

13.2 Give three reasons why the extrapolation of creep data obtained over a short period can be dangerous over long periods.

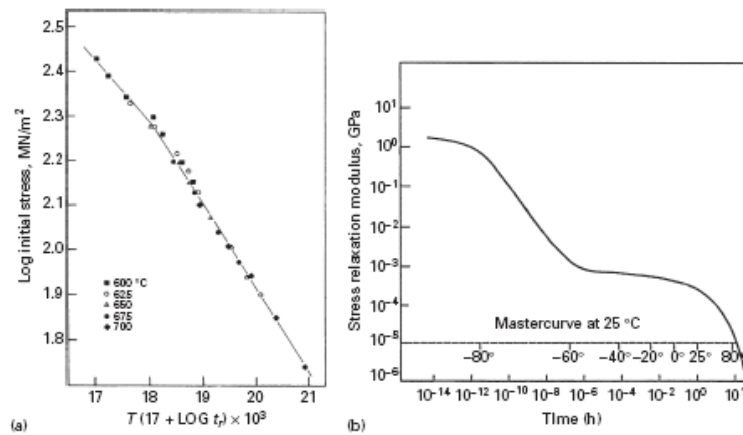
Reliable extrapolation of creep and stress-rupture curves to longer times can be made only when we are sure that no *structural changes* occur in the region of extrapolation. If structural changes did occur, then *they would produce a change in the slope of the curve*. Structural changes generally occur at shorter times for higher temperatures.

Possible structural changes during creep include:

- 1) Slip
- 2) Formation of subgrains, kink bands, and folds at grain boundaries
- 3) Lattice rotations which produce regions of misorientation
- 4) Grain-boundary sliding
- 5) Grain boundary migration
- 6) Internal void formation
- 7) Necking
- 8) Recrystallization
- 9) Grain growth
- 10) Coarsening of precipitate particles
- 11) Diffusional changes in the phases
- 12) Environmental attack

13.4 Howson et al. obtained the following stress-rupture results for the superalloy INCONEL MA 754 (a dispersion-strengthened alloy):

Temperature (°C)	Applied Stress (MPa)	Rupture Life (hours)
760	189.7	—
760	206.9	83.9
760	206.9	111.2
760	224.2	38.6
760	224.2	29.0
760	241.4	6.9
760	258.7	1.8
746	206.9	320.8
774	206.9	65.0
788	206.9	33.2
982	110.4	195.1
982	113.8	136.6
982	113.8	106.9
982	116.5	27.6
982	117.3	106.3
982	120.7	13.0
982	120.7	39.0
996	110.4	52.6
996	110.4	41.3
1010	110.4	20.3
1010	110.4	41.7
1024	110.4	9.4



(a) Verify whether this alloy obeys a Larson--Miller relationship, and find C. Then prepare a master plot, assuming that it does.

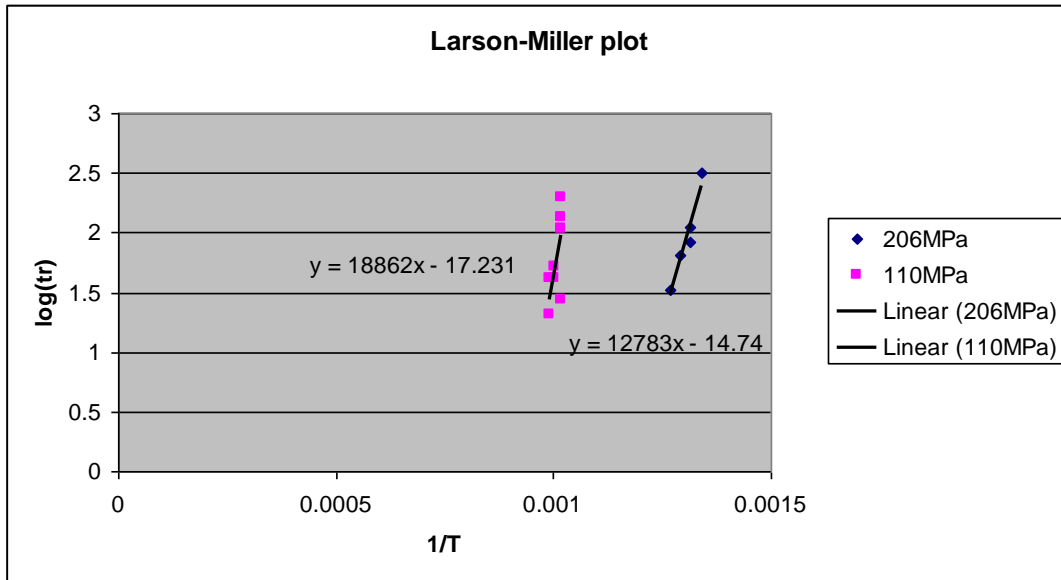
(b) Determine the predicted stress-rupture life if the alloy is stressed at 1,000°C and 50 MPa.

Temp °C	App Stress (MPa)	Rupture life hours	1/Temp (1/°C)	Log(t _r)
760	189.7		0.001315789	
760	206.9	83.9	0.001315789	1.923761961
760	206.9	111.2	0.001315789	2.046104787
760	224.2	38.6		
760	224.2	29		
760	241.4	6.9		
760	258.7	1.8		
746	206.9	320.8	0.001340483	2.50623436
774	206.9	65	0.00129199	1.812913357
788	206.9	33.2	0.001269036	1.521138084
982	110.4	195.1	0.00101833	2.290257269
982	113.8	136.6	0.00101833	2.135450699
982	113.8	106.9	0.00101833	2.028977705
982	116.5	27.6		
982	117.3	106.3	0.00101833	2.026533265
982	120.7	13		
982	120.7	39	0.00101833	1.591064607
996	110.4	52.6	0.001004016	1.720985744
996	110.4	41.3	0.001004016	1.615950052
1010	110.4	20.3	0.000990099	1.307496038
1010	110.4	41.7	0.000990099	1.620136055
1024	110.4	9.4		

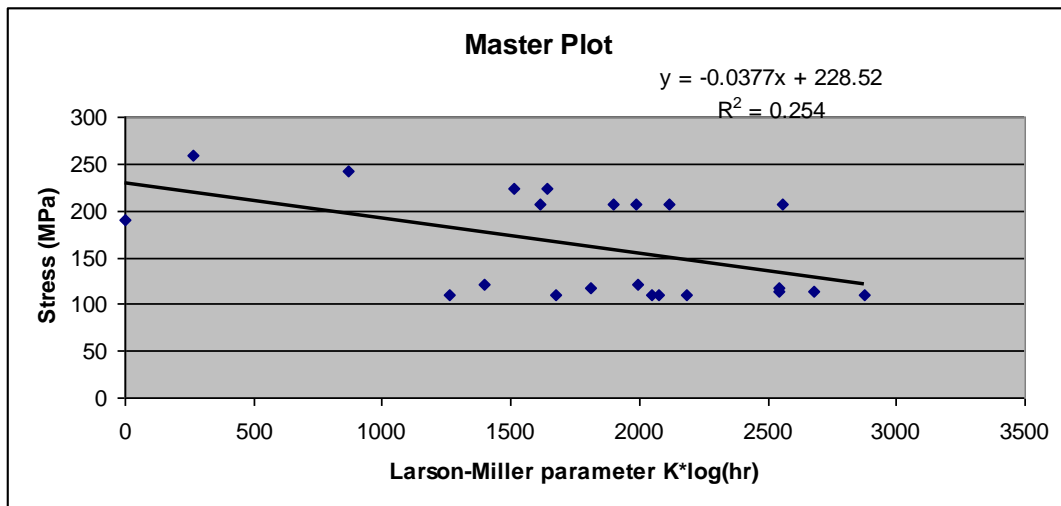
Temp °C	App Stress (MPa)	Rupture life in hours
760	189.7	
760	206.9	83.9
760	206.9	111.2
760	224.2	38.6
760	224.2	29
760	241.4	6.9
760	258.7	1.8
746	206.9	320.8
774	206.9	65
788	206.9	33.2
982	110.4	195.1
982	113.8	136.6
982	113.8	106.9
982	116.5	27.6
982	117.3	106.3
982	120.7	13
982	120.7	39
996	110.4	52.6
996	110.4	41.3
1010	110.4	20.3

1010 110.4 41.7

(a) $c \sim 15$ from Larson-Miller Plot



(b)



$$T(\log t_R + c) = m$$

$$plot, y = -0.0377x + 228.52$$

$$-0.0377 = 1273(\log t_R + 228.52)$$

$$at 50 MPa \& 1273 K$$

$$50 - 228.52 = -0.0377x$$

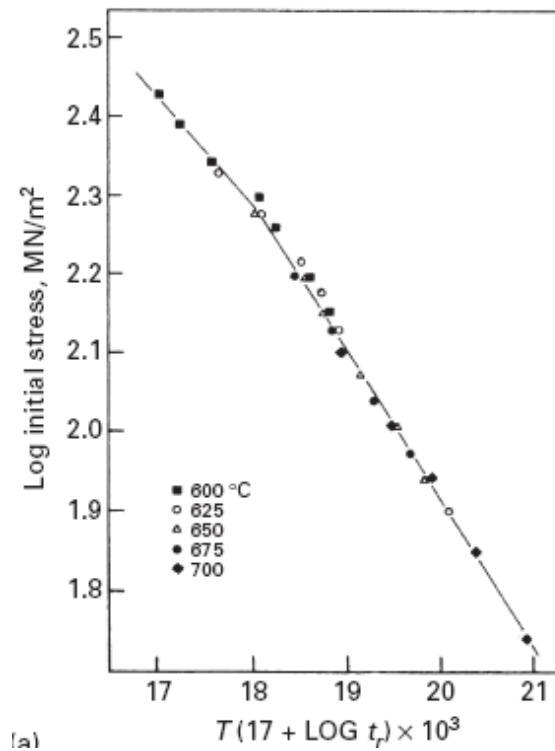
$$x = 4735$$

$$\log(tr) = 4735/1273$$

$$t_R = 10^{3.72}$$

$$t_R = 5.25 * 10^3 h$$

13.5 What is the predicted stress-rupture life of AISI 36 steel (18 %, 8% Ni) at 800 °C and 160 MPa? See figure below.



The initial stress is 160 MPa

$\text{Log } 160 = 2.20$

We can read on the graph that for $\log \sigma = 2.20$,

$$T(17 + \log t_r) = 18.5 \times 10^3$$

where T is the temperature in K and t_r is the time to rupture. $T = 1073 \text{ K}$

$$\log t_r = \frac{18.5 \times 10^3}{T} - 17 = 0.241$$

$$t_r = 1.74 \text{ h}$$

13.6 Verify whether the data of Exercise 13.3 obey the Manson-Haferd correlation.

We use three stress levels:

1.8	MPa
2.0	MPa
2.2	MPa

For each stress level we get values from plot

Stress	$T (17 + \log t_r) \times 10^3$
1.8	20.7
2.0	19.3
2.2	18.7

From these values, we obtain t_r at three temperatures.

T (K)	$\log t_r$ (at 1.8)	$\log t_r$ (at 2)	$\log t_r$ (at 22)
873	6.71	5.11	3.85
923	5.43	3.91	2.72
973	4.23	2.84	1.71

The data are plotted in Manson-Haferd format

$$\frac{\log t_r - \log t_a}{T - T_a} = m$$

$$\log t_a = -16 \quad T_a = 1850 \text{ K}$$

The data fit the Manson-Haferd equation.

13.7 Assuming that pure silver creeps according to the Sherby-Dorn equation, estimate the rupture time at 400 °C when the silver is subjected to a stress of 50 MPa, knowing that at 300 °C and at the same stress level the rupture time is 2000 hours.

Sherby-Dorn equation: $\log t_r - m = 0.43 \frac{Q_c}{kT}$

where t_r ... rupture time
 m ... Sherby-Dorn parameter
 Q_c ... activation energy
 k ... Boltzmann's constant
 T ... temperature

For pure silver (Ag), see figure 13.9, p. 666 in the text: $Q_c = 0.18$ MJ/mole
 Since the activation energy is expressed in J per mole, we must use the universal gas constant, $R = 8.314$ J/mol.K, and not Boltzmann's constant, k .

We need to obtain the Sherby-Dorn parameter, m ; (300 °C → 2000 hours)

$$m = \log t_r - 0.43 \frac{Q_c}{RT} = \log 2000 - 0.43 \frac{0.18 \times 10^6}{8.314 \times 573} = -12.95$$

Applying Sherby-Dorn's equation to 400 °C (673 K yields),

$$\log t_r = m + 0.43 \frac{Q_c}{RT} = -12.95 + 0.43 \frac{0.18 \times 10^6}{8.314 \times 673}$$

$$t_r = 7.7 \text{ hours}$$

13.8 Howson et al. studied the creep and stress-rupture response of oxide-dispersion-strengthened (ODS) superalloys produced by mechanical alloying. They determined that the activation energy for creep Q_c was 619 kJ/mol by conducting tests at a constant applied stress of 558.7 MPa at the three temperatures of 746, 760, and 774 °C.

- a. The results shown in Figure Ex 13.8 were found for experimental alloy MA 6000 E at 760 °C. Estimate the value of n , and discuss this value in terms of the microstructure exhibited by the alloy (made by means of dispersion-strengthening by inert yttrium oxide dispersoids plus precipitation-strengthening gamma prime).

- b. By applying Eq. 13.4, show how the activation energy can be found. Make the appropriate plot, and find the minimum creep rate at the aforementioned three temperatures. Note that the activation energy is given per mole.

a

$$\ln \dot{\epsilon}_{s_1} = \ln A \sigma_1^n - \frac{Q_c}{R} \cdot \frac{1}{T} \quad (1)$$

$$\ln \dot{\epsilon}_{s_2} = \ln A \sigma_2^n - \frac{Q_c}{R} \cdot \frac{1}{T} \quad (2)$$

Subtract (2) from (1):

$$\ln \dot{\epsilon}_{s_2} - \ln \dot{\epsilon}_{s_1} = \ln A \sigma_2^n - \frac{Q_c}{R} \cdot \frac{1}{T} - \ln A \sigma_1^n + \frac{Q_c}{R} \cdot \frac{1}{T}$$

$$\ln \frac{\dot{\epsilon}_{s_2}}{\dot{\epsilon}_{s_1}} = \ln \frac{A \sigma_2^n}{A \sigma_1^n} = \ln \left(\frac{\sigma_2}{\sigma_1} \right)^n = n \ln \sigma_2 / \sigma_1$$

$$\frac{\ln \frac{\dot{\epsilon}_{s1}}{\epsilon_{s1}}}{\ln \frac{\sigma_2}{\sigma_1}} = n$$

$$\dot{\epsilon}_{s1} = \frac{0.86 - 0.32}{(60 - 9.6)} \cdot \frac{1}{100} = 1.07 \times 10^{-4} / \text{hour}$$

$$\dot{\epsilon}_{s2} = \frac{1.39 - 0.39}{(17.8 - 3.6)} \cdot \frac{1}{100} = 7.04 \times 10^{-4} / \text{hour}$$

$$\sigma_1 = 538 \text{ MPa}$$

$$\sigma_2 = 586 \text{ MPa}$$

$$\frac{\ln \frac{7.04 \times 10^{-4} \text{ hour}}{1.07 \times 10^{-4} \text{ hour}}}{\ln \frac{586 \text{ MPa}}{538 \text{ MPa}}} = n = 22.04$$

$n = 22.0$ for MA6000E at 760 °C

Note: Howson, Mervyn, and Tien found $n = 24.0 \pm 2.3$ with 5 data points. Here we used 2 data points, but we still fall within the margin of error, $21.75 \leq n \leq 26.3$

Particle strengthened systems are often characterized by unusually high stress exponents. In many pure metals and solid solution alloys, the stress exponent n is usually between 3 and 5. Stress exponents ranging from 7 to 75 have been observed in oxide dispersion strengthened alloys. In γ \square precipitation strengthened nickel-based superalloys values of n of 7 to 15 have been observed. These anomalies have been rationalized by describing the stress independence of n in terms of an applied stress and a resisting stress against creep. The main contribution to the resisting stress is from the strengthening particles, σ_p , and in these systems it is thought to depend on the particles morphology rather than on applied stress. The equation for n in various precipitation or dispersion-strengthened systems is as follows:

$$n = n_o / [1 - (\sigma_p / \sigma)]$$

where n_o = true stress exponent,

σ = applied stress,

σ_p = particle resisting stress

In MA6000E, it can be argued that the major obstacles to dislocation motion at 70 °C are the γ precipitates. Accordingly, the σ_p should be a reflection of the stress required to shear the precipitates. The high stress exponent n for MA6000E at 760 °C can be described by the above equation. High values of n will result if the particle resisting stress σ_p is a significant fraction of the applied stress σ , and the ratio σ_p/σ for MA6000E at 760 °C was found to be 0.83.

By increasing the matrix strength through solute element additions, stress dependence can be lowered. For a given σ_p , increasing the matrix strength will increase the total resisting stress which will allow an increase in the applied stress necessary to achieve a given creep rate. It follows that for a given σ_p , an increase in the matrix strength can result in a decrease in the ratio σ_p/σ , and thus a decrease in the stress sensitivity of the alloy.

So the large values of n can be attributed to: dispersoids being a major obstacle to dislocation motion at elevated temperature and γ' precipitates being an obstacle to grain boundary sliding at intermediate temperatures.

13.9 In Exercise 13.4 verify how closely the Monkman-Grant relationship is obeyed.

We determine the minimum creep rates from the lines defined by the inflection points:

$$\dot{\epsilon}_1 = 6.9 \times 10^{-4} / h$$

$$\dot{\epsilon}_2 = 1.3 \times 10^{-4} / h$$

$$t_{\dot{\epsilon}_1} = 36.6 h$$

$$t_{\dot{\epsilon}_2} = 180 h$$

Monkman – Grant relationship states

$$\dot{\epsilon} \cdot t_r = \text{constant}$$

$$\dot{\epsilon}_1 \cdot t_{\dot{\epsilon}_1} = 253 \times 10^{-4}$$

$$\dot{\epsilon}_2 \cdot t_{\dot{\epsilon}_2} = 180 \times 10^{-4}$$

A reasonable, but not too close an agreement is found.

13.10 A lead-based alloy (melting point, 327.5°C) was tested at ambient temperature (23 °C) and three engineering stress levels: 8.5, 9 and 10 MPa. The curve that was obtained is shown in Figure Ex13.10.

- (a) From the temperature aspect, establish whether the room temperature is in the creep domain for Pb.
- (b) Obtain the minimum creep rates for the three stress levels.
- (c) Obtain parameters for the curve at 8.5 MPa, as expressed by Equation 13.1.
- (d) Obtain the stress exponent in the Mukherjee--Bird--Dorn equation. Based on this value, what mechanism of creep do you expect?

- a. Let us determine if the room temperature is in the creep domain for Pb.

$$\text{Homologous temperature: } \frac{T}{T_m} = \frac{23 + 273}{327.5 + 273} = 0.5$$

Creep is important in metals when $0.5 T_m < T < T_m$. Thus we are at the beginning of the creep domain.

- b. Obtain the minimum creep rates for the three stress levels. Minimum creep rate = creep rate during stage II (steady-state creep)

$$\text{For } \sigma_e = 8.5 \text{ MPa: } \dot{\epsilon}_s = \frac{\Delta \epsilon}{\Delta t} = \frac{0.08 - 0.07}{1860 - 1140} \approx 1.39 \cdot 10^{-5} s^{-1}$$

$$\text{For } \sigma_e = 9 \text{ MPa: } \dot{\epsilon} = \frac{\Delta \epsilon}{\Delta t} = \frac{0.12 - 0.10}{4140 - 2780} \approx 1.47 \cdot 10^{-5} s^{-1}$$

$$\text{For } \sigma_e = 10 \text{ MPa: } \dot{\epsilon} = \frac{\Delta \epsilon}{\Delta t} = \frac{0.16 - 0.15}{4890 - 4640} \approx 4 \cdot 10^{-5} s^{-1}$$

- c. Obtain parameters for the curve at 8.5 MPa, as expressed by eqn. 13.1 (p. 655)

$$\text{Equation 13.1: } \epsilon_t = \epsilon^o + \epsilon[\gamma - \exp(mt)] + \dot{\epsilon}_s \cdot t$$

At 8.5 MPa:

$$\epsilon^o = 0.04 \text{ (at time } t = 0 \rightarrow \epsilon = \epsilon^o = 0.04)$$

$$\dot{\epsilon} = 1.39 \times 10^{-5} s^{-1} \text{ (from part (b))}$$

13.18 What is the strain undergone by a polymer in tension at 67 °C for one minute if the polymer's strain-rate response is given by $\dot{\epsilon} = 4.5 \times 10^{28} \exp(-200 \text{ kJ}/RT)$?

Using the relationship

$$\epsilon = \dot{\epsilon} \Delta t$$

$$\dot{\epsilon} = 4.5 \times 10^{28} \exp\left(\frac{-200 \times 10^3 \text{ J}}{\left(8.314 \frac{\text{J}}{\text{mole K}}\right) (340 \text{ K})}\right) = 8.43 \times 10^{-3} \text{ s}^{-1}$$

$$\epsilon = (8.43 \times 10^{-3} \text{ s}^{-1})(60 \text{ s}) = 0.5058$$

13.19 A nylon cord has initial stress of 2 MPa and is used to tie a sack. If the relaxation time for this cord is 250 days, how many days will it take for the stress to reduce to 0.1 MPa?

$$\sigma = \sigma_0 \exp\left(-\frac{t}{\tau}\right)$$

$$0.1 = 2 \exp(-t/250)$$

$$t = 978 \text{ days}$$

- 13.20** How much time will it take for a rod of polymer to extend from 20 mm to 30mm at 120°C if it is deformed at a strain rate of

$$\dot{\varepsilon} = 4.5 \times 10^{11} \exp(-100kJ/RT)$$

$$\dot{\varepsilon} = \frac{\Delta\varepsilon}{\Delta t}$$

$$\dot{\varepsilon} = 4.5 \times 10^{11} \exp \left[-100000 / 8.314 \times 393 \right]$$

$$\dot{\varepsilon} = 0.023 \text{ s}^{-1}$$

$$\text{Total strain} = \Delta\varepsilon = \frac{(30-20)}{20} = 0.5$$

$$\therefore \Delta t = \frac{\Delta\varepsilon}{\dot{\varepsilon}}$$

$$\Delta t = \frac{0.5}{0.023} = 21.7 \text{ s}$$

- 13.21** Find the initial stress for a nylon cord, if the relaxation time for the cord is 100 days and in 50 days the stress is reduced to 1 MPa.

$$\sigma = \sigma_0 \exp\left(-\frac{t}{\tau}\right)$$

$$1 = \sigma_0 \exp\left(-\frac{50}{100}\right)$$

$$\sigma_0 = 1.65 \text{ MPa}$$