PART 5: OVERVIEW OF FOUNDRY PROCESSES

Contents

1. Overview of Casting Processes

This section provides a brief description of the major casting processes, for the benefit of readers who are unfamiliar with the industry. Metal casting involves pouring molten metal into a mould containing a cavity of the desired shape to produce a metal product. The casting is then removed from the mould and excess metal is removed, often using shot blasting, grinding or welding processes. The product may then undergo a range of processes such as heat treatment, polishing and surface coating or finishing.

The casting techniques described in this section are variations of the process described in the previous paragraph. The different techniques have been designed to overcome specific casting problems or to optimise the process for specific metals, product designs and scales or other operational considerations such as automation.

All casing processes use a mould, either permanent or temporary, which is a 'negative' of the desired shape. Once the metal is poured and has solidified it forms the 'positive' shape of the desired product. Processes differ in the number of stages that are required to produce the final casting. Die casting is the simplest technique in terms of the number of stages used. The process uses a permanent mould (-ve) to produce the final casting (+ve). Processes, such as sand moulding and shell casting, use a temporary mould (-ve) which is typically produced using a permanent pattern or die (+ve). Investment casting and lost foam casting techniques use a temporary mould (-ve) that is build around a temporary pattern (+ve). For repetitive work, patterns are often produced using a permanent mould or die (-ve). Table 1 summarises the patterns and moulds typically used for these five common casting techniques.

Table 1: Types of Patterns and Moulds Used in the Major Casting Techniques

Die casting	Sand casting	Shell casting	Investment casting and lost foam casting
Permanent die -ve shape	Permanent pattern +ve shape	Permanent pattern +ve shape	Permanent die (optional) -ve shape
			Temporary pattern +ve shape
	Temporary mould -ve shape	Temporary mould -ve shape	Temporary mould -ve shape
Final casting +ve shape	Final casting +ve shape	Final casting +ve shape	Final casting +ve shape

For die casting, the die is typically made of a high-strength metal or graphite material and is expensive to produce. This process, therefore, is most suited to repetitive and high-value casting (Luther, 1999). Sand casting is the most common technique used in Australia and around the world. The process combines good casting quality with flexibility in metal type and casting size. This process is most suited to jobbing foundries that produce a wide variety of products, and for large castings. Permanent patterns are typically made out of wood so are less expensive than die moulds. This pattern is used to make a temporary or destroyable mould out of sand. Metal is poured into the mould, which collapses once the casting has hardened.

The shell casting process was developed to achieve high levels of throughput for repetitive casting operations. The sand:metal ratio is greatly reduced and the dimensional accuracy of the castings is typically higher than for sand moulding, reducing the work involved in cleaning and machining the product. This process is good for routine work but lacks the flexibility of sand moulding, and the size of castings is restricted.

In investment casting and lost foam casting, temporary patterns are made from wax or foam. These patterns can be produced manually using traditional carving tools, carved mechanically using automated tooling, or, for high-volume castings, they can be produced using permanent moulds or dies. These processes are more expensive and limited in terms of casting size but achieve the highest casting quality. Investment casting can be very cost effective for producing complex geometries that would be difficult or impossible to machine. Lost foam also achieves high dimensional accuracy and has many environmental and operation benefits over traditional sand casting.

No casting process is inherently the best. Therefore companies need to select the most appropriate technique or techniques that suit the type of castings produced and the operational constraints. The major casting methods and their more common variants are discussed in the sections that follow. A general comparison of the four main methods is provided in Table 2.

Table 2: Comparison of Several Casting Methods

	Sand casting	Die casting	Sand–shell	Investment casting
Tool costs	Low	High	Average	Average
Unit costs	Average	Low	Average	High
Maximum casting weight	over 1 tonne	30 kg	100 kg	45 kg
Thinnest section castable (mm)	2.5	0.8	2.5	1.6
Typical dimensional tolerance (mm)	0.3	0.25	0.25	0.25
Relative surface finish	Fair to good	Best	Good	Very good
Relative mechanical properties	Good	Very good	Good	Fair
Relative ease of casting complex designs	Fair to good	Good	Good	Best
Relative ease of changing design in production	Best	Poorest	Fair	Fair
Metal options	Most	Low	Average	High

Note: Actual casting characteristics vary depending upon the metal uses, casting geometry and other factors.

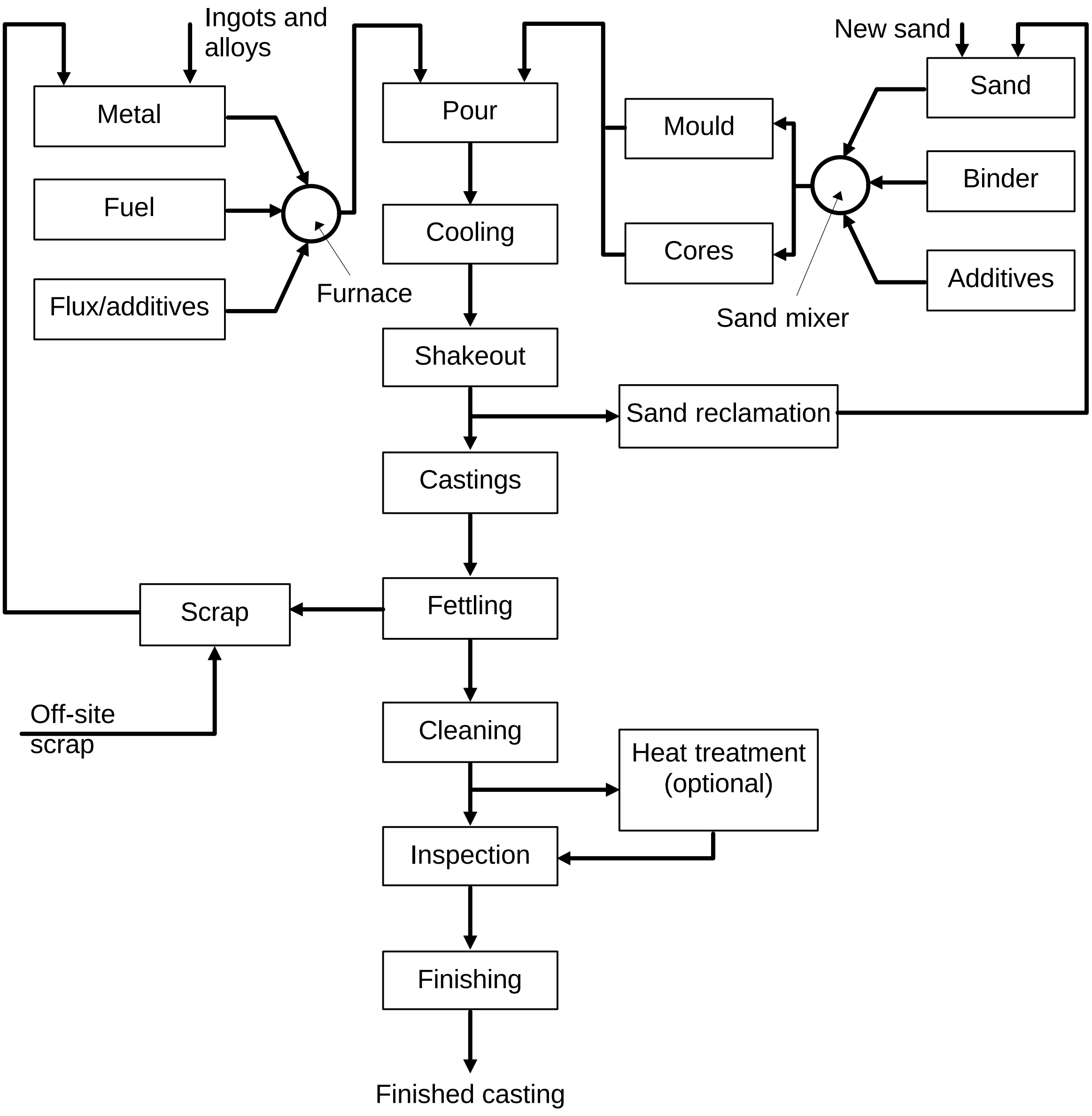
Sources: USEPA (1998) and Hitchener (1999)

2. Casting Processes

2.1 Sand Casting

Sand casting is the most common technique used in Australia, as it is around the world. A generalised process flow diagram of a typical sand casting process is shown in Figure 1.

Figure 1: A Typical Sand Casting Process



Source: Environment Canada (1997)

Sand moulding systems use sand as a refractory material and a binder that maintains the shape of the mould during pouring. A wide range of sand/binder systems are used. Green (wet) sand systems, the most common sand system, use bentonite clay as the binder, which typically makes up between 4% and10% of the sand mixture. Water, which makes up around 2–4% of the sand mixture, activates the binder. Carbonaceous material such as charcoal (2–10% of total volume) is also added to the mixture to provide a reducing environment. This stops the metal from oxidising during the pouring process. Sand typically comprises the remaining 85–95% of the total mixture (Environment Canada, 1997).

Other sand moulding processes utilise a range of chemical binders. Oil binders are combinations of vegetable or animal oils and petrochemicals. Typical synthetic resin binders include phenolics, phenolformaldehyde, urea-formaldehyde, urea-formaldehyde/furfuryl alcohol, phenolic isocyanate, and alkyl isocyanate. Chemical resin binders are frequently used for foundry cores and less extensively for foundry moulds (Environment Canada, 1997).

2.1.1 Pattern Making

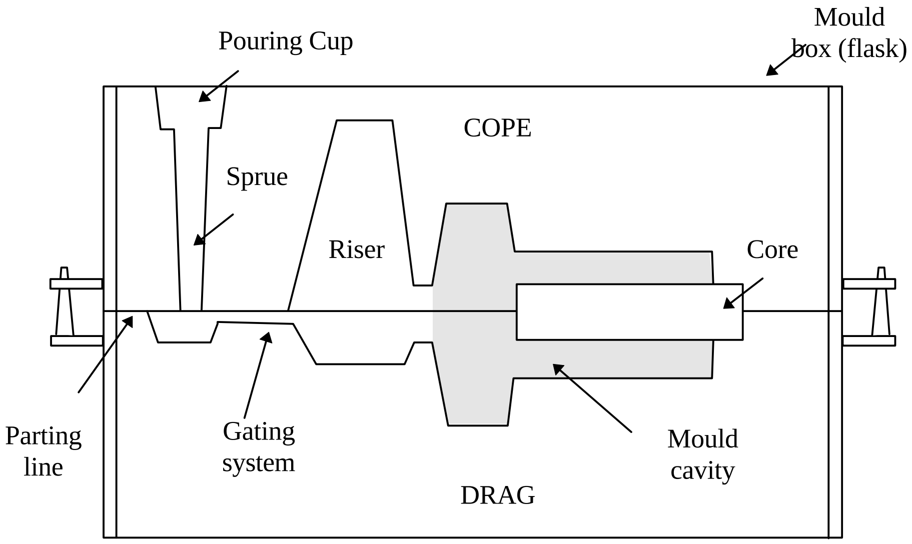
Pattern making is the first stage for developing a new casting. The pattern, or replica of the finished piece, is typically constructed from wood but may also be made of metal, plastic, plaster or other suitable materials. These patterns are permanent so can be used to form a number of moulds. Pattern making is a highly skilled and precise process that is critical to the quality of the final product. Many modern pattern shops make use of computer-aided design (CAD) to design patterns. These systems can also be integrated with automated cutting tools that are controlled with computer-aided manufacturing (CAM) tools (USEPA, 1998). Cores are produced in conjunction with the pattern to form the interior surfaces of the casting. These are produced in a core box, which is essentially a permanent mould that is developed (USEPA, 1998).

2.1.2 Mould Making

The mould is formed in a mould box (flask), which is typically constructed in two halves to assist in removing the pattern. Sand moulds are temporary so a new mould must be formed for each individual casting. A cross-section of a typical two-part sand mould is shown in Figure 2.

The bottom half of the mould (the drag) is formed on a moulding board. Cores require greater strength to hold their form during pouring. Dimensional precision also needs to be greater because interior surfaces are more difficult to machine, making errors costly to fix. Cores are formed using one of the chemical binding systems (Environment Canada, 1997). Once the core is inserted, the top half of the mould (the cope) is placed on top. The interface between the two mould halves is called a parting line. Weights may be placed on the cope to help secure the two halves together, particularly for metals that expand during cooling (USEPA, 1998).

Figure 2: Cross-section of a typical two-part sand mould



Source: Adapted from Hurst (1996)

Mould designs include a gating system which is designed to carry molten metal smoothly to all parts of the mould. The gating system typically includes a sprue, gates, runners and risers. The sprue is where the metal is poured. Gates allow the metal to enter the running system. Runners carry the molten metal towards the casting cavity. Risers may have several functions including vents to allow gases to be released, reservoirs prior to the casting cavity to aid progressive solidification, and waste cavities to allow metal to rise from the casting cavity to ensure it is filled and to remove the first poured metal from the casting cavity, thus avoiding solidification problems (Hurst, 1996).

2.1.3 Melting and Pouring

Many foundries, particularly ferrous foundries, use a high proportion of scrap metal to make up a charge. As such, foundries play an important role in the metal recycling industry. Internally generated scrap from runners and risers, as well as reject product, is also recycled. The charge is weighed and introduced to the furnace. Alloys and other materials are added to the charge to produce the desired melt. In some operations the charge may be preheated, often using waste heat. The furnaces commonly used in the industry are described below.

In traditional processes metal is superheated in the furnace. Molten metal is transferred from the furnace to a ladle and held until it reaches the desired pouring temperature. The molten metal is poured into the mould and allowed to solidify (USEPA, 1998).

2.1.4 Cooling and Shakeout

Once the metal has been poured, the mould is transported to a cooling area. The casting needs to cool, often overnight for ambient cooling, before it can be removed from the mould. Castings may be removed manually or using vibratory tables that shake the refractory material away from the casting.

Quenching baths are also used in some foundries to achieve rapid cooling of castings. This speeds up the process and also helps achieve certain metallurgical properties. The quench bath may contain chemical additives to prevent oxidation (USEPA, 1998).

2.1.5 Sand Reclamation

Most sand foundries recover a significant proportion of the waste sand for internal reuse. This significantly reduces the quantity of sand that must be purchased and disposed of. In Queensland, most sand is reclaimed mechanically; cores and large metal lumps are removed by vibrating screens and the binders are removed by attrition (i.e. by the sand particles rubbing together). Fine sand and binders are removed by extraction and collected in a baghouse. In some systems metals are removed using magnets or other separation techniques. For operations using mechanical reclamation, the recycle rate is often limited to around 70%. This is due to the need to maintain a minimum sand quality. For large iron foundries, where sand quality requirements are less stringent, over 90% reclamation can be achieved by mechanical means . For many processes, mechanically reclaimed sand is not of sufficiently high quality to be used for core production.

Thermal reclamation is becoming more widely used in Queensland. This process heats the sand to the point where organic materials, including the binders, are driven off. This process can return the sand to an ‘as new’ state, allowing it to be used for core making. Thermal reclamation is more expensive than mechanical systems.

Sand can also be reclaimed using wet washing and scrubbing techniques. These methods produce sand of a high quality but are not commonly used because they generate a significant liquid waste stream and require additional energy input for sand drying.

The amount of internal reuse depends on the type of technology used and the quality requirements of the casting process. Reclamation processes, particularly mechanical ones, break down the sand particles and this can affect the quality of some metals. Also, for mechanical reclamation techniques, impurities may build up in the sand over time, requiring a proportion of the material to be wasted. Large iron foundries do not require a high sand quality so typically achieve the highest rate of reuse in the industry. Often sand cycles through the operation until it is ground down to a fine dust and removed by baghouses.

2.1.6 Fettling, Cleaning and Finishing

After the casting has cooled, the gating system is removed, often using bandsaws, abrasive cut-off wheels or electrical cut-off devices. A ‘parting line flash’ is typically formed on the casting and must be removed by grinding or with chipping hammers. Castings may also need to be repaired by welding, brazing or soldering to eliminate defects (Environment Canada, 1997).

Shot blasting — propelling abrasive material at high velocity onto the casting surface — is often used to remove any remaining metal flash, refractory material or oxides. Depending on the type and strength of the metal cast, the grade of shot may vary from steel ball bearings to a fine grit (Environment Canada, 1997).

The casting may undergo additional grinding and polishing to achieve the desired surface quality. The casting may then be coated using either a paint or a metal finishing operation such as galvanising, powder coating or electroplating.

2.1.7 Advantages of Sand Casting

- Use is widespread; technology well developed.
- Materials are inexpensive, capable of holding detail and resist deformation when heated.
- Process is suitable for both ferrous and non-ferrous metal castings.
- Handles a more diverse range of products than any other casting method.
- Produces both small precision castings and large castings of up to 1 tonne.
- Can achieve very close tolerances if uniform compaction is achieved.
- Mould preparation time is relatively short in comparison to many other processes.
- The relative simplicity of the process makes it ideally suited to mechanisation.
- High levels of sand reuse are achievable (USEPA, 1998).

2.1.8 Limitations

- Typically limited to one or a small number of moulds per box..
- Sand:metal ratio is relatively high.
- High level of waste is typically generated, particularly sand, baghouse dust and spent shot.

2.1.9 By-products Generated

Foundries are often perceived as being dirty and environmentally unfriendly. However, most modern foundries are relatively environmentally benign in comparison to other industrial activities in the metal sector (e.g. smelting and surface finishing), and most of the by-products generated by the industry have relatively low impacts. The major issues facing the industry are the large volumes of by-products that are currently being sent to landfill, nuisance odours, and the need to maximise health and safety in the industry.

Sand is the largest by-product generated by volume in this process. Even in operations that undertake a high level of reclamation, some new sand is required to maintain the quality of the sand in the system. As a result some sand is lost from the system. This may be sent to landfill, reclaimed off-site or put to beneficial reuse.

Foundry sands from ferrous foundries are not usually considered to be hazardous, typically passing TCLP (toxic characteristic leaching procedure) tests, and can be sent to unlined landfill. Some non-ferrous sands contain high quantities of heavy metal, which requires them to be sent to secured landfill sites. Most of the chemical binder used in core and mould making is burnt off during the pouring process. Binders in waste sand can become an important issue if large volumes of resin-coated sands are wasted before the pouring stage. Binders and salts can build up to unacceptable levels over many reclamation cycles, so careful monitoring and testing is important.

Baghouse dust from the mould and core shops and from the shotblasting operations is typically the second largest by-product generated by volume in sand casting processes. Sand grains are broken down into fines and dust, particularly after multiple reuse, and this can affect casting quality and also create occupational health and safety issues (e.g. silicosis). Many foundries have invested in baghouses to capture sand dusts and other particulate matter from the working environment and from reclamation processes.

Slag is another significant by-product stream by volume. Flux is a material added to the furnace charge or to the molten metal to remove impurities. Flux unites with impurities to form dross or slag This rises to the surface of the molten metal, from where it is removed before pouring. When cooled this forms a relatively inert complex glass-like structure which can usually be disposed of in unlined landfill or put to beneficial reuse.

Other solid wastes generated in sand casting operations include:

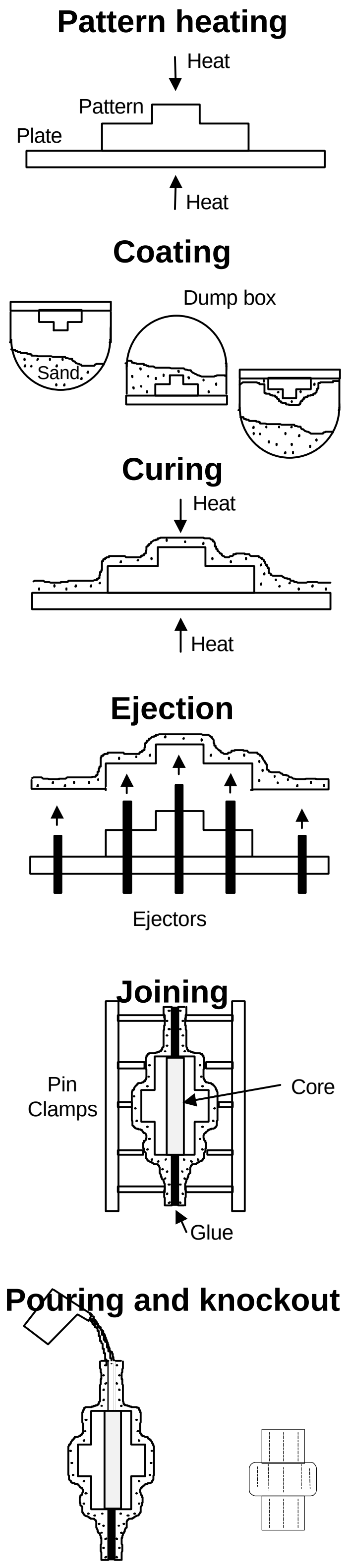
- refractories (furnace and ladle lining);
- drums;
- spent shot;
- metal swarf and shavings;
- timber pallets and timber from the pattern room;
- general foundry waste including packaging and consumables (e.g. rags, gloves, grinding wheels etc).;
- general office and lunchroom wastes.

These materials typically make up a minor proportion of the total waste stream by volume, but can be significant in terms of cost. Timber pallets are a significant issue at a number of Queensland foundries.

Foundries also produce small quantities of liquid by-product streams. The major sources are cutting fluids, hydraulic and other oils, solvents, waste paints and paint sludges, uncured and cured binders and waste catalysts (acids and bases). Water streams are also generated from quenching baths, cooling systems and other minor sources.

Air emissions from the process typically include carbon monoxide, organic compounds, hydrogen sulfide, sulfur dioxide, nitrous oxide, benzene, phenols, and other hazardous air pollutants (HAPs). The actual emissions depend on a number of factors including the type of metal poured, the cleanliness of the charge, the types of binders used and the melting and pouring practices employed. A portion of the metal (around 3%) volatilises during the melting and pouring process. The major environmental issues related to these fugitive emissions are usually those of occupational health within the foundry and nuisance odours outside the foundry (USEPA, 1998).

2.2 Shell Moulding



Source: Adapted from Clegg (1991)

Shell moulding is a process well suited to rapid, automated, repetitive and high-volume production. The most common method for producing shell moulds is to use a dump box as shown in the diagram. The dump box is rotated through 360^0 so that the sand contacts the heated surface. An organic thermosetting resin such as phenol formaldehyde or furane is typically used (2.5–4.5% of sand volume) in conjunction with a catalyst (11–14% of resin volume). Catalysts include weak aqueous acids such as ammonium chloride or hexamine, a white powder (Brown (1994) and UNEP (1997).

The thickness of the shell, typically around 10 mm, is determined by the contact time between the sand and pattern (Clegg, 1991). The mould is heated again to cure the sand, causing it to harden. The mould is released from the pattern using ejector pins. The entire cycle can be completed in a matter seconds, making it suitable for rapid production.

Cores are added to the mould and the two halves of the mould are glued and clamped together before the metal is poured.

Moulds are relatively robust and can therefore be stored for reasonably long periods of time (Luther, 1999). Depending on the cores used, spent sand can be reclaimed successfully using thermal reclamation (Brown, 1994).

2.2.1 Advantages

- Good casting detail and dimensional accuracy are possible.
- Moulds are lightweight and may be stored for extended periods of time.
- Gives superior surface finish and higher dimensional accuracy, and incurs lower fettling costs than conventional sand castings.
- Has better flexibility in design than die-casting.
- Is less expensive than investment casting.
- Capital plant costs are lower than for

mechanised green sand moulding.

- Metal yields are relatively high.
- Sand:metal ratios are relatively low (Luther (1999) and Clegg (1991)).

2.2.2 Limitations

- The weight of castings is limited to 100 kg.
- Because the process requires heat to cure the mould, pattern costs and pattern wear can be higher than for conventional sand moulding.
- Energy costs also tend to be higher.
- Sand inputs need to be of higher quality than traditional sand casting.
- Emissions from the process are noxious, so effective extraction systems are required.
- Material costs tend to be higher than those for conventional sand moulding (Luther (1999) and Clegg (1991)).

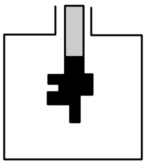
2.2.3 By-products Generated

Significantly less sand is required to make a shell mould than to make a conventional sand mould, so volumes of spent sand are typically smaller. Quantities of binder per tonne of metal are also smaller. Most of the binder is burnt off in the pouring process, so only minor amounts remain in the sand. Broken cores and sand that has set up prematurely or inadequately may have higher levels of resin (UNEP, 1997).

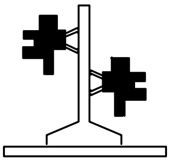
The burnt-off resins create nuisance odour issues for staff and neighbours. Dust emissions are also created in the moulding, handling and sand reclamation processes. If the moulds are water cooled, wastewater may contain traces of metals, phenols, furans and other contaminants, depending on the binder system used (UNEP (1997) and Brown (1994)).

2.3 Investment Casting

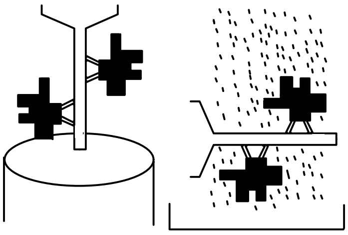
Pattern making



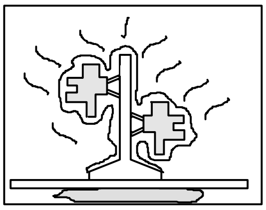
Gating



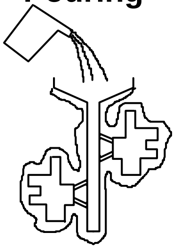
Shell pattern formation



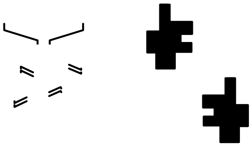
Wax removal



Pouring



Knockout



Source: Adapted from Jain (1986)

Investment casting produces very high surface quality and dimensional accuracy. It is commonly used for precision equipment such as surgical equipment, for complex geometries and for precious metals. This process is commonly used by artisans to produce highly detailed artwork.

The first step is to produce a pattern or replica of the finished mould. Wax is most commonly used to form the pattern, although plastic is also used. Patterns are typically mass-produced by injecting liquid or semi-liquid wax into a permanent die (USEPA, 1998). Prototypes, small production runs and specialty projects can also be undertaken by carving wax models. Cores are typically unnecessary but can be used for complex internal structures. Rapid prototyping techniques have been developed to produce expendable patterns.

Several replicas are often attached to a gating system constructed of the same material to form a tree assembly. In this way multiple castings can be produced in a single pouring (Jain, 1986).

The next stage is to create a one-piece destroyable mould around the pattern (USEPA, 1998). This mould is built up around the wax pattern in stages by alternately coating the assembly with a specially formulated heat-resistant refractory slurry mixture and then applying a granulated refractory ‘stucco’ shell (Jain, 1986). The initial coats use a fine powder, which creates a very smooth and dimensionally accurate negative of the pattern. Subsequent coats use a coarser refractory material to build up sufficient thickness. This material hardens around the assembly at room temperature. This investment shell casting method is the more common process. An alternative process is to use an investment flask, where sand is packed around the mould. This can be desirable where additional mould strength is required and also allows the casting size to be increased.

In both shell and flask casting, the pattern is removed from the mould prior to the pouring stage. The mould is inverted and heated to melt and remove the wax (Jain, 1986). In some operations the melted wax is recovered and reused to make new patterns (USEPA, 1998). After multiple reuses the material needs to be reconditioned to maintain its purity, or disposed of.

The mould is then heated in an oven to remove any residual wax and to further cure and harden the mould. The temperature is raised to 980oC prior to pouring. This is a time- and energy-consuming process: total heating time, from wax removal to pouring, can take up to 15 hours (Jain, 1986).

Molten metal is then poured into the central cavity and flows into the individual moulds (USEPA, 1998). After the metal has cooled, the mould material is removed.

Because of its very high dimensional accuracy the process can achieve a net-shape cast requiring little or no machining. Great care is taken in the pattern-making stage to remove any mould lines because it is more cost effective to remove unwanted material from the wax model than from the final cast.

2.3.1 Advantages

- There is very high dimensional accuracy and surface finish.
- Process is suitable for both ferrous and non-ferrous precision pieces.
- Allows flexibility of design.
- The process can be adapted for mass production.
- Cores are typically eliminated.
- Can virtually eliminate the need for machining.
- Very high metal yields.
- Can produce castings that are impossible or difficult to produce with other casting methods and machining processes.
- Can be cost effective for repetitive casting and specialist jobbing applications (Luther (1999); Jain (1986); and USEPA (1998)).

2.3.2 Limitations

- The size of castings is limited (up to around 5 kg).
- Capital and operating costs are high in comparison with other casting methods.
- Costs of pattern die-making are high, requiring special tooling and equipment.
- There are numerous steps in the process, making automation somewhat more difficult and more expensive than for other casting methods.
- Casting costs make it important to take full advantage of the process to eliminate all machining operations (Luther (1999); Jain (1986); and USEPA (1998)).

2.3.3 By-products Generated

The volume of by-product material produced from the investment casting process are small in comparison to sand casting techniques but larger than for die casting. Waste refractory mould material and waxes (or plastic) represent the largest volume of by-products generated. Investment casting refractory material can be used only once and can be disposed of in unsecured landfill unless it contains high levels of heavy metals. Wax can be reused a number of times before it has to be reconditioned, thus minimising waste. Small losses of wax occur when the moulds are cured and this creates some odours. Odours from the process are relatively low, however, and air emissions comprise mostly particulate matter. Dusts generated from the process contain metal which, in sufficiently high quantities, can be reclaimed economically (USEPA, 1998).

2.4 Lost Foam Casting

The lost foam or expendable pattern-casting process is a relatively new process in commercial terms, but is gaining increased attention due to the environmental and technical benefits that are achievable for some types of casts. In this process, an expendable pattern is formed out of polystyrene foam. Patterns can be made manually, using automated systems or by moulding them using a permanent die.

Manual pattern making typically involves carving blocks and gluing sections together to build up the desired shape. The finished pattern is a single piece (i.e. no cores) incorporating all necessary gating systems. This carving process can be automated using computer-aided manufacturing (CAM) system sand can incorporate rapid prototyping techniques.

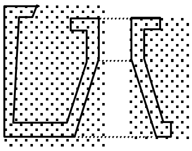
For repetitive castings, patterns can be moulded using a permanent aluminium die. Polystyrene beads are pre-expanded using a vacuum, steam or hot air processes. This helps to minimised the density of the foam as much as possible, to minimise the amount of vapour that is produced during the pouring process. The expanded material is then blown into the aluminium mould. Steam is used to cause the material to expand further, bond together and fill the mould cavity. The mould and pattern are allowed to cool, and the pattern ejected (USEPA, 1998).

As for investment casting, when the casting is small, multiple castings can be joined, often to a central tree, to increase pouring efficiency.

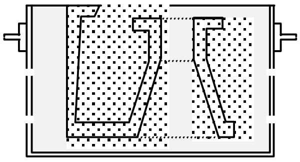
The pattern is coated with a specially formulated gas-permeable refractory slurry (USEPA, 1998). When the refractory slurry has hardened, the assembly is positioned in a flask, and unbonded sand is poured around the mould and compacted into any internal cavities. The refractory coating must be sufficiently strong to prevent the loose sand from collapsing into the cavity as the pattern vaporises, but also permeable to allow styrene vapour to escape from the mould cavity (USEPA, 1998). A vacuum system can also be used to increase sand compaction.

Molten metal is then poured into the polystyrene pattern, which vaporises and is replaced by the metal. This is different from the lost wax process in which the

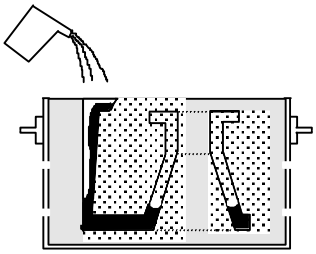
Pattern making



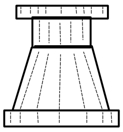
Mould making



Pouring



Cleaning



Source: Adapted from USEPA (1998)

wax is removed before the pouring stage. Vents in the side of the flask allow vapour to escape. If vapour is produced more rapidly than it can be vented, the casting may become deformed. When the metal has solidified, the flask is emptied onto a steel grate for shakeout. The loose sand falls through the grate and can be reused without treatment. The refractory material is broken away from the casting in the usual manner (USEPA, 1998).

2.4.1 Advantages

- Can be used for precision castings of ferrous and non-ferrous metals of any size.
- Fewer steps are involved in lost foam casting compared to sand casting.
- Coremaking is eliminated.
- Binders or other additives and related mixing processes are eliminated.
- High dimensional accuracy can be achieved and thin sections can be cast (i.e. 3 mm).
- There is lower capital investment.
- The flasks used are less expensive and easier to use because they are in one piece.
- The need for skilled labour is reduced.
- Multiple castings can be combined in one mould to increase pouring efficiency.
- Lower operating costs can be achieved for appropriate castings. Complex castings, particularly internal sections, which require high dimensional accuracy and have thin sections, can be produced very cost effectively in comparison with to conventional sand moulding processes.
- Fettling and machining is minimised due to high dimensional accuracy and the absence of parting lines or core fins.
- The shakeout process is simplified and does not require the heavy machinery required for bonded sand systems.
- High levels of sand reuse are possible. As little as 1–2% of the sand is lost as a result of spills. Periodically a portion of sand may need to be removed or reclaimed to avoid the build-up of styrene (Luther, 1999).

2.4.2 Limitations

- The pattern coating process is time-consuming, and pattern handling requires great care.
- Very thin sections can be flimsy, making dimensional accuracy difficult to maintain during sand compaction.
- Good process control is required as a scrapped casting means replacement not only of the mould but of the pattern as well.

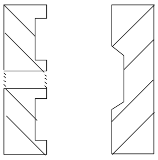
- For simple casings and for jobbing processes, the process is typically not competitive against conventional sand moulding.
- With the exception of aluminium and grey and ductile iron, experience with other metals is limited.
- There are some limitations in using the technique to cast low-carbon alloys (Luther (1999) and USEPA (1998)).

2.4.3 By-products Generated

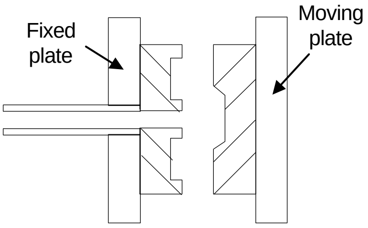
Lost foam is considered to be a cleaner process than many other casting processes due to the elimination of binders. The large quantities of polystyrene vapours produced during lost foam casting, however, can be flammable and may contain hazardous air pollutants. Large volumes of waste foam can be generated from carving operations. This can be a significant cost, particularly for companies that pay by volume and not by weight. Other possible air emissions are of particulate matter related to the use of sand. Waste sand and refractory materials containing styrene may also be generated (USEPA, 1998).

2.5 Die Casting

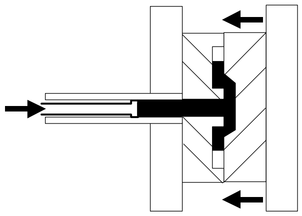
Die making



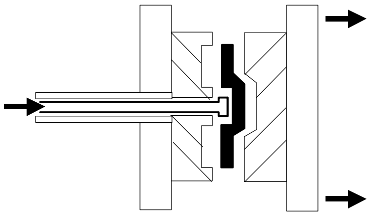
Casting assembly



Metal injection and pressing



Release



Source: Adapted from Clegg (1991)

Die casting is a precision casting technique that uses a permanent metal mould, or die, into which molten metal is poured directly. Metal is typically forced into the mould under pressure but gravity-feed systems are also used. Tooling costs and other capital costs are high due to the cost of designing dies. Operational costs, however, are relatively low, due to the high level of automation and the small number of production steps (i.e. direct pouring into a permanent mould rather than preparing destroyable patterns and/or moulds). The process, therefore, is best suited to mass production.

Die casting is most suitable for non-ferrous metals with relatively low melting points (i.e. around 870oC) such as lead, zinc, aluminium, magnesium and some copper alloys (Luther, 1999). Casing metals with high melting points, including iron, steel and other ferrous metals, reduces die life (Clegg, 1991).

Dies are usually made from two blocks of steel, each containing part of the cavity, which are locked together while the casting is being made. Retractable and removable cores are used to form internal surfaces. Molten metal is injected into the die and held under pressure until it cools and solidifies. The die halves are then opened and the casting is removed, usually by means of an automatic ejection system.

The die is cleaned between each casting cycle, preheated and lubricated to reduce wear on the die, to improve surface quality and to aid ejection. Mould coating material can also be used to protect the molten metal from the relatively cool and conductive surface of the mould. Cooling systems are often used to maintain the desired operating temperature (USEPA, 1998).

2.5.1 Advantages

- Once capital is in place, operating costs are low relative to most other casting processes. This is due to the reduced number of process steps, the elimination of temporary moulds and patterns from the process, and the lower volume of materials that need to be handled.
- Dies can sustain very high production rates (i.e. over 400 shots per hour). Total cost of castings can

be relatively low at high levels of production.

- High design flexibility and complexity allows products to be manufactured from a single casting instead of from an assembly of cast components.
- Good accuracy, consistency and surface finish are possible, with high metal yields.
- Cleaning, machining, finishing and fabrication costs are low.
- There are low levels of waste due to elimination of refractory material ,leading to a cleaner work environment.

2.5.2 Limitations

- Capital costs for equipment and dies are high.
- Pressure dies are very expensive to design and produce.
- Die casting is not applicable to steel and high-melting-point alloys.
- Casting size is limited to a maximum of about 35 kg (Luther (1999) and USEPA (1998)).

2.5.3 By-products Generated

This process generates the smallest volumes of waste of all foundry processes because the use of refractory sands and binders for moulds is eliminated. Fettling is minimised, so only small volumes of swarf and consumables are generated in the grinding and cleaning process.

Some air emissions are released during the melting and casting process. Metal oxide fumes are released as some of the metal vaporises and condenses. The lubricants used also vaporise on contact with the molten metal (USEPA, 1998).

2.6 Special and Innovative Moulding and Casting Processes

The basic techniques described above have all been adapted in various ways to optimise them for specific metals and operational considerations. This section describes some of the major innovations that have been developed from the basic processes.

2.7 The Hitchiner Process

The Hitchiner casting process is a variation of chemically bonded sand moulding processes. It uses a counter-gravity (vacuum) system to fill the mould cavity with molten metal. The flask is partially submerged in a metal bath. Small diameter feeders in the drag (bottom) half of the flask are used to draw metal under vacuum into the mould cavity (Luther, 1999).

Filling moulds by gravity (i.e. by pouring into a sprue) can introduce air into the mould cavity and result in defects. Introduced air can constitute up to 30% of the total volume of metal poured (MCTC, 1995). The Hitchener process achieves better filling consistency and virtually eliminates air ingress and the resulting inclusions and porosity defects. This has been shown to reduce casting repair costs by 50–65% (MCTC, 1995). Such cost savings can compensate for the higher up-front costs.

2.7.1 Advantages

- Produces light section castings in a variety of alloys normally not castable by other processes.
- Gives higher casting definition than conventional sand moulding and similar definition to investment casting.
- Requires less metal cleaning.
- Higher metal yields are achieved than by conventional sand moulding due to smaller gating systems and greater precision.
- Decomposition gases are removed by the vacuum, making emission control easier, reducing emissions and reducing gas inclusions (Luther, 1999).

2.7.2 Limitations

- The process is more expensive than conventional sand casting.
- Production volumes are limited to low to medium throughput.
- The size of the casting is limited to a maximum of 45 kg (Luther, 1999).

2.8 The Shaw Process

The Shaw Process is one of more common variations on the investment casting process. It is designed to eliminate the use of expendable patterns — one of the most costly and time-consuming steps in the casting process. A refractory slurry containing ethyl silicate is used, which initially cures to a flexible gel but can be removed from the pattern in two halves. The flexible mould halves can then be further cured at high temperatures until a hard mould is formed ready for assembly and pouring (USEPA, 1998).

This process is used in Australia by Shaw Process Castings Pty Ltd. in Mortdale, New South Wales.

2.8.1 Advantages

- The process eliminates the need for expendable patterns.

2.8.2 Limitations

- It is more expensive than the conventional investment process.

2.9 Replicast®

Replicast® is a novel precision moulding and casting process that combines many of the advantages of investment casting and lost foam casting techniques. An expanded polystyrene pattern is produced and coated with an inert, fired ceramic mould. The polystyrene is fully burnt out of the mould before casting. This allows a wider range of alloys to be cast in the mould. Because the foam is 92% carbon by weight, the lost foam process is unsuitable for the majority of steel alloys. By removing the foam before casting, the Replicast® system can be used for even ultra-low-carbon stainless steel. This process also offers a higher weight range than is available from investment casting.

2.9.1 Advantages

- Allows larger castings than are possible with investment techniques.
- Full combustion of the polystyrene before casting gives an inert mould suitable for a wider range of alloys than lost foam, including low-carbon steels.
- Air emissions are easier to control than with lost foam.
- The application of a vacuum during casting allows improved fill-out of the mould.
- The support provided by the ceramic shell during casting allows large, thin shells to be easily poured.
- Sand inclusions and other sand mould-related defects can be virtually eliminated.

- As with investment and lost foam casting, there are no cores or parting lines, high dimensional accuracy, and excellent surface finish.
- Ceramic shell does not have to be as thick as for shell casting.

2.9.2 Limitations

- Is not as suitable for thin sections as the lost wax process.
- It is more expensive than the lost foam process.

2.10 Vacuum (‘V‘) Process

The V-Process was invented in Japan in 1971 as an improvement on conventional sand casting. In this process, a thin preheated sheet of plastic film material is placed over a pattern and a vacuum is applied to draw the sheet to the pattern contours. The flask containing the mould is then filled with dry unbonded silica sand which is compacted by vibration. A second plastic sheet is placed at the back of the flask and the mould is further compacted under vacuum. With the vacuum maintained, the pattern is then removed and the two halves of the mould are joined and secured for pouring. After the metal has solidified, the vacuum is removed and the casting is released (Luther (1999) and Foundry Online (1999)).

The original inventors of this proprietary process have established working agreements on a worldwide basis so that today individually licensed foundries using the V-process are producing castings of all sizes and shapes. These range from thin-sectioned curtain walls in aluminium to cast iron pressure pipe fittings, stainless steel valve bodies and massive 8-tonne ship anchors. Other components being routinely cast include bathtubs, railroad bolsters and side frames, machine tools, engine parts and agricultural castings. Any metal (grey, ductile, malleable iron, various grades of steel, or aluminium and copper-base alloys) may be poured in a V-process mould, with the possible exception of magnesium (Luther, 1999).

2.10.1 Advantages

- Gives good dimensional accuracy and surface finish with generally twice the accuracy of sand castings.
- Eliminates gas hole defects.
- Pattern life is longer because there is no contact between the sand and the pattern.
- Eliminates the use of binders and minimises sand waste.
- Is suitable for a wide range of casting sizes from grams to tonnes.
- The process can be used for complex geometries and can be automated to achieve greater consistency and productivity.

- It can be highly cost competitive with other casting processes (Luther (1999) and Foundry Online (1999)).

2.10.2 Limitations

- Requires plated pattern equipment.
- Close synchronisation of mould and metal readiness is essential in foundry practice.
- Is not typically suitable for high rates of production.
- Is not suitable for some casting geometries due to flexibility limitations of the plastic (Luther (1999) and Foundry Online (1999)).

2.11 Centrifugal Casting

For centrifugal casting, molten metal is introduced into a mould that is rotated during solidification. The centrifugal force improves the feed and filling consistency achieving surface detail. This method has been specifically adapted to the production of cylindrical parts and eliminates the need for gates, risers and cores. The process is typically unsuitable for geometries that do not allow a linear flow-through of metal (Luther, 1999).

2.11.1 Advantages

- Centrifugal casting improves homogeneity and accuracy in special circumstances.
- Eliminates the need for gating systems (Luther, 1999).

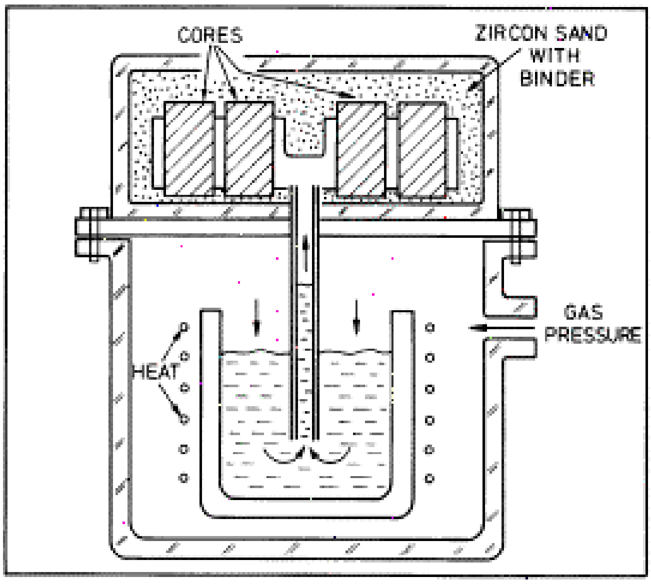
2.11.2 Limitations

- The process imposes limitations on the shape of castings, and is normally restricted to the production of cylindrical geometric shapes (Luther, 1999).

2.12 Cosworth Process

The Cosworth process is a precision sand casting process, which was developed in 1978 for non-ferrous casting, initially aluminium alloys, to engineer the Cosworth engine. The mould and core-making stages are similar to conventional sand casting, although zircon sand is used instead of silicon, due to its greater expansion predictability. The main feature of this process is that the metal is pumped into the mould through the base using pressure-assisted feeding through a simplified gating system. This is shown in Figure 3 (Aalborg University, 1998).

Figure 3: The Cosworth moulding system



Source: Aalborg University (1998)

The absence of conventional gating and feeding systems results in castings free of porosity (due to hydrogen) and inclusions (due to alumina). These are common in sand and gravity die casting and impair the metallurgical integrity and mechanical properties of the casting (Clegg, 1991).

The process also eliminates a number of minor problems associated with conventional techniques including: blowholes from chills, cores and adhesives; inaccurately located cores and mould halves; and metallurgical inadequacies (particularly poor hardness or strength). It also reduces fettling time. The process was more recently extended to a number of commercial castings with the opening of a new foundry in 1984. In 1993 the Ford Motor company selected the Cosworth process for its Windsor, Ontario, Plant (Clegg, 1991).

The American Foundrymen's Society has identified the Cosworth process as being a key emerging process, needing further investigation to develop commercial opportunities (CMC,1998).

2.12.1 Advantages

- Can cast thinner sections, allowing the design of lighter, more robust components and resulting in considerable weight saving.
- Produces exceptionally high strength and ductility due to improved metallurgical consistency during solidification.
- Gives high dimensional accuracy, resulting in minimum fettling and machining.

- Castings are pressure-tight due to the absence of porosity and inclusions.
- Tooling is comparatively inexpensive.
- Is suitable for medium- to high-volume production.
- Gives high metal yields and high sand reclamation (Clegg, 1991).

2.12.2 Limitations

- Is not suitable for a wide range of metals and casting sizes.

2.13 Semi-Solid Metal Casting Process

Semi-solid casting is a modification of the die-casting process which achieves metallurgical benefits similar to forging. Metal billets are heated to a semi-solid state and pressed under pressure into the die. Prior to moulding, the heated material can be picked up and will hold its shape unsupported. Under pressure it flows like a liquid to take the form of the die accurately, as in die casting (WPI, 1997). This lower-energy-intensive process creates a fine and uniform structure that is virtually free of porosity (THRUST, 1997).

In a related process called rheocasting the metal is melted and, during solidification to a semi-solid state, its morphology is altered using mechanical, electromagnetic or other forces to a create a fine microstructure (WPI, 1997).

2.13.1 Advantages

- Gives high dimensional accuracy and metallurgical integrity.
- Extends mould life and part tolerances compared with traditional die casting, due to lower injection temperatures.
- Gives higher structural integrity, quality and soundness compared with cast parts.
- Castings can be heat-treated to obtain characteristics similar to those of permanent mould castings.
- Can achieve lower costs than forging and die-moulding processes for certain parts (WPI (1997) and THRUST (1997)).

2.13.2 Limitations

- As for traditional die casting, size is generally limited (WPI (1997) and THRUST (1997)).

3. Melting Technology

This section provides a general overview of furnace technology most commonly used in the foundry industry.

Energy is a major cost in all foundries. The majority of energy used is in the melting and metal holding processes. Five types of furnaces are commonly used to melt metal in foundries: cupola, electric arc, reverberatory, induction and crucible. Some foundries operate more than one type of furnace and may even transfer molten metal between furnace types in order to make use of the best features of each (USEPA, 1998).

The choice of which furnace or furnaces to use, or the decision to change from one type of furnace to another, is not simple but depends on a number of factors. These include: the scale of the operation, the type of process (e.g. repetition or jobbing), the types of metals required, the raw materials available, the relative cost of fuels (e.g. coal, natural gas, electricity), capital, maintenance and operational costs, and environmental requirements and costs.

3.1 Cupola Furnaces

The use of cupola furnaces is one of the oldest processes for making cast iron and is still among the dominant technologies in the world. In Queensland, most of the larger foundries have replaced their cupola furnaces with more efficient electric furnaces. Some of these foundries still maintain a cupola furnace for specific melts or for reserve capacity.

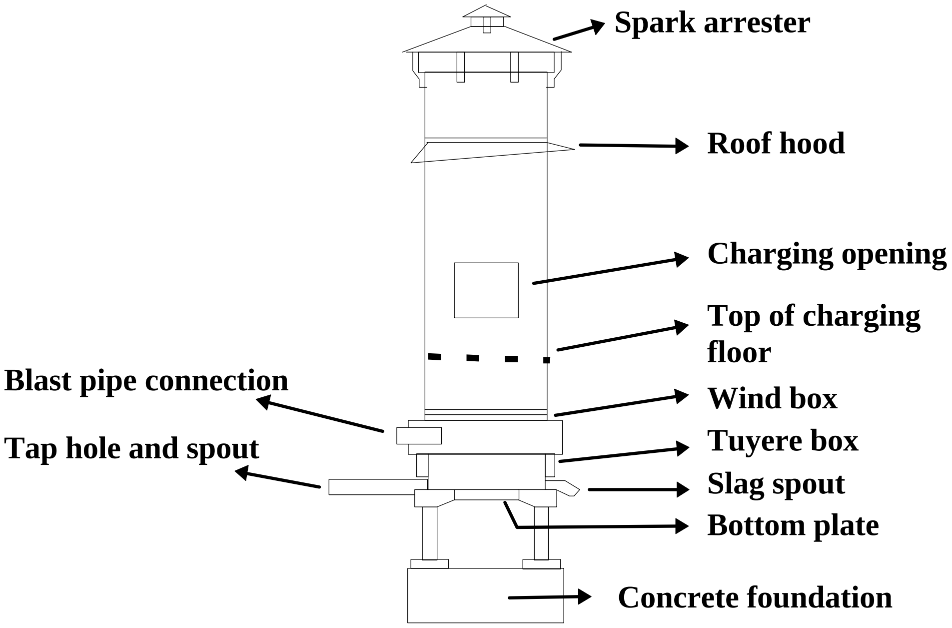
A typical cupola furnace (see Figure 4) consists of a water-cooled vertical cylinder which is lined with refractory material. The process is as follows:

- The charge, consisting of metal, alloying ingredients, limestone, and coal coke for fuel and carbonisation (8–16% of the metal charge), is fed in alternating layers through an opening in the cylinder.
- Air enters the bottom through tuyeres extending a short distance into the interior of the cylinder. The air inflow often contains enhanced oxygen levels.
- Coke is consumed. The hot exhaust gases rise up through the charge, preheating it. This increases the energy efficiency of the furnace. The charge drops and is melted.
- Although air is fed into the furnace, the environment is a reducing one. Burning of coke under reducing conditions raises the carbon content of the metal charge to the casting specifications.
- As the material is consumed, additional charges can be added to the furnace.
- A continuous flow of iron emerges from the bottom of the furnace. Depending on the size of the furnace, the flow rate can be as high as 100 tonnes per hour. At the metal melts it is refined to some extent, which

removes contaminants. This makes this process more suitable than electric furnaces for dirty charges.

- A hole higher than the tap allows slag to be drawn off.
- The exhaust gases emerge from the top of the cupola. Emission control technology is used to treat the emissions to meet environmental standards.
- Hinged doors at the bottom allow the furnace to be emptied when not in use (Larsen et al. (1997); USEPA (1998); and Environment Canada (1997)).

Figure 4: A Typical Cupola Furnace



Source: Abdelrahman (1999)

The cupola furnace has received a lot of negative publicity in recent years. However, the system does have a number of inherent advantages over electric furnaces:

- It is simple and economical to operate.
- A cupola is capable of accepting a wide range of materials without reducing melt quality. Dirty, oily scrap can be melted as well as a wide range of steel and iron. They therefore play an important role in the metal recycling industry
- Cupolas can refine the metal charge, removing impurities out of the slag.
- From a life-cycle perspective, cupolas are more efficient and less harmful to the environment than electric furnaces. This is because they derive energy directly from coke rather than from electricity that first has to be generated.

- The continuous rather than batch process suits the demands of a repetition foundry.
- Cupolas can be used to reuse foundry by-products and to destroy other pollutants such as VOC from the core-making area (Taft (1995); Jain (1986); and FTJ (1996b)).

The use of elevated oxygen in cupola furnaces has been demonstrated to increase the efficiency of the system and the quality of the melt. This use of oxygen enrichment has progressed from simple enrichment of the blast air, to tuyere injection, to supersonic tuyere injection. Each improvement has been found to increase productivity by between 10% and 15% over the previous system (FTJ, 1999a). The main benefits of elevated oxygen include:

- reduced coke rate;
- elevated temperature;
- increased melting rate;
- more consistent metal composition;
- reduced waste gas emissions;
- longer refractory life (FTJ, 1999a).

The migration from cupola furnaces to electric induction furnaces has resulted from a number of factors including:

- greater control over melt temperature and characteristics;
- higher on-site emissions from cupolas than for electric furnaces, requiring more expensive emission control technology;
- a typically dirtier operating environment for cupolas;
- less flexibility in terms of the range of alloys that can be used in cupolas;
- additional environmental, storage and space issues created by on-site storage of coke and fluxes (Abdelrahman, 1999).

Cokeless cupola furnaces have been developed more recently — over the past 20 years. These improved designs, which can be retrofitted onto existing furnaces, achieve a number of efficiency, metallurgical and environmental benefits over traditional cupola furnaces. First, the use of coke is eliminated. A range of fuels including natural gas, propane, diesel oil and powdered coal can be used. Sulfur pick-up in the melting process can be minimised (below 0.01%). Emissions, particularly of particulate material, from the system are greatly reduced; if high-quality scrap is used emissions can be very low, thus reducing the need for complex emission control systems. Tapped metal is cleaner and better quality, wear of the refractory lining is reduced and less slag is typically generated (Taft (1995) and Jain (1986)).

Cokeless cupolas can be used in conjunction with electric furnaces to maximise overall process efficiency. Cupolas are recognised as being highly efficient at melting metal. As the taping temperature is increased, however, the efficiency of the cupola decreases significantly (Brown, 1994). Electric furnaces are the most efficient at superheating the metal. In duplexing systems, cupolas are used to melt the charge and electric furnaces are then used to superheat and to hold the molten metal (Taft, 1995).

The development of cokeless furnaces may reduce the migration to electric furnaces. Another area of research that may improve the performance of these systems is the development of automated controls. At present, cupola furnaces are operated manually. Operator experience is relied upon to achieve the desired melt rate, metal composition and metal temperature. The efficiency of the cupola furnace can be improved significantly by using appropriate sensors and controls. However, the high temperature environment of the cupola, as well as the complex interactions between inputs, outputs and control variables currently makes developing intelligent control technology difficult (Larsen et al., 1997).

A cupola furnace is usually equipped with an emission control system. The two most common types of emission collection are the high-energy wet scrubber and the dry baghouse. Use of the baghouse requires prior cooling of the flue gases, usually by heat exchange with ambient air (Environment Canada, 1997).

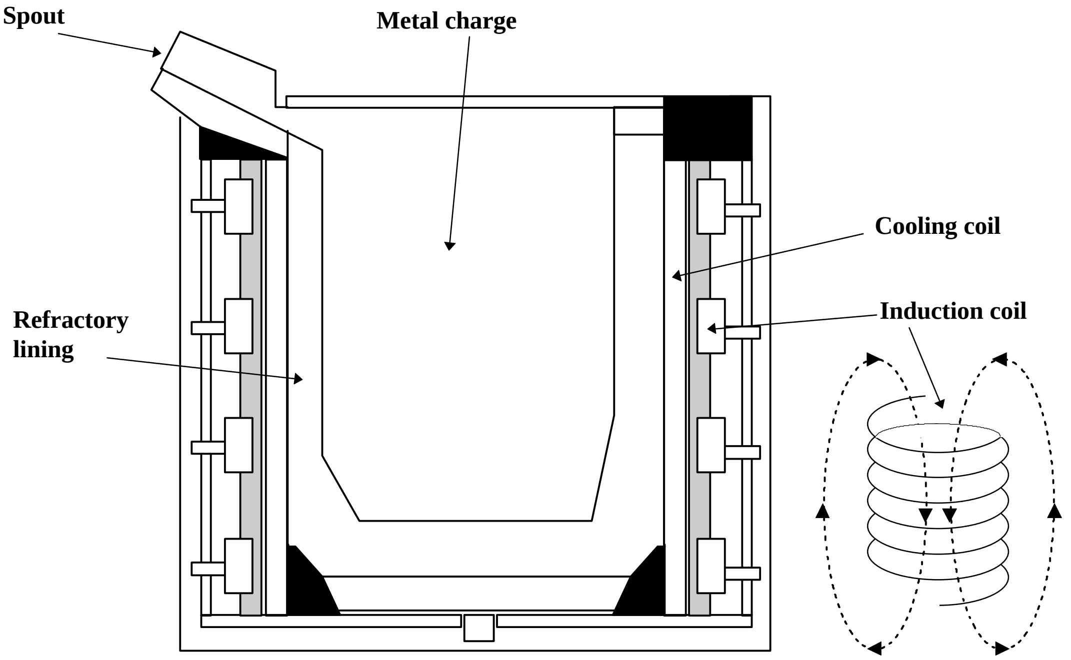
3.2 Electric Induction Furnaces

Induction furnaces have become the most widely used furnaces for melting iron and, increasingly, for non-ferrous alloys. These furnaces have excellent metallurgical control and are relatively pollution free (in comparison to cupola furnaces) (Environment Canada, 1997). The two most common induction furnaces are the coreless furnace and the channel furnace.

The basic principle of induction furnaces is that a high voltage in the primary coil induces a low-voltage, high current across the metal charge which acts as a secondary coil. Because of electrical resistance in the metal this electrical energy is converted into heat which melts the charge (Metal Asia, 1999c). Once the metal is in its molten state the magnetic field produces a stirring motion. The power and frequency applied determine the stirring rate. This is controlled to ensure complete melting of the charge and adequate mixing of alloy and fluxing materials, and to minimise temperature gradients in the charge. Excessive stirring, on the other hand, can increase lining damage, increase oxidation of the alloys, generate excess slag and increase inclusions and gas pick-up (Metal Asia, 1998a).

In a coreless furnace (see Figure 5), the refractory-lined crucible is completely surrounded by a water-cooled copper coil. This prevents the primary coil from overheating. In channel furnaces, the coil surrounds an inductor. Induction furnaces are available in capacities from a few kilograms to 75 tonnes. Coreless induction furnaces are more typically in the range of 5 tonnes to 10 tonnes. Some large channel units have a capacity of over 200 tonnes. Channel induction furnaces are also commonly used as holding furnaces (Environment Canada, 1997).

Figure 5: An Electric Induction Furnace (Coreless)



Source: Metal Asia (1998a)

Induction furnaces are very efficient and are made in many sizes. They are able to melt a wide range of metals but little refining of the metal is possible. Induction furnaces require much cleaner scrap than cupola furnaces and somewhat cleaner scrap than electric arc furnaces (USEPA, 1998). The capital costs are higher than those of electric arc furnaces but the operating costs are lower due to reduced refractory wear (Jain, 1986). Other advantages of induction furnaces are that they are relatively simple, very small quantities of any metal composition can be melted and the melting time is relatively short — around 1 hour — allowing metal to be delivered at small, regular intervals (Jain, 1986).

Approximately 60% of the energy supplied to the furnace is transferred to the charge. Around 30% of the energy is lost to the cooling water, an additional 7% lost from radiation and convection losses, and the remainder is lost in the furnace's electrical system (UNEP, 1997).

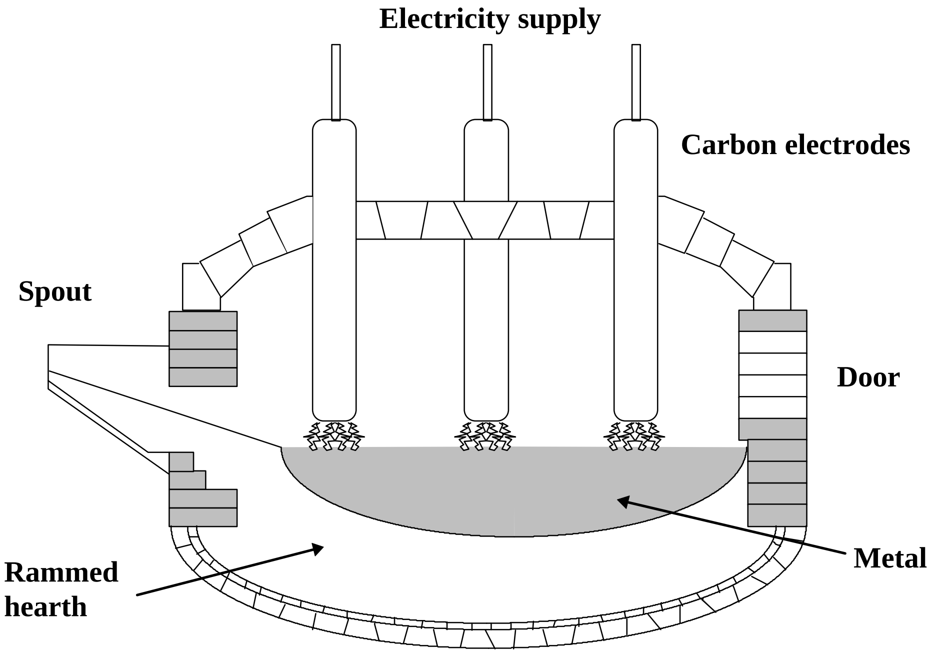
Energy consumption can be as low as 550 kW.h/tonne but these figures are achieved only with high utilisation factors and for higher-frequency furnaces (Taft, 1995). Figures of around 650–750 kW.h/tonne are more typical (Jain, 1986). In comparing the overall efficiency of these systems with that of fuel-based furnaces, it should be remembered that the electricity has to be generated and even modern power stations do not reach a 40% efficiency, which means the overall fuel consumption is well over 2000 kW.h/ tonne (Powell, 1992)

3.3 Electric Arc Furnaces

Electric arc furnaces are used for melting high-melting-point alloys such as steels. The furnace consists of a saucer-shaped hearth of refractory material for collecting the molten metal, with refractory material lining the sides and top of the furnace. The roof can normally swing away to facilitate charging of the furnace. Two or three carbon electrodes penetrate the furnace from the roof or the sides. Doors in the side of the furnace allow removal of alloys, removal of slag and oxygen lancing.

The scrap metal charge is placed on the hearth and melted by the heat from an electric arc formed between the electrodes. In a direct-arc furnace, the electric arc comes into contact with the metal; in an indirect-arc furnace the electric arc does not actually touch the metal . Molten metal is typically drawn off through a spout by tipping the furnace.

Figure 6: A Direct Arc Furnace



Source: Metal Asia (1999c)

As the refractories deteriorate, slag is generated. Fluxes such as calcium fluoride may be added to make the slag more fluid and easier to remove from the melt. Refractory life can also be extended by forming protective slag layers in the furnace, by intentional addition of silica and lime. The slag protects the molten metal from the air and extracts certain impurities (Environment Canada, 1997).

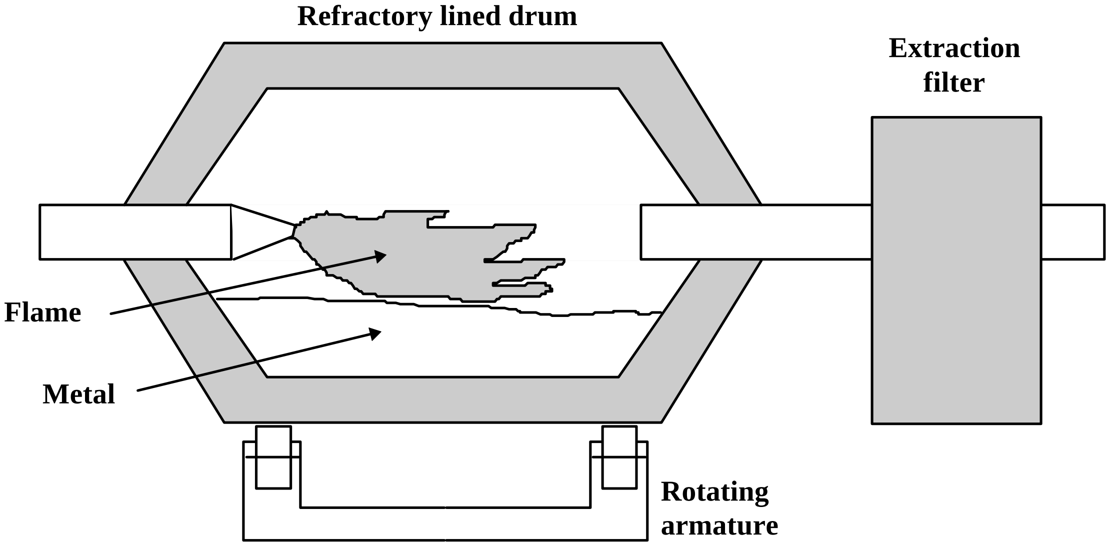
Electric arc furnaces are more tolerant of dirty scrap that induction furnaces and can be used to refine metals, allowing steel to be refined from an iron charge (USEPA, 1998). Direct arc furnaces have a very high thermal efficiency — around 70% — and can function at as little as 450–550 kW.h/tonne of metal melted. Indirect electric arc furnaces typically achieve closer to 700–1000 kW.h/tonne of steel (Jain, 1986).

3.4 Rotating Furnaces

Rotating furnaces consist of a refractory-lined cylinder that rotates slowly around a horizontal axis. The charge is heated directly from an open flame, typically fed by either gas or oil. Exhaust gases are extracted from the opposite end of the chamber. Rotating the furnace helps to mix the charge and utilises heat from the whole refractory surface.

Immediately after melting, the melt is covered with a layer of salt. This reduces slag formation by protecting the melt from oxidisation. Rotating furnaces are relatively inefficient, at around 990–1080 kW.h/tonne of metal melted, but the lower cost of fuel offsets this disadvantage to some extent (UNEP, 1997).

Figure 7: A Rotating Furnace

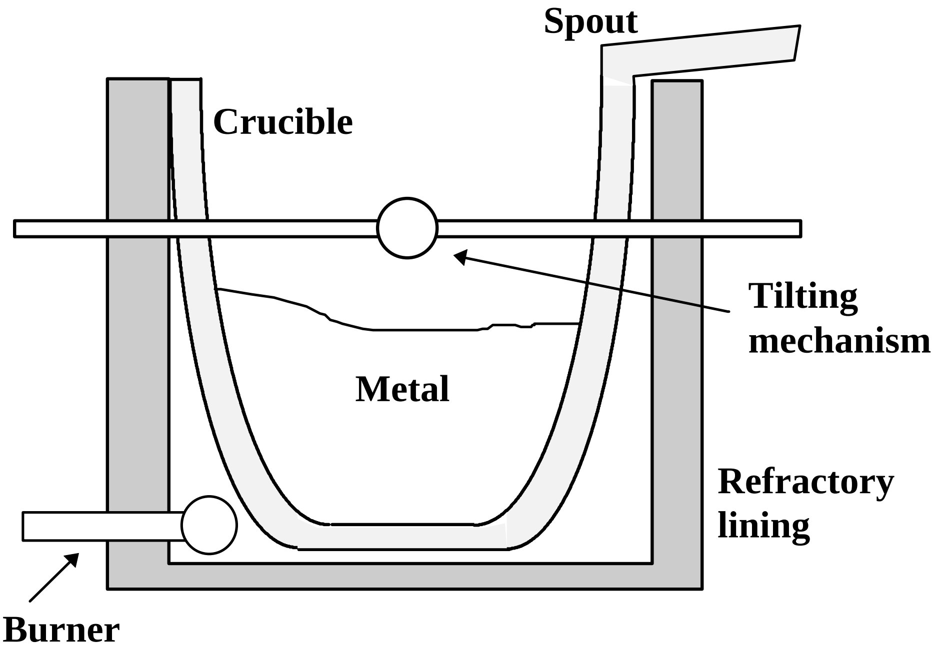


Source: UNEP (1997)

3.5 Crucible Furnaces

Crucible furnaces are among the oldest and simplest furnaces used in the foundry industry. They are primarily used to melt smaller amounts of non-ferrous metals but can also be used for ferrous metals (Metal Asia, 1999c). They are mostly used by smaller foundries or for specialty alloy lines. The crucible or refractory container is heated in a furnace, typically fired with natural gas or liquid propane, although coke, oil or electricity have been used (USEPA, 1998). There are three common crucible furnaces: bale-out furnaces, where molten metal is ladled from the crucible; tilting furnaces, where the metal is poured directly from the furnace; and lift-out furnaces, where the crucible can be removed from the furnace and used as a ladle (Metal Asia, 1999c).

Figure 8: A Crucible Furnace



Source: UNEP (1997)

3.6 Environmental Issues

Cupola, reverberatory and electric arc furnaces may emit particulate matter, carbon monoxide, hydrocarbons, sulfur dioxide, nitrogen oxides, small quantities of chloride and fluoride compounds, and metallic fumes from the condensation of volatilised metal and metal oxides. Induction furnaces and crucible furnaces emit relatively small amounts of particulate matter, hydrocarbons and carbon monoxide (USEPA (1998) and Environment Canada (1997)).

As shown in Table 3, cupola furnaces generate the largest quantity of emissions per tonne of charge. This is largely due the fact that the charge material typically includes greater levels of contamination, but is also due to the use of coke. Cokeless cupola furnaces achieve significantly lower emission rates. Emissions from electric melting furnaces are relatively low. They typically include gases and dust, which originate from contamination in the charge such as oil, dirt and rust. Most emissions occur during a short period after charging. The emissions also include fine metal and oxide particles. Generally, higher-frequency induction furnaces will generate less of this material because lower stirring rates result in less contact between the metal and air (UNEP, 1997). Electric induction furnaces achieve the lowest emissions, particularly for steel foundries where emissions can be virtually eliminated.

Slag is also generated during metal melting operations. Hazardous slag can be generated if the charge materials contain enough toxic metals, such as lead and chromium, or if calcium carbide is used in the metal to remove sulfur compounds (USEPA, 1998).

Table 3: Emission Factors for Uncontrolled Furnaces

Process	**Grey iron foundries (kg/tonne)**	**Steel foundries (kg/tonne)**
Cupola	8.5	
Electric arc	5	6.5
Electric induction	0.75	0.05
Reverberatory	1	

Note: Emissions are expressed as weight of pollutant per weight of metal melted.

Source: Environment Canada (1997)

These emission factors, for fugitive particulate matter from grey iron foundries using an electric arc furnace, are broken down by process in Table 4.

Table 4: Emission Factors for Fugitive Particulates from Grey Iron Foundries (Electric Arc Furnace)

Process	**Emissions (kg/tonne)**	**Emitted to work environment (kg/tonne)**	**Emitted to atmosphere (kg/tonne)**
Scrap and charge handling, heating	0.3	0.25	0.1
Magnesium treatment	2.5	2.5	0.5
Sand handling and preparation	20	13	1.5
Core making, baking	0.6	0.6	0.6
Pouring	2.5	2.5	1
Cooling	5	4.5	0.5
Shakeout	16	6.5	0.5
Cleaning, finishing	8.5	0.15	0.05

Note: Emissions are expressed as weight of pollutant per weight of metal melted.

Source: Environment Canada (1997)