Metal Casting
Design, Materials, Economics

Text Reference: “Manufacturing Engineering and Technology”, Kalpakjian & Schmid, 6/e, 2010
Chapter 12
Design of Cast Parts

- Avoid sharp corners, angles & fillets
  - They act as stress raisers
- Select fillet radii to reduce stress concentrations and ensure proper liquid metal flow
  - 3-25 mm (1/8”-3”)
- Seek uniform cross sections and wall thickness throughout casting
  - Larger sections become hot spots leading to shrinkage cavities and porosity
FIGURE 12.1 Suggested design modifications to avoid defects in castings. Source: Courtesy of the American Die Casting Institute.

- Use radii or fillets to avoid corners and provide uniform cross-section.
- Wall sections should be uniform.
- Sloping bosses can be designed for straight die parting to simplify die design.
- Deep cavities should be on one side of the casting where possible.
- Ribs and/or fillets improve bosses.
- Side cores can be eliminated with this hole design.
FIGURE 12.2 Examples of designs showing the importance of maintaining uniform cross sections in castings to avoid hot spots and shrinkage cavities.
Avoid large flat areas
- May warp during cooling because of temperature gradients
- May have uneven finish due to uneven flow during pouring
- Incorporate staggered ribs & serrations

Allow for metal shrinkage during solidification
<table>
<thead>
<tr>
<th>Metal</th>
<th>Shrinkage allowance (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray cast iron</td>
<td>0.83–1.3</td>
</tr>
<tr>
<td>White cast iron</td>
<td>2.1</td>
</tr>
<tr>
<td>Malleable cast iron</td>
<td>0.78–1.0</td>
</tr>
<tr>
<td>Aluminum alloys</td>
<td>1.3</td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td>1.3</td>
</tr>
<tr>
<td>Yellow brass</td>
<td>1.3–1.6</td>
</tr>
<tr>
<td>Phosphor bronze</td>
<td>1.0–1.6</td>
</tr>
<tr>
<td>Aluminum bronze</td>
<td>2.1</td>
</tr>
<tr>
<td>High-manganese steel</td>
<td>2.6</td>
</tr>
</tbody>
</table>
“The precipitation of graphite during eutectic solidification causes an expansion, which offsets some of the contraction usually experienced during solidification of a metal. In fact a Class 20 iron precipitates enough graphite to create sufficient expansion so that feeding is not required. As the CE of the iron decreases, less graphite is precipitated and feeding requirements increase. A Class 50 iron requires approximately 4% volumetric feeding to offset the contraction of the iron.”
carbon equivalent

(metallurgy)

- An empirical relationship of the total carbon (TC), silicon (Si) and phosphorus (P) content of gray iron:

  \[ CE = %TC + 0.3(%Si + %P). \]
Provide a small draft (taper) to enable removal of pattern without damaging mold.
Design of Cast Parts (continued)

- **Tolerances** should be as wide as possible
  - For small castings: +/- 0.8 mm (1/32\"")
  - For large castings: +/- 6 mm (0.25\")

- **Consider finishing operations**
  - E.g. Locate holes on flat surfaces

- **Select appropriate casting process**
  - Casting process can influence casting design
Design of Cast Parts

- **Location of parting line**
  - Along a flat plane (not contoured)
  - At corners or edges (not on flat surfaces)
  - Locate critical surfaces facing downwards (reduced porosity)
  - Placed to allow ease of metal flow
  - Affects mold design – locate sprue well, gates & runners at parting line in drag (bottom)
Design & locate gates:
- Multiple gates for large parts
- At thick sections of castings
- Use fillet where gate meets casting
- Allow space between sprue and casting
- Minimum gate length 3-5 times diameter
- Cross section smaller than runner but large enough for flow
- Avoid curved gates
Design of Cast Parts (continued)

- Use multiple **runners** for more complicated castings
- **Runners** trap dross
- Use a **pouring basin** to ensure even metal flow into sprue and collect dross
- Use good molten metal
- Pour molten metal evenly, without interruption
Design Issues:
Expendable Mold Casting

- Mold Layout
  - Solidification progress uniformly across mold, risers last
- Machining Allowance
  - Pattern dimensions include material for later finishing; grinding & machining
  - Increase with size & section thickness
Design Issues: Expendable Mold Casting

- Riser Design Rules
  - Riser must solidify after casting
  - Riser volume with sufficient metal to compensate for shrinkage during cooling
  - No hot spots at junction between casting & riser
  - Proper placement of risers so that liquid metal flows where needed
  - Provide sufficient pressure to drive liquid where needed in cavity.
    - More useful for higher density metals
  - Riser pressure head sufficient to encourage complete cavity filling
FIGURE 12.3 Examples of undesirable (poor) and desirable (good) casting designs. Permanent Mold & Die-casting.

Source: Courtesy of American Die Casting Institute.
Computer Modeling of Casting Process

- Casting involves complex interactions among many variables.
- New modeling techniques can simultaneously handle fluid flow, heat transfer, microstructures during solidification, etc.
- Modeling of **fluid flow** uses Bernoulli’s and continuity equations.
- **Heat transfer** models model the effects of surface conditions, thermal properties, convection on cooling.
- **Microstructures** models encompass heat flow, temperature gradients, nucleation, crystal growth, etc.
Casting Alloys

- Important considerations for alloys:
  - Casting characteristics
  - Machinability
  - Weldability
- The tables on the following slides summarize:
  - Properties and applications of cast metals and their alloys
  - Casting and manufacturing characteristics
FIGURE 12.4 Mechanical properties for various groups of cast alloys. Note that even within the same group, the properties vary over a wide range, particularly for cast steels. Source: Courtesy of Steel Founders’ Society of America.
FIGURE 12.4 (continued) Mechanical properties for various groups of cast alloys. Note that even within the same group, the properties vary over a wide range, particularly for cast steels. Source: Courtesy of Steel Founders’ Society of America.
# TABLE 12.2 Typical Applications for Castings and Casting Characteristics

<table>
<thead>
<tr>
<th>Type of alloy</th>
<th>Typical applications</th>
<th>Castability*</th>
<th>Weldability*</th>
<th>Machinability*</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum</td>
<td>Pistons, clutch housings, intake manifolds</td>
<td>E</td>
<td>F</td>
<td>G–E</td>
</tr>
<tr>
<td>Copper</td>
<td>Pumps, valves, gear blanks, marine propellers</td>
<td>F–G</td>
<td>F</td>
<td>F–G</td>
</tr>
<tr>
<td>Ductile iron</td>
<td>Crankshafts, heavy-duty gears</td>
<td>G</td>
<td>D</td>
<td>G</td>
</tr>
<tr>
<td>Gray iron</td>
<td>Engine blocks, gears, brake disks and drums, machine bases</td>
<td>E</td>
<td>D</td>
<td>G</td>
</tr>
<tr>
<td>Magnesium</td>
<td>Crankcase, transmission housings</td>
<td>G–E</td>
<td>G</td>
<td>E</td>
</tr>
<tr>
<td>Malleable iron</td>
<td>Farm and construction machinery, heavy-duty bearings, railroad rolling stock</td>
<td>G</td>
<td>D</td>
<td>G</td>
</tr>
<tr>
<td>Nickel</td>
<td>Gas turbine blades, pump and valve components for chemical plants</td>
<td>F</td>
<td>F</td>
<td>F</td>
</tr>
<tr>
<td>Steel (carbon and low-alloy)</td>
<td>Die blocks, heavy-duty gear blanks, aircraft undercoverage members, railroad wheels</td>
<td>F</td>
<td>E</td>
<td>F</td>
</tr>
<tr>
<td>Steel (high-alloy)</td>
<td>Gas-turbine housings, pump and valve components, rock-crusher jaws</td>
<td>F</td>
<td>E</td>
<td>F</td>
</tr>
<tr>
<td>White iron</td>
<td>Mill liners, shot-blasting nozzles, railroad brake shoes, crushers, and pulverizers</td>
<td>G</td>
<td>VP</td>
<td>VP</td>
</tr>
<tr>
<td>Zinc</td>
<td>Door handles, radiator grills</td>
<td>E</td>
<td>D</td>
<td>E</td>
</tr>
</tbody>
</table>

*E = excellent; G = good; F = fair; VP = very poor; D = difficult.
TABLE 12.5 Properties and Typical Applications of Nonferrous Cast Alloys

<table>
<thead>
<tr>
<th>Alloys (UNS)</th>
<th>Condition</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Yield strength (MPa)</th>
<th>Elongation in 50 mm (%)</th>
<th>Typical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aluminum alloys</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>319 (AO3190)</td>
<td>Heat treated</td>
<td>185–250</td>
<td>125–180</td>
<td>2–1.5</td>
<td>Sand castings</td>
</tr>
<tr>
<td>356 (AO3560)</td>
<td>Heat treated</td>
<td>260</td>
<td>185</td>
<td>5</td>
<td>Permanent mold castings</td>
</tr>
<tr>
<td>Copper alloys</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Red brass (C83600)</td>
<td>Annealed</td>
<td>235</td>
<td>115</td>
<td>25</td>
<td>Pipe fittings, gears</td>
</tr>
<tr>
<td>Yellow brass (C86400)</td>
<td>Annealed</td>
<td>275</td>
<td>95</td>
<td>25</td>
<td>Hardware, ornamental</td>
</tr>
<tr>
<td>Manganese bronze (C86100)</td>
<td>Annealed</td>
<td>480</td>
<td>195</td>
<td>30</td>
<td>Propeller hubs, blades</td>
</tr>
<tr>
<td>Leaded tin bronze (C92500)</td>
<td>Annealed</td>
<td>260</td>
<td>105</td>
<td>35</td>
<td>Gears, bearings, valves</td>
</tr>
<tr>
<td>Gun metal (C90500)</td>
<td>Annealed</td>
<td>275</td>
<td>105</td>
<td>30</td>
<td>Pump parts, fittings</td>
</tr>
<tr>
<td>Nickel silver (C97600)</td>
<td>Annealed</td>
<td>275</td>
<td>175</td>
<td>15</td>
<td>Marine parts, valves</td>
</tr>
<tr>
<td>Magnesium alloys</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AZ91A</td>
<td>F</td>
<td>230</td>
<td>150</td>
<td>3</td>
<td>Die castings</td>
</tr>
<tr>
<td>AZ63A</td>
<td>T4</td>
<td>275</td>
<td>95</td>
<td>12</td>
<td>Sand and permanent mold castings</td>
</tr>
<tr>
<td>E93C</td>
<td>T6</td>
<td>275</td>
<td>130</td>
<td>5</td>
<td>High-strength parts</td>
</tr>
<tr>
<td>E93A</td>
<td>T5</td>
<td>210</td>
<td>110</td>
<td>3</td>
<td>Elevated-temperature parts</td>
</tr>
<tr>
<td>HK31A</td>
<td>T6</td>
<td>210</td>
<td>105</td>
<td>8</td>
<td>Elevated-temperature parts</td>
</tr>
<tr>
<td>QE22A</td>
<td>T6</td>
<td>275</td>
<td>205</td>
<td>4</td>
<td>Highest-strength parts</td>
</tr>
</tbody>
</table>
Aluminum-based Alloys

- High electrical conductivity
- Good atmospheric corrosion resistance
- Poor resistance to some acids and all alkalis
  - Avoid/prevent galvanic corrosion
- Nontoxic, lightweight, good machinability
- Low resistance to wear and abrasion
  - Improves with addition of silicon
Aluminum-based Alloys

Applications:
- Architectural & decorative
- Automobiles
  - Engine blocks
  - Cylinder heads
  - Intake manifolds
  - Transmission cases
  - Suspension components
  - Wheels
  - Brakes
Magnesium-based Alloys

- The lowest density of all commercial casting alloys
- Good corrosion resistance
- Moderate strength
  - Strength depends on heat treatment
- Applications:
  - Automotive wheels, housings, air-cooled engine blocks
Copper-based Alloys

- Relatively expensive
- Good electrical conductivity
- Good thermal conductivity
- Good corrosion resistance
- Nontoxic
Zinc-based Alloys

- Low melting point
- Good corrosion resistance
- Good fluidity
- Moderate strength

Applications:
- Die casting
- Parts with thin walls and intricate shapes
Other Non-ferrous Alloys

- Tin-based
  - Low strength; Good corrosion resistance
  - Use for bearing surfaces
- Lead-based
  - Similar to Tin; toxic
- High-temperature
  - Wide range of properties
  - Require temperatures up to 1650°C (3000°F) for Titanium; higher for Mo, Nb, W, Ta
  - Utilize specialized casting techniques
Ferrous Casting Alloys

- **Cast Irons**
  - Can be easily cast into intricate shapes
  - Good wear resistance
  - High hardness
  - Good machinability

- The term ‘C.I.’ includes a family of alloys
- General properties and applications in Tables 12.3, 12.4
### TABLE 12.3 Properties and Typical Applications of Cast Irons

<table>
<thead>
<tr>
<th>Cast iron</th>
<th>Type</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Yield strength (MPa)</th>
<th>Elongation in 50 mm (%)</th>
<th>Typical applications</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gray</td>
<td>Ferritic</td>
<td>170</td>
<td>140</td>
<td>0.4</td>
<td>Pipe, sanitary ware</td>
</tr>
<tr>
<td></td>
<td>Pearlitic</td>
<td>275</td>
<td>240</td>
<td>0.4</td>
<td>Engine blocks, machine tools</td>
</tr>
<tr>
<td></td>
<td>Martensitic</td>
<td>550</td>
<td>550</td>
<td>0</td>
<td>Wear surfaces</td>
</tr>
<tr>
<td>Ductile (Nodular)</td>
<td>Ferritic</td>
<td>415</td>
<td>275</td>
<td>18</td>
<td>Pipe, general service</td>
</tr>
<tr>
<td></td>
<td>Pearlitic</td>
<td>550</td>
<td>380</td>
<td>6</td>
<td>Crankshafts, highly stressed parts</td>
</tr>
<tr>
<td></td>
<td>Tempered martensite</td>
<td>825</td>
<td>620</td>
<td>2</td>
<td>High-strength machine parts, wear-resistant parts</td>
</tr>
<tr>
<td>Malleable</td>
<td>Ferritic</td>
<td>365</td>
<td>240</td>
<td>18</td>
<td>Hardware, pipe fittings, general engineering service</td>
</tr>
<tr>
<td></td>
<td>Pearlitic</td>
<td>450</td>
<td>310</td>
<td>10</td>
<td>Railroad equipment, couplings</td>
</tr>
<tr>
<td></td>
<td>Tempered martensite</td>
<td>700</td>
<td>550</td>
<td>2</td>
<td>Railroad equipment, gears, connecting rods</td>
</tr>
<tr>
<td>White</td>
<td>Pearlitic</td>
<td>275</td>
<td>275</td>
<td>0</td>
<td>Wear-resistant parts, mill rolls</td>
</tr>
</tbody>
</table>
### Mechanical Properties of Gray Cast Irons

<table>
<thead>
<tr>
<th>ASTM class</th>
<th>Ultimate tensile strength (MPa)</th>
<th>Compressive strength (MPa)</th>
<th>Elastic modulus (GPa)</th>
<th>Hardness (HB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>20</td>
<td>152</td>
<td>572</td>
<td>66–97</td>
<td>156</td>
</tr>
<tr>
<td>25</td>
<td>179</td>
<td>669</td>
<td>79–102</td>
<td>174</td>
</tr>
<tr>
<td>30</td>
<td>214</td>
<td>752</td>
<td>90–113</td>
<td>210</td>
</tr>
<tr>
<td>35</td>
<td>252</td>
<td>855</td>
<td>100–119</td>
<td>212</td>
</tr>
<tr>
<td>40</td>
<td>293</td>
<td>965</td>
<td>110–138</td>
<td>235</td>
</tr>
<tr>
<td>50</td>
<td>362</td>
<td>1130</td>
<td>130–157</td>
<td>262</td>
</tr>
<tr>
<td>60</td>
<td>431</td>
<td>1293</td>
<td>141–162</td>
<td>302</td>
</tr>
</tbody>
</table>
Gray Cast iron

- Relatively few shrinkage cavities
- Low porosity
- Properties vary: ferritic, pearlitic, martensitic
- Applications:
  - Engine blocks, electric-motor housings, pipes, wear surfaces for machines
  - Machine tool bases
- 2-digit ASTM classification
  - Class 20: Minimum 20 ksi (140 MPa) tensile strength
Ductile (Nodular) Iron

- Typically used for machine parts, housings, gears, pipe, rolls for rolling mills, automotive crankshafts
- Grade 80-55-06
  - Minimum 80 ksi (550 MPa) tensile strength
  - Minimum 55 ksi (380 MPa) yield strength
  - 6% elongation in 2” (50 mm)
White Cast Iron

- Has extreme hardness
- Is brittle
- Very good wear resistance
- Primary uses:
  - Rolls for rolling mills
  - Railroad-car brake shoes
  - Liners in machinery for processing abrasive materials
Malleable Iron

- Good ductility, strength and shock resistance

**Applications:**
- R/R equipment
- Hardware & fittings
- Components for electrical applications

**Classification example: 35018**
- 35 ksi (240 MPa)
- 18% elongation in 2” (50 mm)
Compacted-Graphite Iron

- Has the good damping and thermal properties of gray iron
- Has the good strength and stiffness properties of ductile iron
- These properties permit smaller, lighter parts
- Easy to cast and has good machinability
- Used for automotive engine blocks and cylinder heads
Cast Steels

- Require high temperatures (1650°C or 3000°F) to melt
- Steel castings have properties that are more uniform than those made by mechanical working processes
- Can be welded; heat alters microstructure
  - Affects strength, ductility, toughness
  - Restore original properties by heat treatment
- Applications:
  - Mining, chemical plants, oil fields, heavy construction, R/R equipment
Cast Stainless Steels

- Similar to steels
- Possess long freezing ranges and high melting temperatures
- Can be heat treated and welded
- Have high heat and corrosion resistance

**Applications:**
- Chemical & food industries
- In severely corrosive environments
- For very high temperature service
Economics of Casting

- Unit cost (of castings, as for all processes) depends on costs of materials, equipment and labour.
- Preparations for casting include production of molds and dies that also have similar costs.
**TABLE 12.6**  General Cost Characteristics of Casting Processes

<table>
<thead>
<tr>
<th>Casting process</th>
<th>Cost*</th>
<th>Production rate (pieces/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Die</td>
<td>Equipment</td>
</tr>
<tr>
<td>Sand</td>
<td>L</td>
<td>L</td>
</tr>
<tr>
<td>Shell mold</td>
<td>L−M</td>
<td>M−H</td>
</tr>
<tr>
<td>Plaster</td>
<td>L−M</td>
<td>M</td>
</tr>
<tr>
<td>Investment</td>
<td>M−H</td>
<td>L−M</td>
</tr>
<tr>
<td>Permanent mold</td>
<td>M</td>
<td>M</td>
</tr>
<tr>
<td>Die</td>
<td>H</td>
<td>H</td>
</tr>
<tr>
<td>Centrifugal</td>
<td>M</td>
<td>H</td>
</tr>
</tbody>
</table>

*L = low; M = medium; H = high.*
Economics of Casting

- **Cost components:**
  - Molds (extremes: sand - low; die - high)
  - Melting & pouring metal
  - Heat-treating
  - Cleaning
  - Inspection
  - Labour varies according to skill and time required

- Sand casting economic for low volumes
- Sustained high production rates can justify high cost of dies and machinery;
Summary

- General guidelines developed covering shape of casting and design of process to reduce hot spots; important to follow good casting practice for control of metal flow
- Numerous ferrous and non-ferrous alloys with wide range of characteristics and production requirements
- Economic considerations are as important as technical considerations