CHAPTER

CASTING

16

The casting process is the point in manufacture when most of the defects are introduced into the cast part. It is true that the melt might be the wrong composition, and the mould might be the wrong shape or fall apart, but these misfortunes are unusual, and they are usually modest compared with the damage that is inflicted by most filling system designs. Anyway, we shall hope that the earlier chapters in this book have been observed so far as possible, such that these problems are minimised.

In the description of rule 2, the problems of pouring by gravity were emphasised, leading to solutions for gravity pouring which could only be described as damage limitation exercises. This contrasted with the process that minimises the effect of gravity, tilt casting and the elimination of gravity in 'level transfer' and 'counter-gravity' filling systems. Only tilt, level transfer and counter-gravity can produce ideal transfer of metal into the mould, thus manufacturing the best quality of casting. These points are so fundamental that they will arise time after time as we examine the various casting systems. No apology is offered for repetition.

16.1 GRAVITY CASTING

Today's technology for the production of most castings involves gravity pouring. If this were not bad enough in itself, the design of the filling systems usually make this bad situation much worse. This must be kept in mind. Only relatively rarely are castings produced with filling system designs using the principles set out in this book. Naturally, we all hope this poor situation will improve.

16.1.1 GRAVITY POURING OF OPEN MOULDS

Most castings require a mould to be formed in two parts: the bottom part (*the drag*) forms the base of the casting and the top half (*the cope*) forms the top of the casting. I remember these names because the drag can sometimes be moved by being *dragged* along the floor. The cope is reminiscent of coping stone, the stone topping the wall, or from the bishop's cope, the name for his cloak.

Some castings require no shaping of the top surface. In this case, only a drag is required. The absence of a cope means that the mould cavity is open, so that metal can be poured directly in. The foundryman can therefore watch the flow of metal and actively direct it around the mould using his skill during pouring to encourage the flow to fill all parts (Figure 11.1).

Such open top moulds represent a successful and economical technique for the production of aluminium or bronze wall plaques and plates in cast iron, which do not require a well-formed back surface. The first great engineering structure, the Iron Bridge built across the River Severn by the great English ironmaster Abraham Darby in 1779, had all its main spars cast in this way. This spectacular feat is not to be underestimated, with its main structural members more than 23 m long cast in open top sand moulds; it heralded the dawn of the modern concept of the structural engineering casting and still stands to this day.

Other viscous and poorly fluid materials are cast similarly, such as hydraulic cements, concretes and organic resins and resin/aggregate mixtures to form 'resin concretes'. Molten ceramics such as liquid basalt are poured in the same way, as witnessed by the cast basalt curb stones outside the house where I once lived, that have lined the edge of the road for more than 100 years and whose maker's name is still as sharply defined as the day it was cast.

Complete Casting Handbook. http://dx.doi.org/10.1016/B978-0-444-63509-9.00016-9

The remainder of this section concentrates on the complex problem of designing filling systems for castings in which all the surfaces are moulded i.e. the mould is closed. In all such circumstances, a *bottom-gated* system is adopted (i.e. the melt enters the mould cavity from one or more gates located at the lowest point, or if more than one low point, at each lowest point).

16.1.2 GRAVITY POURING OF CLOSED MOULDS

The series of funnels, pipes and channels to guide the metal from the ladle into the mould constitutes our liquid metal 'plumbing', and is known as the *filling system* or *running system*. Its design is crucial; so crucial, that the chapters on the design of the filling system are by far the most important sections of this book.

In addition to them being categorised as pressurised, naturally pressurised and nonpressurised, filling systems are commonly also can be categorised as top gated, gated at the mould joint, or bottom-gated. It will by now be clear that in this book the only pressurisation recommended is natural pressurisation, and the only gate location recommended is bottom-gated.

However, the reader needs to keep in mind that the elimination of a running system by simply pouring into the top of the mould (down an open feeder, for instance) may be a reasonable solution for the filling of a closed mould in some cases. Although apparently counter to much of the teaching in this book, there is no doubt that a top-poured option has often been demonstrated to be preferable to some poorly designed running systems, especially poorly designed bottom-gated systems. There are fundamental reasons for this that are worth examining right away.

In top pouring via, for instance a feeder, the plunge of a jet into a liquid is accompanied by relatively low shear forces in the liquid, since the liquid surrounding the jet will move with the jet, reducing the shearing action. Thus, although damage is always done by top pouring, in some circumstances it may not be too bad, and may be preferable to a costly, difficult, or poor bottom-gated system.

In poor filling system designs, velocities in the channels can be significantly higher than the free-fall velocities. What is worse, the walls of the channels are stationary and so maximise the shearing action, encouraging surface turbulence and the consequential damage from the shredding and entraining of bubbles and bifilms.

Ultimately, however, a bottom-gated system, if designed well, has the greatest potential for success.

It is all the more disappointing therefore that many of our horizontally parted moulds produced on automatic moulding systems practically dictate the use of a poor filling system, resulting in the high-rate production of poor castings to the extent that Al-alloy casting cannot generally be produced on automatic greensand moulding lines. These current designs of automated moulding plants seem perversely designed to produce scrap rather than produce castings. Iron casting is fortunately more tolerant of such abuse of casting principles. The manufacturers of such systems will often deny this assertion, pointing out that a conical basin is not necessarily the only option, and that a three-dimensional milling machine could cut an offset step basin while the cope was upside down. Similarly, a tapered sprue could be cut or moulded at the same time. However, the author has never yet seen such solutions put into practice. They would be a welcome development.

Shrouded Pouring

The problem of the voluminous entrainment of air by the conical pouring basin has often been tackled by the provision of a shroud. This can be a steel or refractory cylinder that surrounds the outlet from a bottom-poured ladle, and nests in the funnel-shaped pouring basin. By this means, the inward flow of air into the conical funnel is reduced. However, even if the shroud were 90% efficient, which would be a surprisingly high efficiency, the remaining 10% of entrained air would still be a serious problem.

Some shrouds have an inert gas piped into them in an additional effort to protect the metal stream. This is clearly helpful, but once again inefficient. Plenty of air will still find its way into the metal stream. In any case, the bursting of bubbles of inert gas will still create some turbulence and splashing in the metal rising in the mould cavity, with consequent creation of defects.

In conclusion, shrouds reduce entrainment problems, but are inefficient. I avoid such unsatisfactory solutions.

Contact Pouring

The sitting of the bottom-pour ladle directly on its mould, so as to align the ladle nozzle and the entrance to the down-sprue of the casting, then raising the stopper to allow the ladle to drain, filling the casting, is the ultimate technique to eliminate the entrainment of air. It is simple, uses no costly inert gas and is 100% efficient. For shaped casting production, the technique has the added advantage that a pouring basin is eliminated. These are all really powerful advantages.

I always thought the contact pour technique would be useful and important, but I have in the past underestimated its importance. I now have come to realise its importance. It is an excellent technique which would, at almost no cost, revolutionise most foundries at a stroke. I now recommend it strongly for most foundries. It represents a major step towards excellent quality of castings, as a kind of low cost halfway development on the road to fundamental and revolutionary changes such as counter-gravity filling of moulds.

If only one casting is to be made from a ladle, effectively emptying the ladle, it is straightforward to calculate a suitable filling system using the head height in the ladle as the initial head height for driving the filling system. However, if several castings are to be filled from one ladle, the reducing head height in the ladle may cause the first casting to fill rather too fast and the last casting to fill too slowly. This must be checked by the casting engineer. Usually, however, the system is particularly tolerant, allowing five or six pours without problem because the changing height effect is reduced by the square root relation between height and velocity (Eqn (13.2)).

The contact between the nozzle in the base of the ladle and the entrance to the sprue is easily sealed with a layer of ceramic fibre blanket. However, the alignment of the nozzle with the sprue entrance can be a minor technical challenge. When pouring steel the alignment is easily seen from the pool of light radiated down from the white-hot stopper, shining on the white ceramic fibre surround of the sprue. For the lower melting point metals line of sight can be good enough but slow, whereas an engineering solution is usually best: laser guidance with feedback control to the crane should not be a problem in these modern times.

The reports of the benefits in the literature of contact pouring are universally positive. Examples include Jeancolas and coworkers (1962) and Schilling and Riethmann (1992). The author also has used the technique to excellent effect for a 50 tonne steel casting that proved to be free from defects as a result of zero air entrainment in the filling system (Kang et al., 2005).

Automatic Bottom Pouring

The automatic bottom pouring technique was invented by Alec Allan in the United Kingdom in 1963 (Allan, 1963, 1968). Although its name refers specifically to the use of a crucible with a hole in its base, through which the melt is poured when it is finally molten, the technique as practised to this day tends to employ only low cost, one-shot consumable crucibles, often made from simple bonded silica sand or from lightweight ceramic fibre. A specially shaped slug of metal which is a close fit in the crucible is melted extremely rapidly, usually within approximately 60 s. The base of the charge melts last, so the melt pours automatically, precisely when the last metal is melted. Sometimes the process is used with a penny-shaped metal disc in the exit nozzle of the crucible, so that the superheat at which the melt is poured can be controlled by the thickness of the disc.

The mould is placed, of course, under the crucible. This simple in-line arrangement involves no moving parts, and thus can provide extremely low-cost melting and casting systems, especially for vacuum melting and casting. The cylindrical vacuum chamber can be a fibreglass-resin tube, allowing the induction coil to be placed outside, once again simplifying the design by avoiding electrical connections through the wall of the chamber. The rather poor vacuum held by the fibreglass tube seems to be no problem for the melting and casting of most alloys. The process continues to be used, being highly productive for the casting of Ni-base superalloys for turbocharger wheels, and iron and steel castings, but Allan also describes its use for magnesium.

Although impressively simple, it is a pity that it is a *pouring* process, consequently demonstrating a constantly varying proportion of scrap from turbulently filled moulds. We really need to get away from *pouring* metals.

Having said this, there may be a way forward for automatic bottom pouring if the melting crucible could be placed in contact with the mould to achieve *contact pouring*. If this process could be successfully developed, it would be immensely attractive. An opportunity awaits someone.

Direct Pour

This name was chosen by the Foseco Company to describe the use of a ceramic fibre sleeve, fitted with a ceramic foam filter in its base, place directly onto and in contact with the casting as a substitute for a combined filling and feeding system. As such, of course, it could be convenient and highly economical (Sandford, 1993). However, despite several notable successes, the system has not always yielded good results.

This technique has been researched. The results are summarised in Figure 12.55, showing that the technique is mainly effective for relatively small falls after the filter in stabilising and making reproducible the casting conditions (the filtering action is insignificant). Because the stable regime promoted by the system may not yield a good casting, this means that if the first trial location for the direct pour sleeve on the casting is not good, all castings are likely to be unacceptable. Conversely, if the first trial location does yield a good result, all results are likely to be good. In the case of the poor result, repeated different locations should be tried if possible. If one is found to work it is probable that all subsequent castings will be good.

Gravity dies (Permanent Moulds)

For dies filled simply by pouring under gravity, in the United Kingdom they are not surprisingly called *gravity dies* (known in the United States as *permanent moulds*).

That the mould is hot and extremely dry means that the liquid aluminium and mould are practically inert towards each other. This is a significant benefit of hot dry metal moulds that is often overlooked. For this reason, subsurface porosity as a result of high hydrogen levels is rarely seen in casting from metal moulds. The use of permanent moulds is usually confined to low melting point metals (e.g. Zn, Pb) and the light alloys (Mg and Al). Only relatively rarely are permanent moulds used for the higher temperature alloys such as brasses and bronzes, and cast iron, although even for these metals, metal moulds can be valuable and successful.

The benefit of high temperature of the mould introduces a challenge for the control of the temperature, of course. Thus the die temperature falls when the casting cycle is interrupted by the fairly common occurrence of metal becoming trapped in the die, or coating repair, or sometimes even the arrival of a new batch of cores that have to be signed for and wheeled into place.

Cast iron or steel moulds used in gravity die casting (permanent moulding) or low-pressure die casting (low-pressure permanent moulding) of aluminium are coated with an oxide wash of rather variable thickness, in the range 0.5–2 mm thick, infringing on the accuracy of the casting. Its purpose is to reduce the thermal shock to the die, and by thus reducing the rate of heat transfer, allow the die to fill without premature freezing. Without the die coat it would be difficult if not impossible to fill the die without the formation of cold laps.

Because the die coat reduces the severity of the thermal loading, the die material can sometimes be grey cast iron. This is welcome because of the ease of obtaining a block of starting material, suitably shaped with a contoured back if necessary, and because of its excellent and easy machining. It has to be admitted that grey iron has limited strength and limited fatigue resistance. Thermal fatigue usually sets in after thousands of casts. This limit to die life can be an important threat to surface finish as the die ages, developing multiple small cracks, often called checks, or occasional large cracks resulting in sudden catastrophic failure. Such failures have disastrous effects on production because dies take time to replace. Such failure is commonly associated with heavy sections of the casting, such as a heavy boss. The iron or steel die in this region suffers from repeated transformation to austenite and back again. The large volume change accompanying this reaction corresponds to a massive plastic strain of several percent, so that steel, and more particularly cast iron, suffers thermal fatigue. The severe strains of thermal fatigue often lead to failure after relatively few cycles.

For dies that are subject to the rigours of volume production and where total reliability is required, the dies are machined from steel. Usually a special grade of hot work die steel, commonly an H13 grade containing 4% Cr is chosen, that is preferably characterised by an especially fine grain size.

For the production of simple two-parted castings, gravity dies are usually constructed with a vertical split line. The moving die half (if only one half moves) is usually arranged to retain the casting. Thus the action of opening the die causes the casting to impact on the ejector pins and so release the casting from the moving side. The casting may be caught on a tray and swung out from between the die halves. Alternatively, it may be simply picked up from where it has fallen. I only once saw a die arranged wrongly by mistake, with the casting retained in the fixed die half. It was an embarrassment to the die designer and a constant source of problems for the die operator until the die could be turned around.

Complex dies such as for automotive cylinder heads are usually provided with vacuum connections to the backs of core prints so as to suck gases out of difficult-to-vent cores such as water jacket cores. The vents usually block by the condensation of tars and other volatiles after 15–25 castings, depending on the casting. Sometimes knockout vents are employed to allow the vents to be cleaned out by drilling. The stopping of production to clean out the vents is a non-trivial hindrance to production rates using gravity dies. The campaign life of a die is usually dictated by the cleaning-out of vents rather than the maintenance and repair of the die coat. If vents are not maintained fully operational, blows from cores increase to become a major source of scrap.

More recently there is hope that difficult-to-vent cores might become producible with the new generation of silicate binders that do not create condensable outgassing products.

Binders that do not create fume on casting are very much to be desired. Fume in the immediate environment of operators is a problem in gravity die operations. The opening of a die containing cores is usually accompanied by a cloud of fume, most of which avoids the fume extraction hood because of side draughts. Sand castings tend to avoid the worst of such fume emissions because the casting and cores remain in the mould for longer and are cooler by the time the mould is opened. In any case, the sand mould is opened in a completely closed environment so that operators can work in a cleaner atmosphere.

The provision of a small steel mesh filter, with an approximately 2 mm mesh opening, is often usefully incorporated into the runner. This can be extracted from the runner while the metal is still hot, so is not recycled with the foundry returns, thus avoiding contaminating the metal with iron.

Turning to the possibility of the casting of cast irons in cast iron dies, the subject is studied at some length by Jones et al. (1974). These authors used grey iron dies coated only with acetylene soot (although the author is aware of other foundries that also coat with an oxide wash in addition to the application of fresh layer of soot after the ejection of each casting). They found good results for grey iron castings at slightly hypereutectic composition, well inoculated, poured close to 1350°C and with mould temperatures up to 300°C. It was also important that the moulds were of good quality, avoiding flash. In this way, carbide formation in the iron could be avoided. They claimed dimensional reproducibility, surface finish and strength properties were consistently superior to comparable aggregate-moulded castings.

These authors went on to check ductile irons. The greater tendency for these irons to solidify with carbides required a higher mould temperature up to 450°C. Even so, conditions for achieving ductile irons completely free from carbide were not found, but the heat treatment to eliminate the carbides was relatively short because of the fine structure.

The production of malleable irons, cast originally of course as white irons, was not considered attractive mainly because of the problem of achieving sound castings without the use of large feeders.

Carbon-based and graphite dies have been found useful for zinc alloys. However, for aluminium alloys, the lives of carbon moulds are short because of the degradation of the carbon by oxidation. (All the more impressive therefore is the use of graphite moulds for steel, used for the casting of millions of railroad wheels by the Griffin Process, described in the next section.) Graphite is often used as a moulding material for titanium, but any benefits of inertness are lost by the reaction to form the so-called alpha case. The details are described in Chapter 6 under the various cast metals.

16.1.3 TWO-STAGE FILLING (PRIMING TECHNIQUES)

There have been several attempts over the years to reduce some of the problems of gravity filling by the introduction of a two-stage filling process. The first stage consists of filling the sprue, after which a second stage of filling is started by the opening of a valve by which the runner and gates etc. are allowed to fill.

After the filling of the sprue, a short dwell for a few seconds with the metal at rest allows bubbles to separate, excluding air, but also allowing the oxide damage created during the first part of the pour to separate, probably becoming glued to the walls of the running system. After this few seconds of quiescence, the melt is allowed to start flowing once again. This second phase of filling has the full head H of metal in the sprue and pouring basin to drive it, but the column has to start to move from zero velocity. It reaches its steady state velocity $(2gH)^{1/2}$ only after a period of acceleration. Thus, the early phase of filling of the runner and gates starts from a zero rate and has a gradually increasing velocity, although at the relatively fast rate of gravitational acceleration this is probably only a minimal benefit.

The benefits of the exclusion of air from the sprue, and the reduced velocity during the early part of stage 2, are benefits that have been recorded experimentally for semi-solid (actually partly solid) alloys. These materials are otherwise extremely difficult to cast without defects, almost certainly because the defects normally entrained during the pour cannot float out of the casting but are trapped in suspension because of the high viscosity of the mixture.

Workers from Alcan (described by Weiss and Rose, 1993 and Cox et al., 1994) developed a system in which the advance of the melt was arrested at the base of the sprue by a layer of ceramic paper supported on a ceramic foam filter (Figure 12.45(a)). When the sprue was filled the ceramic paper was lifted from one corner by a rod, allowing the melt to flow through the filter and into the running system. These authors call their system 'interrupted pouring'. However, the name 'two-stage pour' is recommended as being more positive, and less likely to be interpreted as a faulty pour as a result of an accident.

The two-stage pour has been convincingly demonstrated as beneficial by several investigators. For instance, as early as 1968, Wildermuth describes its use with cast iron and steel using a sheet metal slide valve coated with fireclay, finding that the technique gave significantly cleaner castings. Taghiabadi and colleagues (2003) used the technique for both partly solid and conventional aluminium casting alloys. These authors used Weibull statistics to confirm the reality of the benefits. They used a steel sheet to form a barrier, as a slide valve, in the runner (Figure 12.45(b)). After the filling of the sprue, the sheet was slid aside, opening the runner and allowing the mould to fill.

A fascinating major benefit of the two-stage filling of the down-sprue is that no matter how dreadful the design of the down-sprue, once primed during the first stage of filling, it tends to remain full, operating perfectly with zero entrainment of air. This can easily be demonstrated by a water model.

A second completely different incarnation of the two-stage filling concept is the *bottom-pour ladle*. It is illustrated in Figures 12.3 and 12.45(c). The device is used mainly in the aluminium casting industry, but has been extended with benefit to other casting industries. Instead of transferring metal from a furnace via a ladle or spoon of some kind and pouring into a pouring basin connected to a sprue, the ladle dips into the melt and can be filled uphill via the bottom nozzle. The ladle nozzle is then closed by a stopper and the ladle transferred to the mould. The stopper is raised and can deliver the contents of the ladle into a conventional pouring basin. Preferably, however, it can be lowered onto and sat on the mould, aligning precisely with the entrance to the sprue, and thus delivering the melt directly in the sprue by the *contact pour* technique. This technique is strongly recommended in place of pouring into a pouring basin.

Alternatively again, if the ladle is equipped with an extension (Figure 12.45(d)), converting it to a *snorkel ladle*, the nose of the snorkel can be lowered down through the mould to reach and engage with the runner. Only then is its stopper raised and the melt delivered to the start of the running system with minimal surface turbulence. The approach is capable of producing excellent products. Two-stage filling in its various forms seems to offer real promise for many castings.

16.1.4 VERTICAL STACK MOULDING

The stacking of identical aggregate moulds and pouring into the top has been used for several products, for instance for cast iron piston rings. Although cast iron has a relatively low susceptibility to entrainment problems compared with many other metals, such mistreatment ensures that even this metal does not survive unscathed. Bubbles and oxides are necessarily entrained during the tumbling of the melt down the necessarily non-tapered irregular sprue (Figure 12.49(c)), and these defects find their way randomly into castings, requiring much subsequent testing and sorting. This awful process cannot be recommended. It throws all the principles of good filling design to the wind. Both the castings and the profitability of the foundry suffer lamentably.

16.1.5 HORIZONTAL STACK MOULDING (H PROCESS)

Foundries that are set up based on the H process (another of Fred Hoult's inventions; Hoult, 1979) have a pleasing simplicity. The moulding section of the foundry consists of relatively small core machines making the moulds by blowing into a corebox that forms both the front and back surfaces of the casting (Figure 12.49(b)). The use of identical cores forming both the front and back surfaces of the mould in this way effectively doubles the rate of production of moulds.

The moulds are stacked vertically in a frame, and then clamped, and the frame is turned horizontal and transferred to the casting area. After casting and cooling, the sand can be mainly recycled, and the castings separated from the running system by simply breaking them off.

The overflow of metal from one mould to the next necessarily involves a fall inside the mould cavity. This fundamental problem leads to the entrainment of severe defects if the fall is much over 200 mm, explaining the fact that H Process castings are normally limited in height to about 200 mm and may additionally explain why the process appears to be also limited to cast iron which has least sensitivity to entrainment problems. The one good feature of the fall of metal in the mould is that the fall distance is also minimised (as opposed to castings poured from above the mould via a conical basin, where velocities can become very high) so that the entrainment damage is limited. The production of Al alloy castings by this process would be expected to be problematic.

A computer study by Xiao (1998) shows that if the mould stack is perfectly horizontal, the melt dribbles into more distant cavities, possibly spoiling these castings. If the mould stack is tilted by about 7°, causing the melt to progress upwards from one cavity to the next, this problem is reduced. Furthermore, if the runner linking the cavities has a flat base, as opposed to being of a circular section, that also helps.

16.1.6 POSTSCRIPT TO GRAVITY FILLING

Later we consider an appraisal of counter-gravity filling of moulds, but it is salutary to consider why anyone would go to this trouble when gravity filling appears to be so easy.

There are some advantages to the use of gravity to action the filling of moulds by simply pouring metal. It is simple, low cost and completely reliable because gravity has never been known to suffer a power failure. It is with regret, however, that the advantages finish here, and the disadvantages start. Furthermore, the disadvantages are serious.

Nearly all the problems of gravity pouring arise as a result of the velocity of the fall. After a trivial fall distance corresponding to the few millimetres of the critical fall height, gravity has accelerated the melt to its critical velocity. Beyond this point, the continued acceleration of gravity results in the metal going too fast and having too much energy. Thus the danger of entrainment defects grows alarmingly with the increasing distance of the fall. Because the critical fall distance is so small, nearly all actual falls exceed this limit. In other words, the energy content of the melt, when allowed to fall even only relatively small distances under gravity, are nearly always sufficiently high to cause the breakup of the liquid surface. (It is of little comfort at this time to know that foundries on the moon would fare a little better.)

These high speeds result in gravity filling systems being hypersensitive to small errors. For instance, a tiny mismatch of a millimetre or so in the sprue can easily lead to the creation of volumes of entrainment defects.

A second fundamental drawback of gravity filling is the fact that at the start of pouring, at the time the melt is first entering the ingates, the narrowest part of the mould cross-section where volume flow rate should be slowest, unfortunately, the speed of flow by gravity is highest. Conversely, at a late stage of filling, when the melt is at its coldest and approaching the top of the mould cavity the speed of filling is slowest, endangering the casting because of cold laps and misruns. Thus filling by gravity gives a completely inappropriate filling profile.

Thus, to some extent, there are always problems to be expected with castings poured by gravity. The long section on filling system design in this book is all about reducing this damage as far as possible. It is a tribute to the dogged determination of the casting fraternity that gravity pouring, despite its severe shortcomings, has achieved the level of success that it currently enjoys.

Even so, there is no shortage of viable alternative processes that do not suffer these disadvantages. These are described later and are recommended. The good-natured behaviour of several of these processes, including some tilt processes and counter-gravity systems that use low filling speeds, errors of mismatch of flow channels and sharp, un-radiused corners etc. all become irrelevant.

16.2 HORIZONTAL TRANSFER CASTING

The quest to avoid the gravity pouring of liquid metals has led to systems employing horizontal transfer and counter-gravity transfer. These solutions to avoid pouring are clearly seen to be key developments; both seem capable of giving competitive casting processes that offer products of unexcelled quality. The major approaches to the first approach, horizontal transfer, are described below.

16.2.1 LEVEL POUR (SIDE POUR)

The *level pour* technique was invented by Erik Laid (1978). At that time, this clever technique delivered castings of unexcelled quality. It seems a pity that the process is not more generally used. This has partly occurred as the result of the process remaining commercially confidential for much of its history, so that relatively little has been published concerning the operational details that might assist a new user to achieve success. Also, the technique is limited to the type of castings, being applied easily only to plate, box or cylinder type castings where a long slot ingate can be provided up the complete height of the casting. In addition, of course, a fairly complex casting station over a deep floor pit is required.

The arrangement to achieve the so-called level filling of the mould is shown in Figure 16.1. An insulated pouring basin connects to a horizontal insulated trough that surrounds three of the four sides of the mould (a distribution system reminiscent of a Roman aqueduct). The melt enters the mould cavity via slot gates that extend vertically from the drag to the cope. Either side of each slot gate are guide plates that contain the melt between sliding seals as it flows out of the (stationary) trough and into the (descending) mould.

Casting starts with the mould sitting on the fully raised mould platform, so that the trough provides its first metal at the lowest level of the drag. The mould platform is then slowly lowered whilst pouring continues. The rate of withdrawal of the mould is such that the metal in the slot gate has time to solidify against a water-cooled chill positioned underneath the melt entrance. Thus the melt in the open slot is frozen before it emerges from out of contact with the chill, sliding out into the open air.

In one of the rare descriptions of the use of the process by Bossing (1982), the large area of melt contained in the pouring basin and distribution trough is claimed to smooth the rate of flow from the point of pour to delivery into the mould, despite variations in the rate of pour into the launder system from the ladle. Also in this description is an additional complicated distribution system inside the mould, in which tiers of runners are provided to minimise feeding

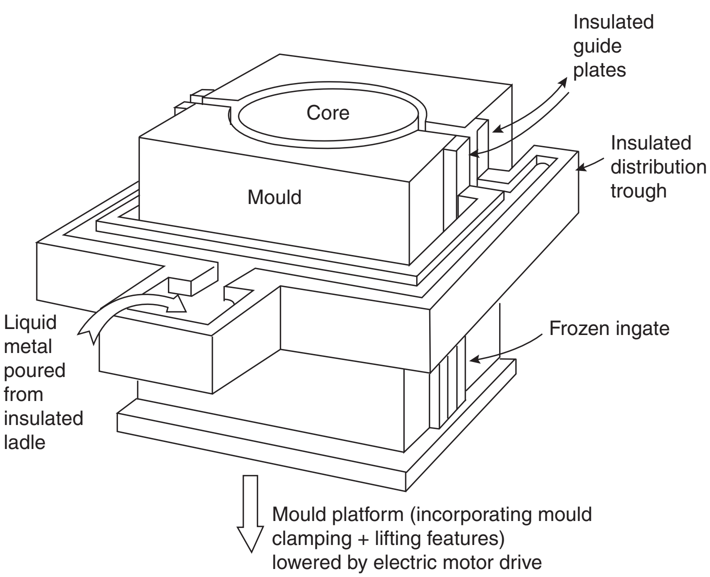


FIGURE 16.1

Level pour technique.

distances and maximise temperature gradients. In general, such sophistication would not be expected to be necessary for most products.

16.2.2 CONTROLLED TILT CASTING

It seems that foundrymen have been fascinated by the intuition that tilt casting might be a solution to the obvious problems of gravity pouring. The result has been that the patent literature is littered with re-inventions of the process decade after decade. Even now, the industry has many completely different varieties of tilt process, so the reader needs to be cautious about exactly what tilt process is being referred to.

Furthermore, the deceptive simplicity of the process conceals some fundamental pitfalls for the unwary. The piles of scrap seen from time to time in tilt-pour foundries are silent testimony to these hidden dangers. Generally, however, the dangers can be avoided, as will be discussed in this section.

Durville Process Casting

The most common form of tilt casting is a process with the unique feature that, in principle, liquid metal can be transferred into a mould by simple mechanical means under the action of gravity, but without surface turbulence. It therefore has the potential to produce very high quality castings. This was understood by the Frenchman, Pierre Gaston Durville (1874–1959), and applied by him for the casting of aluminium bronze in an effort to reduce surface defects in French coinage.

The various stages of liquid metal transfer in Durville's process are schematically illustrated in Figure 16.2(a). A melting crucible and a mould are fixed opposite to each other on a rotatable platform. A short channel section connects the two. The crucible is charged with metal, which is melted and skimmed clear of dross, and the platform is rotated. Some operators of this process have melted elsewhere and transferred the melt to the Durville unit, pouring the melt into the crucible, thus introducing damage. In the process as originally conceived by Durville, the metal is melted in the crucible fixed in the tilt machine. No pouring under gravity takes place at all. Also, because he was casting large ingots in open-ended moulds for subsequent working, he was able to look into the crucible and into the mould, observing the transfer of the melt as the rotation of the mould progressed. In this way, he could ensure that the rate of rotation was correct, carefully adjusting it all the time, to avoid any disturbance of the surface of the liquid. During the whole process of the transfer, careful control ensured that the melt progressed by 'rolling' in its skin of oxide, like inside a rubber sack, avoiding any folding of its skin by disturbances such as waves. The most sensitive part of the transfer was at the tilt angle close to the horizontal. In this condition the melt front progresses by expanding its skin of oxide, whilst its top surface at all times remains horizontal and tranquil. At this critical stage of metal flow, the rate of rotation must be a minimum. If this stage is not kept under good control, the metal surges into the mould as a wave, and splashes upwards against the rear face of the mould, and is damaged during its fall by entraining oxides.

Clearly Durville understood what he was doing. He avoided any pouring action to fill the crucible or ladle, and he controlled the rate of rotation of the assembly to ensure horizontal transfer. Few that claim to follow his process have understood these critical aspects.

The running system for tilt castings, if any, does not necessary follow the design rules for gravity casting because gravity is only marginally influential in this process. The rate of filling of the casting is under the control of the rate of tilt, not necessarily the channels of the filling system. Furthermore, of course, after the mould is filled the filling channels can be used as feeding channels, and thus be sized appropriately. All this is quite different to the design procedure for a gravity-filled mould.

In the United States, Stahl (1961) popularised the concept of 'tilt pouring' for aluminium alloys into shaped permanent mould castings. The gating designs and the advantages of tilt pouring over gravity top pouring have been reviewed and summarised in several papers from this source (Stahl, 1963, 1986, 1989). These benefits include the following.

1. The control over the rate of filling helps to control flash. This is because the rate of increase of pressure due to the head of metal is rather slow, starting from zero, in contrast to normal gravity-poured castings, where there are high

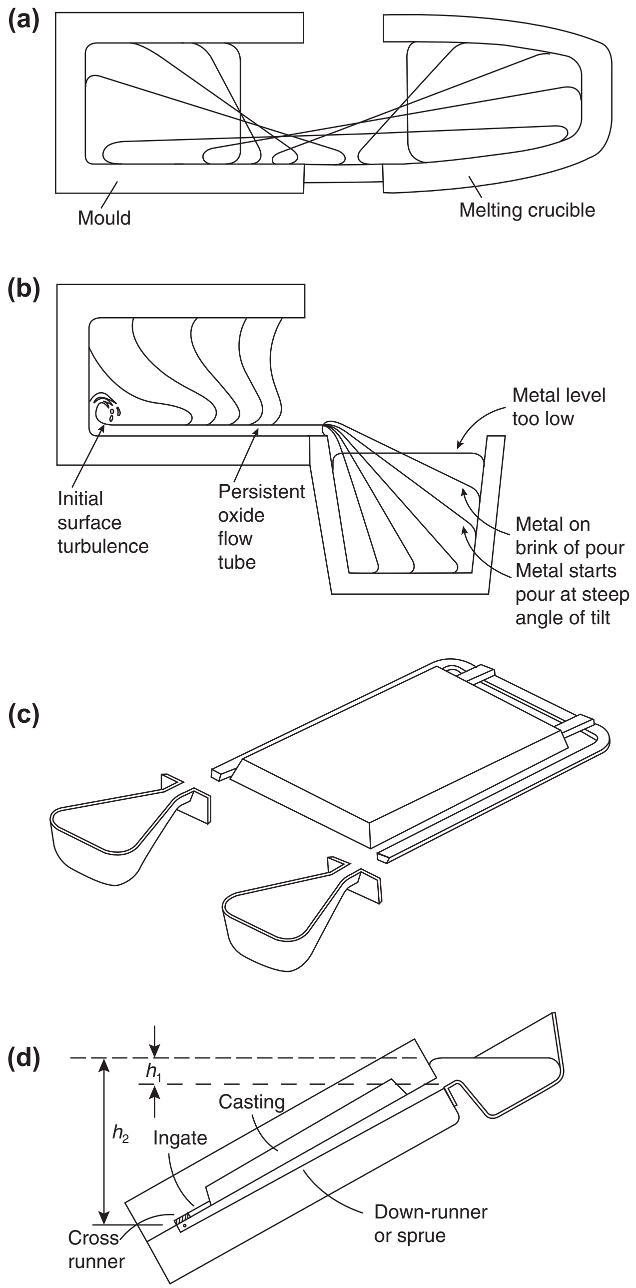


FIGURE 16.2

Tilt casting process (a) Durville; (b) semi-Durville; (c) twin-poured tilting die *(adapted from Nyamekye, 1994.)* and (d) outline of tilt running system at the critical moment that metal reaches the far end of the 'sprue' after the melt has effectively fallen height h_2, unfortunately encouraging damage by surface turbulence.

dynamic pressures and a high rate of attaining the full hydrostatic pressure. The reduced flash is important for castings such as gratings and grills that are otherwise difficult to dress. (This advantage is, of course, available to other gravity-casting techniques, provided a gentle fill is employed; it is less easy to achieve in any of the injection or low-pressure techniques, where the driving force is high, and generally under poorer control.)

2. Automated casting can be arranged relatively easily, with the benefit of consistent results.
3. Two cups can be filled consecutively by one operator, or, alternatively, large cups can be filled by successive charges from a ladle that can be handled by one person. Thus very large castings can be easily produced by one caster. This seems to be a unique benefit for tilt casting, making for considerable economies compared with normal gravity-poured moulds, where several casters may be required at one time, pouring simultaneously, or in an unbroken succession, possibly into several down-sprues.
4. The setting of cores has the flexibility of being carried out in either the horizontal or vertical attitude, or even in some intermediate position, depending on the requirements of the cores.
5. For the ejection of the casting the operator similarly has the option of carrying this out vertically or horizontally.

A useful ‘bottom-gated’ tilt arrangement is shown in Figure 16.2(c). Here the sprue is in the drag, and the remainder of the running and gating system, and the mould cavity, is in the cope. Care needs to be taken with a tilt die to ensure that the remaining pockets of air in the die can vent freely to atmosphere. Also, the die side that retains the casting has to contain the ejectors if they are needed.

Dies made for the Stahl casting method feature a tapered sprue carrying metal down to a gate near its base. A typical arrangement is shown in Figure 16.2(c) and (d). Effectively, the running systems are of the bottom-gated type, which give less good temperature gradients, or side-gated, which is some improvement. Figure 16.3 shows a die with side gates, but arranged so as to allow the melt to fall inside the mould cavity. The transfer of the mould cavity into the top half of the die would have eliminated this relatively small defect (but whose consequences are not easily predicted, and might therefore be non-trivial).

Occasionally, the metal will be poured directly into the mould cavity, eliminating runners entirely and giving the best temperature gradient but poorest filling. It is significant that Stahl reports the disadvantage of the appearance of the flow path down the face of the casting in this case, outlined by streaks of oxide. Such features are a concern because they indicate the presence of flow tubes, thus possibly constituting serious defects. This is a symptom of poor downhill filling, not employing the controlled horizontal fill approach to be described later.

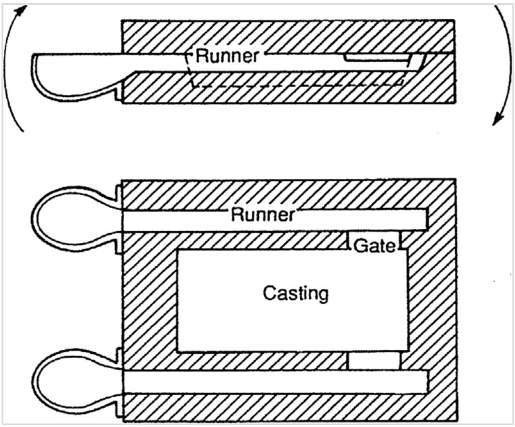


FIGURE 16.3

Tilt pour system that would have benefited from the mould cavity mainly in the upper half of the die, avoiding the fall of metal from the gate. Vents would then have been necessary.

In an effort to understand the process in some depth, Nguyen (1986) simulated tilt casting using a water model of liquid metal flow, and King and Hong (1995) carried out some of the first computer simulations of the tilt casting process. They found that a combination of gravity, centrifugal and Coriolis forces govern tilt-driven flow. However, for the slow rates of rotation such as are used in most tilt casting operations, centrifugal and Coriolis effects contribute less than 10% of the effects resulting from gravitational forces, and could therefore normally be neglected. The angular velocity of the rotating mould also made some contribution to the linear velocity of the liquid front, but this again was usually negligible because the axis of rotation was often not far from the centre of the mould.

However, despite these studies, and despite its evident potential, the process has continued to be perfectly capable of producing copious volumes of scrap castings.

The first detailed study of tilt casting using the recently introduced concepts of critical velocity and surface turbulence was carried out in the author's laboratory by Mi (2000). In addition to the benefits of working within the new conceptual framework, he had available powerful experimental techniques. He used a computer controlled, programmable casting wheel onto which sand moulds could be fixed to produce castings in an Al-4.5%Cu alloy. The flow of the metal during the filling of the mould was recorded using video X-ray radiography, and the consequential reliability of the castings was checked by Weibull statistics.

Armed with these techniques, Mi found that at the slow rotation speeds used in his work the mechanical effect of surface tension and/or surface films on the liquid meniscus could not be neglected. For all starting conditions, the flow at low tilt speeds is significantly affected by surface tension (most probably aided by the effect of a strong oxide film). Thus below a speed of rotation of approximately 7 degree per second the speed of the melt arriving at the end of the runner is reduced in a rather erratic way. Gravity only takes control after tilting through a sufficiently large angle.

As with all casting processes, if carried out too slowly, premature freezing will lead to misrun castings. One interesting case was found in which the melt was transferred so slowly into the runner that frozen metal in the mouth of the runner acted as an obstructing 'ski jump' to the remaining flow, significantly impairing the casting. At higher speeds, however, although ski jumps could be avoided, the considerable danger of surface turbulence increased.

The radiographic recordings revealed that the molten metal could exhibit tranquil or chaotic flow into the mould during tilt casting, depending on (1) the angle of tilt of the mould at the start of casting and (2) the tilting speed. The quality of the castings (assessed by the scatter in mechanical properties) could be linked directly to the quality of the flow into the mould.

We can follow the progress of the melt during the tilt casting process. Initially, the pouring basin at the mouth of the runner is filled. Only then is the tilting of the mould activated. Three starting positions were investigated:

1. If the mould starts from some position in which it is already tilted downward, once the metal enters the sprue it is immediately unstable, and runs downhill. The melt accelerates under gravity, hitting the far end of the runner at a speed sufficient to cause splashing. The splash action entrains the melt surface. Castings of poor reliability are the result.
2. If the mould starts from a horizontal position, the metal in the basin is not usually filled to the brim and therefore does not start to overflow the brim of the basin and enter the runner until a significant tilt angle has been reached. At this stage, the vertical fall distance between the start and the far end of the runner is likely to be greater than the critical fall distance. Thus, although slightly better castings can be made, the danger of poor reliability remains. This unsatisfactory mode of transfer typifies many tilt casting arrangements as seen in Figure 16.2(d) and particularly in the so-called semi-Durville type process shown in Figure 16.2(b). The oxide flow tube from the downhill flow of the stream, plus the entrainment from the splash at the end of the runner can be serious defects. Durville would not have liked to see his name associated with this awful process.
3. If, however, the mould is initially tilted slightly uphill during the filling of the basin, there is a chance that by the time the change of angle becomes sufficient to start the overflow of melt from the basin, the angle of the runner is still somewhat above the horizontal (Figure 16.4). The nature of the liquid metal transfer is now quite different. At the start of filling the runner, the meniscus is effectively climbing a slight upward slope. Thus its progress is totally stable, its forward motion being controlled by additional tilt. If the mould is not tilted further, the melt will not advance. By extremely careful control of the rate of tilt, it is possible in principle to cause the melt to arrive at the

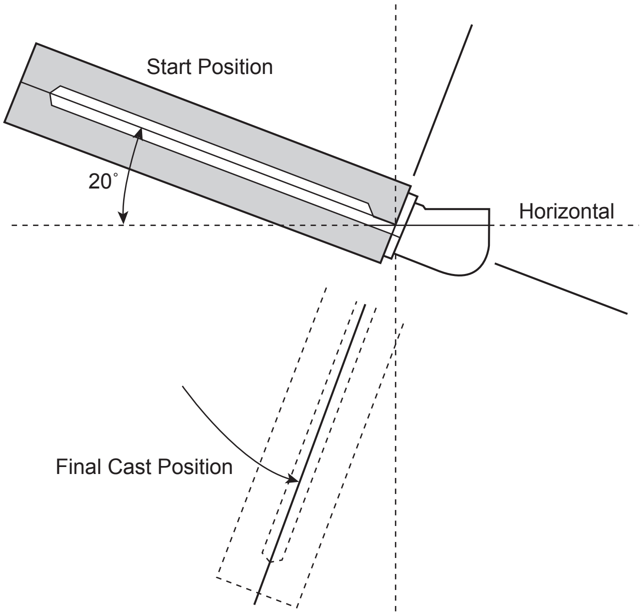


FIGURE 16.4

A tilt pour die starting at a 20° positive tilt, designed to encourage the 'runner' to fill uphill (this is a convenient optical illusion), ensuring that the melt reaches the far end of the runner at a controlled speed.

base of the runner at zero velocity if required. (Such drastic reductions in speed would, of course, more than likely be counter-productive, involving too great a loss of heat, and are therefore not recommended.). Even at quite high tilting speeds of 30 degrees per second as used by Mi in his experimental mould, the velocity of the melt at the end of the runner did not exceed the critical value 0.5 ms^{-1}, and thus produced sound and repeatable castings.

The unique feature of the transfer when started above the horizontal in this way is that the surface of the liquid metal is close to *horizontal* at all times during the transfer process. Thus in contrast to all other types of gravity pouring, this condition of tilt casting does not involve pouring (i.e. a free *vertical* fall) at all. It is a *horizontal* transfer process. It will be seen that in the critical region of tilt near to the horizontal, the liquid transfer occurs essentially horizontally. Durville would have approved.

Thus the optimum operational mode for tilt casting is the condition of horizontal transfer. Horizontal transfer requires the correct choice of starting angle above the horizontal, and the correct tilting speed as found by Cox and Harding (2007). These authors noted that a really accurately controlled tilt speed increased the two-parameter Weibull modulus (the reliability) of Al alloy castings from 2 to 55, an enormous increase. Conversely, a poor choice of rotation parameters created significant surface turbulence.

An operational map can be constructed (Figure 16.5), revealing for the first time an operational window for the production of reliable castings. It is recognised that the conditions defined by the window are to some extent dependent on the geometry of the mould that is chosen. However, the mould in Mi's experiments was designed to be close to the size and shape of many industrial castings, particularly those for automotive applications. Thus although the numerical conclusions would require some adaptation for other geometries, the principles are of general significance and are clear: there are conditions, possibly narrowly restricted, but in which horizontal transfer of the melt is possible, and gives excellent castings.

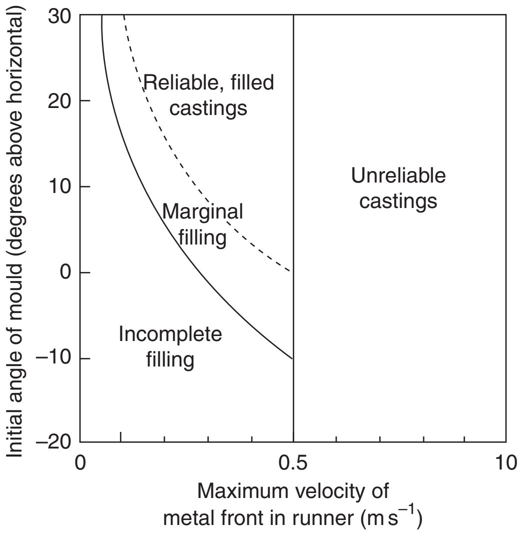


FIGURE 16.5

Map of variables for tilt pouring, showing the operational window for good castings (Mi et al., 2002).

The problem of horizontal transfer is that it is slow, sometimes resulting in the freezing of the ski jump at the entrance to the runner, or even the non-filling of the mould. This can usually be solved by increasing the rate of tilt *after* the runner is primed. This is the reason for the extended threshold, increasing the window of possible filling conditions from the dotted curve to the full line curve on the process map (Figure 16.5). A constant tilt rate (as is common for most tilt machines at this time) cannot achieve this useful extension of the filling conditions to achieve good castings. Programmable tilt rates are required to achieve this solution.

A final danger should be mentioned. At certain critical rates of rise of the melt against an inclined surface, the development of the transverse travelling waves seems to occur to give lap problems on the cope surface of castings (Figure 13.3). In principle, such problems could be included as an additional threshold to be avoided on the operational window map (Figure 16.5). Fortunately, this does not seem to be a common fault. Thus in the meantime, the laps can probably be avoided by increasing the rate of tilt during this part of the filling of the mould. Once again, the benefits of a programmable tilt rate are clear.

In summary, the conclusions for tilt casting are as follows.

1. If tilt casting is initiated from a tilt orientation at or below the horizontal, during the priming of the runner the liquid metal accelerates downhill at a rate out of the control of the operator. The metal runs as a narrow jet, forming a persistent oxide flow tube. In addition, the velocity of the liquid at the far end of the runner is almost certain to exceed the critical condition for surface turbulence. Once the mould is initially inclined by more than 10° below the horizontal at the initiation of flow, Mi found that it was no longer possible to produce reliable castings by the tilt casting process.
2. Tilt casting operations benefit from using a sufficiently positive starting angle that the melt advances into an upward sloping runner. In this way, its advance is stable and controlled. This mode of filling is characterised by horizontal liquid metal transfer, promoting a mould filling condition free from surface turbulence.
3. Tilt filling is preferably slow at the early stages of filling to avoid the high velocities at the far end of the running system. However, after the running system is primed, speeding up the rate of rotation of the mould greatly helps to prevent any consequential non-filling of the castings.

16.2.3 ROLL-OVER AS A CASTING PROCESS

There are casting processes in which the mould is planted upside-down over the mouth of a small melting unit, usually a small induction furnace, and the whole assembly is rotated swiftly through 180°. This technique is widely used in investment casting. However, it is not a process that appears to enjoy much control. It is in reality a kind of dump process for liquid metal. The procedure might not be so bad with a carefully designed filling system in the mould, but this is rarely provided at this time; the melt simply tumbles into the mould. There is little to commend this approach.

The Invocast method by Butler (1980) provides an interesting development which has similarities to the Stahl tilt-pouring method, in that the first action is to fill a pouring cup, and the next is the rotation of the die, which causes the die cavity to fill. It is shown in Figure 16.9. However, there is an important improvement in that the metal does not necessarily run downhill (this will vary somewhat from casting to casting) but fills the cavity progressively as rotation proceeds. Finally, the feeder is sited on top where it can feed most effectively. The preheating of the running system adds to the effectiveness of its action when it reverts to become the feeding system.

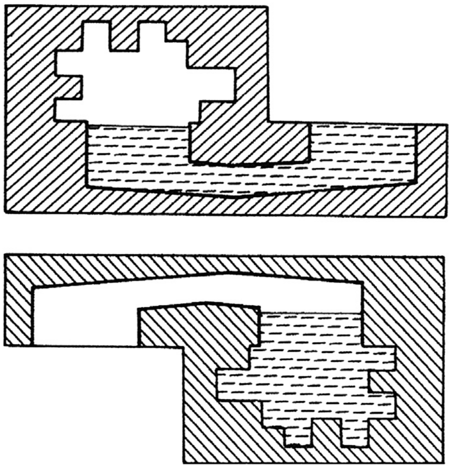


FIGURE 16.6

Inversion casting of a gravity die, showing the start and finish stages.

After Butler (1980).

Rotocast Process

The rotocast process, first used for the production of Al alloy cylinder heads by the Mandl and Berger Company, Austria, is another casting process executed by a roll-over transfer. It is described by Grunenberg et al. (1999). A cylindrical ladle is filled with metal (by pouring of course, so some defects will be added by this initial action) and is then offered up to a permanent mould (Figure 16.6). The mould is then rotated over about its longitudinal axis, transferring the melt from the ladle into the mould. Because the ladle and mould are a pressure-tight system, pressure can be applied during the freezing of the casting. This is said to reduce the feeder size in the sand top core, even though pressure timing and magnitude have to be carefully controlled to avoid metal penetration of the sand cores.

In this same report, these authors go on to describe a second (un-named) process which they seem to consider at the time to be an improvement on the simple rotocast process. The system employs a permanent mould with a top sand core to contain the feeders. This is a variety of the semi-Durville process (Figure 16.7) and shares its same problems; the serious limitations of this incomplete application of Durville's technique are clearly seen: the degree of filling of the ladle, varying from time to time, dictates a varying angle at which the pour can start, resulting in a variable initial

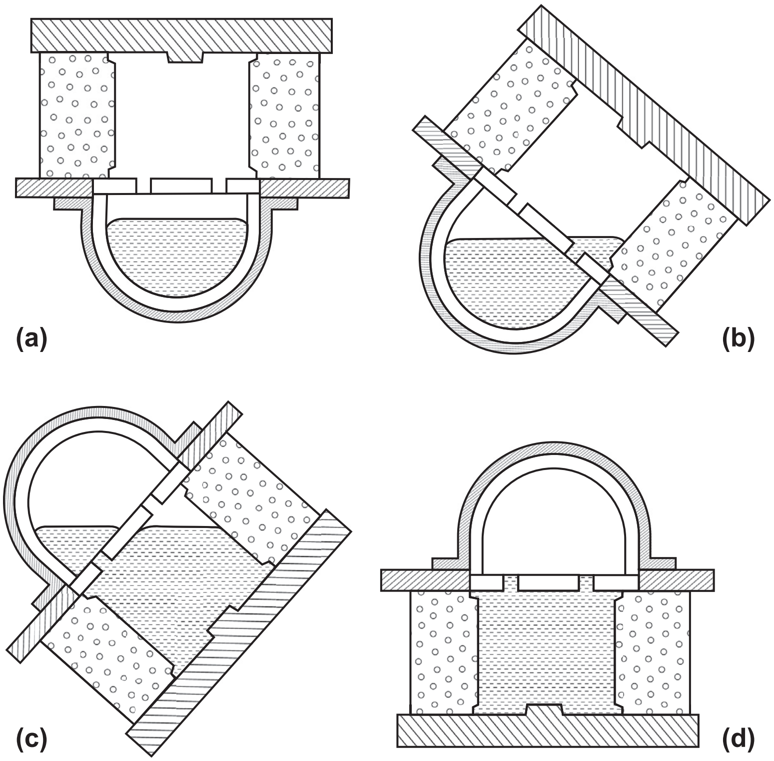


FIGURE 16.7

Rotocast process used for automotive cylinder heads and blocks. (a) start position; (b) metal entering mould; (c) mould almost filled; (d) roll-over casting cycle complete. The roll-over action takes about 10 s.

After Schneider (2006).

downhill flow of the melt, often at a steep angle, achieving high and damaging velocities. A further feature is the use of pressurisation after filling in an effort to reduce feeder size. This need for this complication reveals the poor metal quality, requiring bifilms to be kept closed during freezing. It would surely be better to opt for a technique to improve metal quality and improve filling. I am not aware of this process still being used. Perhaps the users finally had second thoughts about the reality of its capabilities.

16.2.4 ROLL-OVER AFTER CASTING (SOMETIMES CALLED INVERSION CASTING)

Inversion casting is not tilt casting. In fact, it might better be described as a solidification control process rather than a casting process because the pouring action is carried out as a normal gravity fill. It is only after the mould is filled that the whole assembly is rotated through 180° to encourage solidification under improved temperature gradients, and so aid the feeding of the casting.

In 1935, Batty was probably the first to describe simple inversion casting. He gives the example of a heavy-walled cylinder casting that was cast standing upright as shown in Figure 16.8. The gating system was a classical bottom-run method for optimum filling. This would normally result, of course, in a temperature regime in which the highest temperature was at the base of the casting, and any top feeders would be too cold to be effective. He solves this problem by

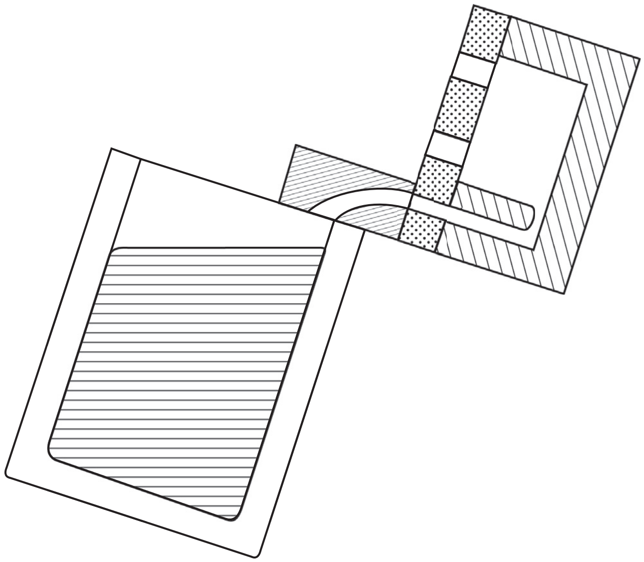


FIGURE 16.8

A tilt-casting process in which the ladle connects directly to a permanent mould with a sand top core containing the feeders (Grunenberg, Escherle and Sturm, 1999). The danger of some downhill flow inside the mould can be seen.

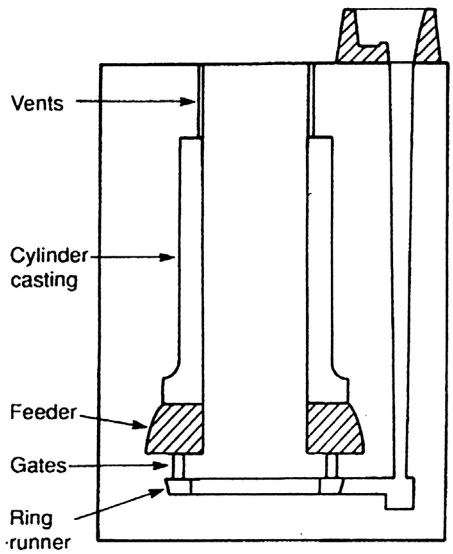


FIGURE 16.9

Cylinder casting-arranged as an inversion casting.

Adapted from Batty (1935), but core and mould assembly details omitted for clarity.

simply turning the whole mould over immediately after casting. The ring runner is then the feeder (and may need to be somewhat larger than normal to fulfil this additional role) and acts effectively because it is preheated, and because the temperature gradients in the casting are all favourably directional towards the feeder.

Let us review this worthy effort by Batty. We now know that the well at the base of the sprue would have introduced significant entrainment defects; thus, this should be eliminated. Personally, I would have eliminated all this fussy runner and ingate complication at the base of the casting, simply turning the sprue and entering the casting tangentially, thus spinning the metal up inside the casting. Finally, Batty's favourable temperature gradients for feeding after roll-over would only be obtained if especially slow pouring was used, thus threatening the formation of cold laps or unfilled castings. In this case, because of the relatively heavy wall section of this casting I would not have employed a roll-over. I would have allowed the casting to have inverted its temperature gradient by itself, simply by the natural action of convection. The feeder then should have been located at the top of the stationary (non-roll-over) casting.

Cosworth Process

After the counter-gravity filling of the mould, the Cosworth Process uses the inversion concept whilst keeping the liquid metal under pressure from the pump during the roll-over. In addition to the feeding of the casting being improved by the filling system becoming the feeding system, the mould, now filled with liquid metal, can be immediately disconnected from the pump and moved on to a cooling conveyer. The casting station is then released for the production of further castings (previously, the casting was fed during freezing by keeping it on the casting station for up to 5 min). The technique speeds up productivity by more than a factor of 5 (Smith, 1986). Green (2005) draws attention to the importance of maintaining the pressure on the melt during the roll-over because otherwise the metallostatic pressure because of depth alone (particularly when, during rotation, the mould is sideways and so generating a much reduced head pressure) may be insufficient to hold expanding gases in cores, therefore leading to the possibility of core blows. Processes that employ roll-over but which are not capable of maintaining the pressurisation of the liquid are therefore at risk.

Core Package System (CPS)

The so-called *core-package system* with its inappropriately widely encompassing name, is in fact a rather specialised form of precision sand core assembly process involving the filling of the sprue by contact pouring by offering up the mould assembly to the underside of a launder (Schneider, 2006). The stopper sealing the nozzle in the bottom of the launder is raised and the mould is filled. This works well. After the mould is filled, it is lowered to disengage with the launder, and a small arm automatically closes the sprue with a cap to prevent it emptying during the roll-over. The mould is then rolled over so that the reservoir under the casting is brought to the top to act as a feeder. However, during filling, the emptying of the high velocity metal into feeder volume creates major problems because the constraint over the liquid is lost, allowing the melt to jet and ricochet throughout the volume, entraining major defects (Figure 16.10). This otherwise good casting process contrasts of course with the true counter-gravity filling of the feeder volume which is gentle and controlled and has the potential to avoid the creation of any defects.

Figure 16.10 does illustrate the other important aspect of the roll-over processes: that chills can be used to good effect to enhance temperature gradients and so enhance feeding. As the figure illustrates, the use of chills dictates which way up the casting is filled; for cylinder heads, the chill is desired on the combustion face, and specifically between exhaust valve seats in four-valve per cylinder engines. For cylinder blocks, the fire face is relatively lightly loaded compared with the main bearings, whose fatigue performance greatly benefits from being chilled.

The roll-over principal, when used appropriately, either as a casting process or post-casting process, seems to be a powerful solution to some of the problems of filling and/or feeding castings. It strongly deserves to be more widely used.

16.3 COUNTER-GRAVITY

My toes curl when I hear the counter-gravity process called '*counter-gravity pouring*'. Pouring it is not. Furthermore, such inaccuracy undermines the thinking that is fundamental to the whole concept of the avoidance of pouring. The word pouring must be eliminated from the vocabulary of those rational souls employing the counter-gravity process. In its place, we need the appropriate and heart warming phrases 'counter-gravity filling' or 'counter-gravity casting'.

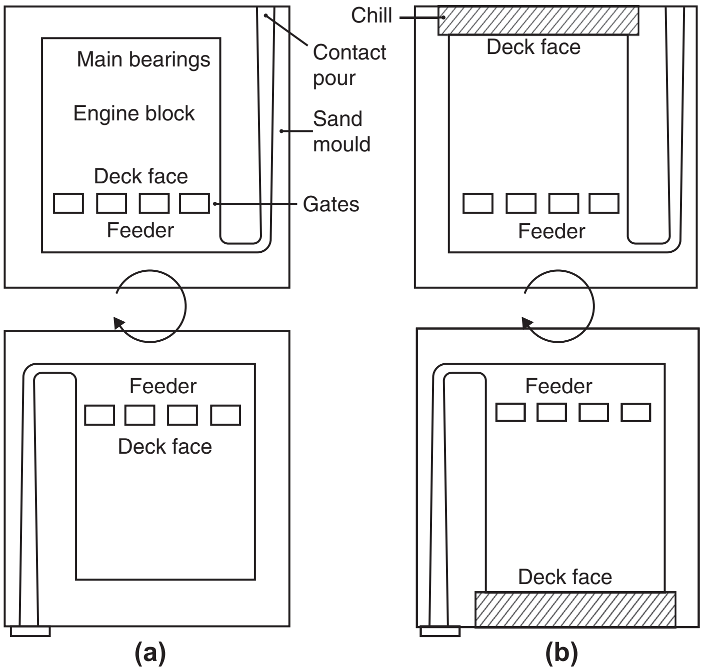


FIGURE 16.10

The so-called core package system (CPS) for engine blocks uses good filling via contact pour, and roll-over for feeding, but the high velocity flow into the volume of the feeder can cause major problems. The feeder can act via the ingates (a) alone; or (b) with a chill to aid feeding.

After Schneider (2006).

Over the past 100 years and more, the fundamental problems of gravity filling have prompted casting engineers to dream up and develop counter-gravity systems.

Numerous systems have arisen. The most common is *low-pressure casting*, in which air or an inert gas is used to pressurise an enclosed furnace, forcing the melt up a riser tube and into the casting (Figure 16.11). Other systems use a partial vacuum to draw up the metal. Yet others use various forms of pumps, including direct displacement by a piston, by gas pressure (pneumatic pumps), and by various types of electromagnetic (EM) action.

The fundamental action at the heart of the counter-gravity concept is that the liquid meniscus can be made to rise at a rate at which its oxide is pinned against the mould walls, the oxide becoming the skin of the casting (Figure 2.2(a)). The oxide on the surface of the advancing meniscus never becomes entrained into the bulk of the melt, creating defects in the casting. Only perfectly executed horizontal filling can match this extraordinary perfection of filling control. Counter-gravity is among the few (the very few) filling processes that can produce uniquely perfect castings.

Clearly, with a good counter-gravity system, it is possible to envisage the filling of the mould at velocities that never exceed the critical velocity, so that the air in the mould is pushed ahead of the metal, and no surface entrainment occurs. The filling can start gently through the ingates, speed up during the filling of the main part of the mould cavity, and finally slow down and stop as the mould is filled. The final deceleration is useful to avoid any final impact at the instant the mould is filled. If not controlled in this way, the transient pressure pulse resulting from the sudden loss of momentum of the melt can cause the liquid to penetrate any sand cores, and can open mould joints to produce flash, and generally impair surface finish.

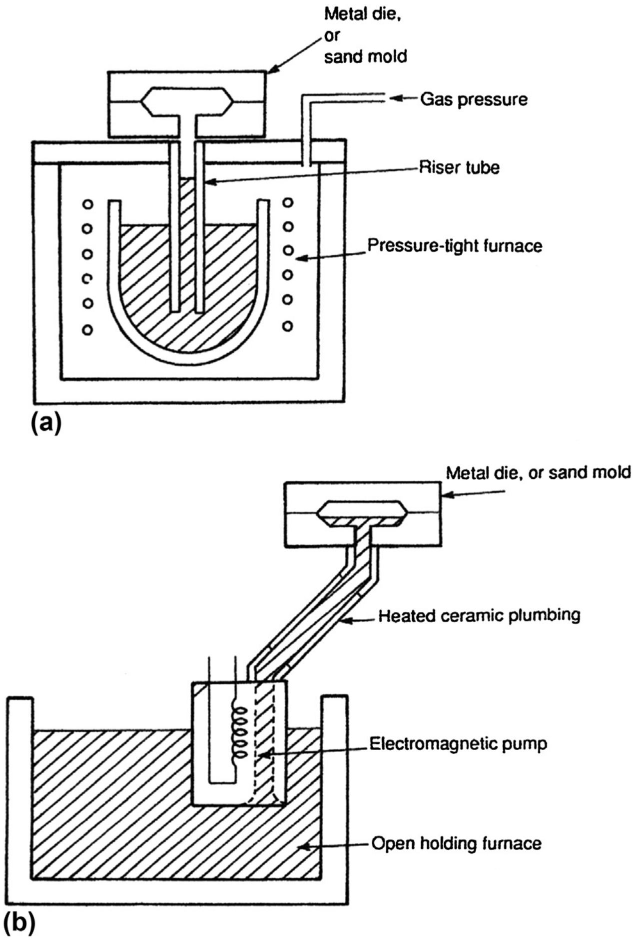


FIGURE 16.11

Counter-gravity castings by (a) conventional low-pressure casting machined using a sealed pressure vessel; (b) electromagnetic pump in an open furnace.

When using a good counter-gravity system, good filling conditions are not difficult to achieve. In fact, in comparison with gravity pouring, in which it is sometimes difficult to achieve a good casting, counter-gravity is such a robust technique that it is often difficult to make a bad casting. This fundamental difference between gravity and counter-gravity filling are not widely appreciated. In general, those who are familiar with gravity filling but have finally accepted a change to counter-gravity are suddenly amazed by the powerful benefits.

A counter-gravity-filled investment casting method that crams a 100 or more steel castings on one wax assembly makes millions of automotive rocker arm castings per year. These show a reject rate in the fractions of a part per million parts, illustrating the astonishing reliability that can be achieved by counter-gravity. Interestingly, however, this mode of casting was devised by Chandley (1976) not initially for its high reliability but because of its low costs. Further developments of this process by the Hitchener Company into aero engine turbine components among other markets have been impressive. They are reviewed by Shendye and Gilles in 2009. Griffiths (2007) confirms that counter-gravity filling of a low alloy steel produced castings with a higher Weibull modulus (higher reliability) than even well-designed gravity filling systems. A vertical stack of aggregate moulds filled with nodular or highly alloyed cast irons produced high volumes of castings with reliable 2.8 mm thickness walls (Purdom, 1992). Brasses are cast into permanent moulds to produce dense, leak-free domestic plumbing fittings required to take a high polish and faultless chromium plate (Lansdow, 1997).

That is not to say that the counter-gravity technique is not sometimes used badly. A common poor practice is a failure to keep the metal velocity under proper control. Entering the mould too quickly, even with a counter-gravity system, can make impressively bad castings. However, in principle, the technique *can* be controlled, in contrast to gravity pouring where, in principle, control is often difficult or impossible.

A concern often expressed about counter-gravity is that the adoption of filling speeds below the critical speed of approximately 0.5 ms^{-1} will slow the production rate. Such fears are groundless. For instance if the casting is 0.5 m tall (a tall casting) it can, in principle, be filled in 1 s. This would be a challenge!

In fact, the unfounded fear of the use of low velocities of the melt leading to a sacrifice of production rate follows from the confusion of (1) flow velocity (usually measured in ms^{-1}) and (2) melt volume flow rate (usually measured in m^3s^{-1}). For instance, the filling time can be kept short by retaining the slow filling velocity but increasing the volume flow rate simply by increasing the areas of the flow channels. Worked examples to emphasise and clarify this point are given in Chapter 13 dealing with the calculation of the filling system.

The other problems relate to the remainder of the melting and melt handling systems in the foundry, that are often poor, involving multiple pouring operations from melt furnaces to ladles and then into the counter-gravity holding vessel. A widespread re-charging technique for a low-pressure casting unit is illustrated in Figure 16.12; much of the entrainment damage suffered in such processes usually cannot be blamed on the counter-gravity system itself.

The lesson is that only limited success can be expected from a foundry that has added a counter-gravity system on to the end of a badly designed melting and melt handling system which generates defect-laden metal. There is no substitute for an integrated approach to the whole production system. Some of the very few systems to achieve this so far have been

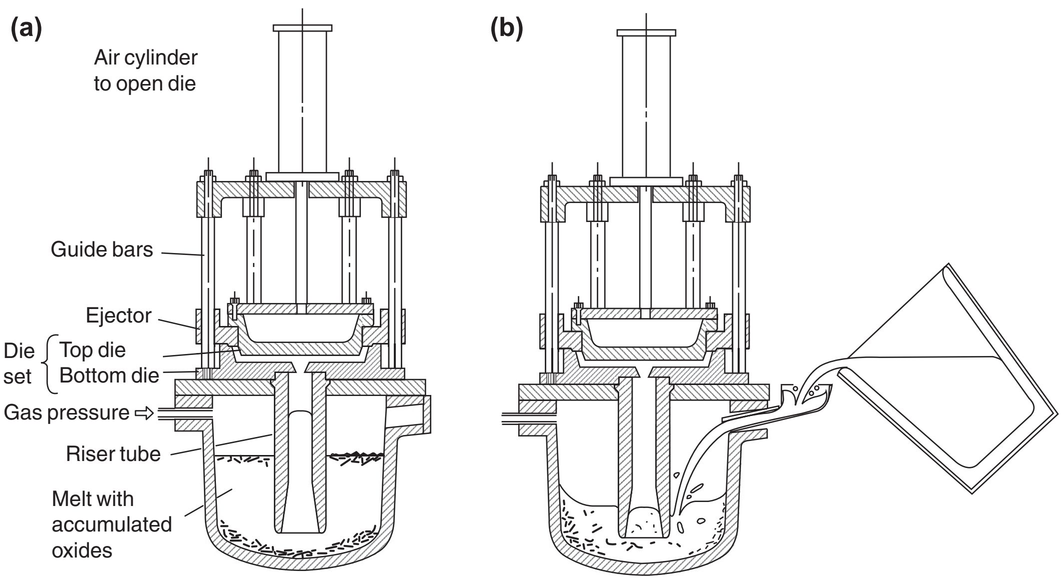


FIGURE 16.12

Low-pressure casting unit showing (a) sink and float of oxide; and (b) the conventional poor filling technique that re-entrains debris.

the processes that the author has assisted to develop; the Cosworth Process and, perhaps at some future date, in the Alotech ablation processes. In these processes, when properly implemented, the liquid metal is allowed to settle to eliminate a proportion of its defects in suspension, and subsequently is never poured, never flows downhill, and is finally transferred into the mould without surface turbulence. It is not difficult to arrange these highly beneficial features of a melt system.

Finally, the concept of an integrated approach necessarily involves dealing with convection during the solidification of the casting. The problem is highlighted by the author as casting rule 7. This serious problem is usually completely overlooked. It has been the death of many otherwise good counter-gravity systems, but is specifically addressed in the Cosworth Process by roll-over after casting.

16.3.1 LOW-PRESSURE CASTING

Low-pressure die casting

The low-pressure die casting (low-pressure permanent mould) process is widely used for the casting of automotive parts such as wheels and cylinder heads which require good integrity and, for wheels, good integrity and good cosmetic appearance when finely machined or polished.

Its name arises from its relatively low pressure (perhaps 0.3–0.5 bar) required to lift the metal into the mould (note that 1 bar will raise an Al melt approximately 4.5 m) followed sometimes by the application of a higher pressure stage in an effort to reduce any porosity in the casting. During this stage, the pressure might be raised to 1 bar. Even these highest pressures are typically only about 1% of the pressures used in high pressure die casting (HPDC).

The process enjoys several advantages, including ease of automation, so that despite its cycle time being longer than that of gravity permanent mould systems, one man can usually control several machines. In addition, in common with most counter-gravity systems, it has metallic yields in the range 80–95%, compared with 50–75% for gravity-poured systems that require oversized feeders as a result of the damage that their filling systems introduce. In common with gravity pouring, sand cores are not a problem provided the applied pressure is under good control (otherwise, with overpressure being sometimes applied to prevent bifilm opening to create microporosity, sand cores can become impregnated with metal. Clearly, if the melt is of good quality, overpressure to suppress porosity is not required).

Low-pressure die casting dies can be made from cast iron or steel, depending on the service requirements, and enjoy the protection of a ceramic die coating applied by spray.

In most low-pressure permanent mould casting the die is split horizontally, with the casting retained in the upper half (ejectors cannot usually be placed in the lower half because of the presence of the furnace under the die). As the upper half is raised after the freezing of the casting, the ejectors impinge against the stripping plate to eject the casting. In this case, the casting is usually caught on a tray swung under the upper die as it is raised. The tray and casting are then swung clear, presenting the casting outside the machine for onward processing.

The dies are often water-cooled by internally drilled water channels. Cooled dies are expensive and complicated, but hold the record for productivity of certain types of casting such as automotive wheels. An uncooled die for a wheel might have a cycle time of 5 min, whereas a cooled die can be less than 2 min. For larger castings, such as some cylinder blocks, a cycle time of 15 min may be usual.

One of the most notable high-temperature developments of low pressure die casting is the famous Griffin Process for steel railway rolling stock (Figure 16.13), described by Hursen (1955). It makes an interesting comparison to the use of the process for Al alloys. The insulated ladle in the pressure vessel can hold up to 7 tonnes of liquid carbon steel. The large density difference between the steel and buoyant defects such as bubbles, bubble trails and other entrained oxides encourages such materials to float out relatively quickly, so that the topping up of the furnace does not necessarily introduce permanent damage; after the metal has been poured into the pressurised vessel, the entrained defects quickly float away from the bottom of the melt where the intake to the riser tube is located. In addition, little or no sediment is to be expected. Thus a good quality of steel has had chance to develop at this location before the filling of the next casting. In this way, a

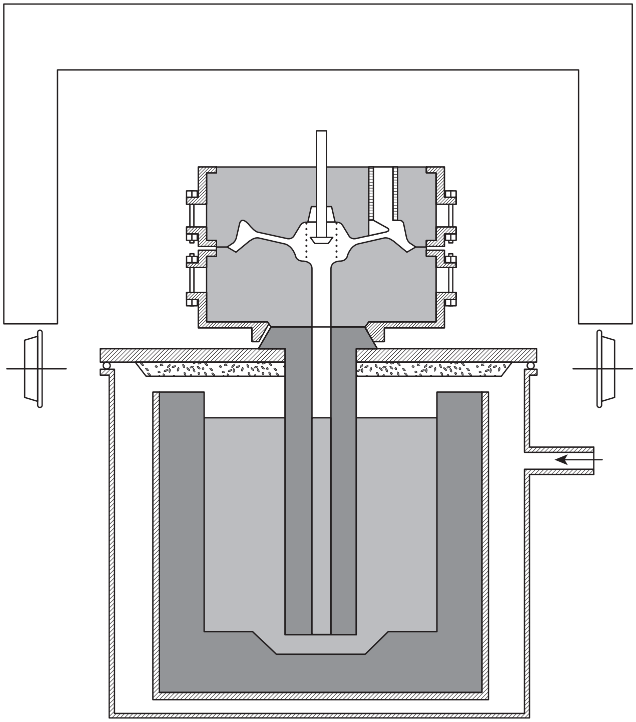


FIGURE 16.13

The counter-gravity casting of steel railroad wheels by the Griffin Process. The mould transfer car (transporting frame shown in outline) carries the mould along the production track, and houses all the gear for lowering, raising and clamping down of the mould and operating the stopper.

After Hursen (1955).

high-integrity, safety-critical product can be routinely produced. Even so, one can imagine that the deoxidation practice, leaving different amounts of Si, Mn and Al, plus others such as Ca, could influence the flotation time significantly.

In this case, the dies are machined from graphite. Although a successful process has been built on this process, the machining of graphite is always a somewhat messy and dirty occupation. There seems little doubt that the process might have been operated with greensand with practically no loss of accuracy and no loss of performance of the steel casting. It might be claimed that greensand may be only slightly less messy and inconvenient, although it would be interesting to see a comparative evaluation of the two types of mould for this high volume product.

In practice, the process is impressively automated and productive. Moulds arrive automatically on a transfer car rolling on a track, and are indexed automatically into place on the casting unit. The filling of the mould with steel at 1620°C is registered by observing the top of one of the three or four sand-lined feeders. When the metal arrives at the feeder tops, the filling is stopped and the timing of other operations is started (the somewhat variable filling time arises because of the falling level of the melt in the holding furnace). After filling, no waiting is required for solidification because the graphite stopper is lowered to seal off the mould (Figure 16.13) and the mould is automatically indexed to the cooling line. The ladle can cast about 20 wheels before being returned to the melting furnace where its remaining metal is returned and the holder can be topped up. The centre of the casting containing the stopper (shown as dotted lines in Figure 16.13) is removed by flame cutting. Only this central bore is machined. The remainder of the casting, including the tread of the wheel that runs directly on the rail, remains cast to size. The cast wheels at least equal if not exceed the reliability of forged and rolled steel wheels. I find all this a deeply impressive achievement.

Unfortunately, in spite of the excellent potential of the low pressure system, the process has some fundamental problems that can produce significant amounts of scrap. The problems arise from several sources.

It is necessary to take stock of the many problems associated with low-pressure casting:

1. The re-filling of the pressurised furnace with metal (Figure 16.12(b)) is usually a major source of entrainment defects that causes all the usual problems of fine scattered porosity often suffered by the process.
   There is one variety of low-pressure casting unit that goes some way towards solving the problem of the massive damage introduced by the conventional topping up operation. It has a separate crucible and furnace assembly that can be detached from the casting machine. This is usually achieved by the pressurised furnace assembly containing the crucible being indexed out from under the machine. Up to three such assemblies are required per casting machine so that one can be melting, another treating the melt by, for instance, rotary degassing and passive holding and the third is in place in the machine making castings. This system is clearly a significant improvement on re-filling of the pressurised vessel by gravity pouring through a port in its side.
2. In the past, many low-pressure die casting machines have been so poorly controlled on flow rate, that the speed of entry into the die could greatly exceed the critical velocity, thus negating one of the most important potential benefits of the low-pressure system. Oxide bifilms and possibly bubbles are generated inside the mould, having little or no time to separate from the casting. Fortunately, most modern machines have significantly improved control so this is no longer a problem.
   I recall an instance in the Cosworth foundry when the melt was pumped too quickly into the mould by mistake. The result was disaster, with the X-ray radiograph displaying hot tears, gas bubbles, apparent shrinkage porosity and sand inclusions. This contrasted with normally defect-free castings when the ingate velocity was correctly controlled below the critical velocity of 0.5 m/s.
3. The melt is usually allowed to fall down the riser tube after the solidification of each casting. This fall leaves a skin of oxide on the inside of the riser tube, which can detach and spoil the subsequent casting, although a filter of some kind at the mouth of the mould is usually in place to help to reduce this problem. Pechiney, France, was probably the first in an attempt to address this issue by providing an inert gas environment for the top of the riser tube (Charbonnier, 1983). However, the problem is best solved by keeping the riser tube filled to within a few millimetres of the top, with the melt ready to enter the next casting. Unfortunately, there is significant resistance within the industry to keep pressurised furnaces pressurised to achieve this mode of operation, said to be a concern of safety. However, processes using EM pumps achieve this maintenance of the level without difficulty and thereby avoid unnecessary oxide generation.
4. The second serious feature of the sudden release of pressure is fall of the melt in the rise tube creating the consequential ‘whoosh’ of melt issuing from its base, efficiently stirring up all those oxides that have settled to the floor of the furnace since the last casting. Thus defects in suspension in the melt are never allowed to settle quiescently on the floor of the furnace; inclusions are re-stirred into suspension between every casting. A controlled, gradual release of pressure would easily solve this problem.
5. The third serious problem arising from the sudden release of pressure is little known. It is further compounded by the application of a higher pressure than is needed to fill the mould in an attempt to induce higher soundness. These actions can be highly counter-productive if the melt is contained in a standard refractory lining in the pressurised furnace. This is because the lining becomes impregnated with the pressurising gas; if the pressure is very high, the volume of impregnated gases is substantial. On the release of pressure after solidification of the casting, the refractory lining releases its gases which bubble up through the melt, creating bubble trails. If air is used for pressurisation the melt is filled with bubble trails of oxide. Nitrogen pressurisation results in nitrides and is known to bring the melt into an uncastable condition after only a few pressurisations. Even argon pressurisation will create some problems as a result of the contamination of oxygen and nitrogen residues in the lining.
   In explanation, although the pressurising gas cannot penetrate the lining covered by the liquid metal, it penetrates the lining from its back, and has several minutes to saturate the lining throughout its thickness at the high pressure.

On rapid release of the pressure, the gas naturally escapes rapidly in whatever way it can, therefore from both front and back, creating bubbles from the front.

The use of minimal pressures, merely for filling rather than enhancing soundness, reduces this serious problem. The use of hydrostatically pressed crucible for containment of the melt rather than a rammed refractory lining is a further effective solution.

6. New riser tubes offering longer life might now create conditions in which the sediment in the furnace now has time to build up to levels for which entrainment of the sediment in the casting becomes unavoidable.
7. Convection of melt up the riser tube and into the mould, delaying the freezing of the casting, can be a serious contributor to poor productivity and poor solidification structure in the casting. I recall an operator who related to me that he timed the freezing of his cylinder head casting, then degassed the melt with an inert gas. On re-checking the freezing time, it was found to have increased. He concluded the reduced hydrogen affected the freezing behaviour. He degassed again and the freezing increased again. This happened three or four times (I forget exactly how many). Clearly, the variations in hydrogen content could not explain these results. I concluded that his original melt convected very little because of its high viscosity resulting from its content of oxide bifilms in suspension. This slurry would move only sluggishly in the rather narrow riser tube. After 'degassing', which would have removed a significant proportion of oxides, the higher fluidity of the melt, as a 'thinned' slurry, would have led to increased thermal convection in the riser tube, conveying heat from the melt in the furnace, up the riser tube and into the casting, delaying its solidification. The progressive cleaning of the melt and progressively worsening productivity illustrated the influence exerted by two powerful factors normally overlooked in casting operations: oxide bifilms and thermal convection.

   Riser tubes that deliver the melt directly into the mould cavity (rather than turning some right-angle corners in a distribution system) are particularly at risk from the convection problem. The use of a filter at the top of the riser tube is a help, but usually does not completely cure the problem. Muller and Feikus (1996) in an excellent article describe the use of a new design of spreader pin sited at the top exit of the riser tube. This device helped to remove some heat from the casting at the top of the riser tube, assisting to control the convective flow of hot metal into the casting at this point, and thus increasing casting quality and productivity.

As a result of all these problems, many of which are not addressed as suggested previously, the performance of many low-pressure casting operations is often disappointing. For serious operators, additional suggestions by Muller and Feikus (1996) are recommended reading.

Medium-Pressure Die-Casting Process

A potentially interesting variant of the low-pressure process has been described as the medium-pressure casting process by Eigenfeld (1988). Essentially the mould is filled exactly as the low-pressure process, but after the mould is filled and the casting partly solidified, the casting is pressurised by one or more small pistons, well known in HPDC as squeeze pins, that collapses the casting surface locally. The internal pressurisation of the melt in this way will reduce the 'air gap' around the casting and thus increase the freezing rate. The process is claimed to give better properties than conventional LP die casting for this reason.

Counter-pressure Casting process

A complication of the usual low-pressure die casting process has been introduced as the *counter-pressure casting process*, in which a pressurised chamber is lowered over the die to apply pressure counter to the pressure in the furnace chamber, so that only the differential pressure raises the melt up the riser tube (Balewsky and Dimov, 1965). The counter-pressure, usually between 3 and 10 bar, acts on the liquid during mould filling and solidification to help to suppress the formation of porosity. The lowering of the counter-pressure chamber and its pressurisation with gas would be expected to slow the production cycle, but Wurker and Zeuner (2004, 2006) claim otherwise. The development is clearly devised as a logical approach to reduce the problems arising from current poor melt practice. However, if the cast metal had a reasonable quality, free from oxide bifilms, no porosity could be generated, so that no counter pressure would be needed.

Vacuum riserless casting and/or pressure riserless casting

Vacuum riserless casting and/or pressure riserless casting is a process using permanent water cooled metal moulds filled by vacuum and/or pressure, so that a riser (i.e. feeder) is not required (Spada, 2004).

This author has to admit to being biased; he cannot get to like this process. It seems to him to be unnecessarily and unbelievably complicated. The permanent mould, possibly sprayed with release agent between every cast, is filled partly or entirely by the application of a vacuum to the mould, drawing metal up from the furnace sited below the mould. Any leakage of the riser tube(s) will introduce air bubbles into the casting. The melt may rise up more than one riser tube, introducing the danger of convection between the tubes (melt rising up one and descending down another, the heat thus transferred from the furnace delaying the solidification of the casting, and impairing structure), although, fortunately, the strong water cooling of the metal mould will reduce this danger. Having filled the mould, additional pressure can now be applied from below to help to suppress pore formation and increase cooling rate by pressurising the casting against the mould. When releasing the pressure, the residual melt in the riser tubes falls back into the furnace, potentially increasing oxide, but certainly re-stirring settled oxides, maintaining them in suspension. Fortunately, the process can be used with pre-treated melts with exchangeable furnaces, or better still, with furnaces kept full from a heated launder distribution system (Spada, 2004, 2005). It is hoped the units use hydrostatically pressed crucibles to reduce the otherwise major impairment from bubble damage to the melt.

The control problems are daunting, involving vacuum cycles, pressure cycles, and complex water cooling, in addition to the normal cycles involving opening and closing the die etc. The capital and maintenance costs must also be daunting. The castings can be excellent of course, but the workforce has to be unusually diligent and well above average capability to succeed with this system. They have my best wishes.

T-Mag Process

A recent interpretation of the tilt casting process for Mg alloy castings named *T-Mag* (presumably T for tilt and Mag for magnesium) has been demonstrated by CSIRO in Australia (Nguyen et al., 2006) using a permanent mould connected to the melting furnace via a heated transfer tube (Figure 16.14). When tilting the assembly, the melt enters the die via a bottom gate, thus having the potential to fill the cavity smoothly. It is therefore better described as a counter-gravity process. The casting solidifies under the hydrostatic pressure because of the height difference ΔH. After solidification, the assembly is rotated back to its vertical position, lowering the melt gently in the riser tube (in contrast to most low-pressure units), the die is opened, and the casting ejected. The casting has the short 'carrot' ingate typical of low-pressure castings, and thus enjoys a good metallic yield in addition to its reasonably high quality. At this time, the direct addition of ingots or foundry returns to the melt introduces the oxide skins of these charge materials, which are almost certainly troublesome with respect to the attainment of the highest and most reproducible properties (Wang, Lett et al., 2011). Thus although at this time performing better than most Mg casting processes, it seems the process is in its early days of development and it is to be hoped that the process will receive further development to achieve its full potential.

16.3.2 LIQUID METAL PUMPS

A pump can be an excellent way to transfer metal into a mould. There are many varieties of pump, but as with all pumps, they are characterised by their particular characteristic curves. These are graphs of the relation between head height and volume flow rate as shown in Figure 16.15. The characteristic curves require to be treated with some caution; they show the *potential* of the pump. When programming the pump to fill some odd-shaped volume, such as a casting, the setting of the pump power to achieve a certain metal height at a certain time will not, in general, deliver metal at that height at that time. This is simply because it takes *time* for the melt to be accelerated by the pump and *time* for the mould cavity to fill the part of the casting volume up to that level. This wide misunderstanding of the necessary lag between the programmed and achieved conditions is easily dealt with by the computer, which can apply Newton's laws of motion to the metal without difficulty or complaint, and get the programming exactly right first time. Alternatively, the problem is dealt with, within the limits of the power of the pump, by feed-back control as described in Section 16.3.5.

We shall consider the main pump options for use in foundries next.

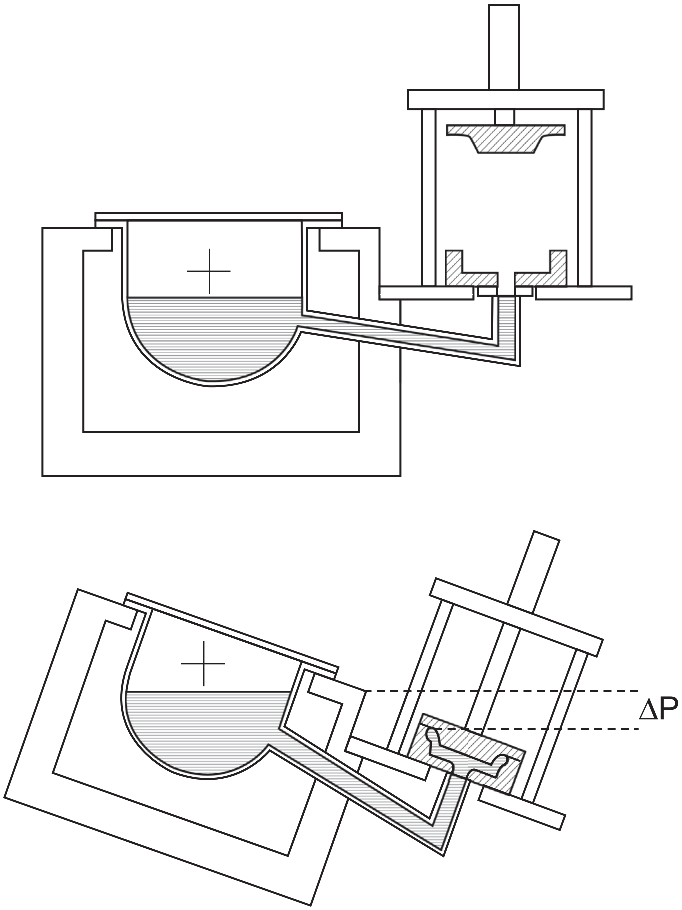


FIGURE 16.14

The 'counter-gravity' casting of Mg alloys using the tilting furnace of the T-Mag technique. The figure shows a permanent mould, but would be expected to work perfectly well with a sand mould, particularly if convection were controlled. Solidification occurs under pressure ΔP. The unit reverts to its upright mode to open the die and eject the casting.

Centrifugal pumps

A brief history of centrifugal pumps is given by Sweeney (1964). He describes the first pumps for molten aluminium in Cleveland, Ohio, in 1945.

Centrifugal pumps usually have carbon based rotors, and can have high volumetric capacity, although the characteristic curves shown in Figure 16.15(a) show the output of a rather small pump with a similar characteristic curves to the EM pump PG450 used for making castings (Figure 16.15(c)). Much larger centrifugal pumps are available for transferring tonnage quantities of melts between furnaces because they can transfer Al at up to 100 kg/s and up to 7 m high. Centrifugal pumps are currently being evaluated for use for filling moulds in Cosworth type operations.

Electromagnetic pumps

The great benefit of EM pumps is that they contain no moving parts and their life in a melt can usually be measured in months. Their relatively high initial costs are usually offset by good reliability and relatively modest maintenance and

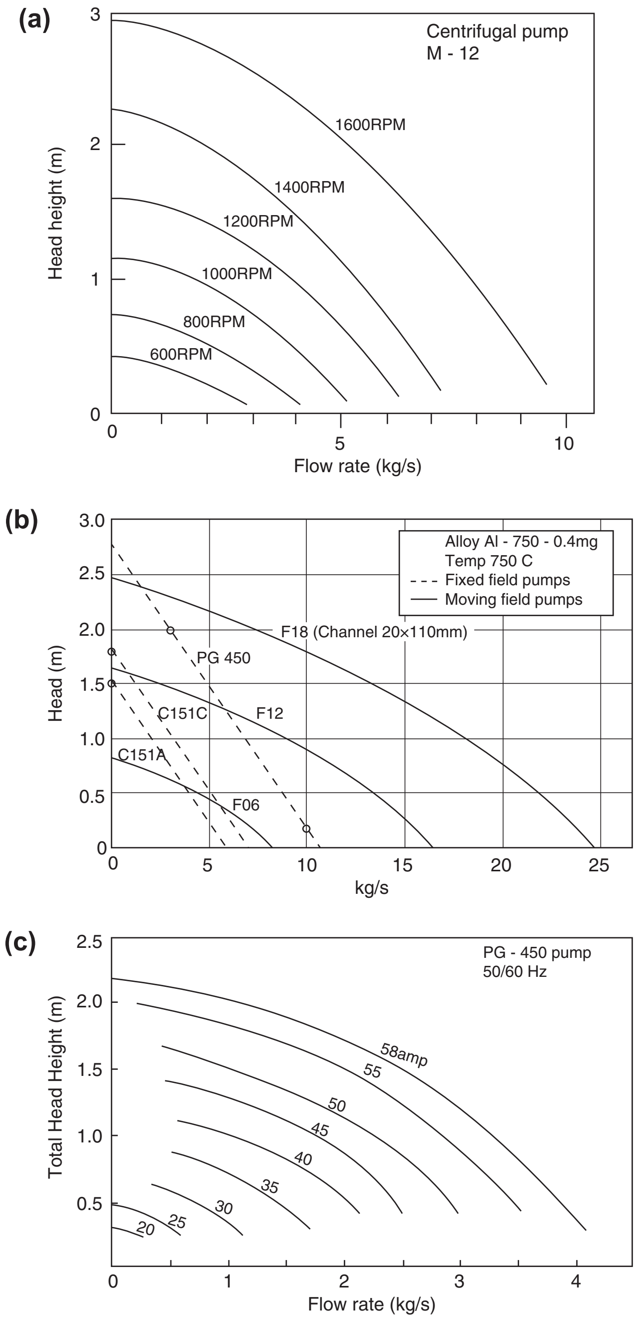


FIGURE 16.15

Characteristic curves for the performance of (a) centrifugal pump; (b) two different varieties of electromagnetic pump at full power; (c) an electromagnetic pump at various power levels.

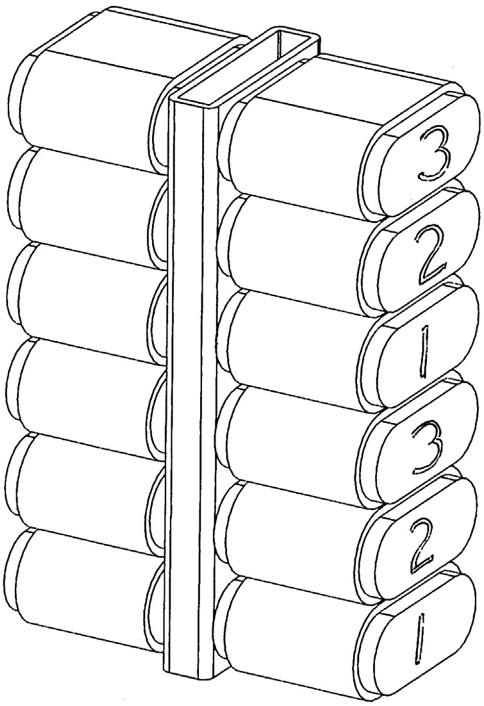


FIGURE 16.16

The moving field electromagnetic pump with simple ceramic tube delivery system.

running costs. Their use in the relatively non-aggressive environments for low melting point metals tin and lead is easily understood. Use for liquid Mg has been more problematical because only ferritic stainless type steels can withstand immersion in Mg and the parts out of the melt have to withstand oxidation at these higher temperatures for long periods. The ferromagnetism of the alloys does hamper the transfer of magnetic fields to act as driver to the melt. Thus there are plenty of fundamental problems for Mg.

There are practical engineering solutions for liquid aluminium alloys making the use of EM pumps for Al now relatively well established. There are two main varieties of EM pumps; both rely on the principles of induction.

a. The three-phase moving field pump. This simple design has at its heart a straight ceramic tube containing the melt. The tube is surrounded by a series of electromagnets, each magnetic coil connected in turn to a single phase of the three-phase electricity supply, with the phases connected to the magnets in the order 1, 2, 3, 1, 2, 3 etc. along the length of the tube. As the phases cycle, so the magnetic field progresses along the length of the tube dragging the liquid metal with it (Figure 16.16).

   In common with all pumps, the performance of EM pumps is described quantitatively by a characteristic curve giving its rate of delivery at various heights. Thus its maximum rate is delivered at zero height, but its rate of delivery falls to zero at its maximum delivery height. At this height, the melt is working hard to just support the column of liquid metal in a kind of stalled mode (Figure 16.15(c)). An increase in electrical current to the coils will increase performance, moving the characteristic curve out to higher rates and greater heights. Thus a family of curves can normally be generated for a series of different currents. This particular set of curves was generated by placing pumps in series. The curves F16, F12 and F18 correspond to one, two or three pump modules assembled together, end to end. Clearly, the volume capacity of the moving field pumps is vastly greater than is required for casting

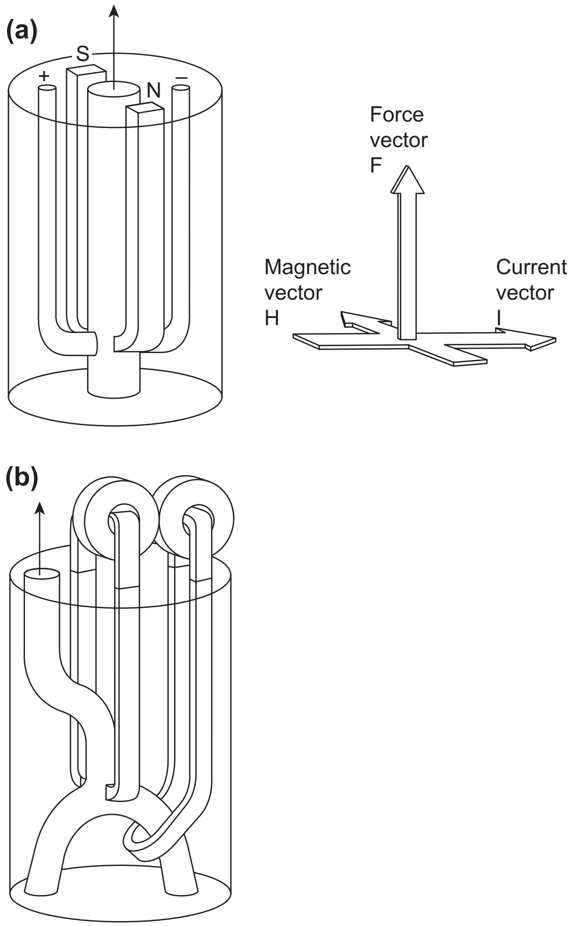


FIGURE 16.17

The fixed field pump built from castable refractory blocks designed for part-way immersion in the melt for periods of months: (a) the principal of employing three vectors at right angles; (b) a simplified model of a real pump.

production, being mainly intended for transfer of melts between furnaces. However, the pumps are easily downgraded by the use of a smaller cross-section central tube. The overheating that might occur during their use in a 'stalled' condition, retaining power input to continue holding metal in a mould that is already full, but taking time to solidify, is relatively easily overcome by additional cooling (otherwise the melt, now stationary, in the moving field becomes highly overheated and might melt parts of the pump).

b. The AC (alternating current) single-phase stationary field pump (Figure 16.17). This pump is a clever but complex design, involving more sophisticated and costly maintenance. It relies on the inductive principle enshrined in Faraday's left hand motor rule. (The mutual relation between the three vectors at right angles is given by the thumb and principal two fingers on the left hand held out at right angles, denoting 'first finger = field; second finger = current; thumb = motion.) Thus, the interaction of the magnetic field vector at right angles to the electrical current vector produces a force vector in the liquid at right angles to both (Figure 16.17).

To understand the AC design, it is perhaps helpful to first consider what an equivalent direct current (DC) design might look like. In Figure 16.17(a), the DC pump has a permanent magnet to give a field vector across the working volume of the liquid metal. Electrodes placed either side are connected to a continuous direct current to give the current vector at right angles to the magnetic field. The liquid in the working volume now experiences a body force, moving it upwards. In principle, as the current is increased the flow would similarly respond. Unfortunately, such a simple incarnation of the EM pump would work excellently for about half an hour if we were lucky, after which the electrodes would be destroyed, having dissolved away in the liquid Al.

The AC pump design avoids any contact by a clever design. It similarly uses an EM field across the working volume, conducted down to this level via soft magnetic armatures, and at the same time induces a current in a loop of liquid metal (once again conducting a field down to the loop via soft magnetic links) that connects outside of the pump via the bulk melt, this providing the electrical current at right angles to the magnetic field. The current in the liquid metal loop is effectively a single turn transformer, linked magnetically to the multi-turn coil above. The motion of the melt is at right angles to both current and field vectors and is taken up a vertical channel, taking its supply from the arms of the loop which connect to the melt. Because the magnetic and current vectors are in phase, they both reverse at the same time, fortunately (as you can demonstrate to yourself with the left hand rule) maintaining the force in the same direction. (Physicists will know that multiplying two negative vectors gives a positive vector.) The pulsating force is smoothed by the mass of metal that is moved, although the 60 Hz electrical supply in the United States gives noticeably better performance than the 50 Hz available in the United Kingdom. Typical characteristic curves for three of these pumps working at maximum output are also shown in Figure 16.15(b). The operation of one of the pumps at variable current is shown in Figure 16.15(c). These pumps are ideally suited in the pressure and flow rate range for making automotive and aerospace castings, and have therefore been in use for variants of the Cosworth Process since about 1980.

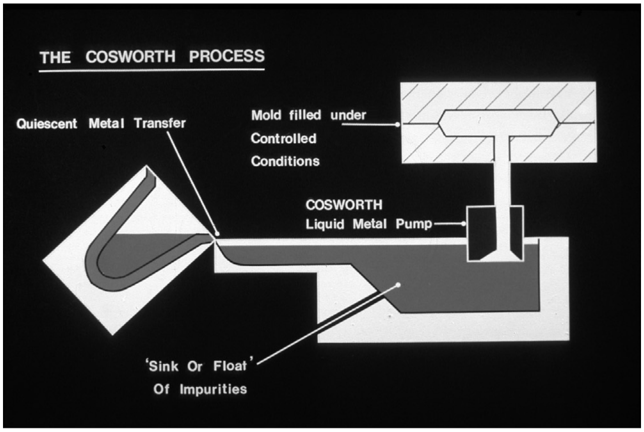
Given reasonably clean metal, the pumps continue to work in the melt for at least 6 months (one pump the author used lasted 15 months!). However, attempts to introduce a chlorine gas mixture in the rotary degassing stage before the pump caused pumps to block with a mixture of liquid chlorides and solid oxides within a few days (Sokolwski et al., 2003).

Cosworth Process

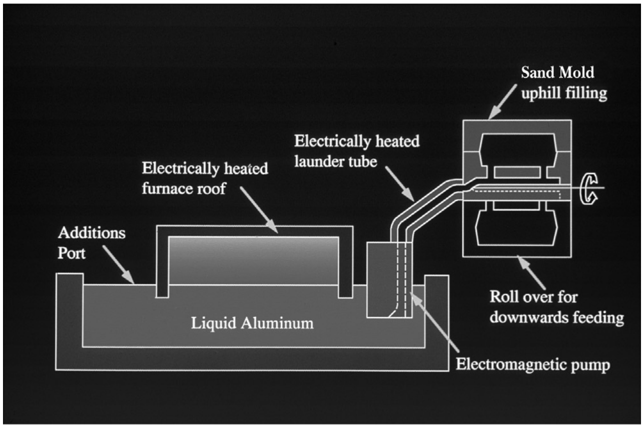
In 1978, the Cosworth Process was the first foundry to be set up to deliver good-quality, bifilm-free metal into a mould. As a result, it was the first to use an EM pump for a production plant. It was funded by Cosworth Engineering to provide the cylinder heads and blocks for their highly successful Formula 1 racing engines, although later diversified its achievements to aerospace castings. Initially the process used zircon for its precision sand core assembly process, although silica was later successfully by licensees. The first form of the process shown in Figure 16.18(a) ran into severe difficulties because of convection problems that prevented the freezing of the castings and nearly brought the company to a stop. The later variant of the process shown in Figure 16.18(b) used a roll-over technique after filling the mould. This cured the convection problems and simultaneously increased production from one casting in a mould every 5 min to two castings per mould every 45 s. The roll-over was the breakthrough that projected the process into a world leading position for making V-shaped cylinder blocks. The process continues to be used in the United Kingdom and in Windsor, Ontario, Canada, originally by Ford, now taken over by Nemak. GM and other major producers have also adopted the process. The process is also capable of making excellent cylinder head castings and aerospace products.

A recent history of the process by me (Quality Castings, 2015) revealed the rather shocking realisation that no one has yet set up the process correctly so as to achieve its full potential. In general, the metal melting and preparation has been poor, contributing to less than optimum properties of the castings. To ensure freedom from bifilms the melting should be carried out in a dry hearth tower furnace, all pouring transfers eliminated, and cleanness enhanced by either good filters or sedimentation in a properly designed holding furnace. The several attempts to set up the process without a proper understanding of these simple principles have led to failure.

The Cosworth Process was the inspiration for many subsequent plants. Rover (UK) used the process in two plants, one using the moving field pump and the other using the stationary field pump. They named this the *low-pressure sand (LPS)* system. The unfortunate lack of roll-over for these plants meant that casting soundness was never under proper control, with the result that 100% impregnation of castings was necessary. Even so, the process was successful to produce the challenging castings required for the K-series engine, a lightweight thin-walled design that was years ahead of its time, and for which no other casting process was at that time capable.



(a)



(b)

FIGURE 16.18

(a) Cosworth Mk I Process which was almost unworkable as a result of convection problems; (b) Cosworth Mk II Process solving convection and productivity by roll-over after mould filling.

Pneumatic Pumps

At the start of the Cosworth development, a simple pneumatic pump (Figure 16.19(a)) was used as a backup in case the newly arrived EM pump did not perform. In the event, the EM pump worked perfectly and the pneumatic pump was neglected. In retrospect this neglect was probably an error. The pneumatic pump made castings of equivalent excellence. Later, an even simpler and higher capacity pump avoiding the complication and volume reduction of the inner vessel was developed (Figure 16.19(b)). Note that the double stopper allows the melt to be retained at the top of the riser tube between castings; this is essential for maintaining the riser tube free from oxide. Another major advantage with the pneumatic concept is the absence of turbulence, in contrast with both centrifugal and EM pumps. An inert gas is required to pressurise the pump to avoid overmuch oxidation of the interior. However, at intervals, as necessary, when the refractories have reached the end of their life, these relatively low cost components immersed in the liquid metal can be discarded and replaced. The relatively complex top plate with its mechanical actions, bellows and sliding seals is a

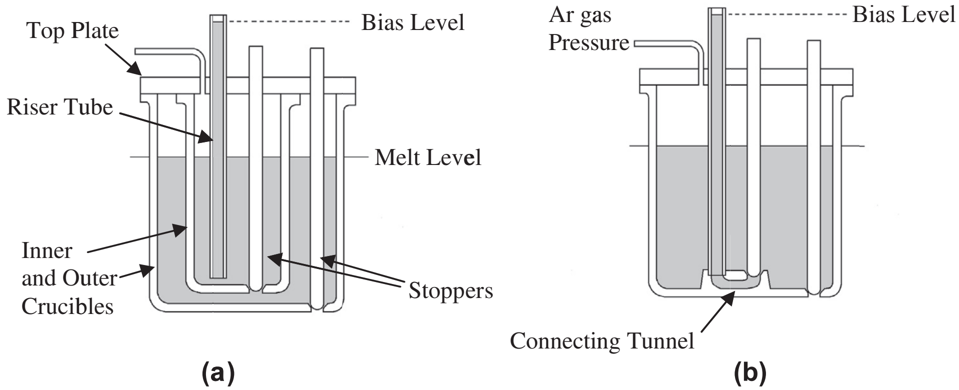


FIGURE 16.19

Pneumatic pumps by the author: (a) pump I: the early pump for low melting point metals including aluminium. (b) Pump II is simpler and less costly development, delivering a much increased volume. The great advantage of pneumatic pumps is the significant freedom from high speed turbulence.

permanent feature. Modest leakages from the pump are to be expected but are relatively unimportant because the gas flow is controlled by pressure rather than flow rate. The extreme simplicity and low cost of the pneumatic pump should help to promote a wide uptake.

16.3.3 DIRECT VERTICAL INJECTION

Direct-acting piston displacement pump

Direct-acting piston pumps for lead and zinc appear to be successful. However, their attempted use for liquid Al alloys has so far not resulted in success. Although such wear-resistant and Al-resistant materials as SiC can be finely and accurately ground to make cylinders and pistons, the damage caused by particles of alumina ensures that the pumps quickly wear and fail. Sweeney (1964) describes how attempts to produce cylinder and piston pumps were rapidly abandoned because of oxide problems. Valves such as the ball check type similarly proved unreliable because of oxides. Such failure is hardly surprising. Films of alumina of thickness measured in nanometres will probably always be present in alloys of liquid Al, and will easily find their way into the most accurately fitting parts, leading inevitably to scoring and wear.

Lost Crucible Technique

A rather different type of direct-acting displacement approach started development under the name '*Rimlock*' (rapid induction melting lost crucible process) as described by Bird and Savage (1996). Commercial changes caused the same project to be continued under a new name, '*Crimson*' (Jolly, 2008). This curious acronym represents 'constrained rapid induction melted single shot net shape casting process'. Despite its name, the process appears to have good potential, representing a significant departure from conventional foundry thinking. In its original form it uses a one-shot ceramic fibre crucible, into which is placed a pre-cast cylindrical slug of metal as a charge (Figure 16.20). The charge material is a sawn off log from continuously cast billet, and thus is of reasonable quality. The induction melting is then carried out at high speed, taking perhaps 60 s, the idea being to subject the melt to minimum time for hydrogen pick-up, or oxidation of alloying elements. When up to casting temperature a piston pushes up the base of the fibre crucible, pushing out the base, and continues to rise, pushing the melt upwards and into the mould cavity sited on the top of

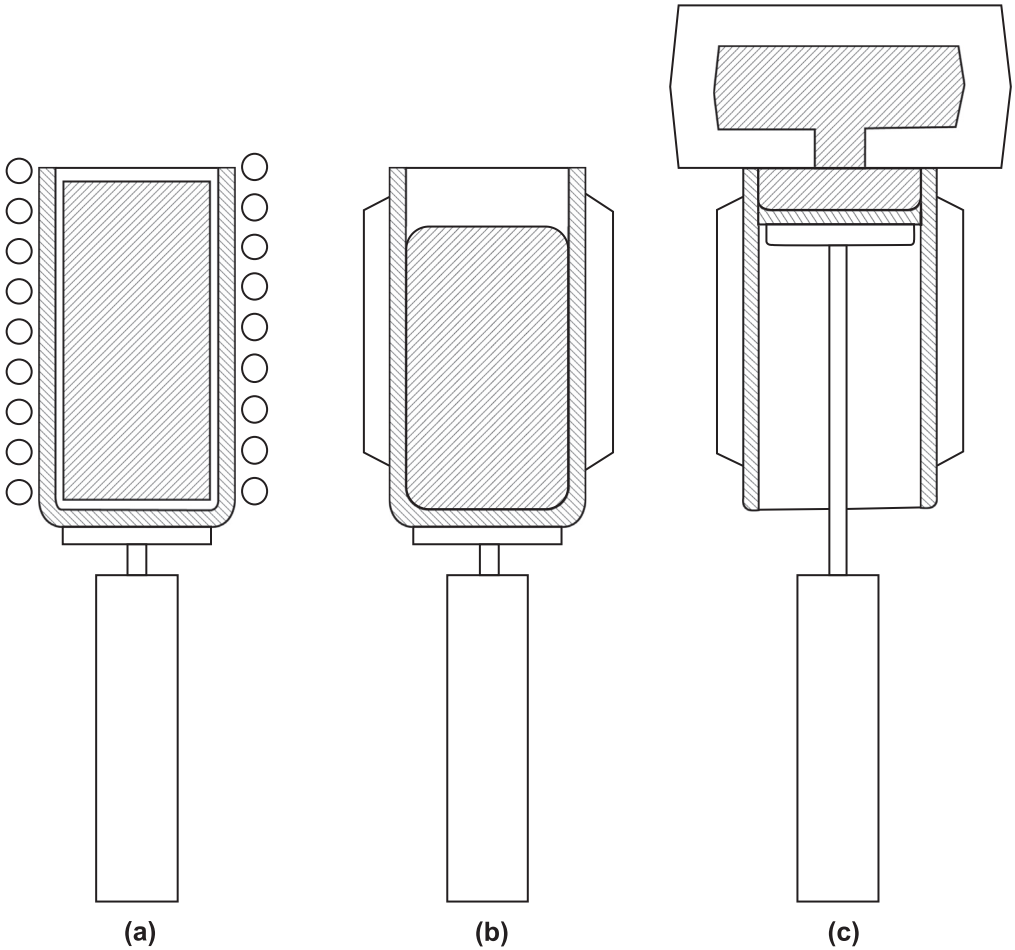


FIGURE 16.20

Counter-gravity with a sacrificial fibre crucible showing (a) rapid melting; (b) clamping to support crucible; (c) casting by pushing up the base of the crucible. After the mould is filled the whole assembly can be rotated through 180° to use the residual melt in the crucible as a feeder.

the crucible. When the mould is full the whole crucible, piston and mould assembly can be rotated through 180°. The temperature gradient in the mould is now favourable for feeding, which can be maintained under pressure from the piston if necessary. More recently the process has been developed for use with a re-useable refractory crucible and moveable base.

This is a process enjoying numerous advantages that clearly demands greater attention. One such advantage is the very directness of injection, so that feedback control from sensing the melt level in the mould is unnecessary. The piston position gives it exactly. Thus a piston actuator driven electrically (by rack and pinion or by screw etc. rather than indirectly by air or hydraulics) can be linked directly to computer control. A modern development is targeting the use of re-useable ceramic crucibles with a sliding base.

The technique seems ideal for light metals, particularly magnesium alloys, because the inventory of liquid metal in the foundry is minimised, being a just-in-time melt preparation procedure. This would be an important and welcome safety feature in Mg casting facilities.

16.3.4 PROGRAMMABLE CONTROL

The varying cross-sectional areas of the metal as it rises in the mould pose a problem if the fill rate through the bottom gate is fixed (as is approximately true for many counter-gravity filling systems that lack any sophistication of programmable control). Naturally, the melt may become too slow if the area of the mould increases greatly, leading to a danger of cold laps or oxide laps. Alternatively, if the local velocity is increased above the critical velocity through a narrow part of the mould, the metal may jet, causing entrainment defects.

Counter-gravity filling is unique in having the potential to address this difficulty. In principle, the melt can be speeded up or slowed down as required at each stage of filling. Even so, such programming of the fill rate is not easily achieved. In most moulds there is no way to determine where the melt level is at any time during filling. Thus, if the pre-programmed filling sequence (called here the filling profile) gets out of step, its phases occurring either early or late, the filling can become worse than that offered by a constant rate system. The mis-timing problems can easily arise from splashes that happen to start timers early, or from blockage in the pump or melt delivery system causing the time of arrival of the melt to be late.

16.3.5 FEEDBACK CONTROL

The only sure way to avoid the difficulties of the driving signal and actual metal level getting out of synchronisation is to provide feedback control from knowledge of the height of the metal. This involves a system to monitor the height of metal in the mould, feeding this signal back to the delivery system, and forcing the system to adhere to a pre-programmed fill pattern. Good feedback control solves many of the filling problems associated with casting production.

Although Lin and Shih (2003) describe a closed loop control system for a low-pressure casting machine, they monitor the pressure response in the low-pressure furnace chamber, using this as feedback to control the level of their pressurisation profile. This is a useful approach for monitoring and compensating for the changes of level in the holding furnace, which is otherwise difficult to monitor accurately; clearly, as castings are produced and the level falls, increasing pressure will be required to fill the castings. Although improvements to their castings were reported, the *rate* of rise of the melt is still unknown and uncontrolled; it will be variable with (1) different castings, (2) different dies with (3) different amounts of leakage of pressurised air from the furnace leading to different back pressure during filling, and (4) possible blockages to the flow path, especially if a filter is used in the riser tube.

A related system for the monitoring of height is the sensing of the pressure of the melt in the melt delivery system. This has been attempted by the provision of a pocket of a few cubic centimetres of inert gas above the melt contained in the permanent plumbing of the liquid metal delivery system close to the pump, and connected to a pressure transducer via a capillary. The system appears to be no longer used, as a result of practical difficulties associated with the blockage of the capillary.

A non-contact system used by the Cosworth sand casting process senses the change in electrical capacitance between the melt and the clamp plate holding down the mould when the two are connected as a parallel plate condenser. This system has been used successfully for many years. However, it is not necessarily recommended because capacitance is powerfully affected by moisture. The Cosworth system with relatively dry moulds countered this problem by zeroing the signal at the instant the melt entered the mould. This was set as the start point for the remainder of the fill profile.

Probably, the use of inductance to monitor the rising of the melt, using an inductive loop above the mould, might have given a more reliable signal because inductance is not affected by moisture. To the author's knowledge, this has never been tested.

The author has demonstrated that archaeological ground-penetrating radar will penetrate aggregate moulds and will deliver a signal indicating the progress of the metal as it rises in the mould. However, a higher frequency system might be beneficial to increase accuracy; an accuracy of defining the level of the melt to at least ± 10 mm is really required.

However, it is a pity that feedback control is little used at this time. The lack of proper control in counter-gravity leads to unsatisfactory modes of filling that explains many of the problems with this otherwise excellent technique.

16.3.6 FAILURE MODES OF LOW-PRESSURE CASTING

Most counter-gravity systems are quite safe, particularly the direct piston action filling, and filling by EM pumps.

I am often asked the question about the danger of leakages from the mould when using an EM pump. I always recall the experience of walking past the casting machine and seeing a gentle flow of liquid aluminium emerging from the base of the mould and spreading over the casting table. With some concern, I pointed this out to Trevor, our casting man, who was sitting reading the newspaper at the time. He carefully folded his newspaper, got out from his chair, walked to a distant stack of ingots, brought one back and placed it against the mould to freeze the stream. He then sat down and continued reading his newspaper.

The purpose of this story is to show how relaxed and safe counter-gravity casting can be. The pressures in the mould are only those that would have been experienced with conventional gravity casting – otherwise, in a sand mould penetration of the mould by metal would occur.

Even in permanent mould low-pressure casting with pressure intensification, pressures are only approximately 1 bar. Pressures in compressed air systems used extensively around the foundry are usually 7 times this value.

Even the most significant danger with a low-pressure system for casting Al or Mg is rather tame; it occurs if the melt level in the furnace becomes too low. A bubble escaping up the riser tube expands as it rises, and can eject metal from the top. However, any danger is avoided because the furnace is only pressurised when the mould is in place, thus the ejected metal, plus air, is easily contained by the strong metal mould. The only item that suffers from this event is the casting.

With dense alloys based on Cu or Fe the situation can be different. As a result of the greater density of these melts, the pressures required are nearly three times those required for light alloys. This is still not a problem for those processes that use a relatively hard pneumatic system to drive the casting process. Such processes are akin to that used by the Griffin Process for the low-pressure casting of steel railroad wheels. In this process, the metal is contained in a ladle which is a relatively close fit in its pressurised container. Thus the process is under relatively good control because relatively little air is required to change the pressure in the container.

It is a mistake to place the steel melting furnace in a large pit, pressurising the pit to force the melt up the riser tube. In this situation at least 10 times the volume of air is required to pressurise the furnace. This introduces significant delay in the response of the casting process, making the control ‘spongy’ and uncertain. Furthermore, this uncertainty in the control of pressure is worsened because cold air introduced to deliver a certain amount of pressure is subjected to significant heating and further uncontrolled expansion in the vicinity of the furnace and the liquid metal. The heating of the gas might increase its pressure by a further factor of two or more. Thus the energy contained in the pressurised gas will be between 30 and 60 times that required for a light alloy casting. If the furnace level now becomes too low, so that air escapes up the riser tube, the expansion of this highly compressed air will eject metal and destroy a sand mould, taking the foundry roof with it. At least one such event has happened in a UK development facility.

This danger is avoided for steel castings by reducing the volume of pressurised air. The building of special induction furnaces with pressurised steel shells is expected to be extremely safe. Furthermore, the control of the melt is improved, being a hard pneumatic system giving more immediate casting process response. Such pressurised furnaces would revolutionise steel foundries. No ladles would be needed, and few would ever see any liquid metal. They might read their newspapers while the casting was made.

16.4 CENTRIFUGAL CASTING

Centrifuge Casting

Casting on a rotating centrifuge table is commonly used for Ti alloys and Nb alloys. The melting furnace and rotating table are enclosed in a vacuum chamber. Moulds to make shaped castings are placed around the periphery of the centrifuge and are connected by a spider of radial runners to a central sprue. This is perhaps usefully called centrifuge casting.

Centrifuge casting is used for the casting of high melting point metals melted in a water cooled copper crucible (the ‘cold crucible’ technique) because, it is believed, the superheat is too low for simple gravity casting, so the mould is required to be filled as quickly as possible. This dubious logic has led to the universal occurrence of entrainment defects in all titanium castings, requiring them all to be subjected to an expensive HIPping (hot isostatic pressing) process to close up voids. Fortunately for Ti and its alloys, oxygen is soluble in Ti with the result that the HIP process not only closes defects, but encourages them to go into solution. We can be grateful that poor Ti casting technology can nevertheless result in a good (if expensive) product.

Guo (2001) studied the filling of automotive exhaust valves with TiAl alloy by this technique, showing that the radial runner only fills along one side with a thin jet, leading to severe turbulence. Other researchers (Changyun, 2006 and Jakumeit, 2007) also show that the direct siting of the radial runner (equivalent to top gating) onto the casting results in very poor filling. Somewhat improved filling is obtained by the equivalent of bottom gating into the mould cavity, in which the runner bypasses the mould and turns back, entering the mould from its outermost side. Even in this case, the results were still impressively turbulent because the velocities are so high. Once again, as is common for castings of all types, the filling systems are greatly oversized, and thus have only a small proportion of their area conveying any liquid metal, allowing a disappointing degree of turbulence from unconstrained flow of the melt. The design of a radial runner of a size to completely fill with liquid along its length, in which the melt is subject to increasing acceleration as it progresses outwards, represents an interesting challenge. The channels can be predicted to be of extreme thinness, and experience extreme drag forces from the walls, whose roughness will be of a similar scale to the dimensions of the channel. Thus there are plenty of unknowns to be explored. Perhaps the answer is that centrifuge casting cannot be optimised. Perhaps it should be abandoned. Alternatively, perhaps we shall have to live with centrifuge casting together with its defects and the expense of HIPping.

Jewellery is similarly produced by centrifuge casting to overcome the capillary repulsion experienced by melts when attempting to fill such narrow channels and fine detail. This process is better engineered because the melt, being at the end of the long rotating arm, travels along only a short radial runner into the mould. It seems, with good reason, both casters and wearers are content with the process as it is.

True Centrifugal Casting

What I call ‘true’ centrifugal casting uses the centrifugal action to hold the melt against the wall of a rotating mould. For interested readers, there is much to be learned from the practical and entertaining account given in an article by one of the leading UK companies (Gibson, 2010) which contrasts with the practical but sober descriptions by the Americans Zuehlke (1943) and Janco (1988).

Rings, hollow cylinders, tubes, pipes and large motor housings are often cast using the centrifugal casting process for several reasons. There is no central core required and the wall thickness can therefore be controlled simply by controlling the volume of metal poured. Neither running system nor feeders are required so the metallic yield can be close to 100%. Rollers or bushings have high concentricity, straightness and uniform wall thickness. Rolls are often cast using a double pour, in which the outer working surface of the roll is composed of a hard wearing alloy, or corrosion resistant alloy, whereas the interior backing alloy is a lower cost cast iron or steel. Centrifugally cast rolls are used in the paper, printing, plastics, foil and textile industries.

The centrifugal action exerts an acceleration v^2/r on the metal whilst it solidifies, where v is the linear velocity of the metal and r is the radial distance from the axis of rotation. This acceleration can be 100 or more times the acceleration from gravity g. Thus contact with the wall of the rotating die is good, and the strong temperature gradient which results assists the feeding under the enhanced g force. The inward advance of the solidification front can push remaining defects (particularly oxide films that may not have centrifuged to the centre as a result of their high drag and consequential low Stokes velocity) concentrating them in the inner bore, which is often cleaned up by machining.

However, the pouring of metal into spinning moulds usually involves considerable surface turbulence as the metal surges into the mould and is then whisked up to speed. In horizontally spun castings the melt may slip for some time, delaying its acceleration up to the mould speed, and so will rain from the upper parts of the mould. If this problem continues until the casting is nearly solid laps and oxide defects are created. Grey cast iron pipes are relatively free from any substantial problems which result from this trauma. This is less true for ductile iron pipes because of the presence of the magnesium-rich strong oxide films. It becomes a major problem for higher-temperature materials such as stainless steels, where deep laps are sometimes seen. These form spiral patterns on the outside of spun-cast tubes. The problem is worst in relatively thin-walled tubes which solidify quickly. In thicker-walled tubes the problem seems to disappear, probably as a result of the extra time available for the re-solution of some of the less stable constituents of the surface film, or possibly the washing away of the film from the surface. If the film is mechanically removed in this way, then it will be expected to be centrifuged to the inner surface of the casting to join and be assimilated with the other low-density impurities such as slags, inclusions and bubbles, which is one of the well-known valuable features of the spin-casting process.

The surface turbulence generated during the pouring of centrifugal castings of all types seems to be a general major fault of centrifugal casting, and seems to be generally ignored. This is surely a mistake. The process spends all of its efforts on centrifuging out those defects that should never have been put in. Worse still, not all of the defects introduced by the pour are eliminated by the centrifugal action. The melt delivery spout might be modified to greatly reduce these problems. Some actions expected to reduce turbulence are as follows.

1. The melt delivery spout should be shaped to deliver a ribbon of melt parallel to the rotating surface and as close as possible to this surface, reducing unwanted excess fall distance of the stream.
2. The spout should guide the flow directly onto the walls in the direction of rotation.
3. The velocity of delivery of the metal (see Eqn (13.2)) should match the speed of travel of the wall. Wall speeds are typically in the range 2–5 m/s, and so are easily matched by velocities from a good filling system.
4. The conical basin delivery into the filling system must be abandoned, together with other aspects of the launder and spout design, so as to fulfil the requirements of a good naturally pressurised filling system. In this way, only metal will be delivered via the filling system, not a mix of metal and air. However, even natural pressurisation might have to be abandoned because at high delivery speeds the delivery system may require to be highly pressurised, reducing the final orifice area, to speed up the flow (of air-free metal) to match the linear wall speed.

When fully up to speed, the liquid in a vertical axis mould takes up a paraboloidal shape, with the result that the wall at the base of the cylinder is thicker than that at the top. Figure 16.21 shows experimentally measured profiles for different speeds by Donoho in 1944, and Figure 16.22(c) shows the effect as more commonly seen. We can calculate the extra machining allowance, b, which is needed to produce a parallel bore. The attempted solution to this problem in *Castings* 1st edition (1991) resulted in equations of the correct form, but whose constant term was regrettably in error. I am happy to confirm that the version here is correct, and further corroborated by comparison with the valuable experimental data discovered in the work recorded by Donoho.

When the liquid surface is in balance, it experiences the simultaneous accelerations of gravity g downwards, and the centrifugal acceleration v^2/r inwards towards the rotation axis, where v is the linear speed of the surface at that point, and r is the radial distance from the axis. The liquid takes up a parabolic form. The equation of the curve given by Donoho is

$$\mathrm{h} = 0.0000142\mathrm{N}^2\mathrm{r}^2$$

where N is in rotations per minute (rpm) and R is in inches. This equation is translated into SI units (and, incidentally, thereby takes up the pleasing simplicity of equations and parameters that can be usually enjoyed in the SI system)

$$h = 2N^2r^2 \tag{16.1}$$

where h is the distance up the vertical axis in metres and N is the rate of rotation in revolutions per second. We can integrate to obtain the relation between h and r as:

$$h_t - h_b = 2N^2\left(r_t^2 - r_b^2\right)$$

Furthermore, $h_t - h_b = H$, the height of the cylindrical casting, and $(r_t^2 - r_b^2)$ can be rewritten in terms of its factors $(r_t + r_b)(r_t - r_b)$. This in turn can be written to a close approximation if the machining thickness $b << r$

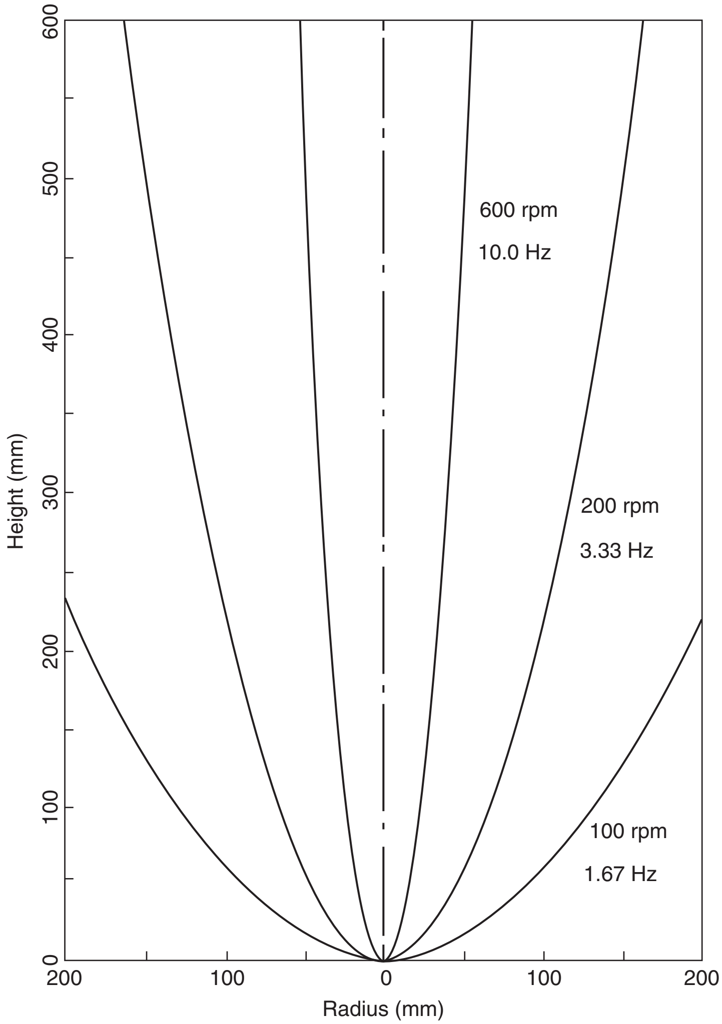


FIGURE 16.21

Profiles of spinning melts found experimentally by Donoho (1944).

$$(r_t + r_b) = 2\text{R} = D$$

where R is accurately the average radius, but is closely similar in size to the radius at the top of the cylinder, where, of course, 2R is the diameter D. Furthermore

$$(r_t - r_b) = b$$

in terms of the extra machining b which will be required to make the bore parallel. Approximating again if $b << D$ we obtain an explicit relation for b

$$b = \left(1/2N^2\right)(H/D) \qquad (16.2)$$

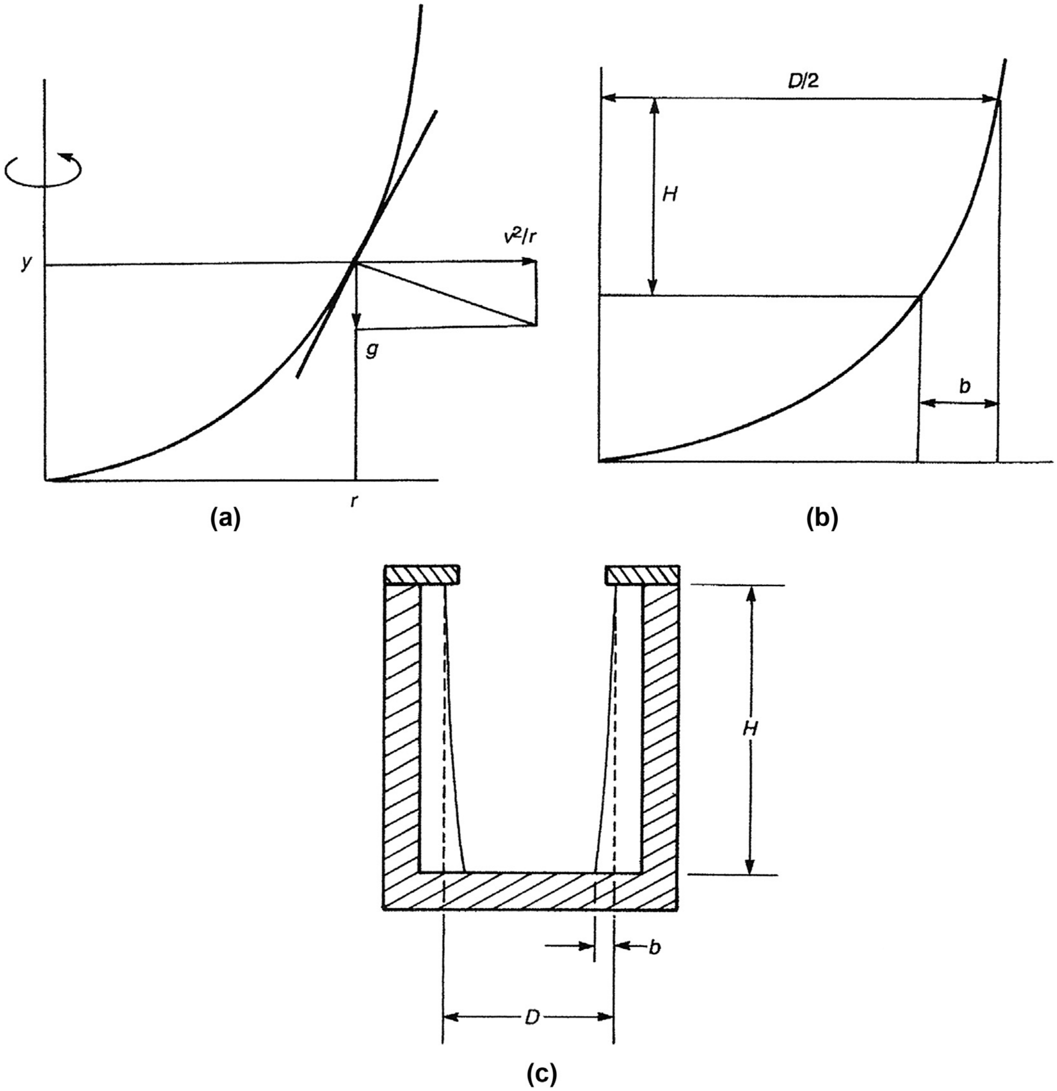


FIGURE 16.22

Vertical axis spinning: (a, b) generation of parabola; (c) consequential additional machining allowance required on the internal bore of a spun-cast tube.

Thus it is clear that when calculating the extra machining b required for a vertically spun tube, the only important parameters are N (which is, of course, intuitively obvious!) and the ratio H/D, which greatly simplifies predictions. The approximate Eqn (16.2) is the basis of Figure 16.23. The figure illustrates the regime at the top of the figure where machining allowance is less than 1 mm, so that extra machining allowance is practically negligible, and the products have virtually parallel bores. For the regime below the 10 mm line, the extra machining for those alloys which are difficult to machine may become so severe that other routes such as horizontal spinning or conventional static casting using an internal core may have to be considered.

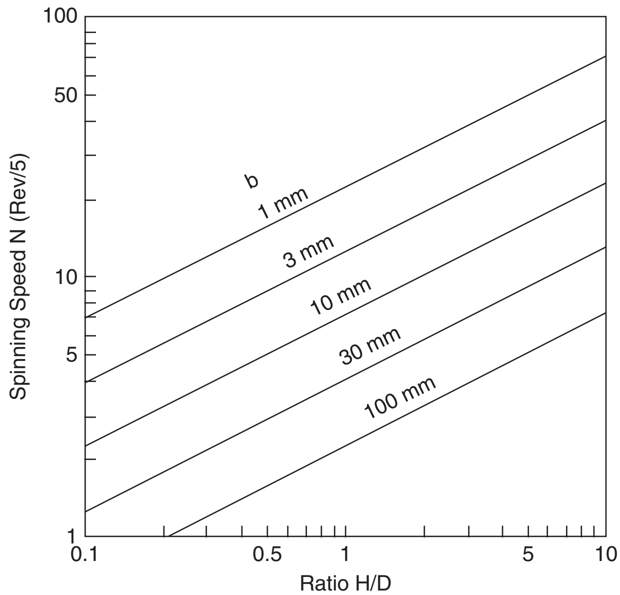


FIGURE 16.23

Machining allowance b from Eqn (16.2) in terms of speed and height/diameter ratio.

The centrifuging of the drosses caused by pouring into the bore of the part represent loss of metal and increased difficulties of machining, increasing the amount of metal suggested by the calculation of the machining allowance *b*. The provision of better pouring systems promises better products at lower cost.

16.5 PRESSURE-ASSISTED CASTING

The application of pressure during the solidification of a casting has, in line with natural expectations, generally been beneficial to soundness and mechanical properties.

In terms of the classical theory of the formation of pores, whether of gas or shrinkage origin, the application of pressure suppresses porosity as described in Chapter 7. In practical detail, it seems that the main reason for the suppression of porosity is probably the effect of pressure to keep bifilms firmly closed, thus negating the action of the various mechanisms that would drive them to open. The maintenance of the population of bifilms in their compact form maintains the reasonably high soundness and properties of the casting. This is the action of hot isostatic pressing (Section 19.3, HIPping).

A second indirect but additive effect may be the action of pressure to maintain better contact between the casting and the wall of the mould, so facilitating heat transfer. Once again, this is an effect that results in the bifilms being frozen in their compact form, before they have much chance to unfurl.

These benefits of the application of pressure have been widely explored and widely reported, as seen for instance in the work of Berry and colleagues (1999 and 2005). These authors survey the long history of the use of pressure back to 1922, although they note that Whitworth patented the process in the 1850s. In particular, they list the benefits of pressure applied to sand castings of steel and aluminium by (1) externally pressurising the casting by solidification in autoclaves or (2) internally pressurising the casting by pressurising the metal in the feeder. Both techniques work, but pressurisation of the feeder would be expected to be especially effective because of its additional actions (a) to establish a pressure gradient to aid feeding and (b) pressurising the casting internally to suppress the formation of any surface-initiated porosity. The benefit of avoiding surface-initiated porosity is not enjoyed by most other general applications of pressure that act both on the outside and inside of the casting.

However, the application of pressure to a feeder noted in earlier work by Berry and Watmough (1961) required caution because an application too early or too severe would result in swelling of the casting and penetration of the sand mould by metal (the pressurisation in an autoclave would not give this problem). A delayed application of pressure would allow the buildup of a strong oxide film, and possibly some surface solidification, resisting the penetration of the liquid metal into the mould. Interestingly, only modest pressures of up to 1 atm were found to be effective in greatly reducing porosity and improving properties.

The use of pressure to suppress pore formation is common to the counter-pressure casting system in which an overpressure of up to 6 bar is applied during the counter-gravity filling. Filling occurs by a relatively small differential pressure (Wurker and Zeuner, 2004).

Experiments are regularly reported in which the application of pressure during solidification is found to benefit castings, but the experiments are often fundamentally flawed. For instance, Mufti et al. (1995) describe solidification of Al alloy casting in a chamber pressurised to 20 bar (2 MPa) that is found to suppress porosity. However, unfortunately, the pouring of the melt from a height of about a metre creates the very problems that the pressure freezing has subsequently to attempt to cure. It is probable that careful mould filling without the application of any pressure would have resulted in sounder castings.

The application of pressure in the case of HPDC is a similar matter; the vicious turbulence of the filling cycle generates massive defects in the form of bifilms and bubbles. In this case the action of pressure is the attempt to reduce the size and deleterious action of these defects. Squeeze casting and counter-pressure casting processes are not so disadvantaged; their tolerable or even good filling retains whatever quality of the melt has already been achieved, so that the pressure is able to act in a fully positive way. These processes are discussed next.

16.5.1 HIGH PRESSURE DIE CASTING

HPDC is known in the United States, confusingly, as die-casting. The reader is recommended to the excellent book by Arthur Street (2nd edition, 1986) for a mass of historical and technical details. In this short account, we can only highlight the fundamental issues.

As readers will be well aware, HPDC is characterised by excellent surface finish and accuracy (at least when the die is new). Although the tooling is expensive, the productivity is high and part price is thereby modest. As such the process is highly popular, so that more than 50% of all Al alloy castings are produced by HPDC.

When used for its common purpose of casting aluminium or magnesium alloys the dies are necessarily made from good quality hot work tool steel, H13. (In this case, grey iron would not have the adequate surface integrity because of the presence of graphite flakes in the material, and would not have the strength or fatigue resistance.) No protective coating is applied to the surfaces of the die. The result is an excellent surface finish. The danger of cold laps is reduced by extremely rapid filling, and by high pressure that is subsequently applied to ensure faithful reproduction of the profile of the mould. Even so, of course, the high speed of filling causes other serious problems that we shall consider below.

Like all dies, however, it is regrettable that they are not really permanent. An aluminium casting weighing up to 1 kg might be produced tolerably well for up to 80,000 or 100,000 shots before the die will require to be refurbished as a result of heat checking (cracks from thermal fatigue of the die surface that produce a network of un-sightly raised fins, which can be razor-sharp, on the surface of the casting).

Magnesium alloy HPDC is much kinder to dies, giving perhaps five times or more life. This is partly the result of the lower heat content of Mg alloys, and partly because of the low solubility of iron in liquid magnesium that reduces its action to dissolve the die surface. In contrast, liquid Al has a relatively high solubility of iron, resulting in a phenomenon known as ’soldering’ of the casting to the die. This action is particularly destructive to dies not only destroying the die surface by dissolution, but the enhanced heat transfer that results from this intimate contact can then take further toll. The soldering problem is countered to some extent by the addition of high levels of iron to HPDC alloys, thus pre-saturating the liquid metal with iron and so greatly reducing the tendency for the melt to dissolve the die.

Attempts have been made to cast molten stainless steels by HPDC. In this case, the only die material capable of withstanding the rigours of this process was a molybdenum-based alloy. Even these ‘moly’ dies suffered early degradation by thermal fatigue cracking, threatening the commercial viability of the process. So far as the author is aware, partially solid (inaccurately called ‘semi solid’) stainless steels have not been extensively trialed. These cooler mixtures have already given up practically half of their latent and specific heat during freezing and would therefore greatly benefit die life. The commercial viability of the somewhat more expensive mixture would remain a potential show-stopper of course.

Turning now to the process itself, there are two main varieties of HPDC: hot chamber and cold chamber. The hot chamber machines are normally used to cast zinc and magnesium alloys, whereas the cold chamber machines mostly make aluminium alloy castings. There are numerous texts describing the technical details of the machinery involved. In fact, the dominance of the machinery aspects of the work dictate that most operators of HPDC do not consider themselves foundry people at all; they consider themselves engineers. The rift between the attitudes of the personnel involved in these two casting industries has been unhelpful in the past. After all, what do HPDC engineers need to know about sands, binders, insulated feeders and the like? However, there are signs of improved relations with developments such as indirect squeeze casting etc., proving the benefits of cross-fertilisation of ideas between the two technologies. Long may this continue and prosper.

HPDC is an injection casting technique. The usual design of cold-chamber machines has a horizontal-stroke injection (Figure 16.24) which is programmed to pressurise the melt as shown in Figure 16.25. However, it is regrettable that optimally controlled filling has proved elusive in this particular mode of injection. In fact, in the past, most HPDC machines have used injection strokes that cause much damage to the integrity of the finished casting. Typically the metal stream jets or sprays to the far end of the die cavity, and then ricochets and splashes backwards down the walls, sealing off routes for the venting of gases from the die cavity, and so entrapping the residual air inside the casting. Not only the air in the cavity is entrained, but so also are the vapours boiling off from the die lubricant and/or coolant.

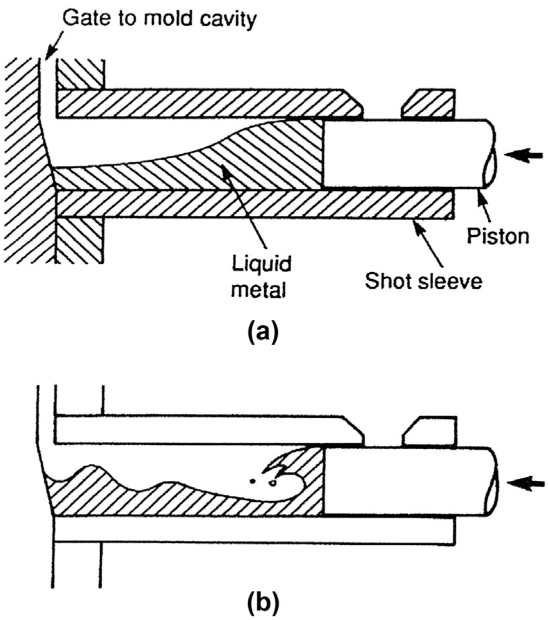


FIGURE 16.24

Injection of metal in a horizontal shot sleeve of a cold chamber die castings machine comparing (a) controlled and (b) uncontrolled first stages of injection.

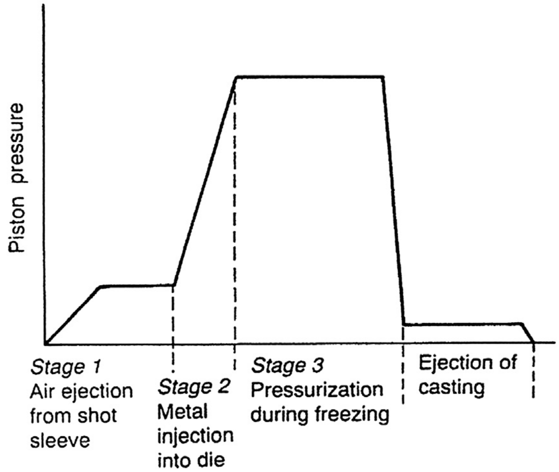


FIGURE 16.25

Typical injection stages during pressure die casting.

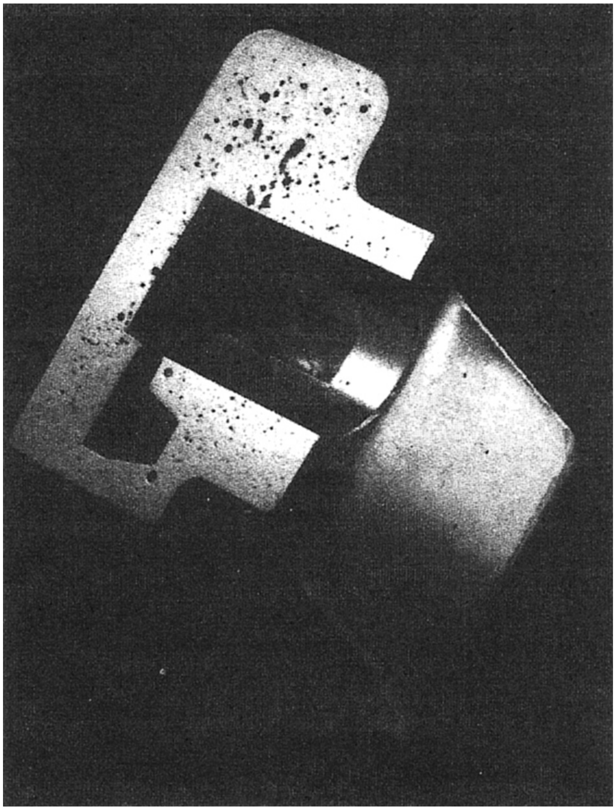


FIGURE 16.26

A pressure die casting in Zn-27Al alloy showing a polished section through a heavy section.

The result is a casting which exhibits the typical 'aero chocolate' structure – a tolerably good skin but full of air bubbles just beneath the surface (Figure 16.26). So much air is entrained in most pressure die castings that Hangai and coworkers (2010) remelt scrap castings as an optimum charge material to make Al alloy foam. In detail, it seems that the average high pressure casting probably has two populations of bifilm defects. These will be (1) oxide flow tubes that have formed around the incoming jets, separating the casting into longitudinal isolated zones as is clear in Figure 2.31; and (2) compact convoluted bifilms resulting from less organised turbulence during filling. That the flow tubes are likely to be often aligned parallel to stresses explains the good performance of some castings. However, the unpredictability of turbulence and consequential bifilms would normally make the application of HPDC to safety-critical parts an unacceptable risk.

Koster and Goehring (1941) have demonstrated the filling action by injecting Wood's metal into transparent dies. They confirm that the spread of the liquid metal around the cavity causes the vents to be sealed first, so that the high pressures are merely required to compress the entrapped gases. The castings have a structure which is full of discontinuities which result from the surrounding of the initial spray of oxidised and already frozen droplets by liquid metal which arrives and freezes subsequently, as can be discerned from interesting micrographs by Bonsack (1962).

For these reasons, pressure die castings have to be treated differently to most other types of castings. For instance:

1. Pressure die castings cannot be subjected to a normal solution heat treated because the reduced strength and creep resistance of the metal at high temperature allows the entrapped gases to expand, causing blisters on the surface or even gross distortion of the casting. The use of pressure die castings for structural parts is therefore restricted because not only are the castings limited in strength by high internal porosity and planes of additional weakness caused by bifilms, but also the presence of these defects in turn prevents any subsequent strength benefit from heat treatment. (Recent work to counter this problem is described later.)
2. Pressure die castings should not be machined at all if possible. Even light machining cuts are likely to penetrate the relatively sound skin (which is actually not particularly sound), encountering the unsatisfactory structure beneath. Deep cuts or drilled holes should be expected, therefore, to connect with the internal network of porosity and so cause leakage of fluids via distant points on the casting.
3. Subsequent chemical treatments in aqueous media, such as electroplating or anodising, are made less easy because of penetration of the aggressive liquids into pores or laps through the relatively sound skin, and the subsequent unsightly spots of corrosion which are caused by the liquid slowly leaking out over a long period.
4. Pressure die castings cannot be welded; in any such attempt the weld pool excels itself in an energetic imitation of Mount Etna!

In view of this apparently damning list of shortcomings, it is nothing short of amazing that pressure die casting has achieved such an important place in manufacturing. In the Western world, aluminium alloy pressure die castings make up more than half of the tonnage of all aluminium alloy castings. The great success of pressure die castings derives from the advantages of accuracy, surface finish, and the ability to reproduce detail, all at low cost and reasonable production rates. It is not surprising, therefore, that much effort has been expended on attempts to overcome the important disadvantages of the process.

A first attempt to improve on the filling of the die came with the adoption of three-stage injection (Figure 16.25). The stages are:

1. A controlled acceleration of the piston to cause a wave of liquid metal in the shot sleeve to expel the air ahead (not trap a bubble of air which was then injected at a part-full stage) as shown in Figure 16.24.
2. A more rapid fill of the die.
3. A high pressure consolidation.

This three-stage technique, whilst being a great step forward in avoiding air injection during the first stage, was still far from perfect during the second stage; the high entrapment of air required high consolidation pressures during the final stage.

Recently, much work has been carried out in an attempt to optimise gating designs and fill rates to promote the progressive filling of the die, to expel air ahead of the metal. In addition entrapment of vapour from coolant sprayed onto the die can be reduced by providing the die with internal cooling passages. Furthermore, there is some move away from water-borne graphite sprayed lubricant towards less volatile substances such as waxes. Substantial progress has also been made using computer simulation to ensure that the pattern of mould filling avoids entrapping major volumes of entrapped gases.

A novel design of runner for HPDC uses a significantly smaller cross-sectional area and has been reported to improve casting soundness (Gunasegaram, 2007). It seems to me to be likely to be the result of improved priming and exclusion of air from the shot sleeve, thus sparing the casting from massive defects that subsequent filling and pressurisation attempts to heal. The action of improvement is unlikely to be any reproducible mechanism within the mould cavity itself because conditions are so dramatically turbulent; one can envisage that the narrower runner will occasionally but not always benefit the filling of the mould, even though there may be additional beneficial effects from a refined structure, such structural benefits to strength and performance are likely to be small (see Section 9.4).

Fundamentally, the Weber numbers are so far from optimum (see Chapter 2) that it is difficult to understand how a really satisfactory filling solution can be achieved. The production of high-quality castings by the use of horizontal shot sleeves for the injection of metal into dies remains a largely unsolved quest. Nevertheless, the huge market tells us that these castings are adequate, if not more than adequate, for the purposes of most customers. Having said this, significant efforts continue in an attempt to improve HPDC further as noted next.

Squeeze Pins

Pressure die castings can be made more sound in local areas by the use of squeeze pins. Such techniques are in the category of keeping the customer happy by appearing to provide a sounder casting. It is doubtful if strength is improved, but leak tightness would, of course, benefit. When investigating the technique for Al-Si-Cu alloys, Wan and colleagues (2002) found that the Cu was squeezed out from the highly pressurised region, reducing in concentration from 2.6% to 1.6% Cu, and was segregated to the surface regions around the pin.

‘Pore free’ Process

The filling of the die with oxygen before the injection of the liquid metal greatly reduces the entrained porosity as a result of the entrapped oxygen reacting with the metal to produce a compact solid oxide. The technique has been mainly used for Al casting, but is also reported for Zn and Pb alloys. However, of course, the oxygen is an additional cost, and productivity is reduced because of the additional time taken to flush with oxygen. Furthermore, bifilms might be expected to be made worse, impairing both mechanical properties and machining although I could find no report of this. The process was useful in the early days of its invention before computer simulation and vacuum techniques, but is much less used today. A good summary of the process is given by Arthur Street (1986).

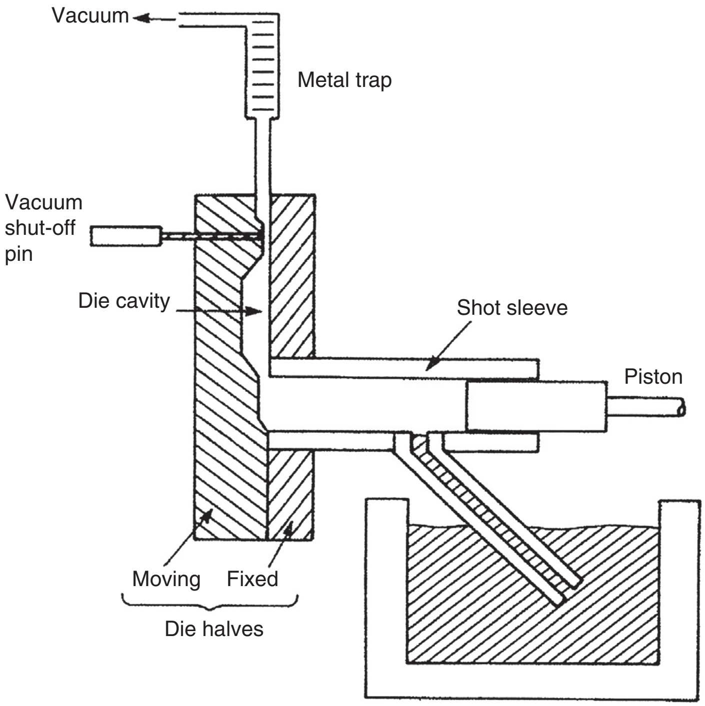
Vacuum Processes

One of the many systems for evacuating the shot sleeve and die is shown in Figure 16.27. The evacuation of the die leads to the melt being drawn up from the holding furnace and filling the shot sleeve. In itself, the counter-gravity filling of the shot sleeve probably significantly reduces defects in the casting. The movement of the piston cuts off the supply of metal from the holder and fills the cavity in the usual way. Naturally, porosity is significantly reduced. Some users claim that the castings are sufficiently sound to be heat treated and welded, although some users have been less than satisfied. Progress probably continues on this issue.

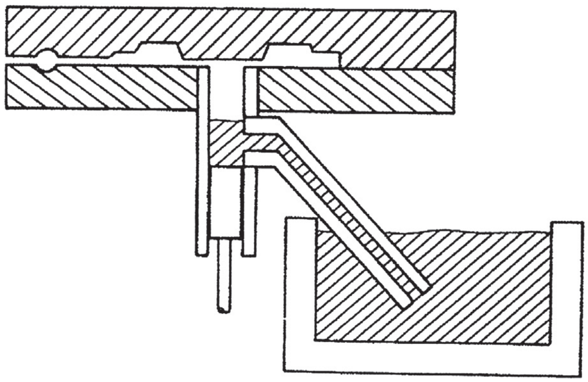
Heat treatment of HPDC

Because rate of diffusion is the process controlling the dendrite arm spacing, refining the spacing with faster cooling, and the rate of diffusion controls the length of heat treatment times, with finer dendrite arm spacing speeding the rate of homogenisation, the rates compensate to the degree that the faster cooling means faster heat treatment.

Because of the fast solidification times for HPDC, the heat treatment homogenisation time can be correspondingly reduced; no longer measured in hours but in minutes. Very short homogenisation times does not permit blister formation to become too advanced, and may therefore remain acceptable. The ageing treatment is at a much lower temperature at which no danger of blistering is experienced, so that a useful T6 strengthening heat treatment can be carried out in full which can double as-cast strength and toughness (Lumley, 2013).



(a)



(b)

FIGURE 16.27

Vacuum delivery systems to the shot sleeves of pressure die casting machines (a) horizontal cold chamber; (b) vertical injection type machine.

Naturally, the use of vacuum during the filling of the die assists significantly by reducing the internal gas content of the casting, permitting longer treatments without danger of un-sightly blisters or distortion.

16.5.2 SQUEEZE CASTING

There are two varieties of squeeze casting. Both subject the solidifying casting to a high pressure partly to suppress the formation of porosity, and partly to achieve good thermal contact between the casting and the die to achieve rapid solidification in the quest for good properties and good productivity.

Indirect Squeeze Casting

The indirect squeeze casting process uses a HPDC machine, but oriented with a vertical shot tube so that the die can be filled via a bottom gate by a kind of counter-gravity process. The machine, in common with conventional HPDC machines, is complex and capital intensive. Installation costs and general difficulty of maintenance are non-trivial matters because its height usually must be set in a deep pit. (The machine contrasts sharply with the simplicity of the forge required for direct squeeze casting discussed later.)

Even so, the indirect process enjoys the important benefit of a counter-gravity filling technique that solves at a stroke many of the problems of the direct process. The simplicity of the filling process makes for easy and precise control. The melt is transferred upwards into the closed die by the vertical displacement of the piston in the shot sleeve. Pressure during freezing is applied directly by the piston. Generation of oxide defects during filling are avoided by keeping the ingate velocity lower than the critical 0.5 m/s. This critical velocity has been confirmed by many investigators (for instance, Xue and Thorpe, 1995, and Itamura, 2002). This is aided by increasing the area of the gate to such a size that the gate must be cut off by sawing rather than simply fracturing or clipping (shearing) as is usual for conventional HPDC. The size of the gate means that metallic yield is often only about 50% for this process.

The counter-gravity filling ensures that the oxide on the liquid meniscus is laid out against the surface of the die as the melt rises, thus protecting the die from direct contact with the metal. For this reason, no welding or 'soldering' occurs, so that low-Fe high-performance alloys can be cast (in contrast to HPDC). In addition, the absence of the momentum impact at the end of the filling stroke gives better dimensional control; no die 'bounce', no pushing back of pins, no flash, allowing greater tolerance for tool fits, encouraging the use of moving parts in the die including squeeze pins. Even so, naturally, such tooling is expensive.

Modest problems reported from time to time include criticism that (1) the narrowest walls are limited to perhaps 4 mm thickness and (2) the machines are slower than conventional HPDC machines. Although some of the slowness is clearly attributable to the wait required for the heavier sections to freeze and cannot therefore be claimed as a justified criticism; any permanent mould process would have suffered a similar disadvantage. Overall, these seem to me to be reasonable penalties if the customer's priorities are the reliability of the casting.

However, it has to be reported that the process has suffered some lack of reliability of its castings as a result of the entrainment of oxide bifilms during the pouring of the melt into the shot sleeve. This fall of only 50–100 mm entrains bubbles (and unseen bifilms of course) which appear on the cope surface, and were originally tolerated by using the drag as the best surface, or providing more machining allowance to the cope. These unsatisfactory solutions have finally been bravely tackled by the counter-gravity filling of the shot sleeve itself via a side port as illustrated schematically in Figure 16.27(b) (Okada et al., 1982). The connecting up of furnaces and casting machines in this way is known to be difficult, and in practice it is not known how successful this technique has been in the years subsequent to its introduction.

Direct Squeeze Casting

When shaping a solid piece of metal by closed die forging, the die is initially open. The work piece is placed in the lower die half, and the top die is then brought down to engage with the work piece. The application of pressure between the slowly closing die halves causes the solid to flow plastically within the constraints of the die, being displaced to fill the outer sections of the die cavity.

There are several casting processes that have much in common with this shaping technique. Their common features are the pouring of the liquid metal into the bottom half of an open die or mould, and the subsequent closing of the die or mould so as to displace the liquid into the extremities of the cavity (Figure 16.28).

This process for the 'forging' of liquid metal has a long and complicated history. It was first suggested by Chernov in 1878 but appears to have been first used before 1930 under the name of Cothias Process in the United Kingdom (Chambers, 1980), although Welter in Germany was studying the effect of pressure on solidifying metals in 1931. However, it was in Russia during the 1960 and 1970s under the name of extrusion casting (Plyatskii, 1965) that the bulk of the early work to develop the process the process was carried out.

In general, no running system is required. Furthermore, because the liquid displacements are rather limited, no great flow distances are involved, so that fluidity, which is normally such an advantage for normal casting alloys, is no longer required. For this reason, squeeze casting, as it has become known, has the unique advantage over all other casting processes of being not limited to casting alloys. In fact, it can operate very satisfactorily with wrought alloy compositions and so benefit from the considerably higher strengths that are attainable with these materials. The users of the process sometimes emphasise this fundamental difference by avoiding the description '*squeeze casting*' and instead calling the process '*squeeze forming*'.

Additional benefits to the metallurgical structure of squeeze-cast material result from the high pressure that is applied during the freezing of the casting. The rate of cooling of gravity and other die castings is normally slowed by the presence of an air gap which forms between the casting and the die as the casting cools and contracts away from the die. This does not occur to such an extent in squeeze casting and the consequent improved cooling rate results in a significantly finer cast structure. Figure 5.8 shows how the freezing rate is twice that of an equivalent gravity die casting, and nearly 10 times faster than conventional sand castings. The application of the high pressure during solidification also tends to suppress the formation of porosity. Squeeze castings are probably more sound than most types of casting.

As always, however, freedom from defects is not infallibly guaranteed. For instance, lap defects are easily formed if the displacement velocity is not correct, especially if a waterfall effect occurs during the displacement of the liquid during die closure. Hong (2000) investigates some of these problems. Even porosity is possible in a heavy section, especially if it is surrounded by thin sections that solidify first, holding the die halves apart, and thus prevent the application of the full die closure pressure to the heavy section during its later solidification.

Interestingly, Herrera and the author (1997), when studying the mechanical properties of direct squeeze forming of copper alloys compared with forgings, the squeeze castings were highly variable and unreliable. The poor results were thought to reflect the inability of the process to close up serious oxide bifilms defects introduced by the poor filling of the die. This result would not be expected to be confined to copper alloys, but would be expected to be a general result applying to squeeze cast alloys of all metals; it reflects the problems introduced by poor filling of the die.

Furthermore, the very high temperature gradient generated by the pressurisation of the casting against the face of the die leads to dendritic segregation (inverse segregation) as described in Section 5.3.3. Even worse, the eutectic can be squeezed out of the alloy, appearing as an un-sightly exudate on the surface of the casting. Although this effect is accentuated with strongly segregating solutes, such as the element Cu in Al alloys, the effect can be so pronounced when using high squeeze pressures that it even occurs in alloys that usually show no segregation problems such as the normally well-behaved Al-7Si-0.4Mg alloy (Britnell and Neailey, 2003).

Squeeze casting, in common with other die processes, has generally been limited to relatively low melting point materials such as zinc-, magnesium- and aluminium-based alloys. Although gravity die casting has been extended to cast iron to a limited degree, such an extension is difficult to envisage for squeeze casting, where the enhanced rate of heat transfer would almost certainly result in rapid deterioration of the die.

The direct squeeze process uses a forging press to make castings. A forge is a simple machine costing a fraction of the capital investment of the indirect squeeze forming machine. Even so, the advantages probably finish at that point. This is because, in general, despite the enormous potential of the process as described previously, its performance in a production environment is often deeply disappointing. It seems that scrap arises from several causes that are not easily overcome. These include the following.

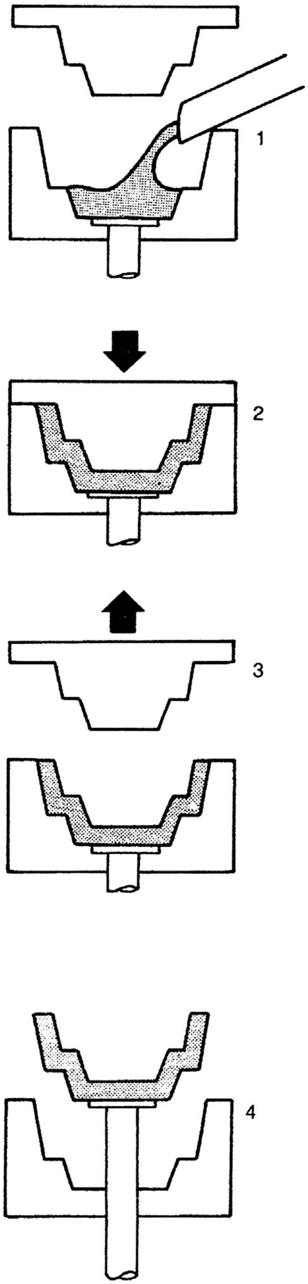


FIGURE 16.28

Squeeze casting.

1. poor melt control before casting (clearly this is not the fault of the casting process!);
2. poor transfer into the die, creating oxide dross in the casting (a bottom-stoppered transfer ladle is recommended to deliver melt into the bottom of the die, preferably into a pocket in the base of the die so that the melt can be constrained during the initial spurt on transfer, and general turbulence in the die can be suppressed);
3. boiling of mould dressing/lubricant in die joints (recommended to provide generous vents out of the back of the die, or ensure nearby cooling water channels to prevent boiling);
4. relatively thick walled castings (compared with HPDC) because of the time required to close the die;
5. dosing weight requires reasonable control to ensure control of casting thickness.

The great simplicity of the process cries out for it to be properly developed to achieve its full potential.

Press Casting

The forging technique has been extended to sand castings, but not for the purpose of applying high pressure during freezing, which would, of course, only lead to metal penetration into the sand, but simply to move the two halves of the mould together immediately after casting so that a thinner section can be cast.

In this way, cast iron gutters were cast in the United Kingdom for more than 50 years (Chadwick and Yue, 1989). For more sophisticated Al alloy products, Miller (1967) describes a Boeing development that demonstrated how aircraft castings of large surface area could be cast at 0.5 mm thickness. The method is, of course, limited to configurations where the thin-wall portions of the casting lie in nearly horizontal planes that do not overlap. High pouring temperatures were required, and excess melt was expelled into feeders and reversed into the filling system during closure of the mould. This movement of high temperature metal was claimed to remelt sufficient solidified skin to permit the full closure of the mould to obtain success in achieving the thinnest sections.

Terashima et al. (2008) outline a further development of this concept using greensand moulds. The open mould receives the melt which is poured into the drag, and the cope is then lowered into place. The process specifically avoids pressurising the melt to any significant extent to reduce sand penetrated by the metal and the impairment of surface finish (Tasaki et al., 2008).

The forging approach to the filling of a sand casting does appear to be an interesting process because fluidity problems are reduced as a result of the only limited displacement of the melt into outer regions of the mould at extremely gentle speeds. This clearly contrasts with conventional filling systems in which flow has to take place through long filling channels and then enter the mould cavity at relatively high speed via limited locations. The complete absence of a filling system (and a feeding system if the wall thickness is relatively small and uniform) is another powerful advantage. The press casting technique promises great potential.

Cast Pre-forms for Forging

There are possibly good reasons for the casting of a material such as ductile cast iron and subjecting this material to hot rolling or forging as described by Neumeier and colleagues (1976). Such a product would have properties that would not be easily achievable by any other process route.

However, I have come across several applications of Al alloy castings as part of development projects loudly heralded as being ‘the way forward’, in which the casting were used as pre-forms for a subsequent forming process in a closed die forging operation. Such developments have never succeeded. The reason is that the casting defects are typically oxide bifilms introduced by the poor casting technique. These defects are not repairable by forging, with the result that the final parts inherit the variable and often poor mechanical properties of the casting.

The cast + forge production route is in any case fundamentally illogical. If the casting had been made without defects, it would have been reliably strong, making a forging step unnecessary because the properties could not have been further improved (the work hardening involved in such simple forging steps is relatively trivial).

16.6 LOST WAX AND OTHER CERAMIC MOULD CASTING PROCESSES

The ‘lost wax process’ was assumed by the lady translator to refer, tragically, to the lost wax-process. It was only much later she realised it should be referred to as the lost-wax process.

Moving on from quaint semantic issues to more serious matters, in the moulding section, it was mentioned that the time of writing, the investment casting industry and its customers suffer from the use of probably the worst mould filling systems anywhere in the casting industry, seemingly devised to deliver the most defective castings possible.

This regrettable fact arises from the conventional way a wax tree is assembled, usually with a central conical pouring basin. As explained earlier in this work, the conical basin is one of the worst possible features. Moreover, the filling channels are nearly always vastly oversize because they have been built to maintain the strength of the wax assembly rather than designed for control of flow during filling. (We shall see how it is not so difficult to devise designs that are mechanically strong and combine good filling designs.)

The cases of poor filling are maximised for vacuum casting, where the melting furnace is typically a metre or more above the mould, creating masses of entrained oxide bifilms as a result of the severe surface turbulence when falling from this height. (This point is covered in Section 16.10 'Vacuum Melting and Casting'.)

Furthermore, convection is common in investment shell castings, creating heterogeneous, irregular structures, containing both fine and coarse regions in adjacent regions of the same casting. Those regions with coarse structures being expected to exhibit poorer properties of course, but in any case often failing customer specifications for grain size, even though the grain size may have little effect on properties.

The one good feature of current filling system designs, that happens by chance to prevent lost wax castings from being worse than they are, is the use of small-sized ingates. Ingates of small area do not permit large bifilms to enter, especially those strong oxide films formed by certain stainless steels as found in the work by Cox et al. (2000). The effect is analogous to the blocking of flow into flash by the bridging of oxide films at the entrance to the thinner section. The effect explains why melts of Al alloys recently grain refined with Ti + B additions to sediment bifilms form a clean melt which suffers significantly increased metal flash on the castings, and increased dressing costs.

In summary, the beautiful surface finish and fine detail of lost wax castings presents an allure in common with HPDCs, in that the surface appearance often covers a poor internal structure with properties much less good than could be achieved. It might be unjust to call these products 'whited sepulchres', but what can be said is that most lost wax castings have some considerable way to go to become properly reliable.

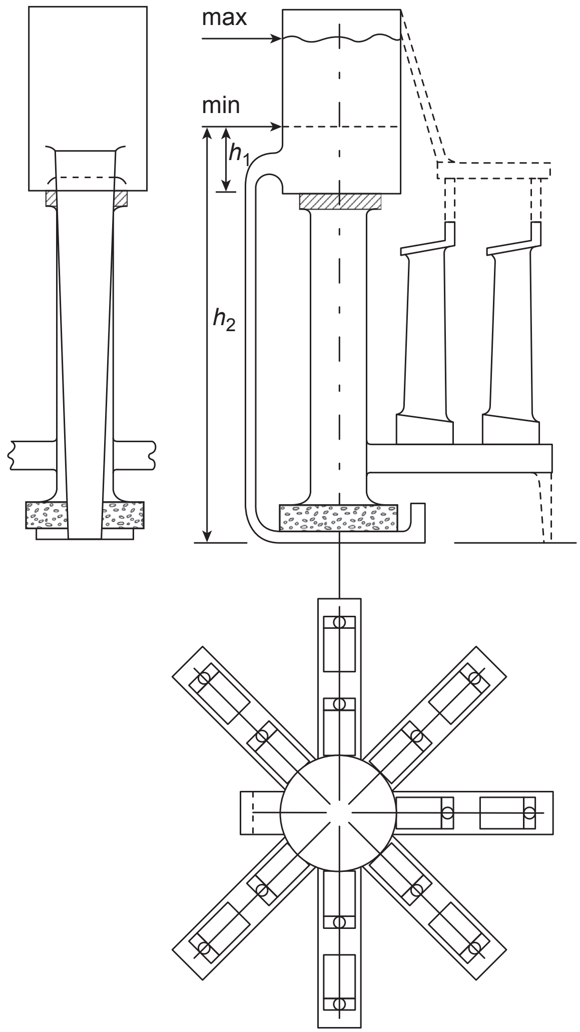
Figure 16.29(a) and (b) illustrate a type of casting cluster which is commonly used, but whose central post is no longer the sprue. The sprue has become a slim piece of sheet wax, cut with a knife to its calculated tapered profile. The vents off the top of the moulds do not connect with the pouring basin so that melt cannot spill down the vents and into the mould, nor can a convective loop be set up to delay the freezing of the casting. Thus these connections have to be plugged at some point to prevent the flow of metal (an offshoot will allow the escape of air if necessary). Figure 16.29(a) shows the concepts of minimum depths in the pouring basin that require to be met to ensure the pressurisation of the filling system; Figure 16.29(b) shows an improved system in which the accessible entrance to the sprue can be sealed with a stopper until the basin is filled and some seconds of delay are imposed before allowing the metal to fill the casting. If this basin can be sized to hold the entire volume of melt required to fill the casting, so much the better.

With some notable exceptions, including probably vacuum investment casting which would require a quite different design of vacuum furnace, these advances are often neither difficult nor costly to make, and promise a better future for both producers and users.

Shaw Process (Two-Part Block Mould)

Shaw process moulds are made by pouring a ceramic slurry into fairly conventional core boxes or patternwork. Thus a cope and drag can be made. The process is described in Section 15.1.3.

The cope and drag technique for mould assembly has advantages in that cores, filters and chills are easily placed. Conventional filling system designs can usually be implemented, for instance the placement of a runner around a horizontal joint line. That the mould can be placed horizontally usually means that the velocities in the filling system are relatively low, especially from lip-poured hand-held crucibles, so that relatively little damage is introduced compared to vacuum-cast investment moulds where the fall heights of the melt are a disaster. The development of the



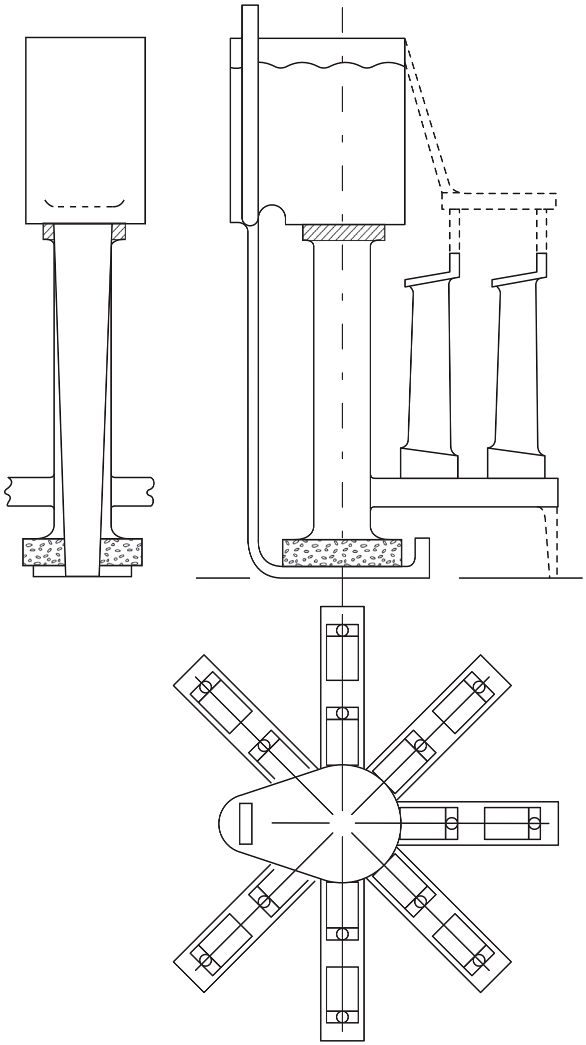
Investment casting, design methodology.

(a)

FIGURE 16.29

Investment mould using (a) an offset basin, natural pressurisation and bottom gating; and (b) an improved design using a stopper, with a basin preferably sufficiently large to make the whole casting without top-up of the basin.

process as a relatively thin shell rather than a block mould has improved the economics (Ball, 1991, 1998). There is no record that the process has ever used a good design of pouring basin, but with very small castings, particularly if poured rather slowly, require such narrow sprues that a conical basin may be acceptable, because surface tension will assist to keep air out of the sprue. Finally, the casting is relatively easily extracted by separating the mould halves after solidification.



(b)

FIGURE 16.29 Cont'd

Plaster Investment (Integral Block Moulds)

The combination of this process with the application of a reduced pressure applied to the base of the permeable moulds (the steel box containing the plaster mould is open at its base) is the principle of the *vacuum-assisted casting process*, allowing the pouring in air of extremely thin-walled castings only a fraction of a millimetre in wall thickness.

From the point of view of achieving high properties from castings made by vacuum assistance in plaster moulds there is a concern that the extremely thin walls fill by a curiously deleterious process I have called micro-jetting. This was first observed by Evans (1997) in plaster moulds and seems to arise because of the small dimensions of the advancing meniscus, having an area of oxide that is beginning to be too small to contain serious defects. Thus this relatively strong oxide film resists the advance of the melt, building up a backpressure. When the back-pressure builds up sufficiently, the film bursts, allowing a jet of melt to shoot forward. This happens repeatedly, with the melt not advancing in the conventional way by the smooth progression of a smoothly curved meniscus, but by a tangled mass of jets, all surrounded by their tube of oxide. The creation of masses of oxides in this way was thought to be the reason for the low reliability (in terms of Weibull modulus) of cast test pieces in Evans's work.

Clearly, more research is required on the phenomenon of micro-jetting. It is not certain whether this is a fundamental limitation to the attainment of good properties in casting sections thinner than a few millimetres. Also, it is not clear at this time whether the phenomenon is limited to plaster moulds or is a feature common to thin sections of any mould. If true, this would be a serious threat to the attainment of high reliabilities in such parts as turbine blades. Although these parts currently have good properties, it may be that even higher properties might be attainable if micro-jetting could be avoided.

16.7 LOST FOAM CASTING

The lost foam technique is a clever and intriguing process for the production of castings, first announced by Wittmoser in 1968. However, whereas precision sand (otherwise known as core assembly) casting is evidently straightforward, the apparent simplicity of the lost foam casting process is misleading. Furthermore, lost foam casting is not without its own special (and serious) problems.

The starting point is the production of polystyrene beads, which are blown into tooling (the patternwork) and expanded in situ by steam to fill the tooling. Heat is then extracted, cooling the expanded foam and causing it to gain strength so that it can be ejected from the tooling. Naturally the tooling has to have high thermal conductivity to maintain a good rate of production when oscillating between the hot and cold parts of its cycle. It is therefore usually made of aluminium alloy, and is sculpted on its reverse side to reduce its thickness as far as possible. The foam pattern is a replica of the finished casting. By gluing together separately produced foam components, complex geometries can be assembled which can be difficult to reproduce by conventional casting techniques. The assembly is then attached to its filling system and dipped into (or poured over by) a refractory wash.

After coating (investing) the foam pattern with the ceramic slurry, the coat takes time to dry. When dry the assembly is ready to cast. Clearly the thin invested shell around the foam will not support the weight of the metal pouring into the foam, so it is backed up with an aggregate. Thus the purpose of the aggregate in this case is mainly to support the ceramic shell and to conduct heat away from the casting.

Early problems of the lost foam production of cylinder heads and other castings requiring some degree of precision were found to be associated with silica sand used for backing, because the alpha/beta quartz transition at around 570°C created unacceptable distortions. Manufacturers therefore changed to artificial ceramic beads based on alumina or mullite ceramics that have a much reduced and uniform coefficient of expansion. This move has been rewarded by an immediate improvement in casting accuracy and reproducibility.

A further advantage of the ceramic beads is that their spherical shape allows them to flow easily, filling all parts of the pattern, sometimes required to be uphill into blind holes, usually with some encouragement from carefully controlled vibration of the mould. The upper surface of the pouring cup attached to the filling system is arranged to remain clear above the aggregate. The cup is then filled with liquid metal, which proceeds to vapourise the foam, progressively replacing it as it advances, thus forming the casting. The final benefit of using an unbonded aggregate is seen after the castings have solidified, when the casting is removed from its mould simply by releasing the bottom doors on the box, or by turning the mould box over and tipping everything out. The casting is caught on a grid, and the aggregate pours through the grid to start its recycling process.

A nice article by Walling and Dantzig (1994) suggests that in the cast of the casting of Al alloys, the foam melts and collapses but very little breakdown of the polystyrene occurs. The rate of pattern elimination at 60–80 mm/s (not the design of the filling system) controls the rate of advance of the liquid metal. The more rapid melting and collapsing of the foam during the casting of iron, plus much greater breakdown of the polystyrene to produce volumes of styrene vapour lead to significantly greater cooling of the iron, but allows its filling rate to be controlled by the filling system.

The volumes of gaseous products evolved from the foam must contain a significant proportion of air because the foam itself contains a high percentage of air, which in turn will expand further when heated by the melt. This large volume of gases must be vented through the ceramic coating, which is why the permeability of the coating appears to be of great importance for the control of the process.

With respect to the competition between castings produced by lost foam processes and other conventional 'lost air' processes there are several issues. These are not easily compared because all processes are operated rather differently by different manufacturers, with different degrees of competence and with different overhead costs, giving different apparently final costs. However, even allowing for this, there are several differences which are fundamental; these are discussed next.

Tooling for lost foam process used to be regarded as complicated as a result of the back of the tool having to be sculpted to reduce overall thickness so that heat could be transferred from the foam at the maximum rate to maintain productivity of the foam patterns. The wide use of computer-aided design and machining has reduced this problem. The tooling is typically machined from aluminium alloy, and so is relatively light in weight. It also has a long life because the polystyrene beads exact almost no wear. Even so, in appearance, the tooling is a mass of tubing for steam and water supplies, in addition to pullbacks and other motions now beautifully engineered with various varieties of linear actuators using roller bearing sleeves and similar bearings as a result of its life in a light engineering, rather than a foundry environment.

Conversely, tooling for nearly every other casting process does suffer wear. Most other tooling suffers either sand or hot metal or both, in addition to foundry personnel! The conventional practice is to introduce hardened steel wear plates into core box tooling which can be replaced from time to time as necessary. However, as designs of core blowing machines improve the fluidisation of sand before blowing, the problem is gradually being reduced. Ultimately, although wear remains a potential threat to accuracy an adequate standard of casting can be achieved with the application of statistical process control techniques to monitor and predict the gradual changes in dimensions of the casting.

The lost foam process is renowned for the accuracy with which it can maintain wall thickness. Also, for small castings, particularly bracketry, the ability to cast bolt holes and to work with zero draft angles so that machining of some faces can be avoided altogether is a further powerful advantage.

However, for larger castings, the slow drift in dimensions of the foam from loss of pentane during the ageing of the beads after the pre-expansion is a constant threat to overall accuracy. Assembly of foam patterns can also introduce errors. Small scale errors include the glue bead which is particularly unwelcome to the designers of such features as aerodynamic ports in cylinder heads. An additional well-known problem contributing to large scale dimensional control and distortion is the problem of maintaining the shape and size of the flimsy polystyrene pattern during the time it is being covered with about half a tonne of sand. It is practically inconceivable that the application of the backing aggregate, no matter how well controlled, can be accomplished without some distortion.

For certain applications, the absence of a parting line in the mould can be a great advantage (the parting line on the polystyrene pattern still exists of course, but this can be well controlled and so is not usually a problem).

Turning to the issue of surface finish, although the industry has made great strides in improving finish of lost foam castings over recent years, there remains from time to time on the patterns an area of poorly consolidated beads, giving a strong 'orange peel' effect on patches of the casting. These impressed patterns in the surface have been the subject of widespread discussion for many years. There has been talk of the roots of such impressions being sites for fatigue initiation but I am not aware of this ever having been demonstrated.

The real problem with the re-entrant pockets in the surface is their content of refractory wash and possibly entrapped sand grains. If these are released into water and oil ways of castings during service, this is clearly a serious matter. This problem is especially acute at the junction of glued patterns, where a local absence of glue will allow the ingress of the refractory slurry, resulting in a casting defect of some kind, depending whether the fin of refractory remains in place to penetrate the wall, or whether it is washed off into the liquid metal to appear elsewhere as an inclusion.

It is necessary to bear in mind that conventional core assembly also suffers cores with occasional poorly compacted sand, resulting in localised areas which may exhibit metal penetration and retained grains of sand in the surface. There seems to be relatively little to choose between the processes on these grounds.

The minimum wall thickness of lost foam castings is typically about 3.5 mm, being dictated by the ability to blow and consolidate the polystyrene beads; a minimum section is said to be about three bead diameters. However, the wall thickness is also dictated to some extent by the fluidity of the metal to fill the section. This appears to be reduced by the evaporation of the polystyrene which is endothermic (requires heat) and thus chills the liquid metal. The permeability of the pattern coating also influences the resistance offered by the pattern to the advancing liquid.

Worse still, the resistance offered by the foam to the advance of the metal will result in the metal taking different routes into the mould on different occasions depending on the precise density of different parts of the pattern. This may result in the serious situation that entrapment of the foam may occur, enclosing foam decomposition products in the casting. Such defects are not uncommon in lost foam products. Even without wholesale entrapment of decomposition products, the advancing surface of the liquid metal seems to have a considerable thickness of a film, of somewhat uncertain composition, but probably mostly oxide which, on meeting other liquid fronts, in a confluence of fronts results in a serious lap defect known generally within the industry as a ‘fold’. It is effectively a highly visible and serious bifilm defect.

The appearance of dispersed gas porosity, entrained decomposition products and film/lap defects is to be expected in lost foam castings. These are serious defects which exceed those to be found in most competitive casting processes. The development of foams which give less undesirable reaction products is reported from time to time. Nevertheless, the majority of the industry appears to be still working with polystyrene as a pattern material which is known to give these serious problems.

Furthermore, the following of the casting process with pressurisation of the casting in a pressure vessel immediately after casting is a further treatment that improves the reliability of lost foam products, although coming at the expense of additional processing complexity and cost (Garat, 1987, 1991). Although this technique clearly improves the castings a little its effectiveness is necessarily limited, and cannot achieve the properties achieved by well-made ‘lost air’ castings.

From observations of the filling of lost foam castings by X-ray radiography, it is clear that a high proportion of damage to the melt comes from the initial fall down the foam-filled sprue. This is particularly chaotic, with liquid metal fighting its way downwards in fragmenting and turbulent masses against the turbulent pockets of liquid styrene and vapour powering and meandering upwards. If the sprue is narrowed, as in conventional ‘lost air’ casting to reduce turbulence, the foam extracts so much heat from the advancing front that the melt freezes, never reaching the base of the sprue. This emphasises the nature of fluidity in lost foam moulds: the front advances by fresh melt arriving at the front by its momentum as illustrated in Figures 3.24 and 5.24(b). This important mode of flow requires plenty of space, with generous-sized filling systems, so that constrained systems such as the naturally pressurised filling designs recommended elsewhere in this book do not work for lost foam castings.

There are numerous studies to illustrate that all attempts to fill lost foam moulds by any kind of gravity pouring technique introduce masses of defects into castings. For Al alloy castings, Katashima (1989) uses a silica window in the mould, revealing horrifyingly messy filling conditions in which islands of foam fragments are surrounded by metal. Bennett (2000) and Tschopp (2000) illustrate micrographs and fractographs of clear fold type defects (i.e. bifilms) and blisters on the surfaces of the castings (again, double oxide defects inflated probably by outgassing vapours). Similarly, Carlson (1989) and Shivkumar (1989) report oxide films and black films, with diameters sometimes measured in centimetres, on fracture surfaces. For iron castings Gallois (1987) identify lustrous carbon films. Metallurgically, therefore, lost foam castings poured by gravity usually contain large numbers of serious defects. The author has to admit he has not earned himself popularity for drawing attention to this relatively lamentable performance over many years (Campbell, 1991).

Counter-gravity filling of lost foam moulds immediately suggests itself as a possible remedy, as actually confirmed by X-ray radiographic studies. However, even this route is not without its challenges because Ainsworth and Griffith (2006) show that a rate of advance of the front of only 5 mm/s in an Al-10Si alloy is the maximum velocity that can be tolerated before the front advances irregularly and entrains foam and its degradation products. Moreover, this velocity was found to be too low to allow the complete filling of their test mould. Furthermore, Weibull analyses of the mechanical properties indicated that even at such low filling speeds the reliability of the castings did not reach those of normal ‘lost air’ castings.

Fan and Ji (2005) used counter-gravity filling of Mg alloy AZ91E, but found rather indifferent properties, which they considered a good result because the properties were as good as their indifferent ‘lost air’ castings.

Clearly, the production of lost foam castings cannot yet achieve the quality that reasonable quality conventional ‘lost air’ castings can achieve, even when produced at glacially slow filling rates that threaten the filling of the mould, or even when subjected to a variety of post-casting HIPping process. Clearly, the process is not yet fully out of serious problems. Perhaps further development to solve its problems may be successful.

In the meantime, admittedly, not all castings require perfection, and quality needs to be appropriate to the product. With all its faults, lost foam remains highly appropriate for such castings as motor housings equipped with closely spaced cooling fins where dressing of flash (extensively required for instance at the parting line of greensand moulded castings) is not easily accomplished between each fin, and does not exist for lost foam products. Other products having long, complex internal passageways may lend themselves to lost foam, whereas to provide such passages by the use of cores might be practically impossible.

Even so, the launch of this process onto an unsuspecting foundry industry before its full development into a reliable process is a charge often heard. The charge can be countered, however, because, clearly, the buyer should have carried out his due diligence, and this would not have been difficult. Sadly, many lost foam operations have struggled and finally shut down their operations as a result of these failures. To close a disappointing chapter in the history of the casting industry, it would be good to think that lost foam might one day emerge to become the reliable process we all would like it to be.

As a postscript to this less than flattering account, based perhaps on my expectations and aspirations that might be set rather high, if not too high, the reader might wish to see the excellent account given by Donahue and Anderson (2008) which is much less pessimistic and does not regard lost foam defects so negatively. The company they work for has a successful lost foam production line which incorporates pressurisation immediately after casting.

Replicast

Replicast is a process in which the invested coating of the foam is built up rather more thickly than for conventional lost foam casting, so that although it remains fragile it can be self-supporting. The foam pattern with its thickened ceramic shell is then fired to burn out the foam. The shell is immersed in an unbonded aggregate to support the shell during casting, and the shell can then be filled with liquid metal (Ashton, 1991). Naturally, the process has many of the benefits of lost foam – plus many of its disadvantages. The major benefit is the elimination of foam, eliminating the major defects that characterise lost foam castings. As a kind of investment casting process, the process has traditionally suffered from the problem typical of most investment casting processes; the provision of a poor filling system. This is, of course, probably not endemic to the process but appears not to have been explored at the time of writing. Developments here are awaited with interest.

16.8 VACUUM MOULDING (V PROCESS)

The vacuum moulding process, or V process, is an interesting hard sand moulding process which can maintain the bonding and rigidity of the mould without requiring control over materials of imprecise chemistry such as resins. It was invented in Japan in 1972 (Akita, 1972) and immediately attracted worldwide interest.

In summary, it uses a dry, unbonded, free-flowing aggregate, usually silica sand. The mould is made in a special moulding box, sealed on top and bottom surface by a plastic film, and the dry, unbonded, free-flowing sand is consolidated by the application of a vacuum (actually a partial vacuum in the region of 0.5 atm). It is significantly different from other moulding processes, and thus possesses several unique advantages plus, of course, some unique disadvantages.

In practice, a plastic film is heated by overhead radiant heaters to soften the film, making it more stretchable. It is then drawn down onto the pattern by the application of a vacuum, drawing air through vents planted in the surface of the pattern. The vents connect through to a hollow base plate through which the vacuum is drawn. In particular, vents on the pattern need to be sited at the bottoms of recesses, or in sharp corners to ensure that the film sucks completely down, faithfully reproducing the contours of the pattern.

The film is subsequently coated by spraying with a ceramic coat. In the move from alcohol- to water-based coatings, the drying time has become a significant disadvantage. When the coating is dry, a moulding box is lowered onto the pattern, and dry sand is poured into the box, being consolidated against the plastic film by vibration. A second plastic film is applied, covering and sealing the top of the mould, and a vacuum is drawn through the walls of the moulding box. The mould then becomes impressively hard. So long as the vacuum is connected to the box the mould can be handled like any other mould. A major disadvantage of some interpretations of the process is the flexible connection to the mould. The floor of the foundry can resemble a snake pit of trip hazards. Fortunately, some good engineering designs for automated plants avoid this problem. Others have valves on the mould that can be turned off to allow the mould to be disconnected from the vacuum line, but this introduces the risk that small leaks in the film or elsewhere will cause the mould to collapse as the vacuum is gradually lost. If this happens during the handling of the mould, the event can be a hazard.

The mould enjoys the benefits of other hard sand processes such as the core assembly process, in claiming to produce among the most dimensionally accurate castings.

A remarkable and useful feature of the V process is that because of the presence of the plastic film which confers a glossy, slippery, almost sensuous smoothness, to the mould surface, moulds can be stripped from patterns with almost zero force without the aid of any taper or draft. Even slight negative draft of a few degrees can be tolerated because the mould can spring back elastically if the deformation is not too severe. The positioning of cores is also delightful because the core slides into place into zero-clearance prints and is gripped by the mould in a unique way. The puncturing of the plastic film at the base of the core print before the insertion of the core ensures that the core can vent; otherwise, core is sealed from the outside world so that core blows could become a serious possibility. (Small holes in the plastic films appear to be harmless to the process while the vacuum continues to be drawn.)

There seems to be little problem with the silica sand aggregate, but although the *moulds* are of excellent accuracy, the *casting* can suffer distortion as a result of the heating up of the sand and its expansion because of the alpha/beta quartz transition. I am not aware of anyone using a non-silica sand for this process, even though the process would be ideally suited to an improved aggregate.

The use of an unbonded sand eliminates, of course, the cost of a binder which is particularly valuable for large castings requiring only a modest rate of production. For this reason, the process has achieved good success for the production of iron castings for piano frames, counter-weights for fork lift trucks and slag buckets for steelworks and the like.

During the filling of the mould with cast iron, the hot metal radiates heat ahead to vapourise the film before its arrival, the vapour recondensing in the nearby cool surface grains of the aggregate to create a temporary binder to that localised region, and thus assisting to avoid the collapse of the surface during the few seconds that the support of the film + vacuum combination is lost. Any film that survives evaporation is submerged by the iron usually without problem as a result of the high density and high surface tension of iron, although Schmied (1988) draws attention to occasional blow holes and spatter from the vaporisation of the film.

These problems are significantly more acute for Al alloys. Negligible heat is radiated ahead by the advancing Al front, so that the plastic film is always over-run by the liquid metal. The film boils and the vapours easily penetrate the metal as oxidising bubbles, forming bubble trails and laminations right through the cast section. The consequential oxide films and bubble trail defects are often misinterpreted as entrained plastic film.

The spray coating of the mould is a significant disadvantage of the process. It seems to be generally required to prevent collapse of the mould during the pouring of the liquid metal. Because the coating is applied to the plastic film on its sand side, away from the pattern, the coating does not affect accuracy. It acts to maintain the surface finish of the casting, reducing metal penetration by the suction of the vacuum. It also supports the maintenance of the vacuum, and hence the integrity of the mould, during the early stages of the filling of the mould. A coating is a significant disadvantage of course, because it costs money, requires drying time thus requires floor space and affects production rate; all of these resources are usually at a premium.

The 15–20% slower cooling rate of evacuated moulds is an advantage for the running of thin sections such as bath tubs (Clark, 1989), but a disadvantage for those products requiring high mechanical properties.

Whereas the moulding of bath tubs does not present undue challenges, there are a large number of cases in which the process will not mould for what appears to be a trivial but enormously frustrating reason. If two upstanding features on the pattern stand nearer together than the depth between them, then the plastic film bridging the upstanding features has difficulty to stretch to reach the bottom of this hollow, the elongation being required is 200% (i.e. stretching to a distance of three times its original length). The film will usually tear, and the mould is spoiled. It is surprising how often this troublesome issue of 1:1 spacing-to-depth ratio occurs. Apparently innocent shapes on the pattern can bring the process to a stop. The problem can be overcome by human intervention, applying a ‘patch’ of plastic film to seal the local leak.

Another concern about the process generally overlooked is the presence of the partial vacuum inside the mould cavity itself. In principle, the mould cavity should not be at a reduced pressure. In fact, if it has feeders open at the top, it will originally be at atmospheric pressure. However, as a result of small leaks in the film, parts of the mould will have air sucked out. Thus as the melt reaches these parts, and if the filling metal cuts off connections to the atmosphere, the melt will accelerate, possibly becoming locally turbulent. Thus the advantages of a nicely designed filling system are potentially lost, the control over the flow being lost in randomly different regions of the mould on different occasions, leading to inconsistent quality of the products.

The vacuum pumps work in an environment full of abrasive silica dust, so that pumps are usually of the water-ring seal variety, avoiding rubbing sealing surfaces. Even so, maintenance of the pumps seems to be a significant process cost. The energy to drive the pumps is another major cost. Other practical costs are listed in the frank article by Enderle (1979).

After pouring and solidification, the casting is released from the mould simply by turning off the vacuum and releasing air into the mould. The mould collapses onto a grid, freeing the casting from its mould with minimum effort.

The sand falls through the grid for recycling. Only 1–2% sand losses are reported (Engels and Schneider, 1986), although this figure seems low for iron castings in view of the dust nuisance reported at shake-out. The dust may result from sand fracture at the higher temperature of iron and steel castings, plus the reversion of the coating to powder when dry, all carried aloft by the strong convection of the air around hot castings.

While the dust ascends skywards, accompanied by a small mushroom cloud of unpleasant smoke and fume from the incomplete burning and pyrolysis of the film, the residual plastic film from the outer areas of the mould remains in a heap on the grid. The film is partly blackened and sticky, with adhering aggregate and remains of broken cores as a tangled, dusty and gritty mess requiring disposal. The volumes of spent plastic for disposal are impressive. It is a messy conclusion to an otherwise elegant and relatively clean process.

16.9 VACUUM-ASSISTED CASTING

Moulds poured in air may be assisted to fill by the application of vacuum to some part of the mould.

A common use is in plaster block moulds. These are formed in steel boxes with open tops and open bases. The open top exposes the sprue entrance for the gravity pour, plus any vents or feeders. The open base is placed on a manifold connected to a vacuum line, and roughly sealed to prevent excessive leakage of air into the vacuum line. Air is drawn through the permeable mould, so that after pouring, the metal is assisted in its flow, effectively being pulled through the mould into all the finest features and corners Figure 16.30. The technique achieves the filling of extremely narrow sections in the region of 0.5 mm.

In a very different application, a sand mould filled by a bottom-gated gravity system may have problems filling completely; the net head for filling decreasing as the melt level builds up in the mould cavity. Some bosses or ears at the top of the casting may have problems to fill. The application of a gentle suction from a domestic vacuum cleaner, applied locally to the top of the sand mould in the region of the unfilled features will greatly assist the filling. This technique has the benefit of not affecting the filling of the main portion of the mould, which is probably filling satisfactorily. The effect is only felt by the metal as it nears the source of suction, so that the ever-decreasing volume above the melt experiences a concentration of the suction effect, accelerating the melt into these remaining volumes.

The great power of a modest amount of suction to transform the filling of moulds is easily explained. For instance, a perfect vacuum of 1.0 atm, as every reader should know, would be capable of sucking up 760 mm height of mercury (whose density is 13,500 kg/m^3). For liquid aluminium of density, only 2400 kg/m^3 this level of suction could raise the level of aluminium by the huge height 4.2 m. Thus, to make a few centimetres difference to the height of an Al casting, we need a maximum of only 0.1 atm (1.5 psi); even this tiny pressure difference can raise the liquid height by an impressive 420 mm.

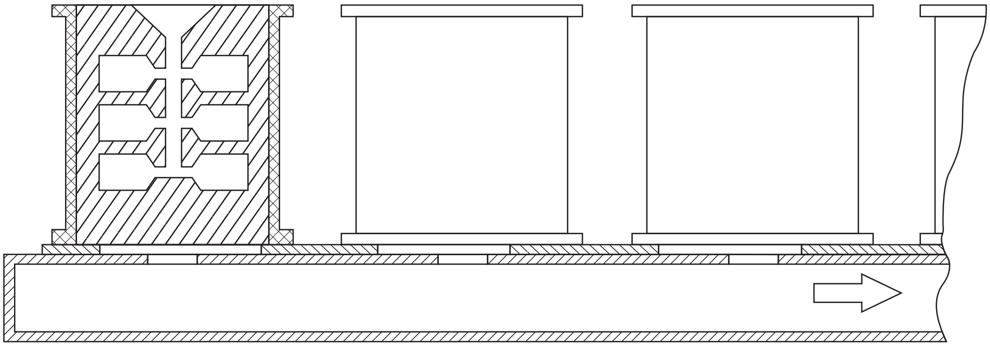


FIGURE 16.30

Vacuum-assisted casting, showing plaster moulds sitting on a vacuum manifold lined up for pouring.

For the ferrous metals and copper-based alloys whose densities are in the region of 7000–8000 kg/m^3 an atmosphere corresponds to a height of approximately 1.3 m.

Vacuum-assisted casting is often misleadingly called vacuum casting, implying the assumed benefits of low gas content and an expensive production process. Buyer beware.

16.10 VACUUM MELTING AND CASTING

In the shaped casting industry, although some melting and casting of Ti and Nb alloys is carried out in vacuum chambers, often under an inert gas atmosphere, the majority of the melting and casting under vacuum (or inert atmosphere) is carried out by the Ni- and Co-based superalloy casters. This and following sections deal mainly with this industry.

When melting under vacuum, the melt attempts to equilibrate with the vacuum environment, thus losing its volatile content, such as volatile alloys and gases. The volatile metals re-condense as dust over the internal surfaces of the vacuum chamber, occasionally flaring off as a flame gently licks around the interior of the furnace, burning the dust to oxide when the vacuum is released and the door is opened to let in air. Vacuum chambers therefore become very dirty environments, coated in black dust. From time to time if burning does not occur naturally the dust may require to be intentionally set alight to become a relatively inert oxide, and then be carefully cleaned off with a suction cleaner.

The loss of alloying elements sometimes has to be compensated by alloy additions, although some losses (such as heavy element contaminants including Pb, As etc.) are of course usually beneficial.

The fundamental problem with the ‘vacuum’ is that it is far from perfect. It seems best to view it as ‘dilute air’. The residual oxygen and nitrogen in the dilute air is effectively ‘gettered’ by the active elements Al and Cr which are universally present in high temperature alloys based on Ni and Co. The pouring of the melt in the dilute air entrains bifilms into the melt in generous amounts. The entrained bifilms are rich in very stable oxides, alumina, chromia and titania. The evidence for this behaviour is compelling. It is set out in Section 6.72.

The foundry generally melts pre-alloyed metal purchased from an alloy manufacturer. The alloy producer mixes pure liquid nickel with the alloying elements, melts it in a large induction furnace to achieve a homogenous melt, then casts it into convenient ‘sticks’ or ‘logs’ of various diameters for remelting and casting by foundries. Unfortunately, massive damage is done to the alloy by the way the alloy is cast into sticks. This is carried out by pouring from the tilting furnace into a series of launders, the melt falling from launder to launder, and finally falling into tall steel tubes. These pouring events, involving a fall totalling several metres, entrain quantities of oxide films, plus probably nitride films. Thus the alloy arrives at the foundry already in a poor condition before being remelted by the foundry and poured for the final time to make shaped castings.

Even if the Ni-base alloy producer were to improve his casting process, the casters of the shaped casting are, at this time, unfortunately likely to undo any good that the alloy caster could provide. This disappointing situation

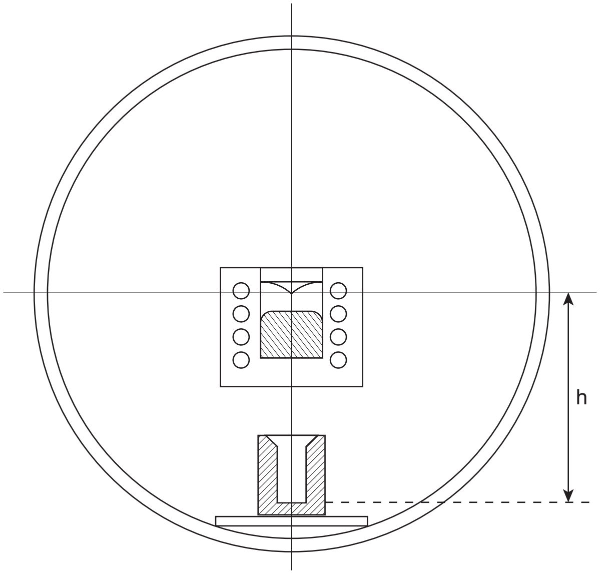


FIGURE 16.31

The unfavourable pouring geometry of a typical vacuum melting and casting furnace.

follows because of the geometry of conventional vacuum melting and casting furnaces used in foundries because the melting crucible is typically a metre or more above the mould. Figure 16.31 shows the problem in the form of the fall distance *h*. Metal entry velocities into the filling system are therefore often in the region of 4–5 m/s. The entrance into the filling system is always a conical funnel, concentrating and accelerating the melt, together with its entrained vacuum, even further, so that damage from turbulence is practically guaranteed. This is the regrettable situation for the current manufacture of nearly all of the world's Ni- and Co-base alloy turbine blades for aircraft engines. For single crystal turbine blades, the melt suffers a similar traumatic filling mode, but moulds are held above the freezing point of the melts during filling, and only slowly withdrawn into a cooling zone to grow the crystal under conditions of controlled speed and temperature gradient. The holding of the melt for this relatively long period probably helps to float out a large proportion (but clearly not all) of the oxide bifilms entrained during the pour. As well, the directional solidification will push oxides ahead rather than entraining them in the solid. Thus there are good reasons why the single crystals blades appear to be more free from bifilms failures than polycrystalline blades. The lack of bifilms is the real reason for the good properties of the single crystal (not that it lacks grain boundaries).

There is an interesting situation with the Ni-base alloys containing hafnium (Hf). It seems that when these alloys are cast, a curious unexplained glassy surface defect on the blades that appears to run down the casting surface like a congealed river. If a filter is placed in the filling system, the defect does not occur. It seems likely that this represents an attack of the ceramic mould by HfO surface films generated by turbulence. The HfO will most likely form a low melting point oxide mixture with the components of the mould, often mainly Al_2O_3. If the filter is present, any HfO already present will be reduced by filtering out, and the reduced turbulence after the filter will not generate more HfO.

Clearly, this is an industry that is very much in need of improved melt handling technology and would greatly benefit from a transition to better mould filling techniques. These are already well proven and demonstrated for aerospace high temperature alloys in the case of gravity systems that reduce defects by approximately a factor of 10 (Li, 2004) and better still, counter-gravity systems (Shendye and Gilles, 2009).