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Development of a Manufacturing Technology of Compacted Graphite Iron Castings from a Cupola Furnace

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Abstract

Compacted graphite iron, also known as vermicular cast iron or semiductile cast iron is a modern material, the production of which is increasing globaly. Recently this material has been very often used in automotive industry. This paper reviews some findigs gained during the development of the manufacturing technology of compacted graphite iron under the conditions in Slévárna Heunisch Brno, Ltd. The new technology assumes usage of cupola furnace for melting and is beeing developed for production of castings weighing up to 300 kilograms poured into bentonite sand moulds.

Keywords: Compacted graphite iron, Cupola furnace, Modification

1. Introduction

In the compacted graphite cast iron, which is also termed vermicular cast iron, graphite appears in a worm-like form. The production of this type of cast iron is increasing worldwide every year and it is gaining popularity (especially) in the automotive industry. This cast iron has been used mainly for diesel engine blocks and cylinder heads in powerful passenger cars, vans and lorries [1,2,3]. The pressure increases up to 20MPa [4] after the ignition of fuel in this engine type. For such stresses, castings produced from lamellar graphite cast iron are in terms of strength insufficient. As replacement for cast iron with lamellar graphite, cast iron with spheroidal graphite or vermicular graphite can be used. One of the very important properties required for engine blocks and cylinder heads is good thermal conductivity and ability to damp mechanical vibration. Damping capacity and thermal conductivity of CGI is lower in comparison with lamellar graphite cast iron but higher then of spheroidal graphite cast iron . Thermal conductivity of CGI (approx. 36 W/m.K) is according to [2] 25% higher than of GJL-250 (approx. 46 W/m.K) but only 10 % lower compared to GJL-300 (approx. 39 W/m.K). With increasing tensile strenght of compacted graphite iron is the C amount decreasing and consequently thermal conductivity is becoming lower. The difference in thermal conductivity between these two cast irons is smaller. Thermal conductivity is also strongly influenced by the amount of spheroidal graphite in cast iron. Thermal conductivity is decreasing with rising amount of spheroidal graphite . CGI provides lower ability to absorb mechanical vibration in comparison with lamellar graphite cast iron but higher than compared to spheroidal graphite cast iron. [5]. Damping capacity of GGI is increasing with decreasing amount of spheroidal graphite.

CGI provides 40% higher tensile strenght than lamellar graphite cast iron. High quality vermicular cast irons with mainly ferritic structure can provide elongation even more than 10 %.

Due to higher strenght, castings produced from CGI have lower wall thickness. It makes possible to lower the weight of castings. As stated in [2], the weight of engine block can be reduced by 10 -25% when using compacted graphite cast iron insted of lamellar graphite cast iron . According to [6], the weight of engine block decreases by 22% and total engine weight decreasses by approx. 9 %.

Very important property of this material is its machinability. Many authors deal with the issue of machinability of vermicular cast iron in comparison with lamellar graphite cast iron [7,8]. Compared to lamellar graphite cast iron, machinability of vermicular cast iron is worse, but it is better in comparison with spheroidal graphite cast iron. [8] presents that the machinability can be worse by 30 až 50 % then of lamellar graphite cast iron. [2] states that optimal machinibility of vermicular cast iron can be achieved, when the Ti amount is lower then 0.02%.

Vermicular cast iron falls in terms of mechanical, physical and pouring properties between lamellar and spheroidal cast iron. The manufacturing technology is similar to lamellar graphite cast iron and mechanical properties to spheroidal graphite cast iron. First experiments with this material started at the US Ford Motor company in the 1960 [9]. In the Czech republic, research and production of vermicular cast iron began in the company Liaz. The production was terminated and unfortunatelly nobody in Czech tied on the production of this material. The above mentioned findings facts show that recently vermicular cast iron has been a very important and promising material in the construction of personal vehicles and trucks. Its production puts much greater emphasis on keeping stable manufacturing conditions and low process variability. Regarding the production of CGI, bigger demands on structure, properties and occurence of another types of casting defects then in the production of lamellar graphite cast iron can be expected as well [10,11].

Slévárna Heunisch Brno, Ltd. (former Slévárna Zetor, a.s.) has produced castings for vehicle industry since the founding. The foundry focuses on the production of complex housings made of lamellar graphite cast iron, f.e. engine blocks, transmission cases, axle shafts etc. Most parts are produced from lamellar graphite cast iron. Within the contect of the project of the Ministry of Industry and Trade of the Czech Republic TIP FR-TI 2/543 „Výzkum a vývoj vysokopevnostních nápravových těles - pouzder náprav z vermikulární litiny"/Development of technology of heavy castings for power and general engineering/, new manufacturing technology of vermicular cast iron has been developed in Slévárna Heunisch Brno, Ltd. This project is about the introduction of production of the new material, that has not been manufactured in this foundry so far. The research focuses on all basic phases of casting production starting with bucking, choice of chemical composition, metallurgical treatment, inspection of structural and surface quality and control of the graphite shape. The new technology has been developed for the production under the manufacturing conditions in Slévárna Heunisch Brno, Ltd. i.e. for melting in cupola furnace and casting into molds with sand mix containing bentonite clay.

2. Experiment conditions

In the course of the research three pilot lots made of vermicular cast iron have been manufactured so far. Goal of the first lot was to verify the proposed production procedure, functionality of the production equipment, obtained chemical composition of the melt as well as cooperation among staff members. Transportation times were defined too. A number of modificated melts – ladles with CGI – were manufactured in the course of this lot. Based on the results obtained from the first lot, experiment plan for the second lot was established, in the course of which other ladles containing vermicular cast iron were casted. Some prototype castings and tests regarding foundry technology were casted from each melt. The results of this lot were used for optimalization and verification of partial production procedures. 13 modifications were carried out in the course of the third lot.

The melting was carried out in hot blast cupola furnace. During bucking the iron charge consisted of 20% pig iron, 50 % steel scrap and 30 % cast iron scrap. The chemical composition of the melt was homogenized in electric induction 35 ton-foreheart Ladles weighing 1050 – 1100kg were gradually modified from the foreheart. Chemical composition was determined from samples taken from tap hole of the cupola and then always from ladle prior to modification. The C content has ranged from 3.60 to 3.76 % and Si content from 1.70 to 2.07 %. Chemical composition of the basic metal was chosen to approximately comply with eutectic composition (Table 1).

Table 1.
Chemical composition of melt in foreheart before modification

	Chemical composition of melt [% by weight]							
Lot-No.	C	Si	Mn	P	S	Cr	Cu	Ce
2	3.58	1.97	0.34	0.040	0.050	0.05	0.09	4.25
3	3.58	1.90	0.26	0.030	0.057	0.04		4.22

Iron and non-iron charge were put together with respect of achievement P and S content in melt as low as possible. Low P content in melt was reached by use of charge with low P content. Low S content was achieved due to use of lower amount of coke in charge, approx. 10.7 % by weight.

Chemical composition of melt before modification shows, that chemical composition is in accordance with eutectic composition (CE = 4.25). Higher Si content in the course of modification and inoculation was taken into account, i.e. eutectic event. hypereutectic chemical composition. Melt tempterature in foreheart ranged between 1470 and 1500 °C. The temperature of metal in the ladle decreased during tapping iron by 20 °C. Afterwards modification of cast iron with wire coil was carried out. Both wire coil without and with content of rare earths was for the modification.

The concentation of Mg between 0.014 – 0.035 % after modification was chosen by means of changing the wire lenght. The use of Mg from wire has ranged from 14 – 19 % at investigated melts. The low usage is related to evaporation of Mg and mainly to bond between Mg and S (desulfurisation). After finishing the modification, metal was transfered from modification ladle to pouring ladle and samples for the analysis of chemical composition were beeen taken from all ladles. The filling time of one mold ranged between 8 – 12 sec. The first and second mold were filled within the takt time of the production line. An approx. 5 minute break followed and the last mold was filled. The time between the end of modification and pouring the last piece was approx. 10 min. Samples for analysis of chemical composition were taken from each ladle 2 and 3 minutes after the last piece had been poured. Sample parts with different wall thickness, technological tests and sample parts were casted from the ladle Inoculation was carried out by setting inoculant into the gating system.

3. Results of experiment

In the course of the experiment parameters for research have been chosen in order to verify the proposed production technology of CGI.

Parameters as follows have been observed:

1. changes in chemical composition after the modification, in the course of leaving the metal in the ladle and in the casting;
2. changes of temperature of the melt in the ladle during iron tap, after modification and during casting;
3. time of modification, pouring time and time of keeping the melt in the ladle;
4. material structure morphology of the casting depending on cooling rate (thickness of the casting) during tensile test and depending on thickness of the casting and chemical composition of the cast iron;
5. mechanical properties of the casting during tensile test depending on thickness of the casting and chemical composition of the cast iron;
6. Influence of rare earths on the obtained structure and fading over time.

Production parameters such as changes in chemical composition of the melt during production, transportation times etc. that have been observed, have been used for determination and description of process. Parameters observed on sample castings have been used for determining relation between chemical composition of cast iron, thickness and material structure as well as mechanical properties of the casting.

3.1. Results from the analysis of chemical composition

Chemical composition of the melt before modification and metal temperature prior to and after modification shows only a small spread on all modification. As a result of that, only a small spread in use of Mg from wire coil ranging from 16 to 19 % in the course of individual modifications has been reached. This circumstance enables a quite exact estimation of the final Mg content in the melt after modification based only on the lenght of added wire. Since the use of Mg has not been influenced by the order of the modificated ladle, it shows constant metal temperature in the ladle prior to and after modification.

Decrease of Mg percentage in the pouring ladle during pouring has shown linear curve at observed melts. On the basis of both Mg percentage after modification and time of keeping the melt in the ladle, linear dependence has been diverted, see equation (1) that enables an exact estimation of Mg content in melt before pouring in t time.

$$Mg_{t.} = 0{,}996 \cdot Mg_{poc.} + 0{,}00084 \cdot t - 0{,}09 \cdot t \cdot Mg_{poc.} \qquad (1)$$

$Mg_{t.}$ – Mg content in melt in the ladle after modification in t time [weight %]
$Mg_{poc.}$ – Mg content in melt in the ladle in the first sample after modification in t time = 0 [weight %]
t – time [min.]

For deviations between the real and calculated Mg content on the basis of diverted linear regression for data in the second lot, see Figure 1.

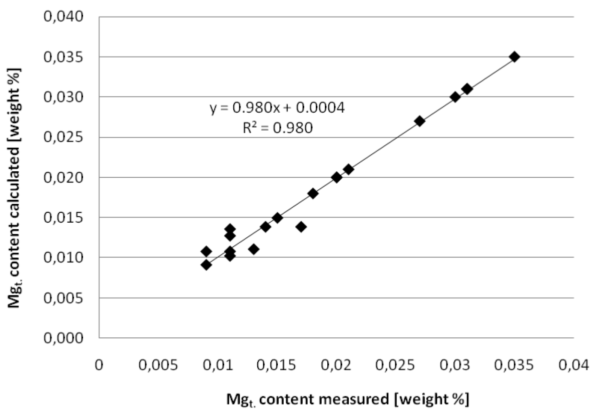


Fig. 1. Comparison of measured Mg content with calculated Mg content in t time

For production management it is necessary to know the dependence between Mg percentage in the ladle and in the casting with specified wall thickness. Linear regression between two independent variables has been used for determination of this dependence again, (wall thickness of the casting, $Mg_{odl.}$ content in the ladle Mg_t in time of modification) and one dependent variable (determined magnesium content in the casting $Mg_{odl.}$). Equation for the determination of Mg content in the part has been obtained with linear regression (2).

$$Mg_{odl.} = 0{,}651 \cdot Mg_{t.} + 0{,}00022 \cdot s - 0{,}0073 \cdot s \cdot Mg_{t.} \qquad (2)$$

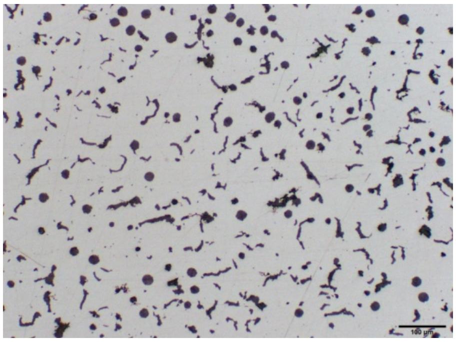
$Mg_{odl.}$ – Mg content in the part with given wall thickness [weight %]
$Mg_{t.}$ –Mg content in the ladle after modification in time t [weight %]
s – wall thickness of the part [mm]

The equation (2) is applicable only in the range, it has been determined for, i.e. $Mg_{t.}$ between 0.017 and 0.031 % and wall thickness in the range between 6 and 40 mm. If we compare the measured $Mg_{odl.}$ content with the calculated value from all samples of the second lot, we come to a conclusion, that the linear regression between the calculated and measured content of rest magnesium in the casting is statistically significant (coefficient of regression $R^2 = 0.809$, i.e. coefficient of determination $R = 0.90$).

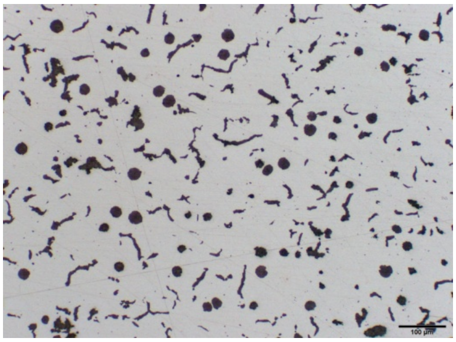
3.2. Results from the evaluation of metallograhy

Classification of metallographic images has been performed on specimens taken from the castings wit variable wall thickness between 6 mm and 40 mm. The classification has been performed by visual analysis, in the course of which the ratio of the contents in compacted graphite and spheroidal graphite as well as graphite size and feritte and pearlite amount have been evaluated. Most customers require that the amount of spheroidal graphite does not exceed 20 %. No lamellar graphite is acceptable.

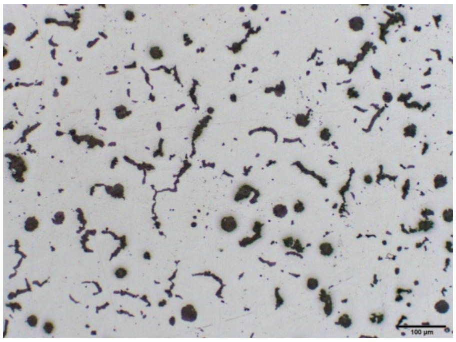
The spheroidal graphite amount in the cast iron is dependent mainly on the wall thickness of the casting and then on the Mg content in the casting. The amount of spheroidal graphite is growing with decreasing wall thickness at the specified Mg concentration in the casting ranging from 0.01 to 0.02 Figure 2 presents metallographic images showing graphite shape, size and arrangement in the casting with changing wall thickness.



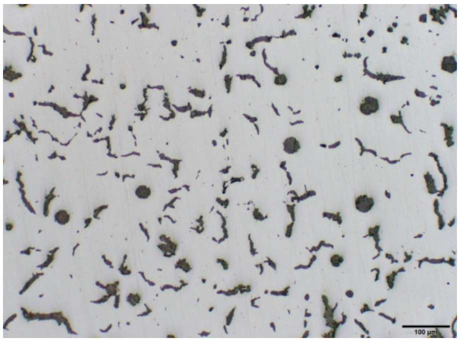
Wall thickness 6mm, 0.01%Mg, 35.8%SGI



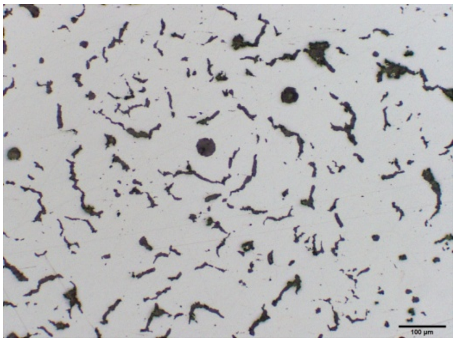
Wall thickness 8mm, 0.013%Mg, 24.9%SGI



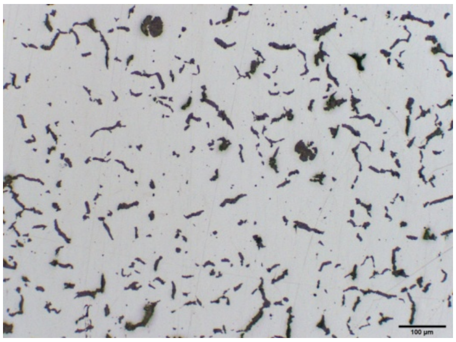
Wall thickness 12mm, 0.012%Mg, 14.8%SGI



Wall thickness 16mm, 0.013%Mg, 15.2%SGI



Wall thickness 20mm, 0.014%Mg, 9.35%SGI



Wall thickness 40mm, 0.013%Mg, 1.5%SGI

Fig. 2. Metallographic images of casting No. 36 with wall thickness 6, 8, 12, 16, 20 a 40 mm

Mg content in the casting has ranged from 0.01 to 0.014% and that is why is obvious, that amount of spheroidal graphite in cast iron depends on Mg content in the casting, but mainly on wall thickness of the casting. The amount of compacted graphite in

CGI in all researched castings is shown in Figure 3. Mg content in these samples has ranged between 0.01 – 0.02 %.

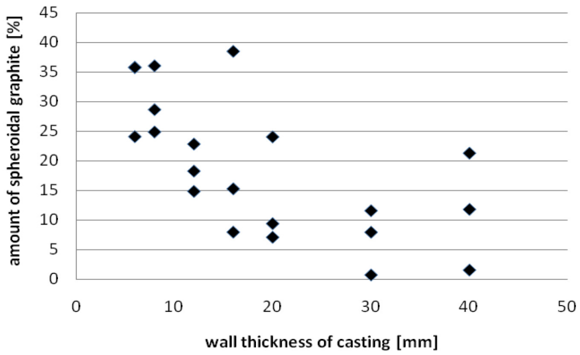


Fig. 3. Amount of spheroidal graphite depending on wall thickness of casting

When using wire coil containing rare earths, the spread in the reached amount of compacted graphite in the part of specified wall thickness has decreased and the compacted graphite amount has been higher when using rare earths and having the same wall thickness of the casting. Feritte and pearlite amount in the casting has ranged between approx. 20 % pearlite in wall thickness 40 mm and 50 % pearlite in wall thickness 6 mm. Chemical composition has been chosen in view of speed of cooling to reach the pearlite amount with this range in the structure. Tensile strength has ranged between 380 -500 MPa at elongation 3 – 10% in wall thickness 20 mm.

4. Summary

Manufacturing technology of compacted graphite cast iron has been proposed and verified in the course of existing results. The bucking, melting, modification and inoculation processes have been managed under the manufacturing conditions in Slévárna Heunisch Brno, Ltd. The conclusion was that chemical composition of cast iron is easily predictable due to low variability of the whole production in all manufacturing phases.

Next, connections between chemical composition of cast iron and wall thickness of the casting have been verified. The proposed technology has made it possible to meet requirements on structural and mechanical properties of compacted graphite cast iron in castings with wall thickness more than 16 mm and fixed chemical composion. The amount of compacted graphite was higher than 80% in researched castings with this wall thickness. The structure was feritte-pearlitic and measured mechanical properties were in specification. In the following phase, this research aims at establishing conditions to fulfil requirements of the standard on thin-wall castings with more than 8 mm wall thickness.

An important factor for establishing production of compacted graphite castings is mainly the possibility to control the graphite modification before pouring. In the present phase of this research programme, analysis of chemical composition and subsequent control by means of mettallographic analysis have been used. Non-destructive control of structure by using ultrasonography has been carried out too. In the next phase, futher verification and use of this method as well as searching for connections between the speed of ultrasound waves and structure and mechanical properties is expected. It has been planned to use the method of direct measurement of oxygen activity in melt for the assesment of modification degree.

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