10

Design for Die Casting

10.1 INTRODUCTION

The die casting process, also called pressure die casting, is a molding process in which molten metal is injected under high pressure into cavities in reusable steel molds, called dies, and held under pressure during solidification. In principle, the process is identical to injection molding with a different class of materials. Die casting can, in fact, produce parts which have identical geometries to injection-molded ones. The reverse is also true, and much of the increase in the use of injection molding over the past decade has been as a substitute for part types which were previously die cast. In many cases, this has been a wise substitution resulting in decreased parts costs. However, for structural parts, particularly those for which thick-wall injection moldings are required, die casting can often be the better selection. The analysis of die casting costs in this chapter closely parallels the early costing procedure for injection molding given in Chapter 8. This is intended to allow comparisons of the two processes to be made with a minimum of redundant effort.

10.2 DIE CASTING ALLOYS

The four major types of alloys that are die cast are zinc, aluminum, magnesium, and copper-based alloys. The die casting process was developed in the 19th century for the manufacture of lead/tin alloy parts. However, lead and tin are now very rarely die-cast because of their poor mechanical properties. A tabulation of the specific gravity, mechanical properties, and cost of commonly used examples of the four principal alloy groups is given in Table 10.1.

Table 10.1 Commonly Used Die Casting Alloys

Alloy[a]	Specific gravity	Yield strength (MN/m^2)	Elastic modulus (GN/m^2)	Cost (\$/kg)
Zamak(1)	6.60	220	655	1.78
Zamak 5(1)	6.60	270	725	1.74
Al3(2)	2.66	130	130	1.65
A360(2)	2.74	170	120	1.67
ZA8(3)	6.30	290	86	1.78
ZA27(3)	5.00	370	78	1.94
Silicon brass 879(4)	8.50	240	100	6.60
Manganese(4) bronze 865	8.30	190	100	6.60
AZ91B(5)	1.80	150	45	2.93

[a] Alloy types: (1) zinc, (2) aluminum, (3) zinc-aluminum, (4) copper, (5) magnesium.

The most common die casting alloys are the aluminum alloys. They have low density, good corrosion resistance, are relatively easy to cast, and have good mechanical properties and dimensional stability. Aluminum alloys have the disadvantage of requiring the use of cold-chamber machines, which usually have longer cycle times than hot-chamber machines owing to the need for a separate ladling operation. The distinction between hot- and cold-chamber machines will be discussed in some detail later in this chapter.

Zinc-based alloys are the easiest to cast. They also have high ductility and good impact strength, and therefore can be used for a wide range of products. Castings can be made with very thin walls, as well as with excellent surface smoothness, leading to ease of preparation for plating and painting. Zinc alloy castings, however, are very susceptible to corrosion and must usually be coated, adding significantly to the total cost of the component. Also, the high specific gravity of zinc alloys leads to a much higher cost per unit volume than for aluminum die casting alloys, as can be deduced from the data in Table 10.1.

Zinc-aluminum (ZA) alloys contain a higher aluminum content (8-27%) than the standard zinc alloys. Thin walls and long die lives can be obtained, similar to standard zinc alloys, but as with aluminum alloys, cold-chamber machines, which require pouring of the molten metal for each cycle, must usually be used. The single exception to this rule is ZA8 (8 percent Al) which has the lowest aluminum content of the zinc-aluminum family.

Magnesium alloys have very low density, have a high strength-to-weight ratio, exceptional damping capacity, and have excellent machinability properties.

Copper-based alloys, brass and bronze, provide the best mechanical properties of any of the die casting alloys, but are much more expensive. Brasses have high strength and toughness, good wear resistance and excellent corrosion resistance. One major disadvantage of copper-based alloy casting is the short die life caused by thermal fatigue of the dies at the extremely high casting temperatures.

Die life is influenced most strongly by the casting temperature of the alloys and for that reason is greatest for zinc and shortest for copper alloys. The typical number of castings per die cavity is given in Table 10.2. However, this is only an approximation since casting size, wall thickness and geometrical complexity also influence the wear and eventual breakdown of the die surface.

10.3 THE DIE CASTING CYCLE

The casting cycle consists of first closing and locking the die. The molten metal, which is maintained by a furnace at a specified temperature, then enters the injection cylinder. Depending on the type of alloy, either a hot-chamber or cold-chamber metal-pumping system is used. These will be described later. During the injection stage of the die casting process, pressure is applied to the molten metal, which is then driven quickly through the feed system of the die while air escapes from the die through vents. The volume of metal must be large enough to overflow the die cavities and fill overflow wells. These overflow wells are designed to receive the lead portion of the molten metal, which tends to oxidize from contact with air in the cavity and also cools too rapidly from initial die contact to produce sound castings. Once the cavities are filled, pressure on the metal is increased and held for a specified dwell time during which solidification takes place. The dies are then separated, and the part extracted, often by means of automatic machine operation. The open dies are then cleaned and lubricated as needed and the casting cycle is repeated.

Table 10.2 Typical Die Life Values per Cavity

Alloy	Die life
Zinc	500,000
ZA	500,000
Aluminum	100,000
Magnesium	180,000
Copper	15,000

Following extraction from the die, parts are often quenched and then trimmed to remove the runners which have been necessary for metal flow during mold filling. Trimming is also necessary to remove the overflow wells and any parting-line flash that is produced. Subsequently, secondary machining and surface finishing operations may be performed.

10.4 DIE CASTING MACHINES

Die casting machines consist of several elements: namely, the die mounting and clamping system, the die, the metal pumping and injection system, the metal melting and storing system and any auxiliary equipment for mechanization of such operations as part extraction and die lubrication.

10.4.1 Die Mounting and Clamping Systems

The die casting machine must be able to open and close the die and lock it closed with enough force to overcome the pressure of the molten metal in the cavity. The mechanical or hydraulic systems needed to do this are identical to those found on injection molding machines and described in Chapter 8. This fact should not be surprising since injection molding machines were developed from die casting technology.

10.4.2 Metal Pumping and Injection Systems

The two basic types of injection systems are hot-chamber and cold-chamber. Hot-chamber systems, in which the pump is placed in the container of molten metal, are used with alloys of low melting temperatures, such as zinc. Cold-chamber machines must be used for high-melting temperature alloys such as aluminum, copper-based alloys, and the ZA zinc alloys which contain large amounts of aluminum. The high-melting-temperature alloys used in a hot-chamber machine would erode the ferrous injection pump components, thereby degrading the pump and contaminating the alloy. Magnesium alloys, although they are cast at high temperatures, can be cast in hot-chamber machines as well as cold-chamber machines because they are inert with respect to the ferrous machine components [1].

10.4.3 Hot-Chamber Machines

A typical hot-chamber injection or shot system, as shown in Fig. 10.1, consists of a cylinder, a plunger, a gooseneck and a nozzle. The injection cycle begins with the plunger in the up position. The molten metal flows from the metal-holding pot in the furnace, through the intake ports and into the pressure cylinder. Then, with the dies closed and locked, hydraulic pressure moves the plunger down into the pressure cylinder and seals off the intake ports. The mol-

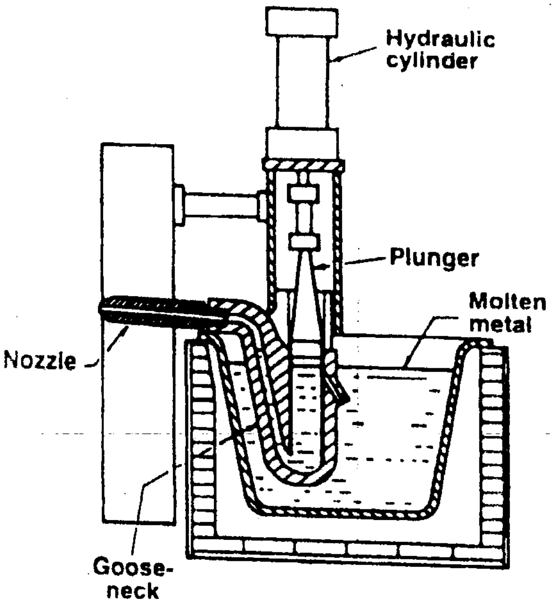

Figure 10.1 Hot-chamber injection system.

ten metal is forced through the gooseneck channel and the nozzle and into the sprue, feed system and die cavities. The sprue is a conically expanding flow channel which passes through the cover die half from the nozzle into the feed system. The conical shape provides a smooth transition from the injection point to the feed channels and allows easy extraction from the die after solidification. After a preset dwell time for metal solidification, the hydraulic system is reversed and the plunger is pulled up. The cycle then repeats. Cycle times range from several seconds for castings weighing a few grams to 30 s or more for large, thick-walled castings weighing over a kilogram [2]. Specifications for a range of hot-chamber machines are given in Table 10.3.

10.4.4 Cold-Chamber Machines

A typical cold-chamber machine, as shown in Fig. 10.2, consists of a horizontal shot chamber with a pouring hole on the top, a water-cooled plunger, and a pressurized injection cylinder. The sequence of operations is as follows: while the die is closed and locked, and the cylinder plunger is retracted, the molten metal is ladled into the shot chamber through the pouring hole. In order to tightly pack the metal in the cavity, the volume of metal poured into the chamber is greater than the combined volume of the cavity, the feed system, and the overflow wells. The injection cylinder is then energized, moving the plunger through the chamber, thereby forcing the molten metal into the die cavity. After the metal has solidified, the die opens and the plunger moves back to its original position. As the die opens, the excess metal at the end of the injection cylinder, called the biscuit, is forced out of the cylinder because it is attached to the casting. Material in the biscuit is required during the die casting cycle in order to maintain liquid metal pressure on the casting while it solidifies and shrinks.

Specifications for a number of cold-chamber machines are given in Table 10.4.

Table 10.3 Hot-Chamber Die Casting Machines

Clamping force (kN)	Shot size (cm^3)	Operating rate ($/h)	Dry cycle time (s)	Max. die opening (cm)	Platen size (cm)
900	750	58	2.3	20.0	48 × 56
1150	900	60	2.5	23.0	56 × 64
1650	1050	62	2.9	25.0	66 × 70
2200	1300	64	3.3	31.0	70 × 78
4000	1600	70	4.6	38.0	78 × 98
5500	3600	73	5.6	45.7	100 × 120
6000	4000	76	6.2	48.0	120 × 150
8000	4000	86	7.5	53.0	120 × 150

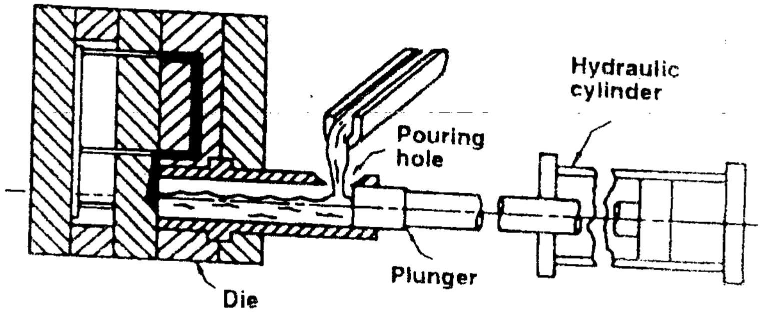

Figure 10.2 Cold-chamber die casting machine elements.

Table 10.4 Cold-Chamber Die Casting Machines

Clamping force (kN)	Shot size (cm^3)	Operating rate (\$/h)	Dry cycle time (s)	Max. die opening (cm)	Platen size (cm)
900	305	66	2.2	24.4	48 × 64
1,800	672	73	2.8	36.0	86 × 90
3,500	1,176	81	3.9	38.0	100 × 108
6,000	1,932	94	5.8	46.0	100 × 120
10,000	5,397	116	8.6	76.0	160 × 160
15,000	11,256	132	10.2	81.0	210 × 240
25,000	11,634	196	19.9	109.0	240 × 240
30,000	13,110	218	23.3	119.0	240 × 240

10.5 DIE CASTING DIES

Die casting dies consist of two major sections—the ejector die half and the cover die half—which meet at the parting line; see Fig. 10.3. The cavities and cores are usually machined into inserts that are fitted into each of these halves. The cover die half is secured to the stationary platen, while the ejector die half is fastened to the movable platen. The cavity and matching core must be designed such that the die halves can be pulled away from the solidified casting.

The construction of die casting dies is almost identical to molds for injection molding. In injection molding terminology, the ejector die half comprises the core plate and ejector housing while the cover die half comprises the cavity plate and backing support plate.

Side-pull mechanisms for casting parts with external cross-features can be found in exactly the same form in die casting dies as in plastic injection molds described in Chapter 8. However, molten die casting alloys are much less viscous than the polymer melt in injection molding and have a great tendency to flow between the contacting surfaces of the die. This phenomenon, referred to as "flashing," tends to jam mold mechanisms, which must, for this reason, be robust. The combination of flashing with the high core retraction forces due to part shrinkage makes it extremely difficult to produce satisfactory internal core mechanisms. Thus, internal screw threads or other internal undercuts cannot usually be cast and must be produced by expensive additional machining operations. Ejection systems found in die casting dies are identical to the ones found in injection molds.

It should be noted that "flashing" always occurs between the cover die and ejector die halves, leading to a thin, irregular band of metal around the parting line. Occasionally, this parting line flash may escape between the die faces. For this reason, full safety doors must always be fitted to manual die casting machines to contain any such escaping flash material.

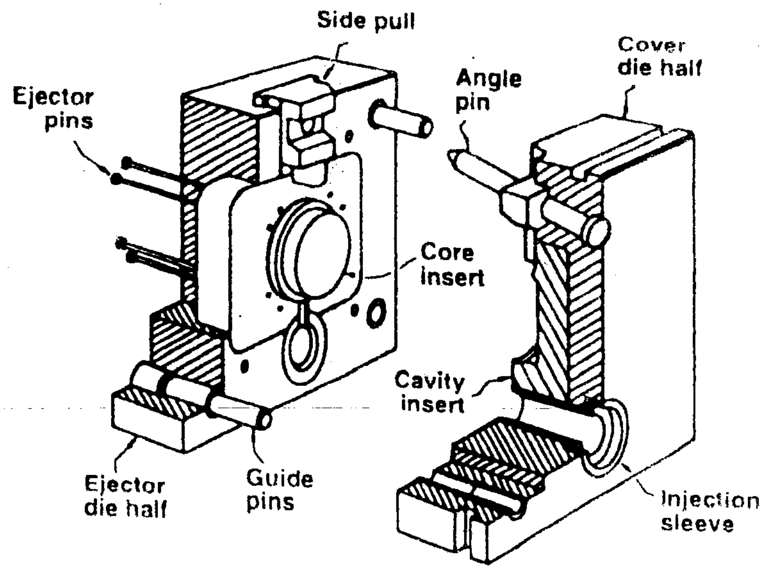

Figure 10.3 Die for cold-chamber die casting machine.

One main difference in the die casting process is that overflow wells are usually designed around the perimeter of die casting cavities. As mentioned earlier, they reduce the amount of oxides in the casting, by allowing the first part of the shot, which displaces the air through the escape vents, to pass completely through the cavity. The remaining portion of the shot and the die are then at a higher temperature, thereby reducing the chance of the metal freezing prematurely. Such premature freezing leads to the formation of surface defects called cold shuts, in which streams of metal do not weld together properly because they have partially solidified by the time they meet. Overflow wells are also needed to maintain a more uniform die temperature on small castings, by adding substantially to the mass of molten metal.

10.5.1 Trimming Dies

After extraction from the die casting machines, the sprue or biscuit, runners, gates, overflow wells and parting-line flash must be removed from the casting. This is done either manually or, if production quantities are larger, with trimming presses. The dies used for trimming operations are similar to blanking and piercing dies used for sheet metal pressworking. They are mounted on mechanical or hydraulic presses, and because the required forces are low, the bed area to tonnage rating ratio is relatively large. The thickness of the metal to be trimmed is usually in the range 0.75–1.5 mm.

It is desirable, when designing a casting, to locate the main gates from the feed channels as well as the gates to the overflow wells around the parting line of the cavity and to design a parting line that is not stepped. This simplifies both the casting die and the trimming die.

10.6 FINISHING

Following trimming, castings are often polished and/or coated to provide corrosion resistance and wear resistance, and to improve aesthetic appearance. Polishing is often the only surface treatment for aluminum castings or it may be the preparation stage for high-gloss painting or plating of zinc castings. Before coating, parts are put through a series of cleaning operations to remove any contamination which could prevent the adhesion of these applied coatings. The cleaning operations usually performed are degreasing, alkaline cleaning, and acid dipping.

Following cleaning, several coatings are available depending on the type of alloy cast. These coatings may be separated into three groups, namely: electroplating, anodizing, and painting. Electroplating is used mainly for zinc alloy castings because aluminum and magnesium alloys oxidize quickly, preventing the electroplate layers from adhering properly. Brass castings, although they may be electroplated after removal of oxides, are often used unfinished.

The most common type of electroplating is a decorative chrome finish on zinc die castings, which consists of several layers of applied metal. First, a very thin layer of copper (0.008 mm) is applied to aid in the adhesion of the subsequent layers. A second layer of copper is then sometimes added to improve the final surface finish. Two layers of nickel, 0.025 mm thick, are then applied. These layers aid in corrosion resistance by diverting the corrosion to the outer layer of nickel because of the difference in electrical potential between the two layers. The final layer is a thin coat of chromium (0.003 mm), which also helps to prevent corrosion by serving as a barrier.

Anodizing, used on aluminum, zinc, and magnesium alloy castings, provides corrosion resistance and wear resistance, and may also serve as a base for painting. Anodizing of aluminum is the formation of a layer, 0.005–0.030 mm thick, of stable oxides on the surface of the base metal by making the casting the anode in an electrolytic cell, with separate cathodes of lead, aluminum or stainless steel. This surface is usually a dull gray and therefore not usually applied for decorative purposes.

The most common form of applied coating for aesthetic appearance and protection is painting. Paint may be applied to bare metal, primed metal, or to surfaces that have additional protective coatings. Paint is often applied by electrostatic painting, which uses powdered paint sprayed through a nozzle of the opposite electrical potential than the castings.

The process of impregnation, while not a surface finishing process, is sometimes performed after the casting and polishing processes have been completed. Impregnation is used on castings where porosity may produce structural problems, as in the case were castings are to be used to hold fluids or to contain fluid pressure. The process of impregnation consists of placing the castings in a vacuum chamber, evacuating the pores, and immersing the castings in a sealant. The sealant is then forced into the pores once the casting is in atmospheric pressure.

The cost of surface treatments is often represented as a simple cost per square area of casting surface. Typical 1991 costs for the more common surface treatments and for sealant impregnation are given in Table 10.5.

10.7 AUXILIARY EQUIPMENT FOR AUTOMATION

Several operations in die casting may be automated in order to reduce cycle times and to produce more consistent quality. These operations, which may utilize mechanized equipment or simple programmable manipulations, are the removal of the casting from the die, transfer of castings to subsequent operations such as trimming, application of die lubricants, and transfer of molten metal to the shot chamber of cold-chamber machines.

Automatic extraction involves the use of a mechanical manipulator that simulates the actions of a human operator in removing the part from the die. The fingers of the manipulator are open upon entry into the die opening, they then close on the casting, which is usually suspended on the ends of the ejector pins, pull it out of the die opening, and drop in onto a conveyor belt or into a trim die. These devices range from simple two-degrees-of-freedom mechanisms to programmable robots that are capable of multiple-axis motions. Note that small nonprecision die castings may be simply dropped from the die in the same manner as small injection moldings.

Table 10.5 Costs of Commmon Finishing Processes

Finishing process	Cost per 50 cm^2 of surface area (cents)
Sealant impregnantion	1.2
Cu/N$_{i/Cr}$ plate	3.0
Polish	0.9
Anodize	1.1
Prime cost	1.4
Finish paint coat	1.6

Die lubricants may be applied automatically by stationary spray heads located near the die, or by reciprocating spray heads located near the die, or by reciprocating spray heads that enter the die after the casting has been extracted. These are sometimes mounted on the back of the extractor arm and are sprayed as the arm is retracting from the die.

Automatic metal transfer systems are used to transfer molten metal from the holding furnace to the shot chamber of cold chamber die casting machines. These systems may be simple mechanical ladles as shown in Fig. 10.4 or a variety of more complex systems, some of which fill at the bottom in order to reduce the transfer of oxides.

10.8 DETERMINATION OF THE OPTIMUM NUMBER OF CAVITIES

Diecasting processing cost is the product of the die casting cycle time and the operating rate of the die casting machine and its operator. In order to determine the operating rate, the machine size must be known. This, in turn, can only be determined if the number of die cavities is known. Since the procedures being developed in this work are to be used in early design, the number of cavities which may be used in later manufacturing cannot be ascertained with certainty. It can only be assumed that the part will be manufactured in an efficient manner. Thus, a value for what is likely to be an optimum number of cavities must be used. The determination of this value is the subject of this section.

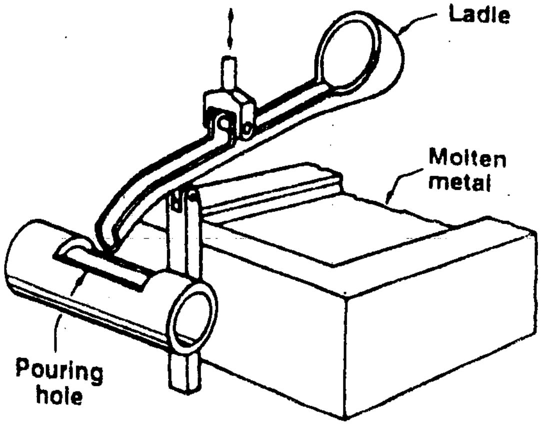

Figure 10.4 Simple mechanical ladle for cold-chamber machine.

The optimum number of die cavities to be used in the die casting die, equal to the number of apertures in the trim die, can be determined for a particular die casting task by first calculating the most economical number of cavities, and then analyzing the physical constraints of the equipment to ensure that the economical number of cavities is practical. The most economical number of cavities can be determined by the following analysis, which is almost identical to the one for injection molding.

$$C_t = C_{dc} + C_{tr} + C_{dn} + C_{tn} + C_{ta}\ \$ \qquad (10.1)$$

where

C_t = total cost for all the components to be manufactured; Nt, \$
C_{dc} = die casting processing cost, \$
C_{tr} = trimming processing cost, \$
C_{dn} = multi-cavity die casting die cost, \$
C_{tn} = multi-aperture trim die cost, \$
C_{ta} = total alloy cost, \$

The die casting processing cost, C_{dc}, is the cost of operating the appropriate size die casting machine, and can be represented by the following equation:

$$C_{dc} = (N_t/n)\, C_{rd} t_d\ \$ \qquad (10.2)$$

where

N_t = total number of components to be cast
n = number of cavities
C_{rd} = die casting machine and operator rate, \$/h
t_d = die casting machine cycle time, h

The hourly operating rate of a die casting machine, including the operator rate, can be approximated by the following linear relationship:

$$C_{rd} = k_1 + m_1 F\ \$/\text{h} \qquad (10.3)$$

where

F = die casting machine clamp force, kN
k_1, m_1 = machine rate coefficients

This relationship, which is identical in form to the one for injection molding, was arrived at through examination of the machine hourly rate data. Linear regression analysis of the data in Tables 10.2 and 10.3 gives the following values:

Hot-chamber: $k_1 = 55.4$, $m_1 = 0.0036$
Cold-chamber: $k_1 = 62.0$, $m_1 = 0.0052$

The form of the relationship is supported by the nature of the variation of die casting machine capital costs with rated clamp force values as shown in Fig. 10.5. This machine cost data, obtained from five machine makers, shows a linear relationship between clamp force and machine costs for hot- or cold-chamber machines up to 15 MN. However, it should be noted that very large cold-chamber machines in the range of 15 to 30 MN are associated with greatly increased cost. For these machines, the smooth relationship results obtained in this section should be applied with caution.

The cost of trimming, C_{tr}, can be represented by the following equation:

$$C_{tr} = (N_t/n)\,C_{rt}t_p\ \$ \qquad (10.4)$$

where

C_{rt} = trim press and operator rate, \$/h

t_p = trimming cycle time, h

In the present analysis, the hourly rate for trimming is approximated by a constant value for trim presses of all sizes. This is done because the cost of trim presses is relatively low due to the small forces required, and therefore only small-capacity presses are necessary in the trimming of die casting alloys. For this reason, C_{rt} is dominated by the hourly rate of the trim press operator rather than by the cost of the press itself.

The trimming cycle time may be represented by the following equation:

$$t_p = t_{p0} + n\Delta t_p\,h \qquad (10.5)$$

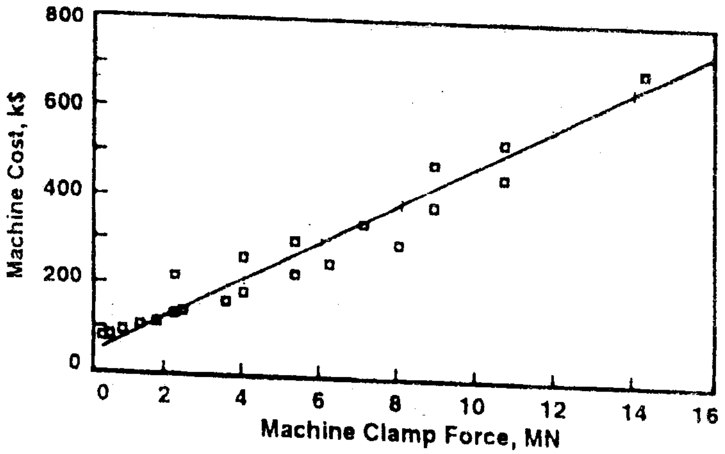

Figure 10.5 Capital costs of die casting machines.

where

t_{p0} = trimming cycle time for a single-aperture trimming operation for a single part, h

Δ_{tp} = additional trimming cycle time for each aperture in a multiaperture trimming die, mainly due to increased loading time of the multicavity casting into the press

The cost of a multicavity die casting die, C_{dn}, relative to the cost of a single-cavity die, C_{d1}, follows a relationship similar to that of injection molding dies. Based on data from Reinbacker [3], this relationship can be represented as the following power law:

$$C_{dn} = C_{d1}n^m\ \$ \qquad (10.6)$$

where

C_{d1} = cost of a single-cavity die casting die, \$

m = multi-cavity die cost exponent

n = number of cavities

The decreased cost per cavity resulting from the manufacture of multiple identical cavities follows the same trend as for the manufacture of injection molds. Thus, as discussed in Chapter 8, a reasonable value for m is 0.7.

The cost of a multiaperture trim die, C_{tn}, relative to the cost of a single-aperture trim die, C_{t1}, will be assumed to follow a similar relationship, namely:

$$C_{tn} = C_{t1}n^m\ \$ \qquad (10.7)$$

where

C_{t1} = cost of a single-aperture trim die, \$

m = multi-aperture trim die cost exponent

It is assumed that the cost exponent for multiaperture trim tools is the same as that for multicavity die casting dies.

The equation for the total alloy cost, C_{ta}, is:

$$C_{ta} = N_tC_a\ \$ \qquad (10.8)$$

where

C_a = alloy cost for each casting, \$

Compiling the previous equations gives

$$\begin{aligned} C_t = {} & (N_t/n)\,(k_1 + m_1F)\,t_d \\ & + (N_t/n)\,t_{p0} + n\Delta t_p)C_{rt} \\ & + (C_d + C_t)\,n^m + N_tC_a \end{aligned} \qquad (10.9)$$

If full die casting machine clamp force utilization is assumed, then:

$$F = nf \text{ kN}$$

or

$$n = F/f \tag{10.10}$$

where

F = die casting machine clamp force kN

f = separating force on one cavity, kN

Substituting Eq. (10.10) into Eq. (10.9) gives

$$\begin{aligned} C_t = {} & N_t(k_1 f/F + m_1 f)t_d \\ & + N_t C_n t_{po} f/F \\ & + N_t C_n \Delta t_p \\ & + (C_d + C_t)(F/f)^m + N_t C_a \end{aligned} \tag{10.11}$$

In order to find the number of cavities which gives the lowest cost for any given die casting machine size, the derivative of Eq. (10.11) with respect to the clamp force, F, is equated to zero. This gives

$$\begin{aligned} dC_t/dF = {} & -N_t f(k_1 t_d + C_n t_{p0})/F^2 \\ & + mF^{(m-1)}(C_d + C_t)/f^m = 0 \end{aligned} \tag{10.12}$$

Finally, rearranging Eq. (10.12) gives

$$n^{(m+1)} = N_t(k_1 t_d + C_n t_{p0})/(m(C_d + C_t)) \tag{10.13}$$

as the equation for the most economical number of die cavities for any given die casting task.

Example:

An aluminum die cast component has an estimated die casting cycle time of 20 s for a single-cavity die and an estimated 7 s trimming cycle time for a single-aperture trim die. The cost of a single-cavity die for this part has been estimated to be $10,000 and the trim die has been estimated to be $2,000. Determine the optimum number of cavities for production volumes of 100,000, 250,000 and 500,000 assuming k_1 = 62$/h, C_n = 35$/h and $m = 0.7$.

Using Eq. (10.13) when N_t = 100,000 components, gives:

$$n_c^{(1.7)} = 100{,}000(62 \times 20 + 35 \times 7)/(3600 \times 0.7 \times 12{,}000)$$

$$n_c = 2.6$$

Similarly, for 250,000 components, $n_c = 4.4$, and for 500,000 components, $n_c = 6.6$. These numbers indicate that for production volumes of 100,000, 250,000 and 500,000, dies with cavity numbers of 3, 4 and 7, respectively, would lead to most efficient manufacture. In practice, it is unusual to have an odd number of cavities, so for these three cases, the likely number of cavities would be 2, 4 and 6, respectively.

Once the most economical number of cavities has been determined for a particular die casting task, the physical constraints of the equipment must be examined. The first consideration is the number and position of sliding cores in the die.

As with injection molds, sliding cores must be located in the die such that they may be retracted, and such that there is space for their driving mechanisms. Also, as with injection molds, cavities that require sliding cores on four sides are limited to single-cavity dies, while cavities with cores on three sides are limited to two-cavity dies. Cavities containing core slides on two sides are restricted to either two- or four-cavity dies, depending on the angle between slides; see Fig. 10.6.

The remaining constraints are on the die casting machine and trim press to be used for the task. The die casting machine must be large enough to provide the required clamp force, as well as to provide a platen area, shot volume, and die opening large enough for the specified casting arrangement. Similarly, the bed area of the trim press must be large enough to accommodate the area of the shot. If the available machines and presses cannot meet all of these constraints, then the number of cavities must be lowered until the corresponding machine size falls within the range of available machines. The process of determining the appropriate machine size will be covered in detail in the next section.

10.9 DETERMINATION OF APPROPRIATE MACHINE SIZE

Several factors must be considered when choosing the appropriate machine size with which to cast a particular die cast component. These factors include the machine performance, as well as the dimensional constraints imposed by the machine. The most important machine performance capability to be considered is the machine clamping force. Dimensional factors that must be considered include the available shot volume capacity, the die opening stroke length, also called clamp stroke, and the platen area.

10.9.1 Required Machine Clamp Force

Die casting machines are primarily specified on the basis of machine clamping force. In order to prevent the die halves from separating, the clamp force, F, exerted by the machine on the die must be greater than the separating force, f, of the molten metal on the die during injection:

$$F > f \tag{10.14}$$

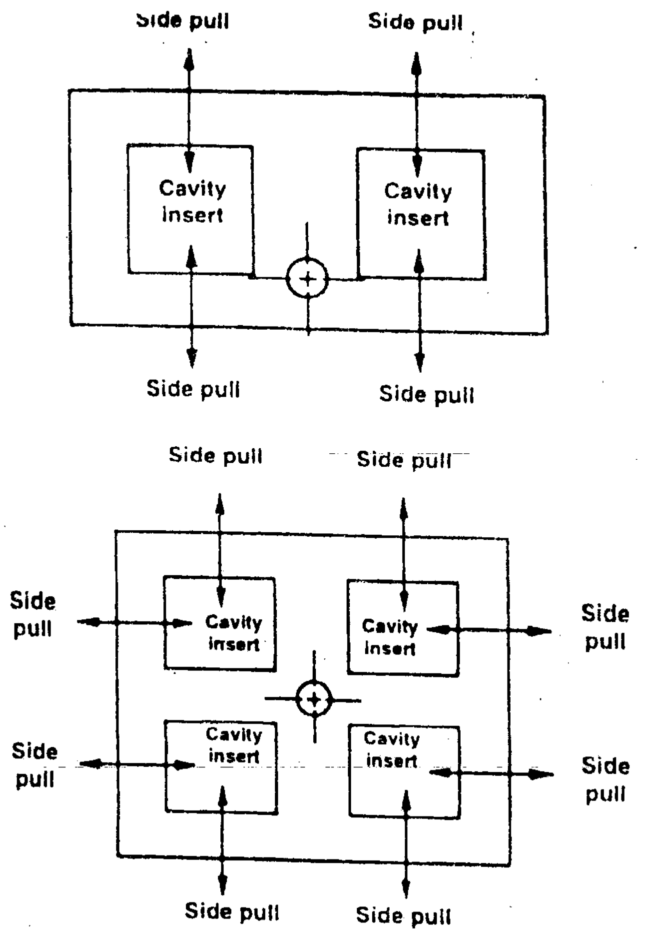

Figure 10.6 Restricted number of cavities with 2 side-pulls.

For a given die casting task, the force exerted by the molten metal may be represented as follows:

$$f = p_m A_{pt}/10 \qquad (10.15)$$

where

f = force of molten metal on die, kN

p_m = molten metal pressure in the die, MPa

A_{pt} = total projected area of molten metal within the die, cm^2

The total projected area, A_{pt}, is the area of the cavities, feed system, and overflow wells, taken normal to the direction of die opening, and can be represented by the following equation:

$$A_{pt} = A_{pc} + A_{po} + A_{pf} \qquad (10.16)$$

where

A_{pc} = projected area of cavities,

A_{po} = projected area of overflow wells

A_{pf} = projected area of feed system

Figure 10.7 shows the relative size of a typical casting before and after trimming. The proportions of A_{pf} and A_{po} to the cavity area, A_{pc}, vary with the size of the casting, the wall thickness and the number of cavities. However, analysis of a wide variety of different castings has failed to establish any logical relationships between the geometry of the cavity and the area of the feed and overflow system. One reason for this situation may be, as stated by Herman [4], that the relationships between casting geometry and overflow size are not well understood. The size of overflow wells is thus a matter of individual diemaker judgment coupled with trial and error modifications during die tryout. The range of variation of $(A_{po} + A_{pf})$, from examination of actual castings, appears to be from 50 percent of A_{pc} to 100 percent of A_{pc}. The mean value of total casting projected area can thus be represented approximately by

$$A_{pt} \approx 1.75\, A_{pc} \qquad (10.17)$$

Equation (10.17) is intended to be used at the sketch stage of design in order to obtain a first estimate of required clamp force from Eq. (10.15). The pressure at which the molten metal is injected into the die depends primarily on the die

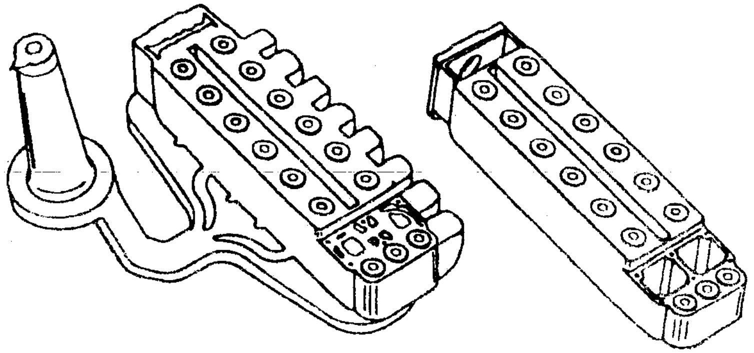

Figure 10.7 Hot-chamber die casting before and after trimming.

casting alloy being used. Typical pressures for the main classes of alloys are given in Table 10.6. It should be noted that the metal pressure is often increased from the instant that the die is filled in order to reduce metal porosity and surface defects which can result from metal shrinkage. However, this intensification of pressure occurs when a skin of solidified metal has already formed from contact with the die surface. This skin acts like a vessel which helps to contain the pressure increase, and for this reason machine builders suggest that the unintensified pressure should be used for clamp force calculations. Thus, the values for p_m in Eq. (10.15) may be taken directly from Table 10.6.

10.9.2 Shot Volume

The shot volume required for a particular casting cycle may be represented by

$$V_s = V_c + V_o + V_f \text{ cm}^3 \qquad (10.18)$$

where

V_s = total shot volume

V_c = volume of cavities

V_o = volume of overflow wells

V_f = volume of feed system

As with the projected area contributions, the volumes of the overflow wells and the feed system represent a significant portion of the shot volume. The proportion of material in the overflow and runner system is usually considerably greater for relatively thin wall castings. Blum [5] analyzed a number of different castings and has suggested that the volumes of the overflow and feed systems can be represented by the approximate relationships

$$V_o = 0.8\, V_c/h^{1.25} \text{ cm}^3 \qquad (10.19)$$

$$V_f = V_c/h \text{ cm}^3 \qquad (10.20)$$

Table 10.6 Typical Cavity Pressures in Die Casting

Alloys	Cavity pressure (MN/m^2)
Zinc	21
Aluminum	48
ZA	35
Copper	40
Magnesium	48

where h is the average wall thickness of the part measured in millimeters. The trend of these relationships is supported in part by Herman [4], who recommends overflow volumes for die design, the average values of which fit almost precisely to the curve

$$V_o = V_c/h^{1.5} \text{ cm}^3 \qquad (10.21)$$

For the present early-design assessment purposes, these tentative relationships will be further reduced to the simple expression for shot size

$$V_s = V_c(1 + 2/h) \qquad (10.22)$$

where again h = average wall thickness, mm. The difference between Eq. (10.22) and Eqs. (10.18), (10.19) and (10.20) over the range h = 1 mm to 10 mm is only 4 to 7 percent.

It should be noted that the feed system and overflow wells, which are trimmed from the casting, cannot be reused immediately as is the case with injection moldings. The scrap material from diecasting must be returned to the material supplier where oxides are removed and the chemical composition recertified. This "conditioning" process typically costs 15 to 20 percent of the material purchase cost. Material cost per part should, therefore, be estimated from the weight of the part, plus say 20 percent of the weight of overflow wells and feed system, using the cost per kilogram given in Table 10.1.

10.9.3 Dimensional Machine Constraints

For a part to be diecast on a particular machine which has sufficient clamp force and shot volume, two further conditions must be satisfied. First, the maximum die opening or clamp stroke must be wide enough so that the part can be extracted without interference. Thus, the required clamp stroke, L_s, for a hollow part of depth D, with a clearance of 12 cm for operator or mechanical extractor, will be

$$L_s = 2D + 12 \text{ cm} \qquad (10.23)$$

The factor 2 is required to achieve separation from both the cavity and core.

The second requirement is that the area between the corner tie bars on the clamp unit, sometimes referred to as the platen area, must be sufficient to accommodate the required die. The size of the die can be calculated in the same way as the mold base for injection molding. Thus, the clearance between adjacent cavities or between cavities and plate edge should be a minimum of 7.5 cm with an increase of 0.5 cm for each 100 cm^2 of cavity area. Reasonable estimates of the required plate size are given by allowing a 20 percent increase of part width for overflow wells and 12.5 cm of added plate width for the sprue or biscuit.

Example:

A 20 cm long by 15 cm wide by 10 cm deep box-shaped die casting is to be made from A360 aluminum alloy. The mean wall thickness of the part is 5 mm and the part volume is 500 cm^3. Determine the appropriate machine size if a 2-cavity die is to be used.

Projected area of cavities is given by

$$A_{pc} = 2 \times 20 \times 15 = 600\,\text{cm}^2$$

and so estimated shot area is

$$A_{pt} = 1.75 \times 600 = 1050\,\text{cm}^2$$

Thus, the die separating force from Eq. (10.15) and Table 10.6 is

$$F_m = 48 \times 1050/10$$
$$= 5040\,\text{kN}$$

The shot size is given by Eq. (10.22) to be

$$V_s = 500\,(1 + 2/5) = 700\,\text{cm}^3$$

The clamp stroke, L_s, must be at least

$$L_s = 2 \times 10 + 12 = 32\,\text{cm}$$

The clearance between the cavities and with the plate edge is likely to be

$$\text{Clearance} = 7.5 + 0.5 \times (20 \times 15)/100$$
$$= 9.0\,\text{cm}$$

Thus, the two cavities may be arranged end to end with 9.0 cm spacing between them and around the edges and with a 20 percent width increase to allow for the overflow wells. If an additional increase of 12.5 cm is then applied to the plate width for the biscuit, a final plate size of 67 × 42.5 cm is obtained. The layout within this plate is shown in Fig. 10.8. The appropriate machine from Table 10.4 would thus be the one with 6000 kN clamp force which can accommodate plate sizes up to 100 cm × 120 cm.

10.10 DIE CASTING CYCLE TIME ESTIMATION

A die casting machine cycle consists of the following elements:

(i) Ladling the molten shot into the shot sleeve (for cold-chamber machines only)
(ii) Injection of molten metal into the feed system, cavities and overflow wells

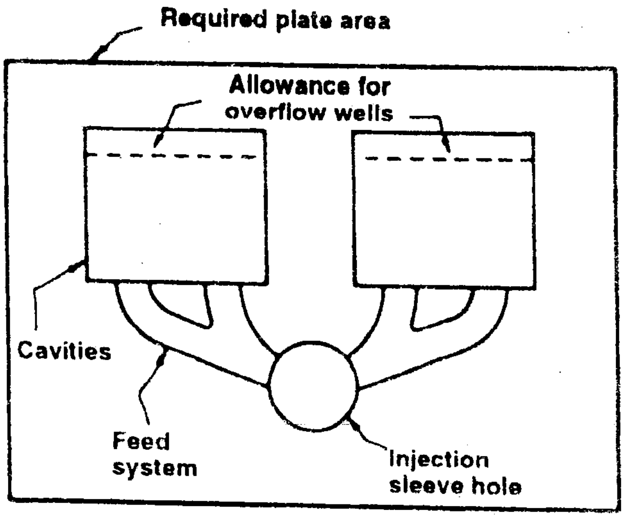

Figure 10.8 Layout of 2-cavity die.

(iii) Cooling of the metal in the feed system, cavities and overflow wells
(iv) Opening of the die and the safety door
(v) Extraction of the diecasting which is usually held on the projecting ejector pins
(vi) Lubrication of the die surfaces
(vii) Closing of the die for the next cycle

10.10.1 Ladling of Molten Metal

The time for manual ladling of the molten metal shot into a cold-chamber machine has been studied by Ostwald [6], who presents time standards for different shot volumes. This can be represented almost precisely by the linear relationship

$$t_{lm} = 2 + 0.0048V_s \tag{10.24}$$

where

t_{lm} = manual ladling time, s
V_s = total shot volume, cm^3

Note that this time does not include the transfer of the ladle to the machine pouring hole which occurs while the die and safety door on the machine are closing.

10.10.2 Metal Injection

Metal injection and the resultant filling of feed system, cavities and overflow wells occurs extremely rapidly in die casting. This is essential to avoid premature solidification, which would prevent complete cavity filling or cause casting defects where partially solidified streams of metal come together with incomplete bonding taking place. It is clear that the problem of premature solidification will be greater for thinner wall diecastings since, during filling, a thinner stream of molten metal, with less heat content, will contact the cooled die walls. The Society of Die Casting Engineers [7] has recommended that fill time should be directly proportional to the average casting wall thickness governed by the following equation:

$$t_f = 0.035\,h\,(T_i - T_f + 61)/(T_i - T_m) \tag{10.25}$$

where

t_f = fill time for feed system, cavities and overflow wells, s
T_i = recommended melt injection temperature, °C
T_f = die casting alloy liquidus temperature, °C
T_m = die temperature prior to shot, °C
h = average wall thickness of diecasting, mm

Typical values of T_i, T_f and T_m for the different families of die casting alloys are given in Table 10.7. Substitution of these values into Eq. (10.25) yields fill times ranging from 0.005 h to 0.015 h. It can be seen that fill times in die casting will rarely exceed 0.1 s and are usually represented in milliseconds. Thus, for the purposes of estimating cycle times, fill time can simply be neglected.

10.10.3 Metal Cooling

As described briefly above, the casting cycle proceeds when molten metal, at temperature T_i, is injected rapidly into the die which is at initial temperature T_m. The casting is then allowed to cool to a recommended ejection temperature T_e, while the heat is being removed from the die through the circulation of cooling water.

During solidification of the metal, latent heat of fusion is released as the metal crystallizes. This additional heat can be represented by an equivalent increase in temperature, ΔT, given by the following equation:

$$\Delta T = H_f/H_s \tag{10.26}$$

where

H_f = latent heat of fusion coefficient, J/kg
H_s = specific heat, J/(kg K)

The equivalent injection temperature, T_{ir}, then becomes

$$T_{ir} = T_i + \Delta T \tag{10.27}$$

This approach to the inclusion of heat of fusion in cooling calculations has been used extensively in the literature. The term ΔT is often referred to as "superheat."

It is accepted in the literature [8] that the main resistance to heat flow from the casting is the interface layer between the casting and the die. This is in direct contrast to injection molding where the resistance to heat flow is provided by the polymer itself. This is because in injection molding, the thermal conductivity coefficient of the thermoplastics is of the order of 0.1 W/(mK) whereas die casting alloys have typical conductivity values of approximately 100 W/(mK). This leads to a cooling problem in die casting which is entirely opposite to that which exists in injection molding. In injection molding, the goal is to cool the polymer as rapidly as possible in order to reduce the major component of cycle times. In die casting, "lubricants" are sprayed onto the die to protect the die surface, but also to provide a heat resistant coating in order to slow cooling for satisfactory die filling.

The resistance of the die interface is represented by its heat transfer coefficient, H_t, which has units kW/(m^{2}K). The rate of heat flow into the die surface is then given by

$$\dot{W} = H_t A (T - T_m) \tag{10.28}$$

where

T = alloy temperature adjacent to die face, °C
T_m = temperature of die adjacent to die face, °C
A = area of contact with die surface, m^2
H_t = heat transfer coefficient, kW/(m^{2}K)
$\dot{W}$ = heat flow rate, kW

Reynolds [9] has shown that for permanent mold (nonpressurized) casting of aluminum alloy, the heat transfer coefficient with a polished die surface is as

Table 10.7 Typical Die Casting Temperatures (°C)

Alloy	Injection temp.	Liquidus temp.	Die temp.	Ejection temp.
Zinc	440	387	175	300
Aluminum	635	585	220	385
ZA	460	432	215	340
Copper	948	927	315	500
Magnesium	655	610	275	430

high as 13 $kW/(m^2K)$. However, with a thin coat of amorphous carbon, the heat transfer coefficient varies between 1 and 2 $kW/(m^2K)$. Sekhar et al. [10] confirmed the pronounced effects on heat transfer of the thin layers of carbon which are produced from the die lubricants by the hot metal contact. They also showed that the heat transfer coefficient is increased by applied pressure on the metal. For typical die casting pressures between 20 and 50 MN/M^2, and carbon layers between 0.05 and 0.2 mm thick, Sekhar's results show an average heat transfer coefficient value of approximately 5 $kW/(m^2K)$.

Dewhurst and Blum [11] have shown that, based on the heat transfer coefficient as the principal heat resistance mechanism, the cooling time may be represented by the simple equation

$$t_c = \rho H_s \log_e[(T_{ir} - T_m)/(T_e - T_m)]h_{max}/2H_t \qquad (10.29)$$

where

ρ = density, Mg/m^3
H_s = specific heat, J/(kgK)
T_{ir} = "super heat" injection temperature, °C
T_m = mold temperature, °C
T_e = casting ejection temperature, °C
h_{max} = maximum casting wall thickness, mm
H_t = heat transfer coefficient, $W/(m^2K)$

Example:

Determine typical cooling times for zinc die castings. For a typical zinc die casting alloy, the following parameter values can be used:

$\rho = 6.6\ Mg/m^3$
$H_s = 419\ J/(kgK)$
$T_i = 440°C$
$T_e = 300°C$
$T_m = 175°C$
$H_f = 112 \times 10^3\ J/kg$
$H_t = 5000\ W/(m^2K)$

Thus, from Eq. (10.26) and (10.27)

$$T_{ir} = 440 + (112 \times 10^3)/419 = 707.3°C \qquad (10.30)$$

Substituting the above values into Eq. (10.29) gives an estimate of nominal cooling time as

$$t'_{cz} = 0.4h_{max}\ s \qquad (10.31)$$

where

t'_{cz} = nominal cooling time for zinc alloys
h_{max} = maximum wall thickness, mm

Similar substitutions into Eq. (10.29) with appropriate parameter values for other die casting alloys give the following simple expressions for cooling time.

$$t'_c = \beta h_{max}\ s \qquad (10.32)$$

where

β = cooling factor

and

$\beta = 0.4$ for zinc alloys
$= 0.47$ for aluminum alloys
$= 0.42$ for ZA alloys
$= 0.63$ for copper alloys
$= 0.31$ for magnesium alloys

Equation (10.32) is based on the assumption that there is negligible resistance to heat flow through the steel die and into the cooling channels. This is a good assumption for basically flat castings where cooling channels can be arranged through the cavity and core blocks to cover the casting surfaces. For complex casting shapes, however, cooling of the dies becomes less efficient and the cooling time increases. Herman [4] has suggested that the cooling time increases with casting complexity in proportion to the ratio of the cavity surface area divided by the cavity projected area. However, comparisons with industrial case studies show that this tends to overestimate the cooling time for geometrically complex castings and that the trend represented by

$$t_c = (A_f/A_p)^{1/2}\beta h_{max} \qquad (10.33)$$

gives a better fit to actual cooling times,
where

A_f = cavity surface area
A_p = cavity projected area

Note that for thin wall castings, the cooling time for the feed system may be longer than for the casting itself. A rule of thumb, obtained from industrial sources, is that the tooling time will never be less than for a flat 3 mm thick casting. Also, in calculating the values for A_p and A_f, the overflow wells and feed systems are neglected.

Example:

Determine the cooling time for a 50 mm diameter by 100 mm deep plain cylindrical cup, with 3 mm wall thickness which is to be die-cast from aluminum alloy.

Cavity area, $A_f = 17671\ \mathrm{mm}^2$

Cavity projected area, $A_p = 1963\ \mathrm{mm}^2$

Thus, from Eq. (10.33), with the appropriate b value of 0.47,

$$t_c = (17671/1963)^{1/2} \times 0.47 \times 3 = 4.23\ \mathrm{s}$$

10.10.4 Part Extraction and Die Lubrication

On die opening, the ejector pins protrude through the core and push the casting, with its feed and overflow system, into the gap between the cavity and core plate. Small nonprecision castings may then be dropped into the gap below the die, usually into a water tank where a conveyer belt transports the part into a bin. However, die castings always stick onto the ejector pins because of flashing around the pin ends in the die and a secondary ejection mechanism must be employed to break the casting free. This usually involves putting small rack and pinion actuators behind a small proportion of the pins, which move these pins further forward at the end of the main ejector stroke.

For larger or precision parts, the casting must be removed from the ejector pins by the machine operator or by a pick-and-place device on an automatic machine. In this case, the time for casting removal depends principally on casting size. Discussions with die casters suggest that a typical time for unloading a 10 cm × 15 cm casting is 3 s and that unloading a 20 cm × 30 cm casting will take 5 s. If it is assumed that the unloading time increases linearly with casting size, then these values give the relationship

$$t_x = 1 + 0.08\,(W + L)\ \mathrm{s} \quad \text{for } W + L > 25\ \mathrm{cm} \qquad (10.34)$$

and

$$t_x = 3\ \mathrm{s}\ \text{otherwise}$$

where

t_x = casting extraction time, s

W, L = width and length of the smallest rectangle which will enclose feed system, cavities and overflow wells, cm

Example:

A box-shaped aluminum alloy casting, 8 cm wide by 10 cm long by 2 cm deep, is to be cast in a 6-cavity die. Estimate the time for extraction of the casting from the die casting machine.

Using the guidelines for casting layout given in section 10.8, the size of each cavity plus overflow wells will be approximately (8 × 1.2) by 10 or 9.6 cm by 10 cm. Assuming a two by three pattern of castings with a separation of 8 cm (7.5 plus 0.5 for a cavity area of approximately 100 cm^2), gives a cavity array size equal to 28 cm × 44.8 cm. Finally, allowing a 12.5 cm width increase for the sprue or biscuit gives a total casting size of 40.5 × 44.8 cm.

The time for part extraction, from Eqn. (10.34) is thus

$$t_x = 1 + 0.08\,(40.5 + 44.8) = 7.8\ \mathrm{s}$$

The time for die opening and closing is estimated in the same way as for injection molding. The only difference is that in die casting, the full clamp stroke is commonly utilized to give adequate access for casting removal. As in injection molding, the die must be opened at less than full clamp speed to allow safe separation of casting from the cores. If 40 percent of full speed is assumed, as discussed in Sec. 8.6.3, then the die opening plus closing time can be given by

$$t_{open} + t_{close} = 1.75\, t_d\ \mathrm{s} \qquad (10.35)$$

where

t_d = machine dry cycle time

Thus if the 6-cavity die above is operated on the 6000 kN cold-chamber machine in Table 10.3, the die opening and closing time will be given by

$$t_{open} + t_{close} = 1.75 \times 5.8 = 10.2\ \mathrm{s}$$

After part extraction, and before the die is closed, the die surfaces are sprayed with an appropriate lubricant. The resulting lubricant film serves two purposes. It forms a barrier to heat flow, as discussed in Sec. 10.10.3, to allow more time for satisfactory cavity filling. It also protects the die surface from erosion by the high-pressure wave of hot metal. The time for application of die lubricant depends on the alloy being cast and on the number of cavities and cavity size. It also increases with the number of side-pulls since the slideways require additional lubricant concentration. Typical times obtained from industrial contacts are given in Table 10.8.

Example:

The box-shaped aluminum castings discussed above have a hole in the side wall which requires one side-pull for each of the six cavities. The average wall thickness is 4 mm and the maximum wall thickness is 10 mm. The projected area, A_p, of each cavity is 80 cm^2 and the cavity surface area, A_f, equals 280 cm^2. The volume of each casting is 85 cm^2. Thus, from Eq. (10.22), the shot volume is given by

$$V_s = 6 \times 85 \times (1 + 2/4) = 765\ \mathrm{cm}^3$$

Referring to Table 10.8, the die lubrication time per cycle is given by

$$t_l = 3 + 1 \times (n_s \times n_c) + 1 \times (n_c - 1) \qquad (10.36)$$

Table 10.8 Lubricant Application Times for Die Casting (Seconds)

Part size	Basic time	Added time: Per side-pull	Added time: Per extra cavity
Small (10 cm × 10 cm)	3	1	1
Medium (20 cm × 20 cm)	4.5	1	2
Large (30 cm × 30 cm)	6	1	3

	Number of machine cycles per lubrication
Aluminum	1
Copper	1
ZA	2
Magnesium	2
Zinc	3

where

n_s = number of side pulls per cavity
$= 1$
n_c = number of cavities
$= 6$

Thus

$$t_l = 14\,\text{s}$$

Note that if the boxes were cast from zinc alloy, then lubrication would occur every three cycles, so the value for t_l would be 4.67 s.

The cooling time for the box castings is given by Eq. (10.33) as

$$t_c = (280/80)^{1/2} \times 0.47 \times 10$$
$$= 8.8\,\text{s}$$

The time for ladling of the molten shot into the cold- chamber machine is given from Eq. (10.24) as

$$t_{lm} = 2 + 0.0048 \times 765 = 5.7\,\text{s}$$

Finally, from Sec. 10.10.2, it can be shown that the fill time will be approximately 0.05 s.

Thus, the complete cycle time for the six-cavity die casting operation is as follows:

Cooling time = 8.8
Part extraction time = 7.8
Die lubrication time = 14.0
Die open/close time = 10.2
Metal ladling time = 5.7
Total = 46.5 s

10.10.5 Trimming Cycle Time

The need for the trimming operation in the die casting process is an important factor distinguishing die casting cost estimation from that of injection molding. The trimming processing cost is the product of the trimming time and the hourly operating rate of the machine and operator. As previously mentioned in the discussion on optimum number of cavities, the hourly trimming rate can be approximated by a constant value for all machine sizes due to the small tonnages of the machines as well as the relatively small range of machine sizes. This small press size requirement means that the hourly rate is dominated by the hourly labor rate of the trim press operator rather than by the cost of the press itself.

The trimming cycle time, including the time to load the shot into the press, is similar to punch press loading and cycle times for sheet metalworking, given by Ostwald [6]. These times vary linearly with the sum of the length and width of the part and can be represented by the following relationship developed from these data:

$$t_s = 3.6 + 0.12\,(L + W)\,\text{s} \qquad (10.37)$$

where

t_s = sheet metal press cycle time, s
L = length of rectangular envelope, cm
W = width of rectangular envelope, cm

Discussion with industrial sources indicates that press loading times of die casting shots are generally longer than sheet metal loading times. One reason for this is that die casting shots are oddly shaped and are, therefore, more difficult to align in the die. Additional time is also required for periodic cleaning of the trimming die, as flash and other scrap create a buildup of debris.

It appears from data on a limited number of castings that trim press cycle times are typically 50 percent higher than manual press operations for sheet metal. Thus, for early costing purposes, the trim press cycle time can be estimated by

$$t_p = 5.4 + 0.18\,(L + W)\,\text{s} \qquad (10.38)$$

Note that for castings with side holes produced by side pulls, trimming is required in both the die opening and side pull directions. In some cases, these separate trimming tasks will be carried out with separate trim tools on separate presses. In these cases, a multiple of the time estimate from Eq. (10.38) would give the appropriate total trimming cycle time. The cost of trim dies and the effect on die cost of multiple trim directions are discussed in Sec. 10.10.3.

10.11 DIE COST ESTIMATION

The tooling used for die casting is somewhat more expensive than for injection molding. There are three main reasons for this. First, because of the much greater thermal shocks to which a die casting die is subjected, finer steels must be used for the die set and cavity and core inserts than are necessary for injection molding. This gives rise to increased costs for the die set even though it is identical in basic construction to an injection-molding mold base. It also results in greater costs for manufacturing the cavity and core inserts from the more difficult to machine material. Second, the overflow wells and larger sprue or biscuit take up more plate area than in injection molding with the requirement for a larger die set than the corresponding mold base for an injection molded part. Third, for other than the smallest production volumes, a separate trim tool must be manufactured to remove the flash, feed system and overflow wells from the finished castings

10.11.1 Die Set Costs

A major supplier of interchangeable die sets and mold bases offers them with three qualities of steel: No. 1 steel (SAE 1030), No. 2 steel (AISI 4130) and No. 3 steel (P-20 AISI 4130). Steels No. 1 and No. 2 are recommended for injection molding, while steels No. 2 and No. 3 are recommended for die casting. For the same plate areas and thicknesses, the average cost of mold bases (steel No. 1 or 2) is compared with the average price of die sets (steel No. 2 or 3) in Fig. 10.9. The line drawn on the graph has a slope equal to 1.25, which means that for the same plate sizes, a die casting die set will be typically 25 percent more expensive than a mold base for injection molding. Thus, from Sec. 8.7.1 in Chapter 8, the cost of a die set, C_d, can be represented by

$$C_d = 1250 + 0.56\,A_c h_p^{0.4}\ \$ \tag{10.39}$$

where

A_c = area of die set cavity plate, cm^2 (which can be estimated from the casting layout rules given in section 10.9.3)

h_p = combined thickness of cavity and core plates in die set, cm.

As with injection molding, typical plate thicknesses should be based on 7.5 cm of plate material separating the casting from the outer plate surfaces. Thus, a 10 cm plain cylindrical cup would typically have the main core mounted onto a 7.5 cm thick core plate and the cavity sunk into a 17.5 cm thick cavity plate.

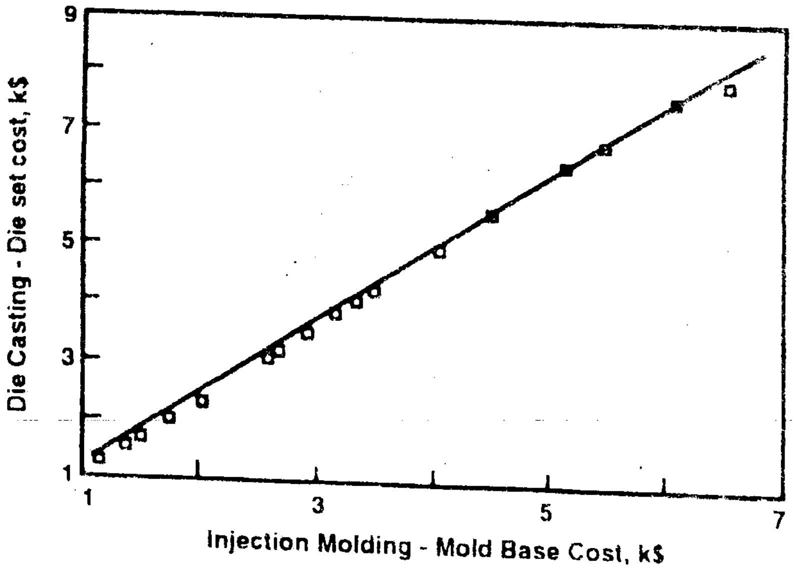

Figure 10.9 Relative cost of die casting die sets.

Also, as for injection molding, the plate area should be increased to allow for any necessary side pulls; see the description in Sec. 8.7.1.

10.11.2 Cavity and Core Costs

The equations developed for estimating the costs of cavities and cores for injection molding in Chapter 8 can be applied directly to die casting with only minor changes. The most important change is the use of a factor to allow for the use of more difficult to machine steels and the machining of overflow wells. A survey of die and mold makers found reasonable agreement that die casting dies are in the range of 20 to 30 percent more expensive than equivalent molds for injection molding. This also agrees with the comparison of die set to mold base costs in the last section. It seems that typically the cavities and cores will be 25 percent more expensive for die casting. The equations in Sec. 8.8.2 of Chapter 8 should, therefore, be applied with a multiplying factor of 1.25.

The range of tolerances which can be achieved with die casting is approximately the same as for injection molding and the effect on cavity and core manufacturing time is as given in Sec. 8.9. However, as opposed to the six different surface finish and appearance factors applicable to injection molding, only three surface finish categories are typically used for die casting. These can be represented as:

(i) **Minimum finish required to achieve clean separation from the die**
(ii) **Medium finish which will allow parts to be buffed or polished**
(iii) **Highest-quality finish, which is usually reserved for zinc alloy parts which are to be chrome-plated to mirror standard**

The percentage increases which should be used in the point cost system of Sec. 8.9 to account for cavity and core finishing are given in Table 10.9.

10.11.3 Trim Die Costs

The basic trim die performs essentially the same function as a sheet metal blanking die. However, the trim die construction is less expensive than for blanking dies because of the smaller forces which are encountered. Examination of a range of industrial trim dies indicates that the cost of a die to trim a casting with a flat parting plane and no internal holes is approximately half the cost of an equivalent sheet metal blanking die. Moreover, if additional punches are required to trim internal holes in a casting, then the cost is approximately the same as for the purchase and fitting of standard punches into a sheet metal die set.

Thus, from the equations developed in Chapter 9, the cost of a trim die can be estimated as follows. Complexity of the outer profile is defined as for sheet metal parts by

$$X_p = P^2/(LW) \qquad (10.40)$$

where

P = outer perimeter of one cast part, cm
L, W = length and width of smallest rectangle which surrounds outer perimeter of one cast part, cm

Taking 50 percent of the basic manufacturing points for blanking dies give

$$M_{to} = 15 + 0.125\,X_p^{0.75}\,h \qquad (10.41)$$

Using the average of the curves used in Chapter 9 for area correction of blanking dies gives

Table 10.9 Surface Finish Effect on Point Score

Appearance	Percent increase
Minimum finish	10
Medium finish	18
Highest quality	27

$$f_{lw} = 1 + 0.04\,(LW)^{0.7} \qquad (10.42)$$

Using the sheet metal value of 2.0 equivalent manufacturing hours for the purchase and fitting of standard punches gives the estimated hours for a basic trim tool as

$$M_t = f_{lw}M_{to} + 2N_h \qquad (10.43)$$

where

M_t = basic tool manufacturing time, h
N_h = number of holes to be trimmed

Two additional factors can substantially increase the cost of the basic trim tool. These are the complexity of the parting line and the existence of through holes, produced by side pulls, which require trimming in a nonaxial direction. Data on trim tool costs obtained from die casters suggests the following approximate relationships for these added cost factors.

(i) Each additional trim direction will require approximately 40 extra hours of tool making. This is the time to produce an extra trim tool with one or more shaving punches, or to incorporate a cam action into the main trim tool for angled punch action.

(ii) Approximately 17 h of additional tool making are associated with each increase in parting line complexity. Parting line complexity is defined according to the levels given in Table 8.8 of Chapter 8. Thus, a casting with parting line complexity 4 will require approximately 68 extra hours of manufacture for the trim tool. This time is required to produce a segmented die with cutting edges on the different levels required to follow the parting line contour.

Example:

A die casting has the following defining characteristics:

Outer perimeter, P = 68.6 cm
Envelope dimension, L = 24.0 cm
Envelope dimension, W = 13.5 cm
Number of holes to be trimmed, N_h = 9
Number of side pulls per cavity, n_s = 2
Number of cavities, n_c = 2
Parting line factor = 2

Estimate the cost of the required trim tool.

Outer profile complexity, X_p = 68.62/(24 × 13.5)
= 14.5

Area correction factor, f_{lw} = $1 + 0.04(24 \times 13.5)^{0.7}$
= 3.3

Basic manufacturing points, $M_{t0} = 15 + 0.125(14.5)^{0.75}$
$= 16$

The base manufacturing hours for the trim tool for a single cast part is given by Eq. (10.43) as

$$M_t = 3.3 \times 16 + 2 \times 9 = 70.8\,\text{h}$$

Two additional trim directions are required for the side-pull features, which will require 40 added hours of tool making. The parting line has several steps, giving a parting line factor of 2 and, thus, 34 added hours to achieve the stepped trim die surface.

If a typical tool making rate of $40/h is assumed, then the cost of the trim tool(s) for one cast part would be approximately

$$C_{t1} = (70.8 + 80 + 34) \times 40 = \$7{,}392$$

In this case a two-cavity die is used, so the trim tool must have two shaving dies and two sets of punches to accommodate the two-part casting. To allow for the manufacture of trim tools for multicavity castings, the multicavity cost index is used exactly as for the cost estimating of multicavity dies and molds. Thus, using a multicavity index value of 0.7 (as used in Sec. 10.8) the estimated total cost of the complete trim tool is

$$C_{tn} = 7{,}392 \times 2^{0.7} = \$12{,}000$$

The actual 1991 purchase cost for the tool for trimming this casting was $14,000.

10.12 ASSEMBLY TECHNIQUES

Die castings can be produced with a variety of features which assist with assembly. Alignment features such as chamfered pins, holes, slots, projecting alignment edges, and so forth have insignificant cost and yet can ensure frustration-free quality assembly work. Unfortunately, there is no analogy of the injection-molded snap fit elements in die casting. The only integral fastening method available seems to be the cold forming of cast projections to achieve permanent fastening. The cast alloy must of course possess sufficient ductility and this limits the assembly method to zinc and ZA alloys. With these alloys, projecting rivet posts, tabs or projecting edges can be upset or bent after assembly to achieve strong attachment.

As with injection molding, the die casting process lends itself to the use of inserts which are simply loaded into the die before injection. This practice is used widely to produce castings with steel screw studs for assembly purposes. However, unlike injection molding, screw thread bushings are not used since cored holes in the casting can be tapped to produce high-strength attachment.

Examples can be found of die castings with spring steel inserts where the spring satisfies a functional requirement in the assembly. This suggests the possible use of spring steel inserts to produce snap fit die cast parts. However, the authors are unaware of any such application.

10.13 DESIGN PRINCIPLES

Die casting and injection molding are closely competing processes and the detail design principles to ensure efficient manufacture are similar for both. Generally accepted guidelines for die casting design are listed below.

1. Die castings should be thin wall structures. To ensure smooth metal flow during filling and minimize distortion from cooling and shrinkage, the wall should be uniform. Zinc die castings should typically have wall thicknesses between 1 and 1.5 mm. Similar size castings of aluminum or magnesium should be 30 to 50 percent thicker than zinc, and copper die castings are usually 2 to 3 mm thick. These thickness ranges result in a fine-grained structure with a minimum amount of porosity and good mechanical properties.

Thicker sections in a casting will have an outer skin of fine metal, with thicknesses about half of the above values, with a center section which has a coarser grain structure, some amount of porosity and poorer mechanical properties. The designer should, therefore, be aware that mechanical strength does not increase in proportion to wall thickness. However, large die castings are often designed with walls as thick as 5 mm and sections up to 10 mm thick. An important consideration in these cases is that, compared to injection molding, little cost penalty is associated with the casting of thick sections. Recall that the cooling time for die castings is proportional to thickness [Eq. (10.33)] while cooling time for injection molding is proportional to thickness squared. Thus, a 5 mm thick injection molded part will typically take about 60 s to cool while a 5 mm thick diecasting may take only about 4 s. Perhaps of greater significance, a 2 mm thick diecasting which may have the same stiffness as the 5 mm injection molded part would only take 2 s to cool. This comparison suggests an economic advantage for die casting where good mechanical properties or heavy walls are required.

2. Features projecting from the main wall of a die casting should not add significantly to the bulk of the wall at the connection point. As with injection molding, this would produce delayed cooling of the localized thickened section of the main wall resulting in contraction of the surface (sink marks) or internal cavitation. A general rule is that the thickness of projections, where they meet the main wall, should not exceed 80 percent of the main wall thickness.

3. Features projecting from the side walls of castings should not, if possible, lie behind one another when viewed in the direction of die opening. In this way, die locking depressions between the features will be avoided which would otherwise require side-pulls in the die. Projections which are isolated when

viewed in the direction of die opening can often be produced by making a step in the parting line to pass over the center of the projection.

4. Internal wall depressions or internal undercuts should be avoided in casting design since moving internal core mechanisms are virtually impossible to operate with die casting. Such features must invariably be produced by subsequent machining operations at significant extra cost.

Notwithstanding the above guidelines, the power of diecasting lies in its ability to produce complex parts with a multitude of features to tight tolerances and with good surface finish. Thus, having made the decision to design for die casting, the most important rule is to get as much from the process as is economically possible. In this way, the structure of the assembly will be simplified with all the resulting cost and quality benefits. The main purpose of the procedures established in this chapter is to help the designer to identify economic applications of the die casting process and to quantify, if necessary, the cost of alternative designs

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