Chapter Ⅱ Carbon Steel

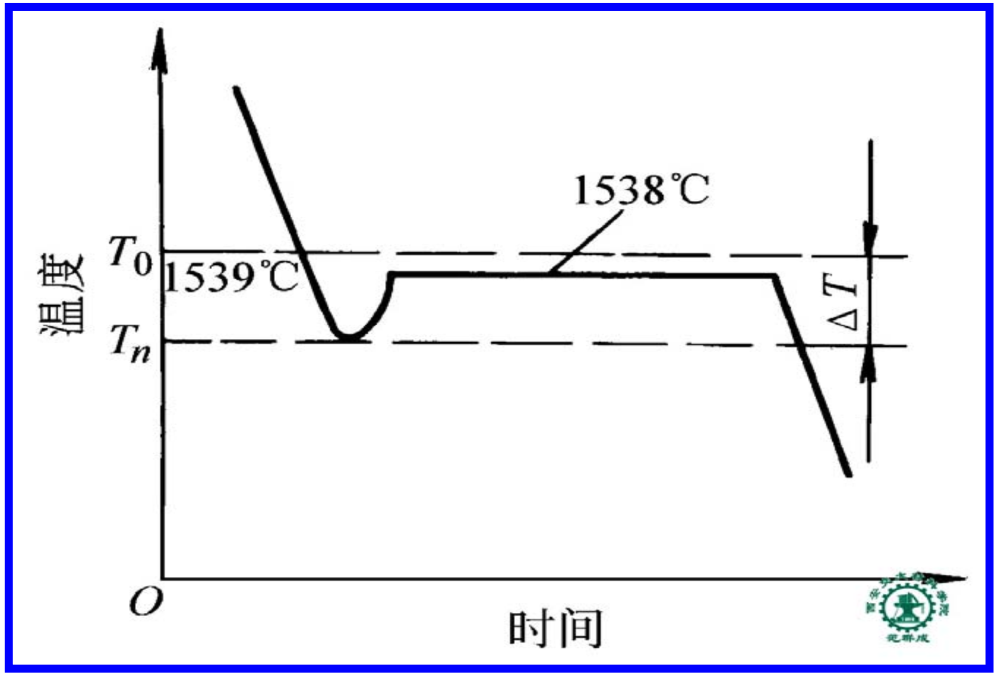
§ 2-1 Structures and properties of pure iron

2.1.1 Crystallization of pure iron

1. Super-cooling phenomenon and super-cooling degree

1) Cooling curve

The cooling curve of pure iron (partial)



2) Super-cooling phenomenon

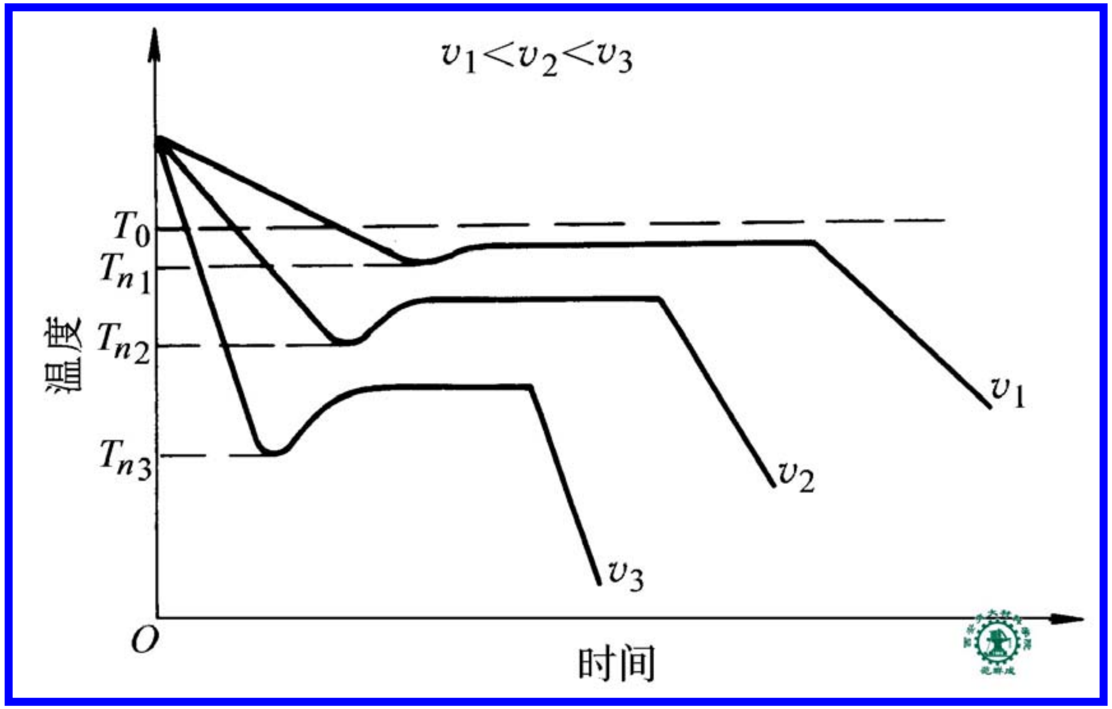
THE END

3) Super-cooling degree — ΔT

$$\Delta T = T_0 - T_n$$

T_0 — Equilibrium crystallization temperature

T_n — The true starting crystallization temperature



Cooling curves under different cooling rates

THE END

4) Necessary condition of crystallization

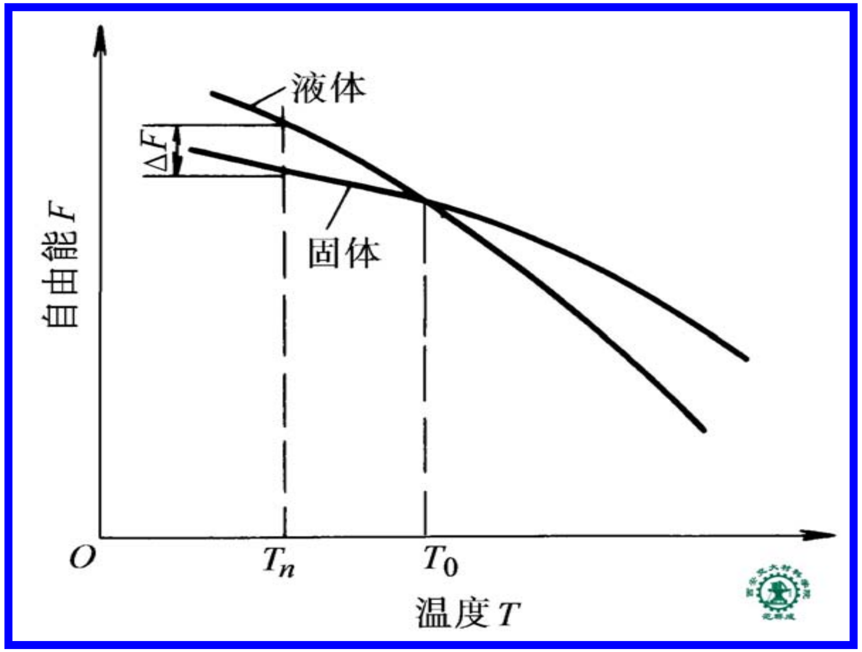
$$\Delta T > 0$$

5) Driving force of crystallization

$$\Delta F = F_S - F_L < 0$$

F_S --- Free energy in solid state

F_L --- Free energy in liquid state



Changes in free energy of liquid and solid with temperature

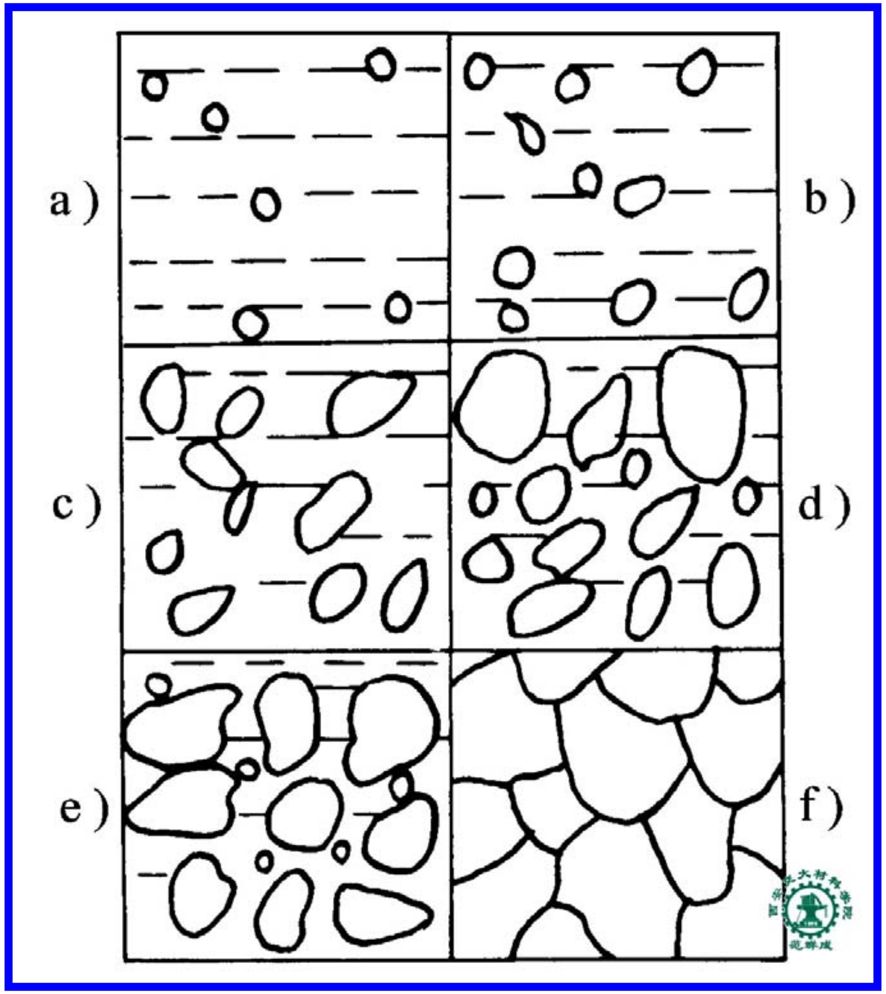
THE END

2. Course of crystallization

   Nucleating ⟶ Growing

3. Fine grain strengthening

4. Ways to fining grain in cast processing



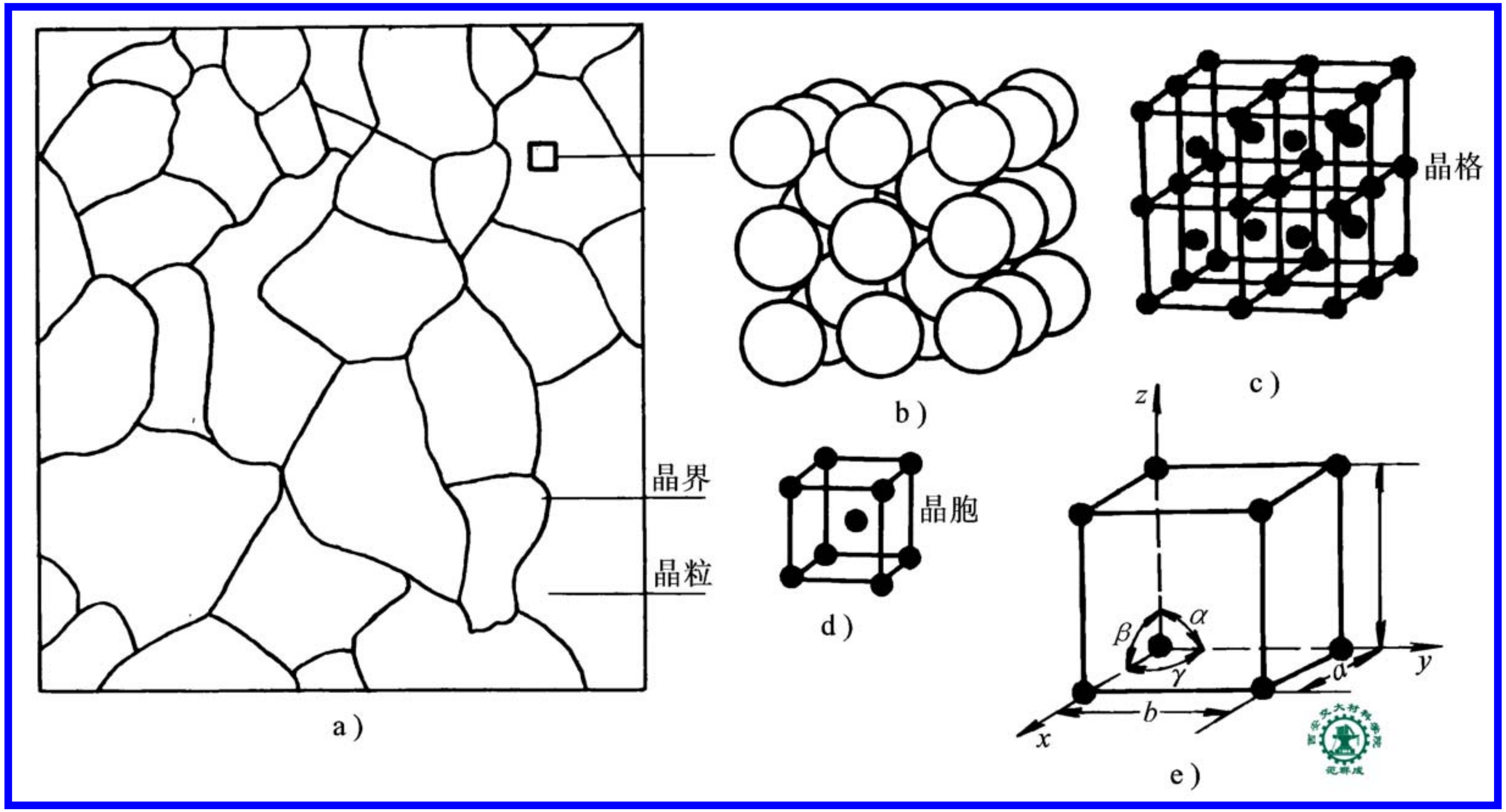
The process of crystallization of pure iron

THE END

2.1.2 Crystal structure of pure iron

1. Basic concept of crystal structure

1) Crystal

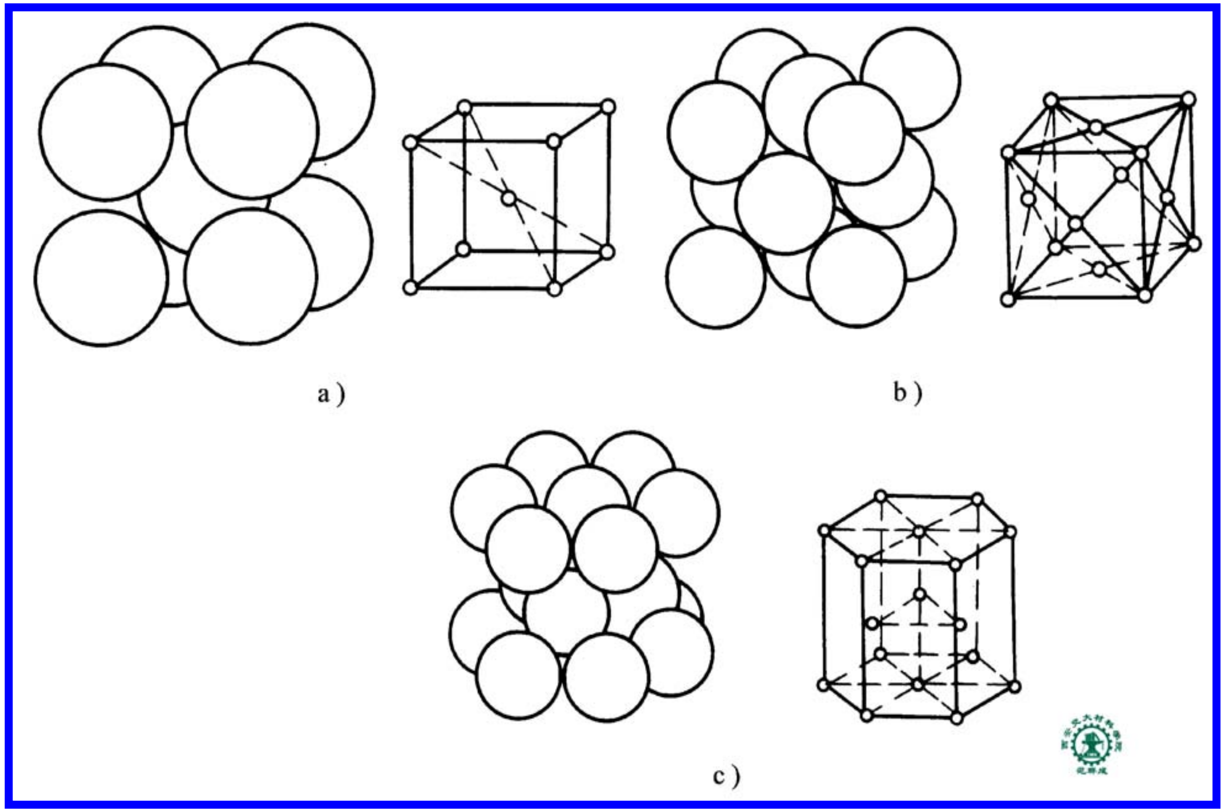


THE END

Internal structure of pure iron grain

2) Crystal structure

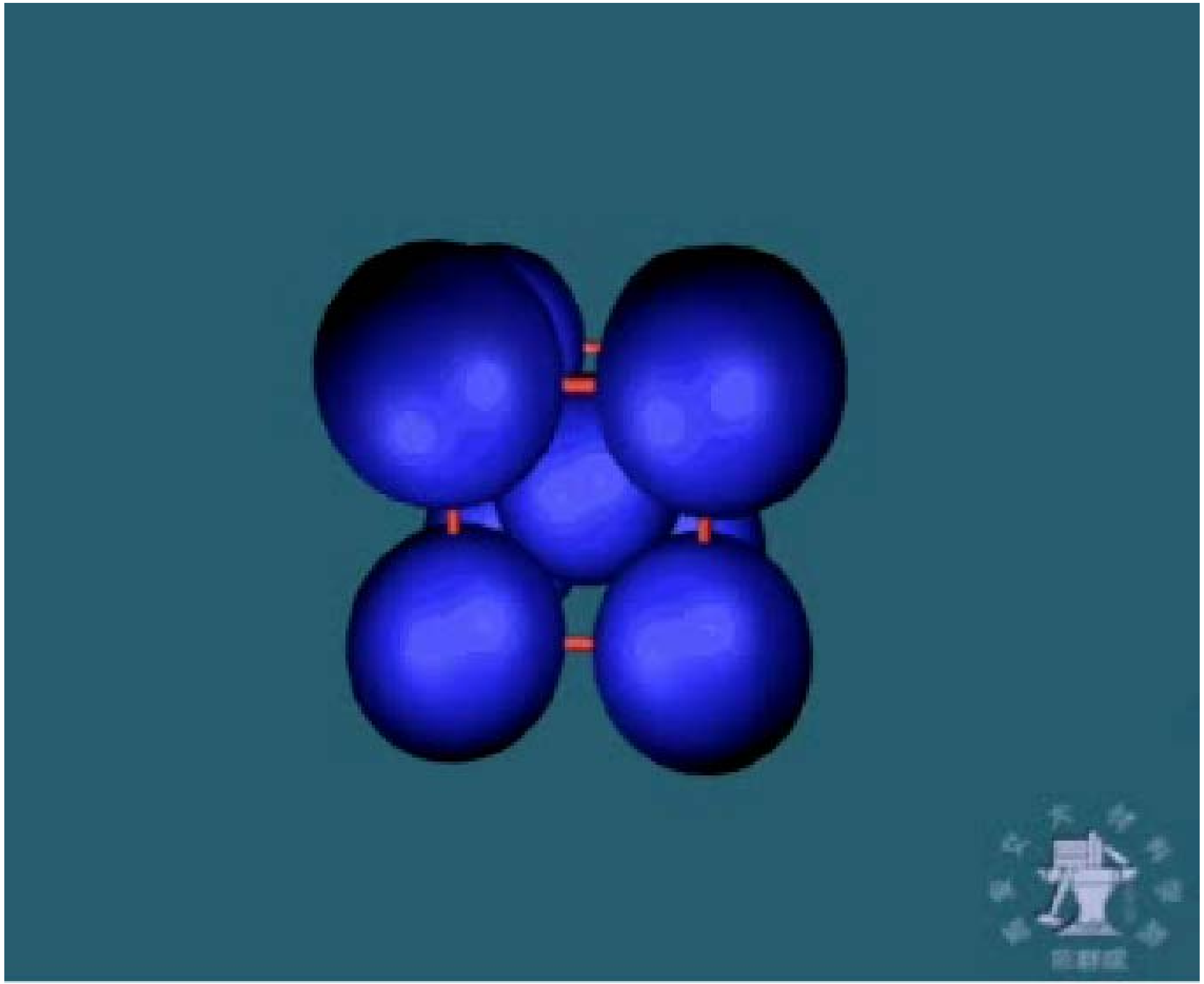
3) Common crystal structures of metals
- Body centered cubic (bcc)
- Face centered cubic (fcc)
- Close packed hexagonal (cph)



THE END

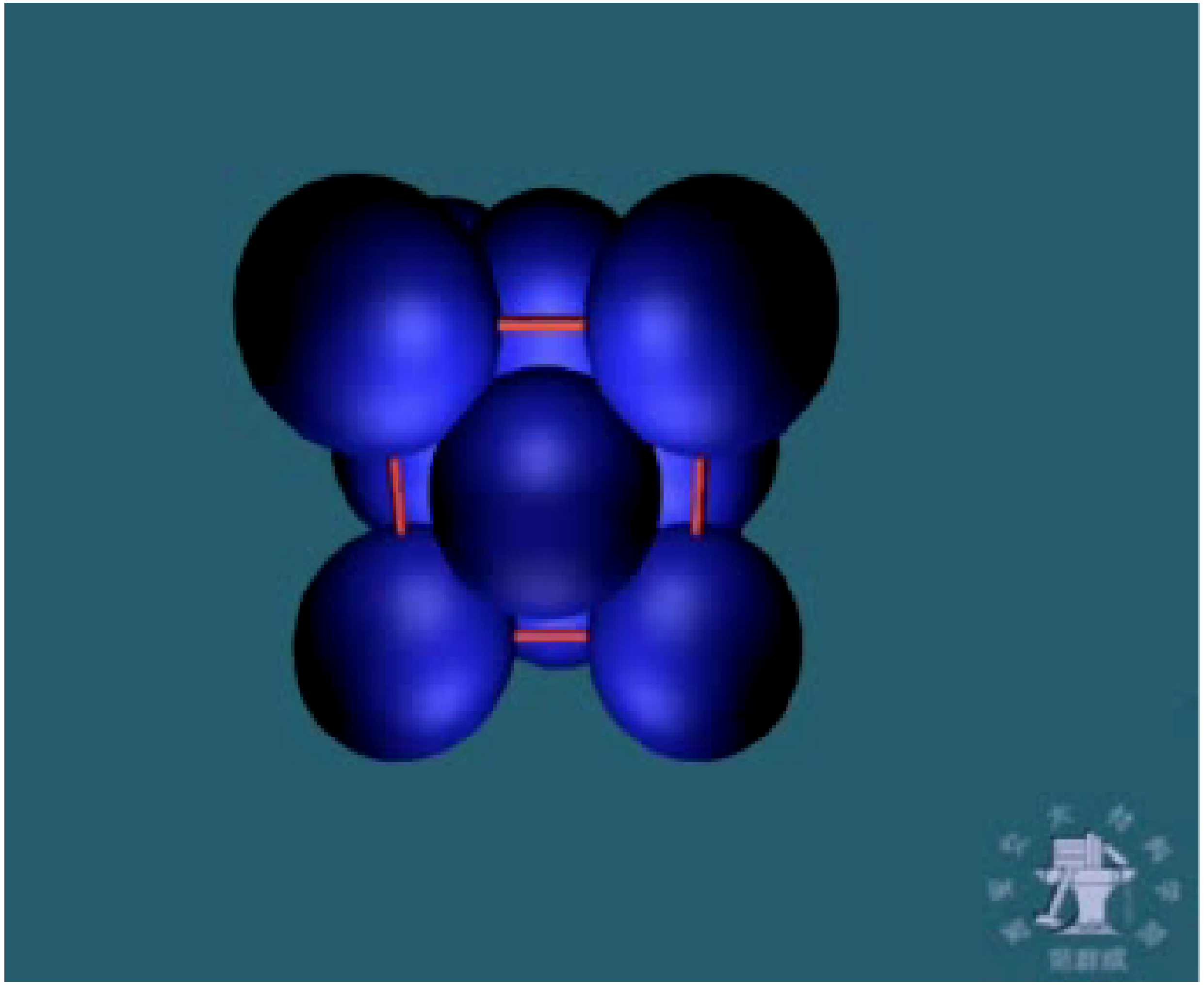
Three kinds of common cell of metals a) bcc b) fcc c) cph

BCC structure



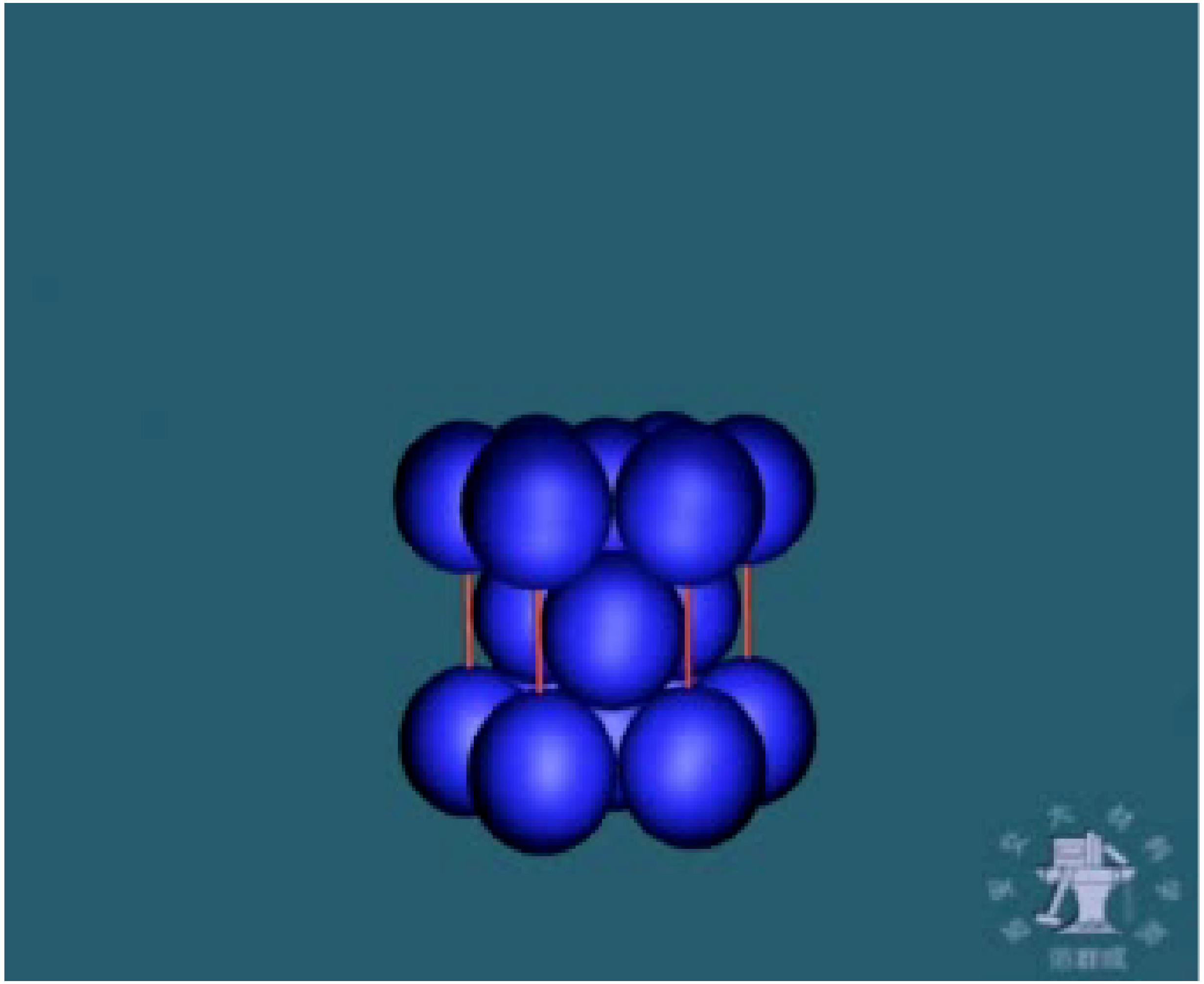
THE END

FCC structure



THE END

CPH structure

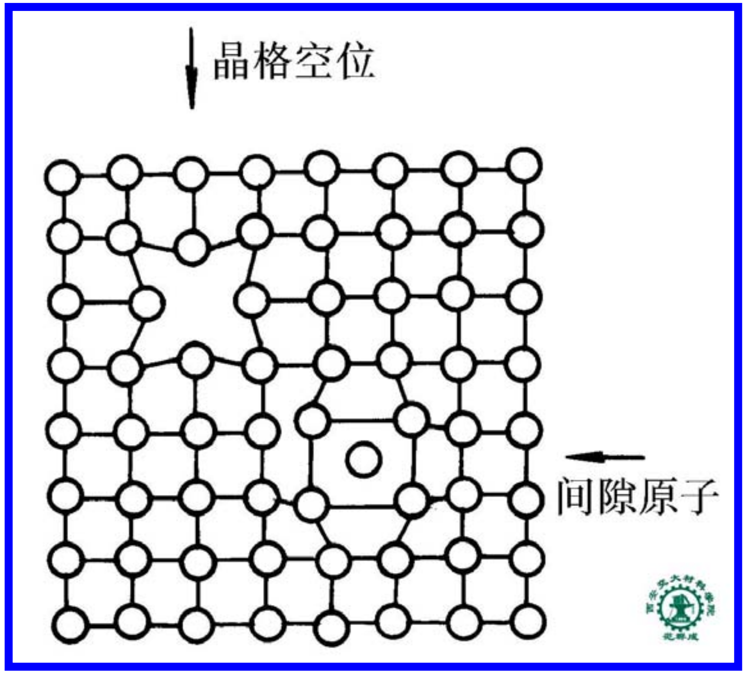


THE END

2. Basic concept of crystal defects

Crystal defects:
- Point defects
- Linear defect (dislocation)
- Planar defects

1) Point defects:
- Vacancy
- Interstitial atom

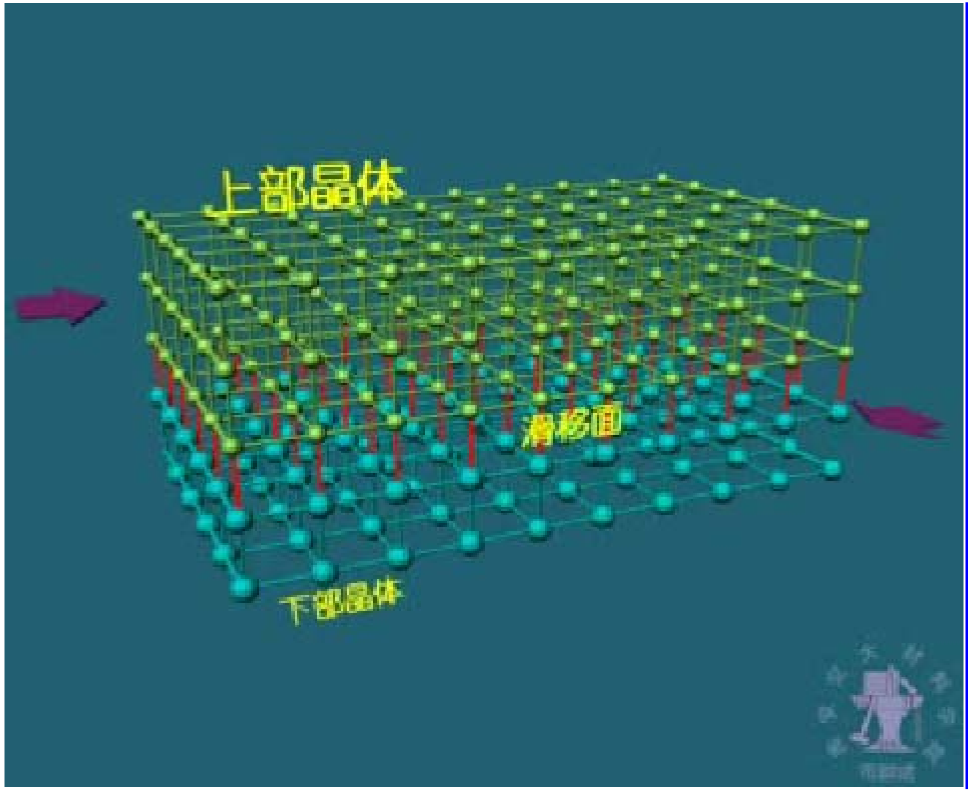


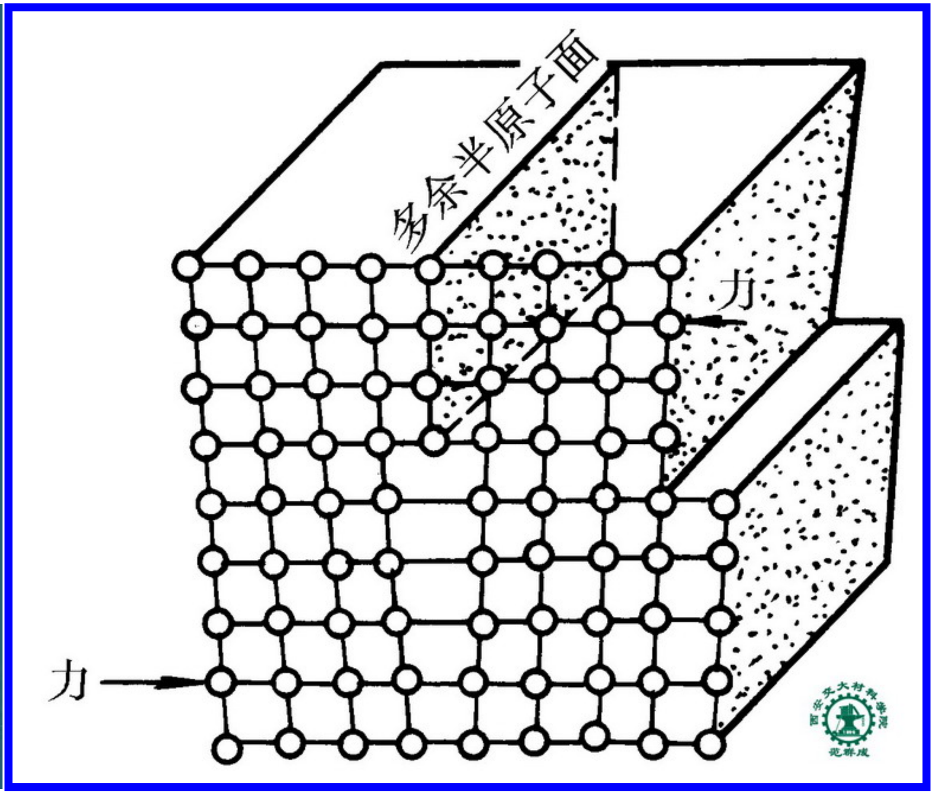
Schematic of point defect

THE END

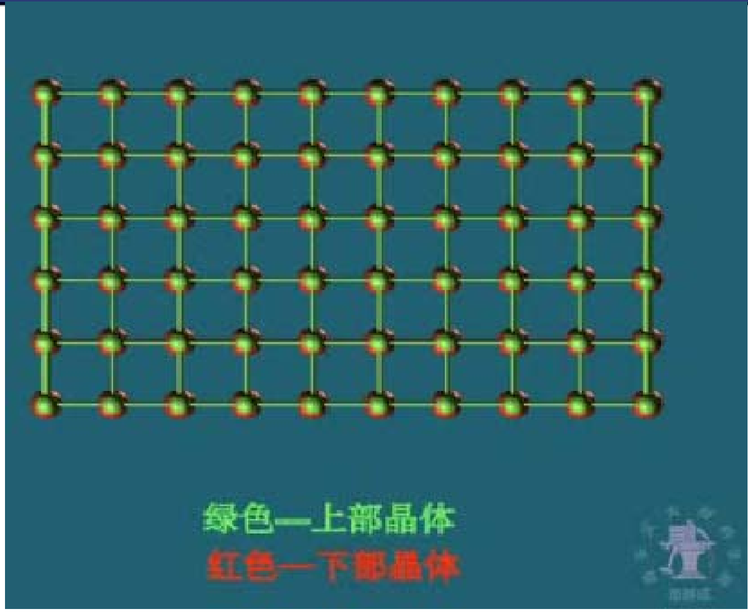
2) Linear defect —— dislocation { Edge dislocation / Screw dislocation

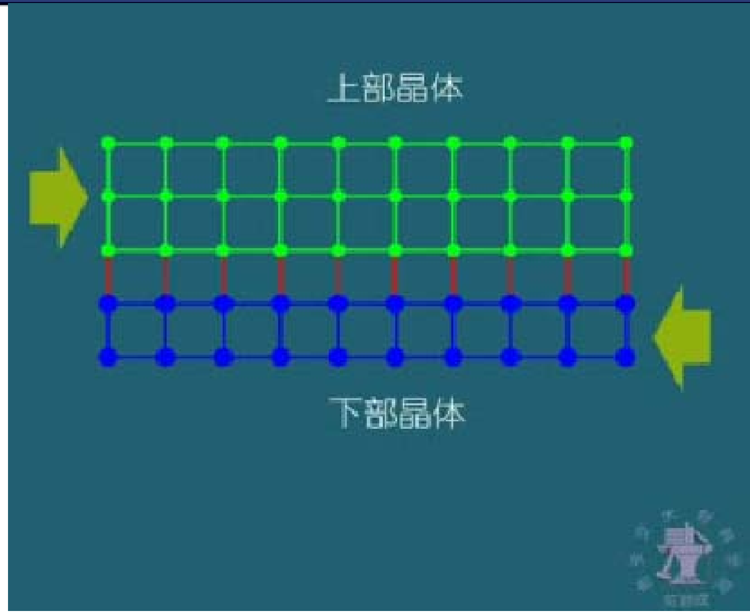
(1) Edge dislocation

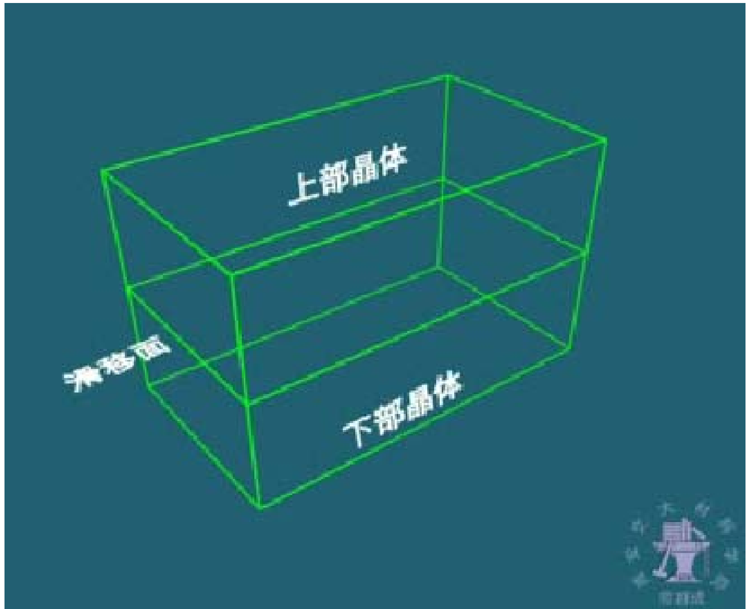


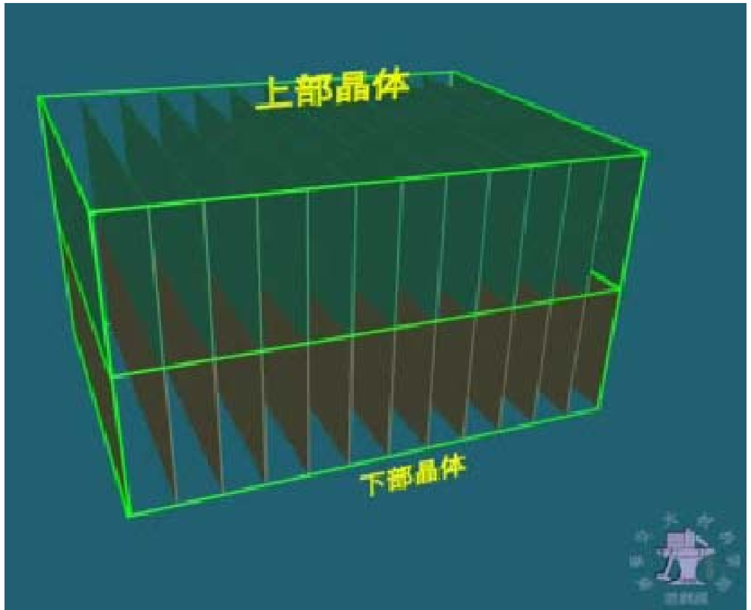


THE END

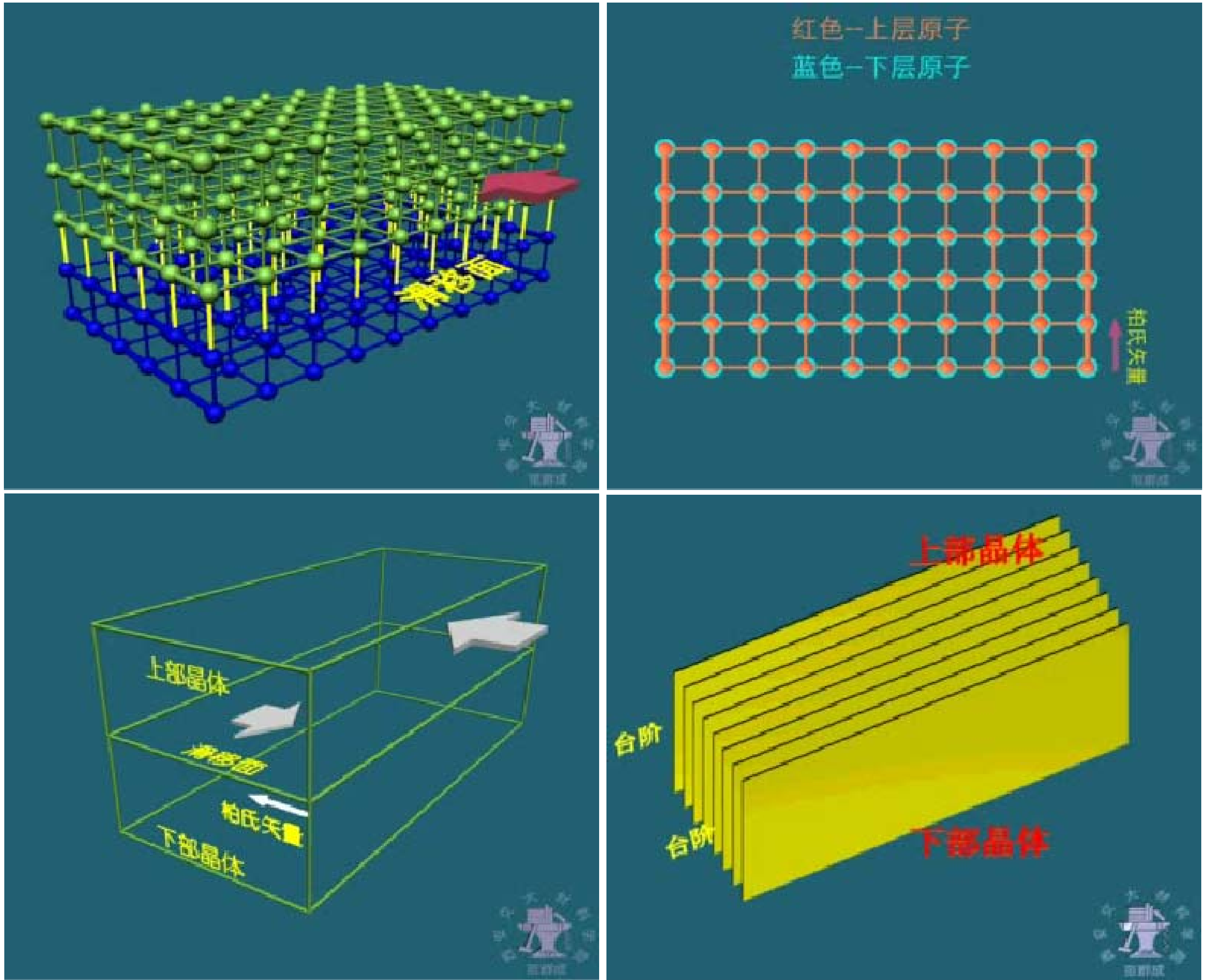

绿色—上部晶体
红色—下部晶体


上部晶体
下部晶体


上部晶体
滑移面
下部晶体

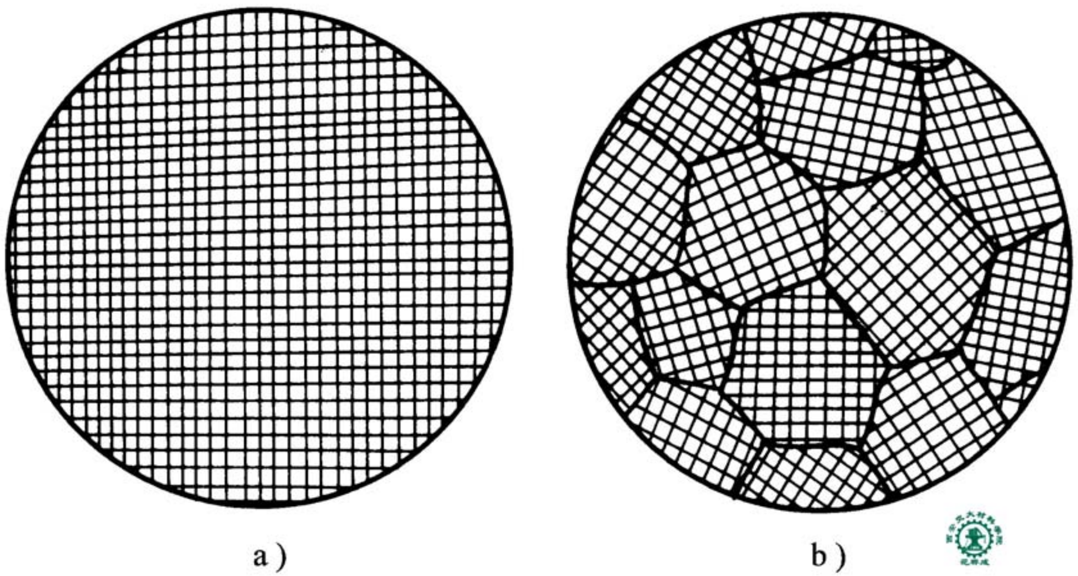

上部晶体
下部晶体

(2) Screw dislocation



3) Planar defects
- Grain boundary
- Sub-grain boundary
- Phase boundary

(1) Single crystal and polycrystalline

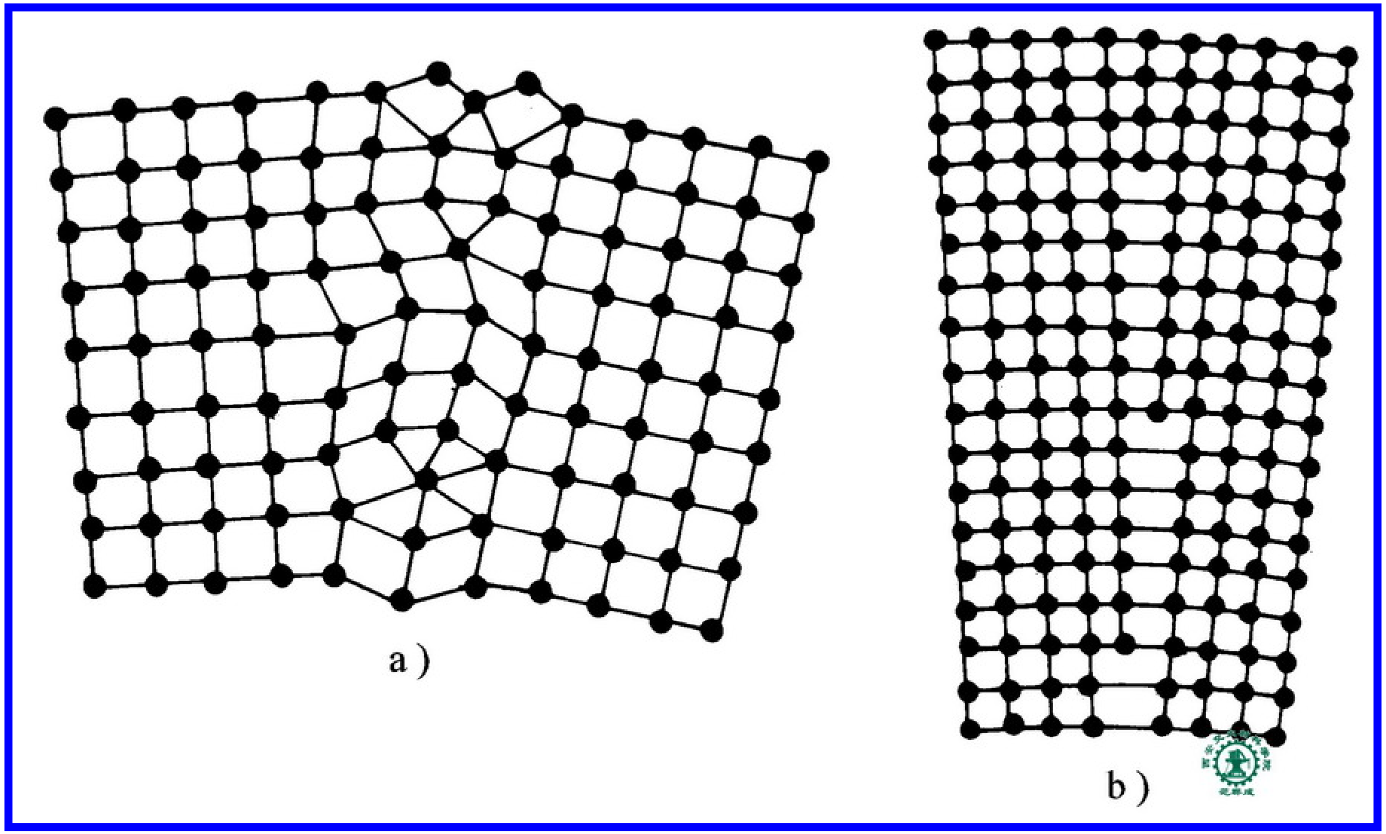


Single crystal (a) and polycrystalline (b)

- Anisotropy of single crystal and isotropy of polycrystalline

THE END

(2) Grain boundary



Grain boundary (a) and sub-grain boundary (b)

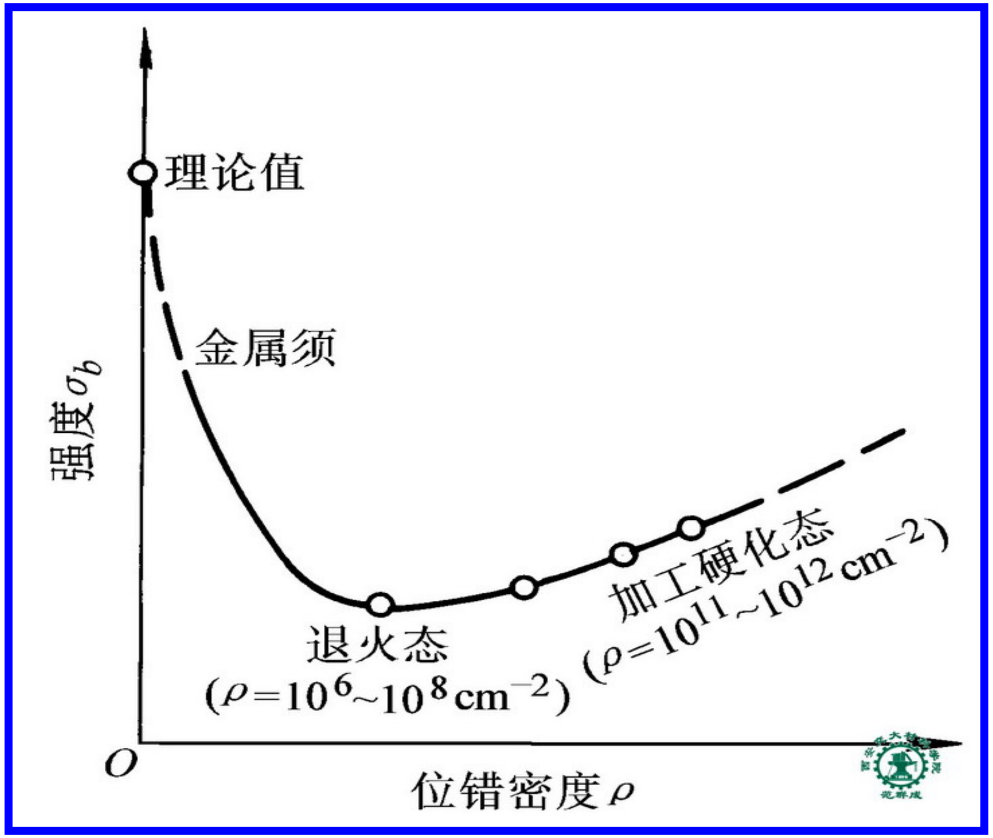
(3) Sub-grain boundary

(4) Phase boundary

THE END

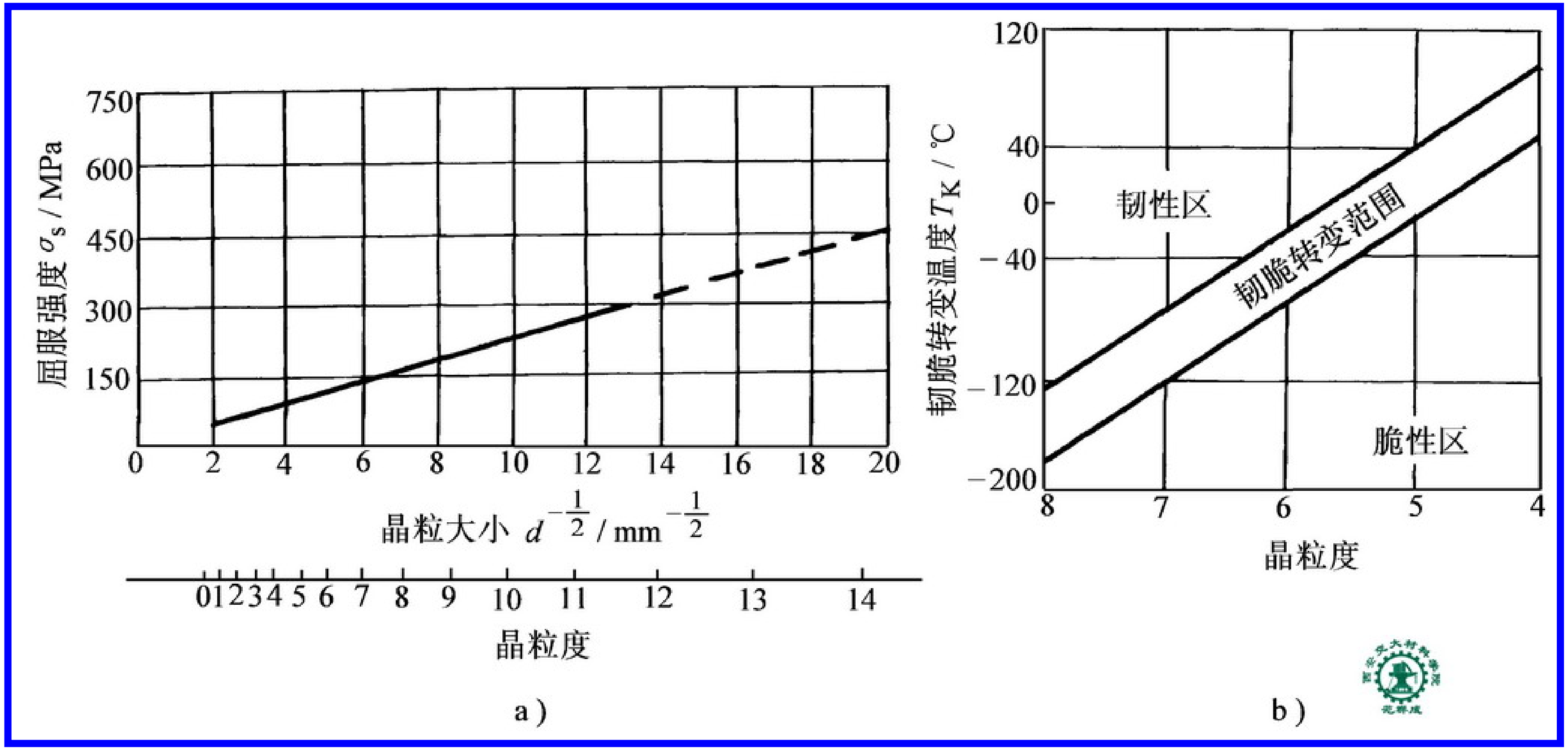
4) Strengthening effect of crystal defect on metal

Crystal defect ⟶ Lattice distortion ⟶ Strengthening



Relationship between yield strength of metals and density of dislocation

THE END

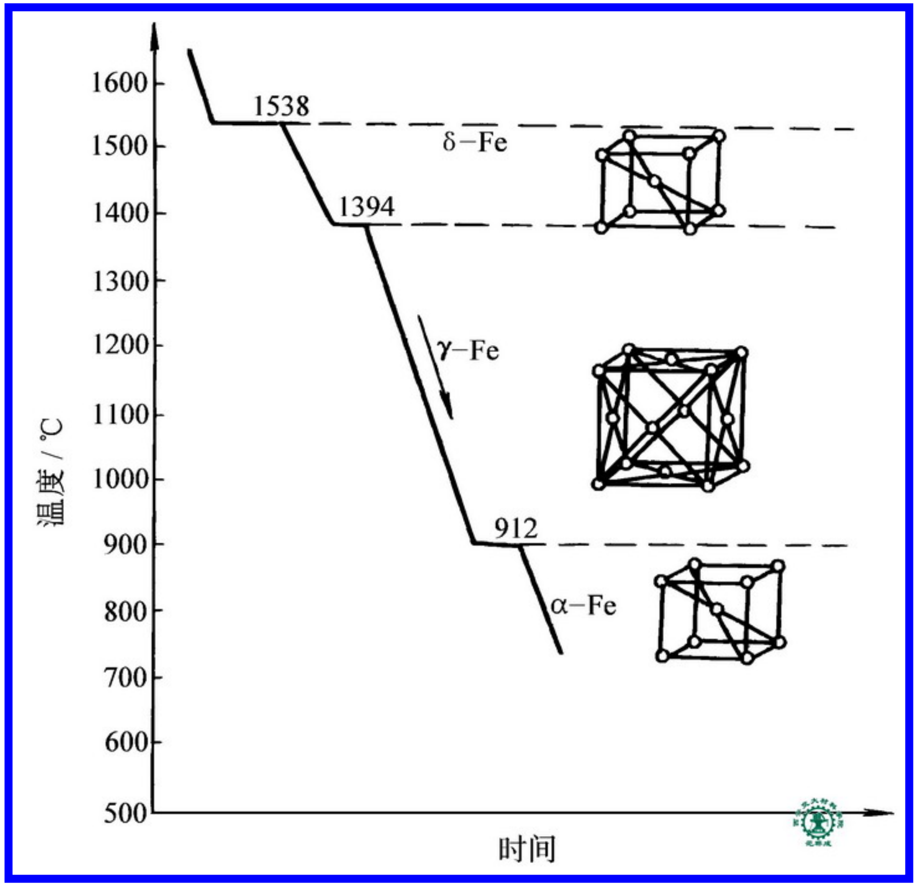


Relationship between yield strength (a) and toughness (b) of pure iron and size of grains

THE END

3. Crystal structure and allotropic transformation of pure iron

$$\underset{bcc}{\alpha-Fe} \xleftrightarrow{912\,^{\circ}C} \underset{fcc}{\gamma-Fe} \xleftrightarrow{1394\,^{\circ}C} \underset{bcc}{\delta-Fe}$$



$$\left.\begin{matrix}\alpha-Fe\\ \gamma-Fe\\ \delta-Fe\end{matrix}\right\}\text{Allotrope of iron}$$

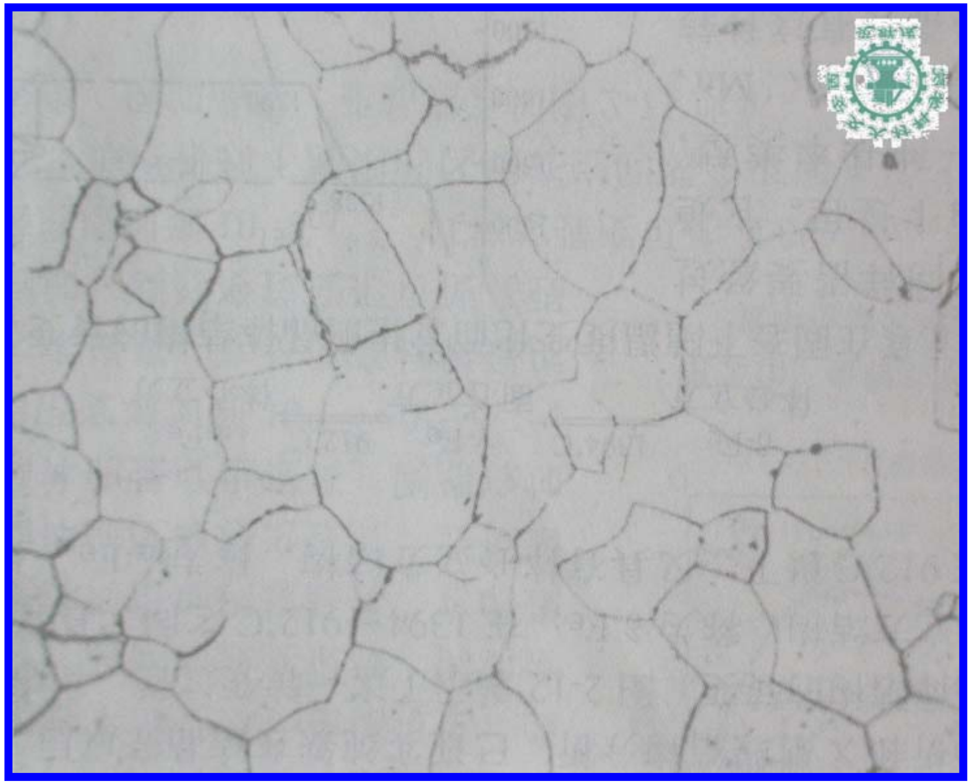
Cooling curve and change in crystal structure of pure iron

THE END

2.1.3 Structure and properties of commercially pure iron

1. Structure of commercially pure iron at room temperature

- polycrystalline
- bcc structure
- $\alpha - Fe$



Microstructure of commercially pure iron ×125

THE END

2. Properties of commercially pure iron at room temperature

- Low strength

  $\sigma_s = 100 \sim 170$ MPa

  $\sigma_b = 180 \sim 230$ MPa

- High plasticity and toughness

  $\delta = 30\% \sim 50\%$

  $\psi = 70\% \sim 80\%$

  $a_K = 160 \sim 200 J/cm^2$

- Ferromagnetic

3. Application of commercially pure iron

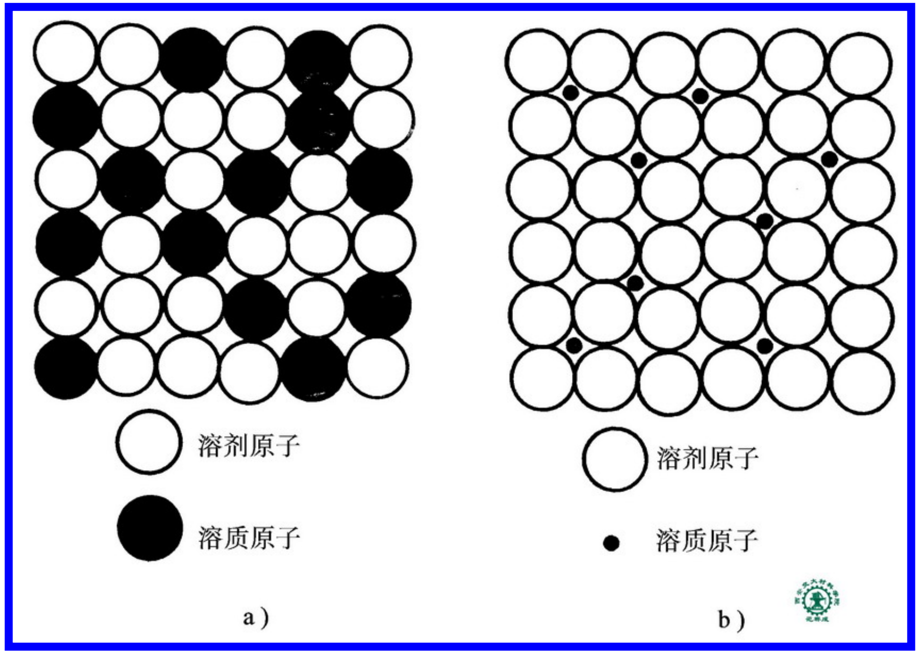
THE END

§ 2-2 The constituent of phase and structure in Fe-C alloy

Phase — Phases in alloy { Solid solution / Compound

2.2.1 Fe and C forming solid solution — ferrite and austenite

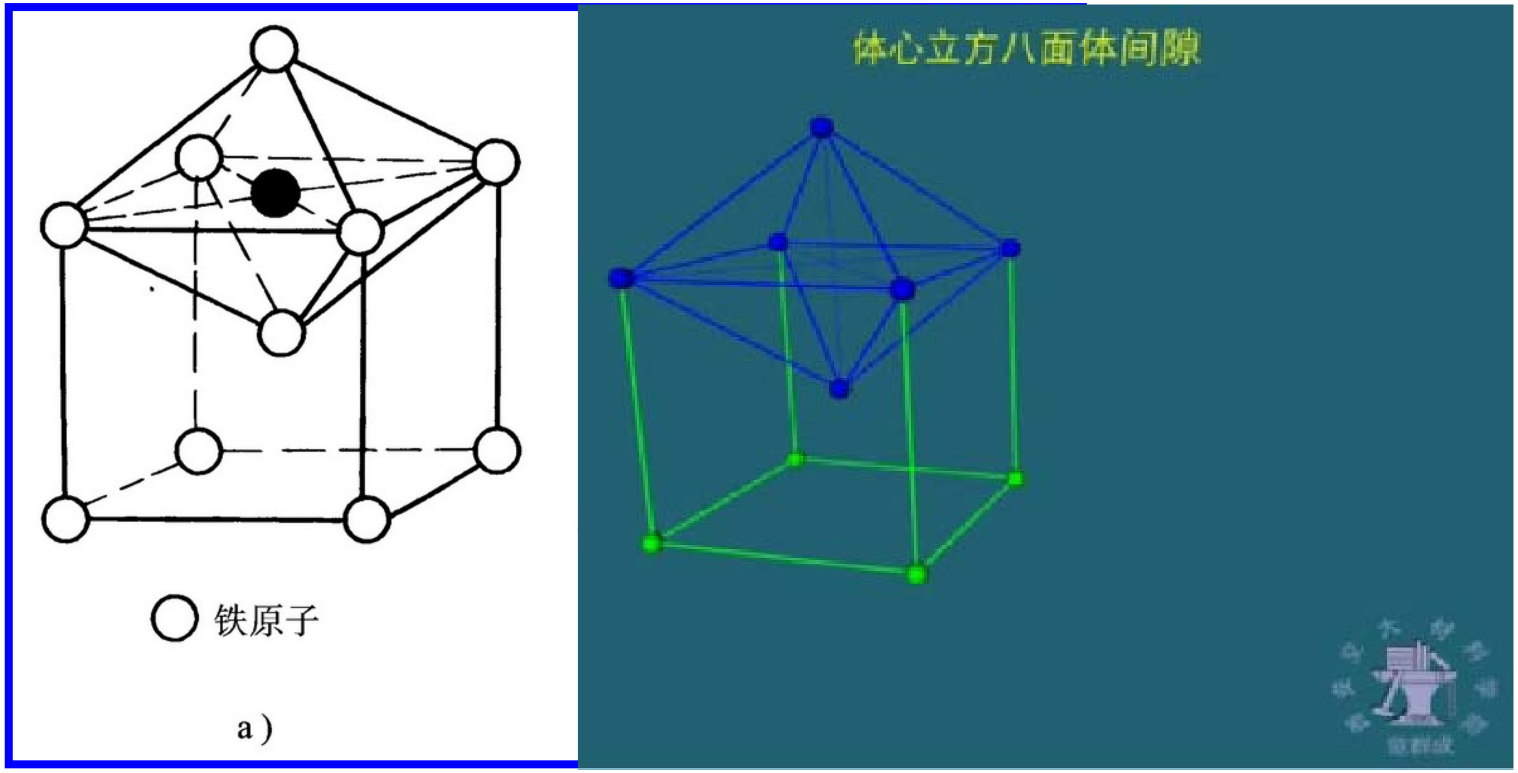
1. Solid solution { Substitutional solid solution / Interstitial solid solution



Schematic of Substitutional solid solution (a) and interstitial solid solution (b)

THE END

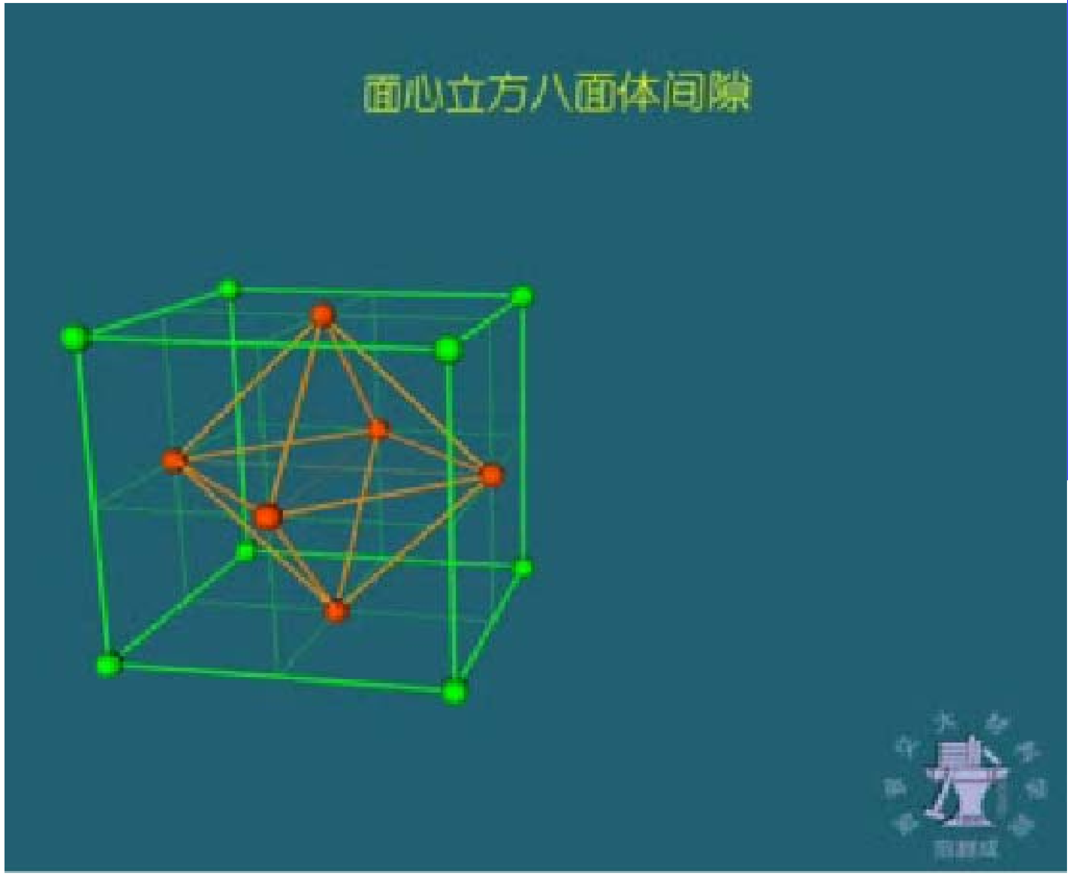
2. Ferrite (F or α)

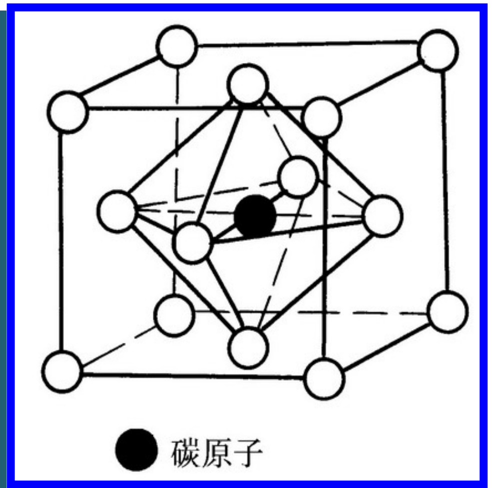


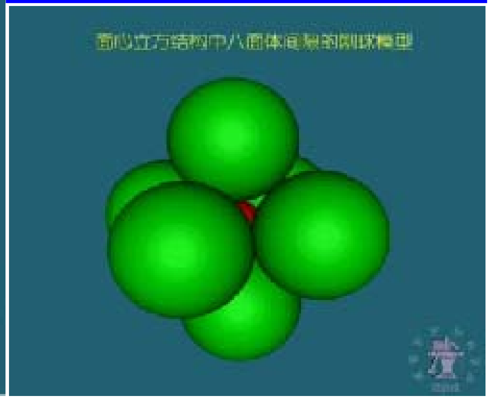
- Crystal structure of the ferrite —— bcc
- Maximum saturated solubility of ferrite—— 0.0218%

THE END

3. Austenite (A or γ)



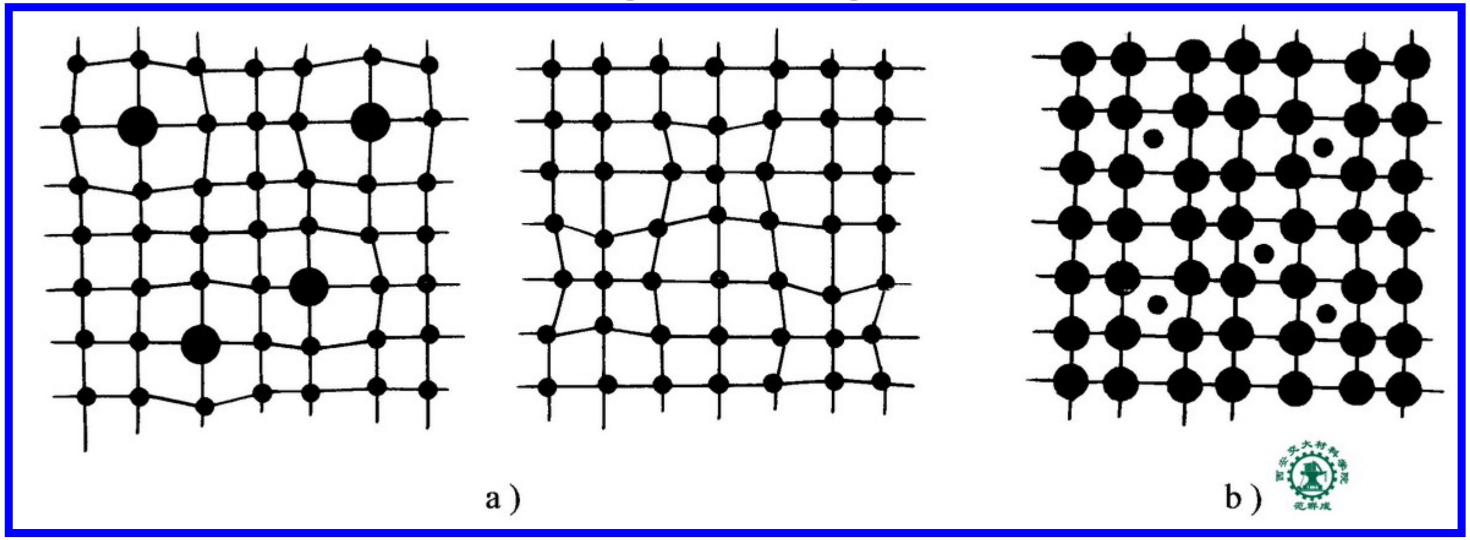




- Crystal structure of the austenite —— fcc
- Maximum saturated solubility of C in austenite —— 2.11%

THE END

4. Solid solution strengthening



Distortion of lattice as forming a) substitutional solid solution and b) interstitial solid solution

5. Feature in mechanical properties of the ferrite and austenite

- Higher hardness and strength (as compared with Fe)
- Higher plasticity and toughness (as compared with Fe_3C)

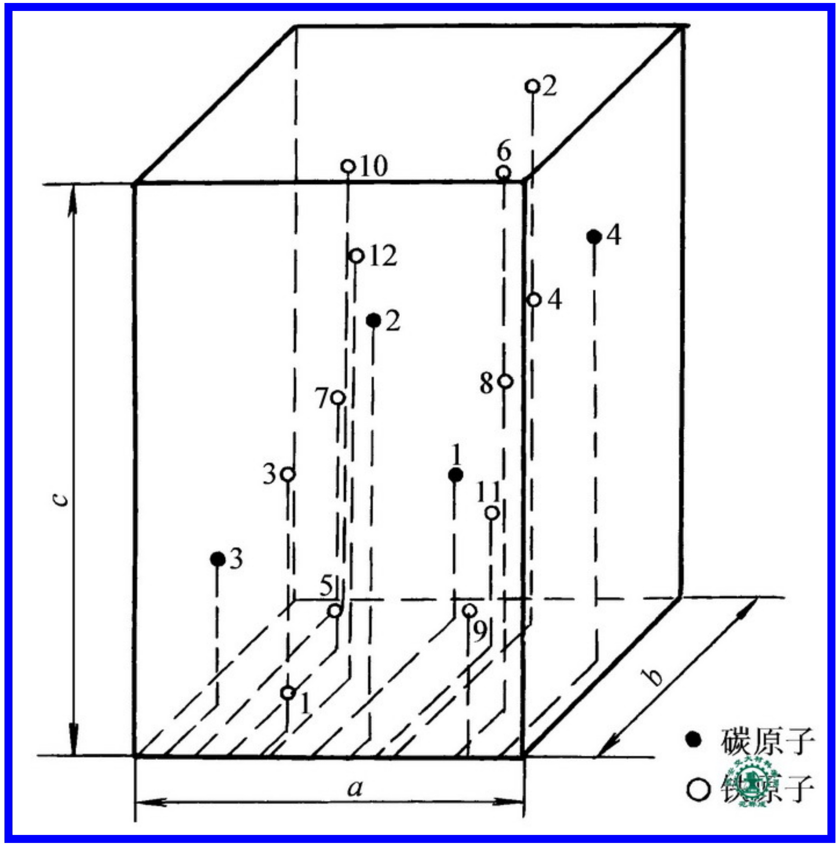
2.2.2 Fe and C forming compound—cementite Fe_3C

1. Crystal structure of Fe_3C

- Very complicated

2. Mechanical propertie features of Fe_3C

- Higher hardness (as compared with F)
- Higher brittleness (as compared with F)



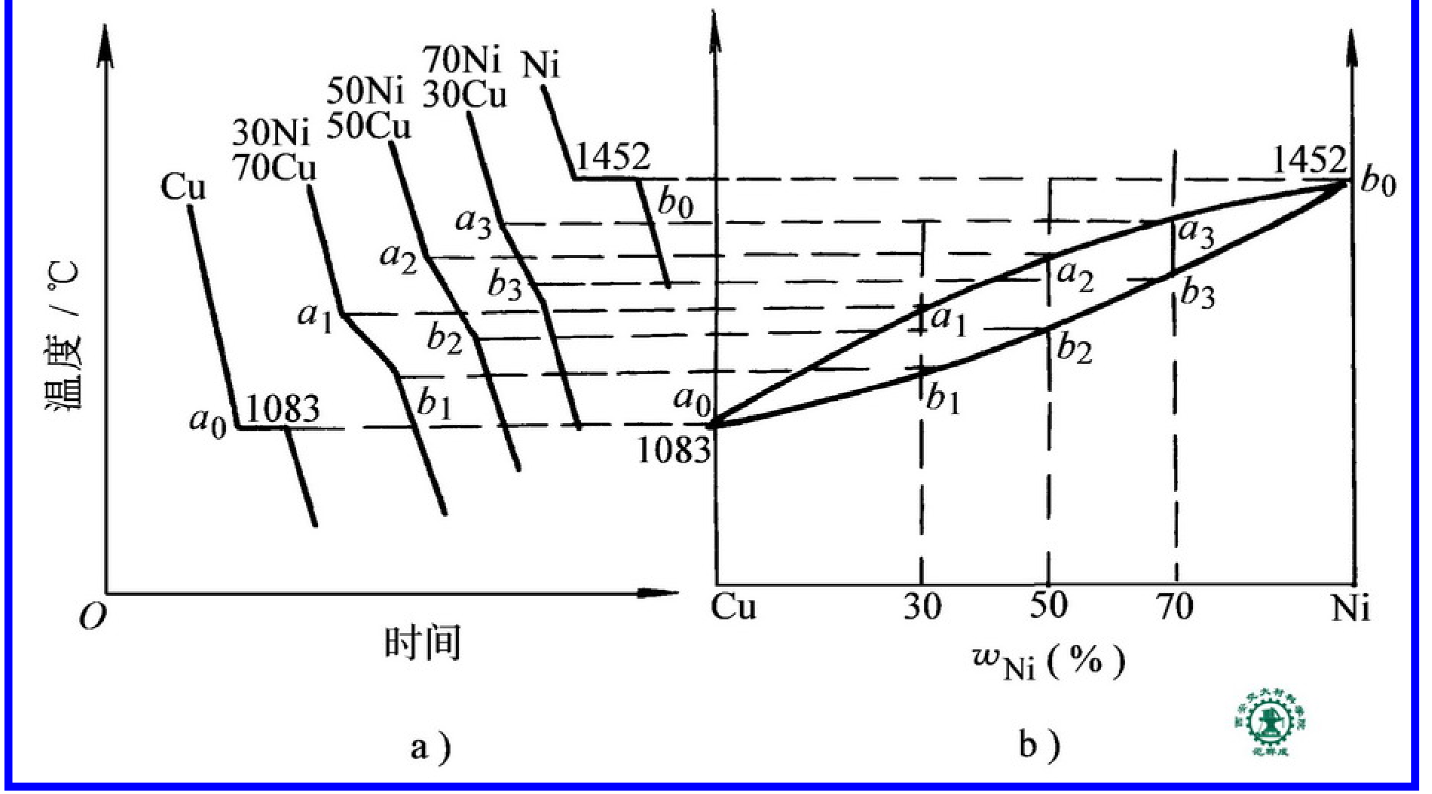
Crystal cell structure of Fe_3C

THE END

§ 2-3 Fe - Fe_3C phase diagram

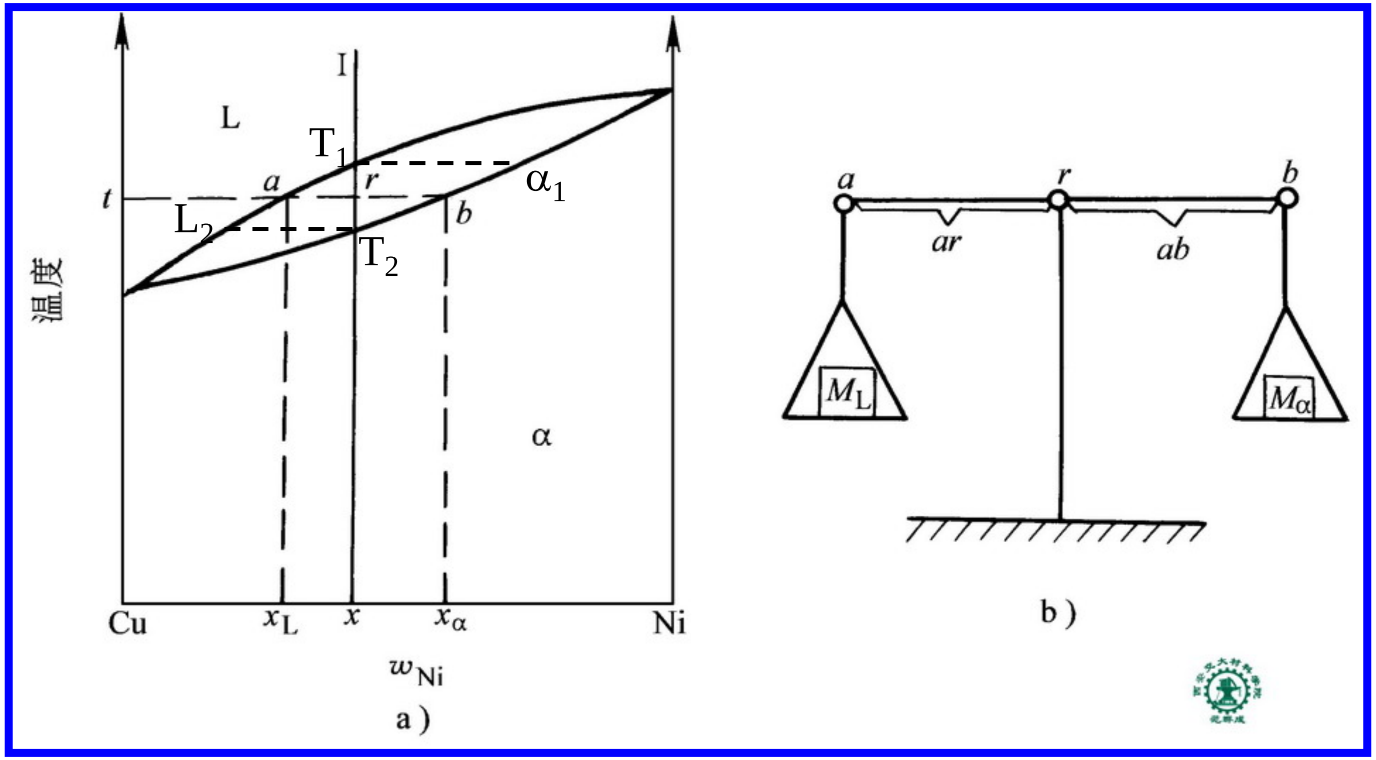
2.3.1 The basic concepts of Phase diagram

1. The establishment of Phase diagram



Establishment of Cu-Ni phase diagram by thermal analysis method

2. What is a phase diagram
3. Analyzing crystallization process with a phase diagram



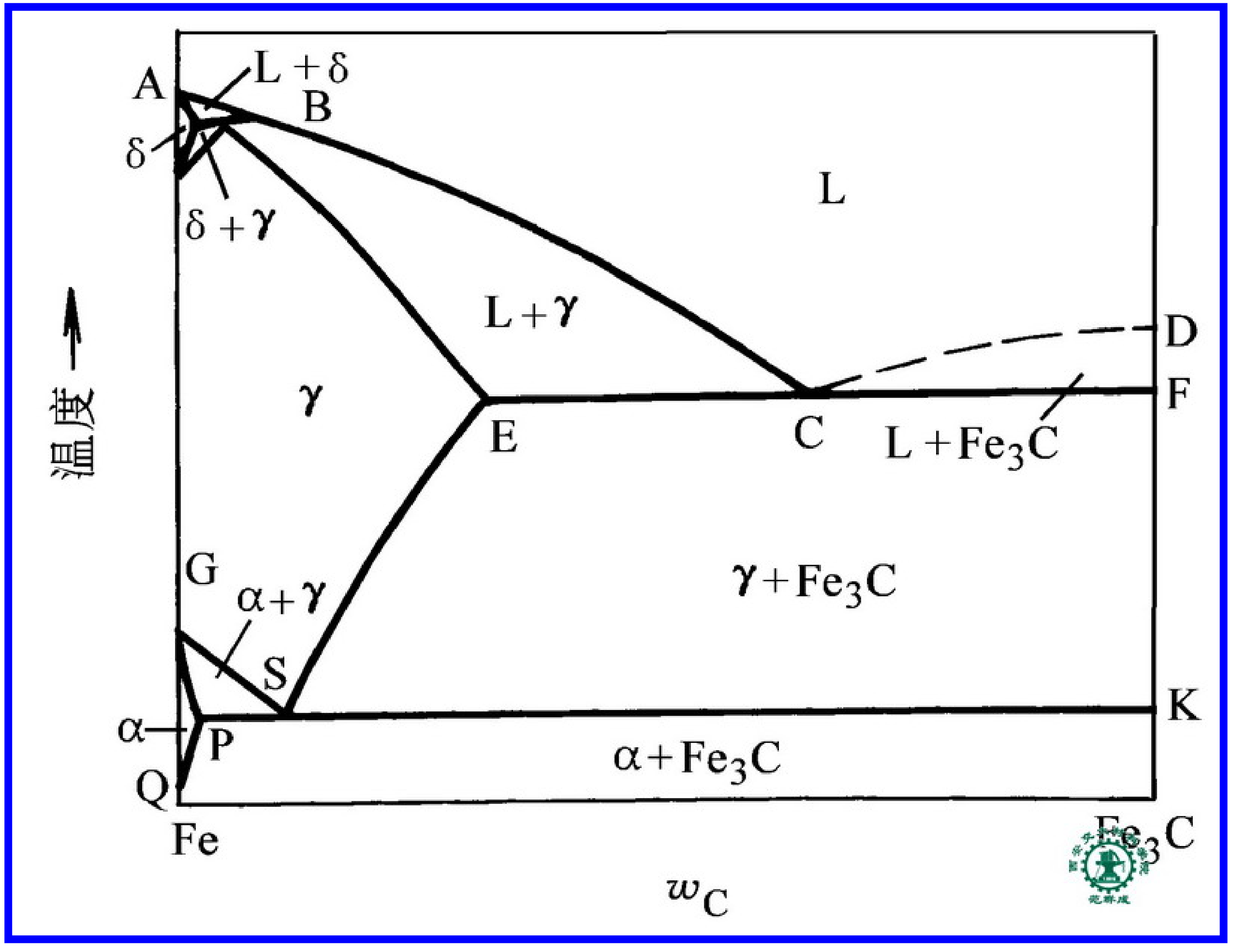
Analyzing crystallization process with a phase diagram a) and analogy of the lever law b)

4. The lever law

THE END

2.3.2 Analysis of Fe - Fe_3C phase diagram

1. Phase fields in the Fe - Fe_3C phase diagram



THE END

Phase fields in the Fe - Fe_3C phase diagram

2. Points and lines in the Fe - Fe_3C phase diagram

表 2-2 Fe-Fe_3C 相图中各主要点的温度、碳的质量分数及意义

点的符号	温度/℃	ω_C（%）	说明
A	1538	0	钝铁溶点
B	1495	0.53	包晶反应时液态合金的浓度
C	1148	4.30	共晶点，
D	1227	6.69	渗碳体溶点（计算值）
E	1148	2.11	碳在γ-Fe 中的最大溶解度
F	1148	6.69	渗碳体
G	912	0	同素异构转变点（A3）
H	1495	0.09	碳在δ-Fe 中的最大溶解度
J	1495	0.17	包晶点
K	727	6.69	渗碳体
N	1394	0	同素异构转变点（A4）
P	727	0.0218	碳在α-Fe 中的溶解度
S	727	0.77	共析点，
Q	室温	0.0008	碳在α-Fe 中的溶解度

THE END

3. Triphase equilibrium transformation in Fe-C alloy

1) Eutectic transformation

$$L_{4.3} \xleftrightarrow{1148^{o}C} (\gamma_{2.11} + Fe_3C)$$

Ledeburite (Ld)

- The ledeburite is very hard and brittle

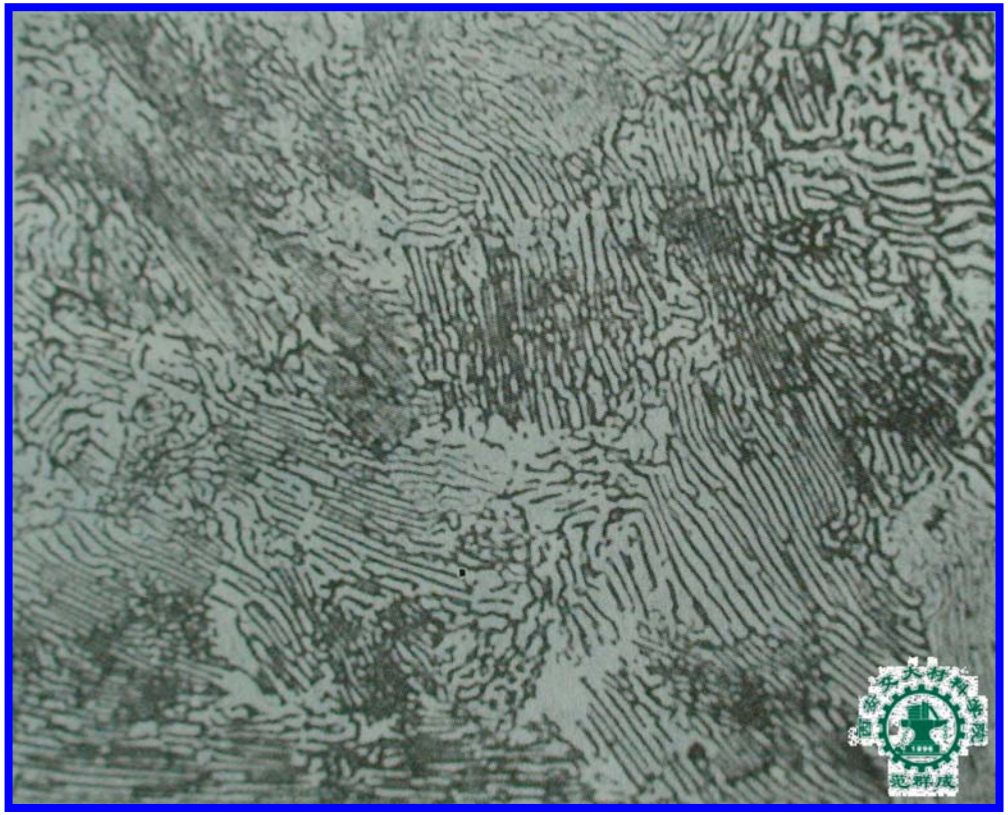
Micrograph of ledeburite at room temperature (×200)

THE END

2) Eutectoid transformation

$$\gamma_{0.77} \xleftrightarrow{727^{o}C} (\alpha_{0.0218} + Fe_3C) \text{ — Pearlite (P)}$$

- The pearlite has very good composite mechanical property



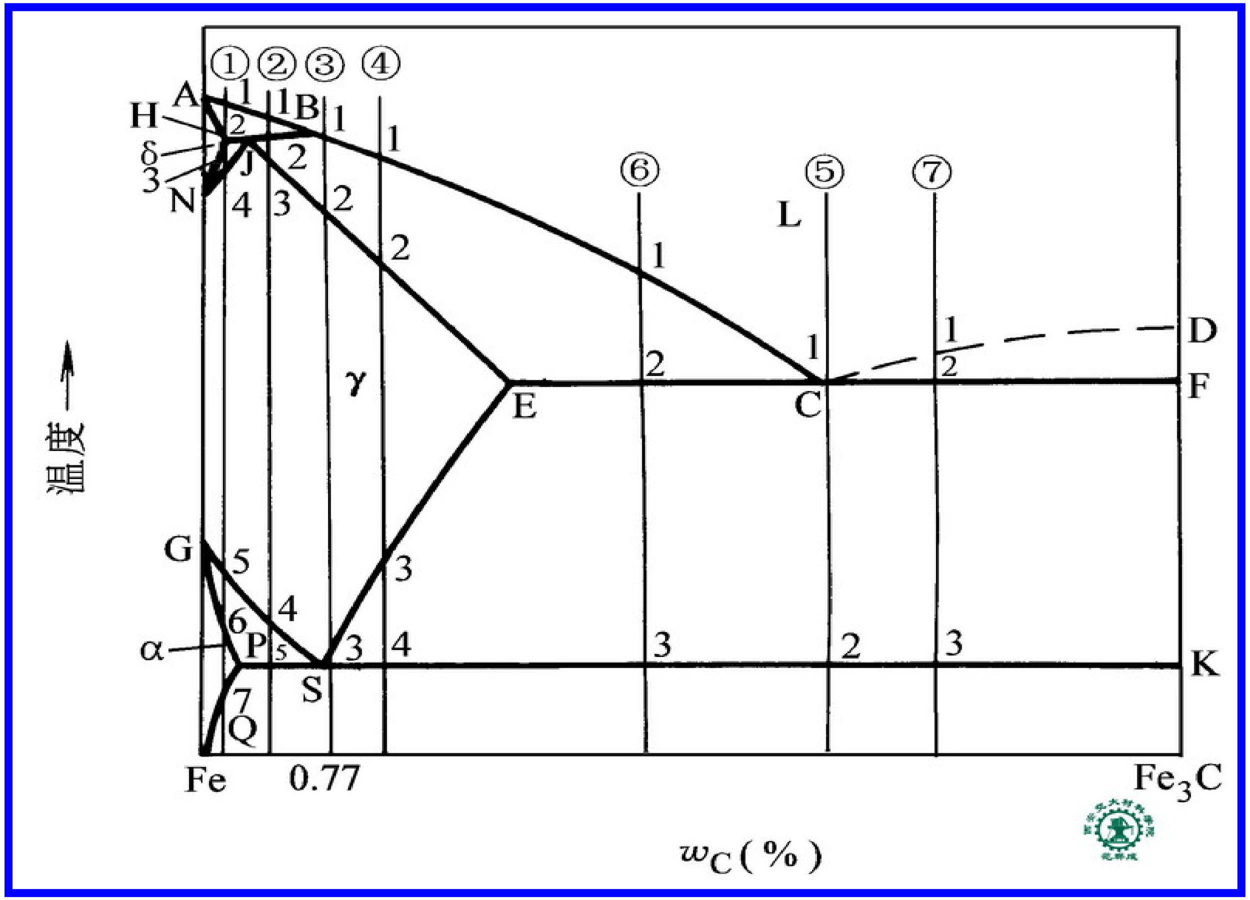
Micrograph of eutectic at room temperature (×500)

3) Peritectic transformation

$$\delta_{0.09} + L_{0.53} \xleftrightarrow{1495^{o}C} \gamma_{0.17}$$

THE END

2.3.3 Analysis of crystallizing process of typical Fe-C alloys

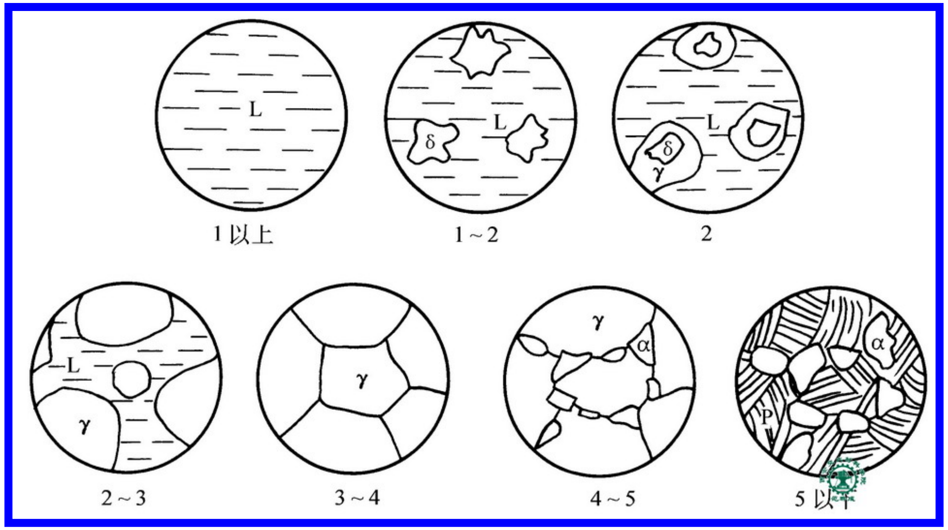


Typical alloys in the Fe-C phase diagram

- Structure ——

THE END

1. Hypoeutectoid steel ($0.0218\% < w_C < 0.77\%$)

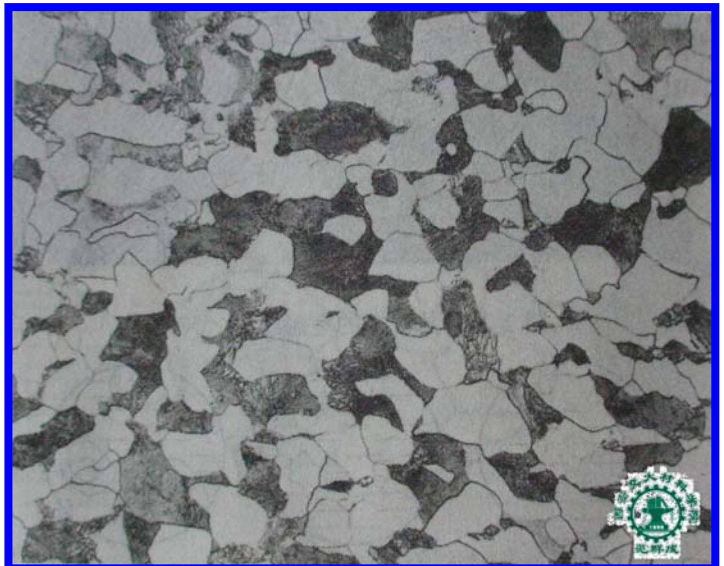


Crystallizing process of hypoeutectoid steel (w_C=0.4%)

- Structure at R.T.

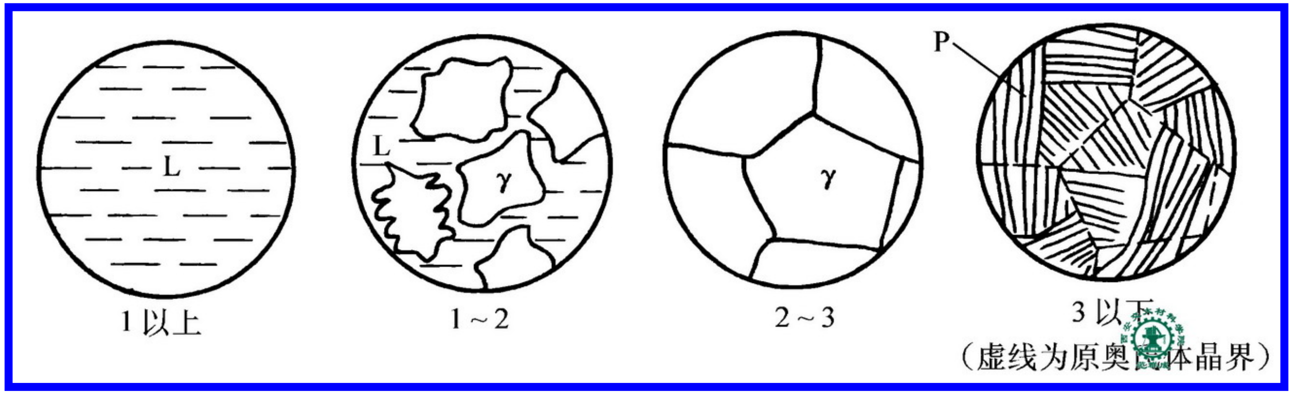
  P + F

  Micrograph of hypoeutectoid steel at room temperature (×500)



THE END

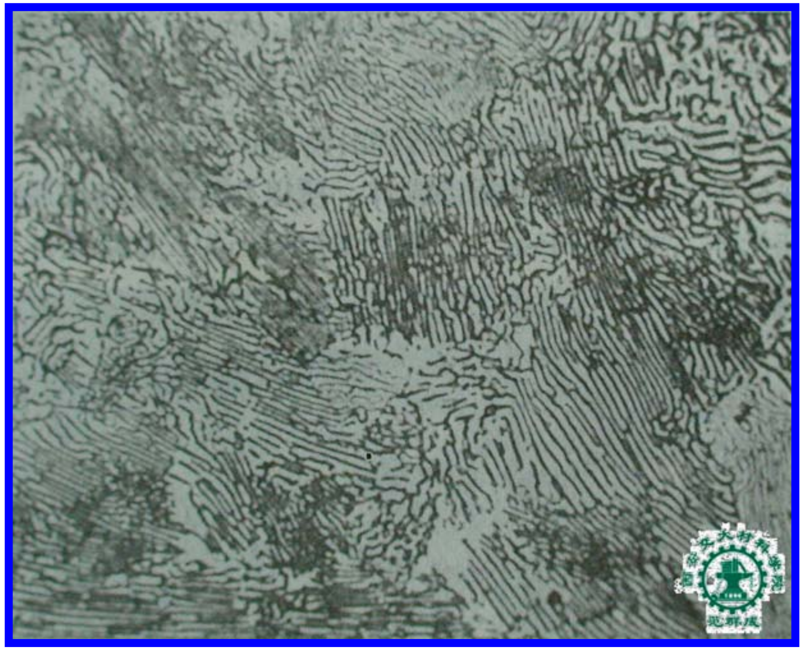
2. Eutectoid steel (w_C = 0.77%)



Crystallizing process of eutectoid steel (w_C =0.77%)

- Structure at R.T.

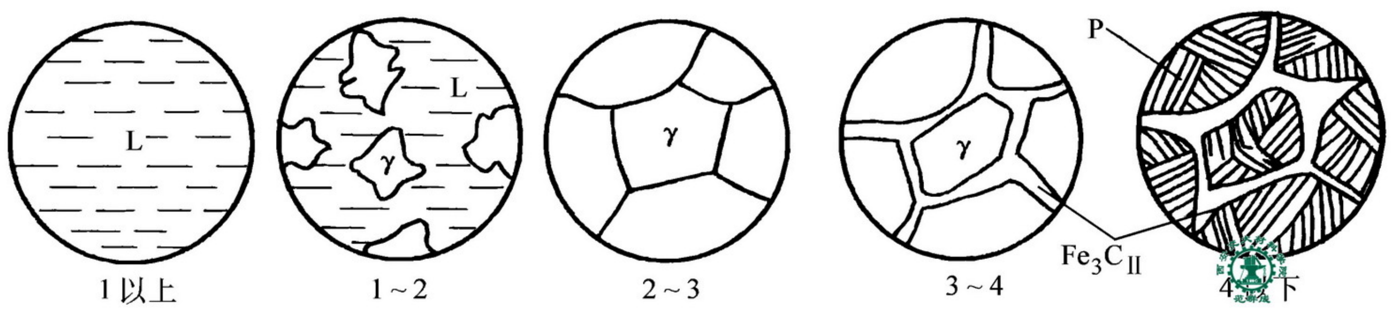
  P



Micrograph of eutectoid steel at room temperature (×500)

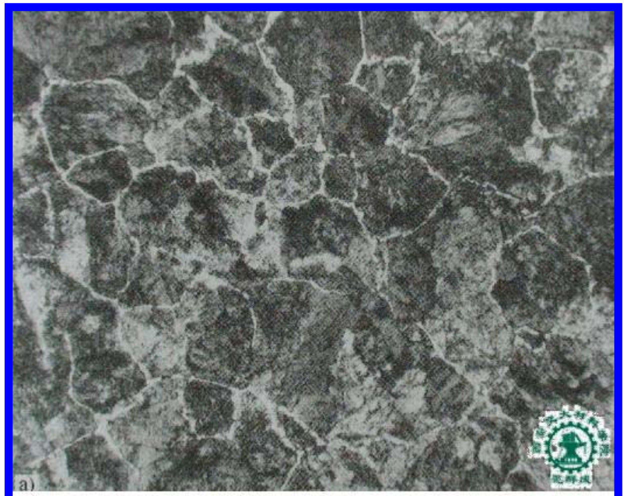
THE END

3. Hypereutectoid steel (0.77% < w_C ≤ 2.11%)

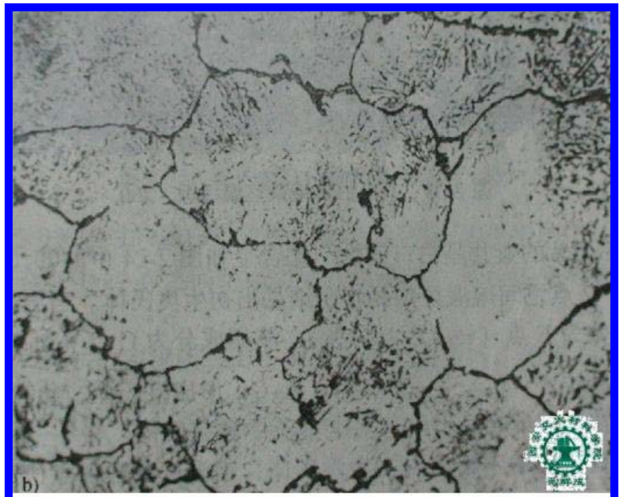


Crystallizing process of hypereutectoid steel (w_C =1.2%)

- Structure at R.T. $P + Fe_3C_{II}$



a）硝酸酒精侵蚀，白色网为二次渗碳体，暗黑色为珠光体×400

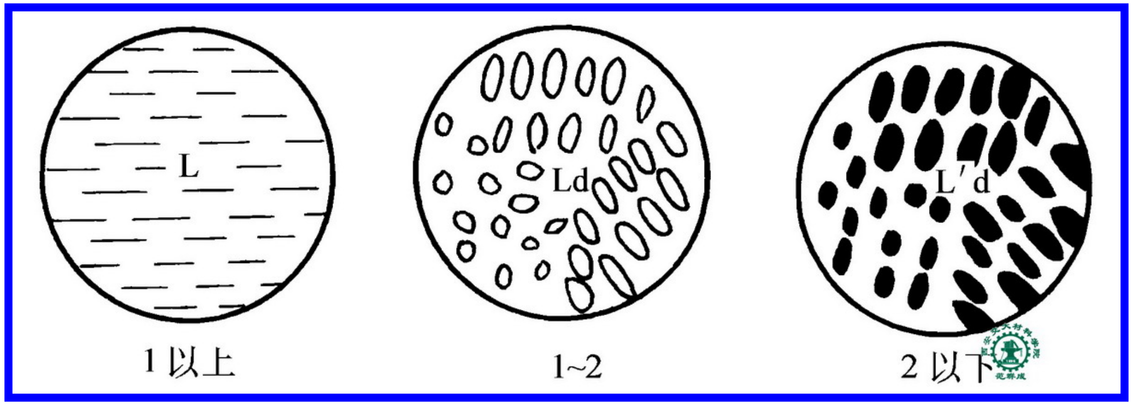


b）苦味酸钠侵蚀，黑色网为二次渗碳体，浅白色为珠光体×500

THE END

Micrograph of hypereutectoid steel at room temperature

4. Eutectic white cast iron (w_C = 4.3%)



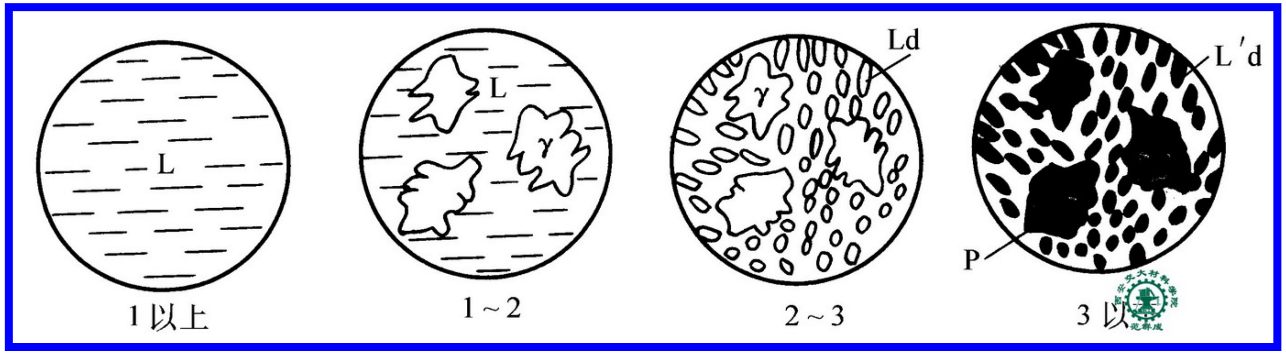
Crystallizing process of eutectic white cast iron (w_C =4.3%)

- Structure at R.T.

Micrograph of eutectic white cast iron at room temperature (×200)

THE END

5. Hypoeutectic white cast iron (2.11% < w_C < 4.3%)

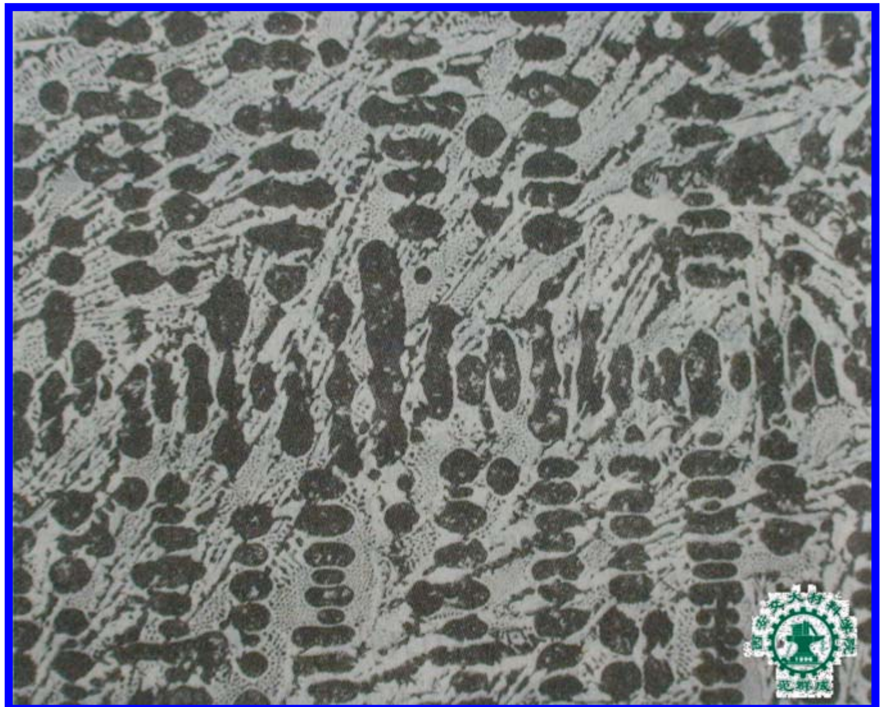


Crystallizing process of hypoeutectic white cast iron (w_C =3.0%)

- Structure at R.T.

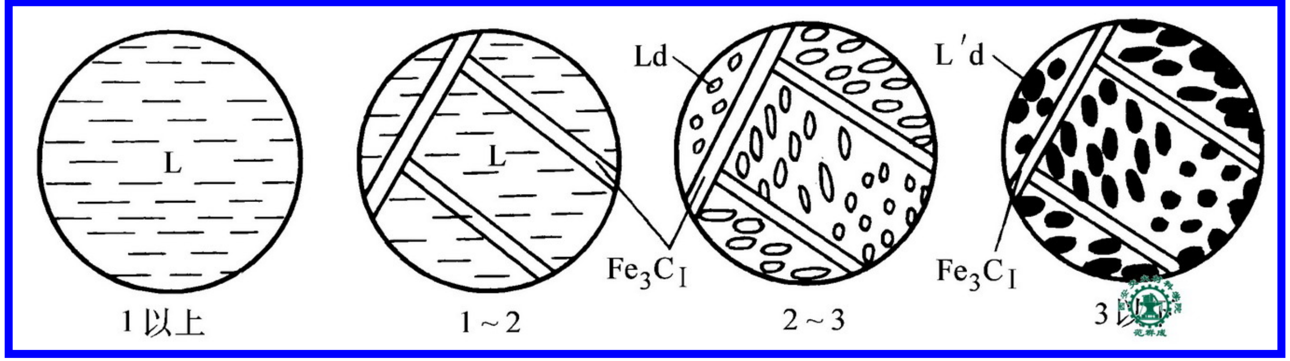
  $+ P + Fe_3C_{II}$

Micrograph of hypoeutectic white cast iron at room temperature (×250)



THE END

6. Hypereutectic white cast iron (4.3% < w_C < 6.69%)

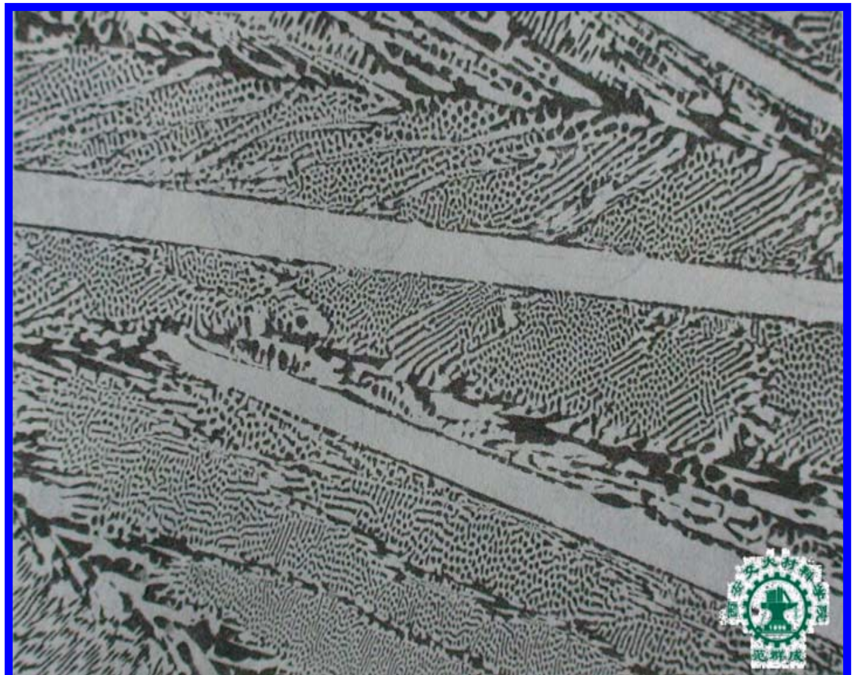


Crystallizing process of hypereutectic white cast iron (w_C =5.0%)

- Structure at R.T.

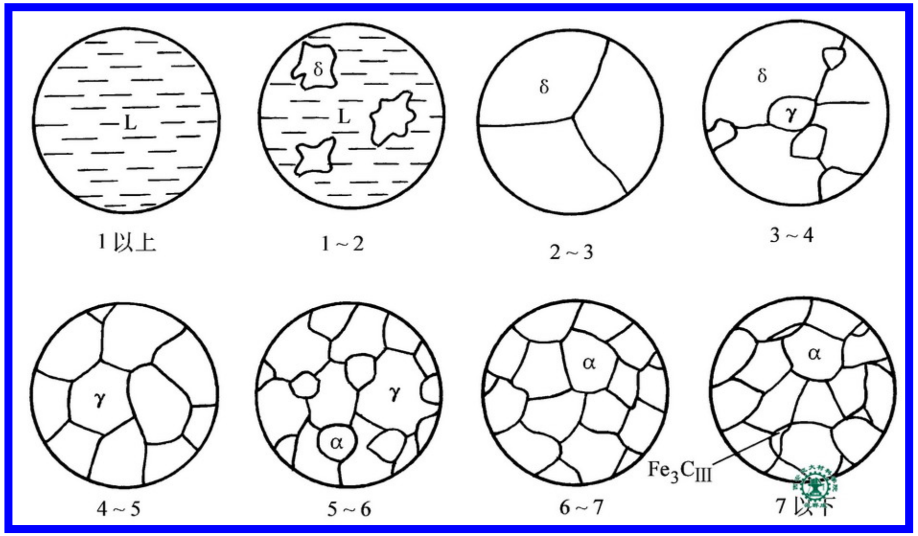
  + Fe_3C_{I}

  Micrograph of hypereutectic white cast iron at room temperature (×100)



THE END

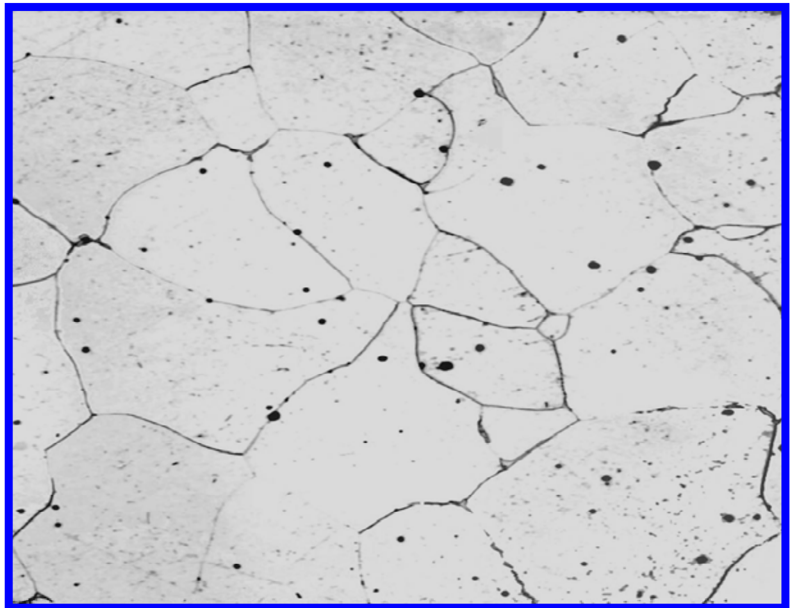
7. Commercially pure iron ($w_C \leqslant 0.0218\%$)



Crystallizing process of commercially pure iron (w_C =0.01%)

- Structure at R.T.

$F + Fe_3C_{III}$



Micrograph of commercially pure iron at room temperature (×125)

THE END

2.3.4 The effects of carbon on the equilibrium structures and properties of Fe-C alloy

1. The effects on equilibrium structures

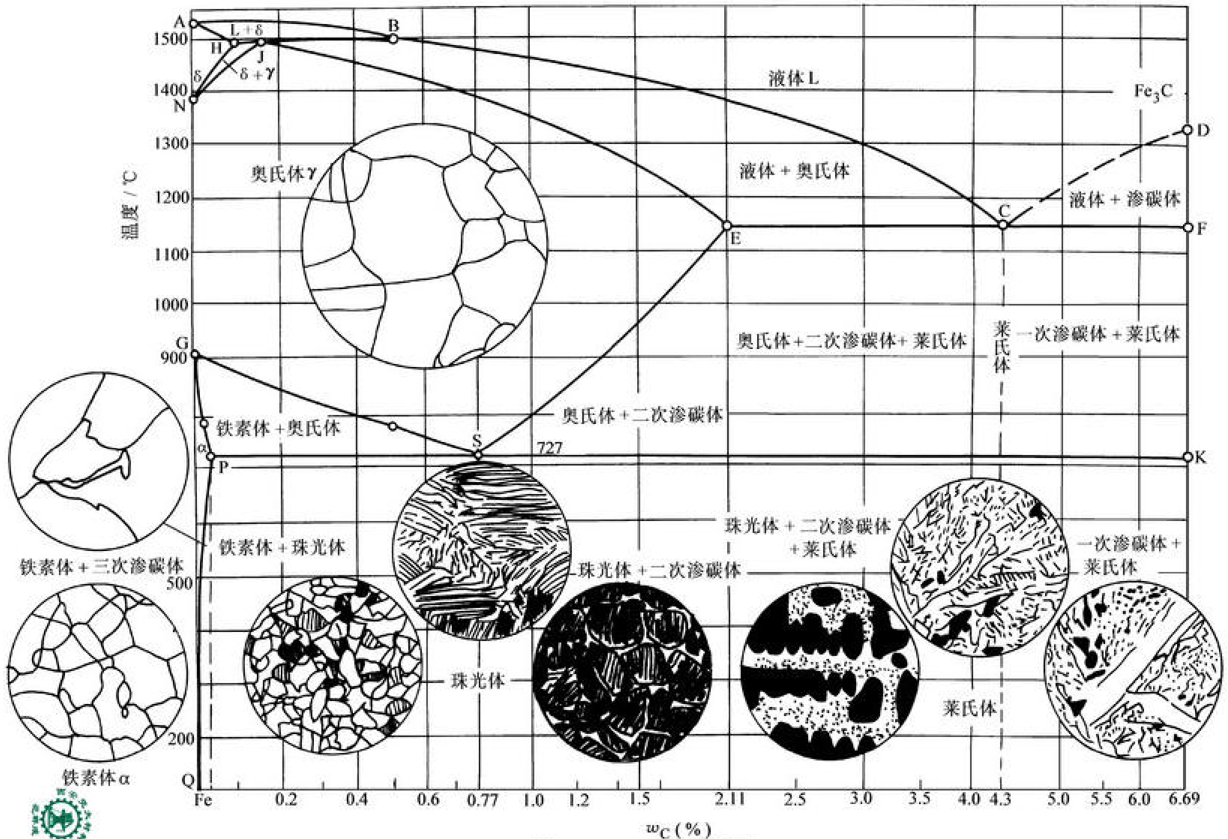
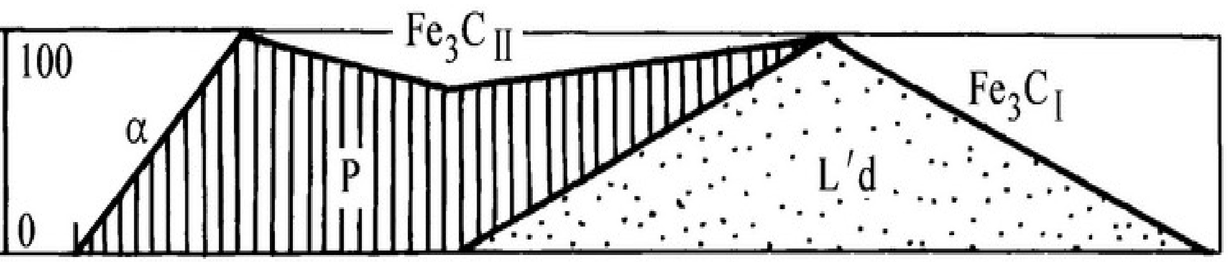
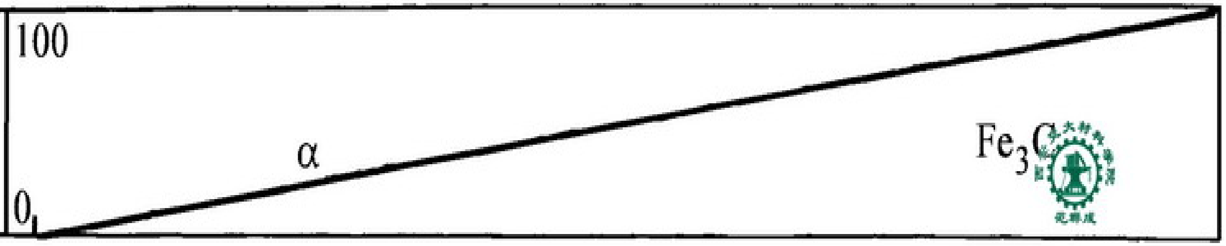


图2-22 Fe-Fe$_3$C相图

THE END

The Fe-Fe$_3$C phase diagram divided into different structure fields

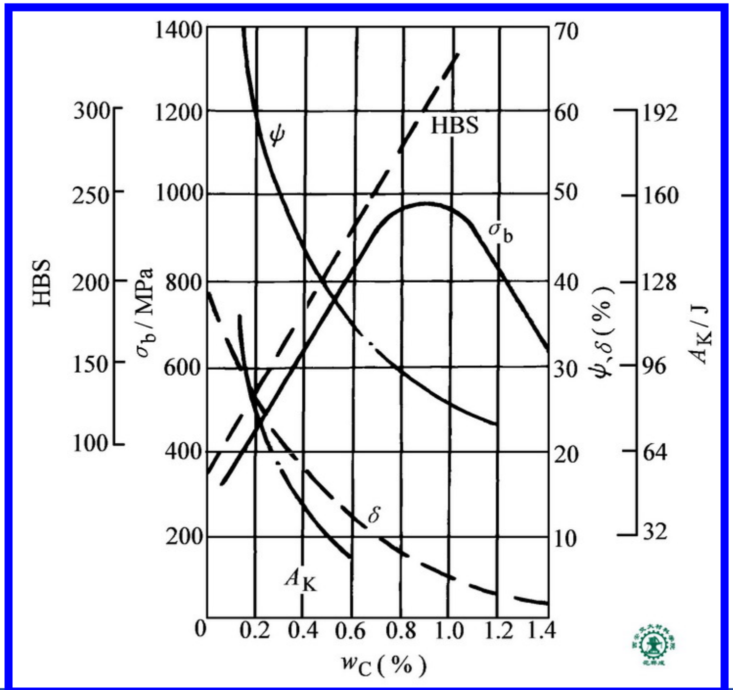
钢铁分类 / 组织与相 / 项目	工业纯铁	钢		白口铸铁	
		亚共析钢	过共析钢	亚共晶白口铸铁	过共晶白口铸铁
成分及组织特征	w_C=0.0218%	w_C=0.77%	w_C=2.11%	w_C=4.3%	w_C=6.69%
		高温固态组织为单相固溶体		组织中有共晶莱氏体	
组织组成物相对量					
相组成物相对量					

THE END

2. The effects on mechanical properties

表 2-3 铁碳合金平组织中几种组织组成物的力学性能

组织成物	σ_b / MPa	硬度	δ（%）	A_K / J
铁素体（α）	230	80HBS	50	160
渗碳体（Fe_3C）	30	800HBS	≈0	≈0
珠光体（P）	750	180HBS	20～25	24～32

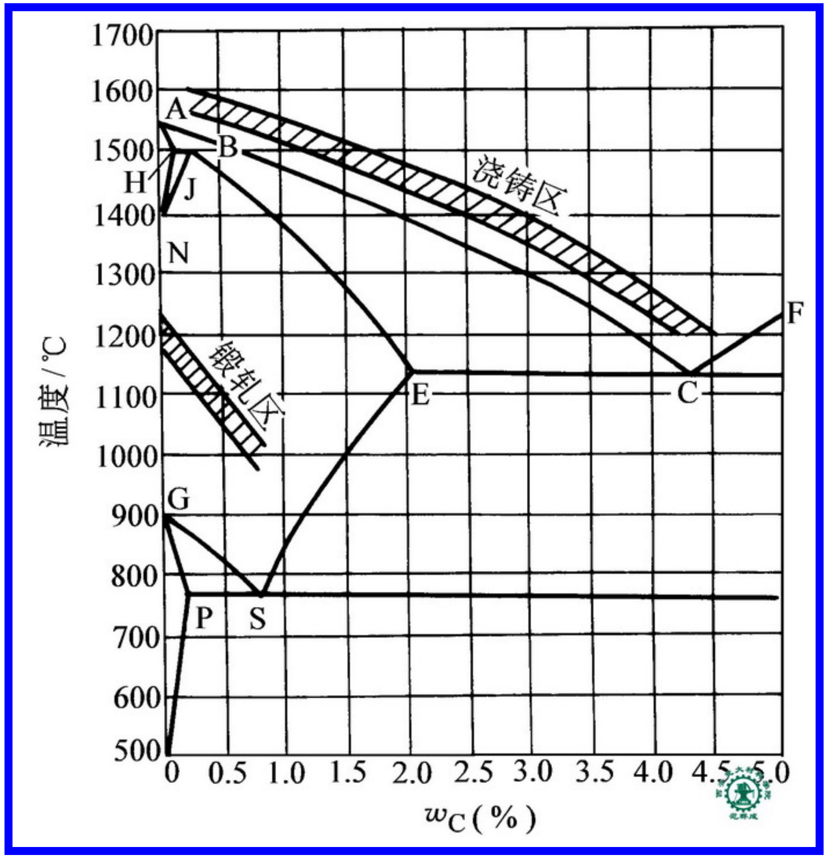


The effects of weight fraction of carbon on the mechanical properties of the slow cooling carbon steels

THE END

2.3.5 Practically use of the Fe-Fe_3C phase diagram

1. Providing a basis of selecting composition of the materials
2. Providing a basis of planning process of hot working



The relationship between the process of casting and forging and Fe-Fe_3C phase diagram

THE END

Casting

THE END

Ingots

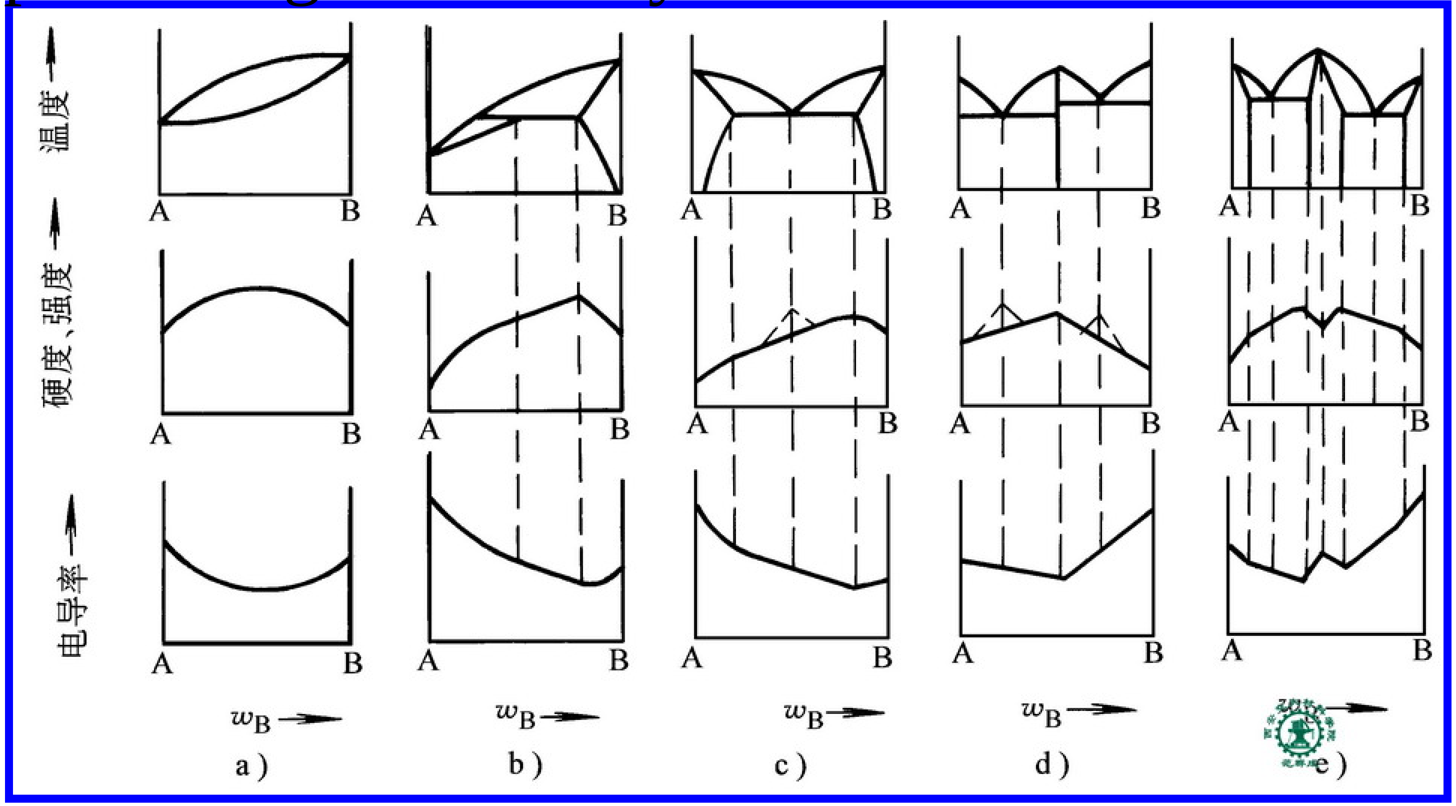
THE END

Rolling

THE END

2.3.6 Summary of relationship between property and phase diagram of alloy

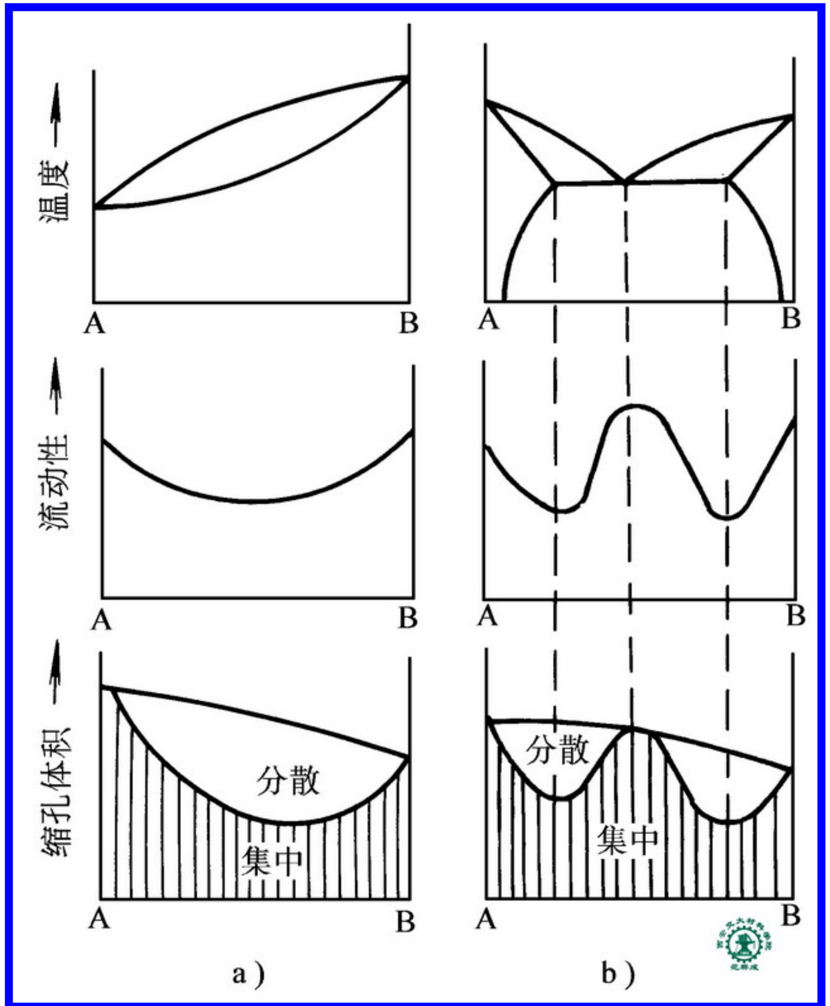
1. The relationship between service performance and phase diagram of alloy



The relationship between service performance and phase diagram of alloy

2. The relationship between processing properties and phase diagram of alloy

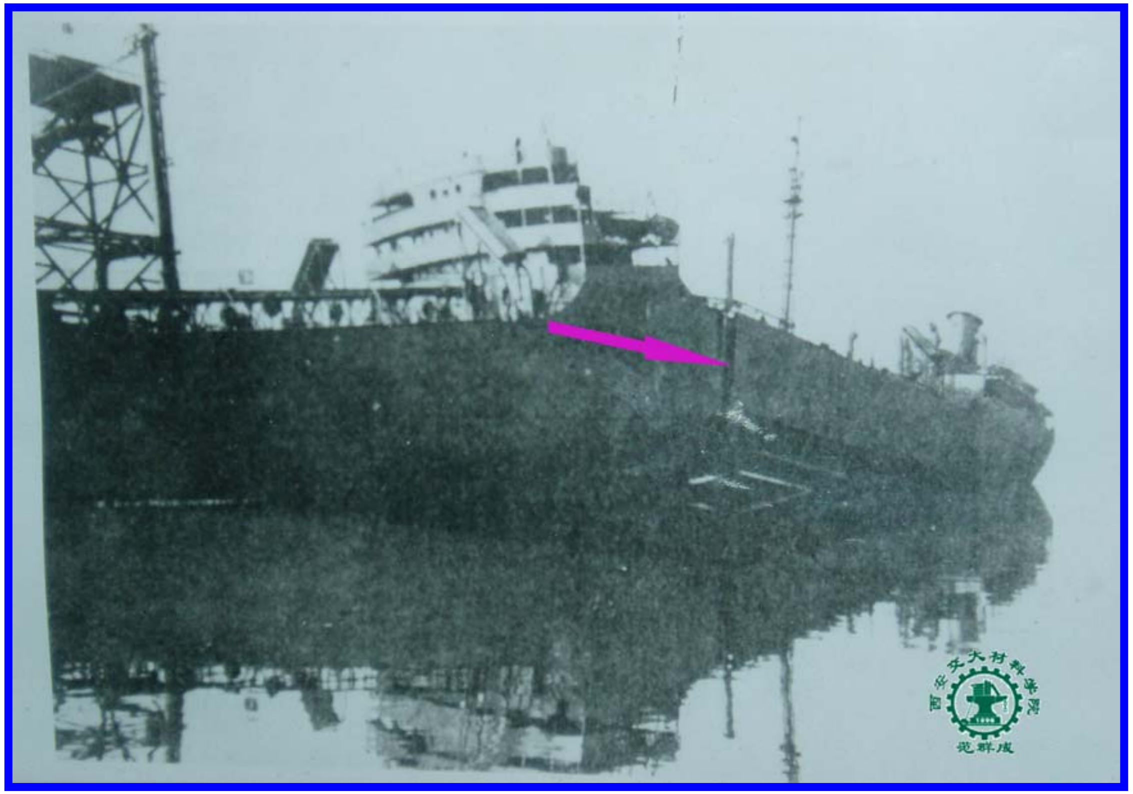
The relationship between casting property and phase diagram of alloy



THE END

§ 2-4 The effects of common impurity elements on properties of steel

1. The effects of S and P

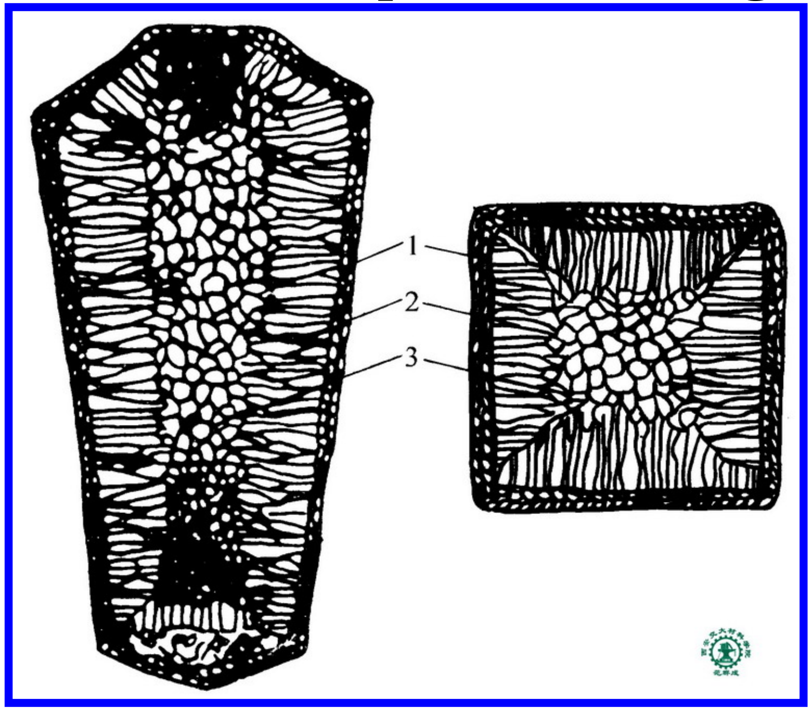


2. The effects of Si and Mn
3. The effects of gases

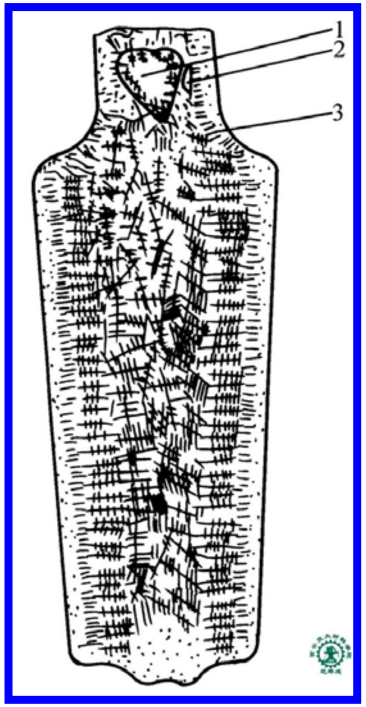
THE END

§ 2-5 The structure and defect of steel ingot

1. The structure of quiet steel ingot
2. The defect in quiet steel ingot



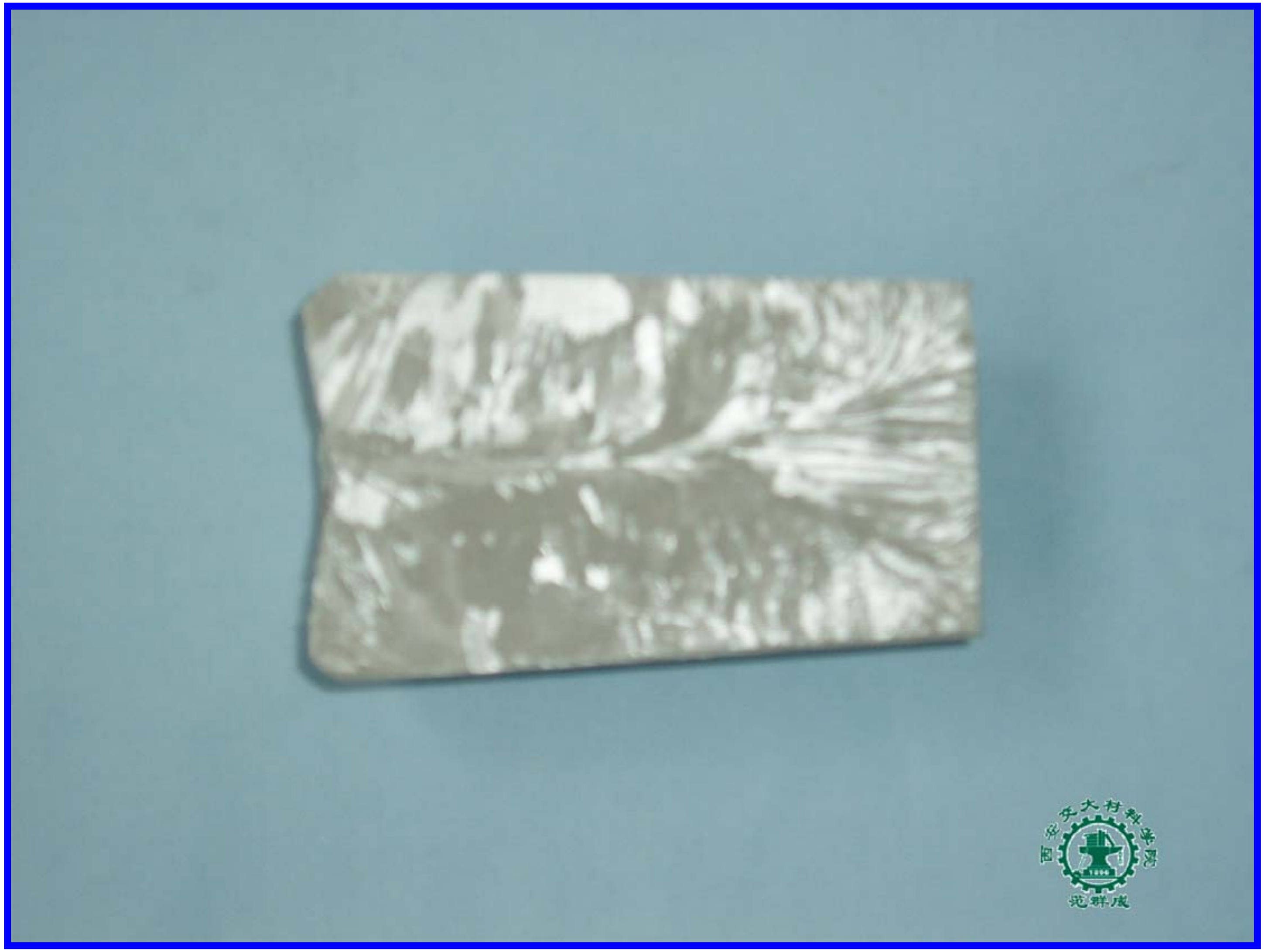
Macrostructures of quiet steel ingot
1—fine-grain zone in surface layer
2—columnar-grain zone
3—isometric-grain zone in center



Defects in quiet steel ingot
1—shrinkage cavity
2—bubble
3—loose

THE END

An aluminum ingot



THE END

§ 2-6 The effects of press processing on structures and properties of steel

2.6.1 The effects of cold press processing on structures and properties of steel

1. The main mode of plastic deformation — slip

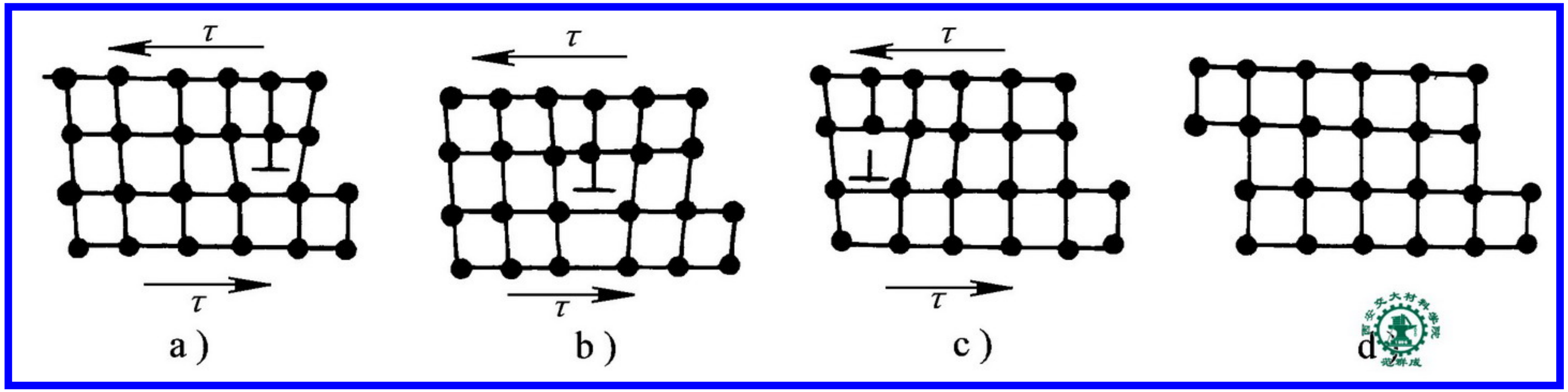
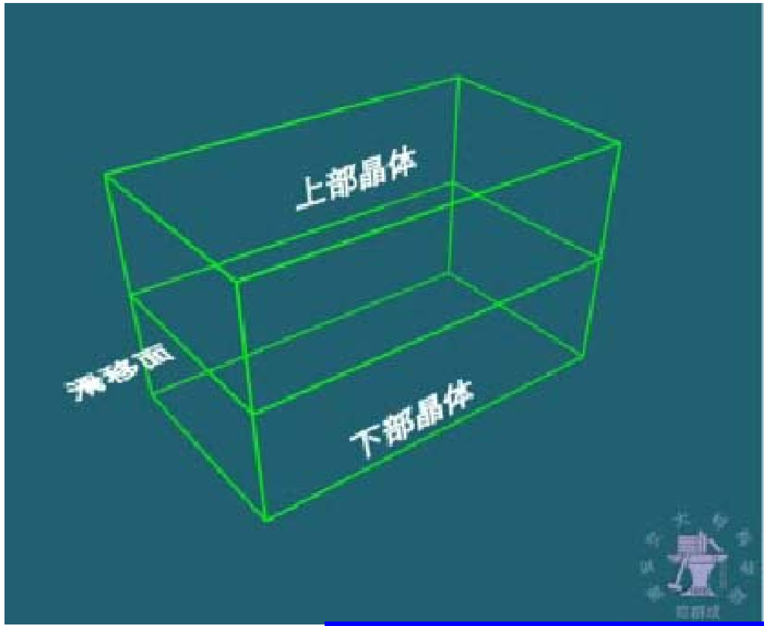
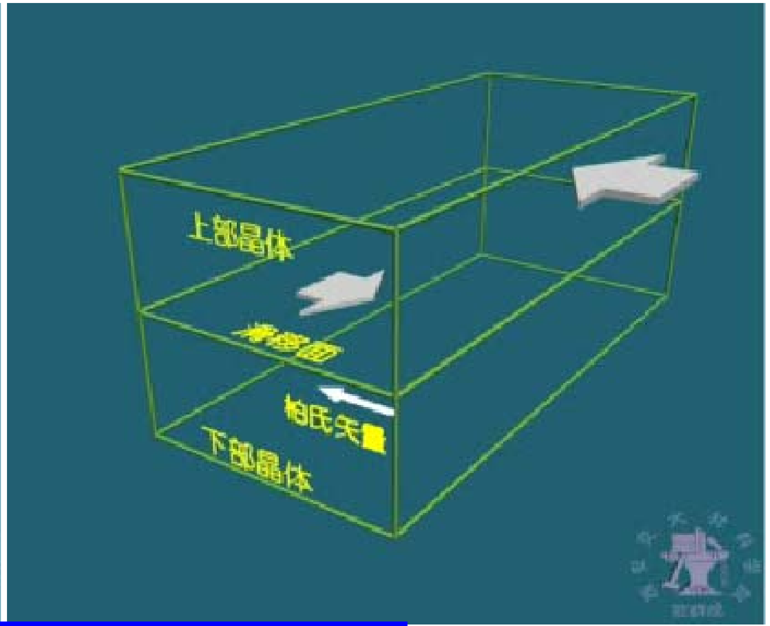


Diagram of slipping through the dislocation movement

THE END





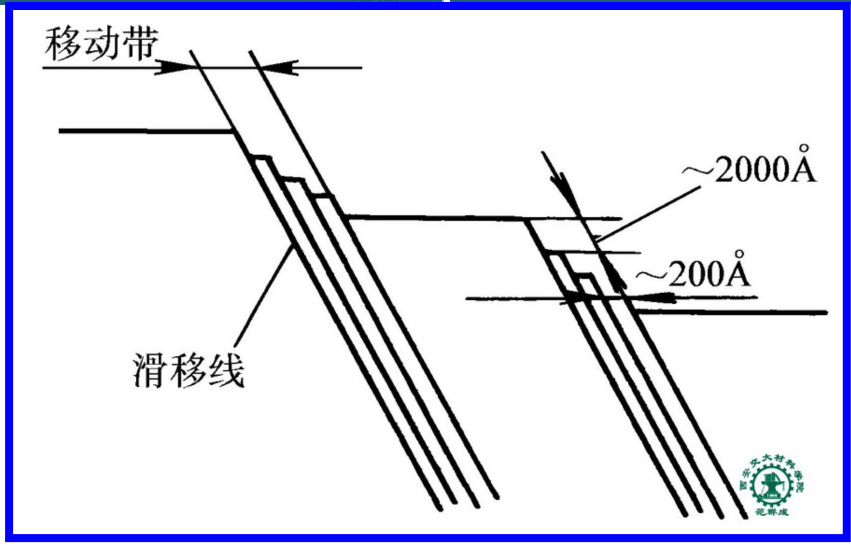


Diagram of slip line and slip band

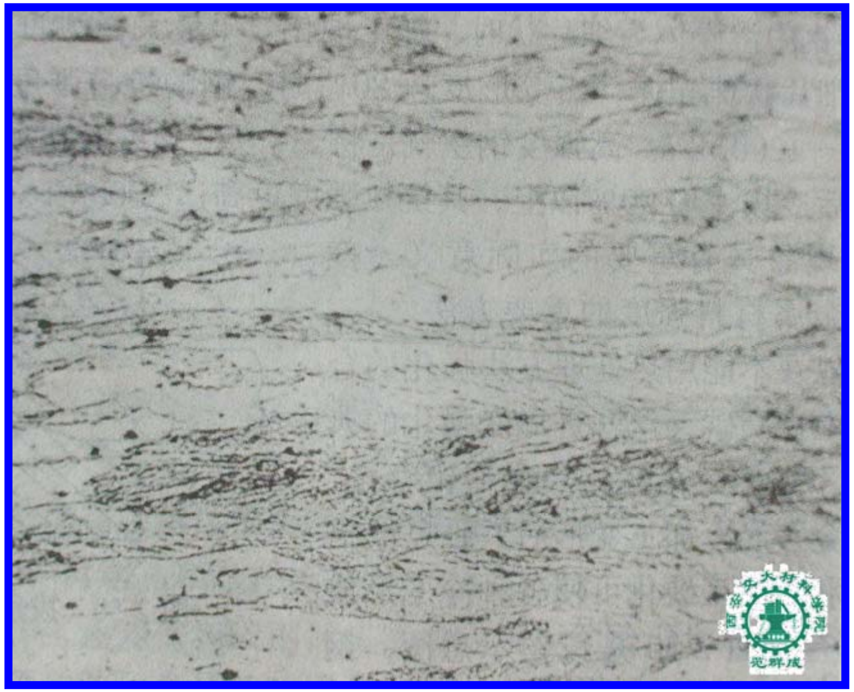
THE END

Slip band

THE END

Micrograph of slip band in the surface of commercially pure iron

2. The changes in structures of pure iron and steel in the process of plastic deformation



Microstructure of commercially pure iron with deformation of 80% (×125)

- The grains being elongated
- The density of dislocation beinhg increased

THE END

- Forming deformation texture

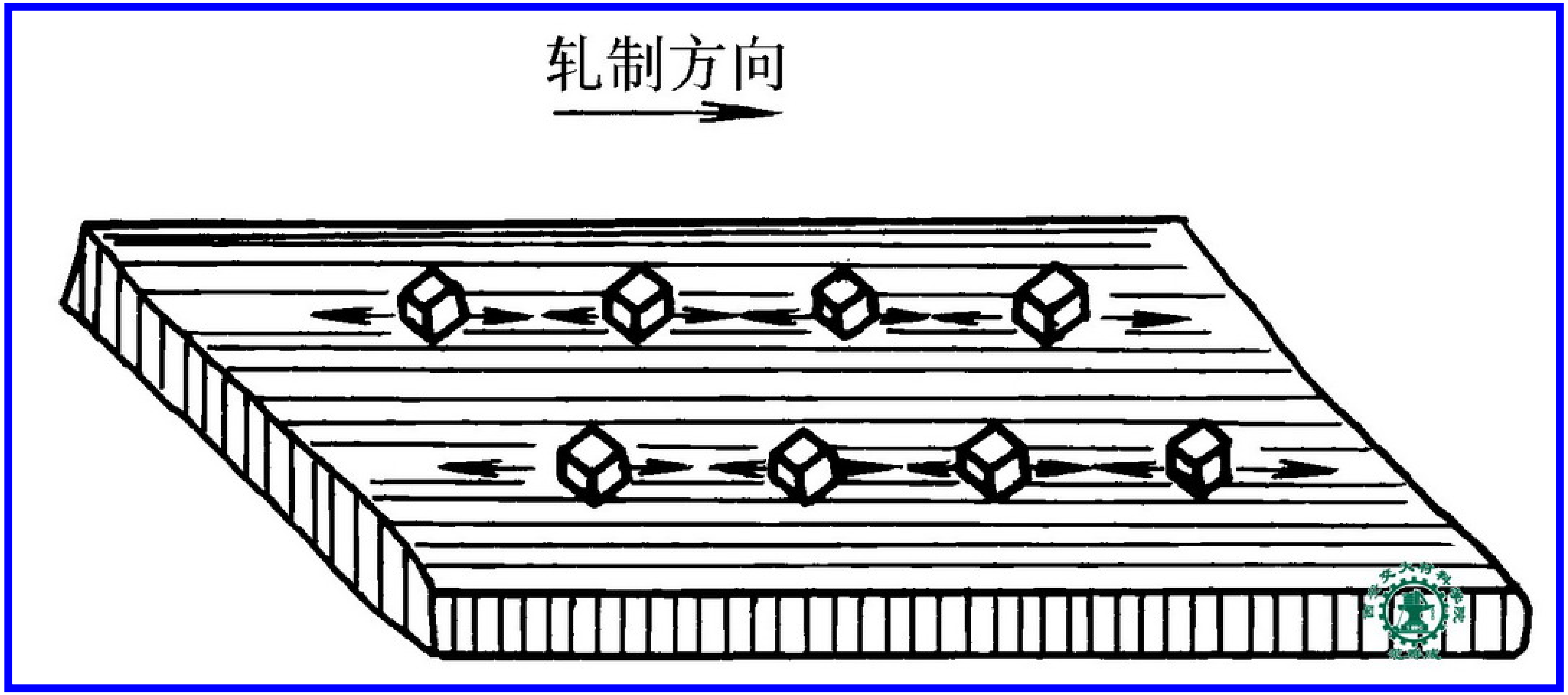
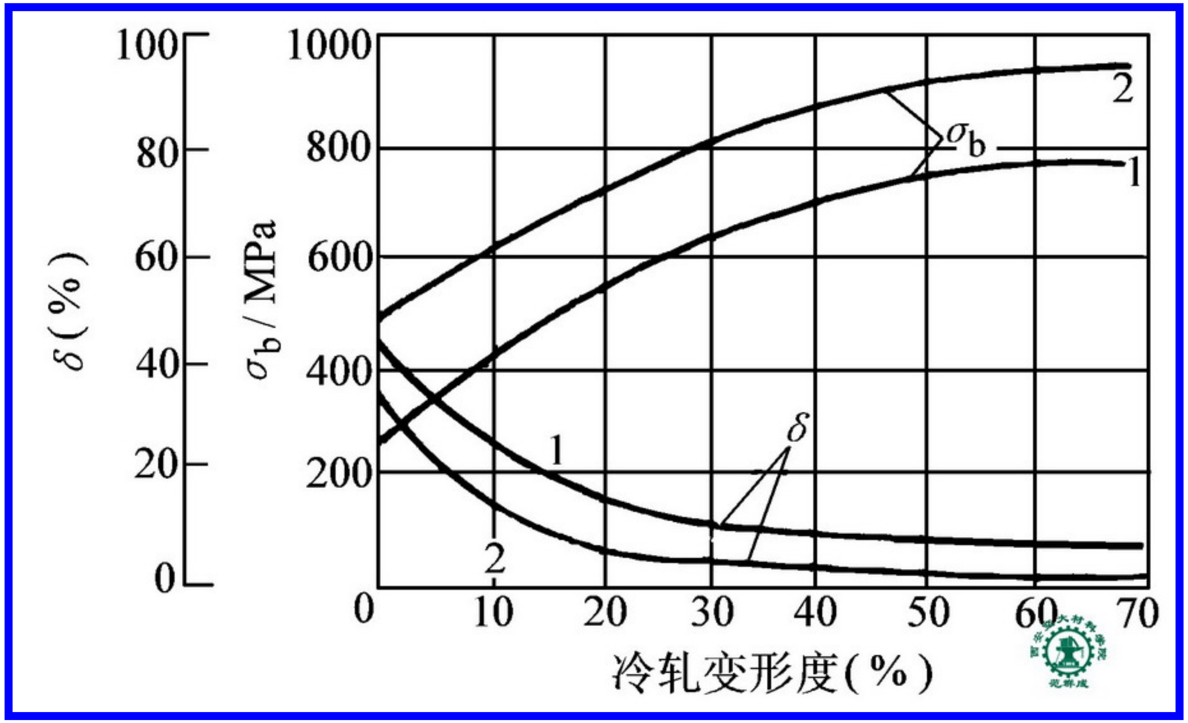


Diagram of texture in commercially pure iron

THE END

3. The changes in properties of pure iron and steel in the process of plastic deformation

- Bring about work hardening (deformation strengthening)



Work hardening of commercially pure iron and low carbon steel

1—commercially pure iron 2— low carbon steel

THE END

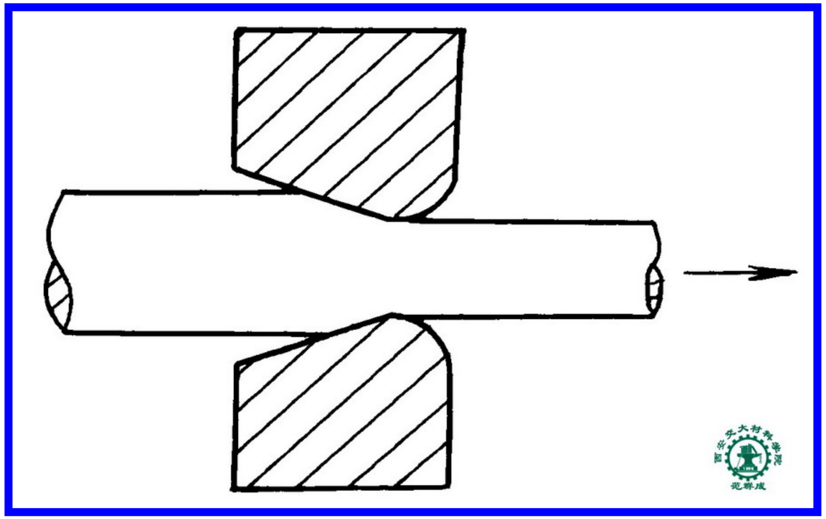
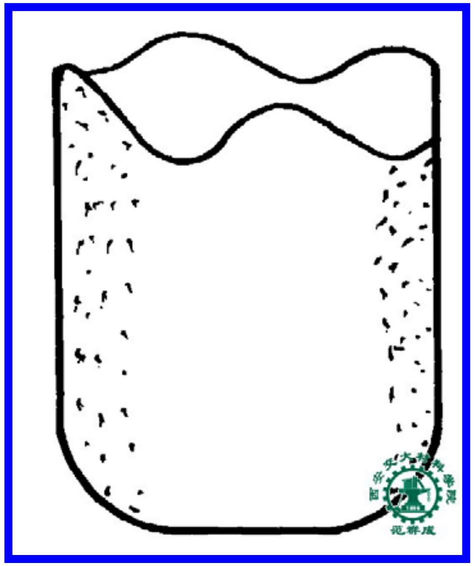


Diagram of wire drawing

- Bring about anisotropy

Ear-producing phenomenon of cold-punched component



- Bring about residual stress

THE END

2.6.2 The changes in structures and properties of cold-deformed steel in process of heating

1. Recovery and recrystallization and grain growth

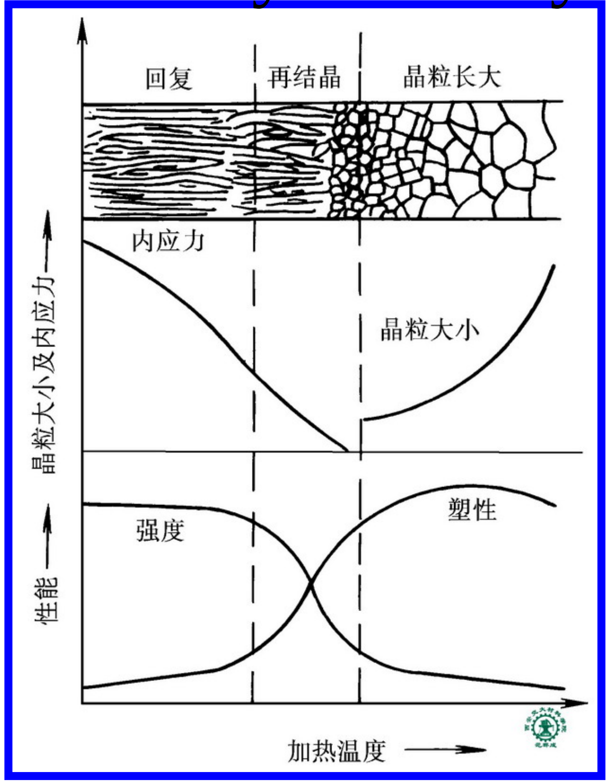
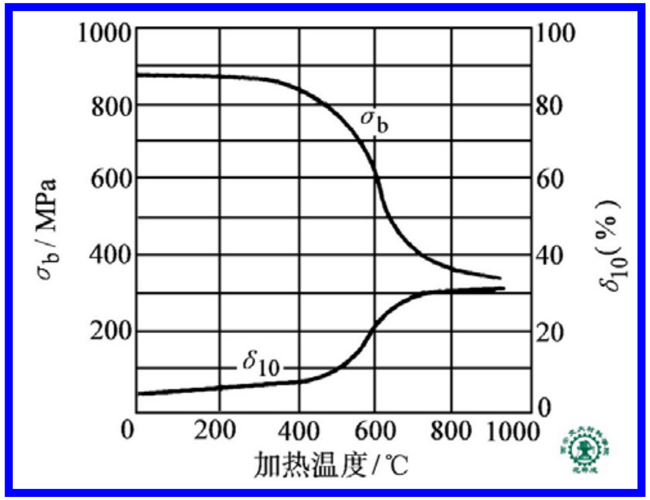


Diagram of change in structures and properties of cold-deformed metal in process of heating at various temperature

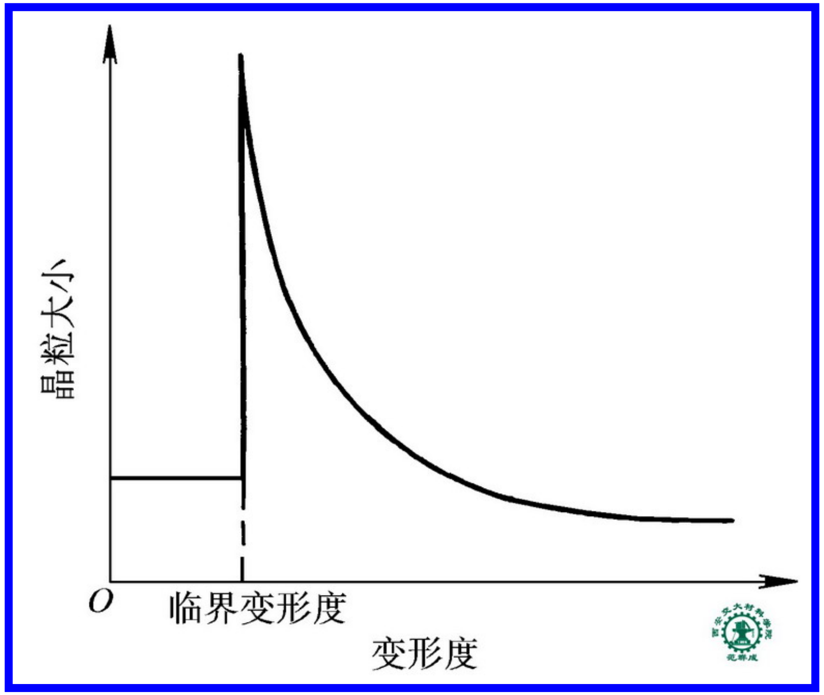


Change in mechanical properties of cold-press-processed pure iron with heating temperature

THE END

2. Factors affecting the size of recrystallized grain

1) Degree of cold deformation



The relationship between the size of recrystallized grain and the degree of cold deformation

- There is a critical degree of deformation

THE END

2) Annealing temperature

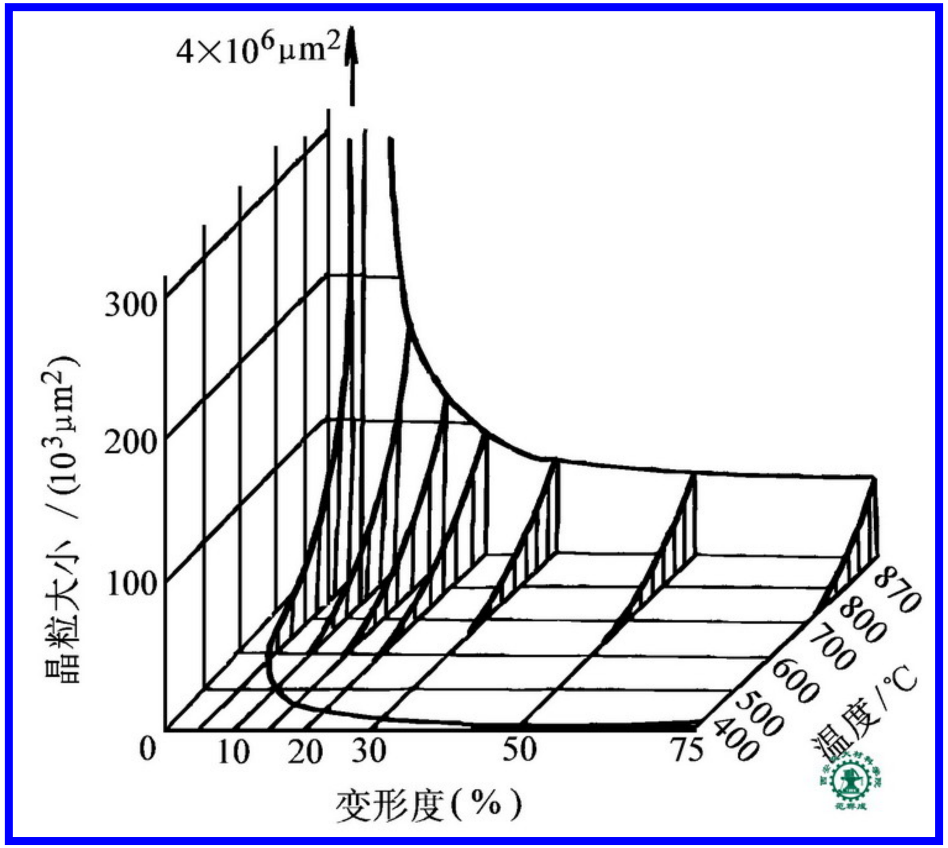
- Minimum recrystallization temperature——T_r

$T_r = 0.4\ T_m$

T_m(K) — melting point of the metal

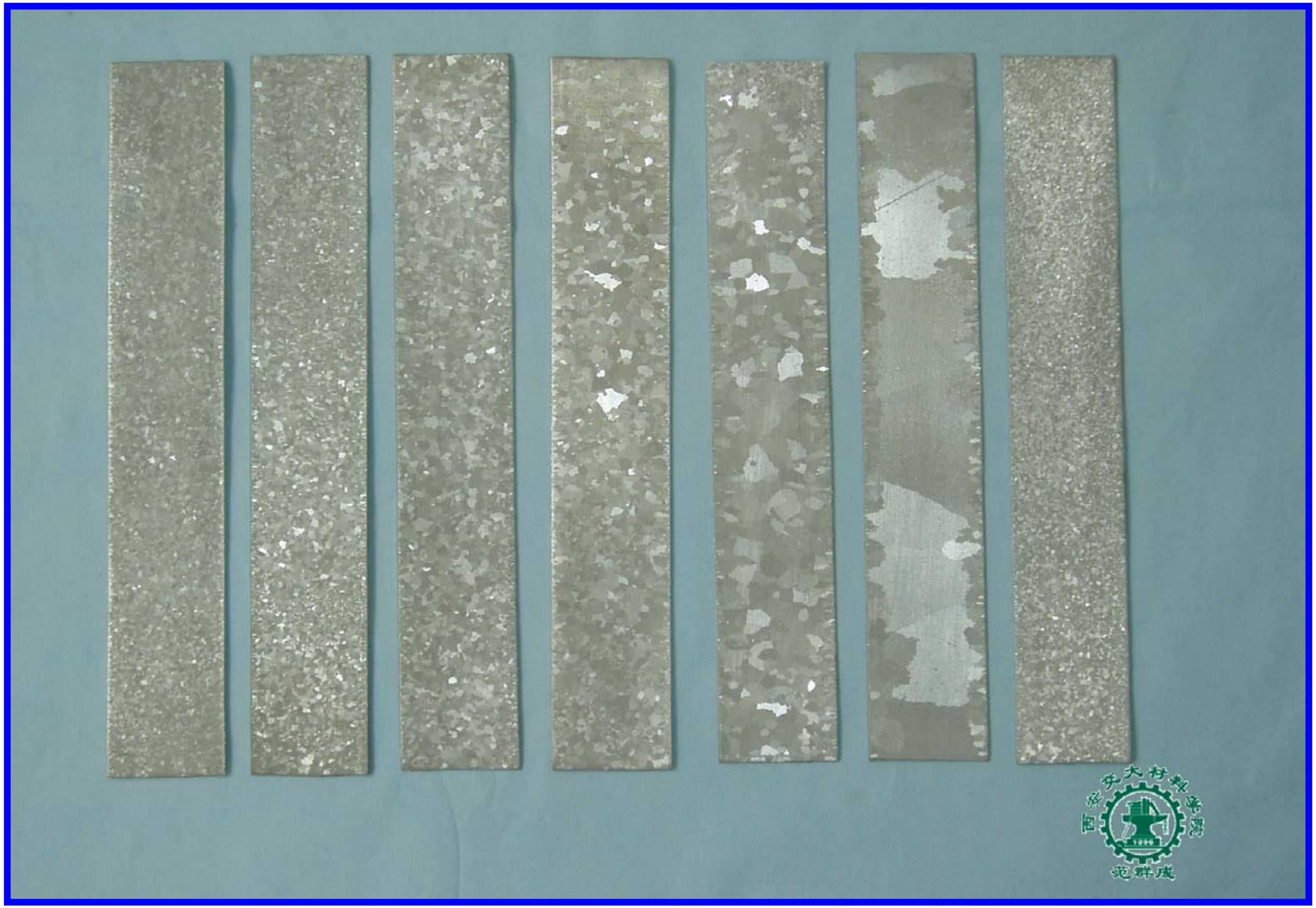
- As $T > T_r$

The higher the T, the larger the grain size



Recrystallization full figure of pure iron

THE END



The grain size of recrystallized aluminum with different degree of cold deformation

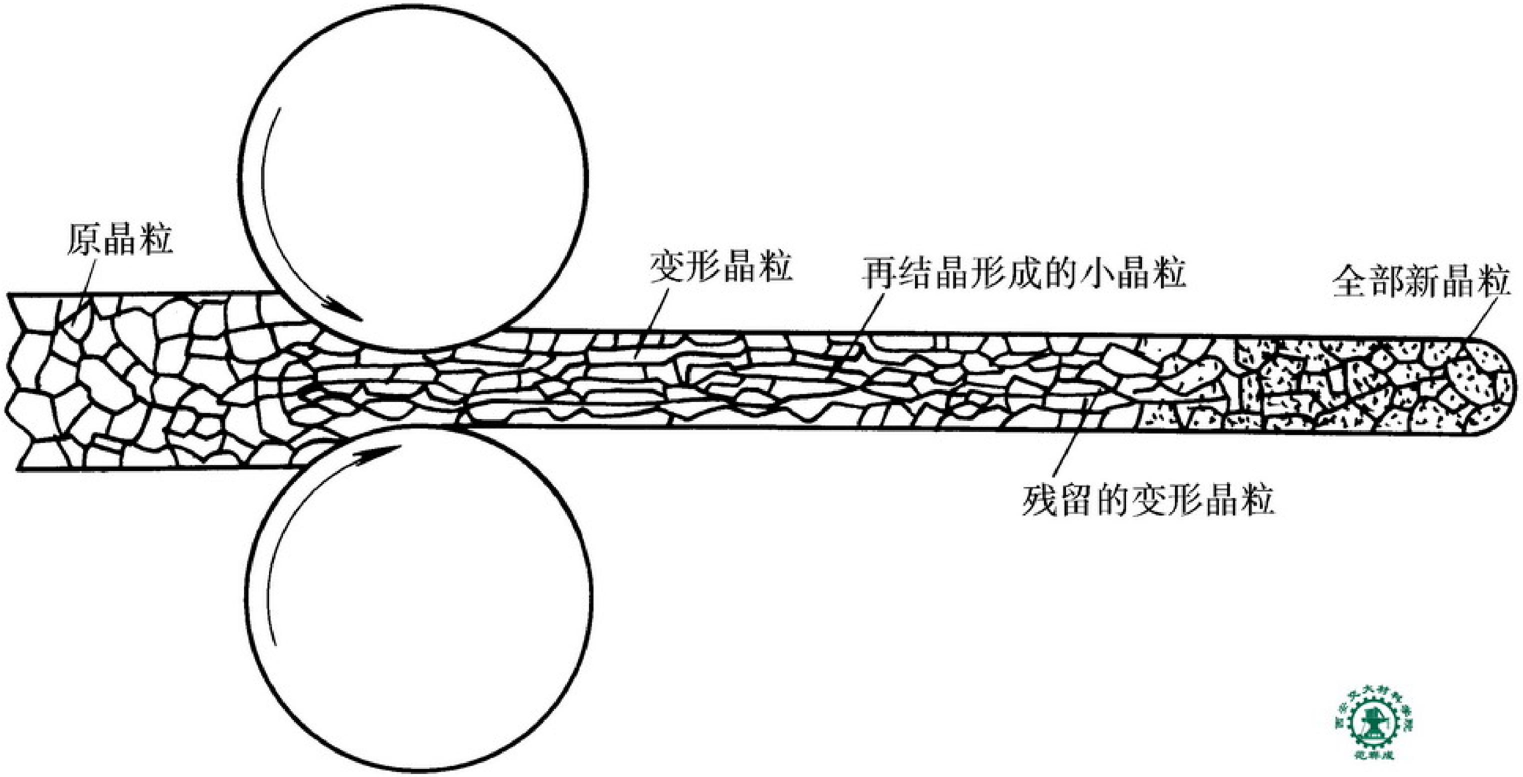
THE END

3. The application of recrystallization theory

- Recovery — stress relieving
- Recrystallization — work-hardening relieving
- Grain growth — single crystal preparing

THE END

2.6.3 The effects of hot-press working on structures and properties of steel



The deforming and recrystallizing of austenite grains in steel as it being hot rolled

THE END

1. The difference between hot working and cold working

- For cold working: $T < T_r$, no recrystallizing
- For hot working: $T > T_r$, recrystallizing

2. The structures and properties of hot-press-worked steel

- Welding pores
- Refining structure
- Forming hot-working flow lines

THE END

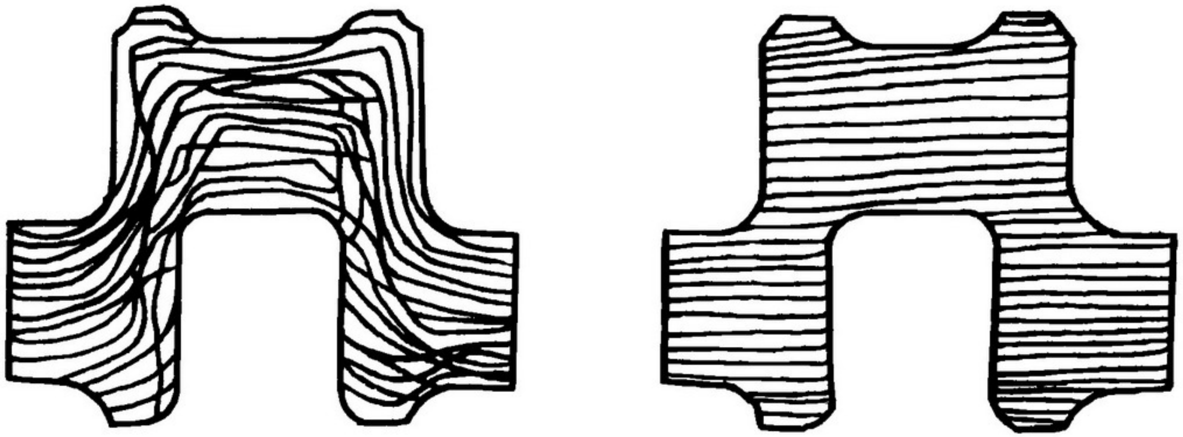


Diagram of arrangement of flow lines in crankshaft

表 2-4 ω_C 为 0.45%的钢经热轧后力学性能与流线方向的关系

试样方向	σ_b / MPa	$\sigma_{0.2} / MPa$	δ（%）	ϕ（%）	a_K /（J·cm^{-2}）
纵向	715	470	17.5	62.8	62
横向	672	440	10.0	31.0	30

THE END

§ 2-7 The classification and name and use of carbon steel

2.7.1 The classification of carbon steel

- By content of carbon
  - Low carbon steel $w_C \leqslant 0.25\%$
  - Medium carbon steel $w_C = 0.30\% \sim 0.60\%$
  - High carbon steel $w_C > 0.60\%$
- By quality
  - Plain carbon steel $w_S \leqslant 0.035\%$, $w_P \leqslant 0.035\%$
  - Quality carbon steel $w_S \leqslant 0.030\%$, $w_P \leqslant 0.030\%$
  - High-duty carbon steel $w_S \leqslant 0.020\%$, $w_P \leqslant 0.030\%$
- By usage
  - Carbon structural steel
  - Carbon tool steel

THE END

2.7.2 The name and use of carbon steel

1. Plain carbon structural steel

表 2-5 普通碳素结构纲的牌号和化学成分（GB/T700-1988）

牌号	等级	化学成分 ω（%）					脱氧方法
		C	Mn	Si	S	P	
				不大于			
Q195	—	0.06～0.12	0.25～0.50	0.30	0.050	0.045	F、b、Z
Q215	A	0.09～0.15	0.25～0.55	0.30	0.050	0.045	F、b、Z
	B				0.045		
Q235	A	0.14～0.20	0.30～0.65(1)	0.30	0.050	0.045	F、b、Z
	B	0.12～0.20	0.30～0.70(1)		0.045		
	C	≤0.18	0.35～0.80	0.30	0.040	0.040	Z
	D	≤0.17			0.035	0.035	TZ
Q255	A	0.18～0.28	0.40～0.70	0.30	0.050	0.045	Z
	B				0.045		
Q275	—	0.28～0.38	0.50～0.80	0.35	0.050	0.045	Z

注：1. Q235A、B 级沸腾钢锰的质量分数上限为 0.60%。
2. “F”沸腾钢，“b”半镇静钢，“Z”镇静钢，“TZ”特殊镇静钢。

表 2-6 普通碳素结构钢的力学性能（GB/T700-1988）

牌号	等级	拉伸试验													冲击试验	
		屈服点 σ_s/ MPa						抗拉强度 σ_b/ MPa	伸长率δ_5/ (%)						湿度/℃	V形冲击功（纵向）/J
		钢材厚度（直径）/mm							钢材厚度（直径）/mm							
		≤16	＞16～40	＞40～60	＞60～100	＞100～150	＞150		≤16	＞16～40	＞40～60	＞60～100	＞100～150	＞150		
		不小于							不小于							不小于
Q195	—	(195)	(185)	—	—	—	—	315～390	33	32	—	—	—	—	—	—
Q215	A	215	205	195	185	175	165	335～410	31	30	29	28	27	26	—	27
	B														20	
Q235	A	235	225	215	205	195	185	375～460	26	25	24	23	22	21	—	—
	B														20	27
	C														0	
	D														-20	
Q255	A	255	245	235	225	215	205	410～510	24	23	22	21	20	19	—	—
	B														20	27
Q275	—	275	265	255	245	235	225	490～610	20	19	18	17	16	15	—	—

THE END

2. Quality carbon structural steel

表 2-7 优质碳素结构钢的化学成分（GB/T 699-1999）

牌号	化 学 成 分 ω（%）							
	C	Si	Mn	P	S	Ni	Cr	Cu
				不大于				
08F	0.05～0.11	≤0.03	0.25～0.50	0.035	0.035	0.30	0.10	0.25
10F	0.07～0.14	≤0.07	0.25～0.50	0.035	0.035	0.30	0.15	0.25
08	0.05～0.12	0.17～0.37	0.35～0.65	0.035	0.035	0.30	0.10	0.25
10	0.07～0.14	0.17～0.37	0.35～0.65	0.035	0.035	0.30	0.15	0.25
15	0.12～0.19	0.17～0.37	0.35-0.65	0.035	0.035	0.30	0.25	0.25
20	0.17～0.24	0.17～0.37	0.35～0.65	0.035	0.035	0.30	0.25	0.25
25	0.22～0.30	0.17～0.37	0.50～0.80	0.035	0.035	0.30	0.25	0.25
30	0.27～0.35	0.17～0.37	0.50～0.80	0.035	0.035	0.30	0.25	0.25
35	0.32～0.40	0.17～0.37	0.50～0.80	0.035	0.035	0.30	0.25	0.25
40	0.37～0.45	0.17～0.37	0.50～0.80	0.035	0.035	0.30	0.25	0.25
45	0.42～0.50	0.17～0.37	0.50～0.80	0.035	0.035	0.30	0.25	0.25
50	0.47～0.55	0.17～0.37	0.50～0.80	0.035	0.035	0.30	0.25	0.25
55	0.52～0.60	0.17～0.37	0.50～0.80	0.035	0.035	0.30	0.25	0.25
60	0.57～0.65	0.17～0.37	0.50～0.80	0.035	0.035	0.30	0.25	0.25
65	0.62～0.70	0.17～0.37	0.50～0.80	0.035	0.035	0.30	0.25	0.25

THE END

表 2-8 优质碳素结构钢的力学性能（GB/T699-1999）

牌号	试样毛坯尺寸/mm	推荐热处理/℃			力学性能					钢材交货状态硬度 HBS	
					σ_b / MP_a	σ_s / MP_a	$\delta_5(\%)$	ϕ（%）	A_K / J	不大于	
		正火	淬火	回火	不小于					未热处理	退火钢
08F	25	930			295	175	35	60		131	
10F	25	930			315	185	33	55		137	
08	25	930			325	195	33	60		131	
10	25	930			335	205	31	55		137	
15	25	320			375	225	27	55		143	
20	25	910			410	245	25	55		156	
25	25	900	870	600	450	275	23	50	71	170	
30	25	880	860	600	490	295	21	50	63	179	
35	25	870	850	600	530	315	20	45	55	197	
40	25	860	840	600	570	335	19	45	47	217	187
45	25	850	840	600	600	355	16	40	39	229	197
50	25	830	830	600	630	375	14	40	31	241	207
55	25	820	820	600	645	380	13	35		255	217
60	25	810			675	400	12	35		255	229
65	25	810			695	410	10	30		255	229

THE END

3. Carbon tool steel

表 2-9 常用碳素工具钢的牌号、成分、热处理和用途（GB/T1298-1986）

钢号	化学成分 ω（%）					热处理					应用举例
						淬火			回火		
	C	Mn	Si	S	P	温度/℃	冷却介质	硬度 HRC（不小于）	温度/℃	硬度 HRC（不小于）	
T7	0.65~0.74	≤0.40	≤0.35	≤0.030	≤0.035	800~820	水	62	180~200	60~62	制造承受振动与冲击载荷 、要求较高韧性的工具，如凿子、打铁用模、各种锤子、木工工具、石钻（软岩石用）等
T7A	0.65~0.74			≤0.020	≤0.030	800~820	水	62	180~200	60~62	
T8	0.75~0.84			≤0.030	≤0.035	780~800	水	62	180~200	60~62	制造承受振动与冲击载荷、要求足韧性和较高硬度的各种工具，如简单模子、冲头、剪切金属用剪刀、木工工具、煤矿用凿等
T8A	0.75~0.84			≤0.020	≤0.030	780~800	水	62	180~200	60~62	
T10	0.95~1.04			≤0.030	≤0.035	760~780	水，油	62	180~200	60~62	制造不受突然振动、在 口上要求有韧性的工具，如刨刀、冲模、丝锥、板牙、手锯锯条、卡尺等
T10A	0.95~1.04			≤0.020	≤0.030	760~780	水，油	62	180~200	60~62	
T12	1.15~1.24			≤0.030	≤0.035	760~780	水，油	62	180~200	60~62	制造不受振动、要求极高硬度的工具，如钻头、丝锥、锉刀、刮刀
T12A	1.15~1.24			≤0.020	≤0.030	760~780	水，油	62	180~200	60~62	

THE END