The production of defect-free iron castings with optimum properties

This paper examines three aspects of production of iron castings. Firstly, what constitutes optimum quality and what its advantages are, secondly, its quality assurance, and finally, how castings of this quality may be produced.

**Formation of cast iron microstructure and its lack of uniformity**

Cast iron is a eutectic alloy, its solidification microstructure can result in only a small number of microstructural constituents: (1) graphite eutectic (the greater part), (2) cementite eutectic (also known as ledeburite which is in most irons undesirable) and (3) primary austenite, a steel-like constituent which determines the iron's strength and which is dependent on the carbon saturation, S(C). A fully eutectic cast iron consists only of graphite eutectic, the most valuable and largest part of the cast iron microstructure. Ledeburite, the cause of white iron solidification, and graphite eutectic, have very different characteristics (fig. 2). Small quantities of ledeburite in grey irons have a detrimental effect on the properties and are therefore undesirable. Because graphite and ledeburite eutectics solidify at different temperatures, both can be shown on the solidification curve. The solidification proportion (proportion of graphite eutectic in the total eutectic in the cast iron) can be revealed with the undercooling temperatures, T (EU), value on the solidification curve. White solidification decreases with increasing graphitisation, and vice versa. White solidification disappears at optimum graphitisation as the grey solidified tip of the wedge chill test demonstrates. The increasing solidification graphitisation is a result of the increasing degree of nucleation, the reduced eutectic undercooling temperature and the reduction in white solidification, if fallen in ledeburite content.

The fluctuation of solidification graphitisation or content of the graphite forming nuclei which is affected by many processing factors causes lack of reproducibility in iron castings. Reproducibility therefore requires measurement of the nuclei content. Hence solidification graphitisation is the most important quality control factor which for cast iron, the foundry operator, who is interested in quality control must master. It is possible to obtain reproducible properties to optimise graphitisation and to manufacture defect-free iron castings with the described characteristics by using the quality controls described below.

**Optimum cast iron quality**

What is optimum cast iron quality and what advantages does it confer? The best cast iron quality should give advantages to the user as well as to the foundry operator, the castings should be economical, reproducible and free from defects and hence should promote the applications of cast irons.

For the reasons given above, the best iron quality contains only graphite eutectic at maximum solidification graphitisation. It can be called 'eutectic' cast iron and designated E-iron, grey or s-g. Because it has many advantages, it is useful to divide these into two groups, those related to the casting process and those related to the application of castings.

The advantages for the casting process are: solidification expansion (fig. 3), a dense, cavity-free microstructure, even in leak-free castings, no hard areas (hence optimum machinability), uniform and defect-free castings, optimum melt flow quality (fig. 4), simple and reliable quality assurance and favourable direct costs (which applies to both grey and s-g irons). In the case of grey iron there is also optimum damping capacity and heat conductivity.

Advantages for the use of cast irons are reproducibility, lack of defects and high toughness and fracture resistance, thin...
walled and hence light castings, optimum machinability even at the edges, and favourable cost. E-σg is superior to standard σg because of the high level of graphitisation. It is homogeneous, particularly dense, free of cavities even in the case of feederless castings, with optimum machinability and thinner walls. For this reason, both E-grey and E-σg can be used for new applications.

Today, iron castings are mainly ordered and supplied according to grey and σg iron standards, which are based mainly on tensile strength, although castings seldom fail due to inadequate strength. For decades past, the development of grey iron was aimed at increasing the tensile strength. Because the tensile strength is an inadequate indicator of the reliability of the structure, it is no measure of quality. The work, which must be applied to cause fracture under load is a prime indicator of the performance of grey iron castings. Therefore, grey and σg irons are better and more reliable, the greater their toughness is, with adequate tensile strength. As the work to be applied in the tensile test corresponds to the area under the stress-strain curve, it may be measured in a tensile test.

The highest quality, 'eutectic' cast iron, contains only graphite eutectic at maximum solidification graphitisation, ie., the maximum possible amount of graphite eutectic. Because this grey iron has higher ductility or fracture resistance, this quality can be designated 'ductile' grey iron (up to 10 times the elongation at fracture in standard test types).

E-grey iron is superior to standard grey iron at maximum graphitisation as it has greater toughness. However, E-σg is homogeneous, particularly dense and free of cavities even in the case of feederless castings, with optimum machinability, and thinner walls. Thus, there are new possible applications for E-grey and E-σg irons. Optimal graphitisation is of prime importance in the production of this quality.

Eutectic quality contains only graphite eutectic, but it may be slightly hyper-eutectic. It has no traces of ledeburite (as a result of the optimal graphitisation) and no primary austenite.

Because the microstructural quality of iron castings originates during solidification, the control of 'eutectic' cast irons is based on solidification control, for which there are two methods of measurement, the solidification curve and the wedge chill tests.

(1) Solidification curve or solidification, behaviour measurement (with Quickcut, without TC, i.e., grey solidification) measures the metallurgical state consisting of three factors: degree of graphitisation, cast microstructural values and level of oxidation, which are shown in the form of print-out measurements in the case of computerised equipment (Fig 5). Table 1 indicates the significance of the measurements. The target values for 'eutectic' cast iron are T(EU).

<table>
<thead>
<tr>
<th>Value</th>
<th>Significance of solidification</th>
<th>Significance of properties</th>
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<tbody>
<tr>
<td>Nucleation (increasing) T(EU), [1,2]</td>
<td>Graphitisation or nucleation (increasing) Expansion, hence cavity-free castings, even without feeder (increasing) White solidification tendency, hard spots (decreased)</td>
<td>Higher ductility (fracture behaviour) Dense, cavity free microstructure, no hard spots (opt. machinability) Maximum damping (with E-grey) and thermal conductivity Thin walls (light parts)</td>
</tr>
<tr>
<td>Casting microstructure (on eutectic or hyper)</td>
<td>Aim for eutectic only opt. flow with eutectic only opt. solidification expansion (hence cavity-free) with eutectic only, even without feeders</td>
<td>High capability for thin walls Dense, cavity-free microstructure</td>
</tr>
<tr>
<td>Level of oxidation (20-50-70)</td>
<td>About 50 optimum &lt;50; oxidised (deoxygenation necessary) &lt;50, underoxidised (deoxygenation necessary)</td>
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</tr>
</tbody>
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**Fig 3 Solidification contraction in cast irons.**

**Fig 4 Fluidity of grey iron.**

An important feature of 'eutectic' iron castings is their freedom from defects; due to the great solidification expansion they are dense and free of cavities even when feederless (which can only be achieved with rigid sand moulds). Oxidation defects, such as slag, blow holes and surface bubbles, can be reliably prevented with the quality control measures mentioned. With a particularly fluid melt (Fig 4) it is possible to produce thin-walled and hence light castings. The primary costs of 'eutectic' castings are attractive due to their high metal yield (feederless, defect-free, thin-walled), which also provide lower energy consumption.

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**Fig 5 Computer cooling curve print out, taken in practice.** T(Max, 1300°C) = 25.3°C T(EU) = 1,158.7°C T(FO) = 1,160°C, 3 C, R = 1.65°C T(I) = 1,163°C β = 0.94 Primary 45°C T(IS) = 1,167°C and Degree of Oxidation CA 81, Target: T(EU) <1,200°C; R <3°C, T(FO) <7,100°C C. **Quality control**

Because the microstructural quality of iron castings originates during solidification, the control of 'eutectic' cast irons is based on solidification control, for which there are two methods of measurement, the solidification curve and the wedge chill tests.
Inoculation

Inoculation is the melt treatment for increasing the degree of nucleation which is of decisive importance for optimum grain refinement. The nucleating agents are mainly oxides, sulphides and also graphite. The inoculation effect in adding an inoculant reveals the difference in the metallurgical state of the melt as shown by the (T(EU) values of the solidification curve before and after the treatment. In the case of oxide inoculants, incubation acts as deoxidation, which can be measured with the solidification curve. This reveals the uncombined, so-called metallurgically effective oxygen (O) dissolved in the melt, in contrast to the bonded oxygen (O) of the oxide nuclei formed.

Effective inoculants which must produce the optimum grain refinement in the manufacture of the 'eutectic' iron castings, have often to be evaluated. The solidification curve is a suitable method for this purpose.

Spheroidisation (Mg treatment)

The most important process for the quality of E-Sg castings is spheroidisation. Recent decades have been marked by an increasing E-Sg production (currently, the world production is about 100 Mt). Quality control is based primarily on %Mg analysis, where the scatter among the various processes is very great.

During spheroidisation, Mg is not just dissolved in the iron melt to form spherical graphite. Other processes occur simultaneously or successively, such as Mg vapourisation [Mg] = Mg (g), oxide formation [Mg] + [O] (MgO) and sulphide formation [Mg] + [S] = MgS. Therefore the Mg yield is low and lies between 20 and 50%, rarely as much as 70%. During Mg treatment, all possible measures must be taken to increase Mg yield; economic factors are less important than quality optimisation and reproducibility.

To produce 'eutectic' cast iron, the aim of spheroidisation must be the optimum grain refinement of the graphite eutectic and at the same time a <95% degree of modularity. The grain refinement problem is paid inadequate attention today's practices.

To produce E-Sg components the graphite eutectic and thus the nucleation must be at an optimum. The eutectic microstructure should not have any primary ausitene with a <95% degree of modularity at the smallest possible %Mg content (Mg excess is a carbide stabiliser).

Spheroidisation with optimum grain refinement provides reproducibility, free from defects, thin walled, lighter castings with optimum machinability and a high level of ductility. Optimum spheroidisation requires grain refinement optimisation at all stages of melting the base iron, Mg treatment and inoculation.

Production

In production of 'eutectic' iron castings it is important to achieve the significant features of their quality: primarily maximum grain refinement by means of maximum nucleation of graphite eutectic with optimum solidification expansion and no cavities or traces of ledeburite, or primary ausitene.

Hypereutectic composition can be achieved with carbon and not with silicon, because only carbon produces the required solidification expansion. The carbon content should be at a high level (approaching 3.7-3.8%) and the 5%S as low as possible, approaching 2%. High graptolisation of the nucleic content can be measured with the solidification curve (T(EU) <1150°C), which leads to a high number of eutectic cells (with grey) or graphite spheroids (with s-g). Such requirements as the optimum nucleic content can be achieved during melting, for example, in the induction furnace, with inoculation of the melt (preferably with Al, fig 7) with either grey or s-g iron. This also applies to the subsequent inoculation and spheroidising stages (Mg treatment).

In production of 'eutectic' iron castings it is necessary to devise a work programme with target values, in order to obtain a microstructure consisting of graphite eutectic with maximum nucleation (T(EU) <1150°C), without ledeburite and primary ausitene and with an oxidation level of 5%. Reproducibility and optimum solidification must be achieved, in the case of s-g iron with <95% degree of modularity.

A comprehensive systematic approach, rather than isolated measures, is necessary to achieve the aim of producing castings in 'eutectic' cast irons with long-term objectives in view towards optimisation of quality.

Fig 7 Effect of Al in inoculants (B), left (high) overoxidised right (low) underoxidised.

The foundry industry in the information age

The fast pace of historical developments in recent years has attracted our attention to the changes affecting us, directly or indirectly. These changes have been just as dramatic in the field of technology. We are not often aware of the extent of past and present developments in technology.

The age of machines began about 200 years ago with the steam engine (1782, J Watt), which was later replaced by the electric motor. The most significant feature of this age was the automation of manual
work by machines.

Today we live in the information age. This began with Neumann's development of the microprocessor in 1940, the invention of the transistor in 1947, the integrated circuit in 1958, and finally by the spread of the personal computer from about 1980. Today the computer automates human intellectual work. The most important factors of intellectual automation are: knowledge (development and innovation), ability (knowledge application and realisation of the innovation) and information (of the innovation and its applications and realisation, as well as development), all of which are immaterial goods which can replace the machines of the machine age. Foundries also must adapt to these changes if they are to be successful in the future. The most important source of raw materials in the information age is imagination (imagination is more important than knowledge, A. Einstein), in particular, that which can be put into practice. The transition from knowledge to application as well as continuing development are extremely important. Because creativity promotes development and innovation, it is the most valuable resource of this age.

A workplace of ideas

Up to the present time, the foundry has been primarily a workplace. The change towards a workplace of ideas must be above all the aim of the future foundry. This aim must be directed towards: (1) optimisation of quality, (2) individualisation of the products (flexibility instead of mass production as at present) and (3) smaller castings (minimisation, in accordance with the general trend of this age). The foundry business must become more and more of high quality, of flexible, individualised and attractively priced products, hence of general innovation.

In such a future, the intelligent deployment of qualified personnel will be a significant factor. This is essential to achieve flexible production of high-quality castings which the future market will demand. For this reason the workplace has to be a factory of ideas where all the production units are also centres of innovation. Hence small factories have a bright future, if they can combine to form networks. The individualised quality product will be a big opportunity, so long as the necessary personnel can be correctly motivated and suitably trained.

As in most technologies, people will be the most important success factor in a future foundry. For this reason, foundries must do more to provide adequate training. The personnel responsible for quality will be particularly important. Their training in the business can start with observation of the melt during the individual stages, eg, by determining the metallurgical state (with the solidification curve). This involves the pleasure of observation as well as the need to develop one's curiosity and creativity. Continuing training and fostering activity, people will ensure future development capacity, flexibility, innovation and internalisation. For these reasons foundries must invest heavily in education and training to remain attractive and competitive.

Conclusions

Both the user and the designer of castings must change their ideas about 'old' grey cast iron in view of the new 'eutectic' cast iron quality or E-grey iron which is more ductile, with excellent machinability and maximum damping capacity and heat conductivity. Such castings can be thinner-walled and, therefore, lighter. We know that castings are becoming increasingly lighter (according to Gern FA, the average weight is about 2% per year). Eutectic cast iron is particularly useful because of the optimum flow ability of the melt and the higher ductility. Training of designers must be intensified and knowledge of the best cast iron eutectic cast iron, E-grey and E-sg) and their application must be expanded to create the basis for optimum casting design with 'eutectic' cast iron.

In 'eutectic' cast iron, the foundry has a quality which makes it easier to reliably produce reproducible defect-free castings. The present paper does not give recipes, only recommendations, which each foundry can use to develop procedures which suit individual situations. These should be carried out with quality controls monitored earlier, and subsequently adapted to any new evaluation.

The simultaneous consideration of E-grey and E-sg in this paper aims to give an overview. The solidification process of both 'eutectic' cast iron is similar, the only difference is the form of graphite (spheroidites or flakes). Optimum nucleation and graphitisation are prerequisites for both, and in both the ductility increases with graphitisation. Both iron is eutectic and solidifies with expansion, resulting in a dense, cavity-free product. The difference between the two types lies in their characteristics, much higher ductility, strength and modulus of elasticity of E-sg compared to E-grey iron.

Strength

Both users and foundry operators currently use the standards based on strength. In fact, few iron castings are subjected to purely static loading in practice. For this reason, tensile strength is useful only for classifying cast iron according to materials standards, and not as a measure of quality.4 The cause of failure of many iron castings lies in inadequate ductility, hence ductility has already been proposed as a measure of quality.5 Accordingly, a cast iron is better and more reliable, the greater its ductility, assuming the tensile strength is the same. In the case of the 'eutectic' cast iron, its quality is defined by the ductility achieved with E-grey iron which is several times higher than in old grey iron. Therefore such a quality can be designated as 'higher ductility' cast iron with flake graphite grey iron. This implies a cast iron quality which permits new applications, which may be important for the future of grey iron.

Many ideas of the present paper have already been published elsewhere. New aspects include (1) a proposal for a cast iron quality based purely on graphite eutectic with optimum graphitisation, (2) the introduction of a simple and accurate method of measuring the degree of nucleation6, and (3) a demand for optimum graphitisation of E-sg castings as well. The increase in knowledge is proceeding at a fast rate. However, every five years, half of it, has been said, becomes obsolete, ie, no longer relevant. This means that after 10 years, only a quarter of the previous knowledge remains useful. On the other hand, the works engineer in charge of the foundry development seldom finds the time necessary to keep up with the literature in his field. Consequently, important knowledge is not incorporated into foundry practice. The gap created between knowledge and industry must be bridged somehow. Those responsible for the technical press should consider this question and find solutions to the above problems of which there are many good examples in existence.

'Kutectic' quality cast iron, E-grey iron, is particularly suitable for engine block (because it is highly resistant to fracture, has optimal thermal conductivity and is suitable for thin-walled designs). It can be considered for heavily loaded road man-hole covers (because it is resistant to fracture), for general engineering castings as well as for turbines and pumps (because it has optimal damping capacity) and for hydraulic equipment (because it is very dense, optimally machinable and free of cavities).

E-sg iron is very ductile, extremely sound, free of cavities and suitable for thin walls, it can be used for automotive castings, particularly for new applications. This demonstrates that 'eutectic' cast iron can lead to new applications and thus to an increase in volume and production of cast iron.

Summary

The case is put forward that the best quality cast iron consists only of graphite eutectic with optimum graphitisation (termed 'eutectic' cast iron, E-grey and E-sg), which often correspond to a slightly hypereutectic composition. Reliable production of castings of this quality depends on appropriate quality assurance based on the microstructure of iron.

Thermal analysis using a solidification curve can indicate the metallurgical state of the iron to include three characteristics (nucleation, casting microstructure and level of oxidation). The nucleation level is a measure of graphitisation. The casting microstructure shows whether this consists only of graphite as desired, and the level of oxidation, whether this has been understood. A simple and easy comprehensible method of continuous monitoring which may be used in addition, is the new wedge test methods, where—unlike in today's practice—the wedge tip must be fully grey for the right quality.

Advantages for the foundry in using E-
New plunging material for the production of nodular iron

Some 30 years ago T W Curry* published an excellent short survey entitled the ‘Manufacture and Metallurgical Control of Nodular Iron’. The author briefly described the then three most widely used methods of adding magnesium to molten iron, i.e. pressure ladle pour on ladle addition and plunging. Seven different types of magnesium alloying material were listed including nickel bearing alloys, iron-silicon magnesium alloys and unmolified magnesium. In general the plunging process required alloys containing less than 50% magnesium. With the addition of the Inomai process and the need for the method the situation is still much the same today but with a decline in the use of plunging. In the latter process a refractory bell, in which the magnesium alloy block is suspended, is forced under the surface of the melt by a ram, simultaneously with this a cover shield is moved into place over the ladle and serves to contain the reaction. The relatively low heat capacity of magnesium combined its low melting and boiling points means that the addition of elemental or conventional magnesium rich alloys to a ladle of molten iron results in violent explosive type reactions and escape of magnesium vapour with consequent low alloying efficiencies. Much use has hence been made of alloys based on the silicon-magnesium eutectic with additions of rare earth metal and calcium for the plunging process, a typical composition being: silicon 45%, magnesium 37%, iron 11%, calcium 5%, rare earth metal 2%. Such alloys have higher melting points than magnesium and are less reactive at molten iron temperatures but are not easy to manufacture and are relatively expensive per unit of magnesium. Iron would obviously be a preferential carrier element for magnesium but it is virtually insoluble in magnesium and although various complicated processes of the finely divided metals have been tried they have not been much used. Some types of steel and iron shot are relatively cheap sources of finely divided iron but when attempts are made to mix molten magnesium with such materials it is difficult to obtain a homogeneous product due to the large density difference between magnesium and iron. Furthermore even when mixtures containing 70-80% iron are achieved it may be found that the reaction rates of magnesium are still fast. Metallurgists at Castex Products have overcome this problem by developing a production process for duplex magnesium — iron plunging blocks which enhances the thermal contact between the particles of iron and the magnesium matrix. The particulate iron is preheated to form a suitable iron oxide coating which is subsequently reacted with an aluminium containing magnesium alloy. The iron oxide film is reduced to metallic iron by the magnesium. Aluminium present reacts with the iron to form iron-aluminium intermetallic compound at the iron/melt interface. The surfaces of the reacted iron particles are readily wetted by the molten alloy the composition of which may be adjusted to a preferred magnesium content. In practice (BP application No 9121454) magnesium alloy compositions are selected with appropriate freezing ranges and mixing of the alloy and iron constituents is completed at temperatures between liquidus and solidus temperatures. The ‘melt’ is then in a suitable pasty consistency with the iron particles held in suspension. Vacuum infiltration methods using liquid magnesium may also be employed. The homogeneous mixtures so obtained are cast into suitable containers to form blocks for plunging purposes. The very good thermal contact between the iron particles and the enveloping magnesium alloy has a marked effect on retarding the reaction rate at molten iron temperatures giving a high magnesium, low reactivity plunging block with recourse to costly alloying ingredients. A further substantial advantage is that the absence of calcium results in low slag formation in the ladle with reduced risk of fluid slag carry over to autoprour units. This has permitted the extended operation of autoprour units before maintenance is required. Plunging blocks manufactured using the above technique are available under the trade name Magnor and in a range of magnesium alloys to suit individual requirements and with optional rare earth metal content.

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Process control technology

An agreement has been signed in Spain by representatives of the Spanish industrial group Fagor and the Swedish SinterCast Group, covering the installation of SinterCast's process control system at one of Fagor's five foundries — Fagor Ederlan — for production of compacted graphite iron for automotive applications. The Fagor Group foundries specialise in supply to the world's automotive industry, including companies such as Ford, General Motors, Renault, SEAT/Volkswagen and Honda.

This contract represents a breakthrough for SinterCast as this will be the first commercial installation in the automotive field, where SinterCast sees the largest potential for compacted graphite iron and for its process.

With its new capability to produce car components, in compacted graphite iron, Fagor expands its market opportunities by responding to increasing customer demand for this high tech engineering material. Full production will start mid-1993.

Fagor is a Spanish industrial group with subsidiaries in 12 other countries. Main activities are in the areas of automotive components, consumer products, industrial components and engineering capital equipment. The Fagor Group turnover for 1992 is expected to reach US$1.2 billion.

SinterCast is a company of Swedish origin, founded 1983 to commercially exploit unique technology for process control in foundries, claiming to have the only known method to produce consistent quality compacted graphite iron in commercial quantities.

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REFERENCES

6. John, W. Laugen VOG Teil 5, Fig 16.

The production of defect-free iron castings are economical due to the high metal yield (because they are defect-free and without feeders) and the resultant lower energy consumption. E-irons solidify under expansion, therefore the castings are very dense and free from cavities even when feedless. They have no hard spots and are therefore optimally machinable. Due to the optimal flow characteristics they are suitable for thin-walled and therefore lightweight components.

For the designer and user E-grey iron has greater ductility (‘ductile’ E-grey) and optimal damping and thermal properties. E-grey castings are very ductile and resistant to fracture and therefore extremely reliable. Both types of E-irons are of interest for new applications and can thus contribute to innovative developments.

‘Eutectic’ cast irons are particularly suitable for the future foundry concept of the present information age in which knowledge and its application are adapted to move towards innovations, their realisation and the corresponding training requirements. The foundry will increasingly become an ideal factory with the prime aim being optimisation of cast iron production.

The production of castings in graphite eutectic irons with maximum graphitisation matches the modern information age’s concept of a foundry with a promising future, where ideas are important in the foundry for the purpose of developing quality, flexibility and cost optimisation, for which the necessary personnel must be recruited and appropriately trained.

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