Gravity diecasting is one of the precision casting methods used to produce near net shape cast parts. In this method, liquid metal is poured under gravity into a permanent, reusable metallic mould.

Rapid solidification permits almost immediate shakeout of castings, greatly reducing production cycle time, and improving the properties of the castings. Gravity diecastings feature exceptional dimensional accuracy and surface quality.

Benefits of gravity diecasting of ductile iron (DI) include all those of the process plus advantages of higher under cooling rate, as compared to sand casting. This results in a reduced amount of magnesium that must be added to the base iron and, subsequently, in a lower residual magnesium content in the finished castings. The latter helps control shrinkage, improves nodularity, enhances mechanical properties and increases overall casting quality.

Today, unfortunately, there are only a few examples of successful applications of gravity diecasting process to produce ductile iron castings. The latter may be attributed to two main reasons: first, some limitations typical for the traditional gravity diecasting of iron and second, lack of practical recommendations on production technology on gravity diecasting of ductile iron. This work emphasises the most important practical aspects of this technology.

**HEAT TREATMENT**

One of the most important parts of gravity diecasting iron is a mandatory high temperature heat treatment of castings. The latter is necessary for decomposition of iron carbides resulting from rapid cooling and the necessity to ensure and regulate the reproducibility of the microstructure and mechanical properties of the casting. It is also essential for developing the good machining qualities necessary in finished castings.

In some cases, particularly in gravity diecasting of relatively thick wall parts intended for non-critical applications, it is possible to avoid heat treatment by applying heavy inoculation combined with pouring into the highly preheated mould, which is detrimental for the mould life.

While the as cast mechanical properties of gravity diecast ductile iron have been the focus of several reports, we are concerned with the traditional method of producing these castings using heat treatment.

**Table 1. Typical heat treatment cycles for ASTM standard grades of gravity diecast ductile iron.**

<table>
<thead>
<tr>
<th>Item</th>
<th>Grade of ASTM</th>
<th>Microstructural group index</th>
<th>Heat treatment cycles</th>
</tr>
</thead>
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<td>A536</td>
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![Graph 1: Silicon content effect on Charpy impact strength of ferritic ductile iron containing 0.11% P.]

![Graph 2: Effect of phosphorus content and cooling rate on Charpy impact strength of ferritic ductile iron.]

Ductile iron cooled in air
Ductile iron cooled through the 600 - 400°C range at 150°C/hr
Ductile iron cooled through the 600 - 400°C range at 80°C/hr
Ductile iron cooled through the 600 - 400°C range at 30°C/hr
When castings are slow cooled in the furnace after annealing through the range of 600-400°C or cooled in the mould after pouring, this can result in significant reduction in Charpy impact strength at room temperature, commonly known as temper embrittlement (TE) of ferritic ductile iron (FDI). Typically, TE does not affect tensile strength and elongation but significantly impairs impact strength of FDI. This phenomenon is similar to that observed for many years in ferritic malleable iron, ferritic chromium steels and in all austenitic chromium nickel steels.

**CHEMISTRY OPTIMISATION**

It is recommended that chemistry optimisation be used to maintain relatively high carbon equivalent (CE) to reduce chill tendency and shrinkage related defects in gravity diecast ductile iron. Increasing CE also reduces time needed for austenitisation and the overall length of two stages annealing cycle.

On the other hand, many researchers associate TE with the concentration of embrittling elements such as silicon, phosphorus and manganese on grain boundaries. The silicon in ferritic ductile cast irons is primarily an alloying element. If the silicon content is increased above a certain range, the ductility and toughness levels are rapidly lowered. The metallic matrix becomes a silico-ferrite, which is less ductile than ordinary ferrite and failure occurs in regions with the highest silicon concentration.

In order to avoid TE some sources recommend keeping silicon and phosphorus levels as low as possible and adding up to 0.15% molybdenum. It is also stated that TE might be prevented by additions of calcium and/or cerium, which have a high adsorption capacity for phosphorus and other embrittling impurities and can bring them from grain boundaries to intergranular locations.

This research is aimed at defining the optimum phosphorous and silicon content and the cooling rate after annealing through the 'dangerous' temperature range, which will not produce ductile iron susceptible to TE. Also investigated was the cause of TE, the reversibility phenomena of TE and the possibility of preventing TE by calcium or cerium additions.

As cast standard 25mm Y-blocs prior to cutting were subject to two stages annealing with a thermal cycle similar to previously mention in Table 1. After rough machining, Charpy bars from each heat were heat treated at 600°C for two hours and cooled in the furnace to 400°C at three different velocities of 30, 65, and 150°C per hour. Test specimens were then machined to size slightly larger than that of the final impact test bar. After heat treatment bars were machined to the final dimensions.

The Charpy impact tests were performed on the standard un-notched rectangular (10 x 10 x 55mm) bars and fractured with a pendulum hammer. The fracture energy and fracture appearance were recorded as a function of phosphorus or silicon content in specimens at various cooling rates after tempering. Each point on the graphs is a mean value of eight to 12 tests.

Fractured Charpy bars were used for microstructure investigations.
Standard metallographic techniques were employed to reveal the nodule count, nodularity and microstructure constituents. Scanning electron microscopy (SEM) along with X-ray microanalysis have been used to study fracture surfaces, distribution and concentrations of phosphorus, silicon, and manganese in grain boundaries and within the grains.

The first series of experiments had the purpose of investigating the acceptable silicon content, which will not make PDI susceptible to TE, while maintaining a relatively high phosphorus content of approximately 0.11% or in other words, to exclude the factors related to silico-ferrite brittleness.

Two sets of samples with silicon contents gradually increased from approximately 2.66-3.86% and 0.11% phosphorus were subjected to cooling through the 600-400°C range in air (series 1) and in the furnace at a velocity of approximately 150°C per hour (series 2).

Results of Charpy impact tests have been plotted against silicon content depending on cooling rate after tempering and are presented in fig 1. As can be seen, the impact strength gradually decreased at a silicon content increase of approximately 3.0-3.2%, and then relatively slowly at higher silicon levels for both series. On the basis of these results, the silicon content in subsequent heats was narrowed to the range of 2.7-2.9%.

Fig 2 illustrates the effect of phosphorus content and cooling rate on impact strength of ductile iron containing approximately 2.8% silicon, tempered at 600°C and cooled through the 600-400°C range at three different velocities: 90°C, 85°C and 150°C per hour. As can be seen, these data confirm the general trend to reduce impact strength with increasing phosphorus content. A slight reduction of impact strength has been noticed in specimens with relatively low (0.04-0.07%) phosphorus content.

Ductile iron containing an increased range of 0.08-0.12% of phosphorus produced a steady reduction of impact strength. The impact strength drastically reduced in specimens containing phosphorus from 0.09-0.12% and cooled at a velocity of 30°C per hour. Ductile iron containing phosphorus from 0.04-0.08% and cooled at the same velocity, did not reveal TE.

It is interesting to note the prevailing role of the cooling rate through the 600-400°C range: only a very slow cooling rate of approximately 30°C per hour generated TE, while cooling with relatively high velocities of approximately 85°C and 150°C per hour did not cause TE. In other words, TE of ductile iron with relatively high phosphorus content may not occur if the cooling rate through 600-400°C intervals are greater than around 85°C per hour.

**Effect of calcium and cerium on TE**

This study included heats to which were added calcium or cerium. Results of impact strength testing are presented in fig 3. As can be seen, in contrary to, none of these additives may prevent TE of ferritic ductile iron containing approximately 0.11% phosphorus. Slightly less reduction of impact strength has been noticed in ductile iron with calcium additions.

**Reversal phenomena of TE**

A set of 18 Charpy test specimens was made from ductile iron with approximately 0.11% phosphorus. Six of these specimens were tested before embrittled heat treatment and 12 specimens were subjected to embrittled heat treatment. Six of 12 specimens were tested at the embrittled stage and six specimens were repeatedly tempered at 600°C and cooled rapidly at 150°C per hour.

Results of this test (fig 4) have shown the reversal phenomena of TE. Impact strength after repeated
tempering and rapid cooling at approximately 150°C per hour has restored approximately the same value, as has been prior to embrittled heat treatment. This procedure may be used in foundry practice as a corrective action when TE occurs.

Microstructure and microfractographic studies showed no phosphorus, silicon or manganese precipitation at the grain boundaries of the samples studied before and after the embrittled heat treatment. Further study revealed a phosphorus rich type of segregation at the sub-grain boundaries.

Examination of impact test specimen fractures showed mostly trans-granular cracks, which originated on the grain boundaries and then propagated through the grains. This fracture mode coincides with the recent studies of microstructure aspects of fracture in ducile and malleable irons.

It is interesting to notice that the above mentioned results were obtained while maintaining a relatively high silicon content (2.7-2.9%) and may be applied to the ductile iron foundry practice where heat treatment is mandatory, as for thin wall castings, centrifugal castings and gravity diecastings.

Another practical application of this study has an economical aspects. In many cases, when ductile iron parts are not intended for use in a low temperature environment, it is not necessary to maintain low phosphorus content in base iron and use expensive low phosphorus raw materials.

MECHANICAL PROPERTIES
Mechanical properties have been tested on the standard 12.5mm diameter test specimens with the 50mm gauge length machined from standard 25mm Y- blocks cast by gravity diecasting. Prior to machining, the blocks were heat treated by applying different cycles to develop specific microstructures (indicated by Group Index) and mechanical properties (indicated by the ASTM grade) as shown in table 1. The Brinell hardness (HB) values and microstructure analyses were obtained from the tension test specimens.

A statistical analysis of the experimental data was performed using dispersion and correlation methods. Fig 5 and fig 6 show cumulative probability plots of tensile strength and hardness for studied grades of gravity diecast ductile iron. Straight plot lines indicate that the distributions are normal. For example, the line 207 (for grade 65-45-12) in fig 5 indicates that the tensile strength has a normal distribution when the hardness value is 207. The mean of the distribution (at the frequency of events of 0.50) is approximately 580 Mpa. The standard deviation is calculated as the difference between the 0.5 and 0.159 of the frequency of events axis. Thus, the parallelism of distribution is evidence of equal deviations of studied mechanical properties.

The mean values and standard deviations for each of the hardness curves, calculated via the computer using all the data, are presented in table 2. As can be seen, the tensile strength values for the DI, which had an HB of 207, was a mean of 582 and a standard deviation of 34.1 versus the graphically determined values of 580 and 35.

Fig 6 indicates the hardness distribution for the four grades of gravity diecast ductile iron. For example, the HB distribution for grade 1 (60-40-18) has a mean of approximately 171HB and a standard deviation of approximately 7.5HB. Fig 6 also indicates that considerable overlap occurs between the hardness ranges for grades 1 (60-40-18) and 2 (65-45-12) and for grades 3 (80-55-08) and 4 (100-70-03). Thus, it is difficult to determine the difference between DI grade 1 and grade 2 on the basis of hardness alone. The grade 1 (60-40-18) has a ferritic matrix, while grade 2 (65-45-12) has a ferrite-pearlite matrix and the pearlite portion of the matrix also tends to increase.

Fig 7 indicates the general trend of decreasing elongation with increasing tensile strength. Also, as the hardness increases, the elongation decreases. It is interesting to note the influence of graphite nodularity on tensile strength and elongation in both ferritic as well as pearlitic irons: when graphite nodularity increases, the tensile strength and the elongation increases.

The relationships between hardness and tensile strength are presented in table 3. As one can see, the value of the correlation coefficient is relatively high, so the variance will be relatively low when using hardness to predict tensile strength.

The inaccuracy of the relationships does not permit an exact evaluation with high confidence, but, for a given hardness value, a confidence can be predicted for a range of tensile strengths. Two different approaches can be used to obtain the given results and apply the data developed. One approach is to calculate the probabilities using statistical relationships, the second is to directly read the results from the charts developed.

GATING CALCULATIONS
When considering gating systems for gravity diecasting of ductile iron, the foundry must always take into account specific features of the material, particularly its tendency towards the formation of dross - non-metallic inclusions in the form of refractory oxides. These non-metallic inclusions are complicated by the presence of residual magnesium, which is reactive and prone to oxidation. Gating systems can exert a decisive influence on the contamination of the DI by preventing or promoting contamination.
the oxidation of the metal surface, the entry of dross into the casting and the entrapment of air during pouring.

The following basic assumptions may be used as guides in selection of gating systems: bottom type gating systems are mostly used for critical application castings of substantial height, but shallow and simple castings with vertical walls are gated from the top or the side.

Pouring time

Recommendations in respect of pouring time, which take into account the specific features of ductile iron, are known for sand moulded ductile iron castings, but not for gravity castings. An attempt was therefore made to derive empirical relationships for the optimum pouring time for gravity diecast ductile iron on the basis of an analysis and generalisation of the experimental data.

The optimum pouring time, providing the best quality castings, was determined by varying the dimensions of the gating system. Based on analysis of the practical data on different gating methods, it was found that the pouring time for all groups of castings coincided closely with the results calculated from the formula (1): \( t = K\sqrt{WxT} \), sec, where \( W \) is the weight of the casting (kg), \( T \) is the average section thickness of the casting (mm), \( K \) is the correcting factor (K1 x K2).

The overall dimensions of the casting (its compactness) are taken into account by coefficient K1, which is determined from the 'bulk' density (2): \( D = \rho + \frac{V}{kg/dm^3} \), where \( V \) is the product of the three overall dimensions in \( dm^3 \), and \( W \) is the weight of the casting (kg). Table 4 gives practical data on relationships between \( K_1 \) and \( D \).

When calculating the pouring time, allowance must be made for the gating method used by using coefficient \( K_2 \), that varies as a function of the gating method used: 1.8, 1.6 and 1.4 respectively for bottom, side and top gating systems.

The constants in the formulae (1) reflect the fact that relatively fast top pouring and relatively slow bottom pouring give better casting quality.

To simplify the calculation of the effect of the chart shown in Fig. 8 is recommended. The sequence of calculations is \( W \rightarrow T \rightarrow R \rightarrow K_2 \rightarrow t \). A typical calculation is illustrated by the following example.

To calculate the pouring time for a ductile iron casting weight \( W = 15kg \), wall thickness \( T = 10mm \), and a coefficient of compactness \( K_1 = 1 \) a straight line is drawn between the two points representing \( W = 15kg \) and \( T = 10mm \). A second straight line is drawn from the point representing \( K_1 = 1 \) through the point of intersection of the first line with reference to line R. The points where the second line intersects the scale of pouring time \( t \) are the pouring times for top and bottom pours respectively - 7.5 sec and 9.5 sec.

Gating calculations

For choke area Aah calculations the following formula has been developed (3): \( A_{ah} = W + (0.31 x t \times f \times n) \), cm², where \( t \) is the pouring time (sec), \( f \) is the friction (flow resistance) coefficient, \( H \) is the effective sprue height (cm) and \( n \) is the fluidity coefficient.

The fluidity coefficient \( n \) is determined from the formula (4): \( n = 0.0036(CE) + 0.0028T + 0.0013T_\alpha \), where \( CE \) is the carbon equivalent, calculated as (5): \( CE = C + (1/3)S + (1 + 2%) \), where \( T_\alpha \) is the gravity die temperature (°C) and \( T_\alpha \) the ductile iron pouring temperature (°C).

Recommended friction (flow resistance) coefficient \( f \) values for gravity cast ductile iron are given in Table 5 and depend upon the method of making the internal cavity in the casting, where the lower values refer to...
poorly vented dies and the higher values to well vented dies.

Comparison of data obtained by this method with practical data on gating systems for industrial gravity cast ductile iron gives satisfactory results.

**TOP POUR GATING SYSTEMS**

Ductile iron gravity diecastings manufactured for critical applications are usually bottom poured to avoid the risk of dross entering the mould. However, the effectiveness of the riser, since it is filled with already chilled metal, is reduced.

Casting such as cylinders, liners, sleeves, drums and rotors may be top poured directly into the riser. This promotes directional solidification, but makes it very difficult to avoid contamination the castings with non-metallic inclusions.

This problem can be overcome by using a top gating system with a floating ceramic foam filter freely located at the bottom of the riser as shown in fig 9.

The filter not only restricts the metal flow rate during pouring, but simultaneously effectively removes non-metallic inclusions. When the mould has filled, the filter float upward connecting the solidified casting to its riser through the riser neck, thus providing the conditions required for directional solidification resulting in elimination of shrinkage related defects. This means that an insulating riser sleeve may be eliminated, which provides an additional opportunity for cost reduction.12

By allowing the filter to float up after the completion of pouring, the feeding efficiency of the riser is improved. Eliminating the need to feed through the filter pore structure allows the use of finer pore filters that are often required to produce clean castings.

Top gating systems incorporating ceramic filters yield a number of technical and economic benefits such as improved casting quality, increased casting yield and reduced energy consumption.

Casting systems with floating filters are very effective in the pouring of gravity diecast ductile iron parts of substantial height, such as machine tool spindles. Their benefits have been confirmed by the improved mechanical properties obtained in different parts of the castings. This system makes possible to remove the filter after completion of pouring therefore avoiding the undesirable condition of having to charge the spent filter and retained inclusion material back into the melting furnace.

**PRODUCTION OF LARGE GRAVITY DIECASTINGS**

Practical utilisation of the gravity diecasting process for production of heavy section large ductile iron castings was possible due to the use of relatively low cost, air cooled dies operated by crane or overhead monorail.

As an example, fig 10 shows a schematic of the gravity diecasting process used for production of ductile iron ingot moulds.13 The die assembly comprises a pouring basin lined with a refractory, an iron die with the base and central sand core. Both the basin and the base have a core print in the centre to hold the central tapered cylindrical core. The basin is placed on the top of central core and the mould. Before pouring, the liner is preheated up to 120-150°C by a gas torch.

A carbon containing coating is applied to protect the liner from the molten iron that also allows the use of the same pouring basin many times. Pencil ingates feed the molten iron to the casting down between the core and die. Gases escape out the bottom of the core through a hole in the base. To remove the casting, the basin is lifted up from the die and the base removed. The finished ductile iron casting has a wall thickness up to 125mm and a weight of approximately 1,207kg.

Fig 11 shows a schematic of the grey iron die used to make ductile iron disk type castings. This mould comprises two halves, the pouring basin is installed in the cope, and central core is in the drag. As in previous designs, the pouring basin and the drag half have a core print in their centres to hold the cylindrical sand core. The pouring basin is also lined with refractory and coated with a carbon based liquid. The basin fits on top of the cope and the cope rests on top of the drag.

Molten iron is poured into the basin and fed through the filter and segment type ingates into the casting, gases escaping through a hole at the bottom of the drag. The finished ductile iron castings have a wall thickness from 50-100mm and weights from 345-910kg.

**Table 5. Friction (flow resistance) coefficient f values for different gaging system in gravity casting of ductile iron.**

<table>
<thead>
<tr>
<th>Internal cavity</th>
<th>Friction (flow resistance) coefficient f for gating</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>Bottom</td>
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</table>

**LINED GRAVITY DIECASTING**

Lined gravity diecasting (LCD) or semi-permanent casting may be considered as one of the technical solutions to the problem of relatively short die life, since die deterioration is a significant factor in casting the iron. Fig 12 provides a schematic outline of the LCD.
with the clearance around the mould equal to the thickness of the future sand liner. Before installation, the pattern is coated with a graphite release agent for ease of removal when the sand lining is moulded. The second position is used for pouring and vibrating the sand slurry into the clearance between the die and the pattern to achieve the proper liner's density. The third position is used for drying and curing of lined dies and the fourth station for pattern removal and gravity die assembly. Finally, the assembly is transported to the pouring station. The sand lining is used only a few times and then the die is relined for reuse. For relatively thick wall spindles, the castable slurry is cast as an 18mm to 25mm wall thickness to achieve the proper cooling characteristics and desirable solidification structure in the castings.

The advantage of LDG is the fact that the use of a die lined with a thin layer of a sand mix or refractory eliminates direct contact between the solidified casting and the mould. This results not only in an as cast iron microstructure without iron carbides but also in unlimited mould life. Energy costs are reduced due to the fact that no heat treatment is necessary when iron castings are poured. It also reduces costs through reduced sand consumption compared to conventional sand moulding.

The LDG technique is currently being used to make diverse industrial ductile iron parts such as diesel engine crankshafts, machine tool spindles and artillery projectiles as well as grey iron automotive camshafts.

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