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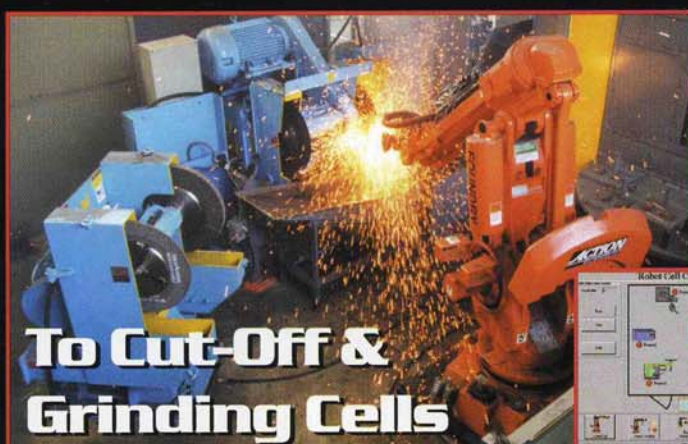
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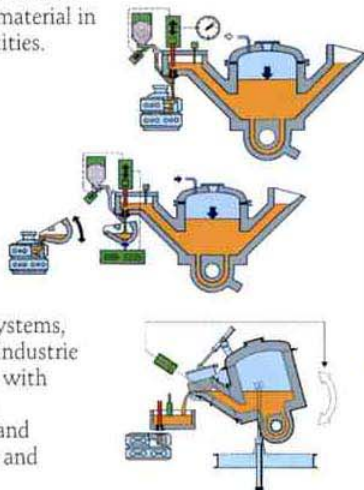
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PROCESS CONTROL FOR THE production of CGI

Compacted graphite iron is allowing automotive engineers design engines that run at higher pressures and are therefore more efficient.

Emissions legislation and the demand for higher performance from smaller engines have together driven the development of diesel engine technology over the past 10 years. One of the most significant of these developments has been the advent of common rail and unit injector fuel management and delivery systems, which allow for higher cylinder pressures in direct injection diesel engines. The higher peak firing pressures provide more efficient combustion, improved performance, reduced emissions and quieter engine operation.

At the same time, the increased firing pressures place increased mechanical loads on the main bearing region of the cylinder block, potentially resulting in premature fatigue failures. The irreversible trend toward higher peak firing pressures is forcing engine designers to seek stronger materials to meet their durability targets without increasing the size or weight of their engines.

With at least 75% increase in UTS, 40% increase in elastic modulus and approximately double the fatigue strength of grey cast iron, compacted graphite iron (CGI) is ideally suited to meet the current and future requirements of car and truck diesel engine design. However, due to the narrow stable range of CGI, production applications have historically been limited to relatively simple, low volume components with wide microstructural tolerances such as flywheels, exhaust manifolds and bedplates.

The production requirements for complex components such as automotive cylinder blocks and heads require a quantum leap in foundry process capability. The production volume is high, the geometric complexity and shrink tendencies are high, the microstructure specification is narrow, and the risk

tolerance for out of specification castings is zero. This article describes the on line process control technology used at the Halberg Guss GmbH foundry in Germany for the production of the Audi 3.3 litre V8 cylinder block produced in CGI.

STABILITY OF CGI

The production and ultimate performance requirements of automotive cylinder blocks and heads provide the basis for defining a product specification. For optimal castability, machinability and thermal conductivity, the nodularity must be kept as low as possible in the nominally 0% to 20% specification range.

More importantly, it is imperative that flake type graphite be avoided to prevent local weaknesses that could lead to premature component failure.

For optimal machinability, carbides must be avoided and titanium additions cannot be used to facilitate nodularity control. Ultimately, CGI cylinder block and head production requires a precise balance of magnesium and inoculant additions to prevent flake graphite formation on the low side and shrinkage defects on the high side.

Although the size of the stable CGI window is different for each product, it generally spans a range of approximately $\pm 0.004\%$ magnesium. However, in practice, the usable magnesium range is even smaller. Because active magnesium fades at a rate of approximately 0.001% every five minutes, the initial starting point of the iron must be sufficiently far away from the abrupt CGI to grey iron transition at the low end of the stable range.

This buffer is necessary to ensure that flake type graphite does not form before the end of pouring, which may be as long as 15 minutes after the initial magnesium addition. Simultaneously, the magnesium starting point must not be too high to minimise the

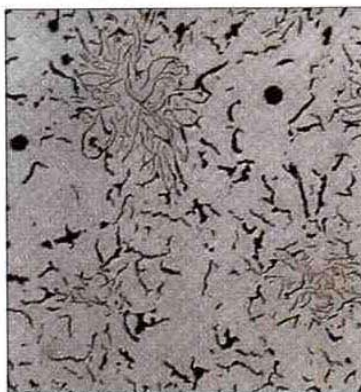
formation of nodular graphite in the faster cooling thin sections. During series production, the total usable magnesium range is less than 0.005%.

A second consideration for volume CGI production is that the stable CGI window is not stationary.

If the active oxygen and/or sulphur contents are high, they will consume the active magnesium and shift the stable CGI window toward higher total magnesium values.

Fig 1. An addition of 0.001% active magnesium is sufficient to convert a flake patch microstructure into a high quality CGI microstructure.

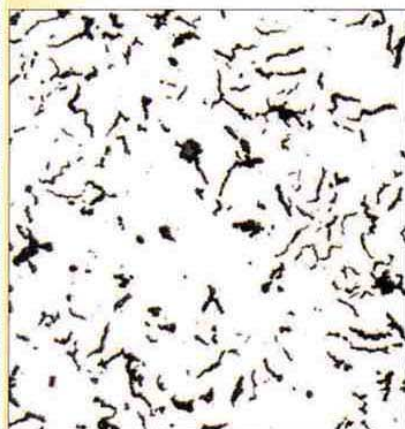
(a) Flake patch (UTS:300MPa)



(b) 3% nodularity (UTS:450MPa)



THE AUTHORS ARE
S DAWSON AND
W TROSCHER, SINTERCAST
LTD AND U DIETERLE,
HALBERG GUSS GMBH.



(a) Before inoculant (3% Nod)



(b) After 0.080% inoculant (21% Nod)

Fig 2. An addition of 0.080% post inoculant can cause the CGI nodularity to increase from 3% to 21% in a 25mm diameter test bar.

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Conversely, if the oxygen or sulphur levels are relatively low, the CGI window will be shifted toward lower magnesium values. For these reasons, variations in the charge material and melting history make it impossible to define a fixed chemistry specification for CGI.

The transition from CGI to grey iron can occur with the loss of as little as 0.001% active magnesium at the low end of the stable range. However, despite this rapid transition, the natural magnesium fading does not immediately result in a fully flake type microstructure.

In the absence of sufficient magnesium, the graphite begins to grow with a flake morphology. As the eutectic solidification proceeds radially outward, the magnesium segregates ahead of the solid liquid interface and, depending on the initial magnesium content, compacted graphite may become stable near the perimeter of the eutectic cell. The result is that flake type graphite first appears in CGI microstructures as discrete flake patches.

The ability of the magnesium segregation effect to convert the graphite from flake to compacted verifies the critical influence that small amounts of

magnesium can have under otherwise equal conditions. The abruptness of the CGI to grey iron transition is illustrated in **fig 1**.

This shows that a flake patch structure (UTS = 300MPa) in a 25mm diameter test bar can be converted to a fully compacted microstructure (UTS = 450MPa) with the addition of only 10gms of magnesium in a one tonne ladle.

The stable CGI window is also sensitive to the addition of inoculant. Higher inoculation levels provide more nuclei therefore promoting the formation of nodular graphite.

Higher inoculation levels must therefore be compensated with lower magnesium additions while lower inoculation levels require higher additions to ensure stable CGI growth.

Factors such as furnace superheat, holding time, charge composition and type and amount of inoculant influence the magnesium requirements. The sensitivity to inoculation is illustrated in **fig 2**, which shows that the addition of 80gms of inoculant to a one tonne ladle can change the nodularity from 3% to 21% in a 25mm diameter test bar.

The 3% nodularity micrograph would result in a sound casting while the 21% nodularity microstructure would certainly result in shrinkage defects in a complex cylinder block casting.

THERMAL ANALYSIS

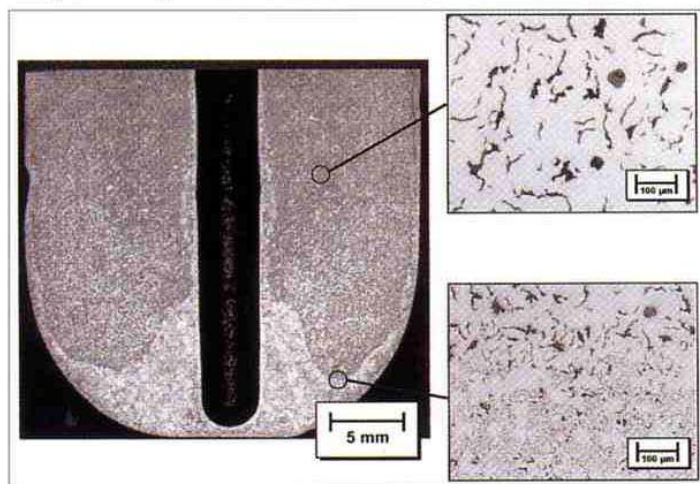
The basis of any process control technology must be an accurate analysis of the molten iron. The reliable control of CGI requires simultaneous measurement of the magnesium behaviour, the proximity of the base treated iron to the abrupt CGI to grey iron transition, the subsequent magnesium fading, and the inoculation level. These parameters are determined by a single thermal analysis measurement.

The 200gm thermal analysis sample is obtained by immersing the patented SinterCast sampling probe into the molten iron after the magnesium and inoculant base treatment has been made. During the three second immersion time, the walls of the sampling cup are heated to thermal equilibrium with the molten iron.

In comparison to conventional thermal analysis sand cups, the thin wall immersion sampler ensures a constant sample volume, prevents oxidation of the iron during pour in filling and provides a more accurate measurement of undercooling because of the elimination of chill solidification. The sampling cup contains two thermocouples, one at the bottom of the probe and one in the centre.

To simulate the natural fading of magnesium that occurs in both the ladle and in the castings, the walls of the sampling cup are coated with a reactive material that consumes active magnesium.

Fig 3. The reactive wall coating and thermal convection currents combine to simulate magnesium fading in the bottom of the SinterCast probe (etched).



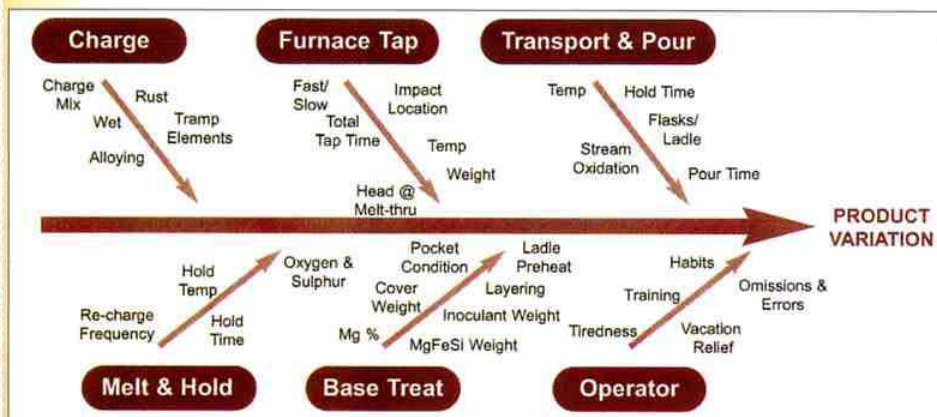


Fig 4. The many sources of process variation in the foundry combine to determine the overall variation in the base treatment recovery.

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The convection currents that develop within the probe rinse the sampled iron along the reactive walls and cause a reacted, low magnesium iron to accumulate in the stagnant flow separated region at the base of the probe.

In the simplest sense, the centre thermocouple monitors the non-reacted iron and therefore determines the start of casting behaviour while the bottom thermocouple predicts the end of casting solidification behaviour. The reactive coating is designed to reduce the magnesium content of the iron in the flow separated region at the base of the probe by 0.003% Mg, or the equivalent of approximately 15 minutes casting (fading) time.

Therefore, if the initial magnesium content of the iron is too close to the CGI to grey iron transition, the flow separated area will solidify as grey iron yielding a grey like cooling curve from the bottom thermocouple.

This result alerts the foundry to add more magnesium before the start of casting to compensate for the inevitable magnesium fade.

Conversely, if the initial magnesium concentration is sufficiently high to prevent flake graphite formation during the approximate 15 minute pouring time, the flow separated region will also solidify with a compacted graphite morphology and the bottom thermocouple will yield a good CGI cooling curve.

An etched cross section of a solidified SinterCast probe (fig 3) shows the separated flow region, the bulk iron and the protective tube in which the re-usable thermocouples are contained. The loss of 0.003% active magnesium in the flow separated region has resulted in the formation of undercooled D-type flake graphite and, due to reduced diffusion distances, a ferritic matrix.

The size of the flake type graphite zone in the bottom of the probe is directly proportional to the initial magnesium content of the bulk iron and can be calculated from the bottom thermocouple cooling curve as the time integrated heat release prior to the eutectic undercooling minima. The r-squared correlation coefficient for the relationship between the calculated heat release and the size of the flake

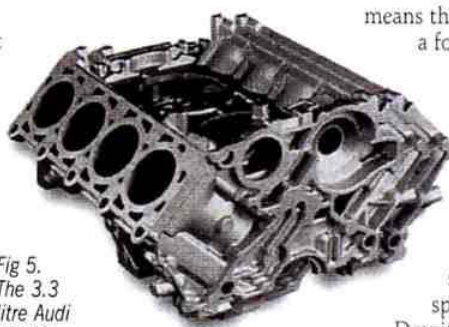


Fig 5. The 3.3 litre Audi V8 TDI cylinder block contains 18 cores and has a nominal minimum wall thickness of 3.5mm.

zone is in excess of 0.9. This insight into the current and simulated after fading end of pour behaviour of the iron allows corrective magnesium additions to be accurately prescribed before casting begins.

PRODUCTION CONSIDERATIONS

Unlike grey and ductile irons, the sensitivity of CGI to magnesium and inoculant additions prevents foundries from adopting the traditionally conservative philosophy of over treatment.

Further, the sensitivity of CGI to both magnesium and inoculant means that CGI is actually stable within a four sided window and not within a simple magnesium concentration range.

Reliable CGI production therefore requires simultaneous control of the magnesium and inoculant, from the start until the end of casting, to stay within the microstructure specification.

Despite all foundry efforts and discipline, variation in the base treatment result is inevitable. Regardless of the state of knowledge of the base iron, one step treatment methods cannot be relied upon to always fall within the narrow CGI window. As shown in the fishbone diagram provided in fig 4, variations in process parameters directly affect the magnesium recovery.

In addition to these variables, the active oxygen and sulphur content of the base iron actually change the size and location of the CGI window while variations in ladle holding, transport and pouring times change the time available for fading. However, the most unpredictable source of variation can be operator error, or the difference in work habits between different operators.

The only certain way to eliminate process variation during the large volume series production of CGI is to evaluate the solidification behaviour of the iron after the base treatment has been made. In this way, all of the variables influencing alloy recovery and the size and location of the CGI window have been exhausted and therefore accounted for.

Corrective additions of magnesium and/or inoculant can thereafter be made, if necessary, to bring each melt to the desired solidification behaviour before the start of casting.

A two step measure and correct control strategy has therefore been adopted to minimise process variation and eliminate the risk of producing out of specification castings.

THE PRODUCTION CASTING

Following the successful production of hundreds of CGI prototypes for advanced development and motor sport activities since 1991, Halberg Guss entered CGI series production in the year 2000 with the Audi 3.3 litre V8 turbo diesel cylinder block. The V8 engine established a new industry benchmark with a specific power output of 50kW/litre.

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According to Audi technical publications, the lightweight construction required CGI to satisfy performance and durability requirements.

A grey iron cylinder block would have required larger overall dimensions and 10% more weight to prevent low cycle fatigue failure. The complex design uses a total of 18 cores with cast in oil galleries and a 3.5mm nominal wall thickness. As shown in fig 5, the net result is a V8 cylinder block with an as cast weight of only 74kg.

The cylinder block material is specified as CGI 400, ensuring a minimal tensile strength in the bearing region of 400MPa. Typical tensile values for the >95% pearlitic matrix are around 450MPa, representing an 80% increase over conventional grey cast iron.

The nodularity in all performance critical sections such as cylinder walls is controlled to less than 10% to optimise machinability and to provide shrinkage free castings without resorting to the use of feeders, which would reduce mould yield and impair foundry economics.

During prototype construction and early production, Halberg developed the technique of ultrasonic testing to non-destructively inspect 100% of the castings. As a result of the stable process control and production processes, the 100% ultrasonic testing is no longer required. Both Halberg and its customer rely on the SinterCast thermal analysis result and normal statistical process control practices to provide good castings.

Production currently proceeds like all other production castings, fully controlled by the normal production workers.

PROCESS FLOW

Base iron preparation is performed in any of Halberg's eight mains frequency induction furnaces (4 x 8 tonnes and 4 x 13 tonnes). The charge composition consists of desulphurised cupola iron, low sulphur pig iron and steel scrap. The typical base iron composition is:-

C	3.3% to 3.5%
S	0.010% to 0.014%
Si	2.10% to 2.25%
Cr	<0.06%
Mn	0.25% to 0.30%
P	<0.03%

Copper and tin are also added to stabilise a fully pearlitic matrix.

The magnesium base treatment is performed by the pour over sandwich technique as the iron is tapped from the holding furnace into the 1,200kg transport ladle. The FeSiMg (5%) granular alloy in the bottom of the ladle is covered by grey iron machining chips to delay the start of the magnesium reaction and provide a consistent magnesium recovery.

Inoculant additions are not specifically included in

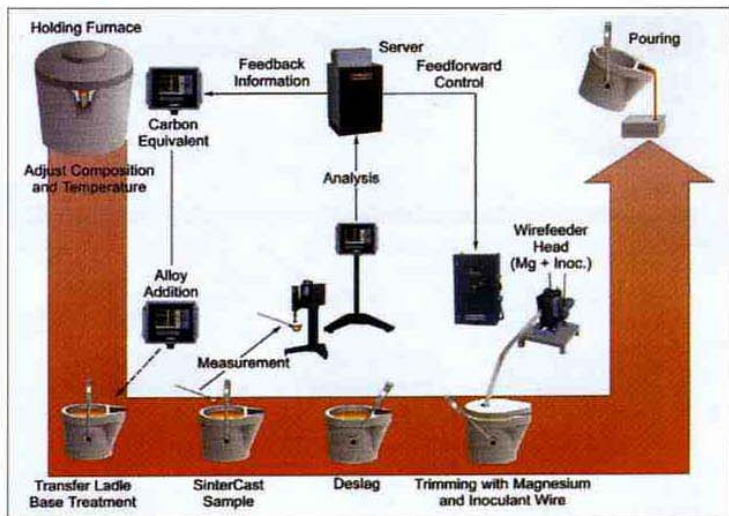


Fig 6. Conducting the thermal analysis after base treatment allows the foundry to accurately measure process variation and make corrective additions of magnesium and/or inoculant cored wire prior to casting.

the sandwich base treatment, rather the inoculation level is evaluated by the thermal analysis measurement and final trimming additions of inoculant are made in cored wire form before pouring.

Following base treatment, the transport ladle is de-slagged and transferred to the moulding line where it is emptied into the dedicated pouring ladle on the automatic pouring car.

The SinterCast sample is thereafter obtained by the production worker and, depending on the result, corrective additions of magnesium and/or inoculant cored wire are made by a wire feeder mounted on the roof of the pouring car. The use of separate ladles for base treatment/transport and pouring is based on the current grey iron process flow and allows for a seamless transition between grey iron production and CGI production.

Neither the sulphur leaching in the walls of the ladles or the use of grey iron machining chips for the sandwich cover material adversely affect magnesium fade behaviour. As the CGI production volumes increase, the foundry can implement combined transport and pouring ladles to eliminate the re-ladling step and therefore reduce the overall process timing. The process flow is schematically illustrated in fig 6.

SUMMARY

The adoption of a two step measure and correct process control strategy has enabled the successful series production of a complex CGI V8 cylinder block with a 0% to 10% nodularity range in all performance critical sections.

The thermal analysis measurement ensures that flake type graphite is avoided while operating at sufficiently low magnesium levels to prevent shrinkage defects without resorting to risers and feeders.

The Halberg foundry is now basing its CGI production planning on this technology as its automotive customers begin to specify their next generation of high volume passenger car and commercial vehicle diesel engines in compacted graphite iron.

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