TEKA Kom. Mot. i Energ. Roln. – OL PAN, 2011, 11, 303–316

THE PROBLEM OF PERFORMANCE LIFE OF STRUCTURAL ELEMENTS UNDER THE CONDITIONS OF THERMAL FATIGUE

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Summary. The article presents an overview of the underestimated in Poland cast iron with vermicular graphite, which can be successfully used for cast parts of machines and equipment, especially working under the conditions of thermal fatigue. Because the vermicular graphite cast iron is capable of offering much better properties than grey cast iron, it can be interchangeably used to produce various components operating in the automotive industry and as parts of agricultural machines. In addition to the literature data, comparative studies were done by the Foundry Research Institute in the scope of mechanical and thermal fatigue testing, and simulation was carried out for the cast iron with flake and vermicular graphite. Studies have been continued within the framework of the POIG.01.03.01-12-061/08-00 project. The technology being currently developed relates to high quality cast iron with spheroidal and vermicular graphite with and without the addition of alloying elements, particularly to the grade resistant to thermal fatigue. Issues discussed in this article are related with properties of the structural material which the cast iron with vermicular graphite certainly is. Examples of the application of this material should raise interest of the designers, mainly as regards possible use of this cast iron grade for different elements of agricultural machines, offering increased mechanical properties, longer life on performance, and the possibility to reduce the cast wall thickness, thereby reducing also the casting weight and production costs.

Keywords: cast iron with spheroidal graphite, cast iron with flake graphite, cast iron with vermicular graphite, castings for agriculture, computer simulation, mechanical properties, thermal fatigue.

INTRODUCTION

The development of industry, particularly of the automotive and engineering applications, and a strong competition in various industrial sectors has forced engineers to develop and produce more advanced and better materials and designers to use them. Due to the use of these materials, it has become possible to increase the durability of structural elements, especially their resistance to the corrosive effects of CO, CO_2, HC, NO_x, and sulphides, which is the subject of numerous studies [1-4]. The weight and manufacturing cost reduction has also become possible, successfully combined with the improved performance qualities of the finished products. Among different alloys, the structural material which currently finds growing application in various sectors of the industry is cast iron. Its popularity has continued unchanged for many years. The development of technique faces an increasing demand for the cast iron of always higher properties. Several varieties of cast iron have been developed, to mention as an example alloyed cast iron, malleable cast iron, ductile iron, austempered cast iron (ADI) [5-12], as well as cast iron with vermicular graphite [13-28].

In this family, the cast iron with vermicular graphite plays quite a specific role, as it has a number of undeniable advantages compared with grey and ductile irons, and its properties are somewhere between the high quality inoculated grey cast iron and ductile iron. From the historical point of view, the cast iron with vermicular or compacted graphite has been known since 1948, when it was produced for the first time [22, 23]. Because of the narrow range of stable foundry production, a large-scale use of this cast iron for complex parts such as cylinder blocks and heads was not possible until the advanced process control technologies with modern electronic measurement devices and computer systems have been developed [22]. In 2006, a new ISO 16112 standard for cast iron with vermicular graphite, using a combined nomenclature of "Cast iron with compacted (vermicular) graphite", was published. Five distinct types of this cast iron were distinguished, based on the minimum tensile strength of samples taken from the separately cast ingots. The standard distinguishes between the following grades of cast iron: ISO 16112/JV/300 (ferritic) 16112/JV/350 ISO, ISO 16112/JV/400, ISO 16112/JV/450 (pearlitic); ISO 16112/JV/500 (alloyed). This cast iron is increasingly used as a structural material for many different elements, especially in the industry making cars, tractors, agricultural machines and trains, but also in metallurgical and glass industries.

Compared with high-quality cast iron with flake graphite, the cast iron with vermicular graphite is characterised by, among others, the following beneficial features [24]:

- higher tensile strength,
- better toughness and resistance to dynamic loads,
- lower sensitivity to wall thickness (the required mechanical properties are equally well preserved in heavy castings),
- lower tendency to oxidation and swelling at high temperatures,
- better resistance to thermal fatigue.

Compared with the ferritic ductile iron, the vermicular graphite cast iron offers the following advantages:

- lower modulus of elasticity,
- lower coefficient of thermal expansion,
- higher thermal conductivity,
- higher resistance to thermal fatigue during very rapid changes in temperature cycles (heating – cooling),
- higher damping capacity,
- better machinability,
- better castability and lower tendency to the formation of shrinkage cavities,
- lower tendency of castings to deformation at high temperatures and better dimensional stability,
- lower tendency to the formation of hard spots,
- lower environmental pollution when manufactured.

GENERAL CHARACTERISTICS OF VERMICULAR GRAPHITE CAST IRON AS A STRUCTURAL MATERIAL RESISTANT TO THERMAL FATIGUE

Cast iron with vermicular graphite is mainly used for elements which should offer higher properties than the grey cast iron, alloyed grades included, can provide. Higher strength of vermicular graphite cast iron allows the casting wall thickness and hence the weight of castings to be effectively reduced. The main advantage of this material is, however, its high resistance to sudden temperature changes as well as tightness. High functional properties of this material make it applicable for elements of the machinery and equipment operating in the agricultural industry, particularly for high-temperature operation. Cast iron with vermicular graphite is one of the cast materials characterised by proper shape of the graphite precipitates. The precipitates of graphite assume the form intermediate between spheroids and flakes. The technical English literature uses the nomenclature “vermicular graphite cast iron (cast iron with worm-like graphite) or “compacted graphite cast iron”; Germans call it „Gusseisen mit Vermiculargraphit.” In short, it is referred to in English literature as CGI, and in German as GGV. The cast iron designation system is included in the Polish Standard PN-EN1560: 2001, while characteristics of the graphite precipitates, the graphite shape reference samples included, are given in PN-EN ISO 945:1999 (the graphite shape reference sample type III in Fig.1 in the standard). Instructions are also available in different countries, which further define and clarify the cast iron with vermicular graphite, for example in Germany this is VDG-Merkblatt W50. In the U.S., the ASTM A842-85 specification is well-known. The basic chemical composition of the vermicular graphite cast iron is usually comprised within the following limits: C = 3,2–3,8%; Si = 2,0–3,2%; Mn = 0,1–0,7%; P up to 0,06%; S up to 0,02%. Depending on the manufacturing process, the cast iron also includes appropriate amounts of elements such as Mg, Ce, Ca, Al, Ti, Y, La. To obtain adequate performance properties, alloying elements such as Cu, Sn, Mo, V, Cr, Sn, etc. are used. The structure of metal matrix can differ, assuming the form of ferritic, ferritic-pearlitic, pearlitic, and also ausferritic (ADI with vermicular graphite.) Figures 1–3 show photographs of various structures of the cast iron with flake graphite, spheroidal graphite, and vermicular graphite (the examinations were performed under an optical microscope); Figure 2 shows a photograph of the vermicular graphite precipitates as seen under the scanning electron microscope.

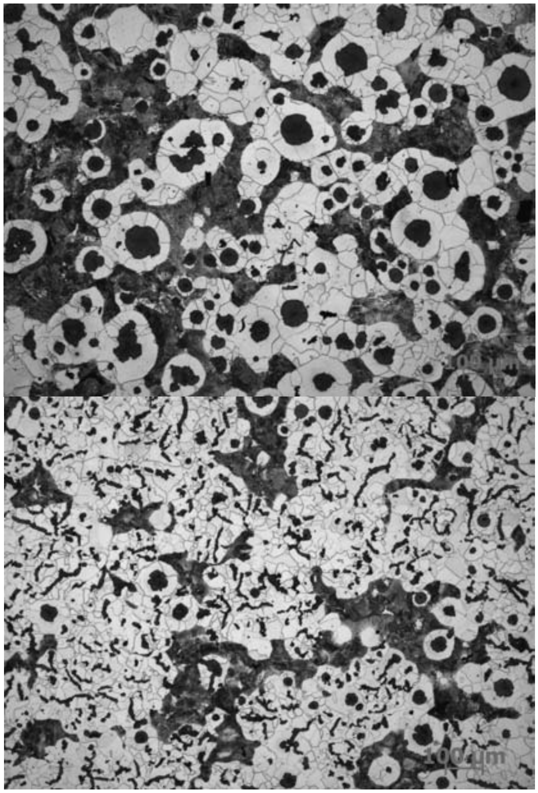

Fig. 1. Cast iron with flake graphite, spheroidal graphite and vermicular graphite

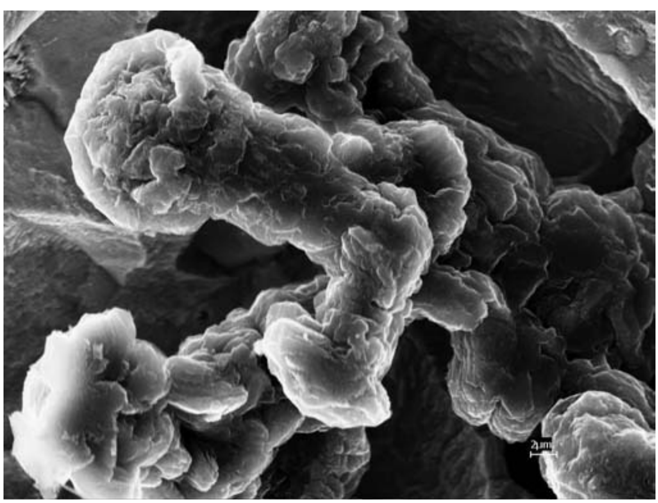

Fig. 2. Vermicular graphite (scanning photograph, 8000x)

The mechanical, physical and technological properties of vermicular graphite cast iron (when controlled by the graphite shape) are somewhere between those that characterise the cast iron with spheroidal graphite and flake graphite. Major parameters of the mechanical, physical, and casting properties of cast iron with different types of graphite and metal matrix are summarised in Table 1 [23, 24].

Table 1. Typical mechanical, physical, and casting properties of the cast iron with flake, spheroidal and vermicular graphite

Selected parameters	Unit	Grey cast iron	Ferritic vermicular graphite cast iron	Pearlitic vermicular graphite cast iron	Ductile iron
Tensile strength, R_m	MPa	100–400	min. 300	400–500	350–900
Yield strength, $R_{p0,2}$	MPa	-	min. 240	340–440	250–600
Elongation, A_5	%	max. 1,5	min. 2	1	3–30
Bending strength	MPa	300–600	600	700	800–1200
Compression strength	MPa	500–1400	min. 500	min. 600	600–1200
Hardness	HB	140–300	130–190	200–280	120–350
Impact strength (unnotched specimen)	J	6–19	max. 10	-	9–196
Impact strength (notched specimen)	J	-	max. 7	-	max. 21
Modulus of elasticity, E_0	GPa	75–155	130–160	130–170	165–185
Density	Mg/m^3	7,0–7,5	7,0	7,1	7,1–7,3
Thermal conductivity, λ (20÷200°)	W/m·K	46 - 59	38–46	34	25–38
Coefficients of linear and thermal expansion, α (20÷200°)	$K^{-1}x10^6$	11–12	11	13	11,3–13
Electrical resistance (20°C)	μΩ·m	0,5–1,0	0,7	0,8	0,5–0,7
Linear shrinkage	%	1,0–1,2	0,9–1,1	0,9–1,1	0,7–1,1
Bulk shrinkage	%	1,0–3,0	1,0–5,0	1–5	7–10

EXAMPLES OF THE APPLICATION OF CAST IRON WITH VERMICULAR GRAPHIT IN INDUSTRY INCLUDING CASTINGS FOR AGRICULTURE

The main directions in the industrial application of cast iron with vermicular graphite are as follows:

a) replacing grey cast iron and reducing casting weight through reduced cast wall cross-sections,

b) replacing alloyed grey cast iron with vermicular graphite cast iron,
c) large-lot production of different thin-walled castings characterised by properties corresponding to ductile iron of medium grade,
d) castings for operation under cyclic temperature changes, subjected to the effect of mechanical stresses.

Cast iron with vermicular graphite has found application for, among others, the following elements:

- castings for the automotive industry: heads, exhaust manifolds, brake discs, brake shoes, crankcases, connecting cables for tractors, hand brake levers [12, 13, 15, 22, 26, 27];
- castings for the shipbuilding industry: heads, covers, and cylinders for diesel engines [12, 13];
- parts of pressure fittings, such as valves, valve bodies, pipes for power hydraulics [26], and distribution systems of different weight for the high-pressure hydraulics [23];
- castings of machine parts: bearing housings, flywheels, gear housings, chain wheels [13];
- castings for the steel industry;
- castings for the automotive and agricultural industries: exhaust manifolds, brake discs, brake shoes, crankcases, connecting cables for tractors [13].

SCOPE AND PURPOSE OF RESEARCH

The aim of the studies was to demonstrate the advantages offered by the cast iron with vermicular graphite, especially as regards its mechanical properties and resistance to thermal fatigue, and possible use of this material for different structural components. The paper gives only a general outline of the research, since in the course of the executed project, an in-depth assessment of the cast materials to know their thermal fatigue behaviour and compare the properties will be possible no sooner than when the special devices for studies of this type are available. Taking the exhaust manifold casting as an example, numerical computations were made for the selected chemical composition of grey and vermicular graphite cast irons.

COMPARATIVE STUDIES OF GREY AND VERMICULAR GRAPHITE CAST IRONS

Cast iron was melted in a Radyne type medium frequency induction furnace in a crucible of 80 kg capacity (basic lining). Cast iron melts were prepared with additions of alloying elements (Mo, Cu, V, Sn, Sb), bearing in mind the fact that these elements affect the mechanical and performance properties of the cast material. Cast iron was poured into bentonite sand moulds in the form of 25 mm thick ingots. For comparative tests, ingots were cast from grey iron (melt no. 5/5882w - Tables 2 and 3) and from vermicular graphite iron (melt nos.: 031, 0.38, 6007). Both cast iron grades had a pearlitic structure.

Studies of the cast iron included:

- analysis of chemical composition,
- observations under the microscope (graphite precipitates, metal matrix structure),
- mechanical properties (R_m, A_5, HB),
- thermal fatigue behaviour,
- numerical computations of selected chemical composition of the grey and vermicular graphite cast irons used for casting of the exhaust manifold.

TESTS AND RESEARCH

The melting process was monitored and samples were taken for spectrographic studies of the chemical composition. The results of the chemical analysis are compiled in Table 2.

Table. 2. Chemical analysis compared for low-alloyed grey cast iron and cast iron after the vermicularising treatment

No.	Melt symbol	Chemical analysis of cast iron, wt.%										
		C	Si	Mn	P	S	Mg	Mo	Cu	V	Sn	**Sb**
1	5/5882w	3,7	1,70	0,23	0,025	0,020	-	0,25	0,34	0,07	0,26	0,031
2	031	3,60	2,35	0,38	0,045	0,015	0,010	0,25	0,33	0,09	0,045	0,031
3	038	3,70	2,30	0,40	0,055	0,020	0,015	0,47	-	0,27	-	0,05
4	6007	3,70	2,30	0,40	0,055	0,020	0,025	0,23	0,35	0,10	0,035	0,031

Note: melt 5/5882w – low-alloyed grey cast iron; melts: 031, 038, 6007 – vermicular graphite cast iron.

After casting of test ingots, specimens for mechanical tests were prepared. Figure 3 shows a specimen for mechanical tests.

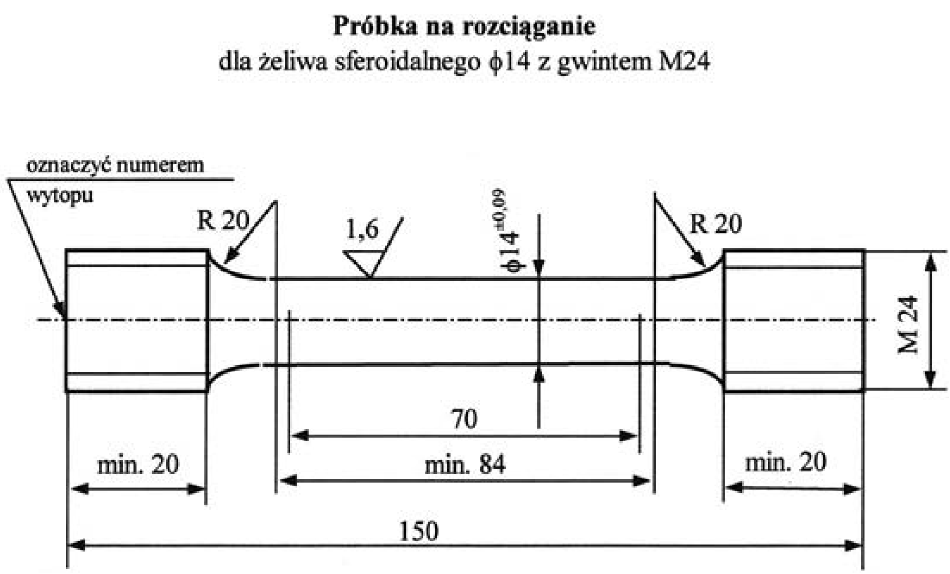

Fig. 3. Specimen for mechanical tests

After fracture of the specimens, the structural examinations of the cast material were carried out. Examples of structures obtained in low-alloyed grey cast iron and in vermicular graphite cast iron are shown in Figures 4 and 5.

Fig. 4. An example of the structure of the tested grey cast iron

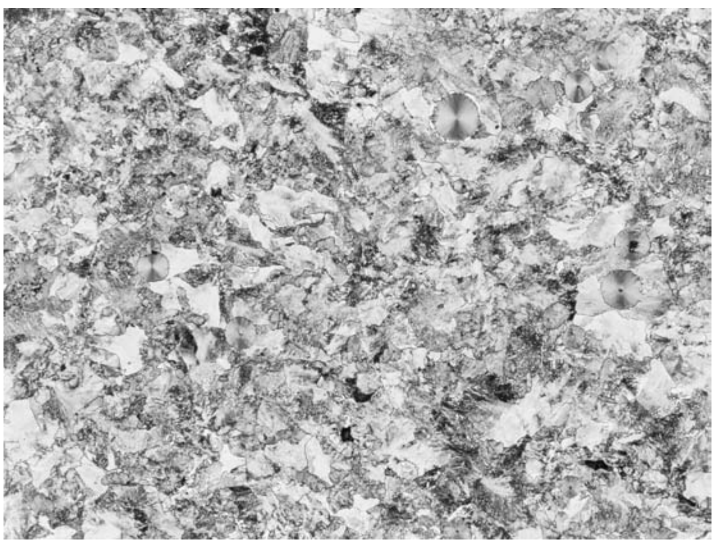

Fig. 5. An example of the structure of the tested vermicular graphite cast iron

The results of the mechanical and thermal fatigue tests of the investigated cast iron are compared in Table 3.

Table 3. The results of the mechanical and thermal fatigue tests of the investigated cast iron

No.	Symbol	Results of me-chanical and thermal fatigue tests	Thermal fatigue				
		Tensile strength	Elastic limit	Yield point	Elongation	Hard-ness	Number of cycles, number of fractures
		R_m MPa	$R_{0,2}$ MPa	$R_{0,02}$ MPa	A_5 %	HB	Temperature, °C
							600
1	5/5882w	394	0	-	0	236	60(3p)
2	031	539	413	287	2,57	184	140(1p) 160(2p)
3	038	427	332	202	3,21	268	180(1p) 340(2p)
4	6007	734	522	-	8,1	285	235

Note: sample designation 5/5882 – grey cast iron

The thermal fatigue behaviour of low-alloyed grey cast iron and of the cast iron with vermicular graphite was tested on samples of own design, using a special-purpose device operating automatically in a preset cycle of heating the samples up to a temperature of 600°C and cooling in water at room temperature. The sample is shown in Figure 6, and the device for thermal fatigue testing is shown in Figure 7.

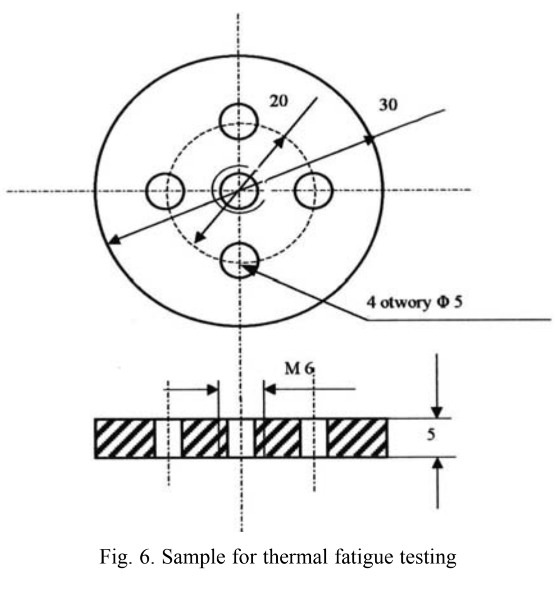

Fig. 6. Sample for thermal fatigue testing

Fig. 7. The device for thermal fatigue testing of metals

Numerical calculations were also performed for the specified chemical composition of cast iron with flake and vermicular graphite, taking as an example the casting of an exhaust manifold. All tests were conducted in accordance with current standards:

- determination of cast iron microstructure: PN-75/H-04661,
- characterisation of graphite precipitates in cast iron: PN-EN ISO 945,
- tensile testing of metallic materials: PN-EN ISO 6892-1,
- Brinell hardness test: PN-EN ISO 6506-1.

NUMERICAL CALCULATIONS PERFORMED FOR THE SPECIFED CHEMICAL COMPOSITION OF CAST IRON WITH FLAKE AND VERMICULAR GRAPHITE SHOWN ON THE EXAMPLE OF A CAST EXHAUST MANIFOLD

The numerical analysis was performed for castings made from the grey and vermicular graphite irons. The potentials offered by MAGMAIron programme were used; the programme allows predicting the final properties of castings basing on the preset boundary parameters. The MAGMAIron module uses a kinetic model of the growth and formation of microstructure, which allows taking into account the local properties of alloy, including thermo-physical changes, especially at the solidification front boundary, as a result of the segregation of elements. The following factors have also been taken into consideration: alloy composition, modification technique, phase transformations in the solid state, the effect of silicon content on the segregation of elements, as well as the impact of major alloying elements on the solidification mode.

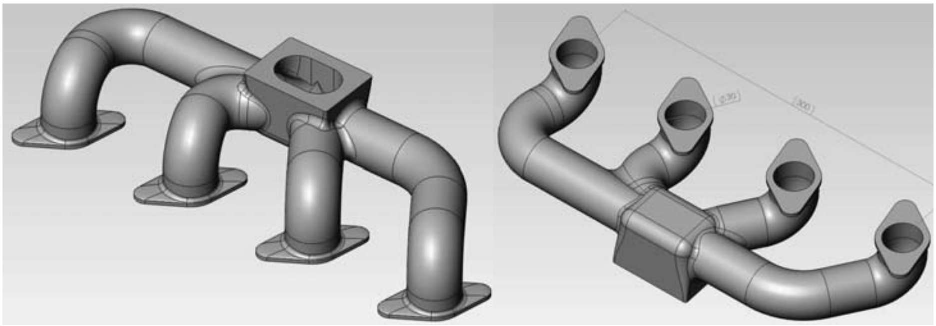

Fig. 8. Drawing of the examined exhaust manifold

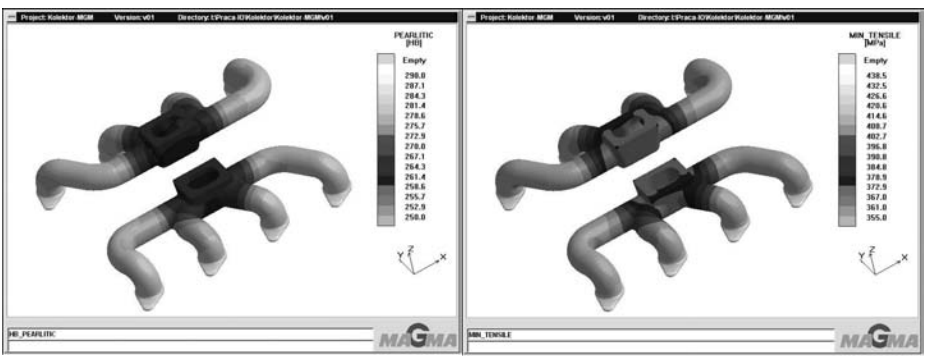

Fig. 9. The distribution of hardness and strength values in grey iron casting

Numerical calculations of the casting process of the exhaust manifold aimed at a determination of the characteristic final properties of the casting allowing for the cast material type (grey cast iron, vermicular graphite cast iron). The form and shape of graphite in the vermicular graphite cast iron determines its final properties. A ramified graphite structure free from the sharp edges increases the strength of the casting matrix. The final properties of iron castings to a large extent depend on the solidification rate. In the case of cast exhaust manifold, thin walls of 4 mm thickness prevail. This part of the grey iron casting has the final strength of about 415 MPa, while casting made of the vermicular graphite iron is capable of reaching in the same place the strength of 800 MPa. Only the area of the exhaust gas take off from the collector, which forms a hot spot, solidifies for a time much longer. Therefore, properties in this area are lower, compared to the area of thin-wall tube and the strength amounts to 370 MPa and 680 MPa for the grey and vermicular graphite cast irons, respectively.

The performed numerical analysis shows that elements operating under the demanding and periodically changing conditions, when made from the vermicular graphite cast iron can considerably prolong the time of their operation.

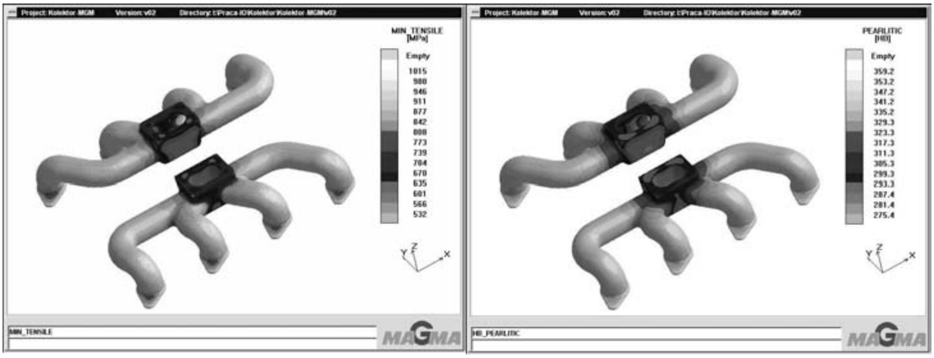

Fig. 10. The distribution of hardness and strength values in vermicular graphite iron casting

RESULTS AND DISCUSSION

Studies of the mechanical properties of low-alloy pearlitic grey cast iron and vermicular graphite cast iron showed the definitely superior properties of the vermicular graphite cast iron. Very high values of the tensile strength (539–734 MPa), elongation A_5 (2,57–8,1), and Brinell hardness (approximately 184–285 HB) were obtained in the cast iron with vermicular graphite. Higher elongation in one set of samples may be due to higher spheroidal graphite content in the structure of cast iron. Low-alloyed cast iron with pearlitic structure and lamellar graphite has the strength of about 394 MPa and a hardness of about 236 HB; the samples showed no elongation.

The microstructure of samples taken from the test ingots showed the pearlitic type cast iron (the amount of pearlite P, P98, P92) with over 70% of vermicular graphite (samples 031, 038 and 6007).

The thermal fatigue tests carried out at a temperature of 600°C confirmed longer life of samples made from the cast iron with vermicular graphite, compared to the cast iron with flake graphite (the number of heating-cooling cycles until the appearance of the first two cracks was 160 to 340 for the vermicular graphite cast iron and about 60 for the three cracks in grey cast iron.

The results provide clear evidence that, compared to grey cast iron, the vermicular graphite cast iron is a material of higher performance characteristics and as such can be successfully used for elements of machines and equipment, including items operating in the agricultural industry.

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This work was supported by Structural Funds operating under the Operational Programme Innovative Economy for the years 2007–2013, Measure 1.3.

ZAGADNIENIE TRWAŁOŚCI ELEMENTÓW KONSTRUKCYJNYCH PRACUJĄCYCH W WARUNKACH ZMĘCZENIA CIEPLNEGO

Streszczenie. W artykule przedstawiono ogólne dane na temat niedocenianego w kraju żeliwa z grafitem wermikularnym, które z powodzeniem nadaje się na odlewy elementów maszyn i urządzeń, szczególnie pracujących w warunkach zmęczenia cieplnego. Ponieważ żeliwo to ma lepsze właściwości od żeliwa szarego może być zamiennie wykorzystane do produkcji różnych elementów w przemyśle motoryzacyjnym i budowy maszyn dla rolnictwa. Oprócz danych literaturowych przedstawiono zarys badań porównawczych wykonanych w Instytucie Odlewnictwa w zakresie badań mechanicznych, zmęczenia cieplnego i symulacyjnych dla żeliwa z grafitem płatkowym i wermikularnym. Prace są w dalszym ciągu kontynuowane w ramach prowadzonego projektu POIG.01.03.01-12-061/08-00. Rozwijana obecnie technologia dotyczy żeliwa wysokojakościowego sferoidalnego i wermikularnego bez dodatków i z dodatkiem pierwiastków stopowych, szczególnie odpornego na zmęczenie cieplne. Przedstawione w artykule zagadnienia właściwości materiału konstrukcyjnego jakim jest żeliwo z grafitem wermikularnym i przykłady zastosowania tego tworzywa powinny wzbudzić zainteresowanie konstruktorów do wykorzystania tego tworzywa również na różne elementy maszyn rolniczych, powodując zwiększenie właściwości wytrzymałościowych odlewnych elementów, trwałości a także możliwości obniżenia grubości ścianek odlewów, a tym samym zmniejszenia ich masy i obniżenia kosztów produkcji.

Słowa kluczowe: żeliwo sferoidalne, żeliwo z grafitem płatkowym, żeliwo z grafitem wermikularnym, odlewy dla rolnictwa, symulacja komputerowa, właściwości mechaniczne, zmęczenie cieplne.