Inclusions from moulds, cores, metal treatment and handling

Since inclusions can result from a variety of different sources, it is vital that an accurate diagnosis of the defect is made initially, so that the correct preventive action can be taken.

Inclusions from the mould and cores

Inclusions emanating from moulds and cores almost invariably consist of either particles of sand, or mould and core dressings. In pouring, the particles are washed into the casting, as a result of molten iron eroding loose material from mould and core surfaces. Usually, the inclusions occur at places remote from the point where erosion originally took place, and they may be found in both surface and sub-surface layers of the casting.

Visual examination

If a casting contains gross inclusions, as shown in Fig. 1, visual examination of the defect, perhaps with a small magnifying glass, may indicate the presence of sand grains. The illustration shows large inclusions observed in a casting after it had fractured. Clearly, the overall influence of the defective area will weaken the casting by reducing its effective section thickness, which is an extremely dangerous situation. Additionally, the inclusions can act as stress raisers, which may cause the casting to fail in service at a stress much lower than the design stress. If pressure testing is a key service requirement, the casting may fail if the defective area is large.

Microscopic examination

In many instances, however, inclusions are too small to identify by a simple visual examination, and a microscope must be used. It is necessary to section the casting through the defective region and polish its surface before examination. Such a preparation is shown in Fig. 2, where the individual sand grains can be observed against the background of the cast iron matrix. Here, etching has revealed the structure of the matrix. Fig. 3 shows the appearance of sand grains examined metallographically under conditions of normal vertical illumination. The sand grains have no regular outline and appear dark grey in colour. Great care must be exercised when sampling to prevent dislodgement of the sand grains. In addition, much evidence of inclusions can be lost when the casting is shotblasted before examination.

Generally, a simple metallographic examination is satisfactory, but further confirmatory examinations can be carried out. For example, identification of inclusions other than sand grains can be made with the aid of a scanning electron-probe micro-analyser. This enables individual particles to be analysed by bombarding them with electrons and measuring the intensity of the X-rays emitted, while simultaneously observing the area at high magnification. This technique is illustrated by an examination carried out at BCIRA, of inclusions in a large grey iron piston casting. The inclusions were first located at a fairly low magnification, (Fig. 4), and then the magnification was increased until the individual particles could be observed—as in Fig. 5—and analysed. In this instance, the white angular inclusions were found to be particles of zircon, and after discussions with the foundry concerned, it was found that a mouldwash containing zircon had been used on one specific area of the mould. This mouldwash, which was never used elsewhere, could be ruled out as the cause.
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Preventing sand inclusions

To prevent the occurrence of sand inclusions in castings, originating from the mould and core, the following production factors should be examined and controlled.

- Pattern and core box equipment
- Moulding boxes
- The moulding process
- Core preparation and core laying
- The running and gating system
- Mould closure
- Box handling
- The pouring operation

Pattern and core box equipment

Badly worn or damaged pattern equipment—This may lead to damaged or broken moulds when drawing patterns. The moulds will require patching, which often results in a friable surface subsequently leading to sand erosion.

Misplacement of the pattern plates—This may lead to cross-jointing, which in turn results in inclusions from the flashes of sand eroded by the metal stream. Patterns should be checked for alignment before they are used.

Insecurely fastened running system—Thin ridges of sand, formed between loose gates and runners on the pattern plate, will almost certainly be washed into the mould cavity by the molten iron. Where possible, the running system should be formed during the moulding operation and not cut out later.

Moulding boxes

The condition of moulding boxes can also influence the presence of inclusions in the final casting. Crusses and cross-jointing may occur as a direct consequence of using:

a) Improperly matched or warped moulding boxes
b) Severely worn location pins and bushes, or pins bound during mould closure.

If large moulding boxes are used, enough reinforcing bars should be fitted to support the sand mass, thereby preventing the mould from cracking and/or sagging.

The moulding process

Moulding sand compaction—Regardless of the moulding process used, it is essential that the mould is compacted as uniformly as possible and that the required mould hardness is achieved. For chemically bonded sand moulds, it is vital the correct curing and hardening rates are used to prevent friability. After compaction, the as-moulded surfaces should not be disturbed. As mentioned earlier, the running system, where possible, should be formed during the moulding operation and not cut out at a later stage.

Mould cleanliness—After the moulding and core laying processes and the application of any surface treatment, the mould should be cleaned and dried. Any remaining debris or surface contamination should be removed to prevent inclusions from adhering during the casting process.
vacuum tube; the mould should be carefully inspected for cleanliness before closing.

Core preparation and core laying

Core box wear—This should be checked to ensure no formation of sand flash at loose piece junctions. In Fig. 6 a thin sand fin at the box joint can clearly be seen, which can easily be eroded by the metal stream. Cross-jointing as shown in Fig. 7, is another obvious cause of inclusions. Oversize cores and core prints, produced from worn coreboxes, require rubbing down, which will disturb the surface layers and make them subject to erosion. The core in Fig. 8 (which shows lumps of the core broken away) will be prone to sand erosion. Crushes, caused by displacement of sand at the core prints, can also result from worn corebox equipment.

Compaction of the core—Loosely adherent particles of sand remaining on the core should be removed before the cores are laid; an example of this is shown in Fig. 9.

Badly compacted cores, as shown in Fig. 10, should be discarded. The illustration shows a poorly compacted core due to blocked corebox vents—these can be seen clearly in Fig. 11. A further example of poor compaction is shown in Fig. 12.

A ‘stickled’ core surface may be friable, and it is important to arrange core production so that stickled surfaces do not come into contact with the metal stream. Inspection of cores is vital, and for a mechanized plant a flowline inspection system is advisable, in order to remove excess sand, flash, blacking fillers, and core glue, which may have exuded from the core joints.

Coreprints—Cores should locate exactly in their prints, and prints should be large enough to support the mass of the core, so that no movement or crushing occurs during the moulding and pouring operation.

The running and gating system

Cutting the running system—It is preferable that the running system should be formed during the moulding operation and not cut out later, since after the sand is compacted, any disturbance will, without doubt, give a friable surface which will be subject to erosion. Additionally, cutting the running system after compaction can lead to breakage of adjacent mould surfaces, necessitating patching; the patched layer is never as resistant to the erosive effect of the molten iron as the original moulded surface.

Design of the running system—The running and gating system should be designed so that metal enters the mould cavity with minimum turbulence. Direct impingement of the metal stream on any part of the mould or cores must be prevented, to avoid sand or coating erosion.

Badly formed running system—It will be found from experience that a high proportion of sand inclusions in castings arise from badly formed pouring bushes and gating systems. Care is required to ensure that these are clean and well compacted, and that no loose flashes of sand are formed, particularly at bush to downsprue entry, as these could easily be washed into the mould cavity during pouring. It is desirable to mould the bush on the squeeze board, or for larger moulds, the bushes should be made separately, using chemically bonded sand. The size and shape of pouring bushes is also important, to avoid ingress of sand and slag. For example, the pouring basin should be smooth sided, with radiused corners to prevent erosion, and deep enough to prevent splashing. Preferably, these basins should be square or rectangular, since round or elliptical basins tend to promote
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Mould closure

Clamping and weighting—This should be done while the locating pins are in position, and the pins should remain in position until pouring has been completed. The closing operation should be carried out slowly and without jolting, to avoid possible crushing and dislodgement of sand particles from the cope. Hammering the clamps can also lead to sand particles being dislodged.

Excessive or uneven weighting should be avoided at all costs, and the application of a weight 50 per cent greater than the upthrust force imposed on the mould during the pouring operation, is normally sufficient for most practical purposes.

Box handling

Mishandling—After closure, any box handling, if not carried out properly, may result in sand inclusions. Before pouring, movement of the mould should be kept to a minimum, to avoid displacement of sand from the cope or any other overhanging sections of the mould. ‘Close pitched’ roller conveyors should be used wherever possible, if box handling is necessary.

Maintenance of conveyor systems—Effective preventive maintenance is required, to ensure that any roller tracks and pallet conveyor systems function effectively—allowing smooth transportation of moulds to the pouring area without jolting or banging.

It is not advisable to move moulds from the moulding area to the pouring station by other methods, for example, on pallets or by fork-lift truck, owing to the degree of handling these methods require, and the unevenness of most foundry floors.

The pouring operation

Effective supervision of the pouring operation is necessary, to ensure that each mould is poured at the correct rate and from as near as possible a constant height. Additionally, it is important to keep the pouring bush full of metal during mould filling.

Sand control tests

Regardless of the effectiveness of all the controls mentioned previously, if the sand properties are unsatisfactory in either the mould or core sands, an increase in incidence of sand inclusions can be expected.

In the case of greensand, frequent determinations of the following should be carried out:

a) Moisture content.
b) Shatter index.
c) Green strength.
d) Dry strength.
e) Permeability.
f) Compactability.

Testing frequency is dependent upon type of foundry. In a fully mechanized foundry, hourly intervals should be considered the maximum.

For example, sands of low moisture content (often the result of high sand temperature) and low shatter index, are likely to lead to friable and brittle moulds; these moulds are prone to inclusion.
Less frequently, further tests of the sand conditions should, ideally, be carried out.

a) Volatile matter.
b) Loss on ignition.
c) Sand gradings.
d) Dead clay and coalsdust content.

Mechanized foundry—daily.
Jobbing foundry—perhaps weekly.

The results of the sand tests should preferably be recorded graphically, as shown in Fig. 13, or using S.P.C. so that any divergent trends based upon the individual foundry’s experience can be highlighted. Corrective action can then be taken, before a critical stage is reached.

In core manufacture, the main requirement is the production of a hard core with close dimensional tolerances. The tests carried out on the core sands will depend upon the type of system used. For example, in the case of shell moulding and hot box processes, the loss on ignition and strength tests are possibly the best controls, although checks on incoming raw materials remain essential.

For cold setting systems, the following tests should be carried out on a regular basis:

a) Bench life.
b) Curing rate.
c) Gas evolution

Very fast-setting sands with a short bench life are prone to friability, resulting in sand inclusions.

**Mould and core dressings**

Mould and core dressings are applied to prevent surface defects. However, unless care is exercised, inclusions may result from their use. Ideally, the thermal expansion characteristics of any coating should be similar to those of the mould or core materials, to prevent a coating cracking or spalling away from the mould wall surfaces.

With proprietary coatings, close attention should be paid to the manufacturer’s recommendations regarding dilution and applications of coating. Where a water-based or spirit-based dressing is used, its viscosity must be controlled. After application, the coating should be completely dried before pouring. Since spirit-based coatings contain a small amount of water, torching of the mould or core should be carried out after completion of the initial firing, to achieve efficient drying and reduce the risk of spalling.

**Example of inclusions arising from mould coatings**

During an examination of a large grey iron compressor body casting, inclusion defects arising from mould and core dressings were highlighted. The casting, with an overall length of 163 cm, 51 cm outside diameter and a wall thickness of 13 cm, weighed 1 tonne. During machining, defective areas were revealed (Fig. 14) in the internal bore, and depending upon the severity of the defect, it was either rectified by metal-arc welding, or the casting had to be scrapped; obviously there was considerable cost to the foundry if the casting was scrapped. Additionally, some seemingly sound castings were found to leak during pressure testing.

The castings were produced in CO₂/silicate sand moulds, the cores being made from furan. All moulds and cores were coated with a spirit-based blacking.

The specimen casting was sectioned through the defective areas for examination. At first, the fissure-like appearance of the cavities as shown in this illustration (Fig. 15) suggested possible nitrogen porosity, but after microscopic examination at a higher magnification, the presence of
coating material in the cavities was revealed. A further section, taken within the defective areas, showed the presence of sand grains (Fig. 16), probably caused by erosion of the underlying mould or core surfaces following cracking or spalling of the coating.

After the foundry practice involved in the production of the castings had been observed, the following factors were highlighted: (Fig. 17).

Viscosity—It was found that the viscosity of the coating material was not being controlled, as the manufacturer’s recommendations regarding dilution were being ignored.

Suspension—The material was allowed to settle, and the coating was not mixed before application.

Application—An excessively thick layer of coating was applied to both moulds and cores, increasing the risk of spalling.

Drying—The coating surfaces were not torched after initial firing. The coating was not, therefore, effectively dried, hence the risk of cracking and spalling.

Subsequent attention to the above factors had a marked effect in reducing the incidence of inclusion defects in the castings produced at the foundry.

Shell moulding

A defect which occurs both when certain air-setting sands are used, and (more commonly) in shell moulding, is sometimes observed. Figs. 18 and 19 illustrate the defect, which is rather like a cold lap. It is usually referred to as a lustrous carbon surface defect, and it occurs on the top surfaces of castings, where the surface area is large. Closer examination indicates a type of seam or lap between the metal surfaces, which contain a sooty deposit.

The defects are caused by evolution by hydro-carbon gases from the breakdown of resin material, produced during the pouring operation; these decompose inside the mould cavity, to form a carbonaceous film which deposits on the uppermost part of the mould cavity. In some instances, particularly during turbulent flow of the metal, the carbon deposit may be deeply embedded into the casting surface.

A complete solution to the problem of lustrous carbon defects has not been found, although attention to the gating systems, to reduce turbulence during pouring, or to overflowing the mould cavity to remove the film formed on the metal, will help reduce the incidence of this type of defect.

Probably the most important factor influencing lustrous carbon defects is pouring temperature, and an increase in the temperature will usually help to solve the problem. Other factors, including adequate venting arrangements, the use of mould coatings, a reduction in the binder level of the sand, or even rebaking the shells before casting, have sometimes eliminated the defect.

Inclusions resulting from metal treatment and handling

Many types of inclusion defect can occur in castings as a direct result of poor treatment and handling techniques.

A complex of oxides of metal and refractory forms on the metal surface once melting is complete and continues to form on the liquid metal surface. Therefore, as metal is transferred to receiving bell
or by automatic pouring unit, a surface layer is continually forming on the metal. In grey irons this is usually called slag. In ductile irons this is normally referred to as dross. Fig. 20 shows an open top ladle with a thick layer of slag. This is very likely to result in a slag inclusion defect in the casting.

**Formation of slag and dross**

Slag or dross can be formed by:

a) Furnace slag entering the transfer vessel.
b) Oxidation of the metal surface.
c) Fusion of, or fluxing of, refractories.
d) From residual slag coagulant.
e) Additions to the liquid metal.
f) From metal splashes, turbulence during pouring and as a result of interruptions in the filling of the mould.

**Furnace slag**—This should not be a normal occurrence but some transfer can occur, particularly with intermittent tapping of cupolas or if the furnace level is run very low in electric melting, making complete removal of slag difficult. Furnace slag is usually acid in nature and is very adherent to the refractories, with which it comes into contact and likely therefore to concentrate in launders and receivers. Cupola slag is rare in castings, but can be identified readily as clear, glassy particles, often containing small metal beads. Cupola slag particles in a cylinder casting are illustrated in Fig. 21.

Build-up of slag in receivers generally occurs continuously during the day through oxidation of the metal surface, particularly where a large surface area of metal is exposed. This slag must be confined to the receiver and this is best achieved by the use of a well designed teapot pouring spout. Any transfer of slag quickly contaminates the next vessel, such as the ladle or an autoupour unit. A severely contaminated vessel should be taken out of service for chipping out and relining.

In order to prevent excessive slag generation, it is also important to avoid excessively long and wide launders, which promote rapid oxidation.

**Surface oxidation**—Oxidation increases as metal cools and the surface oxides which form in the ladle, receiver or transfer vessel react to form complex iron/manganese silicates on the surface of grey iron. Magnesium rich complexes form in the case of ductile irons and are relatively easy to remove because they remain ‘dry and granular’. In grey irons, however, manganese sulphide rich slags can occur, which, if they enter the mould cavity, form defects normally referred to as manganese sulphide blowholes. These defects are illustrated in Figs. 22 and 23, which show typical blowholes due to the generation of carbon monoxide gas, as a result of the slag reacting with the graphite formed on solidification in the iron.

The blowholes are usually located in the top surface of the casting and the microstructure shows distinct segregates of manganese sulphide. The defect is associated with low pouring temperature and is made worse by high Mn or S contents in the iron.

A common and technically dangerous practice is that of refilling ladles containing cold-metal dregs. Cold metal dregs are normally coated with a slag layer rich in MnS and this can create defects even when the refilled ladle contains hot metal, because it cannot redissolve. This bad practice should be discouraged and there should be adequate pigging facilities.

**Refractories**—The metal in transfer comes into contact with a range of refractory materials, all of which must be non-wetting to the iron and of sufficient refractoriness to resist attack at temperatures up to 1500 °C. An example of a commonly used refractory which can give problems is cupola botting.
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plugs. The low fusion point constituents in some of these botts can find their way into the transfer ladle. The botts must be made up therefore of a high fusion point fire-clay and the use of red sand botts, which contain low melt point materials (1250 °C in some cases), must be avoided. See Fig. 24.

Ganister, which is made up of siliceous pebble or grog, together with sand and clay, can also be low in refractoriness. The presence of discrete quartz in the defects is often a tell-tale sign that refractory has been eroded, probably due to a low fusion point clay in the mix. Some of the grog can be volcanic in origin, (i.e. a pearlite) and may have a very low melting point, as can some slag coagulants of similar composition. In some slag coagulants the melt point of the constituents can be as low as 1200 °C, which leads to slag production on contact with liquid metal. It is necessary therefore, to remove all traces of slag coagulant in the skimming operation. Any slag coagulant left on the metal surface will continue to form a highly fluid and low melting point complex as the temperature falls.

Additions to liquid metal—Increasing use is made of inoculation and a range of inoculant materials is available to the foundry. It is vital that these are taken completely into solution in the metal. Poor solution can occur if:

1. Metal is too cold.
2. Excessive quantities are added.
3. There is inadequate mixing leading to inclusion defects.
4. Slag is not removed from the metal surface.

Defects resulting from an addition of ferrosilicon to cold metal are illustrated in Figs. 25, 26 and 27.

Other ferro-alloy additions need care to ensure solution. Ferromolybdenum and ferrochromium are sometimes added to make high-grade irons. The melting point of FeMo is 1900 °C and it is denser than iron. Consequently it is a difficult material to dissolve. Fig. 28 illustrates undissolved ferromolybdenum particles in a casting and Fig. 29, the acicular structure which can form adjacent to these particles, leading to extreme difficulty in machining. Undissolved ferrochromium promotes hard spots and leads to machining problems and this is illustrated in Fig. 30.

When cupola melting, it is important that alloys are added to the metal while it is flowing down the launder and as near to the taphole as possible. A maximum addition level of 1% is a useful guideline. During electric melting operations, it is preferable to add non-inoculating alloys to the furnace and there is no practical limit to the amount that can be added.

An often neglected source of oxide, slag and dross entrapment is turbulent pouring and in particular, interruptions in pouring or pouring arrests. Arrests allow slag to pass through spinners and traps and turbulence promotes the formation of cold beads of metal and also sand erosion.

Two important additional defences are available to prevent inclusion problems.

1. Fig. 31 illustrates graphically a record of improvements achieved by increased ladle care and the use of teapot spouts. A word of warning—a facility to pour down excess iron over the back of the ladle is vital as any ingress of slag up the teapot spout can give rise to prolonged slag generation.
2. Foam and cellular ceramic filters have greatly assisted in the prevention of dross/slag inclusions, particularly in the ductile iron foundry. However, care is needed, particularly in the choice of filters and its correct positioning in the running system. A positive print should be moulded to fully support the filter to avoid breakup of the filter and ironically the formation of a defect from this source often of greater severity than a defect from an unfiltered system.

Finally, another defect which can be easily overlooked and which occurs due to excessively high carbon equivalent, is the formation of kish graphite. This graphite floats onto top casting surface
Fig 1  Fracture in castings weakened by large inclusions

Fig 2  Section through defect revealing individual sand grains

Fig 3  Sand grains under microscope vertical illumination

Fig 4  Inclusion first located at low magnification

Fig 5  Inclusion examined at high magnification
Fig. 6 Sand flash resulting from corebox wear.

Fig. 7 Cross jointing of cylinder block core

Fig. 8 Damaged core which will be prone to sand erosion
Fig. 9. Adhering particles of sand on baked oil sand core

Fig. 10. Badly compacted core

Fig. 11. Close up of badly compacted core showing blocked vent

Fig. 12. A further example of poor core compaction
Fig. 13. Sand test recording chart

Fig. 14. Defect in large casting caused by coatings
1. Viscosity
2. Suspension
3. Application
4. Drying

Fig. 17. Factors to consider when using mould and core coatings
Fig. 18. Carbonaceous lap defect in shell moulded castings

Fig. 19. Lap defect with carbon deposit deeply.
Fig. 20. Ladle of molten iron covered with dross.

Fig. 21. Cupola-slag particles in a cylinder casting.

Fig. 22. Manganese sulphide blowhole defects on the top surface of a casting.

Fig. 23. Photomicrograph of silicate slag and manganese sulphide segregation.