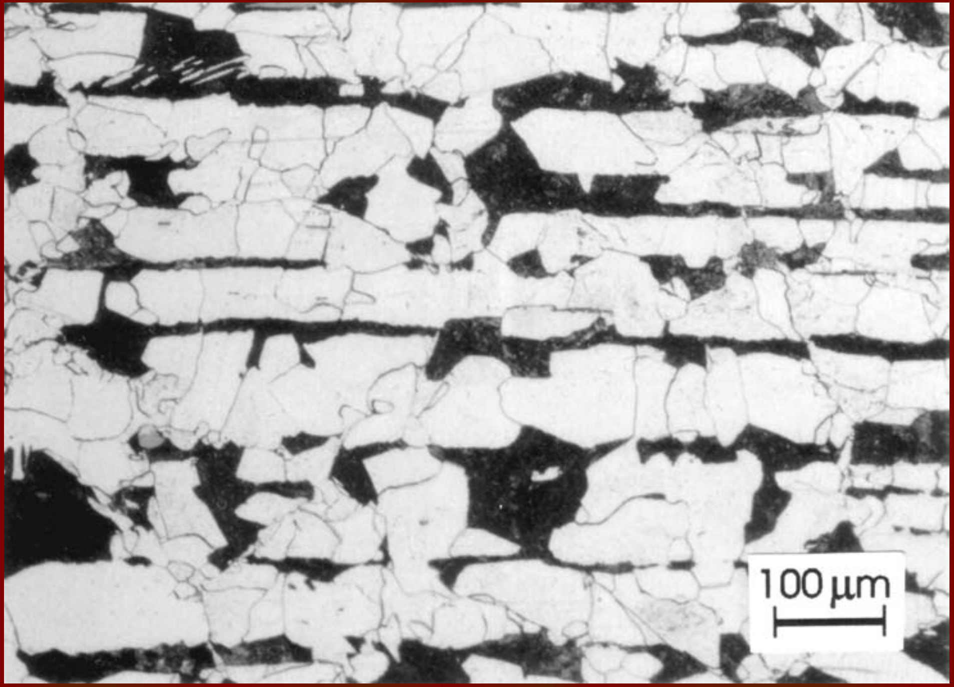
Physical Metallurgy Principles Applied to Steels and Other Ferrous Alloys



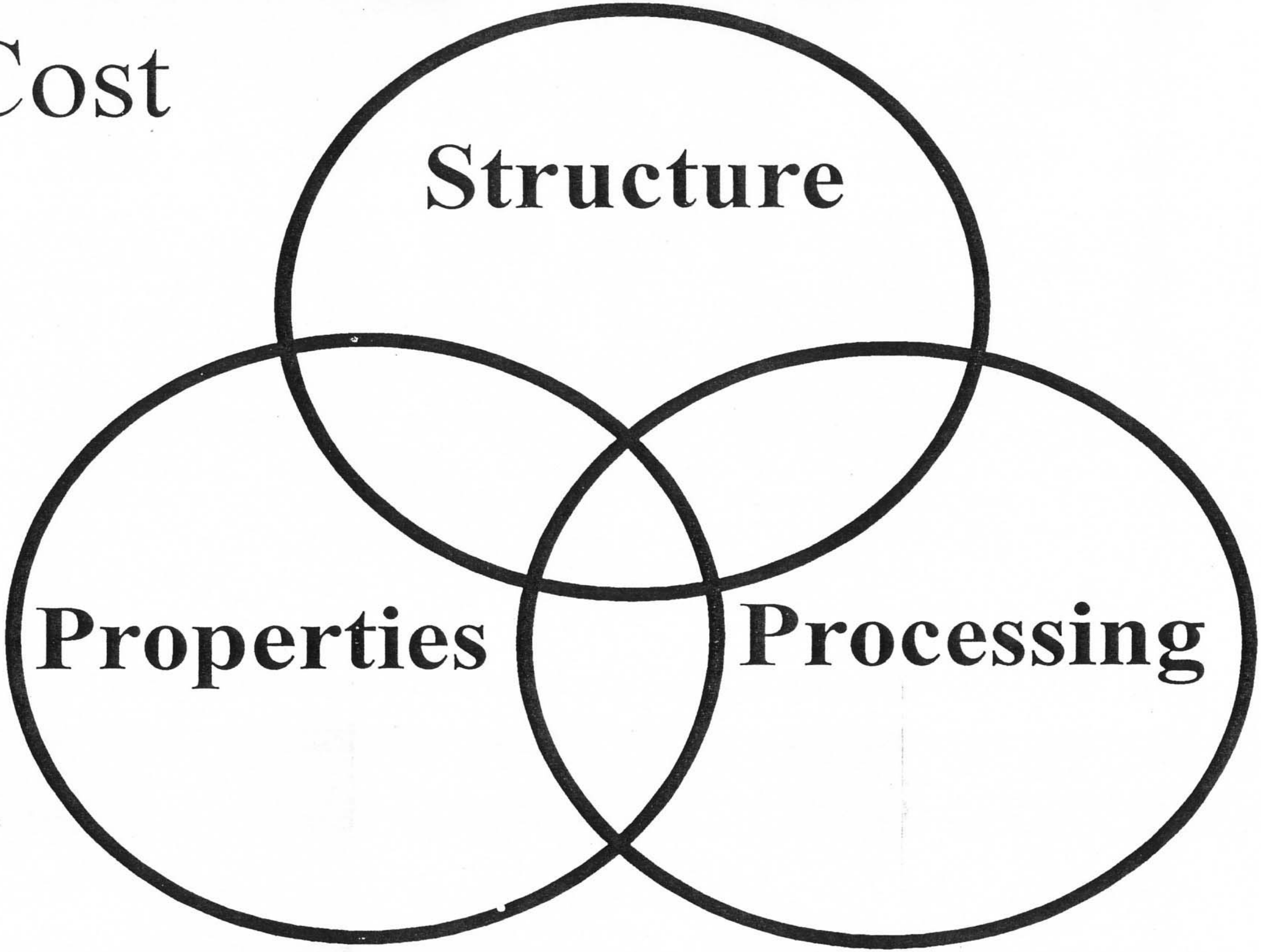
R. R. Biederman

June 7, 2005

Outline

1. General Physical Metallurgy Concepts common to all alloy systems
2. Chemical Bonding, Atom Size, Lattices, Crystals and Crystalline Defects, Solid Solutions, Alloying and Microstructures
3. Grains and Grain Size Control, Role of Deformation and Deformation Processing
4. Phases, Invariant Reactions, Equilibrium Phase Diagrams and Phase Transform - ations in Cast Irons and Steels.
5. Non Equilibrium Transformations in Ferrous Alloys, Time Dependency, Microstructure – Property Relationships

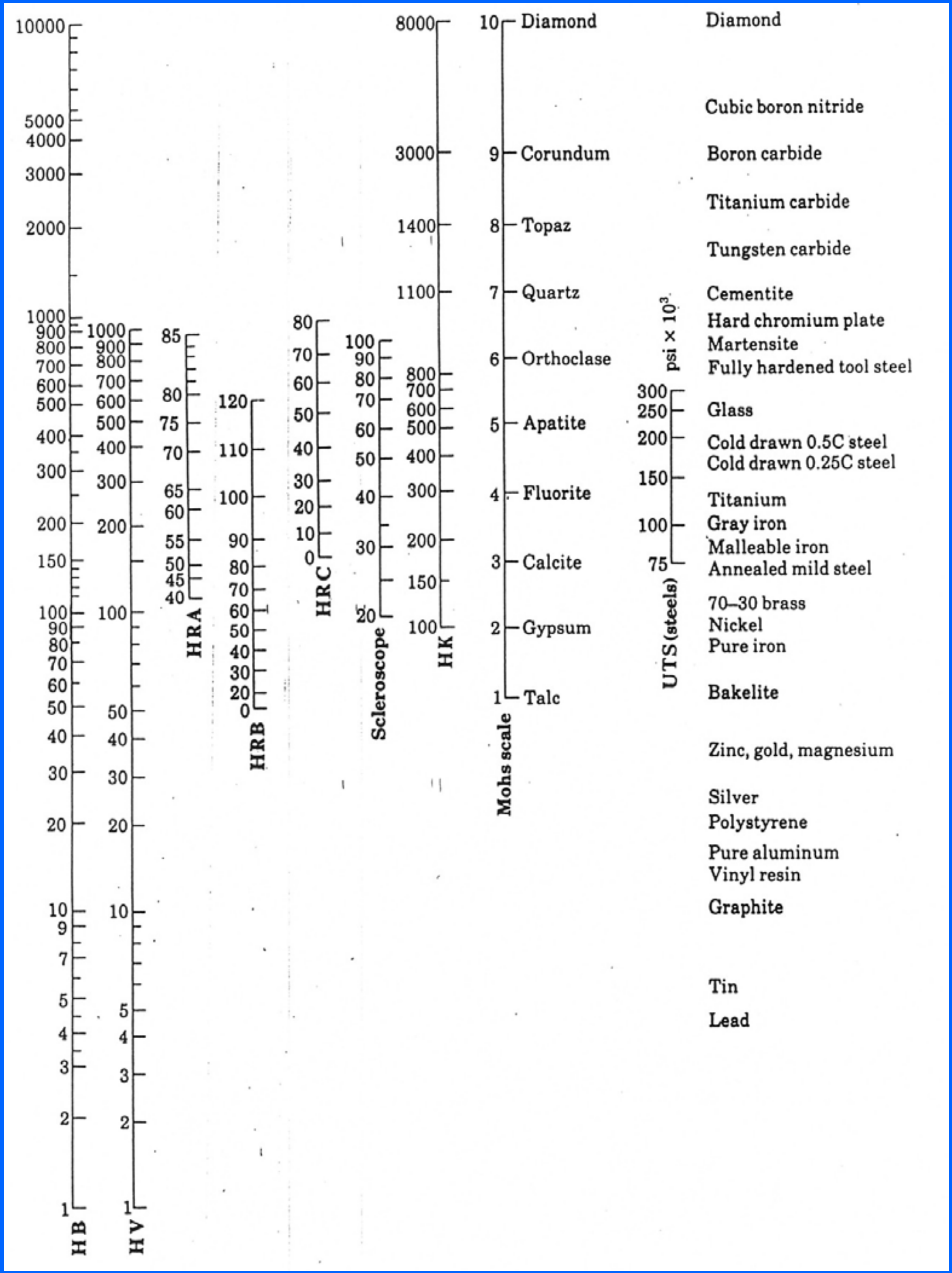
Cost



Structure

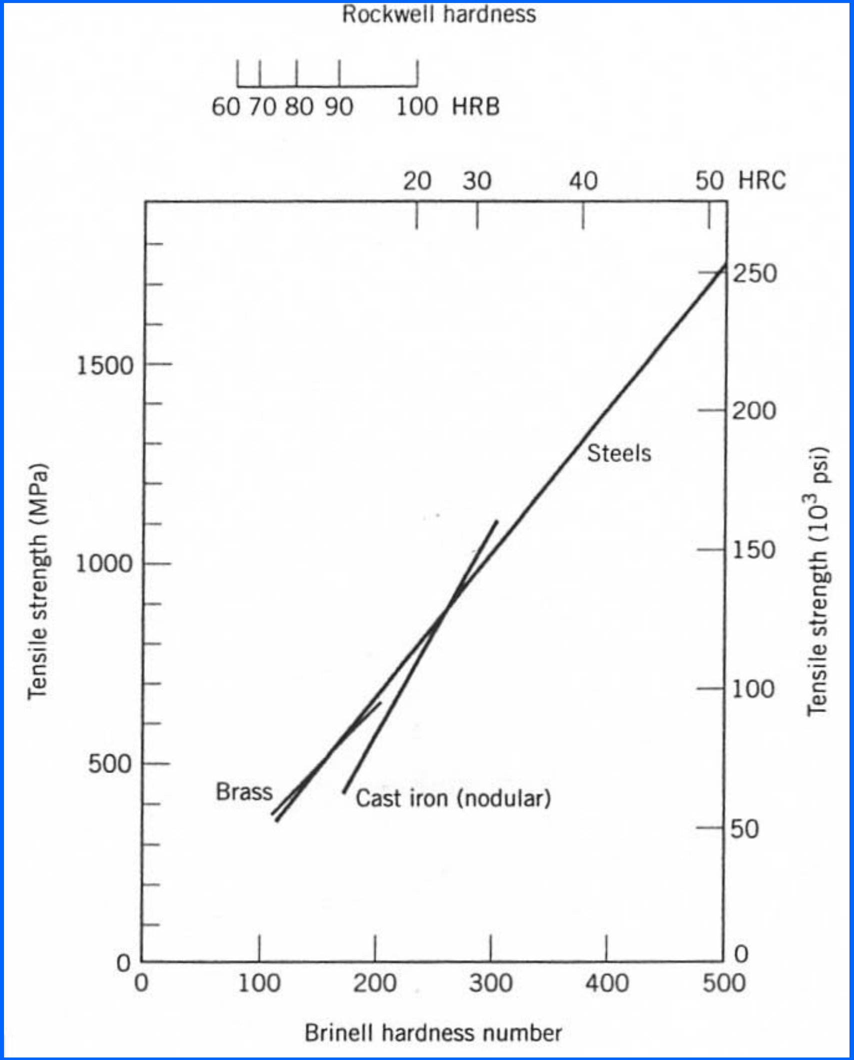
Properties

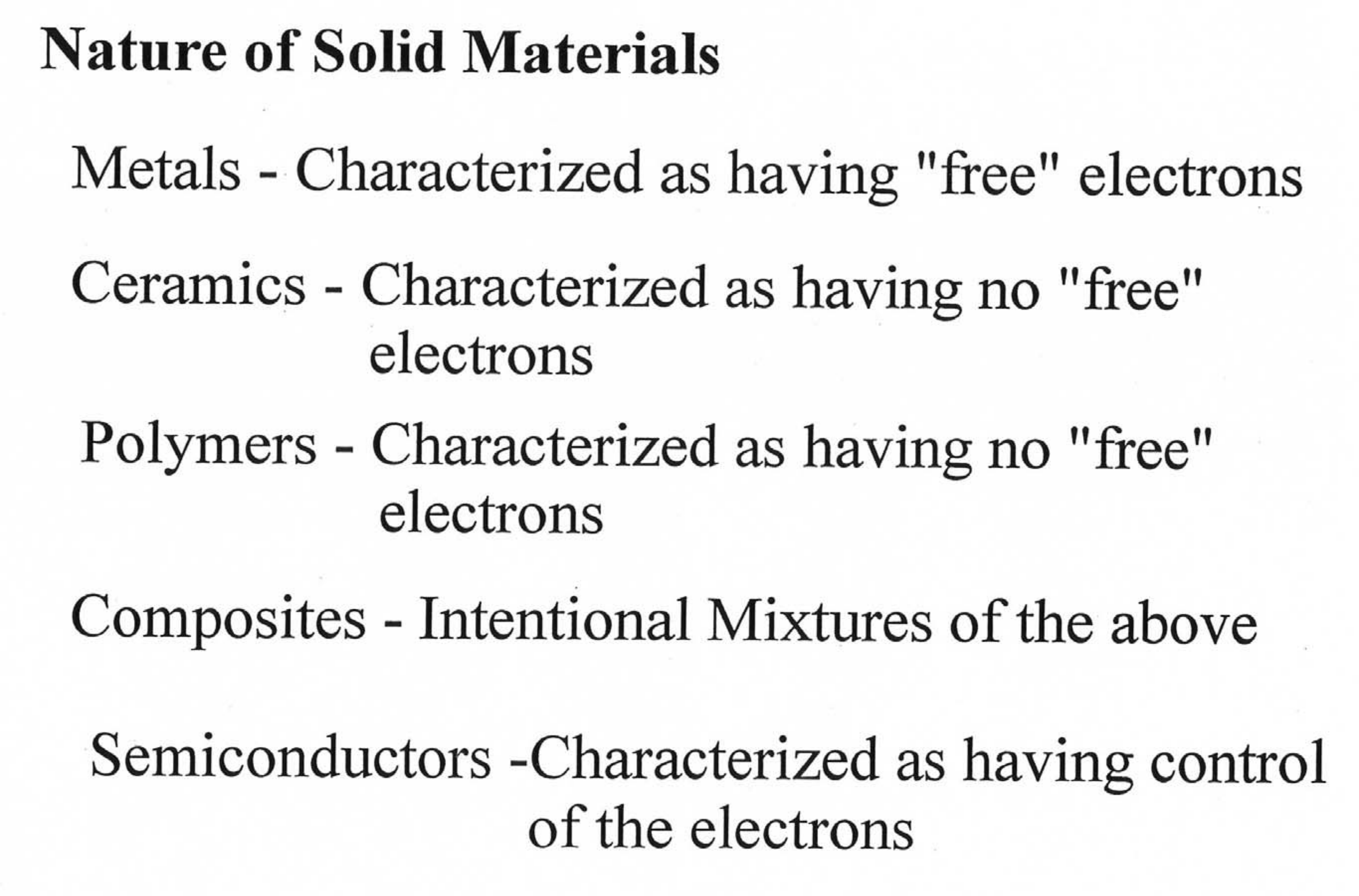
Processing



$$UTS(MPa) = 3.45(HB)$$

$$UTS(psi) = 500(HB)$$





Nature of Solid Materials

Metals - Characterized as having "free" electrons

Ceramics - Characterized as having no "free" electrons

Polymers - Characterized as having no "free" electrons

Composites - Intentional Mixtures of the above

Semiconductors -Characterized as having control of the electrons

Primary Atomic Bonds

These are the major bonds that are a result of the large interatomic forces that hold atoms or ions together.

Ionic Bonds.	Large interatomic forces are created due to the electron transfer from one atom to another resulting in the creation of anions and cations which are bonded together by coulombic forces.
Covalent Bonds	Large interatomic forces are created by the sharing of electrons. In particular the outer shell electrons.
Metallic Bonds.	Large interatomic forces are created by tightly bonding of inner electrons while maintaining a much looser tie with the outer valence electrons.

1	Atomic number
H	Symbol
1.00794	Atomic weight

Transition Metals

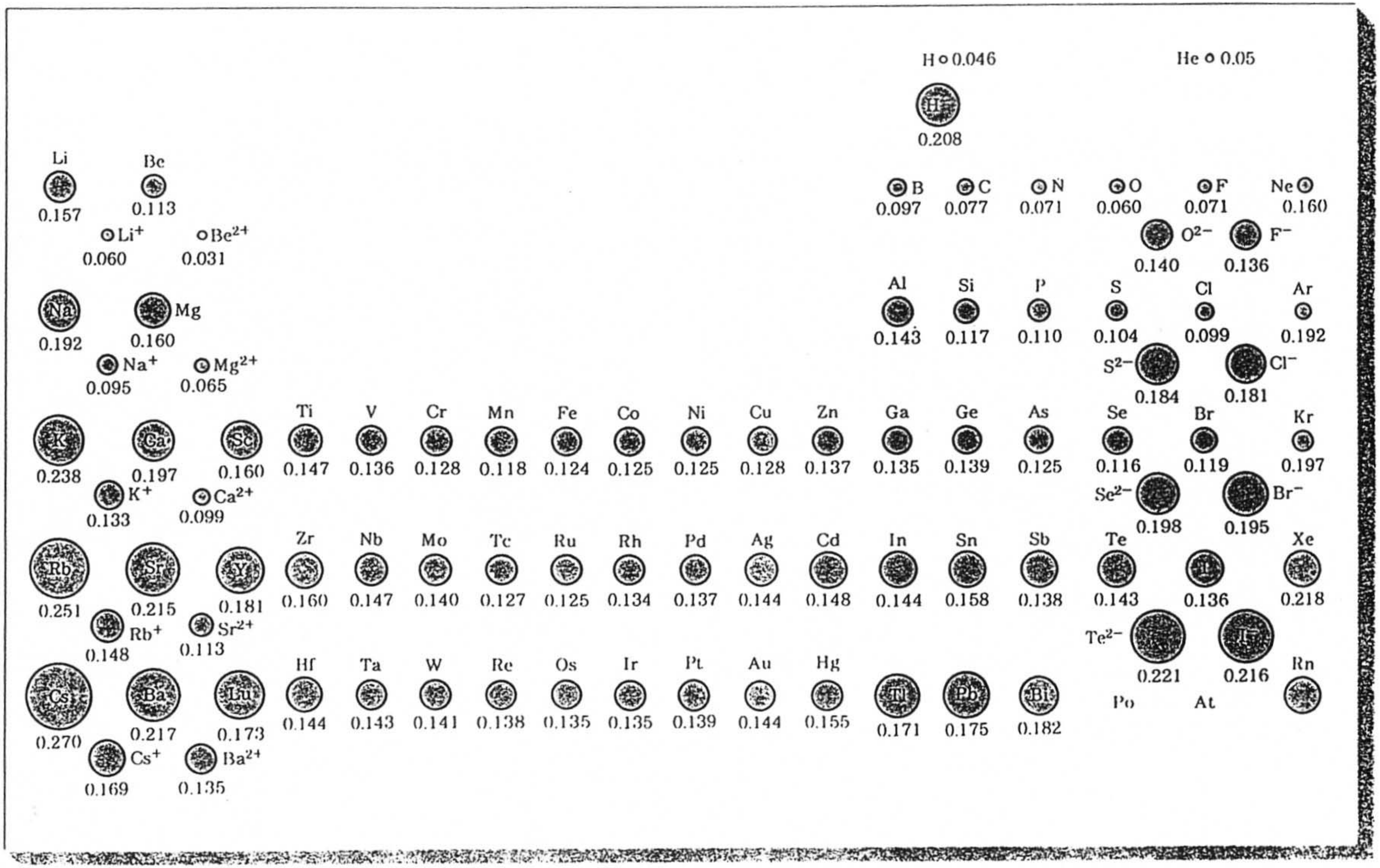
Period	IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIIIB			IB	IIB	IIIA	IVA	VA	VIA	VIIA	VIIIA
1	1 H 1.00794																	2 He 4.00260
2	3 Li 6.941	4 Be 9.01218											▨ 5 B 10.81	6 C 12.011	7 N 14.0067	8 O 15.9994	9 F 18.998403	10 Ne 20.179
3	11 Na 22.98977	12 Mg 24.305											13 Al 26.98154	▨ 14 Si 28.0855	15 P 30.97376	16 S 32.06	17 Cl 35.453	18 Ar 39.948
4	19 K 39.0983	20 Ca 40.08	21 Sc 44.9559	22 Ti 47.88	23 V 50.9415	24 Cr 51.996	25 Mn 54.9380	26 Fe 55.847	27 Co 58.9332	28 Ni 58.69	29 Cu 63.546	30 Zn 65.38	31 Ga 69.72	▨ 32 Ge 72.59	▨ 33 As 74.9216	34 Se 78.96	35 Br 79.904	36 Kr 83.80
5	37 Rb 85.4678	38 Sr 87.62	39 Y 88.9059	40 Zr 91.22	41 Nb 92.9064	42 Mo 95.94	43 Tc (98)	44 Ru 101.07	45 Rh 102.9055	46 Pd 106.42	47 Ag 107.8682	48 Cd 112.41	49 In 114.82	50 Sn 118.69	▨ 51 Sb 121.75	▨ 52 Te 127.60	53 I 126.9045	54 Xe 131.29
6	55 Cs 132.9054	57 Ba 137.33	57 La* 138.9055	72 Hf 178.49	73 Ta 180.9479	74 W 183.85	75 Re 186.207	76 Os 190.2	77 Ir 192.22	78 Pt 195.08	79 Au 196.9665	80 Hg 200.59	81 Tl 204.383	82 Pb 207.2	83 Bi 208.9804	84 Po (209)	▨ 85 At (210)	86 Rn (222)
7	87 Fr (223)	88 Ra 226.0254	89 Ac** 227.0278	104 † (261)	105 † (262)	106 † (263)	107	108 †	109 †									

†Element synthesized, but no official name assigned

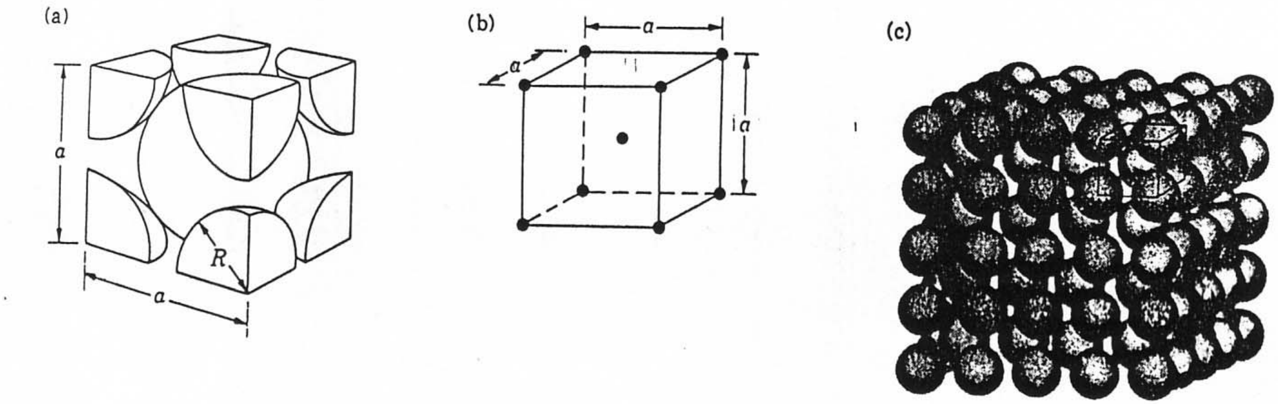
Inner-Transition Metals

* Lanthanides	58 Ce 140.12	59 Pr 140.9077	60 Nd 144.24	61 Pm (145)	62 Sm 150.36	63 Eu 151.96	64 Gd 157.25	65 Tb 158.9254	66 Dy 162.50	67 Ho 164.9304	68 Er 167.26	69 Tm 168.9342	70 Yb 173.04	71 Lu 174.967
** Actinides	90 Th 232.0381	91 Pa 231.0359	92 U 238.0289	93 Np 237.0482	94 Pu (244)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (251)	99 Es (252)	100 Fm (257)	101 Md (258)	102 No (259)	103 Lr (260)

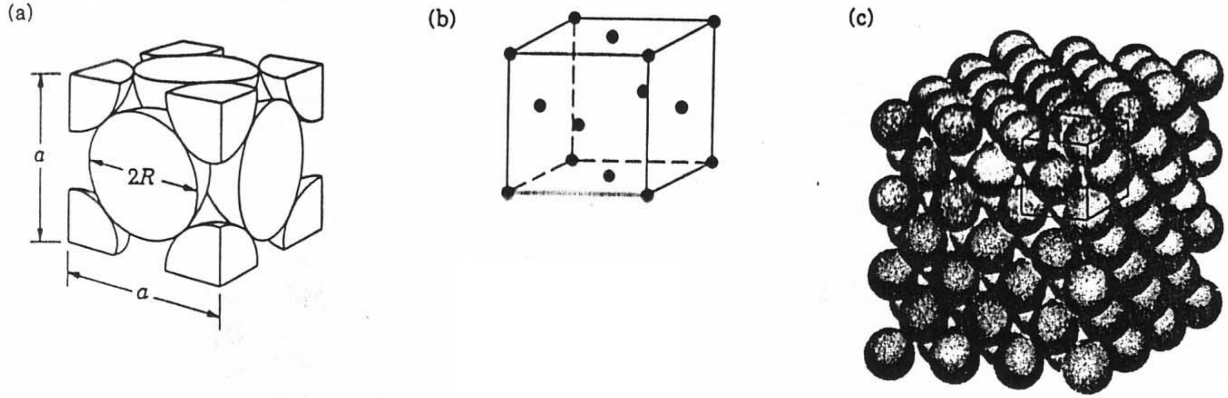
☐	Metal
▨	Metalloid
☐	Nonmetal



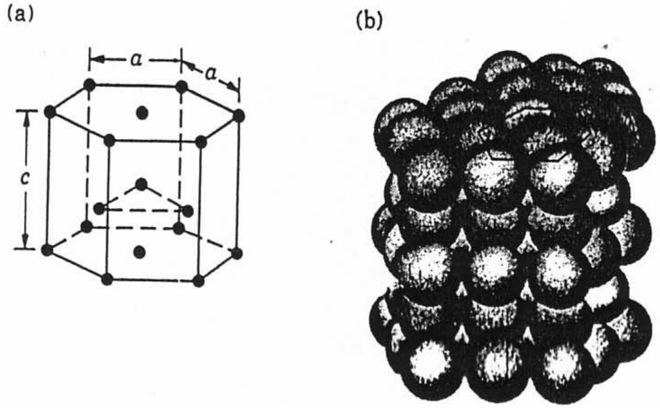
Relative sizes of some atoms and ions. Values are given in nanometers for the radii of the atoms and ions. Metallic radii are given for atoms where applicable. (*Adapted from F. M. Miller, "Chemistry: Structure and Dynamics," McGraw Hill, 1984, p. 176.*)



BCC

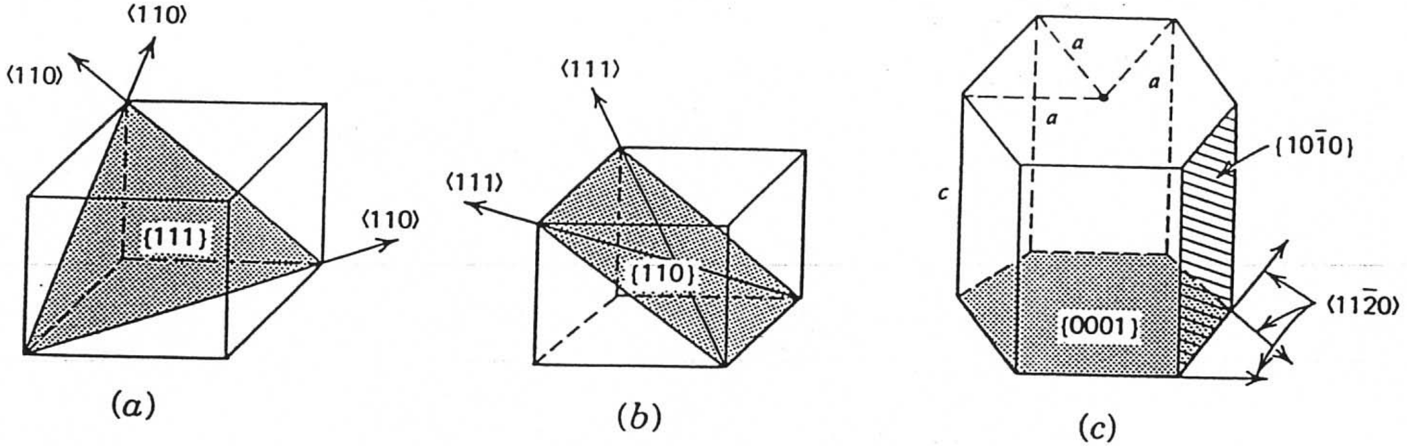


FCC



HCP

Predominant Slip Systems

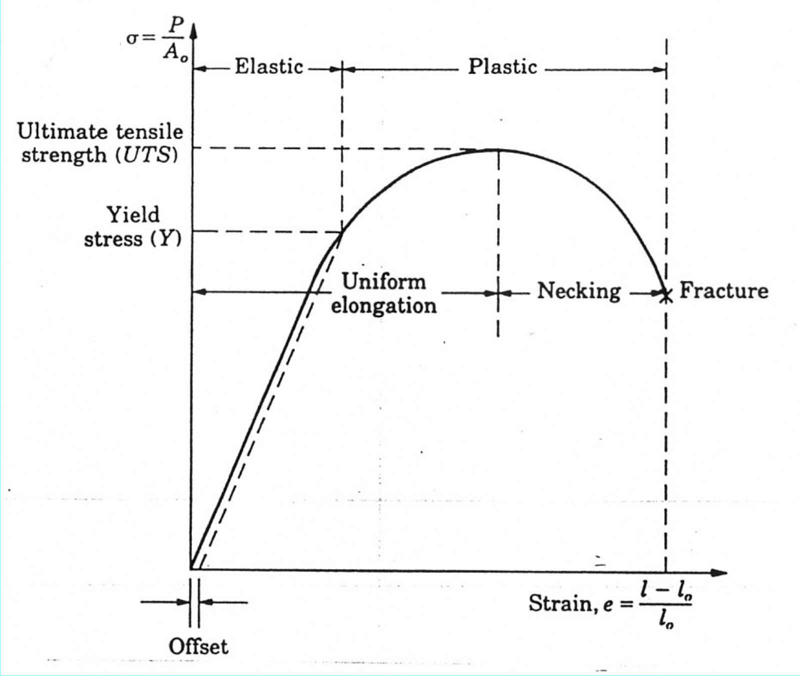


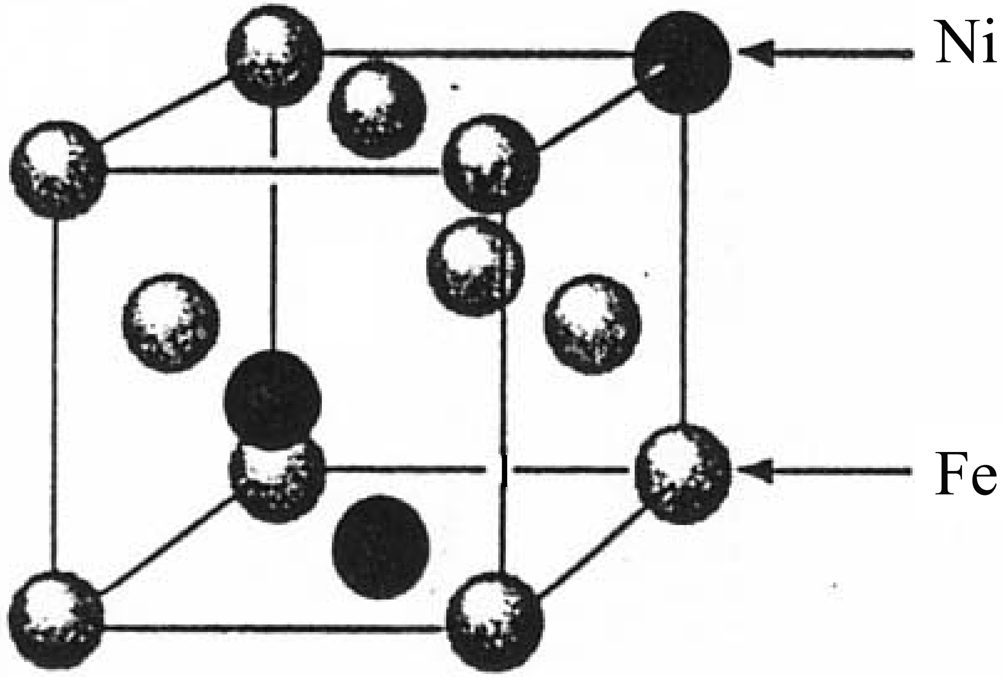
FCC	BCC	HCP
{111}<110>	{110}<111>	{0001}<11-20>
12	48	3

Control of slip is essential to achieve maximum toughness in a crystalline material

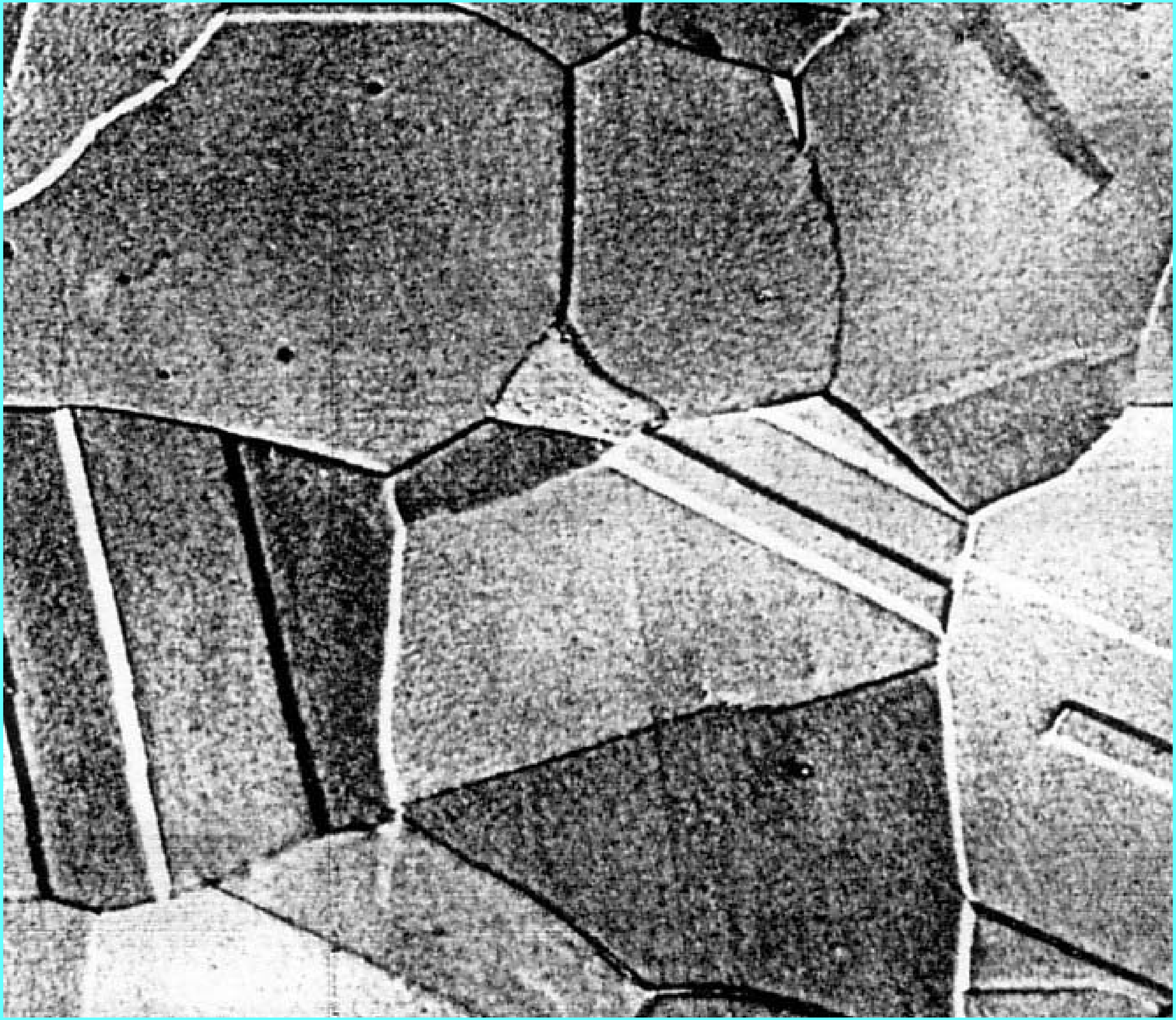
Toughness = (Ductility) X (Strength)

= f{strain x stress}

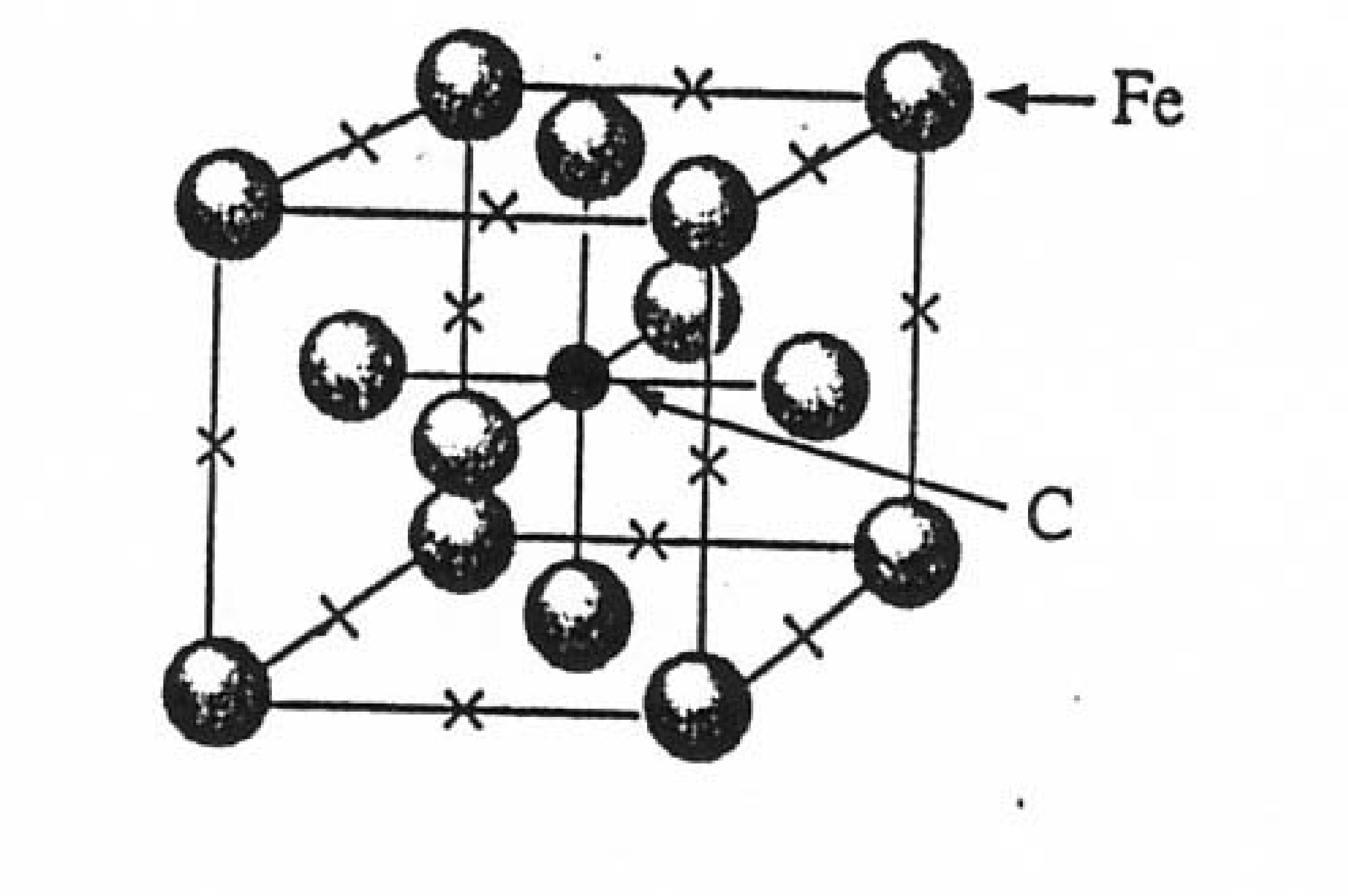




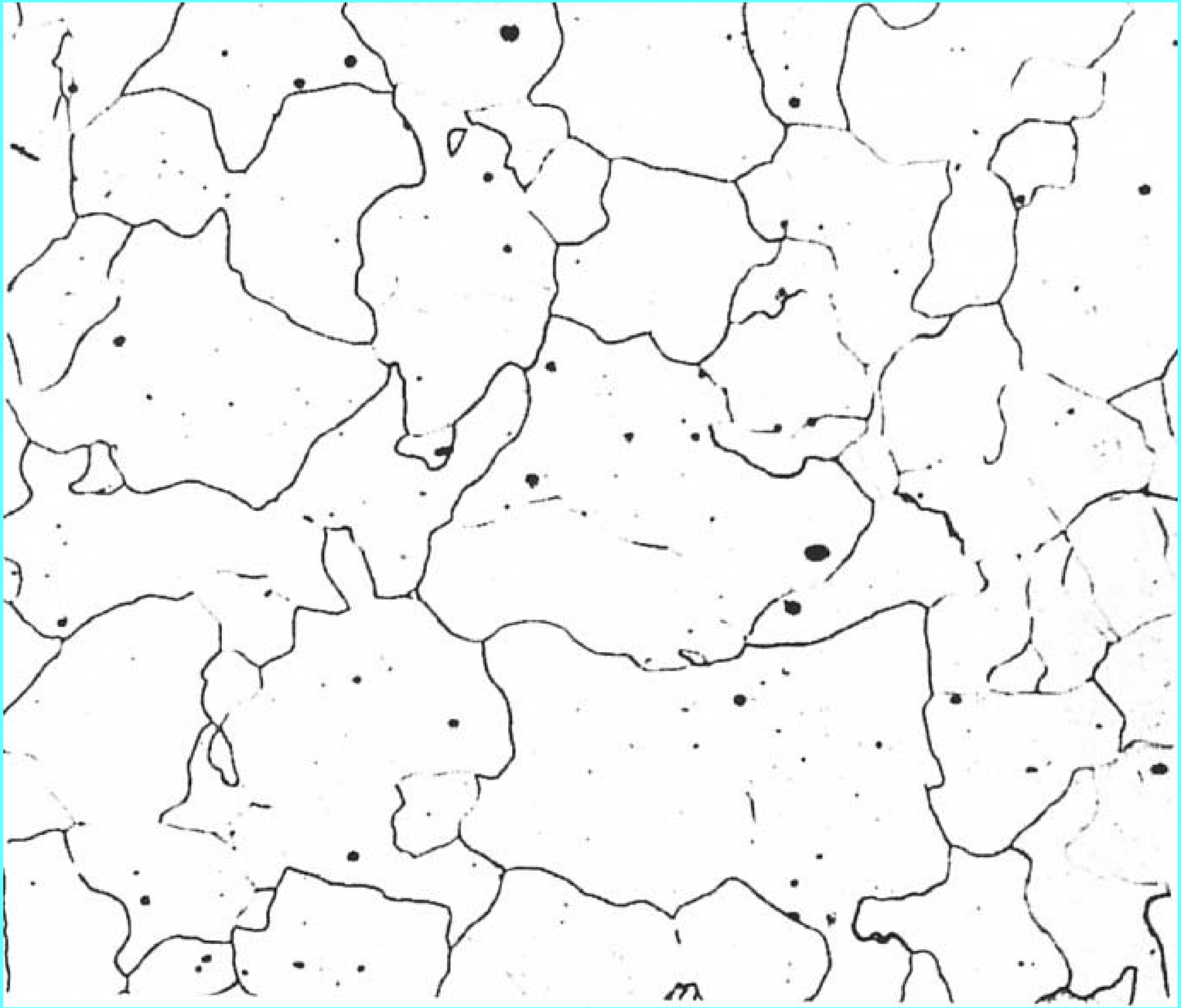
Substitutional Solid Solution



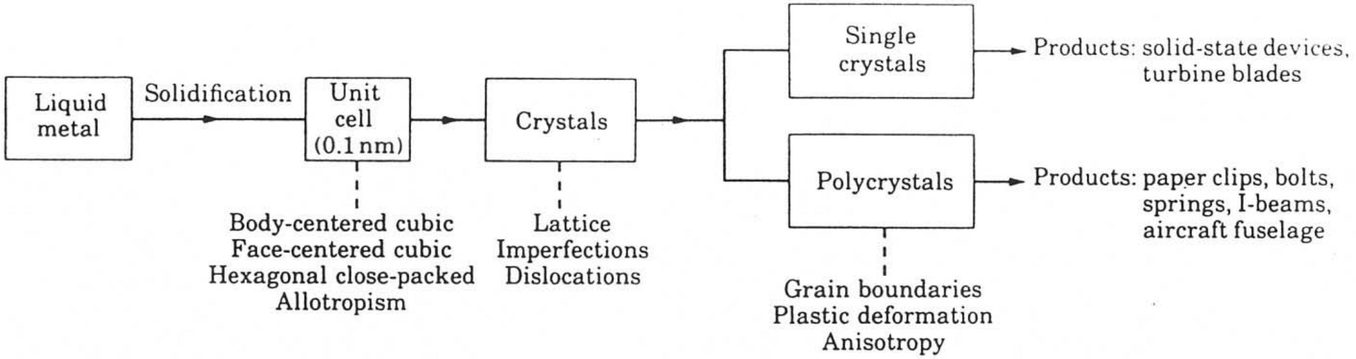
Austenite – FCC form of Iron



Interstitial Solid Solution



Ferrite – BCC form of Iron



Liquid metal

Solidification

Unit cell (0.1 nm)

Body-centered cubic
Face-centered cubic
Hexagonal close-packed
Allotropism

Crystals

Lattice
Imperfections
Dislocations

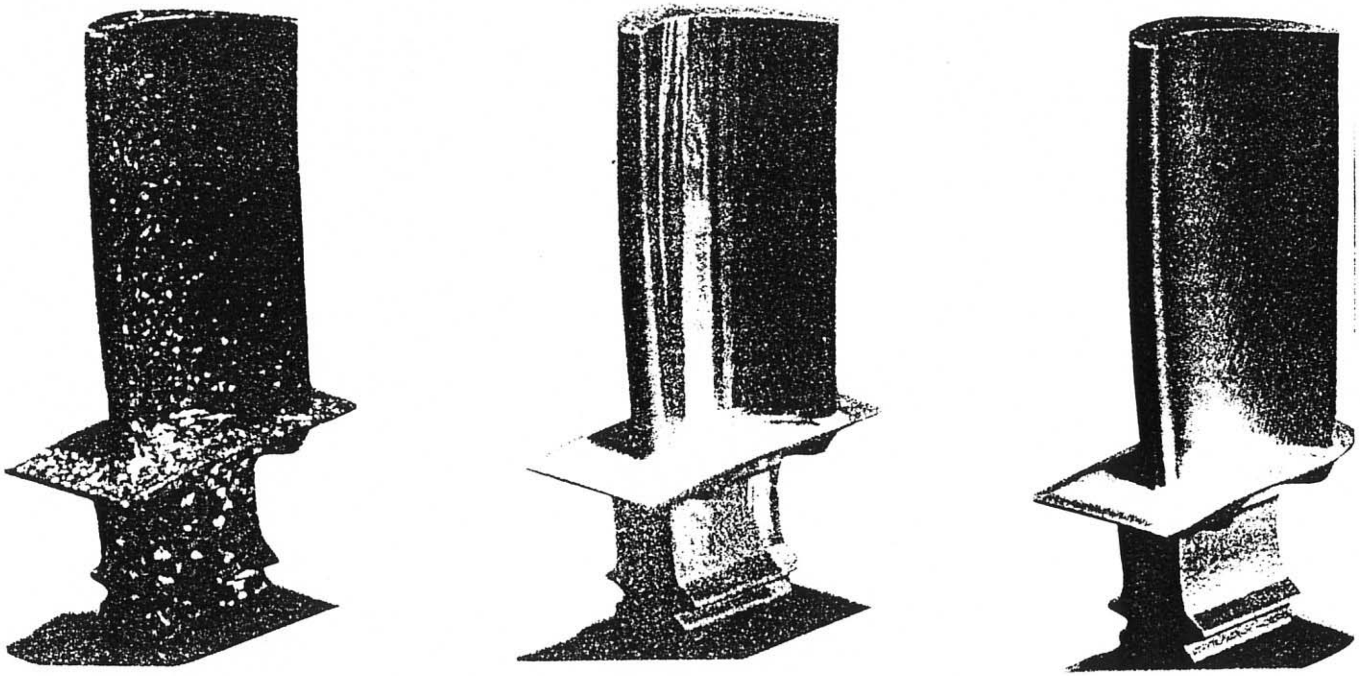
Single crystals

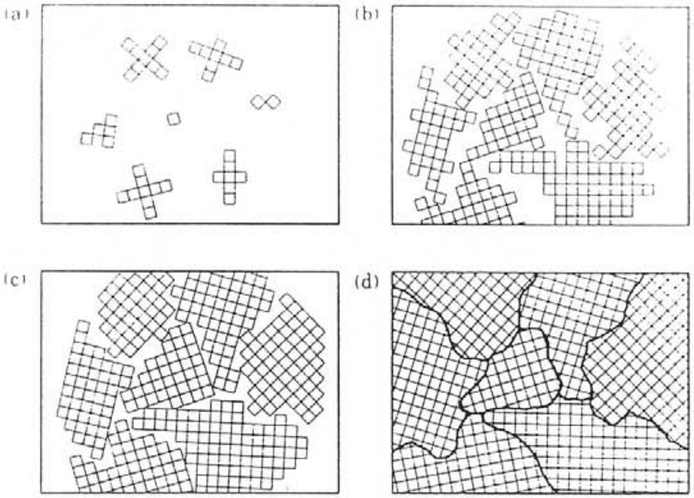
Products: solid-state devices, turbine blades

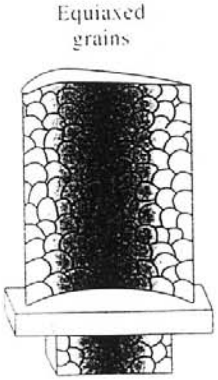
Polycrystals

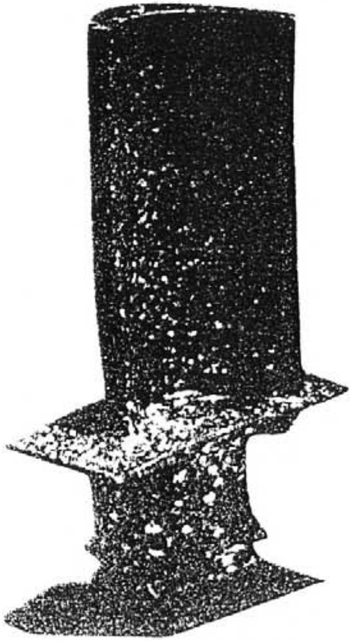
Grain boundaries
Plastic deformation
Anisotropy

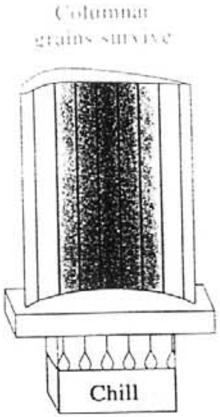
Products: paper clips, bolts, springs, I-beams, aircraft fuselage

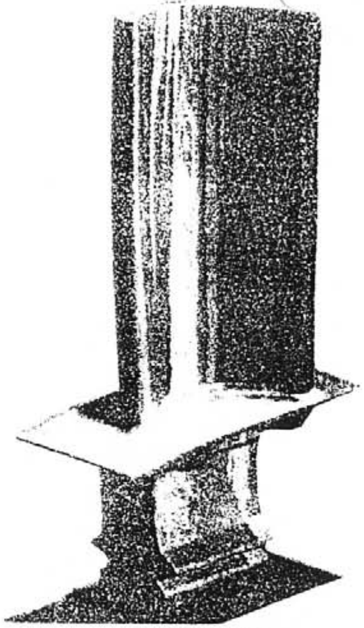


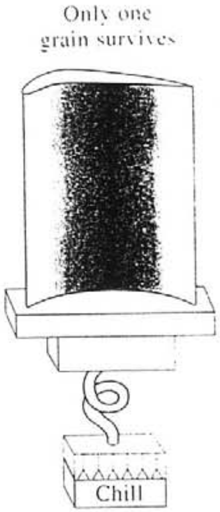

(a)
(b)
(c)
(d)

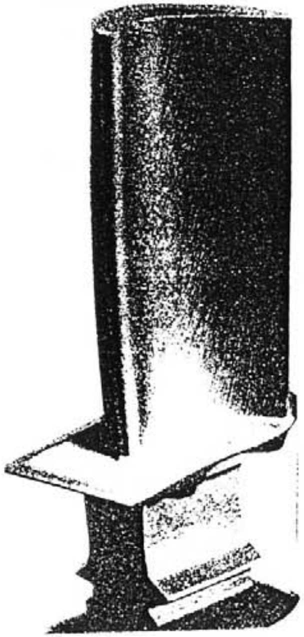

Equiaxed grains




Columnar grains survive
Chill




Only one grain survives
Chill



Casting Issues

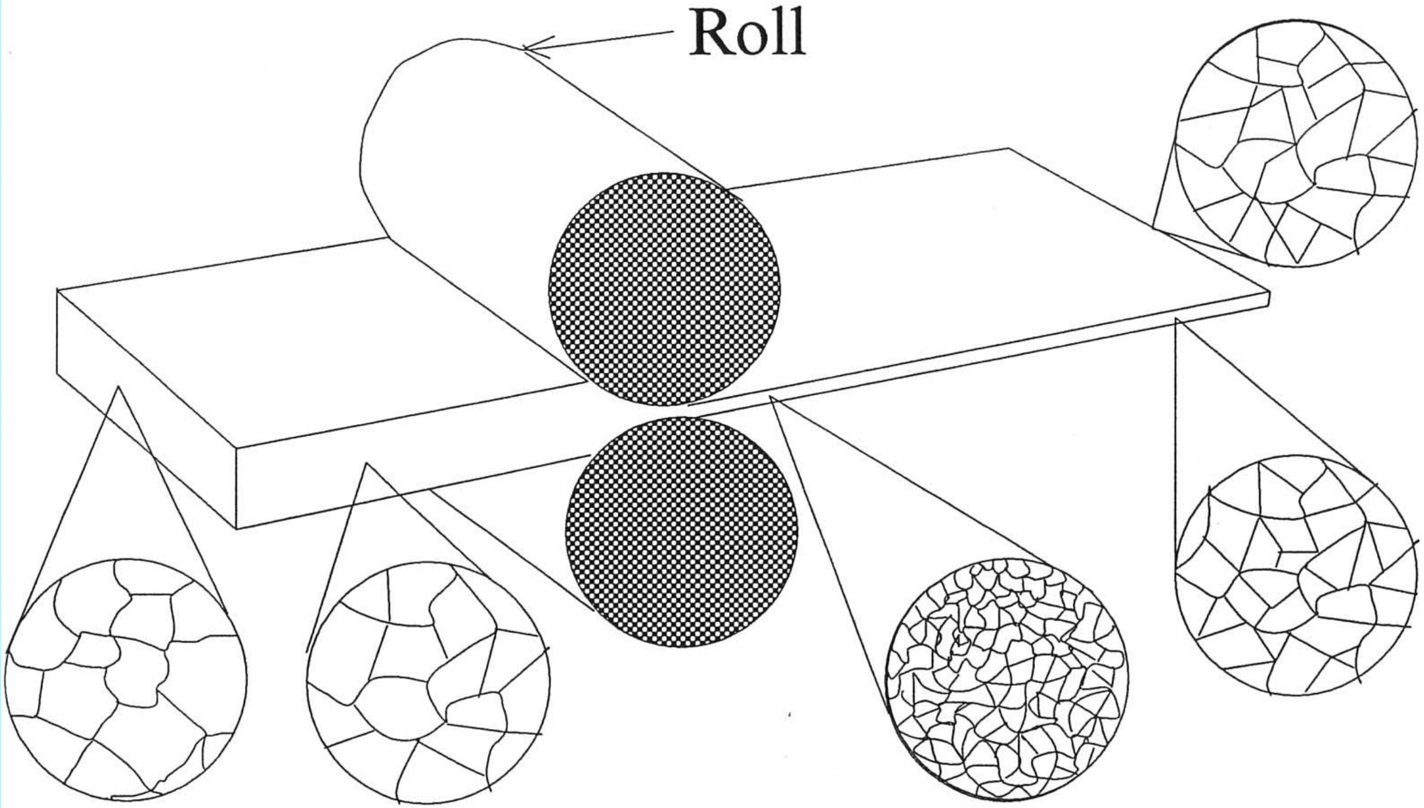
1. Chemical Segregation and Porosity Issues
2. Often Coarse Non-Uniform Grain Size Issues
3. Inconsistent Properties Issues due to 1 & 2

Corrective Approaches

1. Carefully Hot Work the Casting to Breakup Microstructural Segregation and close the Porosity [Classical Wrought Product]

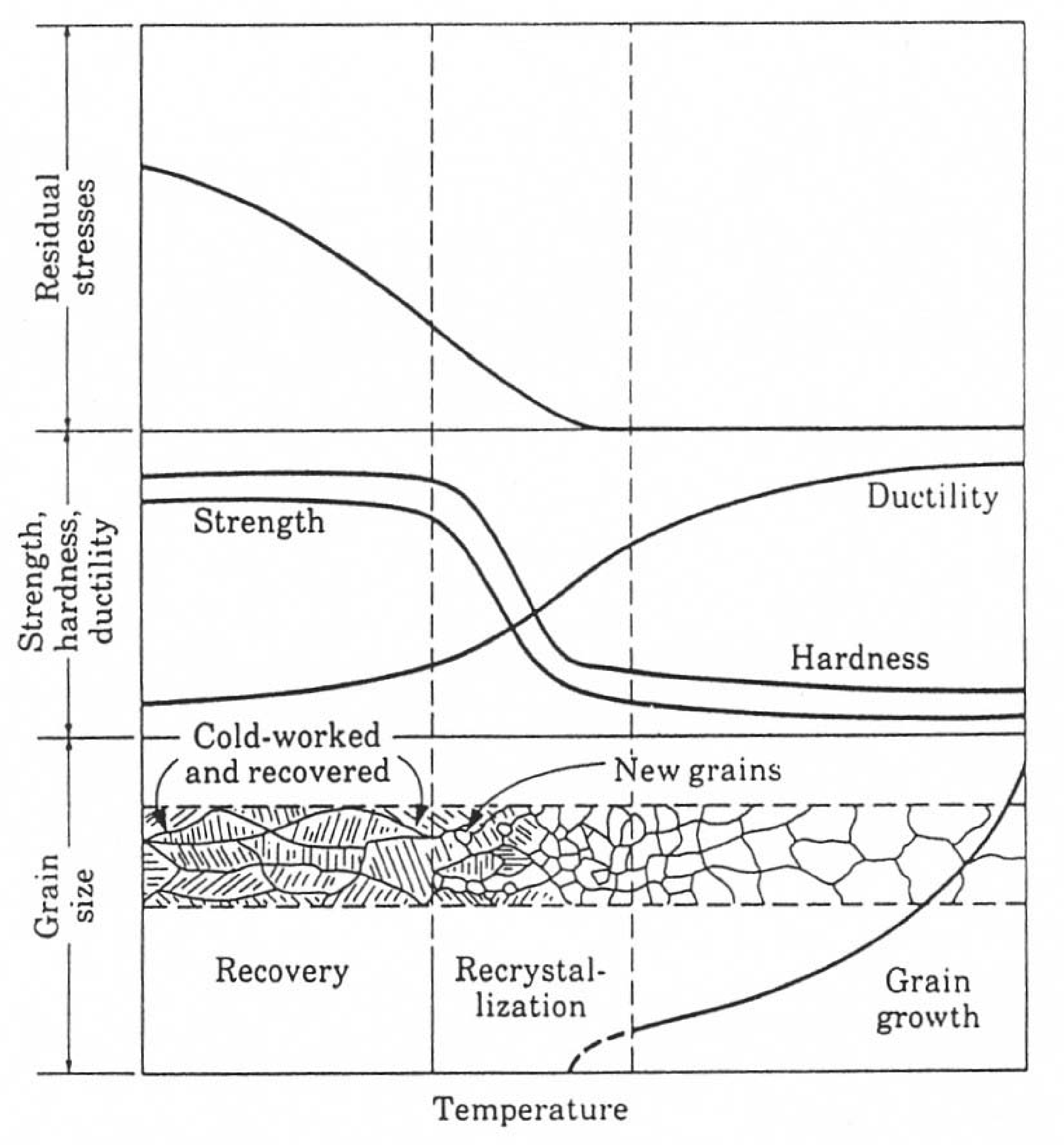
2. Make Very Small Castings (Powder) and Recombine by Hot Forming in an Inert Environment [" High Tech" Wrought Product]

Hot Working Process



During the hot rolling process, constancy of volume is maintained as in the cold working process. However, there is sufficient energy in the system to cause recrystallization and grain growth during the process.

Which Microstructure is the Finish Microstructure ?



Hot Working

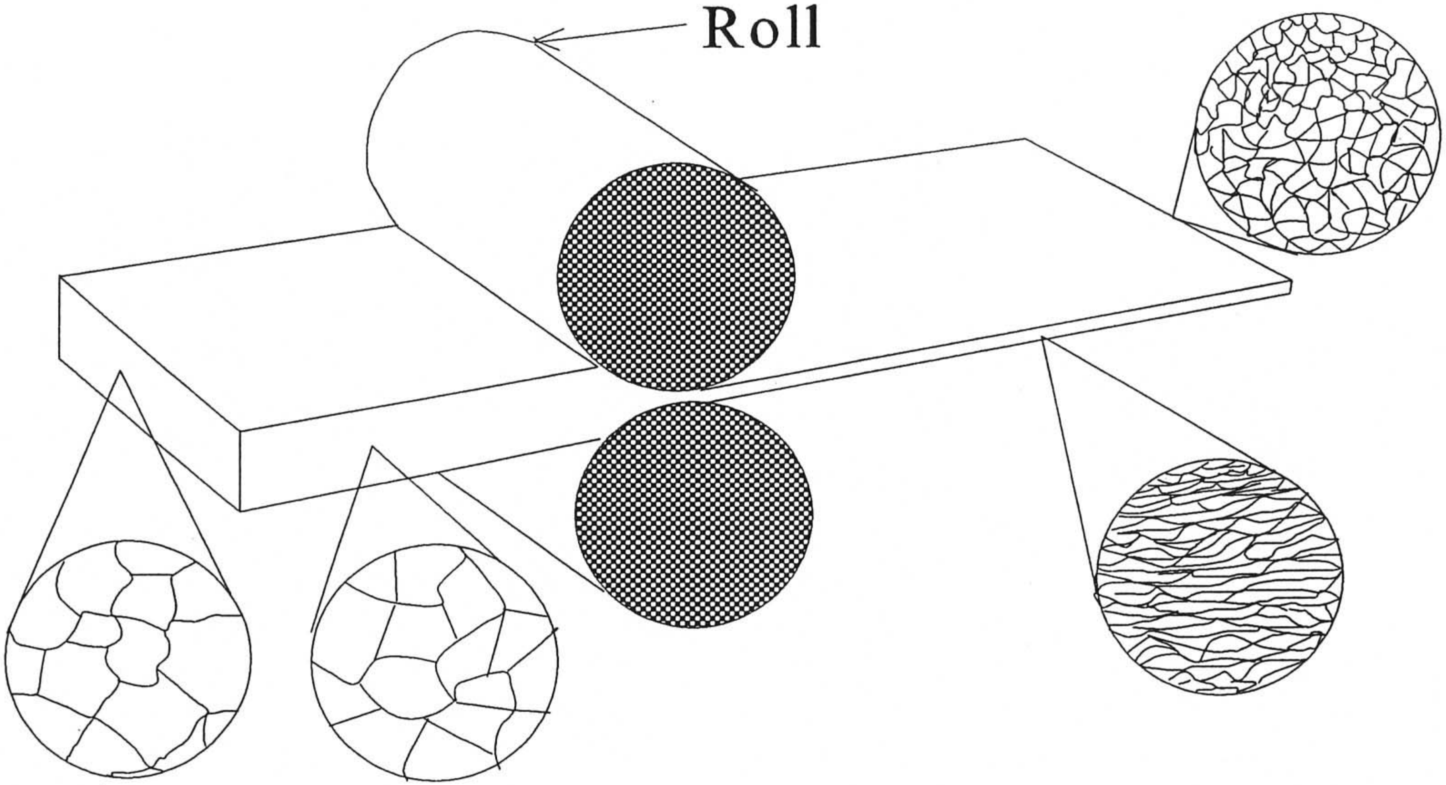
=

Cold Working

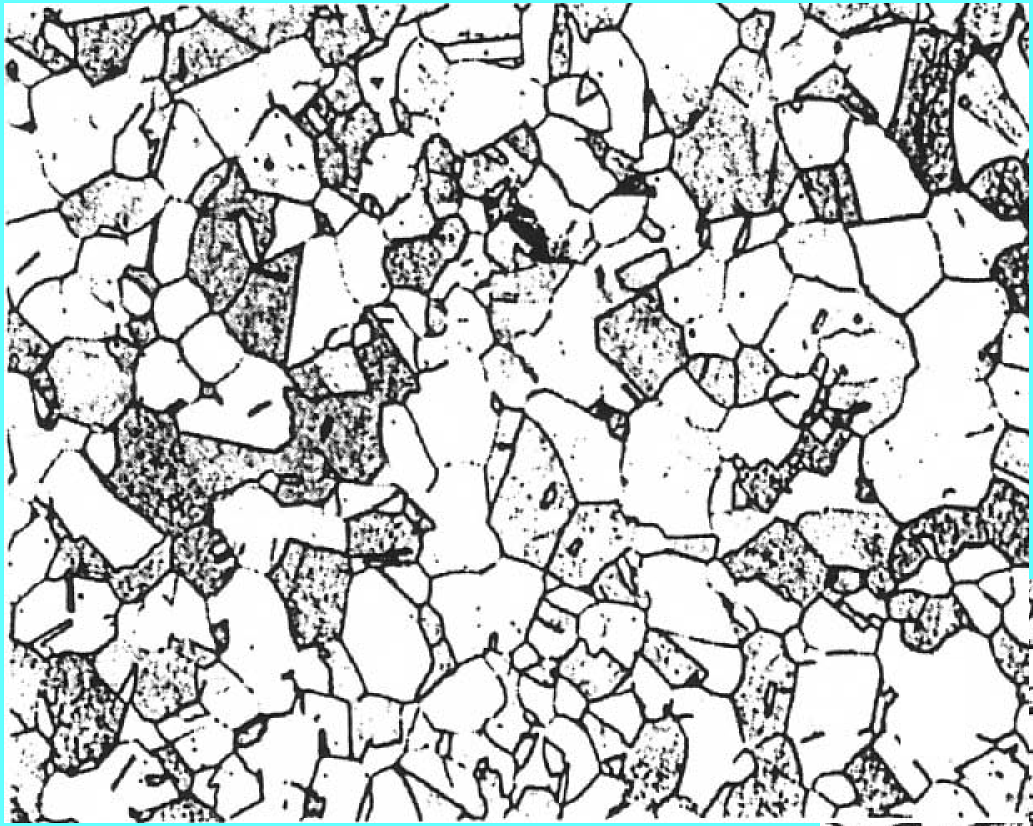
+

Recovery,
Recrystallization,
and Grain Growth

Cold Working Process

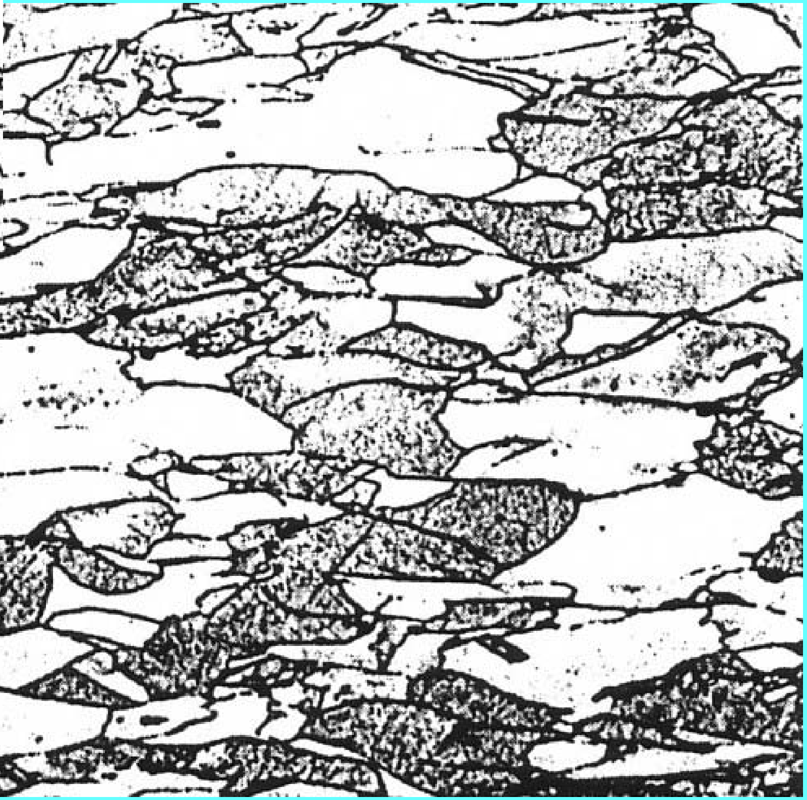


During the cold rolling process in a ductile crystalline material the atoms in the material are rearranged by the deformation such that the volume essentially remains constant or $V_o = A_o L_0 = V_F = A_F L_F$

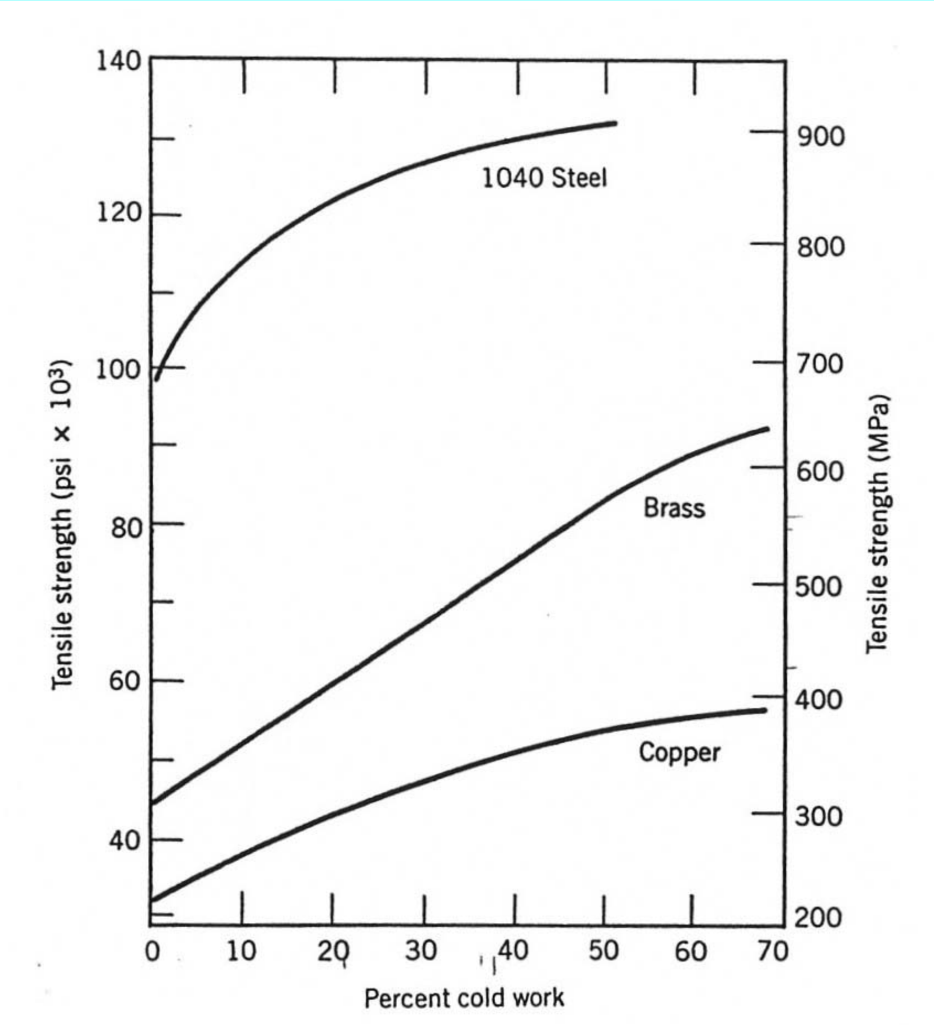


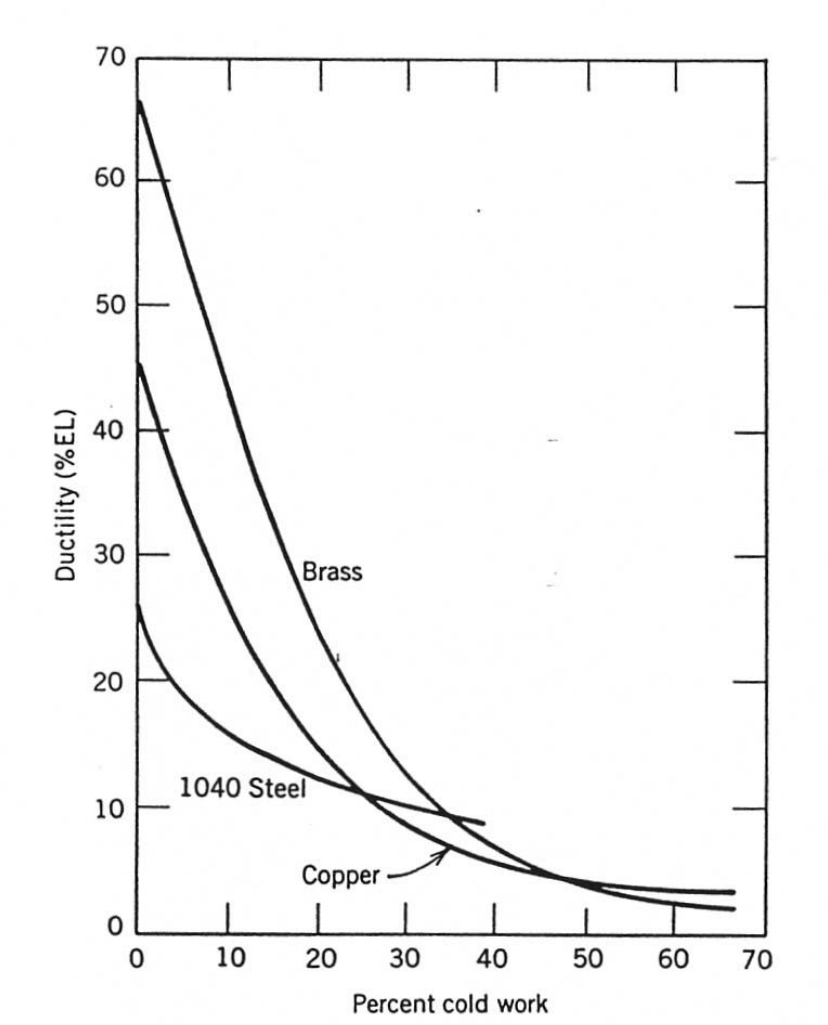
Before Cold Work

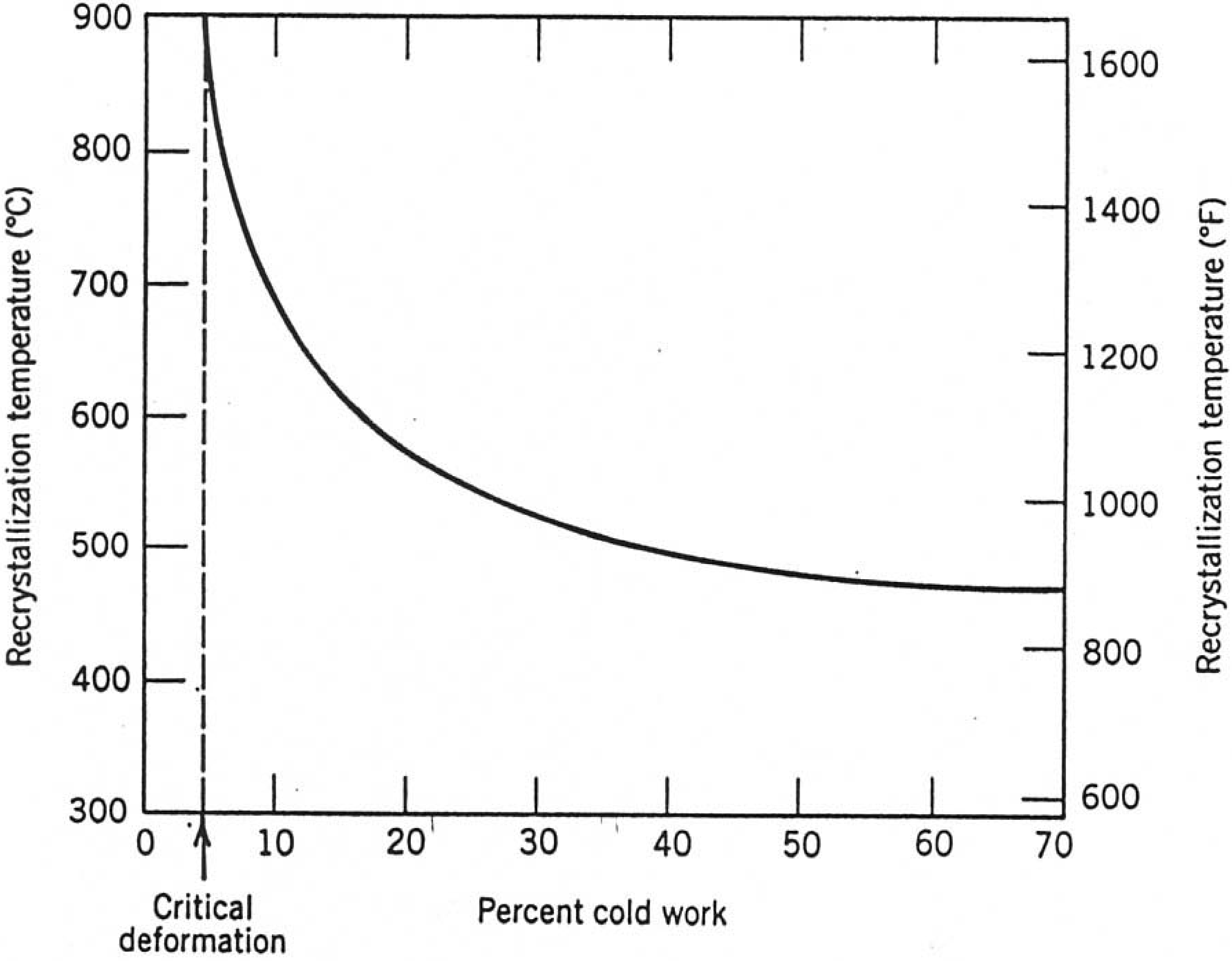
After Cold Work



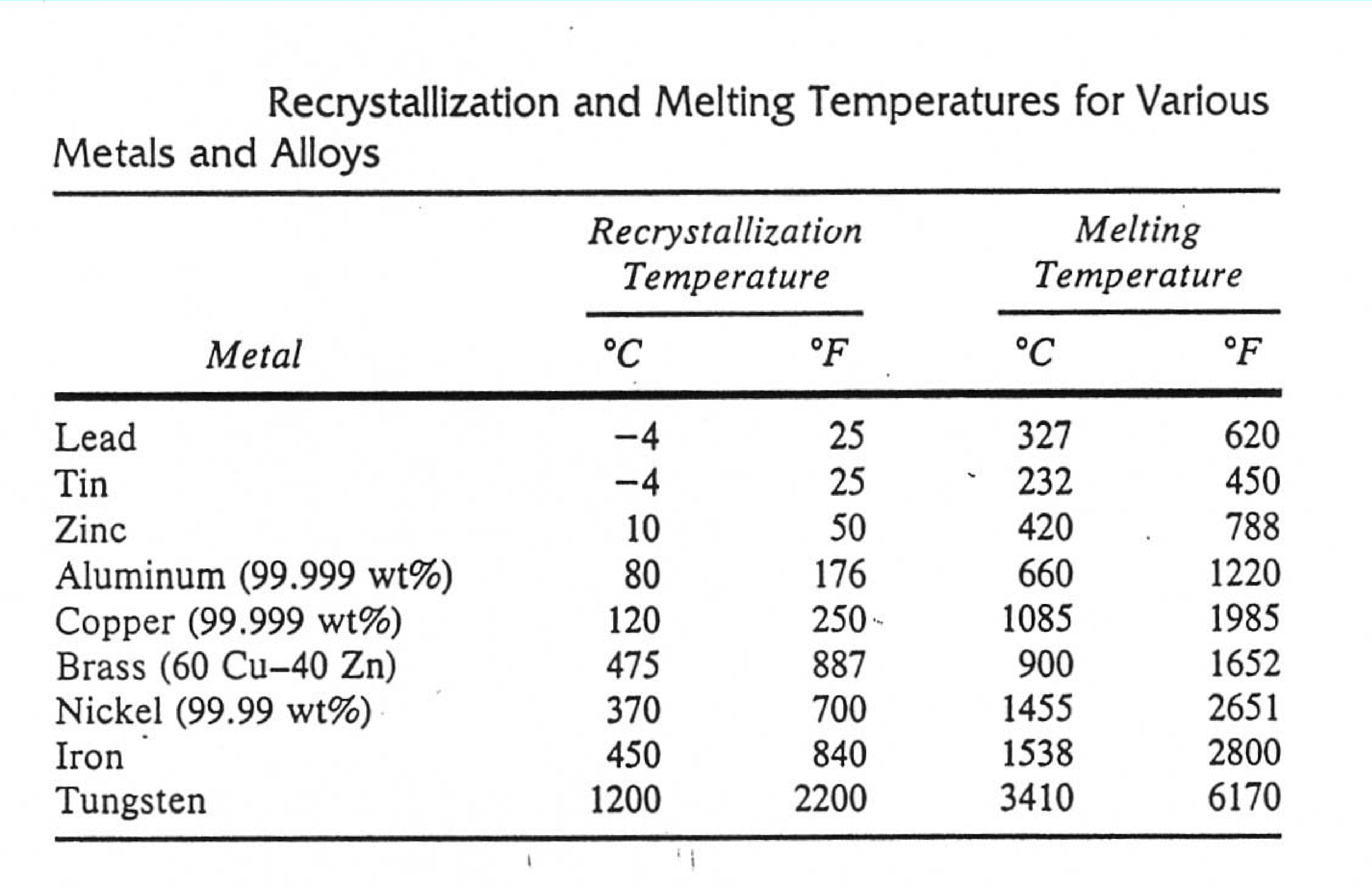
Effect of Cold Working Metals







The variation of recrystallization temperature with percent cold work for iron. For deformations less than the critical (about 5%CW), recrystallization will not occur.



Recrystallization and Melting Temperatures for Various Metals and Alloys

	Recrystallization Temperature		*Melting Temperature*	
Metal	*°C*	*°F*	*°C*	*°F*
Lead	−4	25	327	620
Tin	−4	25	232	450
Zinc	10	50	420	788
Aluminum (99.999 wt%)	80	176	660	1220
Copper (99.999 wt%)	120	250	1085	1985
Brass (60 Cu–40 Zn)	475	887	900	1652
Nickel (99.99 wt%)	370	700	1455	2651
Iron	450	840	1538	2800
Tungsten	1200	2200	3410	6170

Understanding of Fe –C Phase Equilibrium - 1946

Tool Available at the time:

*X-ray Diffraction

*Optical Metallography

*Thermocouples

Delta – BCC

Austenite – FCC

Ferrite – BCC

Cementite - Orthorhombic

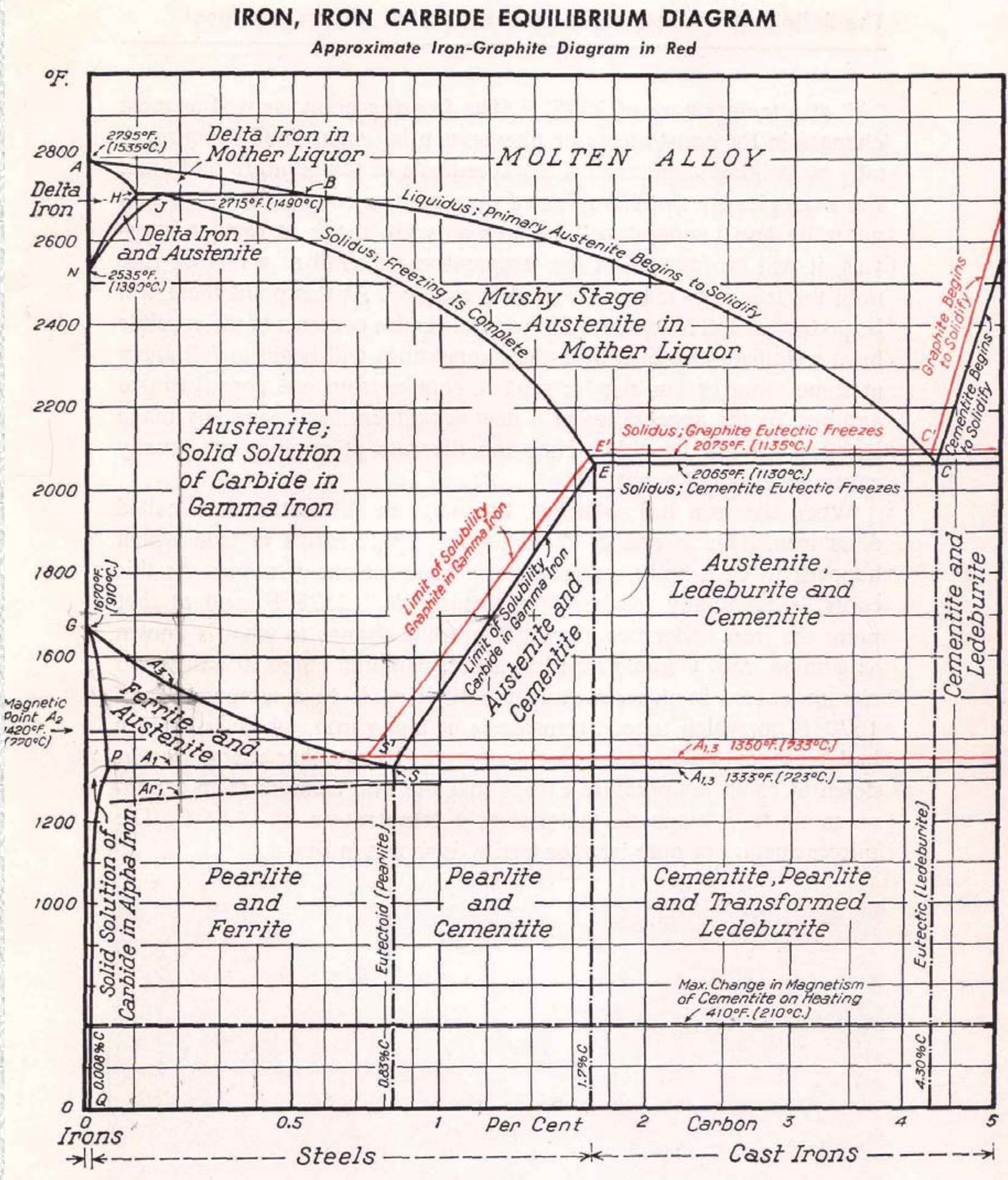
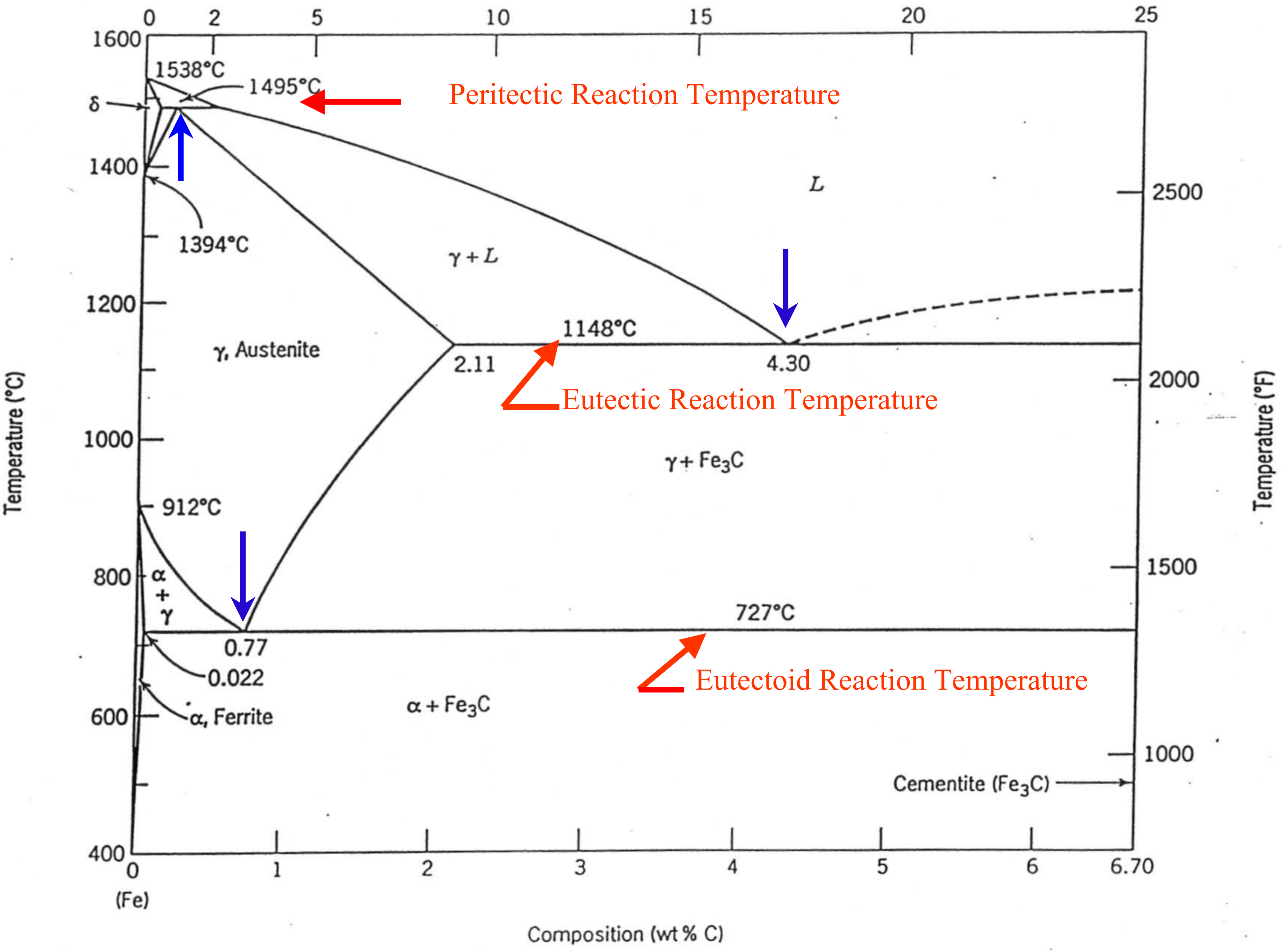


Fig. 3—The Iron-Carbon Equilibrium Diagram (Metal Progress July, 1946)



Peritectic Reaction Temperature

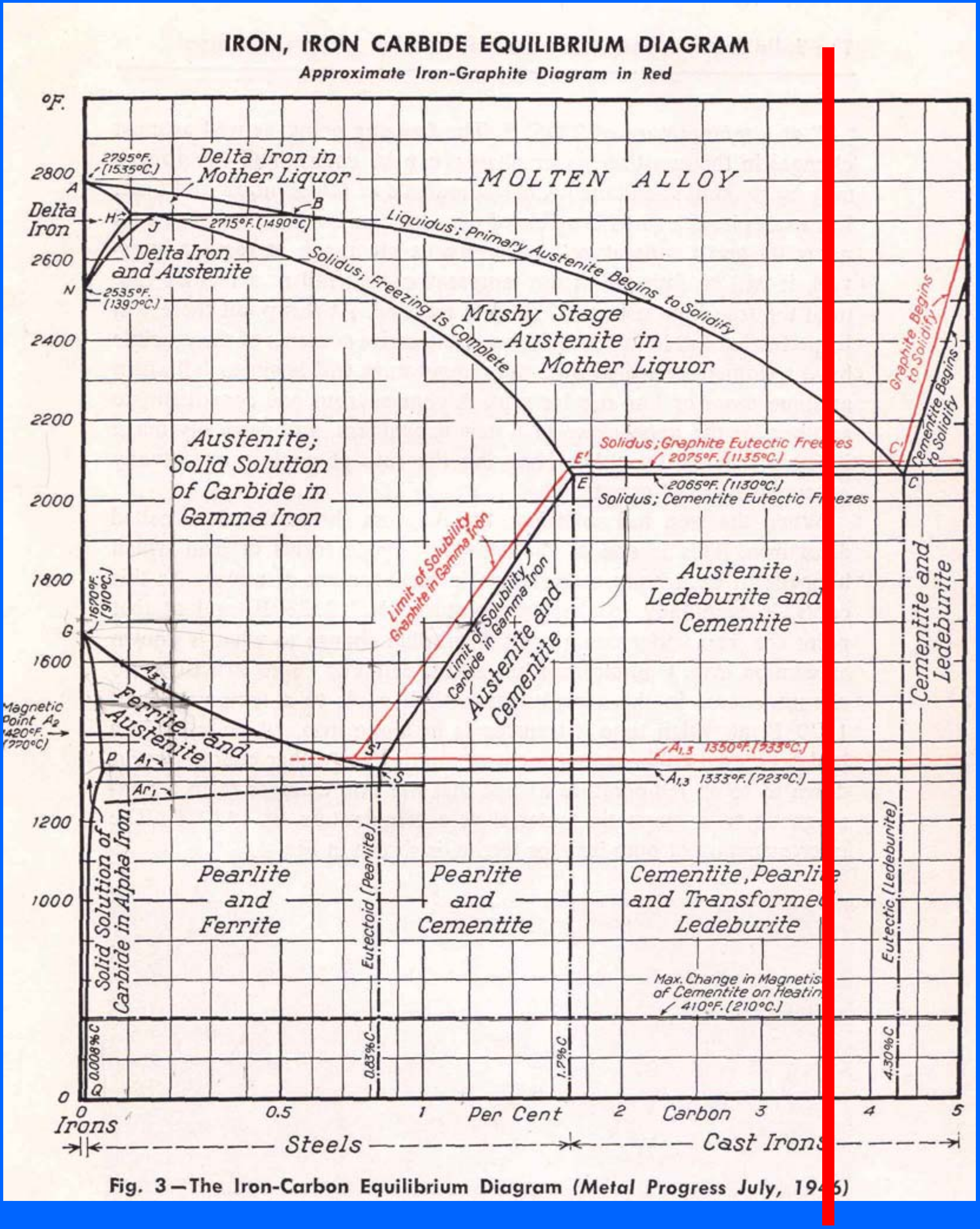
Eutectic Reaction Temperature

Eutectoid Reaction Temperature

The iron–iron carbide phase diagram.

Cast Irons

White Cast Iron

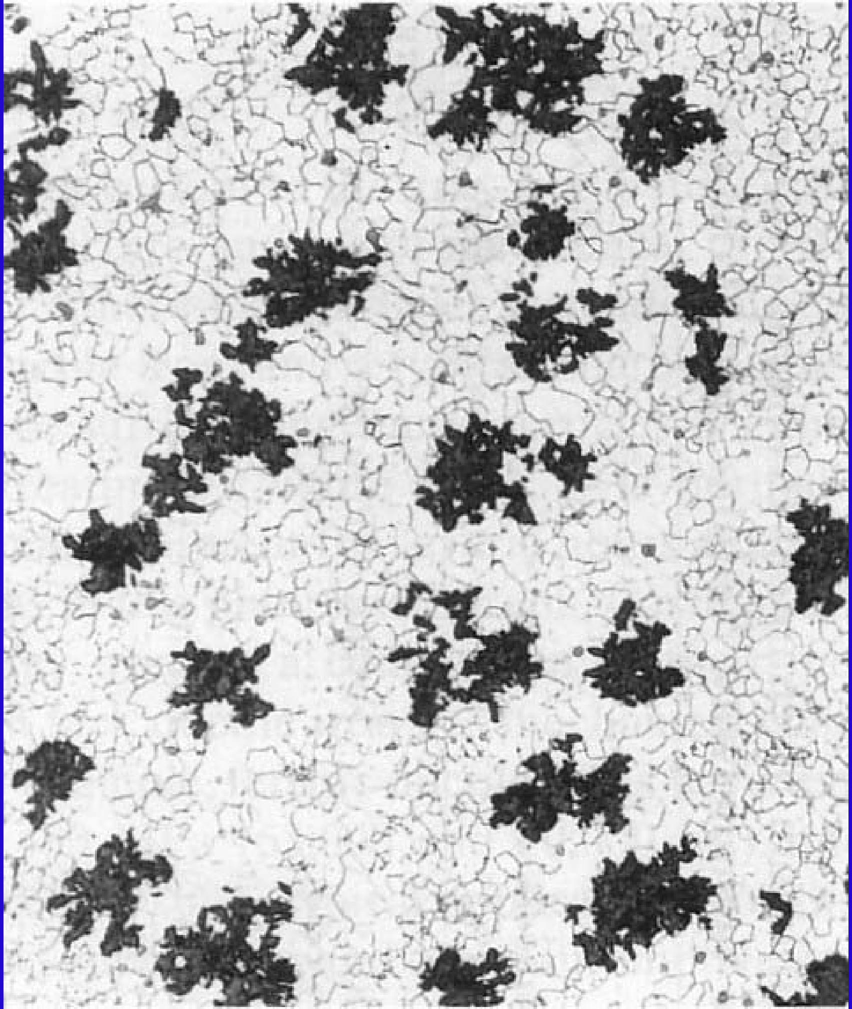


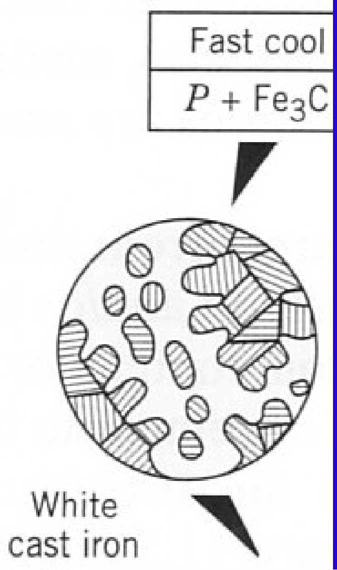
IRON, IRON CARBIDE EQUILIBRIUM DIAGRAM

Approximate Iron-Graphite Diagram in Red

Fig. 3—The Iron-Carbon Equilibrium Diagram (Metal Progress July, 1946)

Malleablizing White Cast Iron

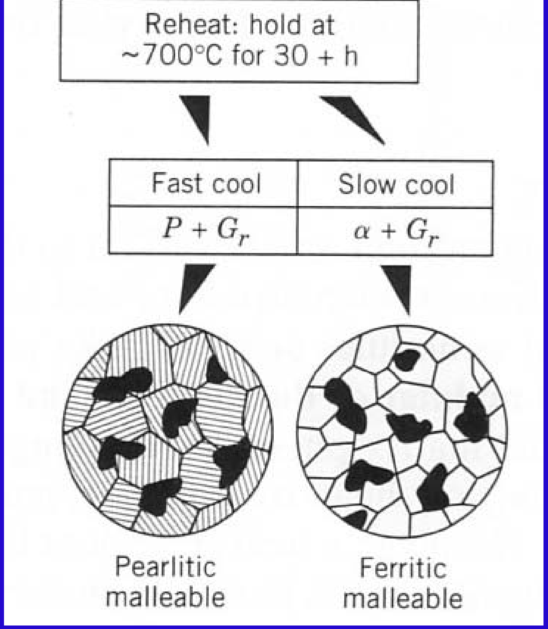




Fast cool

$P + Fe_3C$

White cast iron

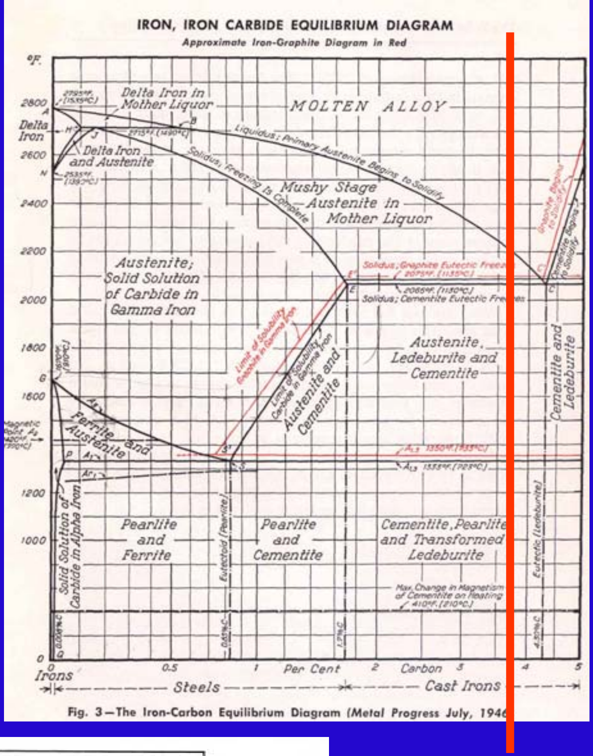


Reheat: hold at ~700°C for 30 + h

Fast cool	Slow cool
$P + G_r$	$\alpha + G_r$

Pearlitic malleable

Ferritic malleable



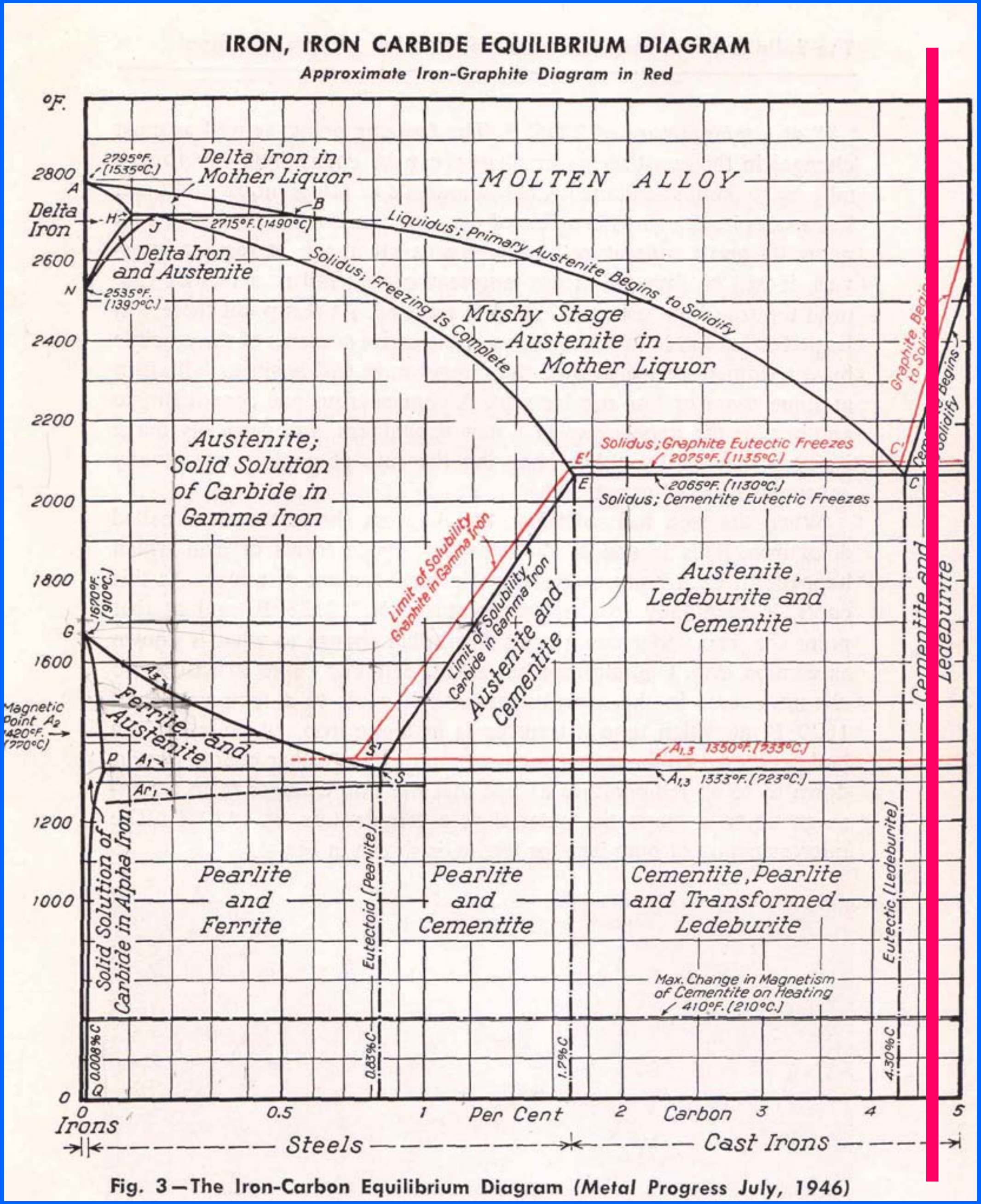
IRON, IRON CARBIDE EQUILIBRIUM DIAGRAM

Approximate Iron-Graphite Diagram in Red

Fig. 3—The Iron-Carbon Equilibrium Diagram (Metal Progress July, 1946

Cast Irons

Ferritic Gray CI

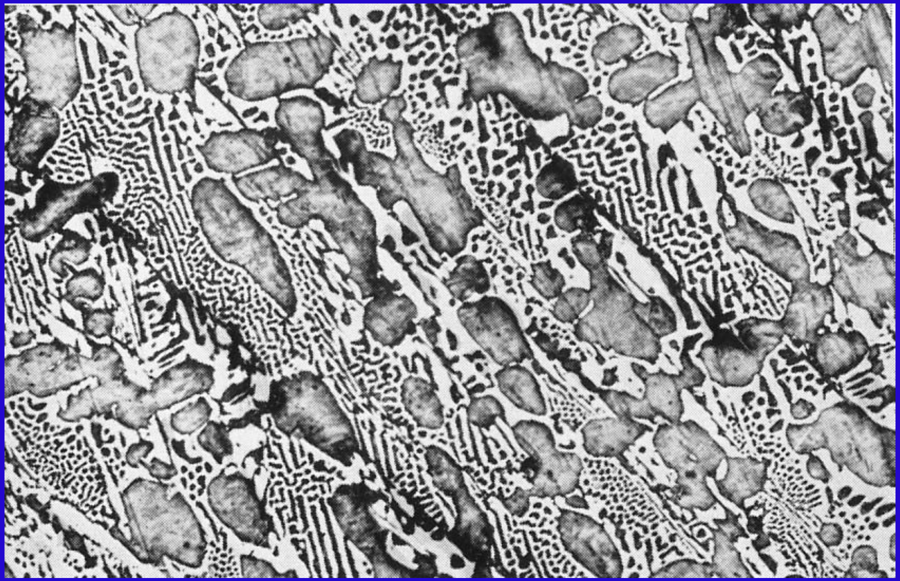


IRON, IRON CARBIDE EQUILIBRIUM DIAGRAM

Approximate Iron-Graphite Diagram in Red

Fig. 3—The Iron-Carbon Equilibrium Diagram (Metal Progress July, 1946)

Lebedurite

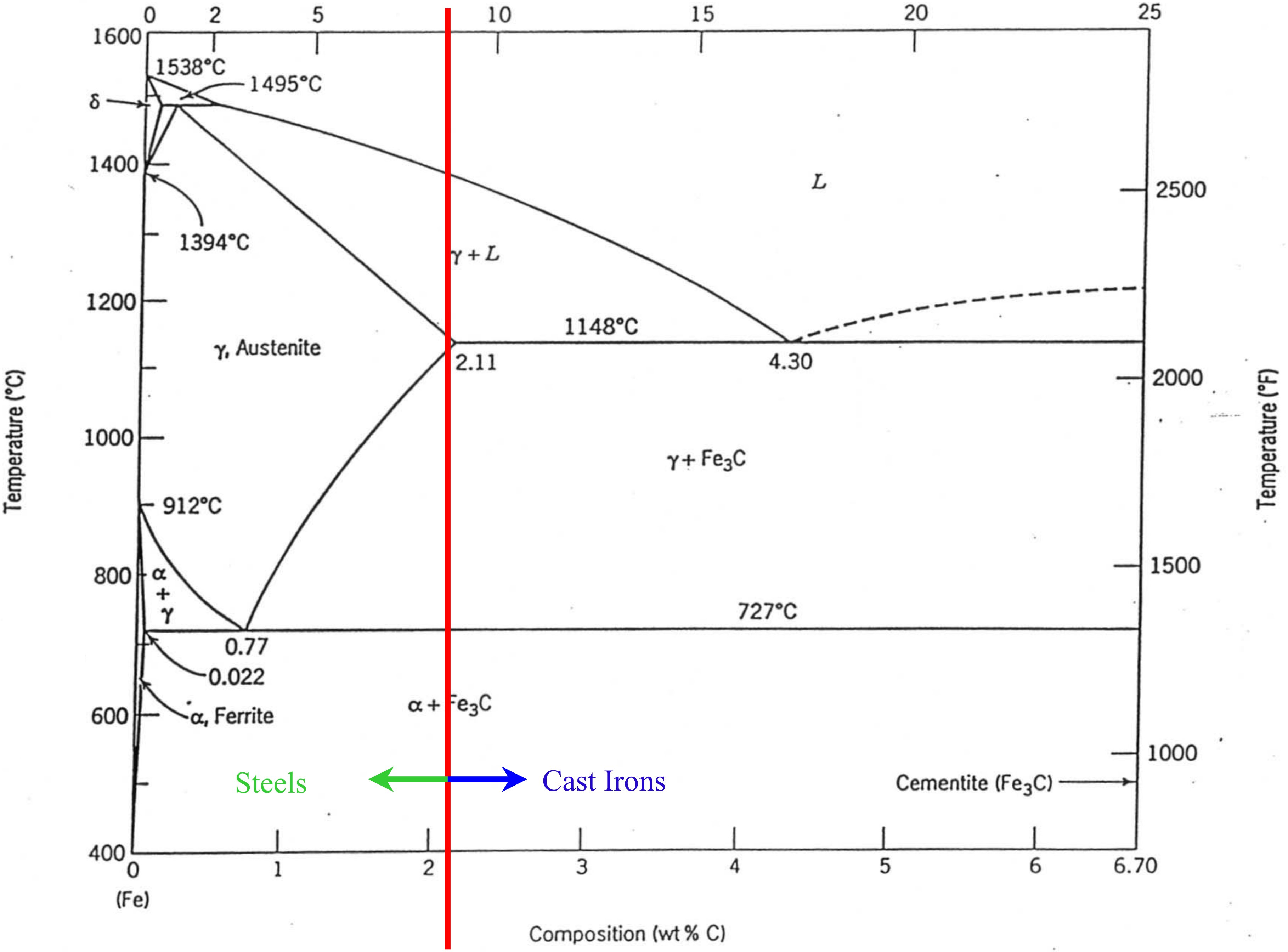


Hypoeutectic Composition

←

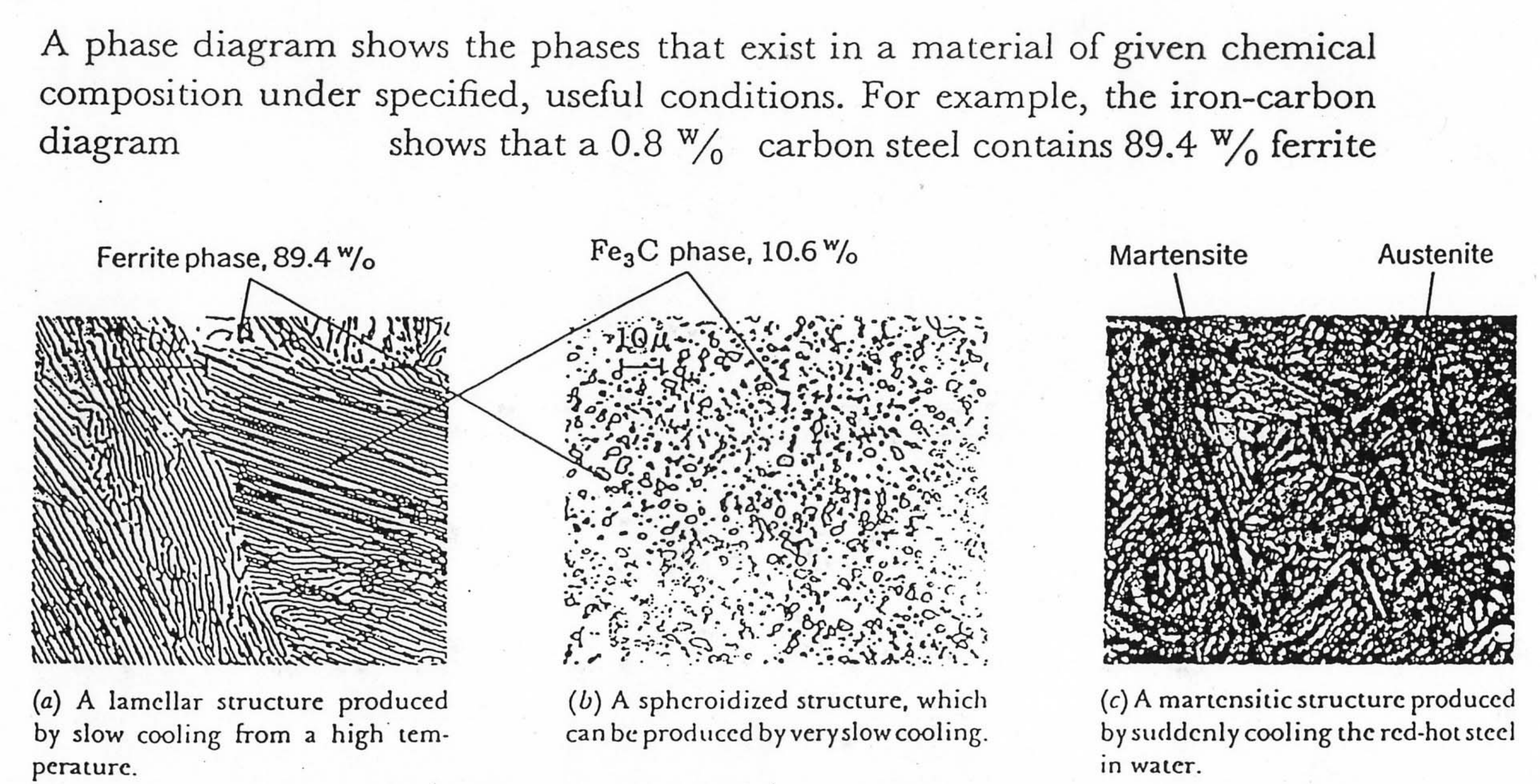
Hypereutectic Composition

→



The iron–iron carbide phase diagram.

Steel Phase Equilibria



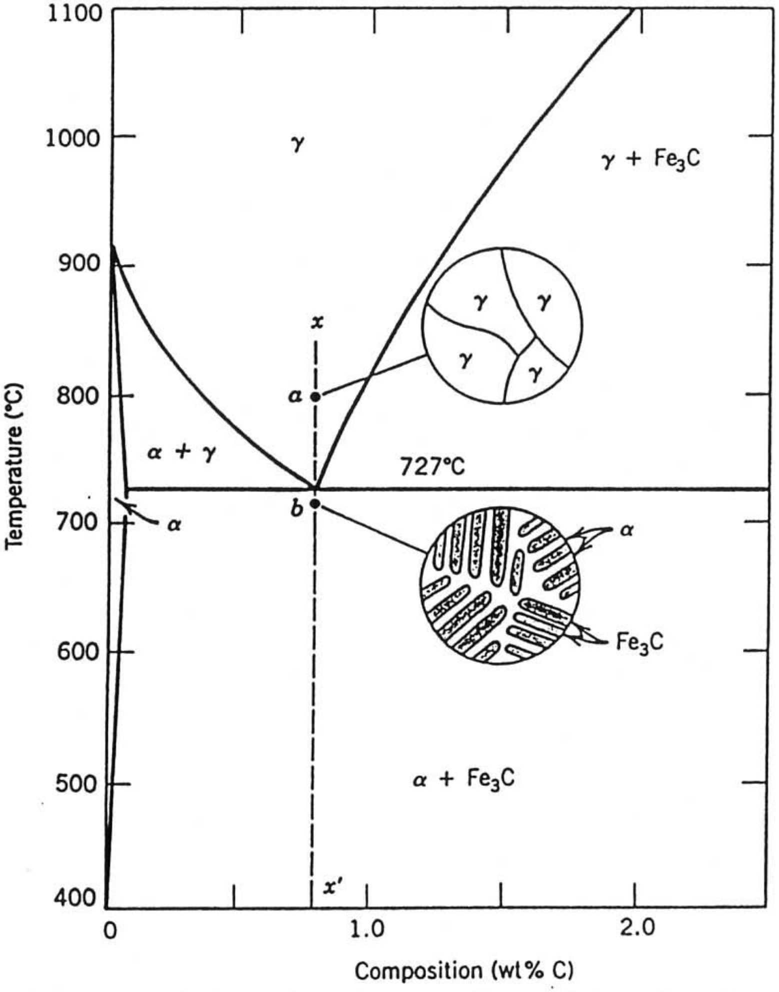
A phase diagram shows the phases that exist in a material of given chemical composition under specified, useful conditions. For example, the iron-carbon diagram shows that a 0.8 $^{w}/_{o}$ carbon steel contains 89.4 $^{w}/_{o}$ ferrite

(*a*) A lamellar structure produced by slow cooling from a high temperature.

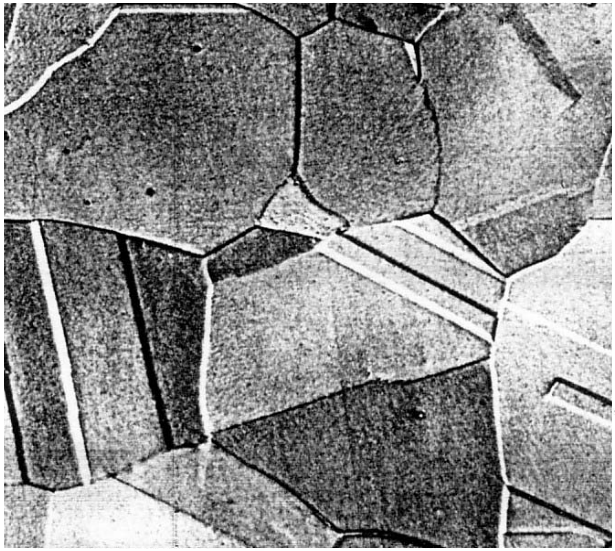
(*b*) A spheroidized structure, which can be produced by very slow cooling.

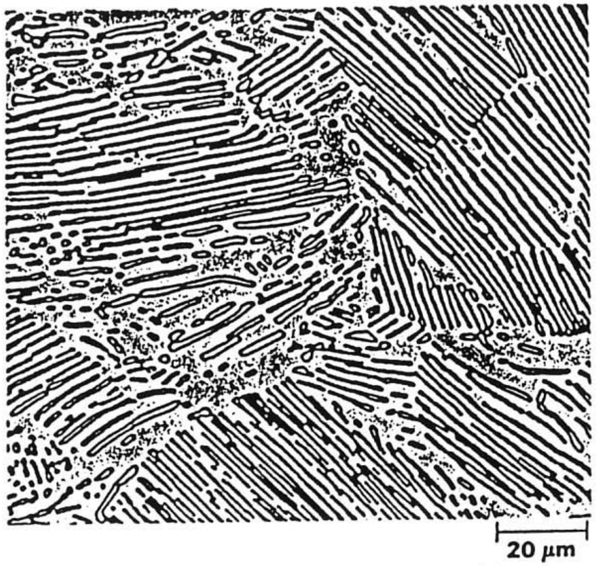
(*c*) A martensitic structure produced by suddenly cooling the red-hot steel in water.

Eutectoid Steel Equilibrium Transformation

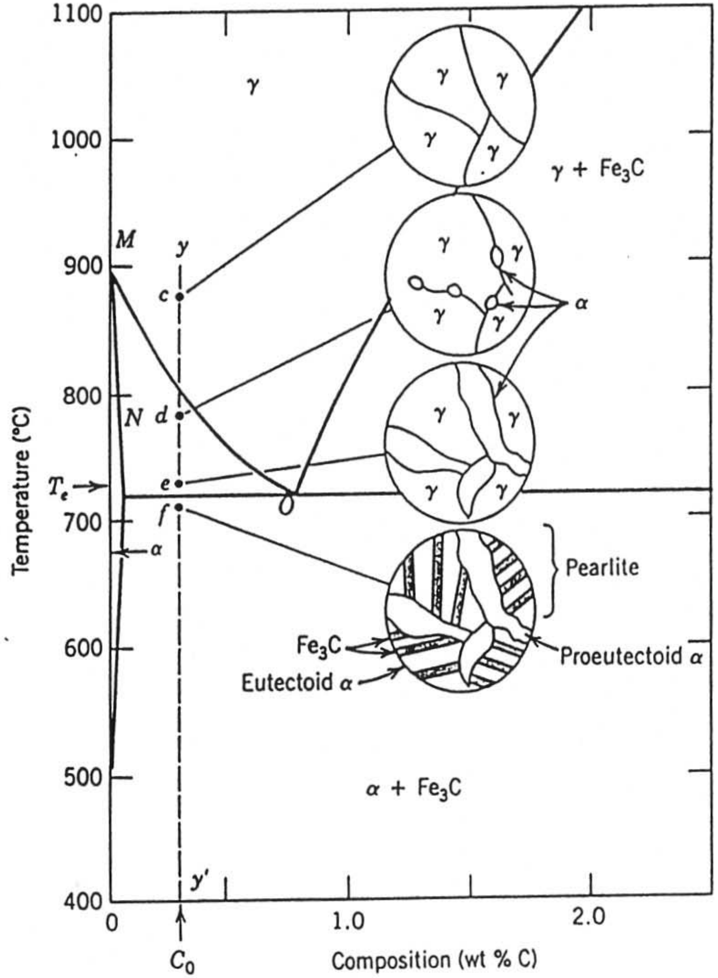


Schematic representations of the microstructures for an iron–carbon alloy of eutectoid composition (0.77 wt% C) above and below the eutectoid temperature.



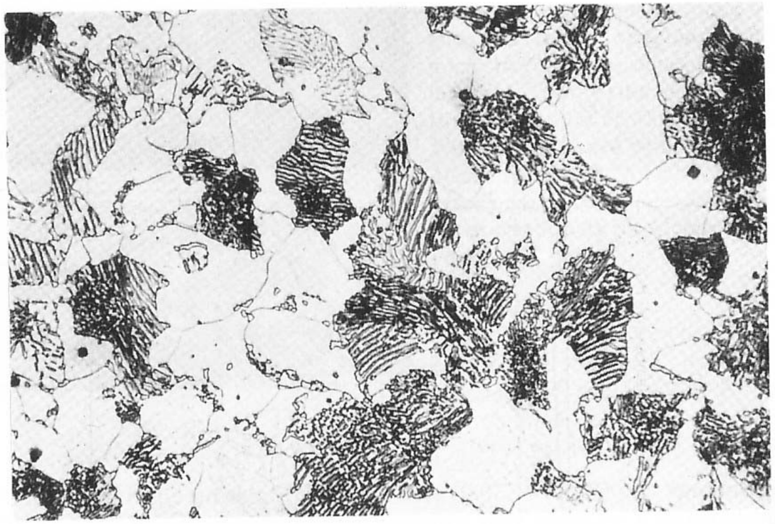


Hypo-Eutectoid Steel Equilibrium Transformation

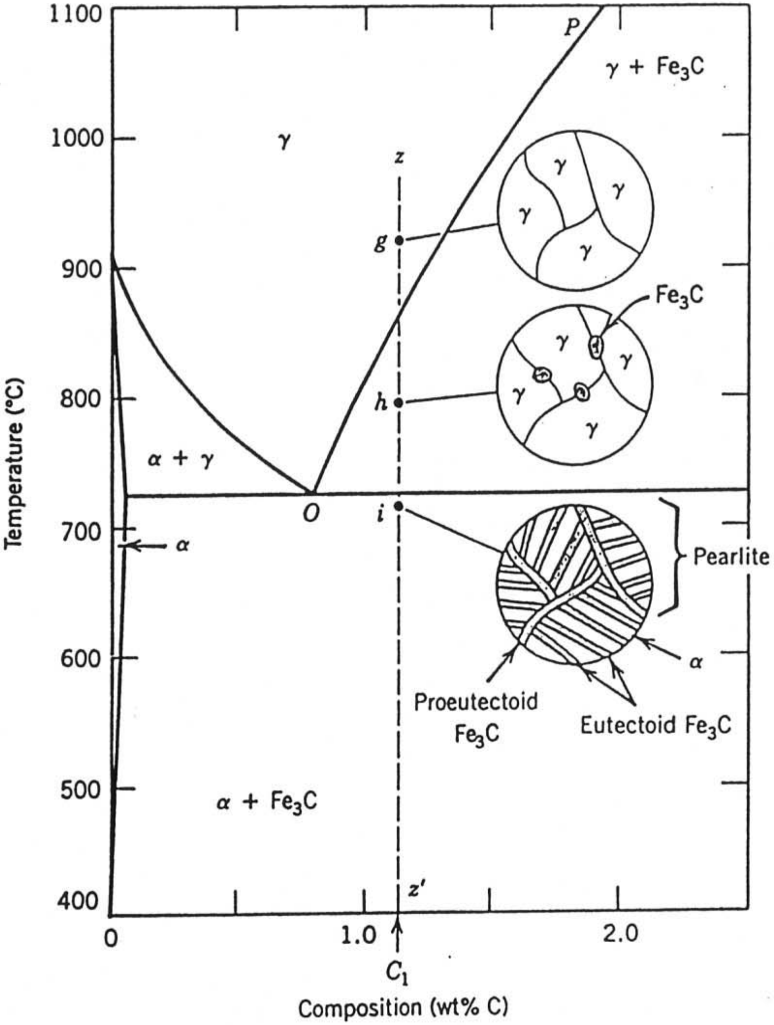


Schematic representations of the microstructures for an iron–carbon alloy of hypoeutectoid composition C_0 (containing less than 0.77 wt% C) as it is cooled from within the austenite phase region to below the eutectoid temperature.

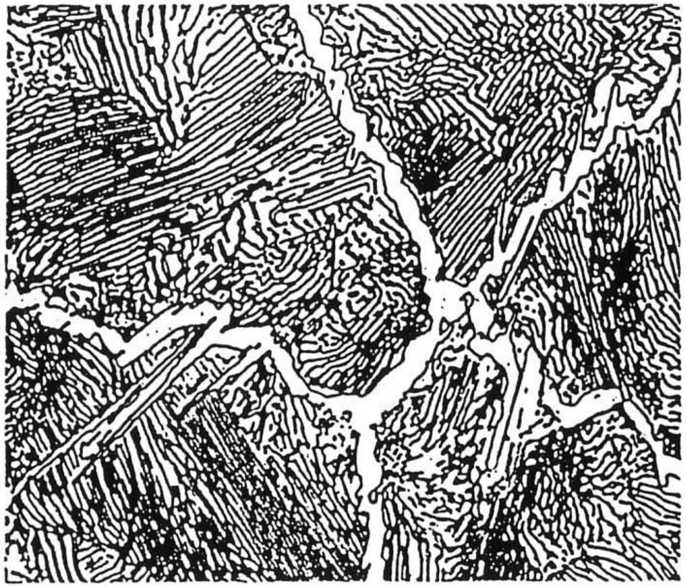
Photomicrograph of a 0.38 wt% C steel having a microstructure consisting of pearlite and proeutectoid ferrite. 635×. (Photomicrograph courtesy of Republic Steel Corporation.)



Hyper-Eutectoid Steel Equilibrium Transformation

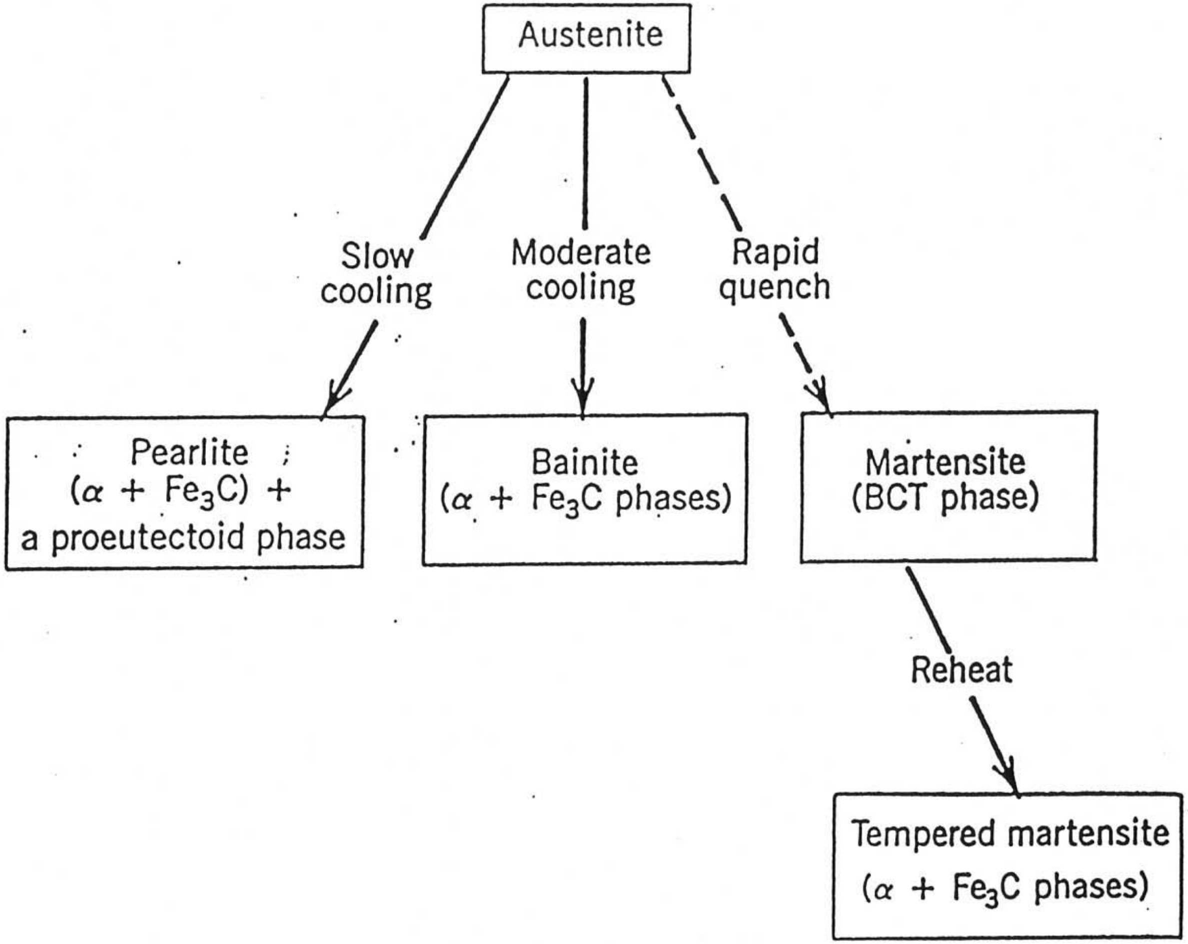


Schematic representations of the microstructures for an iron–carbon alloy of hypereutectoid composition C_1 (containing between 0.77 and 2.1 wt% C), as it is cooled from within the austenite phase region to below the eutectoid temperature.



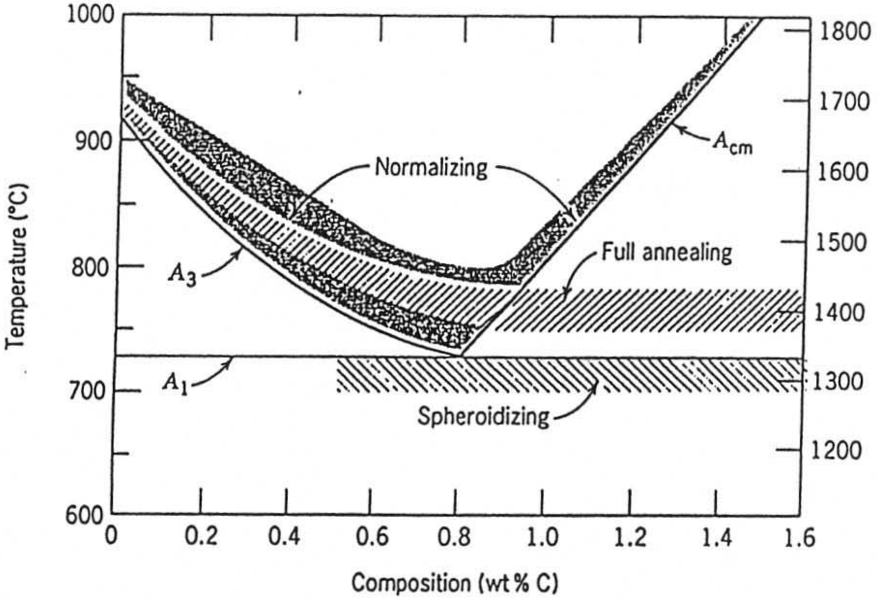
Photomicrograph of a 1.4 wt% C steel having a microstructure consisting of a white proeutectoid cementite network surrounding the pearlite colonies. 1000×. (Copyright 1971 by United States Steel Corporation.)

Austenite Transformation Products in Steels

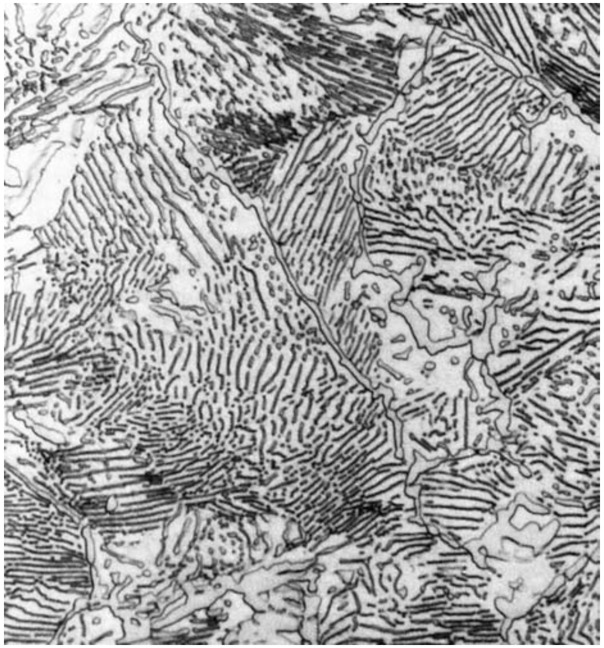


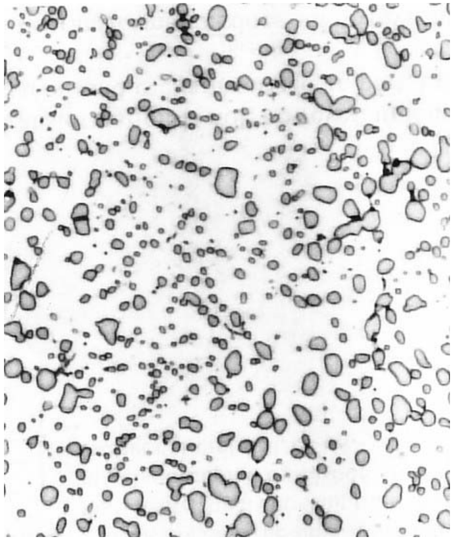
Possible transformations involving the decomposition of austenite. Solid arrows, transformations involving diffusion; dashed arrow, diffusionless transformation.

Dependence of Properties on Microstructure



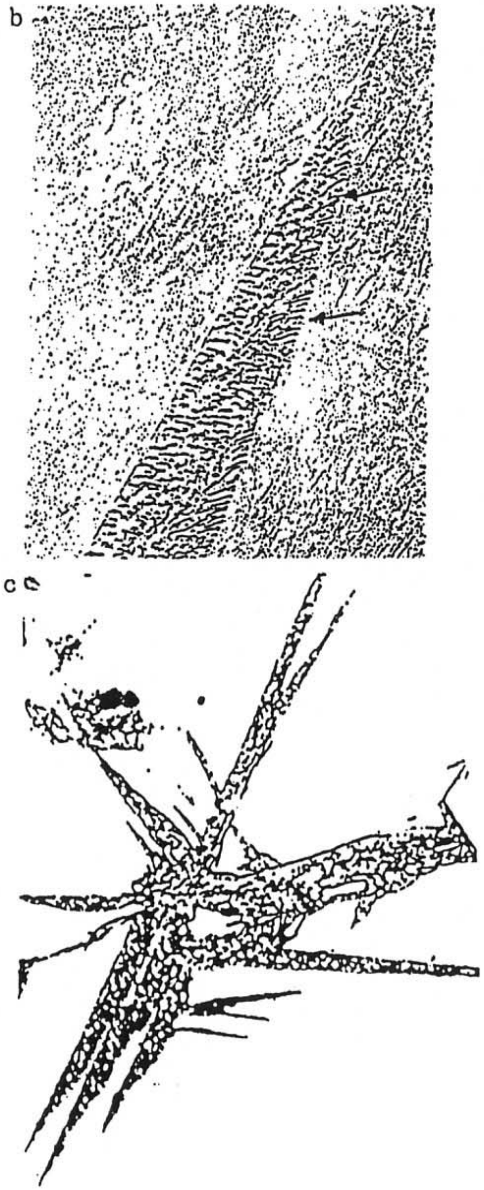
The iron–iron carbide phase diagram in the vicinity of the eutectoid, indicating heat treating temperature ranges for plain carbon steels. (Adapted from *Metals Handbook,* T. Lyman, Editor, American Society for Metals, 1948, p. 661.)





Pearlite

Bainite



Martensite

Pearlite & Bainite Microstructures

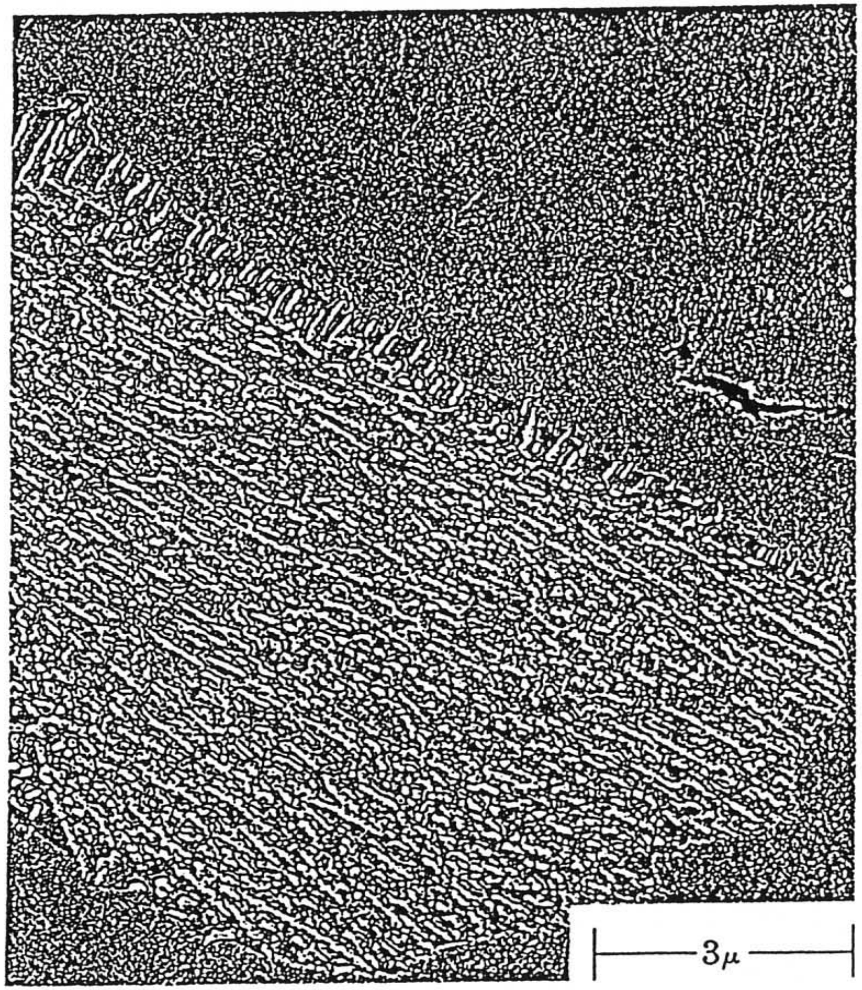
- Both microstructures contain Ferrite (α) and Cementite (Fe_3C).

- Pearlite forms at prior austenite grain boundaries by nucleating Fe_3C first then α.

- Bainite forms at prior austenite grain boundaries by nucleating α first then Fe_3C.

- The bainite transformation generally occurs at lower temperatures than the pearlite transformation in most steels resulting in a finer carbide size and distribution in bainite product.

Bainite & Pearlite Microstructures



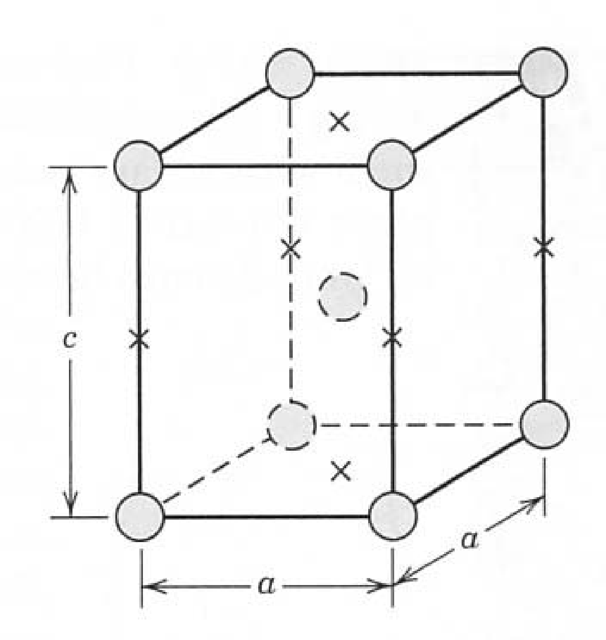
Bainite

Pearlite

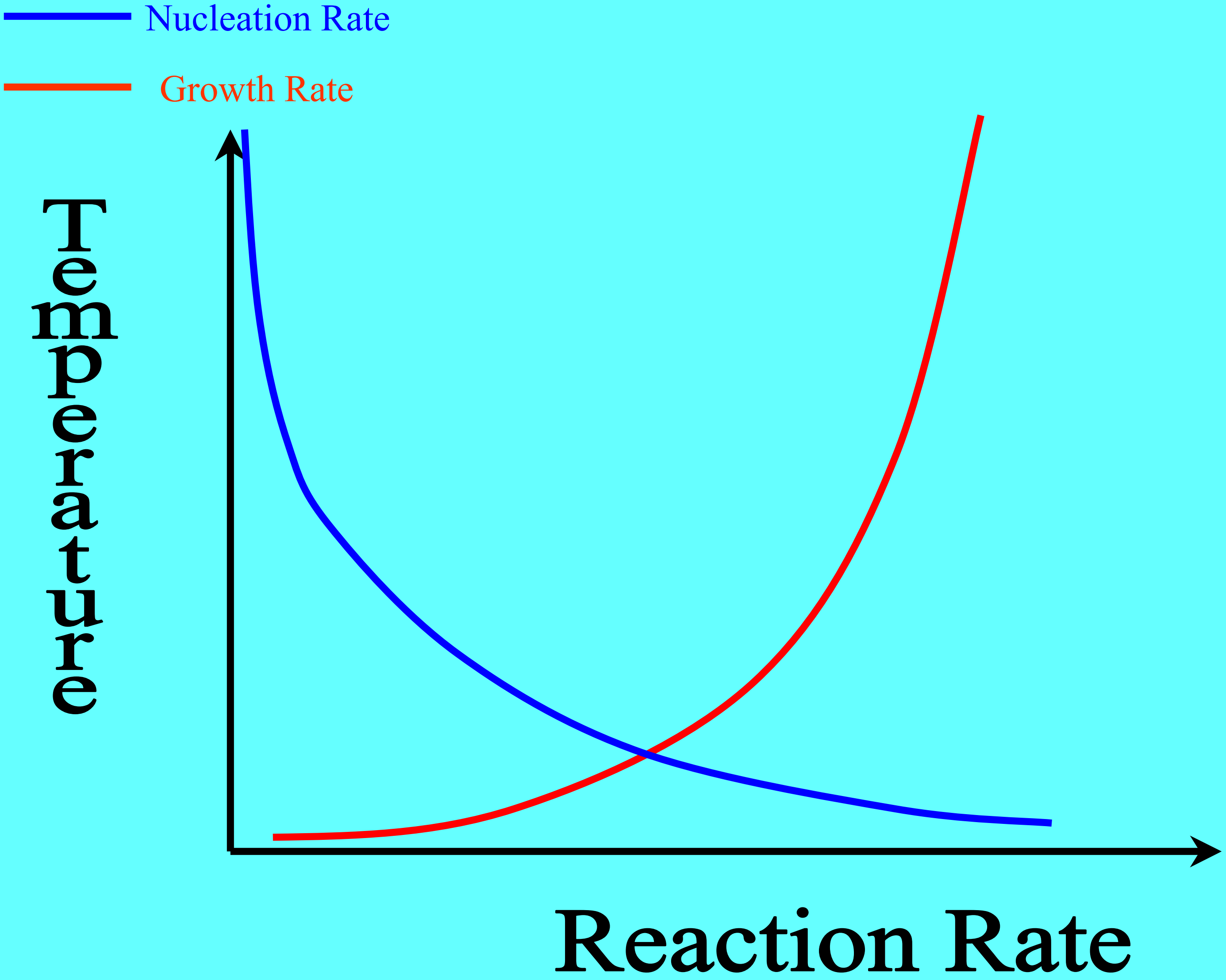
Martensite Transformation

Retained Austenite

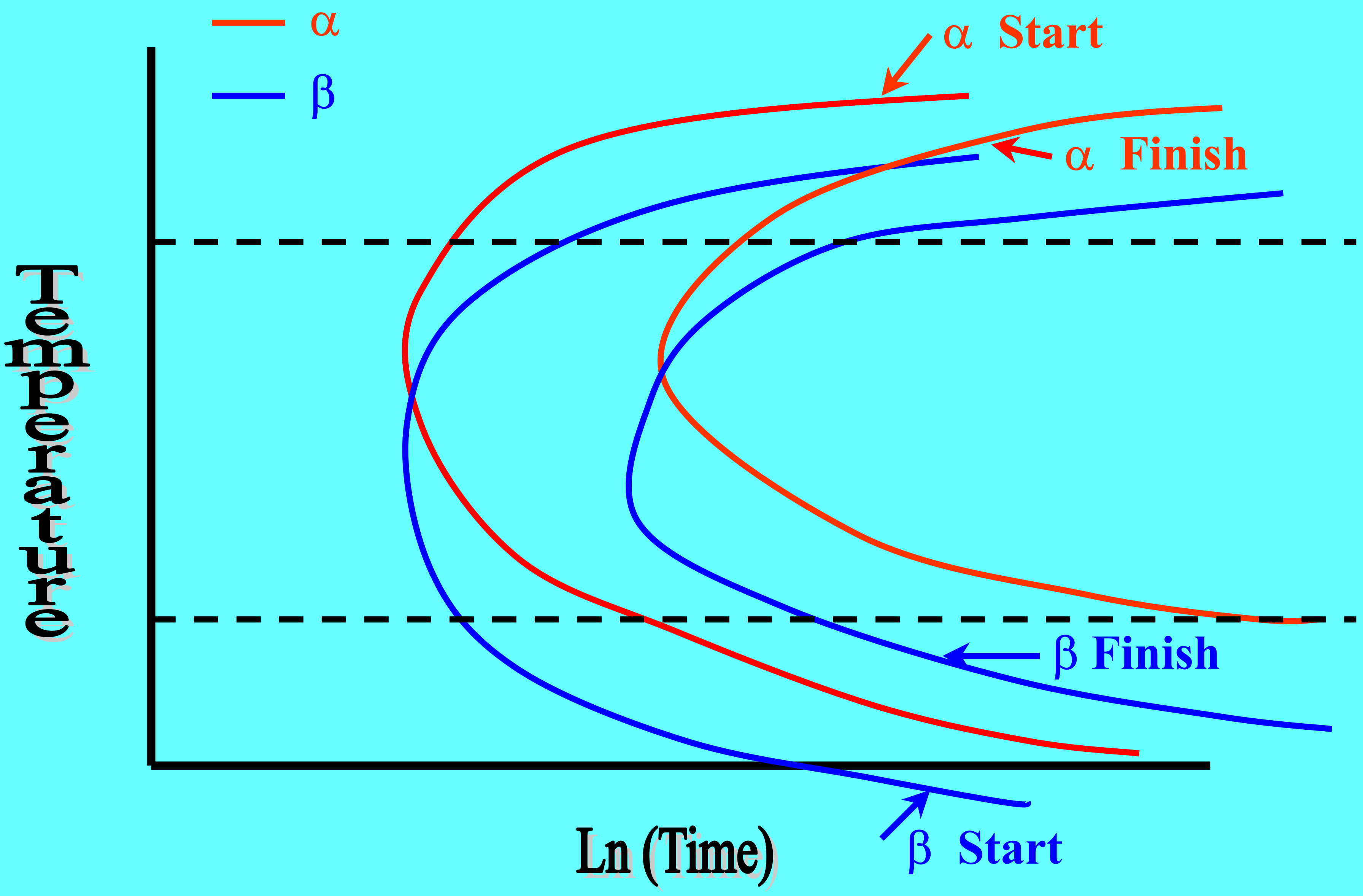
"As Quenched" Martensite



Nucleation & Growth Kinetics



Isothermal Time Dependence of Phase Transformation Reaction Rate

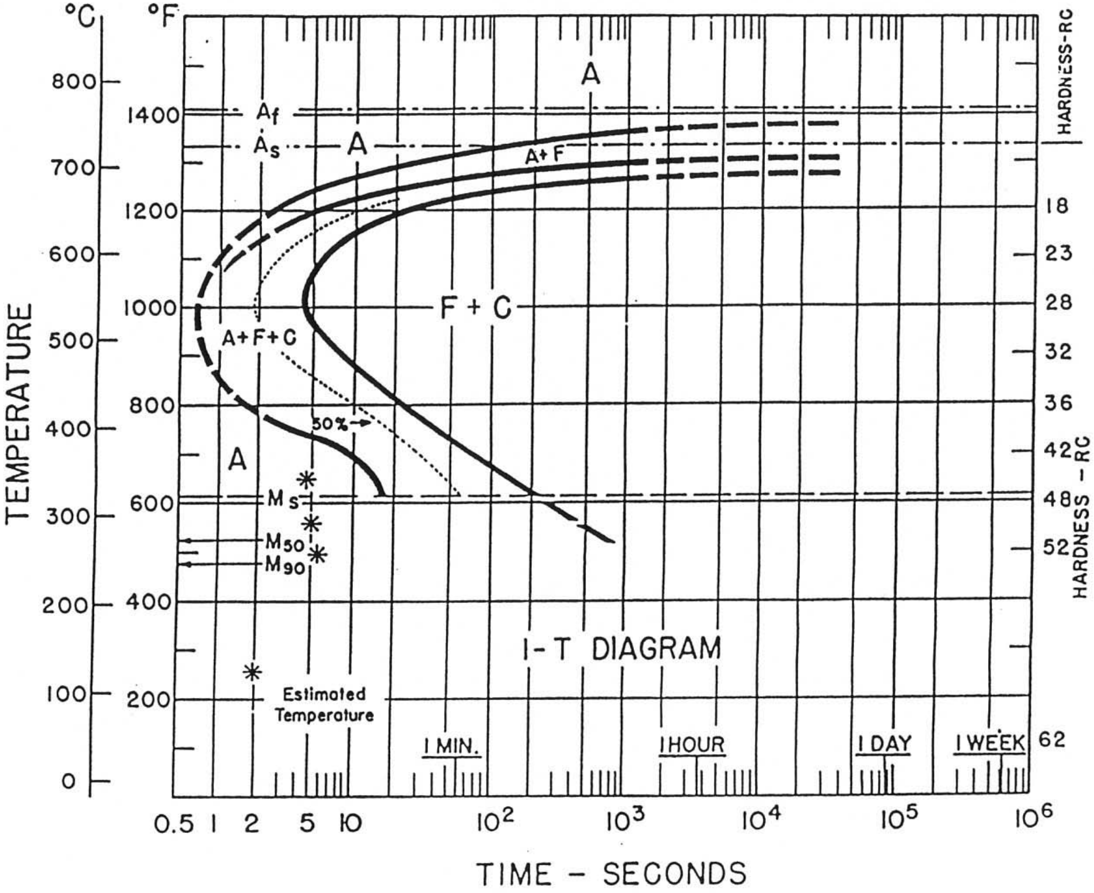


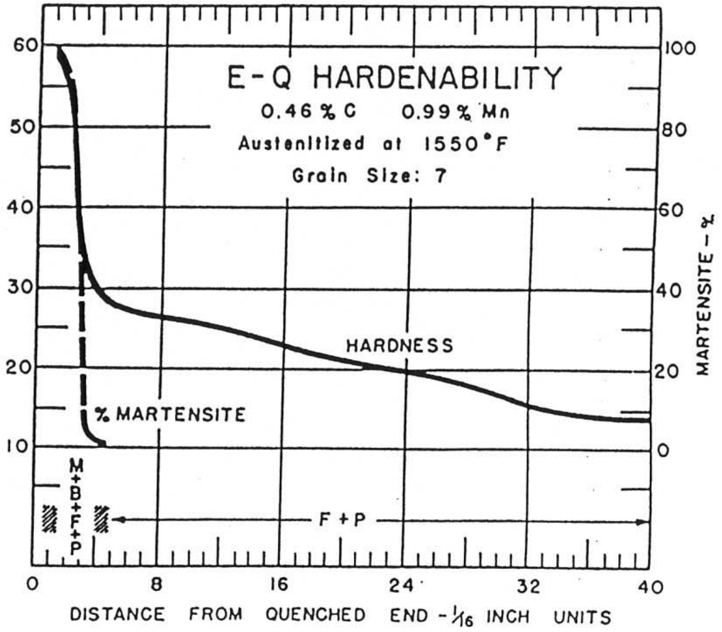
Isothermal Transformation Diagram
1050 Steels

C-0.50
Mn-0.91

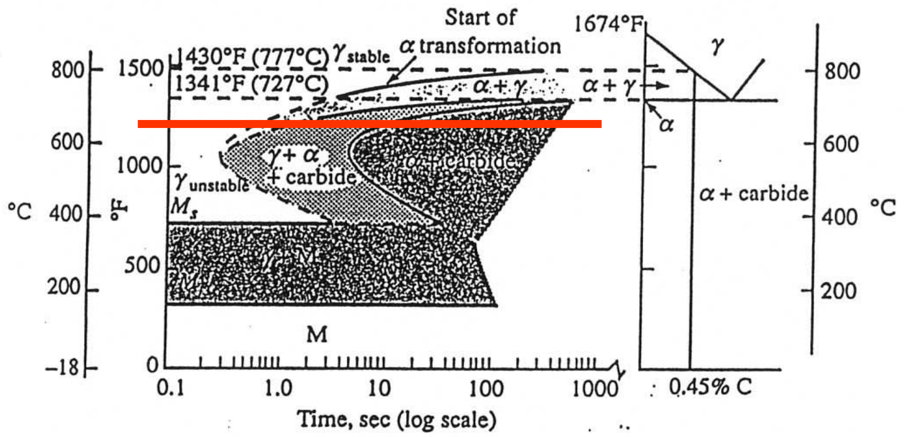
Carbon Steels: 1050 Austenitized at 1670°F

Grain Size: 7-8



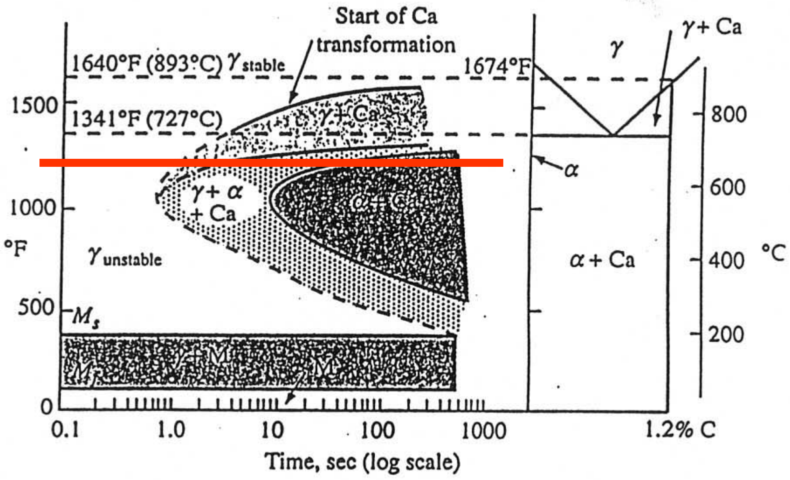


Relating Isothermal Transformation Diagram to Equilibrium Phase Diagrams

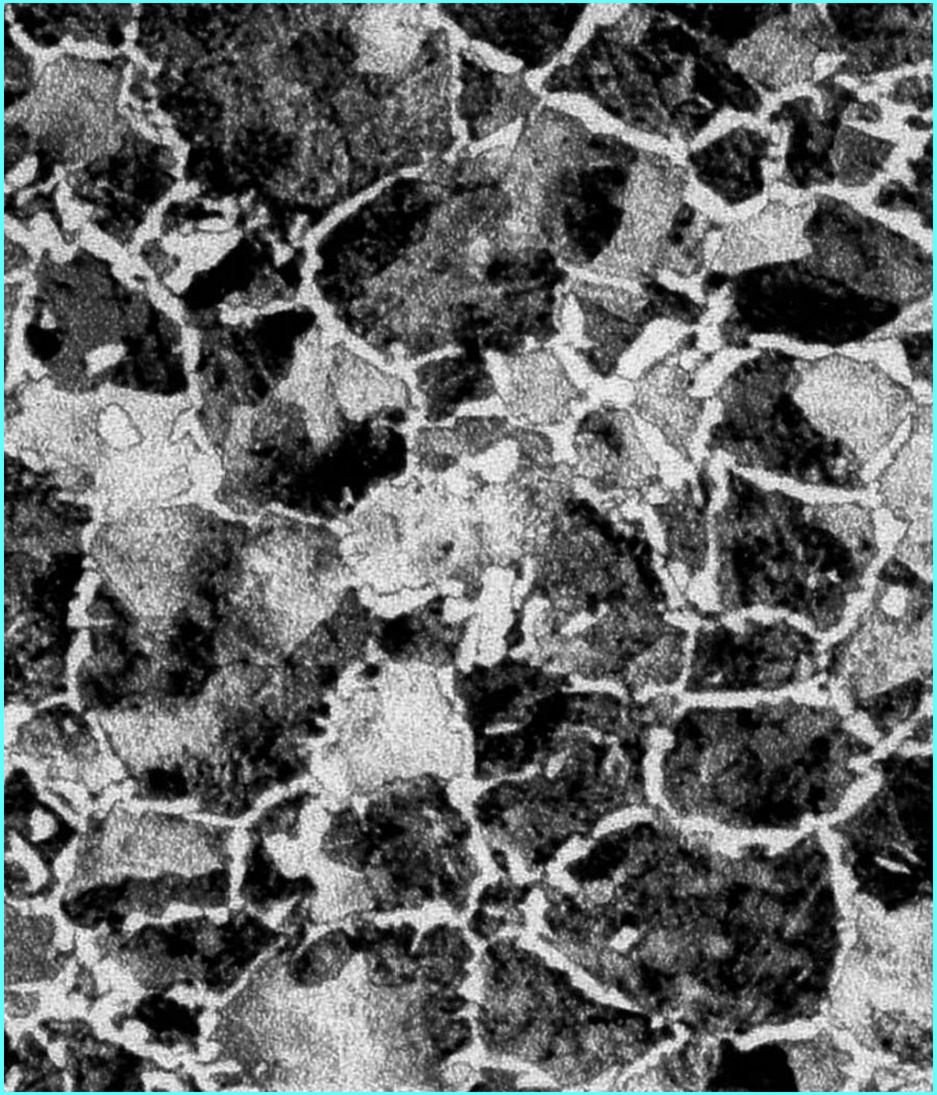


TTT curve for 0.45% carbon steel. There is an additional region above e nose of the curve that is not found with 1080 steel. A portion of the iron–iron-car- le diagram is included to show why primary α occurs.

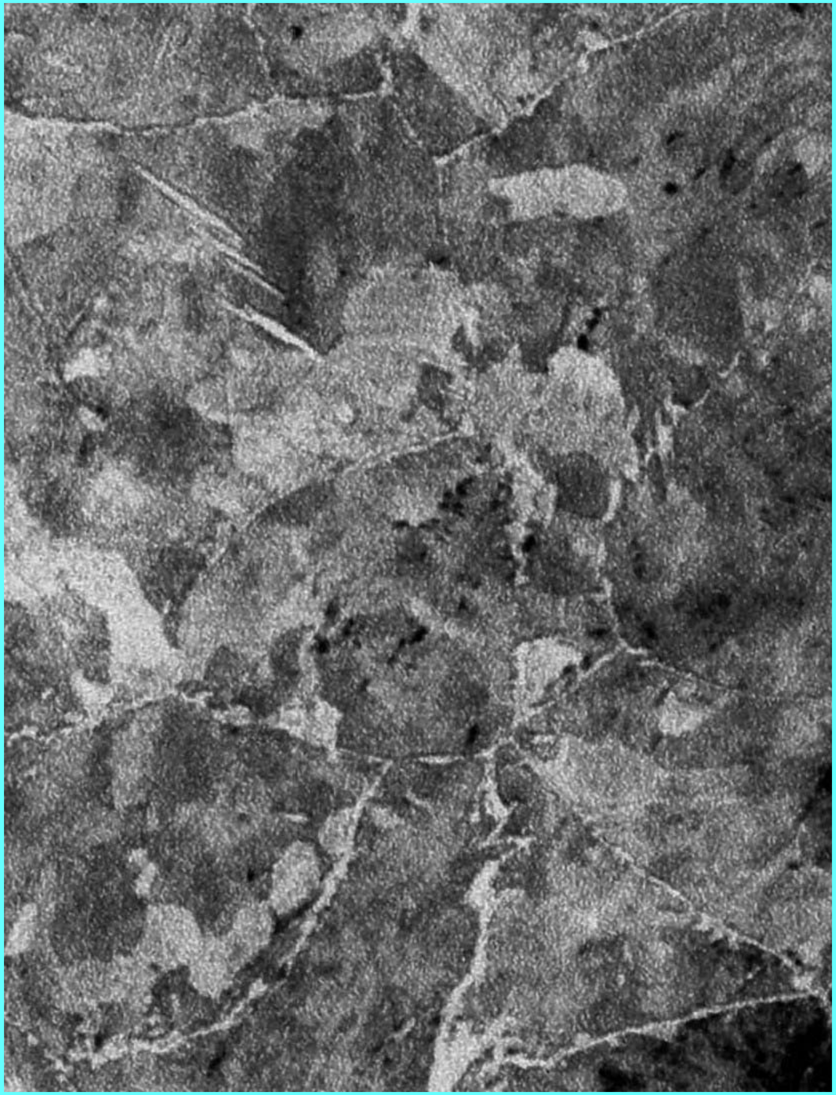
apted from L. H. Van Vlack, *Elements of Materials Science*, 2d ed., Addison-Wesley, Reading, Mass., 1964, p. 292]



TTT curve for hypereutectoid steel (1.2% carbon)



1045 Steel



1.2%C Steel

Isothermal Transformation Diagram

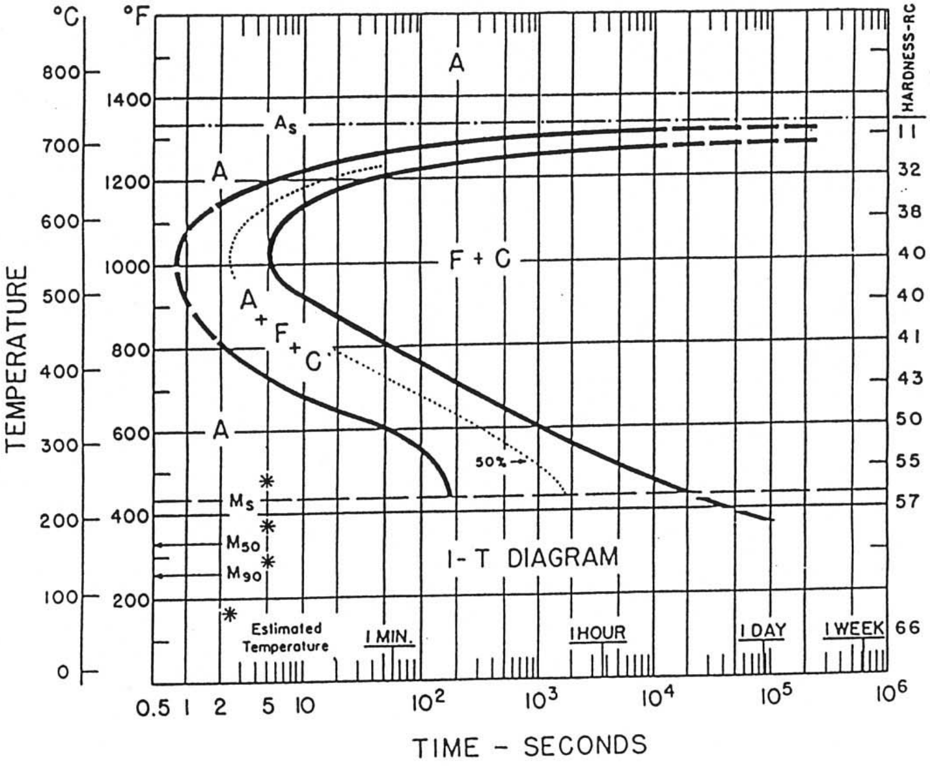
1080 Steel

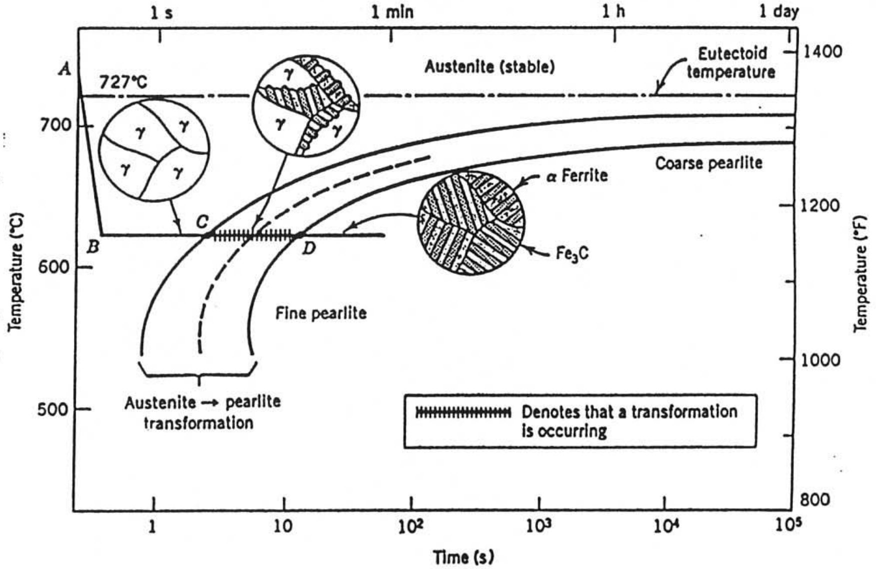
C-0.79
Mn-0.76

Carbon Steels: 1080

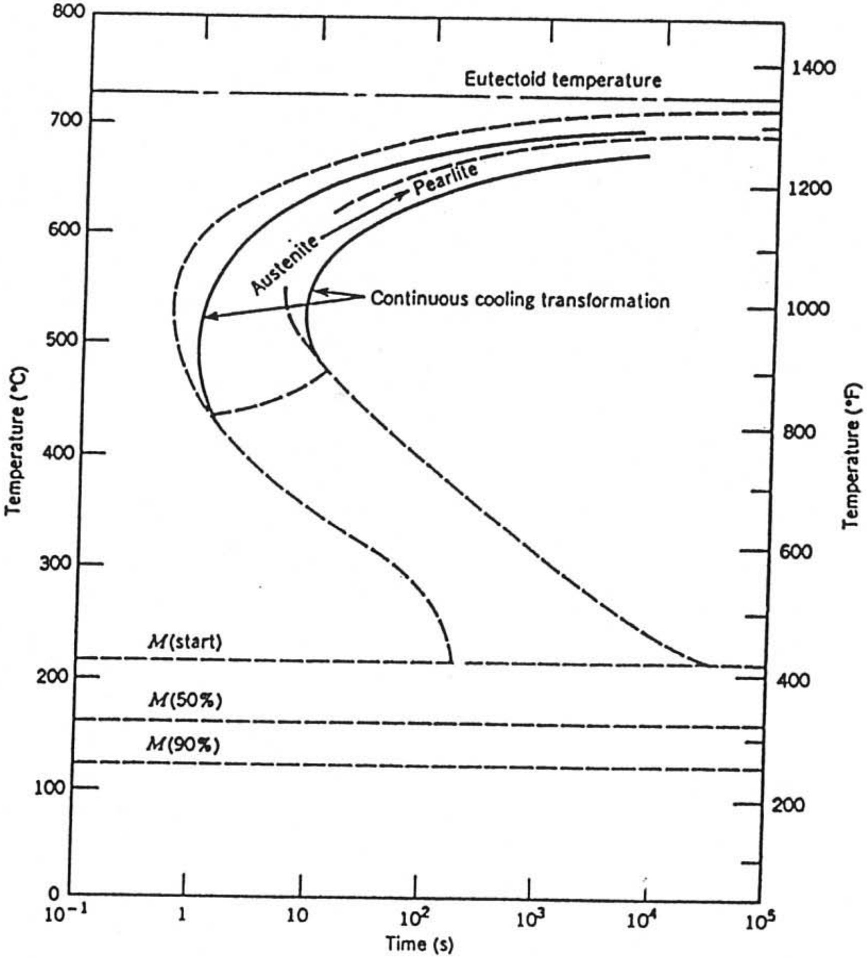
Austenitized at 1650°F

Grain Size: 6





Overlay of Isothermal and Continuous Cooling Transformation Diagrams for a Eutectoid Steel

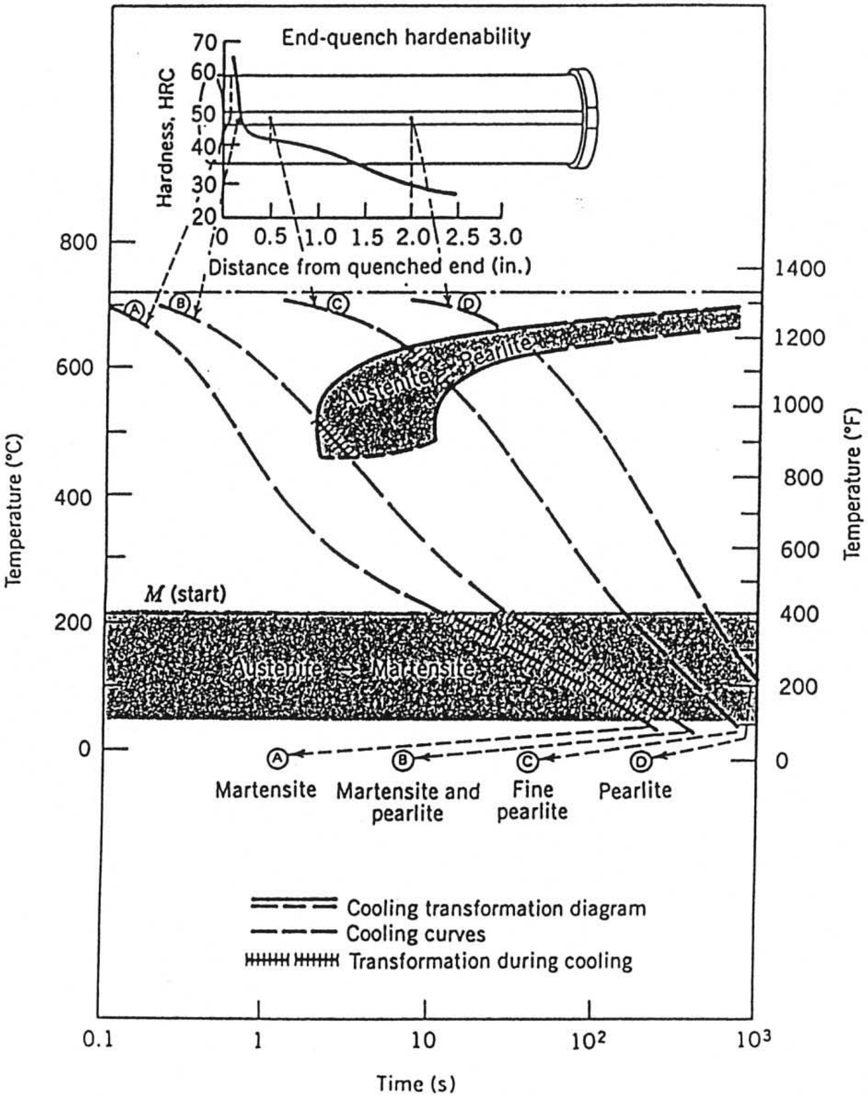


Hardness vs. Hardenability

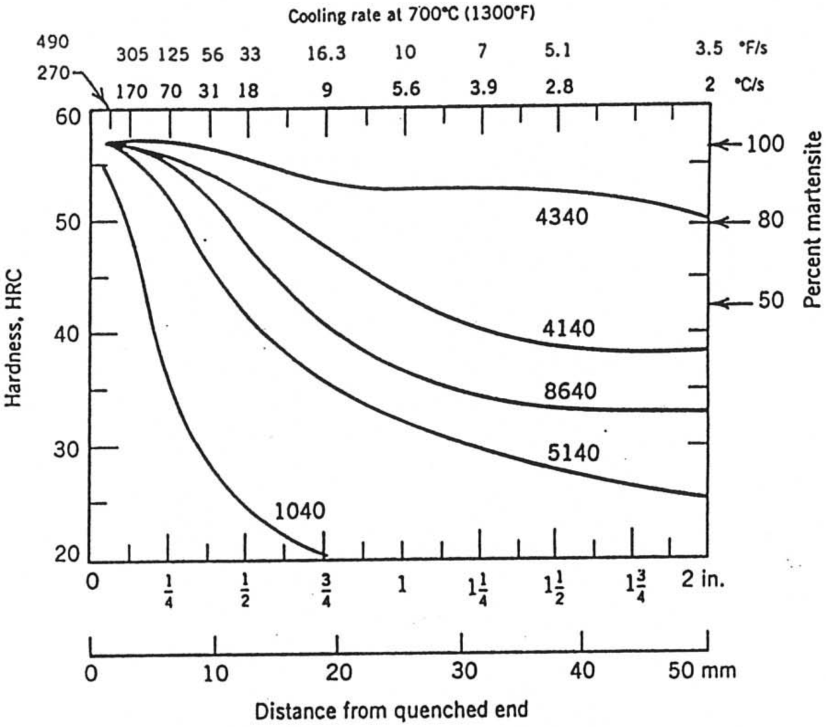
- Hardness is a measure of the strength of the material. It depends on the microstructure. In steels, the hardness of martensite is dependent on the carbon content. It does not change significantly with substitutional alloying elements but can be changed by other interstitial elements such as nitrogen.

- Hardenability is the ability to get hardness in depth in a material. For martensitic steels, this is a measure of the ability to transform austenite to martensite over a wide range of cooling rates. In steels, hardenability depends primarily on austenite substitutional alloying elements.

Hardenability

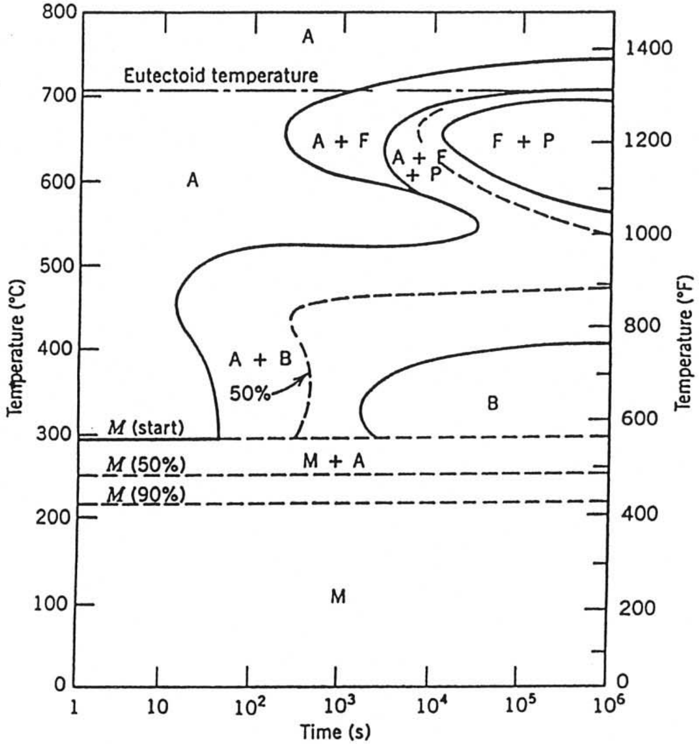


Correlation of hardenability and continuous cooling information for an iron–carbon alloy of eutectoid composition. (Adapted from H. Boyer, Editor, *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, American Society for Metals, 1977, p. 376.)

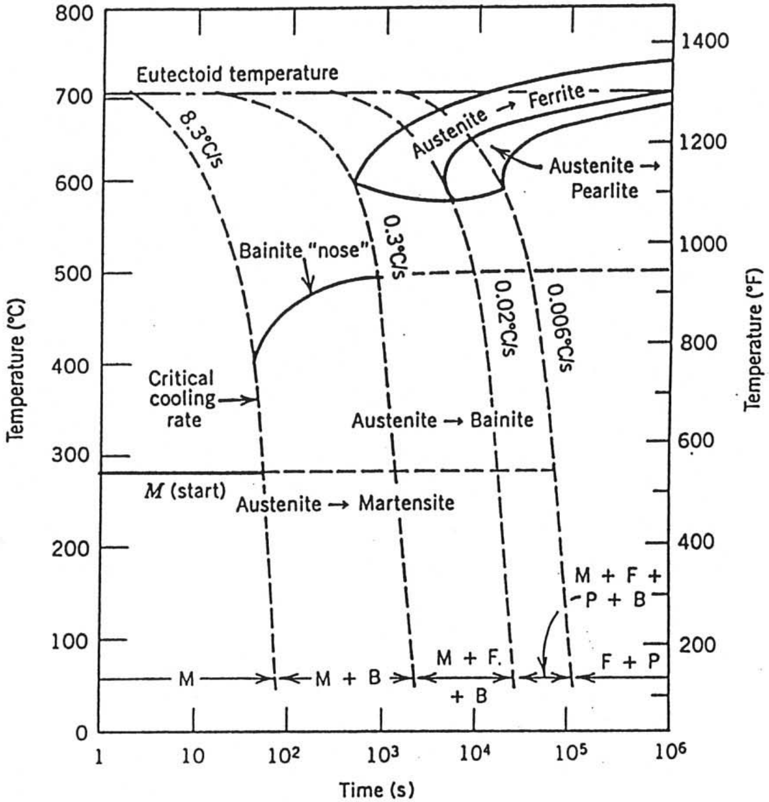


Hardenability curves for five different steel alloys, each containing 0.4 wt% C. Approximate alloy compositions (wt%) are as follows: 4340–1.85 Ni, 0.80 Cr, and 0.25 Mo; 4140–1.0 Cr and 0.20 Mo; 8640–0.55 Ni, 0.50 Cr, and 0.20 Mo; 5140–0.85 Cr; 1040 is an unalloyed steel. (Adapted from figure furnished courtesy Republic Steel Corporation.)

Isothermal and Continuous Cooling Transformation Diagrams - 4340 Steel

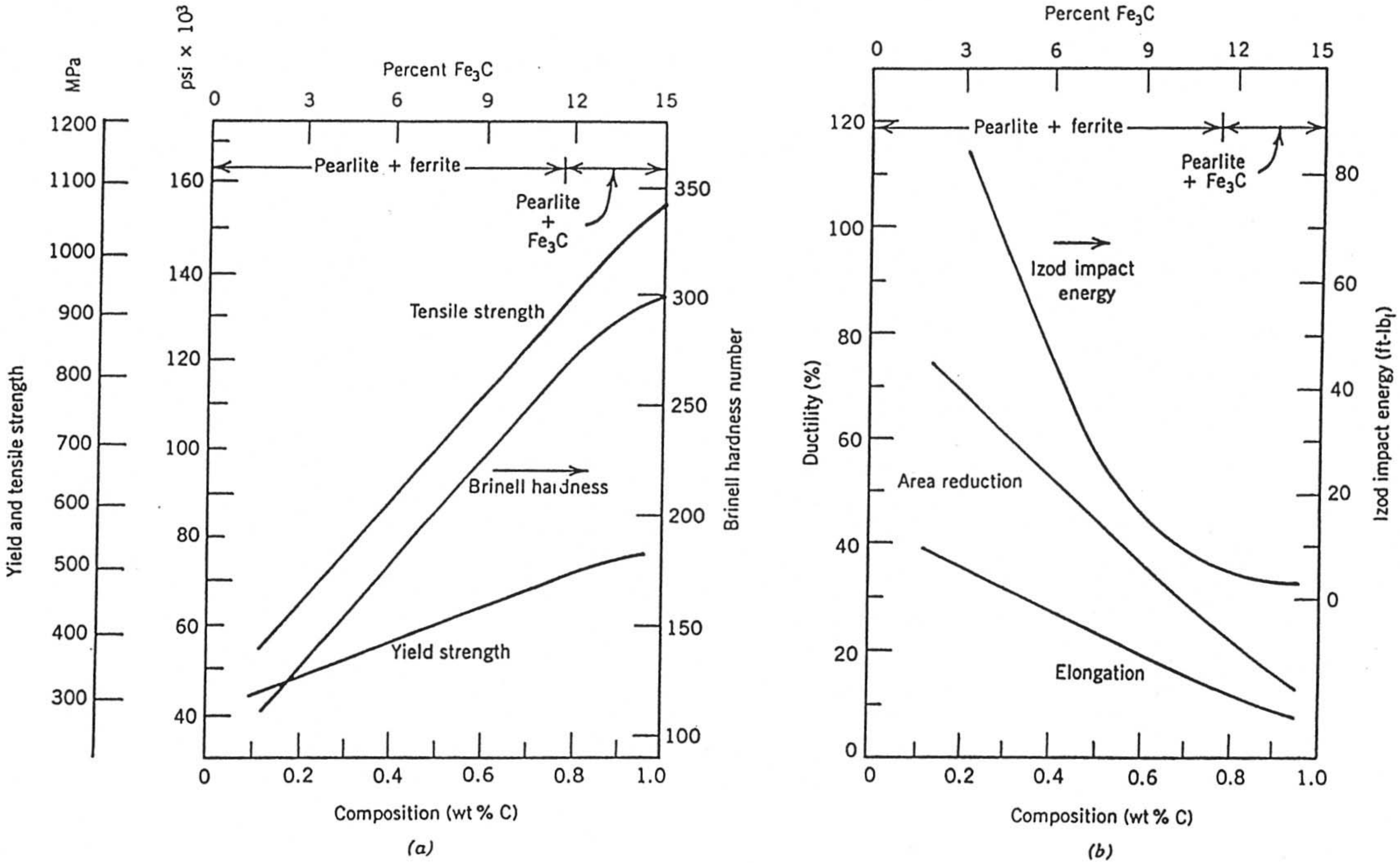


Isothermal transformation diagram for an alloy steel (type 4340)



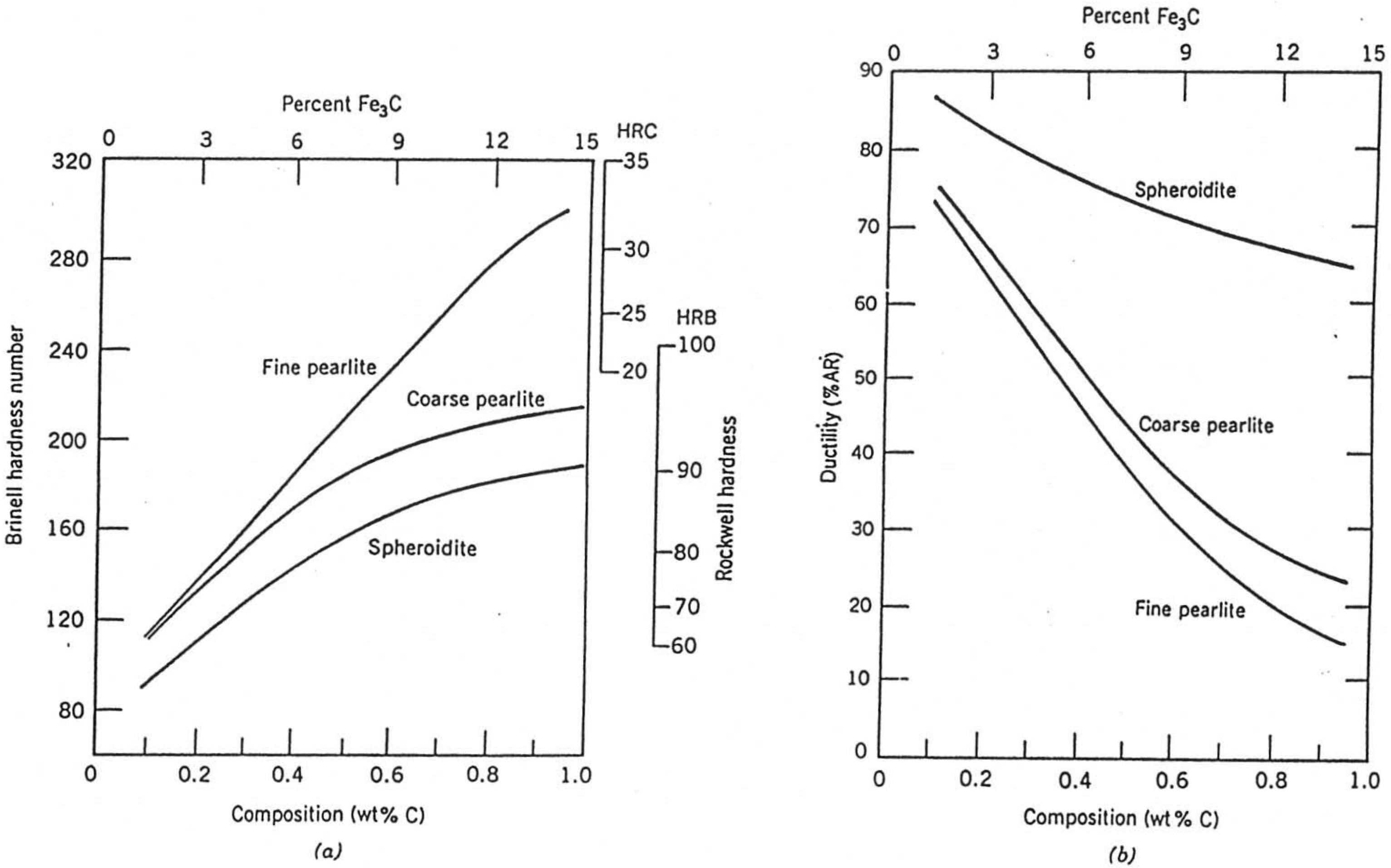
Continuous cooling transformation diagram for an alloy steel (type 4340)

Dependence of Properties on Microstructure



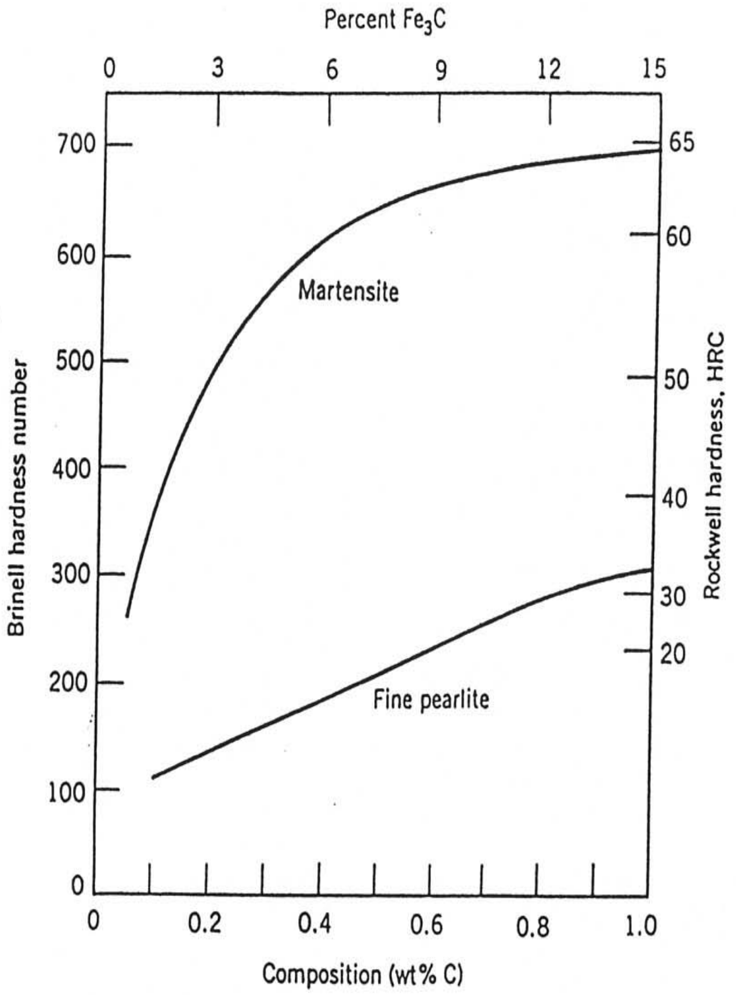
(*a*) Yield strength, tensile strength, and Brinell hardness versus carbon concentration for plain carbon steels having microstructures consisting of fine pearlite. (*b*) Ductility (%EL and %AR) and Izod impact energy versus carbon concentration for plain carbon steels having microstructures consisting of fine pearlite. (Data taken from *Metals Handbook: Heat Treating,* Vol. 4, 9th edition, V. Masseria, Managing Editor, American Society for Metals, 1981, p. 9.)

Dependence of Properties on Microstructure

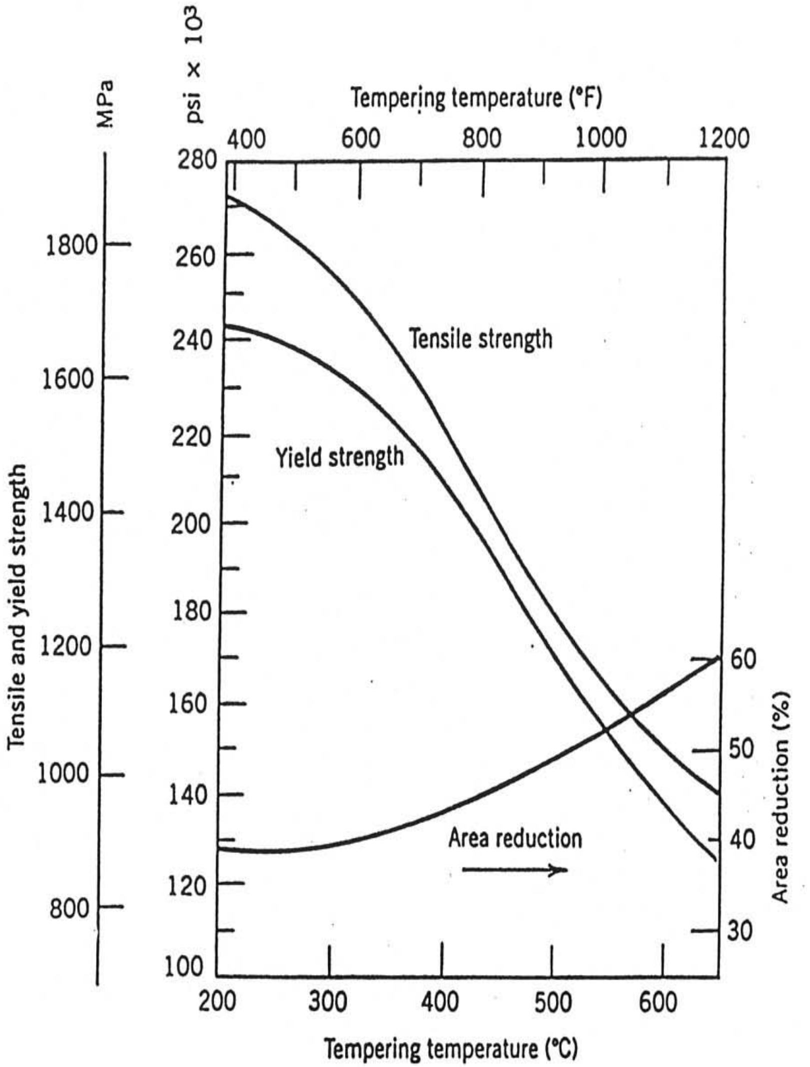


(*a*) Brinell and Rockwell hardness as a function of carbon concentration for plain carbon steels having fine and coarse pearlite as well as spheroidite microstructures. (*b*) Ductility (%AR) as a function of carbon concentration for plain carbon steels having fine and coarse pearlite as well as spheroidite microstructures. (Data taken from *Metals Handbook: Heat Treating,* Vol. 4, 9th edition, V. Masseria, Managing Editor, American Society for Metals, 1981, pp. 9 and 17.)

Dependence of Properties on Microstructure



Hardness as a function of carbon concentration for plain carbon martensitic and fine pearlitic steels. (Adapted from Dr. Edgar C. Bain, *Functions of the Alloying Elements in Steel*, American Society for Metals, 1939, p. 36.)



Tensile and yield strengths and ductility (%AR) versus tempering temperature for an oil-quenched alloy steel (type 4340). (Adapted from figure furnished courtesy Republic Steel Corporation.)

So:

How do you make a "Damascus" Sword?

The End