

Dross inclusions in repetition automotive ductile iron castings - *an example of foundry and supplier working in partnership to solve a problem.*

Introduction

The use of ductile iron crankshafts in high performance engines is placing ever higher demands on the quality of the cast components. Parts such as crankshafts, which are used in high fatigue applications, must fulfil the strength requirements of the specification and have the specified microstructure. In addition, it is of great importance that the castings are free from internal and surface defects in all critical areas.

During development of process security for such a casting, close co-operation between the foundry and supplier proved to be critical.

The Development Project:

The crankshaft, for the new five cylinder engine of a leading German automotive manufacturer [1], is a casting with particularly high quality demands. The engine is 2.3 litre, with a maximum output of 110 kW and torque of 205 Nm at 3200 revs.

The construction principle of this manufacturer [2], the so called 'VR' design, is a combination of straight and 'V' cylinder engine blocks. The resulting engine has several advantages, including a shorter length than a straight cylinder version and narrower than a normal 'V' engine. In addition, there is only one cylinder head and one bearing per cylinder. The 'V' configuration puts particularly high flexing and torsional stresses on the crankshaft. The casting in question has been critically designed to reduce weight, so that in order to achieve the required torsional fatigue properties, the castings must be of the highest quality and defect free.

Figure 1 shows the machined crankshaft, with the six main bearings, five hub bearings and ten counter weights. Due to the complex geometry of the crankshaft, in terms of a single parting line, the casting is poured 'standing' in a vertically parted shell mould. The shells are supported in metal shot, and the castings are poured with a running system using an integrated filter as shown in figure 2.

This proven manufacturing process ensures optimum mould filling and feeding conditions are guaranteed consistently.

In comparison with previously used crankshafts, the new design, with ten counter weights, has a significantly larger surface area. This in turn will increase the relative amount of oxygen available in the shell mould, which can subsequently lead to oxidation of the magnesium present. To ensure the correct degree of nodularity in the graphite, a clean melt and residual magnesium of 0.040 - 0.055% is required, in addition to optimum inoculation. [3-7]



Figure 1: Machined VR crankshaft. The arrow illustrates the defect position in counter weight 2

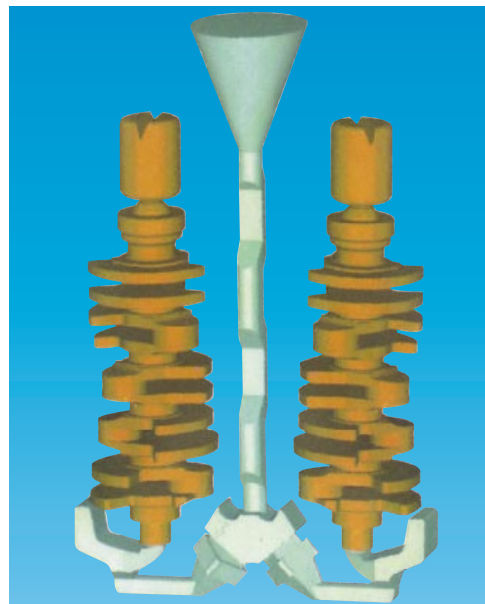


Figure 2: Crankshaft casting in vertically parted shell mould. Runner system with integrated filters

Table 1

Rm	≥ 720 MPa
Rp0,2	≥ 420 MPa
A ₅	≥ 3%
HB 5/750	= 235 - 285
Percentage of perlite:	90±5%
Nodularity:	Graphite shape VI according to DIN EN ISO 945 ≥ 95%

During the prototype development of the crankshaft, many castings were subjected to fatigue testing, before the design could be released for production. Although the material properties - table 1- were all within specification, many castings failed to reach the required level of cycles in torsional fatigue testing.

In all cases, analysis of the scrap components confirmed the following:

The failure was due to dross inclusions, always in the same area of the casting - side wall 2 - sometimes concealed under the casting skin. (see figure 3).

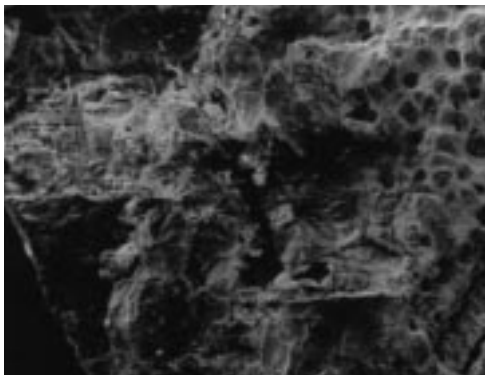


Figure 3: Dross inclusion in a crankshaft. Cause of early failure in torsional fatigue testing

Metallurgical Investigation:

Electron micro probe analysis confirmed that the dross inclusions were predominantly MgO, Al₂O₃ and SiO₂. In order to have statistically significant data, 40 micro probe analyses were carried out, and according to the proportion of MgO, Al₂O₃ and SiO₂ present, an attempt was made to identify the main oxide phases present - using the ternary phase diagram in figure 4.

With few exceptions, the inclusions examined were all high melting point phases such as: Forsterite, Periclase, Corundum, Spinnel and Mullite. (Melting point ranges 1750 - 2200°C). In addition, smaller traces of MnO, FeO and MgS were found, which would lower the melting point range. These materials are formed during the magnesium

treatment of the iron and the subsequent reaction with oxygen and SiO₂, the latter available in surplus from the inoculation process.

Investigation of the running system:

Due to the consistent position of the defect, always on side wall two, it was decided to examine the running and ingate system. The shell mould contains two casting cavities with a downsprue positioned in the middle. In the lower part of the mould, two runner bars branch left and right and the castings are gated from the bottom. In order to avoid defects caused by the presence of inclusions, a ceramic foam filter is integrated into the running system before the ingate. To reduce the melt velocity, the downsprue incorporates a switch over from one mould half to the other, so called "zigzag" format. In addition, before each casting there is a chamber which is also designed to reduce the iron velocity. It is important to control the iron velocity before the filter, as this can adversely affect the filtration efficiency. This combination of design modifications had previously proved to give optimum casting quality, in the production of other similar castings.

As the inclusions which had been found were reaction products from the magnesium treatment, it was initially assumed that they were due to a slag which had formed in the ladle. This slag had then been "pushed" through the filter due to the relatively high ferostatic pressure and metal velocity. These inclusions then passed into the casting cavity where, due to cooling effects and adhesion, they came to rest in the critical area of the mould surface. It was therefore decided as the next step to involve the filter manufacturer.

Ceramic foam filters are recognised as being the most efficient type to remove non-metallic inclusions, including oxides and sulphides. Non-metallic inclusions smaller than 0.1mm are known to be removed by the filter structure.

The high level of filtration efficiency is based upon the flow of liquid metal through the tortuous, reticulated structure, with constant changes of velocity and direction. The inclusions are captured in the pores of the filter, which can be represented as shown in figures 5a and b. [8,9,10]

Due to the relative size of the inclusion defects in the casting, some of which were several times larger than the average filter pore diameter, it was concluded that they had not in fact been pushed through the filter. It was proposed that the inclusions were actually being formed behind the filter, due to turbulence in the casting cavity. The cause must therefore be somewhere else in the system. See figure 3.

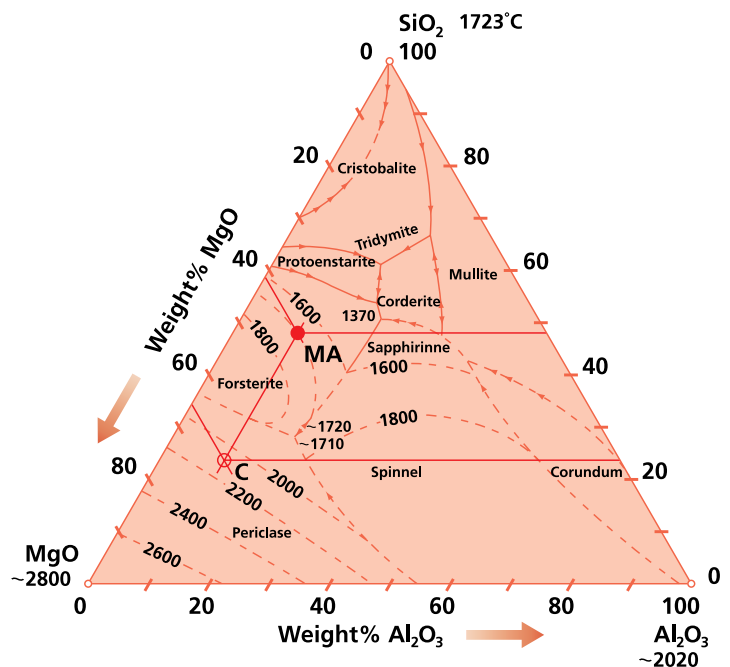


Figure 4: Ternary phase diagram MgO-Al₂O₃-SiO₂ Periclase, forsterite, enstatite, spinnel, mullite

Actions undertaken:

- Increase the efficiency of the filter, by changing from the standard 10ppi ductile iron filter grade, to the finer 20ppi structure - normally used for grey iron.

Result: No consistent success, no process security.

- Application of melt cleaning materials.

Result: Reaction of these materials with the neutral ladle lining resulted in increased slag formation. No positive results.

- Change of ladle lining material, from acid to neutral.

Result: General improvement, but no process security.

- Reduction of the residual magnesium and silicon content, in order to reduce the potential formation of magnesium silicate.

Result: Poor graphite nodularity and low yield strength.

- NFT Furnace Procedure: In order to reduce the oxygen potential of the melt, the iron is superheated in the furnace for an extended period. This resulted in some improvement. The inclusion defects reduced in size with increasing pouring temperature, which confirmed that the defect mechanism was related to the formation of finely dispersed Forsterite ($(MgO)_2SiO_2$). Nevertheless, this action failed to give the required degree of process security.

As the actions listed in 1-5, either individually or in combination, did not give significant improvement, it was decided to begin further investigations.

- Investigation of the mould filling characteristics in the area of the defect: It was possible to observe the metal stream in the casting cavity through a mould with an open side wall. The process was photographed and subsequent examination of these images confirmed a significant amount of turbulence in the area of the defect. (see figure 6). Through vortexing and jetting of the metal stream, and the relatively high oxygen availability, the re-formation of slag/dross was accelerated. It was therefore decided to make changes to the design of the running system in an attempt to minimise turbulence and ensure a quiet mould filling.
- The application of Fluid Flow simulation: The filter supplier, had some time ago acquired a software programme, MAGMA, to provide support for customers in simulating mould filling and fluid flow. In order to reduce the lead time in simulating the crankshaft with the MAGMA software, the foundry supplied a surface model of the part (as an STL file). After adding the geometry of the mould, including the running and feeding system, the software can calculate the fluid flow characteristics of the filling process. The system can run automatically with 3D data, allowing night and weekend time to be utilised for the calculation.

Figure 7 shows the result of the programme simulation for the original running system, at the beginning of pouring with about 20% of the casting full. At this point the full ferrostatic pressure is still effectively on the filter, as essentially no back pressure has formed in the casting cavity. The light colours in the upper half of the ingate, indicate a relatively high metal velocity (ca. 1.6m/sec). The result is obviously a turbulent metal surface, with vortexing and jetting of the iron. Reference to the original running system confirms that it is essentially pressurised, explaining why the highest metal velocities are observed at the ingates. Assuming we calculate for each crankshaft a downsprue area of half of the total area of 706mm², then the following cross sectional ratios apply: Downsprue: Runner bar: Ingate 1: 1.5: 0.72 (or 353, 529 and 253mm² respectively).

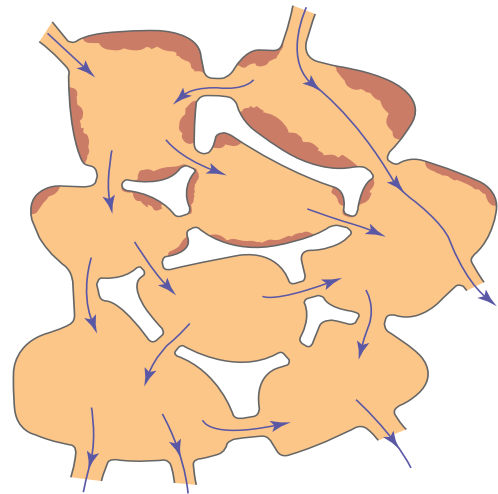


Figure 5a: Flow of liquid metal through a ceramic foam filter with separation of inclusions (schematic)

On the basis of these results, a "virtual" running system was constructed on the screen of the computer, with an appropriately modified gating system ratio. The downsprue and runner bar cross sectional areas were reduced, whilst the ingate area was significantly increased. The modified ratios were: 1:1.06 :1.15 (or 300, 319 and 344mm² respectively). Simulation of the revised gating system indicates, at the same point of mould filling, that the velocity of the metal in the ingate position has been reduced from 1.6 to 1.2 m/sec, i.e. 25% reduction. The result is that the filling process is much quieter and the surface of the metal much smoother. (see figure 8).

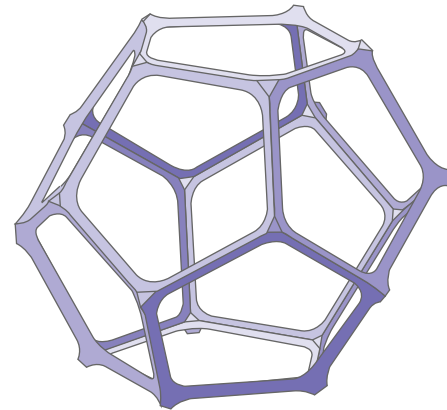


Figure 5b: Representation of the dodecahedron structure of a filter pore

Despite the reassuring results from the simulation, there is always doubt as to whether the same results would be achieved in practice. The next step was therefore to produce real castings with the new running system design.

Following pattern plate modifications, the first step was to observe and photograph mould filling through the open side wall of a shell. This confirmed that practical observation and the result predicted by simulation agreed.

On the basis of this confirmation, a further series of castings were produced. It was obvious on the very

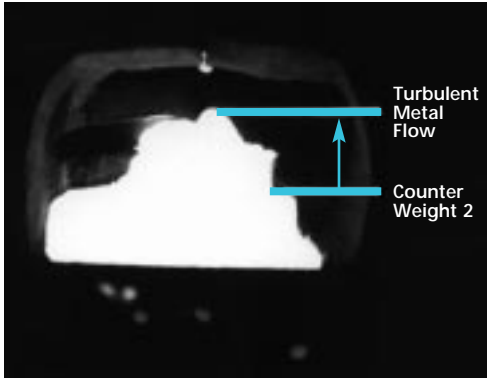


Figure 6: Photographic documentation of strongly turbulent metal flow in the region of counter weight 2

first castings produced that the previously described defect had completely disappeared. In addition, none of the castings submitted for fatigue testing prematurely failed. To date ca.15,000 crankshaft castings have now been produced.

Before the work to optimise the running system, approximately 20% of castings were scrapped following visual and ultra sound inspection. Following the work to redesign the gating system, the scrap rate has been reduced to less than 0.05%. Based upon the degree of process security which has now been achieved, only a sample of castings are submitted for ultra sound examination.

Summary:

Through the co-operation between the foundry and supplier, it has been possible to solve a major inclusion quality problem in the production of a demanding automotive crankshaft. In addition to metallurgical actions, which had only limited success; the investigation of mould filling characteristics and simulation of fluid flow, have resulted in a successful optimisation of the gating system. The scrap rate has been reduced to < 0.05% for the production of ca.15,000 castings. Using careful layout and calculation of the running system, with an integrated ceramic foam filter, it has been possible to prevent excessively high metal velocity into the casting cavity.

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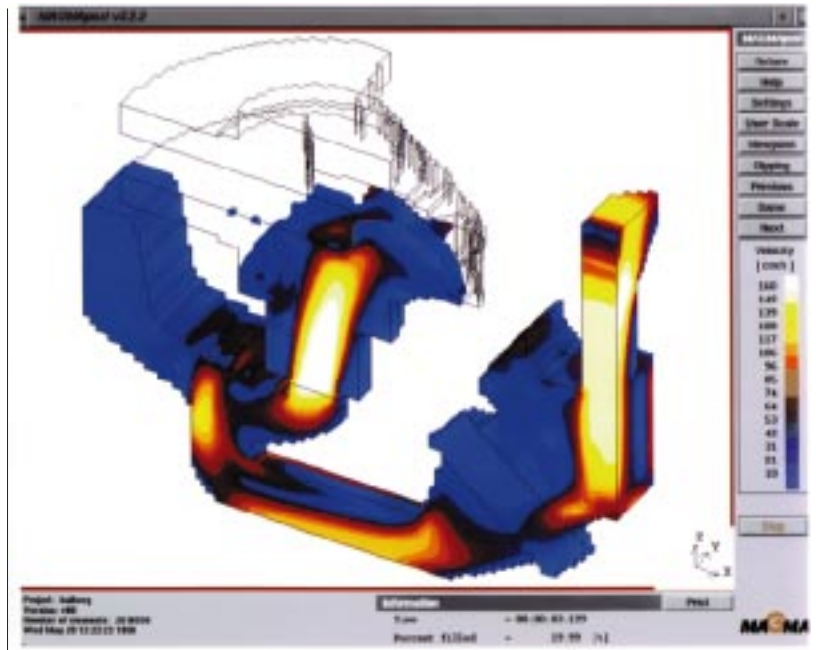


Figure 7: Original method. Mathematical simulation of mould filling in the region of counter weight 2. Turbulence in the area of defect owing to the metal flow being constricted by the narrow ingate

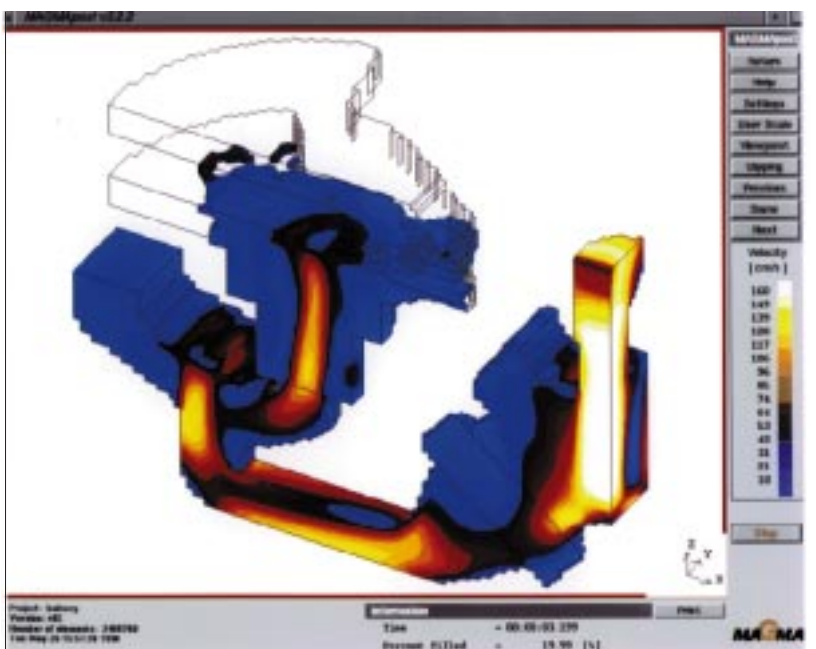


Figure 8: Optimized design of the runner system. Increased ingate area, elimination of turbulence in the area of defects of counter weight 2