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Vermicular cast iron production in the "Inmold" technology (in the Metalpol casting house) and the assessment of its thermal fatigue resistance

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Abstract

The method of obtaining the vermicular cast iron in the "Inmold" technology and the results of the thermal fatigue investigations, are presented in the paper. The influence of the maximum cycle temperature (T_{max}) on the thermal fatigue resistance was examined by means of the L.F. Coffin method. The cast iron structure change caused by the thermal fatigue is presented in the paper. When the vermicular cast iron is subjected to the thermal fatigue the matrix ferritisation occurs, which leads to the strength, $R_{m.,}$ decrease. The heating process of the vermicular cast iron is slower as compared to the spheroidal cast iron, whereas the cooling process is faster. Under the same conditions of heat exchanging the vermicular cast iron is heated to a much lower temperature than the spheroidal one. Together with the maximum heating temperature increase the thermal fatigue resistance decreases.

Keywords: Thermal fatigue, Inmold method, Vermicular cast iron, Structure

1. Introduction

A significant technical and technological progress has been recently occurring. It is related to introduction of new devices, machines, cars etc., their modifications and applications of new and of a better quality materials.

One of such materials applied more and more often by design engineers is the vermicular cast iron. The cast iron with such graphite form is characterised by relatively good mechanical properties, high thermal conductivity and good technological properties. It has been known for many years, however due to difficulties in its obtaining only a few cases of the serialised production on automated foundry lines are heard of.

The chemical composition of the vermicular cast iron is similar to the composition of spheroidal cast iron and is contained within: C = 3.2 – 3.8%, Si = 1.7 – 3.2%, Mn = 0.1 – 0.7%, P up to 0.06%, S up to 0.02%. In addition, cast iron can contain trace amounts of such elements as magnesium, cerium, calcium, aluminium, titanium, lanthanum, etc. – in dependence of the production method.

The basic mechanical properties of non-alloyed vermicular cast iron in as-cast state (without the heat treatment) are usually within the following range: R_m = 300-500 MPa, A_5 = 1-9%, HB = 140 - 260.

In order to increase strength properties, or to obtain special functional properties of cast iron alloying additions are applied, e.g. copper, tin, nickel, chromium and molybdenum – in a similar fashion as in grey and spheroidal cast iron.

2. Technological assumptions

After the detailed analysis of the basic production methods of the vermicular cast iron as well as the analysis of the technical and technological options of the casting house, the in-mold method with the magnesium preliminary alloy was chosen as the optimal one, providing the highest probability of achieving the reproducible results in the serialized casting production on the mechanized moulding line.

However, this method is technologically difficult since the magnesium content range in the cast iron at which graphite crystallises in a vermicular form, is very narrow. An excess of magnesium leads to obtaining a nodular graphite, while too small amount of Mg – to formation of a flake graphite.

The “Inmold” technology, as any other technology has its advantages and faults. The main advantage of this technology is a short time in between the procedure of introducing a modifier (spheroidising agent) and filling the mould cavity with liquid metal. Usually it allows to increase the number of eutectic cells and to improve plastic properties, elongation and impact strength of the cast iron. Difficulties related to this technology are as follows:

- Necessity of applying the cast iron of a low sulphur content, S < 0.01%;
- Possibility of inclusions (MgS, MgO, etc.) transfer into castings;
- Requirements of maintaining high stability of process parameters (cast iron composition, temperature, composition and granulation of foundry alloys);
- Necessity of the gating system extension;
- Requirements of selecting the reaction chamber dimension for each mould, to assure a uniform foundry alloy solution;
- Danger of diversified Mg content in various parts of a casting;

Necessity to perform a trial series at implementing this technology.

The recommended chemical composition of cast iron:
A chemical composition of the vermicular cast iron is selected in dependence on the required pearlite fraction in a matrix or the cast iron grade or the casting wall thickness.

Table 1.
Pearlite fraction in dependence on the chemical composition

Pearlite fraction [%]	Chemical composition. [%]								
	C	**Si**	**Mn**	**P**	**S**	**Mg**	**Ce**	**Cu**	**Sn**
<15	3,6-3,8	2,5-2,7	0,1-0,2	do 0,04	0,005-0,022	0,006-0,015	0,01-0,03	-	-
25	3,6-3,8	2,4-2,6	0,2-0,3	do 0,04	0,005-0,022	0,006-0,015	0,01-0,03	-	-
50	3,6-3,8	2,4-2,6	0,2-0,4	do 0,06	0,005-0,022	0,006-0,015	0,01-0,03	-	-
75	3,6-3,8	2,1-2,5	0,2-0,4	do 0,06	0,005-0,022	0,006-0,015	0,01-0,03	0,3-0,6	0,03-0,05
99	3,6-3,8	2,1-2,5	0,2-0,4	do 0,06	0,005-0,022	0,006-0,015	0,01-0,03	0,6-0,9	0,08-0,10
Cr_{max} = 0,03%, Al_{max} = 0,008%									

Pouring temperature (T_{pou}):

- should be stable and selected according to the casting structure ($\Delta T_{pou} < 35$°C),
- should not be lower than app.: $T_{pou} > 1350$°C,
- should be contained within range: T_{pou} = 1350-1480°C,
- should be selected for the foundry alloy grain size.

Mould technology and the gating system structure

The gating system with the reaction chamber should assure:

- a quiet metal flow into the reaction chamber,
- that particles of not dissolved spheroidising agent are not flowing out of the chamber,
- that the chamber output is not in a straight line with the input,
- a flow damping (cross-section decrease) at the chamber output,
- ceramic filters in the gating system to catch oxides and slag,
- the synchronisation of the pouring time, related to the casting structure, with the foundry alloy dissolving time.

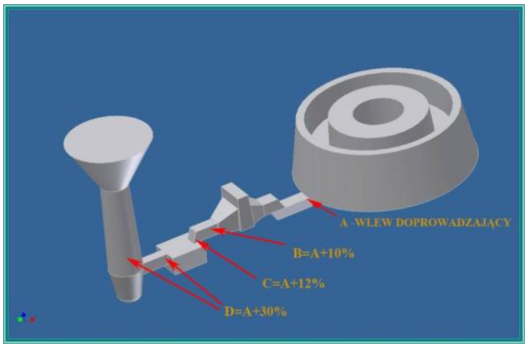


Fig.1. Cross-sections of individual sections of the gating system

The foundry alloy amount:

A foundry alloy amount, which should be placed in the reaction chamber is calculated from the general dependence applied at a secondary metallurgy of the spheroidal cast iron. In the inmold technology it is difficult to estimate the magnesium assimilation coefficient since it depends on several factors: kind of foundry alloy, its grain size, reaction chamber structure, etc.

$$Q_{alloy} = \frac{(Mg_{cr} + 0{,}75(S_{init} - S_{fin})}{Mg_{alloy} * \eta_{Mg}} * 100\%$$

Q_{alloy} - amount of the spheroidising foundry alloy [%]
Mg_{cr} –critical magnesium content (Mg = 0.006-0.015 %)
η_{Mg} – assimilation coefficient of magnesium
S_{init}, S_{fin}. – initial and final sulphur content in the cast iron [%]

Reaction time and pouring time

The mould pouring time and dissolving time of the foundry alloy should be similar to each other. The optimal pouring time depends on the casting size and structure and due to that the dissolving time should be ‘adjusted’ to the mould pouring time.

$$\tau_{pour} = \frac{W_{cast}}{\%Mg_{alloy} * (B - \frac{c}{T_{pour}})^{n}}$$

n, B, C – constants, depending on the spheroidising agent grain size and gating system structure.

The formula indicates the temperature influence on the pouring (dissolving) time.

Dissolution coefficient:

The upper surface of the reaction chamber is selected in such a way as to have – at the calculated pouring time (rate of filling of the gating system) - the dissolution coefficient within experimentally developed limits.

$$f_{d} = \frac{V(velosity.pouring)[{}^{kg}/_{s}]}{F_{FCH}(cross.section.chamber)[cm^{2}]}$$

f_R – dissolution coefficient value: 0.05 – 0.07 [kg/cm^2*s]

- This range (f_R)was estimated for the pouring temperature: 1370-1430°C.
- If f_R< 0.04 – the spheroidising agent will be used out too early, if f_R>0.10 – the cast iron saturation ratio with magnesium will be too low.

Efficiency of chamber filling:

$$f_{K} = \frac{V_{zap}(volume\_spheroidisining\_agent)}{V_{KR}(volume\_reactions\_chamber)[cm^{u}])}$$

f_K = 30 – 40%.

At a lower chamber filling the dissolution is too fast, while at a higher – the dissolution is difficult, which can lead to a weak saturation with magnesium.

3. Vermicular cast iron melts under the casting house conditions

The formation of the vermicular cast iron melts is being done on the mechanised BMD foundry line with a horizontal parting plane and box size: 840x740x; 2x250.

The mould, allowing to perform the planned examinations, was specially designed and the reaction chamber dimension were selected according to the casting wall thickness.

The melt was carried out in the crucible induction furnace of a medium frequency (capacity 6 tones).

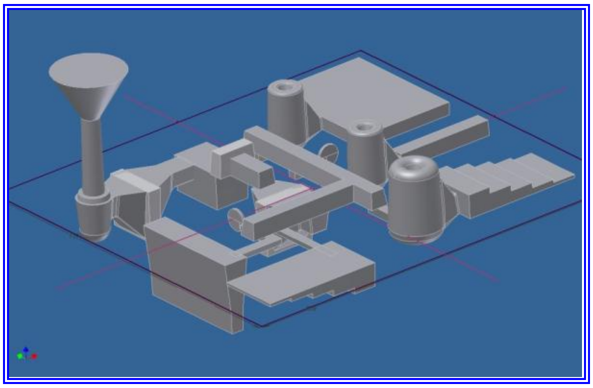


Fig. 2. Castings with the gating system

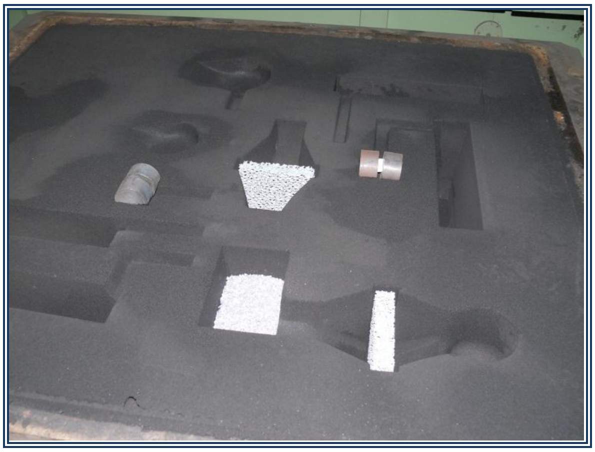


Fig. 3. Casting mould

Charge structure:

Special pig iron – 600 kg; Steel scrap W4 – 2400 kg; Foundry returns – 3000 kg; Carburising agent – 98 kg; FeSi75 – 32 kg; FeMn – 6 kg.

Fig. 4. Furnace. Temperature checking

A mass of charged materials, a temperature in individual stages of the melt and a chemical composition of the cast iron were controlled during the melt. When the optimal assumed parameters were obtained, the initial cast iron was poured into the siphon ladle (of a 1 ton capacity) and transported to the pouring device on the BMD line. Several test runs with a various content of the magnesium preliminary alloys of brand names: BJOMET, LAMET and COMPACTMAG were carried out.

Table 2.
Chemical composition treatment alloys

	Chemical composition. [%]					
	Si	Mg	RE	Ca	Al	
BJOMET 4 5-10 mm	44-48	5-5,6	1,8-2,3	1,9-2,4	1,0 max	ELKEM
LAMET 5540 1-4 mm	44-48	5-6	La 0,25-0,4	0,4-0,6	0,8-1,2	
COMPACTMAG 1-4 mm	44-48	5-6	5-7	0,8-1,2	1,0 max	

The obtained results allowed to verify positively: the reaction chamber dimension, foundry alloy amount, gating system cross-sections, pouring rate. In effect the answer - at which parameters the positive and reproducible results in castings of the vermicular cast iron for the given thickness of the casting wall are obtained - was also verified.

Fig. 5. Moulds pouring

Microstructure and mechanical properties of the vermicular cast iron produced by the in-mold technology.

Examinations of mechanical properties: tensile strength R_m, yield strength $R_{0,2}$ and elongation A_5 were performed. The best results were obtained when using the Compactmag preliminary alloy. The Mg content in the cast iron, at which the vermicular cast iron was obtained was within the range: 0.008 – 0.015%. In this case there was also the smallest sensibility for the casting wall thickness (improvement by app. 50% as compared to other magnesium preliminary alloys). An increased content of rare-earth elements in the Compactmag alloy stabilizes the vermiculising process, and limits a negative influence of despheroidising agents.

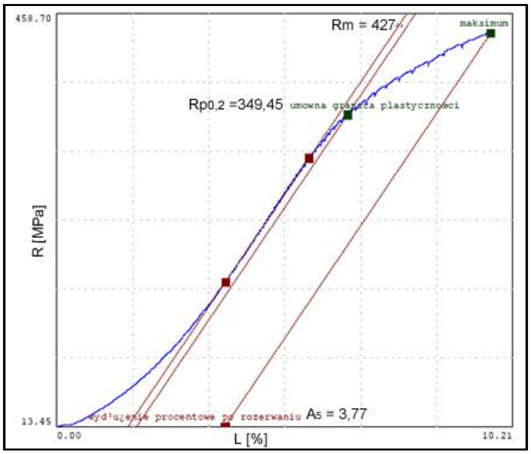


Fig. 6. Mechanical properties

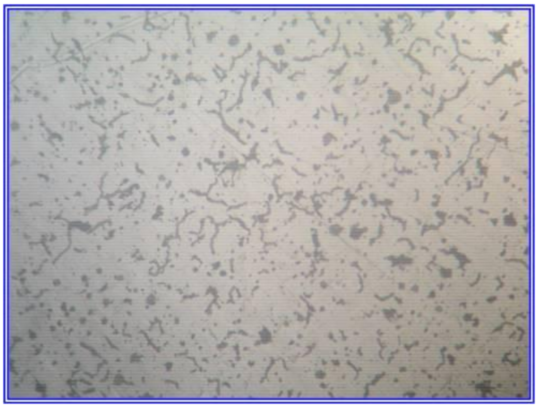


Fig. 7. Graphite form

4. Thermal fatigue

The resistance heating method was applied for thermal fatigue investigations of samples shown in Figure 9. Samples fixed on both sides allow, at their cyclic heating, to realise the fatigue process at the uniaxial state of stress. The heating cycle is established for the 'arbitrary' selected range $T_{min} - T_{max}$. The temperature range decides on the thermal stresses level and deformations of the sample material in each, individual heat cycle and decides on the cycle number up to the moment of the sample crack. This number is the measure of the material heat fatigue resistance realised under the selected heat-stress conditions. A heat fatigue resistance is the most essential feature of materials intended for operations at variable temperatures and constitutes the applicability assessment of this material for work under thermal load conditions. Generally as heat fatigue we call a destruction of structural elements under the influence of multiple, cyclic temperature changes causing a periodically changing stress field, without any additional loads from external forces [1-6]. This process is related to the cracking energy dissipation, being the result of plastic deformations occurring during each thermal cycle. These deformations lead to a fast forming of micro-cracks.

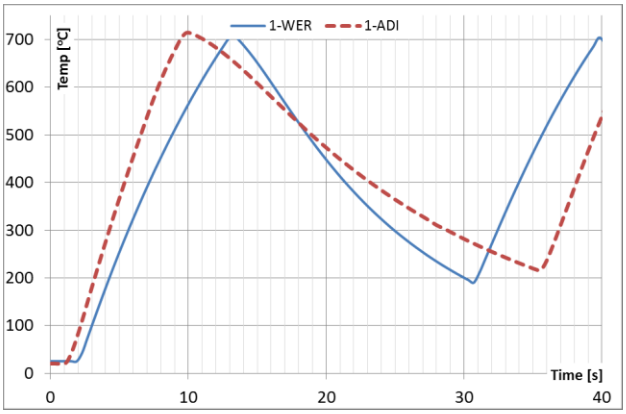
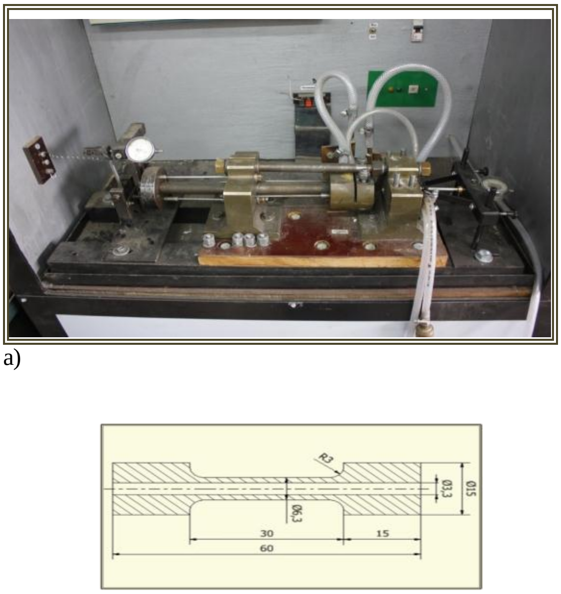


Fig. 8. Heating and cooling of the vermicular and spheroidal cast iron samples; Range: T = 200 - 700°C



a)

b)

Fig. 9. Stand (a) and sample (b) for the heat fatigue testing of metals and alloys

The experimental stand used for thermal fatigue examinations is the modified version of the stand applied by L.F. Coffin. The tested sample, shown below, is fixed in water-cooled jaws. One of the jaws is immovable while the other one is joined with the auxiliary jaw by means of the deformative rods system, which can shift during heating and cooling. If, during heating the sample undergoes plastic deformations, then during cooling tensile stresses are formed. This cycles of heating and cooling are recorded automatically up to the moment of the sample braking (cracking) [1-5].

4.1. Results of investigations

The thermal fatigue process causes several changes in the cast iron structure, and in consequence changes of the mechanical properties. The vermicular cast iron sample is longer heated to T_{max}, whereas it cools much faster to T_{min} than the spheroidal cast iron sample.

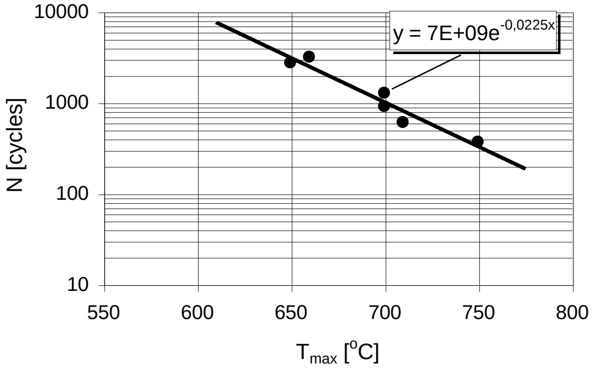


Fig. 10. Influence of the maximum temperature T_{max} of the heating cycle on the thermal fatigue of the vermicular cast iron. T_{min}=200°C

By increasing the maximum temperature of a cycle the material heat fatigue accelerates. Deformations in the single thermal cycle increase, which in effect limit the cycle number preceding the micro-cracks formation and finely the sample cracking. The influence of T_{max} on the thermal fatigue resistance of the vermicular cast iron is shown in Figure 10.

Changes in the cast iron structure in the vicinity of cracks (Fig.11) of samples undergoing the thermal fatigue allows to draw the following conclusion: a fast heating and a relatively fast cooling of the vermicular cast iron, leads to the transformation of pearlitic structure into ferritic matrix. This process proceeds up to the total matrix ferritisation.

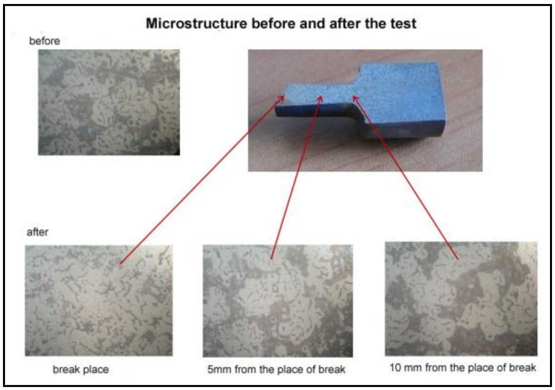


Fig. 11. Thermal fatigue influence on structure changes

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4.2. Ability to heat transfer

The experimental device for the examination of the temperature distribution in the casting wall, was in a form of sleeve. It enabled to estimate the material from the point of view of its ability for the heat abstraction.

The test allowing to measure a temperature in the sleeve wall in three places (internal, middle and external) was carried out. Permanent moulds of three materials: grey, vermicular and spheroidal cast iron were made. Permanent moulds were poured with the Al alloy.

The results of heating and cooling curves of the permanent mould walls in individual samples are shown in Figure 13.

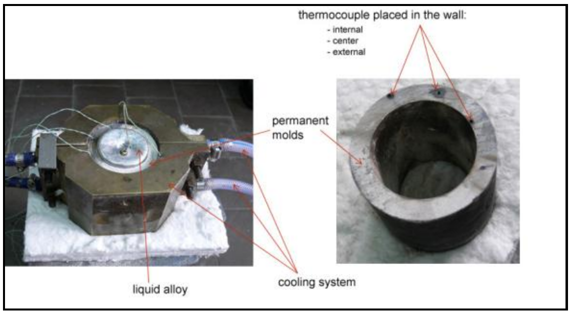

Fig. 12. Experimental stand

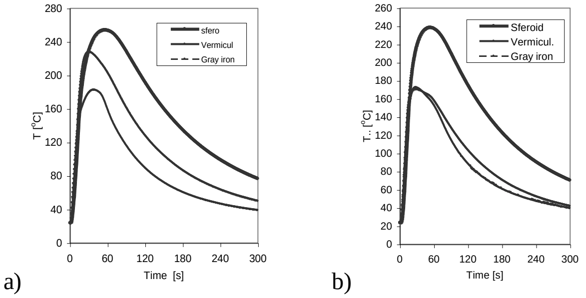

Fig. 13. Temperature distribution in the permanent mould wall; a) - in centre, b) in outside

5. Conclusions

1. At the stabilised technological conditions it is possible to produce, on the BMD line, castings of the vermicular cast iron in the in-mould technology.
2. The heating process of the vermicular cast iron proceeds more slowly than of the spheroidal cast iron, while the cooling process much faster .
3. Under the same conditions of heat exchanging the spheroidal cast iron is heated to the highest temperature and the grey cast iron to the lowest, while the vermicular one locates in between.
4. With an increase of T_{max} the material heat fatigue resistance decreases, including the vermicular cast iron.
5. During the cyclic heating of the cast iron with a pearlitic - ferritic matrix the ferritisation process occurs, which results in decreasing strength R_m.

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