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Guidelines for the manufacture of heavy ductile iron castings

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Abstract

This study is devoted to the analysis of the impact that the basic constituents of ductile iron (carbon and silicon) and spheroidising treatment combined with inoculation exert on the final properties of heavy ductile iron castings. To evaluate the possibility of the application of ductile iron technology in the manufacture of castings for wind power plants, simulations were conducted on cast hubs of the rotor blades for wind turbines. For this type of product, it is necessary to produce castings characterised by a ferritic matrix (over 90% ferrite) and to reduce the amount of pearlite and graphite to a minimum, both of which are considered as the main structural constituents that affect the casting properties. The key guidelines for the manufacture of heavy castings from ductile iron, wind turbines included, were discussed, with particular emphasis placed on the process of spheroidising treatment and inoculation, both of which are aimed at producing in the structure of castings a spheroidal graphite of a size from 5 to 12 mm (class V to VI) and a ferritic structure in an amount exceeding 90%. This article is the result of the work done by Krakodlew S.A to implement research project No. POIG 01.04.00-12-116/12, supported by the National Centre for Research and Development and financed by the European Regional Development Fund, measure 1.4 POIG (*Execution of industrial research and development in the company Krakodlew S.A.*, 2014).

Keywords: ductile iron, heavy castings, wind farms

1. Introduction

The phenomena that occur in a solidifying casting-foundry mould system are essential in the manufacture of castings. Not only the chemical composition of cast iron but also the properties of the foundry mould determine the casting solidification process. Therefore, a better understanding of the phenomena taking place in a casting-mould system can help to explain numerous causes of defects in castings and the type of metal structure obtained, thus largely contributing to the upgrading of casting technology.

With this in mind, the Krakodlew SA Company, in collaboration with the national research programs, has developed a research programme and implemented a solution, the essence of which consists of cooling a core placed in the mould interior using a proper cooling agent (air and water mist) and ensuring an effective discharge of gas from all parts of the mould to enable the manufacture of massive heavy-wall castings from high-quality ductile iron characterised by a "healthy" homogeneous structure and high mechanical properties. The homogenisation of ductile iron structures by control of the speed and course of the solidification process and mould degassing reduces the risk of the occurrence of harmful structures containing degenerated and highly dispersed 'chunky' graphite and the risk of the occurrence of zones containing blowholes and non-metallic inclusions called "dross". The presence of structures affected by these detrimental phenomena deteriorates the mechanical properties of cast iron. The parameters to be obtained are shown in Table 1.

The fulfilment of quality acceptance conditions for such castings made of "ice class" ductile iron is not easy, especially if one takes into account the solidification characteristics of this casting alloy, namely the occurrence of a binary equilibrium system in Fe-C alloys during their solidification (the stable and metastable system), which consequently gives a structure with the eutectic precipitates of graphite (austenite + graphite) or cementite (austenite + cementite or, in a broader sense, austenite + carbide phase). The result is the spontaneous formation of a non-homogeneous structure composed of a metal matrix in the cross section of the iron casting with products of the eutectoid reaction comprising ferrite and/or pearlite and precipitates of graphite (the structure of grey cast iron with different characteristics , i.e. with precipitates of spheroidal graphite varying in both size and quantity), possibly also the undesirable precipitates of hard cementite present as a constituent of so-called 'edge chills'. Parameters that control the content of the above-mentioned constituents in the structure of cast iron include the chemical composition of the cast iron, particularly the content of carbon, silicon, manganese, phosphorus and trace elements (i.e. despheroidisers), the cooling rate of the metal cast into the foundry mould and solidifying in this mould (depending on the temperature of the metal poured into the mould, the type of mould and the casting wall thickness) and the ladle treatment of the metal, i.e. the spheroidising treatment and inoculation. Important in this respect is achieving the required structure and thus the optimum properties for a given wall thickness designed in castings that require high reliability. The response to changes in the cooling rate of metal cast into a mould is defined as the 'casting sensitivity to the cooling rate'. Identifying the value of this sensitivity facilitates the manufacture of iron castings which, at a preset target chemical composition, are able to create a homogeneous structure through the entire wall cross section. The rate of metal cooling in the mould depends on many factors, including the physical and chemical state of the metal at the time of casting (shaped mainly by the graphitising treatment and inoculation) as well as the temperature, the type of material, the temperature of the foundry mould, the design of the casting including its wall thickness, and also the number of risers in one mould.

The variety and complexity of chemical, physico-chemical and physical characteristics affecting the degree of structural homogeneity, and thus the properties of castings, is a serious obstacle in the development of the best technology for the manufacture of castings characterised by the required properties and structural homogeneity. In this case, the use of a suitable metallurgical treatment can prove helpful in obtaining a uniform distribution of the spheroidal graphite. Thus, to produce the required structure through the entire cross section of the casting wall, many complicated issues have to be resolved, which shows the essence of the intended purpose of the project.

The problems to be solved are as follows:

considering the operating conditions of casting, in the casting wall cross--section a specific structure must appear, namely the structure composed of a ferritic metal matrix (at a given content of silicon) with an optimal content of the graphite eutectic containing precipitates of spheroidal graphite of the possibly most regular shape included in class V and VI;

the structure should be free from the undesirable precipitates of the hard cementite Fe_3C, and additionally from pearlite, phosphorus eutectic and inclusions of sulphides.

These quality requirements regarding the structure of castings are intended to confer some specific mechanical properties to the ductile iron to work in freezing temperatures. sub-zero applications.

2. The methodology and results of a virtual experiment based on the simulation of the casting process of rotor hubs weighing 11 and 5 tonnes

Starting the experiment it has been assumed that the developed technology for the manufacture of heavy castings from ductile iron can be used in the performance of large castings for wind power plants. For the assessment of the viability of this technology, a simulation of the casting process has been scheduled.

The analysis was conducted on two 11 and 5 tonne castings of the hub of the rotor blades for a wind turbine. The weight of the casting determines the time and rate of its solidification and cooling. These massive castings with varying wall thicknesses may contain a varying content of the ferrite precipitates scattered through the cross section of the casting.

A common casting material used in the manufacture of parts for wind turbines is class GJS-400-18U-LT ductile iron. Characterised by its high impact strength at low temperatures, it is commonly known as ice-class cast iron. This cast iron is suitable for operation at freezing temperatures, i.e. the weather conditions under which the wind turbines are expected to operate. Castings of rotor hubs should be characterised by the lowest possible level of material defects. It is necessary to produce a homogeneous casting structure through the entire wall cross section, combined with high fatigue strength (Larker, 2009). The blades of the wind turbines are directly attached to these castings, which are subjected to the effect of high stress during operation. The requirement is therefore high impact strength at low temperatures (-20°C), it means increased brittleness threshold at these temperatures.

As a starting cast iron composition, the composition typical of the EN-GJS-400-18U-LT grade was adopted (*The Sorelmetal Book of Ductile Iron*, 2006) (Table 2). There was analysed the influence of factors:

- two principal alloying elements (carbon and silicon),
- the quality of spheroidisation and inoculation

on:

- the distribution and quantity of the precipitates of pearlite,
- the distribution and quantity of the graphite spheroids,
- the final mechanical properties, including the tensile strength R_m, elongation A_5 and hardness obtained in two cast hubs of the rotor blades weighing 11 and 5 tonnes.

The analysis of the effect of the adopted process variables (the content of carbon and silicon, the spheroidising treatment and the number of nuclei) on the distribution of pearlite precipitates and on the strength and other parameters which significantly influence the properties of castings exposed to the impact of temperatures ranging from -40 to 30°C. Additionally, the impact of variable loads was performed in a MAGMA program using a genetic algorithm for process optimisation.

Castings like rotor hubs are the main structural elements of wind turbines. Their task is to transfer all the working loads acting on the blades, and they are therefore subjected to the impact of variable forces resulting from the rotational speed of the blades and to the impact of other external factors. Their strength depends on the internal structure of the casting. High fatigue strength and ductility reduce the risk of crack propagation. An important element deteriorating the fatigue strength of the casting is the presence of pearlite in its structure. Pearlite is a mixture of ferrite and cementite (Fe_3C), the latter being an iron carbide that is hard but brittle, and as such, is generally considered to be a weak link in the structure, speeding up the formation of microcracks. Therefore, one of the goals of the analysis of the significance of the adopted parameters of the casting process was determination of the amount of pearlite formed in the cross section of the cast hub. This factor is widely considered to be a serious limitation, aside from the fact that the traditional way to achieve higher strength by producing more of a harder yet more brittle pearlite in the matrix must also reduce the impact strength tested on notched specimens. It has been found (Bleicher, Kaufmann, Meltz, Wagener, 2014) that in the ductile iron of the same tensile strength (500 MPa), the matrix of solution-hardened ferrite and the conventional combination of ferrite and pearlite have a similar impact strength tested on Charpy specimens and a similar level of energy, whereas ferritic cast iron with a lower Si content and lower strength shows a higher level of impact energy.

Another evaluated parameter important for casting quality is the shape and amount of graphite precipitates. Graphite by itself has a minimum tensile strength but its circular shape prevents stress concentration in the structure. This increases the casting ductility and allows the construction to perform its duties in an alternating field of stress. The number of graphite precipitates is critical, since any excessive amount will reduce the toughness, which at -20°C should amount to about 12J; too low a value of this parameter deteriorates the tensile strength R_m and elongation A_5 (Table 3).

The range of changes in the variable parameters adopted in the studies of a virtual casting process is shown in Table 2. The number of performed iterations was 40, which allowed for changes in the process variables and for the evaluation of the general trend in the impact of the adopted parameters on the amount of pearlite and on the amount of graphite precipitates. In all calculations in the conducted studies, the content of manganese was kept at a constant level of 0.171%, since this element is also considered to be responsible for the final properties of castings.

Calculations showed a very high content of pearlite in the as-cast microstructure occurring in the case of the spheroidising treatment of low effectiveness. The purpose of the spheroidising treatment and inoculation, also known as ladle metallurgy, is to create favourable conditions in liquid metal for the formation of spheroidal graphite. There should be a sufficient amount of nuclei of crystallisation, and these nuclei should remain active throughout the entire process of mould pouring. The increasing number of graphite spheroids decreases the distance between them. When the casting is cooling, the first regions with an austenitic structure which will be converted to ferrite are usually located near the graphite spheroids, since the solubility of carbon is much lower in ferrite than in austenite. Due to the increasing distance, the released atoms of carbon diffuse through the growing ferrite towards the spheroids of graphite at a rapidly decreasing rate, which promotes the formation of pearlite. Therefore, reducing the distance by increasing the number of spheroids reduces the risk of pearlite formation.

Comparing (Fig. 2) of two castings with the same composition (C = 3.8, Si = 2.0) obtained in the process where the effectiveness of the spheroidising

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treatment is either very high or low indicates that the amount of pearlite can rise to over 40% when the magnesium yield is low, which classifies the microstructure as a ferritic-pearlitic and is thus obviously unacceptable in castings used for the wind turbine hubs.

A plot in parallel coordinates (Fig. 3) show the results of studies of the quantitative impact of individual process parameters on the distribution of pearlite in the casting cross section and confirms that the low content of pearlite in the casting structure can be achieved by the application of the very effective spheroidising process even at different levels of the carbon (3.4 to 3.8%) and silicon (2.0 to 2.4%) content.

Plotted graphs of the observed trend (Fig. 4) confirm this statement, indicating that effective spheroidisation is essential for obtaining cast iron with a minimum amount of pearlite. The respective graphs also show that a high carbon content can raise the amount of pearlite, while a high silicon content can reduce this amount. A lower amount of pearlite decreases the tensile strength R_m (Fig. 3), but even then, the strength is still at a level above 400 MPa and thus meets the accepted standard assumptions. Very effective spheroidising treatment and the inoculation of cast iron increases the amount of spheroidal graphite (Fig. 5), which is favourable for the operating parameters of rotor hub.

The sensitivity of cast iron to the solidification rate is another important parameter shaping the casting structure and therefore also its characteristics. The analysis of the rotor hub castings weighing 5 tonnes and 11 tonnes has demonstrated the effect of the solidification rate on the distribution of pearlite within the casting volume when the same variables were maintained, i.e. C = 3.4, Si = 2.2%, a very high magnesium yield and a large number of nuclei. In the casting of the rotor hub weighing 5 tonnes, the amount of the precipitates of pearlite was at a level of 3%, while in the casting weighing 11 tonnes, it was at a level of about 1.5% (Fig. 6). The reason for this was the higher rate of temperature drop in lighter casting and thus shorter time available for carbon to move to the graphite spheroids. On its way to the graphite spheroids, this carbon was combined with iron forming Fe_3O, which further combined with ferrite formed pearlite.

3. Guidelines for the process of making heavy ductile iron castings for wind turbines

The proposed technology for casting rotor hubs is based on the self-feeding ability of ductile iron. The use of this property in iron castings, including castings made of ductile iron, is associated with the transformation of austenite into pearlite or ferrite where carbon, due to its lower solubility in ferrite, is precipitated in the form of graphite. It is also associated with the secondary expansion occurring in the solid state, which also involves the precipitation of graphite. The process of self-feeding depends on the composition of cast iron and on the thermal module of casting. Castings with thinner walls have limited self-feeding capabilities. The rotor hub is a casting with a medium wall thickness of 100 mm, and therefore, in this particular case, the use of the self-feeding process was possible.

The final properties of cast rotor hub were examined for the selected four compositions of cast iron of the class GJC-400 shown in Table 4, and for the two technologies depicted in Fig. 7.

The results of the analysis of the size and distribution of porosity in cast rotor hubs prompt the use of self-feeding technology without the need to design risers. The main area of the occurrence of porosity in casting is at the mid-height of the casting in the vicinity of the mould parting line, and is related with the conditions of casting solidification. In the bottom pouring technology, the metal is overheating the lower part of casting and this region takes the longest time to solidify (Fig. 8). When the metal is introduced at the mid-height of the casting (near the mould parting line), this area of the casting solidifies last (Fig. 9).

Porosity in casting walls is as a rule milder with the technique of bottom pouring (Fig. 10). The extent of the porosity is influenced by the cast iron composition. The cast iron compositions 1 and 4 show a lower tendency towards the formation of porosity. The extent of the porosity also depends on the parameters of metal preparation, mainly on the amount of time the metal was help in the ladle and on the temperature of pouring.

4. Summary

The conducted simulations helped to optimise the gating and feeding system. The gating system for bottom pouring used in both castings enabled a uniform filling of the mould cavity. The use of filters helped to maintain quiet metal movement in the mould cavity (the reduced speed of metal flowing from the down gate); filters retained the contaminants and caused a laminar flow of metal. The use of risers in exothermic sleeves partially eliminated the porosity. A metal temperature in the range of 1,385–1,390°C ensured optimum pouring conditions. The conducted simulations showed the great impact of metal quality on the formation of a ferritic matrix spread evenly in the casting and a reduced level of porosity due to the increased capacity of graphite to compensate for shrinkage defects. The inoculation process involving both primary and secondary treatment characterised by a high effectiveness of the adopted method produced the required microstructure.

The conducted tests and studies show that it is possible to control the process of casting solidification in such a way as to obtain changes in the microstructure through changes in the cooling rate during casting solidification and cooling. The course of this process can vary depending on the cast iron chemical composition and casting wall thickness. A structure with precipitates of pearlite is produced more easily by changing the rate of cooling in the cast iron of the composition containing a certain amount of the pearlite-forming elements.

Tables

Table 1. arameters to be obtained as a result of project implementation (own study)

Parameter	Parameters of products available on the market at the time of submitting project application which are identical or similar to the product implemented by the project	Parameters to be achieved by project implementation
tensile strength R_m elongation A_5 hardness **weight**	R_m – min. 400 MPa min A_5 = 15% in castings with wall thickness above 80 mm above 130 units HB **up to 28 tonnes**	R_m – min. 410 MPa min A_5 = 18% in massive castings with wall thickness above 80 mm below 130 units HB **up to 50 tonnes**

Table 2. The starting composition of cast iron (*The Sorelmetal Book of Ductile Iron*, 2006)

	C	**Si**	Mn	P	S	Effective-ness of the spheroidising treatment	Inoculation treatment (the content of active nuclei in %)
Starting composition in %	**3.41**	**2.2**	**0.171**	**0.033**	**0.06**		
Range of changes in parameters	**3.4 to 3.8 at every 0.2**	**2.0 to 2.4 at every 0.2**	**–**	**–**	**–**	**low medium very high**	**80 to 120% at every 20**

Table 3. Characteristics of cast iron in ice class according to EN-1563 (own study)

EN-GJS-400-18U-LT				
Average wall thickness [mm]	Tensile strength R_m [MPa]	Yield strength 0.2% $Rp_{0.2}$ [MPa]	Elongation A_5 [%]	Impact strength* KV [J]
<30	**min. 400**	**min. 240**	**min. 18**	**min. 12**

* The minimum impact strength at -20°C is the average of three tests calculated for a single value of KV = 9 [J].

Table 4. Selected chemical compositions of cast iron in the class GJC-400 (own study)

	C	Si	Mn	Mg	P	S	Cu	CE
Composition 1	3.6	2.65	0.15	0.036	0.016	0.02	0.1	4.48
Composition 2	3.5	2.80	0.40	0.045	0.016	0.02	0.1	4.43
Composition 3	3.7	2.60	0.40	0.045	0.016	0.02	0.1	4.57
Composition 4	3.6	2.80	0.20	0.040	0.016	0.02	0.1	4.54

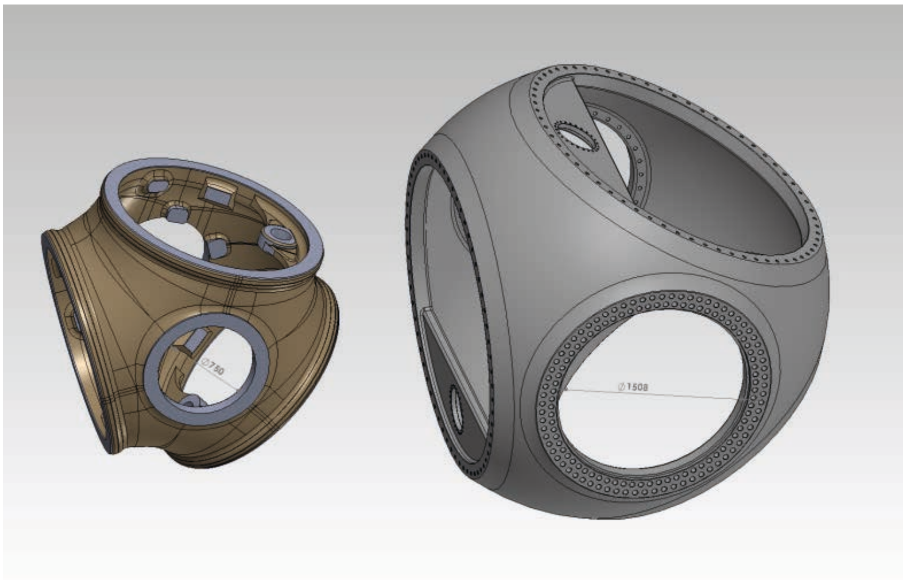

Fig. 1. Solid models of 5 and 11 tonne cast weighing rotor hubs designed for operation in wind power plants (author's work)

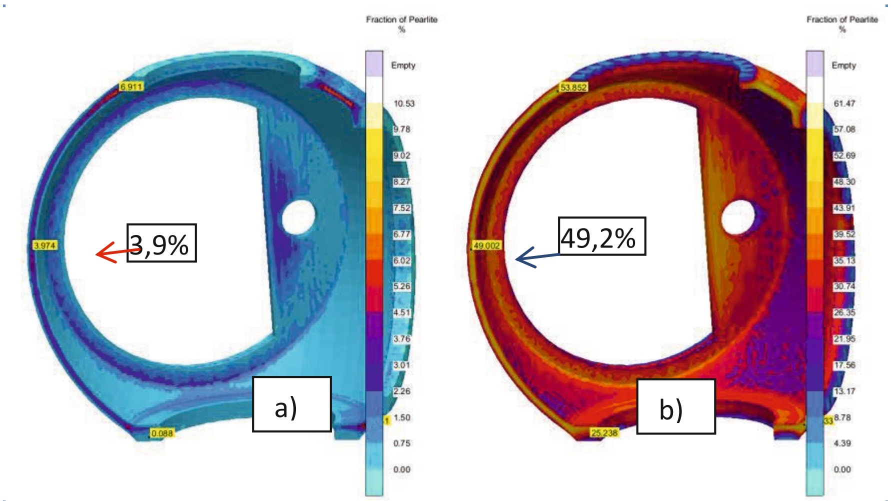

Fig. 2. Pearlite distribution in the cross section of an 11 tonne weighing rotor hub for C = 3.8 and Si = 2.0 and the spheroidising treatment process of: a) very high effectiveness and b) low effectiveness (author's work)

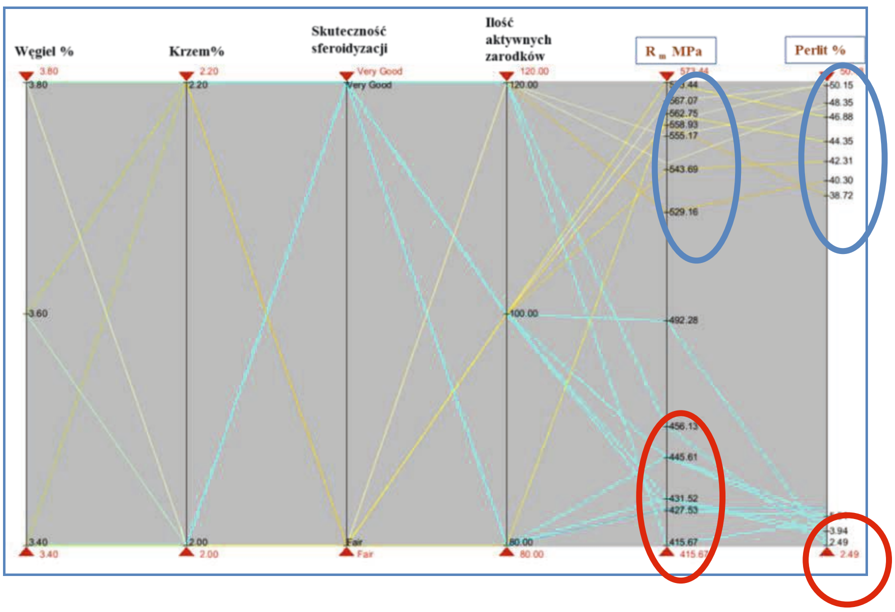

Fig. 3. Quantitative assessment of quality criterion in terms of the strength and pearlite content depending on the variables plotted in a system of parallel coordinates (author's work)

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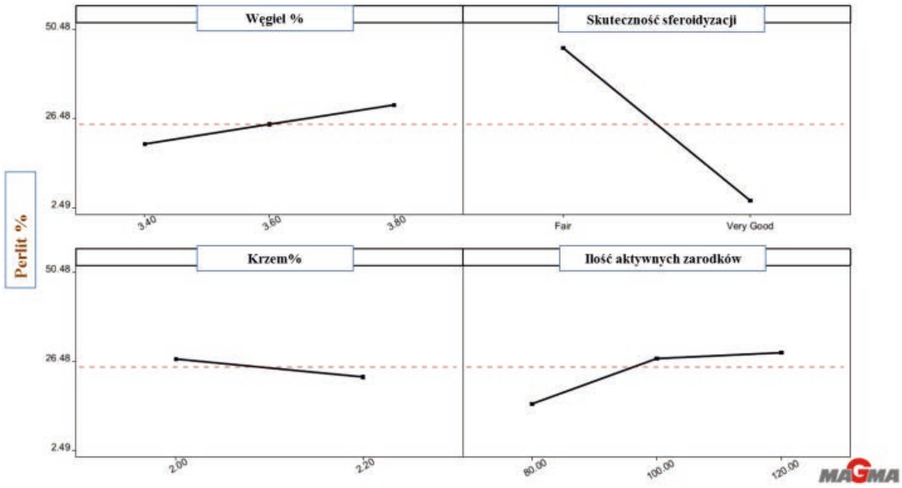

Fig. 4. Trend charts showing the impact of adopted process variables on the average content of pearlite in the casting cross section (author's work)

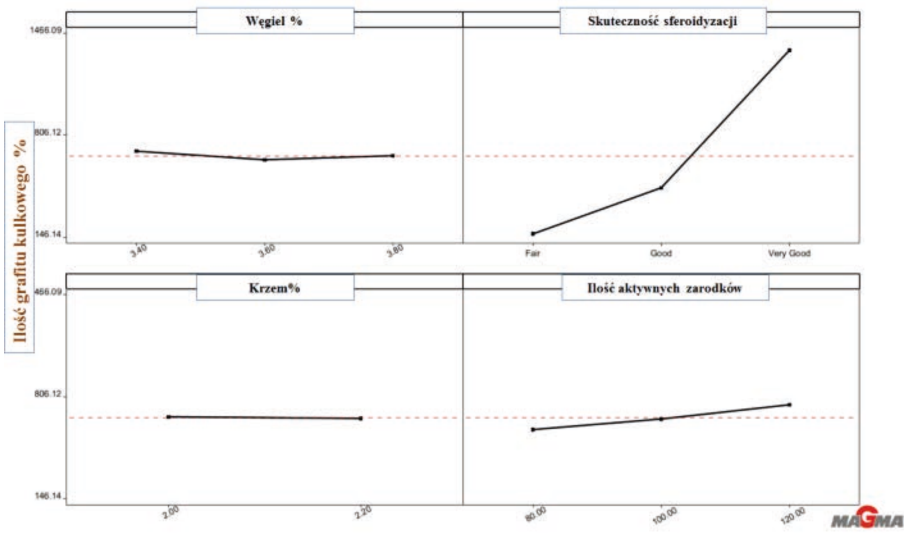

Fig. 5. Trend charts showing the impact of the adopted process variables on the average content of spheroidal graphite in the casting cross section (author's work)

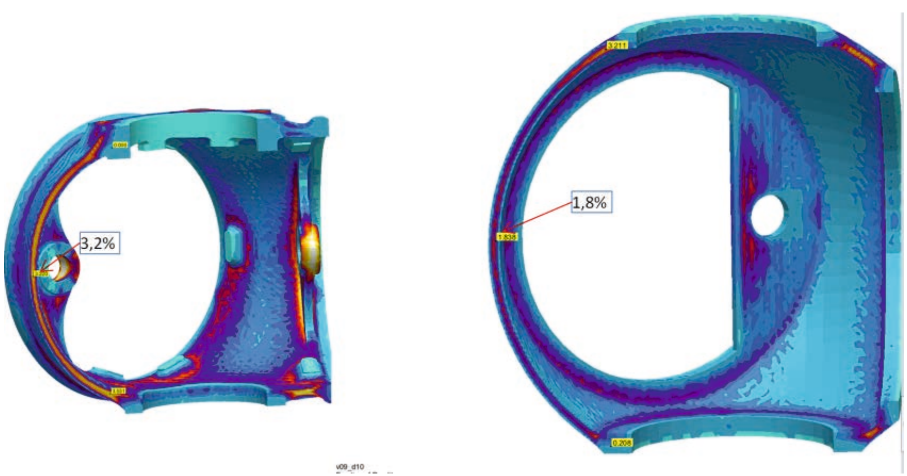

Fig. 6. Pearlite distribution in the cast hub weighing: a) 5 tonnes and b) 11 tonnes for C = 2.4 and Si = 2.2% and the spheroidising treatment of very high effectiveness (author's work)

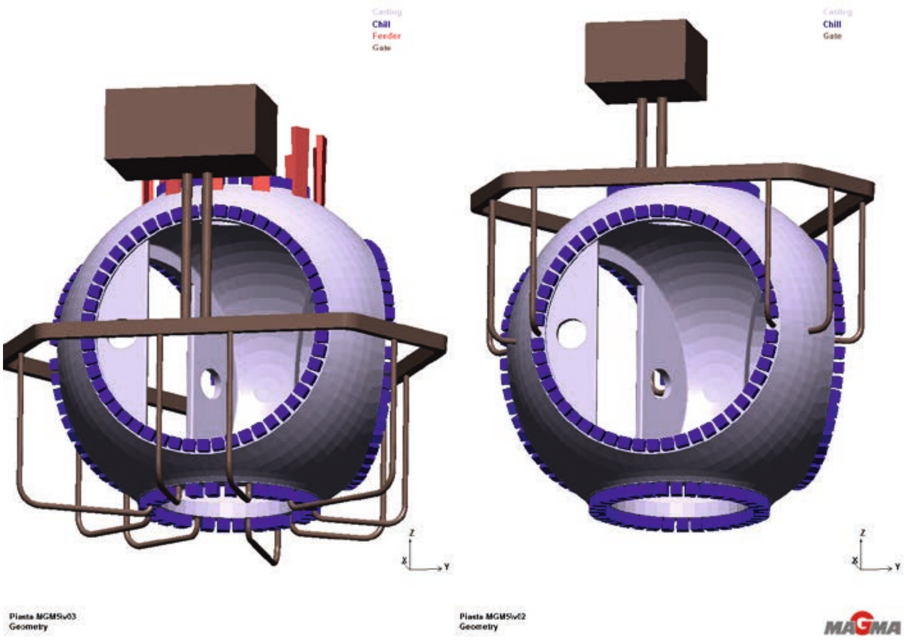

Fig. 7. Bottom pouring of the mould and pouring at the parting line (author's work)

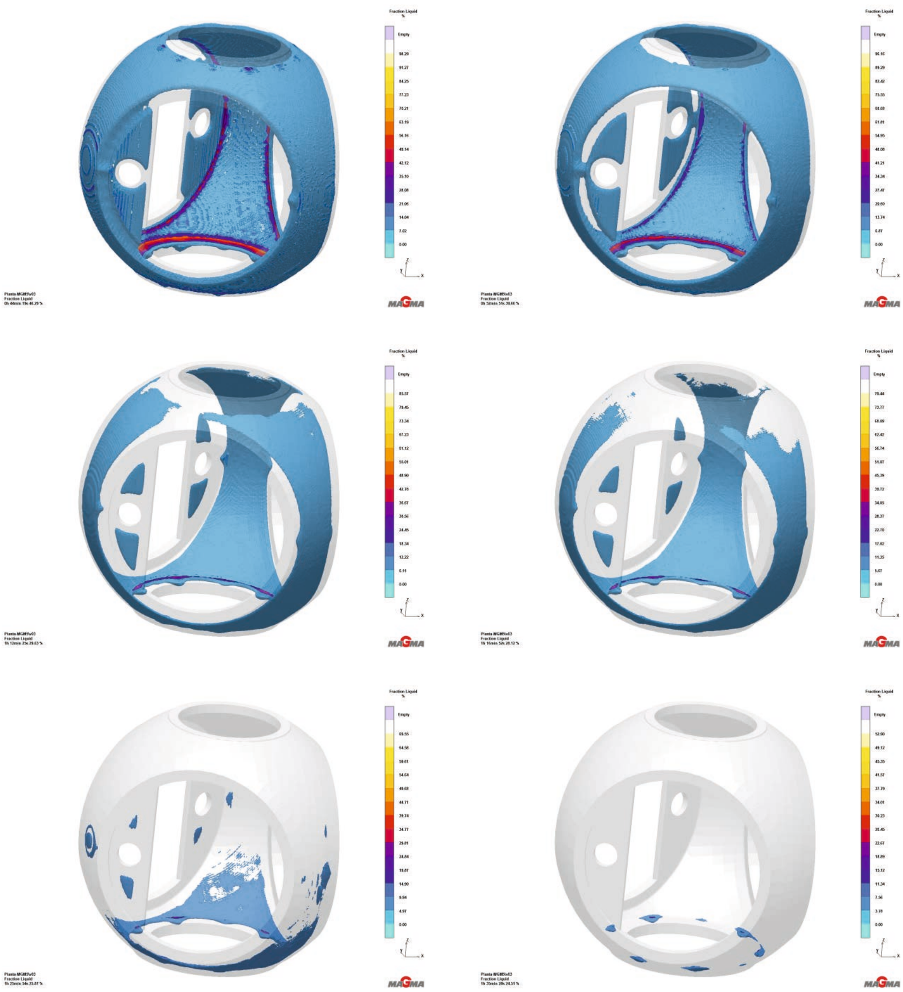

Fig. 8. Successive stages of the solidification process of the cast rotor hub – the technology of bottom pouring of the mould (author's work)

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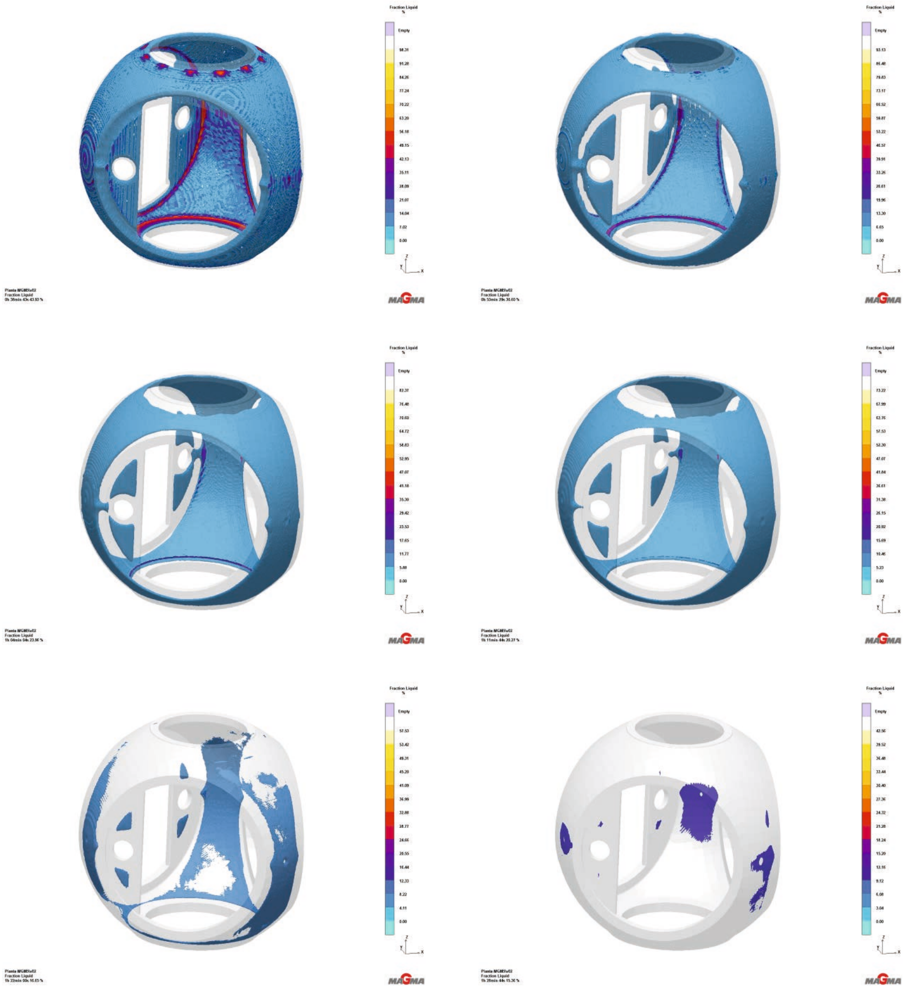

Fig. 9. Successive stages of the solidification process of cast rotor hub – the technology of mould pouring at the parting line (author's work)

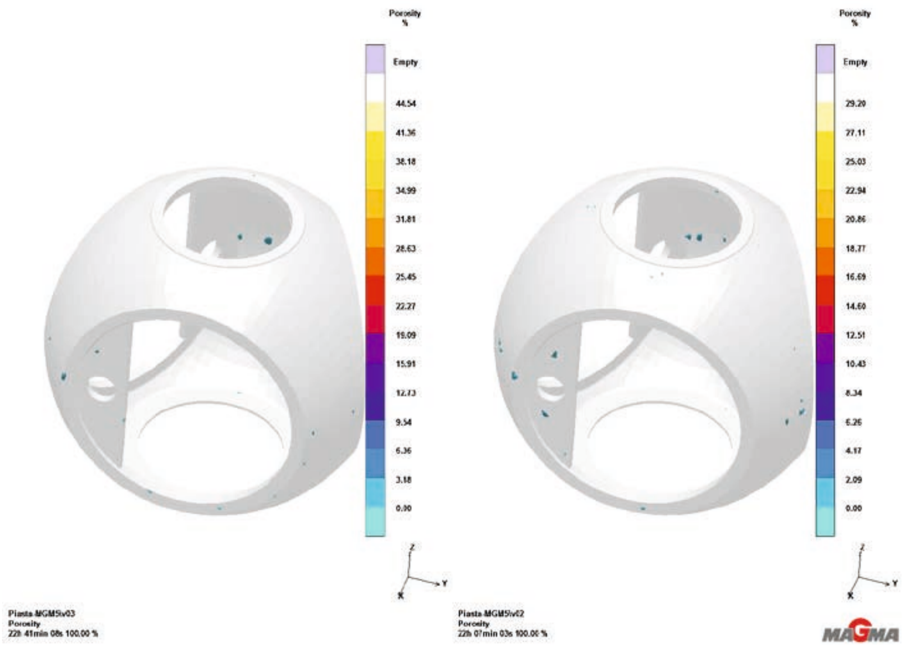

Fig. 10. Porosity distribution for composition no. 1 in the technology of bottom pouring and in the technology of mould pouring at the parting line (author's work)

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Założenia do wytwarzania ciężkich odlewów z żeliwa sferoidalnego

Streszczenie

W pracy przedstawiono analizę zarówno wpływu podstawowych pierwiastków żeliwa sferoidalnego, takich jak węgiel i krzem, jak i procesów sferoidyzacji oraz modyfikacji na końcowe właściwości ciężkich odlewów z żeliwa sferoidalnego. Do oceny możliwości wykorzystania technologii do wykonywania odlewów w energetyce wiatrowej przeprowadzono badania symulacyjne odlewu piasty śmigła wirnika w elektrowni wiatrowej. Dla tego typu wyrobów zachodzi konieczność otrzymania odlewów o strukturze ferrytycznej (powyżej 90% ferrytu) i ograniczenia do minimum ilości perlitu oraz grafitu jako kluczowych składników strukturalnych mających wpływ na właściwości odlewów. Omówiono założenia wykonywania ciężkich odlewów z żeliwa sferoidalnego, w tym dla elektrowni wiatrowych, ze szczególnym uwzględnieniem procesów sferoidyzacji i modyfikacji, które mają zmierzać do osiągnięcia w strukturze odlewu grafitu kulkowego o wymiarach 5 do 12 mm (klasa V do VI) oraz struktury ferrytycznej powyżej 90%. Artykuł powstał w wyniku realizacji przez Krakodlew S.A. projektu badawczego nr POIG 01.04.00-12-116/12, objętego wsparciem Narodowego Centrum Badań i Rozwoju, finansowanego ze środków Europejskiego Funduszu Rozwoju Regionalnego, działanie 1.4 POIG.

Słowa kluczowe: żeliwo sferoidalne, ciężkie odlewy, elektrownie wiatrowe