CHAPTER

11 Metal-casting Processes and Equipment

- Building upon the fundamentals of solidification, fluid flow, and heat transfer described in the preceding chapter, this chapter describes the industrial casting processes.
- Casting processes are generally categorized as permanent-mold and expendable-mold processes; expendable-mold processes are further categorized as permanent-mold and expendable-pattern processes.
- The characteristics of each process are described, together with typical applications, advantages, and limitations.
- Special casting processes that produce single-crystal components as well as amorphous alloys are then described.
- The chapter ends with a description of inspection techniques for castings.

Typical products made by casting: Engine blocks, crankshafts, power tool housings, turbine blades, plumbing parts, zipper teeth, dies and molds, gears, railroad wheels, propellers, office equipment, and statues. Casting is extremely versatile and suitable for a wide variety of products.

Alternative processes: Forging, powder metallurgy, machining, rapid prototyping, and fabrication.

11.1 Introduction

The first metal castings were made during the period from 4000 to 3000 B.C., using stone or metal molds for casting copper. Various casting processes have been developed over time, each with its own characteristics and applications (see also Fig. I.5a), to meet specific design requirements (Table 11.1). A very wide variety of parts and components are made by casting (Fig. 11.1), such as engine blocks, crankshafts, automotive components and powertrains, agricultural and railroad equipment, pipes and plumbing fixtures, power-tool housings, gun barrels, frying pans, jewelry, orthopedic implants, and very large components for hydraulic turbines.

Two trends have had a major impact on the casting industry. The first is the mechanization and automation of casting operations, which has led to significant changes in the use of equipment and labor. Advanced machinery and automated process-control systems have replaced traditional methods of casting. The second major trend has been the increasing demand for high-quality castings with close dimensional tolerances.

This chapter is organized around the major classifications of casting practices (given in Fig. II.3 in the Introduction to Part II). These classifications are related to

TABLE 11.1

Summary of Casting Processes

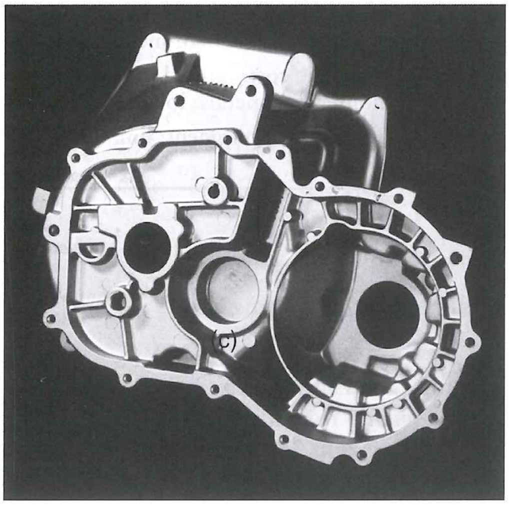
Process	Advantages	Limitations
Sand	Almost any metal can be cast; no limit to part size, shape, or weight; low tooling cost	Some finishing required; relatively coarse surface finish; wide tolerances
Shell mold	Good dimensional accuracy and surface finish; high production rate	Part size limited; expensive patterns and equipment
Evaporative pattern	Most metals can be cast, with no limit to size; complex part shapes	Patterns have low strength and can be costly for low quantities
Plaster mold	Intricate part shapes; good dimensional accuracy and surface finish; low porosity	Limited to nonferrous metals; limited part size and volume of production; mold-making time relatively long
Ceramic mold	Intricate part shapes; close-tolerance parts; good surface finish; low cooling rate	Limited part size
Investment	Intricate part shapes; excellent surface finish and accuracy; almost any metal can be cast	Part size limited; expensive patterns, molds, and labor
Permanent mold	Good surface finish and dimensional accuracy; low porosity; high production rate	High mold cost; limited part shape and complexity; not suitable for high-melting-point metals
Die	Excellent dimensional accuracy and surface finish; high production rate	High die cost; limited part size; generally limited to nonferrous metals; long lead time
Centrifugal	Large cylindrical or tubular parts with good quality; high production rate	Expensive equipment; limited part shape

mold materials, pattern production, molding processes, and methods of feeding the mold with molten metal. The major categories are:

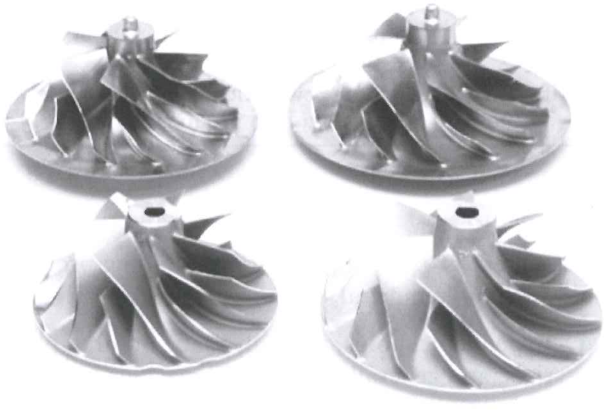
1. **Expendable molds**, typically made of sand, plaster, ceramics, and similar materials, and generally mixed with various binders (*bonding agents*) for improved properties. A typical sand mold consists of 90% sand, 7% clay, and 3% water. As described in Chapter 8, these materials are *refractories* (i.e., they are capable of withstanding the high temperatures of molten metals). After the casting has solidified, the mold is broken up to remove the casting, hence the word *expendable*.

   The mold is produced from a pattern; in some processes, and although the mold is expendable, the pattern is reused to produce several molds. Such processes are referred to as *expendable-mold, permanent-pattern casting processes*. On the other hand, investment casting requires a pattern for each mold produced, and is an example of an *expendable-mold, expendable-pattern process*.
2. **Permanent molds**, made of metals that maintain their strength at high temperatures. As the name implies, the molds are used repeatedly, and are designed in such a way that the casting can be removed easily and the mold used for the next casting. Metal molds are better heat conductors than expendable nonmetallic molds (see Table 3.1), hence the solidifying casting is subjected to a higher rate of cooling, which in turn affects the microstructure and grain size within the casting.
3. **Composite molds**, made of two or more different materials (such as sand, graphite, and metal), combining the advantages of each material. These molds have a permanent and an expendable portion, and are used in various casting processes to improve mold strength, control the cooling rate, and optimize the overall economics of the casting operation.

(a)



(b)



(c)

FIGURE 11.1 (a) Die-cast magnesium housing for the Olympus E-3 camera; *Source:* Courtesy of Olympus Inc. (b) A cast transmission housing. (c) Cast aluminum impellers for automotive turbo chargers. *Source:* (b) and (c) Courtesy of American Foundry Society.

The general characteristics of sand casting and other casting processes are summarized in Table 11.2. As it can be seen, almost all commercial metals can be cast. The surface finish obtained is largely a function of the mold material, and can be very good, although, as expected, sand castings generally have rough, grainy surfaces. Dimensional tolerances generally are not as good as those in machining and other net-shape processes; however, intricate shapes, such as engine blocks and very large propellers for ocean liners, can be made by casting.

Because of their unique characteristics and applications, particularly in manufacturing microelectronic devices (described in Part V), basic crystal-growing techniques also are included in this chapter, which concludes with a brief overview of modern foundries.

TABLE 11.2

General Characteristics of Casting Processes

	Sand	Shell	Evaporative pattern	Plaster	Investment	Permanent mold	Die	Centrifugal
Typical materials cast	All	All	All	Nonferrous (Al, Mg, Zn, Cu)	All	All	Nonferrous (Al, Mg, Zn, Cu)	All
Weight (kg):								
Minimum	0.01	0.01	0.01	0.01	0.001	0.1	<0.01	0.01
Maximum	No limit	100+	100+	50+	100+	300	50	5000+
Typical surface finish (R_a in μm)	5–25	1–3	5–25	1–2	0.3–2	2–6	1–2	2–10
Porosity[1]	3–5	4–5	3–5	4–5	5	2–3	1–3	1–2
Shape complexity[1]	1–2	2–3	1–2	1–2	1	2–3	3–4	3–4
Dimensional accuracy[1]	3	2	3	2	1	1	1	3
Section thickness (mm):								
Minimum	3	2	2	1	1	2	0.5	2
Maximum	No limit	—	—	—	75	50	12	100
Typical dimensional tolerance (mm)	1.6–4 mm (0.25 mm for small parts)	±0.003		±0.005–0.010	±0.005	±0.015	± 0.001–0.005	0.015
Equipment	3–5	3	2–3	3–5	3–5	2	1	1
Pattern/die	3–5	2–3	2–3	3–5	2–3	2	1	1
Labor	1–3	3	3	1–2	1–2	3	5	5
Typical lead time[2]	Days	Weeks	Weeks	Days	Weeks	Weeks	Weeks to months	Months
Typical production rate[2] (parts/mold-hour)	1–20	5–50	1–20	1–10	1–1000	5–50	2–200	1–1000
Minimum quantity[2]	1	100	500	10	10	1000	10,000	10–10,000

Notes: 1. Relative rating, from 1 (best) to 5 (worst). For example, die casting has relatively low porosity, mid to low shape complexity, high dimensional accuracy, high equipment and die costs, and low labor costs. These ratings are only general; significant variations can occur, depending on the manufacturing methods used.
2. Approximate values without the use of rapid-prototyping technologies; minimum quantity is 1 when applying rapid prototyping.
Source: Data taken from J.A. Schey, *Introduction to Manufacturing Processes*, 3rd ed., McGraw-Hill, 2000.