Structure and mechanical properties of vermicular cast iron in cylinder head casting

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Abstract
The paper discusses the problem of grain density and ferrite content in microstructure of vermicular graphite iron cast in bars of different section diameters and cylinder head casting. The experimental results regarding the section effect demonstrate that the nodule count, grain density and ferrite content are all function of the cast bar diameter in this particular case ranging from 0.6 to 8.0 cm and microstructure and mechanical properties in the cylinder head. The nodule count (or grain density) has been reported to increase, while ferrite content was decreasing with decreasing casting diameter. The density number of the grains \(N_v\) has been related (by regression analysis) to the undercooling degree \(\Delta T\). This paper describes the results of using a high-magnesium ferrosilicon alloy in cored wire (Mg recovery 40\%) for the production of vermicular graphite cast irons at “WSK-Rzeszów” Metallurgical Plant Ltd. for first series of cylinder head. The results of calculations and experiments have indicated the length of the cored wire to be injected basing on the initial sulfur content and weight of the treated melt. The paper presents a microstructure matrix and vermicular graphite in standard sample and different walled cylinder head castings. The results of numerous trials have shown that the magnesium cored wire process can produce high quality vermicular graphite irons, which its ideally suited to meet the current and future requirements of engine design and performance.

Keywords: Vermicular cast iron; Structure; Mechanical properties; Cylinder head casting

1. Introduction

Based on the European and American experience, the primary path to achieving improved engine performance is to increase the peak firing pressure \(P_{\text{max}}\) in the combustion chamber. In the European commercial vehicle sector, \(P_{\text{max}}\) has increased from approximately 180 bar in 1999 to 220-240 bar in 2007. The resulting increase in thermal and mechanical properties have required a change from conventional inoculation grey cast iron to vermicular graphite iron (GJV) \[1\]. Although vermicular graphite iron has existed for more than 20 years, its applications have been limited to simple, low-volume components with wide microstructural tolerances, pump housings, brackets, box, diesel engine blocks, etc.. Cast iron with vermicular graphite is included in new ISO 16112 international standard from 2006 was published using the combined name: “Compacted (Vermicular) Graphite Cast Iron”.

The ISO standard designation for CGI has been abbreviated as “GJV” and five Grades have been specified in separately cast test pieces, including: minimum values of UTS- MPa GJV-300 (ferritic) GJV-350, GJV-400, GJV- 450 (pearlitic) and GJV-500 (alloyed). Minimum values of elongation \(A_5\) equal from 3 to 1\%.

Examining closely the properties of vermicular graphite cast iron it is easy to see some of its specific advantages, specially when a comparison is made with the high-performance inoculated cast iron (with flake graphite \(FG\)) and ferritic ductile iron (with nodular graphite-\(NG\)).
As regards the most important mechanical, physical and utilization properties, they can be arranged in an increasing order shown below (for the sake of clarity the following designations have been used: FG, NG and VG for inoculated, ductile and vermicular cast irons, respectively) [2].

- Tensile strength UTS - FG, VG, NG;
- Elongation (plastic properties) A – FG, VG, NG;
- Yeld strength YTS - FG, VG, NG;
- Fatigue strength Z - FG, VG, NG;
- Modulus of elasticity E - FG, VG, NG;
- Brinell hardness HB- comparable within the same metallic matrix;
- Damping capacity - NG, VG, FG;
- Coefficient of thermal expansion - comparable;
- Thermal conductivity K - NG, VG, FG;
- Resistance to oxidation at elevated temperatures - FG, VG, NG;
- Thermal fatigue resistance (shock resistance) - NG, VG, FG.

Notwithstanding its undeniable advantages, the cast iron with vermicular graphite GJV has not been in wide use so far, specially compared to ductile iron. From the comparison made above it follows that the cast iron with vermicular graphite surpasses the inoculated grey cast iron in mechanical properties (specially plastic properties) and in most of the engineering and utilization properties, while being inferior in the damping capacity and thermal fatigue resistance.

A comparison between the cast iron with vermicular graphite and that with nodular graphite gives just opposite results. The cast iron with vermicular graphite is an excellent engineering material, taking an intermediate position between the high-performance iron with vermicular graphite and that with nodular graphite gives just opposite results. The cast iron with vermicular graphite is an excellent engineering material, taking an intermediate position between the high-performance iron with vermicular graphite and that with nodular graphite.

The solidification and structure of iron castings in as-cast condition depend on the chemical composition of cast iron and on some technological factors which control the physical and chemical condition of liquid metal and the casting cooling rate in foundry mould. Speaking briefly, the technology of casting fabrication consists in making proper choice of the metal foundry mould. Speaking briefly, the technology of casting fabrication consists in making proper choice of the metal foundry mould.

By changing these parameters, we can change the kinetics of metal solidification, and hence its structure as well as the utilization properties. Quite well known and described in technical literature [2-4] is the effect of chemical composition on the type of structure produced in cast irons with nodular or vermicular graphite.

Generally speaking, the rate of casting cooling depends on the casting shape and dimensions, on the thermo-physical properties and on pouring temperature, as well as on the dimensions and configuration and thermo-physical properties of moulding material (expressed by the coefficient of heat accumulation and mould temperature). An example of microstructure observed in nodular (spheroidal) graphite cast iron plates is described in [2,5].

The aim of the present study has been determination of changes in microstructure of the cast iron with vermicular graphite examined in cast bars on different sections (effect of cooling rate) of diameters: 0.6; 1.6; 2.0; 3.2; 4.4; 5.6; 7.0 and 8.0 cm and application of vermicular cast iron GJV for cylinder head casting.

2. Cored Wire- production of vermicular cast iron and method of investigation

An important stage in the production of high-quality vermicular cast iron is its treatment with different method, e.g. with magnesium FeSiMgCeCa, FeSiMgTi master alloys or RE (Rare Earths). Full success has already been achieved in this respect as regards the implementation into industrial practice of various techniques of introducing the reagents into molten iron, either in bells made from different materials, or by pouring the reagents placed on the bottom of a ladle (Sandwich or Tundish process) or directly in mould (Immold process). In Poland, in 1995, for the first time a most modern and fully mechanised technique of the nodularising or vermicularising treatment of cast iron by means an elastic cored wire (PE - Fig. 1), known also under the name of “Cored Wire Injection Method”, was mastered [2]. From practical experience it follows that both the PE and 2PE techniques (using two elastic wires - one cored with magnesium, and another with inoculant) ensure low manufacturing costs and stabilization of magnesium content at a level of about 0.04%, necessary to obtain nodular graphite, and at a level of 0.015-0.02% Mg, necessary to obtain vermicular graphite. Changing of magnesium level in cast iron is very easy; it is just enough to change the time of feeding the wire on a roller conveyor (at a constant feeding rate). This solution effectively eliminates the time- and labour-consuming operation of repeated weighing of the individual batches of the nodulariser and inoculant, typical of other techniques of the nodularisation or vermicularising and inoculation (2PE method).

Fig. 1. Schematic representation of the cored wire treatment (PE method): 1 - ladle with liquid metal, 2 – cover (lid), 3 – wire feed machine, 4 – coil (basket) with cored wire, 5- set up with electrical control cabinet, 6- exhaust

Over the past 14 years, the PE technique of the cast iron treatment has roused vivid interest of the Polish foundry industry and has been implemented, among others, in several domestic foundries, the Chair of Alloys and Composites Casts Engineering at the (AGH) University of Science and Technology being responsible for implementation of this process in at least 13 foundries [2].

The following formula is used as a main tool for calculation of the wire length L injected to metal and magnesium recovery:

\[ L = \frac{1000 \cdot (100 - YTS)}{YTS} \]
where:
\[ \Delta S = S_1 - S_2 \] is the difference between sulfur content before and after treatment, wt %;
\[ \eta_{Mg} \] is magnesium addition for GJV; 0.015-0.018 wt %;
\[ M_z \] is the cast iron volume, kg;
\[ M_{gp} \] is magnesium content in 1 metre of the cored wire, kg/m,
0.76 – is the coefficient of sulfur and magnesium count, at%.

2.1. Experimental procedure

Melts of the cast iron with vermicular graphite were conducted at the “WSK-Rzeszów” Metallurgical Plant Ltd. where the operations of vermicularising treatment and inoculation have been well mastered during the process of making high-performance cast iron. The metal after melting in a furnace is preheated to a temperature of 1520°C and held at that temperature for about 5 minutes. Then, at a temperature of about 1490-1450°C, the metal is tapped to a slender ladle.

The ladle (capacity 1.5Mg) is handled to the vermicularising treatment post where the treatment is carried out using a cored wire; this technique is described in literature as a PE method [2]. In this particular case, the treatment was carried out by means of a flexible wire with magnesium core (Mg=25%). After treatment the metal is transferred to a pouring ladle and inoculated in the ladle.

When the molten metal is ready (treated to produce vermicular graphite, inoculated and handled in a pouring ladle), a mould provided with a measuring system is poured to investigate the cooling rate in bars of different diameters and to examine what effect this cooling rate may have on the type of microstructure formed in cast iron and on the type of the vermicular graphite precipitates in function of bar diameter.

In this particular case, the treatment was carried out by means of a flexible wire with magnesium core SKW Trostberg; 120g Si/mb, 64g Mg/mb and to 2%RE. After treatment the metal is transferred to a pouring ladle and inoculated in the ladle. After vermicularising, metal is poured into a distribution ladle where it is modified with inoculant SRF75. Having prepared liquid metal, a casting mould has been poured in, which made of bentonite substance.

Changes of temperature during solidification and cooling were recorded in individual bars by a HEWLETT PACKARD HP-34970. In this way it was possible to record the lowest temperature of eutectic transformation at the initial stage of the nucleation process which, in turn, enabled determination of maximum cooling rate \( \Delta T \). The equilibrium temperature allowing for silicon and phosphorus concentration was determined from the following equation:

\[ T_{e,\text{eq}} = 1427.6 + 5.25 Si - 14.88 P \] (2)

At the same time, standard „Y-II type” keel blocks and a bar of \( \varnothing \) 3.0x30cm diameter were cast to test the mechanical properties, such as UTS, YTS, As and hardness HB.

3. Results and analysis

Using solidification and cooling curves plotted for the individual cast bars, a maximum undercooling degree \( \Delta T \) was calculated at the final stage of the nucleation process for the examined bars of different diameters; the results of the metallographic examinations of cast iron structure are compiled in Figure 2 with some examples depicted in Figures 3 and 4. Analysing microstructures of the examined bars of different diameters it has been observed that the content of ferrite in matrix as well as the size of vermicular graphite precipitates increase with increasing casting section (bar diameter), while the density of precipitates decreases quite obviously.

In the Figure 2 gives compiled values of the cast iron undercooling degree \( \Delta T_{max} \) (the process of graphite nucleation has been completed), ferrite content and vermicular graphite content in the structure as well as the number of graphite grains in a unit volume and on a unit surface \( N \) of the casting, calculated from equation [6]:

\[ N_v = \frac{\Pi}{6f_c}(N)^3 = 2.69(N)^3 \] (3)

Where;
\[ f_c \] - carbon volume content = (13.8)$^{-1}$

![Fig. 2. The number of graphite grains in a unit volume as a function of the maximum undercooling degree \( \Delta T \) in bars of diameters from 1.6cm to 8.0cm,](image-url)
Fig. 3. Microstructure of the vermicular graphite iron cast in the bar castings: a) 3.2cm, b) 8.0cm

Fig. 4. Microstructure of cast iron with precipitates of vermicular graphite and traces of nodular graphite. A JEOL - SEM photograph; specimen after deep etching

In bars of 4.4 and 7.0cm diameters the casting solidification and cooling curves were not recorded due to technical reasons - the thermocouples were damaged when the metal was poured into a foundry mould. In a bar of 0.6cm diameter the degree of undercooling was so high that the measuring system was not capable of recording changes on the cooling curve (the reason was the thermocouple inertia). Undercooling so high must have affected the metallic matrix and resulted in numerous precipitates of cementite (Fe₃C) appearing in the structure cast iron.

The density of nuclei, and hence the number of the graphite eutectic grains in the examined cast iron can be determined from the theoretical rules of homogeneous and heterogeneous nucleation. This number was determined on cast iron specimens after deep etching, using images obtained under the scanning electron microscope, which revealed the special structure of graphite precipitates and enabled their correct counting. An example of this microstructure used to calculate the quantity \( N \) is shown in Figure 4. In the case under discussion, the values of the nuclei count \( N \) and of the undercooling degree \( \Delta T \) were statistically interrelated following a general relationship \( N = a(\Delta T)^n \):

\[
N_1 = 8758 (\Delta T)^2 \quad R^2 = 0.97 \tag{4}
\]

\[
N_2 = 3371.2 (\Delta T)^{2.26} \quad R^2 = 0.99 \tag{5}
\]

Equations (4) and (5) shown in Figure 2; in the former case exponent \( n=2 \) was assumed \( a'priori \) in calculations of \( \Delta T \) (4). Using these equations it is possible to determine with satisfactory accuracy the density of the precipitates of vermicular and nodular graphite (nuclei, grains), providing the undercooling degree vs cast bar diameter relationship is known. The structure may include a number of pre-eutectic graphite precipitates, since the cast iron composition has been slightly shifted in respect of the zone of coupled growth of graphite eutectic (a composition slightly hypereutectic).

Mechanical tests conducted on a sample taken from the „YII” keel block gave the following results: UTS=394 MPa, YTS=265 MPa, \( A_3=9.6\% \) and hardness HB=163 units. In a test bar of 3.0 cm diameter, the following values of the mechanical properties were obtained: UTS=413 MPa, YTS=310 MPa, \( A_3=6.0\% \) and hardness HB=179 units.

From these values it follows that the cooling rate in cast bar is higher than in the „YII” keel block. The consequence is higher strength (more pearlite in the structure) and lower cast iron elongation. So, in the latter case, in the lower wall of the „YII” keel block of 2.5cm cross-section, the microstructure of cast iron is different than it is in a bar of the same diameter, this results from the values of the reduced wall thickness amounting to \( \frac{x}{4} \) and \( \frac{x}{2} \), respectively.

The qualitative and quantitative analysis of microstructure in bars of diameters from 0.6 to 8cm cast from vermicular graphite iron enables determination of graphite shape (the content of nodular and vermicular graphite) and the type of metal matrix with ferrite and pearlite content. In the case of the cast bar of the smallest diameter, i.e. 0.6cm, the structure of cast iron had some precipitates of eutectic and pre-eutectic cementite. Therefore, in a simplified form, it is possible to forecast (in reality there is an interaction between different wall cross-sections present in castings) the type of the produced microstructure in respect of the density and size of the vermicular graphite precipitates as well as the type of metal matrix in the examined cast bars of different diameters.

The number of graphite precipitates in a unit volume of this cast iron grade referred to the undercooling degree \( \Delta T \) can be determined from equation (4).
The cast iron with vermicular graphite is a material suitable for cylinder heads operating in high-capacity diesel engines, and at present it is used, among others, for the above-mentioned cast parts of engines operating in motor cars, like BMW, Audi, Opel Calibra [2] and Daimler Chrysler, Ford, Hyundai, John Deere [1]. During engine running, the part most exposed to cyclic changes of temperature is the internal casting wall. Because of cooling cycles to which the cylinder head is exposed, a temperature gradient occurs and the result is formation of some specific casting defects, like cracks and crazes. Hence, follow very high requirements imposed on the cast iron for cylinder heads operating in modern high-capacity engines with self-ignition systems, and all these requirements can be satisfied by the cast iron with vermicular graphite. The structure of this iron should contain minimum 80% of the vermicular graphite (the rest is nodular graphite) with a ferritic matrix containing pearlitic in an amount not exceeding 15%. The presence of eutectic cementite in the structure is not allowed.

Until now, at the “WSK - Rzeszów” Metallurgical Plant Ltd., the cylinder heads for diesel engines have been made for a foreign client from the low-alloy inoculation grey iron, grade EN-GJL-350. Analysing the results of the investigations of an effect of the casting wall thickness on cast iron microstructure, it can be expected that under given conditions of the cast iron vermicularising treatment and inoculation, it will be possible to forecast the type of the obtained microstructure in respect of the metallic matrix and the shape, amount and distribution of graphite, assuming a general rule that the heavier is the wall section, the higher is the content of vermicular graphite and ferrite. It should also be remembered that in practical operation of the process there is an interrelation between different wall cross-sections present in a casting [7]. The amount and shape of vermicular graphite in a casting wall of a given thickness strictly depend on the content of magnesium in cast iron, and on the technique of inoculation as well as on the amount of inoculant introduced to this cast iron.

Considering the results obtained in an investigation described previously, related with forecasting the microstructure of vermicular graphite iron in a casting with varied wall cross-sections, a task was undertaken to manufacture from this cast iron a pilot cylinder head to operate in an engine. The casting was characterised by an intricate geometry of both external and internal parts, as illustrated on a computer-made drawing (Fig. 5). From the drawing it clearly follows that the casting has different wall cross-sections; it is, moreover, subjected to a strict quality control. It is generally assumed that the application of vermicular graphite cast iron with a ferritic matrix gives higher mechanical properties in casting, successfully combined with reduced manufacturing costs, as the low-alloy grey cast iron used so far contains additions of Mo, Ni, Cr, Sn and Cu.

Molten metal was tapped and subjected to vermicularising treatment and inoculation carried out under the same regime as the treatment used for cast bars. It was next poured into moulds reproducing the cast cylinder head, casting also standard specimens for mechanical testing, the same ones as used in the case of ductile iron (“YII” keel blocks) and bars of Ø 3,0x30 cm diameter. The conditions of melting and the technique of mould pouring were described in details in [7,8].

Table 1. Results of mechanical properties of vermicular cast iron (GJV)

<table>
<thead>
<tr>
<th>“YII” keel block</th>
<th>Diameter test bar</th>
<th>Cylinder head casting (wall casting)</th>
</tr>
</thead>
<tbody>
<tr>
<td>standard</td>
<td>Ø 3,0x30cm</td>
<td></td>
</tr>
<tr>
<td>UTS=340-395MPa</td>
<td>UTS=320-420 MPa</td>
<td>UTS=300-340 MPa</td>
</tr>
<tr>
<td>YTS=245-295 MPa</td>
<td>YTS=270-330 MPa</td>
<td>YTS=240-285MPa</td>
</tr>
<tr>
<td>$A_1 = 4.5 - 10.5$ %</td>
<td>$A_1 = 4.0 - 8.0$ %</td>
<td>$A_1 = 3.5 - 10.0$ %</td>
</tr>
<tr>
<td>HB = 145 -170</td>
<td>HB = 140 -180</td>
<td>HB = 140 -160</td>
</tr>
</tbody>
</table>

Comparing the results of mechanical tests obtained on standard keel blocks and in castings, and some similarities that prevail in both cases, one can observe that the obtained properties are grouped in certain ranges of values reflected in the utilisation properties of casting. This is shown on a schematic diagram (Table 1) below giving the ranges of values obtained on standard “YII” keel blocks, in bars of Ø 3,0x30 cm, and in casting cylinder head walls.

Fig. 5. The view of the cylinder head casting test prepared by the SolidWorks software
The ranges of properties obtained in individual parts of the cast cylinder head are due to the differences in casting wall cross-section and to the cooling rate effect on the type of metallic matrix produced and on the size of the vermicular and nodular (up to 20% volume content permitted) graphite precipitates in structure as illustrated in Figure 6.

Compared with other techniques, the method of vermicularising treatment by the technique of PE offers the following advantages: it ensures process stability expressed by target magnesium content in cast iron of and 0.015-0.018% Mg range for vermicular graphite (Figs. 3, 4 and 6).

4. Conclusions

Based on conducted studies of vermicular cast iron in bar and cylinder head casting following conclusions have been formulated:
1. From observations of the vermicularising treatment of cast iron carried out by the method of PE under the conditions of foundry “WSK - Rzeszów” Metallurgical Plant Ltd. it follows that this technique has gained full approval of the foundry industry. Therefore it is used more and more often at home and abroad in manufacture of cylinder head casting from quality vermicular cast iron (GJV).
2. An important technological parameter of the PE technique, determining essentially the length of the cored wire injected to molten metal and the cost of the treatment, is the level of magnesium recovery $\eta_{Mg}$ expressed by equation (1), which depends on the technical conditions of the equipment designed and actually used by the foundry for this purpose.
3. The experimental results regarding the section effect demonstrate that the nodule count, grain density and ferrite content are all function of the cast bar diameter, in this particular case ranging from 0.6 to 8.0cm. The values of the nuclei count $N_v$ of vermicular graphite and of the undercooling degree $\Delta T$ were statistically interrelated following a general relationship $N_v = a(\Delta T)^n$; equations $N_v = 8758 (\Delta T)^2$ or $N_v = 3371.2 (\Delta T)^2.26$ (correlation coefficient $R = 0.97-0.99$).
4. The metallic matrix of the cylinder head casting condition is about 90% ferrite and 10% pearlite. The size vermicular and nodular (up to 20% volume content permitted) graphite precipitates in structure of casting.

References