Investmech: Creep fatigue

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- Recovery
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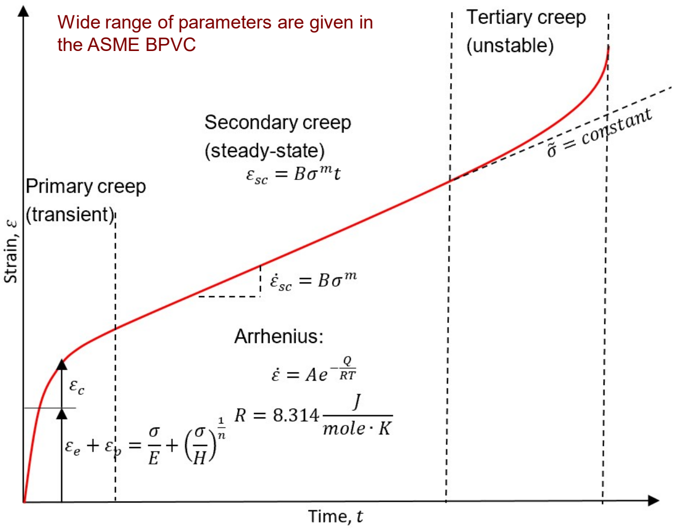
Stages of creep



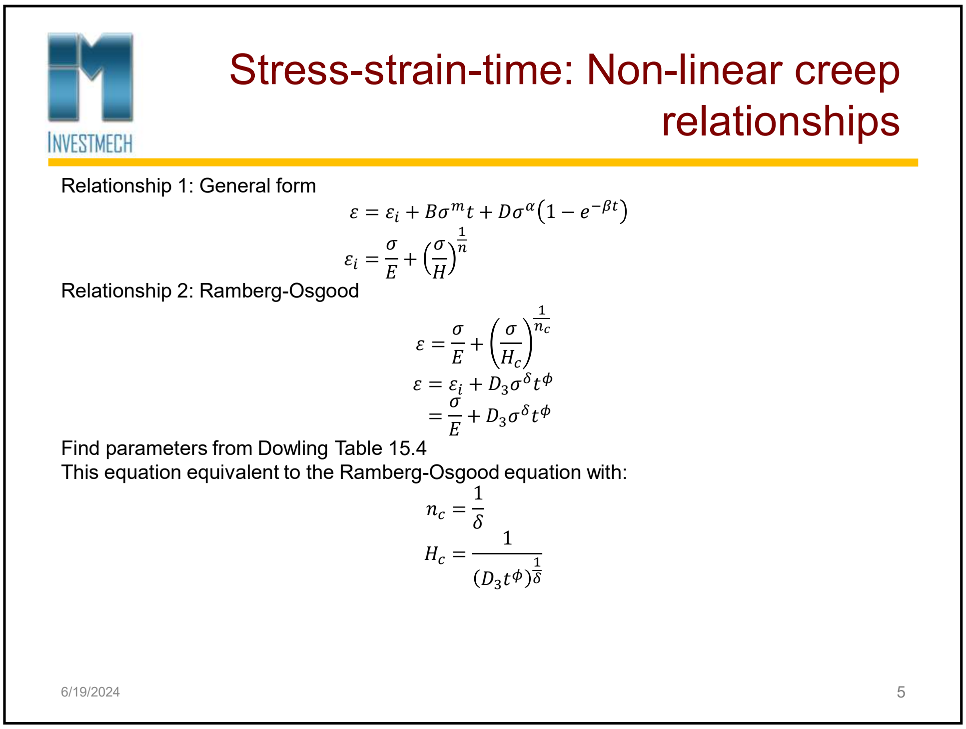
Stress-strain-time: Linear viscoelasticity relationships

$$\varepsilon = \frac{\sigma}{E_1} + \frac{\sigma t}{\eta_1} + \frac{\sigma}{E_2}\left(1 - e^{-\frac{E_2 t}{\eta_2}}\right)$$

Elastic $\varepsilon_e = \frac{\sigma}{E_1}$ $\dot{\varepsilon}_e = 0$

Secondary creep $\varepsilon_{sc} = \frac{\sigma t}{\eta_1}$ $\dot{\varepsilon}_{sc} = \frac{\sigma}{\eta_1}$

Tertiary creep $\varepsilon_{tc} = \frac{\sigma}{E_2}\left(1 - e^{-\frac{E_2 t}{\eta_2}}\right)$ $\dot{\varepsilon}_{tc} = \frac{\sigma}{\eta_2} e^{\frac{-E_2 t}{\eta_2}}$



Stress-strain-time: Non-linear creep relationships

Relationship 1: General form

$$\varepsilon = \varepsilon_i + B\sigma^m t + D\sigma^\alpha\left(1 - e^{-\beta t}\right)$$

$$\varepsilon_i = \frac{\sigma}{E} + \left(\frac{\sigma}{H}\right)^{\frac{1}{n}}$$

Relationship 2: Ramberg-Osgood

$$\varepsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{H_c}\right)^{\frac{1}{n_c}}$$

$$\varepsilon = \varepsilon_i + D_3\sigma^\delta t^\phi$$

$$= \frac{\sigma}{E} + D_3\sigma^\delta t^\phi$$

Find parameters from Dowling Table 15.4

This equation equivalent to the Ramberg-Osgood equation with:

$$n_c = \frac{1}{\delta}$$

$$H_c = \frac{1}{(D_3 t^\phi)^{\frac{1}{\delta}}}$$

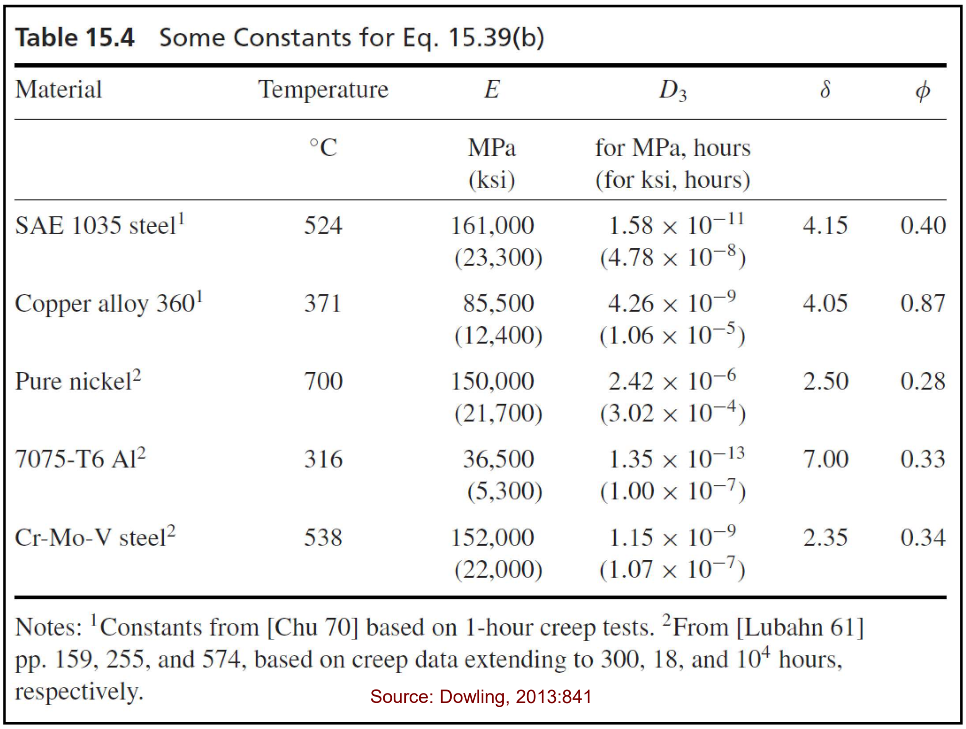


Table 15.4 Some Constants for Eq. 15.39(b)

Material	Temperature	E	D_3	δ	ϕ
	°C	MPa (ksi)	for MPa, hours (for ksi, hours)		
SAE 1035 steel[1]	524	161,000 (23,300)	1.58×10^{-11} (4.78×10^{-8})	4.15	0.40
Copper alloy 360[1]	371	85,500 (12,400)	4.26×10^{-9} (1.06×10^{-5})	4.05	0.87
Pure nickel[2]	700	150,000 (21,700)	2.42×10^{-6} (3.02×10^{-4})	2.50	0.28
7075-T6 Al[2]	316	36,500 (5,300)	1.35×10^{-13} (1.00×10^{-7})	7.00	0.33
Cr-Mo-V steel[2]	538	152,000 (22,000)	1.15×10^{-9} (1.07×10^{-7})	2.35	0.34

Notes: [1]Constants from [Chu 70] based on 1-hour creep tests. [2]From [Lubahn 61] pp. 159, 255, and 574, based on creep data extending to 300, 18, and 10^4 hours, respectively.

Source: Dowling, 2013:841

Variable step loading

Stress range of ith step:

$$\Delta\sigma_i = \sigma_i - \sigma_{i-1}$$

The stress during the ith step:

$$\sigma_i = \sum \Delta\sigma_i$$

Note, the time since stress change $\Delta\sigma_i$:

$$\Delta t = t - t_i$$

The strain at any time:

$$\Delta\varepsilon_i = \Delta\sigma_i f(t - t_i)$$

The total strain is then:

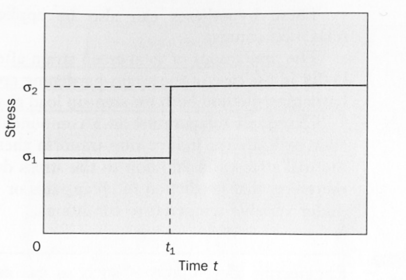
$$\varepsilon = \sum \Delta\varepsilon_i = \sum \Delta\sigma_i f(t - t_i)$$

Strain at any time and stress:

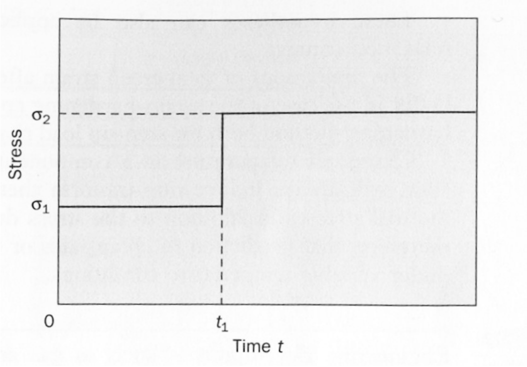
$$\varepsilon = \varepsilon_i + D_3\sigma^{\delta}t^{\Phi}$$
$$= \frac{\sigma}{E} + D_3\sigma^{\delta}t^{\Phi}$$

Creep during variable load or temperature

- Data typically for constant load and constant temperature conditions during creep
- However, in some engineering problems the loading conditions change from time to time at high temperature as shown below



Creep during variable load or temperature



The load is not necessarily cyclic stress in the fatigue sense, but result in different creep rates during each different load sequence

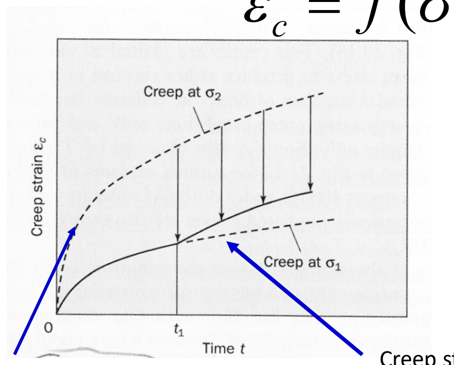
The following hypotheses are proposed to predict the creep behaviour of the metal under the following conditions:

1. Time-hardening
2. Strain hardening

Creep during variable load or temperature

Time hardening

$$\dot{\varepsilon}_c = f(\sigma, t)$$



Creep strain if only σ_2 was applied

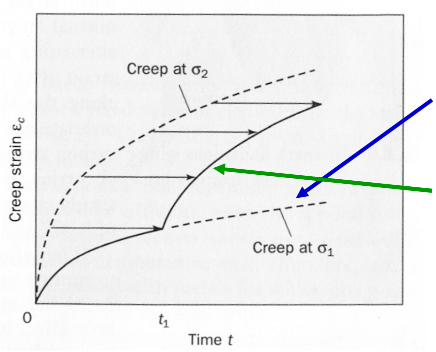
Creep strain if only σ_1 was applied

Creep rate is a function only of the stress and the current time

Creep after the change in stress from σ_1 to σ_2 has the same shape as the constant stress curve from the time change – curve is moved vertically up at same slope as σ_2 curve = **stays parallel to top line as shown**

Creep during variable load or temperature

Strain hardening $$\dot{\varepsilon}_c = f(\sigma, \varepsilon_c)$$



Strain rate depends only on the stress and current plastic strain

Same shape of curve is assumed for σ_1, but now the appropriate portion of the curve, σ_2, from the time of change is moved horizontally – curve shape is essentially repeating itself

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Creep during variable load or temperature

- These hypotheses can also be applied in variable strain-stress relaxation context
  - The prediction of total creep strain after load (stress) change are
    - ❑ Better in the case of the strain-hardening approach compared with time-hardening approach
      - Both for step-up and step-down load change
- Change of temperature
  - Unless extremely slow
    - ❑ Will induce non-uniform thermal strain gadients
    - ❑ Thermal stresses with the stress due to load is applied
    - ❑ Very difficult to predict creep rates under variable temperature conditions

Creep fatigue

- Applications
  - Gas and steam turbines
  - Rockets and supersonic aircraft
- Use metals at very high temperatures and with dynamic fluctuating stresses
  - Mean stress causes creep
  - Alternating component may lead to fatigue failure
  - Problem of fatigue at high temperature
    - ❑ Phenomenon can be unaccompanied by creep for fully reversed or zero mean stress

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Creep fatigue interaction

Rough estimates with Palmgren-Miner rule

Creep only:

$$\sum \frac{\Delta t_i}{t_{ri}} = 1$$

$$B_f \left(\sum \frac{\Delta t_i}{t_{ri}} \right) = 1$$

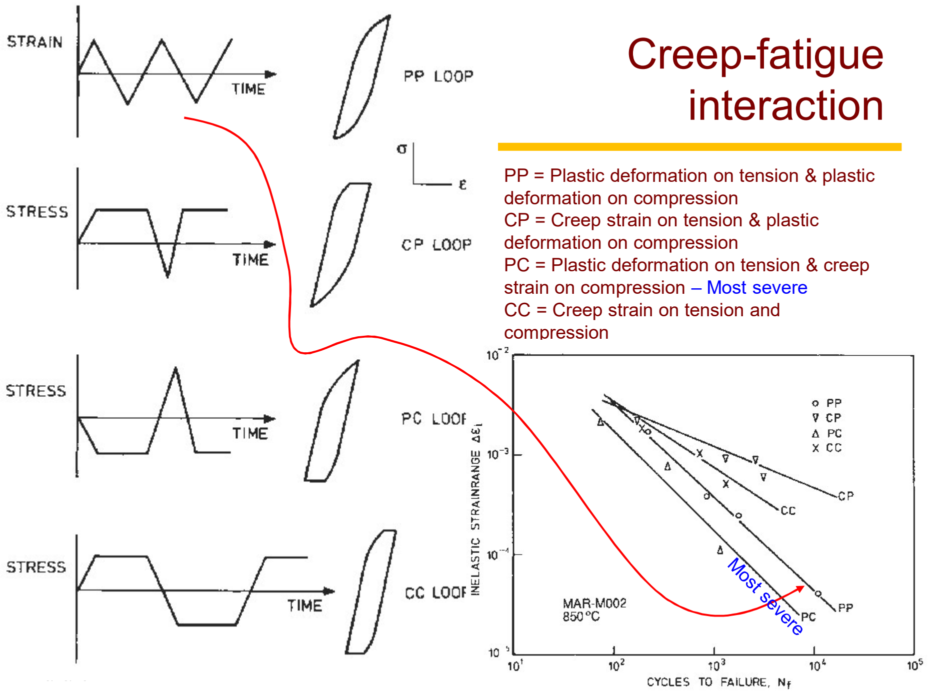
Creep & Fatigue:

$$\sum \frac{\Delta t_i}{t_{ri}} + \sum \frac{N_i}{N_{fi}} = 1$$

Creep fatigue interaction

- Physical processes of creep & fatigue are distinct
- Creep damage may involve grain boundary cracking in engineering materials
- Damage due to fatigue may be concentrated in slip bands within crystal grains
- Frequency of cycling dependent:
  - Slow frequency: Creep have more time
  - High frequency: Fatigue might cause failure
  - Use frequency-modified fatigue approach
- Time variation of stress & strain (figure on next page):
  - Loading with creep in compression only (PC) most severe
    - ❑ Oxide layer cracking
      - Oxidising environment: Oxide surface layer form during compressive creep loading
      - Cracks form under subsequent rapid loading into tension
      - Early cracking results
  - Creep in tension only (CP) gives longest fatigue life

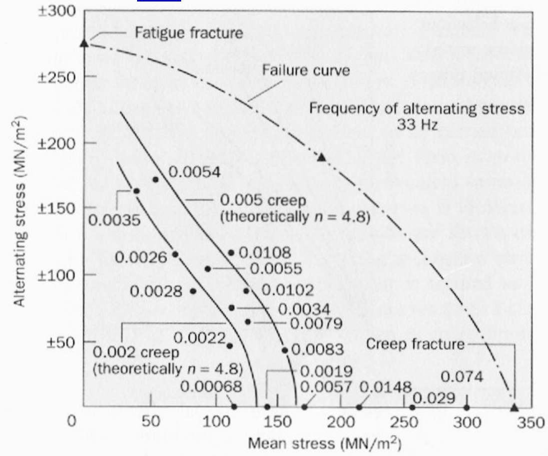
Creep-fatigue interaction



PP = Plastic deformation on tension & plastic deformation on compression
CP = Creep strain on tension & plastic deformation on compression
PC = Plastic deformation on tension & creep strain on compression – Most severe
CC = Creep strain on tension and compression

Creep fatigue

Total creep of 0.26% carbon steel occuring in **100 hours** at **400˚C**



Typical behaviour of creep fatigue in terms of a diagram in which fatigue failure is the criterion within certain stress and temperature limits, and beyond these, creep is the predominant factor

Remember: fatigue is a cycle-dependent mechanism whereas creep is time-dependent

Creep fatigue

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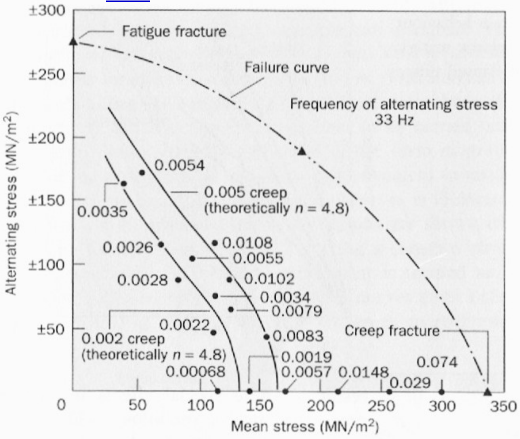

Time to rupture is also important in certain metals because of the greater dependency of fatigue life on cyclic frequency at high temperature

The data on the figure is the combination of alternating and mean stress to produce either rupture or a specified creep strain after a particular **number of hours** at a **constant temperature**

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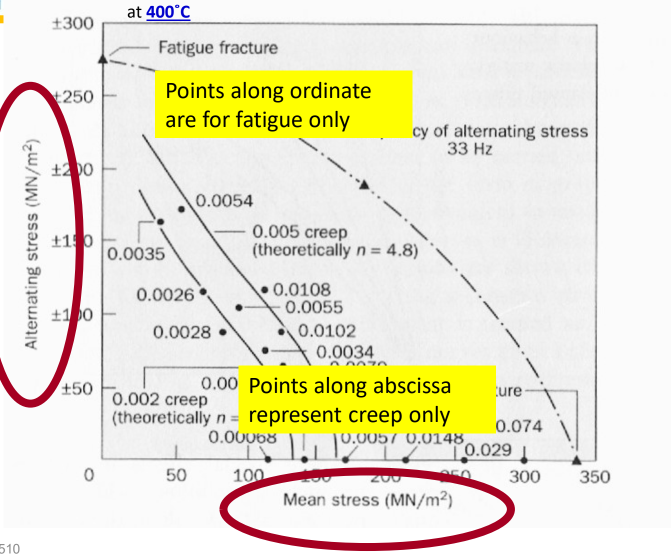
Creep fatigue

Total creep of 0.26% carbon steel occuring in **100 hours** at **400˚C**



Points along ordinate are for fatigue only

Points along abscissa represent creep only

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Creep fatigue

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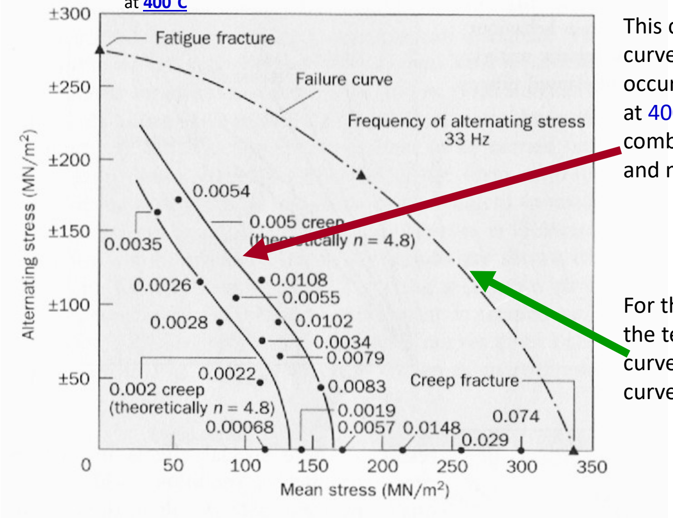
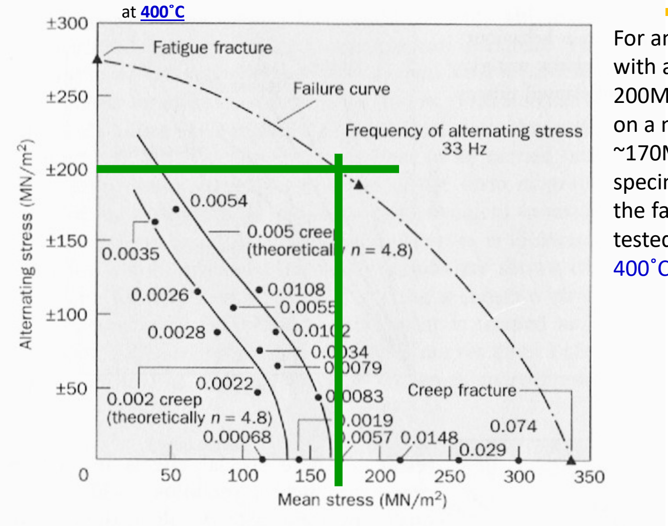


This curve presents a curve where 0.005 creep occurred after 100hours at 400˚C under various combinations of cyclic and mean stress loading

For this material under the test conditions, this curve indicates the failure curve

Creep fatigue

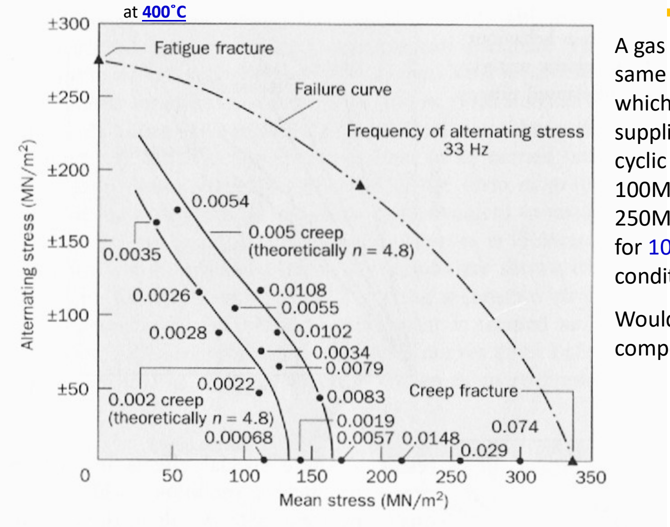
Total creep of 0.26% carbon steel occuring in **100 hours** at **400˚C**



For an alternating stress with amplitude of 200MPa superimposed on a mean stress of ~170MPa, failure of the specimen is predicted by the failure curve when tested for 100hours at 400˚C

Creep fatigue

Total creep of 0.26% carbon steel occuring in **100 hours** at **400˚C**



A gas turbine blade of same material than for which curve on left is supplied, is exposed to a cyclic load with amplitude 100MPa and mean 250MPa and will be used for 100h under these conditions at 400˚C.

Would you expect the component to fail?

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Creep fatigue

- Influence of alternating stress on minimum creep rate and time to rupture
  - ○ Varies considerably with temperature, material and length of time
  - ○ At higher temperatures or long life, alternating stress appear to have little effect on creep rate
    - ☐ There are cases where creep strengthening has resulted under these conditions
  - ○ At lower temperatures or shorter rupture times
    - ☐ Fatigue appears to play more detrimental part – giving higher creep rate

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Remanent Life Assessments

- Classification of creep damage

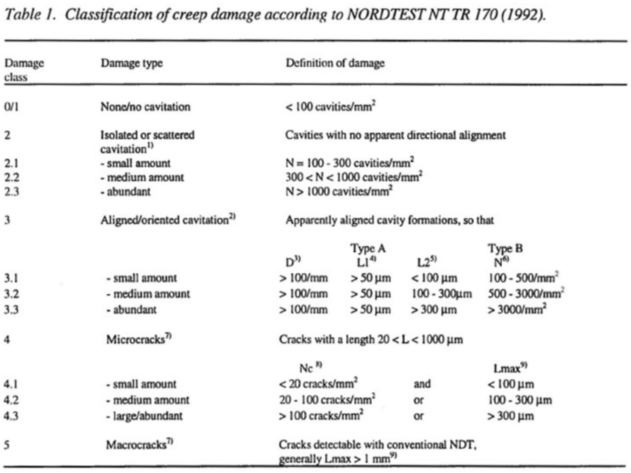
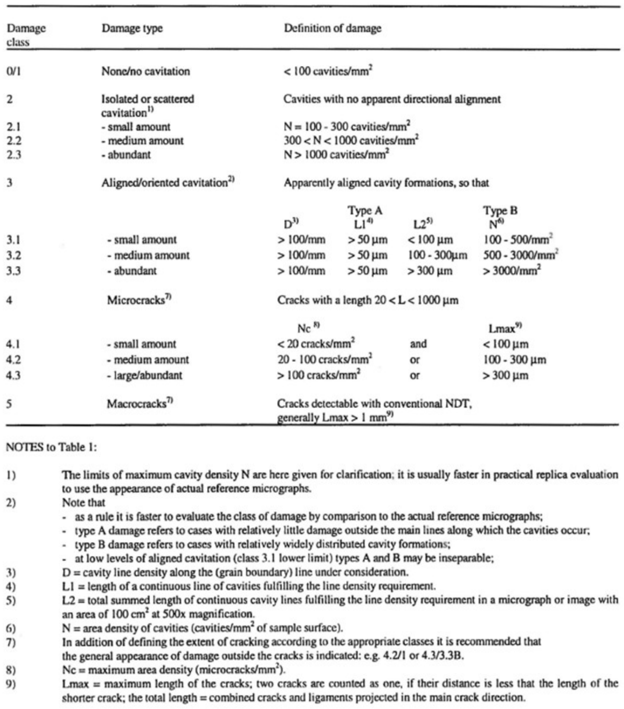


Table 1. Classification of creep damage according to NORDTEST NT TR 170 (1992).

Damage class	Damage type	Definition of damage			
0/1	None/no cavitation	< 100 cavities/mm^2			
2	Isolated or scattered cavitation[1]	Cavities with no apparent directional alignment			
2.1	- small amount	N = 100 - 300 cavities/mm^2			
2.2	- medium amount	300 < N < 1000 cavities/mm^2			
2.3	- abundant	N > 1000 cavities/mm^2			
3	Aligned/oriented cavitation[2]	Apparently aligned cavity formations, so that			
			Type A		Type B
		D[3]	L1[4]	L2[5]	N[6]
3.1	- small amount	> 100/mm	> 50 µm	< 100 µm	100 - 500/mm^2
3.2	- medium amount	> 100/mm	> 50 µm	100 - 300µm	500 - 3000/mm^2
3.3	- abundant	> 100/mm	> 50 µm	> 300 µm	> 3000/mm^2
4	Microcracks[7]	Cracks with a length 20 < L < 1000 µm			
		Nc[8]			Lmax[9]
4.1	- small amount	< 20 cracks/mm^2		and	< 100 µm
4.2	- medium amount	20 - 100 cracks/mm^2		or	100 - 300 µm
4.3	- large/abundant	> 100 cracks/mm^2		or	> 300 µm
5	Macrocracks[7]	Cracks detectable with conventional NDT, generally Lmax > 1 mm[9]			



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3	Aligned/oriented cavitation$^{2)}$	Apparently aligned cavity formations, so that			
		Type A			Type B
		D$^{3)}$	L1$^{4)}$	L2$^{5)}$	N$^{6)}$
3.1	- small amount	> 100/mm	> 50 µm	< 100 µm	100 - 500/mm^2
3.2	- medium amount	> 100/mm	> 50 µm	100 - 300µm	500 - 3000/mm^2
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5	Macrocracks$^{7)}$	Cracks detectable with conventional NDT, generally Lmax > 1 mm$^{9)}$			

NOTES to Table 1:

1) The limits of maximum cavity density N are here given for clarification; it is usually faster in practical replica evaluation to use the appearance of actual reference micrographs.
2) Note that
   - as a rule it is faster to evaluate the class of damage by comparison to the actual reference micrographs;
   - type A damage refers to cases with relatively little damage outside the main lines along which the cavities occur;
   - type B damage refers to cases with relatively widely distributed cavity formations;
   - at low levels of aligned cavitation (class 3.1 lower limit) types A and B may be inseparable;
3) D = cavity line density along the (grain boundary) line under consideration.
4) L1 = length of a continuous line of cavities fulfilling the line density requirement.
5) L2 = total summed length of continuous cavity lines fulfilling the line density requirement in a micrograph or image with an area of 100 cm^2 at 500x magnification.
6) N = area density of cavities (cavities/mm^2 of sample surface).
7) In addition of defining the extent of cracking according to the appropriate classes it is recommended that the general appearance of damage outside the cracks is indicated: e.g. 4.2/1 or 4.3/3.3B.
8) Nc = maximum area density (microcracks/mm^2).
9) Lmax = maximum length of the cracks; two cracks are counted as one, if their distance is less that the length of the shorter crack; the total length = combined cracks and ligaments projected in the main crack direction.

- Average size after 1 000 h at T

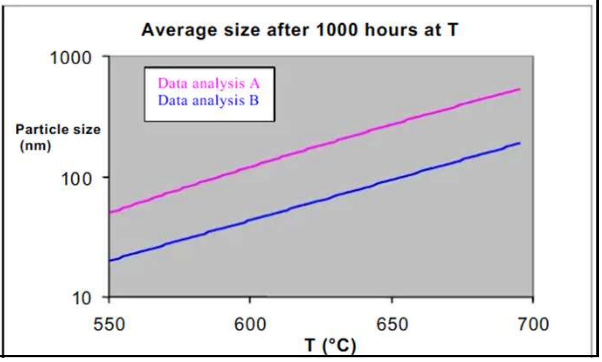


Table 5 Creep Damage and expended life fraction

Damage level	Expended life fraction
1	0.181
2	0.442
3	0.691
4	0.889
5	1.000

Figure 5 Example of Creep Damage Classification and Creep Curve

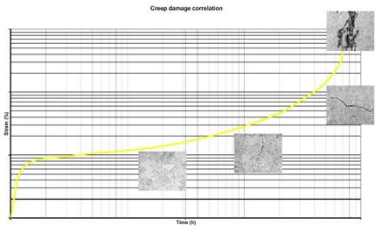
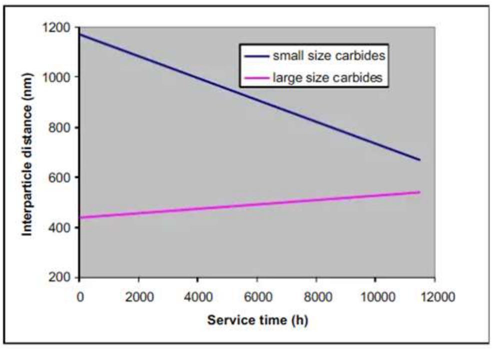


Figure 15 Inteparticle distance and service time for welded X20 steel



Microvoid formation at grain boundaries

- Neubauer classification one of the best to use.
- Micro-cavities appear some time before rupture.
  - Also called micro-voids or micro-cavities.
- Cavities form micro-cracks by interlinkage.
  - Size & density increase as creep progresses from secondary to tertiary stages.
  - Cavity size largely dependent on material type.
  - Cannot be detected by conventional NDT techniques (PT, UT, MT, RT).
    - ☐ Metallographic investigation is required.

How to model

- Linear elastic fracture mechanics (LEFM)
- Use size associated with the classification of creep damage

Standards used for Remaining Life Assessements

- API 617