Chapter Ⅰ Failure analysis of machine element

Common failure classes:

Excessive deformation

Fracture

Fatigue

Wear

High temperature creep

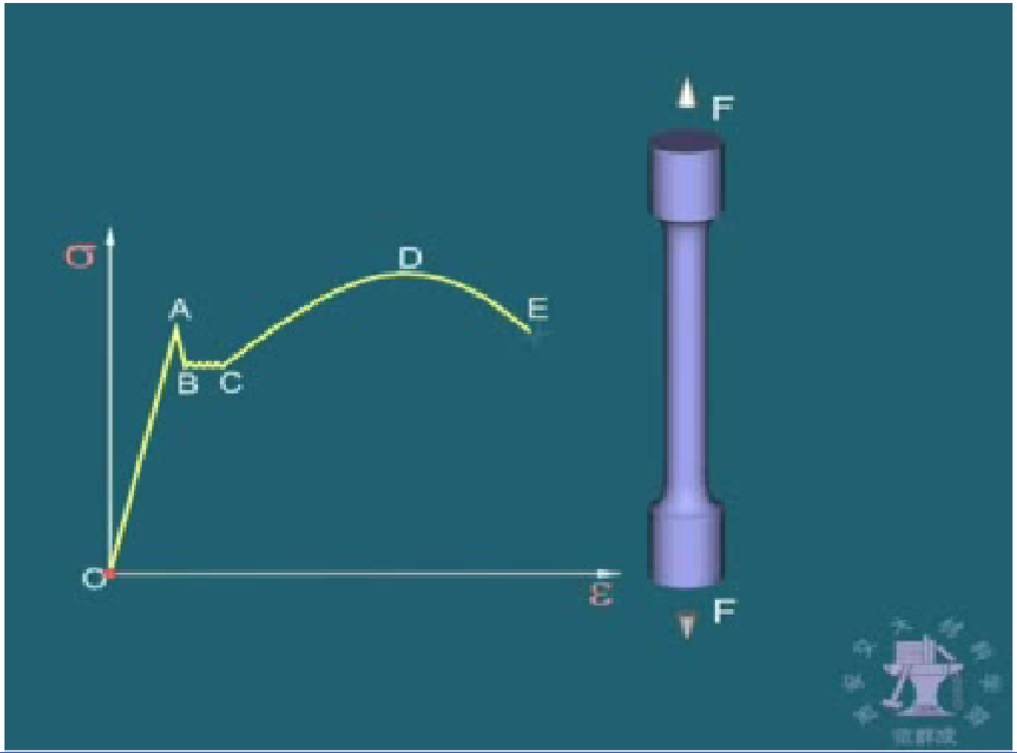
Corrosion

THE END

§ 1-1 The excessive deformation of parts at room temperature and on dead load

1.1.1 Stress-strain behavior of engineering materials in dead tension

1. Stress-strain behavior of annealed low carbon steel



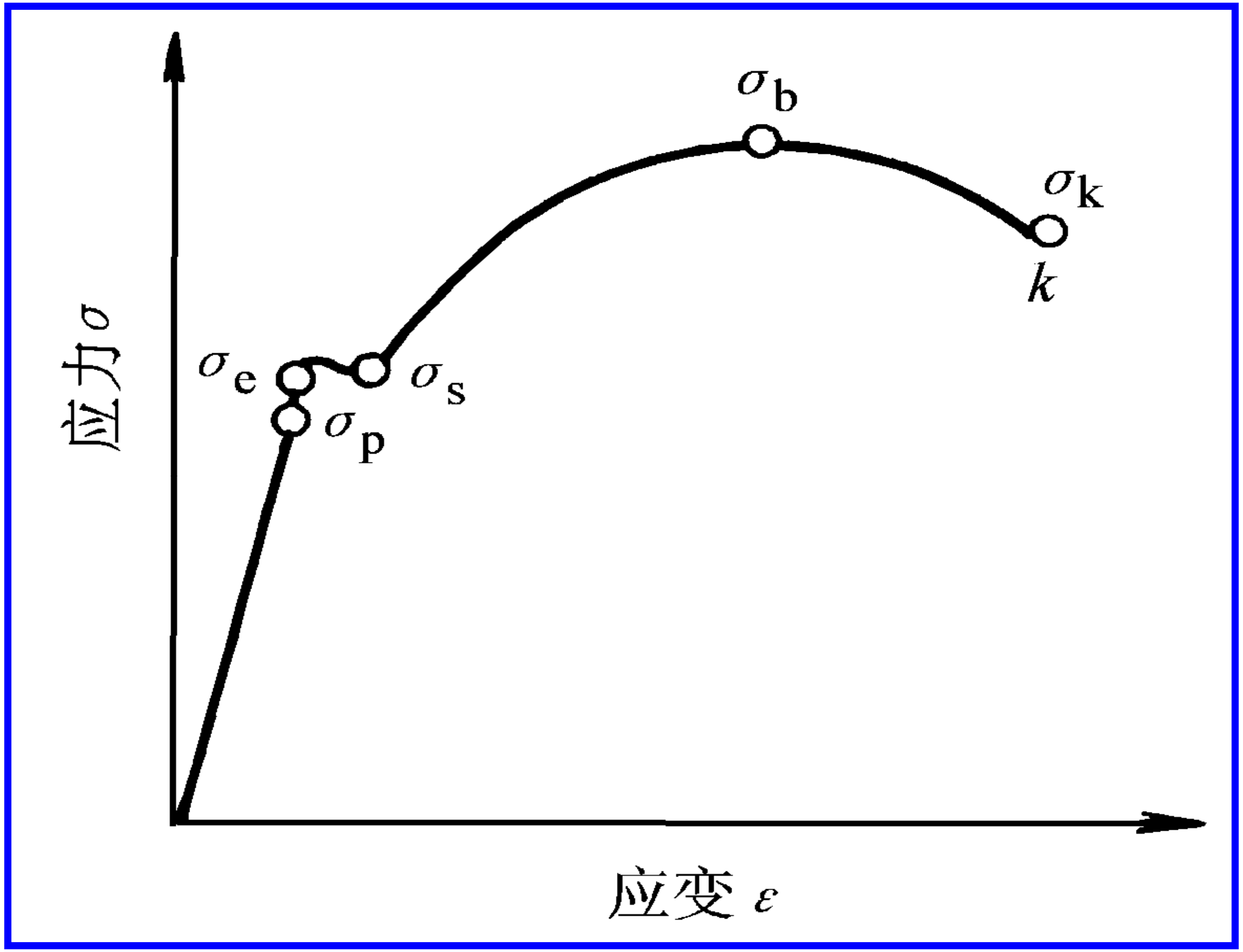
OA: elastic deformation

ABC: yield

CDE: plastic deformation

E: fracture

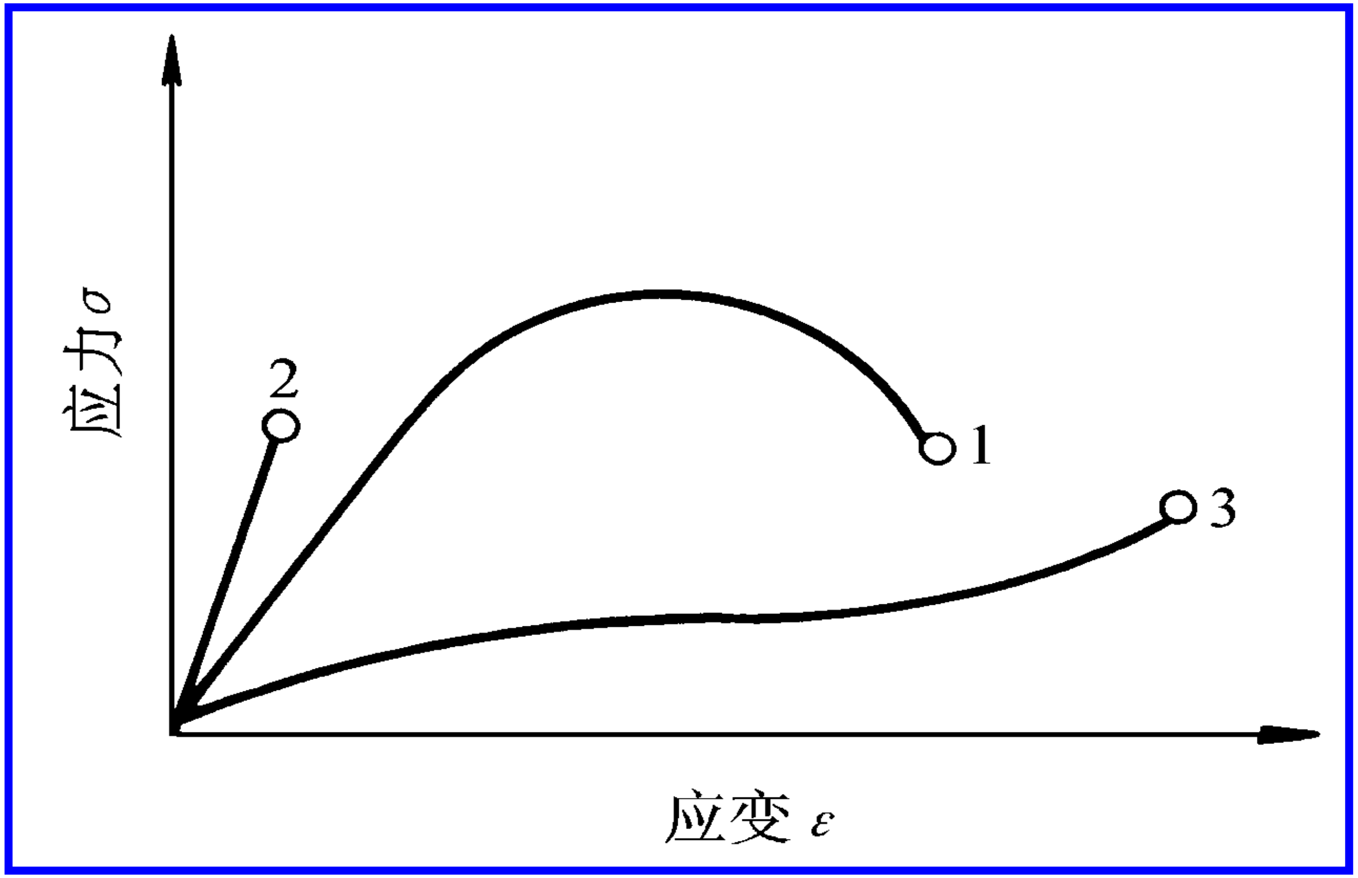
THE END



Stress-strain curve of annealed low carbon steel

THE END

2. Stress-strain behavior of other type of materials



Stress-strain curves of other materials

1-- pure metals, 2-- brittle materials, 3-- high elastic materials

THE END

1.1.2 Indexes of property on dead load

1. Stiffness

- For one-way tension (or compression):

E — elastic modulus

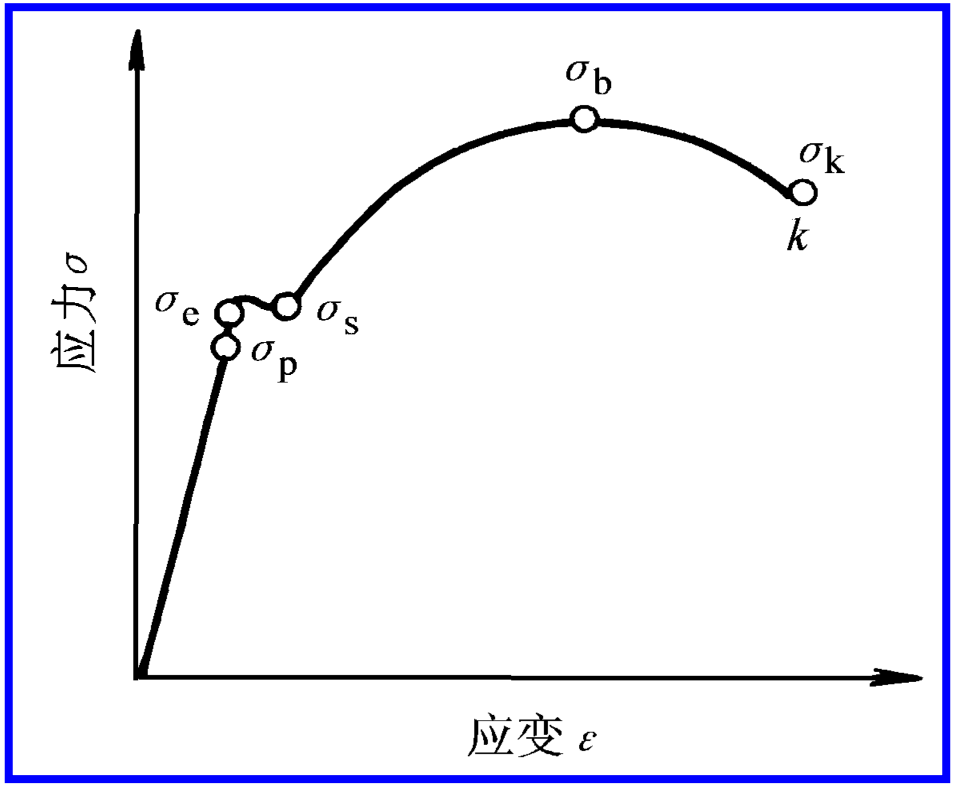
- For pure shear:

G — shear modulus

THE END

2. Strength

- σ_p — proportional limit
- σ_e — elastic limit
- σ_s — yield strength
- σ_b — tensile strength
- σ_k — fracture strength



Stress-strain curve of annealed low carbon steel

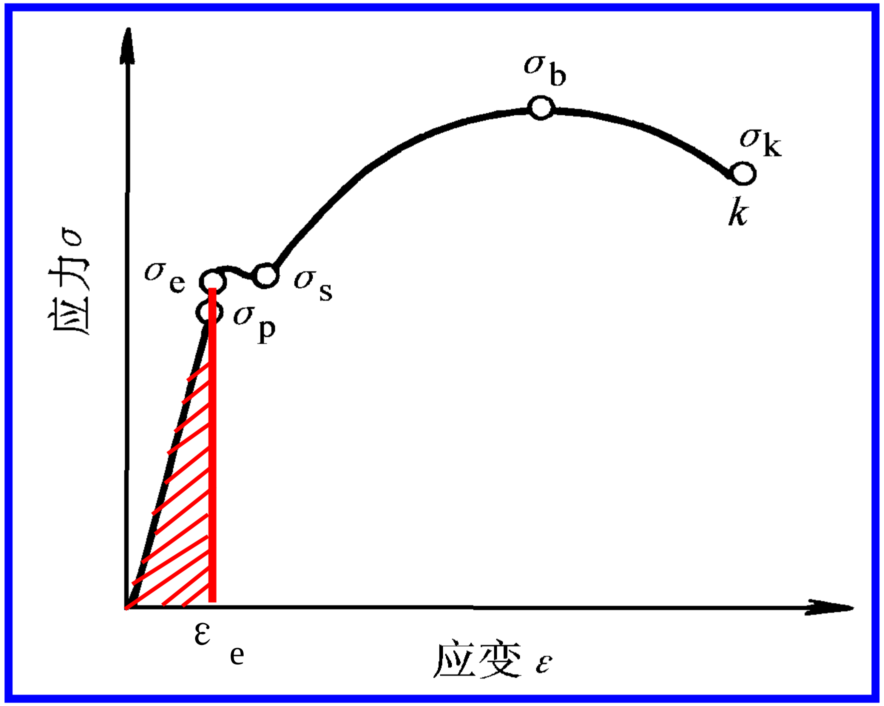
THE END

3. Elasticity

- E — elastic modulus $E = \dfrac{\sigma}{\varepsilon}$
- G — shear modulus $G = \dfrac{\tau}{\gamma}$
- ε_e — max-elastic strain
- u — elastic energy

$$u = \frac{1}{2}\sigma_e \varepsilon_e = \frac{1}{2}\frac{\sigma_e^2}{E}$$

THE END



Elastic energy

4. Plasticity

- Tensile elongation

$$\delta = \frac{L - L_0}{L_0} \times 100\%$$

- Contraction ratio of area at fracture face

$$\psi = \frac{A_0 - A}{A_0} \times 100\%$$

THE END

5. Hardness

- Brinell hardness HBS

THE END

- Rockwell hardness HRC

THE END

- Vickers hardness HV

THE END

1.1.3 Failure of excessive elastic deformation

1. Phenomenon

2. Cause

Insufficient Stiffness $$\frac{P}{\varepsilon} = EA$$

3. *Solution*
   - select materials that have higher E
   - increase A of parts

THE END

表 1-1　各类材料的室温弹性模量 E

材　料	E/(10⁴MPa)	材　料	E/(10⁴MPa)
金钢石	102	铜(Cu)	12.6
WC	46～67	铜合金	12.2～15.3
硬质合金	41～55	钛合金	8.1～13.3
Ti,Zr,Hf 的硼化物	51	黄铜及青铜	10.5～12.6
SiC	46	石英玻璃	9.5
钨(W)	41	铝（Al）	7.0
Al_2O_3	40	铝合金	7.0～8.1
TiC	39	钠玻璃	7.0
钼及其合金	32.5～37	混凝土	4.6～5.1
Si_3N_4	30	玻璃纤维复合材料	0.7～4.6
MgO	25.5	木材(纵向)	0.9～1.7
镍合金	13～24	聚酯塑料	0.1～0.5
碳纤维复合材料	7～20	尼龙	0.2～0.4
铁及低碳钢	20	有机玻璃	0.34
铸铁	17．3—19．4	聚乙烯	0.02～0.07
低合金钢	20.4～21	橡胶	0.001～0.01
奥氏体不锈钢	19.4～20.4	聚氯乙烯	0.0003～0.001

1.1.4 Failure of excessive plastic deformation

1. Phenomenon

2. Cause

Insufficient strength

σ_e or σ_p or σ_s

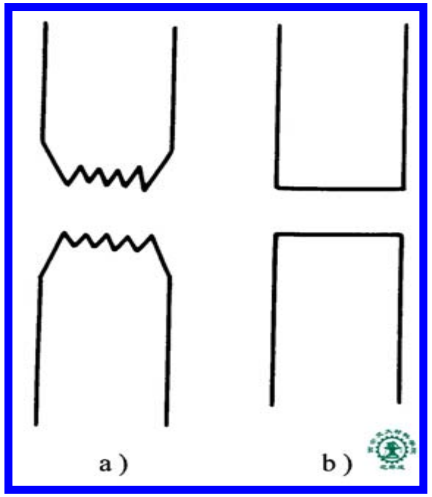
3. *Solution*
- select materials that have higher σ_e or σ_p or σ_s
- increase the σ_e or σ_p or σ_s of materials

THE END

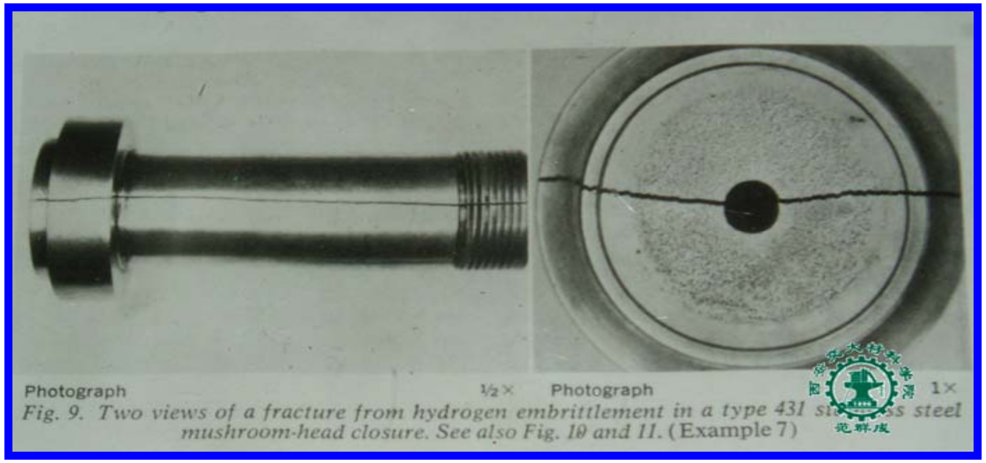
§ 1-2 Fracture of parts on dead or impact load

1.2.1 Basic concepts of ductile fracture and brittle fracture

1. Ductile fracture



2. Brittle fracture



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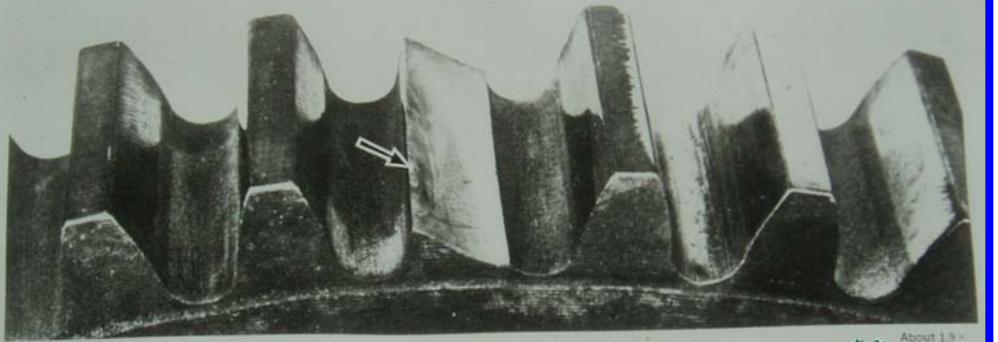


Failure-Analysis Fractographs: Bending-Fatigue Fractures in a 1045 Steel Transmission Gear and a 1045 Steel Crankshaft

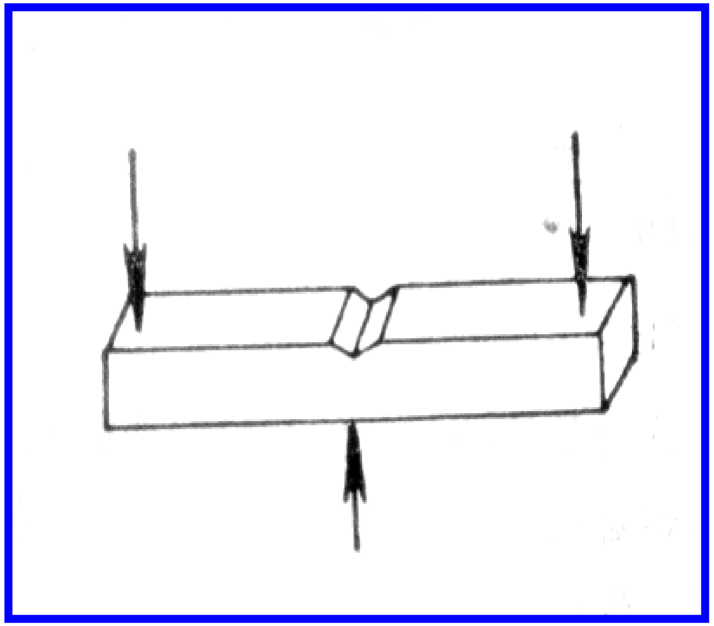
About 1.9 ×

Photograph 4877 A bending-fatigue fracture in a ⅝-in. constant-mesh transmission gear of 1045 steel, induction hardened to [illegible] 55 at the surface. The arrow indicates the crack origin at the left edge of the fracture, where a small pit existed ne[illegible] the contact area on the pressure side of the tooth. See also fractograph 4878, below.

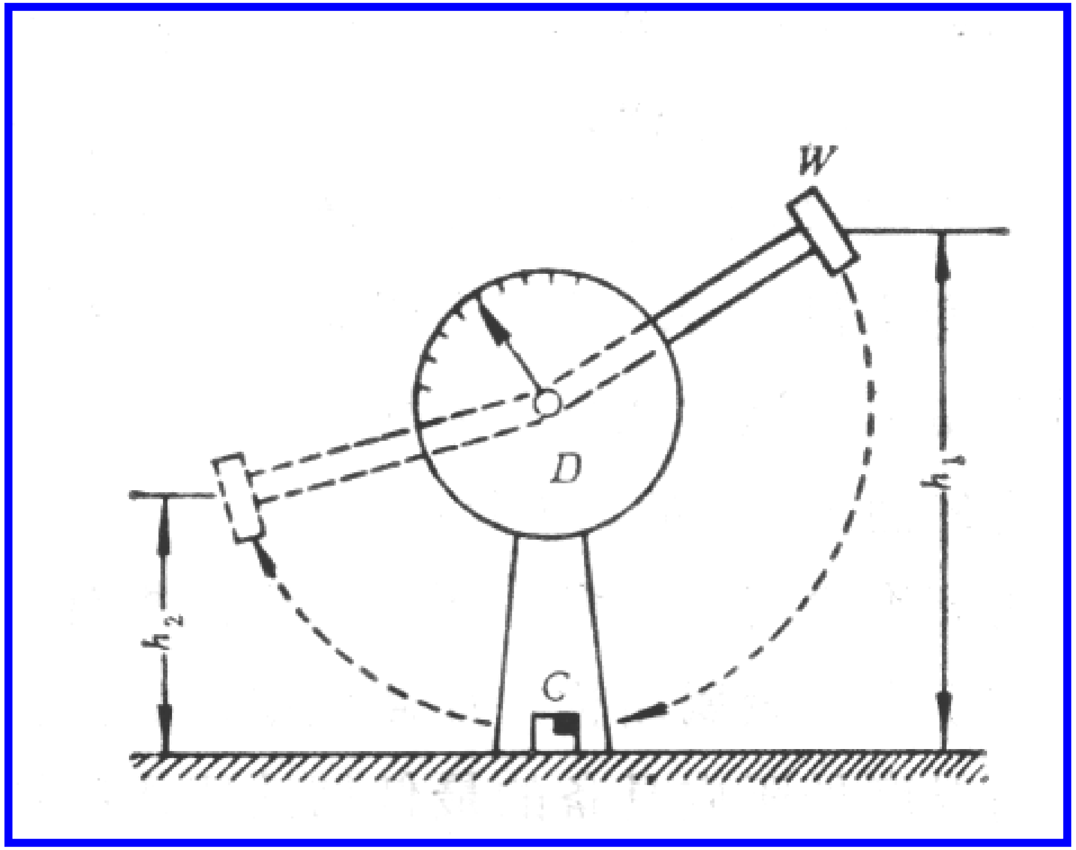
THE END

1.2.2 Impact toughness and its index

1. Impact test



The specimen for impact test



Principle illustration of impact test

THE END

2. Impact toughness

3. Impact toughness index — a_K

$$a_K = \frac{A_K}{F_K} \quad (J \cdot cm^{-2})$$

A_K --- Impact work (J)

F_K --- Area of fracture face (cm^2)

THE END

4. The relationship between the impact toughness and temperature

- The impact toughness decreases with decreasing temperature

- There is a ductile-brittle transition temperature

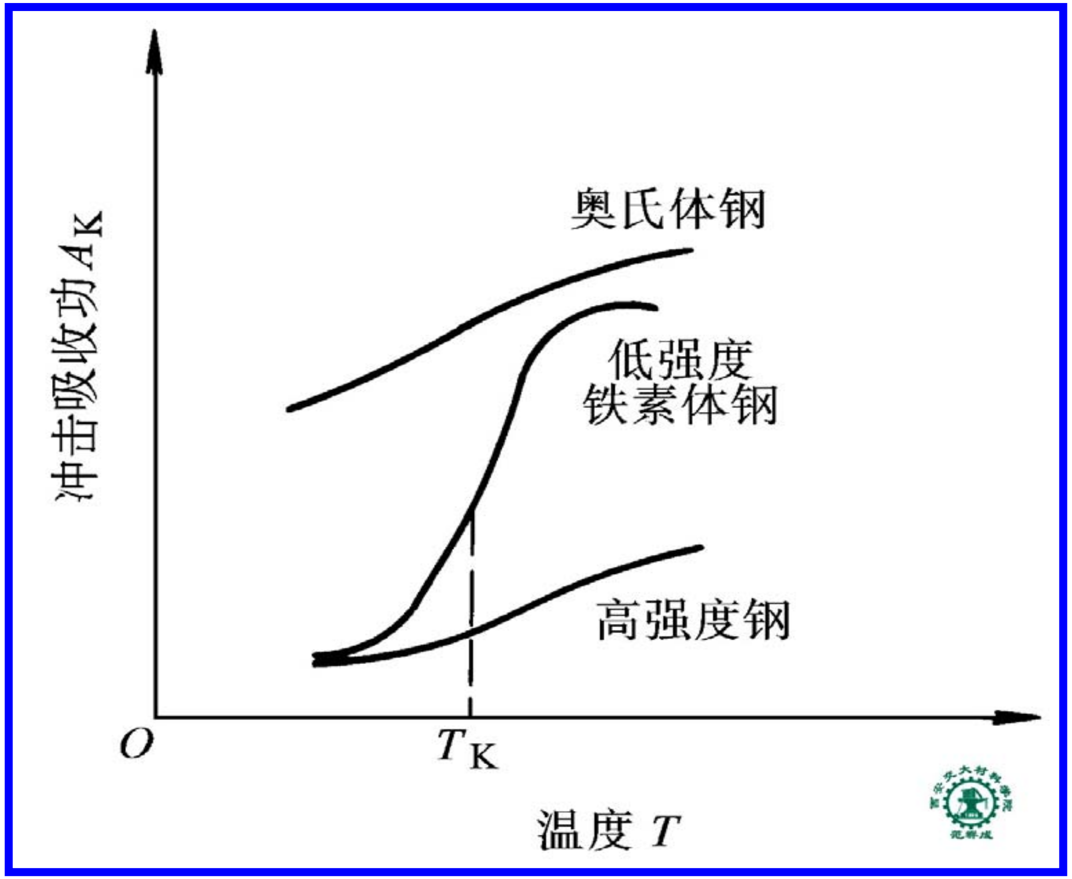


Diagram of change in impacttoughness of three kinds of steels with temperature

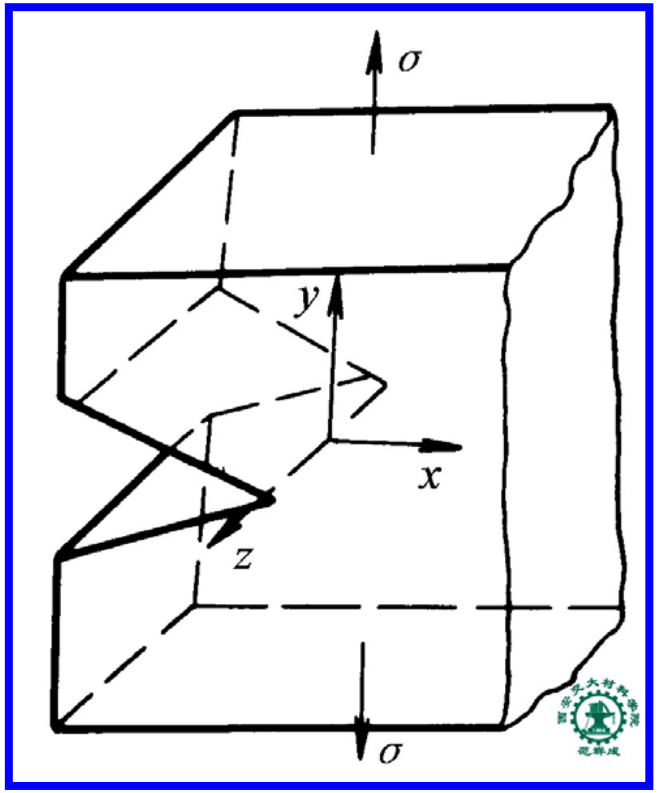
THE END

1.2.3 Fracture toughness and its index

1. Fracture toughness
2. Fracture toughness index

For the crack of type Ⅰ

$$K_{IC} = Y\sigma\sqrt{a} \quad (MPa \cdot m^{1/2})$$



open-crack (type I)

σ — tensile stress

a — length of half a crack

Y — a factor of geometric form of the crack of type Ⅰ

$Y \approx 1 \sim 2$

THE END

3. Application of K_{IC} to engineering design

- Application to selection of materials

As the known σ and a , $K_{IC} > Y\sigma\sqrt{a}$

- Application to definition of maximum tensile stress σ_{max}

As the known K_{IC} and a_{max}, $\sigma_{max} < \dfrac{K_{IC}}{Y\sqrt{a_{max}}}$

- Application to definition of maximum length of crack a_{max}

As the known K_{IC} and σ , $a_{max} < \left(\dfrac{K_{IC}}{Y\sigma}\right)^2$

THE END

4. Solutions of increasing K_{IC} of materials

- By alloying
- By heat treatment

THE END

1.2.4 Influence factors on the brittle fracture

- Nature of materials

表 1-2 常见工程材料的断裂韧度 K_{IC} 值

材料	$K_{IC}/MN.m^{-3/2}$	材料	$K_{IC}/MN.m^{-3/2}$
塑性钝金属(Cu、Ni、Al、Ag等)	100～350	聚苯乙烯	2
转子钢（A533 等）	204～214	木材，裂纹平行纤维	0.5～1
压力容器钢（HY130）	170	聚碳酸酯	1.0～2.6
高强度钢	50～154	Co/WC 金属陶瓷	14～16
低碳钢	140	环氧树脂	0.3～0.5
钛合金(Ti6Al4V)	55～115	聚脂类	0.5
玻璃纤维(环氧树脂基体)	42～60	Si_3N_4	4～5
铝合金(高强度-低强度)	23～45	SiC	3
碳纤维增强的聚合物	32～45	铍	4
普通木材，裂纹和纤维垂直	11～13	MgO	3
硼纤维增强的环氧树脂	46	水泥/混凝土，未强化的	0.2
中碳钢	51	方解石	0.9
聚丙烯	3	Al_2O_3	3-5
聚乙烯（低密度）	1	油页岩	0.6
聚乙烯（高密度）	2	苏打玻璃	0.7～0.8
尼龙	3	电瓷瓶	1
钢筋水泥	10～15	冰	0.2[①]
铸铁	6～20		

THE END

- Loading mode
- Temperature and loading velocity
- Stress concentration

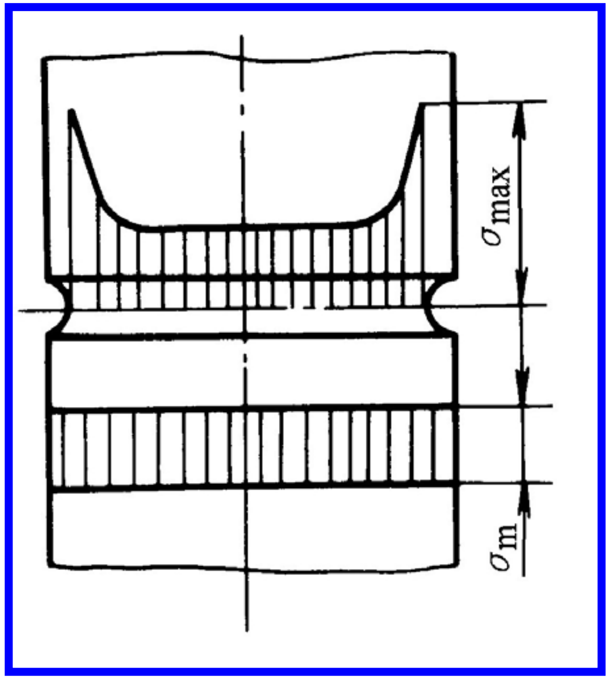


Diagram of stress concentration at notch on dead load

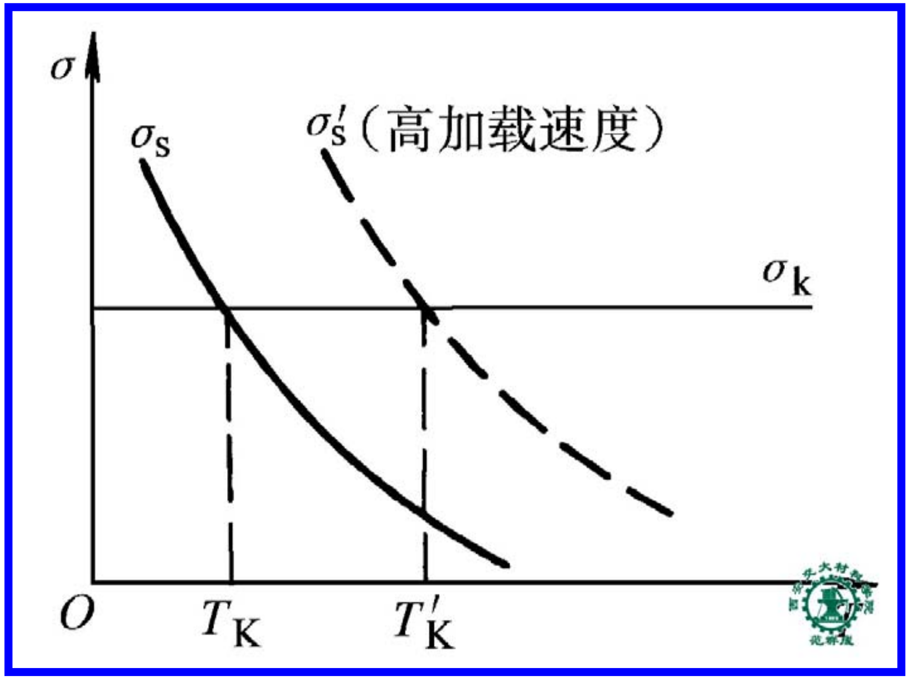


Diagram of change in yield strength with temperature

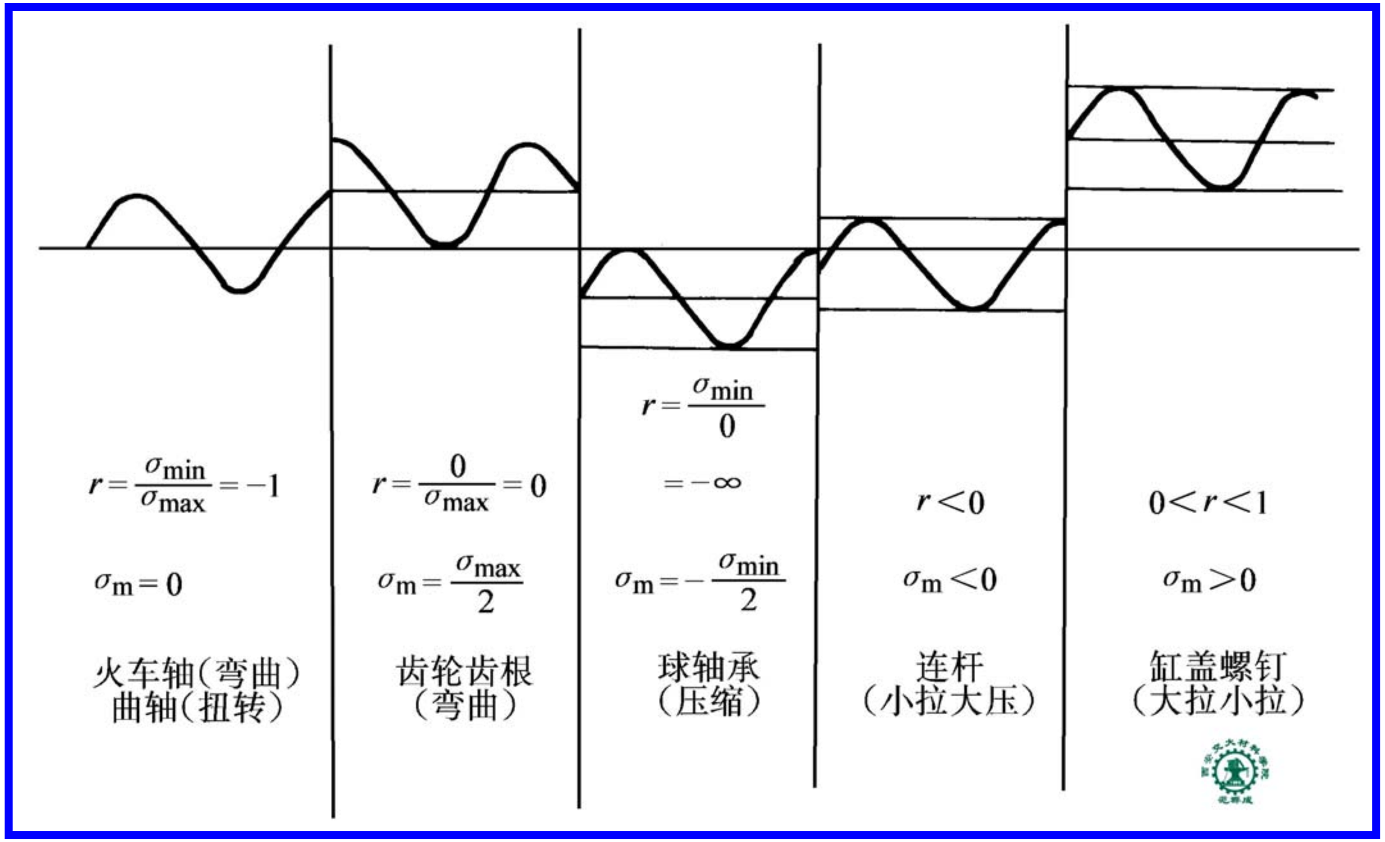
- Size of parts

THE END

§ 1-3 Fatigue fracture of parts on alternating load

1.3.1 Basic concepts of fatigue fracture

1. Alternating load



THE END

Several common kinds of alternating stress

THE END

THE END

THE END

THE END

THE END

2. Feature of fatigue fracture

- lower stress $\sigma < \sigma_s$

- Suddenness and brittle fracture

- Course of fracturing

Crack forming $\longrightarrow$ Crack propagating $\longrightarrow$ Final fracturing

THE END

1.3.2 Feature of fatigue fracture face

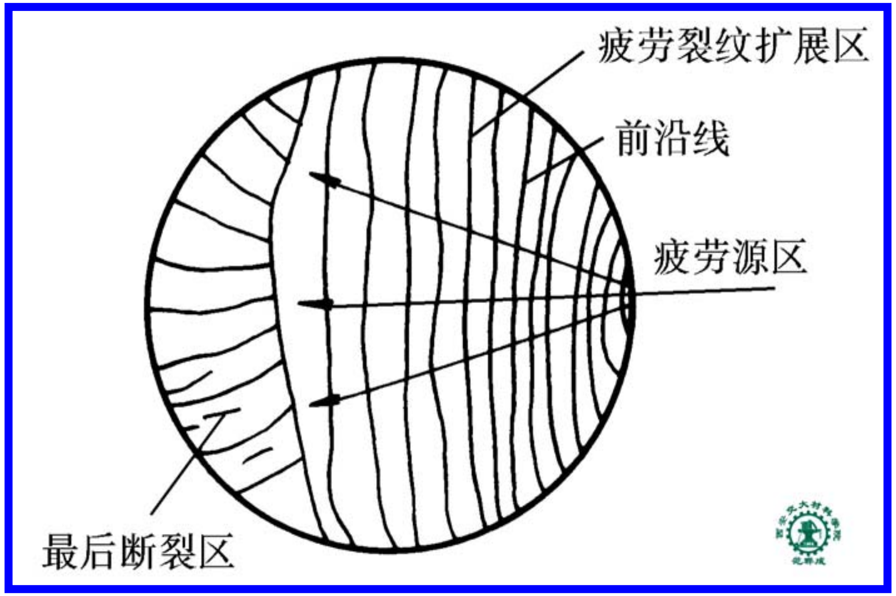


Diagram of fatigue fracture face

There are three zones in the fatigue fracture face

- Fatigue crack source zone
- Fatigue crack propagating zone
- Final fracturing zone

THE END

1. The fatigue crack source zone

Forming at place where the stress concentrating
- Internal defects (impurity, hole)
- Processing defects (tool marks, micro-crack)
- Unseasonable design (suddenly change in cross section)

2. The fatigue crack propagating zone

There are fatigue streak lines like "shell streak" or "sea beach"

3. The final fracturing zone

There are Radial streak lines

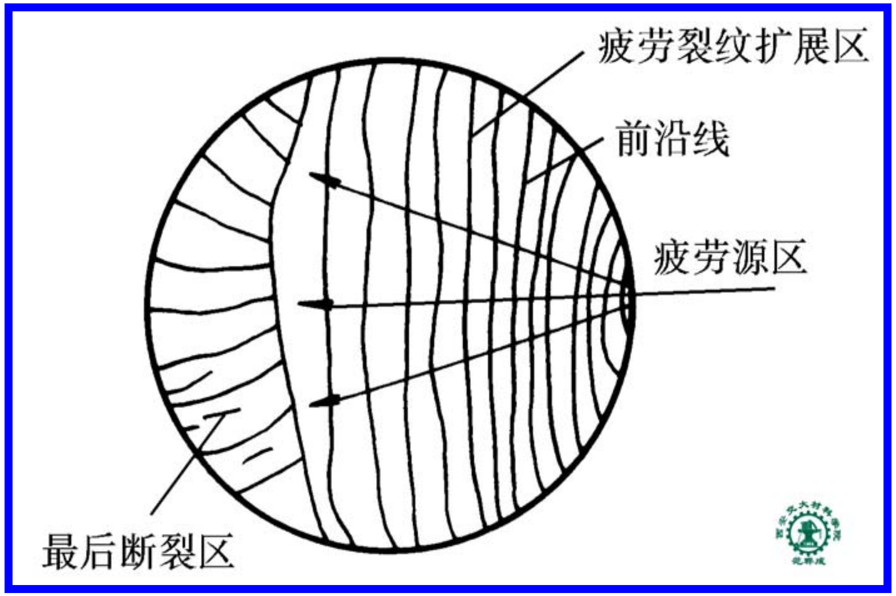


Diagram of fatigue fracture face

THE END

1.3.3 The fatigue resistance index of no-crack parts (components)

1. Fatigue limit and overload endurance value
   1) Fatigue curve

Rotating bending fatigue test

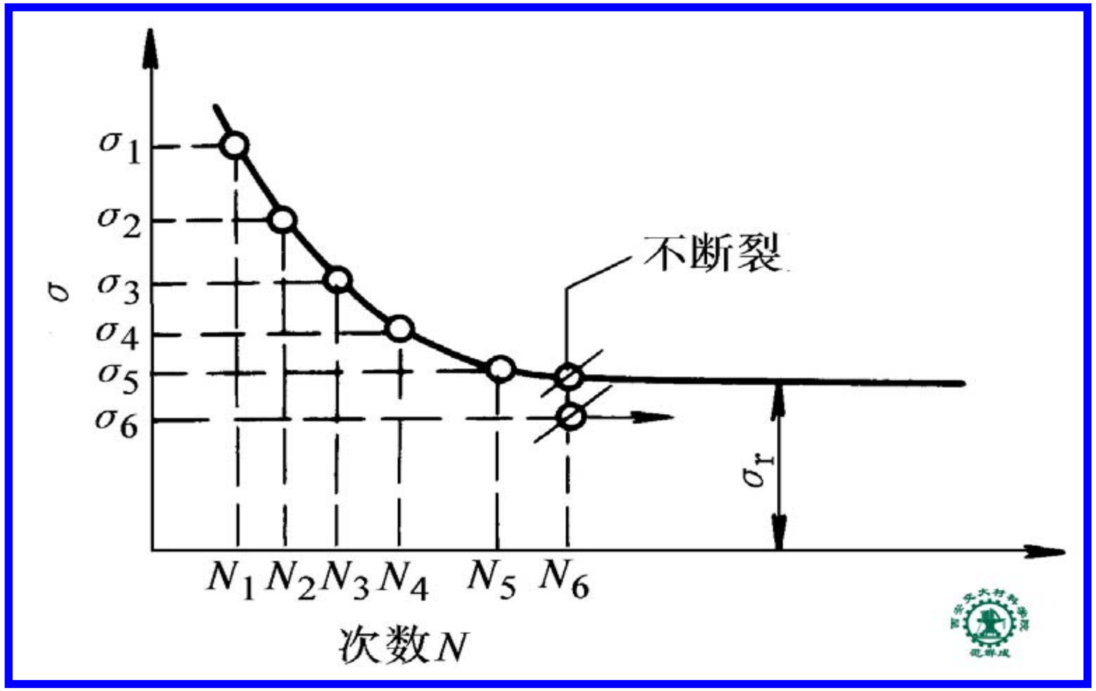
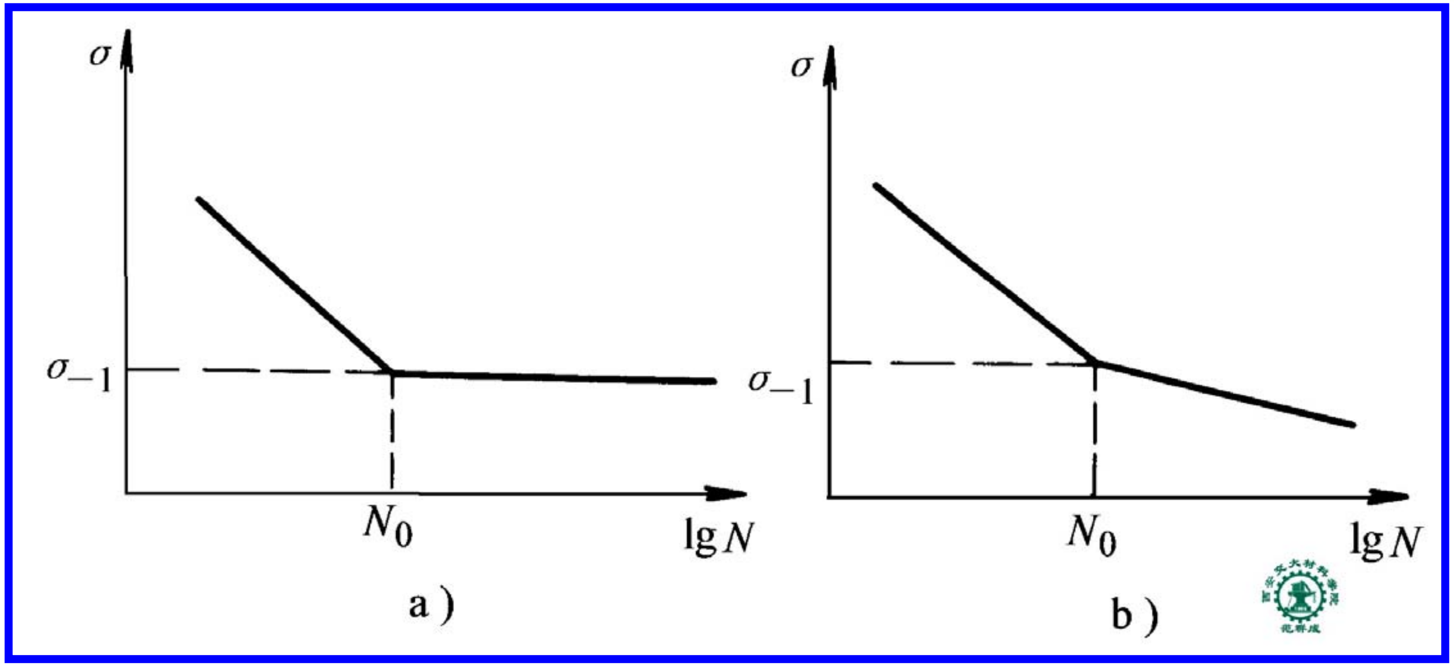


Diagram of fatigue curve

THE END



Two types of fatigue curve a) for ferrous and b) for some non-ferrous (e.g, Al alloys)

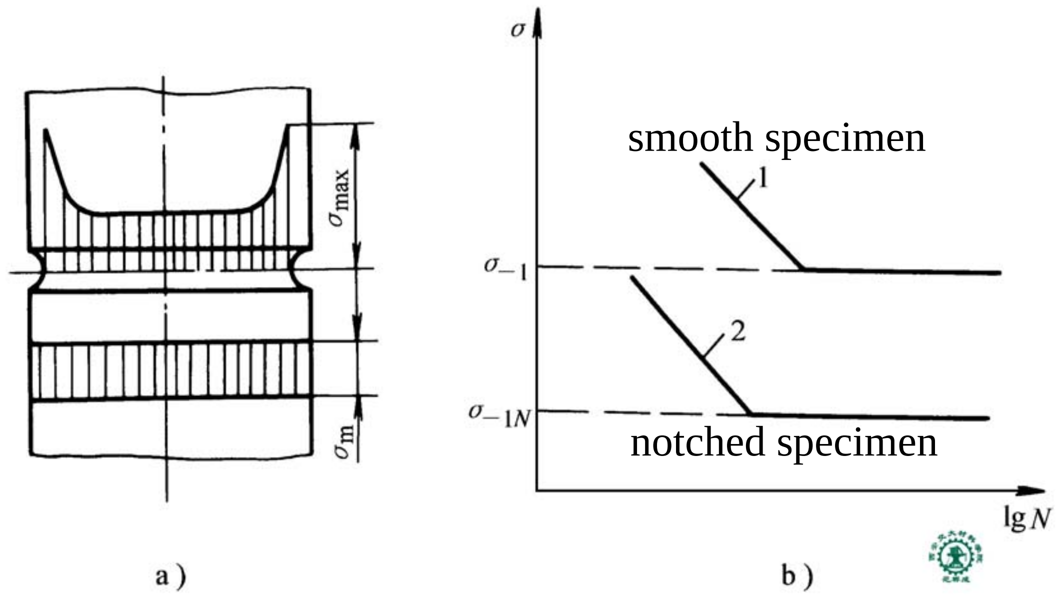
2) Fatigue limit — σ_{-1}

3) Conditional fatigue limit

4) Overload endurance value

THE END

2. sensitivity of fatigue to



Stress concentration at notch on dead load (a) and effect of the stress concentration on fatigue limit (b)

$$q = \frac{K_f - 1}{K_t - 1} \quad (0<q<1) \qquad K_f = \frac{\sigma_{-1}}{\sigma_{-1N}} \qquad K_t = \frac{\sigma_{\max}}{\sigma_m}$$

σ_{-1} — Fatigue limit of the smooth specimen

σ_{-1N} — Fatigue limit of the notched specimen

σ_{max} — Maximum stress at stress concentration

σ_m — Mean stress at stress concentration

THE END

1.3.4 Factors affecting fatigue resistance

1. Load types

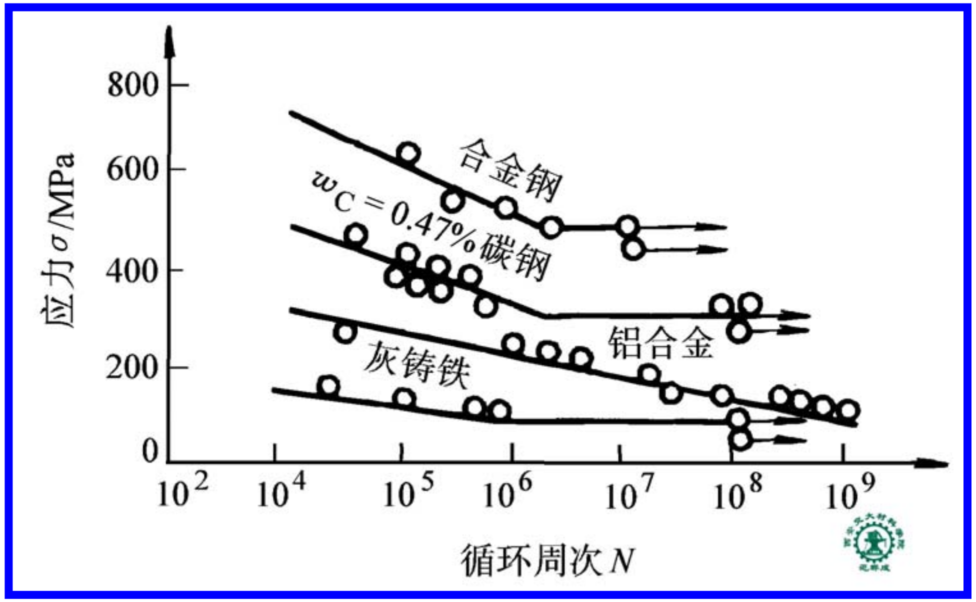
   Tension-compression fatigue

   Torsion fatigue

   Tension-tension fatigue

2. Nature of materials

1) Different materials have different σ_{-1}



The fatigue curves of some materials

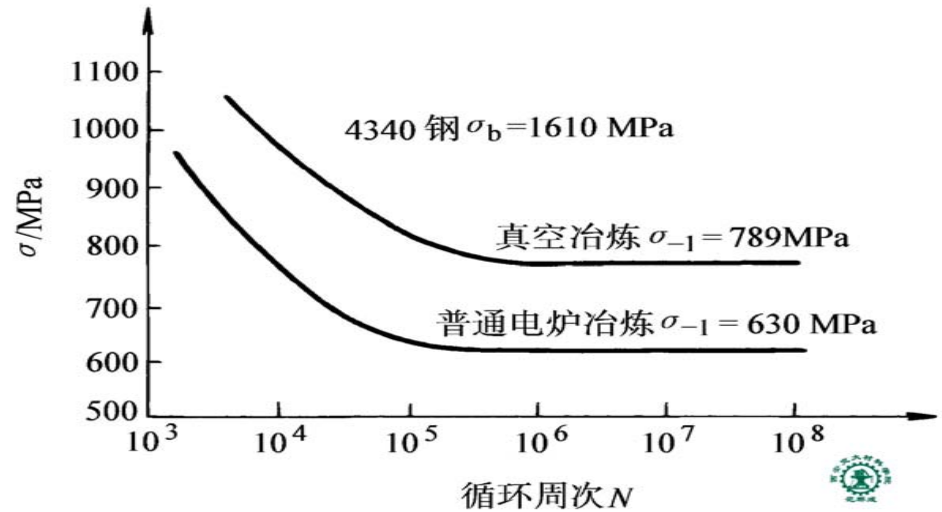
THE END

2) Different microstructures for the same material have different

表 1-3 40Cr 钢组织类型对疲劳极限的影响

组织状态	σ_b / MPa	σ_{-1} / MPa
退火（铁素体+珠光体）	650	341
淬火（马氏体）	2080	775

3) Purity of materials has enormous affect



THE END

The effect of perity of 4043 steel on the fatigue curves

3. Surface state of parts

1) Smoothness of surface

表 1-4　试样表面轻微刀痕对抗拉强度和疲劳极限的影响

材　料	表面状态	抗拉强度 σ_b / MPa	疲劳极限 σ_{-1} / MPa
45 钢（正火）	光滑试样	656	280
	有刀痕试样	654	145
40Cr 钢（淬火+200℃回火）	光滑试样	1947	780
	有刀痕试样	1922	300

2) Stress state of surface

4. Temperature

5. Corrosive medium

THE END

§ 1-4 The wear failure of parts

Common wear failure classes:
- Adhesive wear
- Grain abrasion
- Corrosive wear
- Contact fatigue

THE END

1.4.1 Adhesive wear

1. Phenomenon

2. Mechanism

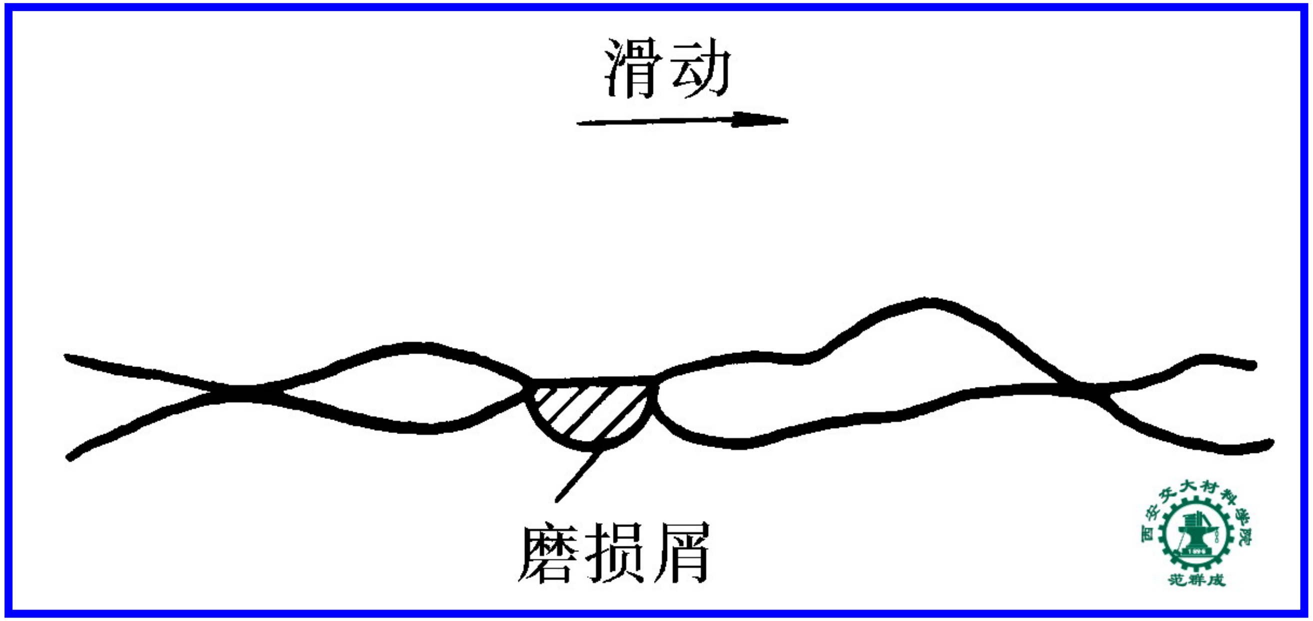


Diagram of mechanism of the adhesive wear

3. Solution

THE END

1.4.2 Grain abrasion

1. Phenomenon

THE END

2. Mechanism

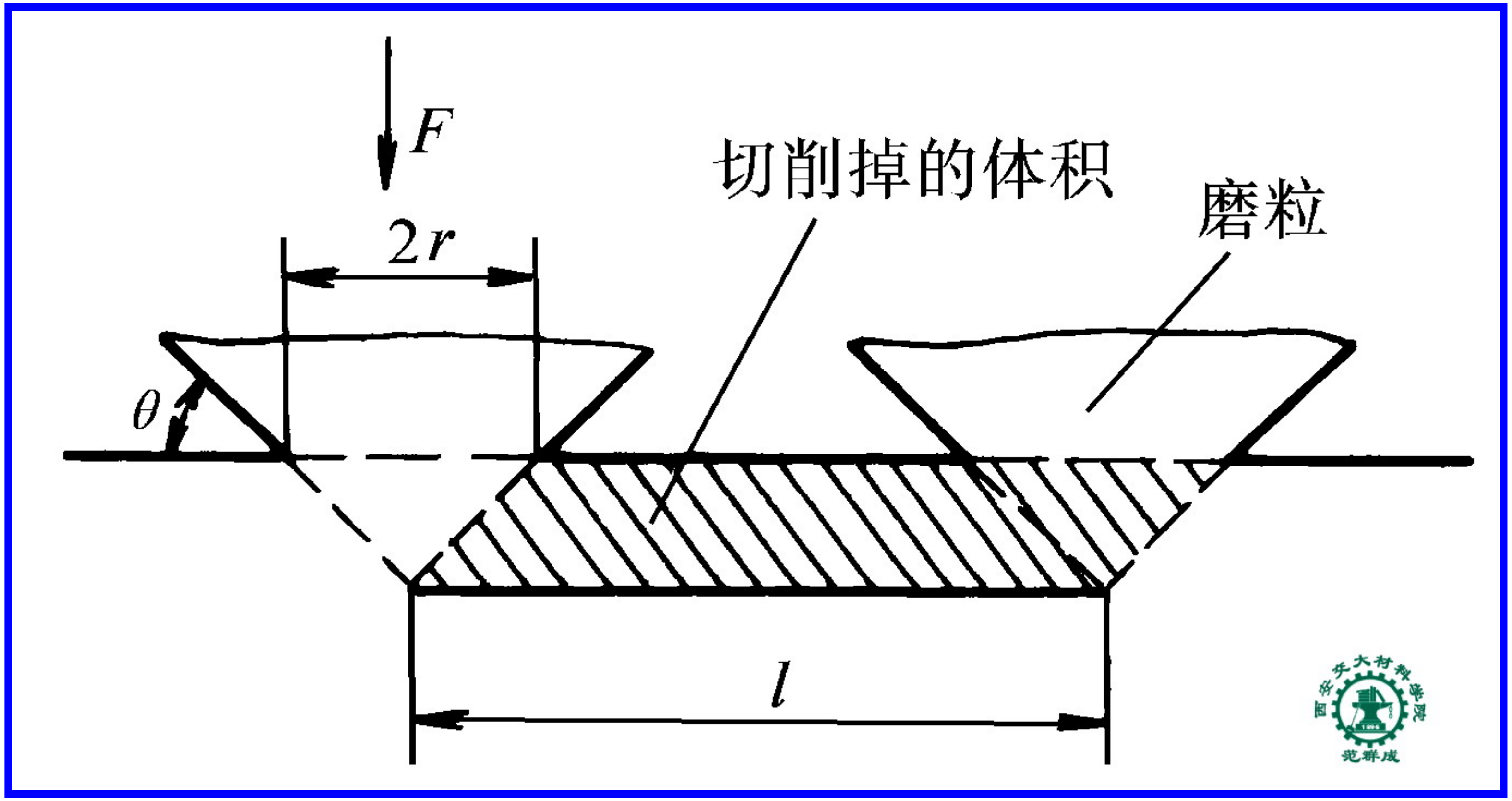
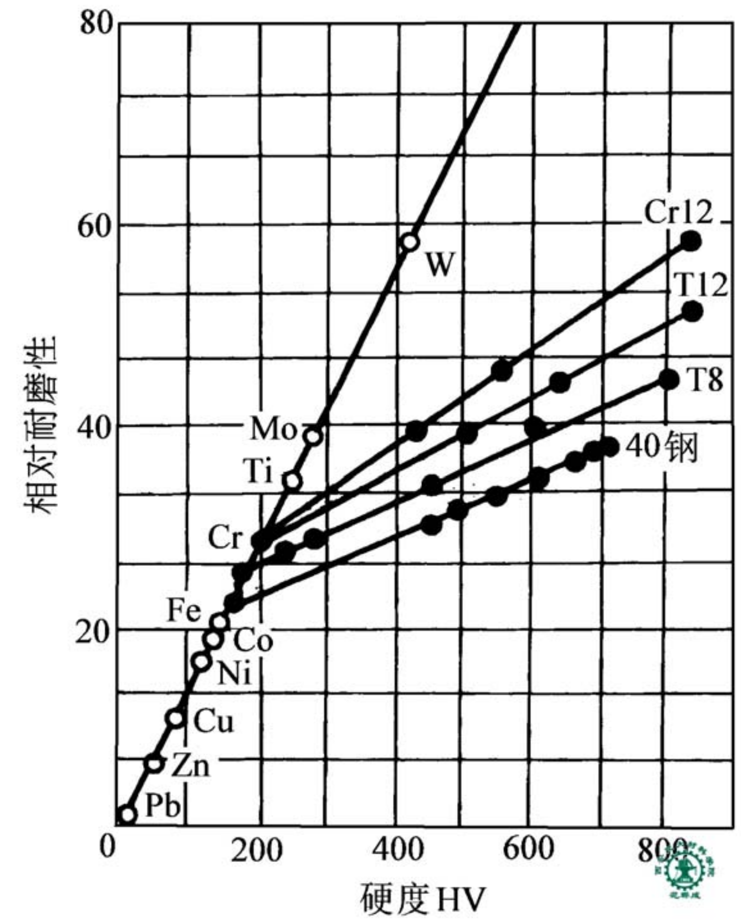


Diagram of mechanism of the grain abrasion

THE END

3. Solution



The relationship between relative wear resistance and hardness of materials enduring grain-abrasion

THE END

1.4.3 Corrosive wear

1. Oxidative wear

1) Phenomenon

2) Cause

3) Solution

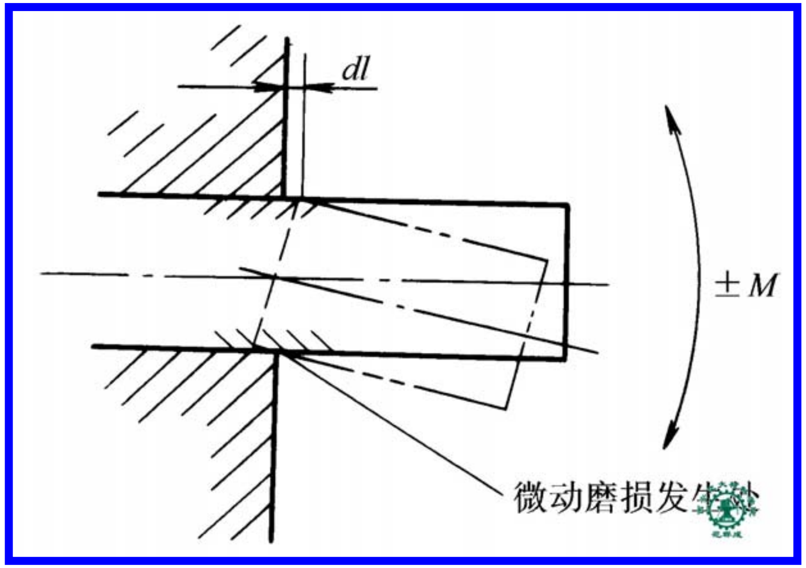
THE END

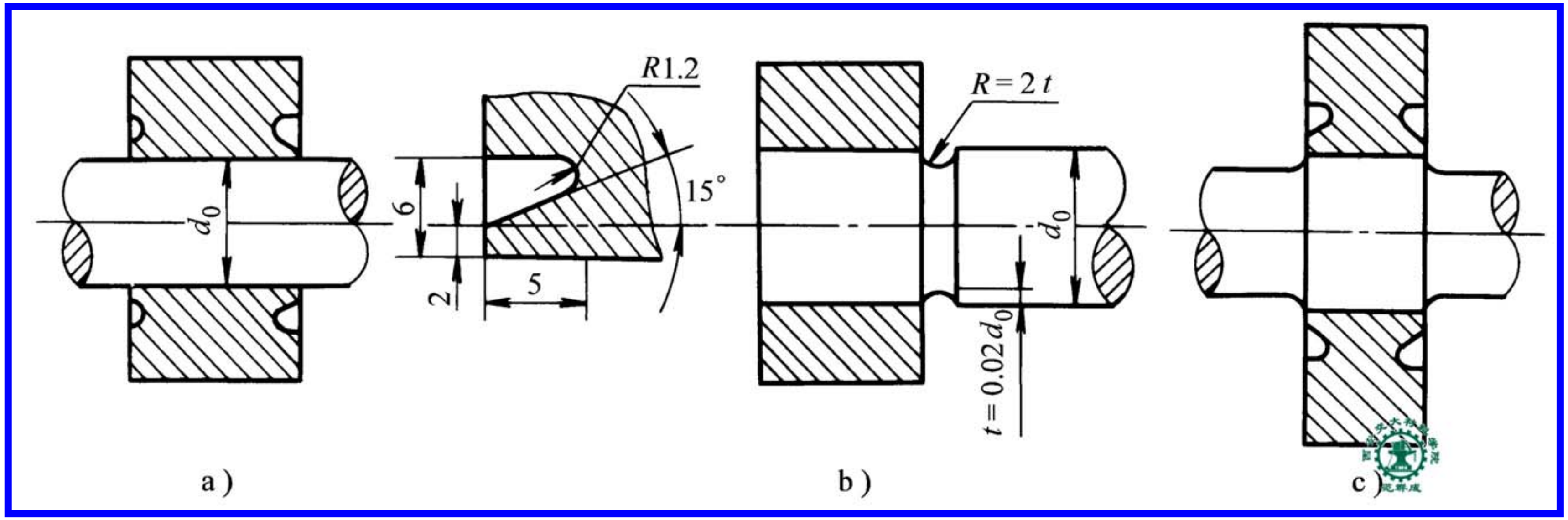
2. Fretting wear

1) Phenomenon

2) Cause

3) Solution

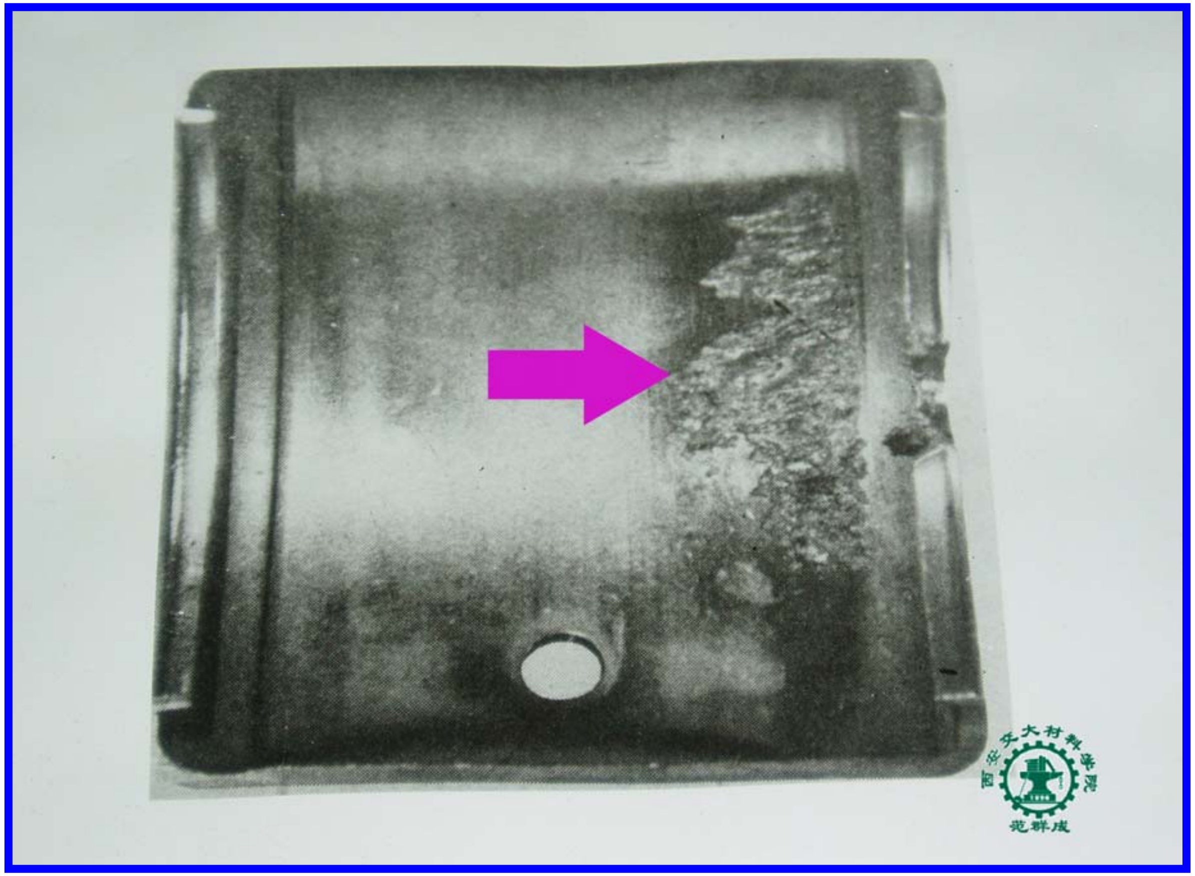




Schematic of examples in design of fitted axle by pressing

1.4.4 Contact fatigue

1. Phenomenon



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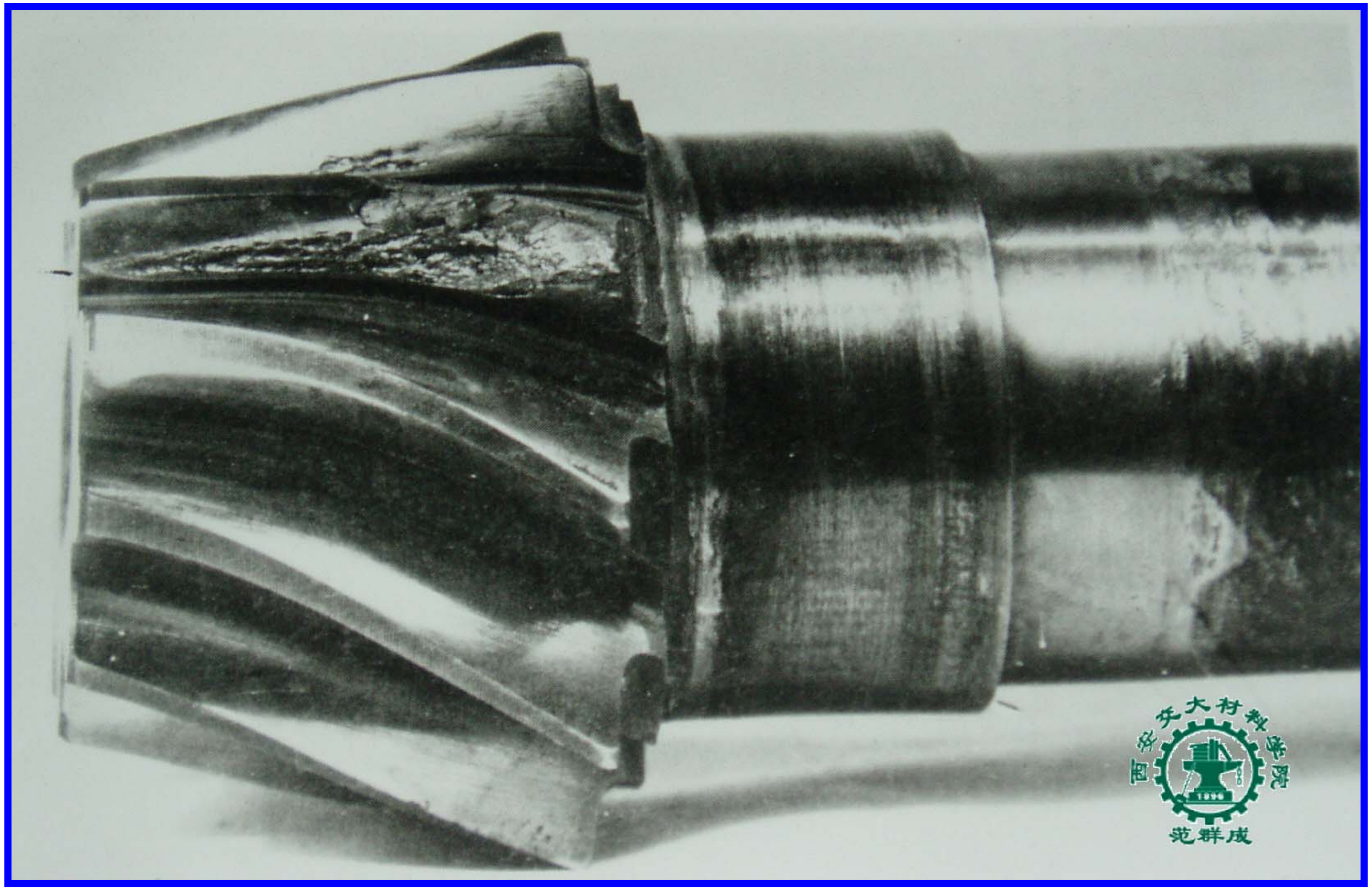


THE END

2. Mechanism
3. Solution

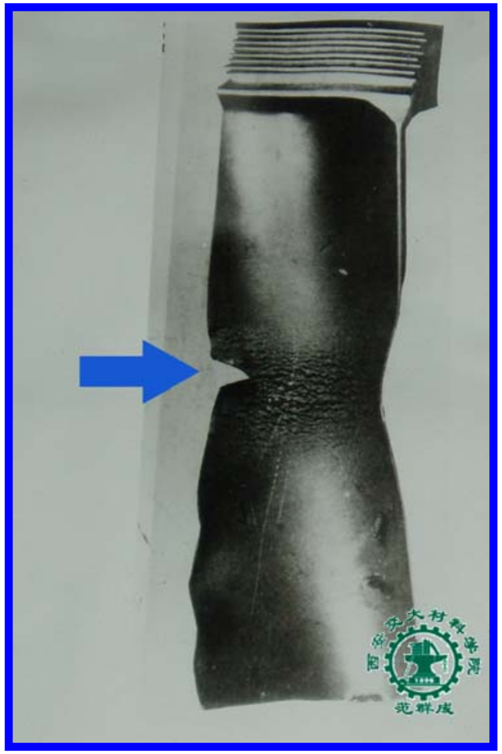
THE END

THE END

§ 1-5 The creep deformation and fracture of parts at high temperature

1.5.1 Failure of parts at high-temperature

1. High-temperature creep



THE END

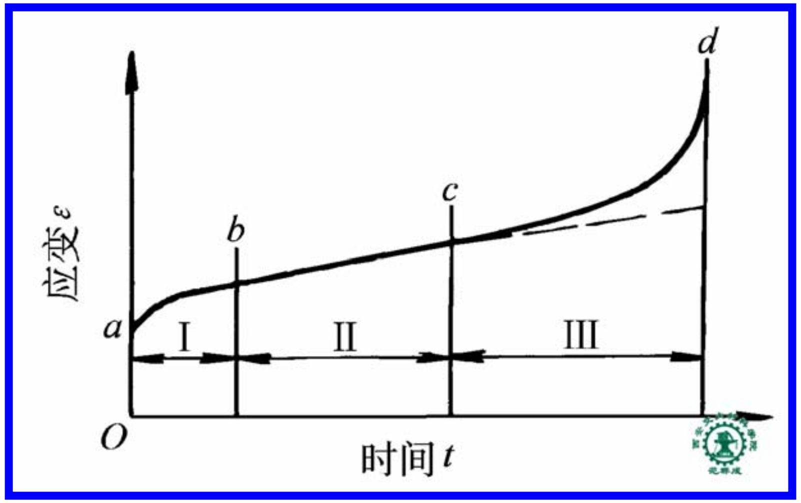
2. High-temperature oxidation

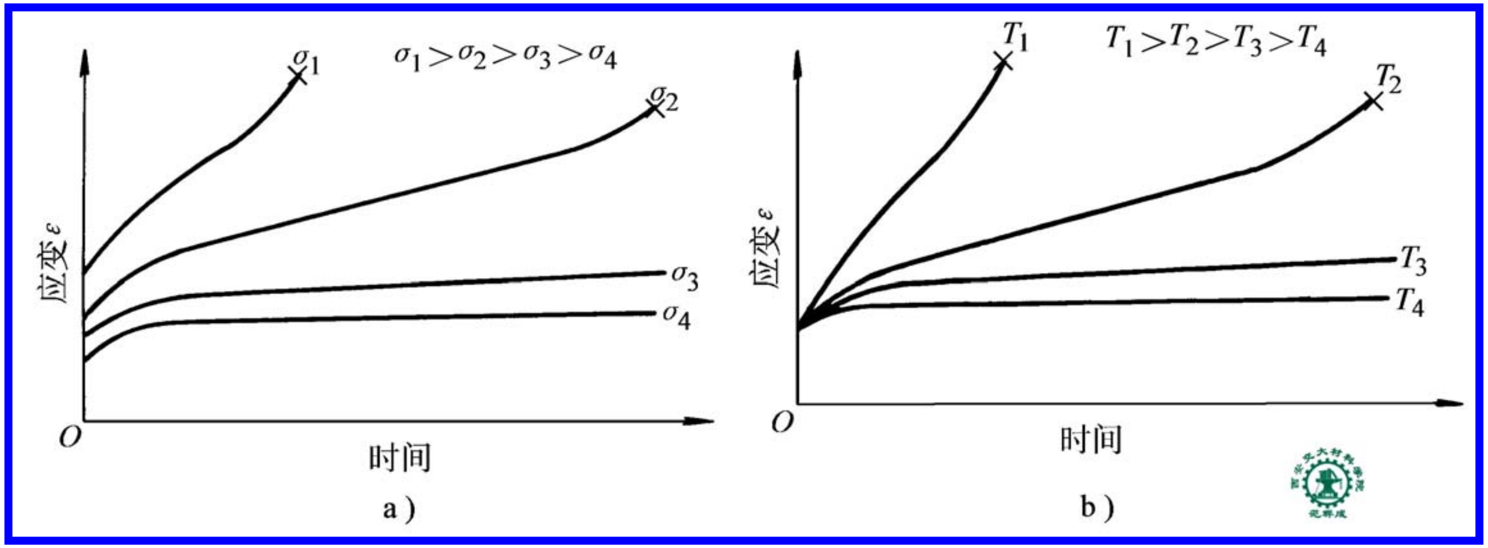
THE END

1.5.2 Creep limit and endurance strength

1. Typical curve of creep

Typical curve of creep





The effects of stress (a) and temperature (b) on curves of creep

THE END

2. Creep limit

$$\sigma^{T}_{\&}$$

$$\sigma^{T}_{\delta/t}$$

3. Endurance strength

$$\sigma^{T}_{t}$$

1.5.3 The way to increase mechanical properties of metals at high-temperature

THE END