Physical Metallurgy Principles Applied to Steels and Other Ferrous Alloys

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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


\[
\text{UTS(MPa)} = 3.45(\text{HB})
\]
\[
\text{UTS(psi)} = 500(\text{HB})
\]
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.

<table>
<thead>
<tr>
<th>Ionic Bonds</th>
<th>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.</th>
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<tbody>
<tr>
<td>Covalent Bonds</td>
<td>Large interatomic forces are created by the sharing of electrons. In particular the outer shell electrons.</td>
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<tr>
<td>Metallic Bonds</td>
<td>Large interatomic forces are created by tightly bonding of inner electrons while maintaining a much looser tie with the outer valence electrons.</td>
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</table>
### Periodic Table

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<tr>
<th>Period</th>
<th>Group IA</th>
<th>Group IIA</th>
<th>Group IIIB</th>
<th>Group IVB</th>
<th>Group VB</th>
<th>Group VIIB</th>
<th>Group VIIIB</th>
<th>Group IB</th>
<th>Group IIB</th>
<th>Group IIIA</th>
<th>Group IVA</th>
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*Element synthesized, but no official name assigned

### Inner-Transition Metals

- **Metal**
- **Lanthanides**
- **Metalloid**
- **Actinides**
- **Nonmetal**

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</table>
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.)
Predominant Slip Systems

FCC
{111}<110>
12

BCC
{110}<111>
48

HCP
{0001}<11-20>
3
Control of slip is essential to achieve maximum toughness in a crystalline material.

Toughness = (Ductility) \times (Strength)

\quad = f\{\text{strain} \times \text{stress}\}
Substitutional Solid Solution
Austenite – FCC form of Iron
Interstitial Solid Solution
Ferrite – BCC form of Iron
Liquid metal $\xrightarrow{\text{Solidification}}$ Unit cell (0.1 nm) $\xrightarrow{\text{Crystals}}$ Single crystals $\xrightarrow{\text{Products: solid-state devices, turbine blades}}$

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

Polycrystals $\xrightarrow{\text{Products: paper clips, bolts, springs, I-beams, aircraft fuselage}}$

- Lattice
- Imperfections
- Dislocations

- Grain boundaries
- Plastic deformation
- Anisotropy
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 \( V_o = A_o L_o = V_F = A_F L_F \)
Effect of Cold Working Metals

- Tensile strength (psi x 10^3) vs. Percent cold work
- Ductility (%EL) vs. Percent cold work

Graphs showing the effect of cold working on the tensile strength and ductility of 1040 Steel, Brass, and Copper.
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

<table>
<thead>
<tr>
<th>Metal</th>
<th>Recrystallization Temperature</th>
<th>Melting Temperature</th>
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<tbody>
<tr>
<td></td>
<td>°C</td>
<td>°F</td>
</tr>
<tr>
<td>Lead</td>
<td>-4</td>
<td>25</td>
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<tr>
<td>Tin</td>
<td>-4</td>
<td>25</td>
</tr>
<tr>
<td>Zinc</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Aluminum (99.999 wt%)</td>
<td>80</td>
<td>176</td>
</tr>
<tr>
<td>Copper (99.999 wt%)</td>
<td>120</td>
<td>250</td>
</tr>
<tr>
<td>Brass (60 Cu–40 Zn)</td>
<td>475</td>
<td>887</td>
</tr>
<tr>
<td>Nickel (99.99 wt%)</td>
<td>370</td>
<td>700</td>
</tr>
<tr>
<td>Iron</td>
<td>450</td>
<td>840</td>
</tr>
<tr>
<td>Tungsten</td>
<td>1200</td>
<td>2200</td>
</tr>
</tbody>
</table>
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
Peritectic Reaction Temperature
Eutectic Reaction Temperature
Eutectoid Reaction Temperature

The iron–iron carbide phase diagram.
Cast Irons

White Cast Iron
Malleablizing White Cast Iron

1. Reheat: hold at ~700°C for 30 + h
2. Fast cool: $P + G_r$
3. Slow cool: $\alpha + G_r$

**Diagram:**
- Fast cool
- Slow cool
- Pearlitic malleable
- Ferritic malleable
Cast Irons

Ferritic Gray CI
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% carbon steel contains 89.4% ferrite.

- Ferrite phase, 89.4%: A lamellar structure produced by slow cooling from a high temperature.
- Fe₃C phase, 10.6%: A spheroidized structure, which can be produced by very slow cooling.
- Martensite: 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.)
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 Microstructures

- Both microstructures contain Ferrite (α) and Cementite (Fe₃C).

- Pearlite forms at prior austenite grain boundaries by nucleating Fe₃C first then α.

- Bainite forms at prior austenite grain boundaries by nucleating α first then Fe₃C.

- 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

Temperature

Reaction Rate

Nucleation Rate

Growth Rate
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

I-T DIAGRAM

E-Q HARDENABILITY

0.46% C 0.99% Mn
Austenitized at 1550°F
Grain Size: 7

HARDNESS - RG

% MARTENSITE

TIME - SECONDS

DISTANCE FROM QUENCHED END - \( \frac{1}{16} \) INCH UNITS
Relating Isothermal Transformation Diagram to Equilibrium Phase Diagrams

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

Isothermal Transformation Diagram

1080 Steel

C-0.79
Mn-0.76

Carbon Steels: 1080  Austenitized at 1650°F

Grain Size: 6

---

Temperature

- F
- A
- A
- A

I-T Diagram

- Estimated Temperature
- Time - Seconds

- Eutectoid temperature
- Austenite (stable)
- Coarse pearlite
- Fine pearlite

- Fe₃C

Denotes that a transformation is occurring

---

Temperature (°C)

Time (s)
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


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.)
(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