Steel and cast iron

 Metals

<table>
<thead>
<tr>
<th>Ferrous alloys</th>
<th>Non-ferrous alloys</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steels (0.05-2.0 wt% C)</td>
<td>Al alloys</td>
</tr>
<tr>
<td>Carbon steels</td>
<td>Mg alloys</td>
</tr>
<tr>
<td>Low-alloy steels</td>
<td>Ti alloys</td>
</tr>
<tr>
<td>High-alloy steels</td>
<td>Nickel-base superalloys</td>
</tr>
<tr>
<td>Tool steels</td>
<td>......</td>
</tr>
<tr>
<td>Stainless steels</td>
<td></td>
</tr>
<tr>
<td>Superalloys</td>
<td></td>
</tr>
<tr>
<td>Cast irons (2.0-4.5 wt% C)</td>
<td></td>
</tr>
</tbody>
</table>
Chapter 11 - 4

1. Other terms: plain steel, mild steel, low-carbon steel
2. Available in almost all product forms: e.g. sheet, strip, bar, plate, tube, pipe etc.
3. Designation: e.g. 1040 steel - 0.40 wt% C
4. Up to 2 wt% C
5. Limitation for other alloying elements:
   - Si up to 0.6 %
   - Cu up to 0.6 %
   - Mn up to 1.65 %

Carbon steel

Taxonomy of Metals

Adapted from Fig. 11.1, Callister 7e.
### High-strength low-alloy steels

Containing about 0.2% C and about 1% other alloying elements, such as Mn, P, Si, Cr, Ni, and Mo

| **Table 11.1a** Compositions of Five Plain Low-Carbon Steels and Three High-Strength, Low-Alloy Steels |
|---|---|---|---|
| **Designation** | **AISI/SAE or ASTM Number** | **UNS Number** | **Composition (wt%)** |
| **Plain Low-Carbon Steels** | | | C | Mn | Other |
| 1010 | G10100 | 0.10 | 0.45 | | |
| 1020 | G10200 | 0.20 | 0.45 | | |
| A36 | K02600 | 0.29 | 1.00 | 0.20 Cu (min) | |
| A516 Grade 70 | K02700 | 0.31 | 1.00 | 0.25 Si | |
| **High-Strength, Low-Alloy Steels** | | | | | |
| A440 | K12810 | 0.28 | 1.35 | 0.30 Si (max), 0.20 Cu (min) | |
| A653 Grade E | K12002 | 0.22 | 1.35 | 0.30 Si, 0.08 V, 0.02 N, 0.03 Nb | |
| A656 Grade 1 | K11804 | 0.18 | 1.60 | 0.01 Si, 0.1 V, 0.20 Al, 0.015 N | |

* The codes used by the American Iron and Steel Institute (AISI), the Society of Automotive Engineers (SAE), and the American Society for Testing and Materials (ASTM), and in the Uniform Numbering System (UNS) are explained in the text.

* Also a maximum of 0.04 wt% P, 0.05 wt% S, and 0.30 wt% Si (unless indicated otherwise).

---

### Hot-rolled steels and typical applications

<table>
<thead>
<tr>
<th><strong>AISI/SAE or ASTM Number</strong></th>
<th><strong>Tensile Strength</strong> [MPa (ksi)]</th>
<th><strong>Yield Strength</strong> [MPa (ksi)]</th>
<th><strong>Ductility [%EL in 50 mm (2 in.)]</strong></th>
<th><strong>Typical Applications</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Plain Low-Carbon Steels</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1010</td>
<td>325 (47)</td>
<td>180 (26)</td>
<td>28</td>
<td>Automobile panels, nails, and wire</td>
</tr>
<tr>
<td>1020</td>
<td>380 (55)</td>
<td>205 (30)</td>
<td>25</td>
<td>Pipe; structural and sheet steel</td>
</tr>
<tr>
<td>A36</td>
<td>400 (58)</td>
<td>220 (32)</td>
<td>23</td>
<td>Structural (bridges and buildings)</td>
</tr>
<tr>
<td>A516 Grade 70</td>
<td>485 (70)</td>
<td>260 (38)</td>
<td>21</td>
<td>Low-temperature pressure vessels</td>
</tr>
<tr>
<td><strong>High-Strength, Low-Alloy Steels</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>A440</td>
<td>435 (63)</td>
<td>290 (42)</td>
<td>21</td>
<td>Structures that are bolted or riveted</td>
</tr>
<tr>
<td>A633 Grade E</td>
<td>520 (75)</td>
<td>380 (55)</td>
<td>23</td>
<td>Structures used at low ambient temperatures</td>
</tr>
<tr>
<td>A656 Grade 1</td>
<td>655 (95)</td>
<td>552 (80)</td>
<td>15</td>
<td>Truck frames and railway cars</td>
</tr>
</tbody>
</table>
**AISI**: the American Iron and Steel Institute  
**SAE**: the Society of Automotive and Engineering  
**ASTM**: the American Society for Testing and Materials  
**UNS**: the Uniform Numbering System

**High alloys:**

- **Tool steels**
  - A shock-resistant tool steels
  - A cold-work tool steels
  - A hot-work tool steel
  - A high-speed tool steel

- **Stainless steels**
- **Superalloys**


## Tool Steels

<table>
<thead>
<tr>
<th>Prefix</th>
<th>Specific Types</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>W1, W2, W5</td>
</tr>
<tr>
<td>O</td>
<td>O1, O2, O6, O7</td>
</tr>
<tr>
<td>A</td>
<td>A2, A4, A6, A7, A8, A9, A10, A11</td>
</tr>
<tr>
<td>D</td>
<td>D2, D3, D4, D5, D7</td>
</tr>
<tr>
<td>S</td>
<td>S1, S2, S4, S5, S6, S7</td>
</tr>
<tr>
<td>H</td>
<td>H10–H119 chromium types (H11 and H13)</td>
</tr>
<tr>
<td>M</td>
<td>Molybdenum types: M1, M2, M3-1, M3-2, M4, M5, M7, M10, M33, M34, M44, M47, M48, M50</td>
</tr>
<tr>
<td>T</td>
<td>Tungsten types: T1, T4, T5, T6, T8, T15</td>
</tr>
<tr>
<td>P</td>
<td>Mold steels: P9, P20, P21</td>
</tr>
<tr>
<td>L</td>
<td>Special-purpose steels: L1, L6</td>
</tr>
</tbody>
</table>

*Note: The most available grades are shown in bold in this and other tables in this chapter.*

### Designations, compositions and applications for six tool steels

<table>
<thead>
<tr>
<th>AISI Number</th>
<th>UNS Number</th>
<th>Composition (wt%)*</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>M1</td>
<td>T11301</td>
<td>C: 0.85 Cr: 3.75, Ni: 0.30 max, Mo: 8.70, W: 1.75, V: 1.20</td>
<td>Drills, saws; lathe and planer tools</td>
</tr>
<tr>
<td>A2</td>
<td>T3002</td>
<td>C: 1.00 Cr: 5.15, Ni: 0.30 max, Mo: 1.15, V: 0.35</td>
<td>Punches, embossing dies</td>
</tr>
<tr>
<td>D2</td>
<td>T30402</td>
<td>C: 1.50 Cr: 12, Ni: 0.30 max, Mo: 0.95, V: 1.10 max</td>
<td>Cutlery, drawing dies</td>
</tr>
<tr>
<td>O1</td>
<td>T31501</td>
<td>C: 0.95 Cr: 0.50, Ni: 0.30 max, Mo: 0.50, V: 0.30 max</td>
<td>Shear blades, cutting tools</td>
</tr>
<tr>
<td>S1</td>
<td>T41901</td>
<td>C: 0.50 Cr: 1.40, Ni: 0.30 max, Mo: 0.50 max, V: 2.25</td>
<td>Pipe cutters, concrete drills</td>
</tr>
<tr>
<td>W1</td>
<td>T72301</td>
<td>C: 1.10 Cr: 0.15 max, Ni: 0.20 max, Mo: 0.10 max, V: 0.15 max, W: 0.10 max</td>
<td>Blacksmith tools, woodworking tools</td>
</tr>
</tbody>
</table>

*The balance of the composition is iron. Manganese concentrations range between 0.10 and 1.4 wt%, depending on alloy; silicon concentrations between 0.20 and 1.2 wt% depending on alloy.*

### Carbon Steels vs. Alloy Steels vs. Tool Steels

<table>
<thead>
<tr>
<th>Manufacture:</th>
<th>Alloy Steels</th>
<th>Tool Steels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cold-finished,</td>
<td>Hot-finished</td>
<td>Hot-finished bars, forgings, and special QC</td>
</tr>
<tr>
<td>hot-finished bars,</td>
<td>bars, some plate</td>
<td></td>
</tr>
<tr>
<td>plate, sheet, strip</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| Composition:          |                                                  |                                                  |
|-----------------------|                                                  |                                                  |
| Fe + C + Mn            |                                                  |                                                  |
| Options: S, P          |                                                  |                                                  |
| Fe + C + Mn            |                                                  |                                                  |
| Options: Cr, Ni, Mo,   |                                                  |                                                  |
| Si, V, S, P         |                                                  |                                                  |
| Fe + C                |                                                  |                                                  |
| Options: Cr, Ni, Mo,   |                                                  |                                                  |
| Mn, Si, W, Co, S, V,  |                                                  |                                                  |
| Al                    |                                                  |                                                  |

| Microstructure:        |                                                  |                                                  |
|------------------------|                                                  |                                                  |
| Hard = martensite      | Hard = martensite                                | Hard = martensite + alloy carbides               |
| Soft = ferrite +      | Soft = ferrite +                                | Soft = ferrite + carbides, pearlite in w series  |
| pearlite               |                                                |                                                  |

**Carbon steels**

- **Hardness:**
  - HRC
  - Temper temperature

- **Abrasion resistance:**
  - Wear volume
  - Time

**Alloy steels**

- **Hardness:**
  - HRC
  - Temper temperature

**Tool Steels**

- **Hardness:**
  - HRC
  - Temper temperature
Figure 12-15
Common hardness scales showing their relationship to absolute hardness and the hardness of various wear-resistant materials. The Knoop and Vickers scales are different tests but the numbers vary by less than 10%. (262°C = 504°F; 371°C = 700°F).
Stainless steels

1. More resistant to rusting and staining than carbon- and low-alloy steels
2. Chromium addition, usually above 10 wt% (4-30%)

Four groups of the stainless steels

1. The austenitic stainless steels
   Austenite (fcc) is stabilized by nickel etc. elements
2. The ferritic stainless steels
   Without the high nickel content, bcc structure is stable at room temperature
3. The martensitic stainless steels
   bct (body-centered tetragonal) structure at room temperature
4. Precipitation-hardening stainless steels

<table>
<thead>
<tr>
<th>AISI Number</th>
<th>UNS Number</th>
<th>Composition (wt %)</th>
<th>Condition</th>
<th>Ultimate Tensile Strength (MPa, kpsi)</th>
<th>Yield Strength (MPa, kpsi)</th>
<th>Ductility [%EL in 2 in, 51 mm]</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>409</td>
<td>SA6900</td>
<td>0.08 C, 11.8 Cr, 1.0 Mn, 0.33 Ni, 6.25 Ti</td>
<td>Annealed</td>
<td>600 (85)</td>
<td>205 (30)</td>
<td>20</td>
<td>Automotive exhaust components, tanks for agricultural sprays, valves (high temperature), glass molds, combustion chambers</td>
</tr>
<tr>
<td>446</td>
<td>SA4600</td>
<td>0.20 C, 25 Cr, 1.5 Mo</td>
<td>Annealed</td>
<td>515 (75)</td>
<td>275 (40)</td>
<td>20</td>
<td>Valves (high temperature), glass molds, combustion chambers</td>
</tr>
<tr>
<td>304</td>
<td>SA0400</td>
<td>0.08 C, 19 Cr, 0.4 Ni, 2.0 Mo</td>
<td>Annealed</td>
<td>515 (75)</td>
<td>205 (30)</td>
<td>40</td>
<td>Chemical and food processing equipment, oxygen vessels</td>
</tr>
<tr>
<td>316L</td>
<td>SA31603</td>
<td>0.08 C, 17 Cr, 12 Ni, 2.5 Mn, 2.0 Mo</td>
<td>Annealed</td>
<td>485 (70)</td>
<td>170 (25)</td>
<td>40</td>
<td>Welding, construction</td>
</tr>
<tr>
<td>410</td>
<td>SA6100</td>
<td>0.15 C, 12 Cr, 1.0 Mn</td>
<td>Annealed</td>
<td>485 (70)</td>
<td>275 (40)</td>
<td>20</td>
<td>Rifle barrels, cold-worked steels, engine parts</td>
</tr>
<tr>
<td>40C94</td>
<td>SA48002</td>
<td>0.70 C, 17 Cr, 0.75 Mo, 1.0 Mn</td>
<td>Annealed</td>
<td>725 (105)</td>
<td>415 (60)</td>
<td>20</td>
<td>Cylinder heads, surgical tools</td>
</tr>
<tr>
<td>17-7PH</td>
<td>SA17700</td>
<td>0.09 C, 17 Cr, 7 Ni, 1.0 Al</td>
<td>Precipitation hardened</td>
<td>1550 (220)</td>
<td>1310 (190)</td>
<td>1-6</td>
<td>Springs, knives, pressure vessels</td>
</tr>
</tbody>
</table>

Notes:
- The balance of the composition is iron.
- Q & T denotes quenched and tempered.

Figure 14-2
Iron-chromium diagram

Phase diagrams
**Ferrous Alloys**

**Iron containing – Steels - cast irons**

Nomenclature: AISI & SAE

- 10xx Plain Carbon Steels
- 11xx Plain Carbon Steels (resulfurized for machinability)
- 15xx Mn (10 ~ 20%)
- 40xx Mo (0.20 ~ 0.30%)
- 43xx Ni (1.65 - 2.00%), Cr (0.4 - 0.90%), Mo (0.2 - 0.3%)
- 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

---

**Steels**

- **Low Alloy**
  - Low carbon: <0.25 wt% C
  - Med carbon: 0.25-0.6 wt% C
  - High carbon: 0.6-1.4 wt% C

- **High Alloy**

<table>
<thead>
<tr>
<th>Name</th>
<th>Plain</th>
<th>HSLA</th>
<th>Heat Treatable</th>
<th>Plain</th>
<th>Tool</th>
<th>Austenitic Stainless</th>
</tr>
</thead>
<tbody>
<tr>
<td>Additions</td>
<td>none</td>
<td>Cr, V</td>
<td>Cr, Ni, Mo</td>
<td>none</td>
<td>Cr, V</td>
<td>Cr, Ni, Mo</td>
</tr>
<tr>
<td>Example</td>
<td>1010</td>
<td>4310</td>
<td>1040</td>
<td>4340</td>
<td>1095</td>
<td>4190</td>
</tr>
<tr>
<td>Hardenability</td>
<td>-</td>
<td>+</td>
<td>+</td>
<td>++</td>
<td>++</td>
<td>++</td>
</tr>
<tr>
<td>TS</td>
<td>-</td>
<td>0</td>
<td>+</td>
<td>++</td>
<td>+</td>
<td>++</td>
</tr>
<tr>
<td>EL</td>
<td>+</td>
<td>+</td>
<td>0</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

- **Uses**
  - Auto struc. bridges, sheet, towers, press., vessels
  - Crank shafts, bolts, hammers, blades
  - Pistons, gears, wear, applic.
  - Drills, saws, dies

- **High T applic. turbines, furnaces, V. corros. resistant**

Based on data provided in Tables 11.1(b), 11.2(b), 11.3, and 11.4, Callister 7e.

Increasing strength, cost, decreasing ductility
Cast Iron

- Ferrous alloys with > 2.1 wt% C
  - more commonly 3 - 4.5 wt% C
- low melting (also brittle) so easiest to cast

- Cementite decomposes to ferrite + graphite
  \[ \text{Fe}_3\text{C} \rightarrow 3 \text{Fe (a)} + \text{C (graphite)} \]
  - cementite (Fe₃C) a metastable phase
  - graphite formation promoted by
    - Si > 1 wt%
    - slow cooling

Fe-C True Equilibrium Diagram

Graphite formation promoted by
- Si > 1 wt%
- slow cooling

Cast iron
1. Gray iron
2. Nodular (ductile) iron
3. White iron
4. Malleable iron
5. Compacted graphite iron (CGI)
Types of Cast Iron

Gray iron

- 1 - 3 % Si, 2.5 – 4% C
- graphite flakes plus ferrite/pearlite
- brittleness due to the flake-like graphite
  - weak & brittle under tension
  - stronger under compression
  - excellent vibrational dampening
  - wear resistant

Ductile (nodular) iron

- a small amount (0.05 wt%) of Mg or Ce
- spheroidal graphite precipitates (nodules) rather than flakes
- matrix often pearlite or ferrite
- Ductility increased by a factor of 20, strength is doubled

Optical micrograph of a grey iron (Fe-3.3C-2.1Si-0.5Cr-0.5Mo-1.0Cu)

Microstructure of pearlite in the grey iron (Fe-3.3C-2.1Si-0.5Cr-0.5Mo-1.0Cu). TEM.
Types of Cast Iron

White iron

- <1wt% Si, harder but brittle
- eutectic carbide plus pearlite
- large amount of Fe₃C formed during casting

Malleable iron

- the result of annealing white iron castings, 800°-900° C
- cementite→ graphite precipitates, clusters or rosettes
- more ductile
Types of Cast Iron

Compacted graphite iron (CGI)

1. C: 3.1-4.0%, Si: 1.7-3.0%
2. Lower content of Mg or Ce
3. Worm-like (vermicular) graphite particles

- higher thermal conductivity
- better resistance to thermal shock
- lower oxidation at elevated temperature

Production of Cast Iron

Adapted from Fig. 11.5, Callister 7e.
Cast iron

Mechanical Properties

<table>
<thead>
<tr>
<th>Grade</th>
<th>UNS Number</th>
<th>Composition (wt%)</th>
<th>Matrix Structure</th>
<th>Tensile Strength [MPa (ksi)]</th>
<th>Yield Strength [MPa (ksi)]</th>
<th>Ductility [%EL. in 2 in.]</th>
<th>Typical Applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>SAE G1000</td>
<td>F1000</td>
<td>2.0-3.7 C, 1.5-2.5 Si, 0.5 Mn Fe + Pearlite</td>
<td>120 (18)</td>
<td>—</td>
<td>—</td>
<td>Miscellaneous softer castings in which strength is not a primary consideration</td>
<td></td>
</tr>
<tr>
<td>SAE G2000</td>
<td>F1000</td>
<td>2.2-3.5 C, 2.0-2.5 Si, 0.5 Mn Fe + Pearlite</td>
<td>171 (25)</td>
<td>—</td>
<td>—</td>
<td>Small cylinder heads, cylinder heads, pistons, clutch plates, transmission cases</td>
<td></td>
</tr>
<tr>
<td>SAE G4000</td>
<td>F1000</td>
<td>2.5-3.2 C, 2.0-2.5 Si, 0.5 Mn, Fe + Pearlite</td>
<td>255 (38)</td>
<td>—</td>
<td>—</td>
<td>Diecast engine castings, gears, cylinder, and piston</td>
<td></td>
</tr>
</tbody>
</table>

Ductile (Nodular) Iron

| ASTM A530 | No. 40-14 | 2.3-3.8 C, 2.0-3.5 Si, 0.65 Mg, <0.05 Mn | Pearlite | 414 (60) | 270 (40) | 16 | Pressure-containing parts such as valve and pump bodies |
| ASTM A530 | No. 70-40 | 690 (100) | 463 (68) | 3 | High-strength gear and machine components |
| ASTM A530 | No. 90-45 | Tempered martensitic | 827 (120) | 621 (90) | 2 | Pinions, gears, sprockets, slides |

Malleable Iron

| ASTM A452 | Grade 29 | 2.0-2.7 C, 1.6-2.7 Si, <0.55 Mn | Pearlite + Pearlite | 347 (51) | 274 (40) | 10 | General engineering service at normal and elevated temperatures |
| ASTM A452 | Grade 40 | 2.6-2.7 C, 1.2-2.5 Si, <0.55 Mn | Pearlite | 446 (65) | 310 (45) | 6 | |

Compacted Graphite Iron

| ASTM A452 | Grade 29 | 2.1-4.8 C, 1.3-3.5 Si, 0.64-0.85 Mg | Pearlite | 250 (36) | 175 (25) | 3 | Diecast engine blocks; high-carbon steels, brake dies for high-speed tools |
| ASTM A452 | Grade 40 | 0.65-0.85 Mg | Pearlite | 459 (65) | 315 (46) | 1 | |

* The balance of the composition is iron.


Which type of cast iron is in the pictures illustrated below?

A  B  C  D
Limitations of Ferrous Alloys

1) Relatively high density
2) Relatively low conductivity
3) Poor corrosion resistance

Metal Fabrication

• How do we fabricate metals?
  – Blacksmith - hammer (forged)
  – Molding - cast

• Forming Operations
  – Rough stock formed to final shape

Hot working vs. Cold working
- $T$ high enough for recrystallization
- Larger deformations
- well below $T_m$
- work hardening
- smaller deformations
Metal Fabrication Methods - I

**FORMING**
- Forging (Hammering; Stamping) (wrenches, crankshafts)
  - force
- Rolling (Hot or Cold Rolling) (I-beams, rails, sheet & plate)
  - force
  - often at elev. T

**CASTING**
- Drawing (rods, wire, tubing)
  - force
  - tensile force
  - die must be well lubricated & clean
- Extrusion (rods, tubing)
  - force
  - ductile metals, e.g. Cu, Al (hot)

Adapted from Fig. 11.8, Callister 7e.

---

Metal Fabrication Methods - II

**CASTING**
- Casting- mold is filled with metal
  - metal melted in furnace, perhaps alloying elements added. Then cast in a mold
  - most common, cheapest method
  - gives good production of shapes
  - weaker products, internal defects
  - good option for brittle materials
Sand Casting
(large parts, e.g., auto engine blocks)
- trying to hold something that is hot
- what will withstand >1600°C?
- cheap - easy to mold => sand!!!
- pack sand around form (pattern) of desired shape

Investment Casting
- pattern is made from paraffin.
- mold made by encasing in plaster of paris
- melt the wax & the hollow mold is left
- pour in metal
Metal Fabrication Methods - II

**FORMING**

- Sand Casting
  (large parts, e.g., auto engine blocks)
- Investment Casting
  (low volume, complex shapes e.g., jewelry, turbine blades)

**CASTING**

- Die Casting
  (high volume, low T alloys)
- Continuous Casting
  (simple slab shapes)

**JOINING**

Metal Fabrication Methods - III

**FORMING**

- Powder Metallurgy
  (materials w/low ductility)

**CASTING**

- Welding
  (when one large part is impractical)

**JOINING**

- Heat affected zone:
  (region in which the microstructure has been changed)

Adapted from Fig. 11.9, *Callister 7e.*
(Fig. 11.9 from *Iron Castings Handbook,* C.F. Walton and T.J. Opar (Ed.), 1981.)
**Thermal Processing of Metals**

**Annealing:** Heat to $T_{\text{Anneal}}$, then cool slowly.

- **Stress Relief:** Reduce stress caused by:
  - plastic deformation
  - nonuniform cooling
  - phase transform.

- **Process Anneal:** Negate effect of cold working by (recovery/recrystallization)

- **Spheroidize** (steels): Make very soft steels for good machining. Heat just below $T_E$ & hold for 15-25 h.

- **Full Anneal** (steels): Make soft steels for good forming by heating to get $g$, then cool in furnace to get coarse $P$.

- **Normalize** (steels): Deform steel with large grains, then normalize to make grains small.

**Types of Annealing**

---

**Heat Treatments**

- **a) Annealing**
- **b) Quenching**
- **c) Tempered Martensite**

Adapted from Fig. 10.22, Callister 7e.
Figure 11.9 The on-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.]
Hardenability--Steels

- Ability to form martensite
- Jominy end quench test to measure hardenability.

![Diagram of Jominy end quench test](image)

- Hardness versus distance from the quenched end.

![Graph showing hardness versus distance from quenched end](image)

Why Hardness Changes With Position

- The cooling rate varies with position.

![Diagram showing temperature and hardness over time](image)
Hardenability vs Alloy Composition

- Jominy end quench results, \( C = 0.4 \) wt% C (table 11.2a p363)

"Alloy Steels" (4140, 4340, 5140, 8640) --contain Ni, Cr, Mo (0.2 to 2wt%)
--these elements shift the "nose".
--martensite is easier to form.

Adapted from Fig. 11.14, Callister 7e. (Fig. 11.14 adapted from figure furnished courtesy Republic Steel Corporation.)

Quenching Medium & Geometry

- Effect of quenching medium:
  
<table>
<thead>
<tr>
<th>Medium</th>
<th>Severity of Quench</th>
<th>Hardness</th>
</tr>
</thead>
<tbody>
<tr>
<td>air</td>
<td>low</td>
<td>low</td>
</tr>
<tr>
<td>oil</td>
<td>moderate</td>
<td>moderate</td>
</tr>
<tr>
<td>water</td>
<td>high</td>
<td>high</td>
</tr>
</tbody>
</table>

- Effect of geometry:
  When surface-to-volume ratio increases:
  --cooling rate increases
  --hardness increases
Summary

- Steels: increase TS, Hardness (and cost) by adding
  --C (low alloy steels)
  --Cr, V, Ni, Mo, W (high alloy steels)
  --ductility usually decreases with additions.
- Non-ferrous:
  --Cu, Al, Ti, Mg, Refractory, and noble metals.
- Fabrication techniques:
  --forming, casting, joining.
- Hardenability
  --increases with alloy content.
- Precipitation hardening
  --effective means to increase strength in
  Al, Cu, and Mg alloys.