

# Aspects of foundry practice and their influence on the machinability of iron castings

## Introduction

There are many foundry, metallurgical and machine shop factors which influence the machinability or machining characteristics of graphitic iron castings. All too often these are not fully comprehended by either the foundry or the machine shop, but it is important for foundries to understand and control the factors that influence machinability, because:

- It is very rare for a casting to be used without some kind of machining operation and this is particularly the case for mass produced high integrity castings
- Machine shops are very sensitive to productivity and cost so that small changes in tool wear or variability in the machining of castings are easily detected and the foundry is often blamed
- Machine shops frequently ask casting suppliers to pay extra costs relating to instances of poor machinability
- Metal removal rates (speeds and feeds) are increasing and to satisfy this trend foundries must supply castings which are both consistent and machinable.
- The cost of machining often far exceeds the value of the raw casting

Therefore: Improvements in the machinability of iron castings will increase the foundry's competitive advantage and market share over forgings or over competing foundries.

One of the difficulties the foundry faces is the lack of a definition of machinability, there being no clear-cut unambiguous meaning to the term, so that a material may have good machinability by one criterion but poor machinability by another. In the broadest sense machinability is the manufacture of a fit-for-purpose part at the lowest cost by machining. However it is typically assessed in the machine shop by measurement of the following:

- Tool life and tool wear
- Chip formation (not so critical for graphitic irons)
- Surface finish
- Cutting forces or power requirement

A variety of standard tests are used to assess machinability including a single point turning test to measure tool wear/life, a face milling test, and a drilling test which assesses the internal characteristics of the work piece, rather than surface behaviour.

## Foundry Factors Affecting Machinability

The foundries' customers very often specify little more than dimensions and grade of grey or ductile iron and the machinist believes that if the Brinell hardness is the same and the composition is the same then machinability must be the same. At the same time his experience is that apparently similar castings, all within specification, from different foundries (or even the same foundry) often have different machining behaviour. Consistency of machining is the wish of the machinist, and a foundry which delivers consistently machinable castings will have a competitive advantage over its competitors.

The machinist demands three areas of consistency:

- Consistent metallurgical characteristics and microstructures: lack of this results in variable edge build-up on the tool and variable tool life.
- Consistently free from non-metallic inclusions and surface defects: these defects cause abrasive wear of the tool and sometimes can cause tool breakages.
- Dimensional accuracy and reproducibility: variable dimensions will also cause variable tool wear and breakages because depth of cut is unpredictable.

## Metal Factors

### Microstructure

The foundry metallurgist's job is to control the microstructure, and thus properties of castings. Hardness is universally specified but is only useful as a specification in castings of consistently identical microstructure. Hardness above 250 - 260 Brinell is generally regarded as unsatisfactory. It is necessary to look deeper into the form and quantity of each phase to understand the effect of microstructure on machinability. Microstructure is influenced by cooling rate, and a higher cooling rate in the mould gives finer graphite and smaller more 'close-grained' eutectic cells.

**Graphite** in the form of flakes or nodules assists machinability by providing discontinuities which aid chip breaking. It also acts as a lubricant preventing the welding of iron (ferrite) to the tool tip to form a built-up edge. The amount of graphite appears to be more important than its form or the size of the flakes or nodules, and so the total carbon, combined carbon and graphitic carbon content should be controlled and consistent, with the highest possible amount of graphitic carbon. The Brinell hardness number indicates the hardness of the matrix and is too blunt a test to show any variation in graphite form or amount.

**Pearlite** is the predominant matrix phase in most grades of engineering iron castings. It confers the properties of reasonable machinability, good wear resistance, and good mechanical properties with low ductility. The hardness of the pearlite phase varies from 150 - 330 HB depending on fineness and composition. Pearlite hardening and promoting elements include chromium, nickel, tin and copper. A higher ratio of pearlite in the matrix decreases machinability. The coarseness of the pearlite lamellae also has an effect, coarse pearlite being more machinable than fine pearlite. In a fully pearlite ductile iron about 0.6% carbon is present as combined carbon. It is crucial to control mould cooling time to ensure a long enough cooling time in the mould that castings are shaken out below the austenite temperature.

**Ferrite** in iron castings usually has a hardness of 100 - 150 HB and irons containing large amounts of ferrite are freely machinable. Some elements have a hardening effect on ferrite (e.g. silicon over 3%), and should be controlled because they reduce machinability, as should the amount of ferrite in the microstructure. Free sulphur in grey iron strongly eliminates ferrite and promotes pearlite and carbide and thus sulphur must be neutralised with manganese according to the time-honoured formula  $Mn\% = (1.7S\% + 0.3)$ , thus ensuring most sulphur and manganese is present in the solid

casting as MnS. As Mn is a weak carbide stabiliser the net effect is to prevent the formation of carbides, to mildly reduce ferrite and promote pearlite.

### Phosphide eutectic

Occurs as a separate phase whenever phosphorus is present in amounts above 0.05%. The eutectic is a separate carbide-phosphide network at grain boundaries which becomes more apparent at higher phosphorus levels. Having a very high hardness (420 - 560HV) more than 0.5% of phosphide eutectic reduces machinability. The ternary form is associated with free carbides and is very hard and unmachinable, the carbides having a hardness over 750 HV.

### Carbides

When dispersed through the matrix in small amounts, they cause a marked reduction in tool life because of their high hardness. Such carbides are found at eutectic cell boundaries because most trace elements segregate to the cell boundaries, i.e. the last liquid to solidify, giving a concentration of carbide-promoting elements such as chromium, phosphorus, nickel, tin, antimony etc. Free carbides (*chill*) are also found in areas of high cooling rate such as corners, fins or flash and these can be catastrophic for the machinist causing tool breakage. (see figure 1).

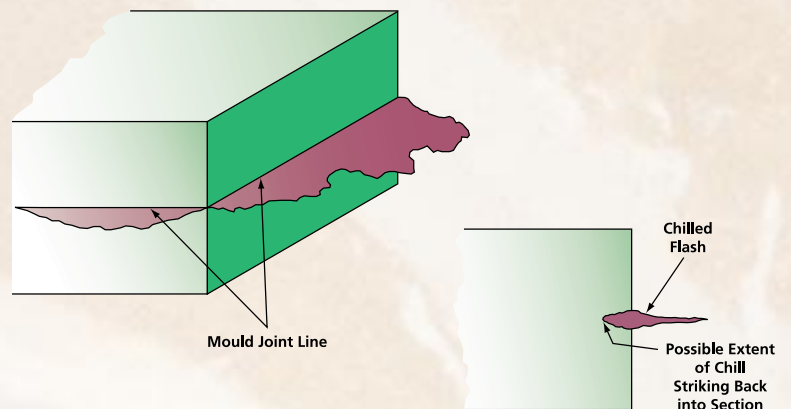


Figure 1: Chilled area caused by flash

### Surface decarburising

Sometimes occurs and is seen on iron castings as a **graphite-free rim** (see figure 2). This is due to partial decarburisation during cooling in the mould and it results in increased tool wear during surface machining owing to greater hardness and lack of graphite. An incomplete or non-uniform rim will result in areas of different hardness so that the power requirements will vary, resulting in tool vibration. A **ferritic rim** arises from more severe decarburisation in which both the graphitic and combined carbon are eliminated. Here the predominant outcome is an increase in the rate at which a built-up edge develops, shortening the tool life. Extreme decarburisation will also cause

oxides and oxide penetration (along graphite flakes) at the surface; these abrasive oxides can give heavy tool wear during the roughing cut which removes this unwanted surface structure. Correct control of coal dust in greensand is vital to prevent decarburisation and control surface structures.

Foreign particles or **non-metallic inclusions** have a catastrophic effect on machinability. Because of their random nature the machinability is variable and they can even cause sudden tool breakage.

- Iron castings with the best machinability will have a microstructure consisting of a high percentage of graphite, a ferritic matrix, no free carbides, less than 0.5% of phosphide eutectic and free graphite all the way to the surface. They are also free of non-metallic inclusions at the surface and throughout the matrix.



Figure 2: Graphite free rim in a pearlitic grey iron

### Melting and Metal Treatment

The foundry metallurgist begins his job of controlling microstructure at the melting plant with good quality raw materials. Steel scrap and pig iron must be analysed for tramp elements such as chromium, tellurium, titanium, vanadium, boron, lead etc. Each of these elements has an adverse effect on machinability and should be held at the lowest possible level. Similarly other materials must be specified and checked; poor quality or out of specification refractories, slag coagulants, inoculants and nodularisers will all result in non-metallic inclusions finding their way into the castings and causing tool wear or tool breakage. Return scrap should be free of sand otherwise slag levels will be high. Nodularising and inoculation practice must be of the highest quality to ensure good microstructures.

### Electric furnace practice

This can affect machinability. The carbon and silicon contents affect properties and these elements are lost due to oxidation at the surface of the bath; reduction in carbon and silicon would result in

increases in tensile strength, hardness and chilling tendency, i.e. significant variation of machinability. A suitable slag cover can prevent losses during prolonged holding. Many foundries believe that de-oxidation is essential. This can be done with silicon carbide additions to the electric melting or holding furnace at the rate of 0.4 per cent, but good solution must be achieved. Metallurgical grade SiC of the correct size grading (2-6mm), must be used (dust will oxidise, fail to dissolve and thus form inclusions) and added at a minimum temperature of 1450 °C with good stirring, just prior to tapping. Poor quality SiC, too fine a grading of SiC, low temperatures or poor stirring can all result in undissolved abrasive particles entering the casting and causing poor machinability (1,2). Addition too early before tapping means that the iron will re-oxidise so that the microstructure is less well inoculated and graphite form is less good.

Recarburiser added to the induction furnace should preferably be good quality, low in ash and sulphur and of good solubility. Electrode graphite is very suitable but natural graphite can be difficult to dissolve and can generate slaggy non-metallic inclusions. Before furnace tapping good slagging practice with a high quality slag coagulant is essential.

An important difference between electric- and cupola-melted iron is the level of sulphur obtained. Normally cupola-melted iron will contain between 0.08% and 0.12% sulphur, compared to induction furnace iron with between 0.02% and 0.08% depending on the amount and type of steel scrap melted. At holding temperatures the sulphur is not combined and so will affect the responsiveness to inoculation. Irons with sulphur levels below 0.07% are difficult to inoculate. Some foundries add iron sulphide to ensure consistently well-inoculated iron and thus uniform machining characteristics. Choosing the right inoculant such as INOCULIN 25 containing calcium and zirconium is particularly effective. On the other hand inoculants with calcium or strontium alone, are known to be less effective in low sulphur iron.

### Nodularisation

This practice must be controlled to achieve good consistent nodularity and microstructure and clean metal. In this respect the modern wire feed systems such as Foseco's IMPREX wire are particularly beneficial. Process reliability and consistency are achieved by the automatic process control which measures treatment weight, metal chemistry and temperature in order to adjust every treatment. Clean metal comes from lower addition rates and the lower levels of silicon, calcium, aluminium and rare earth in the IMPREX wire.

## Inoculation

Although the mechanical properties (tensile strength and hardness) of iron which affect machinability are mainly governed by the carbon, silicon and phosphorus contents there can be a wide scatter as a result of inconsistent degree of nucleation and trace element contents. The inoculant should be a high quality, clean, well graded alloy which dissolves rapidly. The inoculant should be low in aluminium, and rare earth because these oxides separate from the melt slowly and may be found in the casting where they affect machinability. INOCULIN 25 is a ladle inoculant which is consistently very low in non-metallic gangue and uniform in composition. It dissolves at lower temperatures than other foundry ferro-silicon alloys, but is also a powerful inoculant so that lower additions can be used. Late stream inoculation, if done with good quality, correctly graded alloys such as INOCULIN 90 will give clean, consistent and powerful inoculation at very low addition rates. The zirconium content of the INOCULIN products promotes ferrite and reduces carbides.

As well as having a uniform graphite structure and correct mechanical properties correctly inoculated iron will be completely free from carbides and chill. Hard spots and chilled edges will either damage tools or prevent machining altogether. The most common causes are inadequate inoculation, too low a carbon equivalent value, unbalanced manganese/sulphur ration and contamination with carbide promoting trace elements such as chromium. Worn pattern equipment can result in flash which has a high cooling rate so that chill can strike back into the casting section and although the flash is ground off a hard spot remains as shown in figure 1.

## Control of trace elements

Individually or cumulatively trace elements have marked effects on machinability. They can be classed into two groups according to their effects:

- Elements promoting the formation of carbides or white iron. These include chromium, tellurium, bismuth and boron, which are most powerful, and vanadium, nitrogen, molybdenum and arsenic which have similar but weaker effects. Some of these elements also promote pearlite and can be beneficial used in a controlled way in some grades of iron, but are damaging in ferritic grades of ductile iron. In either case it is vital to control their levels in the metal to ensure consistency of machining behaviour.
- Elements promoting pearlite formation such as tin, copper and nickel. These are used effectively in pearlitic grades, and are preferred for this purpose to the carbide promoters above, but are detrimental in ferritic grades.

It is clear that steel scrap of correct and consistent quality must be used to bring about the correct level of trace elements, either to give useful pearlite promotion, or at a low level for production of ferritic grades.

## Non-metallic Inclusions

The metallurgist guarantees clean machinable consistent castings with no hard abrasive **non-metallic inclusions** by good foundry practice, enhanced and supported by filtering with SEDEX or CELTEX filters. Filtering will also remove undesirable, hard, metallic inclusions such as undissolved ferro-silicon or silicon carbide. Inclusions formed inside the mould include loose sand, mould erosion, oxides due to turbulence in the gating system or mould cavity, particles of coating, reaction products from in-mould treatments (nodularising or inoculation), unreacted mould treatment alloys, products of mould-metal reactions and non-metallics rejected from solution (such as manganese sulphide). If these are formed in the mould downstream from a SEDEX or CELTEX filter the filter will have no effect other than to reduce turbulence.

## Slag, refractories and reaction products

Slag is generated at every stage of the melting, treatment and handling of molten iron (5). Preventing slag inclusions means preventing carry-over of slag from the previous stage of metal treatment or handling and also preventing slag formation, especially oxidation of the metal. Low density slags and fluid slags are more buoyant and more easily separated from the metal. Low melting point slags are likely to solidify and build up in the ladles and furnaces. Fluxing with FERROGEN therefore is a common practice used to lower melting point in ladles and electric furnaces. Correct use of SLAX coagulant will ensure that the separated slags are removed. This must be done correctly otherwise these fluxed slags, which are more fluid, can become entrained in the metal. In grey irons smaller volumes of slag are generated than in ductile iron, but fluidity, reactivity and density make them more difficult to handle. This difficulty extends to gating systems and filters. Finer filters are used for grey iron, 20 or 30 ppi SEDEX filters instead of 10 ppi, and 300 csi CELTEX filters instead of 100 csi.

KALTEK ladle liners provide more consistent pouring temperatures and clean ladles with less slag generation and carry-over. See figures 3 & 4.

Most inclusions are formed outside the mould, and an almost endless list of causes exists, but the most common inclusions and controls include:

## Inclusions from the mould

- Ensure patterns are properly constructed, matched and undamaged

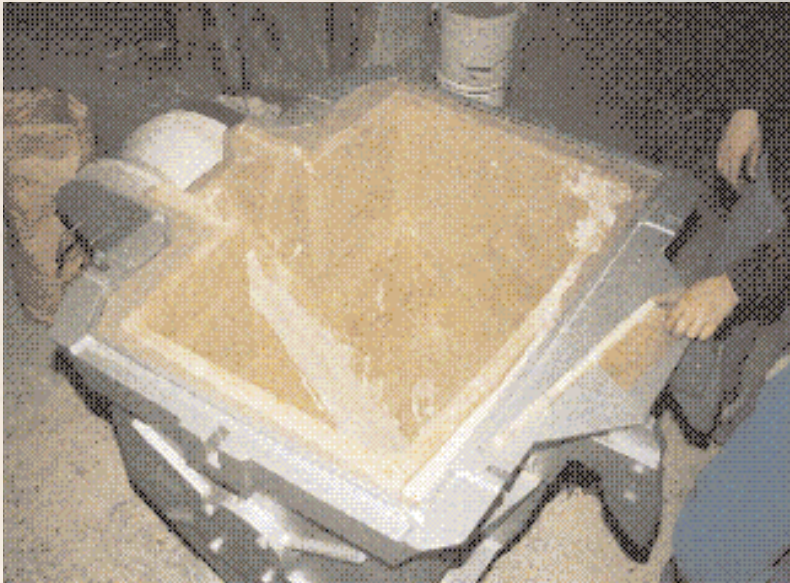


Figure 3: KALTEK ladle lining for an iron foundry pouring unit

- Moulding boxes should locate properly and not be warped
- The mould should be uniformly hard and not friable
- The mould should be blown out or vacuumed clean
- Cores and other inserts must sit precisely in their prints
- Gates should be designed to reduce turbulence and direct impingement of metal onto cores
- Mould movement and jolting should be avoided
- Sand properties must be properly specified and controlled
- Mould and core washes must be properly applied and of good quality
- Filter with SEDEX or CELTEX to remove inclusions

#### Inclusions from metal processing

- Use clean dry charge materials to avoid oxidising conditions
- Use teapot spouts and siphons for slag separation; ensure they are not eroded
- FERROGEN fluxes can be used to allow inclusions to escape from liquid metal and to keep ladles clean, but their use must be managed properly
- SLAX slag coagulant should be used to remove slag, but its use must be correctly controlled.
- Ladles should be relined frequently; KALTEK cold ladle linings should be used for cleanliness as well

as more consistent pouring temperatures (figures 3 & 4)

- Temperature control is vital, especially at the nodularising station; both high and low temperatures should be avoided
- Gate and filter with SEDEX or CELTEX to remove inclusions

#### Inclusions from Metal Oxidation

- Avoid oxidising conditions
- Use temperatures that are neither excessively high nor too low
- Minimise handling and transfers
- Deoxidation, e.g. with silicon carbide can reduce FeO.MnO.SiO<sub>2</sub> slags
- Gate and filter to remove inclusions
- Use SEDEX and CELTEX filters in an unpressurised gating system to prevent turbulence and reoxidation during mould filling

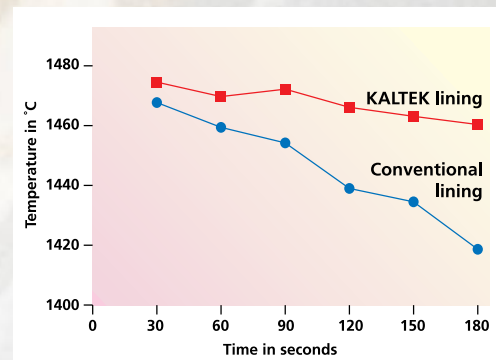


Figure 4: Temperature losses in 200kg ladle

#### Inclusions precipitated during Solidification

- In grey iron sulphur should be balanced by manganese
- In grey iron sulphur should be below the range 0.12% to 0.15%
- In grey and ductile iron silicon should be as low as possible
- In ductile iron base metal sulphur should be as low as possible
- Magnesium should not exceed 0.045%

All of the above good practice will be enhanced by correct application of SEDEX or CELTEX filters, giving great benefits in the machine shop, both by eliminating sporadic catastrophic tool failures and by improving the overall level of machinability.

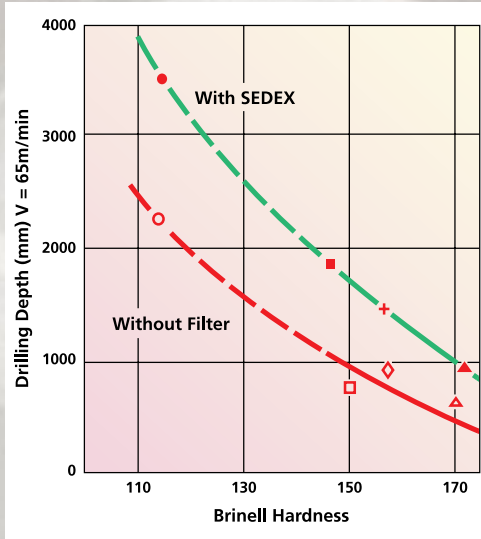


Figure 5: Tool wear when drilling filtered and unfiltered iron

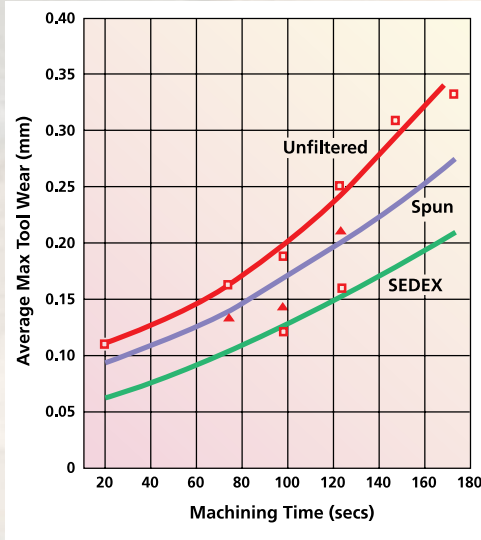


Figure 6: Tool wear when turning pearlitic ductile iron

The use of SEDEX and CELTEX filters has been proven to reduce tool wear and improve machinability. Drill wear measurements have shown that removal of internal inclusions with SEDEX filters gives a major increase in tool life, (as shown in figure 5) (3). Similarly removal of surface inclusions reduces tool wear when turning grey and ductile irons and allows more components to be machined from each tool. See figures 6 & 7 (3,4). This is confirmed in industrial foundry experience; use of filters has been shown to reduce machining scrap and machining costs (1,6), as in the following example:

|   |                      |
|---|----------------------|
| Annual Production                         | 2.4 million castings |
| Casting Price                             | Rp 810               |
| Value of machined casting                 | Rp 2950              |
| Castings per filter                       | 2                    |
| Price of filter A<br>- fine strainer type | Rp 9.3               |
| Price of filter B<br>- foam type          | Rp 11.2              |

|  | Unfiltered Castings | Filter A              | Filter B               |
|--|---------------------|-----------------------|------------------------|
| Machining scrap                        | 0.6%                | 0.32%                 | 0.15%                  |
| Value of machined scrap                | Rp 42.5 million     | Rp 22.7 million       | Rp 10.6 million        |
| Cost of filters                        | -                   | Rp 11.2 million       | Rp 13.4 million        |
| <b>Value of saving in machine shop</b> | -                   | <b>Rp 8.3 million</b> | <b>Rp 18.5 million</b> |

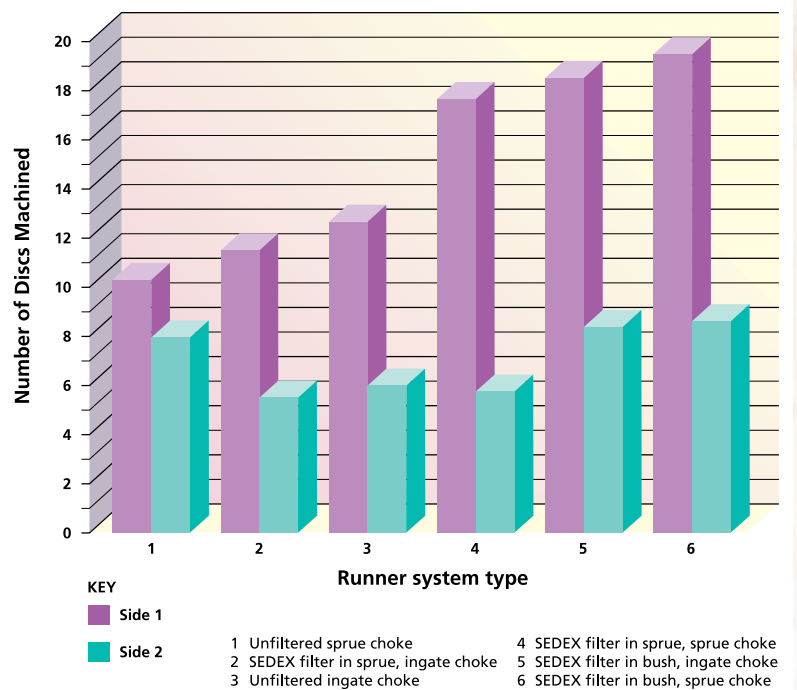


Figure 7: Effect of a SEDEX filter on machinability of discs cast on a DISAMATIC moulding machine

## Mould and core factors

### Effects of casting quality

Key aspects of mould and core effects which affect the machine shop are dimensional accuracy and reproducibility, freedom from casting defects, inclusions and adverse surface structures.

**Dimensional accuracy** and reproducibility of dimensions are essential to ensure consistent machinability because the amount of stock to be removed must be uniform from one work piece to the next, so that the depth of cut is consistent. Inconsistent dimensions means variable depth of cut and tool wear, power requirements, and surface finish. Foundries must supply castings of accurate consistent dimensions. This means control of the moulding process, sand properties, metallurgy, inoculation and fettling. Core coatings must give consistent application and uniform layer deposition thus ensuring dimensional consistency of the coated cores; modern coatings such as RHEOTEC XL coatings ensure that uniform layers are formed. Soft greensand moulds will result in outbreaks of eutectic swelling and oversize castings.

Excessive tool wear and even tool breakage is often caused by *casting surface defects*. These include burnt-on sand, metal penetration and veining on inadequately cleaned castings, which are all abrasive and cause excessive tool wear. A proper sand/binder system with correct properties, and the use of premium core coatings, such as RHEOTEC XL coatings which prevents metal penetration and veining, can guarantee prevention of such surface defects and ensure that variable machinability from insufficient or excessive fettling and surface defect is eliminated. RHEOTEC XL coatings are particularly applicable where good cast surface finish is required, sand adhesion in internal passageways must be prevented, and veining occurs - all defects which reduce machinability. Veining is also made worse by phosphorus levels below 0.05%, and this element must be controlled in the range 0.04 - 0.06% to keep to the fine line between finning tendency and phosphide eutectic formation.

### Fettling shop factors

Excessive tool wear is often attributable to inadequately cleaned castings, which since burnt-on sand consists mainly of silica gives extremely abrasive conditions. Similarly heat treatment scale is abrasive and should be removed by blasting or pickling.

On the other hand excessive shot blasting can give surface stresses and local hardening and is very difficult to identify as a cause of variable machinability. In a similar way excessive heat from heavy grinding has been known to create local hard spots.

## Machine Shop Factors

The foundry should have a basic understanding of the commoner aspects of machine shop factors since it is not unknown for machining difficulties to be a result of incorrect practice in the machine shop (7). Some of the reasons are now considered.

*Lack of machine rigidity and power available* can both cause tool chatter, rapid wear and poor surface finish. As the tool wears the power requirement goes up and so the machine must have a reserve of power and rigidity.

*Incorrectly ground tools* can affect the quality of surface finish and lose efficiency very quickly.

*Open grain* is frequently mistaken for shrinkage. This is a pitted appearance on the machined surface caused by a very heavy roughing cut or a blunt tool which plucks out the graphite and breaks off pieces of iron adjacent to graphite flakes, (see figure 8), a too shallow finishing cut then fails to remove the pitting.

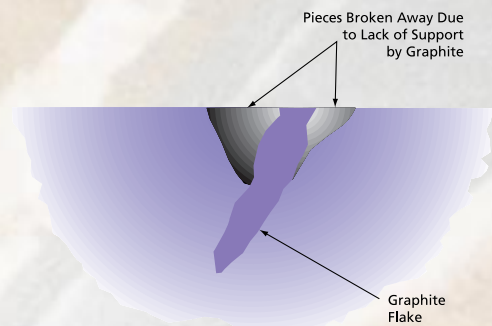


Figure 8: Creation of "Open Grain" on a machined casting (often confused with porosity)

## Conclusions

By good controlled foundry practices and good machine shop practice the inherently good machinability of grey and ductile iron can be fully exploited to establish a commercial advantage for the foundry. It is vital that:

- The grade of iron specified is correct for the section thickness, especially avoiding chill.
- Control of microstructure and properties is maintained by correct application of good quality refractories, nodularisers, inoculants, binders and coatings in an environment of good practice. A key variable to be controlled is cooling of the casting in the mould.
- Use of KALTEK insulating ladle liners and SEDEX or CELTEX molten metal filters can provide a further uplift in quality and machinability over and above that from good foundry practices.

- Casting dimensions must be consistent and castings should be free from surface defects.
- Foundries should develop a basic understanding of machining so as to be able to develop a partnership relationship with the machinist.

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