Chapter 12.

Metal Casting: Design, Materials, and Economics

12.1 Introduction

- So far, successful casting practice requires the proper control of a large number of variables: characteristics of the metals (or alloys) casts, method of casting, mold/die materials, mold/die design, and various process parameters.
- The flow of the molten metal in the mold cavities, the gating systems, the rate of cooling, and the gases evolved all influence the quality of a casting.
- This chapter describes general design considerations and guidelines for metal casting and presents suggestions for avoiding defects.

12.2 Design Considerations in Casting

12.2.1 General design considerations in castings

- Two types of design issues in casting are: a) geometric features, and b) mold features.
- Robust design of castings usually involves the following steps:
  1. Design the part so that the shape is cast easily.
  2. Select a casting process and material suitable for the part, size, mechanical properties, etc.
  3. Locate the parting line of the mold in the part.
  4. Locate and design the gates to allow uniform feeding of the mold cavity with molten metal.
  5. Select appropriate runner geometry for the system.
  6. Locate mold features such as sprue, screens and risers, as appropriate.
  7. Make sure proper controls and good practices are in place.

A. Design of cast parts. Following considerations are important:

- **Corners, angles and section thickness**: avoid using sharp corners and angles (act as stress raisers) and may cause cracking and tearing during solidification. Use fillets with radii ranging from 3 to 25 mm.

![Figure 12.1 Suggested design modifications to avoid defects in castings. Note that sharp corners are avoided to reduce stress concentrations.](image)

(a) Poor

(b) Good
Sections changes in castings should be blended smoothly into each other. Location of the largest circle that can be inscribed in a particular region is critical so far as shrinkage cavities are concerned (a & b). Because the cooling rate in regions with large circles is lower, they are called hot spots. These regions can develop shrinkage cavities and porosity (c & d). Cavities at hot spots can be eliminated by using small cores (e).

It is important to maintain (as much as possible) uniform cross sections and wall thicknesses throughout the casting to avoid or minimize shrinkage cavities. Metal paddings or chills in the mold can eliminate or minimize hot spots.
✓ **Flat areas:** large flat areas (plain surfaces) should be avoided, since they may warp during cooling because of temperature gradients, or they develop poor surface finish because of uneven flow of metal during pouring. To resolve this one can break up flat surfaces with staggered ribs.

✓ **Shrinkage:** pattern dimensions also should allow for shrinkage of the metal during solidification and cooling. See table 12.1.

<table>
<thead>
<tr>
<th>Metal</th>
<th>%</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>

✓ **Draft:** a small draft (taper) typically is provided in sand mold pattern to enable removal of the pattern without damaging the mold. Drafts generally range from 5 to 15 mm/m. Depending of the quality of the pattern, draft angles usually range from 0.5° to 2°.

✓ **Dimensional tolerances:** tolerances should be as wide as possible, within the limits of good part performance; otherwise, the cost of the casting increases. In commercial practices, tolerances are usually in the range of ± 0.8 mm for small castings. For large castings, tolerances may be as much as ± 6 mm.

✓ **Lettering and markings:** it is common practice to include some form of part identification (such lettering or corporate logos) in castings. These features can be sunk into the casting or protrude from the surface.

✓ **Machining and finishing operations:** should be taken into account. For example, a hole to be drilled should be on a flat surface not a curved one. Better yet, should incorporate a small dimple as a starting point. Features to be used for clamping when machining.

**B. Selecting the casting process.** Casting process selection can not be separated from discussions of economics. However, Table 11.1 lists some of the advantages and limitations of casting processes that have and an impact on casting design. Specific design rules for expendable and permanent mold operations are discussed next.

**C. Locating the parting line.** A part should be oriented in a mold so that the large portion of the casting is relatively low and the height of the casting is minimized.

✓ The parting line is line or plane separating the upper (cope) and lower (drag) halves of mold. In general, the parting line should be along a flat plane rather than be contoured.
The parting line should be placed as low as possible relative to the casting for less dense metal (such as aluminum alloys) and located at around mid-height for denser metals (such as steels).

Figure 12.5  Redesign of a casting by making the parting line straight to avoid defects.

D. Locating and designing gates. The gates are connections between the runners and the part cavity. Some of the considerations in designing gating systems are:

- Multiple gates often are preferable and are necessary for large parts.
- Gates should feed into thick sections of castings.
- A fillet should be used where a gate meets a casting; this feature produces less turbulence than abrupt junctions.
- The gate closest to the sprue should be placed sufficiently far away so that the gate can be easily removed. This distance may be as small as a few mm for small casting and up to 500 mm for large parts.
- The minimum gate length should be three to five times the gate diameter, depending on the metal being cast. The cross-section should be large enough to allow the filling of the mold cavity and should be smaller than the runner cross-section.
- Curved gates should be avoided, but when necessary, a straight section in the gate should be located immediately adjacent to the casting.

E. Runner design. The runner is a horizontal distribution channel that accepts the molten metal from the sprue and delivers it to the gates.

- One runner is used for simple parts, but-two runner systems can be specified for more complicated castings.
- The runners are used to trap dross (dross is a mixture of oxide and metal and forms on the surface of the metal) and keep it from entering the gates and the mold cavity.
- Commonly, dross traps are placed at the ends of the runners, and the runner projects above the gates to ensure that the metal in the gates is trapped below the surface.

F. Designing other mold features.

- The main goal in designing a aprue is to achieve the required metal flow rates while preventing aspiration or excessive dross formation.
- Flow rates are determined such that turbulence is avoided, but the mold is filled quickly compared to the solidification time required.
A pouring basin can be used to ensure that *the metal flow into the sprue is uninterrupted*; also, if the molten metal is maintained in the pouring basin during pouring, then the dross will float and will not enter the mold cavity.

- **Filters** are used to trap large contaminants and to slow metal velocity and make the flow more laminar.
- **Chills** can be used to speed solidification of the metal in a particular region of a casting.

### G. Establishing good practices.

Some *quality control* procedures are necessary:

- Starting with a *high-quality molten* metal is essential for producing superior castings. Pouring temperature, metal chemistry, gas entrainment, and handling procedures all can affect the quality of the metal being poured into a mold.
- The pouring of the metal should **not be interrupted**, since it can lead to dross entrainment and turbulence.
- The different cooling rates within the body of a casting cause residual stresses. Stress relieving (section 4.11) thus may necessary to avoid distortions of castings in critical applications.

### 12.2.2 Design for expendable-mold casting

#### A. Mold layout.

- One of the most important goals in mold layout is to have solidification initiate at one end of the mold and progress in a uniform font a cross the casting with *risers solidifying last*.
- Traditionally, this depends on experience and consideration of fluid flow and heat transfer.
- More recently, commercial computer programs based on finite-difference algorithms have become available.

#### B. Riser design.

Risers (size and location) are extremely useful in affecting-front progression across a casting and are essential feature in the mold layout. *Blind risers* are good design features and maintain heat longer than open risers. Risers are designed according to six basic rules:

1. The riser **must not** solidify before the casting.
2. The riser volume must be large enough to provide a sufficient amount of liquid metal to *compensate for shrinkage* in the cavity.
3. Junctions between casting and feeder should not develop a hot spot where shrinkage porosity can occur.
4. Risers must be placed so that the liquid metal can be delivered to locations where it is **most needed**.
5. There must be **sufficient pressure** to drive the liquid metal into locations in the mold where it is most needed.
6. The pressure head from the riser should **suppress** cavity formation and encourage complete cavity filling.

#### C. Machining allowance.

- Machining allowances, which are included in pattern dimensions, depend on the type of casting and increase with size and thickness of the casting.
- Allowances usually range from about **2 to 5 mm** for small castings to more than **25 mm** for large castings.
12.2.3 Design for permanent-mold casting

Example 12.1 shows several examples of poor and good designs in permanent-mold and die casting:

a. Lower portion of the design has a thin wall which may fracture under high forces. The good design eliminates this problem and also may simplify die and mold manufacturing.

b. Large flat surfaces may warp and develop uneven surfaces. We may break up the surfaces with ribs and serrations on the reverse side of the casting.

c. It is difficult to produce sharp internal radii or corners. Placement of a small radius at the corners at the bottom of the part

d. This part may represent a knob to be gripped and rotated. The casting die for the good design is easier to manufacture.

e. Poor design has sharp fillets. Good design prevents the die edges from chipping off.

f. The poor design has threads reaching the right face of the casting. The good design uses an offset on the threaded rod, eliminating this problem.

Figure 12.3 Examples of undesirable (poor) and desirable (good) casting designs.

12.2.4 Computer modeling of casting processes

Rapid advances in computers and modeling analysis led innovations in modeling different aspects of casting including: fluid flow, heat transfer, and microstructures developed during solidification; under various casting-process conditions.

Specifically, software may provide:

- Modeling fluid flow in molds (Bernoulli’s and continuity). Predict velocity and pressure of the molten metal in the gating system all the way into the mold cavity.
- Modeling of heat transfer in casting.
- Fluid flow and heat transfer (with surface conditions, thermal properties of materials) are coupled.
The benefits of such user-friendly software are to increase productivity, improve quality, and easily plan and estimate cost. Also quicker response to design changes.

Several commercial software programs now are available for modeling of casting processes:
1. Magmasoft,
2. ProCast,
3. Solidia, and
4. AFSsolid.

12.3 Casting Alloys

This section describes the properties and applications of cast metals and alloys; their properties and casting & manufacturing characteristics are summarized in Fig. 12.4 and Tables 12.2 – 12.5.

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.
Table 12.2 shows Casting Applications and 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 undercarriage 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.

12.3.1 Nonferrous Casting Alloys (see Table 12.5)

A. Aluminum-based alloys.
- High electrical conductivity and generally good atmospheric corrosion resistance; except for some acids.
- Nontoxic, lightweight, and good mach inability.
- Generally low resistance to wear except for alloys with silicon.
- Used in architectural and decorative applications. Used in automobiles for engine blocks, cylinder heads, transmission cases, wheels, and brakes.
- Parts made of Aluminum-based and magnesium-based alloys are known as light-metal castings.

A. Magnesium-based alloys.
- Lowest density of all commercial casting alloys.
- Good corrosion resistance and moderate strength.
- Used in automotive wheels, housings, and air-cooled engine blocks.

B. Copper-based alloys.
- Somewhat expensive.
- Good electrical and thermal conductivity, corrosion resistance, and non toxicity.

C. Zinc-based alloys.
- Low-melting point.
- Good corrosion resistance, good fluidity, and sufficient strength for structural applications.
- Used in die casting.
D. Tin-based alloys.
- Low in strength.
- Good corrosion resistance, and typically used for bearing surfaces.

E. Lead-based alloys.
- Application similar to tin-based alloys.
- Toxicity is a major drawback of lead.

F. High-temperature alloys
- Typically require temperature of up to 1650 for casting titanium and higher for refractory alloys (Molybdenum-2617°C, Niobium-2468°C, Tungsten-3410°C).
- Special techniques are used to cast these alloys.

<table>
<thead>
<tr>
<th>TABLE 12.5</th>
</tr>
</thead>
<tbody>
<tr>
<td>Properties and Typical Applications of Nonferrous Cast Alloys</td>
</tr>
<tr>
<td>Alloys (UNS)</td>
</tr>
<tr>
<td>Aluminum alloys</td>
</tr>
<tr>
<td>Heat treated</td>
</tr>
<tr>
<td>Heat treated</td>
</tr>
<tr>
<td>Copper alloys</td>
</tr>
<tr>
<td>Red brass (C83600)</td>
</tr>
<tr>
<td>Yellow brass (C86600)</td>
</tr>
<tr>
<td>Manganese bronze (C86100)</td>
</tr>
<tr>
<td>Leaded tin bronze (C92500)</td>
</tr>
<tr>
<td>Gun metal (C90500)</td>
</tr>
<tr>
<td>Nickel silver (C97600)</td>
</tr>
</tbody>
</table>

12.3.2 Ferrous Casting Alloys

1. Cast Irons. Represent the largest quantity of all metal cast. They process several desirable properties such as wear resistance, hardness, and good machinability. Represent a family of alloys (section 4.6) – see Tables 12.3 & 12.4:
   a. Gray cast iron.
   b. Ductile (nodular) iron.
   c. White cast iron.
   d. Maleable iron.
   e. Compacted graphite iron.
2. **Cast Steels.** Need high temperature to melt cast steels (up to 1650°). Casting requires considerable experience. If welded, need to be heat treated to restore mechanical properties. Used in equipment for railroads, mining, chemical plants, oil fields, and heavy constructions.

3. **Cast Stainless Steels.** Generally have long freezing ranges and high melting temperatures. Available in various compositions, and they can be heat treated and welded. Such products have high heat and corrosion resistance, specially in the chemical and food industry.
12.4 **Economics of Casting**

- The cost of the cast part (unit cost) depends on several factors: including materials, tooling, equipment, and labor.
- Preparations for casting a product include the production of molds and dies that require raw materials, time, and effort – all of which also influence product cost.
- As shown in table 12.6, relatively little cost is involved in molds for sand casting. On the other hand, molds for various processes and die-casting dies require expensive materials and a great deal of preparation.

<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.

- There are also major costs involved in making patterns for casting.
- Costs also are involved in melting and pouring the molten metal into molds and in heat treating, cleaning, and inspecting the casting.
- Heat treatment is an important part of the production of many alloys groups (especially ferrous castings) and may be necessary to produce improved mechanical properties.
- The equipment cost per casting will decrease as the number of parts cast increase. Sustained high-production rates, therefore, can justify the high cost of dies and machinery.
- However, if the demand is relatively small, the cost-per-casting increases rapidly. It then becomes more economical to manufacture the parts by sand casting.