MOULDS AND CORES

As in so much technology, the production of moulds and cores is a complex subject that we can only touch upon here. Although this text is about the metallurgy of the casting, the mould can be profoundly influential. The mould and the casting co-exist for sufficiently long, and at a sufficiently high temperature, that the two cannot fail to have an important mutual impact. Essentially, this section is about the *science* of mould and casting interactions.

In the later part of the book, *Casting Manufacture*, we concentrate on the *technology* of moulds and castings, outlining the main benefits and problems of the various types of moulds and cores to allow a user to make a more informed choice of manufacturing route.

4.1 MOULDS: INERT OR REACTIVE

Very few moulds and cores are really inert towards the material being cast into them. However, some are very nearly so, especially at lower temperatures. This short section lists those types of moulds and cores that in general do not react with their cast metals.

The usefulness of a relatively inert mould is emphasised by the work of Stolarczyk (1960), who suffered 4.5% porosity in gunmetal test bars cast in greensand moulds compared with 0.5% porosity for identical castings into steel-lined moulds. This simple experiment confirms one of the most important advantages of metal moulds: they are impressively inert towards their liquid metal and cast product. Thus all of the gravity and low pressure dies (permanent moulds) are reassuringly inert.

Unfortunately, the inertness of high pressure die casting dies and some squeeze casting dies is compromised by die coolants and lubricants which definitely impair the casting to varying degrees.

Greensand moulds that have been dried in an oven (i.e. dry sand moulds) have been found to be largely inert, as shown by Locke and Ashbrook (1950).

This behaviour contrasts with that of the original greensand in its various forms. The water and hydrocarbon contents of greensand mixes lead to masses of outgassing and very rapid attack, leading to oxidation or deposit of carbon on the liquid metal front, plus the generation of copious amounts of lower hydrocarbons (such as methane) and even more hydrogen. At first sight, it is perhaps amazing that any useful casting could be produced by such a reactive system. However, greensand remains, justifiably, the most important volume producer of good castings worldwide. Its many benefits, particularly its unbeatable moulding speed, are discussed in more detail in Chapter 15.

Whereas the various resin binders used for sand moulds do not outgas as impressively as greensand, the quantities and nature of the various volatiles that are attempting to escape during the dramatic early seconds and minutes of attack by the melt are seen in Figures 4.1 and 4.2. Clearly, there is plenty of chemistry involved, and the high temperatures ensure that this is energetic.

In recent years, several synthetic aggregates have become available in tonnage quantities. The hardness, wear and fracture resistance of these new moulding materials has meant that their high cost can sometimes be justified because of the very high efficiency with which they can be recycled because of low losses. The materials are mainly based on highly stable, high melting point oxides such as alumina and silica. A mixture of these two oxides to give a crystal composition such as mullite has the great benefit of avoiding the alpha/beta quartz transition, and so has the potential to improve the accuracy of castings. The synthetic grains so far available are produced in two ways, both of which result in beautifully spherical grains which have excellent flowability. However, they can have quite different results for some castings.
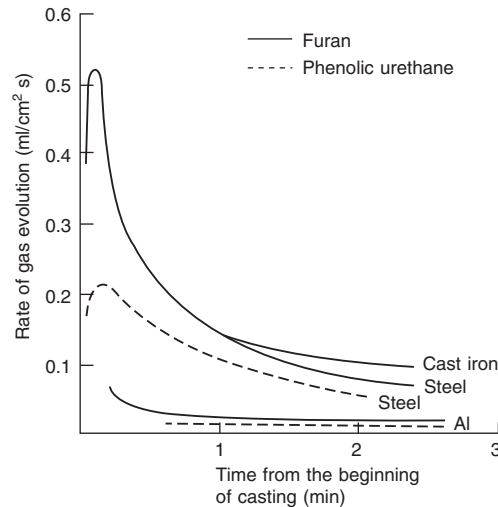
FIGURE 4.1

Measured gas evolution rates from castings of aluminium, iron and steel in chemically bonded sand moulds (Bates and Monroe, 1981).

1. Aggregates can be produced in the solid state, aggregating powders with an organic binder, by rolling around on oscillating trays. The weakly bonded spherical grains are then sintered, eliminating the temporary binder, and forming strong grains but containing several percent of porosity, some closed and some continuously linked through the grain. My experience with this variety of aggregate is that the mould binder tends to enter the pores of the grains, unfortunately boiling and exploding when contacted with liquid aluminium alloy, thus punching vapour pores into the surface of the casting. It is not known whether such 'microblows' occur with other metals and alloys. Such microblows will, of course, occur in addition to the chemical reactions normally to be expected between the binder and the liquid metal.
2. Aggregates can be produced by a melting route, one of which employs a jet of liquid oxide which is atomised by a blast of air. Such grains tend to be perfectly sound and can still be very respectably spherical. Moulds made from such aggregates would be expected to react only by reason of the presence of the aggregate binder.

4.2 TRANSFORMATION ZONES

As the hot metal is poured into a greensand mould, the blast of heat from the melt at temperature greatly exceeding the boiling point of water, very rapidly heats the surface of the mould, boiling off the water (and other volatiles). As the heat continues to advance into the mould, the moisture continues to migrate away, only to condense again in the deeper, cooler parts of the mould. As the heat continues to diffuse in, the water evaporates again and migrates further. This is of course a continuous process. Dry and wet zones travel through the mould like weather systems in the atmosphere. The evaporation of water in greensand moulds has been the subject of much research.

Looking at these in detail, four zones can be distinguished, as shown in Figure 4.3.

1. The dry zone is where the temperature is high and all moisture has been evaporated from the binder. It is noteworthy that this very high temperature region will continue to retain a relatively stagnant atmosphere composed of nearly 100% water vapour as a hot dry gas. However, of course, some of this superheated and very dry steam will be reacting at the casting surface to produce oxide and free hydrogen.
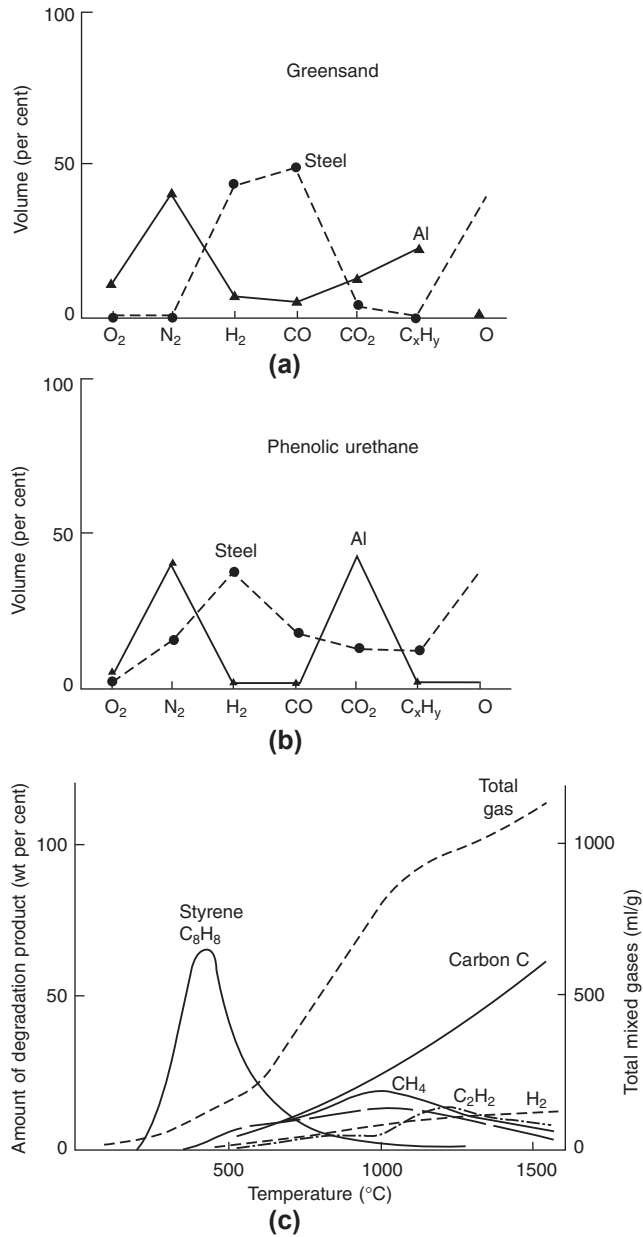
FIGURE 4.2

Composition of mould gases (a) from greensand (Chechulin, 1965); (b) phenolic urethane (Bates and Monroe, 1981) and (c) thermally decomposing expanded polystyrene (Goria et al., 1986).
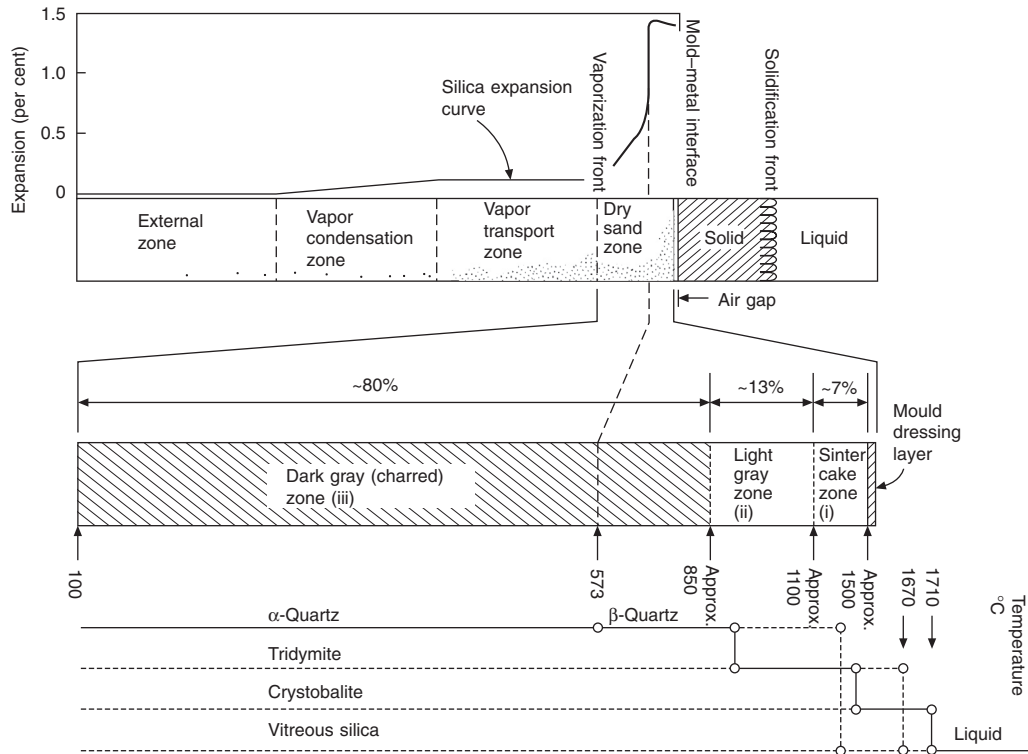
FIGURE 4.3

Structure of the heated surface of a greensand mould against a steel casting and the forms of silica (after Sosman, 1927), with solid lines denoting stable states and broken lines denoting unstable states.

2. The vapour transport zone, essentially at a uniform temperature of 100°C, and at a roughly constant content of water, in which steam is migrating away from the casting.
3. The condensation zone, where the steam re-condenses. This zone was for many years the subject of some controversy as to whether it was a narrow zone or whether it was better defined as a front. The definitive theoretical model by Kubo and Pehlke (1986) has provided an answer where direct measurement has proved difficult; it is in fact a zone, confirming the early measurements by Berry, Kondic and Martin (1959). This zone gets particularly wet. The raised water content usually greatly reduces the strength of greensand moulds, so that mechanical failure is most common in this zone.
4. The external zone where the temperature and water content of the mould remain as yet unchanged.

It is worth taking some space to describe the structure of the dry sand zone. When casting light alloys and other low-temperature materials, the dry sand layer has little discernible structure.

However, when casting steel it becomes differentiated into various layers that have been detailed from time to time (e.g. Polodurov, 1965; Owusu and Draper, 1978). These are, counting the mould coating as number zero:

1. Dressing layer of usually no more than 0.5 mm thickness, and having a dark metallic lustre as a result of its high content of metal oxides.
2. Sinter cake zone, characterised by a dark brown or black colour. It is mechanically strong, being bonded with up to 20% fayalite, the reaction product of iron oxide and silica sand. The remaining silica exists as shattered quartz

grains partially transformed to tridymite and cristobalite, which is visible as glittering crystals (explaining the origin of the name cristobalite). This layer is largely absent when casting grey iron at ordinary casting temperatures.

3. Light-grey zone, with few cracked quartz grains and little cristobalite. What iron oxides are present are not alloyed with the silica grains. This zone is only weakly bonded, and disintegrates on touch.

4. Charred zone, of dark-grey colour, of intermediate strength, containing unchanged quartz grains but significant levels of iron oxide. Polodurov speculates that this must have been blown into position by mould gases.

The pattern of these zones is further complicated by convection effects inside the mould or core for a relatively long period after casting, carrying carbonaceous vapours back into the heated zones, chemically 'cracking' the compounds to release hydrogen and depositing carbon. The inner layers therefore become black, with the sand grains seen under the microscope to be coated with a kind of fibrous, furry layer of graphite. Churches and Rundman (1995) studying a phenolic urethane mould found this reaction to occur between 15 min and 3 h, and at temperatures down to about 540°C for their grey iron castings. Highly heated cores had lost up to 50% of their carbon after finally cooling to room temperature.

The changes in form of the silica sand during heating are complicated. An attempt to illustrate these relations graphically is included in Figure 4.3. This complexity, and particularly the expansion accompanying the phase change from alpha to beta quartz, has prompted a number of foundries to abandon silica sand in favour of more predictable moulding aggregates. This advantageous move is expected to become more widespread in future especially as interesting new synthetic aggregates become available.

4.3 **EVAPORATION AND CONDENSATION ZONES**

As the heat diffuses from the solidifying casting into the mould (Figure 4.4), the transformation zones migrate deeper into the mould. We can follow the progress of the advance of the zones by considering the distance d that a particular isotherm reaches as a function of time t. The solution to this simple one-dimensional heat-flow problem is

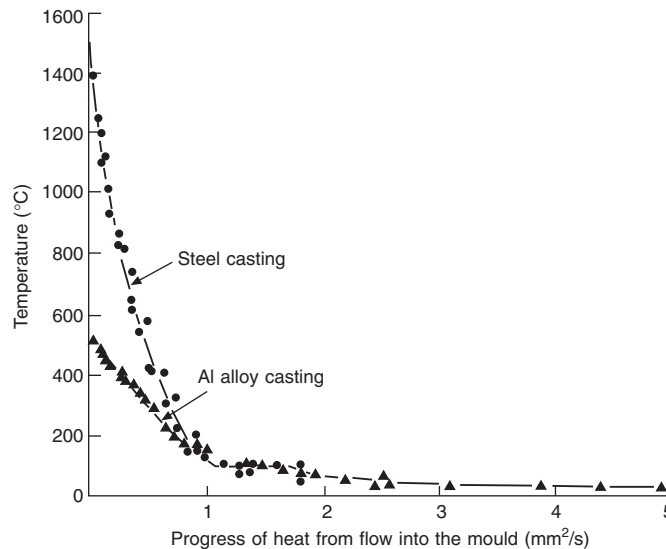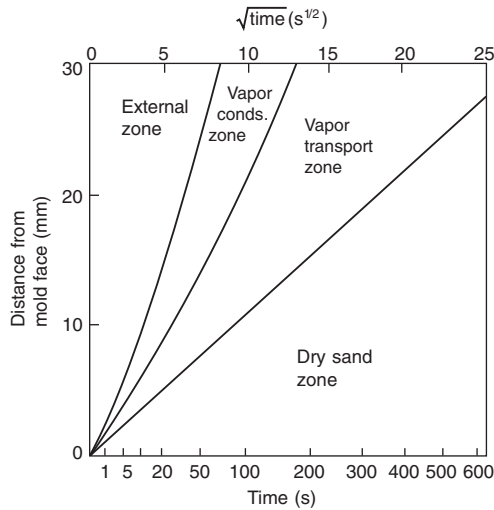$$d = (Dt)^{1/2} \tag{4.1}$$

FIGURE 4.4

Temperature distribution in a greensand mould on casting an aluminium alloy (Ruddle and Mincher, 1949, 1950) and a steel (Chvorinov, 1940).

FIGURE 4.5

Position of the vapour zones after the casting aluminium in a greensand mould.

Data from Kubo and Pehlke (1986).

where D is the coefficient of diffusion. This solution is of course equivalent to the solute diffusion given earlier (Eqn (1.5)).

In the case of the evaporation front, the isotherm of interest is that at 100°C. We can see from Figures 4.4 and 4.5 that the value of D is close to 1 mm^2s^{-1}. This means that the evaporation front at 1 s has travelled 1 mm, at 100 s has travelled 10 mm, and requires 10,000 s (nearly 3 h!) to travel 100 mm. It is clear that the same is true for aluminium, as well as steel. (This is because we are considering a phenomenon that relies only on the rate of heat flow in the mould—the metal and its temperature are not involved.)

For the condensation zone the corresponding value of D is approximately 3 mm^2s^{-1}, so that the position of the front at 1, 100, and 10,000 s is 1.7, 17, and 170 mm, respectively.

These figures are substantiated to within 10 or 20% by the theoretical model by Tsai et al. (1988). This work adds interesting details such as that the rate of advance of the evaporation front depends on the amount of water present in the mould, higher water contents making slower progress. This is to be expected, because more heat will be required to move the front, and this extra heat will require extra time to arrive. The extra ability of the mould to absorb heat is also reflected in the faster cooling rates of castings made in moulds with high water content. Measurements of the thermal conductivity of various moulding sands by Yan et al. (1989) have confirmed that the apparent thermal conductivity of the moisture-condensation zone is about three or four times as great as that of the dry sand zone.

An earlier computer model by Cappy et al. (1974) also indicates interesting data that would be difficult to measure experimentally. They found that the velocity of the vapour was in the range of 10–100 mms^{-1} over the conditions they investigated. Their result for the composition and movement of the zones is given in Figure 4.6. Kubo and Pehlke calculate flow rates of 20 mms^{-1}. These authors go on to show that moisture vapourises not only at the evaporation front, but also in the transportation and condensation zones. Even in the condensation zone a proportion of the water vapourises again at temperatures below 100°C (Figure 4.5).

The pressure of water vapour at the evaporation front will only be slightly above atmospheric pressure in a normal greensand mould. However, because the pressure must be the same everywhere in the region between the mould-metal interface and the evaporation front, it follows that the dry sand zone must contain practically 100% water vapour. This is
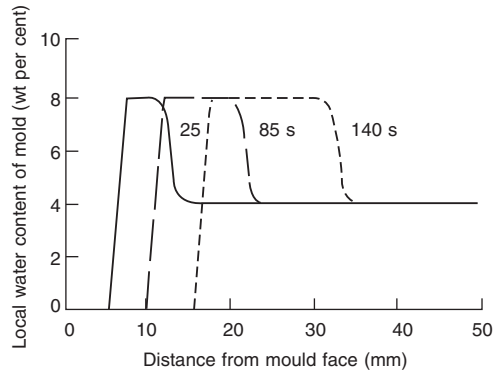
FIGURE 4.6

Water content of the vapour transport zone with time and position (smoothed computed results of Capp et al., 1974).

surprising at first sight. However, a moment's reflection will show that there is no paradox here. The water vapour is very dry and hot, reaching close to the temperature of the mould-metal interface. At such high temperatures, water vapour is highly oxidising. There is no need to invoke theories of additional mechanisms to get oxygen to this point to oxidise the metal—there is already an abundance of highly oxidising water vapour present (the breakdown of the water vapour also providing a high-hydrogen environment, of course, to enter the metal, and to increase the rate of heat transfer in the dry sand zone).

Kubo and Pehlke (1986) confirm that gas in the dry sand and transportation zones consists of nearly 100% water vapour. In the condensation zone, the percentage of air increases, until it reaches nearly 100% air in the external zone (water vapour would be expected to be present at its equilibrium vapour pressure, 32 mmHg or 42 mb at 30°C).

It is found that similar evaporation and condensation zones are present for other volatiles in the greensand mould mixture. Marek and Keskar (1968) have measured the movement of the vapour transport zone for benzene and xylene. The evaporation and condensation fronts of these more volatile materials travel somewhat faster than those of water. When such additional volatiles are present they will, of course, contribute to the 1 atm of gas pressure in the dry zone, helping to dilute the oxidising effect of water vapour and helping to explain part of the beneficial effect of such additives. In the following section, we will see that many organics decompose at these high temperatures, providing a deposit of carbon, which further assists, in the case of such metals as cast iron, in preventing oxidation and providing a non-wetting metal surface of carbon which contains the liquid iron and helps to prevent its contact with the sand mould.

It is to be expected that vapour transport zones will also be present to various degrees in chemically bonded sands. The zones will be expected to have traces of water mixed with other volatiles such as organic solvents. Little work appears to have been carried out for such binder systems, so it is not easy to conclude how important the effects are, if any. In general, however, the volatiles in such dry sand systems usually total less than 10% of the total volatiles in greensand, so that the associated condensation zones will be expected to be less than one-tenth of those occurring in greensand. It may be, therefore, that they will be unimportant. However, at the time of writing we cannot be sure; it would be nice to know.

What is certain is that silicate binders appear to have a high chilling effect in ferrous castings because of their water content. The loss of the water will create evaporation and condensation zones that will carry heat away from the casting.

All of these considerations on the rate of advance of the moisture assume no other flows of gases through the mould. This is probably fairly accurate in the case of the drag mould, where the flow of the liquid metal over the surface of the mould effectively seals the surface against any further ingress of gases. A certain amount of convection is expected in the mould, but this will probably not affect the conditions in the drag significantly.

In the vertical walls of the mould, however, convection may be significant. Close to the hot metal, hot gases are likely to diffuse upwards and out of the top of the mould, their place being taken by cold air being drawn in from the surroundings at the base of the mould, or the outer regions of the cope.

General conditions in the cope, however, are likely to be more complicated. It was Hofmann in 1962 that first emphasised the different conditions experienced during the heating up and outgassing of the cope. He pointed out that the radiated heat from the rising melt would cause the cope surface of the mould to start to dry out before the moment of contact with the melt. During this pre-contact period two different situations can arise:

1. If the mould is open, as the cope surface heats up, the water vapour can easily escape through the mould cavity and out via the opening (Figure 4.7). The rush of water vapour through an open feeder can easily be demonstrated by holding a piece of cold metal above the opening. It quickly becomes covered with condensate. The water vapour starts its life at a temperature of only 100°C. It is therefore a relatively cool gas, and is thus most effective in cooling the surface of the mould as it travels out through the surface of the cope on its escape route.
2. If the mould is closed, the situation is quite different. The air being displaced and expanded by the melt will force its way through the mould, carrying away the vapour from the interface (Figure 4.7). The rate of flow of air is typically in the 10–100 $ls^{-1}m^{-2}$ range (the reader is encouraged to confirm this for typical castings and casting rates). This is in the same range of flow rate as the transport of vapour given in computer models. Thus if the casting rate is relatively low, then the vapour transport zone is likely to be relatively unaffected, although perhaps a little accelerated in its progress. When the casting rate is relatively high, then the vapour transport zone will be effectively blown away, diluted with the gale of air so that no condensation can occur.

Because the water vapour is driven away from the surface and into the interior of the mould, its beneficial cooling effect at the surface is not felt, with the result that the surface reaches much higher temperatures as a result of the direct

(a)

Open mould cavity

(b)

Closed mould cavity **(c)**
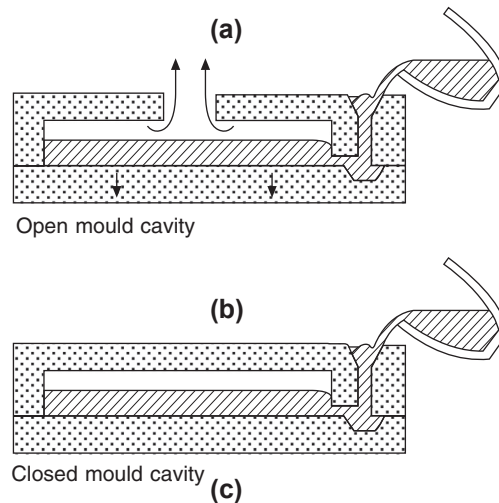
FIGURE 4.7

Three conditions of vapour transport in moulds: (a) unrestricted free evaporation from the cope; (b) evaporation from the cope constrained to occur via the cope mould; (c) evaporation from the drag confined by the cover of metal, and possibly confined by the substrate on which the mould sits, and possibly at its sides by a moulding box, leaving no option but for bubbling through the metal.
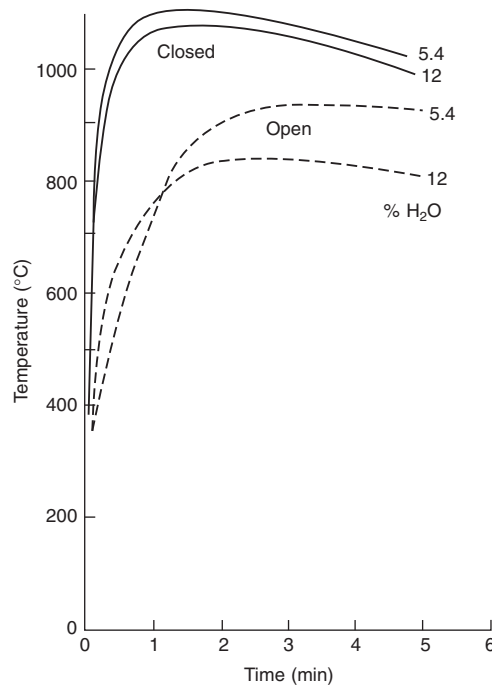
Partly from Hofman (1962).

radiation of heat from the melt, as is seen in Figure 4.8. The prospect of the failure of the cope surface by expansion and spalling of the sand is therefore much enhanced.

However, the rate of heating of the surface by radiation from the melt may be reduced by a white mould coat, such as a zircon- or alumina-based mould wash, now widely applied for large castings of iron and steel. Boenish (1967) confirmed that light-coloured mould coats resist scabbing for up to 400% longer than the jet-black graphitic surfaces commonly used for cast iron.

One final aspect of vapour transport in the mould is worth noting. There has been much discussion over the years about the contribution of the thermal transpiration effect to the flow of gases in moulds.

Although it appears to have been widely disputed, the effect is certainly real. It follows from the kinetic theory of gases and essentially is the effect of heated gases diffusing away from the source of heat, allowing cooler gases to diffuse up the temperature gradient. In this way it has been argued that oxygen from the air can arrive continuously at the casting to oxidise the surface to a greater degree than would normally have been expected.

Williams (1970) described an experiment that demonstrated this effect. He took a sample of clay approximately 50 mm long in a standard 25 mm diameter sand sampling tube. When one end was heated to $1000°C$ and the other was at room temperature, he measured a pressure difference of 10 mmHg if one end was closed, or a flow rate of 20 ml per min if both ends were open. If these results are typical of those that we might expect in a sand mould, then we can make a comparison as follows. The rate of thermal transpiration is easily shown to convert to $0.53 \, \mathrm{ls^{-1}m^2}$ for the conditions of temperature gradient and thickness of sample used in the experiment. From the model of Cappy et al. (1974), we obtain an estimate of the rate of transport of vapour of $100 \, \mathrm{ls^{-1}m^2}$ at approximately this same temperature gradient through a similar thickness of mould. Thus thermal transpiration is seen to be less than 1% of the rate of vapour transport.

FIGURE 4.8

Temperature in the cope surface seen to be significantly lowered by open moulds and high moisture levels.

Data from Hofman (1962).

Additional flows such as the rate of volume displacement during casting and the rate of thermal convection in the mould will further help to swamp thermal transpiration.

Thermal transpiration does seem to be a small contributor to gas flow in moulds. It is possible that it may be more important in other circumstances. More work is required to reinstate it to its proper place, or lay it to rest as an interesting but unimportant detail.

4.4 MOULD ATMOSPHERE

4.4.1 COMPOSITION

On the arrival of liquid iron or steel in the mould, a rich soup of gases boils from the surface of the mould and the cores. The air originally present in the cavity dilutes the first gases given off, but this is quickly expelled through vents or feeders or may diffuse out through the cope. After the air is forced out, the composition of the mould gas is relatively constant. The speed at which the original gas in the mould is expelled by the arrival of the metal is the reason why attempts to fill the mould with inert gases to avoid oxidising reactions are practically always a waste of effort. The casting of Al alloys is rather less dramatic, and the original air is expelled only gradually as seen from experiments described in the following section.

In the case of steel being cast into greensand moulds, the mould gas mixture has been found to contain up to 50% hydrogen (Figure 4.2). The content of hydrogen depends almost exactly on the percentage water in the sand binder, with dry sand moulds having practically no hydrogen as found by Locke and Ashbrook (1950, 1972). Other changes brought about by increased moisture in the sand were a decrease in oxygen, an increase in the CO/CO_2 ratio and the appearance of a few% of paraffins (it is not clear whether these originated from the use of lubricant sprayed on to the pattern). The presence of cereals in the binder was found to provide some oxygen, even though the concentration of oxygen in the atmosphere fell because of dilution with other gases (Locke and Ashbrook, 1950). Chechulin (1965) describes the results for greensand when aluminium alloys, cast irons and steels are cast into them. His results are given in Figure 4.2(a). Irons and steels produce rather similar mould atmospheres, so only his results for steel are presented.

The high oxygen and nitrogen content of the atmosphere in the case of moulds filled with aluminium simply reflects the high component of residual air (originally, of course, at approximately 20% oxygen and 80% nitrogen). The low temperature of the incoming metal is insufficient to generate enough gas and expand it to drive out the original atmosphere. This effective replacement of the atmosphere is only achieved in the case of iron and steel castings.

The atmosphere generated when ferrous alloys are cast into chemically bonded sand moulds is, perhaps rather surprisingly, not so different from that generated in the case of greensand (Figure 4.2(b)). The mixture consists mainly of hydrogen and carbon monoxide.

The kinetics of gas evolution have been studied by a number of researchers. Jones and Grim (1959) found some clays evolved significant water at just over 100°C, particularly Western bentonite, although Southern bentonite results went wildly off scale. A second peak of evolution at around 550°C was relatively unimportant. Scott and Bates (1975) found that hydrogen evolution peaked within 4–5 min for most chemical binders. However, for the sodium silicate binder, a rapid burst of hydrogen was observed which peaked in less than 1 min.

Scarber et al. (2006) measured 200 ml gas from about 100 g (they do not give the exact weight of their samples) of a core bonded with some resin binders which rose to more than 500 ml if the core was coated with a water-based wash even though the core had been thoroughly dried. Even this paled into insignificance when compared with the outgassing of greensand which they found to be nearly 10 times that from resin-bonded sands. In addition, they found multiple peaks associated with solvent evaporation, and, probably, water evaporation. The process seemed to be complicated by the re-condensation of these volatiles in the cooler centres of cores, and their final re-evaporation (a re-enactment of the condensation and evaporation zones previously discussed in Section 4.3). Yamamoto et al. (1980) described the variation in output they observed as (1) peak I attributed to the expansion of air plus the evaporation of free moisture and other volatiles in the core when the core was first covered with liquid metal; (2) peak II after about 30 s identified as the release of combined water (water of crystallisation) in the binder and/or aggregate; and finally (3) a broad smooth peak III, constituting a nearly constant pressure output period for about 50–80 s, attributed to the general breakdown of the organics in the binder. They confirmed that peak II was much higher for sodium silicate/CO_2 cores.

Lost-foam casting, where the mould cavity is filled with polystyrene foam (the 'full mould' process), is a special case. Here it is the foam that is the source of gases as it is vapourised by the molten metal. At aluminium casting temperatures the polymerised styrene merely breaks down into styrene, but little else happens, as is seen in Figure 4.2(c). It seems that the liquid styrene soaks into the ceramic surface coating on the foam, so that the coating will temporarily become completely impermeable. This unhelpful behaviour probably accounts for many of the problems suffered by aluminium alloy castings made by the lost foam process.

At the casting temperatures appropriate for cast iron, more complete breakdown occurs, with the generation of hydrogen and considerable quantities of free carbon. Rao and Lee (1984) show how even methane is largely decomposed at these temperatures, forming less than 1% of a $C–H_2–O_2$ mixture at 1 atm. The carbon deposits on the advancing metal front as a pyrolytic form of carbon widely known as 'lustrous carbon'. Once formed, the layer is rather stable at iron-casting temperatures, and can therefore lead to serious defects if entrained in the metal. The problem has impeded the successful introduction of lost foam technology. For steel casting the temperature is sufficiently high to cause the carbon to be taken into solution. Steel castings of low or intermediate carbon content are therefore contaminated by pockets of high-carbon alloy. This problem has prevented lost-foam technology in the form of the full mould process being used for low- and medium-carbon steel castings.

Lost-foam iron castings are not the only type of ferrous castings to suffer from lustrous-carbon defects. The defect is also experienced in cast iron made in phenolic urethane-bonded moulds, and at times can be a serious headache. The absence of carbon is therefore a regrettable omission from the work reported in Figure 4.2(a). At the time Chechulin carried out this study, the problem would not have been known. Later, Gloria (1986) does report carbon as a product of decomposition of polystyrene foam.

It seems reasonable to expect that carbon may also be produced from the pyrolysis of other binder systems. More work is required to check this important point.

4.4.2 MOULD GAS EXPLOSIONS

The various reactions of the molten metal with the volatile constituents of the mould, particularly the water in many moulding materials, would lead to explosive reactions if it were not for the fact that the reactions are dampened by the presence of masses of sand in mould materials or cores. Thus although the reactions in the mould are fierce, and not to be underestimated, in general they are not of explosive violence because the 90% or more of the materials involved are inert (simply sand and nitrogen) and have considerable thermal inertia. Taleyarkhan (1998) draws attention to the important role of non-condensable gases (e.g. nitrogen) in the suppression of explosive reactions. Outgassing reactions are therefore rather steady and sustained.

When carrying out a series of experiments in about 1992, liquid aluminium was poured while the interior of a polyurethane-bonded mould was recorded by video though a glass window, Helvaee was surprised to note that in every case, on arrival of the metal in the mould, a flicker of flame licked across the mould cavity, sometimes more energetically than others. On no occasion was there an explosion. Much earlier, in 1948, Johnson and Baker recorded similar flashes of light when recording the filling of open greensand moulds by molten steel at 1650°C. It seems such phenomena might be common or even normal.

It is noteworthy that the gases from the outgassing of an aggregate mould may contain a number of potentially flammable or explosive gases. These include a number of vapours such as hydrocarbons such as methane, other organics such as alcohols and a number of reaction products such as hydrogen and carbon monoxide.

Because of the presence of these gases, explosions sometimes occur and sometimes not. The reasons have never been properly investigated. This is an unsatisfactory situation because the explosion of a mould during casting can be an unpleasant event. The author has witnessed explosions a number of times in furan-bonded boxless moulds when casting an aluminium alloy casting weighing more than 50 kg: there was a muffled explosion, and large parts of the sand mould together with liquid metal flew apart in all directions. After several repeat performances, the operators developed ways of pouring this component at the end of long-handled ladles to keep as far away as possible, never knowing whether the mould would explode. The cause always remained a mystery. Everyone was relieved when the job came to an end.

Explosions in and around moulds containing iron or steel castings are relatively common. One of the most common is from under the mould, between the mould and its base plate, after the casting has solidified, so that there is less danger either to personnel or casting. The sound of muffled explosions from the mix of CO and air under moulds is common in many greensand foundries.

With subsequent experience, and in the absence of any other suggestions, the following is suggested as a possible cause of the problem in the case of the light alloy casting.

Explosions can, of course, only happen when the flammable components of the gas mix with an oxidising component such as oxygen from the air. The mixing has to be efficient, which suggests that turbulence is important. Also, the mix often has to be within close compositional limits, otherwise either no reaction occurs, or only slow burning takes place. The limits for the carbon monoxide, oxygen and inert (carbon dioxide and nitrogen) gas mixtures are shown in Figure 4.9.

In the first edition of this book the mixing with air, which is essential for explosions, was thought to occur only under certain conditions including feeder heads open to the air and the use of two sprues which would be not easily synchronised. Subsequent experience has modified these conclusions, even though definitive reasons are still not known. It is now clear that at least 50% of the mixture arriving at the base of the sprue is air, scrambled in with the hot metal, as a result of the pumping action of the conical trumpet entrance to the sprue, and the fact that most sprues are oversized and therefore allow the ingress and entrainment of air. Thus bubbles of air, together with hot splashes of metal, mixing turbulently with the mould gases are a recipe for explosive conditions.

We can surmise that contact pouring, together with a slim 'naturally pressurised' filling system design would eliminate explosions as a result of the melt displacing the air in the filling system, then filling the mould uphill, with minimal mixing of the hot mould gases in contact with the melt; melt and gases will both tend to rise steadily through the mould as progressive layers. In a system filling quiescently from the bottom upwards, the outgassing of the mould and cores will provide a spreading blanket of gas over the liquid. There will be almost no air in this cover, so no burning or explosion can occur. The air will be displaced ahead and will diffuse out of the upper parts of the mould. Where the flammable gas blanket meets the air, it is expected to be cool, well away from the liquid metal. Thus any slight mixture that will occur at the interface between these layers of gases is not likely to ignite to cause an explosion.
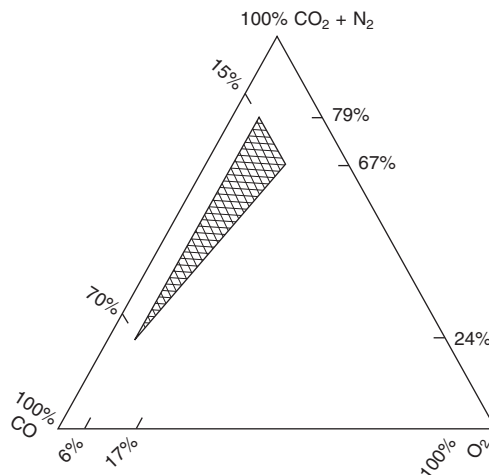
FIGURE 4.9

Shaded region defines the explosive regime for mixtures of CO, O_2, and a mixture of $CO_2 + N_2$ (Ellison and Wechselblatt, 1966).

Occasionally, Al-Si alloys which have been usually docile during pouring have been known to explode after the addition of Sr as a modifier. This is thought to be the enhanced reactivity of the Sr, converting moisture to hydrogen gas. The elimination of the trumpet intake and the provision of a properly calculated filling system should both help, as would the reduction or elimination of the Sr addition.

4.5 MOULD SURFACE REACTIONS

4.5.1 PYROLYSIS

When the metal has filled a sand mould, the mould becomes hot. A common misconception is to assume that the sand binder then burns; however, this is not true. It simply becomes hot. There is insufficient oxygen to allow any significant burning. What little oxygen is available is consumed in a minor, transient oxidation which quickly comes to a stop. What happens then to the binder is not burning, but pyrolysis.

Pyrolysis is the decomposition of compounds, usually organic compounds, simply by the action of heat. Oxygen is absent, so that no burning (i.e. high temperature oxidation) takes place. Pyrolysis of various kinds of organic binder components to produce carbon is one of the more important reactions that take place in the mould surface. Carbon is poorly wetted by many liquid metals, so the formation of carbon on the grains of sand, as a pyrolysed residue of the sand binder, produces a non-wetted mould surface, which can lead to an improved surface finish to the casting (although, as will become clear, the effect on the surface film on the liquid metal is probably more important).

This non-wetting feature of residual carbon on sand grains is at first sight curious, because carbon is soluble in many metals, and so should react, and should therefore wet. Cast iron would be a prime candidate for this behaviour. Why does this not happen?

In the case of ductile iron, sand cores do not need a core coat because the solid magnesium oxide rich film (probably a magnesium silicate) on the surface is a mechanical barrier that prevents penetration of the metal into the sand.

In the case of grey cast iron in a greensand mould the atmosphere may be oxidising, causing the melt surface to grow a film of liquid silicate. This is highly wetting to sand grains, so that the application of a core coating such as a refractory wash may be necessary to prevent penetration of the metal into the core.

However, in the case of grey iron cast in a mould rich in hydrocarbons (i.e. greensand with sufficient additions of coal dust or certain resin-bonded sands), metal penetration is prevented when the hydrocarbons in the atmosphere of the mould pyrolyse on contact with the surface of the hot liquid metal to deposit a thin film of solid carbon on the liquid. Thus the reason for the robust non-wetting behaviour is that a solid pyrolysed carbon film on the liquid contacts a solid, pyrolysed carbon layer on the sand grains of the mould surface. This carbon-against-carbon behaviour explains the excellent surface finish that grey irons can achieve if bottom-gated and filled in a laminar fashion (Figure 6.34).

For the casting of iron, powdered coal additions or coal substitutes are usually added to greensands to improve surface finish in this way, providing a carbon layer to both the sand grains and the liquid surface. The reactions in the pyrolysis of coal were originally described by Kolorz and Lohborg (1963):

1. The volatiles are driven out of the coal to form a reducing atmosphere.
2. Gaseous hydrocarbons break down on the surface of the liquid metal. (Kolorz and Lohborg originally thought the hydrocarbons broke down on the sand grains to form a thin skin of graphite, but this is now known to be not true.)
3. The coal swells, and on account of its large expansion, is driven into the pores of the sand. This plastic phase of the coal addition appears to plasticise the binder temporarily and thereby eases the problems associated with the expansion of the silica, allowing its expansion to be accommodated without the fracture of the surface. As the temperature increases further and the final volatiles are lost, the mass becomes rigid, converting to a semi-coke. The liquid metal is prevented from contacting and penetrating the sand by this in-filling of carbon that acts as a non-wetted mechanical barrier.

Kolorz and Lohborg recommend synthetically formulated coal dusts with a high tendency to form anthracitic carbon, of good coking capacity and with good softening properties. They recommend that the volatile content be near 30% and sulphur less than 0.8% if no sulphur contamination of the surface is allowable. If some slight sulphurisation is

permissible, then 1.0–1.2% sulphur could be allowed. Peterson and Blanke (1980) emphasise the bituminous nature and low ash content of desirable coals.

In the case of phenolic urethane and similar organic chemical binders based on resin systems, the thermal breakdown of the binder assists the formation of a good surface finish to cast irons and other metals largely in the manner described previously. The binder usually goes through its plastic stage prior to rigidising into a coke-like layer. The much smaller volume fraction of binder, however, does not provide for the swelling of the organic phase to seal the pores between grains. So in principal, the sand remains somewhat vulnerable to penetration by the liquid metal. The second aspect of non-wettability is discussed next.

The founder should be aware of binder pyrolysis reactions that can have adverse effects on the surface quality of the casting. These are more likely to occur with binders that contain nitrogen (phenol urethanes and some furans) which can be converted to cyanide and amine gases. Different reactions occur in the case of furans, where problems may arise from the use of the sulphonic acid or phosphoric acid catalysts which become cumulative, being least when new sand is used and progressively more concentrated as the content of mechanically reclaimed sand in the mix increases. Sulphonic acids react with iron and iron oxide residues in the sand, with feldspars, with limestone often present in poor quality sand, and with certain types of coatings, to form the corresponding sulphonates. These will in turn be reduced to sulphides during casting and these may then cause sulphide damage to cast parts.

Phosphoric acid damage is caused by a different mechanism because phosphates are stable under casting conditions. It seems that the damage caused is primarily from the reaction of its vapour with iron^{II} oxide (or chromite) dust, leading to the formation of iron^{II} phosphate which coats the sand grains. Both the phosphoric acid vapour and the iron^{II} phosphate can interact with components in the (ferrous) metal being cast.

4.5.2 LUSTROUS CARBON FILM

The carbonaceous gases evolved from the binder complete their breakdown at the white hot surface of the advancing front of liquid metal, giving up carbon and hydrogen to the advancing liquid front. For steel, the carbon dissolves quickly and usually causes relatively little problem. For cast iron, the carbon dissolves hardly at all, because the temperature is lower, and the metal is already nearly saturated with carbon; thus the carbon cannot dissolve away into the liquid iron as quickly as it arrives, so that it accumulates on the surface as a film. The time for dissolution seems to be about the same as the time for mould filling and solidification; thus the film has a life sufficiently long to affect the flow of the liquid for good or ill, depending on the circumstances.

If the metal is rising nicely in the mould, the surface film migrates across the liquid surface as it splits and reforms and then thickens with time on its approach to the side walls. The rising metal causes the liquid iron to rolls out on the surface of the mould, rolling out and laying down its surface film as the liquid advances. This laying down of the surface film can be likened to the laying down of the tracks of a track-laying vehicle. The film confers a non-wetting behaviour on the liquid itself because the liquid is effectively sealed in a non-wetting, dry solid skin. The skin forms a mechanical barrier between the liquid and the mould. This barrier is laid down as the liquid progresses because of friction between the liquid and the mould, the friction effectively stretching the film and tearing it near the centre of the meniscus where it immediately re-forms to continue the process (Figures 2.2 and 6.34). The strength and rigidity of the carbon film helps the liquid surface to bridge unsupported regions between sand grains or other imperfections in the mould surface. By this mechanism the surface of the casting is smoothed to a significantly finer finish that could be achieved by surface tension alone attempting to bridge between the sand grains.

The benefits of laying out a solid film as the liquid iron rolls out on the mould surface is only achieved if the liquid is encouraged to fill progressively, as a rolling action up against the mould surface. The mechanism for the improvement of surface finish can only operate effectively if the progress of the meniscus is steady and controlled, i.e. in the absence of surface turbulence. The casting surface can then take on an attractive, smooth glossy shine. It makes sense to fill the casting nicely using a properly designed bottom-gated technique. However, if the melt is top-poured, splashing and hammering the mould, no benefit is obtained; in fact, the liquid penetration can be severe giving a casting surface so spiky, sharp and rough to take the skin off your hands.

In addition to surface finish problems, a further problem arises if surface turbulence causes the carbon film to become entrained in the liquid. The film will necessarily become entrained as a double film, a carbon bifilm (because single films cannot be entrained) constituting a serious crack-like defect. Fortunately, in heavy-section castings, the entrained double film defect has time to dissolve, and never seems to be a problem. Light-section castings should only be attempted using binder systems that produce little lustrous carbon because defects will not have time to dissolve and will therefore be effectively permanent. Alternatively, a preferable strategy would of course be the use of a running system that could guarantee the absence of surface turbulence.

The lustrous carbon film, in contrast to all other surface films on other metals that I know, appears to detach easily from the iron during cooling. This curious behaviour means that after breaking the casting out of the mould, the film is sometimes seen attached to the surface of the mould, covering the surface as a smooth, glossy sheet, leading many observers to the mistaken conclusion that the film had initially formed on the mould surface (Naro, 2004). This is clearly not possible, of course, because pyrolysis reactions can only occur in high temperature conditions, such as on the melt surface, in contrast to the sand grains which are relatively cold.

4.5.3 SAND REACTIONS

Other reactions in the mould surface occur with the sand grains themselves. The most common of sand reactions is the reaction between silica (SiO_2) and iron oxide (wustite, FeO) to produce various iron silicates, of which the most commonly quoted (but not necessarily the most common nor the most important) is fayalite (Fe_2SiO_4). This happens frequently at the high temperatures required for the casting of irons and steels. It causes the grains to fuse and collapse as they melt into each other, because the melting point of some of the silicates is below the casting temperature. (The much quoted melting point of fayalite at only $1205°C$ may be an error because fayalite may have a significantly higher melting temperature. A more likely candidate to melt is grunerite, $FeSiO_3$). The reacted grains adhere to the surface of the casting because of the presence of the low-melting-point liquid 'glue'. This is known as burn-on.

The common method of dealing with this problem is to prevent the iron oxidising to form FeO in the first place. This is usually achieved by adding reducing agents to the mould material, such as powdered coal to greensand or aluminium powder additions to mould washes and the like. The problem is also reduced in other sands that contain less silica, such as chromite sand. However, the small amounts of silica present in chromite can still give trouble in steel castings, where the extreme temperature causes the residual silica to fuse with the clay. At these temperatures, the chromite may break down, releasing FeO or even droplets of Fe on the surface of the chromite sand grains. Metal penetration usually follows as the grains melt into each other, and the mould surface generally collapses. The molten, fused mass is sometimes known as 'chromite glaze'. It is a kind of burn-on, and is difficult to remove from steel castings (Petro and Flinn, 1978). Again, carbon compounds added to the moulding material are useful in countering this problem (Dietert et al., 1970).

Peterson and Blanke (1980) draw attention to the potential role of hydrogen released during the pyrolysis of coal dust in greensand, proposing that hydrogen plays an important part in avoiding the formation of oxides and silicates, and which may explain its contribution to good surface finish and the avoidance of burn-on. If hydrogen is actually valuable in this way, it clearly cannot arise from the main carbon constituent of coal, but must be generated from its minor hydrocarbon content, strongly suggesting that coal might be eliminated in favour of a more targeted binder addition.

4.5.4 MOULD CONTAMINATION

There are a few metallic impurities that find their way into moulding sands as a result of interaction between the cast metal and the mould. We are not thinking for the moment of the odd spanner or tonnes of iron filings from the steady wearing away of sand plant. Such ferrous contamination is retrieved in most sand plants by a powerful magnet located at some convenient point in the recirculating sand system. (The foundry maintenance crew always have interesting stories to tell of items found from time to time attached to the magnet.) Nor are we thinking of the pieces of tramp metal such as flash and other foundry returns. Our concern is with the microscopic traces of metallic impurities that lead to a number of problems, particularly because of the need to protect the environment from contamination.

Foundries that cast brasses find that the grains of their moulding sand become coated with a zinc-rich layer, with lead-rich nodules on the surface of the zinc (Mondloch et al., 1987). The metals are almost certainly lost from the casting by evaporation from the surface after casting. The vapour condenses among the cool sand grains in the mould as either particles of metallic alloy, or reacts with the clay present, particularly if this is bentonite, to produce Pb-Al silicates. If there is no clay present, as in chemical binder systems such as furan resins, then no reaction is observed so that metallic lead remains (Ostrom et al., 1982). Thus ways of reducing this problem are: (1) the complete move, where possible in simple castings, to metal moulds; (2) the complete move, where possible, from lead-containing alloys; or (3) the use of chemical binders, together with the total recycling of sand in-house. This policy will contain the problem, but the sand will have a fair degree of toxicity. If the metallic lead can be separated from the sand in the sand recycling plant, the proceeds might provide a modest economic return, and the sand toxicity could be limited.

There has been a suggestion that iron can evaporate from the surface of a ferrous casting in the form of iron carbonyl $Fe(CO)_5$. This suggestion appears to have been eliminated on thermodynamic grounds; Svoboda and Geiger (1969) show that the compound is not stable at normal pressures at the temperature of liquid iron. Similar arguments eliminated the carbonyls of nickel, chromium and molybdenum. These authors carry out a useful survey of the existing knowledge of the vapour pressures of the metal hydroxides and various sub-oxides but find conclusions difficult because the data is sketchy and contradictory. Nevertheless, they do produce evidence that indicates vapour transport of iron and manganese occurs by the formation of the sub-oxides $(FeO)_2$ and $(MnO)_2$. The gradual transfer of the metal by a vapour phase, and its possible reduction back to the metal on arrival on the sand grains coated in carbon might explain some of the features of metal penetration of the mould, which is often observed to be delayed, and then occur suddenly. More work is required to test such a mechanism.

The evaporation of manganese from the surface of castings of manganese steel is an important factor in the production of castings. The surface depletion of manganese seriously reduces the surface properties of the steel. In a study of this problem, Holtzer (1990) found that the surface concentration of manganese in the casting was depleted to an impressive non-trivial depth of 8 mm and the concentration of manganese silicates in the surface of the moulding sand was increased.

The process of Mn evaporation can be observed to occur from a drop of liquid steel placed on a water-cooled copper substrate. A 'halo' is seen to develop around the drop, indicating mainly Mn condensation, although Cr and Fe can also contribute (Nolli and Cramb, 2008).

Figure 6.26 confirms that the vapour pressure of manganese is significant at the casting temperature of steel. However, the depth of the depleted surface layer is nearly an order of magnitude larger than can be explained by diffusion alone. It seems necessary to assume, therefore, that the transfer occurs mainly while the steel is liquid, and that some mixing of the steel is occurring in the vicinity of the cooling surface.

It is interesting that a layer of zircon wash on the surface of the mould reduces the manganese loss by about half. This seems likely to be the result of the thin zircon layer heating up rapidly, thereby reducing the condensation of the vapour. In addition, it will form a barrier to the progress of the manganese vapour, keeping the concentration of vapour near the equilibrium value close to the casting surface. Both mechanisms will help to reduce the rate of loss. If, however, the protective wash is applied after the moulding sand has already become significantly contaminated with Fe and Mn oxides in the recycling process, the underlying sand may partially melt and collapse (Kruse, 2006). This instability of the underlying sand will cause mechanical penetration of the zircon wash, and extensive permeation of the metal into the underlying partially melted sand. The carryover of such contamination should be eliminated by careful control of the recycling process or revised selection of moulding aggregate (see the section on mould aggregates).

Gravity die casters that use sand cores (semi-permanent moulds) will be all too aware of the serious contamination of their moulds from the condensation of volatiles from the breakdown of resins in the cores. The buildup of these products can be so severe as to cause the breakage of cores, and the blocking of vents. Both lead to the scrapping of castings. The blocking of vents by tar-like deposits in permanent moulds is the factor that controls the length of a production run prior to the mould being taken out of service for cleaning. On carousels of dies in Al alloy cylinder head production, a die may need to be taken out of service every 10th or 15th casting. The absence of such problems in sand moulds is a natural advantage, aiding the already high productivity of sand moulding that is usually overlooked.

4.5.5 **MOULD PENETRATION**

Svoboda (1994) reviews the wide field of mould penetration by melts, and concludes that (1) mechanical balance between the driving pressure and capillary effects lead to liquid state penetration in 75% of cases, (2) chemical reactions cause 20% of cases of penetration, and (3) vapour-state reactions may control 5% of penetration problems. We shall examine his categories in detail next. In addition, the time dependence of penetration is an interesting behaviour that requires explanation.

4.5.5.1 Liquid penetration: effect of surface tension and pressure

Any liquid will immediately start to impregnate a porous solid if the solid is wetted by the liquid. The effect is the result of capillary attraction. For this reason, moulding materials are selected for their non-wetting behaviour, so that penetration by liquid metals is resisted; the resistance is known as capillary repulsion.

It was the French workers Portevin and Bastien (1936) that first proposed that capillary forces should be significant for the penetration of liquid metals into sand. However, this prediction was neglected until the arrival of Hoar and Atterton (1950) who first set out the basic physics, creating a quantitative model in which the surface tension γ of the melt would hold back the penetration of a liquid subjected to gradually increasing pressure against the surface of a porous, non-wetted aggregate. The liquid interface bridging the inter-particle spaces would gradually swell out, its bulging action progressively confined to a steadily smaller radius until it became hemispherical (radius r in Figure 4.11). Up to this critical value, the melt could be held back, but beyond this condition, further advance of the meniscus would cause the radius of curvature to increase as indicated by the formula that follows, lowering the resistance. The balance condition at the critical pressure for penetration is that quoted in Eqn (3.11), $P = 2\gamma/r$.

If we substitute $\rho g H$ for pressure from depth H in a metal of density ρ, we have the critical depth of metal for penetration

$$H = 2\gamma/r\rho g$$

Thus, beyond this critical point, penetration would instantly occur as a runaway effect; Figure 4.10 shows the meniscus expanding rapidly away after the narrowest point between sand grains is passed. Penetration might subsequently only be stopped by the advancing front losing its heat and freezing. Such elementary physics is helpful to understand why finer grain size of the aggregate or the provision of any extremely fine-grained surface coating are both helpful to reduce penetration for any fixed value of H by this simple mechanical model.

Resistance to penetration until some critical pressure is achieved has been demonstrated many times. For instance, Draper and Gaindhar (1975) find a metal depth of approximately 300 mm is required for steel to penetrate consistently into greensand moulds in their experiment. This critical depth was influenced to some degree by mould compaction, oxidising conditions and the temperature of mould hot-spots. If we assume a density of 7000 kg/m^3, surface tension approximately 2 N/m and acceleration from gravity of about 10 m/s^2, we find the radius r is approximately 0.02 mm, indicating the interparticle diameter to be roughly 0.04 mm (40 μm) in their moulds which seems a reasonable value.

All of the discussion so far has assumed perfect non-wetting between the metal and the mould (i.e. a contact angle of 180°). Hayes et al. (1998) go to some lengths to emphasise the effect of conditions intermediate between wetting and non-wetting, taking account of the contact angle between the melt and its substrate. They find a good correlation between the contact angle and the penetration of liquid steel into silica sand moulds. Petterson (1951) suggests that the penetration of steel into sand moulds would be aided by a gradual fall in the contact angle as is commonly seen between liquids and substrates. There may be some truth in this in some situations, particularly for some alloys where vapour transport or chemical reactions are occurring. However, Hayes and colleagues measure the change in contact angle in their work and find the change insignificant. In their careful study the penetration appeared to be a simple mechanical process involving varying degrees of capillary repulsion.

Levelink and Berg have investigated and described conditions in which they suggested dynamic conditions were important (Figure 4.11). They claimed that iron castings in greensand moulds were subject to a problem that they suggested was a water explosion. This led to a severe but highly localised form of mould penetration by the metal. However, careful evaluation of their work indicates that it seems most likely that they were observing a simple
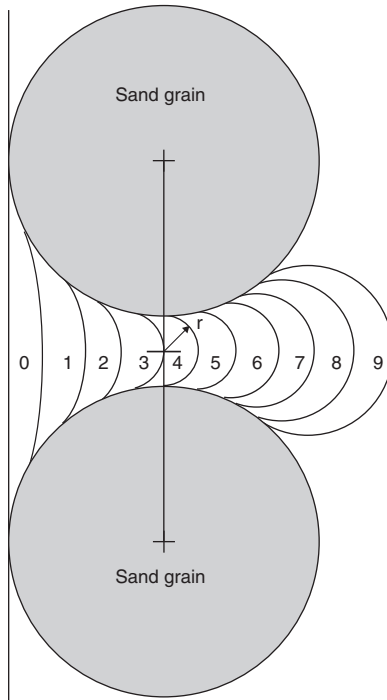
FIGURE 4.10

Metal penetration between two cylinders to simulate two sand grains. Surface tension resists the applied pressure up to the minimum radius *r*. Beyond this curvature penetration is a run-away instability.
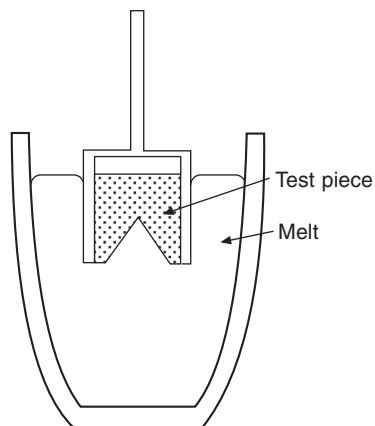
FIGURE 4.11

Water hammer (momentum effect) test piece (Levelink and Berg, 1971).

conservation of momentum effect. As the liquid metal fills their conical mould, it accelerates as the area of the cone decreases. As the melt nears the tip it reaches its maximum velocity, slamming the melt into the ever-decreasing space. The result is the generation of a high shock pressure, forcing metal into the sand. The effect is similar to a cavitation damage event associated with the collapse of a bubble against a ship's propeller. Although they cite the presence of bubbles as evidence of some kind of explosion, the oxides and bubbles present in many of their tests seem to be the result of entrainment in their rather poor filling system, rather than associated with any kind of explosion.

The impregnation of the mould with metal in last regions to fill is commonly observed in all metals in sand moulds. A pressure pulse generated by the filling of a boss in the cope will often also cause some penetration in the opposite drag surface of a thin-wall casting. The point discontinuity shown in Figure 2.27 will be a likely site for metal penetration into the mould. If the casting is thin-walled, the penetration on the front face will also be mirrored on its back face. Such surface defects in thin-walled aluminium alloy castings in sand moulds are highly unpopular, because the silvery surface of an aluminium alloy casting is spoiled by these dark spots of adhering black sand (sometimes called 'the black plague'!) and thus will require the extra expense of being removed by hand, or blasting with shot or grit.

Levelink and Berg (1968) report that the problem is increased in greensand by the use of high-pressure moulding. This may be the result of the general rigidity of the mould accentuating the concentration of momentum (weak moulds will yield more generally, and thus dissipate the pressure over a wider area). They list a number of ways in which this problem can be reduced:

1. Reduce mould moisture.
2. Reduce coal and organics.
3. Improve permeability or local venting; gentle filling of mould to reduce final filling shock.
4. Retard moisture evaporation at critical locations by local surface drying or the application of local oil spraying.

The reduction in the mechanical forces involved by reduced pouring rates or by local venting is understandable as reducing the final impact forces. Similarly, the use of a local application of oil will reduce permeability, causing the air to be compressed, acting as a cushion to decelerate the flow more gradually.

The other techniques in their list seem less clear in their effects, and raise the concern that they may possibly be counter-productive! It seems there is plenty of scope for additional studies to clarify these problems.

Work over a number of years at the University of Alabama, Tuscaloosa (Stefanescu et al., 1996), has clarified many of the special issues relating to the penetration of sand moulds by cast iron. Essentially, this work concludes that hot spots in the casting, corresponding to regions of isolated residual liquid, are localised regions in which high pressures can be generated in the residual liquid inside the casting by the expansion of graphite, forcing the liquid out via microscopic patches of unfrozen surface and causing local penetration of the mould. The pressure can be relieved by careful provision of 'feed paths' to allow the expanding liquid to be returned to the feeder. The so-called feed paths are, of course, allowing residual liquid to escape, working in reverse of normal feeding.

Naturally, any excess pressure inside the casting will assist in the process of mould penetration. Thus large steel castings are especially susceptible to mould penetration because of the high metallostatic pressure. This factor is in addition to the other potential high temperature reactions listed previously. This is reason for the widespread adoption in steel foundries of the complete coating of moulds with a ceramic wash as an artificial barrier to penetration.

4.5.5.2 Natural barriers to penetration

We have seen previously that in some conditions cast iron can develop a strong carbon film (the lustrous carbon film) on its advancing meniscus which is pulled down into the gap between the mould and the metal. Here it effectively separates the liquid from the aggregate, providing a mechanical barrier to prevent penetration, and retain a smooth shiny surface on the casting. Also, as we shall see, oxidising conditions can eliminate the carbon film replacing it with a liquid silicate. Penetration in oxidising conditions can then be practically guaranteed.

In copper-based foundries, the alloy aluminium bronze is renowned for its ability to resist penetration of the mould. The reason is also certainly the mechanical barrier presented by the strong alumina film; the high content of Al, in the 5–10% range, and the high temperature combine to create one of the most tenacious films in the casting world. In contrast, those bronzes not protected by a strong film in the liquid state, tin-, lead- and phosphor-bronze, all suffer penetration problems.

Similarly, Gonya and Ekey (1951) compared the behaviour of the common copper-base alloy 85-5-5 to 5-5 and the Al-5Si alloy, investigating a number of moulding variables. However, their most significant result related to pressure. They gradually increased pressure, finding penetration in the copper alloy at a critical pressure 17 kPa (2.5 psi), whereas the Al alloy continued to resist penetration up to the maximum they were able to provide in their experiment, about 30 kPa (4.5 psi). These pressures correspond to head of liquid metal of approximately 230 and 1240 mm, respectively. Clearly the low density of Al combined with the presence of the alumina film on the surface of the liquid alloy is a major benefit in avoiding mould penetration.

4.5.5.3 Temperature and time dependence of penetration

Clearly, the metal cannot penetrate the mould if the metal has solidified. Taking this impressively undeniable basic logic to heart, Brookes et al. (2007) draw attention to the importance of the mould temperature. By both computer model and experiment, they were able to demonstrate that as the mould surface temperature increased on contact with the melt and later decreased during cooling, penetration of liquid steel did not occur until the mould temperature exceeded a critical value. The penetration subsequently continued, causing the penetration effect to worsen while the temperature remained above the critical temperature. Penetration finally stopped when the temperature fell once again below the critical value. It is interesting that this relatively simple model appears to provide an explanation for the time dependence of penetration as has been known for many years (Jones, 1948; Shirey and Williams, 1968).

It should be noted, however, that the reduction of contact angle, i.e. progressively increasing effectiveness of wetting, also has been observed for many metal/mould combinations to be a function of time (for instance Wu et al., 1997; Shen et al., 2009). Also, of course, mould atmosphere greatly affects wetting ability; this too is a function of time. Thus a reducing or neutral atmosphere is useful to reduce penetration in low carbon steels in greensand moulds, whereas an oxidising atmosphere encouraged penetration as found by Draper and Gaindhar in 1975.

4.5.5.4 Chemical interactions

There seems little doubt that the contact angle between the mould particles and the melt can change with both time and temperature. Hayes et al. (1998) noted a reduction of the contact angle of liquid steel on silica sand from 110° to 93° over a 30 minute period. However, this lengthy period and relatively small change are not likely to greatly affect most steel castings because the majority will have frozen in this time.

To effect a major change in behaviour would require a major change in contact angle over a relatively short period such as a few minutes. The penetration of grey irons into silica sand moulds in oxidising condition is exactly such a candidate as has already been noted previously.

### 4.5.5.5 Effects of vapour transport

For a general overview of the knowledge of vapour transport, the reader is referred to the excellent review by Svoboda and Geiger (1969). It is salutary to reflect that it seems relatively little additional knowledge on this important subject has been gained since this early date.

On a microscale, the effects of vapour transport are likely to be complicated. Ahn and Berghezan (1991) studied the infiltration of liquid Sn, Pb and Cu inside metal capillaries using a scanning electron microscope. They found evidence of the deposition of metal vapours over a region up to 0.1 mm ahead of the advancing front. Clearly, the presence of this freshly deposited metal influenced the effect of the wetting of the liquid that followed closely behind.

Shen et al. (2009) drew similar conclusions from experiments with sessile drops in vacuum. They found that the contact angle of a zirconium/copper-based alloy on an alumina substrate fell from about 90° to 0° in about 10 min. They found Zr adsorption at the liquid/solid interface, followed by a Zr-Cu precursor film that accounted for the excellent wetting.

On a macroscale, vapour transport from metals into moulds is a common feature in foundries and will be referred to repeatedly elsewhere in this book. To give just two contrasting instances here:

a. Foundries casting magnesium into plaster moulds filled with vacuum assistance (Sin et al., 2006) find that Mg diffuses into the plaster, reacting with the SiO_2, taking the oxygen to form MgO, and reducing the Si to Mg_2Si according to the reaction

$$4Mg + SiO_2 = 2MgO + Mg_2Si$$
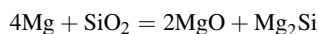
b. Bronze foundries casting classical tin-bronzes and lead-bronzes find that both alloys suffer mould penetration. However, only lead has any significant vapour pressure at the casting temperature, its pressure being between 100 and 1000 times greater than tin (see Figure 6.26). We can conclude therefore that in this particular case, vapour pressure is seen to be of minor, if any, importance; a high vapour pressure does not necessarily lead to enhanced penetration. The expected absence of any significant mould reactions or any strong surface films leaves only the relatively weak action of surface tension to inhibit penetration. Thus mould penetration for these alloys seems possible only by mechanical means: the provision of a fine mould aggregate, or a ceramic surface coat.

4.6 METAL SURFACE REACTIONS

Easily the most important metal/mould reaction is the reaction of the metal with water vapour to produce a surface oxide and hydrogen, as discussed in Chapter 1.

However, the importance of the release of hydrogen and other gases at the surface of the metal, leading to the growth of porosity in the casting, is to be dealt with in Chapter 6. Here we shall devote ourselves to the many remaining reactions. Some are reviewed by Bates and Scott (1977). These and others are listed briefly next.

4.6.1 OXIDATION

Oxidation of the casting skin is common for low carbon–equivalent cast irons and for most low-carbon steels. It is likely that the majority of the oxidation is the result of reaction with water vapour from the mould, and not from air which is expelled at an early stage of mould filling as shown earlier. Carbon additions to the mould help to reduce the problem.

The catastrophic oxidation of magnesium during casting, leading to the casting (and mould) being consumed by fire, is prevented by the addition of so-called inhibitors to the mould. These include sulphur, boric acid, and other compounds such as ammonium borofluoride. More recently, much use has been made of the oxidation-inhibiting gas, sulphur hexafluoride (SF_6) which is used diluted to about 1–2% in air or other gas such as CO_2 to prevent the burning of magnesium during melting and casting. However, since its identification as a powerful ozone-depleting agent, SF_6 is being discontinued for good environmental reasons. A return is being made to dilute mixtures of SO_2 in CO_2 and other more environmentally friendly atmospheres are now under development.

In any case, the burning of Mg alloys during pouring of the mould is almost certainly the result of surface turbulence. For instance, if liquid Mg can be introduced into a mould quiescently, so that it rises steadily with a substantially flat liquid surface in the mould, the huge heat of oxidation released on the surface is rapidly conveyed away into the bulk of the melt so that the surface temperature never rises to a dangerous level. Such a quiescent fill is therefore safe. Conversely, if the melt is jumping and splashing, the heat of oxidation will diffuse into the thin liquid splash from both sides of the splash surface, and quickly heats the small amount of metal in the splash. The ignition temperature of the melt is quickly exceeded, with disastrous results. There is a saying, which regrettably probably reflects some truth, that the few Mg foundries in existence nowadays are the result of most of them having burned down. True or not, the turbulent handling of Mg alloys is clearly dangerous but mostly avoidable. The use of an offset step basin and stopper, and a naturally pressurised filling system would make a huge difference to Mg foundries.

Titanium and its alloys are also highly reactive. Despite being cast under vacuum into moulds of highly stable ceramics such as zircon, alumina or yttria, the metal reacts to reduce the oxides of the mould, contaminating the surface of the casting with oxygen, thereby stabilising the alpha phase of the alloy. The 'alpha case' usually has to be removed by chemical machining.

4.6.2 CARBON (PICKUP AND LOSS)

Mention has already been made of the problem of casting titanium alloy castings in carbon-based moulds. The carburisation of the surface, again results in the stabilisation of the alpha phase, and requires to be subsequently removed.

The difficulty is found with stainless steel of carbon content less than 0.3% cast in Croning resin-bonded shell moulds (McGrath, 1973). The relatively high resin binder content of these moulds, generally in the region of 2.5–3.0 wt%, causes steels to suffer a carburised layer between 1 and 2 mm deep. Tordoff (1996) also found significant carbon pickup in stainless steels from phenolic urethane binders which rarely exceed 1.0–1.2 wt% based on sand. The carburisation, of course, appears more severe the lower the carbon content of the steel. Naturally, the problem is worse on drag than on cope faces as a result of the casting sitting hard down on the drag face of the mould, and contracting away from the upper surfaces. Tordoff also found that iron oxide in the moulding sand reduced the effect, whereas the use of a furan resin eliminated pickup altogether. The author could not find a record of the effect of silicate-based binders, although their usually low content of organics would be expected to give minimal problems.

Carbon pickup is the principal reason why low carbon steel castings are not produced by the lost-foam process. The atmosphere of styrene vapour, which is created in the mould as the polystyrene decomposes, causes the steel to absorb carbon (and presumably hydrogen). The carbon-rich regions of the casting are easily seen on an etched cross-section as swathes of pearlite in an otherwise ferritic matrix.

In controlled tests of the rate of carburisation of low carbon steel in hydrocarbon/nitrogen mixtures at 925°C (Kaspersma, 1982), methane was the slowest and acetylene the fastest of the carburising agents tested, and hydrogen was found to enhance the rate, possibly by reducing adsorbed oxygen on the surface of the steel. At high ratios of H_2/CH_4 at this temperature, hydrogen decarburises steel by forming methane (CH_4). This may be the important reaction in the casting of steel in greensand sand moulds containing only low carbonaceous additions.

Decarburisation can also be a problem. For instance, surface decarburisation of steels is often noted with acid-catalysed furan resin binders (Naro and Wallace, 1992).

In the investment casting of steel in air, the decarburisation of the surface layer is particularly affected because atmospheric oxygen persists in the mould as a consequence of the inert character of the mould and its permeability to the surrounding environment. Doremus and Loper (1970) have measured the thickness of the decarburised layer on a low carbon steel investment casting and find that it increases mainly with mould temperature and casting modulus. The placing of the mould immediately after casting into a bin filled with charcoal helps to recarburise the surface. However, Doremus and Loper point out the evident danger that if the timing and extent of recarburisation is not correct, the decarburised layer will still exist below a recarburised layer!
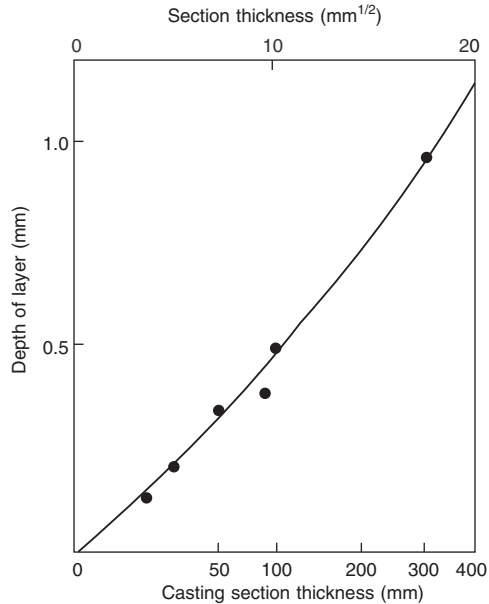
In iron castings, the decarburisation of the surface gives a layer free from graphite. This adversely affects machinability, giving pronounced tool wear, especially in large castings such as the bases of machine tools. The decarburisation seems to be mainly the result of oxidation of the carbon by water vapour because dry moulds reduce the problem. An addition of 5–6% coal dust to the mould further reduces it. Rickards (1975) found that the reaction seems to start at about the freezing point of the eutectic, 1150°C, and proceeds little further after the casting has cooled to 1050°C (Figure 4.12). Stefanescu et al. (2009) find that the depth of the casting skin in ductile iron is controlled by diffusion to only about 0.5 mm if the liquid in the casting is relatively quiescent, whereas the strong convection currents during solidification of larger castings causes mixing, increasing the skin depth to nearly 3 mm.

4.6.3 NITROGEN

Nitrogen pickup in grey cast irons appears to be directly related to the nitrogen content of mould binders (Graham et al., 1987). Ammonia is released during the pyrolysis of urea and amines contained in hot box and Croning shell systems when they become recycled into a greensand system. Ammonia appears to be reversibly absorbed by the bentonite clays and is released on heating. The pyrolysis of ammonia releases nascent nitrogen and nascent hydrogen by the simple decomposition

$$NH_3 = N + 3H$$
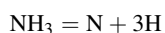
Graham and coworkers confirmed that subsurface porosity and fissures in irons do not correlate well with the total nitrogen content of the sand, but were closely related to the total ammonia content. Lee (1987) confirms the usefulness of an ammoniacal nitrogen test which in his work pointed to wood flour as a major contributor of ammonia in his greensand system.

Section thickness (mm$^{1/2}$)

FIGURE 4.12

Depth of decarburisation in grey iron plates cast in greensand.

Data from Rickards (1975).

The link of ammonia and the so-called nitrogen fissures in iron castings suggests the formation of nitride bifilms which might be opened, becoming visible, by inflation with the copious amounts of hydrogen released by the decomposition of ammonia.

At the other end of the casting value system, vacuum-cast Ni-based superalloys suffer severely from nitrogen pickup from the moment the door of the vacuum furnace is opened, allowing air to rush in and react while the casting is still hot. Casting returns in such foundries are known to contaminate the new melts, although the contamination would be expected not to be nitrogen in solution, but nitride bifilms in suspension. These conjectures require more research to clarify the situation.

4.6.4 SULPHUR

The use of moulds bonded with furane resin catalysed with sulphuric and/or sulphonic acid causes problems for ferrous castings because of the pickup of sulphur in the surface of the casting (Naro and Wallace, 1992). This is especially serious for ductile iron castings, because the graphite reverts from spheroidal back to flake form in the high-sulphur surface layer. This has a serious impact on the fatigue resistance of the casting.

4.6.5 PHOSPHORUS

The use of moulds bonded with furane resin catalysed with phosphoric acid leads to the contamination of the surfaces of ferrous castings with phosphorus (Naro and Wallace, 1992). In grey iron, the presence of the hard phosphide phase in the surface causes machining difficulties because of rapid tool wear.

4.6.6 SURFACE ALLOYING

There has been some Russian (Fomin, 1965) and Japanese work (Uto, 1967) on the alloying of the surface of steel castings by the provision of materials such as ferrochromium or ferromanganese in the facing of the mould. Because the alloyed layers that have been produced have been up to 3 or 4 mm deep, it is clear once again that not only is diffusion involved but also some additional transport of added elements must be taking place by mixing in the liquid state. Omel'chenko further describes a technique to use higher-melting-point alloying additions such as titanium, molybdenum and tungsten by the use of exothermic mixes. Predictably enough, however, there appear to be difficulties with the poor surface finish and the presence of slag inclusions. Until this difficult problem is solved, the technique does not have much chance of attracting any widespread interest.

4.6.7 GRAIN REFINEMENT

The use of cobalt aluminate ($CoAl_2O_4$) in the primary mould coat for the grain refinement of nickel and cobalt alloy investment castings is now widespread as described in early reports by Rappoport (1964) and Watmough (1980). The mechanism of refinement is not yet understood. It seems unlikely that the aluminate as an oxide phase can wet and nucleate metallic grains. That the surface finish of grain refined castings is somewhat rougher than that of similar castings without the grain refiner indicates that some wetting action has occurred. This suggests that the particles of $CoAl_2O_4$ decompose to some metallic form, possibly CoAl. This phase has a melting point of $1628°C$. It would therefore retain its solid state at the casting temperatures of Ni-based alloys. In addition it has an identical face-centred–cubic crystal structure to nickel. On being wetted by the liquid alloy, it would be expected to constitute an excellent substrate for the initiation of grains.

Watmough also investigates a number of other additives to coatings for Ni-base high temperature alloy castings including cobalt oxide, CoO. Because oxides are almost certainly not effective nuclei for solid formation and because CoO is not especially stable (Llewelyn and Ball, 1962), it is likely that the compound decomposes at casting temperature forming metallic cobalt which would be expected to be an effective nucleus for the alloy. Although its melting point is not significantly higher than the alloy, that the Co particles sit at the mould wall will ensure that they remain cool and therefore will resist melting and continue to act as nucleating particles.

It is to be expected that there can be no refinement if all the CoAl particles are either melted or dissolved, or if the newly nucleated grains are themselves re-melted. Unfortunately, such re-melting problems are common in investment castings as a result of (1) casting at too high a temperature and (2) convection problems that have so far been overlooked. It is regrettable that the beautifully fine grain structure produced by these techniques is often lost by subsequent convection in the casting, conveying so much heat from hotter regions that parts of the surface in the path of the flow re-melt, destroying the nuclei and the early grains, and replacing these with massive grains of uncontrolled size. In addition, the small depth of grain refinement (Watmough reports only 1.25 mm) is another probable consequence of uncontrolled convection. It is expected that control and suppression of convection in investment castings would greatly improve cast structures in polycrystalline high temperature alloy castings. These issues are dealt with in *Casting Manufacture* in Casting Rule 7 'Avoiding Convection'.

Cobalt addition to a mould coat is also reported to grain-refine malleable cast iron (Bryant, 1971), presumably by a similar mechanism to that enjoyed by the vacuum-cast Ni-base alloys.

The use of zinc in a mould coat by Bryant and Moore to achieve a similar aim in iron castings must involve a quite different mechanism, because the temperature of liquid iron ($1200–1450°C$) greatly exceeds not only the melting point, but even the boiling point ($907°C$) of zinc! It may be that the action of the zinc boiling at the surface of the solidifying casting disrupts the formation of dendrites, detaching them from the surface so that they become freely floating nuclei within the melt. Thus the grain refining mechanism in this case is grain multiplication rather than nucleation.

The zinc-containing coating and others listed next all appear to induce grain multiplication as a result of the rafts of dendrites attempting to grow on an unstable, moving and collapsing substrate. The effect seems analogous to that described in Section 3.2.6 for the enhancement of the fluidity of Al alloy castings by coatings of acetylene black or hexachlorethane on moulds.

Nazar et al. (1979) report the use of hexachlorethane-containing coatings for the grain refinement of Al alloys.

4.6.8 MISCELLANEOUS

Boron has been picked up in the surfaces of stainless steel castings from furane bonded moulds that contain boric acid as an accelerator (McGrath, 1973).

Tellurium is sometimes deliberately added as a mould wash to selected areas of a grey iron casting. This element is a strong carbide former, and will locally convert the structure of the casting from grey to a fully carbidic white iron. Chen et al. (1989) describe how TeCo surface alloying is useful to produce wear-resistant castings.

In other work, the carbide-promoting action of Te is said to reduce local internal shrinkage problems, although its role in this respect seems difficult to understand. It has been suggested that a solid skin is formed rapidly, equivalent to a thermal chill (Vandenbos, 1985). The effect needs to be used with caution: tellurium and its fumes are toxic, and the chilled region causes difficulties in those parts requiring to be machined.

The effect of tellurium converting grey to white irons is used to good purpose in the small cups used for the thermal analysis of cast irons. Tellurium is added as a wash on the inside of the cup. During the pouring of the iron, it seems to be well distributed into the bulk of the sample, not just the surface, so that the whole test piece is converted from grey to white iron. This simplifies the interpretation of the cooling curve, allowing the composition of the iron to be deduced.

4.7 MOULD COATINGS
4.7.1 AGGREGATE MOULDS

Although we have dealt at length with reactions that can occur between the metal and the mould, the purpose of a mould coating is to prevent such happenings by keeping the two apart. It has to be admitted that for many formulations, these attempts are of only limited success. Some useful reviews of coatings from which the author has drawn are given by Vingas (1986), Wile et al. (1988) and Beeley (2001). Vingas in particular describes techniques for measuring the thickness of coatings in the liquid and solid states. All describe the various ways in which coatings can be applied by dipping, swabbing, brushing and flow-over. These issues will not be dealt with here.

With regard to the definition of a coating, it is a creamy mixture made up from of a number of constituents:

1. *Refractory,* usually oxides of many kinds ground to a particle size of 50 μm or less, but for cast irons carbonaceous material is common in the form of graphite or ground coke etc.
2. *Carrier* nowadays becoming more commonly water (alcohols and chlorinated hydrocarbons have environmental problems). This has to be removed after the coating has been applied, usually requiring the application of heat.
3. *Suspension agent* required to maintain a uniform dispersion of the refractory. Commonly used materials include sodium bentonite clay or cellulose compounds. Beeley (2001) describes a problem with the clay addition, as a result of the water soaking into the mould surface, but being hindered during the subsequent drying because of the presence of the impervious clay coat. The development of a coating without the clay addition doubled the rate of drying.
4. *Binder* which is often the same as that used for bonding moulds. Thus, organic resins, colloidal silica and sodium silicate-based binders are common. Interesting incompatibilities are sometime experienced, such as the fact that magnesite coatings for steel castings may be difficult to use with sand bonded with furan resins because of the acid content of the resin, whereas magnesite coatings perform excellently when used in conjunction with silicate-bonded moulds and cores.
5. *Sundry chemicals* including surfactants to improve wettability, antifoaming agents and bactericides.

The advantages of coatings include the following

1. Reduction of cleaning costs because of improved surface finish (finer surface, reduced or eliminated veining, reduced penetration and/or burn-on and reduced reactions between metal and mould, for instance between (a) manganese steel and silica sand, and (b) binder gases such as sulphur compounds from furan binders)

2. Improved shake-out because of improved sand peel.
3. Reduced machining time and tool wear.

However, an important aspect to bear in mind, as with the provision of feeders, the best action (if possible) is to avoid coatings. There are many reasons for avoiding coatings. Disadvantages include the following

1. Cost of materials, especially those based on expensive minerals such as zircon.
2. Potential loss of accuracy because of difficulty of controlling coat thickness and coating penetration.
3. Possibility of cosmetic defects from runs and drops.
4. Floor space for coating station.
5. Energy cost to dry and possible capital cost and floor space for drying ovens and extraction ducting and fans.
6. Floor space to dry if dried naturally (this might exceed moulding space because drying is slow).
7. Drying time can severely reduce productivity.
8. Cores appear to be never fully dried, despite all attempts, after the application of a coating, so that there is enhanced danger of blow defects if the core cannot be vented to the atmosphere.
9. Environmental problems: at this time many coatings are still alcohol (ethanol) based, and so burned off rather than dried. This reduces floor space and energy, but does add to the loading of volatile organic compounds in the environment. This approach is likely to be banned under future legislation, forcing the use of water-based coatings.

The water-based coatings pose a significantly increased drying problem. Puhakka (2009) describes the novel use of a remote infra-red camera to monitor the drying process; while water is still evaporating the surface will remain cool. Only when fully dry will the surface temperature of the mould rise to room temperature.

Coating costs for the foundry are usually justified on (1) and (2) of the previous advantages and should be based on the dry refractory deposited. Naturally, costs are directly related to the surface area to volume ratio of the castings, and so will vary from foundry to foundry. Alternatively, surface area per ton of castings is a useful measure.

Coatings are not required in general for the lower melting point metals such as the zinc-based alloys and the light metals, Al- and Mg-based alloys, but are widely used for cast iron, copper-based alloys and steels.

The use of coatings on cores to prevent core blows is usually a mistake. Although the coating does reduce the permeability of the surface, assisting to keep in the expanding gases, the additional volatiles from the coat, which appear to be never completely removed by drying, are usually present in excess to overwhelm the coating barrier.

Another interesting mistake is the use of coatings to prevent sand erosion. The presence of sand defects in a casting is never, in my experience, the fault of the sand. It immediately signals that the filling system is faulty. A turbulent filling system that entrains air will splatter and hammer against the sand surface, oxidising away any binder, and so erode away cores and moulds. Although, of course, a coating will reduce the problem, it is often less costly and more effective to upgrade the filling system to a naturally pressurised design. In this way, the moulds and cores are at all times gently pressurised by the melt, causing the sand grains of the mould to be held safely in place. An additional bonus is a better casting, enjoying more reliable properties and freedom from other defects such as porosity and cracks.

4.7.2 PERMANENT MOULDS AND METAL CHILLS

Permanent moulds or chills in grey iron or steel are practically inert, so any mould coat is not required to prevent chemical reactions between the two. A coat will help to

1. protect the mould from thermal shock;
2. avoid the premature chilling of the metal that might result in cold lap defects and
3. confer some 'surface permeability' on the impermeable surface to allow the melt to flow better over the surface, and allowing the escape of any volatiles or condensates (particularly from the surface of chills).

It is often seen that two different mould coatings are used on a permanent mould. A thin smooth coating is applied to the mould cavity which forms the casting, whereas a thick, rough, insulating coating is applied to the running system in an effort to avoid temperature losses during mould filling. This is a mistake. The metal is in the running system for

perhaps only 1 to 2 s (because its velocity is in the range of metres per second, and the distance involved is usually only a metre or less) that any loss of temperature is negligible. Furthermore, the roughness of this coat endangers the flow because of the consequential turbulence. It is far better, much less trouble, less time-consuming and less costly simply to coat the whole die with the same thin, smooth coat. The castings will probably be improved.

4.7.3 DRY COATINGS

Dry coatings are of course an attractive concept because no drying is involved and there is no danger of introducing additional volatiles into moulds or cores.

Greensand moulds have benefited somewhat from the use of dusting powders of various kinds and more recently by the electrostatic precipitation of dry zircon flour (precoated with an extremely thin layer of thermosetting resin, activated by the heat of the metal during casting). This development appears to have been resistant to extension to dry sand processes because of the generally poorer electrical conductivity of dry sand moulds particularly when bonded with a phenol-urethane resin. It would be interesting to know whether more success might be expected from moulds made with materials having higher electrical conductivity such as sand bonded with acid-catalysed resins, silicates or alkaline phenolics, or with chromite sand.

A successful technique for the application of dry coatings to dry sand moulds has therefore proved elusive. Simply dusting on dry powder, or attempting to apply it in a fluidised bed, suffers from most of the powder being blown off as clouds of dust when the mould is cleaned by blowing out with compressed air prior to closure.

A Japanese patent (Kokai, 1985) describes how fine refractory powder in a fluid bed is drawn into the surface pores of an aggregate mould or core by applying a vacuum via some far location on the mould or core. However, of course, despite probably being useful for simple geometries, this technique fails for complex shapes. Another Japanese patent describes how fine powder in a fluid bed is forced into the pores of a mould by a mechanical brushing action. A Canadian automotive foundry has developed a fluid bed containing a mixture of the fine coating powder together with relatively heavy zircon grains. The jostling of the zircon grains effectively hammers the powder into the mould pores.

These dry coating techniques deserve wider use. When correctly applied, the coating simply fills the interstices between the surface grains of the mould, not adding any thickness of deposit. Thus the technique has the advantage of preserving the accuracy of the mould while improving surface finish with no drying time penalty.