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UTMATTNING, FKM090

Chapters: 2, 3, 4, 10, 14, 15, 16

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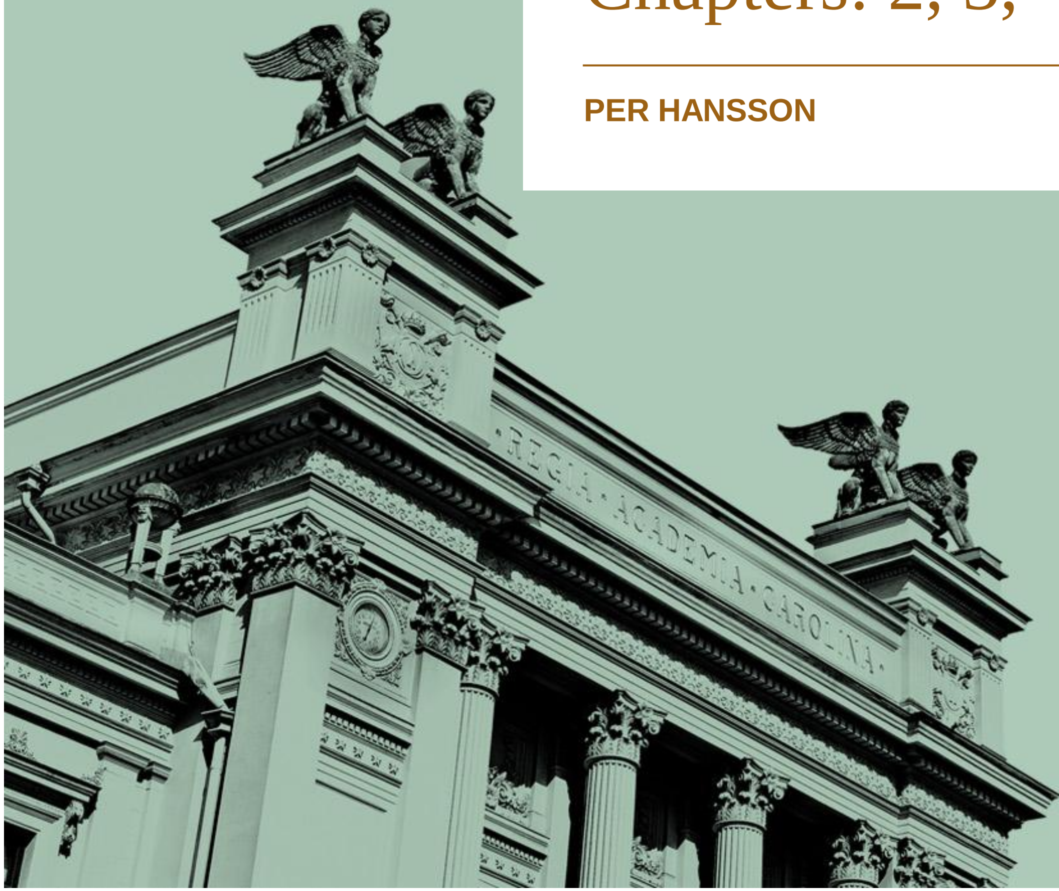

Chapter 3. Cyclic deformation in polycrystalline ductile solids

- Polycristalline metals and alloys.
- Brittle materials are discussed in chapter 5 and 6 (not included in the course).
- A number of different observations and effects have been observed during experiments.

Chapter 3.1 Effects of grain boundaries and multiple slip

- The mechanisms for cyclic damage in single crystals can be applied for the deformation in near surface grains in polycrystalline metals of high purity.
- In most commercial materials precipitates, impurities and GB exists, resulting in different fatigue characteristics than that for monocrystalline materials.
- Exists a lot of data and theories for different classes of materials. Here an representative experimental data and mechanistic interpretation in a broad class of materials on the effect of GB and other impurities.

Chapter 3.1 Effects of grain boundaries and multiple slip (2)

- Studies in polycrystalline metals have found that PSBs can form also within the bulk. Can not pass high angle GBs.
- Also labyrinth and cell structures has been observed at higher strain amplitude.

Chapter 3.1.1 Monocrystalline versus polycristalline FCC metals

- FCC metals oriented for multiple slip usually don't get well defined PSBs and only has a weak plateau (Fig 2.2b).
- Instead a labyrinth structure due to multiple slip and cross slip is formed.
- To better understand the response from polycrystals studies of monocrystal Cu, oriented for multiple slip, have been performed.

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Chapter 3.1.1 Monocrystalline versus polycristalline FCC metals (2)

- The cyclic stress-strain curve for many fine-grained FCC metals can be approximated by a power law equation:

$$\frac{\Delta\sigma}{2} = k\left(\frac{\Delta\epsilon_{\mathrm{pl}}}{2}\right)^{n_{\mathrm{f}}}, \tag{3.1}$$

- This equation can be modified for use on single crystals by employing the Taylor factor M_T.

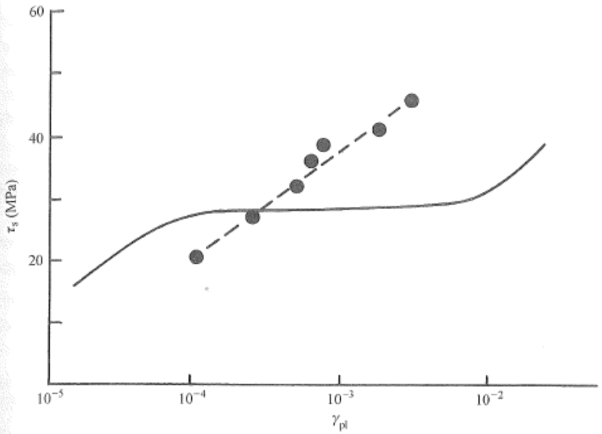

Fig. 3.1. A comparison of the cyclic stress–strain (CSS) curves of Cu single crystals (—) and polycrystals (- - -) at 20 °C. The dashed line is a plot of the stress–strain response of Cu polycrystals (from Lukáš & Kunz, 1985), corrected by the Taylor factor, M_T. The symbols (●) denote the CSS response of Cu single crystals oriented for multiple slip with the loading axis along [001]. (After Gong, Wang & Wang, 1997.)

Chapter 3.1.1 Monocrystalline versus polycristalline FCC metals (3)

- Two general differences distinguishing polycrystalline FCC metals from single crystals oriented for single slip:

  - Grains in a polycrystalline metal have many slip orientations

  -The incompatibility of elastic and plastic deformation between grains promotes local loading and multiple slip.

- For fine-grained FCC metals this leads to multiple slip deformation resembling the response of single crystals oriented for multiple slip.
- For coarse-grained materials resembles that of single-slip oriented monocrystals with low strain hardening or a mild plateau.

Chapter 3.3 Cyclic hardening and softening in polycrystals

- Uniaxial loading of alloys subjected to cyclic loading is characterized by the cyclic stress-strain curve. Different cases depending on type of loading.

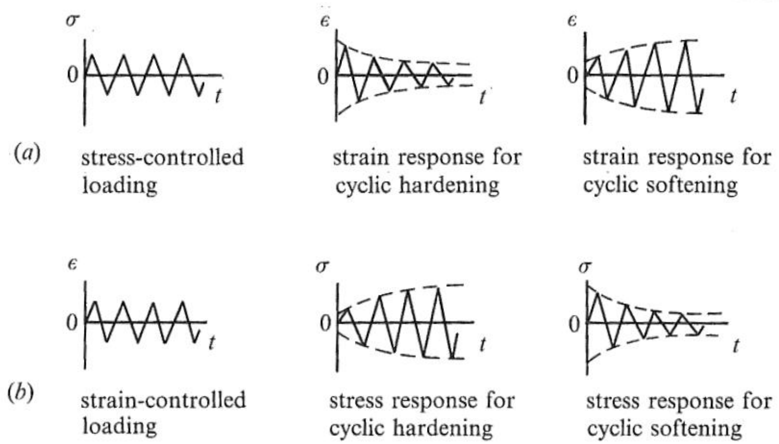

Fig. 3.3. Phenomena associated with transient effects in fatigue. σ, ϵ and t denote stress, strain and time, respectively.

- In both cases a stable saturation value is reached after some initial ‘shakedown’ period. Results in a stable hysteresis loop. During shakedown the dislocation structure changes until a stable configuration is reached.

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Chapter 3.3 Cyclic hardening and softening in polycrystals (2)

- Strain and stress controlled fatigue is extreme cases and usually something in-between is the case. In real engineering components often some structural constraints at fatigue critical sites. Therefore more sense to use strain controlled conditions to obtain a CSS curve.

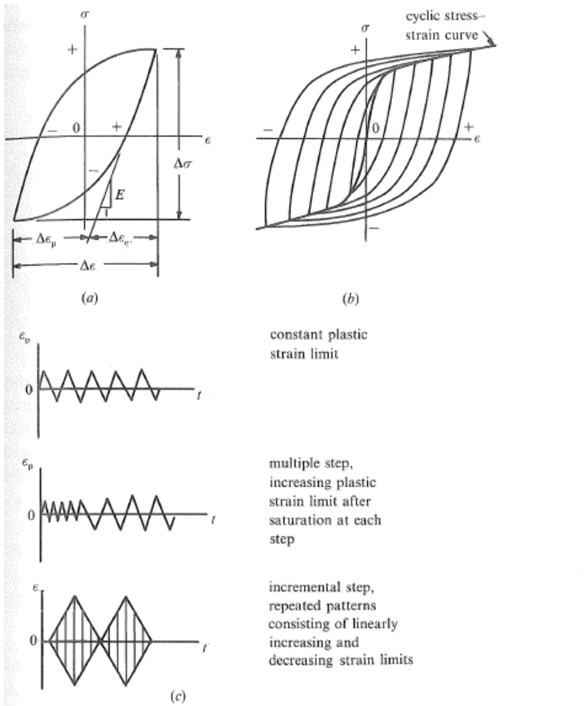

Fig. 3.4. (*a*) A schematic of a stable hysteresis loop and the nomenclature. $\Delta\epsilon_e$, $\Delta\epsilon_p$ and $\Delta\epsilon$ denote the elastic, plastic and total strain range, respectively. (*b*) Cyclic stress–strain curve drawn through the tips of stable hysteresis loops. (*c*) Procedures for obtaining cyclic stress–strain curves.

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Chapter 3.3 Cyclic hardening and softening in polycrystals (2)

- The monotonic stress-strain behavior for ductile solids under tension is represented by a constitutive law, Ramberg-Osgood relation-ship:

$$\epsilon = \frac{\sigma}{E} + \left(\frac{\sigma}{A}\right)^{1/n_m}, \tag{3.4}$$

- For the cyclic stress-strain response:

$$\frac{\Delta\epsilon}{2} = \frac{\Delta\sigma}{2E} + \left(\frac{\Delta\sigma}{2A'}\right)^{1/n_f}, \tag{3.5}$$

- General rule: -Well annealed polycrystalline metals of high purity exhibit cyclic hardening due to dislocation multiplication.

  -Work hardened materials undergo softening due to rearrangement of dislocation networks

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Chapter 3.3 Cyclic hardening and softening in polycrystals (3)

Table 3.1. *Monotonic and cyclic stress–strain characteristics of some common engineering alloys.*

Alloy	Condition	σ_y/σ_y' (MPa)/(MPa)	n_m/n_f
Copper-base			
OFHC	Annealed	20/140	0.40/0.24
Brass 365	As-rolled	172/248	0.13/0.21
Cu–Be 172	As-drawn	641/490	0.02/0.15
Aluminum-base			
2024	T4	303/448	0.20/0.09
6061	T651	290/296	0.04/0.10
7075	T6	469/517	0.11/0.10
Iron-base			
SAE 1015	Normalized	225/240	0.26/0.22
Ferrovac E	Annealed	48/159	0.36/0.19
SAE 1045	Q+T	1365/825	0.08/0.15
AISI 4340	Q+T	1172/814	0.07/0.15
Mar M-300	Annealed	952/800	0.03/0.08

σ_y and σ_y' refer to monotonic and cyclic yield strengths, respectively.
Q and T refer to quenched and tempered conditions, respectively.
Source: Landgraf (1978) and Hertzberg (1995).

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Chapter 3.6 The Bauschinger effect

- The Bauschinger effect is an experimental result that after a certain amount of plastic deformation, in tension or compression, the yield stress is lowered if the loading direction is reversed.
- Essential for development of constitutive models for complex cyclic deformation, understanding of work hardening and for rationalizing fatigue effects such as mean stress relaxation and cyclic creep.
- Example: Many Al alloys are stretched prior to temper treatments. Exhibits Bauschinger effect when loaded in compression resulting in low flow stress. Can persist even after stable hysteresis loop are stabilized.

Chapter 3.6 The Bauschinger effect

- Mechanism: Originates from the change in dislocation structure due to change in loading direction. In polycrystalline materials dislocation walls and subgrain boundaries forms during forward straining. Dissolves upon stress reversal contributes to the Bauschinger effect.
- Quantifying the Bauschinger effect

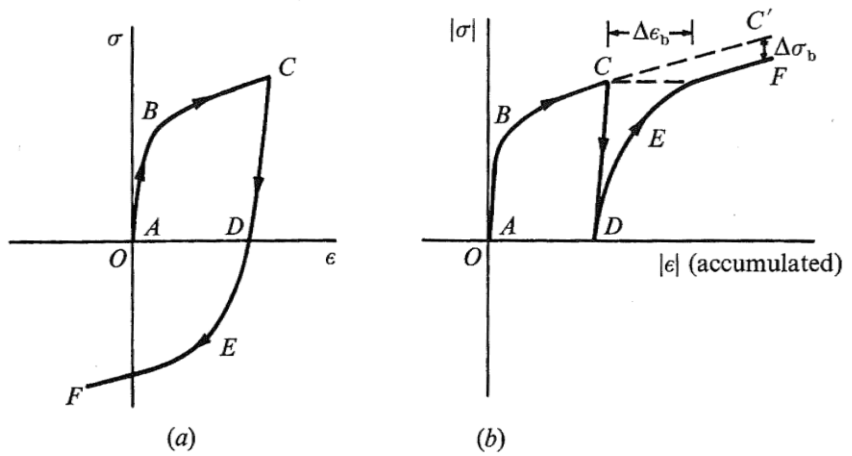

Fig. 3.6. (*a*) Schematic of the stress–strain curve for fully reversed loading. (*b*) Only the magnitudes of the stress and the accumulated strain are replotted to illustrate the Bauschinger effect.

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Chapter 3.7 Shakedown

- Ductile metals are often subjected to cyclic loads which build up residual stresses for example in ball bearings and railway rails.
- Can be of such magnitude that when steady state is reached, after some load cycles, the deformation is entirely elastic. No net accumulation of plastic strain in following load cycles, *shakedown*. Note, the maximum applied load is above the yield stress. The limit value for the applied load for this to occur is called *shakedown limit*.
- If the limit is exceeded plastic strain continuous to accumulate in each cycle. This is commonly called *ratchetting*, *cyclic creep* or *incremental collapse*.

Chapter 3.7 Shakedown

- Conditions governing the occurance of shakedown, called shakedown theorems.
  - Statical, lower-bound theorem
  - Kinematical, upper-bound theorem
- *Elastic shakedown*, development of residual stresses results in a steady state that is purely elastic.
- *Plastic shakedown*, close cycle of alternating plasticity without accumulation of plastic strains, ratchetting or incremental collapse (Chapter 13).

Chapter 3.9 Cyclic creep and ratchetting

- A fixed cyclic stress amplitude can give rise to *cyclic creep* or *ratchetting* if the plastic deformation during loading is not opposed by equal amount of yielding during reverse loading.
- Two examples for an fatigue softening material:

  a) tensile mean stress

  b) compressive mean stress

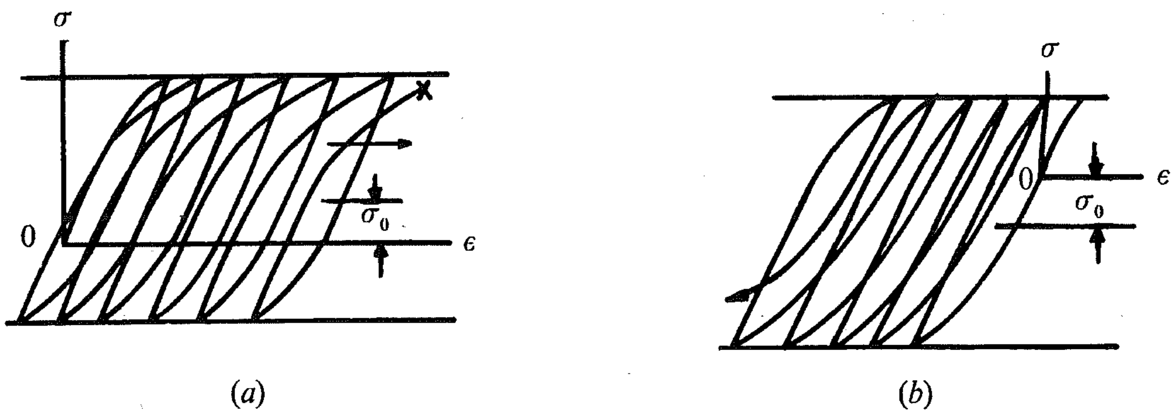

Fig. 3.13. Cyclic creep under (*a*) tensile and (*b*) compressive mean stress.

Chapter 3.9 Cyclic creep and ratchetting (2)

a) Cyclic creep in the direction of the increasing tensile strain. Damage accumulation due to two processes.

1) Increase of plastic strain cycle by cycle due to cyclic softening

2) Displacement of the mean strain to higher strain levels

b) Increases the tendency for buckling (Fig. 3.13b)

- Can also be found in the case of equal tension-compression loading in materials with yield anisotropy e. g. cast iron and composite materials.

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