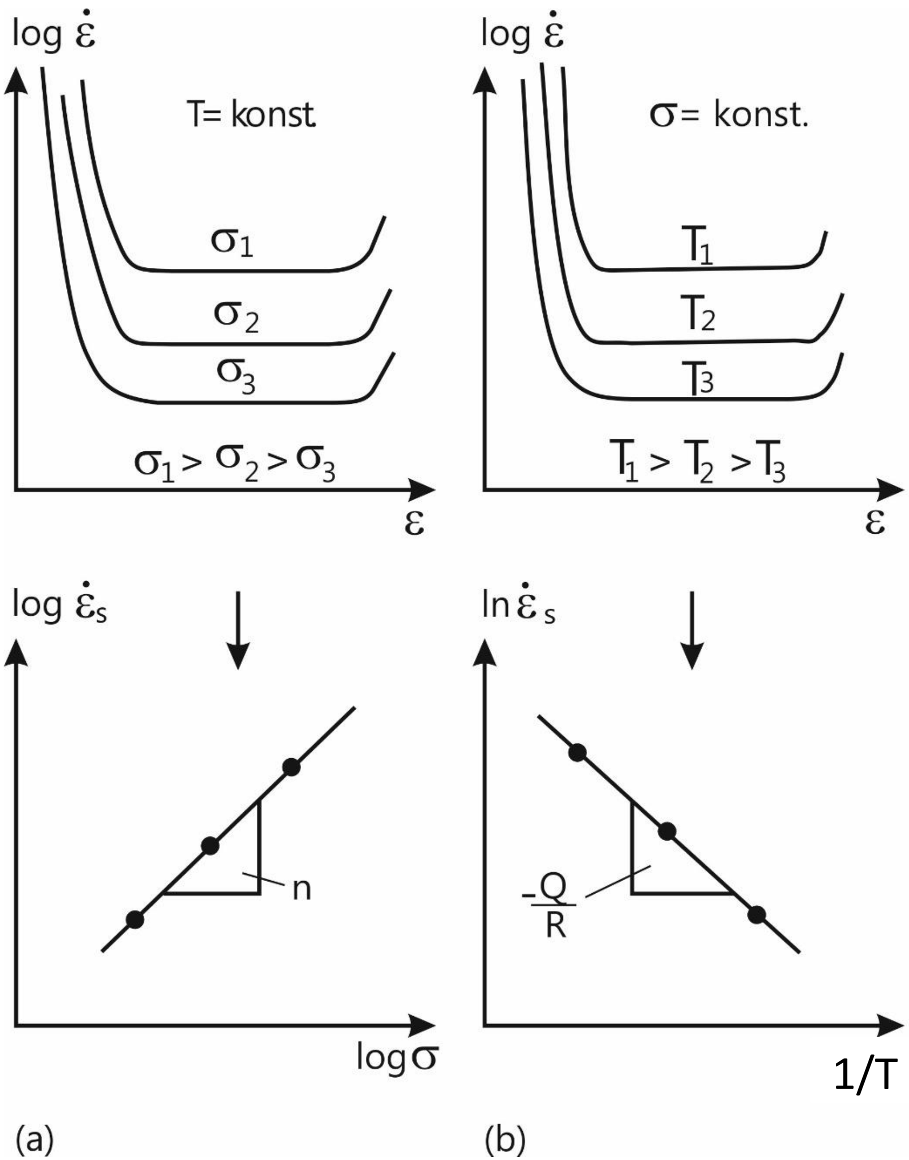
3 – creep rate increases again – tertiary creep



Material scientists sometimes prefer to plot strain rate as a function of strain.



One often finds that most of the life is spent in the secondary creep regime.



Stress and temperature dependence of secondary creep rate: n und Q

$$\dot{\varepsilon}_S = A' \cdot \sigma^n \cdot exp\left(-\frac{Q_{eff}}{RT}\right)$$

typical values:

n: 5 – 15
Q: 100 – 500 kJ / mole

Phenomenological equation for secondary creep:

$$\dot{\varepsilon}_S = A' \cdot \sigma^n \cdot exp\left(-\frac{Q_{eff}}{RT}\right)$$

Symbols:

$\dot{\varepsilon}_s$ – secondary creep rate

A' – constant

σ – stress

n – stress exponent (z.B. 5-10)

Q_{eff} – apparent activation energy (z.B. 200 kJ/mol)

R,T – gas constant and temperature

Comparison: elastic deformation and creep

Hookes law:

$$\varepsilon_{el} = \sigma / E$$

Simple linear relationship.

Sherby-Dorn equation:

$$\dot{\varepsilon}_S = A' \cdot \sigma^n \cdot \exp\left(-\frac{Q_{eff}}{RT}\right)$$

strong, non linear dependencies

strongly affects three areas:

- testing
- mechanics, design
- plant/engine operation

Uniaxial creep testing

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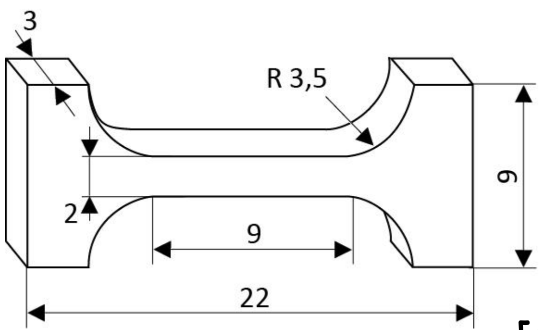
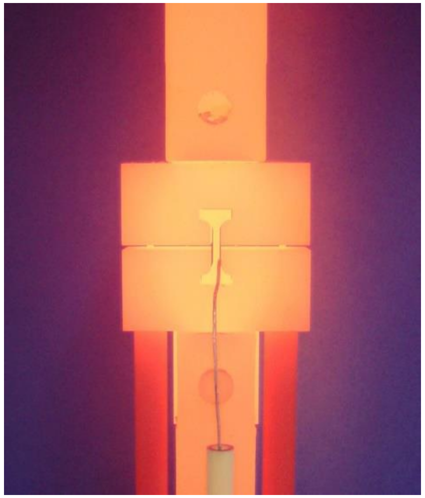
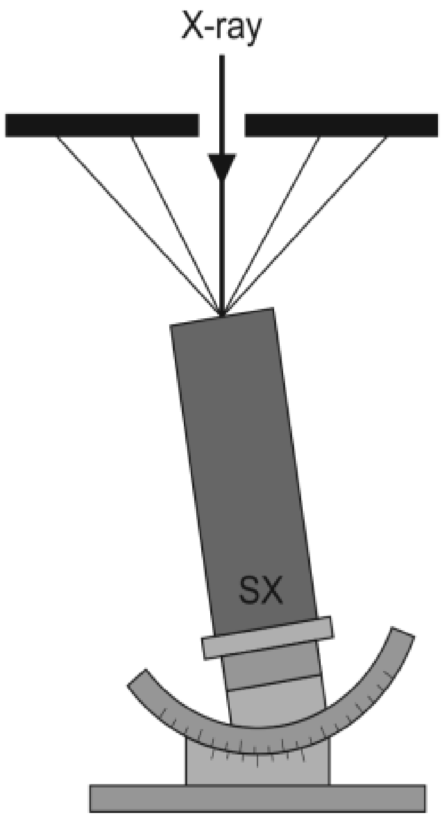
Creep testing single crystal superalloys (SX)



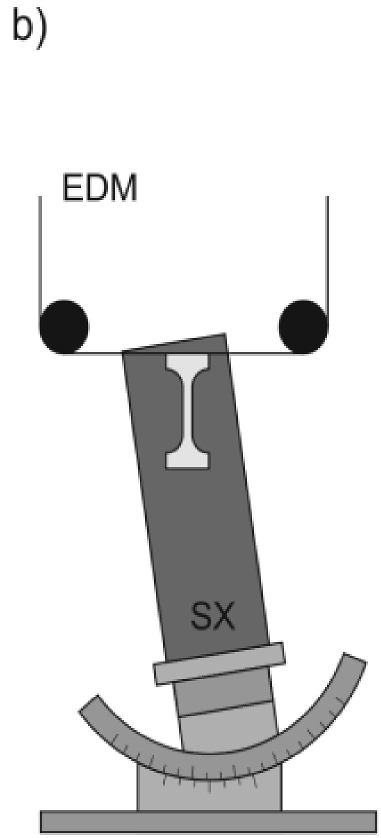
[mm]



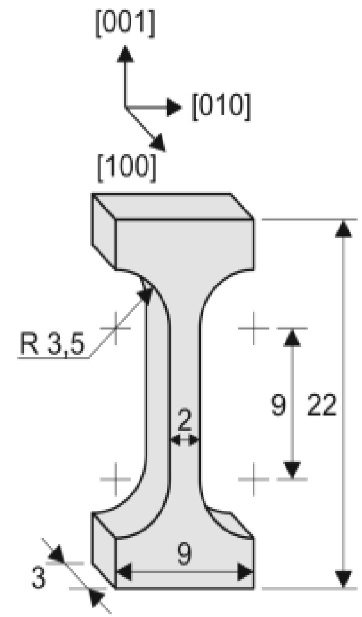
We adjust temperature, we apply a load, we measure strain ε as a function of time t.



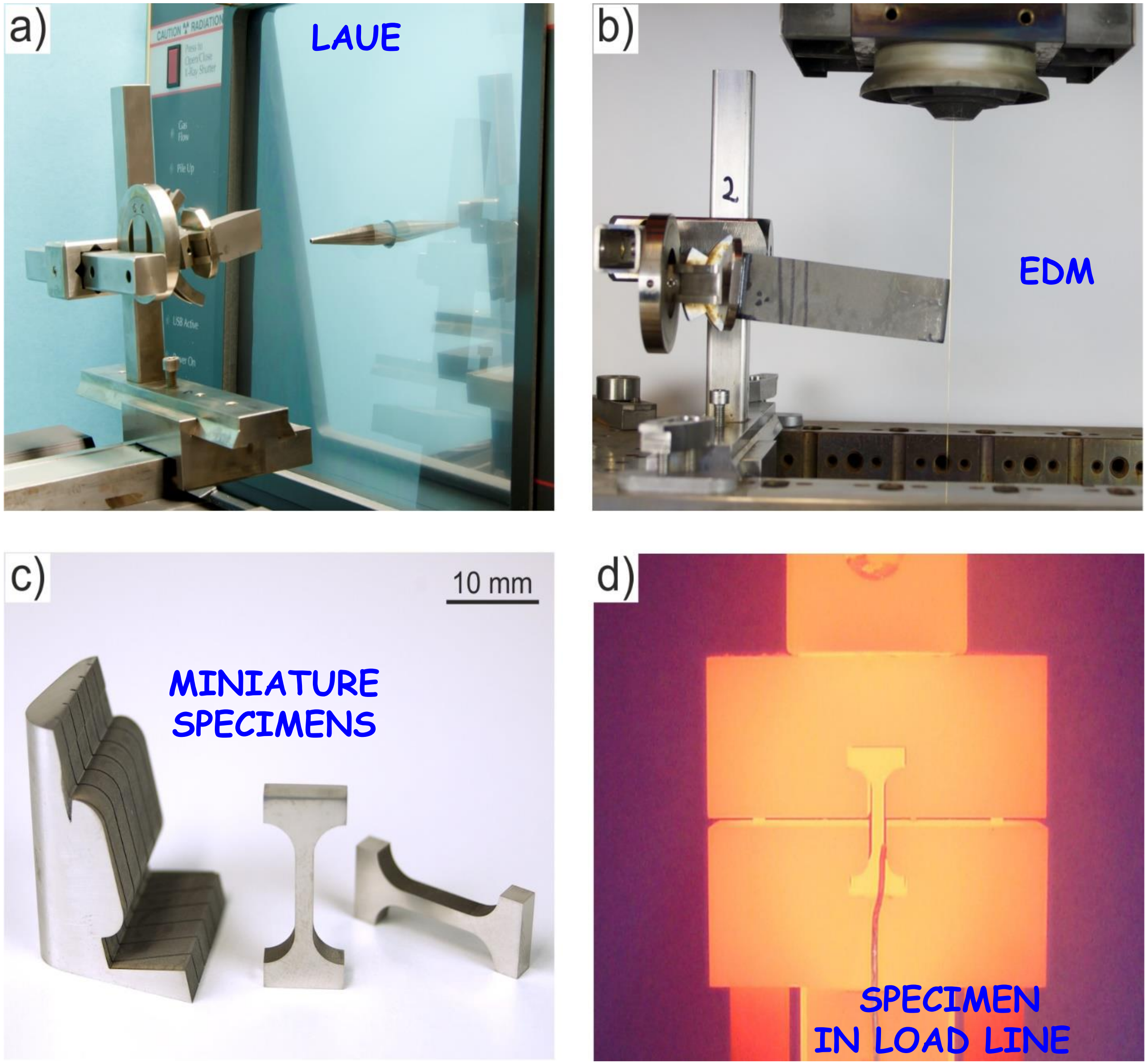
Laue camera

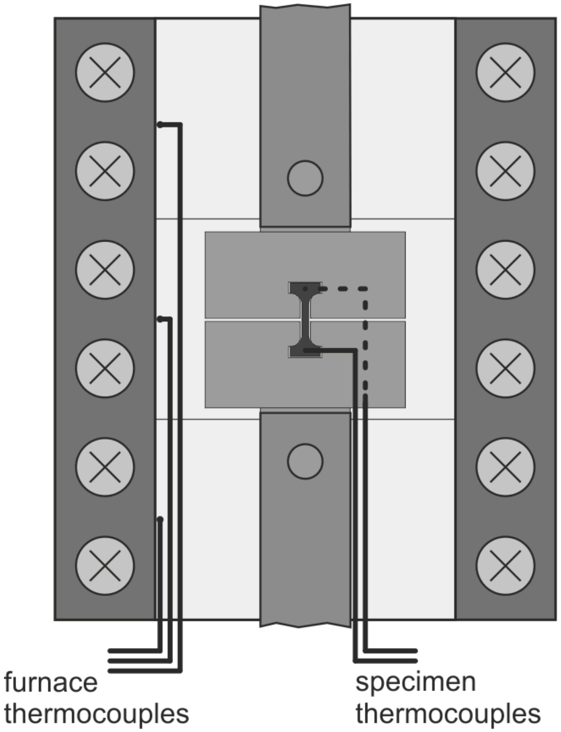


Electro discharge machining (EDM)

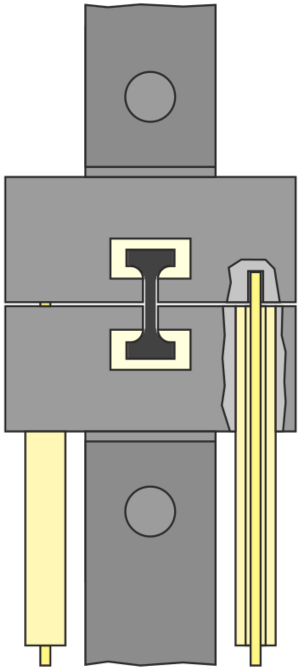


Miniature creep specimen

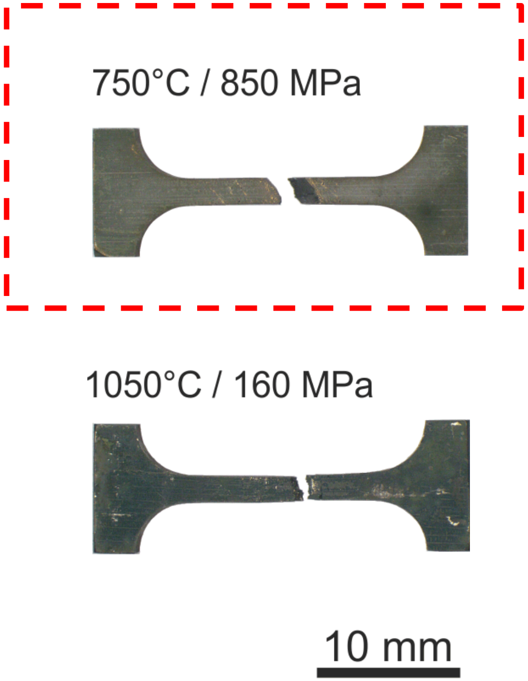

a)
LAUE
b)
EDM
c)
10 mm
MINIATURE
SPECIMENS
d)
SPECIMEN
IN LOAD LINE



3 zone furnace



rod in tube
extensometry



rupture in middle
of gauge length

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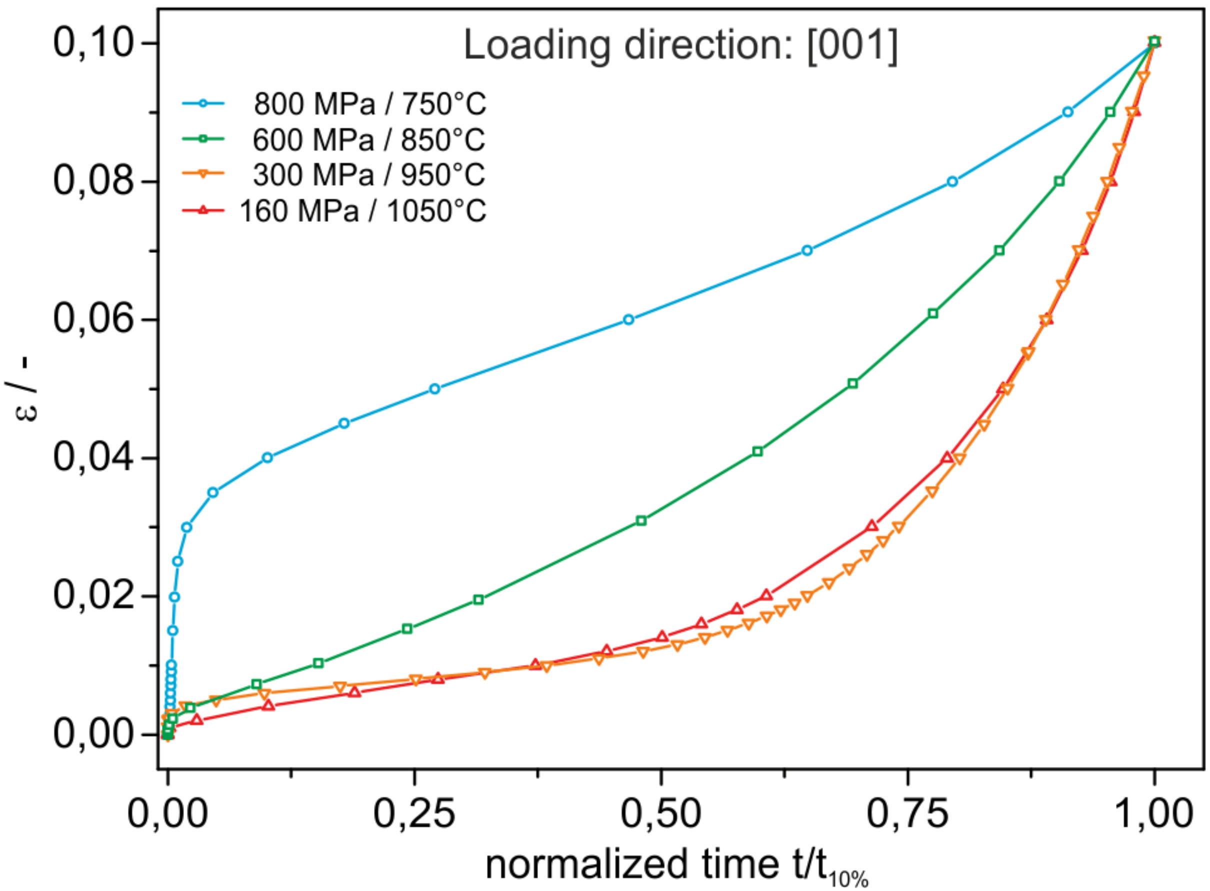
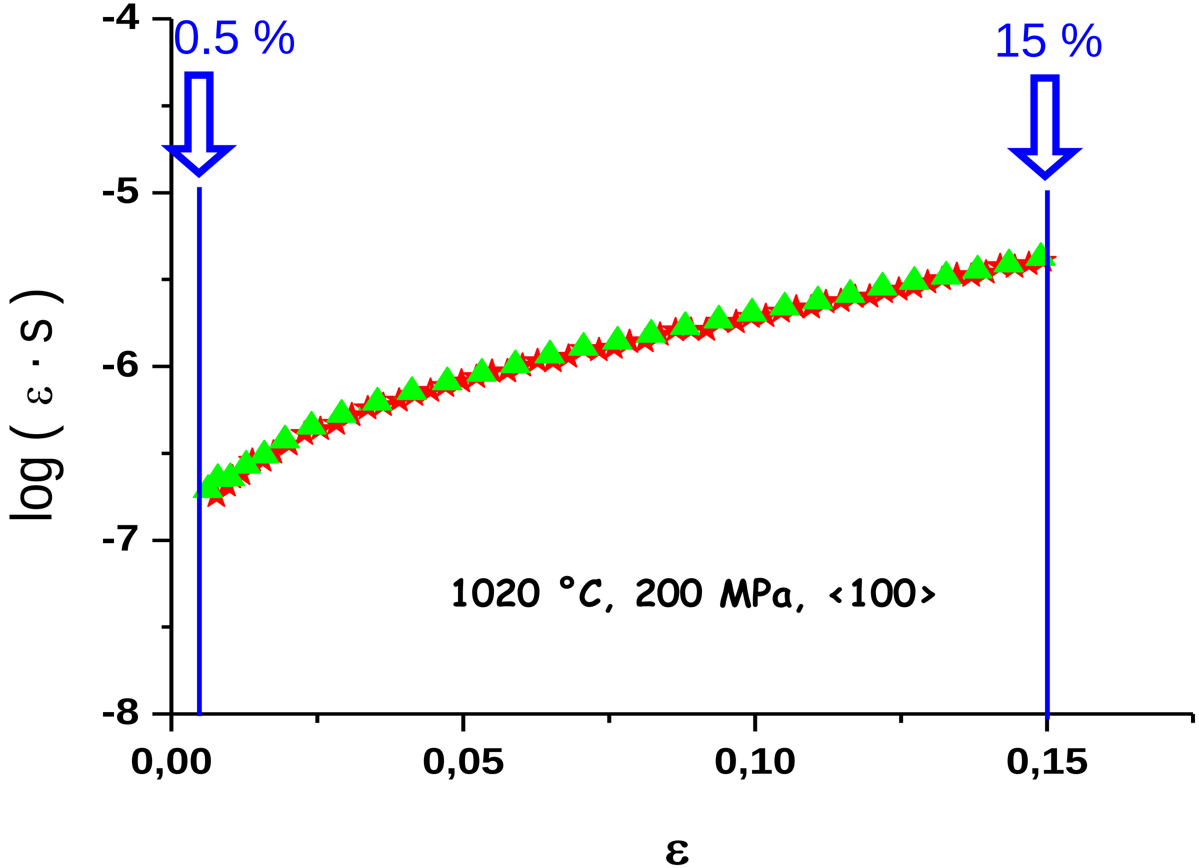
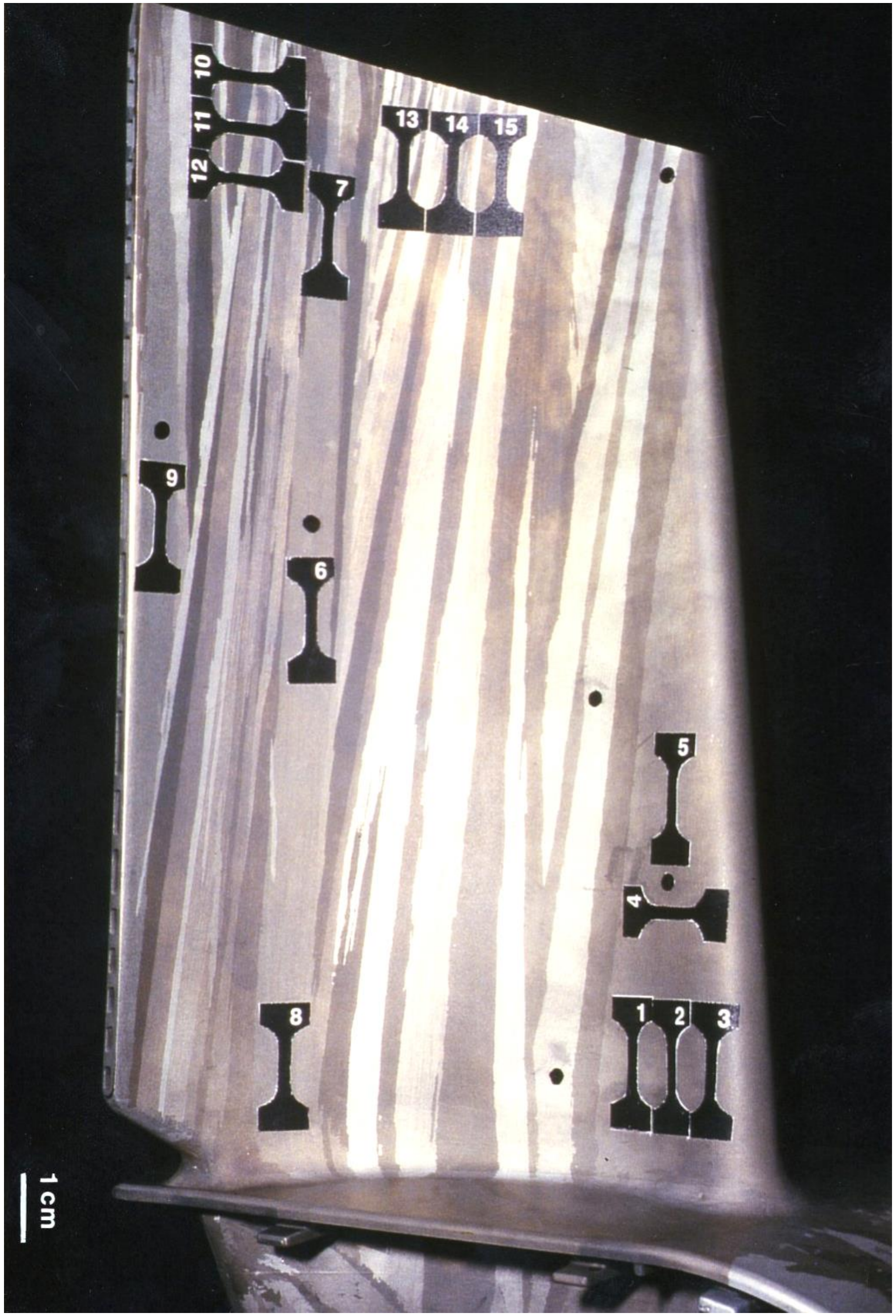

Loading direction: [001]
800 MPa / 750°C
600 MPa / 850°C
300 MPa / 950°C
160 MPa / 1050°C
0,10
0,08
0,06
0,04
0,02
0,00
ε / -
0,00
0,25
0,50
0,75
1,00
normalized time t/t10%

Comparison between miniature and standard creep specimen:



G.Mälzer, R.W.Hayes, T.Mack, G.Eggeler,
Met. and Mat. Trans., 38A (2007) 314-327



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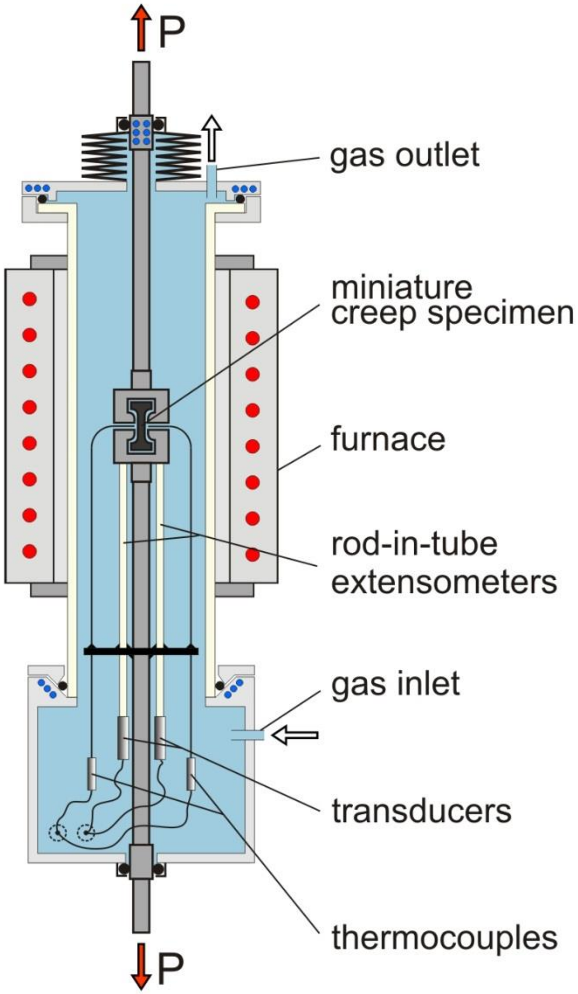
M.Kolbe, J.Murken, D.Pistelok, H.J.Klam, G.Eggeler, Materialwissenschaft und Werkstofftechnik, 30 (1999) S. 465-472


P
gas outlet
miniature
creep specimen
furnace
rod-in-tube
extensometers
gas inlet
transducers
thermocouples
P

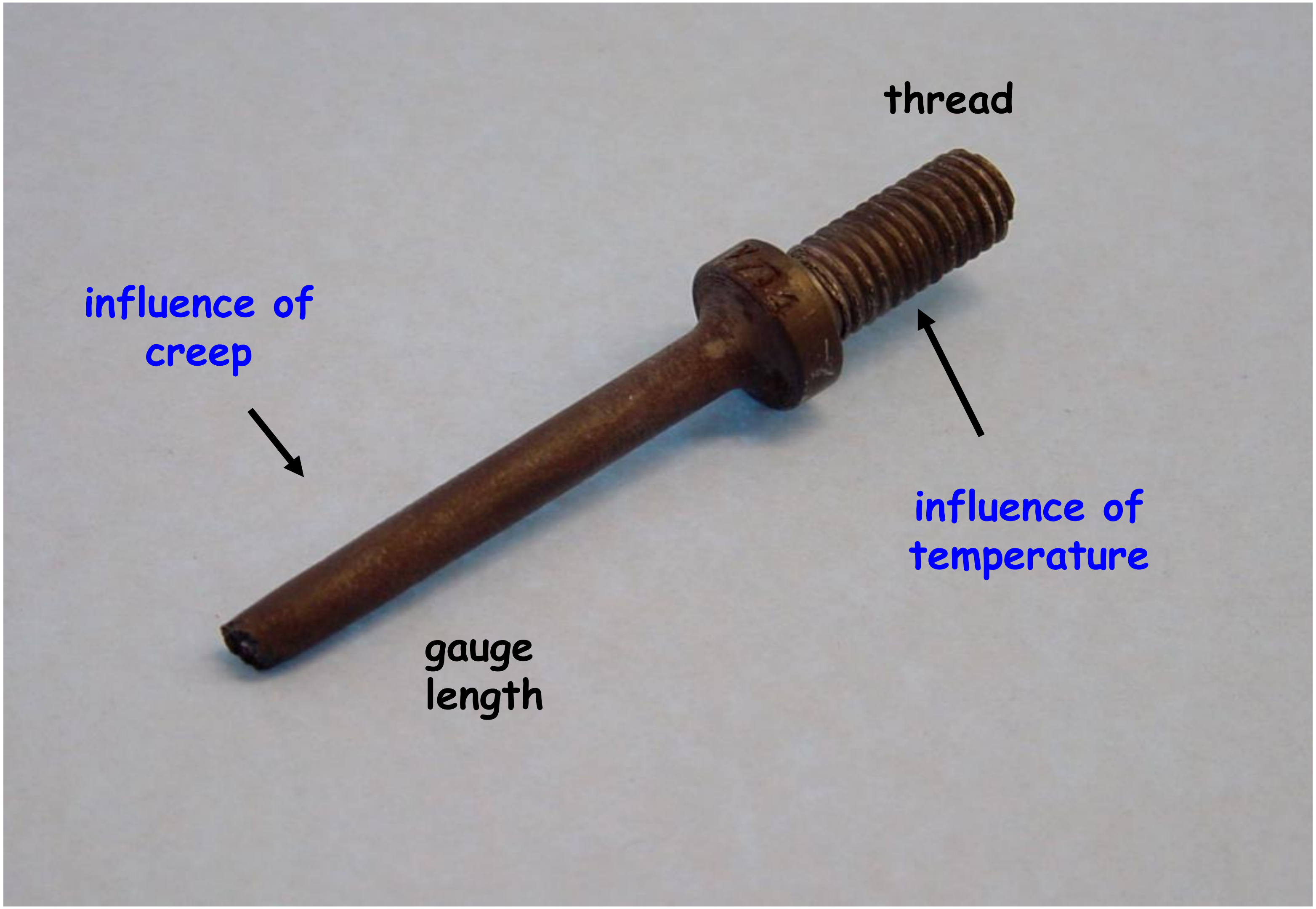
Dennis Peter (heute: STEAG, Essen)

Frederik Otto (heute: Infineon, Warstein)

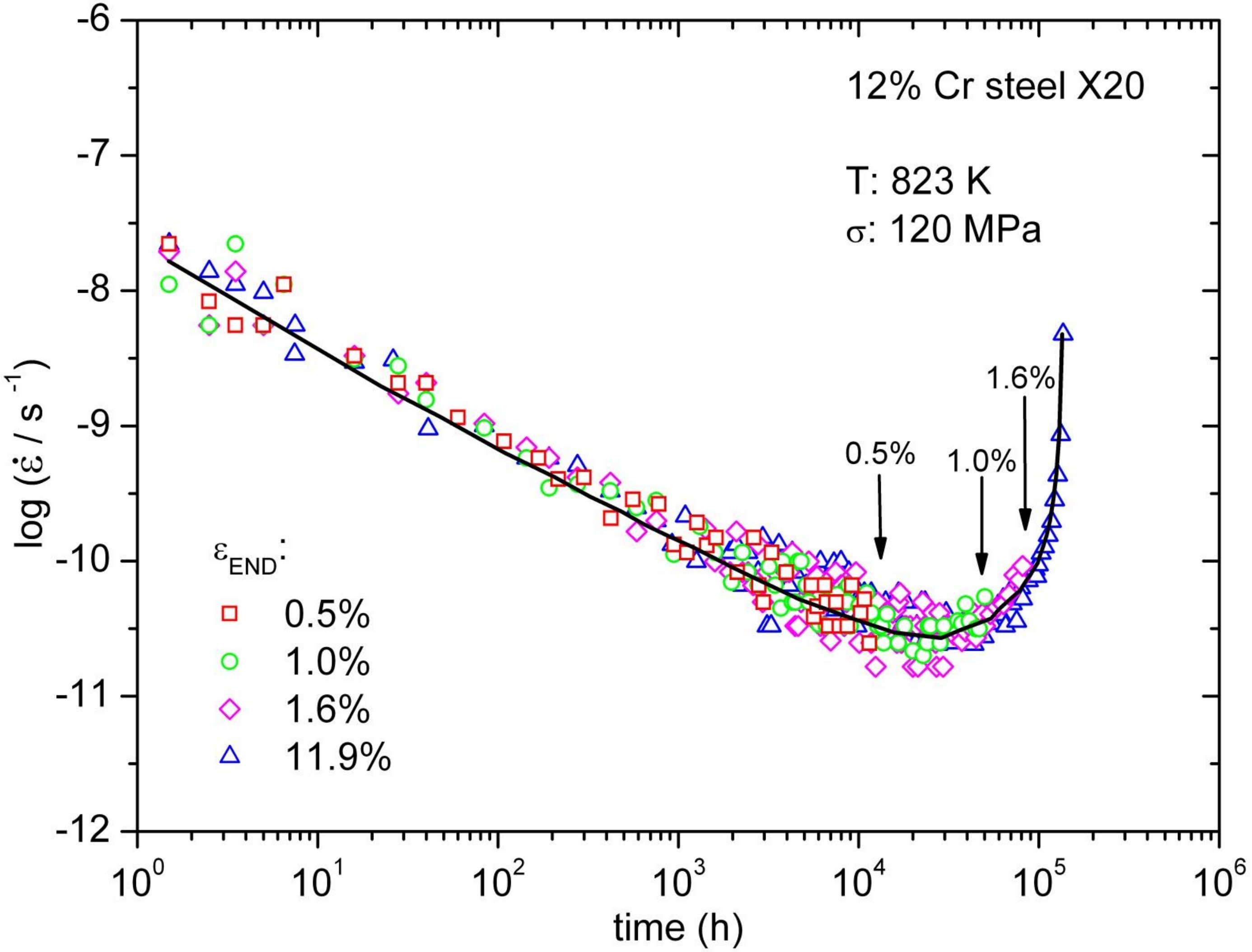
Jenna Heyer (Deutsche Edelstahlwerke, Witten)

Timo Depka (heute: Siemens, Mülheim a.d. Ruhr)

Creep testing tempered martensite ferritic steels (TMFSs)



specimen from
Dr. W. Bendick,
SMFI Duisburg



creep data and specimen from Dr. W. Bendick, SMFI Duisburg

Well known creep concepts:

steady state creep

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Second half of the second century:

Constitutive equations. Mechanical equations of state.

Allow to predict the evolution of strain rate. Deformation history can be characterized by an internal state variable.

First example: Steady state creep

E.W. Hart, A phenomenological theory for plastic deformation of polycrytalline materials, Acta Metallurgica, 18 (1970) pp. 599-610

Hart's theory on steady state creep:

we look at the total differential of the change of the dislocation density during creep

$$d\,\rho_{total} = \left(\frac{\delta\rho}{\delta t}\right)\cdot dt + \left(\frac{\delta\rho}{\delta\varepsilon}\right)\cdot d\,\varepsilon = r\cdot dt + h\cdot d\,\varepsilon$$

decrease of dislocation density with time
recovery - r

increase of dislocation density with strain
(strain) hardening - h

Hart's assumption: there is steady state creep

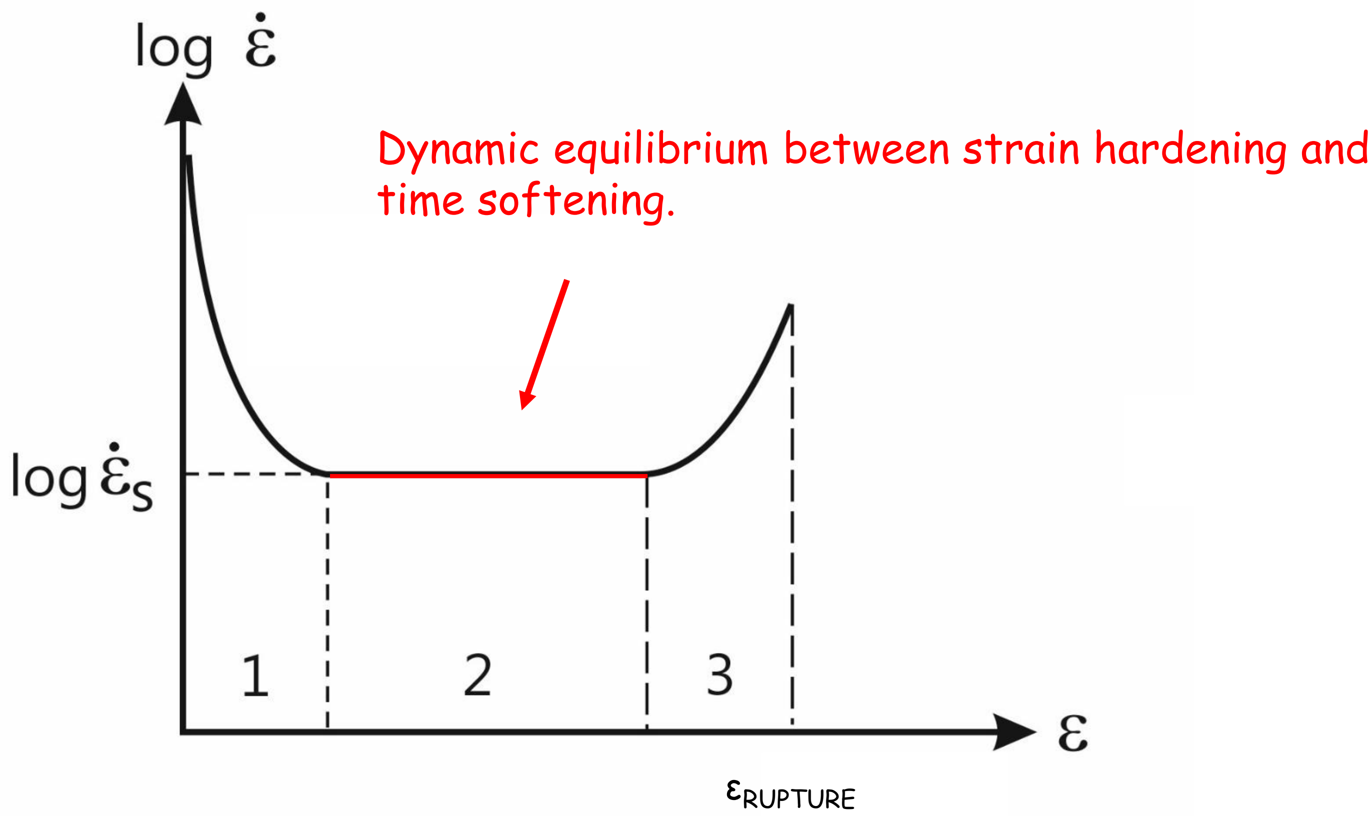
$$d\rho_{total} = 0 \longrightarrow r \cdot dt + h \cdot d\varepsilon = 0$$

$$\frac{d\varepsilon}{dt} = -\frac{r}{h} \longrightarrow \dot{\varepsilon}_s = -\frac{r}{h}$$

$$\boxed{\dot{\varepsilon}_s = -\frac{r}{h}}$$

Hart:

a material creeps fast, when recovery is fast and when Strain hardening is weak



Early prominent concept: steady state creep.

Well known creep concepts:

stress exponent n and apparent activation energy Q

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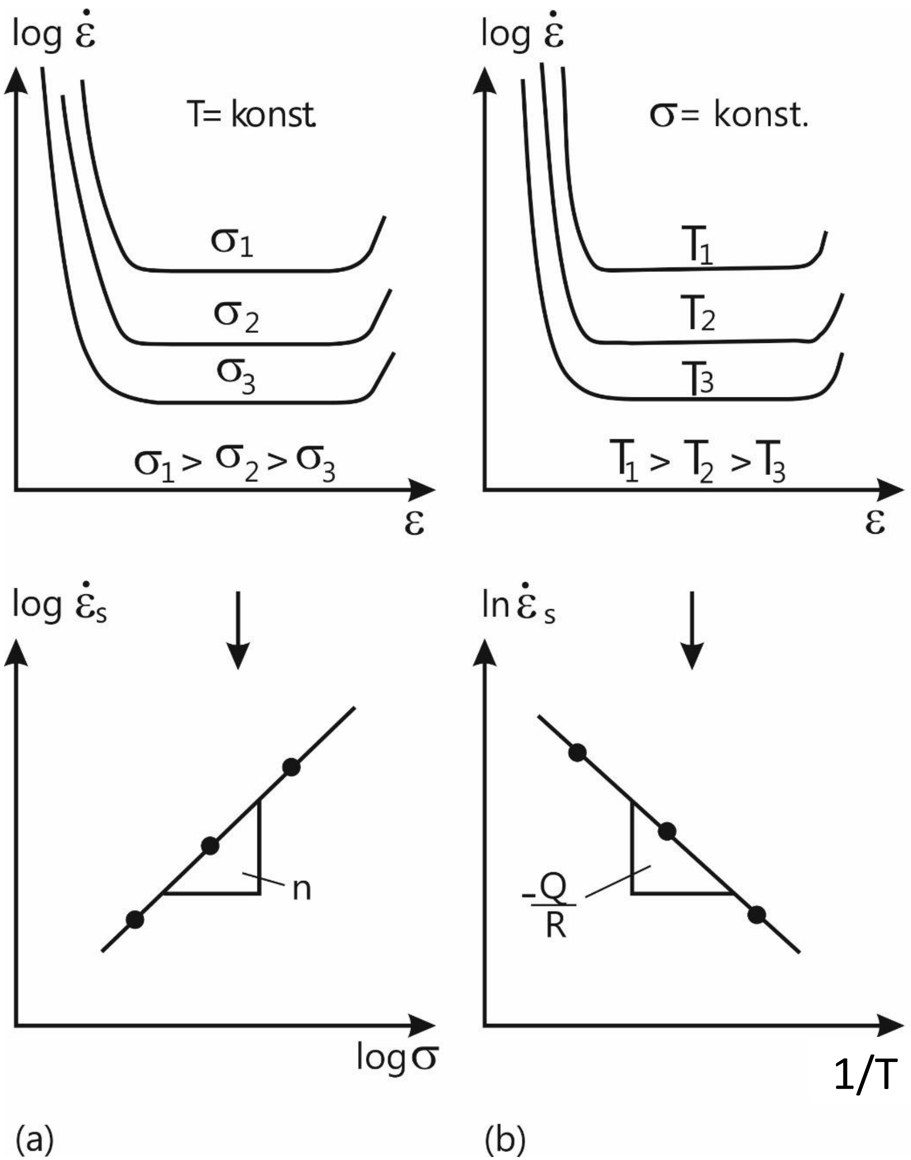

We know how to determine n and Q

$$\dot{\varepsilon}_S = A' \cdot \sigma^n \cdot exp\left(-\frac{Q_{eff}}{RT}\right)$$

Plot of logarithmic creep rate (common logarithm, base 10) vs. Logarithm of stress (common logarithm, base 10) to determine the stress exponent n.

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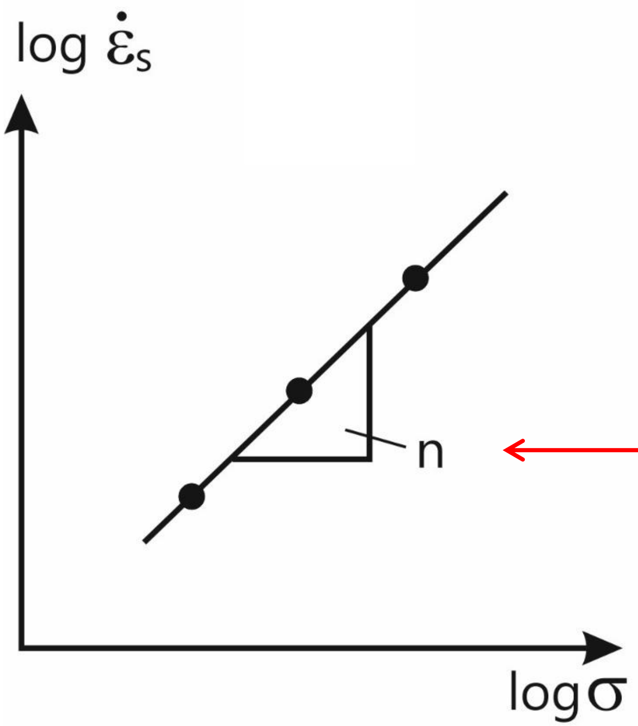
$$\dot{\varepsilon}_S = A'' \cdot \sigma^n$$

calculation rules for logarithm

equation of a line with slope n

$$\log\left(\dot{\varepsilon}_S\right) = \log A'' + n \cdot \log(\sigma)$$



(as engineers we like the common logarithm, because we know that 0,1,2,3 correspond to 1, 10, 100 und 1000)

We plot the logarithmic creep rate (natural logarithm, base e) against the reciprocal value of the absolute temperature, to determine the apparanet activation energy of creep Q

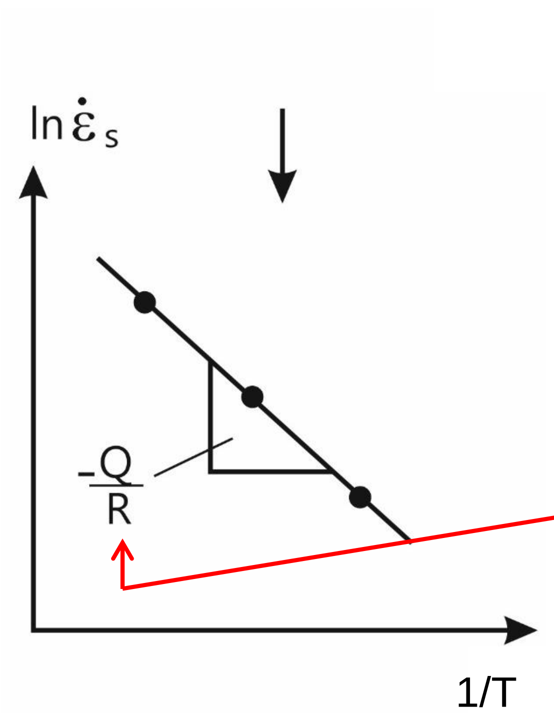
$$\dot{\varepsilon}_S = A''' \cdot exp\left(-\frac{Q_{eff}}{RT}\right)$$

calculation rules for logarithm

equation of a line with slope

-Q/R

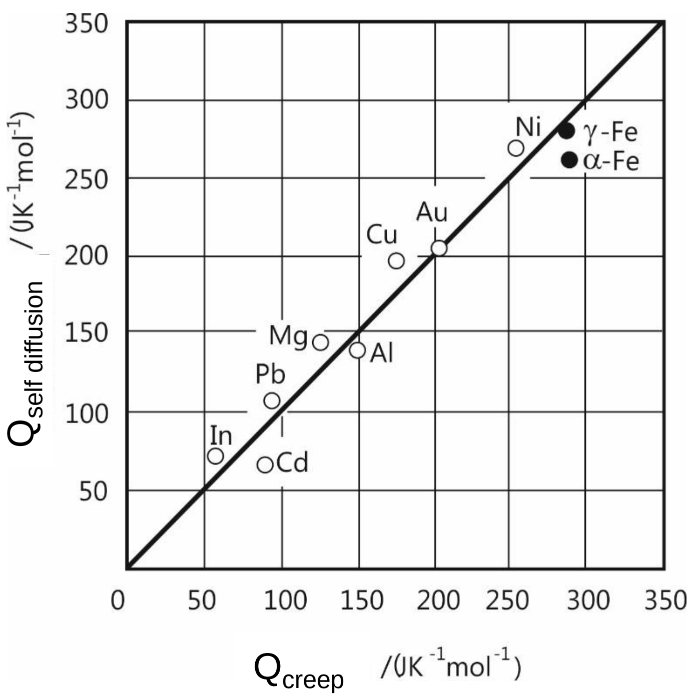
$$ln\left(\dot{\varepsilon}_S\right) = ln\left(A'''\right) - \left(\frac{Q}{R}\right) \cdot \frac{1}{T}$$



(here we take the natural logarithm, because it inverses the exp-function)

pure metals: we find a good correleation between the activation energy of creep and the activation energy of self diffusion

because: diffusion controlled climb of dislocations governs the temperature dependence of creep



activation energies of creep

and self diffusion

BASIC IDEA ON Q:

DIFFUSION GOVERNS THE TEMPERATURE DEPENDENCE OF CREEP

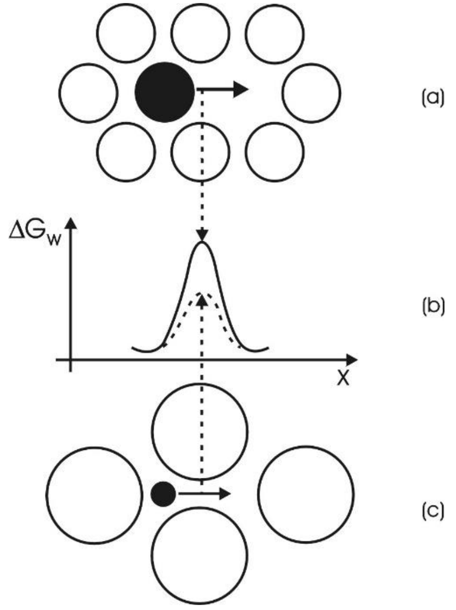
$$Q_{creep} = Q_{self\ diffusion}$$

First reminder physics / diffusion:

Boltzmannn Statistics

How many particles have an energy larger than ε_1:

$$N_{\varepsilon > n \cdot \varepsilon_1} = N \cdot e^{-\frac{n \cdot \varepsilon_1}{kT}}$$

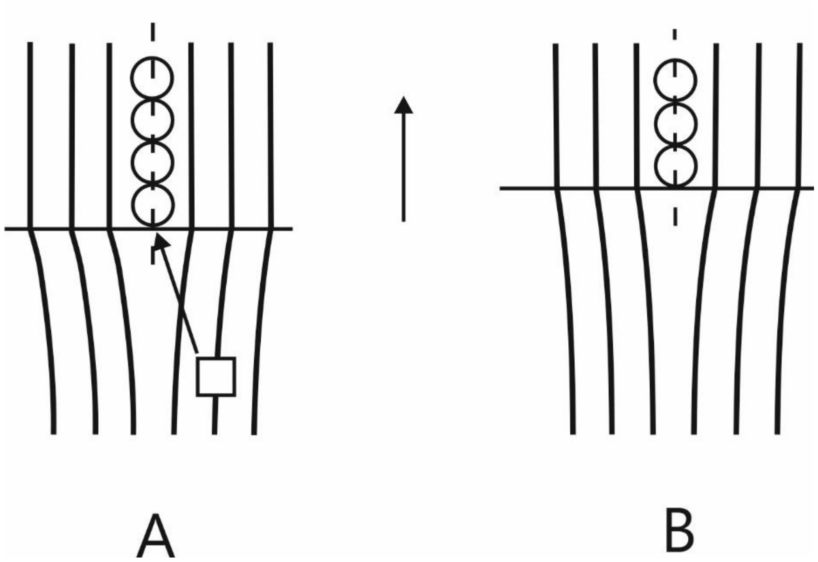


large atoms: need vacancies

both: must overcome activation barrier

small atoms: squeeze as interstitials through lattice

Second reminder mechanical property class:



Climb of an edge dislocation.

When edge dislocations climb they leave their glide plane. This requires adding/taking away of vacancies/atoms.

The climb of dislocations, which is important to rationalize creep, requires diffusion.

Dislocation density based deformation rate:

$$\dot{\varepsilon} = \rho \cdot b \cdot v$$

ρ - average dislocation density

b - Burgers vector

v - mean dislocation velocity

Early metal physics research:

$\rho \sim \sigma^2$

$v \sim \sigma^1$

BASIC IDEA ON n: $\dot{\varepsilon} \sim \sigma^3$

Defense of basic ideas I and II:

O.D.Sherby, J.Weertman, Diffusion controlled dislocation creep – denfense, Acta Metallurgica, 27 (1979) pp. 387-400

However, often: $n >> 3$, $Q_{creep} >> Q_{self\ diffusion}$

Critical remarks on basic ideas I and II:

A.M.Brown, M.F.Ashby, On the power law creep equation, Scripta Metallurgica, 14 (1980) pp. 1297-1302

Recent discussion of basic ideas I and II:

P. Wollgramm, H. Buck, K. Neuking, A.B. Parsa, S. Schuwalow, J. Rogal, R. Drautz, G. Eggeler, On the role of Re in the stress and temperature dependence of creep of a Ni-base single crystal super alloy, Mat. Sci. Eng. A, 628 (2015) pp. 382-395

Creep concepts

internal back stress and damage

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What can we do?

We can for example introduce an internal back stress term σ_i which reflects the evolutionof microstructure:

$$\dot{\varepsilon} = C_1 \cdot (\sigma - \sigma_i)^n$$

$\dot{\varepsilon}$ – creep rate

C_1– constant

σ – stress, σ_i – internal back stress

n – stress exponent

σ_i represents a inner resistance against deformation. It can for example increase with increasing dislocation density ρ_i in a metallic material.

We go ahead and generalize this idea.
We include a damage parameter ω.
Here: example single crystal super alloys

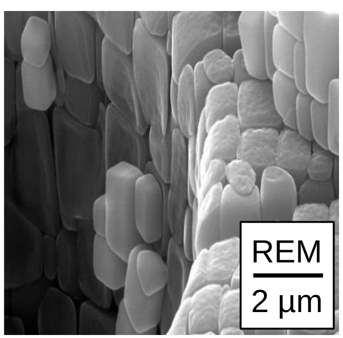
- $\dot{\varepsilon}$ – creep rate
- C_2 , β, α – constants,
- σ – stress, σ_i – internal back stress
- n – stress exponent
- ω – damage parameter (0 < ω < 1)
- G – shear modulus, b – burger's vector
- d – particle distance (here: channel width)
- ρ – dislocation density

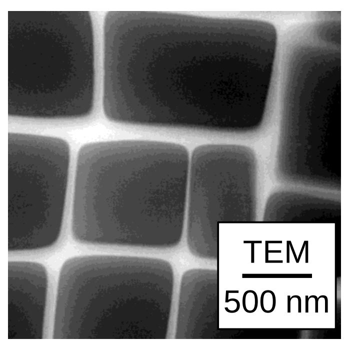
$$\dot{\varepsilon} = C_2 \cdot \left(\frac{\sigma}{1-\omega} - \alpha \cdot \frac{G \cdot b}{d} - \beta \cdot G \cdot b \cdot \sqrt{\rho} - \sigma_{i,\,alloy\ elements} \right)^n$$

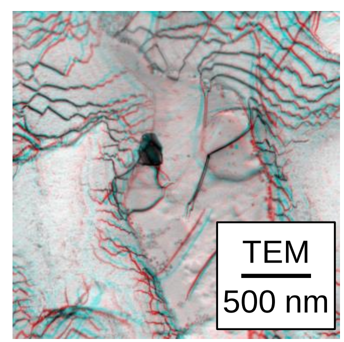
pores

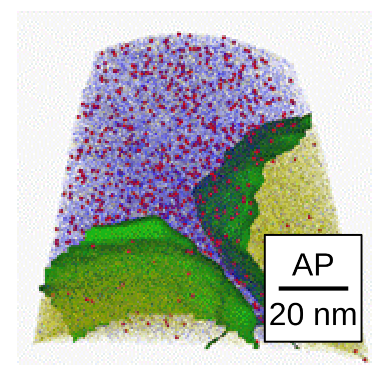
γ-channel width

dislocation density









Creep concepts

deformation mechanism maps
from Frost and Ashby

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Frost and Ashby subdivided deformation mechanisms into five groups:

1.Collapse at the ideal strength (flow when the ideal shear strength is exceeded).

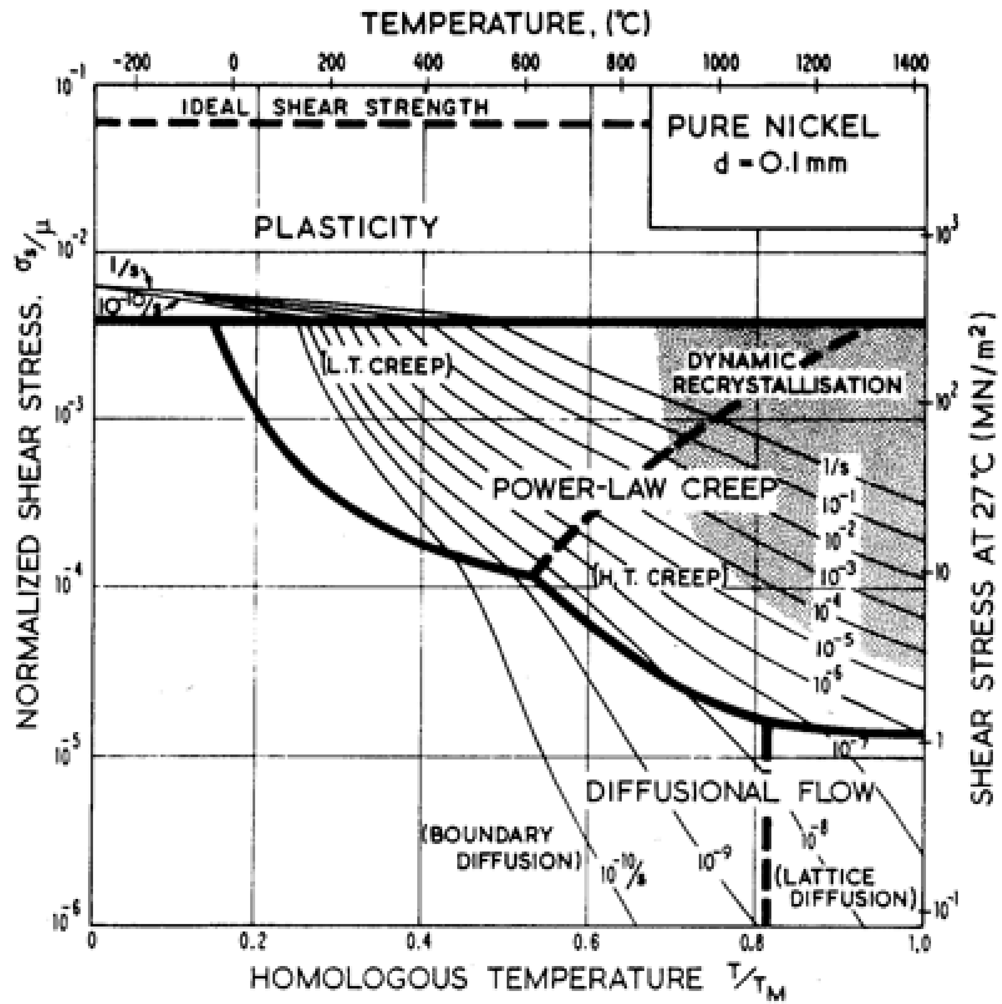
2.Low-temperature plasticity by dislocation glide (limited by lattice resistance/Peierls' stress, or by discrete obstacles, or by phonon or other drags and influenced by adiabatic heating).

3. Low-temperature plasticity by twinning.

4. Power-law creep by dislocation glide, or glide-plus-climb (limited by glide processes, or by lattice-diffusion controlled climb ("high-temperature creep"), or by corediffusion controlled climb ("low-temperature creep"), Harper-Dorn creep, dynamic recrystallization.

5. Diffusional Flow (lattice diffusion: Nabarro-Herring creep, grain boundary diffusion: Coble Creep, interface-reaction controlled diffusional flow.

These mechanisms may superimpose in complicated ways. Certain *other mechanisms* (such as superplastic flow) appear to be examples of such combinations.



Very important book:

H.J.Frost, M.F.Ashby: Deformation Mechanism Maps, Pergamon Press, Oxford, 1982

Outlook - creep materials science:

- Post mortem microstructural analysis (new methods: Synchrotron, OIM SEM, TEM, 3D AP, advanced diffraction, ….)
- In-situ observation of elementary creep processes
- Influence of stress / stress state (thermodynamic and kinetic aspects) on microstructural stability
- Mechanics - FEM, micromechanics – mechanism based constitutive equations
- Scale bridging creep modelling
- Multiaxial stress states
- Indentation creep testing
- Nano indentation creep testing

Summary

- Creep rupture
- Creep curve and minimum creep rate
- Creep testing
- Stress and temperature dependence of minimum creep rate
- A few basic concepts
- Outlook

Questions for self control

1. Which critical components of a high temperature fossil fired power plant do you know?
2. What is creep?
3. What is a stress rupture plot (text and drawing)?
4. Why is there a need to extrapolate from short term creep data into the long term regime (text and drawing)?
5. What is the Larson Miller parameter (formula)? What is the merit of a Larson miller plot (text and drawing)?
6. How is a creep experiment performed? (Keywords: specimen, furnace, temperature control, thermocouples, extensometers).
7. How does a generic creep curve look like (plots: strain vs. time, log strain rate vs. strain)?
8. For pure metals: why is the effective creep activation energy often similar as the apparent activation energy for diffusion?
9. What are the three periods during creep? What happens in each of them?
10. Explain the concept of steady state creep.
11. Schematically draw an Ashby map and explain the principle behind it.