2019 Fall

Introduction to Materials Science and Engineering

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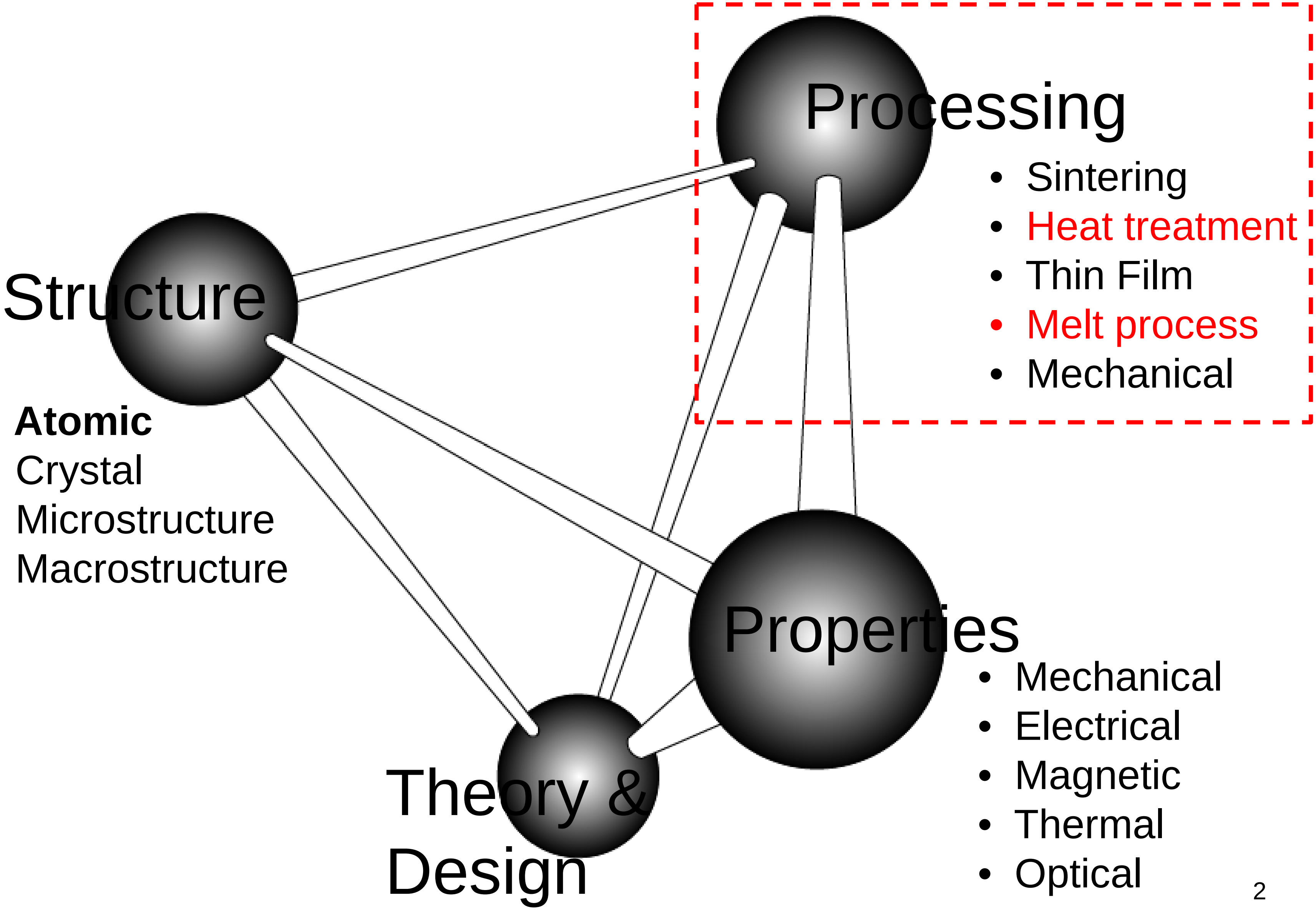
Materials Science and Engineering



Structure

- **Atomic**
- Crystal
- Microstructure
- Macrostructure

Processing

- Sintering
- Heat treatment
- Thin Film
- Melt process
- Mechanical

Properties

- Mechanical
- Electrical
- Magnetic
- Thermal
- Optical

Theory & Design

*** Contents for previous class: 철-탄소 합금에서 미세조직과 특성의 변화**

Transformations & Undercooling

- Eutectoid transf. (Fe-Fe_3C system): $\gamma \Rightarrow \alpha + Fe_3C$
- For transf. to occur, must cool to below 727° C (i.e., must "undercool")

0.76 wt% C

0.022 wt% C

6.7 wt% C

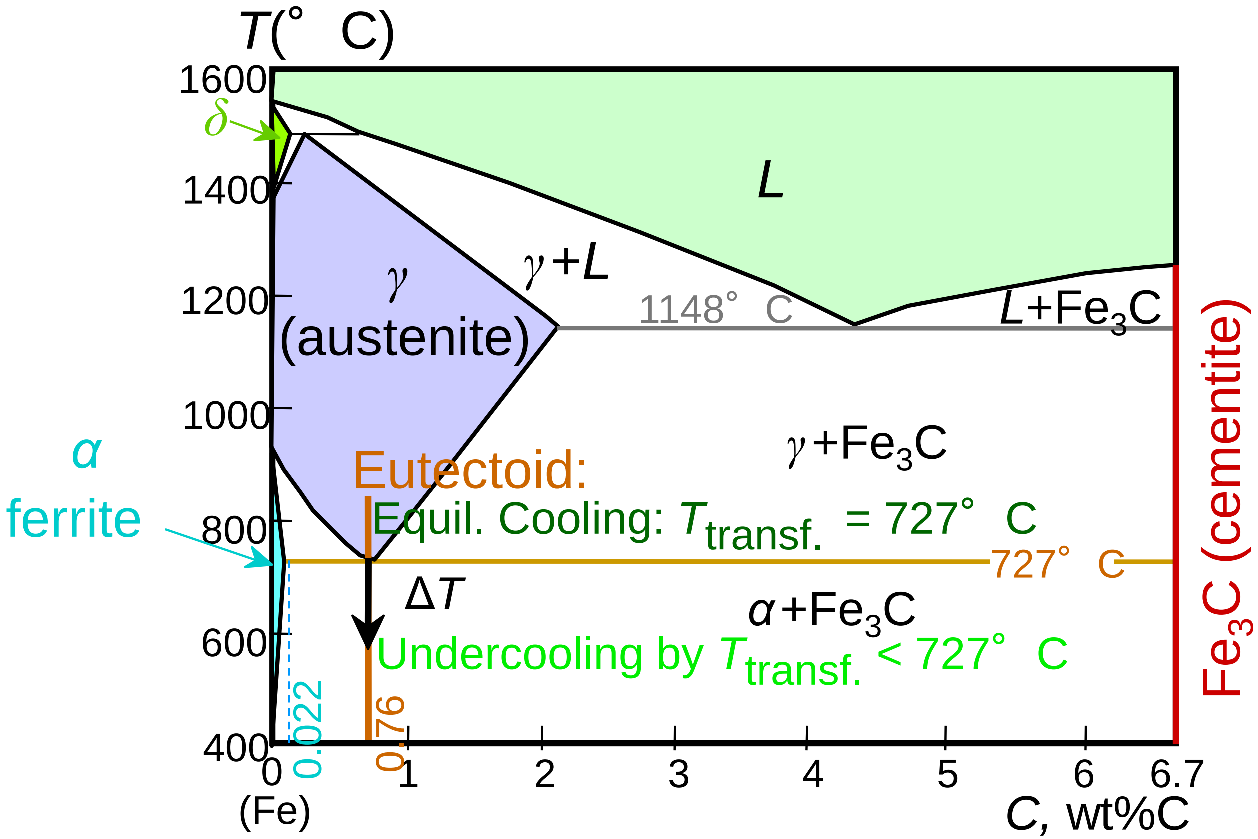
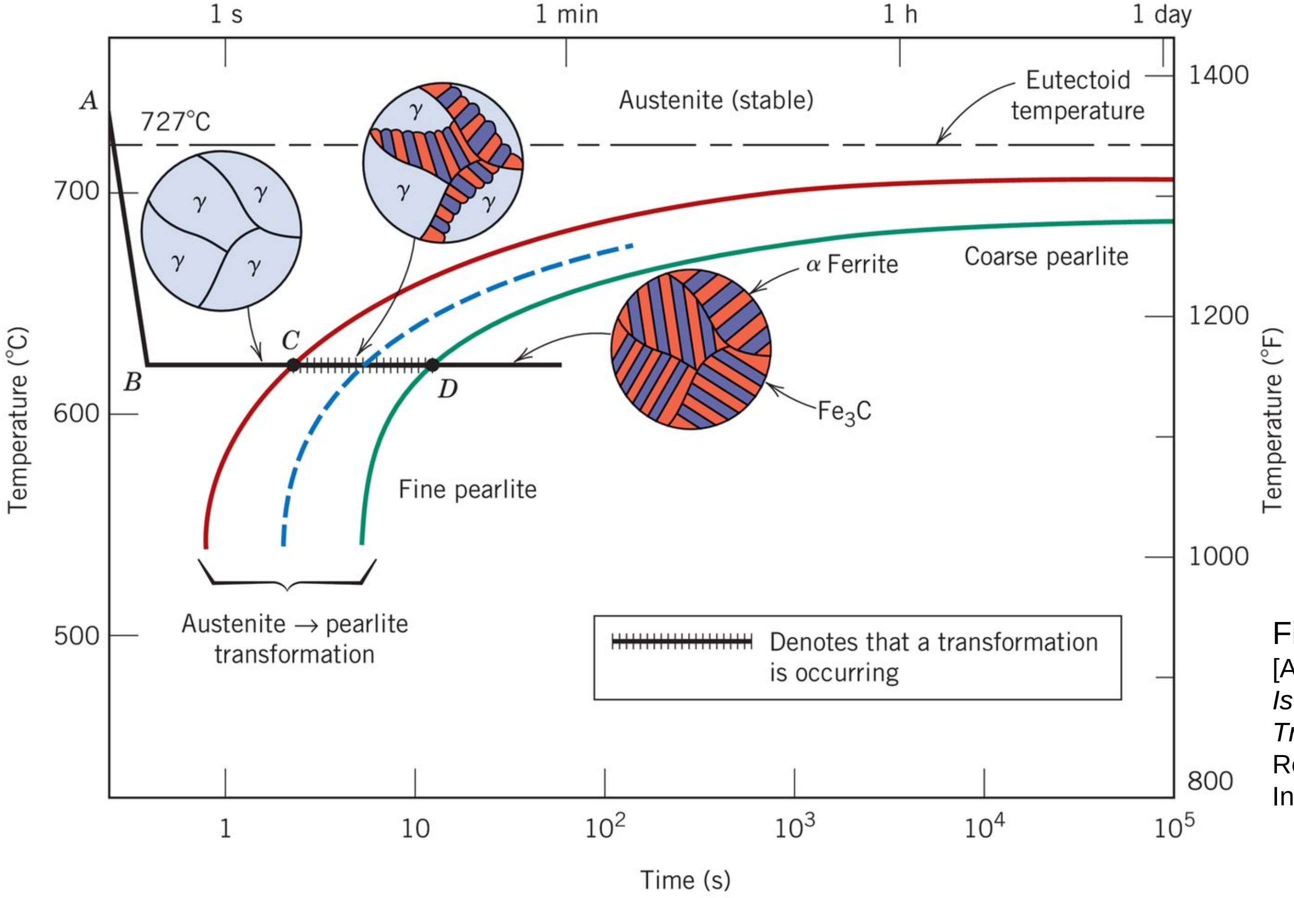


Fig. 11.23, Callister & Rethwisch 9e.

[Adapted from Binary Alloy Phase Diagrams, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

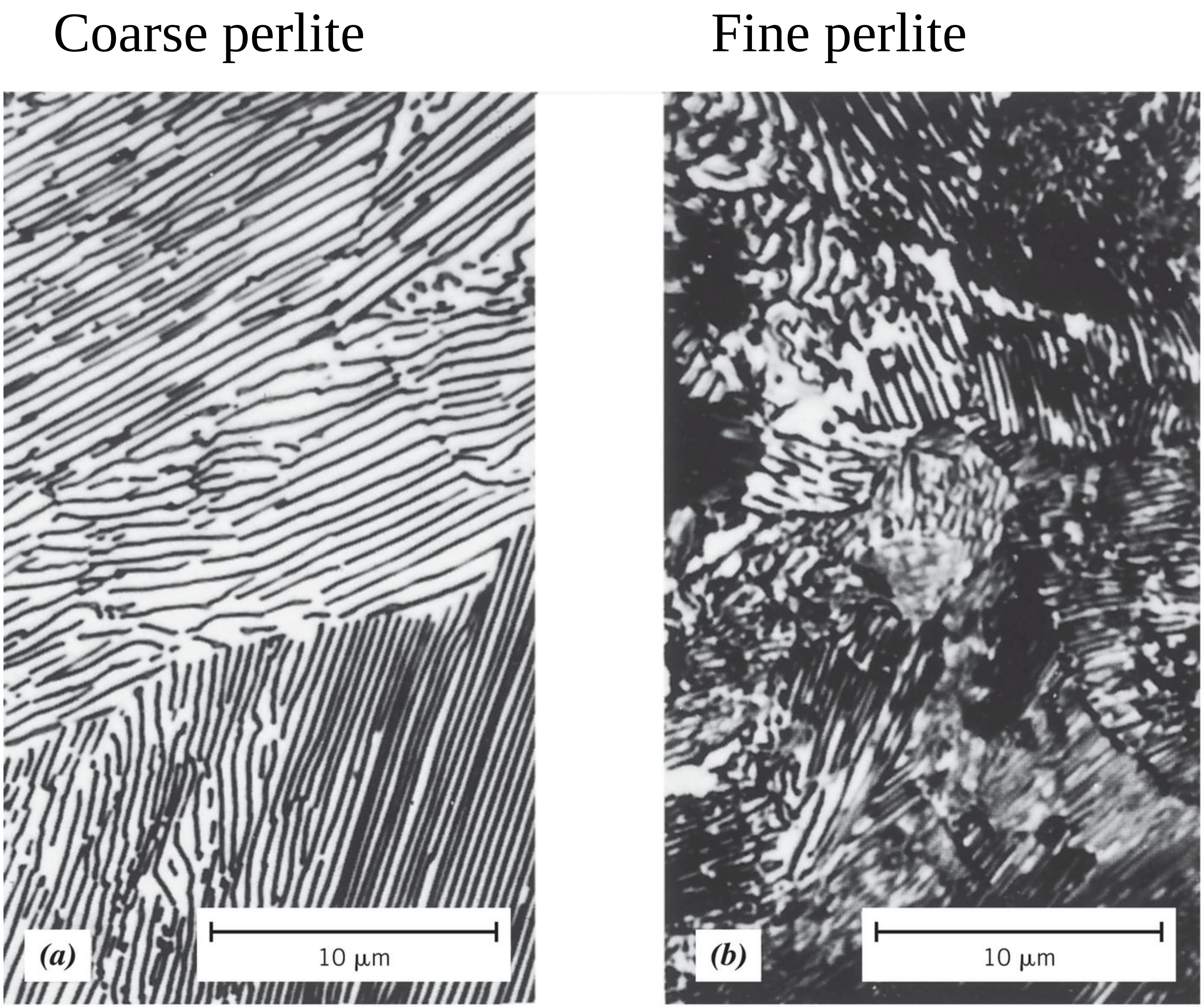
Austenite-to-Pearlite Isothermal Transformation

- Eutectoid composition, C_0 = 0.76 wt% C
- Begin at T > 727° C
- Rapidly cool to 625° C
- Hold T (625° C) constant (isothermal treatment)



Adapted from H. Boyer (Editor), Atlas of Isothermal Transformation and Cooling Transformation Diagrams, 1977. Reproduced by permission of ASM International, Materials Park, OH.

Fig. 12.14, *Callister & Rethwisch 9e.*
[Adapted from H. Boyer (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, 1977. Reproduced by permission of ASM International, Materials Park, OH.]



Coarse perlite

Fine perlite

From K. M. Ralls et al., An Introduction to Materials Science and Engineering, p. 361. Copyright © 1976 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

Transformations Involving noneutectoid compositions

Consider C_0 = 1.13 wt% C

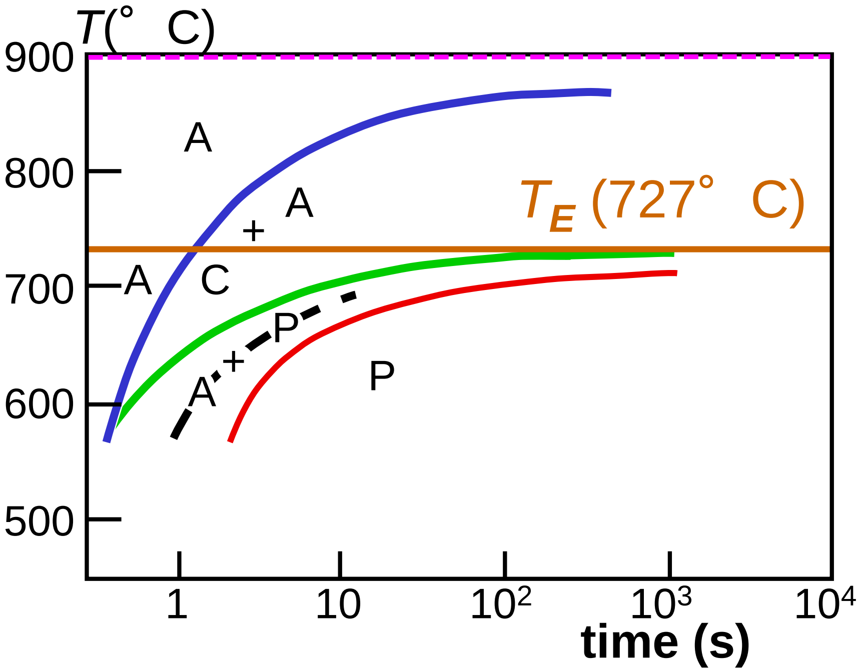


Fig. 12.16, *Callister & Rethwisch 9e.*
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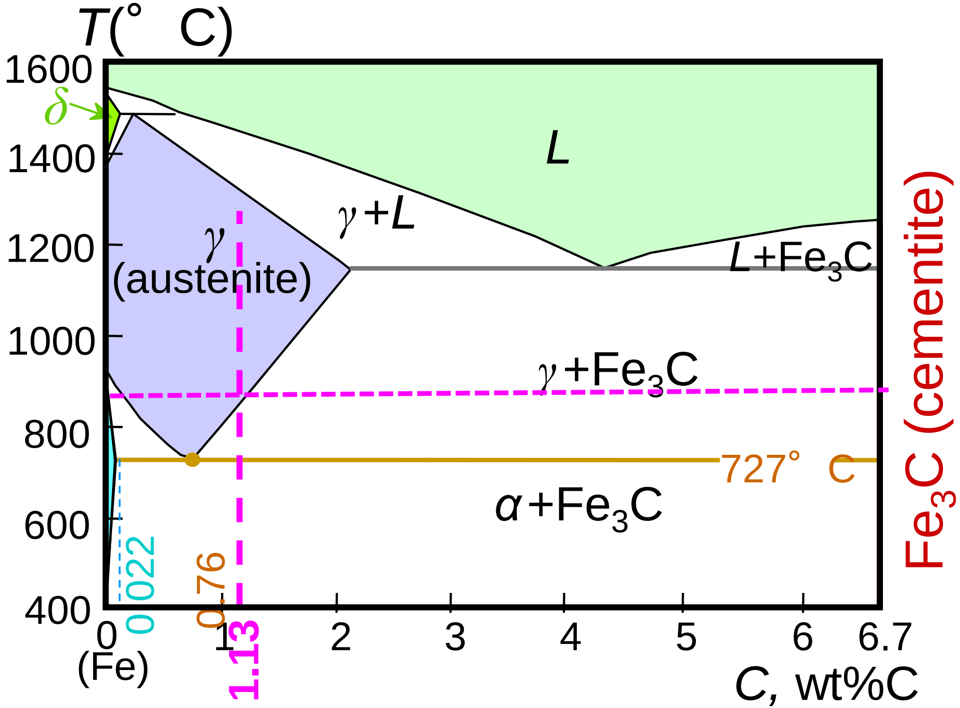


Fig. 11.23, Callister & Rethwisch 9e.
[Adapted from *Binary Alloy Phase Diagrams*, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

Hypereutectoid composition – proeutectoid cementite

Bainite: Another Fe-Fe_3C Transformation Product

- Bainite:
  - -- elongated Fe_3C particles in α-ferrite matrix
  - -- diffusion controlled
- Isothermal Transf. Diagram, C_0 = 0.76 wt% C

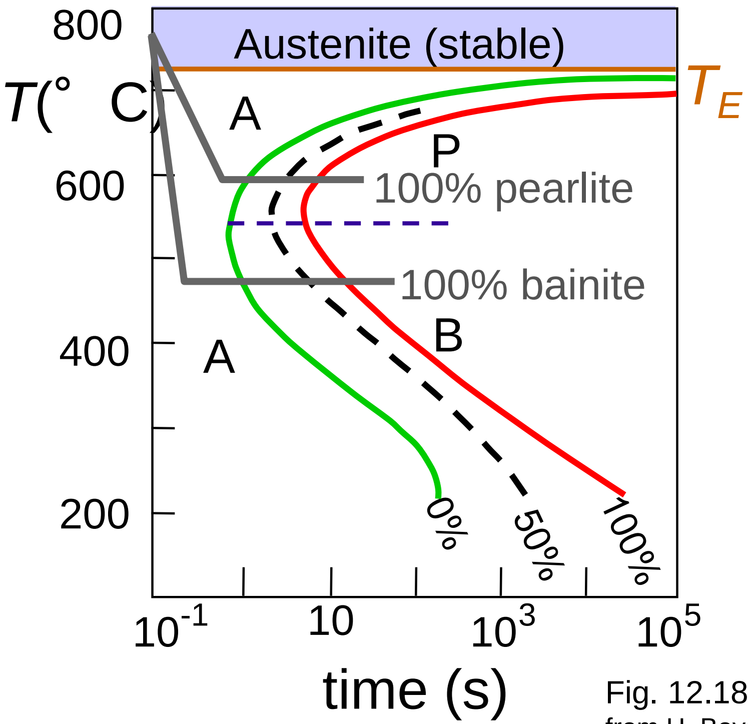


Fig. 12.18, *Callister & Rethwisch 9e.* [Adapted from H. Boyer (Editor), *Atlas of Isothermal Transformation and Cooling Transformation Diagrams*, 1977. Reproduced by permission of ASM International, Materials Park, OH.]

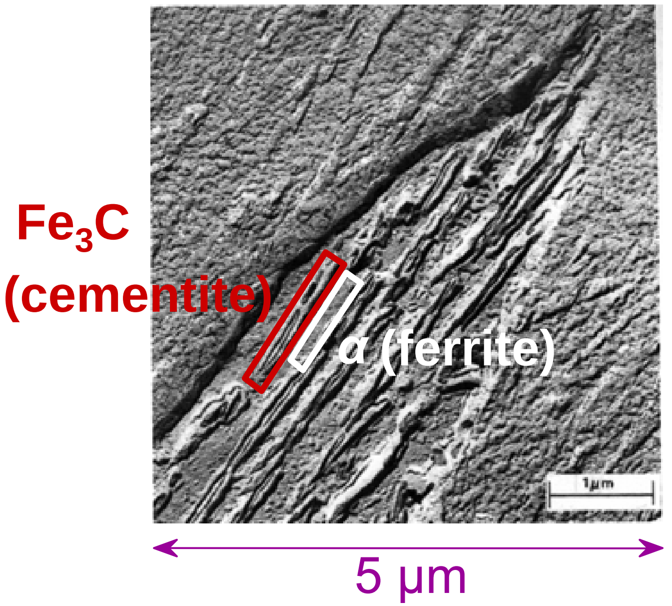


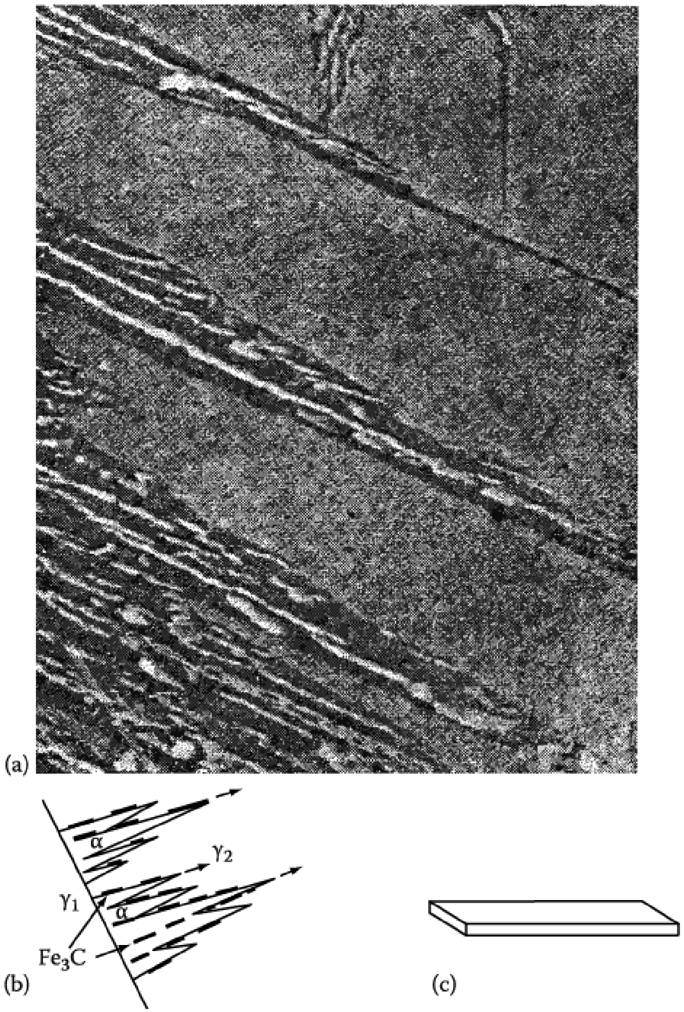
Fig. 12.17, *Callister & Rethwisch 9e.* (From *Metals Handbook*, Vol. 8, 8th edition, *Metallography, Structures and Phase Diagrams*, 1973. Reproduced by permission of ASM International, Materials Park, OH.)

5.8.2 Bainite Transformation

The microstructure of bainite depends mainly on the temperature at which it forms.

Upper Banite in medium-carbon steel

At high temp. 350 ~ 550°C, ferrite laths, K-S relationship, similar to Widmanstäten plates

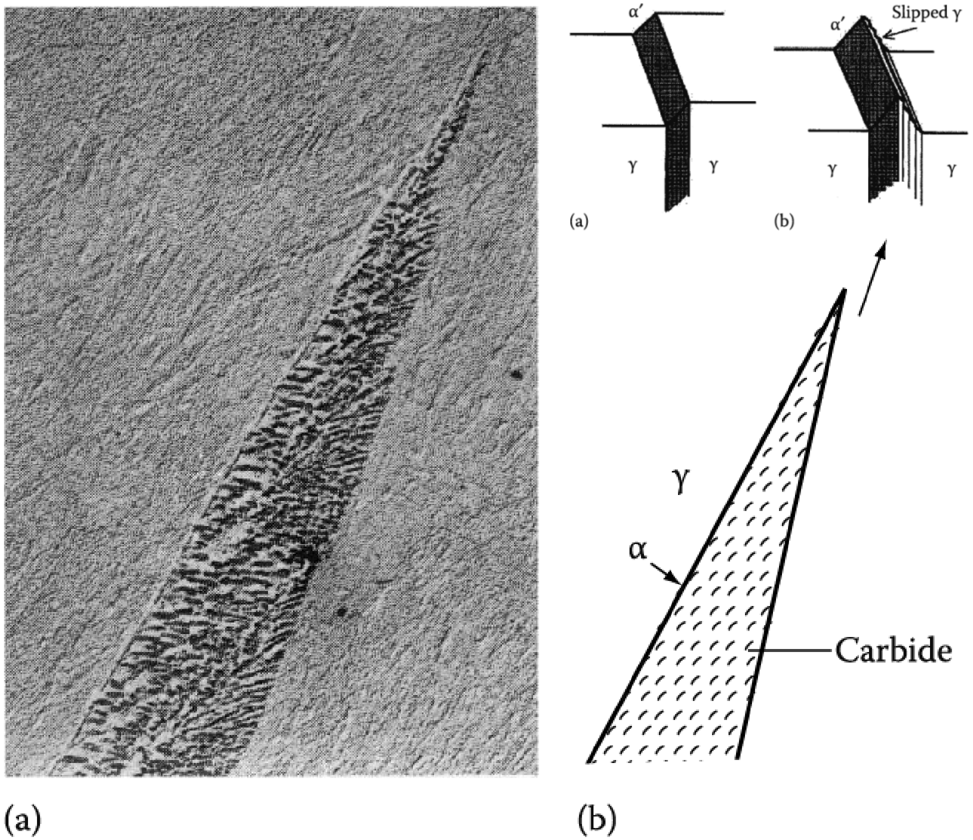


(b) Schematic of growth mechanism. Widmanstatten ferrite laths growth into γ_2. Cementite plates nucleate in carbon-enriched austenite.

Lower Bainite in 0.69wt% C low-alloy steel

At sufficiently low temp. laths → plates

Carbide dispersion becomes much finer, rather like in tempered M.

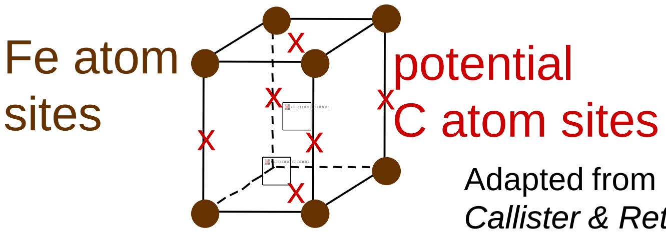


Surface tilts by bainite trans. like M trans.
Due to Shear mechanism/ordered military manner

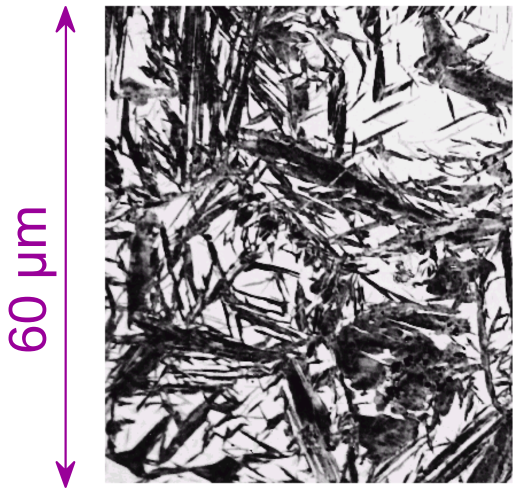
(b) A possible growth mechanism. α/γ interface advances as fast as carbides precipitate at interface thereby removing the excess carbon in front of the α.

Martensite: A Nonequilibrium Transformation Product

- Martensite:
  -- γ(FCC) to Martensite (BCT)



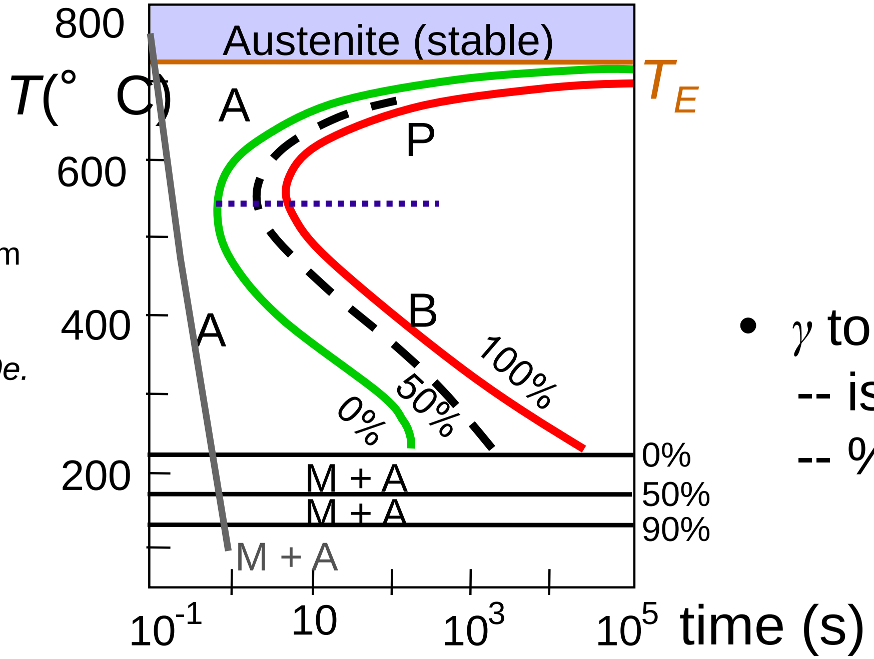
Adapted from Fig. 12.20, *Callister & Rethwisch 9e.*



▬ Martensite needles
▬ Austenite

Fig. 12.21, *Callister & Rethwisch 9e.*
(Courtesy United States Steel Corporation.)

- Isothermal Transf. Diagram



Adapted from Fig. 12.22, *Callister & Rethwisch 9e.*

- γ to martensite (M) transformation.
  -- is rapid! (diffusionless)
  -- % transformation depends only on T to which rapidly cooled

Tempered Martensite

Heat treat martensite to form tempered martensite

- tempered martensite less brittle than martensite
- tempering reduces internal stresses caused by quenching

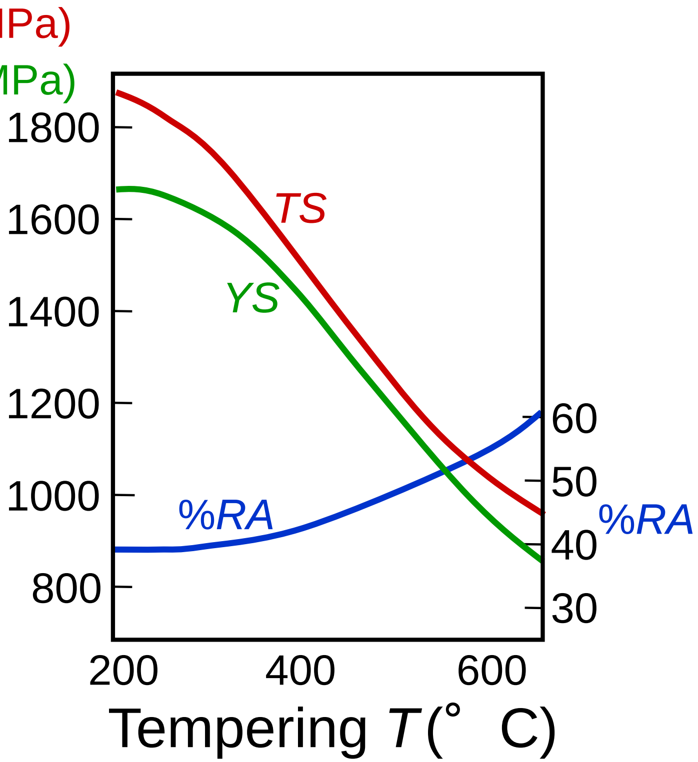


Fig. 12.34, *Callister & Rethwisch 9e.* (Adapted from Edgar C. Bain, *Functions of the Alloying Elements in Steel*, 1939. Reproduced by permission of ASM International, Materials Park, OH.)

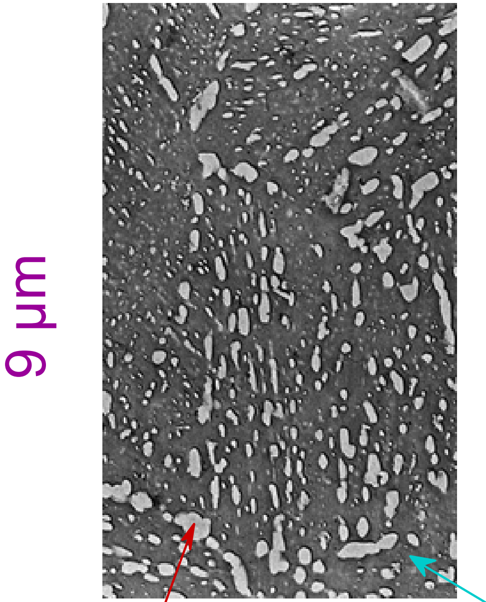
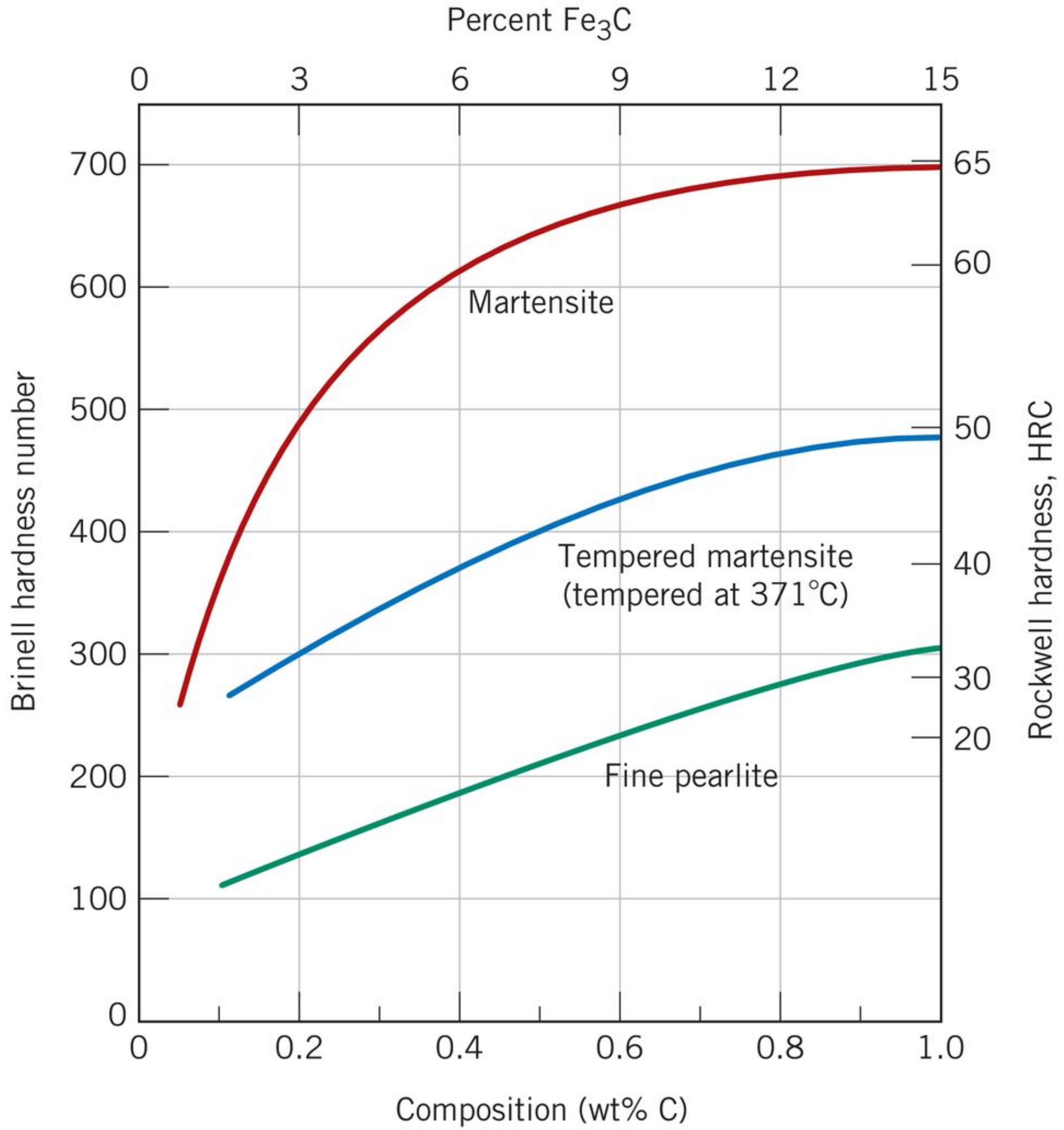


Figure 12.33, *Callister & Rethwisch 9e.* (Copyright 1971 by United States Steel Corporation.)

- tempering produces extremely small Fe_3C particles surrounded by α.
- **tempering decreases *TS*, *YS* but increases %RA**

그림 12.32

순 탄소 마텐자이트강, 템퍼링된 마텐자이트강 [371°C 템버링], 펄라이트 강의 탄소농도에 따른 상온 경도값



Adapted from Edgar C. Bain, Functions of the Alloying Elements in Steel, 1939; and R. A. Grange, C. R. Hribal, and L. F. Porter, Metall. Trans. A, Vol. 8A. Reproduced by permission of ASM International, Materials Park, OH.

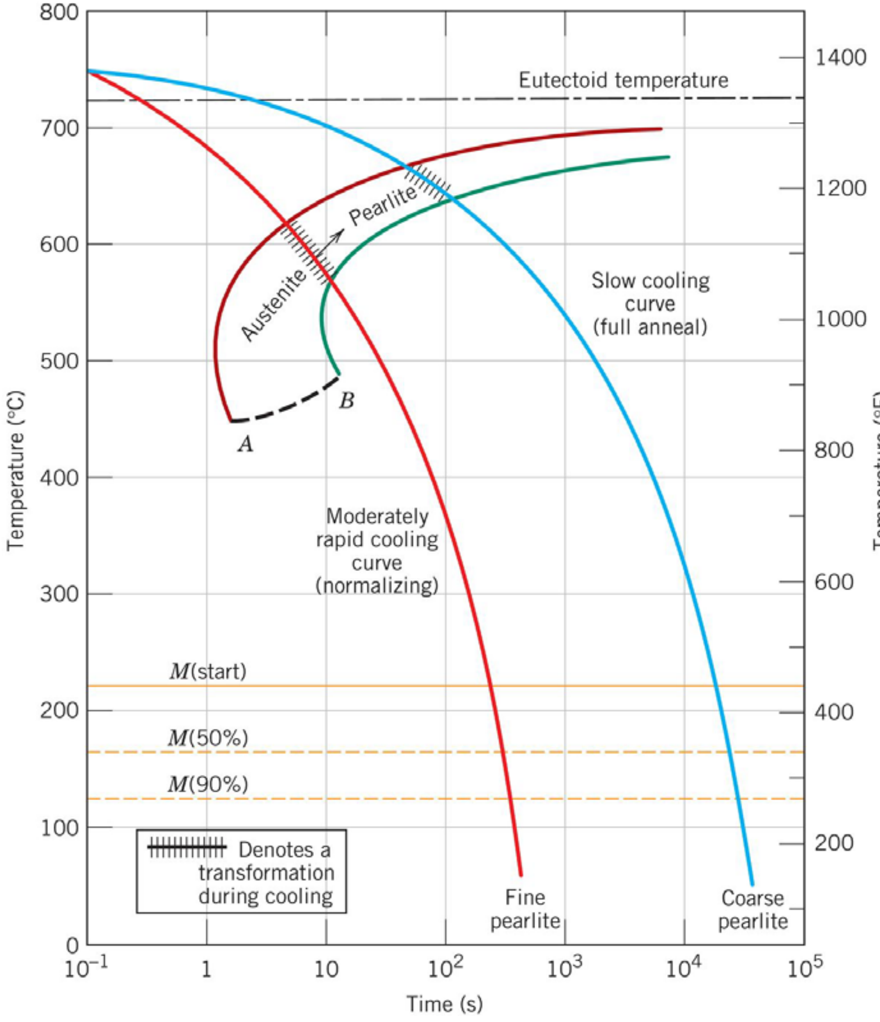


그림 12.26 공석 조성을 갖는 철-탄소 합금의 연속 냉각 변태도 위에 그려진 적당한 급랭과 서냉온도 곡선

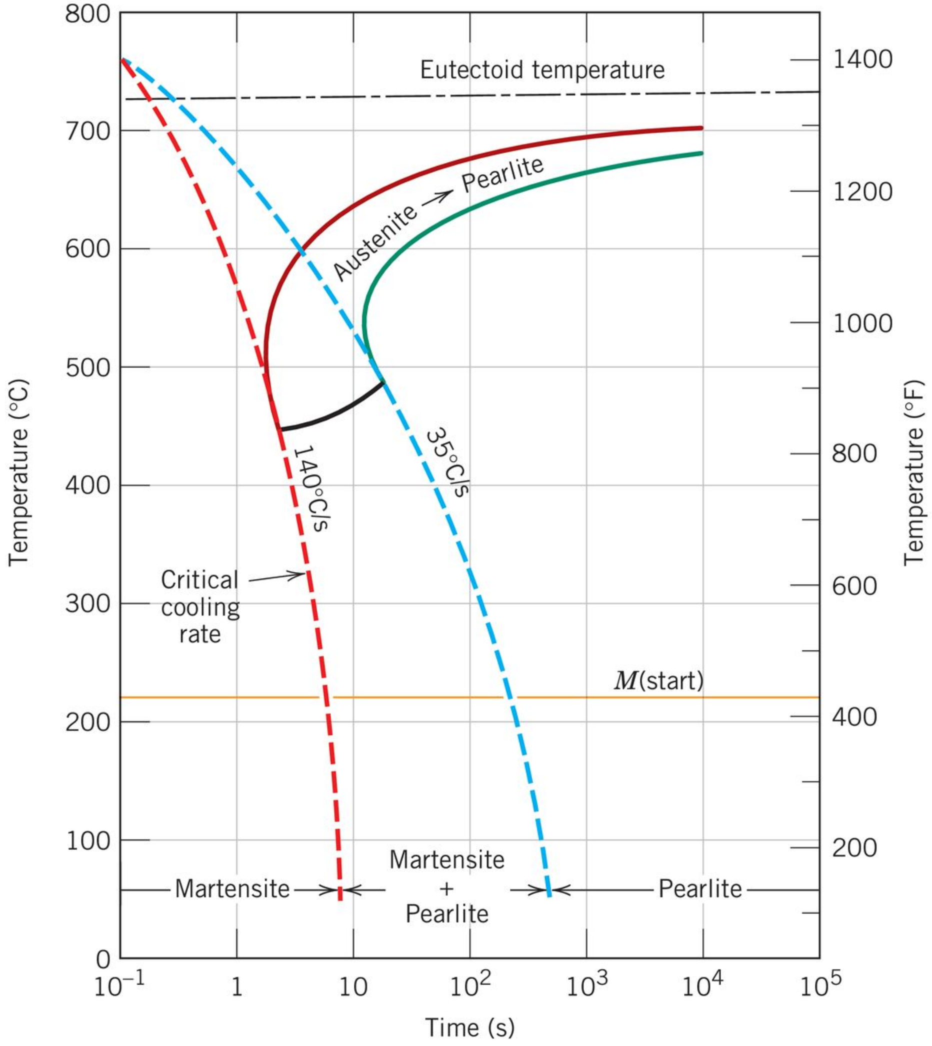
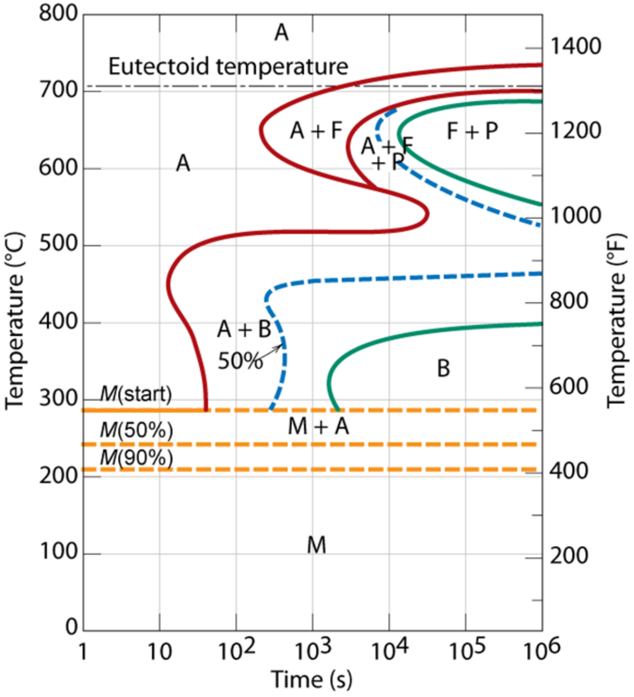
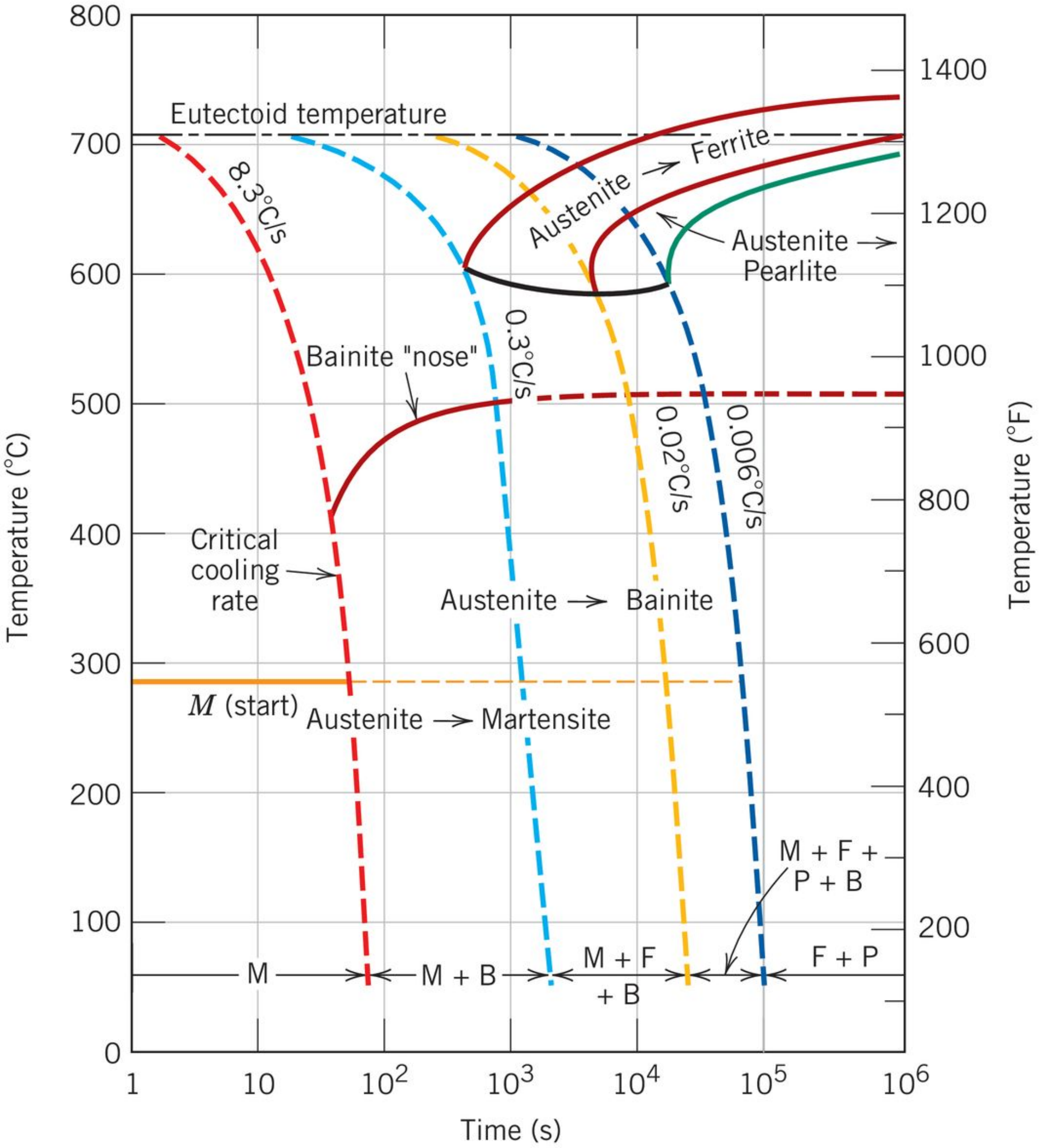


그림 12.27 공석 조성의 철-탄소 합금의 연속 냉각 변태도와 냉각 곡선. 냉각 중에 일어나는 변태에 따른 최종 미세조직 변화를 볼 수 있다.

그림 12.27

4030 합금강의 연속 냉각 변태도와 여러 조건의 냉각 곡선. 냉각 중에 일어나는 변태에 따른 최종 미세조직의 변화를 볼 수 있다.

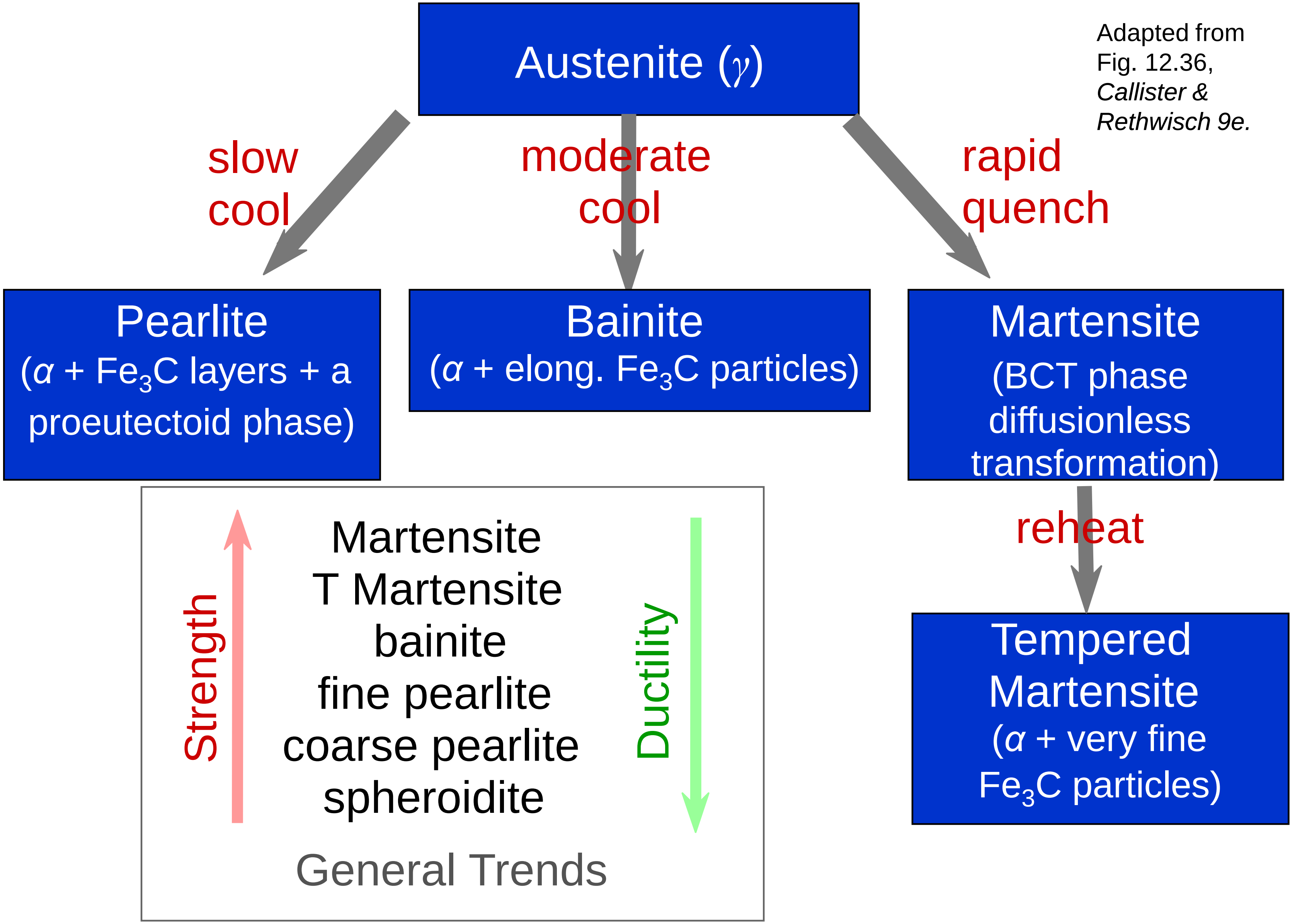




Adapted from H. E. McGannon (Editor), The Making, Shaping and Treating of Steel, 9th edition, United States Steel Corporation, Pittsburgh, 1971, p. 1096.

Summary of Possible Transformations in Fe-C binary phase diagram

Adapted from Fig. 12.36, *Callister & Rethwisch 9e.*



Austenite (γ)

slow cool

moderate cool

rapid quench

Pearlite
(α + Fe_3C layers + a proeutectoid phase)

Bainite
(α + elong. Fe_3C particles)

Martensite
(BCT phase diffusionless transformation)

reheat

Tempered Martensite
(α + very fine Fe_3C particles)

Strength

Martensite
T Martensite
bainite
fine pearlite
coarse pearlite
spheroidite

Ductility

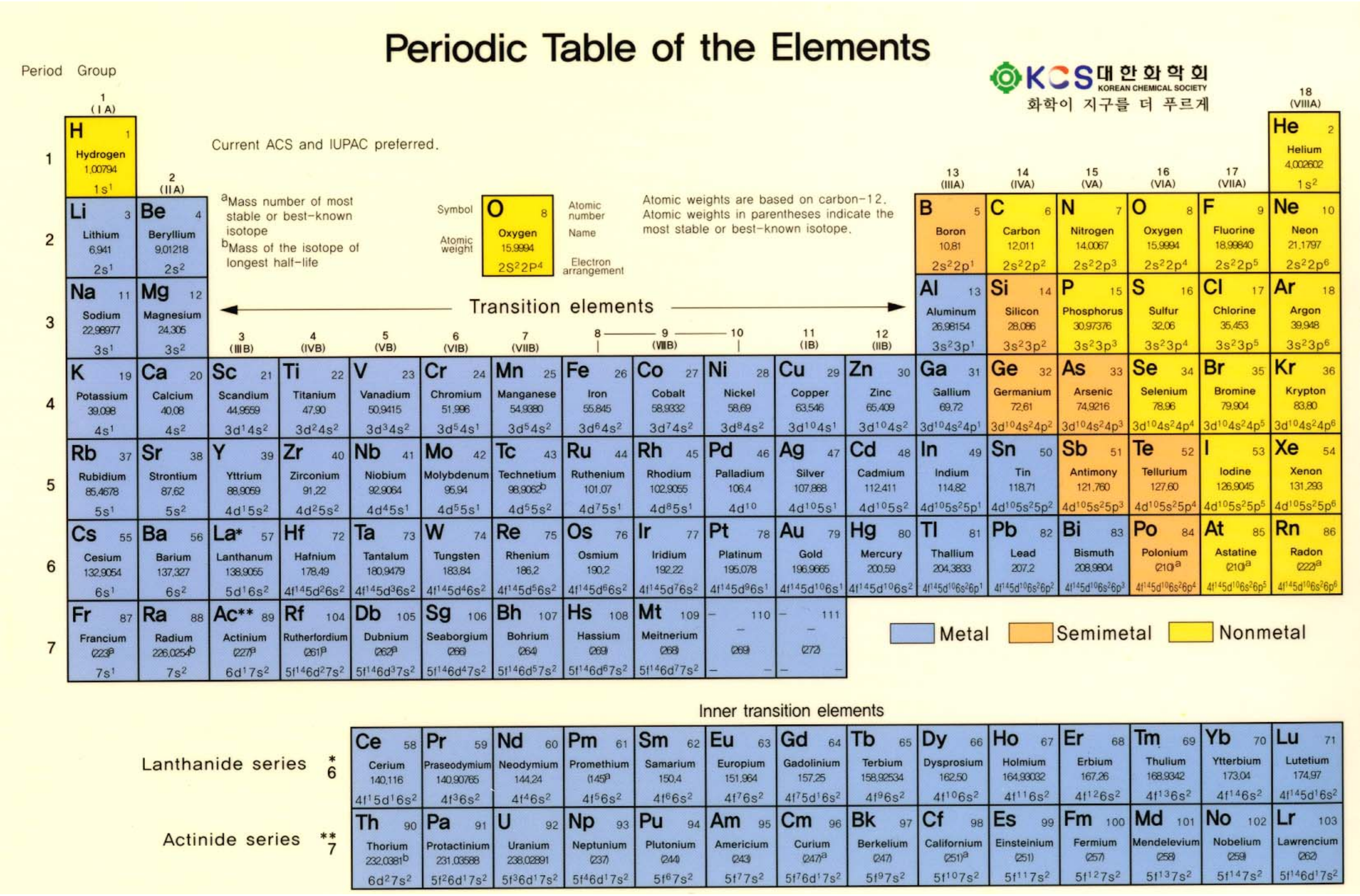
General Trends

Chapter 13:
Properties and Applications of Metals

ISSUES TO ADDRESS...

- How are metal alloys classified and what are their common applications?
- What are the microstructure and general characteristics of cast irons?
- What are the distinctive physical and mechanical properties of nonferrous alloys?

Materials Design-for-Properties : "Alloyed Pleasure"



Periodic Table of the Elements

KCS 대한화학회
KOREAN CHEMICAL SOCIETY
화학이 지구를 더 푸르게

Current ACS and IUPAC preferred.

[a] Mass number of most stable or best-known isotope
[b] Mass of the isotope of longest half-life

Symbol: O; Atomic number: 8; Name: Oxygen; Atomic weight: 15.9994; Electron arrangement: $2S^22P^4$

Atomic weights are based on carbon-12. Atomic weights in parentheses indicate the most stable or best-known isotope.

Transition elements

Period	1 (IA)	2 (IIA)	3 (IIIB)	4 (IVB)	5 (VB)	6 (VIB)	7 (VIIB)	8	9 (VIIIB)	10	11 (IB)	12 (IIB)	13 (IIIA)	14 (IVA)	15 (VA)	16 (VIA)	17 (VIIA)	18 (VIIIA)
1	**H** 1 Hydrogen 1.00794 $1s^1$																	**He** 2 Helium 4.002602 $1s^2$
2	**Li** 3 Lithium 6.941 $2s^1$	**Be** 4 Beryllium 9.01218 $2s^2$											**B** 5 Boron 10.81 $2s^22p^1$	**C** 6 Carbon 12.011 $2s^22p^2$	**N** 7 Nitrogen 14.0067 $2s^22p^3$	**O** 8 Oxygen 15.9994 $2s^22p^4$	**F** 9 Fluorine 18.99840 $2s^22p^5$	**Ne** 10 Neon 21.1797 $2s^22p^6$
3	**Na** 11 Sodium 22.98977 $3s^1$	**Mg** 12 Magnesium 24.305 $3s^2$											**Al** 13 Aluminum 26.98154 $3s^23p^1$	**Si** 14 Silicon 28.086 $3s^23p^2$	**P** 15 Phosphorus 30.97376 $3s^23p^3$	**S** 16 Sulfur 32.06 $3s^23p^4$	**Cl** 17 Chlorine 35.453 $3s^23p^5$	**Ar** 18 Argon 39.948 $3s^23p^6$
4	**K** 19 Potassium 39.098 $4s^1$	**Ca** 20 Calcium 40.08 $4s^2$	**Sc** 21 Scandium 44.9559 $3d^14s^2$	**Ti** 22 Titanium 47.90 $3d^24s^2$	**V** 23 Vanadium 50.9415 $3d^34s^2$	**Cr** 24 Chromium 51.996 $3d^54s^1$	**Mn** 25 Manganese 54.9380 $3d^54s^2$	**Fe** 26 Iron 55.845 $3d^64s^2$	**Co** 27 Cobalt 58.9332 $3d^74s^2$	**Ni** 28 Nickel 58.69 $3d^84s^2$	**Cu** 29 Copper 63.546 $3d^{10}4s^1$	**Zn** 30 Zinc 65.409 $3d^{10}4s^2$	**Ga** 31 Gallium 69.72 $3d^{10}4s^24p^1$	**Ge** 32 Germanium 72.61 $3d^{10}4s^24p^2$	**As** 33 Arsenic 74.9216 $3d^{10}4s^24p^3$	**Se** 34 Selenium 78.96 $3d^{10}4s^24p^4$	**Br** 35 Bromine 79.904 $3d^{10}4s^24p^5$	**Kr** 36 Krypton 83.80 $3d^{10}4s^24p^6$
5	**Rb** 37 Rubidium 85.4678 $5s^1$	**Sr** 38 Strontium 87.62 $5s^2$	**Y** 39 Yttrium 88.9059 $4d^15s^2$	**Zr** 40 Zirconium 91.22 $4d^25s^2$	**Nb** 41 Niobium 92.9064 $4d^45s^1$	**Mo** 42 Molybdenum 95.94 $4d^55s^1$	**Tc** 43 Technetium 98.9062[b] $4d^55s^2$	**Ru** 44 Ruthenium 101.07 $4d^75s^1$	**Rh** 45 Rhodium 102.9055 $4d^85s^1$	**Pd** 46 Palladium 106.4 $4d^{10}$	**Ag** 47 Silver 107.868 $4d^{10}5s^1$	**Cd** 48 Cadmium 112.411 $4d^{10}5s^2$	**In** 49 Indium 114.82 $4d^{10}5s^25p^1$	**Sn** 50 Tin 118.71 $4d^{10}5s^25p^2$	**Sb** 51 Antimony 121.760 $4d^{10}5s^25p^3$	**Te** 52 Tellurium 127.60 $4d^{10}5s^25p^4$	**I** 53 Iodine 126.9045 $4d^{10}5s^25p^5$	**Xe** 54 Xenon 131.293 $4d^{10}5s^25p^6$
6	**Cs** 55 Cesium 132.9054 $6s^1$	**Ba** 56 Barium 137.327 $6s^2$	**La*** 57 Lanthanum 138.9055 $5d^16s^2$	**Hf** 72 Hafnium 178.49 $4f^{14}5d^26s^2$	**Ta** 73 Tantalum 180.9479 $4f^{14}5d^36s^2$	**W** 74 Tungsten 183.84 $4f^{14}5d^46s^2$	**Re** 75 Rhenium 186.2 $4f^{14}5d^56s^2$	**Os** 76 Osmium 190.2 $4f^{14}5d^66s^2$	**Ir** 77 Iridium 192.22 $4f^{14}5d^76s^2$	**Pt** 78 Platinum 195.078 $4f^{14}5d^96s^1$	**Au** 79 Gold 196.9665 $4f^{14}5d^{10}6s^1$	**Hg** 80 Mercury 200.59 $4f^{14}5d^{10}6s^2$	**Tl** 81 Thallium 204.3833 $4f^{14}5d^{10}6s^26p^1$	**Pb** 82 Lead 207.2 $4f^{14}5d^{10}6s^26p^2$	**Bi** 83 Bismuth 208.9804 $4f^{14}5d^{10}6s^26p^3$	**Po** 84 Polonium (210)[a] $4f^{14}5d^{10}6s^26p^4$	**At** 85 Astatine (210)[a] $4f^{14}5d^{10}6s^26p^5$	**Rn** 86 Radon (222)[a] $4f^{14}5d^{10}6s^26p^6$
7	**Fr** 87 Francium (223)[a] $7s^1$	**Ra** 88 Radium 226.0254[b] $7s^2$	**Ac**** 89 Actinium (227)[a] $6d^17s^2$	**Rf** 104 Rutherfordium (261)[a] $5f^{14}6d^27s^2$	**Db** 105 Dubnium (262)[a] $5f^{14}6d^37s^2$	**Sg** 106 Seaborgium (266) $5f^{14}6d^47s^2$	**Bh** 107 Bohrium (264) $5f^{14}6d^57s^2$	**Hs** 108 Hassium (269) $5f^{14}6d^67s^2$	**Mt** 109 Meitnerium (268) $5f^{14}6d^77s^2$	– 110 – (269) – –	– 111 – (272) – –							

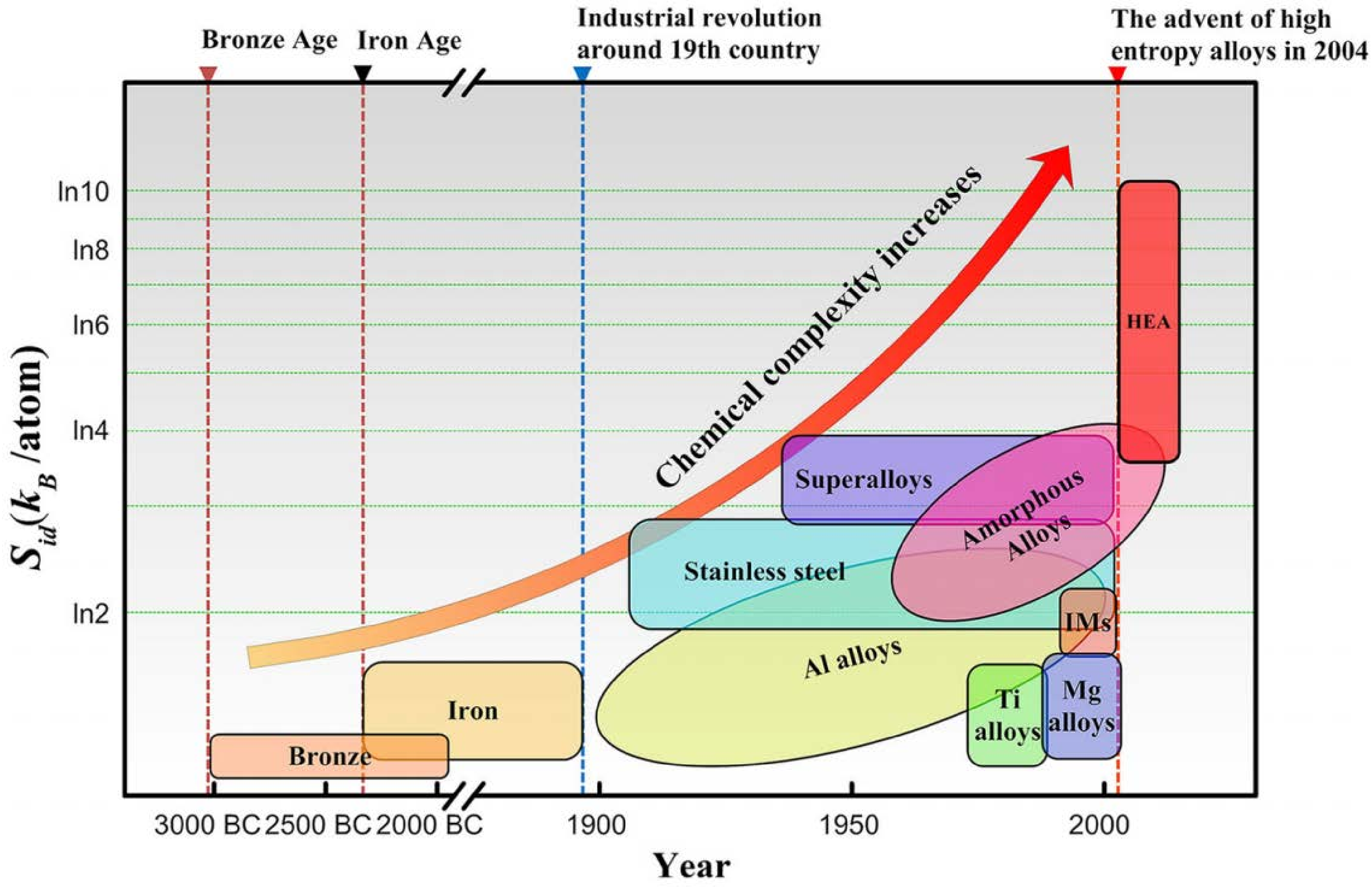
🟦 Metal 🟧 Semimetal 🟨 Nonmetal

Inner transition elements

	58–71													
Lanthanide series * 6	**Ce** 58 Cerium 140.116 $4f^15d^16s^2$	**Pr** 59 Praseodymium 140.90765 $4f^36s^2$	**Nd** 60 Neodymium 144.24 $4f^46s^2$	**Pm** 61 Promethium (145)[a] $4f^56s^2$	**Sm** 62 Samarium 150.4 $4f^66s^2$	**Eu** 63 Europium 151.964 $4f^76s^2$	**Gd** 64 Gadolinium 157.25 $4f^75d^16s^2$	**Tb** 65 Terbium 158.92534 $4f^96s^2$	**Dy** 66 Dysprosium 162.50 $4f^{10}6s^2$	**Ho** 67 Holmium 164.93032 $4f^{11}6s^2$	**Er** 68 Erbium 167.26 $4f^{12}6s^2$	**Tm** 69 Thulium 168.9342 $4f^{13}6s^2$	**Yb** 70 Ytterbium 173.04 $4f^{14}6s^2$	**Lu** 71 Lutetium 174.97 $4f^{14}5d^16s^2$
Actinide series ** 7	**Th** 90 Thorium 232.0381[b] $6d^27s^2$	**Pa** 91 Protactinium 231.03588 $5f^26d^17s^2$	**U** 92 Uranium 238.02891 $5f^36d^17s^2$	**Np** 93 Neptunium (237) $5f^46d^17s^2$	**Pu** 94 Plutonium (244) $5f^67s^2$	**Am** 95 Americium (243) $5f^77s^2$	**Cm** 96 Curium (247)[a] $5f^76d^17s^2$	**Bk** 97 Berkelium (247) $5f^97s^2$	**Cf** 98 Californium (251)[a] $5f^{10}7s^2$	**Es** 99 Einsteinium (251) $5f^{11}7s^2$	**Fm** 100 Fermium (257) $5f^{12}7s^2$	**Md** 101 Mendelevium (258) $5f^{13}7s^2$	**No** 102 Nobelium (259) $5f^{14}7s^2$	**Lr** 103 Lawrencium (262) $5f^{14}6d^17s^2$

Design-for-properties (since the Bronze Age!)

Materials Design-for-Properties : “Alloyed Pleasure”



Rising trend of alloy chemical complexity versus time. Note that ‘‘IMs’’ stands for intermetallics or metallic compounds and ‘‘HEA’’ for high-entropy alloy.

Classification of Metal Alloys

- Metal Alloys
  - **Ferrous**
    - Steels <1.4 wt% C
    - Cast Irons 3-4.5 wt% C
  - **Nonferrous**

Adapted from Fig. 13.1, *Callister & Rethwisch 9e.*

microstructure: ferrite, graphite/cementite

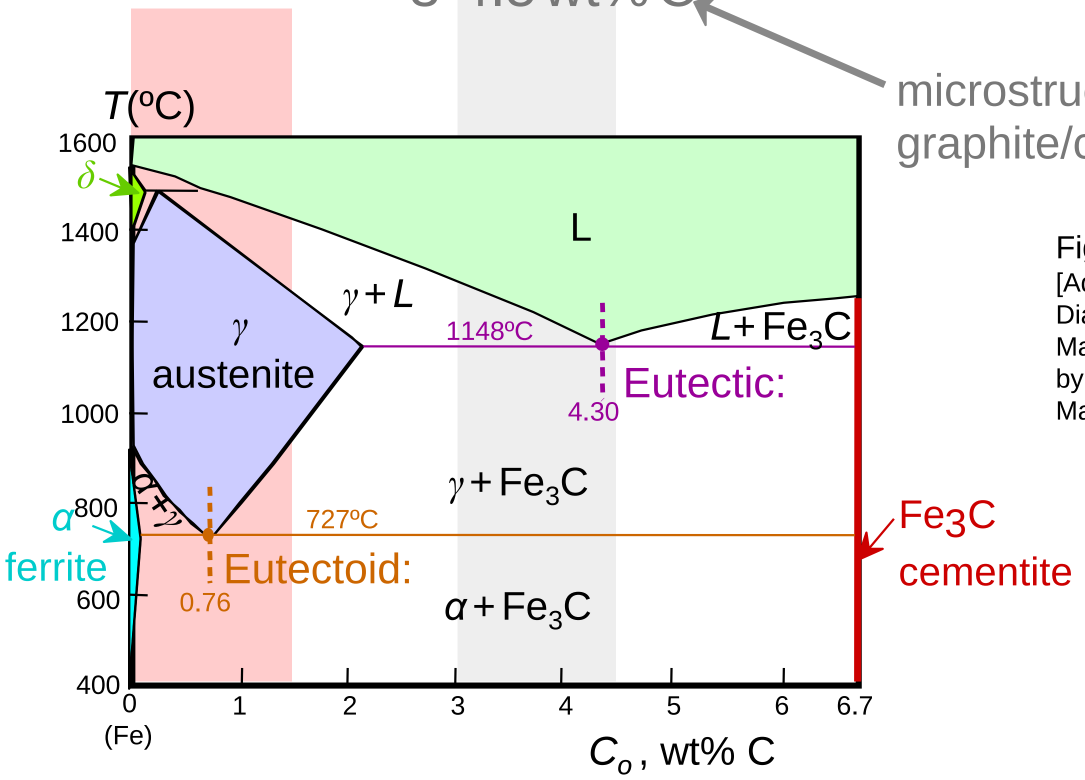


Fig. 11.23, *Callister & Rethwisch 9e*.
[Adapted from Binary Alloy Phase Diagrams, 2nd edition, Vol. 1, T. B. Massalski (Editor-in-Chief), 1990. Reprinted by permission of ASM International, Materials Park, OH.]

1. Ferrous Alloy

Merits: (1) iron-containing compounds exist in abundant quantities within the Earth’s crust

지구 전체를 구성하는 원소의 중량 비율로는 **철(Fe)이 35%로 제일 많이 있는 원소**이다. 철은 특히 지구 내부 코어 중량의 90.8%를 차지하는 것으로 추정되고 있다. 그 다음으로는 **산소(O)가 30%, 실리콘(Si) 15%, 마그네슘(Mg) 13% 순**이다.

하지만, **지각을 구성하는 원소**를 기준으로 중량 비율을 살펴보면 **산소**가 제일 많다. **철은 산소 46.60%, 실리콘 27.70%, 알루미늄 8.13%에 이어 지각 중량의 5.0%를 차지**하며 금속 중에서는 알루미늄에 이어 두 번째로 많다.

재미있는 것은 지각을 구성하는 물질 가운데 비중이 큰 4개 원소(산소, 실리콘, 알루미늄, 철)의 누적 중량 비율이 87.4%이고 상위 9개 원소(상기 4개 원소 외 칼슘, 나트륨, 칼륨, 마그네슘 및 티타늄)의 총 중량이 지각 전체의 99.0%를 차지한다는 점이다. **이 외 다른 원소의 중량의 합은 지각 전체의 1.0%에도 미치지 못하는 것이다.** 예를 들어 구리, 니켈 및 납 등 금속들은 지각에서 존재하는 비중이 겨우 각각 75ppm, 55ppm, 13ppm 밖에 되지 않는다.

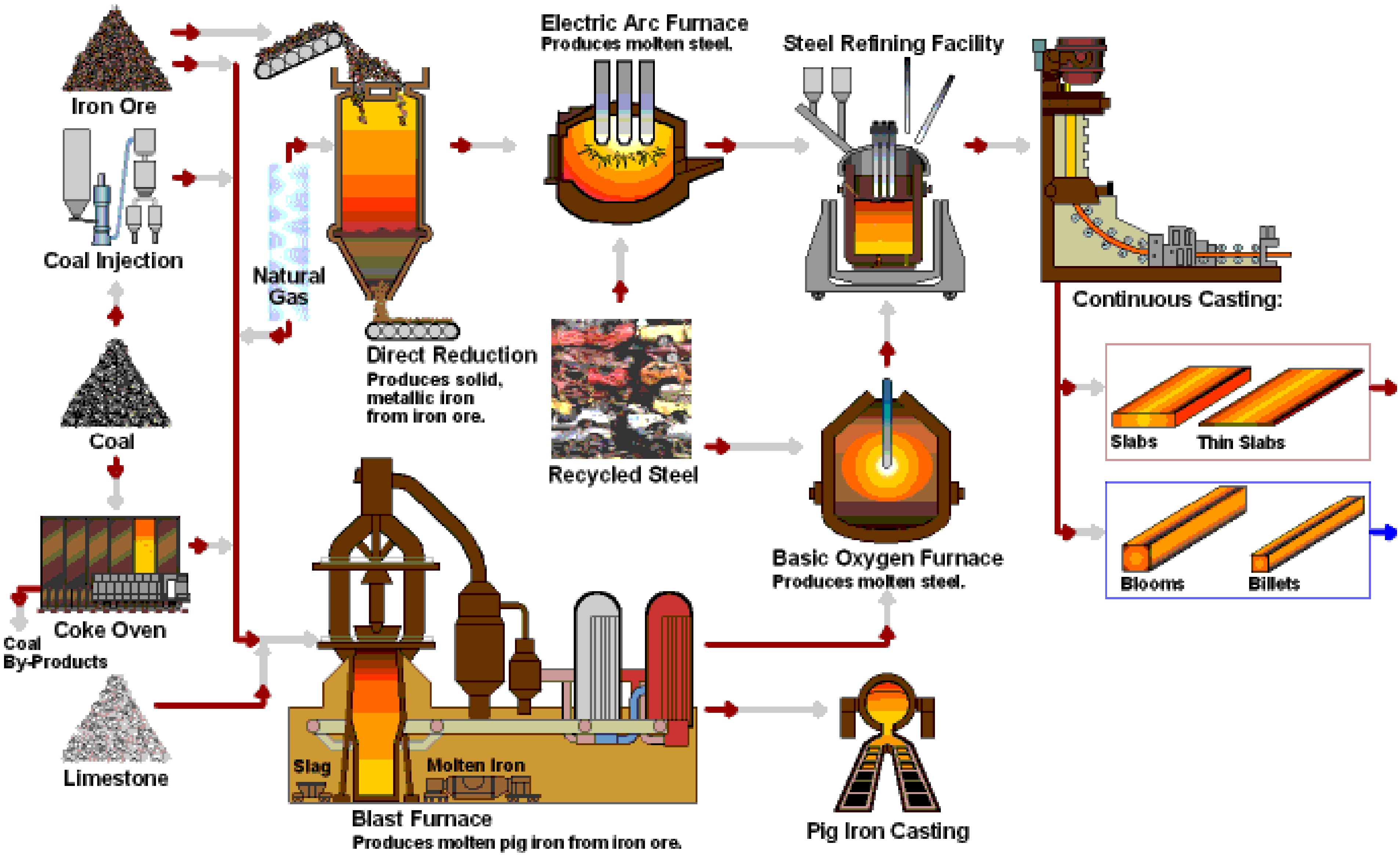
지각에 55ppm 수준으로 존재하는 구리 같은 자원이 지각 속에서 균등하게 분포한다면 이를 채취하여 자원으로 만드는 것은 거의 불가능 → 비교적 농집된 형태로 지역에 존재 (광산)

1. Ferrous Alloy

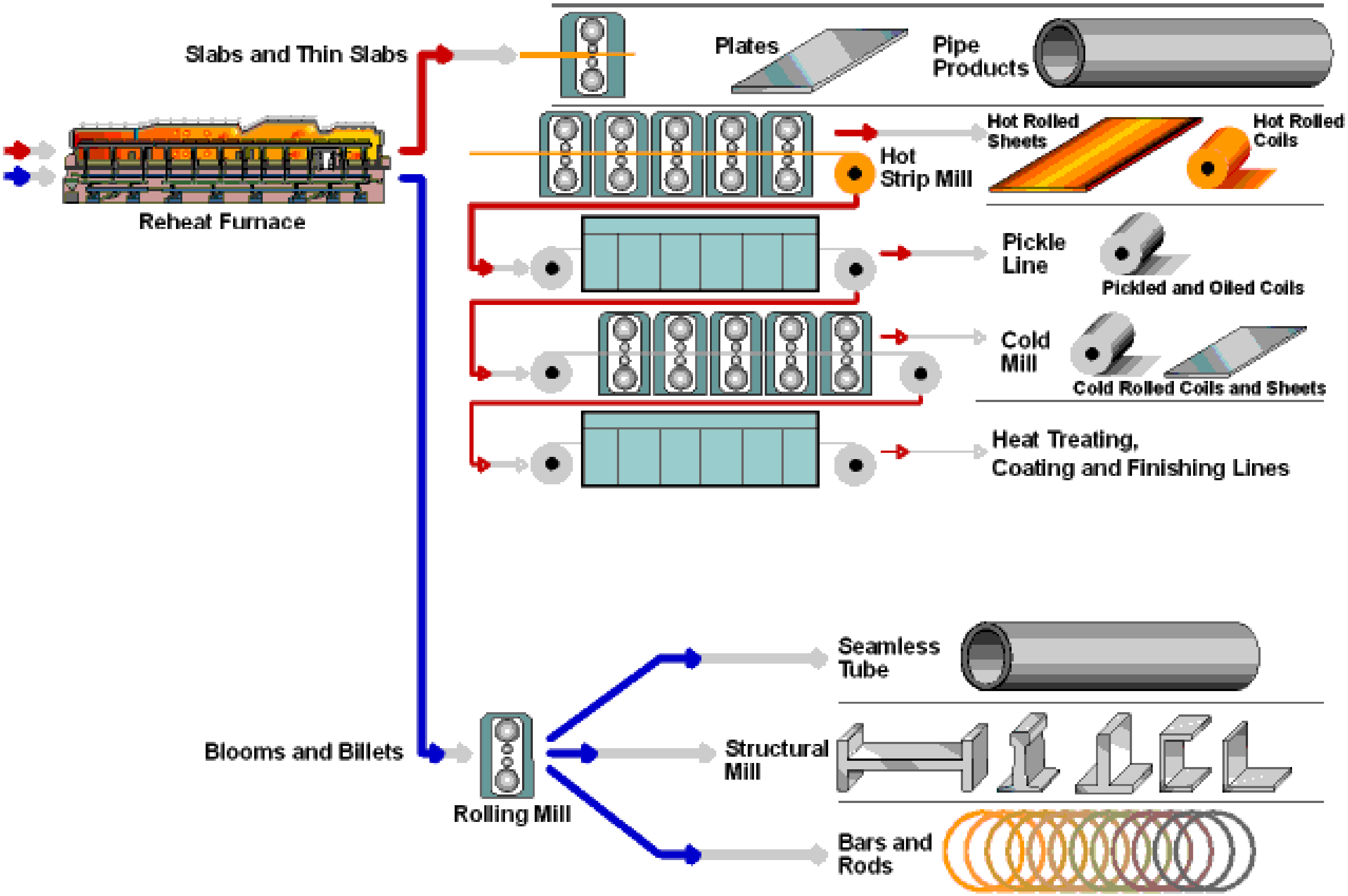
Merits: (1) iron-containing compounds exist in abundant quantities within the Earth’s crust.

(2) metallic iron and steel alloys may be produced using relatively economical extraction, refining , alloying, and fabrication techniques.

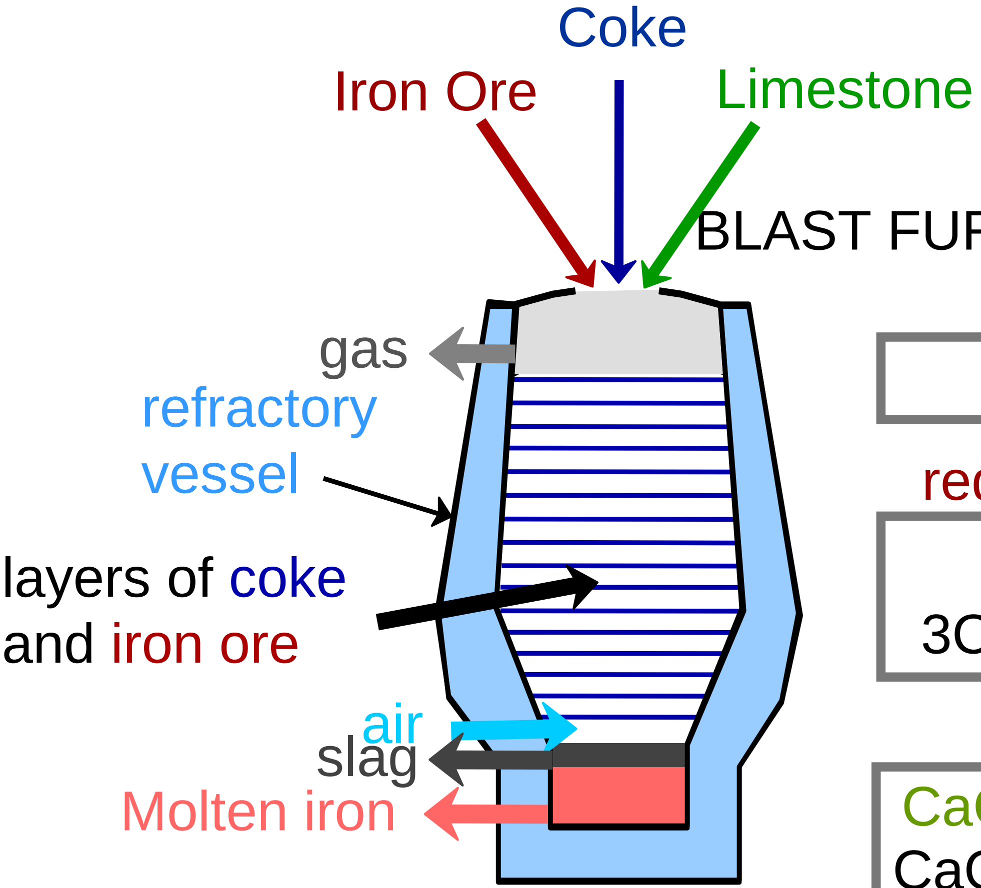
철강의 생산과정 : Iron making → Steelmaking → Rolling



철강의 생산과정 : Iron making → Steelmaking → Rolling



a. Refinement of Steel from Ore



Coke

Iron Ore

Limestone

BLAST FURNACE

gas

refractory vessel

layers of coke and iron ore

air

slag

Molten iron

heat generation

$$C + O_2 \rightarrow CO_2$$

reduction of iron ore to metal

$$CO_2 + C \rightarrow 2CO$$

$$3CO + Fe_2O_3 \rightarrow 2Fe + 3CO_2$$

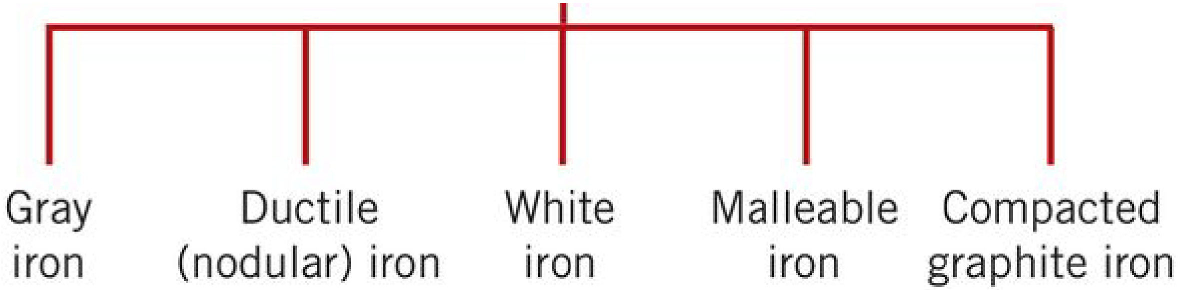
purification

$$CaCO_3 \rightarrow CaO + CO_2$$

$$CaO + SiO_2 + Al_2O_3 \rightarrow \text{slag}$$

처음 생산된 Pig Iron = 선철(銑鐵) = 용선(溶銑) = 쇳물 = 물쇠 = 무쇠

Cast Irons (주철)



Gray iron 회주철

Ductile (nodular) iron 연성(구상)주철

White iron 백주철

Malleable iron 가단주철

Compacted graphite iron 조밀흑연주철

- Ferrous alloys with > 2.1 wt% C
  - – more commonly 3 - 4.5 wt% C

- Low melting – relatively easy to cast

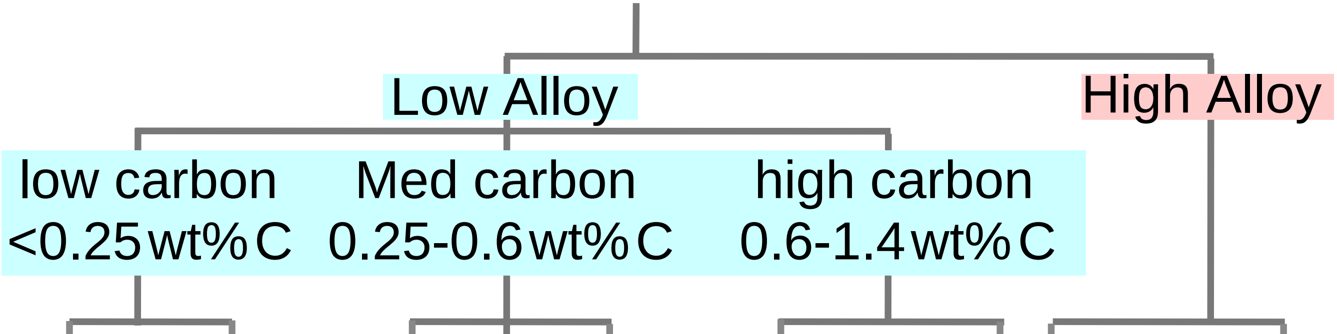
- Generally brittle

- Cementite decomposes to ferrite + graphite

  $Fe_3C \rightarrow 3\ Fe\ (\alpha) + C\ (graphite)$

  - – generally a slow process

Steels



Low Alloy

High Alloy

low carbon
<0.25 wt% C

Med carbon
0.25-0.6 wt% C

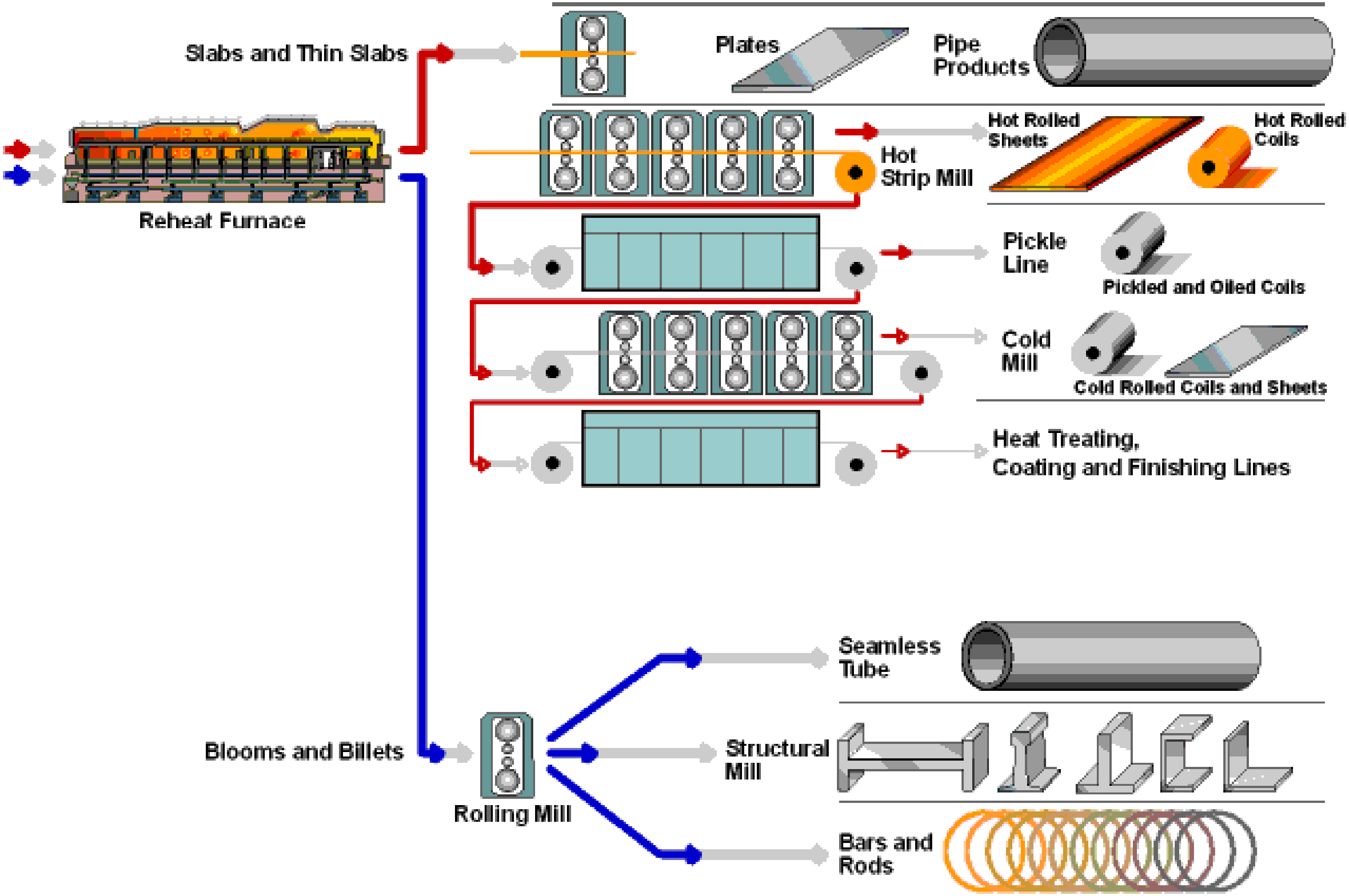
high carbon
0.6-1.4 wt% C

Name	plain	HSLA	plain	heat treatable	plain	tool	stainless
Additions	none	Cr,V Ni, Mo	none	Cr, Ni Mo	none	Cr, V, Mo, W	Cr, Ni, Mo
Example	1010	4310	1040	4340	1095	4190	304, 409
Hardenability	0	+	+	++	++	+++	varies
TS	-	0	+	++	+	++	varies
EL	+	+	0	-	-	--	++
Uses	auto struc. sheet	bridges towers press. vessels	crank shafts bolts hammers blades	pistons gears wear applic.	wear applic.	drills saws dies	high T applic. turbines furnaces Very corros. resistant

increasing strength, cost, decreasing ductility

Based on data provided in Tables 13.1(b), 14.4(b), 13.3, and 13.4, *Callister & Rethwisch 9e.*

철강의 생산과정 : Iron making → Steelmaking → Rolling



I. Ferrous Alloy

Merits: (1) iron-containing compounds exist in abundant quantities within the Earth’s crust.

(2) metallic iron and steel alloys may be produced using relatively economical extraction, refining , alloying, and fabrication techniques.

(3) ferrous alloys are extremely versatile, in that they may be tailored to have a wide range of mechanical and physical properties.

Limitations: (1) Relatively high densities

(2) Relatively low electrical conductivities

(3) Generally poor corrosion resistance

Ferrous Alloys

Iron-based alloys

- Steels
- Cast Irons

Nomenclature for steels (AISI/SAE)

10xx	Plain Carbon Steels
11xx	Plain Carbon Steels (resulfurized for machinability)
15xx	Mn (1.00 - 1.65%)
40xx	Mo (0.20 ~ 0.30%)
43xx	Ni (1.65 - 2.00%), Cr (0.40 - 0.90%), Mo (0.20 - 0.30%)
44xx	Mo (0.5%)

where xx is wt% C x 100

example: 1060 steel – plain carbon steel with 0.60 wt% C

Stainless Steel >11% Cr

Ferrous Alloys

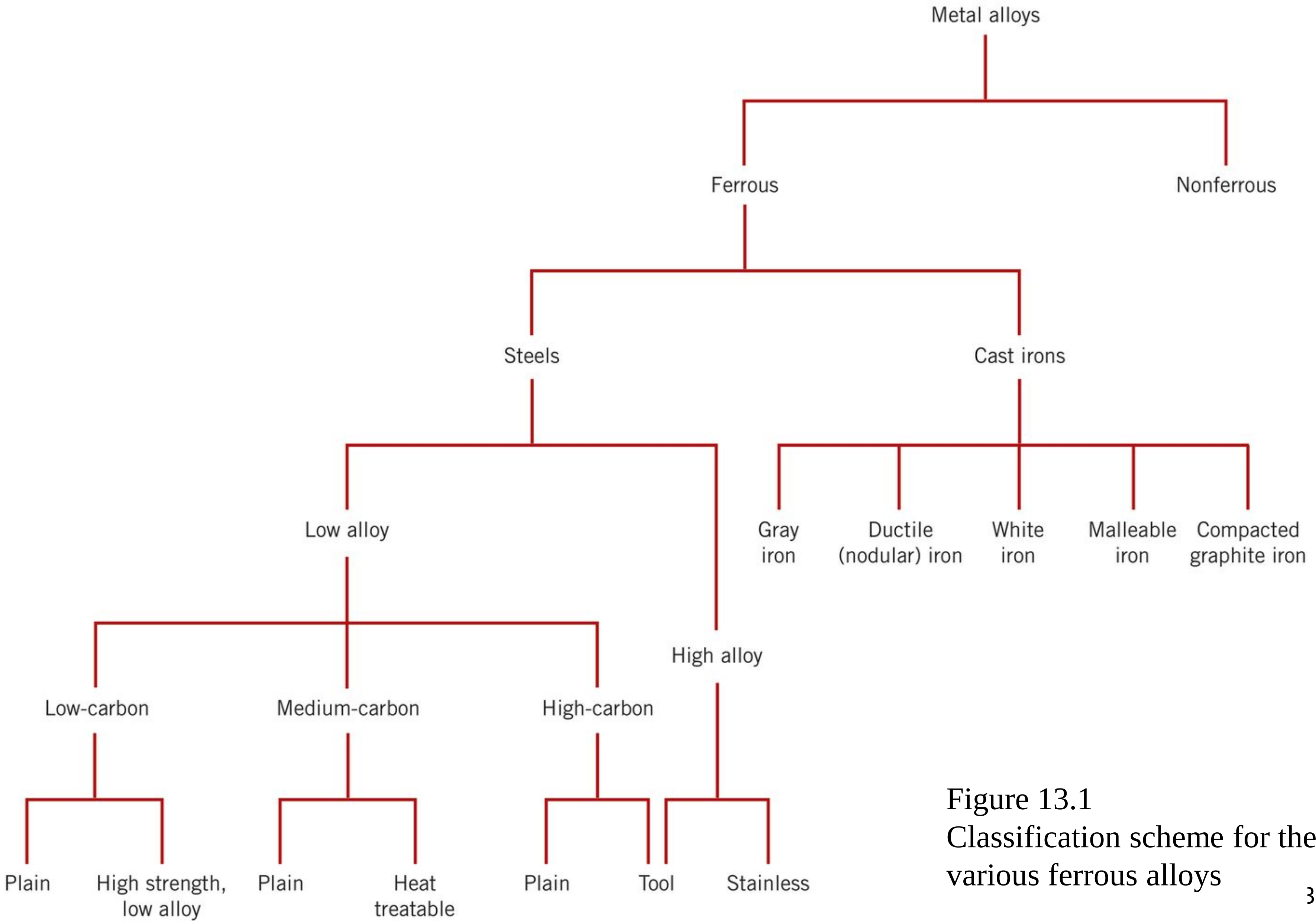
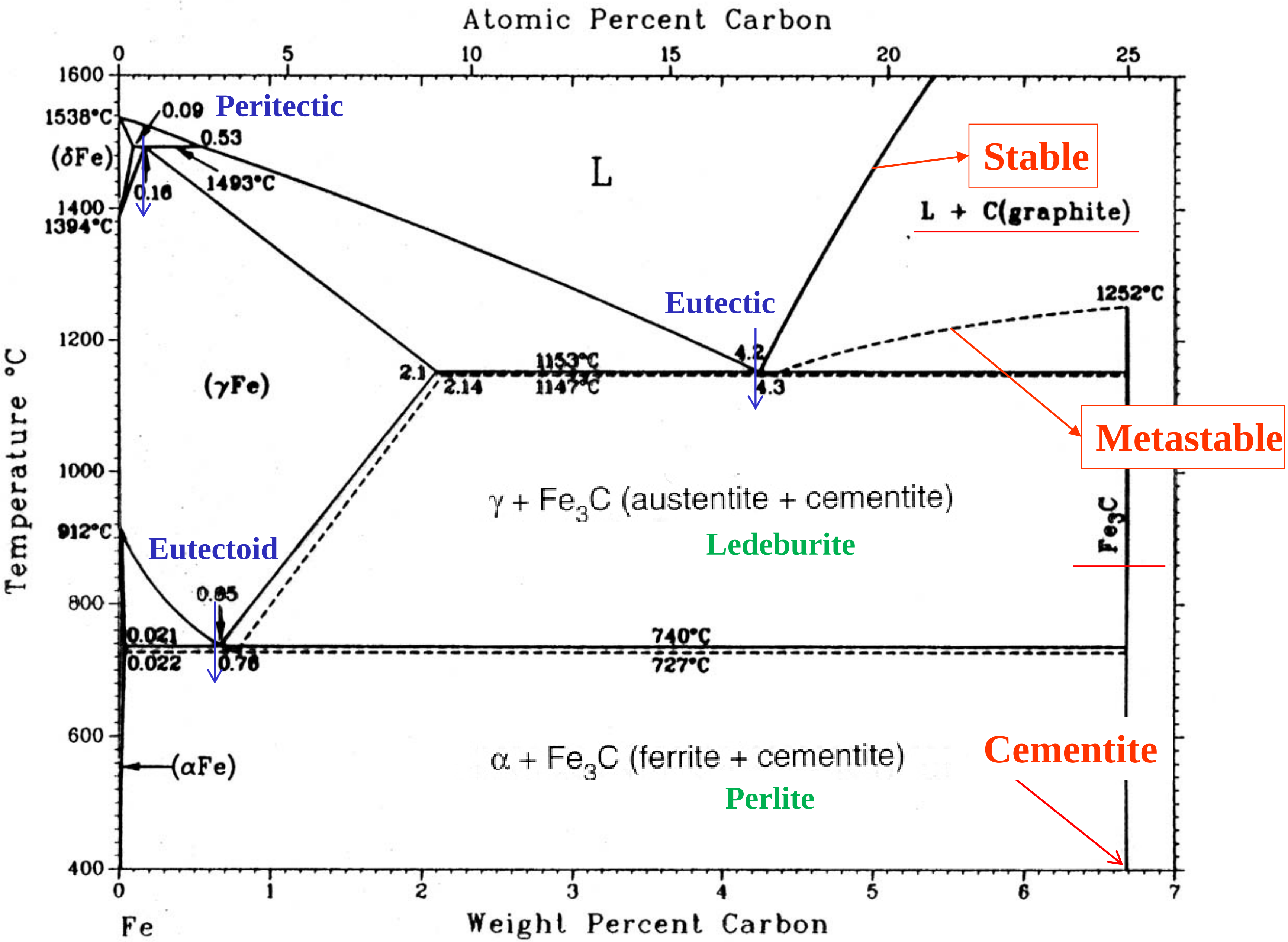


Figure 13.1
Classification scheme for the various ferrous alloys

* Cast Iron: Fe-C alloy (1.7 ≤ c ≤ 4.5%)



* Two eutectic system: Fe-graphite & Fe-Fe_3C (cementite)

: If there is no other additive element, the Fe-graphite system is stable & Fe-Fe_3C eutectic is formed by rapid cooling of liquid phase

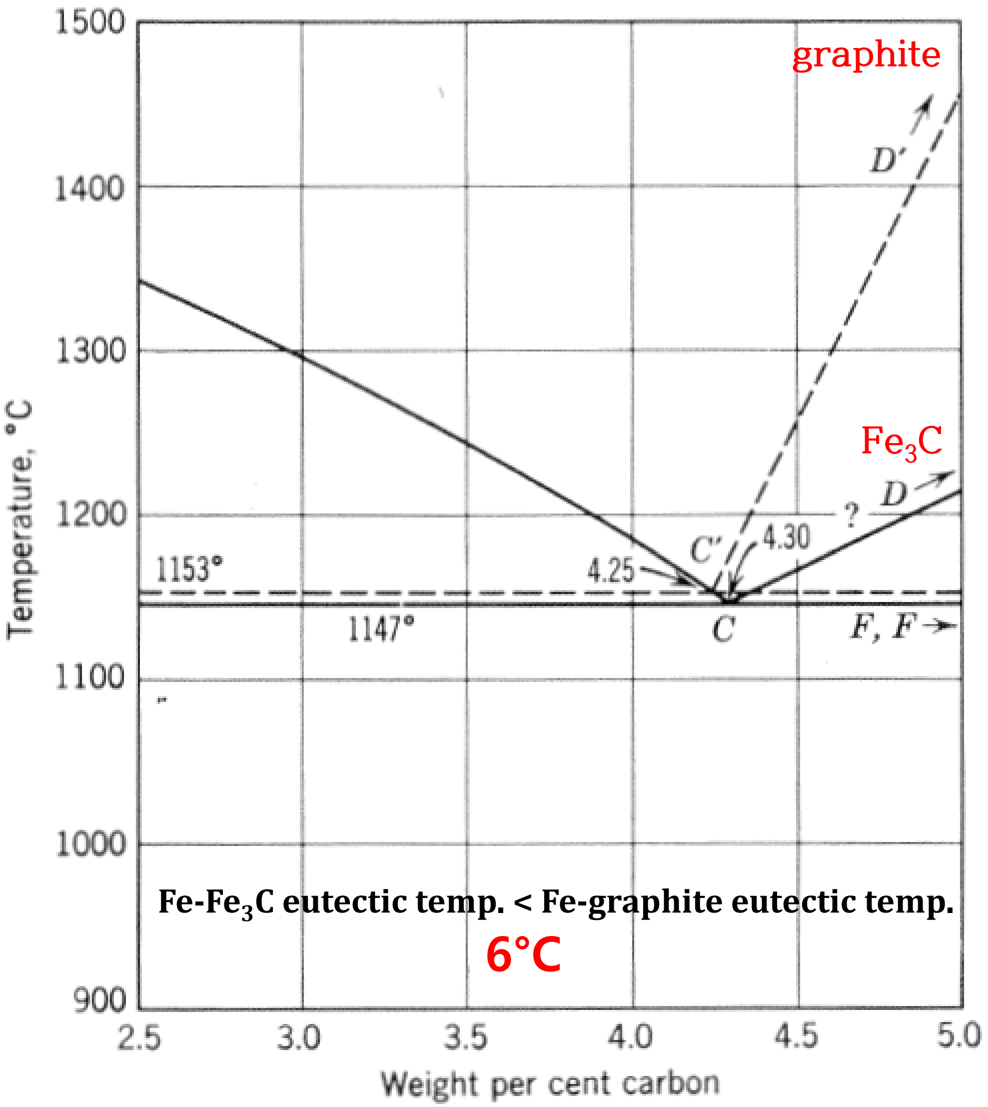
*** If solidification proceeds at interface temperature above the cementite eutectic temperature, Graphite eutectic formation**

① Carbon → **graphite**

→ **Gray cast Iron** 회주철

*** If the solidification proceed below Cementite eutectic temperature due to lower the liquidus temperature through fast quenching and a suitable nucleation agent to form an over-solute layer,** ② **Carbon → Fe_3C**

→ **White cast Iron** 백주철



Fe-Fe_3C eutectic temp. < Fe-graphite eutectic temp.

6°C

Fig. 6.35. Eutectic region of the iron carbon system.

Types of Cast Iron

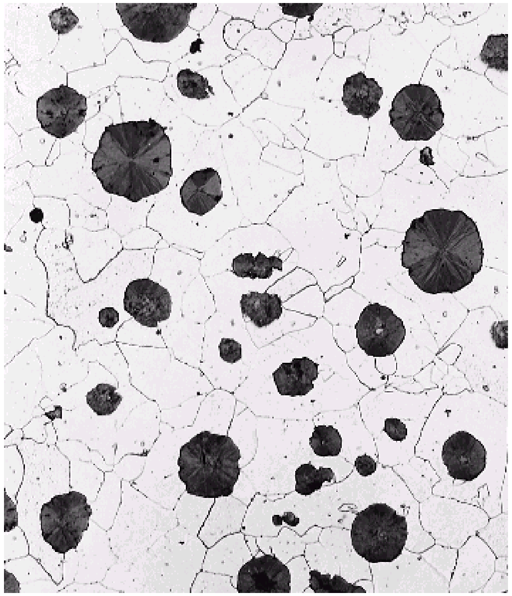
Gray iron 회주철

- graphite flakes
- weak & brittle in tension
- stronger in compression
- excellent vibrational dampening
- wear resistant

Figs. 13.3(a) & (b), *Callister & Rethwisch 9e.* [Courtesy of C. H. Brady and L. C. Smith, National Bureau of Standards, Washington, DC (now the National Institute of Standards and Technology, Gaithersburg, MD]

Ductile iron 연성(구상)주철

- add Mg and/or Ce
- graphite as nodules not flakes
- matrix often pearlite – stronger but less ductile



Types of Cast Iron (cont.)

White iron 백주철

- < 1 wt% Si
- pearlite + cementite
- very hard and brittle

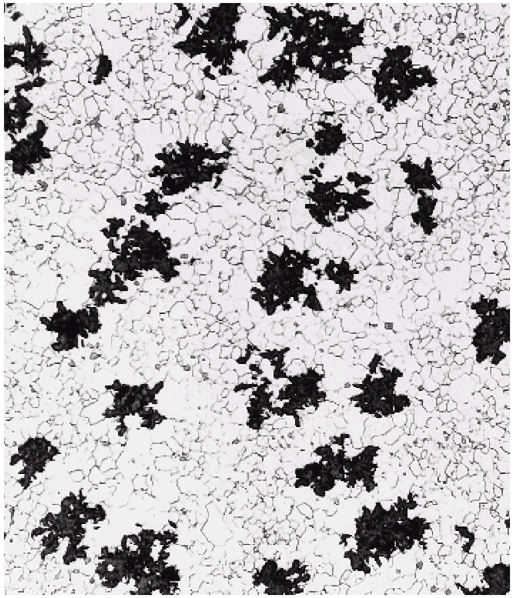
조밀흑연주철

Figs. 13.3(c) & (d), *Callister & Rethwisch 9e.*

Courtesy of Amcast Industrial Corporation

Malleable iron 가단주철

- heat treat white iron at 800-900° C
- graphite in rosettes (장미상 조직)
- reasonably strong and ductile

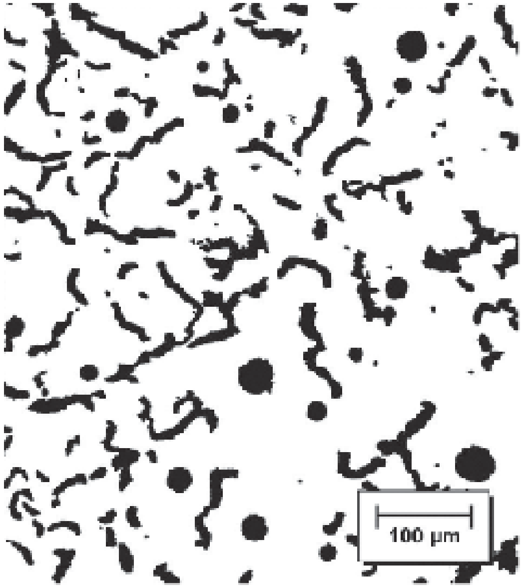


Reprinted with permission of the Iron Castings Society, Des Plaines, IL.

Types of Cast Iron (cont.)

Compacted graphite iron 조밀흑연주철

- relatively high thermal conductivity
- good resistance to thermal shock
- lower oxidation at elevated temperatures



Courtesy of Sinter-Cast, Ltd.

Fig. 13.3(e), *Callister & Rethwisch 9e.*

Production of Cast Irons

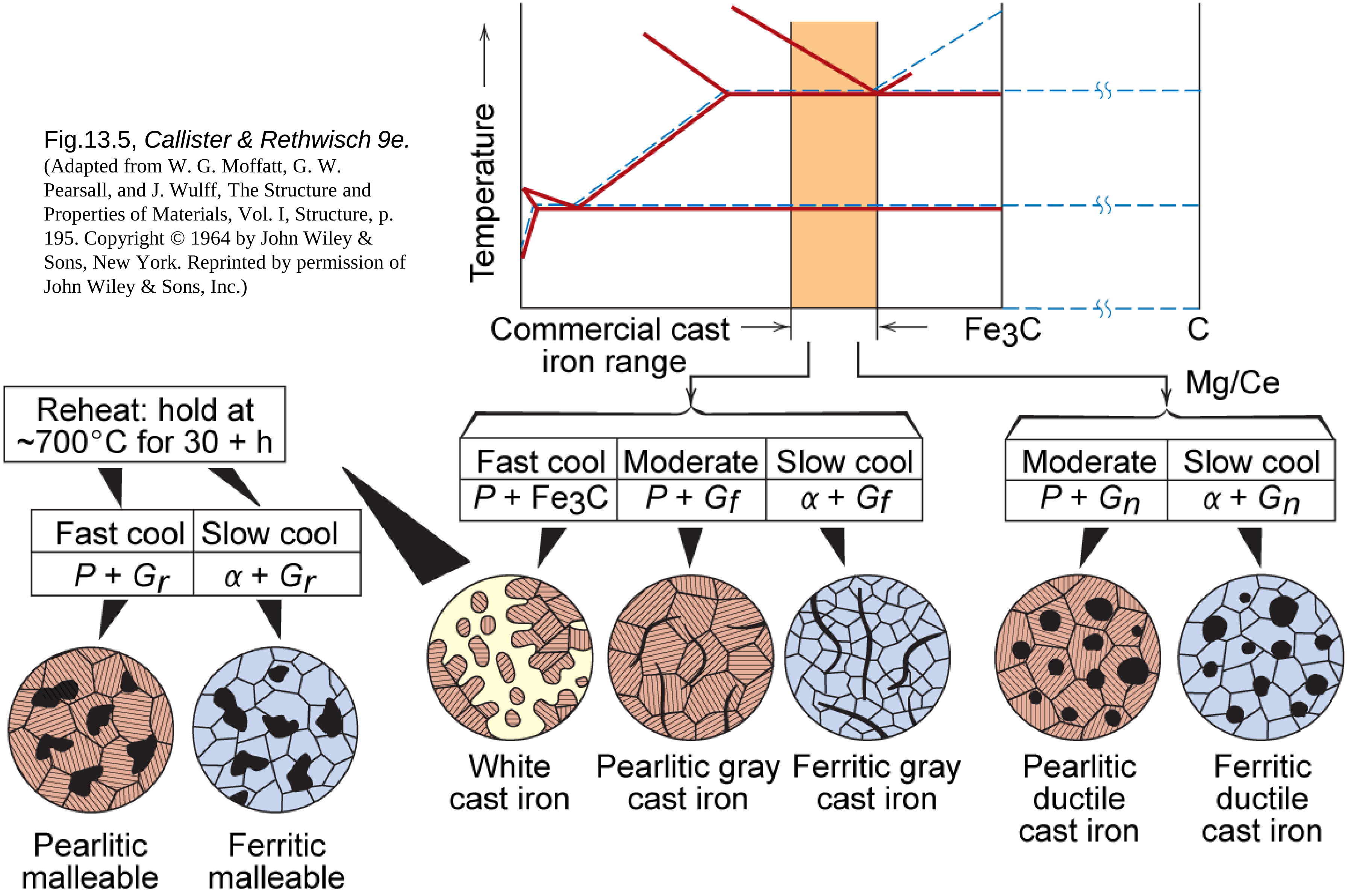
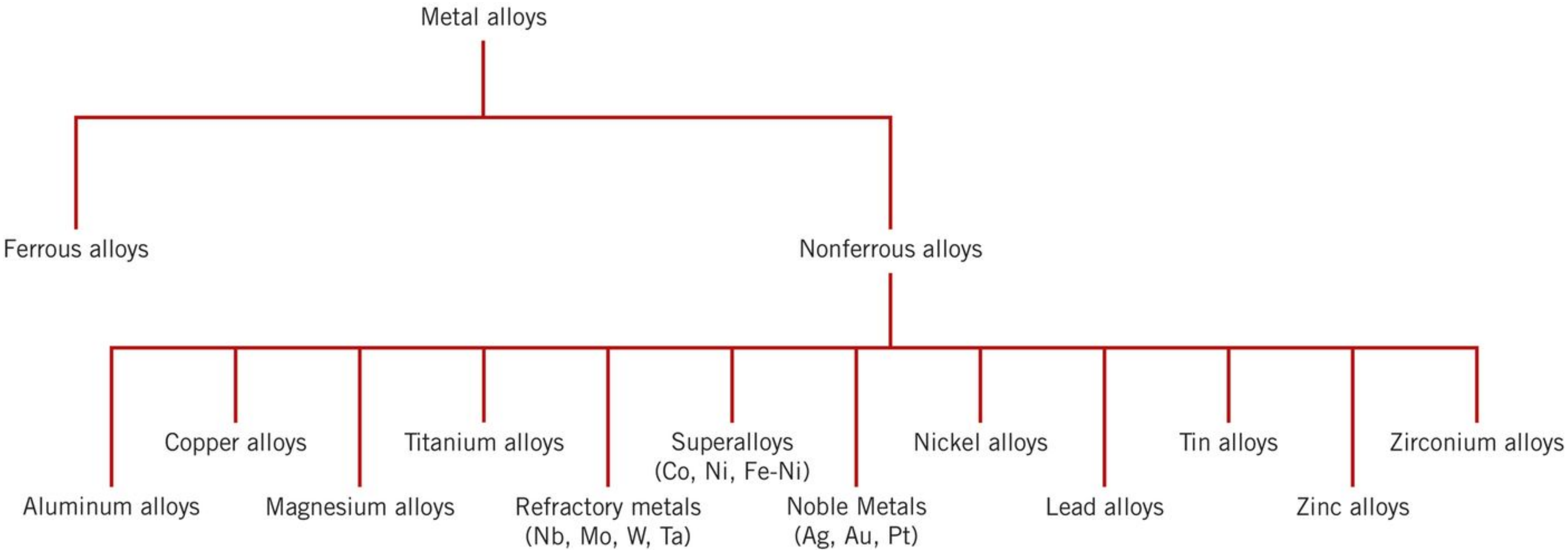


Fig.13.5, *Callister & Rethwisch 9e.*
(Adapted from W. G. Moffatt, G. W. Pearsall, and J. Wulff, The Structure and Properties of Materials, Vol. I, Structure, p. 195. Copyright © 1964 by John Wiley & Sons, New York. Reprinted by permission of John Wiley & Sons, Inc.)

II. Nonferrous Alloys



II. Nonferrous Alloys

NonFerrous Alloys

- **Cu Alloys**

Brass: Zn is subst. impurity (costume jewelry, coins, corrosion resistant)

Bronze : Sn, Al, Si, Ni are subst. impurities (bushings, landing gear)

Cu-Be: precip. hardened for strength

- **Al Alloys**

-low ρ: 2.7 g/cm^3

-Cu, Mg, Si, Mn, Zn additions

-solid sol. or precip. strengthened (struct. aircraft parts & packaging)

- **Mg Alloys**

-**very low ρ**: 1.7 g/cm^3

-ignites easily

-aircraft, missiles

- **Ti Alloys**

-relatively low ρ: 4.5 g/cm^3 vs 7.9 for steel

-reactive at high *T*'s

-space applic.

- **Noble metals**

-Ag, Au, Pt

-oxid./corr. resistant

- **Refractory metals**

-high melting *T*'s

-Nb, Mo, W, Ta

Based on discussion and data provided in Chapter 13, *Callister & Rethwisch 9e.*

III. Advanced Engineering Alloys

a. Superalloys

Definition: A superalloy is a metallic alloy which can be used at high temperatures, often in excess of 0.7 of the absolute melting temperature.
Creep and oxidation resistance are the prime design criteria.

There are three types of superalloys based on the principal constituting element:

1. Nickel based (m.p. of Ni: 1455 °C)
2. Cobalt based (m.p. of Ni: 1495 °C)
3. Iron based (m.p. of Ni: 1538 °C)

Ni-based superalloys are the most complex and widely used among the three types of superalloys due to their high performance capabilities.

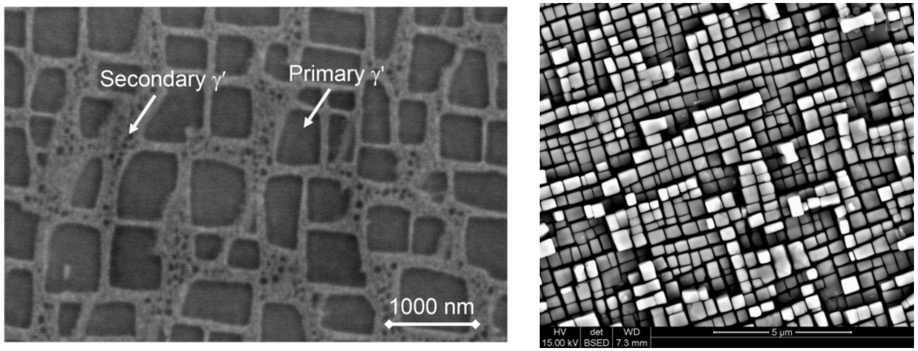
Properties of Superalloys:

- Capable of high temperature application
- Excellent oxidation resistance
- Good corrosion and erosion resistance across wide temperature range
- Strong and ductile at cryogenic temperatures

Microstructure

The superior property at high temperature comes from the optimized microstructure consisting of various phases. The representative phases are listed below:

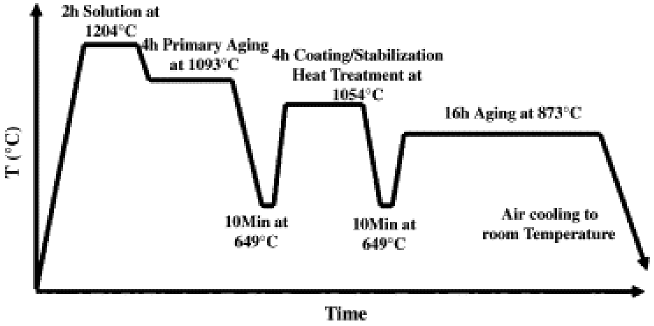
- Gamma (γ) phase: It forms the matrix of the alloy. The volume fraction of γ in certain superalloys maybe as low as 30% due to the precipitates.
- Gamma’ (γ’) phase: coherent precipitate composed of $Ni_3(Al/Ti)$ strengthen the alloy.
- Carbides: they form at grain boundaries inhibiting grain boundary motion.



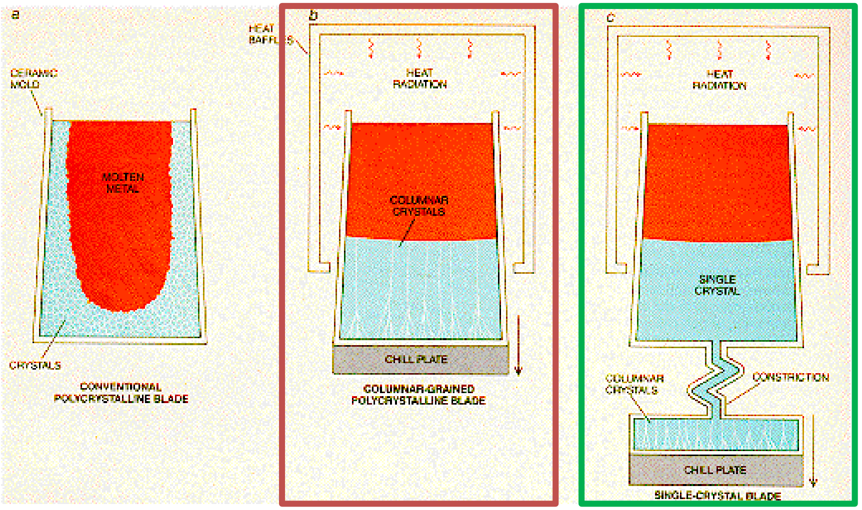
Microstructure of some superalloys exhibiting γ- γ’ structure

Processing Techniques

To obtain the desired microstructure, various heat treatments such as variation of cooling rate and one/two step aging processes are employed.



Since grain boundary has great influence on the creep resistance, directionally solidified or single crystal superalloys are fabricated.



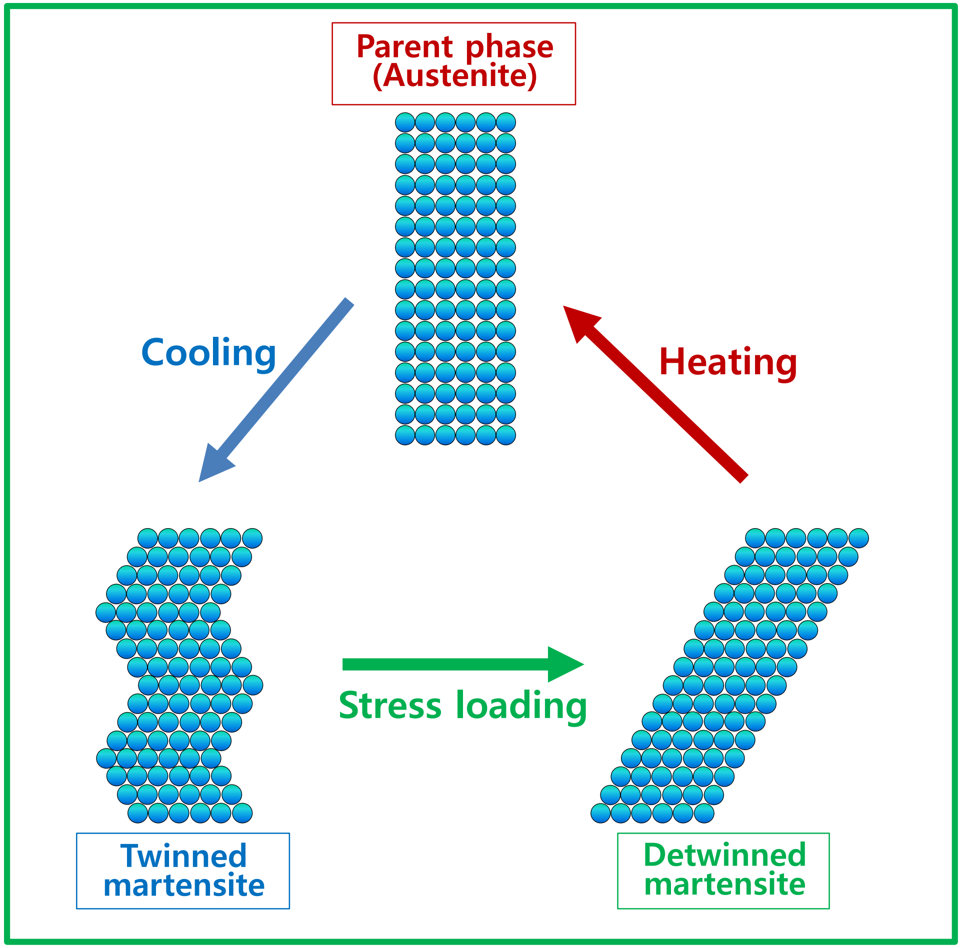
Application

- Aircraft gas turbines: disks, combustion chambers, blades, vanes, afterburners, thrust reversers
- Steam turbine power plants: blades, stack gas re-heaters
- Metal processing: hot work tools and dies
- Space vehicles: rocket engine parts, aerodynamically heated skins
- Nuclear power systems: control rod drive mechanisms, springs, valve stems
- Chemical and petrochemical industries: bolts, fans, valves, reaction vessels, piping, pumps
- Coal gasification and liquefaction systems: heat exchangers, re-heaters, piping.

Various machine and engine components made from superalloys

Picture of a turbine blade

Principles - b. Shape Memory Alloys



Parent phase
(Austenite)

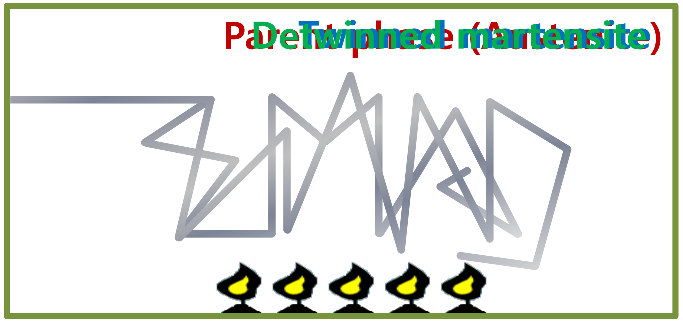
Cooling

Heating

Stress loading

Twinned
martensite

Detwinned
martensite

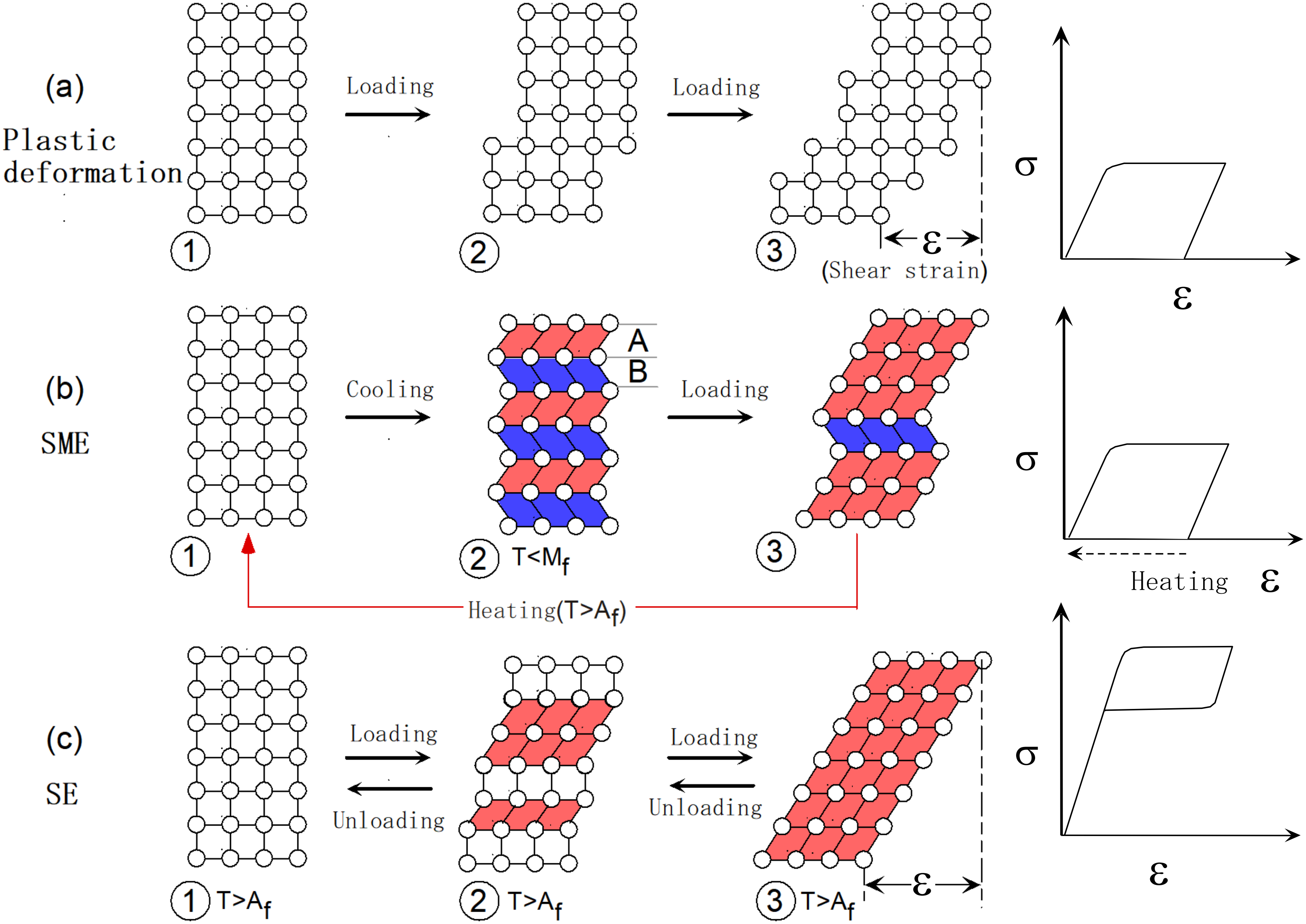


1. A_f 이상의 온도로 열처리를 통해
   Austenite 상에서 형상 기억

2. M_s 이하의 온도로 냉각시
   Twinned martensite 생성

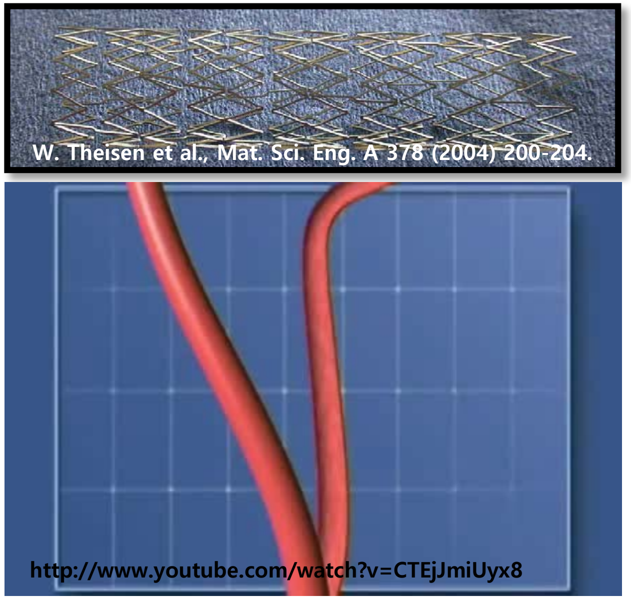
3. 항복강도 이상의 응력을 가하면 Twin
   boundary의 이동에 의한 소성 변형

4. A_f 이상으로 가열해주면 martensite
   에서 다시 Austenite로 변태
   ➡ 기억된 형상으로 회복


(a)
Plastic deformation
①
Loading
②
Loading
③
ε
(Shear strain)
σ
ε
(b)
SME
①
Cooling
② T<M$_f$
A
B
Loading
③
σ
Heating
ε
Heating(T>A$_f$)
(c)
SE
① T>A$_f$
Loading
Unloading
② T>A$_f$
Loading
Unloading
③ T>A$_f$
ε
σ
ε

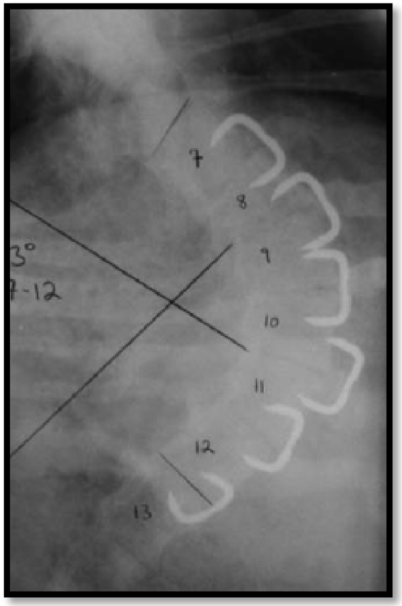
Applications - Medical device

- 체온에 감응하여 형상회복이 일어나도록 변태 온도를 조절한 형상기억합금 (Austenite 변태 종료 온도 A_f가 체온보다 낮은 경우) ➜ 의학적으로 널리 활용


W. Theisen et al., Mat. Sci. Eng. A 378 (2004) 200-204.

http://www.youtube.com/watch?v=CTEjJmiUyx8

△ SMA stents

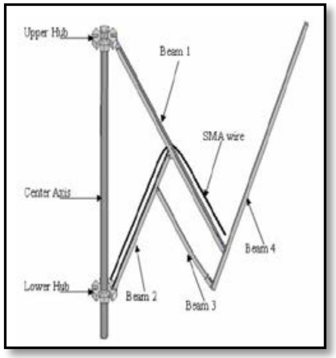


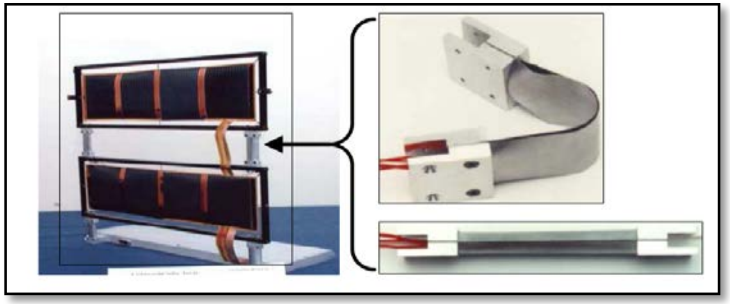
△ Staples of SMA


△ SMA teeth brace

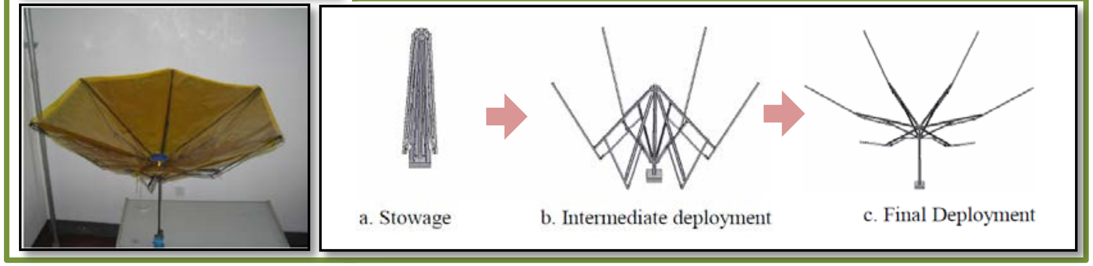
Applications - Aerospace

- 우주 공간과 같이 모터-기어에 의한 구동이 어려운 극저온 환경에서 태양열 등에 의한 온도변화를 감지하여 자동으로 전개되는 안테나와 태양 집광판을 제작하기 위해 형상기억합금을 사용





△ Solar panel deployment hinge



a. Stowage

b. Intermediate deployment

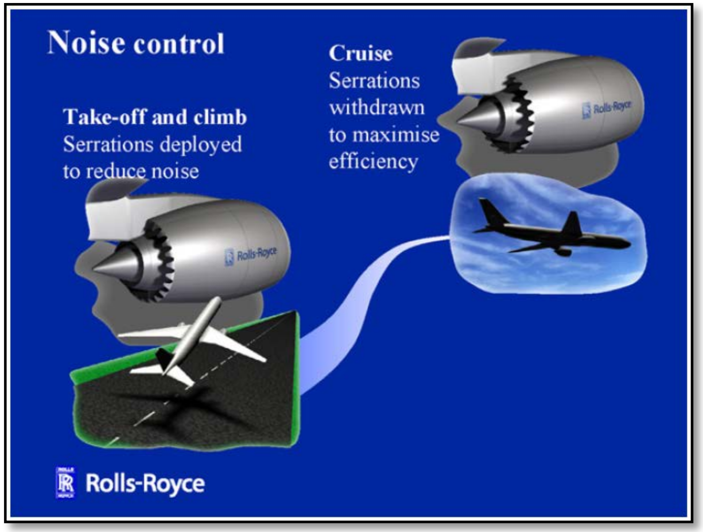
c. Final Deployment

△ SMA wire를 이용한 antenna와 전개 과정

http://www.youtube.com/watch?v=fDNbGOwT2hI

Applications - Aerospace

- 높은 배기관 온도가 형성되는 이착륙시에는 fan nozzle이 열리게 하여 배출구가 최대 단면적을 갖게 함.
- 높은 고도로 순항 중에는 낮은 대기 온도로 인해 nozzle이 닫히면서 소음을 줄이고, 엔진의 효율을 높힘.

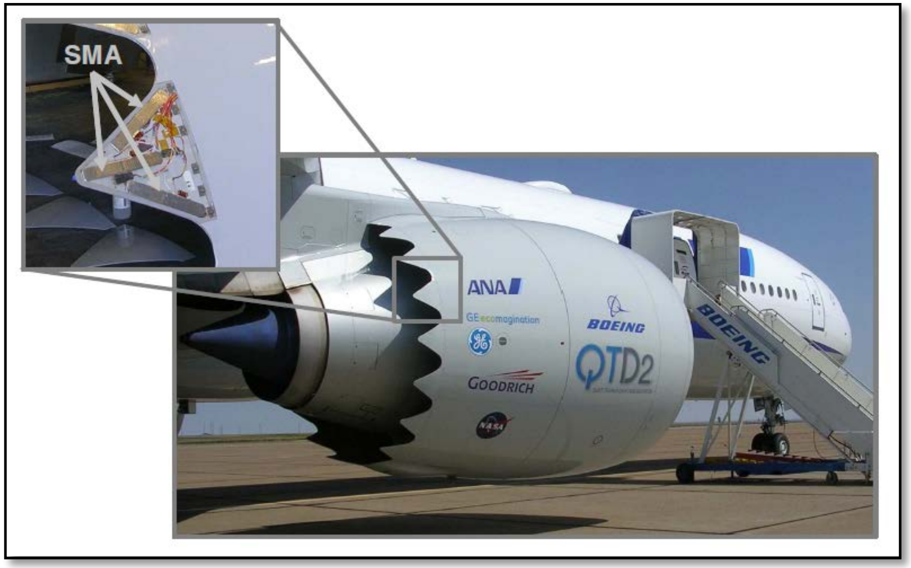


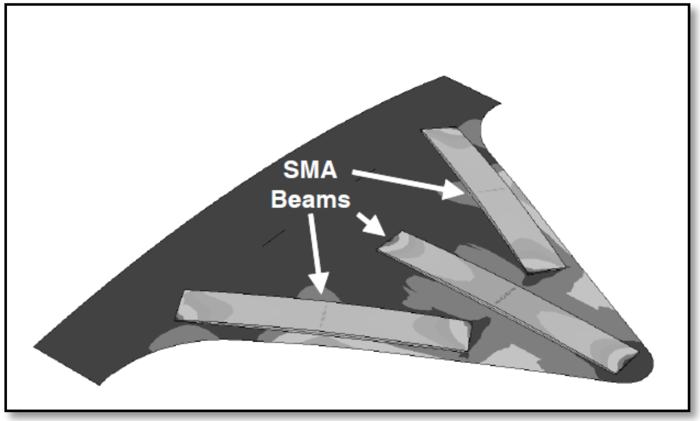
Noise control

Take-off and climb
Serrations deployed
to reduce noise

Cruise
Serrations
withdrawn
to maximise
efficiency

Rolls-Royce





△ Serrated Nozzle tip의 구조

c. Quasicrystals

Crystal with 5 fold symmetry *Mathematically impossible but exist*

1984 $Al_{86}Mn_{14}$ *alloy* : rapidly solidified ribbon_*Shectman et al.*

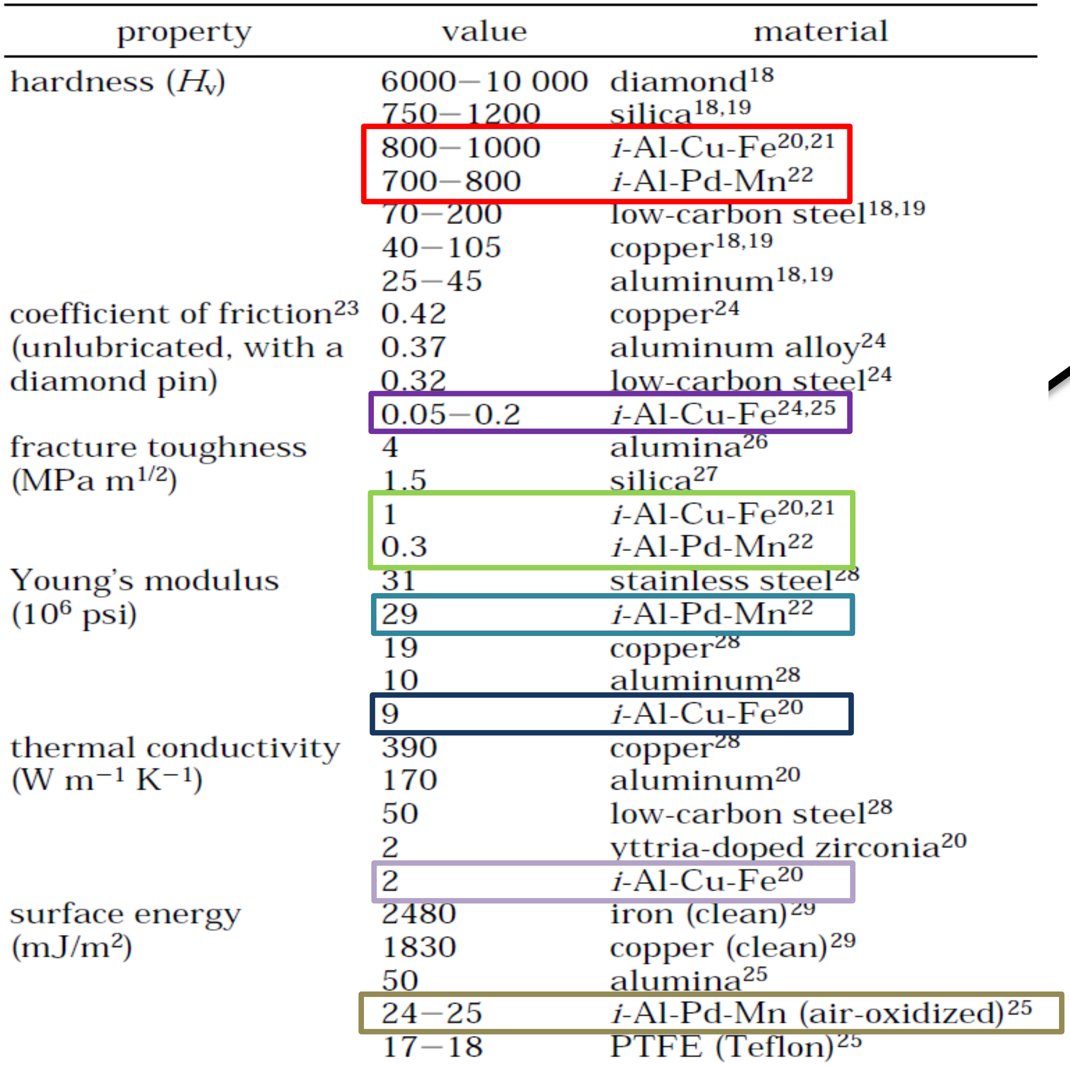
: materials whose structure cannot be understood within classical crystallography rules.

"Quasiperiodic lattices", with long-range order but without periodic translations in three dimensions

- long range order: quasiperiodic
- no 3-D translational symmetry
- sharp diffraction patterns

http://www.youtube.com/watch?v=k_VSpBI5EGM

Quasicrystal



property	value	material
hardness (H_v)	6000–10 000	diamond[18]
	750–1200	silica[18,19]
	800–1000	*i*-Al-Cu-Fe[20,21]
	700–800	*i*-Al-Pd-Mn[22]
	70–200	low-carbon steel[18,19]
	40–105	copper[18,19]
	25–45	aluminum[18,19]
coefficient of friction[23] (unlubricated, with a diamond pin)	0.42	copper[24]
	0.37	aluminum alloy[24]
	0.32	low-carbon steel[24]
	0.05–0.2	*i*-Al-Cu-Fe[24,25]
fracture toughness (MPa m$^{1/2}$)	4	alumina[26]
	1.5	silica[27]
	1	*i*-Al-Cu-Fe[20,21]
	0.3	*i*-Al-Pd-Mn[22]
Young's modulus (10^6 psi)	31	stainless steel[28]
	29	*i*-Al-Pd-Mn[22]
	19	copper[28]
	10	aluminum[28]
	9	*i*-Al-Cu-Fe[20]
thermal conductivity (W m^{-1} K^{-1})	390	copper[28]
	170	aluminum[20]
	50	low-carbon steel[28]
	2	yttria-doped zirconia[20]
	2	*i*-Al-Cu-Fe[20]
surface energy (mJ/m^2)	2480	iron (clean)[29]
	1830	copper (clean)[29]
	50	alumina[25]
	24–25	*i*-Al-Pd-Mn (air-oxidized)[25]
	17–18	PTFE (Teflon)[25]

Superior mechanical properties

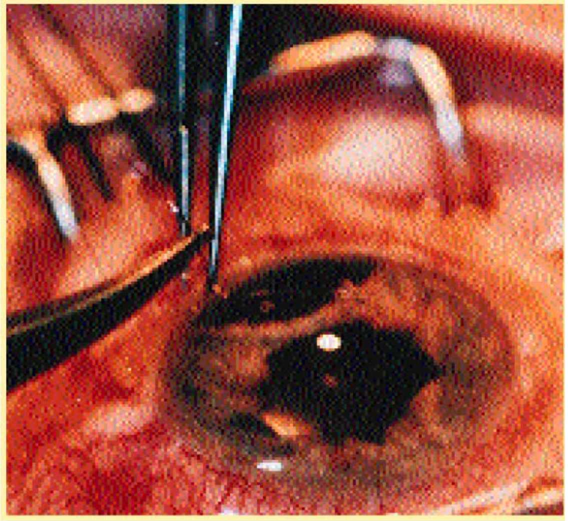
Low surface energy
: oxidation resistive

Table. Example and comparison of properties of some icosahedral structures

※ The properties can be different to composition, particle size and etc.

Quasicrystal

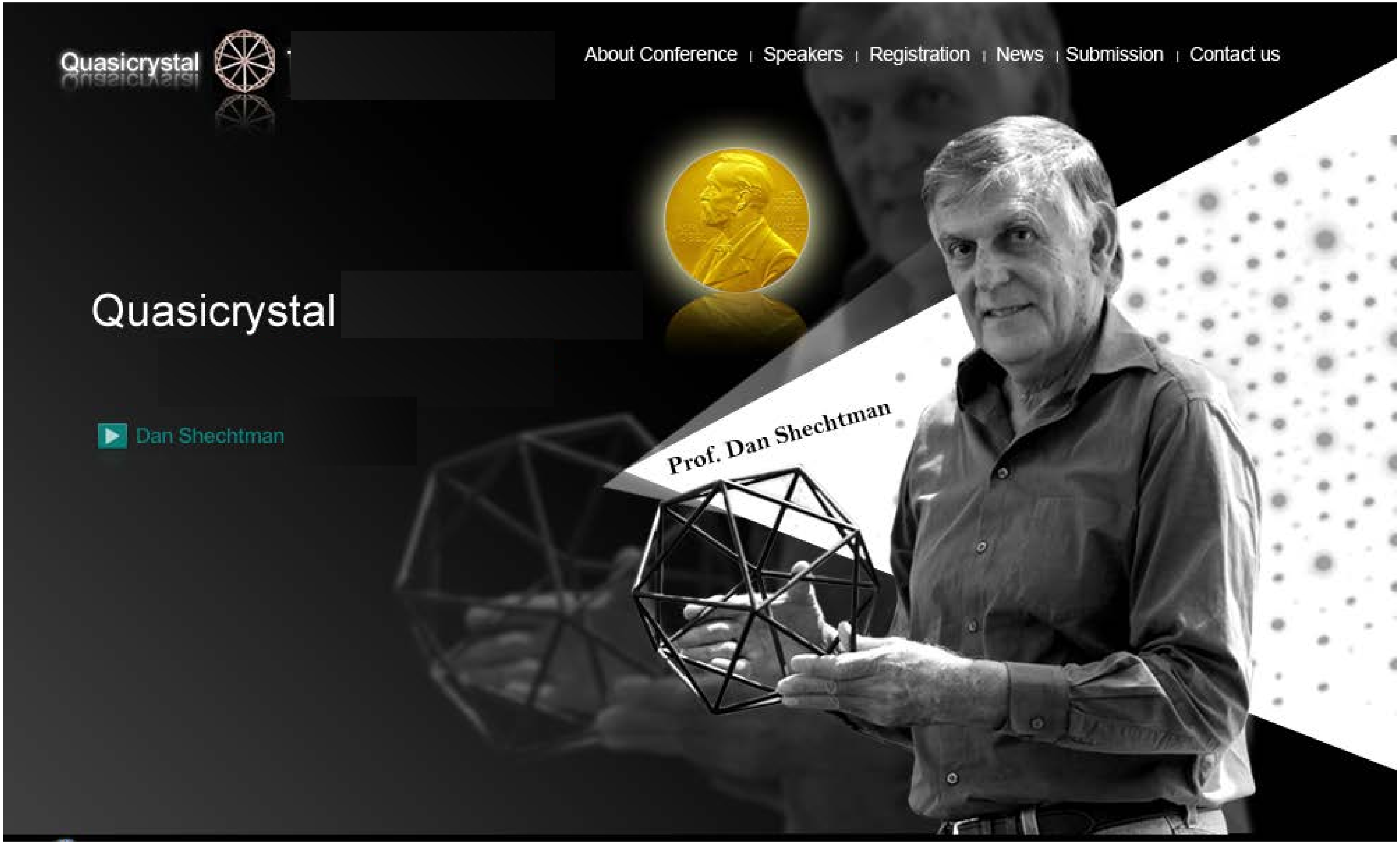
Quasicrystal material coated frying pan that uses the surface endurance of it.



medical instruments that must be easy to form, yet very strong, to avoid breakage during use.

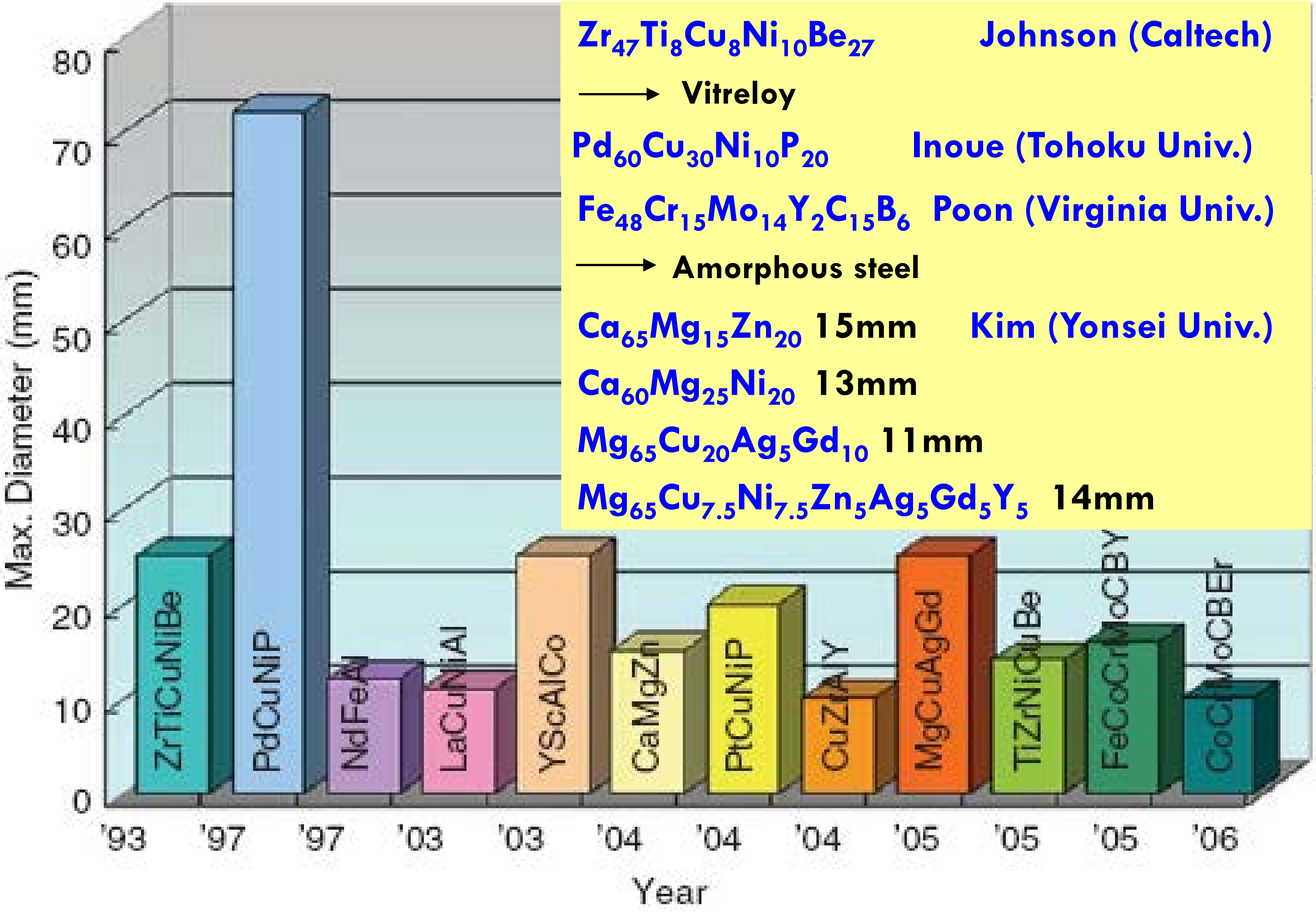
Thermal barrier material in Engine that should have high thermal efficiency

2011 Nobel Prize in Chemistry: Quasicrystal



A new ordered phase showing the apparent fivefold symmetry was observed by Sastry et al. [Mater. Res. Bull. 13: 1065-1070] in 1978 in a rapidly solidified Al-Pd alloy, but was interpreted to arise from a microstructure Consisting of a series of fine twins. This was later shown to be a two-dimensional (or decagonal) qasicrystal.

d. Bulk Metallic Glasses_Recent BMGs with critical size ≥ 10 mm



$Zr_{47}Ti_8Cu_8Ni_{10}Be_{27}$ Johnson (Caltech)

⟶ Vitreloy

$Pd_{60}Cu_{30}Ni_{10}P_{20}$ Inoue (Tohoku Univ.)

$Fe_{48}Cr_{15}Mo_{14}Y_2C_{15}B_6$ Poon (Virginia Univ.)

⟶ Amorphous steel

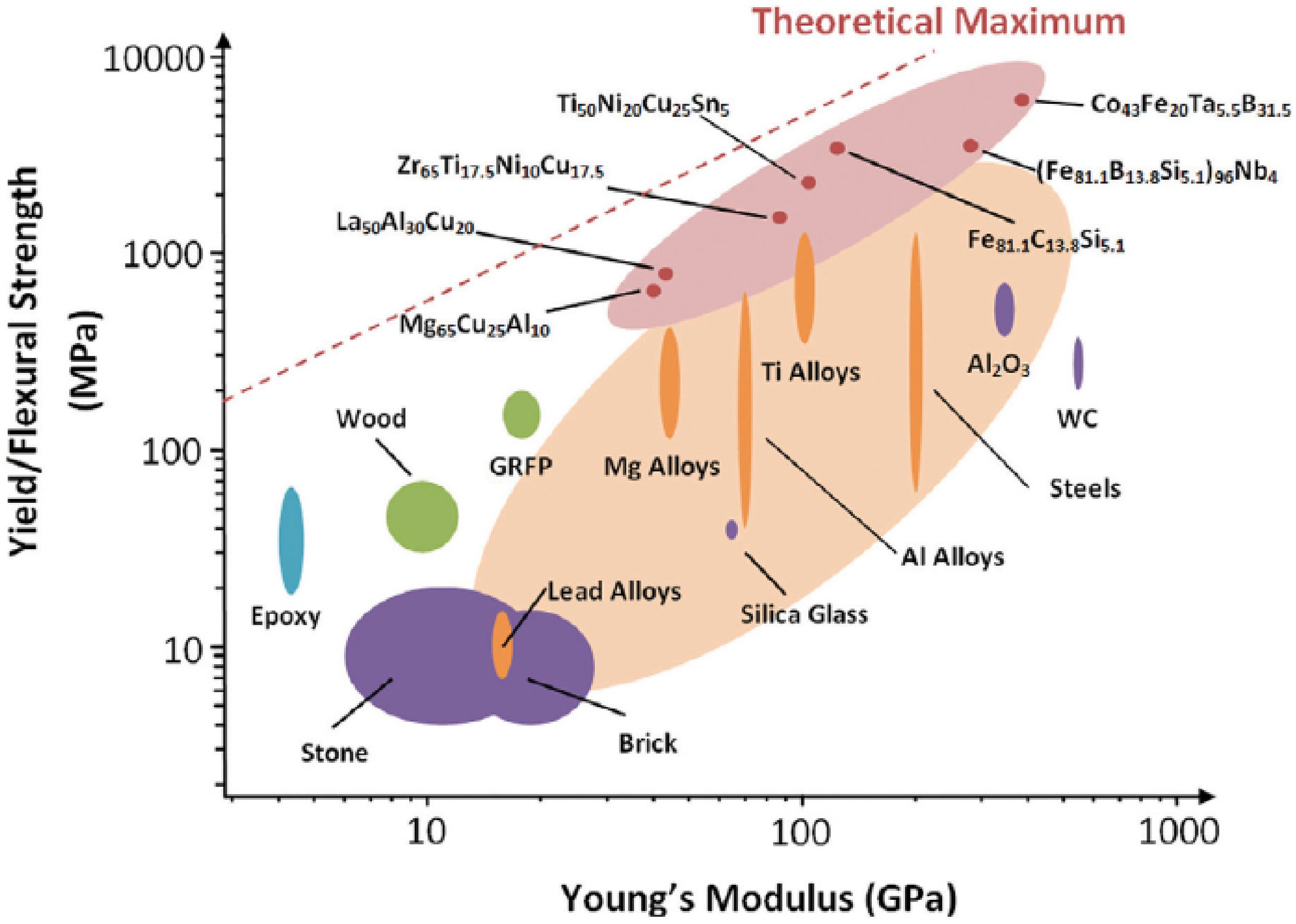
$Ca_{65}Mg_{15}Zn_{20}$ 15mm Kim (Yonsei Univ.)

$Ca_{60}Mg_{25}Ni_{20}$ 13mm

$Mg_{65}Cu_{20}Ag_5Gd_{10}$ 11mm

$Mg_{65}Cu_{7.5}Ni_{7.5}Zn_5Ag_5Gd_5Y_5$ 14mm

(1) High strength of BMGs



High fracture strength over 5 GPa in Fe-based BMGs

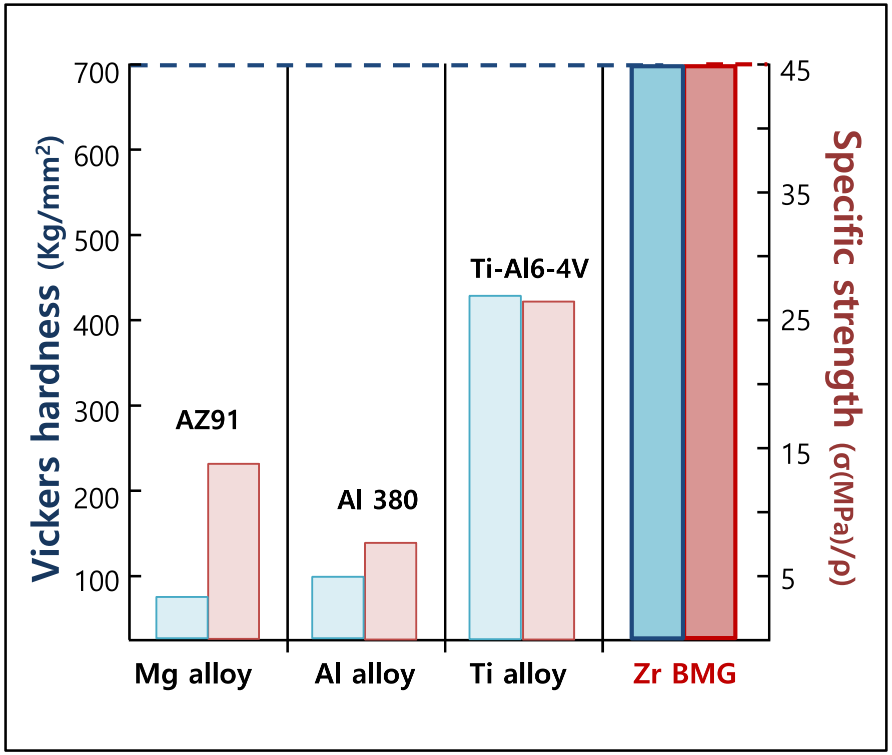
A.L. Greer, E. Ma, MRS Bulletin, 2007; 32: 612.

Bulk metallic glasses with high strength

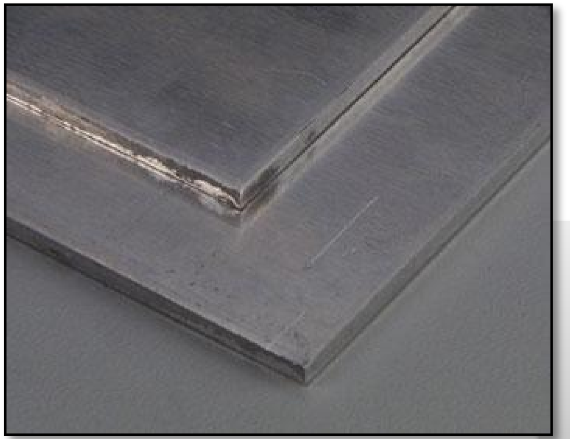
- **"High specific strength"** → Ultra-thin product with reasonable strength

: Possible to reduce more thickness with same standard strength than conventional light alloys due to superior specific strength

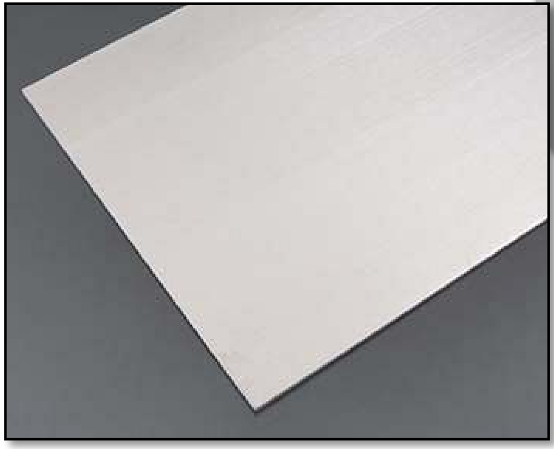
→ **Flexible / Wearable electronics**



Comparison of specific strength among Zr based BMG and conventional light alloys

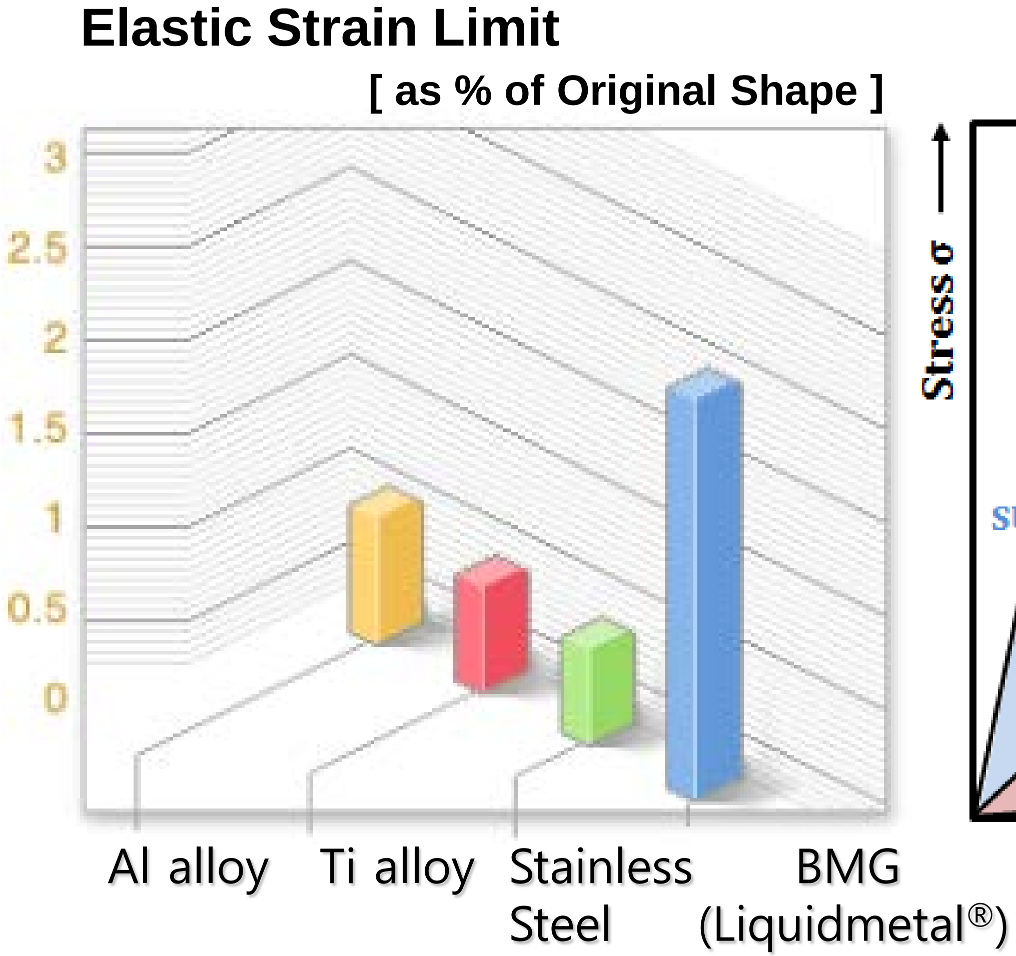


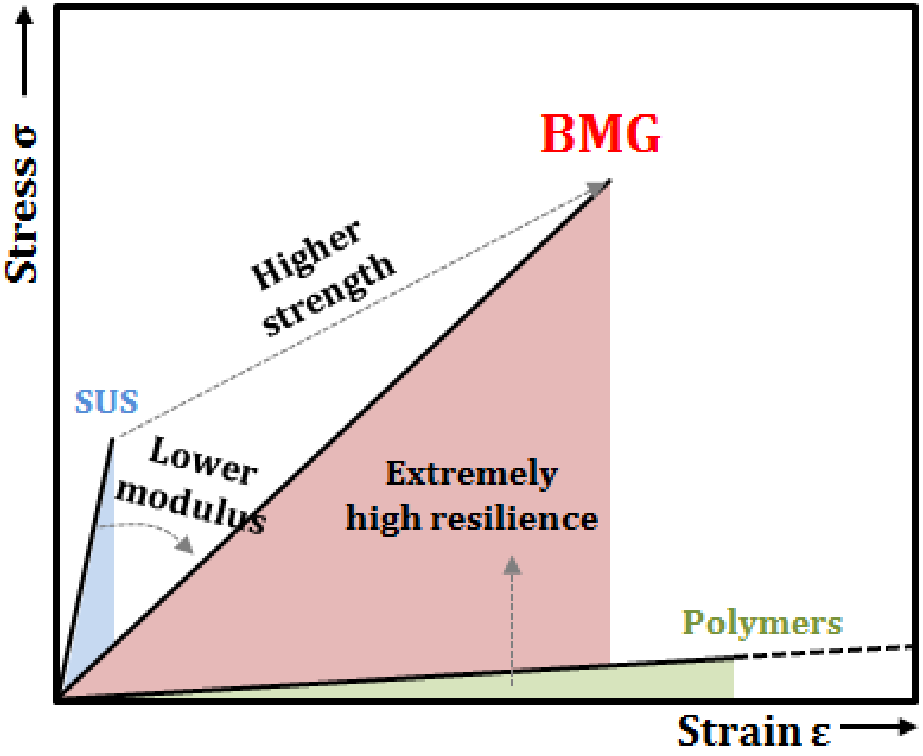
Mg – AZ91



Thinner plate: BMG

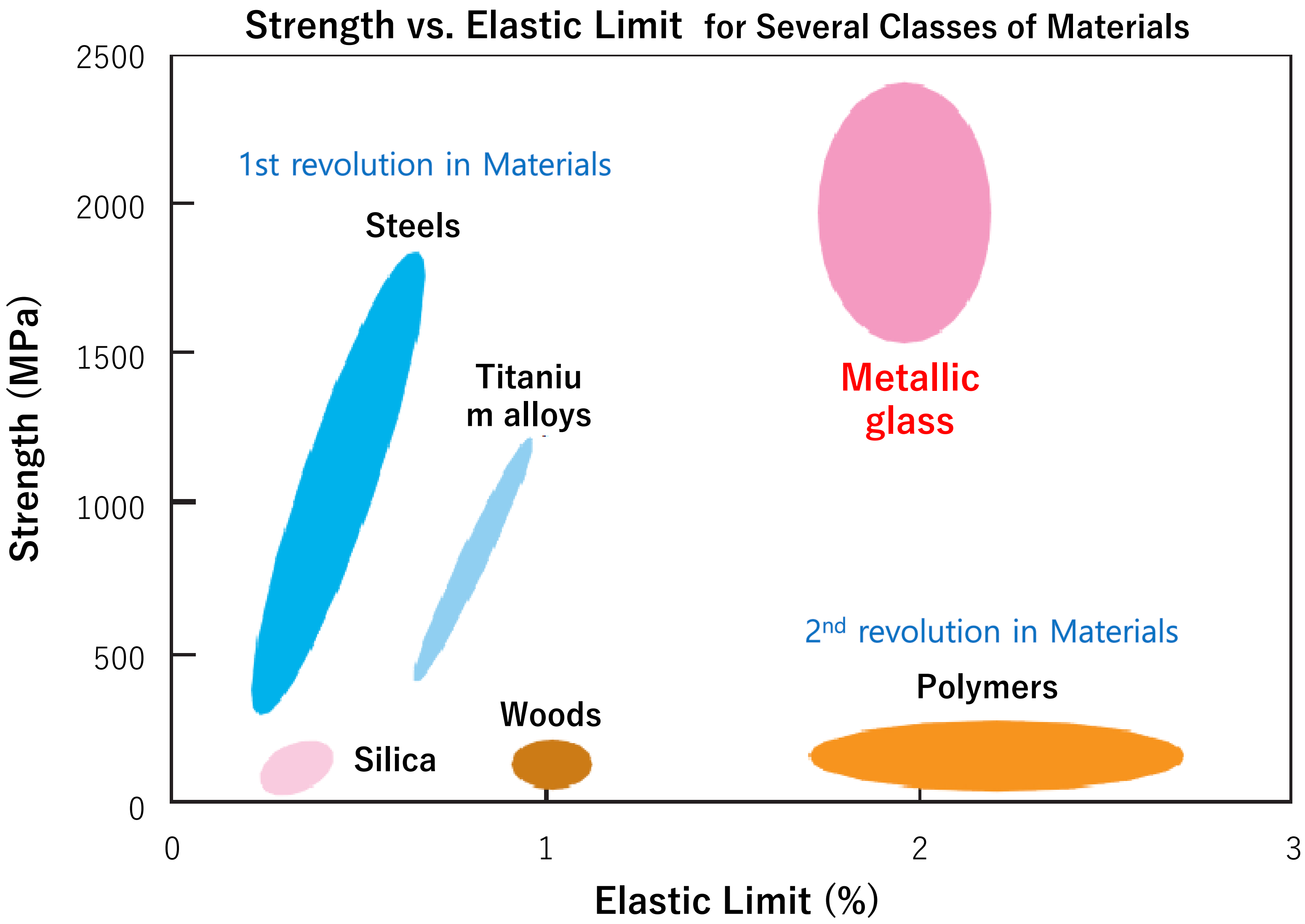
(2) Large elastic strain limit of BMGs





* Resilience: ability to return to the original form, position, etc. → $U = \frac{\sigma_y 2}{2E}$

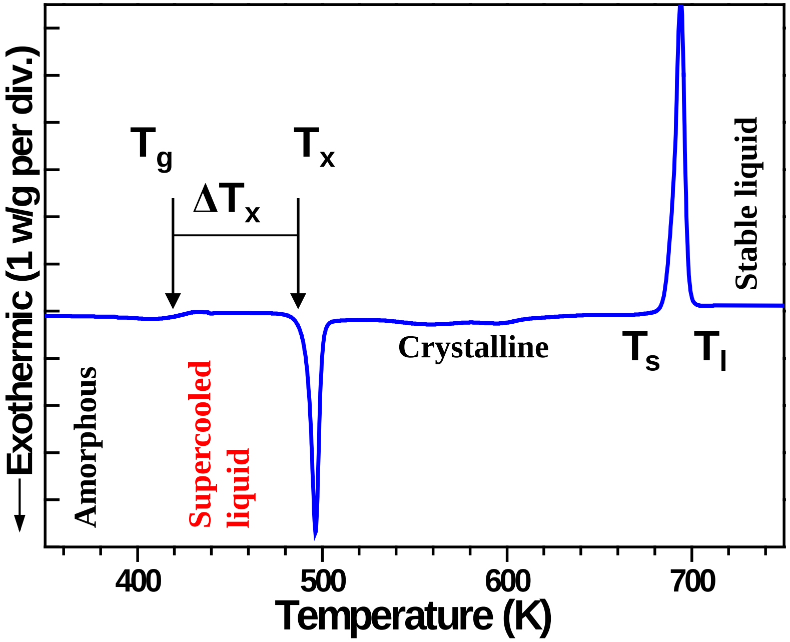
Bulk Metallic Glass: the 3rd Revolution in Materials?

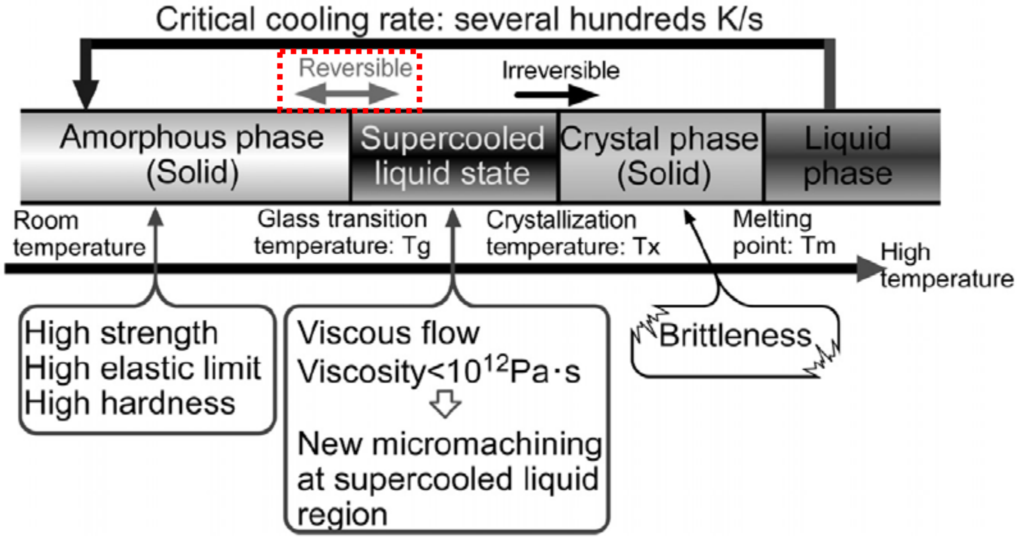


: Metallic Glasses Offer a Unique Combination of High Strength and High Elastic Limit

(3) Processing metals as efficiently as plastics

Thermoplastic forming





Critical cooling rate: several hundreds K/s

Reversible

Irreversible

Amorphous phase (Solid)

Supercooled liquid state

Crystal phase (Solid)

Liquid phase

Room temperature

Glass transition temperature: Tg

Crystallization temperature: Tx

Melting point: Tm

High temperature

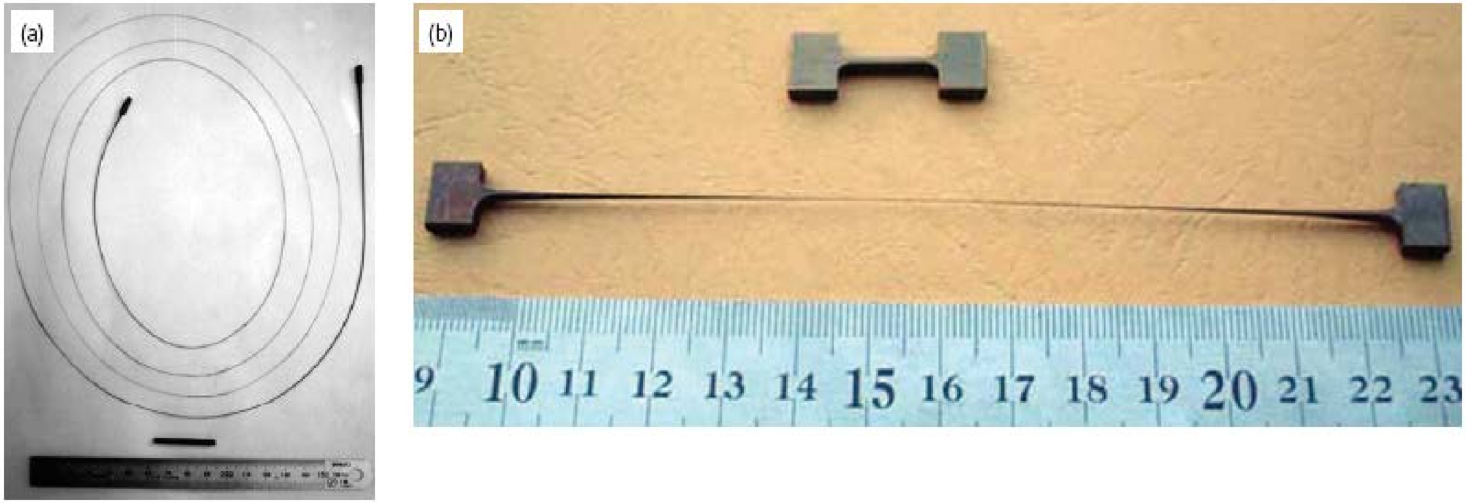
High strength
High elastic limit
High hardness

Viscous flow
Viscosity<10^{12}Pa·s

New micromachining at supercooled liquid region

Brittleness

Tensile specimens following superplastic forming in supercooled liquid region

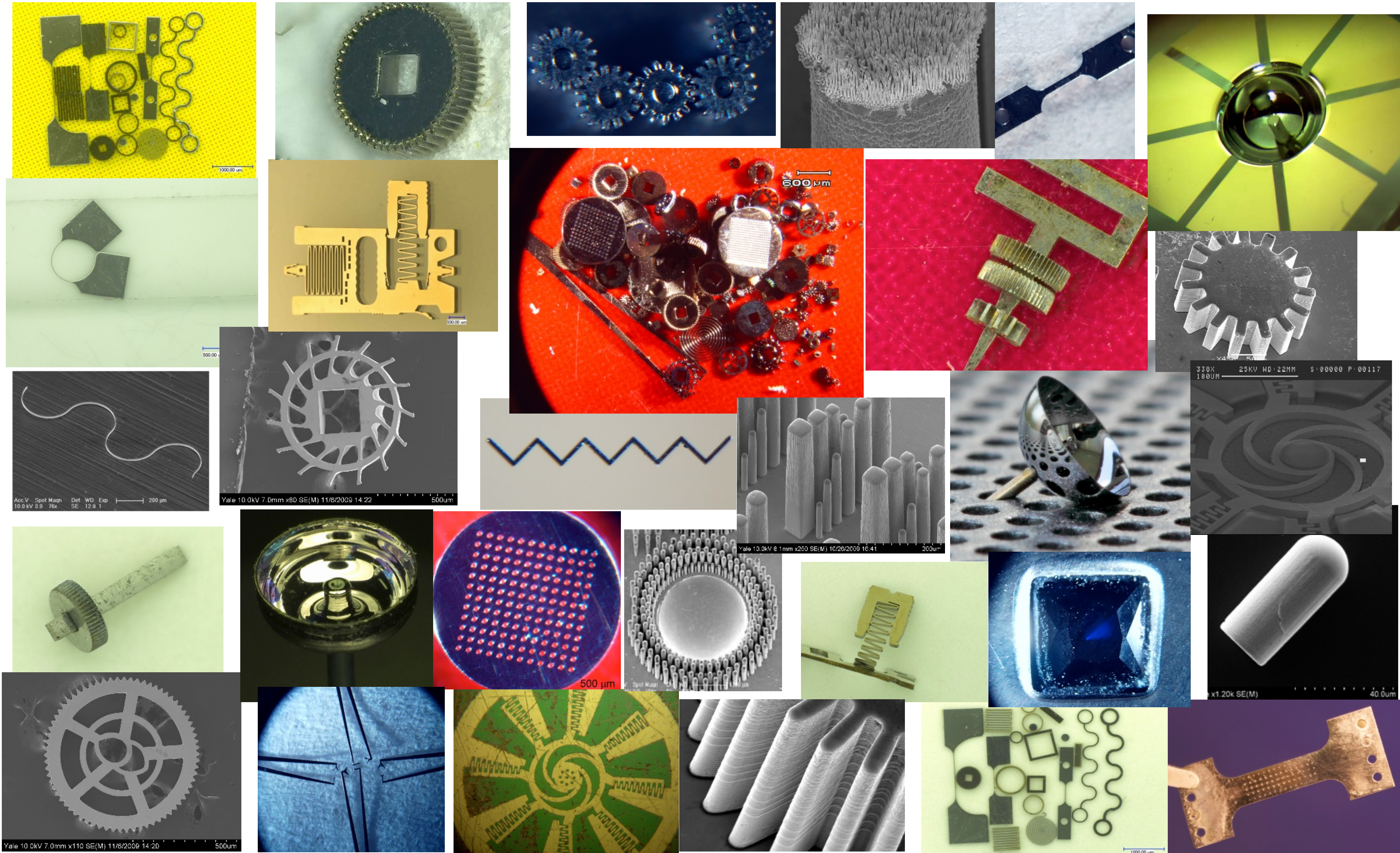


Materials Views
www.MaterialsViews.com

ADVANCED MATERIALS
www.advmat.de

Processing of Bulk Metallic Glass

Adv. Mater. **2009**, *21*, 1–32



Processing metals as efficiently as plastics: net-shape forming!

Seamaster Planet Ocean Liquidmetal® Limited Edition

- **Superior thermo-plastic formability**

  : possible to fabricate complex structure without joints

  ↳ Multistep processing can be solved by simple casting

  ↳ Ideal for small expensive IT equipment manufacturing

METAL MIXOLOGY

Representative FCC high entropy alloy: $Fe_{20}Cr_{20}Mn_{20}Ni_{20}Co_{20}$

ELSEVIER

Materials Science and Engineering A 375–377 (2004) 213–218

MATERIALS SCIENCE & ENGINEERING A

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Microstructural development in equiatomic multicomponent alloys

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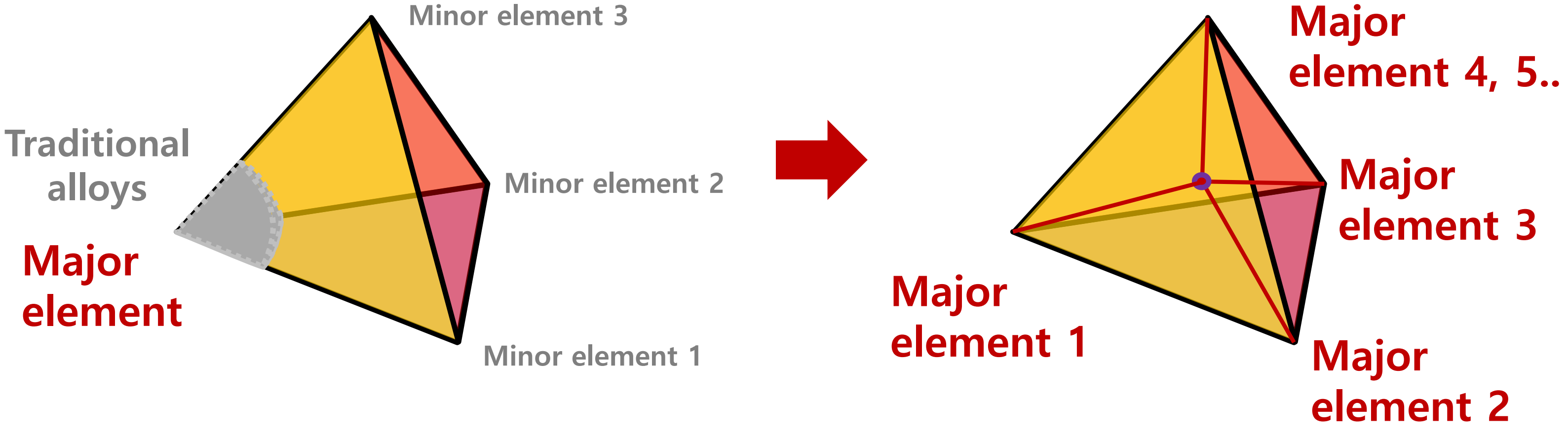
School of Metallurgy and Materials, Birmingham University, Birmingham B15 2TT, UK

Abstract

Multicomponent alloys containing several components in equal atomic proportions have been manufactured by casting and melt spinning, and their microstructures and properties have been investigated by a combination of optical microscopy, scanning electron microscopy, electron probe microanalysis, X-ray diffractrometry and microhardness measurements. Alloys containing 16 and 20 components in equal proportions are multiphase, crystalline and brittle both as-cast and after melt spinning. A five component $Fe_{20}Cr_{20}Mn_{20}Ni_{20}Co_{20}$ alloy forms a single fcc solid solution which solidifies dendritically. A wide range of other six to nine component late transition metal rich multicomponent alloys exhibit the same majority fcc primary dendritic phase, which can dissolve substantial amounts of other transition metals such as Nb, Ti and V. More electronegative elements such as Cu and Ge are less stable in the fcc dendrites and are rejected into the interdendritic regions. The total number of phases is always well below the maximum equilibrium number allowed by the Gibbs phase rule, and even further below the maximum number allowed under non-equilibrium solidification conditions. Glassy structures are not formed by casting or melt spinning of late transition metal rich multicomponent alloys, indicating that the confusion principle does not apply, and other factors are more important in promoting glass formation.

Keywords: Multicomponent alloys; Equiatomic; Casting

Basic concepts of high entropy alloy (HEA)



Conventional alloy system

Ex) 304 steel - $Fe_{74}Cr_{18}Ni_{8}$

High entropy alloy system

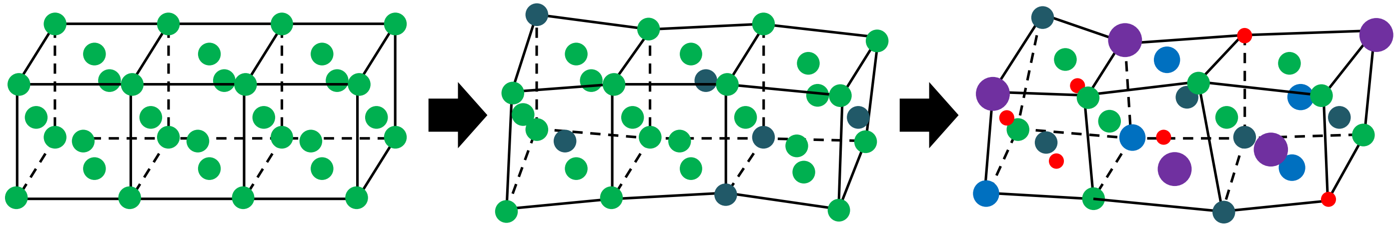
Ex) $Al_{20}Co_{20}Cr_{20}Fe_{20}Ni_{20}$

(1) Thermodynamic : high entropy effect

(2) Kinetics : sluggish diffusion effect

(3) Structure : severe lattice distortion effect

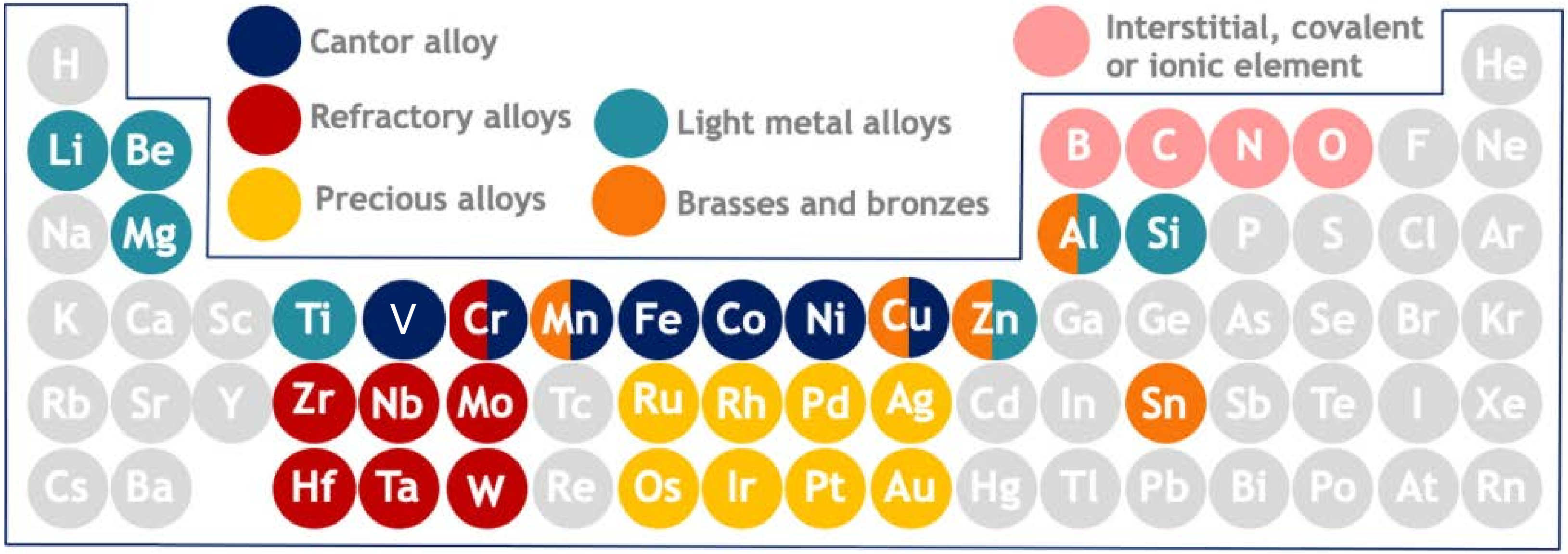
(4) Property : cocktail effect



Pure metal Conventional alloy High entropy alloy

Severe lattice distortion → Sluggish diffusion & Thermal stability

Classification of HEA



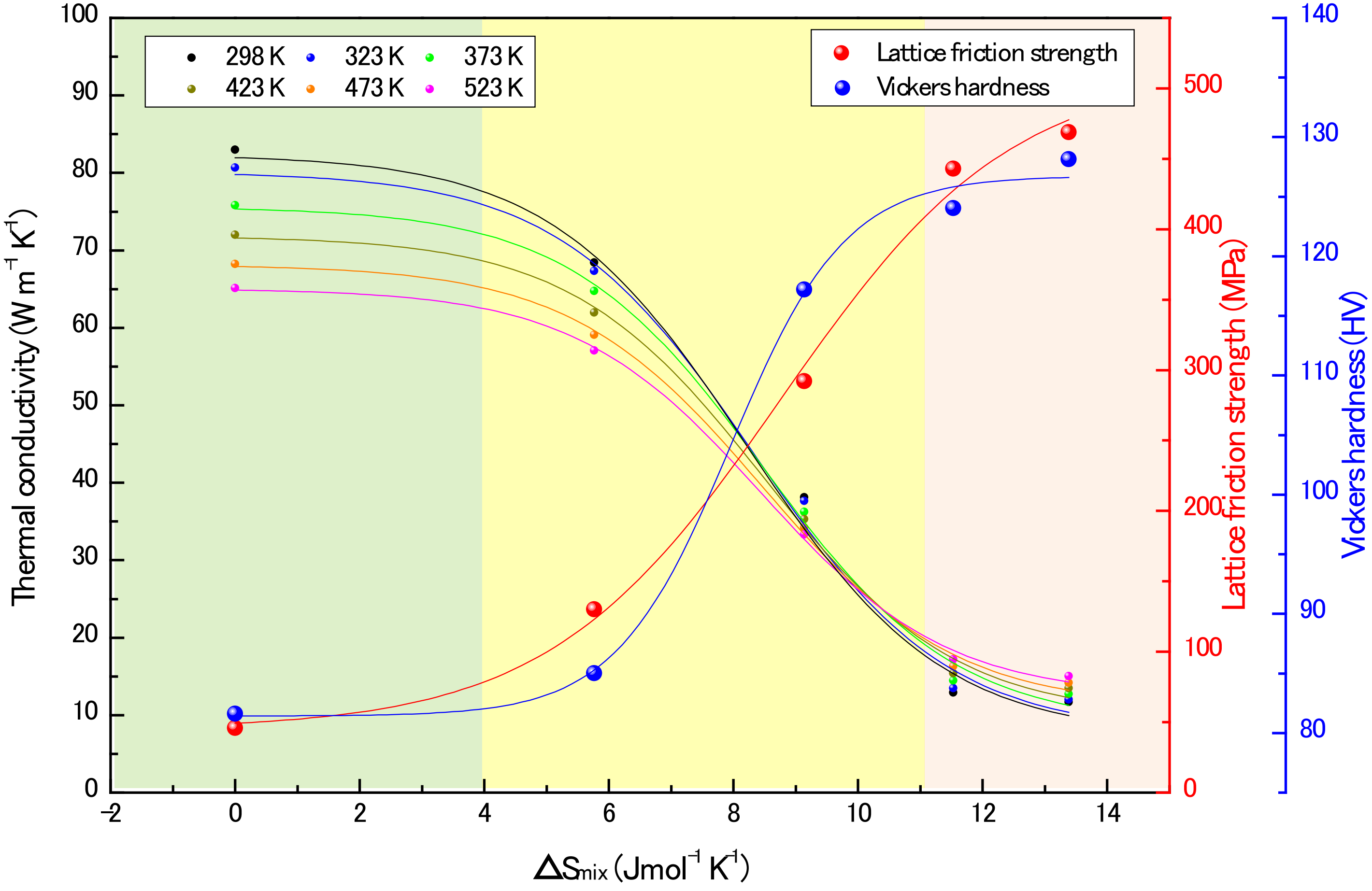
Solid solution strengthening in Cantor-like high entropy alloy?

Properties of high entropy alloys

Higher σ_y/κ ratio

$\kappa \downarrow$

Sluggish diffusion



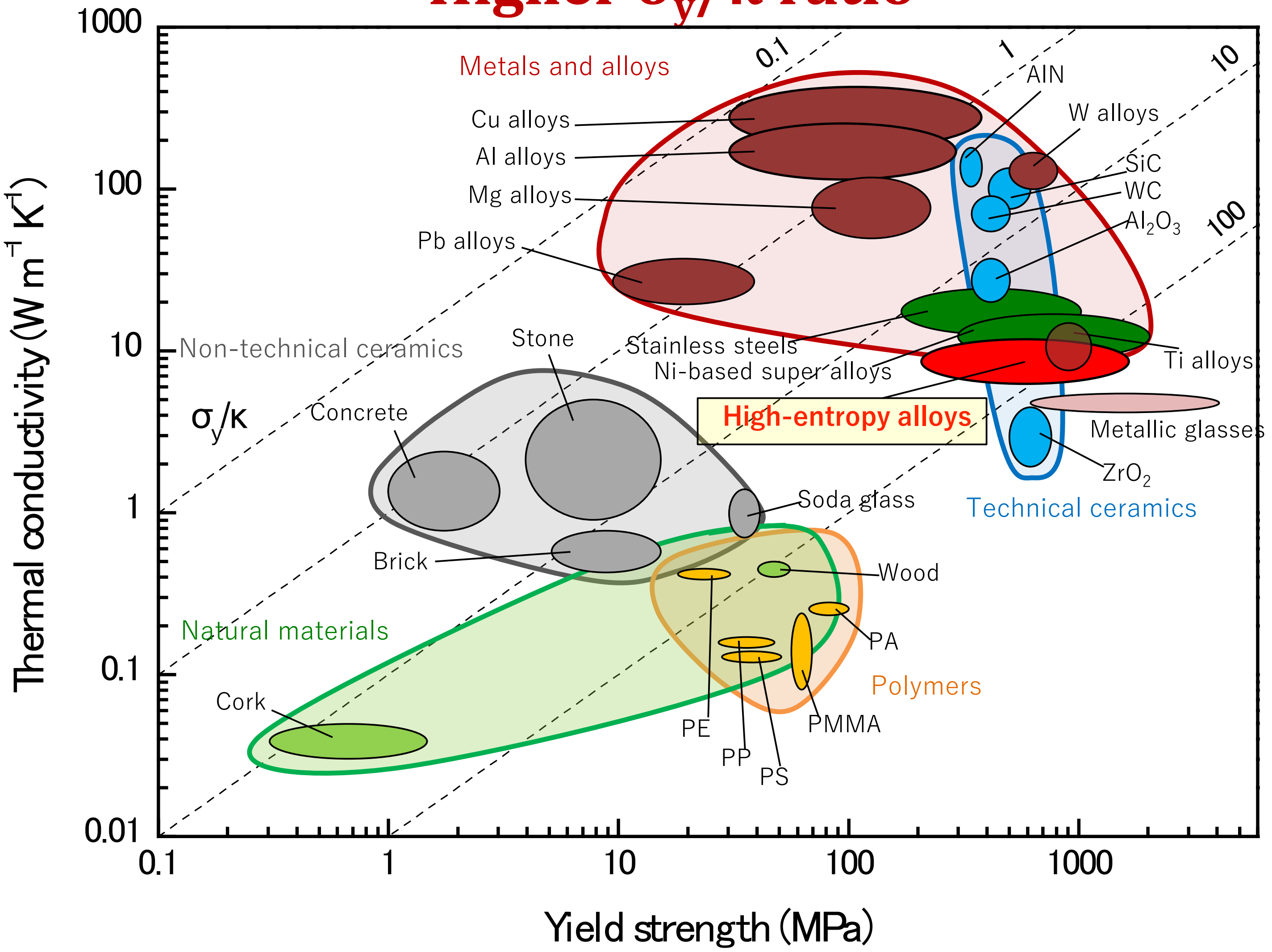
$H, \sigma_y \uparrow$

Lattice distortion

Possible to develop novel alloys with unique properties

Properties of high entropy alloys

Higher σ_y/κ ratio



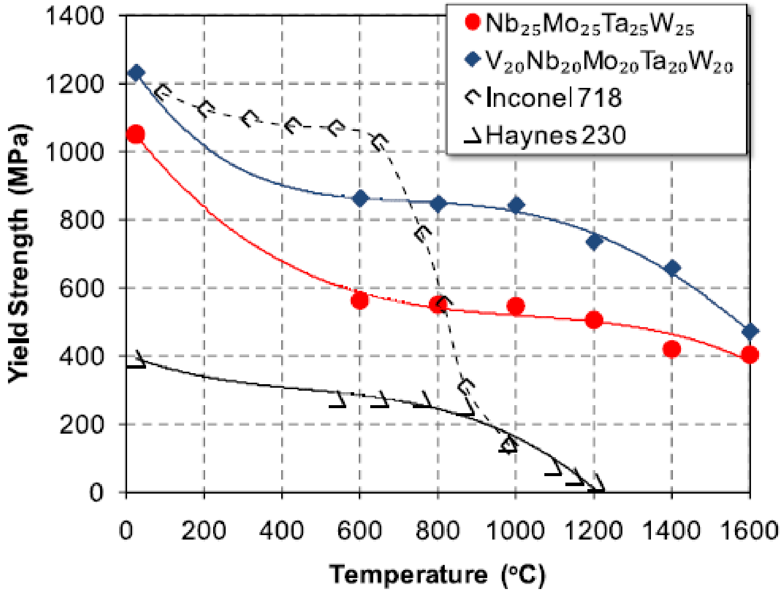
Possible to develop novel alloys with unique properties

Properties of high entropy alloys

"HEA = Structural material with good thermal stability"

High temperature strength in BCC HEA

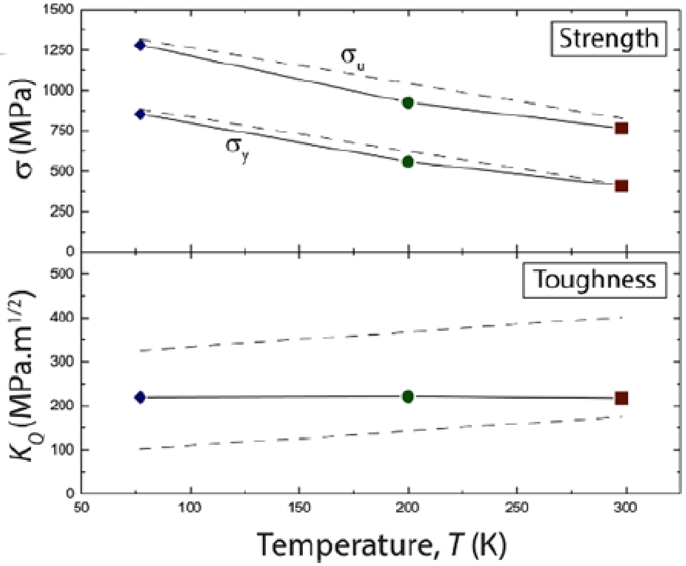
O.N.Senkov, et al., Intermetallics, vol19 (2011)



$V_{20}Nb_{20}Mo_{20}Ta_{20}W_{20}$ HEA has higher strength than $Nb_{25}Mo_{25}Ta_{25}W_{25}$, which means significant solid solution hardening effect in high temperature.

Low temperature toughness in FCC HEA

B.Gludovatz, et al., Science , vol345 (2014)



The toughness of the HEA remains unchanged, and by some measures actually increases at lower temp due to change of deformation mechanism.

* Development strategy of completely new materials

a. Alloyed pleasures: Multi-metallic cocktails

b. Synthesize metastable phases

Equilibrium conditions → Non-equilibrium conditions

: non-equilibrium processing = "energize and quench" a material

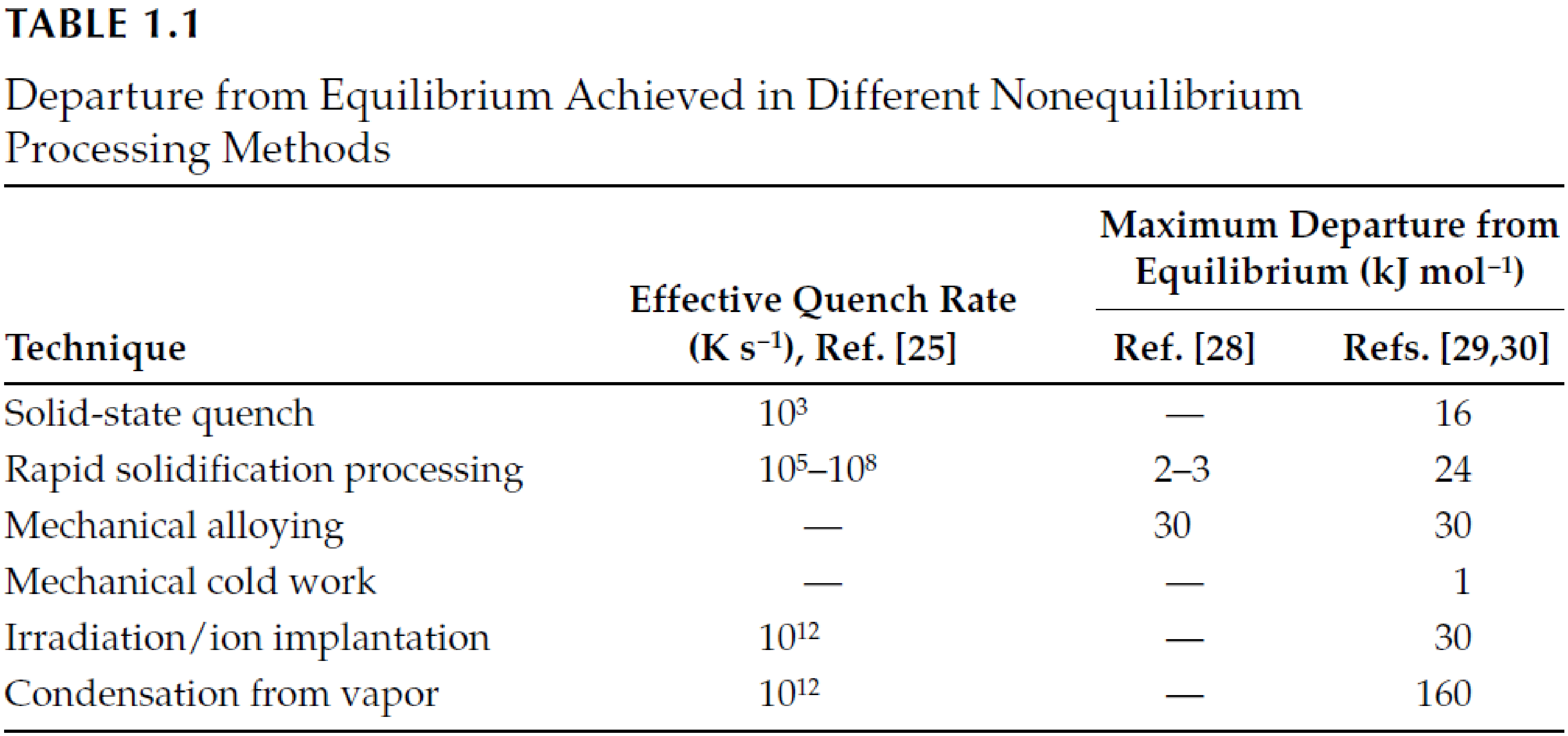
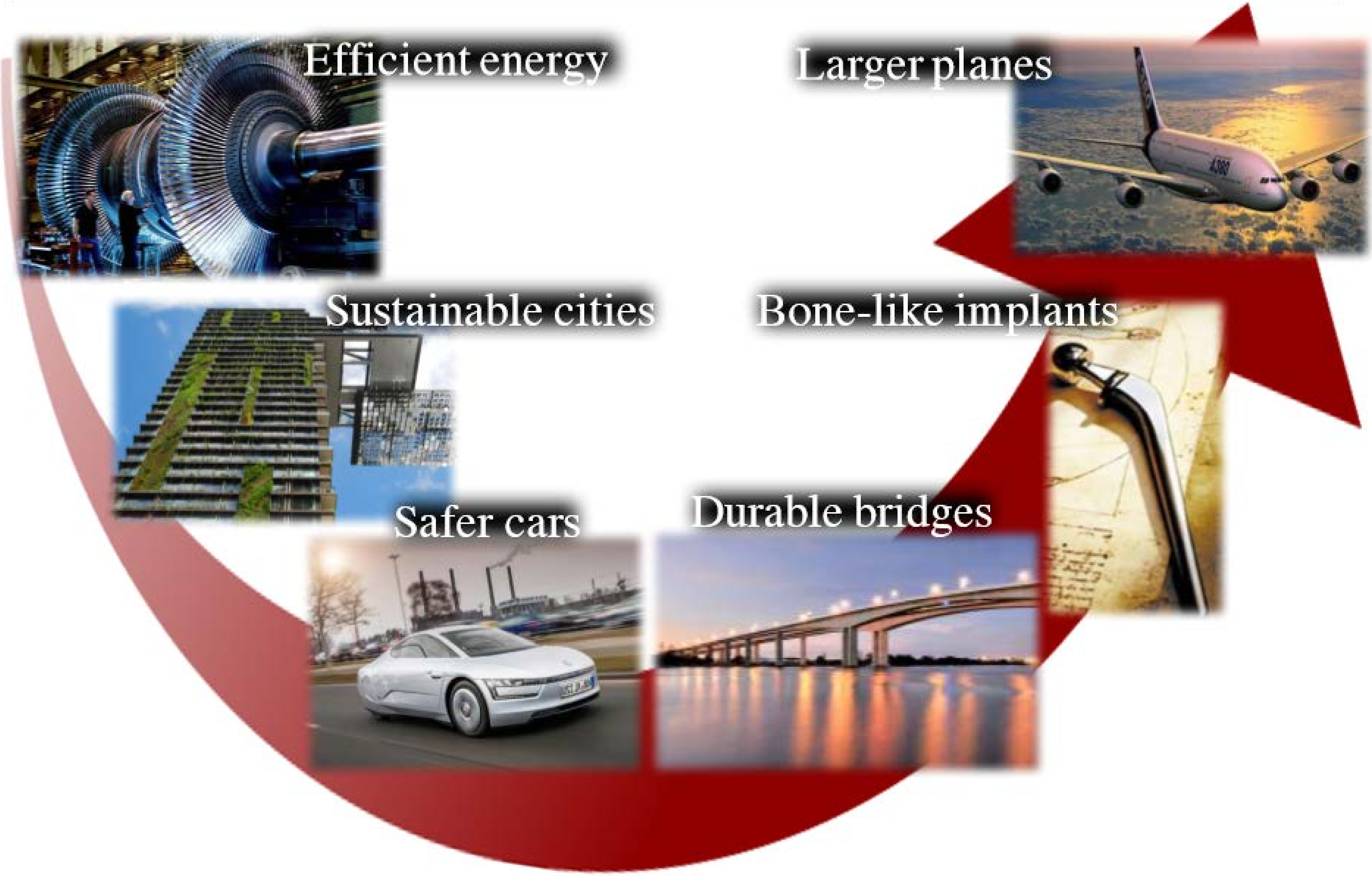


TABLE 1.1

Departure from Equilibrium Achieved in Different Nonequilibrium Processing Methods

Technique	Effective Quench Rate (K s^{-1}), Ref. [25]	Maximum Departure from Equilibrium (kJ mol^{-1}) Ref. [28]	Maximum Departure from Equilibrium (kJ mol^{-1}) Refs. [29,30]
Solid-state quench	10^3	—	16
Rapid solidification processing	10^5–10^8	2–3	24
Mechanical alloying	—	30	30
Mechanical cold work	—	—	1
Irradiation/ion implantation	10^{12}	—	30
Condensation from vapor	10^{12}	—	160

Still design-for-properties, to enable new technologies



Efficient energy

Sustainable cities

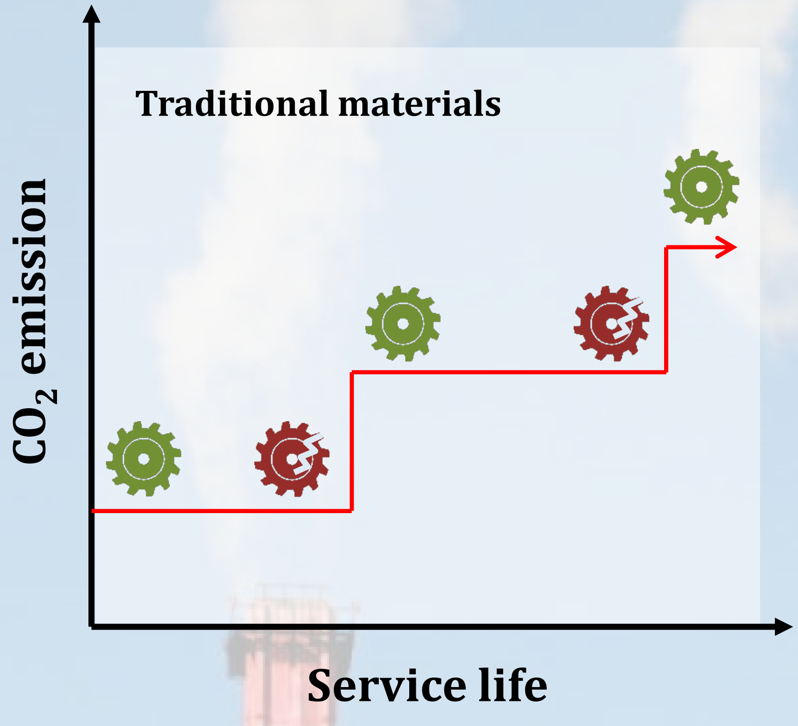
Safer cars

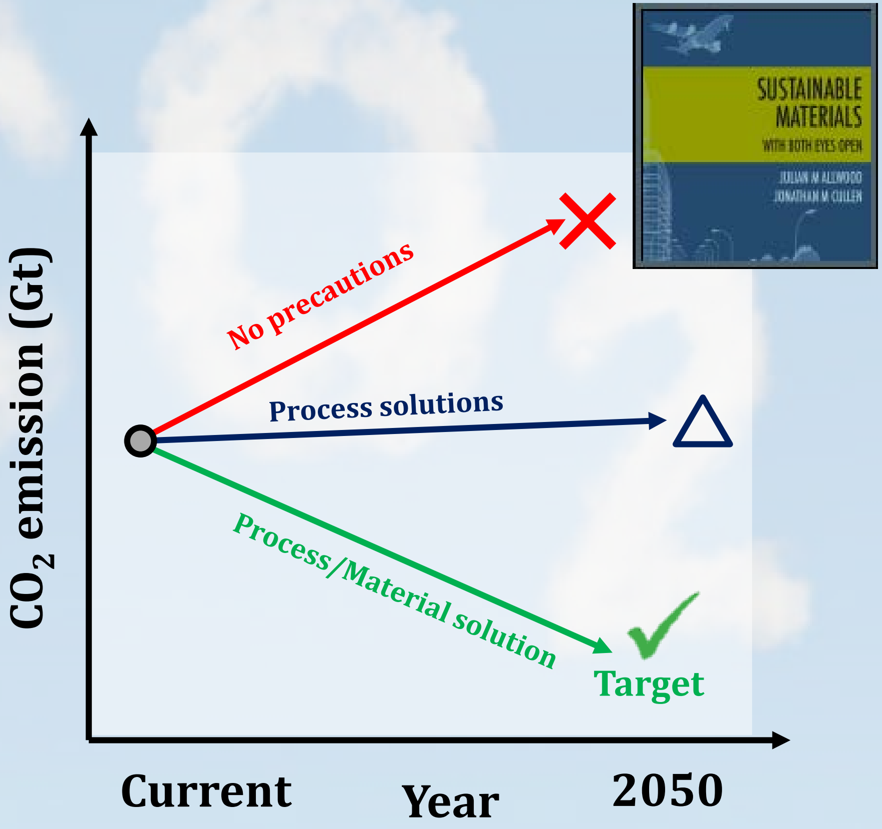
Durable bridges

Bone-like implants

Larger planes

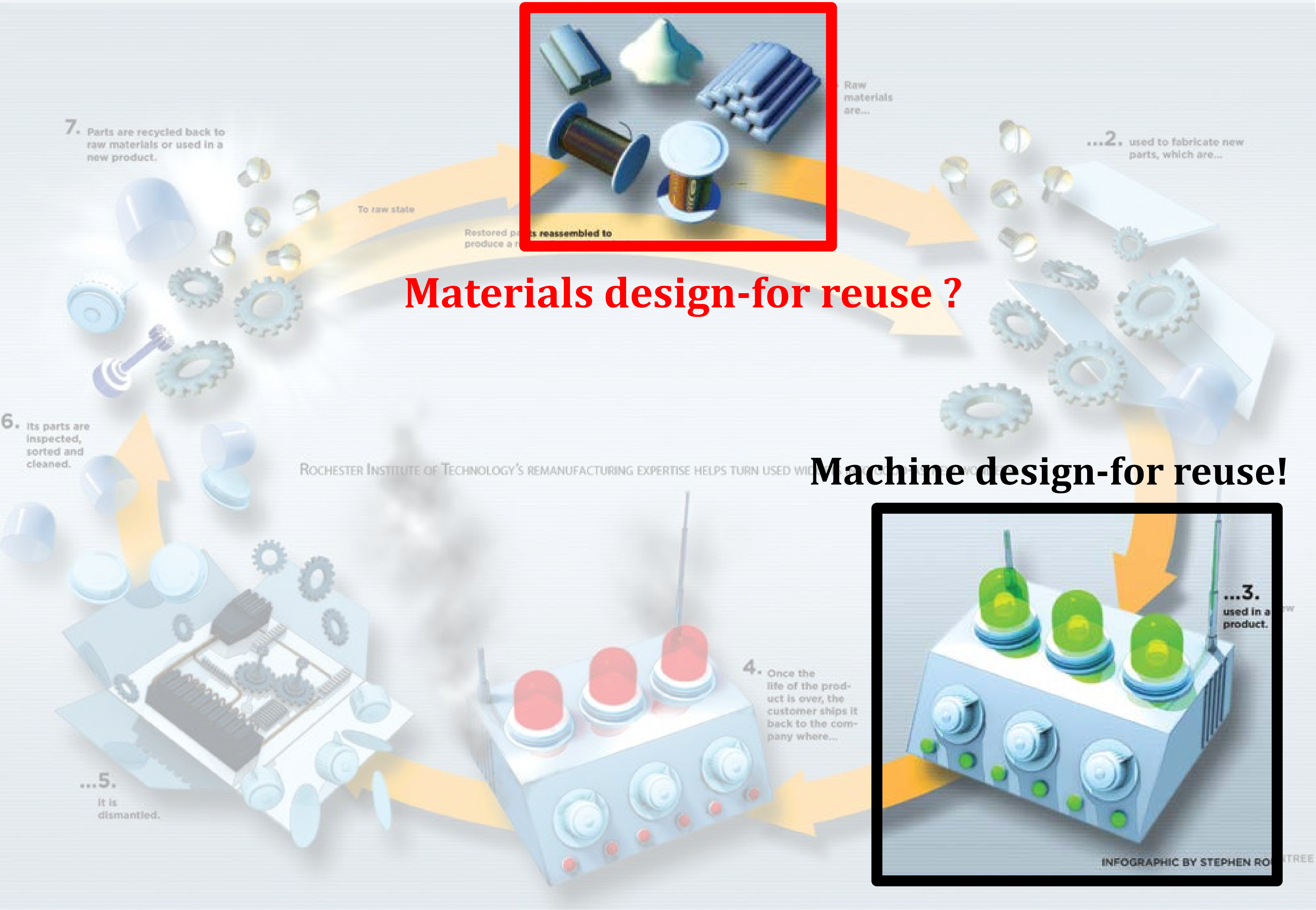
New challenges : *Less use, Extend lifetime, Reuse!*





Extend lifetime, where possible, *Reuse!*

Remanufacturing : Machine design-for-reuse!



Materials design-for reuse ?

Machine design-for reuse!

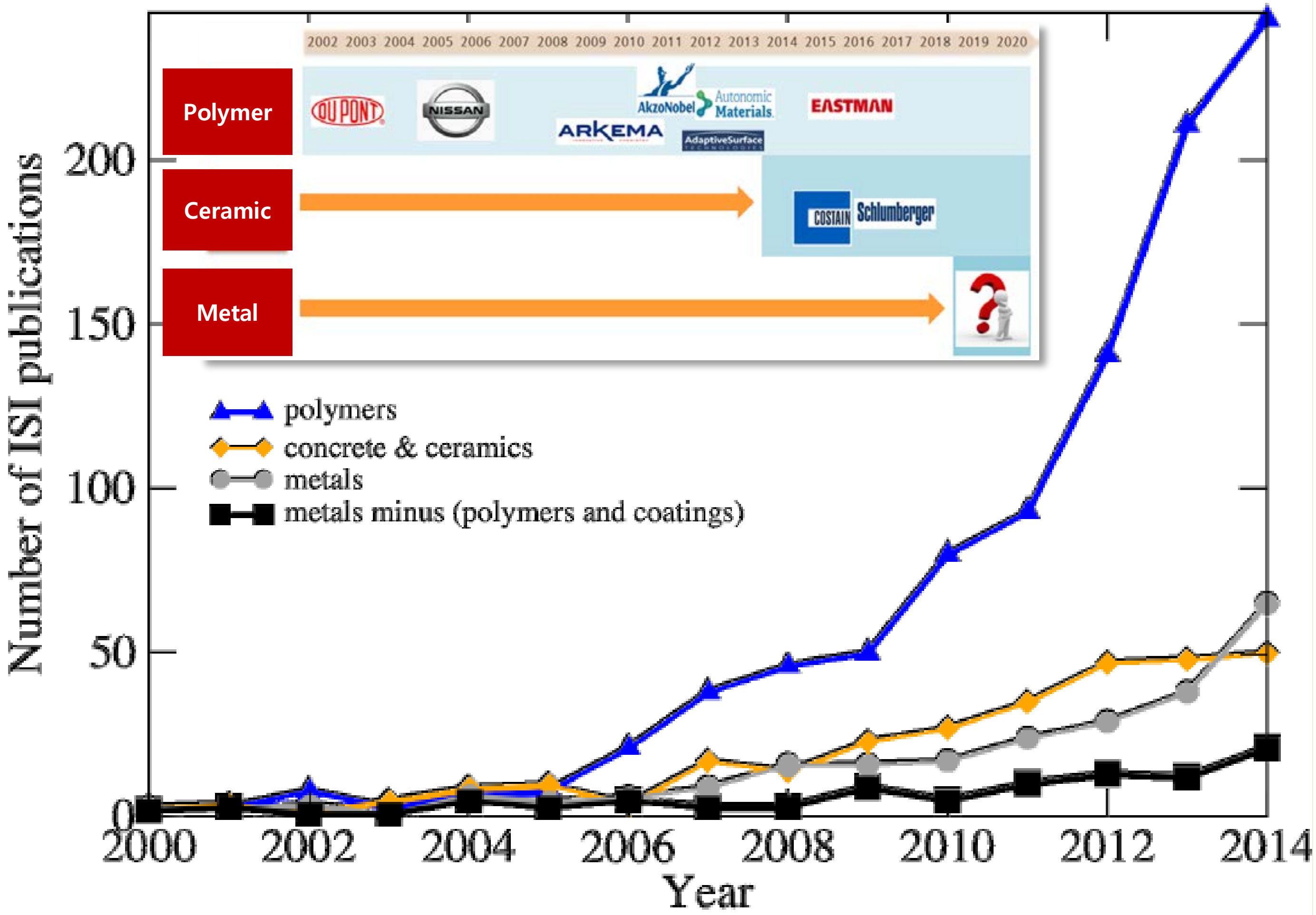
Materials design for reuse

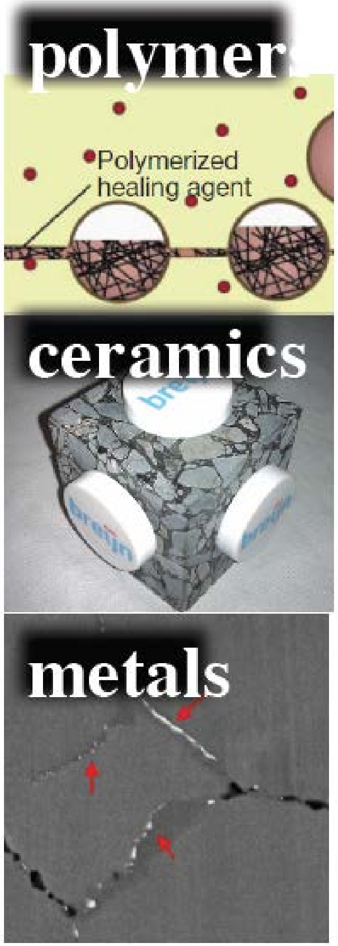
Damage process is incremental, and often local → repair opportunity

Two damage repair options possible:

- The metal autonomously repair damage → ***Self-healing***
- Damage is repaired by an external treatment → ***Resetting***

Self Healing New paradigm for structural material development





- Transformation kinetics in metals are slow at room temperature!

Commercialized self-healing polymer

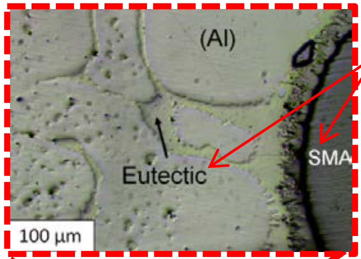
Healing agent's movement and reaction occurs even with small energy at room temperature

Self-healing metals

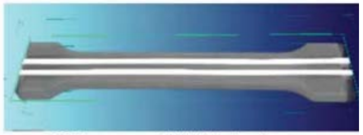
Current technical level

Prevention of microcrack propagation via healing agent

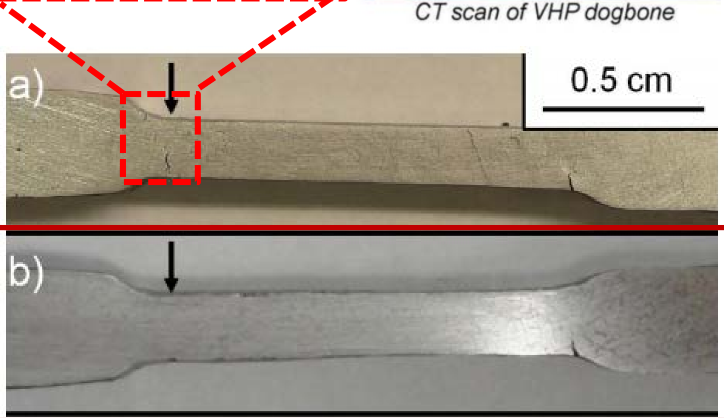
Al-3at% Si composite reinforced with 2 vol% NITI SMA wire



a. Healing agent
(ex. SMA wire etc.)



CT scan of VHP dogbone

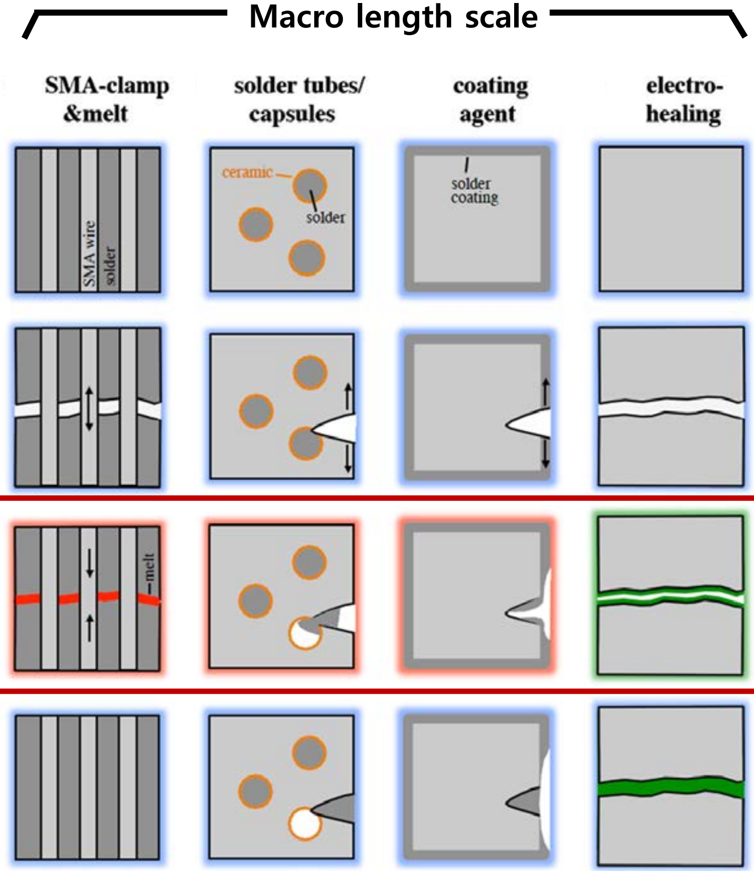


heating

b. Healing Treatment & **c. Local melting**
(ex. Aging, electro pulse etc.) (ex. Eutectic phase, Sn etc.)

➡ **Prevention of Macroscale crack propagation**

Grabowski & Tasan, Self-healing Metals (2016).

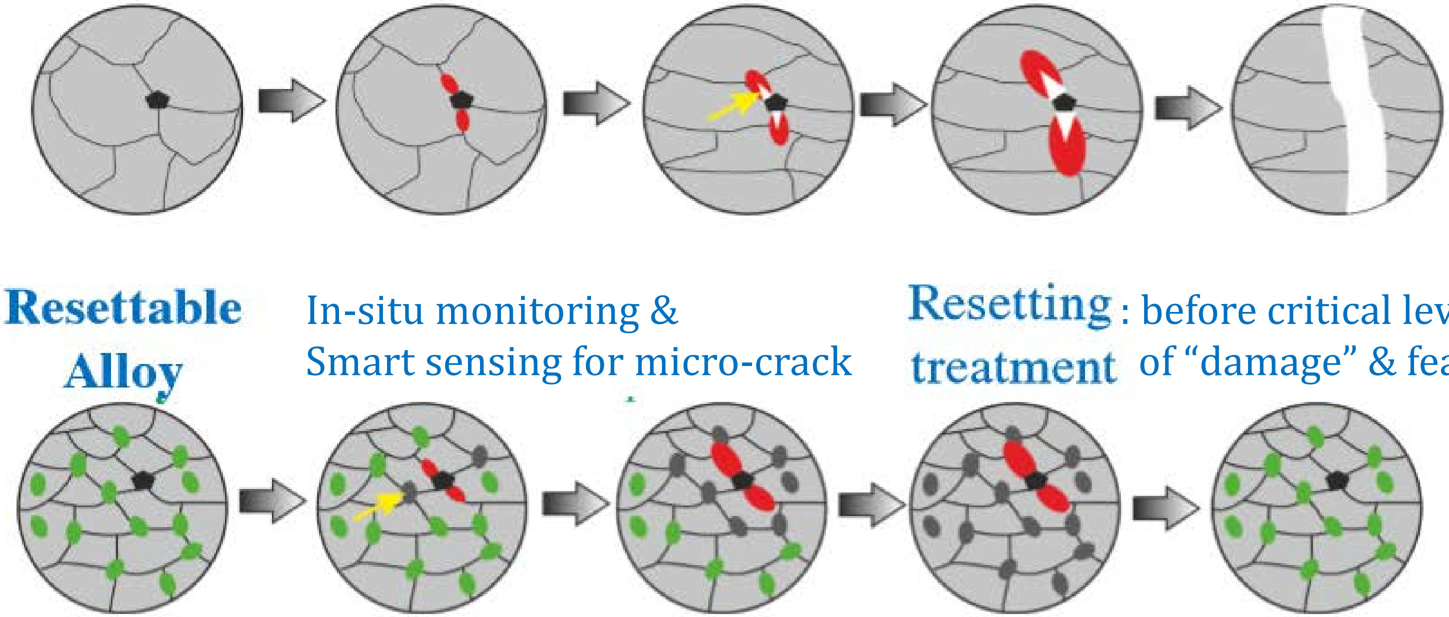


Heating or E field

For metals, restrictive thermodynamic / kinetic driving force for self-healing at RT!

Self-healing metals vs Resettable alloys

- self-healing: "*autonomic closure of micro-cracks*"
- resetting: "*non-autonomic retrieval of crack-arresting ability*"



Conventional Alloy

Increasing local stress

Micro-crack nucleation

Macro-crack

Resettable Alloy

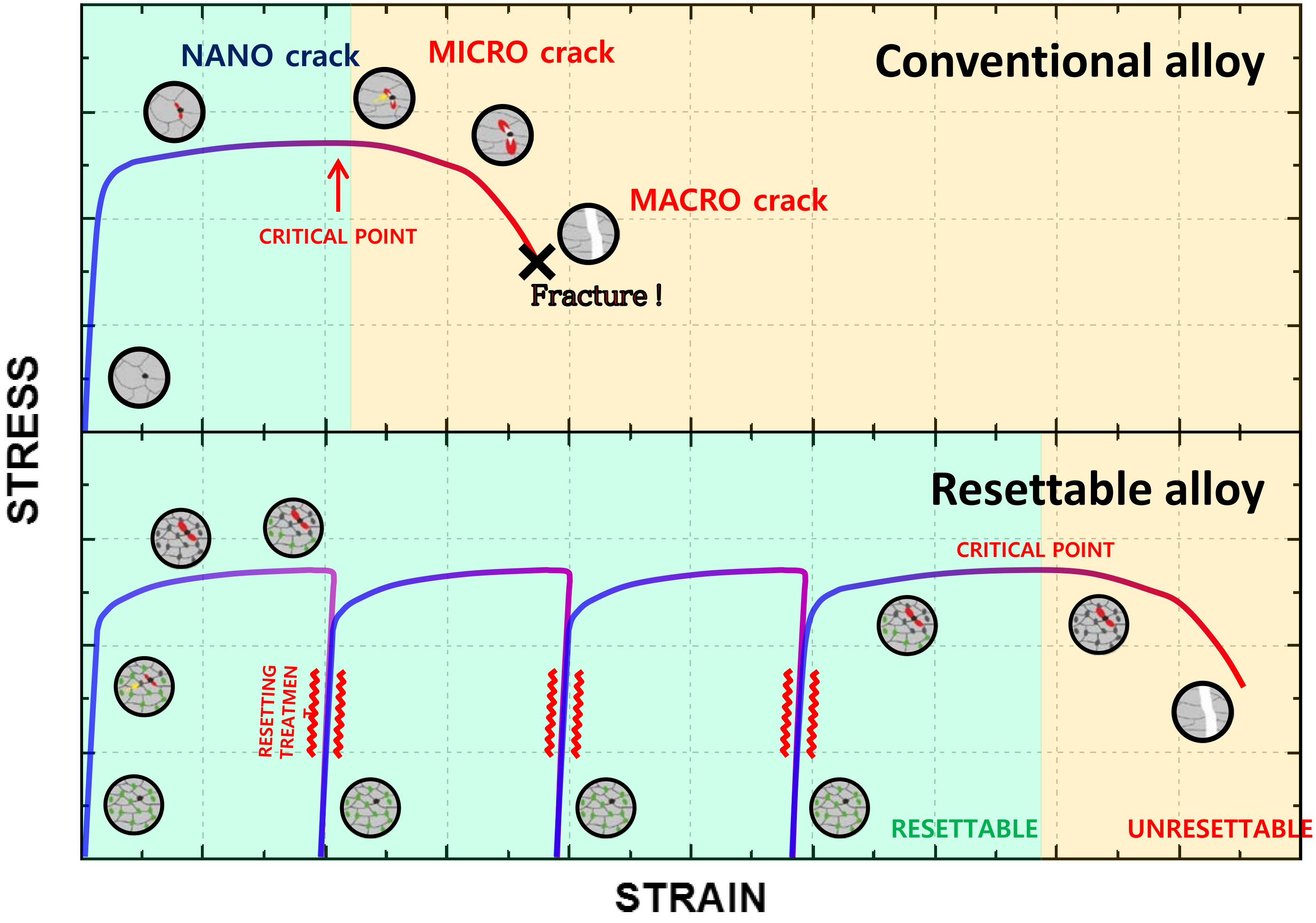
In-situ monitoring &
Smart sensing for micro-crack

Resetting treatment : before critical level of "damage" & feasible

: revert to the original microsturcture

Different failure mechanisms require different resetting strategies

New challenges : *Resettable alloys!*



Resetting treatment 를 통해 초기 미세구조로 회복 가능한 Resettable alloy!

Urgent need for mission change:

Materials design-for-“properties” & “reuse”